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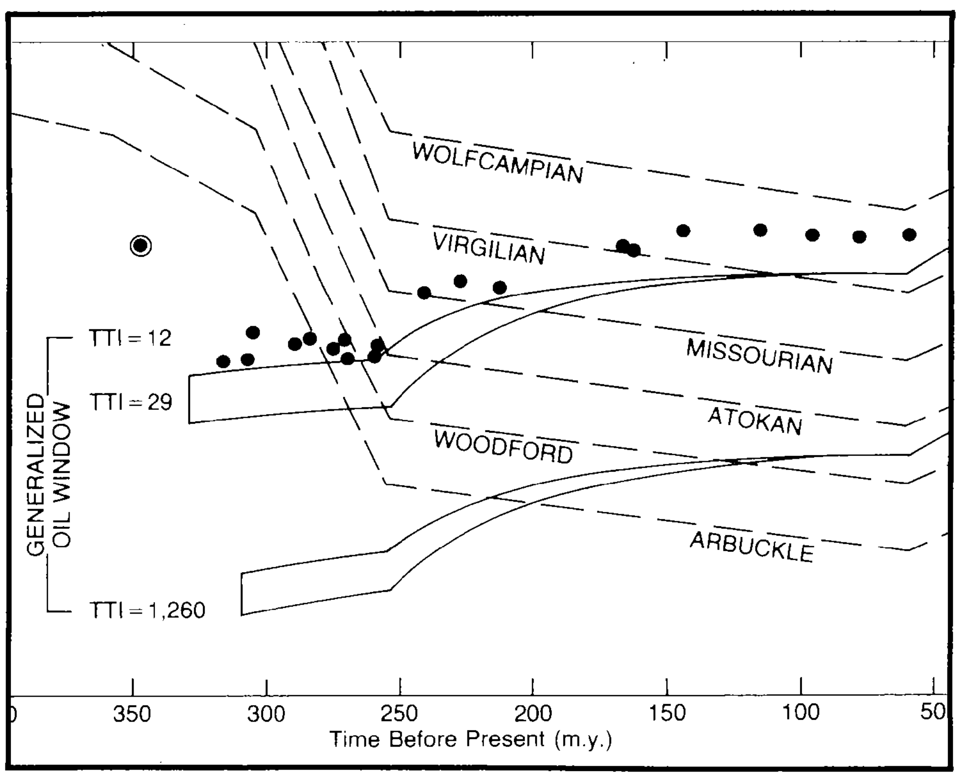

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OIL GENERATION IN THE ANADARKO BASIN, OKLAHOMA AND TEXAS: MODELING USING LOPATIN'S METHOD

James W. Schmoker

U.S. Geological Survey
Denver, Colorado

Statement of Cooperation

This report has been prepared for the U.S. Geological Survey's Evolution of Sedimentary Basins Program, and represents work done as part of a cooperative effort with the Oklahoma Geological Survey to study the Anadarko basin and its petroleum occurrences.

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James W. Schmoker

ABSTRACT

Lopatin's time-temperature index (TTI) of thermal maturity is calculated from Paleozoic time to the present for representative strata at five widely separated areas in the central Anadarko basin of Oklahoma and Texas. Present-day thermal maturity can be estimated from depth of burial ($\underline{Z}$ in ft) throughout the study area, using the equation

$$TTI = 1.38e^{\underline{Z}/1,970}.$$

The correlation between TTI and depth for the Anadarko basin progressively deteriorates for ages >150 m.y., as age of deposition and early burial history exert relatively more control upon thermal maturation.

TTI is calibrated to published vitrinite-reflectance ($\underline{R}_0$) measurements by the equation

$$TTI = 351.8\underline{R}_0^{4.86}.$$

The onset of the oil window ($\underline{R}_0$ = 0.5-0.6%) corresponds to TTI = 12-29, and the transition to wet-gas generation ($\underline{R}_0$ = 1.3%) corresponds to TTI = 1,260. For a given $\underline{R}_0$, this calibration for the Anadarko basin gives a TTI value somewhat higher than that of Waples's (1980) generic calibration, which is based on many, diverse samples.

TTI computations are used to estimate the evolution of the oil window in the central Anadarko basin through time. The oil window migrates upward ~7,500 ft (~2,300 m) relative to the surface between Pennsylvanian time and the present and is subdivided into three distinct segments by major shifts in basin tectonic patterns. Oil possibly was generated as long as 350 m.y. ago in the deepest parts of the southern Oklahoma aulacogen, and significant volumes of sediment entered the zone of oil generation during the Pennsylvanian and Permian. Hydrocarbons have been generated in the Anadarko basin for >300 m.y., in an unusually long and continuous history that has contributed to the high oil and gas productivity of this Paleozoic province.

INTRODUCTION

Modeling of Thermal Maturity

Laboratory measurements of thermal maturity are widely accepted as indicators of the status of hydrocarbon generation in sedimentary sequences. However, a substantial difference exists between a set of analytical measurements and a predictive thermal-maturity model by which one can project beyond available data and trace maturity evolution into the past.

A number of models have been put forward for estimating thermal maturity at points in the sedimentary section and in time where direct measurements are not available. Lopatin's model, as described and evaluated by Waples (1980), is used here. Lopatin's approach has a conceptual elegance and computational simplicity commensurate with practical, applied ideas of kerogen maturation. Its utility is demonstrated by a number of recent applications (e.g., Cercone, 1984; Furlong and Edman, 1984; Edman and Surdam, 1984; Ejedawe and others, 1984; Moshier and Waples, 1985; Nwachukwu, 1985; Hatch and Morey, 1985; Baird, 1986).

Lopatin's time-temperature index of thermal maturity (TTI) is based on the idea that hydrocarbon generation depends on both the temperature and the duration of heating. The maturity accumulated by a given rock unit over a period of time t_1 to t_2 is summed according to the equation

$$TTI = \sum_{i=t_1}^{t_2} 2^{[(T_i/10) - 10.5]}, \qquad (1)$$

where time is measured in million-year increments and T_i is the formation temperature (°C) during the ith time increment. For easier manual calculations, Waples (1980) rounded temperature to the nearest 10°C (T_i = 95, 105, 115, etc.), making the exponent in equation (1) a whole number.

Calculation of TTI according to equation (1) is deceptively straightforward: thermal maturity accumulates linearly with time and doubles with each 10°C rise in temperature. The complexity of TTI computations lies in the definition of thermal and burial histories from which formation temperatures are estimated.

Scope of Work

In the study reported here, present-day TTI values are compared to published vitrinite-reflectance (R_0) data in order to specifically calibrate Lopatin's model for the Anadarko basin of Oklahoma and

Texas. TTI is calculated for Paleozoic time to the present for Lower Ordovician to mid-Permian strata in five areas of the central Anadarko basin (Fig. 1). Estimated depths of the oil window are plotted as a function of geologic time. Implications as to past geothermal gradient, the fundamental relation between time-temperature history and $\underline{R}_0$, and hydrocarbon generation relative to basin subsidence are addressed.

REGIONAL THERMAL AND BURIAL HISTORIES

Formation temperatures used to compute TTI (equation 1) are derived from geothermal-gradient, surface-temperature, and burial-depth histories. Because indicators of past geothermal gradients and surface temperatures are relatively subjective compared to the sedimentary strata that document burial history, thermal inputs to TTI modeling are more speculative than depth inputs.

Geothermal Gradient

The geothermal-gradient history shown in Figure 2 is assumed to be representative of the study region as a whole (Fig. 1). Although this assumption is almost certainly an oversimplification, ancient thermal variations on a more local scale are much easier to propose than to establish.

The thermal gradient associated with the early Paleozoic southern Oklahoma aulacogen--of which the present-day Anadarko basin occupies a part--is derived from theoretical calculations of Feinstein (1981, fig. 10). His model shows a heat pulse due to Cambrian rifting that decays over a 100-m.y. period to a regional gradient that is equated here to

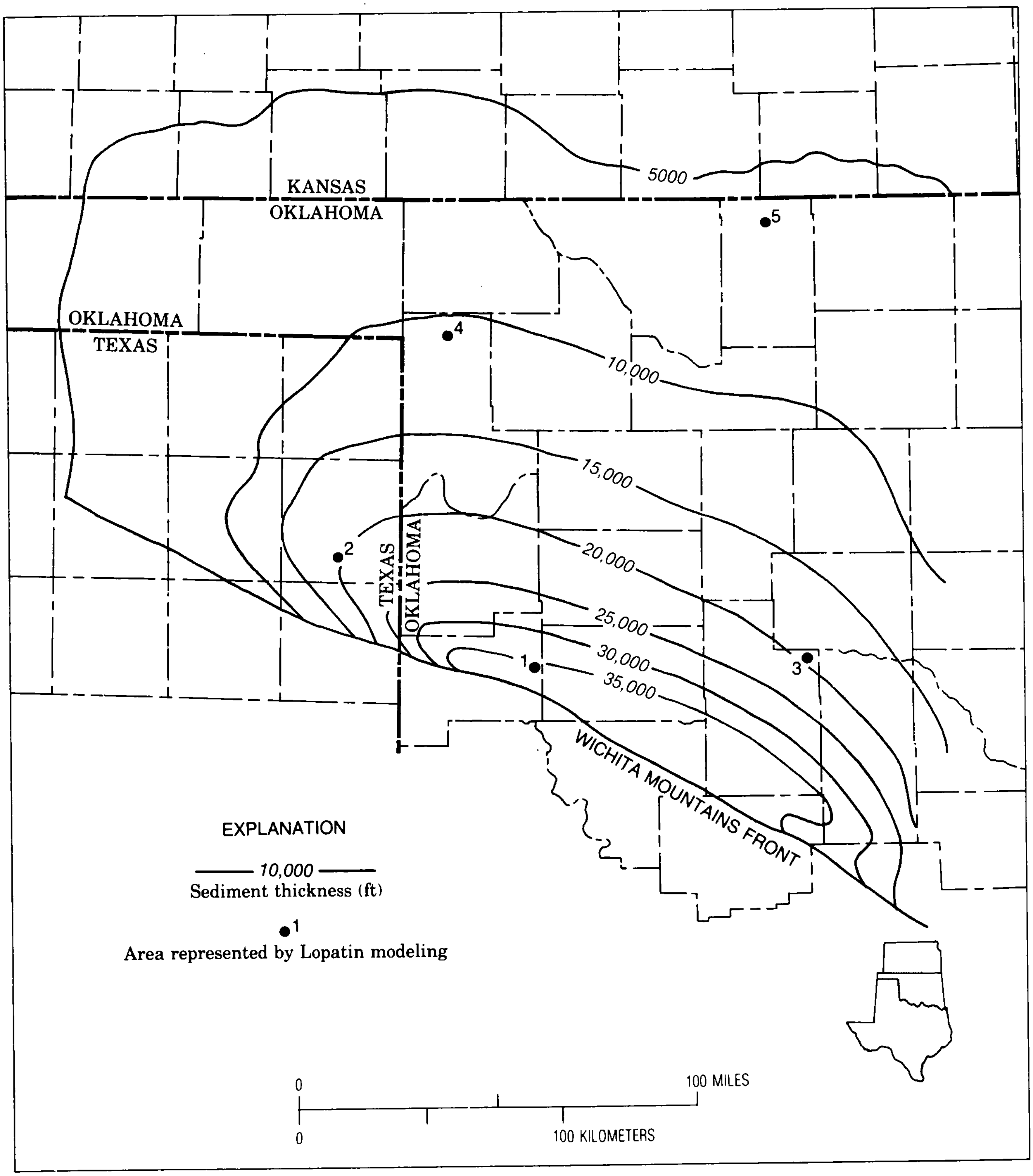

Figure 1. Sediment thickness in the Anadarko basin, and areas represented by Lopatin modeling: (1) Deep-basin area of Beckham and western Washita Counties, Oklahoma; depth to organic-rich Devonian-Mississippian Woodford Shale ~28,000 ft (~8,500 m). (2) Hemphill and Wheeler Counties, Texas; depth to Woodford ~19,500 ft (~5,900 m). (3) Caddo, Canadian, and Grady Counties, Oklahoma; depth to Woodford ~14,000 ft (~4,300 m). (4) Ellis and Harper Counties, Oklahoma; depth to Woodford ~9,000 ft (~2,700 m). (5) Shelf area of Alfalfa County, Oklahoma; depth to Woodford ~5,000 ft (~1,500 m).

