Porosity Trends of Pennsylvanian Sandstones With Respect to Thermal Maturity and Thermal Regimes in the Anadarko Basin, Oklahoma

By Timothy C. Hester

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ABSTRACT

A thermal model by Gallardo (1989) shows that the Anadarko Basin can be divided stratigraphically into three thermal regimes based on large-scale changes in thermal gradient. In addition, the model reveals a fourth thermal regime, an anomalously cool zone, that extends along and adjacent to the Wichita Mountains front and vertically downward through Pennsylvanian and lower Paleozoic strata. Empirical vitrinite reflectance-depth curves corroborate these multiple thermal regimes and provide a means of relating sandstone porosity and thermal maturity as measured by vitrinite reflectance in the Anadarko Basin.

Treating porosity as a function of thermal maturity normalizes the overprint of burial history on porosity evolution and allows porosity data from areas having different thermal histories to be combined and (or) compared in the same context. Porosity-vitrinite reflectance trends of Pennsylvanian sandstones of the Anadarko Basin are characterized using three data sets—two representing Anadarko Basin sandstones and one, from basins exclusive of the Anadarko, representing sandstones in general. The two Anadarko Basin data sets are termed reservoir sandstones, those specifically documented in the literature as hydrocarbon reservoirs, and nonreservoir sandstones, those interpreted directly from well logs. By comparing these data sets, sandstone porosity trends for the Anadarko Basin are evaluated relative to each other and to a framework of sandstones in general.

Nonreservoir sandstone porosity data for the Anadarko Basin consist of a less thermally mature population and a more thermally mature population, separated at a vitrinite reflectance value of 1.1 percent. Each population reflects a different rate of porosity decline with increasing vitrinite reflectance. Compared to sandstones in general, the porosity of the less mature trend decreases rapidly, whereas that of the more mature trend decreases slowly.

The porosity of Anadarko Basin reservoir sandstones decreases more slowly than that of nonreservoir sandstones for vitrinite reflectance of less than 1.1 percent and of sandstones in general. The almost parallel trends of Anadarko Basin reservoir and nonreservoir sandstones for vitrinite reflectance of greater than 1.1 percent suggest that Anadarko Basin sandstones as a whole may retain sufficient porosity for economic accumulations of hydrocarbons, even at the high thermal maturities associated with depths of 15,000 ft (4,572 m) and greater.

INTRODUCTION

In this report, I explore a concept introduced by Gallardo (1989) of multiple, discrete thermal regimes in the Anadarko Basin of Oklahoma and, in addition, identify and characterize an anomalously cool zone adjacent to the Wichita Mountains front where, along the dip of stratigraphic horizons, temperature and depth vary inversely. Empirical relations of vitrinite reflectance and depth corroborate the thermal model of Gallardo (1989) and provide a means with which to investigate the primary topic of this report, the relation between porosity and thermal maturity for Pennsylvanian sandstones of the Anadarko Basin (Hester and Schmoker, 1990).

Treating porosity as a function of thermal maturity has advantages over the more common treatment as a function of depth. As a function of thermal maturity, the overprint of burial history on porosity evolution is normalized, allowing porosity data from basins or areas having different thermal histories to be combined and (or) compared in the same context (Schmoker and Gautier, 1988). An additional advantage is that porosity change in the subsurface is linked to the maturation of kerogen and petroleum by a common variable, vitrinite reflectance (Schmoker and Hester, 1990).

Porosity-vitrinite reflectance trends of Pennsylvanian sandstones of the Anadarko Basin are characterized in this report using three data sets; two data sets represent Anadarko Basin sandstones (fig. 1), and one data set, from basins

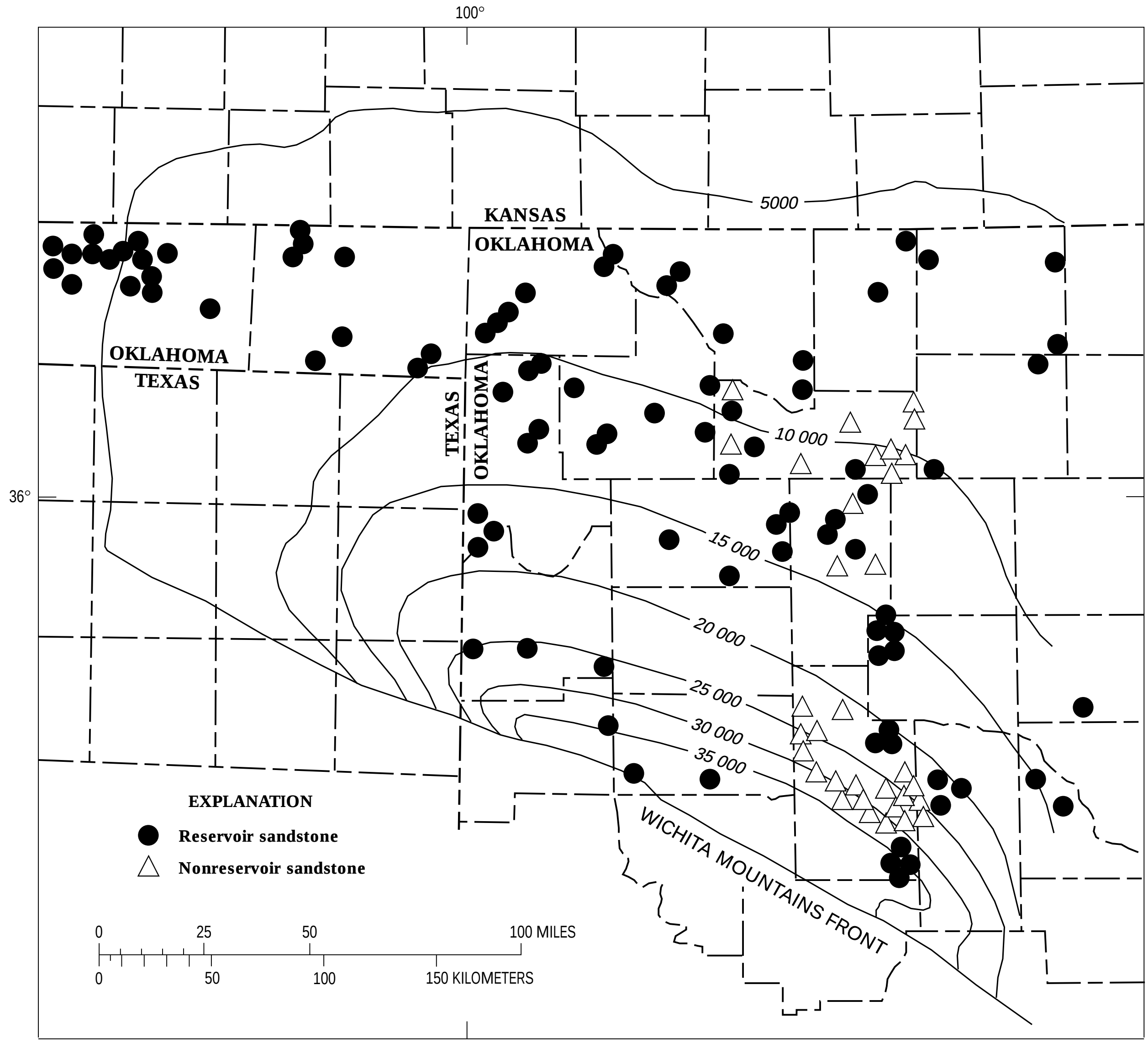


Figure 1. Map showing total sediment thickness isopach and data locations, Anadarko Basin, Oklahoma. Contour interval 5,000 ft (1,524 m). Sandstone hydrocarbon reservoir locations are listed in table 1. Nonreservoir sandstone well locations are listed in table 2.

exclusive of the Anadarko, represents sandstones in general (Schmoker and Hester, 1990). The porosity–vitrinite reflectance trends of Anadarko Basin sandstones are compared with trends from basins other than the Anadarko. In this way, Anadarko Basin sandstone porosity trends are evaluated relative to a framework of sandstones in general (Schmoker and Hester, 1990). The Anadarko Basin data sets, termed reservoir sandstones (those specifically documented in the literature as hydrocarbon reservoirs) and nonreservoir sandstones (those interpreted directly from well logs), are also compared to each other. In this way, porosity trends of commercially producing sandstone hydrocarbon reservoirs are evaluated relative to trends of Anadarko Basin sandstones as a whole. These three data sets are discussed in detail in a following section.

This report establishes regional vitrinite reflectance–depth and porosity–vitrinite reflectance trends that can be extrapolated to the deep, relatively unexplored parts of the Anadarko Basin. These trends thus provide (1) a means of predicting thermal maturity (vitrinite reflectance) and sandstone porosity in the deep Anadarko Basin; (2) comparative insights into porosity trends of Anadarko Basin reservoir and nonreservoir sandstones; and (3) a standard with which to identify anomalous thermal maturity or porosity trends and individual sandstones in the Anadarko Basin having anomalously high or low porosity.

THERMAL REGIMES IN THE ANADARKO BASIN

The Anadarko Basin can be divided stratigraphically into three thermal regimes, primarily defined by changes in thermal conductivity and thermal gradient (Gallardo, 1989). Because thermal conductivity, and thus thermal gradient, varies with rock type (among other things; Robertson, 1988), the boundaries of the thermal regimes generally reflect lithologic (stratigraphic) changes. In particular, the boundaries coincide with the major lithologic changes that mark the transitions from one stage of Anadarko Basin tectonic evolution (Perry, 1989) to the next.

During each stage of Anadarko Basin evolution, a lithologically distinct group of strata was deposited: (1) lower Paleozoic (Mississippian and older) strata, which are mostly carbonate rocks with minor amounts of shale and sandstone; (2) Pennsylvanian strata, which are mostly shale, with some sandstone and limestone, and minor amounts of granite wash (arkose or arkosic sandstone); and (3) Permian strata, which are mostly redbeds (defined by Gallardo [1989] as a separate lithology of red shale and evaporite), with some anhydrite, limestone, and sandstone, and minor amounts of granite wash and dolomite.

Each of these three groups of strata is dominated by a single lithology—carbonate, shale, or redbed—that more or less characterizes that particular stage of basin development and accounts for the distinct thermal conductivity and thermal gradient of that group. The thermal conductivity of each group is a weighted average of the thermal conductivities of all lithologies in the group; thus, the average thermal conductivity of a group is significantly influenced by that of its dominant lithology. Thermal conductivities of the lower Paleozoic and Permian groups of strata are generally high relative to that of the Pennsylvanian group. The three thermal regimes, therefore, result primarily from the separation of two thermally conductive groups of strata by an insulating blanket of Pennsylvanian shale.

