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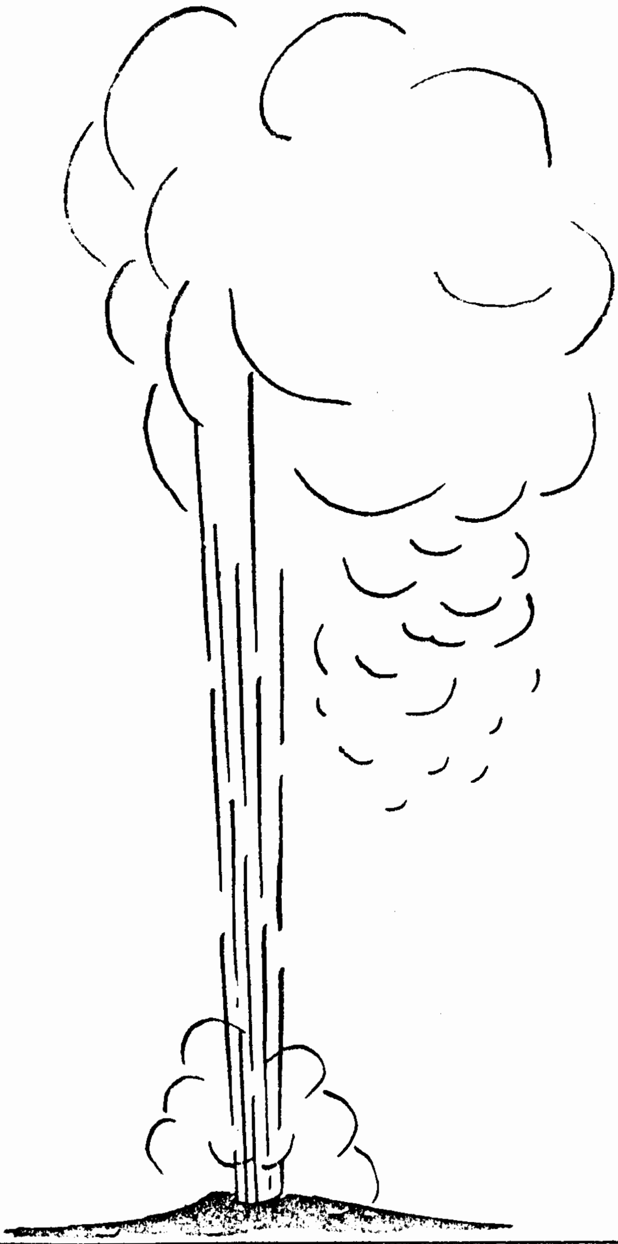

GEOTHERMAL RESOURCES, WILCOX GROUP, TEXAS GULF COAST

By
D. G. Bebout
V. J. Gavenda
A. R. Gregory

January 1978

Work Performed Under Contract No. EY-76-S-05-4891

Bureau of Economic Geology
The University of Texas at Austin
Austin, Texas

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Geothermal Energy

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GEOTHERMAL RESOURCES, WILCOX GROUP, TEXAS GULF COAST

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Prepared for

The U. S. Department of Energy, Division of Geothermal Energy

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January 1978

Bureau of Economic Geology

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W. L. Fisher, Director

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INTRODUCTION

Areas with the potential for containing geopressured geothermal fluids in economic quantities (geothermal fairways) occur in the Wilcox Group where the gulfward-dipping sandstone/shale wedge thickens abruptly across a complex growth-fault system.

This regional study of the sandstone distribution in the Wilcox Group is part of much broader investigation aimed at assessing the potential for the production of geothermal energy from the geopressured zone of the onshore Tertiary along the Texas Gulf Coast (Dorfman and Deller, 1975, 1976). The objective of the study is to identify areas where the Wilcox Group contains significant thicknesses of sandstone with subsurface fluid temperatures higher than 300°F. These favorable areas are termed geothermal fairways and are areas in which additional, more detailed work is recommended in the search for prospective geopressured geothermal test-well sites. Reports summarizing similar studies of regional assessment of the Frio Formation and a prospective test-well site have been published by the Bureau of Economic Geology (Bebout, Dorfman, and Agagu, 1975; Bebout, Agagu, and Dorfman, 1975; Bebout, Loucks, Bosch, and Dorfman, 1976; Bebout, Loucks, and Gregory, 1977). The geothermal potential of the Vicksburg Formation is summarized by Loucks (1978). Funding for the entire geopressured geothermal assessment program has been provided by the Division of Geothermal Energy, U. S. Department of Energy.