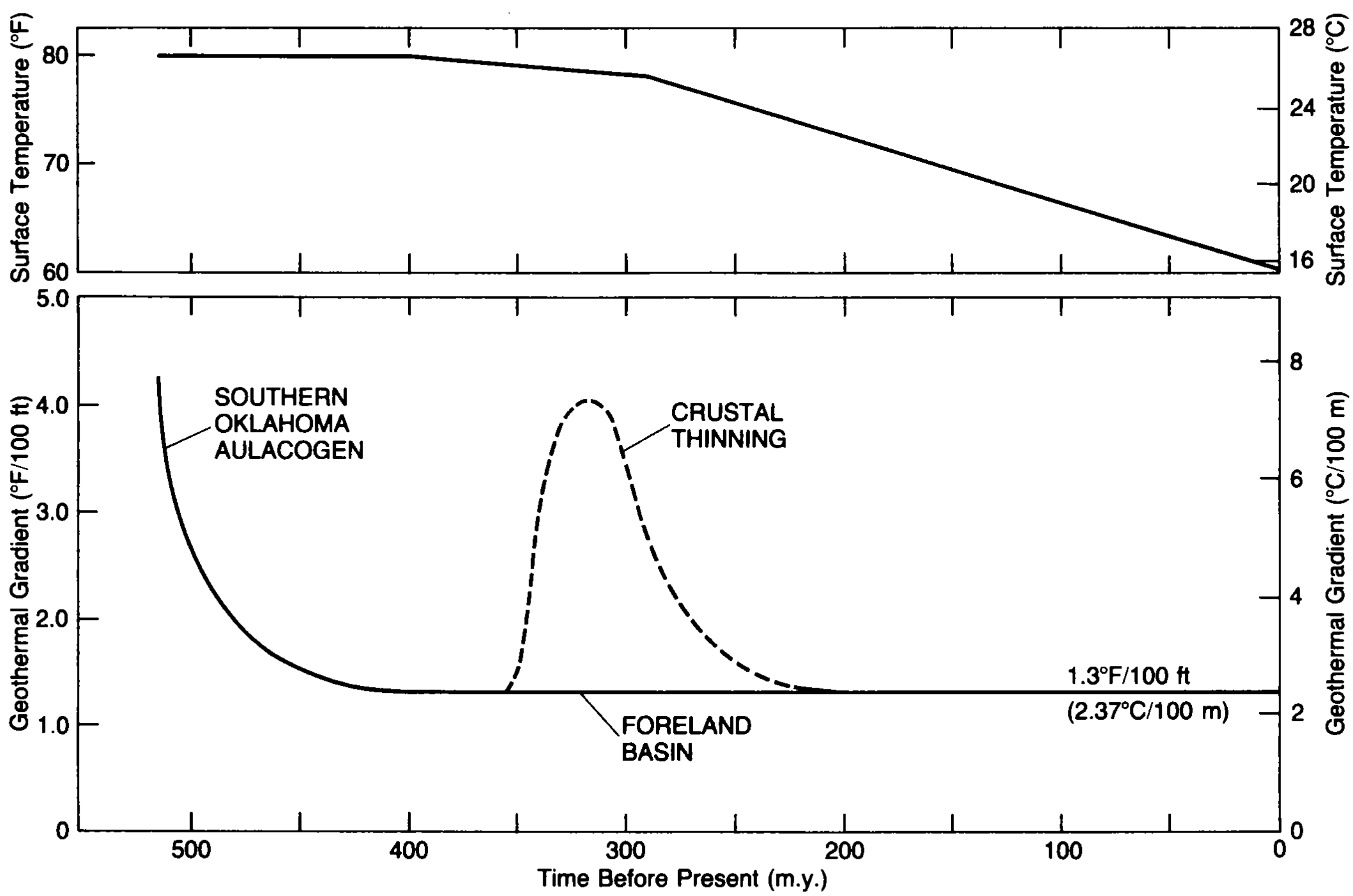

Figure 2. Surface-temperature and geothermal-gradient histories for Lopatin modeling of the study area in the central Anadarko basin. The foreland-basin model of geothermal gradient (solid line) is used in the final TTI calculations.

the present regional gradient of 1.3°F/100 ft (2.37°C/100 m) (Harrison and others, 1983; Luza and others, 1984).

Two interpretations are shown (Fig. 2) for the second major period of subsidence that shaped the present-day basin, during which thick Pennsylvanian and Permian sediments accumulated. The solid line, with no elevated geothermal gradient, reflects a foreland basin dominated by vertical lithospheric flexure (e.g., Webster, 1977; Brewer and others, 1983; Gilbert, 1983). Mathematical models predict a time-invariant heat flow in such basins (Beaumont and others, 1985).

The dashed line, showing the geothermal gradient rising relatively rapidly and then decaying to present levels, reflects a heat pulse associated with crustal extension and thinning. The elevated gradient is based on heat-flow calculations by Garner and Turcotte (1984, fig. 11) for a rifting event in the Anadarko basin beginning in the Mississippian. For reasons discussed below, the foreland-basin model (Fig. 2, solid line) is favored here and is used in final TTI calculations.

Surface Temperature

Present-day mean surface temperature in western Oklahoma is ~60°F (~16°C). Surface temperatures in the past are uncertain, but shallow-water carbonates and lower paleolatitudes suggest a warmer climate for the Anadarko basin in Paleozoic time. Mean surface temperatures assumed for TTI modeling decline from 80°F (27°C) to 60°F (16°C) from early Paleozoic to present, as shown in Figure 2.

Burial Depth

Figure 3 shows time-depth burial histories typical of those constructed for each of five areas in the Anadarko basin (Fig. 1). The oldest horizon modeled, the top of the Upper Cambrian and Lower Ordovician Arbuckle Group, varies in present depth from ~5,700 ft (~1,740 m) at the shelf edge (area 5) to ~33,450 ft (~10,200 m) in the deep basin just north of the Wichita Mountains front (area 1). Four to eight horizons subdividing the Paleozoic section are modeled for each of the five areas.

The burial history of a given horizon is represented by only a few straight-line segments (Fig. 3). Additional detail would be inconsistent with other uncertainties of thermal-history reconstructions. Also, because of the exponential temperature dependence of equation 1, TTI calculations are little affected by details of the burial curve at relatively shallow depths.

From early Paleozoic to present, the burial curves of Figure 3 (and also those representing the four other areas) reflect moderate subsidence during the latter history of the southern Oklahoma aulacogen, rapid subsidence associated with formation of the Anadarko basin, a long period of quiescence and slow sediment accumulation, and uplift and erosion in the Tertiary.

Tertiary erosion of ~1,000-4,000 ft (~300-1,200 m) is suggested by stratigraphic considerations, the projection of $\underline{R}_0$-depth plots to $\underline{R}_0$ = 0.2% (Cardott and Lambert, 1985; data of fig. 6), and reconstructions by Waples (1982) and Dutton and Land (1985, fig. 13). Erosion of 2,600 ft (790 m), a value supported by the consistent $\underline{R}_0$-depth data of Cardott and Lambert (1985), is assumed here for the study area.

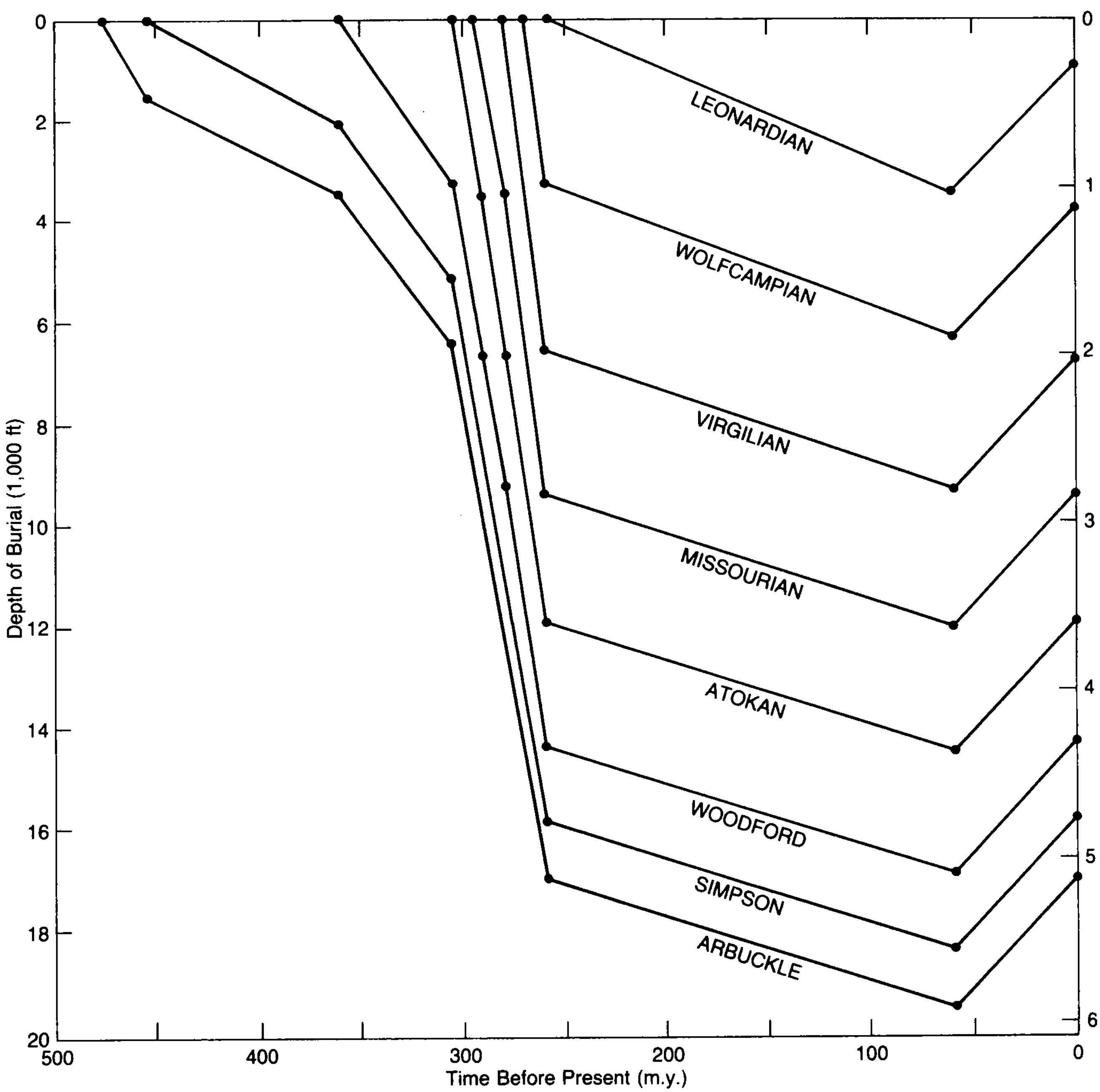

Figure 3. "Decompacted" burial curves for the Paleozoic section in the area of Caddo, Canadian, and Grady Counties (Fig. 1, area 3). General features of the curves are typical of the study region as a whole. Data sources for burial histories are listed in Table 1.

Decompaction

Because sedimentary rocks tend to lose porosity during burial, in a process that does not reverse itself upon uplift, the thickness of a given rock unit decreases from time of deposition to the present. To correct for this effect, burial histories for the study area (e.g., Fig. 3) are "decompacted" from present-day thicknesses according to the assumption that the height of solid material in a given stratigraphic unit remains constant through time (Perrier and Quiblier, 1974). That is

$$\text{(unit thickness) (1 - porosity) = constant.} \qquad (2)$$

The porosity function somewhat arbitrarily assumed here is

$$\phi = 0.35e^{-\underline{Z}/7{,}500}, \qquad (3)$$

where ϕ is fractional porosity and $\underline{Z}$ is depth in feet.

In theory, the sedimentary column should be decompacted using small thickness and depth increments to approximate a closed-form solution of equation 2. However, in practice uncertainties associated with the porosity function and the time-depth reconstruction are such that detailed numerical evaluation is not warranted, and thickness changes during burial can be adequately estimated from equation 2 using rather large thickness and depth increments and a hand-held calculator.