Gallardo's (1989) model also reveals a fourth thermal regime, an anomalously cool zone, that extends along and adjacent to the Wichita Mountains front where accumulations of granite wash (high thermal conductivity) replace the otherwise ubiquitous Pennsylvanian shale. In this area, thermal conductivity contrasts between the three lithologic groups are smaller, thus decreasing the thermal gradients and the temperature differences across stratigraphic boundaries. As a result, the highest temperatures, which should be in the deepest parts of the basin, are shifted updip, creating an anomalously cool zone along the Wichita Mountains front in which temperature and depth (measured along stratigraphic horizons) vary inversely. This cool zone is described in detail in a following section.

Except for the Wichita Mountains front area, relative percentages of the lithologies of each group of strata (lower Paleozoic, Pennsylvanian, and Permian) remain fairly constant across much of the basin (Gallardo, 1989). Thermal characteristics of each group, therefore, also remain more or less laterally continuous. The result, in the greater Anadarko Basin, is blanketlike groups of strata that have vertically contrasting thermal conductivities and gradients. Along the Wichita Mountains front, however, thermal conductivities are uniformly high and thermal gradients are low. The present-day temperature structure of the basin, therefore, reflects normal variations in conductive heat flow through these groups of strata (Gallardo, 1989). A thermal anomaly, such as that inferred by Cardott and Lambert (1985), is not required to produce the observed thermal maturity patterns (Gallardo, 1989).

CALIBRATION OF VITRINITE REFLECTANCE WITH DEPTH

An empirical vitrinite reflectance–depth relation (exponential) for the Pennsylvanian group of strata (fig. 2), analogous to that used by Schmoker (1986) for the Anadarko Basin in general, is used here to approximate actual vitrinite reflectance measurements for the porosity–vitrinite reflectance plots (power law) that follow. A second empirical vitrinite reflectance–depth relation for the Upper Devonian and Lower Mississippian Woodford Shale (fig. 3), considered here to be representative of the lower Paleozoic group of strata as a whole, is used for statistical comparison. A third empirical vitrinite reflectance–depth relation for an anomalously cool zone along the Wichita Mountains front that includes both Pennsylvanian and lower Paleozoic strata (fig. 4, discussed in detail in the following section) is used to predict vitrinite reflectance for Pennsylvanian age strata in that area. Data for these calibrations are from published sources referenced by Schmoker (1986), from Brian J. Cardott, Oklahoma Geological Survey (personal commun., 1986), and from Pawlewicz (1989) and are subdivided based on the thermal regimes of Gallardo (1989). No vitrinite reflectance–depth data are available for the Permian group of strata.

Temperature, and thus thermal maturation, in the Anadarko Basin generally increases with depth. Vitrinite reflectance values used in this study range from about 0.5 to 5.0 percent; depths range from about 5,000 to 30,000 ft (1,500–9,100 m). Correlation coefficients (r) for the least-squares regression lines (using a ln vitrinite reflectance transformation) fit to vitrinite reflectance–depth measurements of Pennsylvanian strata (fig. 2) and Woodford Shale (fig. 3) show a strong dependence of vitrinite reflectance on depth (r=0.97 and r=0.95, respectively) for most of the basin. For the anomalously cool zone (fig. 4), the dependence of vitrinite reflectance on depth is not as strong (r=0.81) but is still significant.

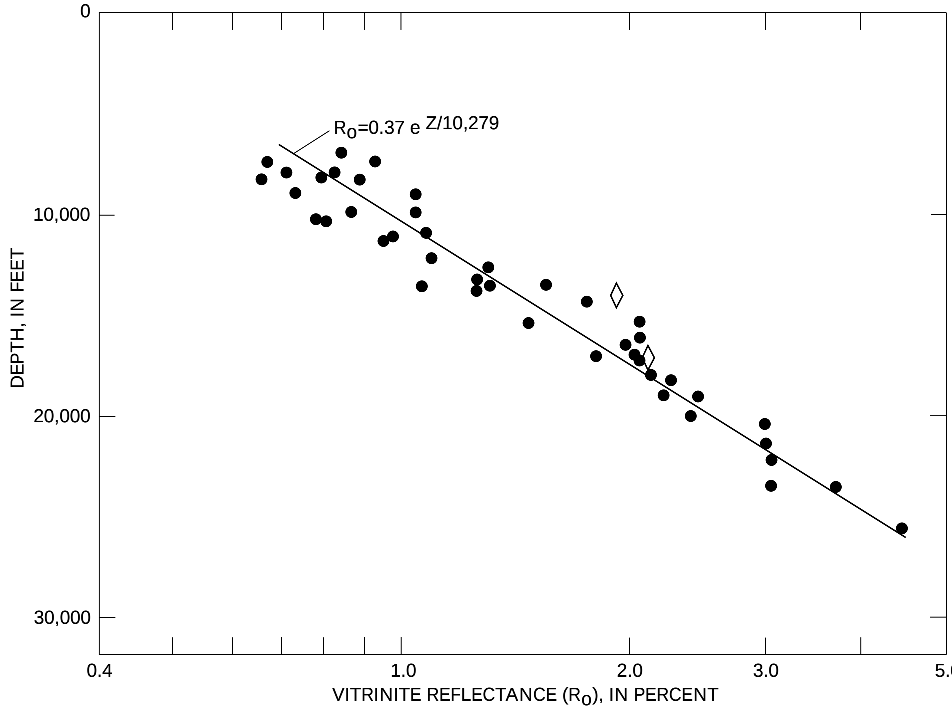


Figure 2. Vitrinite reflectance versus depth for Pennsylvanian strata in the Anadarko Basin. Least-squares regression line is also shown. Diamonds represent data from anomalously cool zone of figure 5.

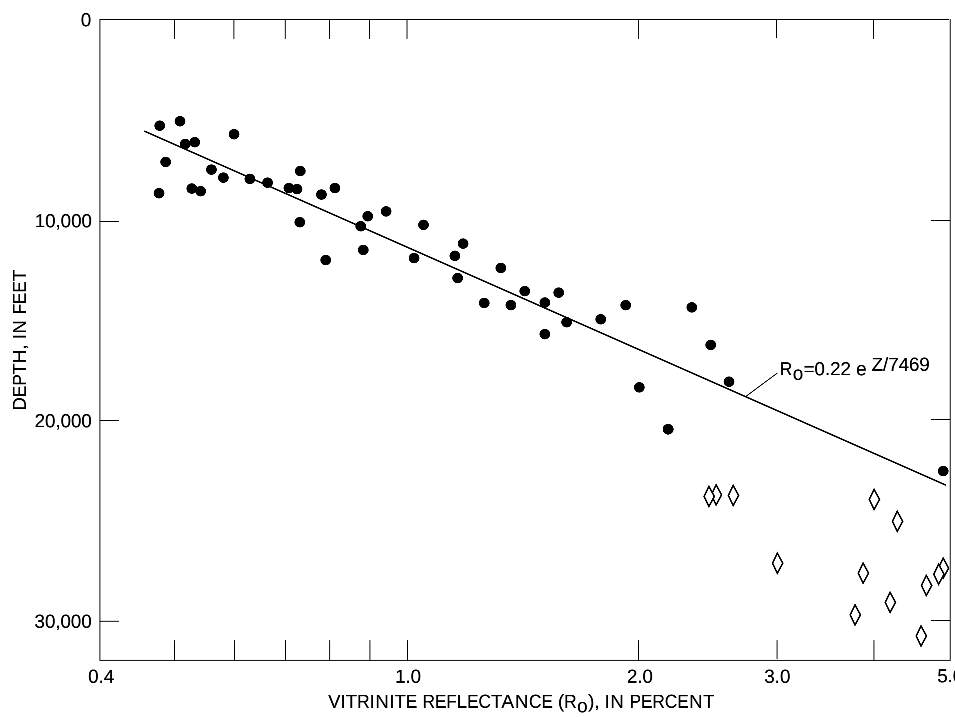


Figure 3. Vitrinite reflectance versus depth for lower Paleozoic strata in the Anadarko Basin. Least-squares regression line is also shown. Diamonds represent data from anomalously cool zone of figure 5.

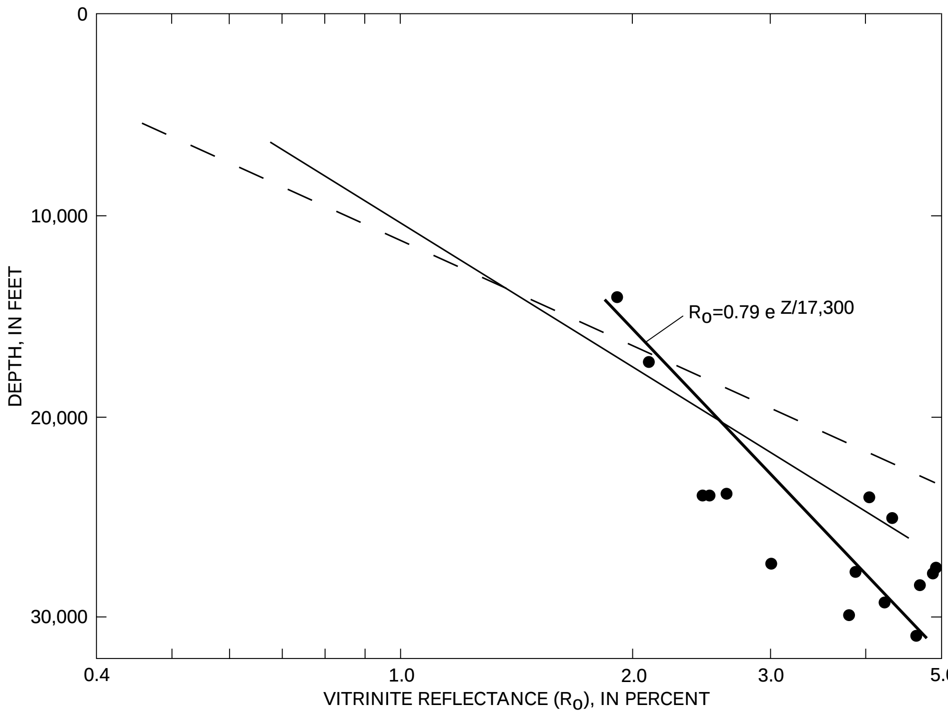


Figure 4. Vitrinite reflectance versus depth for all strata in the Anadarko Basin within the anomalously cool zone of figure 5. Least-squares regression line for anomalously cool zone (heavy line) and least-squares regression lines fit to vitrinite reflectance–depth data for Pennsylvanian (fine line) and lower Paleozoic strata (dashed line) are also shown.