The Wilcox and Midway Groups, Lower Eocene, comprise the oldest thick sandstone/shale unit of the Gulf Coast Tertiary (fig. 1). The Wilcox sandstones and shales outcrop in a 10 to 20 mile-wide band which occurs subparallel to and 100 to [illegible]0 miles inland from the present-day coastline (fig. 2). From the outcrop, the Wilcox dips into the subsurface as one of at least eight sandstone/shale wedges (Hardin, 1961; fig. 3). The sediments of the updip portion of the wedges were deposited primarily by fluvial processes. Downdip, the sediments transported across the fluvial plain were deposited in huge deltaic complexes and some sediments were reworked by marine processes into barrier bars and strandplains. An understanding of the environmental setting was developed almost 40 years ago as noted by Deussen and Owen (1939) and has been expanded and refined since then by Culbertson (1940), Echols and Malkin (1948), and Hargis (1962) and emphasized most recently by Fisher and McGowen (1967).

Growth faults developed at the ancient shorelines of several of the larger wedges where thick sections of sand and mud were deposited on the unconsolidated offshore mud of the previous wedge (fig. 3). Subsidence along these faults resulted in the isolation of thick sandstone and shale units and prevented escape of pore fluids laterally during subsequent compaction resulting from loading; vertical escape of pore fluids was prevented by the low vertical permeability of the shales. The lack of circulation in these growth-faulted sections is responsible for the increase in pressure gradient from the normal .464 psi per foot to between .7 and 1.0 psi per foot and the increase in the temperature gradient from the normal 1.0°F per 100 feet to between 1.5 and 2.0°F per 100 feet. This downdip section with high pressure gradient and temperature exceeding 300°F comprises the Wilcox geothermal corridor (fig. 2).

SYSTEM	SERIES	GROUP/FORMATION
Quaternary	Recent	Undifferentiated
	Pleistocene	Houston
Tertiary	Pliocene	Goliad
	Miocene	Fleming
		Anahuac
	?——?	
	Oligocene	Frio
		Vicksburg
	Eocene	Jackson
		Claiborne
		Wilcox
		Midway

Figure 1. Tertiary formations, Gulf Coast of Texas. The Wilcox Group, the subject of this geothermal report, is shown by the diagonal pattern; the geothermal potential of the Frio and Vicksburg Formations, shown by the dot pattern, has been reviewed in other Bureau of Economic Geology reports (Bebout et.al., 1975a, 1975b, 1976, in press; Loucks, 1978).