Assuming shallow-water sedimentation, so that calculated thickening of rock units cannot be accommodated upward, decompaction tends to increase estimates of burial depths (Fig. 3), and therefore always acts to increase calculated thermal maturity. For the Anadarko basin, TTI values are increased by as much as 20% by decompaction of the sedimentary column. The influence of decompaction on TTI is thus measurable and could affect the calibration between TTI and $\underline{R}_0$ (Waples, 1984). However, on the logarithmic plots generally used to display thermal maturity, a shift of 20% amounts to fine tuning and usually would not change fundamental interpretations.

Formation Temperature

A formation-temperature history (Fig. 4) with features characteristic of the study region shows that estimates of paleotemperatures depend significantly on the tectonic style assumed to have caused late Paleozoic subsidence. A foreland-basin model implies maximum formation temperatures in the early Tertiary, but with near-maximum temperatures as early as 250 m.y. ago. By comparison, a crustal-thinning model implies earlier development of maximum formation temperatures and a sustained period of higher temperatures in the Paleozoic. In either case, details of formation-temperature history in the Mesozoic and Tertiary are difficult to quantify, because of the long hiatus in the sedimentary record.

A crustal-thinning event for the Anadarko basin (distinct from that which formed the southern Oklahoma aulacogen) has been proposed by Garner and Turcotte (1984), and a thermal anomaly in the deep Anadarko basin reported by Cardott and Lambert (1985) could be interpreted as supporting evidence. However, both sets of authors assume that any crustal extension and thinning in the latter half of the Paleozoic was not extensively developed, and therefore produced only a locally elevated heat flow atypical of the study region as a whole. Considered regionally, geologic evidence for a foreland-basin model

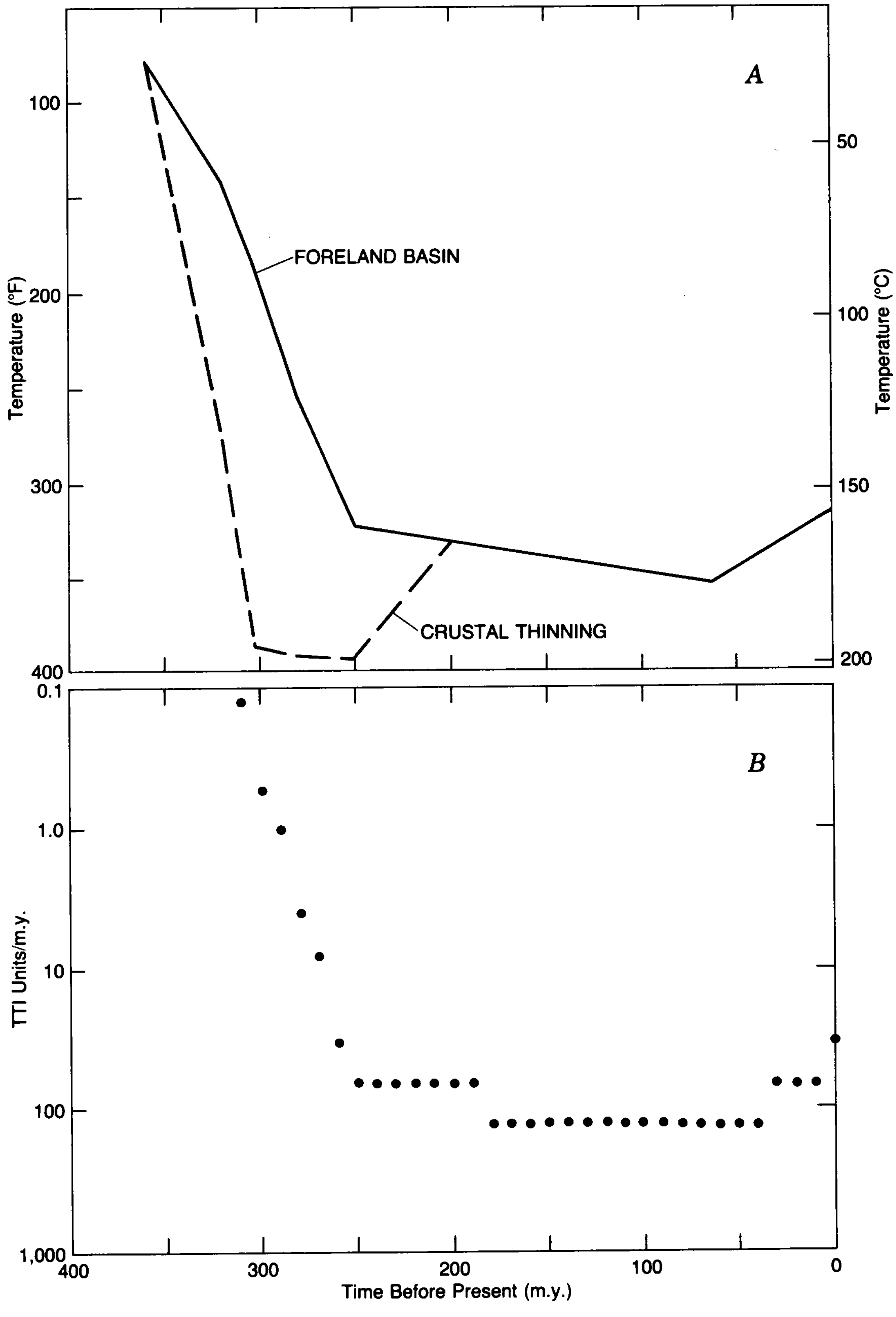

Figure 4. A, formation-temperature reconstructions derived from surface-temperature, geothermal-gradient, and burial-depth histories for the Devonian-Mississippian Woodford Shale in the area of Hemphill and Wheeler Counties, Texas (Fig. 1, area 2). General features of the curves are typical of the study region as a whole. B, accumulation of TTI units per 1-m.y. interval, calculated using the foreland-basin model for geothermal gradient (note logarithmic scale). Stair-step appearance results from rounding formation temperatures to 10°C intervals (see Introduction).

seems well founded (Webster, 1977; Brewer and others, 1983; Gilbert, 1983), and figure 8 shows that there is no requirement for a time-temperature history "hotter" than that of the foreland basin. For these three reasons, the geothermal gradient representative of a foreland basin (Fig. 2) is used here in final regional TTI calculations.

Rates of thermal maturation relative to formation temperatures are illustrated in Figure 4 by a semi-logarithmic plot of TTI accumulation per 1-m.y. interval. This graphical representation of equation 1 demonstrates that thermal maturity is strongly controlled by those parts of the burial curve associated with near-maximum temperatures.

TTI-$\underline{R}_0$-DEPTH CALIBRATIONS

TTI Versus Present Depth

Present-day TTI values calculated for the Paleozoic section in five widely separated areas in the central Anadarko basin (Fig. 1) span seven orders of magnitude. Over this large range, the semi-logarithmic graph of TTI versus present depth (Fig. 5) describes a straight line, with very little data scatter, represented by the regression equation

$$TTI = 1.38e^{\underline{Z}/1,970}, \qquad (4)$$

where $\underline{Z}$ is depth in feet. The internal consistency of these data (Fig. 5) is good evidence that additional Lopatin modeling at closer geographic spacing is not necessary for regional representation of the central Anadarko basin.

The relation between TTI and present depth is remarkably straightforward. Using equation 4, thermal maturity in terms of TTI can be estimated from depth of burial throughout the study area.

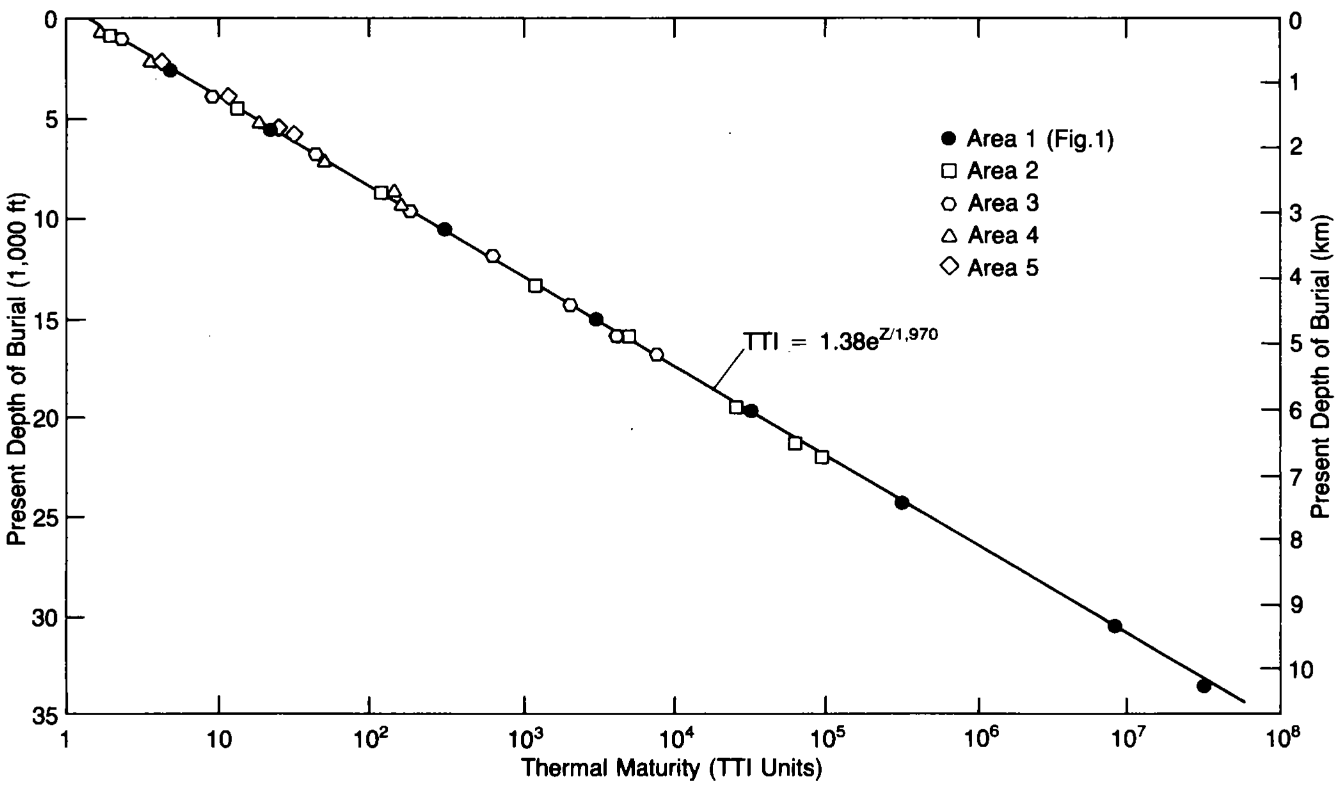

Figure 5. TTI values for the study region in the central Anadarko basin versus present depth of burial. TTI can be predicted from burial depth, $\underline{Z}$ (ft).

The good correlation between TTI and depth is somewhat unexpected, in that TTI is determined by summing over time (equation 1), whereas depth reflects only the present. However, in terms of present-day thermal maturity, each stratigraphic horizon is essentially the "same age" (~250 m.y.), because most TTI units accumulate in post-Permian time (Fig. 4), after the development of present-day basin structure. Present depth is a proportional measure of the time-temperature history of this 250-m.y. period, and therefore correlates well with TTI.

R_0 Versus Present Depth

A linear semi-logarithmic relation between R_0 and present depth analogous to that between TTI and present depth (Fig. 5) would independently corroborate some of the assumptions used in the Lopatin modeling of this study. Such a relation does in fact hold for the Woodford Shale (Cardott and Lambert, 1985, fig. 5), as well as for R_0 measurements more broadly representative of the central Anadarko basin (Fig. 6).