ANOMALOUSLY COOL ZONE

Along the Wichita Mountains front, accumulations of Pennsylvanian granite wash replace the otherwise ubiquitous Pennsylvanian shale, changing regional thermal conductivity patterns. Where granite wash is concentrated, thermal conductivity increases and thermal gradients decrease. This effect offsets the highest temperatures (which should be in the deepest parts of the basin) updip, away from the deepest depths (Gallardo, 1989), creating an anomalously cool zone in which temperature and depth (measured along the dip of stratigraphic horizons) vary inversely. This cool zone extends through the stratigraphic section from about the top of the Pennsylvanian to basement rocks.

The upper and lower boundaries of the Pennsylvanian part of the cool zone are constructed here using temperature and structure maps of Gallardo (1989) on top of Pennsylvanian and lower Paleozoic strata, respectively, and are approximated in plan view in figure 5. The contrasting shapes and geographic positions of the boundaries indicate an irregular configuration of the cool zone as it extends through the Pennsylvanian section with both downward and oblique components. The shape and position of the cool zone at a given horizon, between the boundaries mapped in figure 5, are uncertain but must vary as temperature and structural patterns change with depth. Consequently, wells within the boundary mapped on top of the Pennsylvanian (fig. 5, shaded area) may only intersect the cool zone at its upper part, while at depth, the main body of the cool zone (hachured area) is not penetrated. In contrast, temperature and structure maps at the base of the Arbuckle Group (Gallardo, 1989) indicate that the cool zone probably continues from the base of the Pennsylvanian vertically downward through the lower Paleozoic to the basement with its plan view shape virtually unchanged.

Temperature-depth profiles (fig. 6, using modeled temperatures of Gallardo [1989]) along the dip of stratigraphic horizons at the top of the Pennsylvanian and the lower Paleozoic (fig. 5) are taken along the lines shown in figure 5. Each profile intersects the highest temperatures of that stratigraphic horizon and shows that temperatures increase basinward, along the horizon, to the northern edge of the cool zone and then decrease sharply (fig. 6). The profile along the top of the Pennsylvanian (fig. 6, inset) shows that, within the shallowing area between the southern edge of the cool zone and the Wichita Mountain front (fig. 5), temperature and depth (along the stratigraphic horizon) again co-vary. In this area (fig. 5, adjacent to the mountains front, bounded by the dashed lines), the cooling trend no longer increases basinward but remains constant (illustrated by the hachured area, fig. 6, inset).

If cooling did not occur, temperatures would continue to increase along the profiles as projected by the dashed lines (with arrows) of figure 6. The temperature differential (that is, the cooling effect) between projected

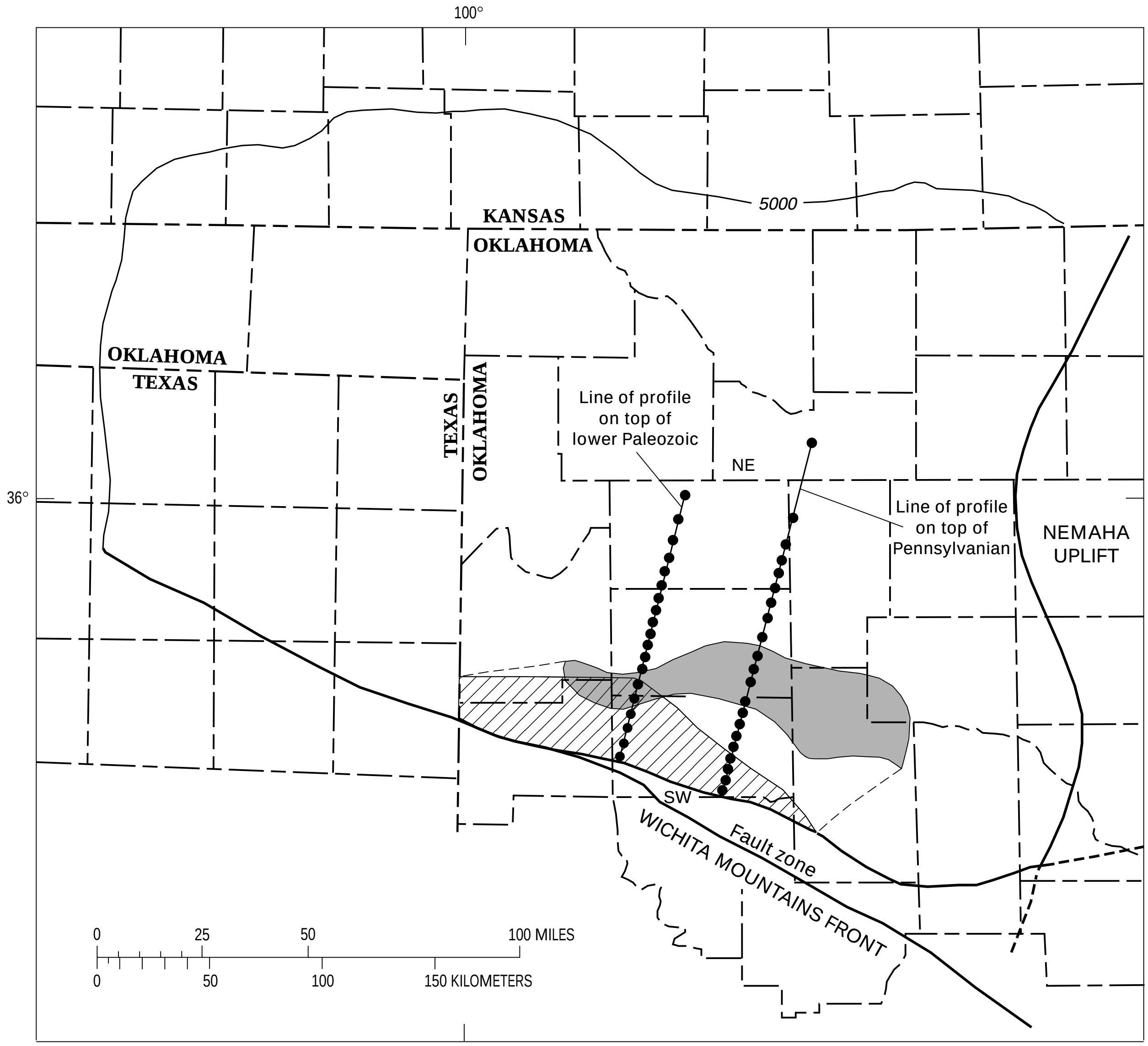
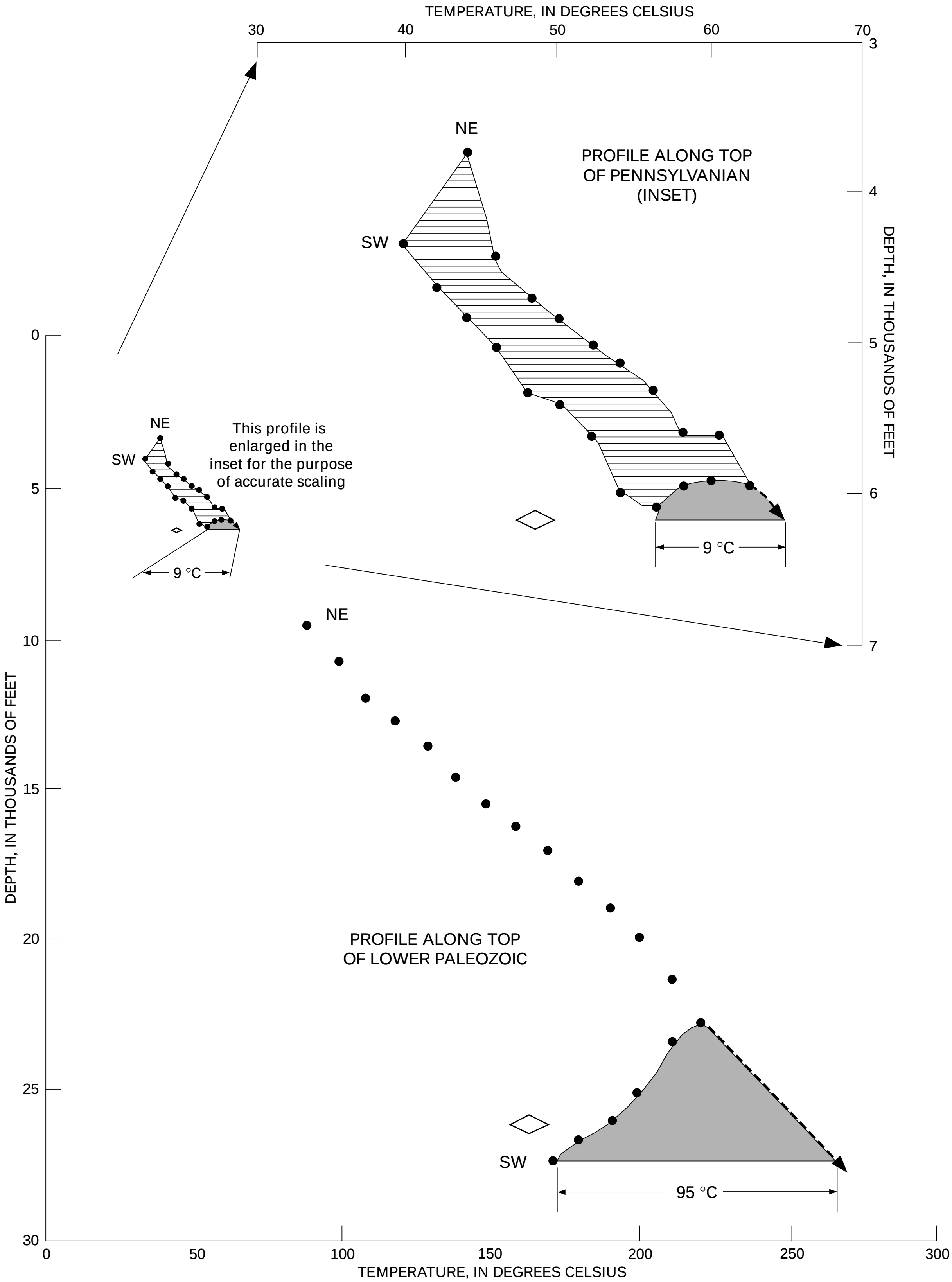