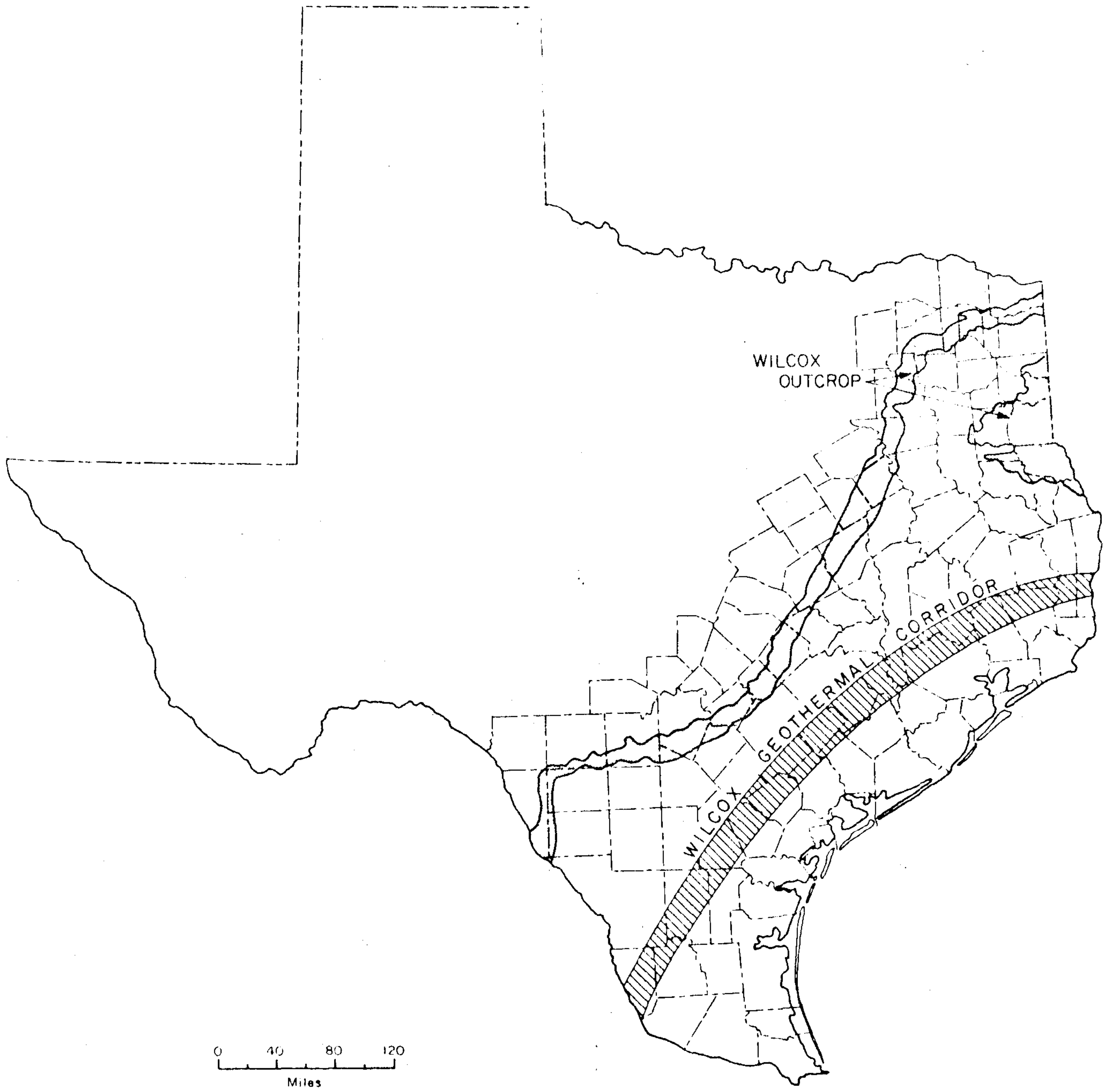

Figure 2. Wilcox geothermal corridor characterized by high pressure gradients and temperatures exceeding 300°F.

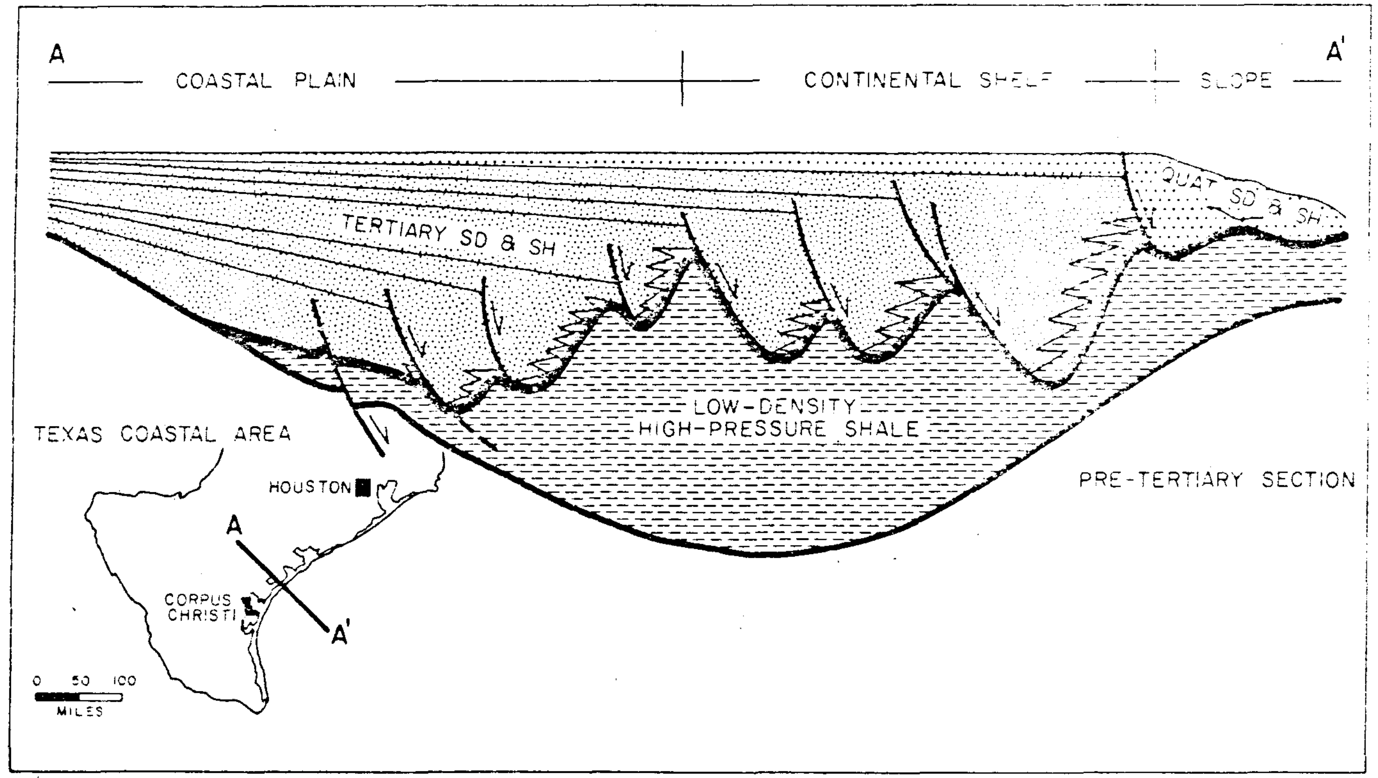

Figure 3. Depositional style of the Tertiary along the Texas Gulf Coast (Bruce, 1973).

WILCOX REGIONAL SETTING

The Wilcox Group is less than 2,000 feet thick updip, near the outcrop, and more than 8,000 feet thick downdip, at depths greater than 10,000 feet.