Figure 6 combines vitrinite-reflectance profiles of two deep wells--the Lone Star Producing Co. 1 Bertha Rogers (27-10N-19W) and the Shell Oil Co. 5 Rumberger (16-10N-21W)--with 38 R_0 measurements of the Devonian and Mississippian Woodford Shale and 16 R_0 measurements of the uppermost Morrowan shale. Data are from Price and others (1981), Olson (1982), Katz and others (1982), Tsiris (1983), Jones (1984), Bond (1984) combined with Hood and others (1975), and Cardott and Lambert (1985). R_0 values of Friedman and others (1984,

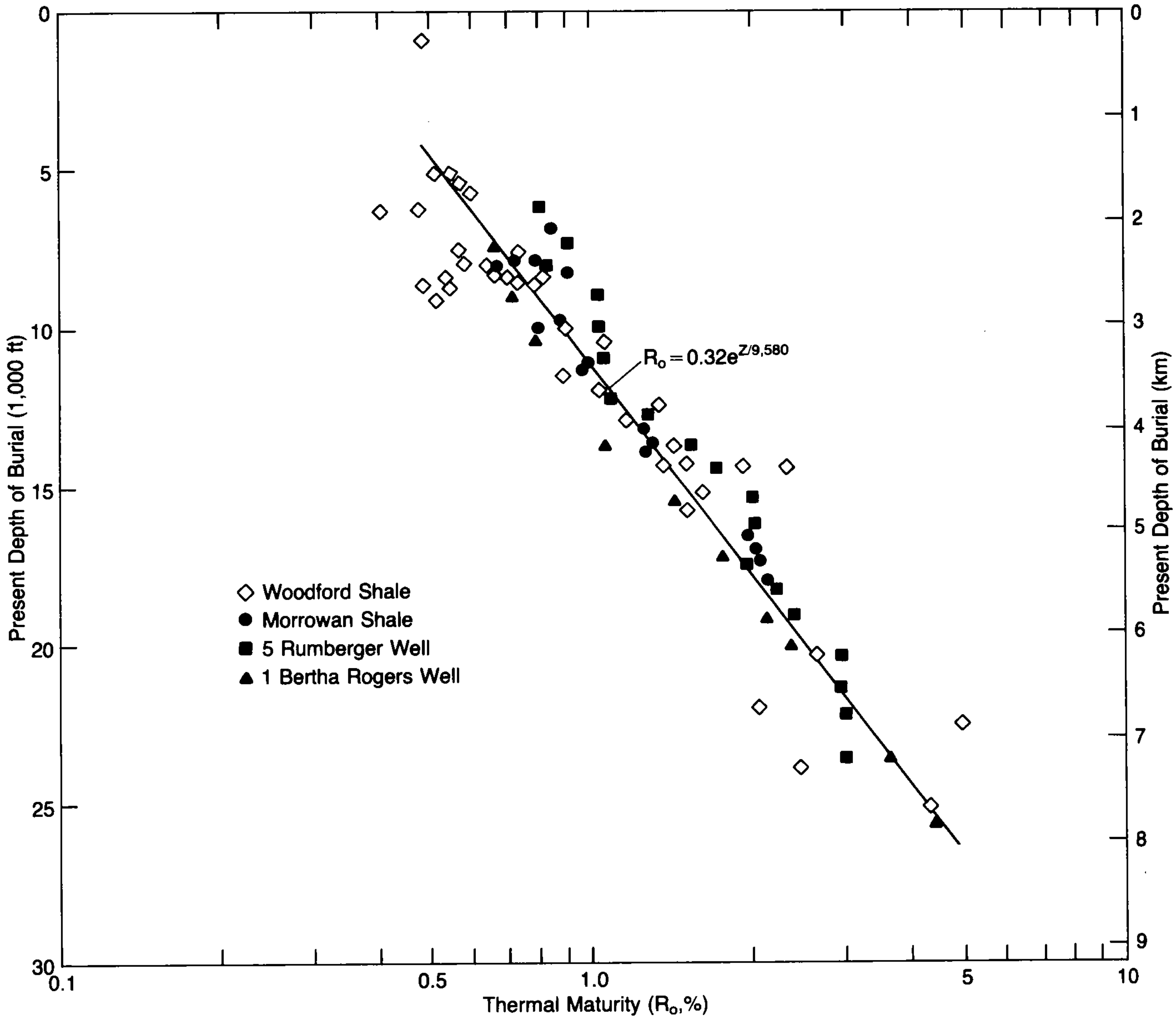

Figure 6. Vitrinite-reflectance values for the study region versus present depth of burial. R_0 can be predicted from burial depth, Z (ft). Data sources are listed in text.

fig. 4) for the Bertha Rogers well are extremely low compared to data from the aforementioned sources, and are not included in Figure 6.

Vitrinite reflectance can be estimated from present depth of burial by the regression equation

$$\underline{R}_0 = 0.32e^{\underline{Z}/9,580}, \quad (5)$$

where $\underline{Z}$ is depth in feet. Data scatter about the regression line (Fig. 6) is probably due to several factors. In addition to random experimental error, there is some suggestion of systematic bias due to differences in laboratory practices or to influences other than thermal maturation, such as suppression of $\underline{R}_0$ in organic-rich rocks. Localized paleogeothermal anomalies are not considered to be a significant factor contributing to the data scatter.

The data defining equation 5 represent an unusually large range of thermal maturities (Fig. 6). At $\underline{R}_0 = 0.4\%$, kerogen usually has not generated hydrocarbons in significant quantities; at $\underline{R}_0 = 5.0\%$, rocks are approaching the greenschist facies of mineral metamorphism. Stages of present-day hydrocarbon generation and preservation as related to $\underline{R}_0$ measurements of the Woodford Shale have been discussed by Cardott and Lambert (1985).

TTI Versus R_0

TTI values are not yet directly linked with chemical processes of hydrocarbon generation, so that calibration to an established empirical indicator of thermal maturity such as $\underline{R}_0$ is necessary. The correlation between TTI and $\underline{R}_0$ used here, derived from equations 4 and 5, graphs as a straight line on logarithmic axes (Fig. 7) and is specifically

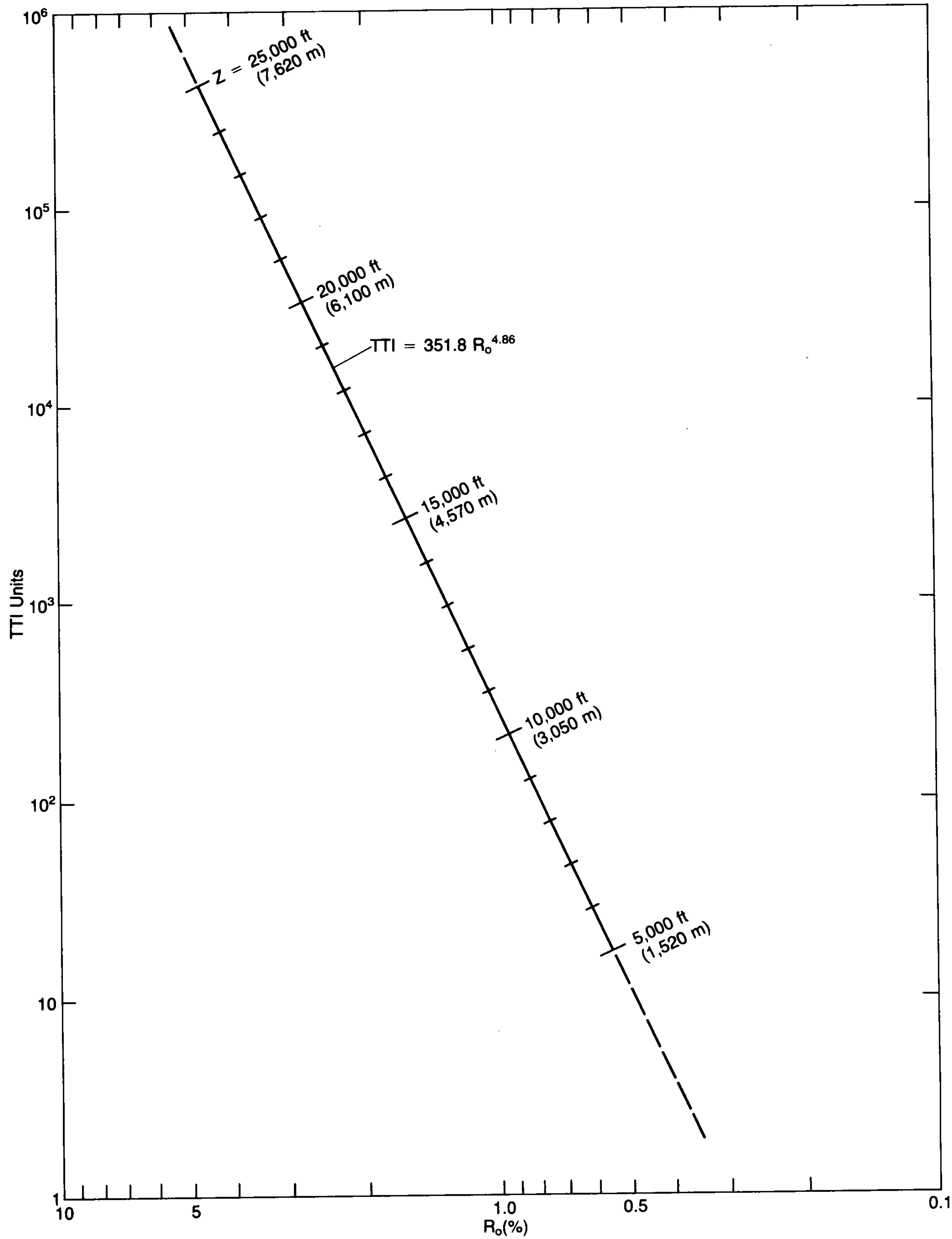

Figure 7. Relations among TTI, vitrinite reflectance, and present depth of burial for the study region in the central Anadarko basin.

developed for the Paleozoic rocks of the study region in the central Anadarko basin

$$TTI = 351.8 \underline{R}_0^{\ 4.86}. \qquad (6)$$

Although TTI and $\underline{R}_0$ can be equated numerically (equation 6), they are not conceptually equivalent. $\underline{R}_0$ is a physical property that can be extended to unsampled areas only by interpolation or extrapolation of existing measurements; TTI is a computed attribute that can be extended to unsampled areas or unsampled time periods by calculations based on fundamental geologic inputs. Neither is a direct indicator of hydrocarbon generation, evolution, or preservation.

Comparison of Calibration Curves

The relation between TTI and $\underline{R}_0$ developed here (equation 6) for the central Anadarko basin is compared in Figure 8 to Waples's generic calibration. The two curves are not in close agreement, although the Anadarko-basin calibration does fall within Waples's (1980, fig. 5) envelope of data points. Adjustment of Waples's calibration for effects of decompaction upon TTI calculations does not significantly reduce the disparity between the two curves.