Figure 5. Map showing plan view of upper and lower boundaries of Pennsylvanian-age part of cool zone and lines of temperature-depth profiles (fig. 6), Anadarko Basin. Boundaries and lines are mapped on top of Pennsylvanian (shaded area) and lower Paleozoic (hachured area) strata. Dots locate temperature and depth measurements for profiles of figure 6. Dashed lines show hypothetical link between upper and lower boundaries through Pennsylvanian strata. 5,000-foot contour same as in figure 1.

and modeled temperatures increases from northeast to southwest through the cool zone along each horizon, as shown by the width of the shaded areas of figure 6. Thus, the cooling effect, as shown in figure 6 for the Pennsylvanian part of the cool zone, is manifested in two directions: increasing basinward, along stratigraphic horizons, and increasing with depth, from the top of the Pennsylvanian to the top of the lower Paleozoic. It is important to note here that temperature-depth profiles along stratigraphic horizons, as used here to define the anomalously cool zone, do not reflect vertical temperature profiles. Vertical profiles show that, in all areas of the basin,

Figure 6 (following page). Temperature-depth profiles along dip of stratigraphic horizons at top of Pennsylvanian (small upper profile) and top of lower Paleozoic strata (lower profile) (data from maps of Gallardo, 1989). Inset shows upper profile enlarged. Dots are temperature and depth measurements (in fig. 5). Shaded areas show differential between modeled temperatures (dots; Gallardo, 1989) and projected “normal” temperatures (dashed lines with arrows). Hachured area shows temperatures stabilized at about 9°C below normal in area between cool zone and Wichita Mountains front (fig. 5). Diamonds show uncorrected bottom-hole temperatures from Lone Star, 1–Bertha Rogers well, interpolated for horizons at top of Pennsylvanian and top of lower Paleozoic strata.



temperature increases with depth. The cooling effect noted here serves only to decrease the temperature gradient relative to areas outside the cool zone.

Uncorrected bottom-hole temperatures, measured at various stages of drilling in the Lone Star, 1–Bertha Rogers well (sec. 27, T. 10 N., R. 19 W.) and interpolated for horizons at the top of the Pennsylvanian and lower Paleozoic (fig. 6, shown as diamonds), are about 10˚C–30˚C below those modeled by Gallardo (1989). Because mud temperatures in the borehole, from which bottom-hole temperatures are taken, are almost always unequilibrated with the surrounding rock, these low temperatures are expected. Corrections based on curves by Scott (1982) increase measured bottom-hole temperatures to within a few degrees of, but still lower than, those modeled by Gallardo (1989), supporting the concept of anomalous cooling in this area. Based on the model given here (using data of Gallardo, 1989), actual temperatures may be as much as 95˚C below normal in the Pennsylvanian part of the cool zone (fig. 6) and as much as 125˚C below normal through the cool zone of the lower Paleozoic.

Vitrinite reflectance values for the lower Paleozoic part of the cool zone are significantly low relative to the normal vitrinite reflectance–depth trend for that group of strata (fig. 3), reflecting the anomalously low temperatures in that area and supporting the cool zone model. In contrast, vitrinite reflectance values from Pennsylvanian strata, from wells within the boundaries of the cool zone mapped on top of the Pennsylvanian (fig. 5), are within or near the normal range for that group (fig. 2). Whether the two "anomalous" vitrinite reflectance values of figure 2 (shown by diamonds) are from the northern edge of the zone where cooling is minimal or from outside the cool zone altogether (because of its irregular configuration in the subsurface) is unclear. In any case, taken together, the vitrinite reflectance–depth data from wells within the mapped areas representing the cool zone form a separate trend (fig. 4), albeit somewhat loosely constrained (r=0.81).

As expected, the cool zone vitrinite reflectance–depth trend diverges from the lower Paleozoic and Pennsylvanian trends (fig. 4) as cooling increases both downward and toward the Wichita Mountains front. The modeled cool zone temperature profiles (fig. 6) indicate, however, that the cooling effect begins at the top of the Pennsylvanian, at depths as shallow as 6,000 ft (1,800 m). In contrast, the empirical vitrinite reflectance–depth trend for the cool zone (fig. 4) shows that vitrinite reflectance values apparently are unaffected until much deeper. This apparent contradiction probably arises more from a lack of vitrinite reflectance–depth data from the shallow, Pennsylvanian part of the cool zone than from inaccuracies in the cool zone model. It is suggested here that additional vitrinite reflectance measurements from the cool zone at the low end of the thermal maturation scale where the onset of cooling occurs would result in a better defined and much flatter curve in closer agreement with that part of the model. The more important part of the curve (fig. 4), the high-maturity end where the cooling effect is maximized, agrees more closely with the model and probably would not change significantly with additional data. Therefore, when calculating vitrinite reflectance values for the cool zone, only the lower part of the curve (below 19,500 ft [5,940 m], fig. 4) is used.

STATISTICAL COMPARISON OF VITRINITE REFLECTANCE–DEPTH TRENDS

Exponential relations between vitrinite reflectance and depth have been successfully applied to thermal maturation studies of the Woodford Shale (Cardott and Lambert, 1985; Cardott, 1989), and to the Anadarko Basin in general (Schmoker, 1986), and are used here to approximate vitrinite reflectance values where actual measurements are not available. The parameters *a* (intercept) and *b* (relative rate of increase) of the exponential equation

$$Y=ae^{bX} \quad (1)$$

define exponential profiles in general and, where X is depth (in feet) and Y is vitrinite reflectance (in percent), define the vitrinite reflectance–depth relation, in particular. Whether the profiles presented in this paper are different from each other is determined using confidence intervals for the parameters *a* and *b* (fig. 7). The location and width of the confidence intervals depend on the vitrinite reflectance–depth data set and a specified probability, or confidence level. The separation of the confidence intervals along the horizontal axis (fig. 7) reflects the degree to which the parameters, and thus the profiles, are different. At a given level of confidence, the width of the interval increases with variation in the sample population (Walpole and Myers, 1985); thus, a narrower interval, which reflects less variation in the data, is preferred.

Figure 7 shows confidence intervals for parameters *a* and *b* at the 95 percent confidence level for a number of vitrinite reflectance–depth profiles. Widely separated intervals for early Paleozoic and Pennsylvanian groups of strata and for the anomalously cool zone indicate discrete vitrinite reflectance–depth profiles that independently corroborate the thermal regimes of Gallardo (1989) and the anomalously cool zone described herein. In contrast, overlapping intervals for the Pennsylvanian and for the Anadarko Basin as a whole (this report) indicate profiles that are not statistically different. Figure 7 suggests that the profiles for Pennsylvanian-age strata and for the Anadarko Basin as a whole (Schmoker, 1986; this report) are reasonable approximations of the vitrinite reflectance–depth relation for the Anadarko Basin in general. Individual groups of strata, however, are probably best represented by their respective profiles. Thus, vitrinite reflectance (R_o) data for the porosity–vitrinite reflectance plots of this report are calculated using vitrinite reflectance–depth profiles for the Pennsylvanian group of strata (fig. 2),

$$R_o=0.37e^{Z/10,279}, \quad (2)$$

or the anomalously cool zone (below 19,500 ft [5,940 m], fig. 4),

$$R_o=0.79e^{Z/17,300}. \quad (3)$$

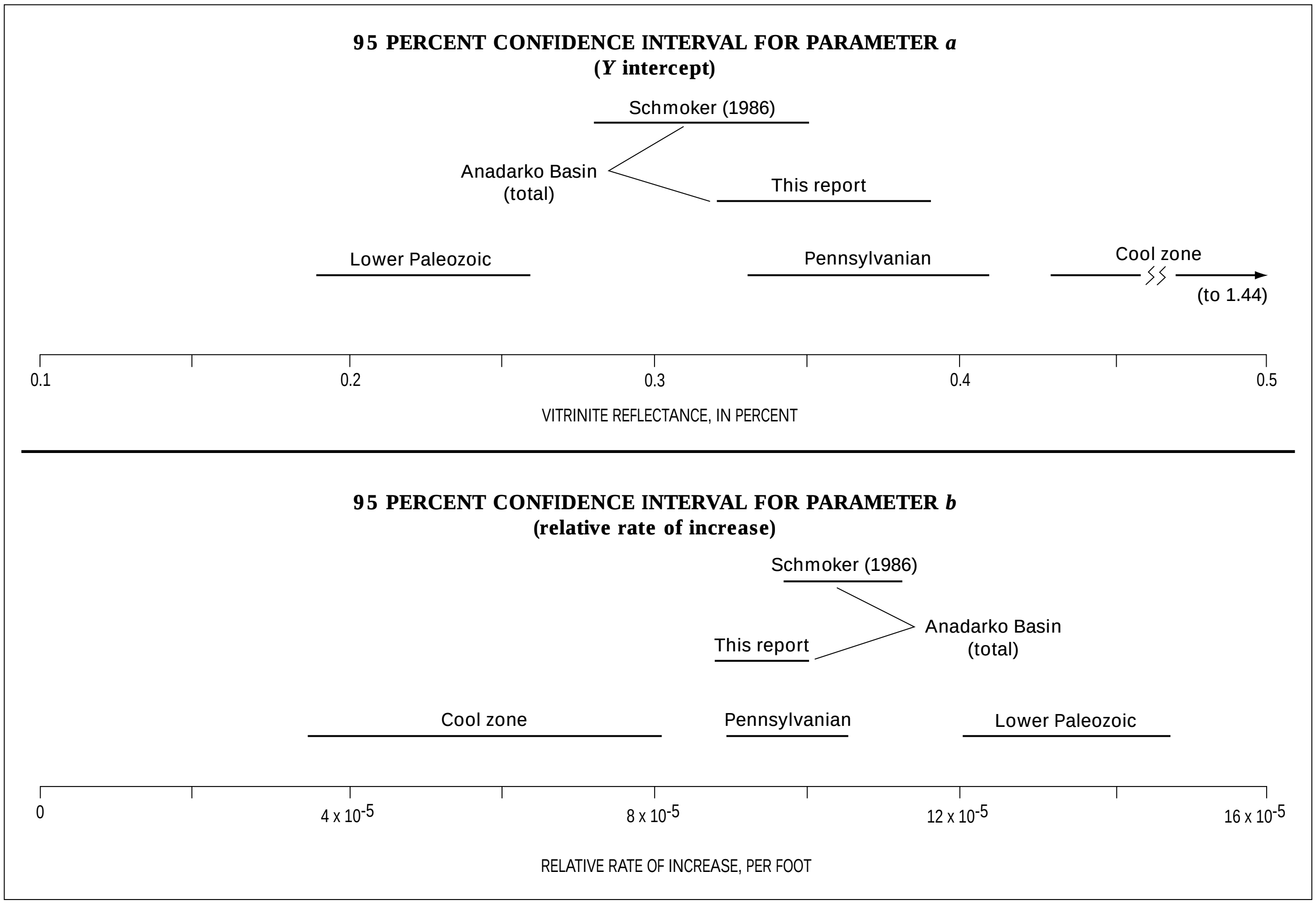


Figure 7. Confidence intervals (solid lines) at 95 percent level for parameter *a* (*Y*-intercept) and *b* (relative rate of increase) of exponential equation $Y=ae^{bX}$ where *X* is depth (in feet) and *Y* is vitrinite reflectance (in percent) (text equation 1) representing vitrinite reflectance–depth profiles for lower Paleozoic, Pennsylvanian, and cool zone strata and the Anadarko Basin as a whole (Schmoker, 1986; this report).