The Wilcox Group comprises a wedge of sandstone and shale which outcrops several hundred feet above sea level at its updip limit; downdip more than 100 miles, the Wilcox is deeper than 10,000 feet below sea level (figs. 4 and 6). Regional dip averages 100 feet per mile. Where the Wilcox depocenter prograded gulfward of the underlying Lower Cretaceous Stuart City shelf margin (Edwards and Sligo) a 20 mile-wide band of growth faults formed (fig. 5) suggesting that the rigid carbonate shelf controlled the location of growth-fault formation. The Wilcox sandstone and shale section thickens abruptly downdip of the Stuart City shelf margin (fig. 4, between wells 7 and 8). The area of steeper contours on the structure and thickness maps (figs. 6 and 7) in the central part of the trend coincides with the area where growth faulting is best developed.

The base of the Wilcox Group has been recognized as transitional with the underlying marine Midway Group and the upper Midway is believed by many to be a marine facies of the lowermost Wilcox fluvial and deltaic facies (Culbertson, 1940; Echols and Malkin, 1948; Johnston, 1977; Townsend, 1954). The top of the Wilcox Group is picked by us and by many others (Culbertson, 1940; Echols and Malkin, 1948; Fisher, 1969; and Murray, 1955) as the top of the Carrizo Sandstone because of the similarity in composition and depositional style of the Carrizo with the underlying upper Wilcox. Johnston (1977) considers that the Carrizo genetically belongs to the upper Wilcox but classifies it with the Claiborne Group because the original definition of the Carrizo by Plummer (1932) placed the formation in the Claiborne. Others have considered the Carrizo Formation as part of the overlying Claiborne Group because of the presence of an unconformity at the base of the Carrizo (Townsend, 1954) and of reworked Wilcox sandstone within the Carrizo (Todd and Folk, 1957). However, these criteria are not considered valid because unconformities and evidence of reworking are common within fluvial sections (Fisher, Brown, Scott, and McGowen, 1969).