At a given $\underline{R}_0$, TTI for the Anadarko basin is high relative to Waples's calibration, and becomes slightly higher still if a heat pulse representing crustal thinning in the Carboniferous is introduced (Fig. 8). TTI versus $\underline{R}_0$ data presented by Ritter (1984) show the same pattern, with TTI of Anadarko-basin samples high relative to values from other sites. However, Ritter's results are not entirely

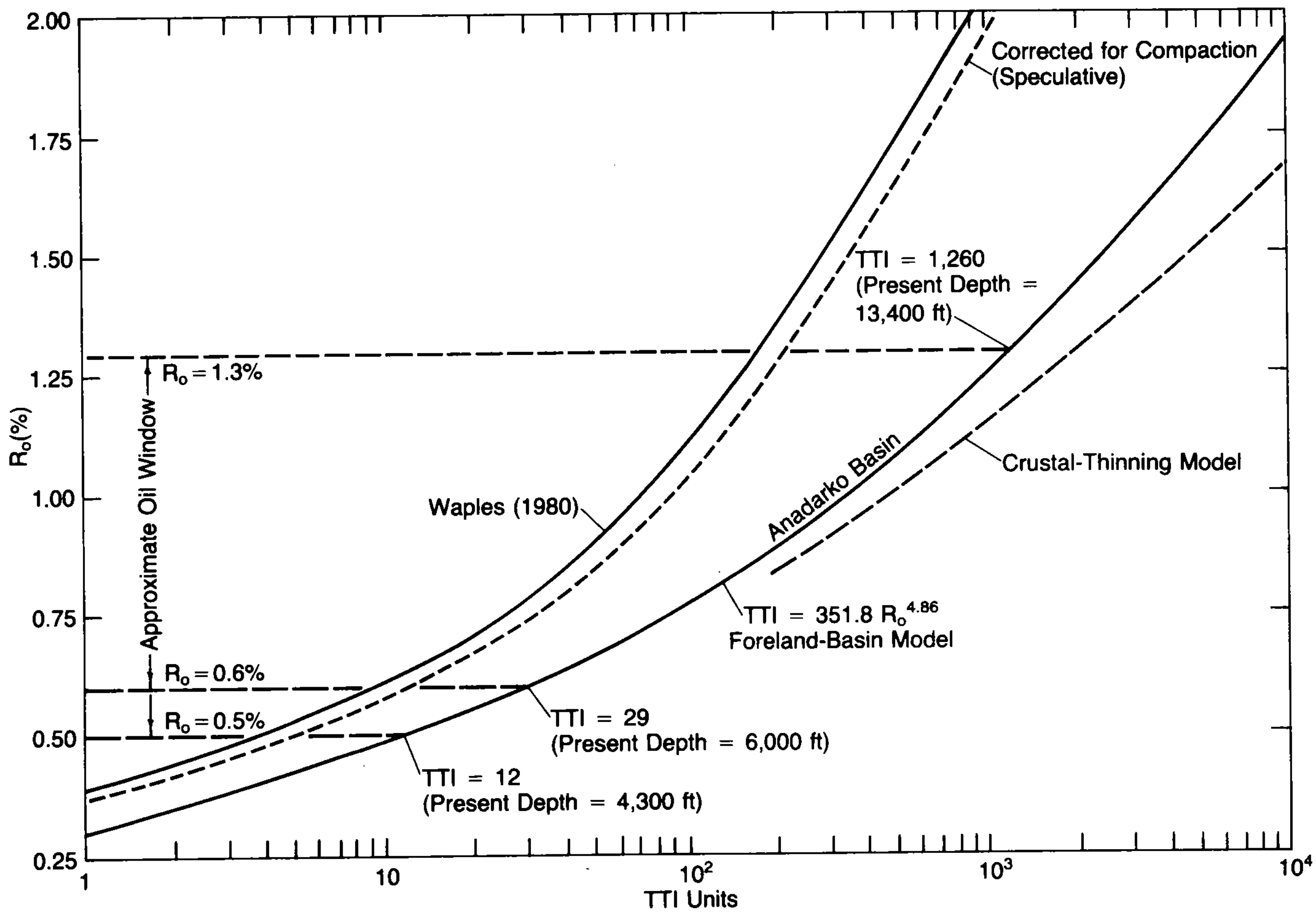

Figure 8. Comparisons of TTI versus $\underline{R}_0$ relations. Curve labeled "Waples (1980)" is the center line of a data envelope representing several hundred worldwide samples of various ages and lithologies; short-dashed curve modifying Waples's generic calibration assumes that decompaction increases TTI by 20% (see Decompaction). Curve defined by equation 6 is derived specifically for the study region in the central Anadarko basin; long-dashed curve indicates effect if thermal gradient representing crustal thinning in Carboniferous is assumed.

independent of those presented here, in that his Anadarko-basin data are those of Hood and others (1975) from the 5 Rumberger well.

The population of $\underline{R}_0$ measurements (Fig. 6) on which the calibration between TTI and $\underline{R}_0$ is based shows considerable scatter and possible systematic differences between classes of data. The $\underline{R}_0$-versus-depth trend used here may be biased toward the low side by inclusion of Woodford Shale data, for example. Conversely, data from the 5 Rumberger well fall on the high side of the general trend. At the present time, there is insufficient justification for editing the $\underline{R}_0$ data population of Figure 6. In the future, refinement of the $\underline{R}_0$-versus-depth trend based on additional data and on fundamental studies of controls upon $\underline{R}_0$ may require adjustment of the TTI-$\underline{R}_0$ calibration curve of this report.

TTI-$\underline{R}_0$ data representing rocks of different ages, lithologies, and tectonic settings show much scatter when grouped together (Waples, 1980; Ritter, 1984). The fundamental relation between TTI and $\underline{R}_0$ may be very complex, and nuances in the TTI-$\underline{R}_0$ calibration would almost certainly be lost in simplifying such data from an envelope to a single line. In consequence, time-temperature reconstructions should not necessarily be adjusted to affirm Waples's generic calibration. As Waples (1984, p. 49) has noted, such facile adjustments are likely to obscure fundamental geologic questions.

Comparison to Bakken Formation of Williston Basin

The upper and lower shale members of the Devonian and Mississippian Bakken Formation in North Dakota and the Woodford Shale of the Anadarko basin are close physical and stratigraphic equivalents, but these source rocks have significantly different time-temperature histories (Fig. 9; Table 1). At a given present-day or maximum temperature, TTI of the Woodford is considerably higher than TTI of the Bakken because the timing of major basin subsidence has placed the Woodford near maximum burial temperature some 200 m.y. earlier. Nevertheless, TTI-$\underline{R}_0$ calibrations of the two formations are very similar, with essentially equal deviations from Waples's generic calibration (Fig. 10). Lopatin modeling of the Bakken Formation (done by the author using decompacted burial histories) thus supports the TTI-$\underline{R}_0$ calibration developed here for the Anadarko basin.

TABLE 1. SOURCES OF DEPTH DATA FOR BURIAL MODELS

Location*	Source	Wells Used
Anadarko basin, area 1	Subsidence diagram by Garner and Turcotte (1984, fig. 10); formation tops below drill estimated from Feinstein (1981)	Lone Star Producing Co. 1 E. R. Baden (28-10N-22W); Lone Star Producing Co. 1 Bertha Rogers (27-10N-19W)
Anadarko basin, area 2	Synthesis by author of two wells; formation tops from logs and completion cards	Union Oil of California 1-89 Bradstreet (H&GN survey-M1-89); Chevron USA-Freeport Oil Co. 1 Ruth Ledbetter (J.M. Lindsey survey-L-21)
Anadarko basin, area 3	Formation tops from Adkison (1960, well #15)	Denver Producing and Refining Co. 1 School Land (16-10N-9W)
Anadarko basin, area 4	Formation tops from composite log constructed by Clausing and others (1958)	?
Anadarko basin, area 5	Formation tops from Adkison (1960, well #3)	Ohio Oil Co. 1 W. O. Parr (9-28N-10W)
Williston basin	Time-depth diagrams for Bakken Formation by Webster (1982, fig. 40), representing three areas in North Dakota	California Oil Co. 1 Rough Creek Unit (13-148N-98W); Marathon Oil Co. 18-44 Dobrinski (18-151N-87W); Placid Oil Co. 36-5 Rosendahl (36-163N-80W)

*Numbered areas in the Anadarko basin are shown in Figure 1.

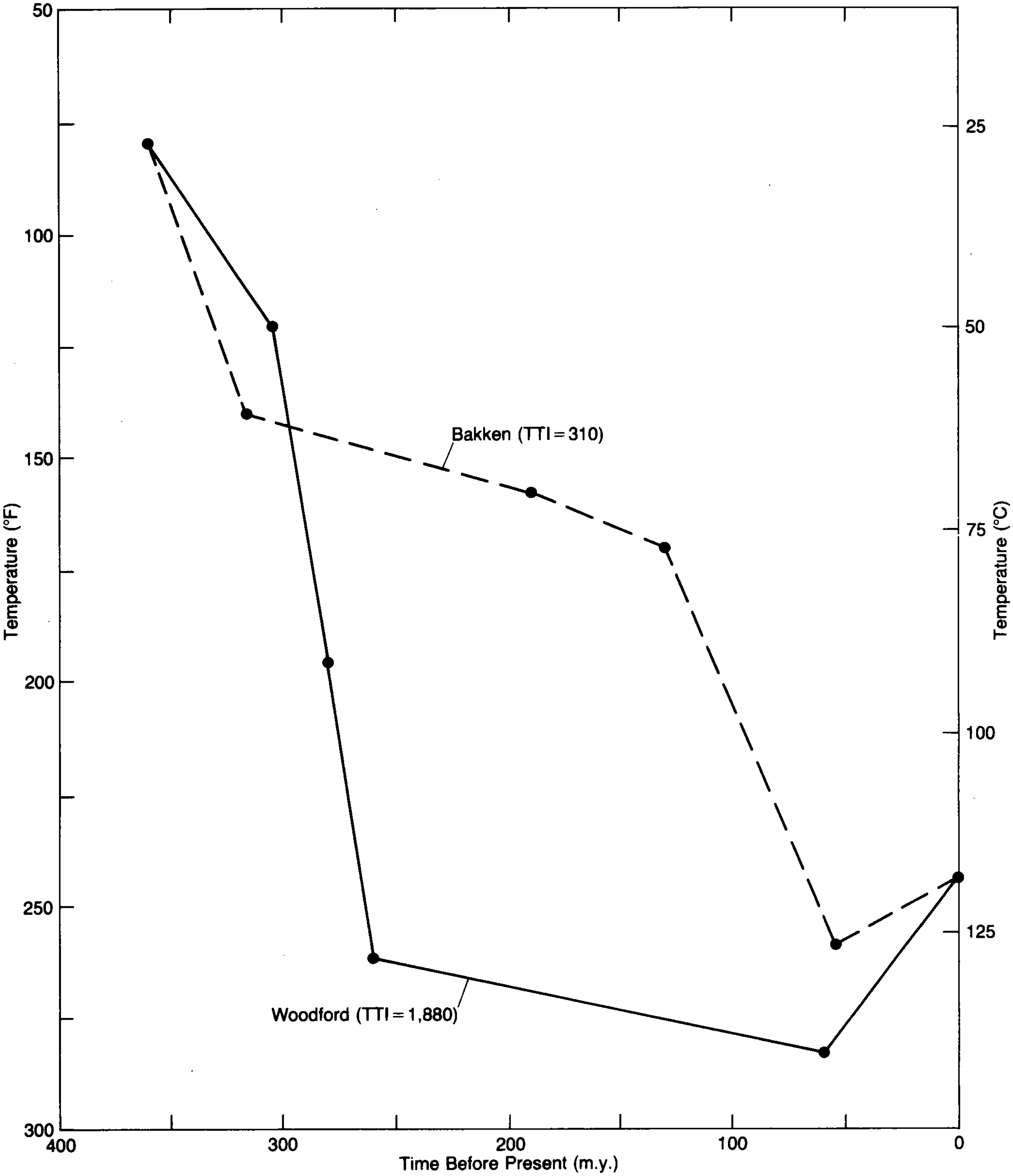

Figure 9. Formation-temperature reconstructions for organic-rich Devonian-Mississippian Woodford Shale in the area of Caddo, Canadian, and Grady Counties, Oklahoma (Fig. 1, area 3), and for shale members of the Devonian-Mississippian Bakken Formation, McKenzie County, North Dakota, that are close physical and stratigraphic equivalents of the Woodford. Data sources are listed in Table 1. Because of different subsidence histories, TTI of the Woodford is significantly higher than that of the Bakken for equal present-day or maximum temperatures.