POROSITY–VITRINITE REFLECTANCE DATA SETS

To best characterize porosity trends of Pennsylvanian sandstones in the Anadarko Basin, three data sets are used: two data sets representing Anadarko Basin sandstones (Pennsylvanian only) and one composite data set (Schmoker and Hester, 1990) of sandstones from numerous basins exclusive of the Anadarko representing sandstones in general (all ages). Each of the three data sets consists of many sandstone porosity–vitrinite reflectance data pairs that provide trends representative of that particular subset of sandstones. The two Anadarko Basin data sets are termed reservoir sandstones, those specifically documented in the literature as commercially producing hydrocarbon reservoirs, and nonreservoir sandstones, those which are interpreted directly from well logs.

The important distinction between the two Anadarko Basin data sets is that reservoir sandstones are all documented hydrocarbon-bearing commercially producing sandstone reservoirs, whereas the nonreservoir sandstones are not. Therefore, the reservoir sandstones data set represents precisely as the term implies. Nonreservoir sandstones, on the other hand, are exclusively log derived. The nonreservoir data set represents, in effect, a systematic and thorough sampling from surface casing to total depth of every sandstone in each of 33 wells. Some of the nonreservoir sandstones may be charged with hydrocarbons and in some areas may contribute to hydrocarbon production, but the majority probably do not. Thus, the nonreservoir sandstone data set more or less represents Anadarko Basin sandstones (Pennsylvanian) as a whole.

The reservoir data set provides a porosity–vitrinite reflectance trend typical of Anadarko Basin Pennsylvanian, hydrocarbon-bearing commercially producing sandstone reservoirs. The porosity data consist of averaged measurements of 88 Pennsylvanian-age sandstone oil and gas reservoirs of the Anadarko Basin (fig. 1, table 1) from published oil- and gas-field compilations (Cramer and others, 1963; Berg and others, 1974; Pipes, 1980; Harrison and Routh, 1981). Vitrinite reflectance values for reservoir sandstones

Table 1. Oil and (or) gas reservoirs in the Anadarko Basin, Oklahoma, from which reservoir porosity data were obtained.
[Field and reservoir names are from oil- and gas-field compilations cited in this report]

Approximate location	Field name	Reservoir
T. 27 N., R. 18 W.	Avard, N.W.	Tonkawa.
T. 27 N., R. 18 W.	Avard, N.W.	Desmoinesian.
T. 10 N., R. 10 W.	Binger and East	Middle Marchand.
T. 10 N., R. 10 W.	Binger-Cogar	Lower Marchand.
T. 10 N., R. 10 W.	Binger, East	Upper Marchand.
T. 17 N., R. 26 W.	Bishop	Tonkawa.
T. 16 N., R. 26 W.	Bishop	Tonkawa.
T. 1 N., R. 22 ECM	Camrick Area	Morrow.
T. 12 N., R. 21 W.	Carpenter	Morrow.
T. 5 N., R. 11 ECM	Carthage Dist., N.E.	Morrow.
T. 5 N., R. 11 ECM	Carthage Gas Area	Morrow.
T. 23 N., R. 17 W.	Cedardale, N.E.	Missourian.
T. 22 N., R. 17 W.	Cedardale	Cottage Grove.
T. 5 N., R. 9 W.	Cement (all areas)	Hoxbar Group.
T. 5 N., R. 9 W.	Cement (all areas)	Wade.
T. 5 N., R. 9 W.	Cement (all areas)	Medrano.
T. 6 N., R. 9 W.	Cement (all areas)	Missourian.
T. 13 N., R. 10 W.	Calumet	Morrow.
T. 18 N., R. 14 W.	Canton, S.W.	Morrow.
T. 18 N., R. 12 W.	Carleton, N.E.	Atoka-Morrow.
T. 18 N., R. 12 W.	Carleton, N.E.	Morrow.
T. 23 N., R. 25 W.	Catesby-Chaney	Morrow.
T. 27 N., R. 9 W.	Cherokita Trend	Cherokee.
T. 27 N., R. 10 W.	Cherokee, N.E.	Cherokee.
T. 23 N., R. 13 W.	Cheyenne Valley	Desmoinesian.
T. 21 N., R. 15 W.	Cheyenne Valley	Red Fork.
T. 13 N., R. 24 W.	Cheyenne, West	Upper Morrow.
T. 8 N., R. 8 W.	Chickasha, N.W.	Missourian.
T. 7 N., R. 3 W.	Dribble, North	Red Fork.
T. 10 N., R. 21 W.	Elk City	Missourian.
T. 2 N., R. 23 ECM	Elmwood	Morrow.
T. 4 N., R. 10 ECM	Eva, N.W.	Cherokee.
T. 5 N., R. 23 ECM	Forgan, South	Morrow.
T. 21 N., R. 24 W.	Gage, South	Morrow.
T. 20 N., R. 24 W.	Gage, South	Morrow.
T. 13 N., R. 10 W.	Geary	Morrow.
T. 8 N., R. 17 W.	Gotebo Area, North	Springer.
T. 6 N., R. 21 ECM	Greenough, West	Desmoinesian.
T. 3 N., R. 17 ECM	Hardest, North	Morrow.
T. 18 N., R. 26 W.	Higgins, South	Morrow.
T. 17 N., R. 11 W.	Hitchcock	Atoka.
T. 24 N., R. 4 W.	Hunter, South	Layton.
T. 5 N., R. 9 ECM	Keys Area	Morrow.
T. 5 N., R. 9 ECM	Keys	Keys.
T. 26 N., R. 25 W.	Laverne	Hoover.

Table 1. Oil and (or) gas reservoirs in the Anadarko Basin, Oklahoma, from which reservoir porosity data were obtained—Continued.

Approximate location	Field name	Reservoir
T. 26 N., R. 25 W.	Laverne	Tonkawa.
T. 26 N., R. 25 W.	Laverne	Morrow.
T. 18 N., R. 18 W.	Lenora	Morrow.
T. 5 N., R. 21 ECM	Light Gas Area	Upper Morrow.
T. 5 N., R. 21 ECM	Light Gas Area	Basal Morrow.
T. 1 N., R. 26 ECM	Logan, South	Morrow.
T. 1 N., R. 26 ECM	Logan, South	Tonkawa.
T. 28 N., R. 21 W.	Lovedale	Morrow.
T. 28 N., R. 21 W.	Lovedale	Tonkawa.
T. 24 N., R. 24 W.	Luther Hill	Lower Tonkawa.
T. 24 N., R. 24 W.	Luther Hill	Lower Morrow.
T. 28 N., R. 3 W.	Mayflower, N.W.	Red Fork.
T. 8 N., R. 7 W.	Minco, S.W.	Springer.
T. 27 N., R. 24 W.	Mocane-Laverne	Morrow.
T. 5 N., R. 15 ECM	Mouser	Morrow.
T. 7 N., R. 8 W.	Norge & Verden, N.W.	Marchand.
T. 24 N., R. 13 W.	Oakdale, N.W.	Red Fork.
T. 17 N., R. 14 W.	Oakwood, North	Morrow.
T. 18 N., R. 14 W.	Oakwood, N.W.	Morrow.
T. 20 N., R. 11 W.	Okeene, N.W.	Red Fork.
T. 19 N., R. 11 W.	Okeene, N.W.	Red Fork.
T. 11 N., R. 2 W.	Oklahoma City	Prue.
T. 5 N., R. 13 ECM	Postle	Morrow.
T. 5 N., R. 13 ECM	Postle	Cherokee.
T. 4 N., R. 13 ECM	Postle-Hough	Upper Cherokee.
T. 5 N., R. 13 ECM	Postle-Hough	Upper Morrow.
T. 4 N., R. 14 ECM	Postle-Hough	Upper Morrow.
T. 4 N., R. 14 ECM	Postle-Hough	Morrow.
T. 16 N., R. 16 W.	Putnam	Desmoinesian.
T. 13 N., R. 26 W.	Reydon, W. and N.W.	Upper Morrow.
T. 5 N., R. 12 ECM	Richland, Central, N.	Morrow.
T. 25 N., R. 3 W.	Saltfork, S.E.	Skinner.
T. 20 N., R. 16 W.	Seiling, N.E.	Cottage Grove.
T. 8 N., R. 20 W.	Sentinel, West	Granite Wash.
T. 21 N., R. 21 W.	Sharon, West	Morrow.
T. 21 N., R. 21 W.	Sharon, West	Sharon.
T. 20 N., R. 8 W.	Sooner Trend	Desmoinesian.
T. 5 N., R. 10 ECM	Sturgis, East	Morrow.
T. 23 N., R. 22 W.	Tangier	Morrow.
T. 28 N., R. 8 W.	Wakita Trend	Cherokee.
T. 8 N., R. 4 W.	Washington, E.	Osborne.
T. 14 N., R. 10 W.	Watonga-Chickasha	Morrow.
T. 14 N., R. 10 W.	Watonga-Chickasha	Springer.
T. 14 N., R. 10 W.	Watonga-Chickasha	Atoka.
T. 25 N., R. 16 W.	Waynoka, N.E.	Cottage Grove.
T. 22 N., R. 19 W.	Woodward, S.E.	Morrow.

Table 2. Wells in the Anadarko Basin, Oklahoma, from which nonreservoir porosity data were obtained.