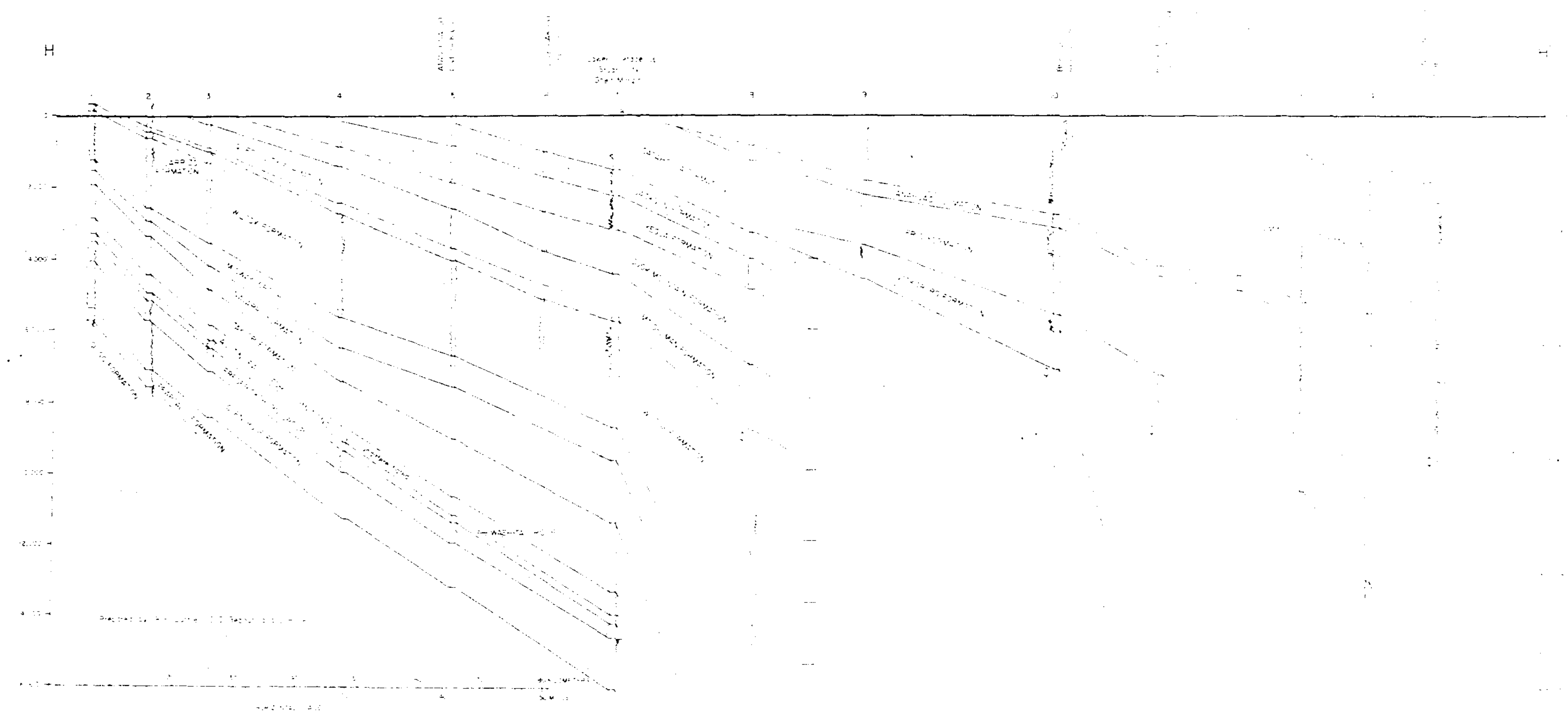

Figure 4. Regional dip section (Bebout, Luttrell, and Seo, 1975; section HH'). The Wilcox Group thickens abruptly just downdip of the Lower Cretaceous Stuart City shelf margin by means of a complex system of growth faults. The location of this section is shown on Figure 5.

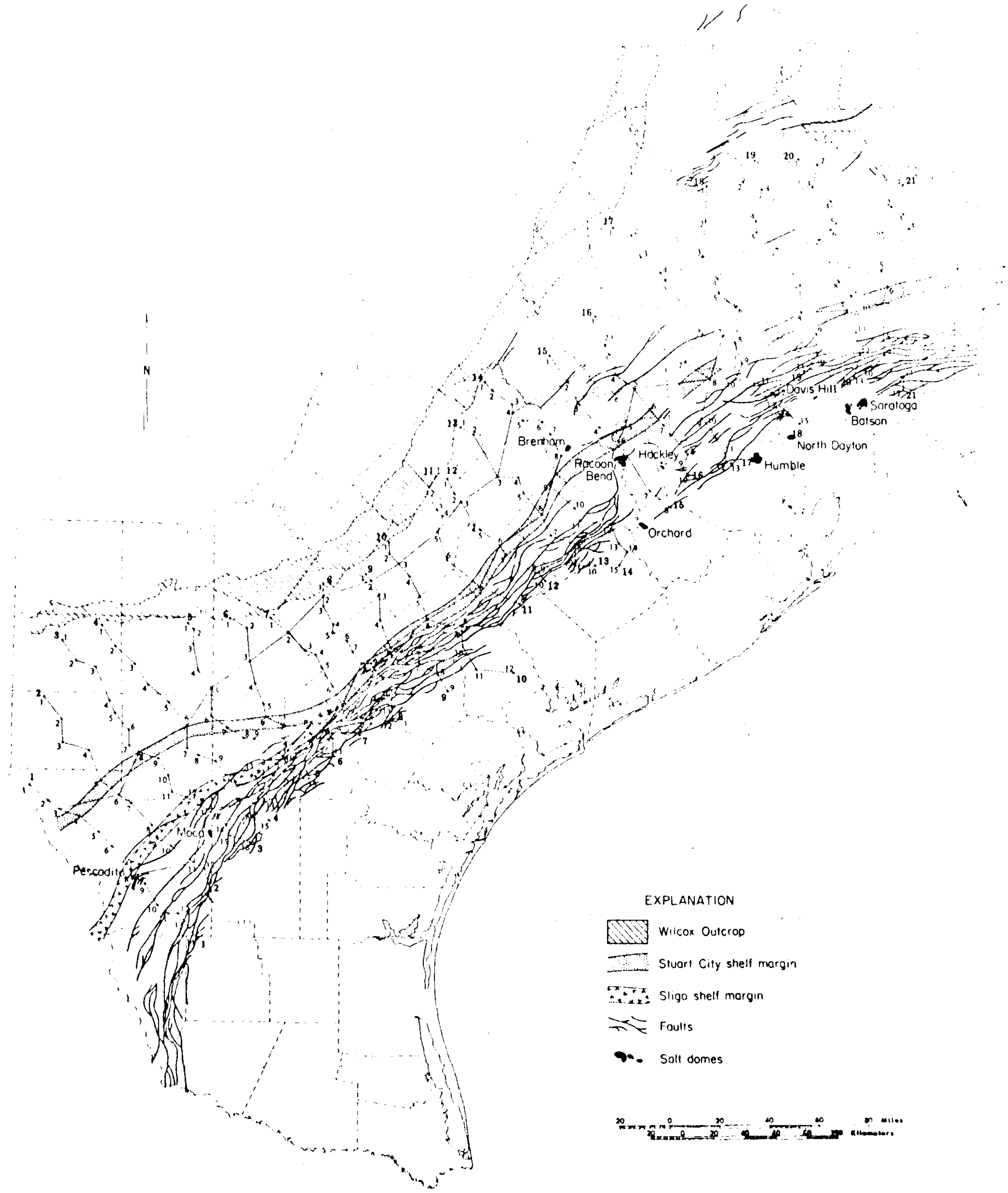

Figure 5. Faults in the Wilcox Group. Most of these faults are growth faults which were active during deposition of the Wilcox. Courtesy of Geomap Company, Houston, Texas. The location of **the regional dip section (fig. 4) is also shown.**