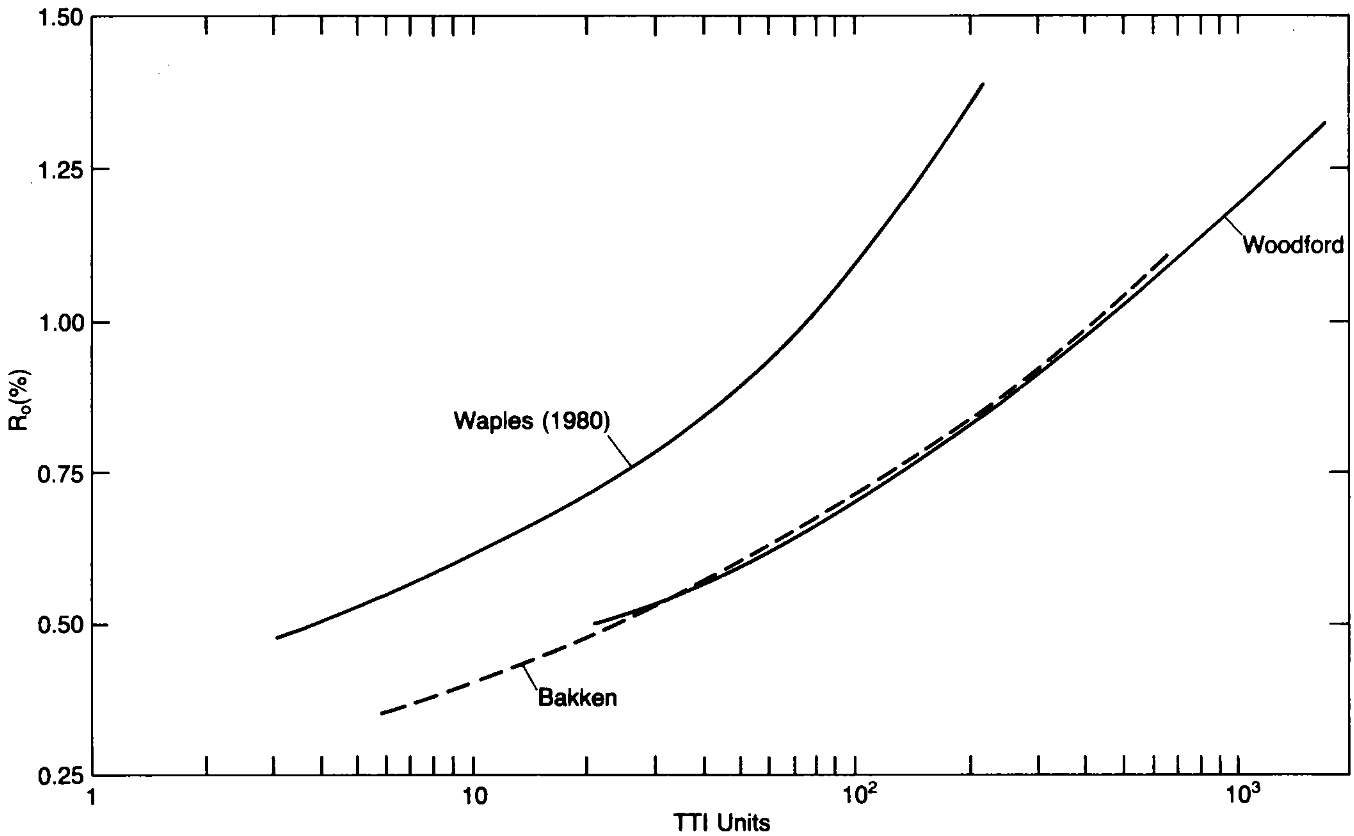

Figure 10. Comparisons of TTI versus R_0 relations for the Woodford Shale of the Anadarko basin and shale members of the Bakken Formation of the Williston basin in North Dakota. R_0 data are from Cardott and Lambert (1985) and Dembicki and Pirkle (1985); data sources for burial histories are listed in Table 1. A thermal gradient equal to the present-day regional value of 1.8°F/100 ft (3.28°C/100 m) is used for the Williston basin. Curve labeled "Waples (1980)" is Waples's generic calibration representing the center line of a data envelope comprising several hundred worldwide samples.

An important assumption implicit in TTI interpretation is that TTI-$\underline{R}_0$ calibrations such as equation 6 are valid not only for the present day, but also for the past, when relative contributions of time and temperature to thermal maturation were different. The close agreement between TTI-$\underline{R}_0$ curves for the Woodford and Bakken (Fig. 10), considered in view of their very different time-temperature histories (Fig. 9), supports this assumption.

OIL WINDOW--PAST AND PRESENT

TTI Boundaries of Oil Window

Because direct calibrations of TTI to stages of hydrocarbon generation are not yet established, general TTI limits for the onset and end of oil generation are usually assumed relative to $\underline{R}_0$. The transition from oil to wet-gas generation is commonly correlated to $\underline{R}_0$ = 1.3%, which corresponds to TTI = 1,260 in this study and occurs at a present depth of ~13,400 ft (~4,100 m) in the central Anadarko basin (Fig. 8).

A threshold for oil generation of $\underline{R}_0$ = 0.6% is considered representative of many source rocks, and thresholds as low as $\underline{R}_0$ = 0.5% are characteristic of some kerogens (Waples, 1985, table 9.5). Changes in formation resistivity as oil displaces water indicate that the onset of oil generation in the Bakken Formation--a Woodford Shale equivalent--occurs at $\underline{R}_0$ = 0.5%, or even slightly lower (T. C. Hester, personal communication, 1986). Oil generation in the central Anadarko basin probably begins when source rocks reach TTI values between

12 and 29, at present depths of ~4,300-6,000 ft (~1,300-1,800 m) (Fig. 8).

Oil Window in the Past

TTI values for the Anadarko basin of 100 m.y. ago, like those of the present day, describe a straight line on a semi-logarithmic graph (Fig. 11). In mid-Cretaceous time, thermal maturation at near-maximum depths already overshadowed that resulting from earlier burial history. During the past 100 m.y., TTI isopleths moved upward ~3,000 ft (~900 m) relative to the surface in response to erosional removal of overlying strata, and secondarily in response to increased heating time.

TTI values of 250 m.y. ago scatter when plotted against depth (Fig. 11). At the close of the Permian, levels of thermal maturity reflected age of deposition and details of early burial history--that is, formation and location--as well as depth of burial. In consequence, regional thermal maturity at this time is represented by an envelope of depths that is ~1,500 ft (~460 m) thick at the transition to wet-gas generation and ~2,000 ft (~600 m) thick at the onset of oil generation. At lower thermal maturities, where porosity decrease by pressure solution (Schmoker, 1984) and early changes in kerogen structure may occur, effects of formation and location upon TTI are equivalent to depth changes of as much as 3,500 ft (1,070 m).

The evolution of the oil window in the central Anadarko basin is shown as a function of time in Figure 12. Reliability undoubtedly decreases as TTI values are projected hundreds of millions of years into the past, so that determinations of individual oil windows for specific formations or locations are not justified. The data points defining the

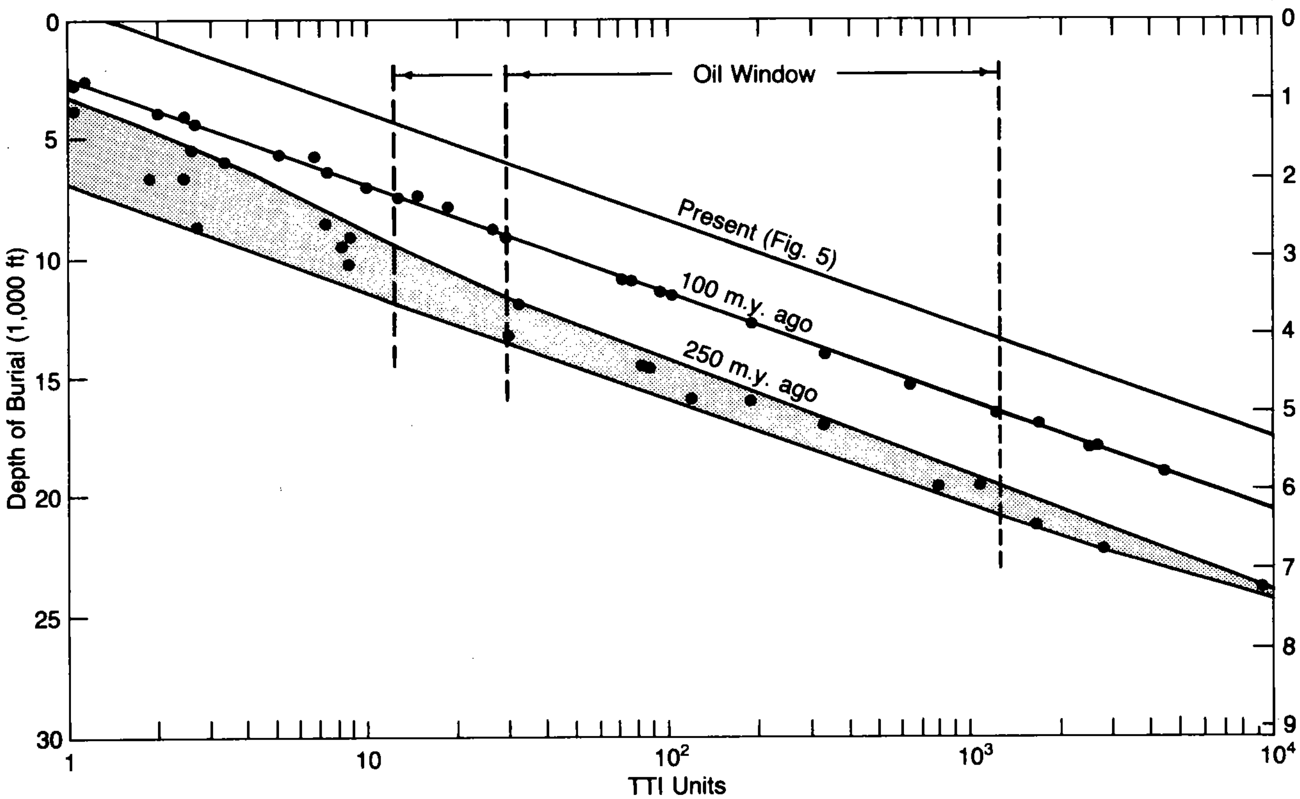

Figure 11. TTI values for the study region in the central Anadarko basin versus depth of burial for 250 m.y. ago, 100 m.y. ago, and the present.

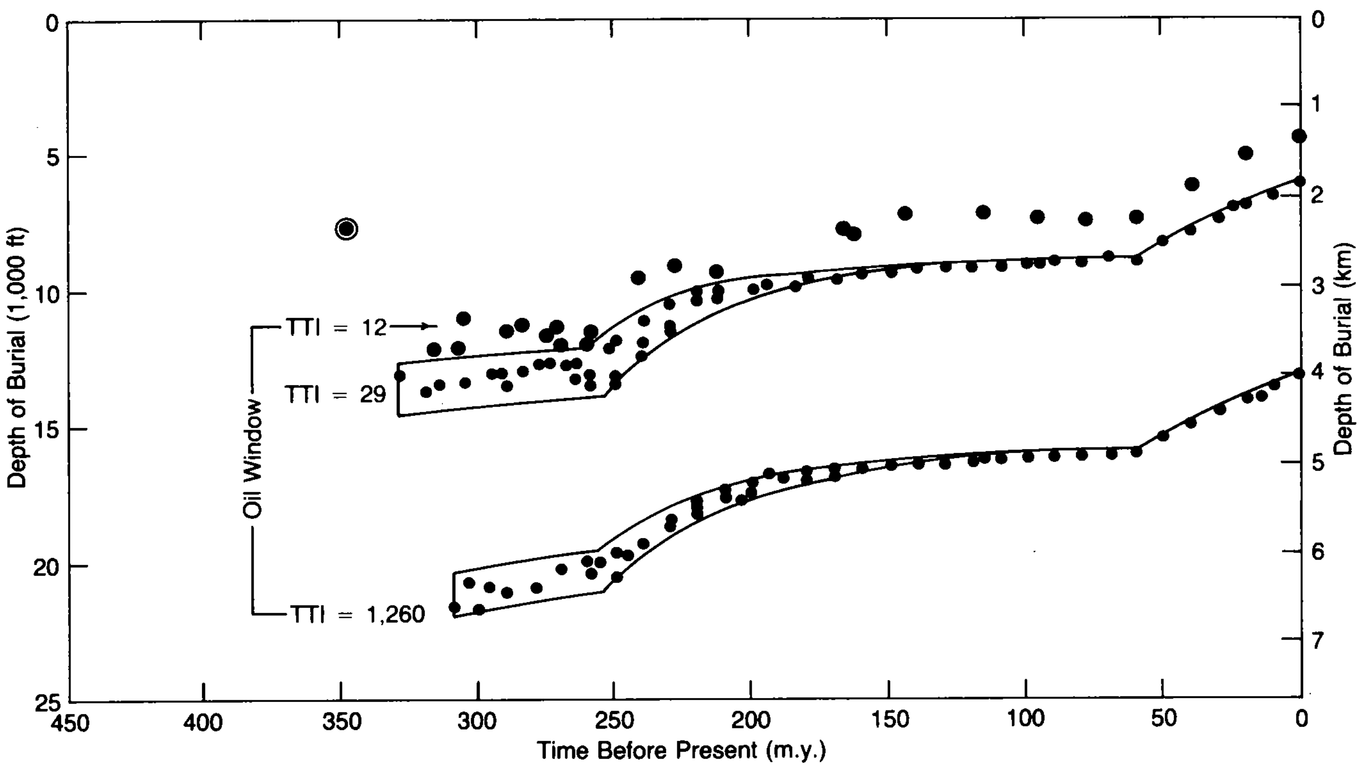

Figure 12. Generalized oil window for Paleozoic rocks of the study region in the central Anadarko basin, as a function of time before present. TTI limits for the oil window are defined in Figure 8.

oil window show combinations of depth and time before present for which calculated TTI values are 12, 29, or 1,260. Figure 12 merges results from each of the five areas modeled (Fig. 1).