Location	Operator	Well name
Sec. 21, T. 8 N., R. 12 W.	Sohio Petroleum	1–21 Stockton.
Sec. 1, T. 7 N., R. 12 W.	Sohio Petroleum	1–1 Cay.
Sec. 24, T. 10 N., R. 13 W.	Helmerich and Payne	1 Phifer.
Sec. 32, T. 8 N., R. 9 W.	Sohio Petroleum	1–32 Harper.
Sec. 29, T. 7 N., R. 9 W.	Shell Oil	1–29 Bruer.
Sec. 25, T. 7 N., R. 11 W.	Helmerich and Payne	1–25 Charles Adams.
Sec. 18, T. 9 N., R. 13 W.	L.G. Williams Inc	1–18 Allred.
Sec. 19, T. 10 N., R. 13 W.	Hadson Petroleum Corp	1–19 Adams.
Sec. 10, T. 8 N., R. 13 W.	Dyco Petroleum Corp	1–10 Moses Caley.
Sec. 6, T. 7 N., R. 9 W.	Cotton Petroleum Corp	1 Mary.
Sec. 18, T. 8 N., R. 9 W.	Cotton Petroleum Corp	1–A Cox.
Sec. 28 T. 8 N., R. 11 W.	GHK	1–28 Didier.
Sec. 33, T. 8 N., R. 10 W.	Sanguine LTD	1 Griffitis.
Sec. 13, T. 7 N., R. 10 W.	Shell Oil	1–13 Moore.
Sec. 26, T. 7 N., R. 9 W.	Sanguine LTD	1 Mae West.
Sec. 4 T. 7 N., R. 11 W.	Sohio Petroleum	1–4 Nikkel.
Sec. 10, T. 7 N., R. 9 W.	Cotton Petroleum Corp	1–10 Kvasnica.
Sec. 26, T. 7 N., R. 10 W.	Davis Oil	1–26 J.D. Miles.
Sec. 19, T. 11 N., R. 13 W.	Lear Pet. Expl. Inc	1–19 Horn.
Sec. 25, T. 11 N., R. 12 W.	Cotton Petroleum Corp	1–A Dorsey.
Sec. 10, T. 16 N., R. 12 W.	Davis Oil	1 Pickett.
Sec. 7, T. 16 N., R. 10 W.	Bogert Oil	1–7 Bernhardt.
Sec. 4, T. 18 N., R. 11 W.	Bogert Oil	1–4 Henry.
Sec. 34, T. 22 N., R. 9 W.	Arapaho Petroleum	2–34 Cottons.
Sec. 3 , T. 21 N., R. 9 W.	Berry Petroleum	1–3 Perry.
Sec. 19, T. 20 N., R. 9 W.	Western Pacific Pet.	1–1 Patterson.
Sec. 16, T. 21 N., R. 11 W.	Ladd Petroleum Corp	4 Shiddell.
Sec. 31, T. 20 N., R. 13 W.	Nobel Operating Inc	2 Sholters.
Sec. 25, T. 20 N., R. 10 W.	Bogert Oil	1–25 Frank.
Sec. 36, T. 20 N., R. 10 W.	Cuesta Energy Corp	1–36 Seelke.
Sec. 28, T. 20 N., R. 10 W.	Prime Energy Corp	1–28 Bierig.
Sec. 21, T. 22 N., R. 16 W.	Shell Oil	2–21 Foster.
Sec. 16, T. 20 N., R. 16 W.	TXO Production Corp	1–A Hoskins.

are calculated using either equation 2 or equation 3 (fig. 2 or 4, respectively).

The nonreservoir data set provides porosity-vitrinite reflectance trends typical of Anadarko Basin Pennsylvanian sandstones as a whole. The porosity data consist of about 650 values representing more than 5,500 ft net (1,675 m) of sandstone from 33 well locations (fig. 1, table 2) in the central and southern Anadarko Basin. Sandstone is identified in each well using compensated-neutron and formation-density logs run on limestone matrix and is then subdivided into intervals of uniform log character. The neutron and density porosity of each interval (4 ft [1.2 m] or more thick) is averaged and its true porosity determined using standard neutron-density crossplots. To exclude shaley sandstones from the data set, the shift of true porosity toward the "shale-point" of the neutron-density crossplot is allowed only two porosity units. Vitrinite reflectance values are calculated for nonreservoir sandstones using either equation 2 or equation 3 (fig. 2 or 4, respectively).

The third data set represents a sampling of sandstones of diverse ages, geologic settings, diagenetic facies, and thermal histories and provides a framework of porosity–vitrinite reflectance trends typical of sandstones in general (Schmoker and Hester, 1990) with which to compare both Anadarko Basin reservoir and nonreservoir sandstone porosity data. The framework data consist of many thousands of individual porosity and vitrinite reflectance measurements from Mesozoic and Cenozoic sandstones in 27 locations in the Northern Hemisphere, exclusive of the Anadarko Basin. The framework data set presented in this report is represented by least-squares regression lines fit to the 10th, 25th, 50th, 75th, and 90th porosity percentiles (Cleveland, 1985), analogous to those of Schmoker and Hester (1990).

POROSITY–VITRINITE REFLECTANCE TRENDS

A least-squares regression line fit (using a power-function transformation) to the porosity–vitrinite reflectance data for Anadarko Basin nonreservoir sandstones shows that nonreservoir sandstone porosity generally decreases with increasing thermal maturity (fig. 8). The data appear to consist, however, of two separate populations—a less thermally mature population for which vitrinite reflectance is less than 1.1 percent and a more thermally mature population for which vitrinite reflectance is greater than 1.1 percent. Correlation coefficients (*r*) of the least-squares regression lines fit to each of the two data populations (fig. 9) show a much stronger dependence of porosity on vitrinite reflectance for the less mature trend of nonreservoir sandstones (where vitrinite reflectance <1.1 percent, $r=-0.63$) than for nonreservoir sandstones taken as a whole (fig. 8, $r=-0.39$). The higher correlation of the less mature trend compared to that of the data set as a whole suggests that the two data populations (vitrinite reflectance <1.1 percent and vitrinite reflectance >1.1 percent) might best be considered as separate trends. The two trends probably overlap to some extent as the more mature trend diverges from the less mature trend. Also, additional porosity data might show the rapid porosity loss of the less mature trend continuing beyond a vitrinite reflectance level of 1.1 percent (fig. 9), thereby revealing two diagenetic pathways of porosity loss for vitrinite reflectance >1.1 percent. The separation of the more mature and less mature populations by a single, preliminary boundary at vitrinite reflectance=1.1 percent is used here for convenience and does not necessarily imply a direct causal link between the change in rate of porosity loss and a specific level of thermal maturation.

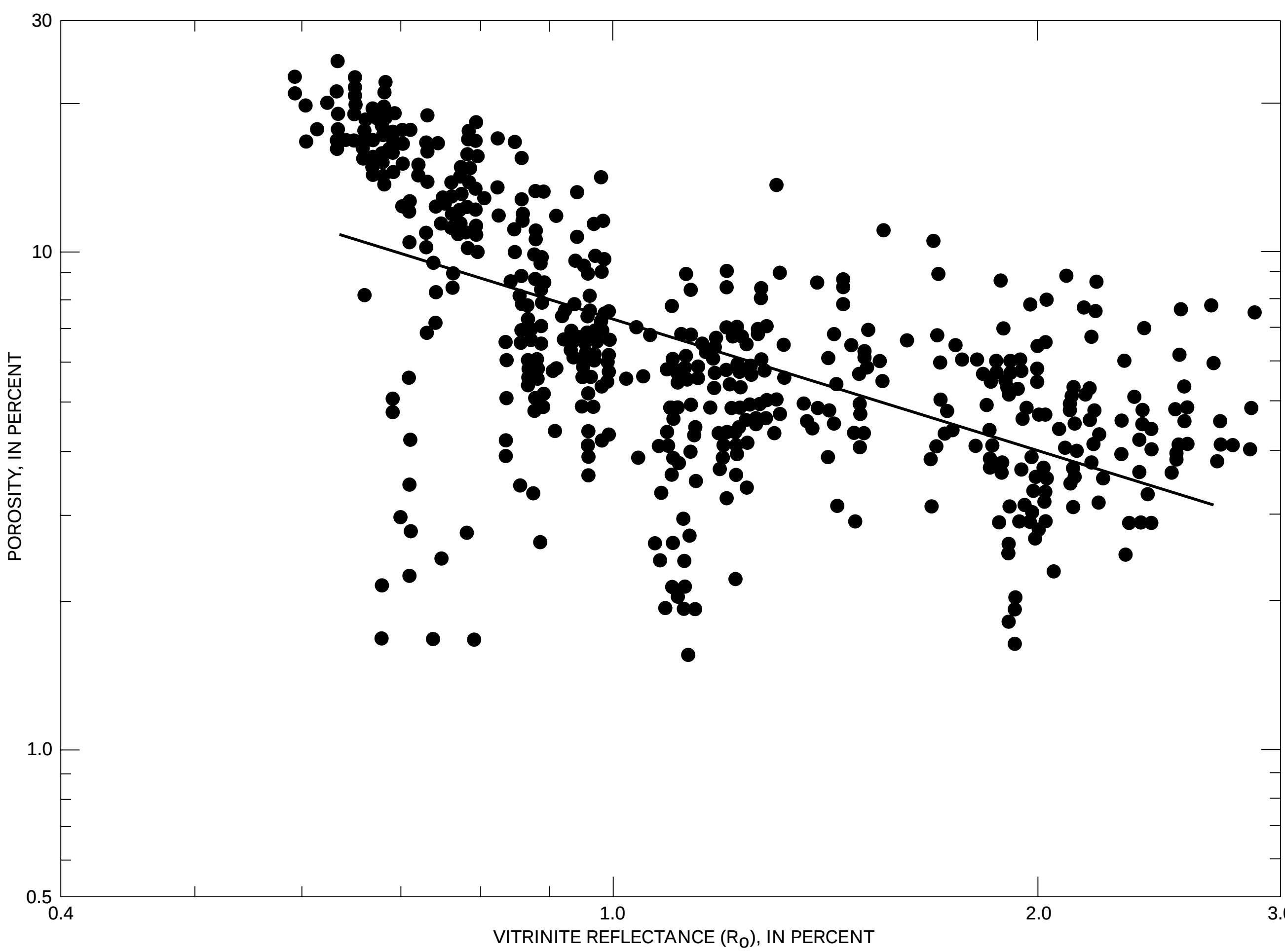


Figure 8. Porosity of Anadarko Basin nonreservoir sandstones (Pennsylvanian) versus vitrinite reflectance (calculated using text equation 2 or 3). Least-squares regression line fit to entire data set is also shown.