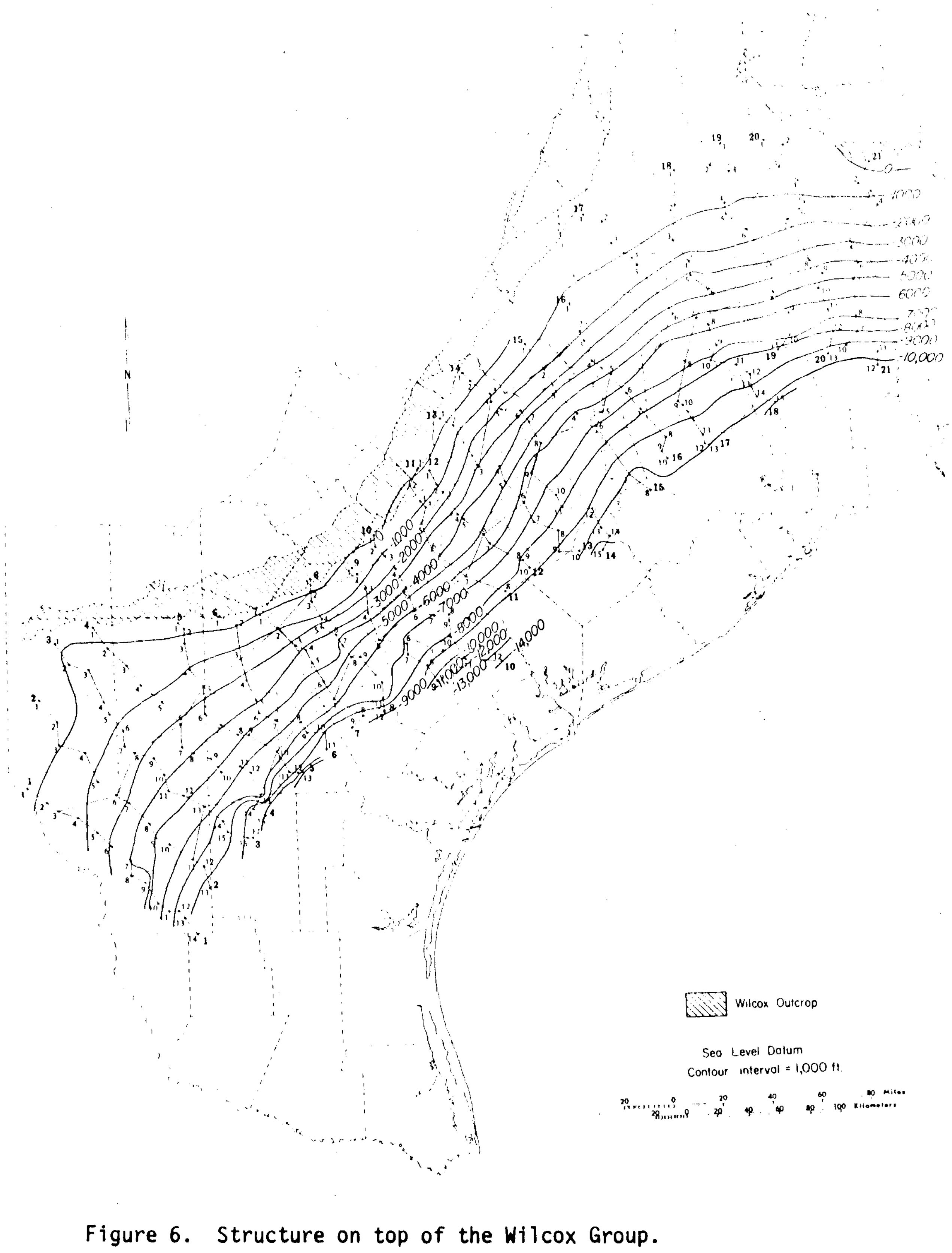

Figure 6. Structure on top of the Wilcox Group.