Scatter in depths of the regional oil window decreases toward the present, as discussed with respect to Figure 11. Taken as a whole, the oil window migrates upward ~7,500 ft (~2,300 m) relative to the surface from Pennsylvanian time to the present, and decreases in total thickness from ~10,500 to ~9,000 ft (~3,200 to ~2,750 m).

The envelopes defining the oil window (Fig. 12) can be subdivided into three segments by discontinuities in slope that correspond to major shifts in basin subsidence patterns (Fig. 3). The oldest segment, in which the oil-window envelopes rise quite slowly, reflects a period of rapid sediment burial. The middle segment, corresponding to gradual subsidence in a quiescent basin, migrates upward in response to TTI accumulation with the passage of time; the rate of upward migration of the middle segment decreases as cooling of the oil window due to shallowing and to dropping surface temperatures slows the accumulation of TTI. The renewal of upward migration relative to the surface that defines the youngest oil-window segment primarily reflects erosional removal of overlying rocks (Fig. 3).

With the single exception discussed in the following paragraph, individual points in Figure 12 representing the onset of oil generation form a well-defined trend which terminates 330 m.y. ago, near the end of the Mississippian. TTI values of earlier times do not attain the oil window. A number of horizons enter the oil window in the Pennsylvanian and Permian, indicating that significant volumes of sediment were within the zone of oil generation during these periods.

A single data point in Figure 12, circled for emphasis, falls well off the general trend for the beginning of the oil window. This value represents the top of the Arbuckle Group in the deep basin (the most mature horizon modeled) and is the only evidence developed here for a significant influence upon oil generation by the southern Oklahoma aulacogen. TTI calculations thus suggest that some oil could have been generated ~350 m.y. ago in the ancestral Anadarko basin if adequate source rocks were present.

SUMMARY

Figures 13-17 form a largely self-explanatory sequence showing the relation of representative strata at each of the five locations modeled to the generalized regional oil window of Figure 12. The horizons plotted (Figs. 13-17) provide a framework for interpolation and do not necessarily represent source rocks. Burial reconstructions of the Woodford Shale are grouped together in Figure 18 as an example illustrating the relation throughout the basin of a single formation to the oil window.

During the rapid subsidence of initial basin development, burial curves cut sharply across the oil window, and time spent in the oil-generation zone is as short as 20 m.y. (Figs. 13,14,18). Through the subsequent period of quite gradual subsidence, burial curves remain in the oil window much longer. Burial and oil-window curves are nearly parallel through the period of Tertiary erosion. For a given formation, the zone of active oil generation migrates upward relative to the surface and outward toward the basin shelf with the passage of time.

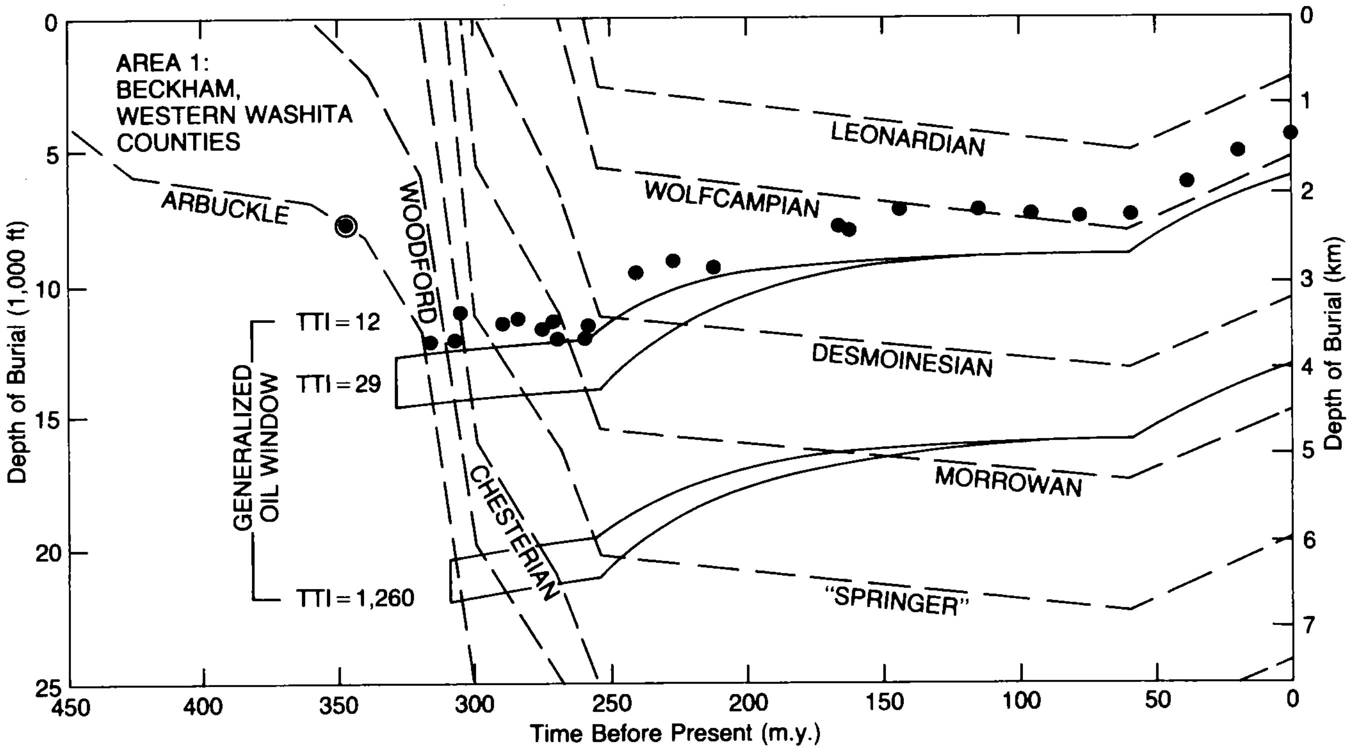

Figure 13. Burial curves for the deep-basin area of Beckham and western Washita Counties, Oklahoma (Fig. 1, area 1), superimposed on the regional oil window of Figure 12.

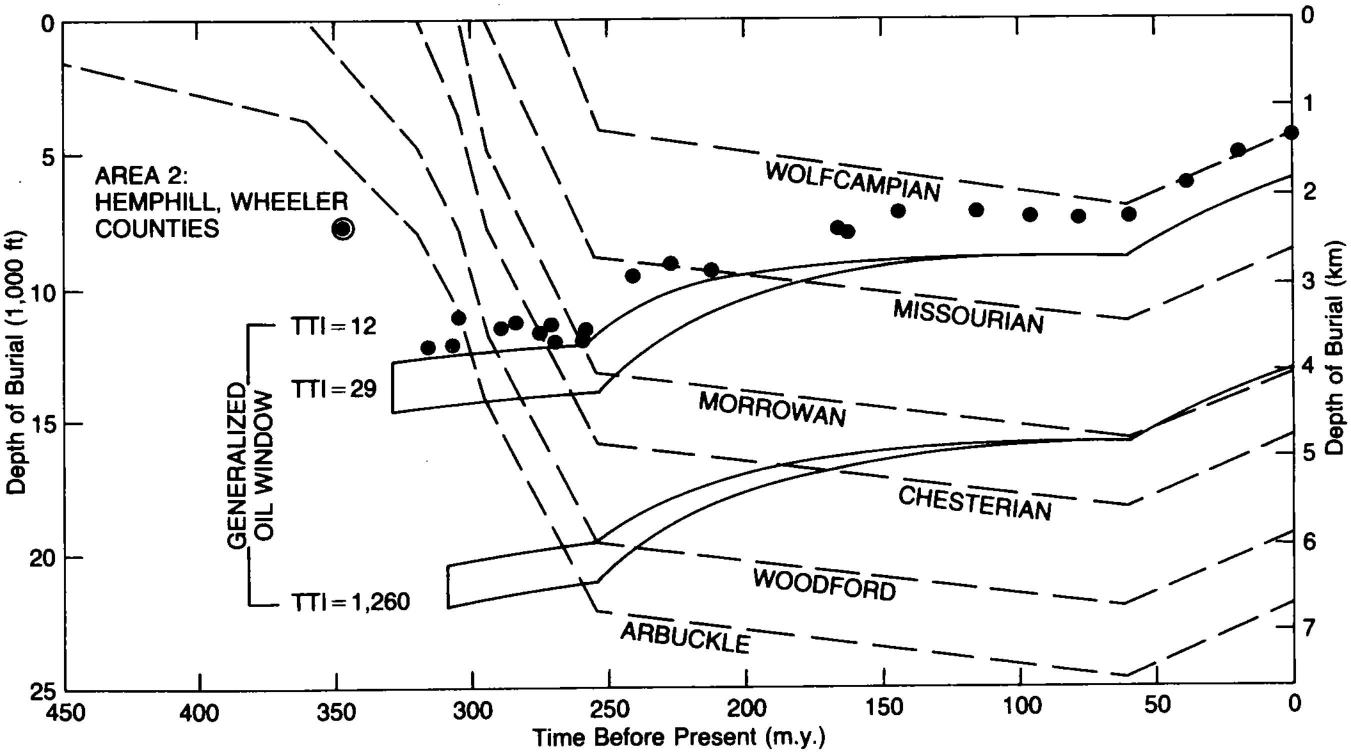

Figure 14. Burial curves for Hemphill and Wheeler Counties, Texas (Fig. 1, area 2), superimposed on the regional oil window of Figure 12.

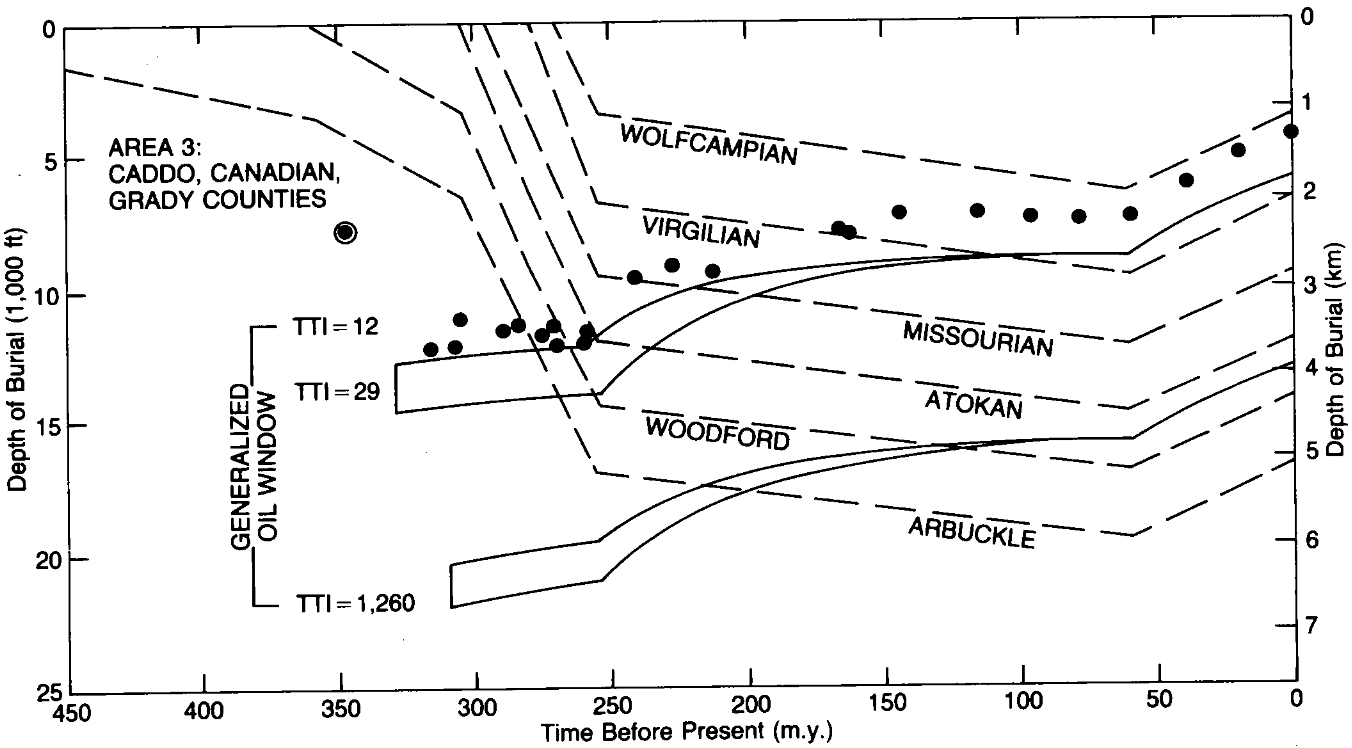

Figure 15. Burial curves for Caddo, Canadian, and Grady Counties, Oklahoma (Fig. 1, area 3), superimposed on the regional oil window of Figure 12.