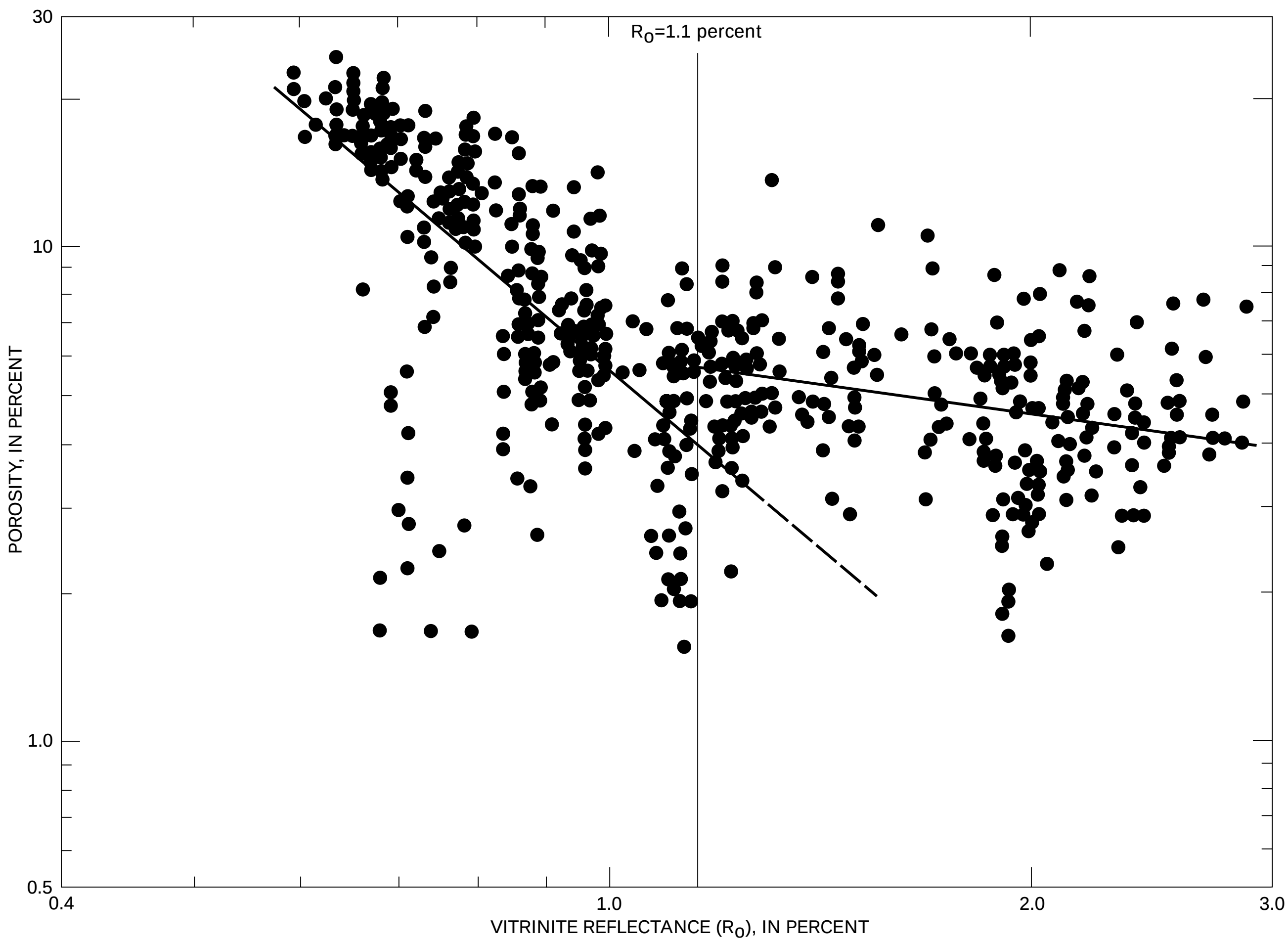


Figure 9. Porosity of Anadarko Basin nonreservoir sandstones (Pennsylvanian) versus vitrinite reflectance (calculated using text equation 2 or 3). Least-squares regression lines fit to each of two data populations separated at vitrinite reflectance=1.1 percent are also shown (dashed where extrapolated).

In both populations of points shown in figure 9, porosity generally decreases as a power function (Schmoker and Gautier, 1988, equation 1) of increasing thermal maturity. The least-squares regression lines fit to the data show that for vitrinite reflectance <1.1 percent, the rate of porosity decrease with increasing vitrinite reflectance for nonreservoir sandstones is more rapid than that for the framework data which represent sandstones in general (fig. 10). For vitrinite reflectance >1.1 percent, the rate of porosity decrease for Anadarko Basin nonreservoir sandstones is less rapid than that of sandstones in general.

The reasons for the change of slope of the porosity trend for Anadarko Basin nonreservoir sandstones are not yet clear. To speculate, the two populations of nonreservoir sandstone porosity data (apparent in figures 8–12) may represent sandstones from different depositional environments or subsurface pressure regimes or sandstones having different burial or diagenetic histories. Identification and stratigraphic correlation of the nonreservoir sandstones, with the addition of petrographic and subsurface-pressure information, are suggested here as a first approach to examining the nature of the two populations of Anadarko Basin nonreservoir sandstones.

The porosity–vitrinite reflectance trend of Anadarko Basin hydrocarbon-reservoir sandstones (fig. 11) follows a different pattern. The least-squares regression line for this trend shows that the rate of porosity loss for reservoir sandstones is much less rapid than that of both Anadarko Basin nonreservoir sandstones (vitrinite reflectance <1.1 percent) and sandstones in general (fig. 12). This relatively low rate of porosity decrease with increasing vitrinite reflectance could be due to geologic factors such as overpressuring or the inhibiting effects of hydrocarbon emplacement on sandstone diagenesis and (or) to economic factors such as the bias inherent in the selection of economically producible (commercial) sandstone hydrocarbon reservoirs.

As vitrinite reflectance increases from low levels to about 1.1 percent, the porosity trends of Anadarko Basin reservoir and nonreservoir sandstones cross (figs. 11, 12). Thus, as thermal maturity increases, the porosity of reservoir

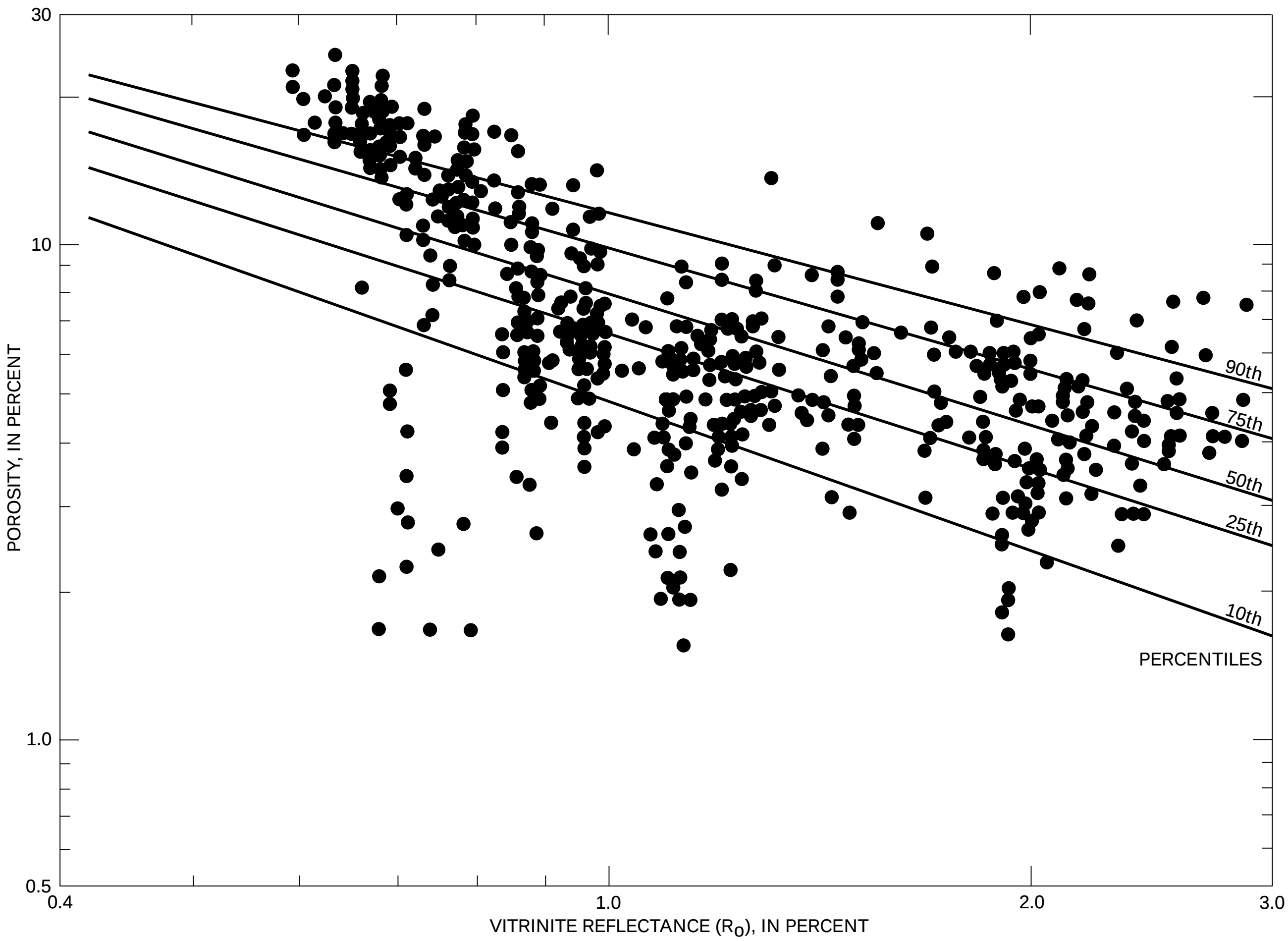


Figure 10. Porosity of Anadarko Basin nonreservoir sandstones (Pennsylvanian) versus vitrinite reflectance (calculated using text equation 2 or 3). Least-squares regression lines fit to 10th, 25th, 50th, 75th, and 90th porosity percentiles of a framework data set representing sandstones in general (Schmoker and Hester, 1990) are also shown.

sandstones is increasingly restricted to the upper range of porosity percentiles of nonreservoir sandstones. If these trends were to continue diverging, porosity sufficient for commercially producing sandstone hydrocarbon reservoirs would become extremely rare at only moderate levels of thermal maturity. At a vitrinite reflectance level of about 1.1 percent, however, the slope of the porosity trend for Anadarko Basin nonreservoir sandstones flattens (figs. 8–12). The average porosity of Anadarko Basin reservoir sandstones then remains within about the upper 10 percent of the porosity range of nonreservoir sandstones (fig. 11). As thermal maturity levels increase above about 1.1 percent vitrinite reflectance, the similar slopes of the porosity trends of Anadarko Basin reservoir and nonreservoir sandstones (fig. 12) suggest that a portion of Anadarko Basin sandstones retains sufficient porosity for economic accumulations of hydrocarbons, even at high thermal maturities.