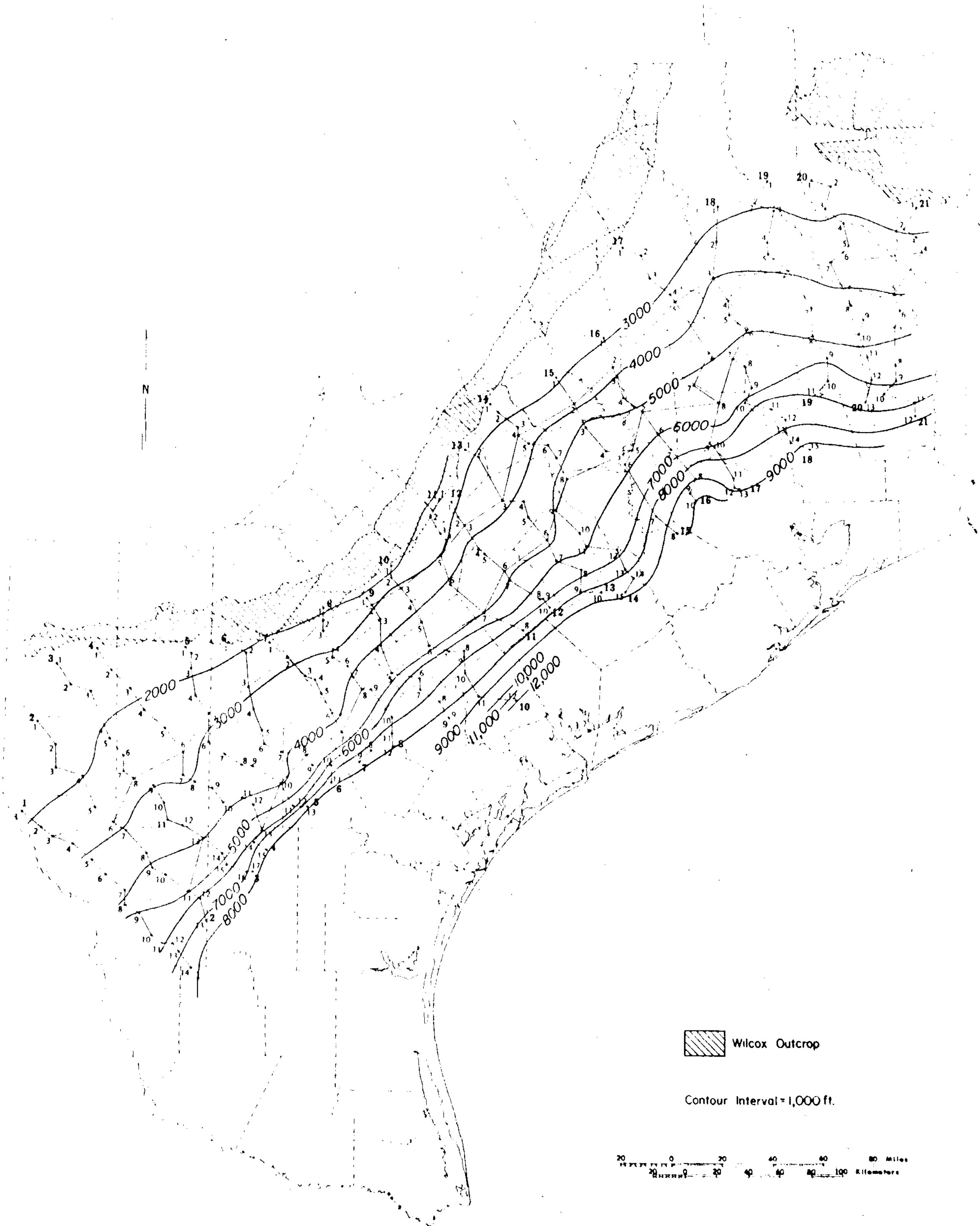

Figure 7. Total thickness of the Wilcox Group.

WILCOX STRATIGRAPHIC SECTIONS

The upper and lower Wilcox are two major progradational cycles separated by a transgression.

Control for this study was based on wells chosen so as to provide stratigraphic dip sections spaced 15 to 20 miles apart along the entire Texas Gulf Coast (fig. 8). The resulting 21 sections consist of 10 to 15 wells each and extend from near the Wilcox outcrop to the most downdip limit of correlation of the formation. Strike sections were constructed to insure consistency between dip sections. Data from these sections are supplemented by denser control used by Fisher and McGowen (1967). Datum for the sections is the top of the Wilcox Group. Growth faults present at the downdip end of the sections have been omitted from the sections because they tend to obscure correlation of sandstones from well to well.

The Wilcox Group is divided into the upper and lower parts based on the recognition of two major progradational cycles (fig. 9). Each cycle consists dominantly of shale at the base and grades to dominantly sandstone at the top. The upper and lower Wilcox are most easily separated in the middle part of the dip sections and are more difficult to recognize updip, where the section is dominantly sandstone, and downdip, where the section is dominantly shale. The lower Wilcox in many places appears to be made up of several smaller cycles such as in Dip Section 4, Wells 5 to 9 (fig. 13). The lower Wilcox of this report corresponds essentially with the lower Wilcox of Fisher and McGowen (1967). The upper Wilcox consists of the Carrizo Formation, upper Wilcox, and middle

Wilcox of Fisher and McGowen.