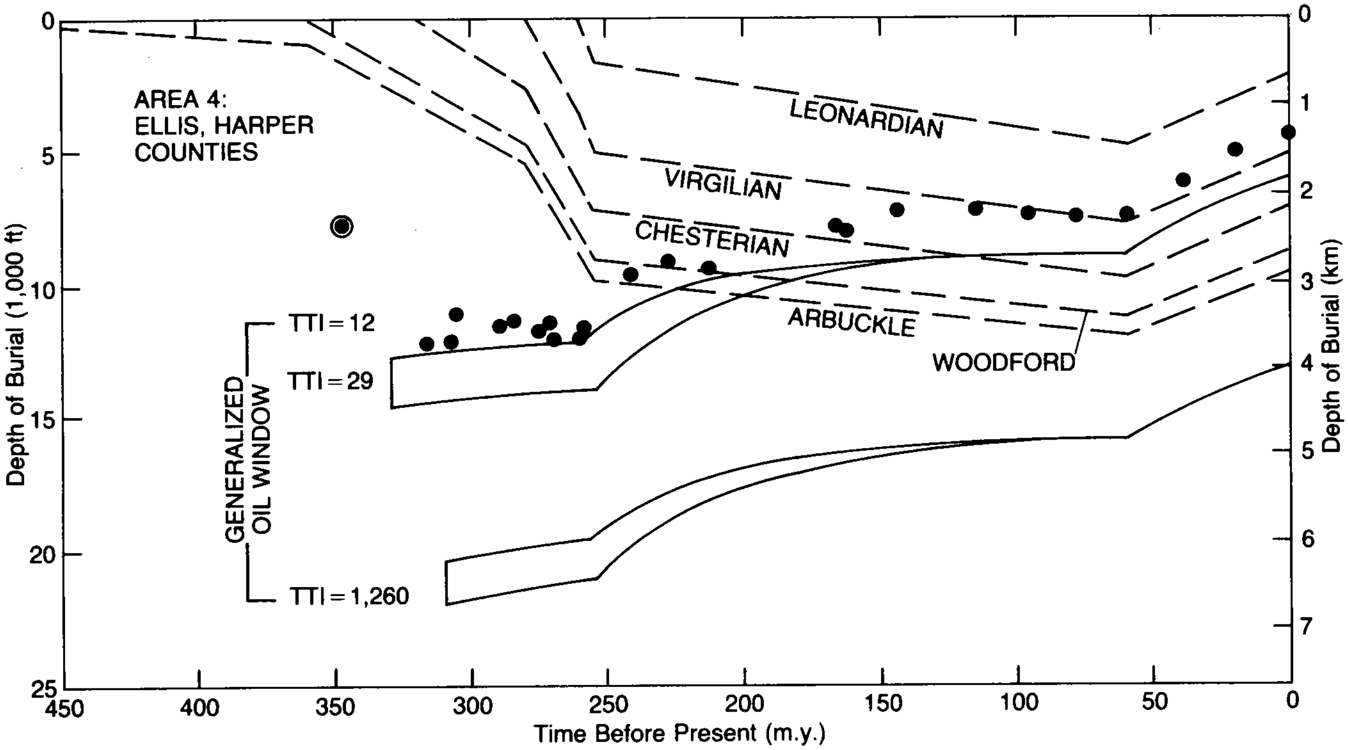

Figure 16. Burial curves for Ellis and Harper Counties, Oklahoma (Fig. 1, area 4), superimposed on the regional oil window of Figure 12.

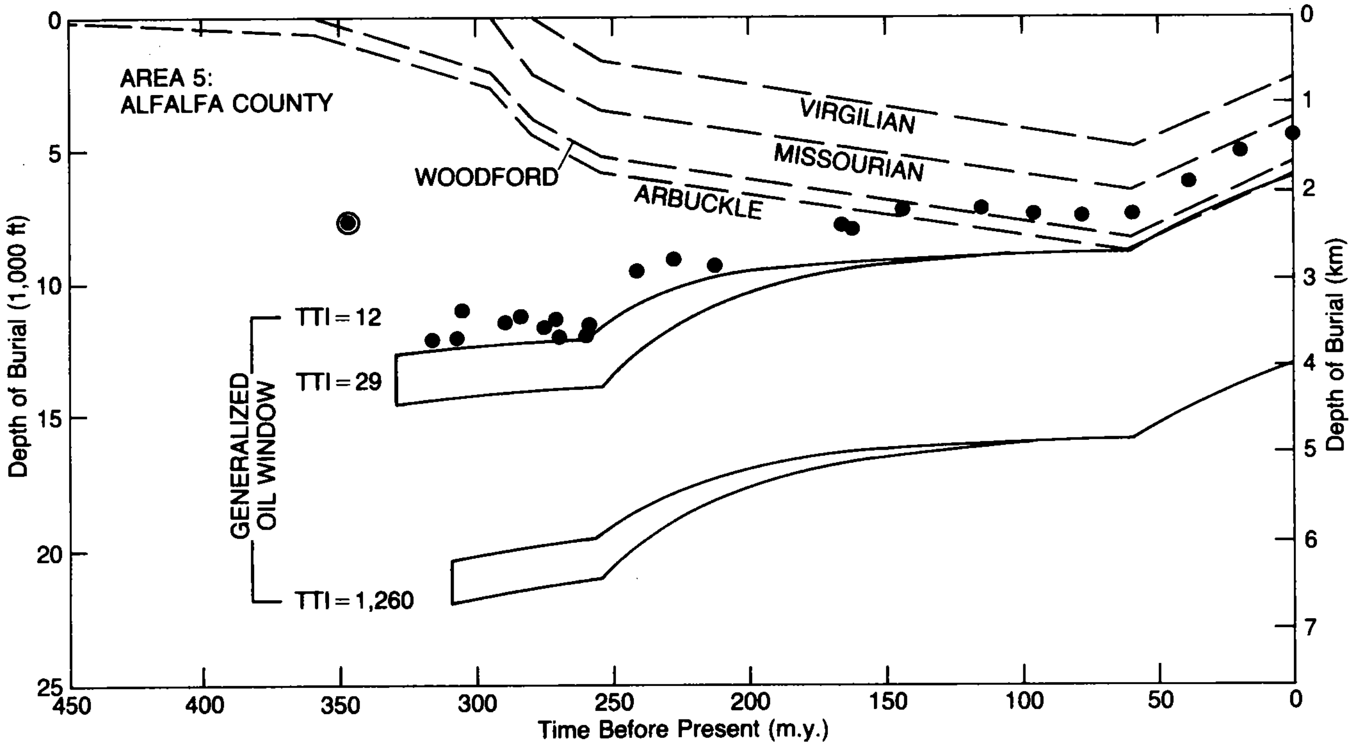

Figure 17. Burial curves for shelf area of Alfalfa County, Oklahoma (Fig. 1, area 5), superimposed on the regional oil window of Figure 12.

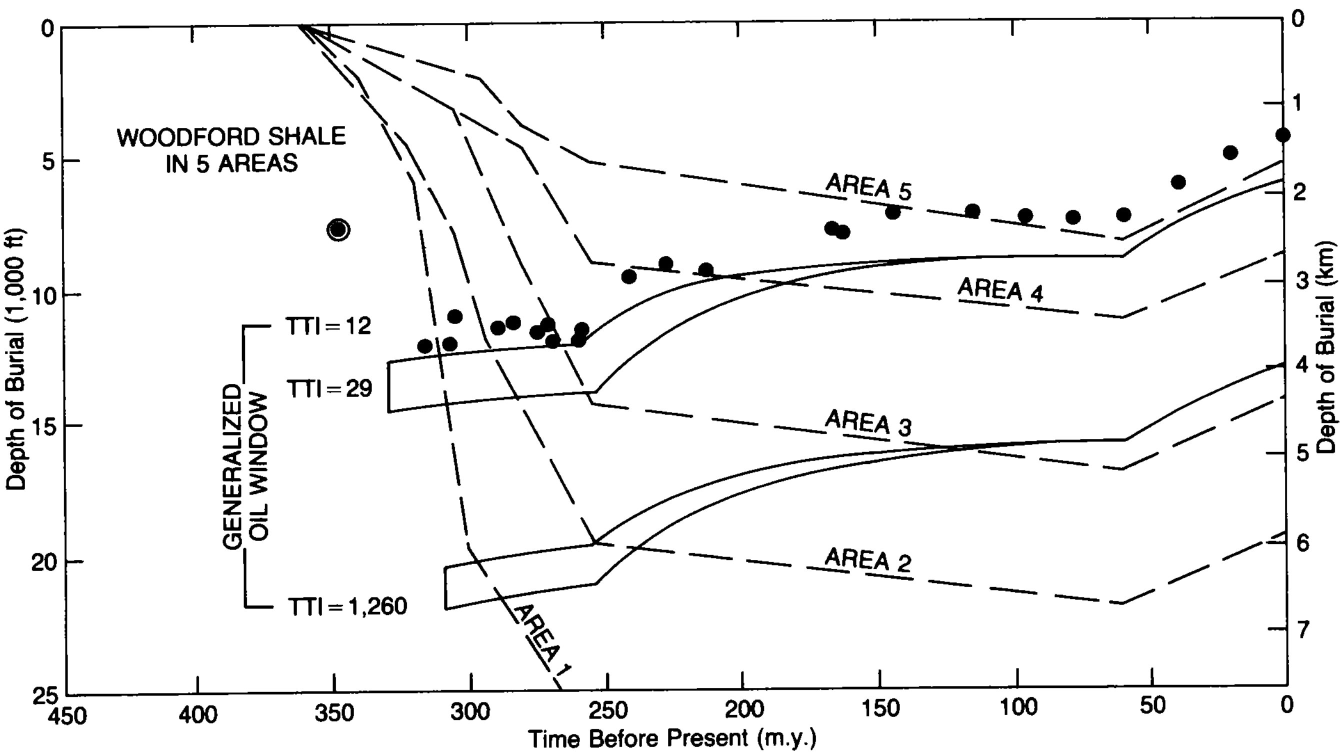

Figure 18. Burial curves for the Woodford Shale in the five modeled areas of the central Anadarko basin (Fig. 1), superimposed on the regional oil window of Figure 12.

Because significant uncertainties exist in the burial histories, the calculation of the oil window, and even in the geochemical specifications of the oil window, the data of Figures 13-18 probably should be regarded as semiquantitative. Specific questions relative to individual formations can be addressed, but rigorous interpretation of these figures in terms of precise ages and depths is not warranted.

Hydrocarbons have been generated in an exceptionally long and unbroken history for ~350 m.y. in the Anadarko basin. Since the Permian, the basin has been relatively stable. Such conditions would appear to favor the generation of large volumes of oil and gas, extensive and diverse migration paths, the widespread distribution of oil and gas both areally and throughout the section, and the preservation of petroleum accumulations. These circumstances contribute to the unusual richness of the Anadarko basin as a Paleozoic hydrocarbon province.

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