The six porosity measurements of nonreservoir sandstones in the anomalously cool zone (fig. 12, shown as dots) are all above average as compared to those of similar thermal maturity in the Anadarko Basin as a whole and are more or less within the upper quartile of the framework data set representing sandstones in general (fig. 12). Two of the nonreservoir sandstones from the cool zone have porosities of about 8 percent and are almost on trend with porosities of Anadarko Basin reservoir sandstones. These few data points, albeit statistically insignificant, again suggest that, even at high thermal maturities, sandstone porosity in the Anadarko Basin, particularly in the anomalously cool zone, may be sufficient to host commercial, hydrocarbon accumulations.

SUMMARY

A single, straight-line thermal gradient for the Anadarko Basin of Oklahoma as a whole is somewhat oversimplified. A more detailed model, based on Gallardo (1989), subdivides the Anadarko Basin stratigraphically into three regimes, each having a different, but almost linear thermal gradient. In addition, the model indicates an anomalously

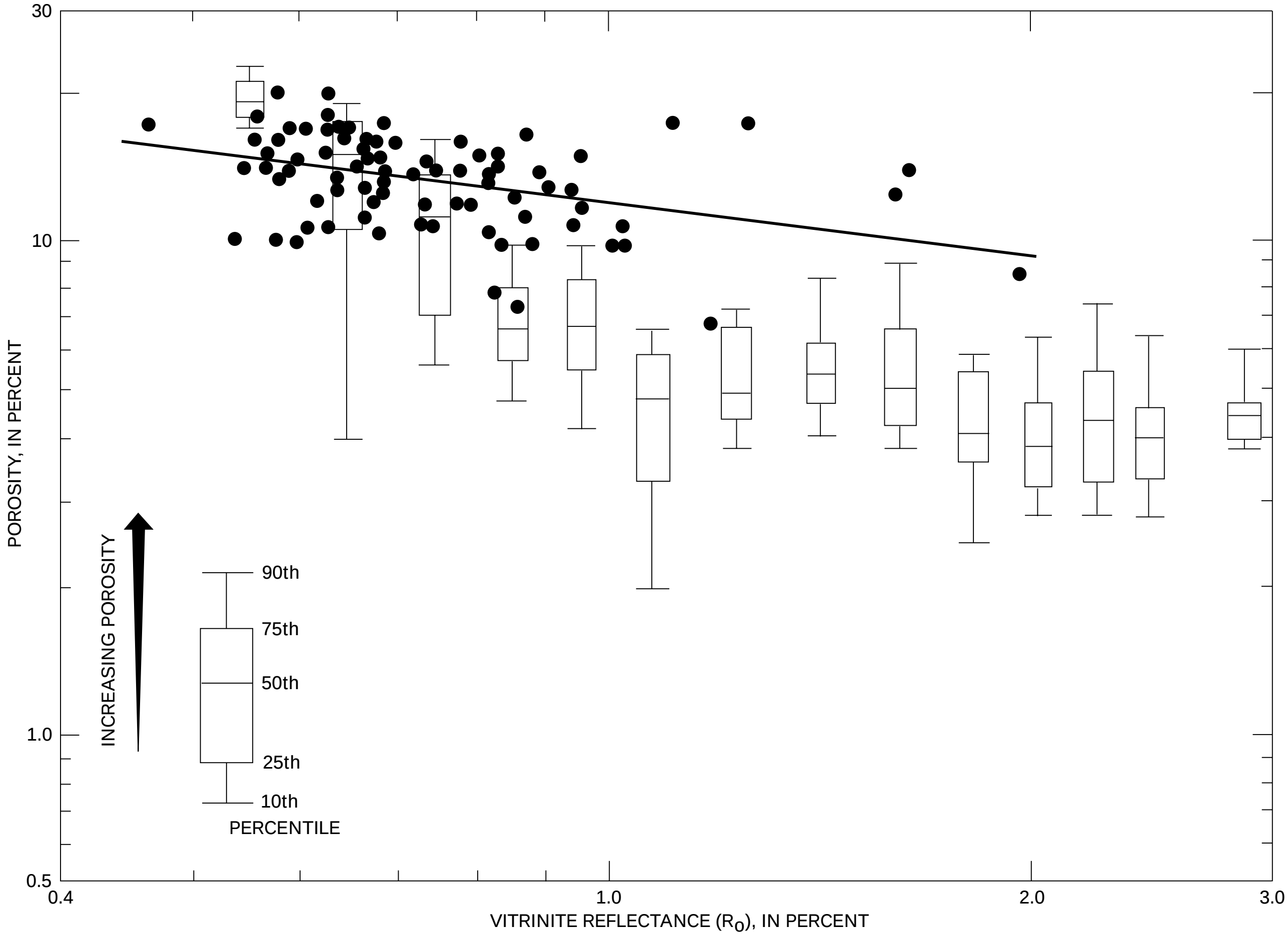


Figure 11. Porosity of Anadarko Basin reservoir sandstones (Pennsylvanian) versus vitrinite reflectance (calculated using text equation 2). Least-squares regression line is also shown. Box diagrams (explained at lower left) represent Anadarko Basin nonreservoir sandstone data.

cool zone along and adjacent to the Wichita Mountains front that extends through Pennsylvanian and lower Paleozoic strata. Empirical vitrinite reflectance–depth profiles (exponential), based on the thermal regimes, corroborate Gallardo's thermal model and provide trends with which to predict thermal maturity in areas for which vitrinite reflectance measurements are not available.

In this report, I investigate the relation between porosity and thermal maturity (vitrinite reflectance) for Pennsylvanian sandstones of the Anadarko Basin. To this end, three data sets are compiled—two representing Anadarko Basin sandstones and one from numerous basins exclusive of the Anadarko representing sandstones in general. Anadarko Basin reservoir sandstones represent precisely as the term implies, whereas nonreservoir sandstones more or less represent Anadarko Basin sandstones as a whole. By comparing data sets, Anadarko Basin sandstones are evaluated with respect to each other and with respect to sandstones in general. The regional porosity-vitrinite reflectance trends established here (using a power-function transformation) can also be extrapolated to unexplored areas of the deep Anadarko Basin.

Anadarko Basin nonreservoir sandstone porosity data consist of two overlapping populations separated herein at a vitrinite reflectance level of 1.1 percent. Compared to sandstones in general, porosity of the less thermally mature trend (vitrinite reflectance <1.1 percent) decreases rapidly, whereas that of the more thermally mature trend (vitrinite reflectance >1.1 percent) decreases slowly. Above a vitrinite reflectance level of 1.1 percent, the Anadarko Basin reservoir sandstone porosity trend is only a few porosity percent above the 90th percentile trend of the nonreservoir sandstones, and both lose porosity at about equal rates. This fact suggests that Anadarko Basin sandstones may retain sufficient porosity for economic accumulations of hydrocarbons, even at high thermal maturities.

The six sandstone porosity measurements in the anomalously cool zone are all above average for Anadarko Basin nonreservoir sandstones and for sandstones in general. These few measurements again suggest that the porosity of

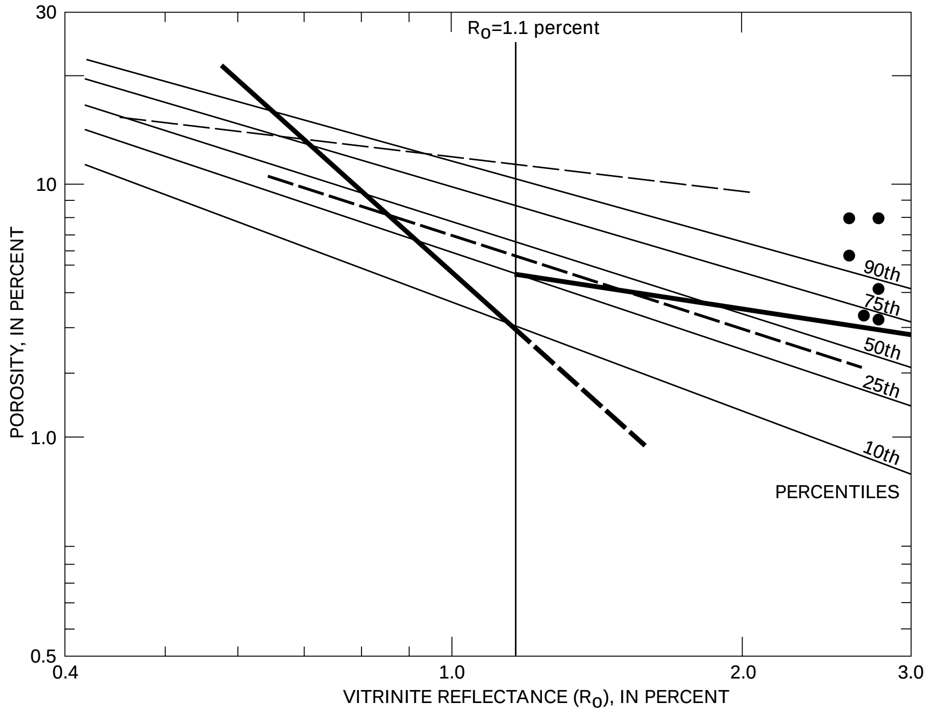


Figure 12. Summary diagram showing least-squares regression lines fit to the following data sets: Anadarko Basin nonreservoir sandstones (medium dashed line); each of two populations of Anadarko Basin nonreservoir sandstones separated at vitrinite reflectance=1.1 percent (heavy solid lines, dashed where extrapolated); 10th, 25th, 50th, 75th, and 90th porosity percentiles of a framework data set representing sandstones in general (Schmoker and Hester, 1990)(fine solid lines); and Anadarko Basin reservoir sandstones (fine dashed line). Dots represent sandstones from the anomalously cool zone. All sandstones are of Pennsylvanian age.

some sandstones in the Anadarko Basin, particularly those in the anomalously cool zone, may be sufficient to host commercial, hydrocarbon accumulations, even at high thermal maturities. The cool zone described in detail in this report represents an anomalous cooling trend of considerable proportion, considering the magnitude of cooling and the volume of sedimentary rock involved, and thus should be considered along with the three thermal regimes of Gallardo (1989) when modeling thermally controlled processes in the Anadarko Basin.

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