The Wilcox sections (figs. 10-32) show high sandstone content throughout except for the downdip end where growth faults are abundant and the proportion of shale increases significantly. Most sections show a marked decrease in the amount of sandstone within the downdip-most wells indicating a very low probability of the occurrence of significant quantities of sandstone basinward of present control. The sandstone distribution in the Wilcox is considerably different from that of the Frio (Bebout, Dorfman, and Agagu, 1975; Bebout, Agagu, and Dorfman, 1975; and Bebout, Loucks, Bosch, and Dorfman, 1976). Frio stratigraphic dip sections are readily divided areally from updip to downdip into three parts: the updip part which consists of thin, scattered sandstones in a dominantly shale section; the main-sandstone depocenter which consists of thick sandstones and thin shales; and the downdip part which is dominantly shale.

The top of geopressure, marked by the black arrow on the stratigraphic sections (figs. 10-32), occurs well beneath the base of the Wilcox along the updip two-thirds of the dip sections; within the zone of growth faulting, along the downdip third of the sections, the top of geopressure occurs mostly within the upper Wilcox. Subsurface fluid temperature of 300^{O}F, also indicated on the cross sections, occurs 1,000 to 1,500 feet beneath the top of geopressure.

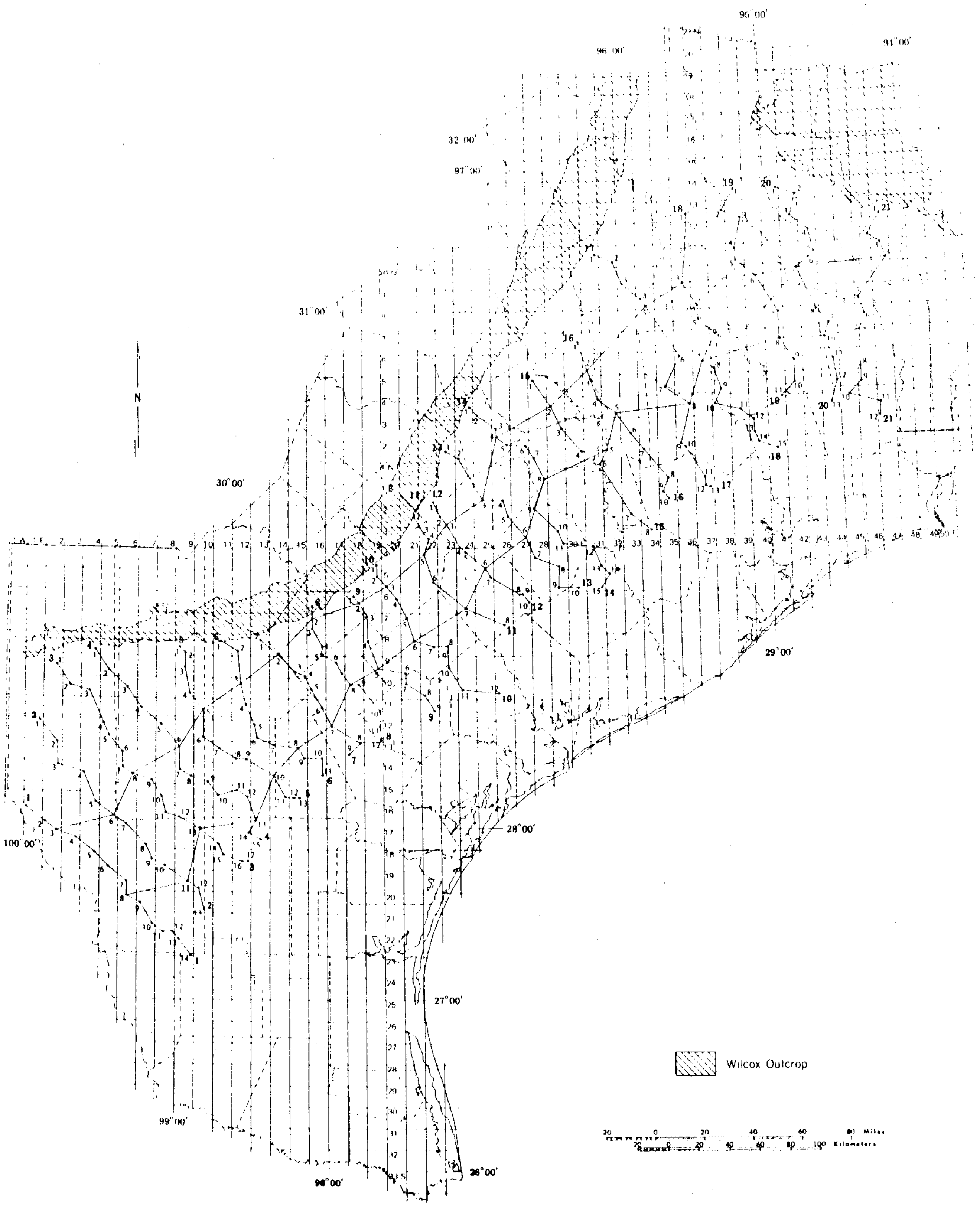

Figure 8. Well-log control and location of cross sections (figs. 10 to 32). Supplemental well data from Fisher and McGowen (1967) and Fisher (1969) are not shown.

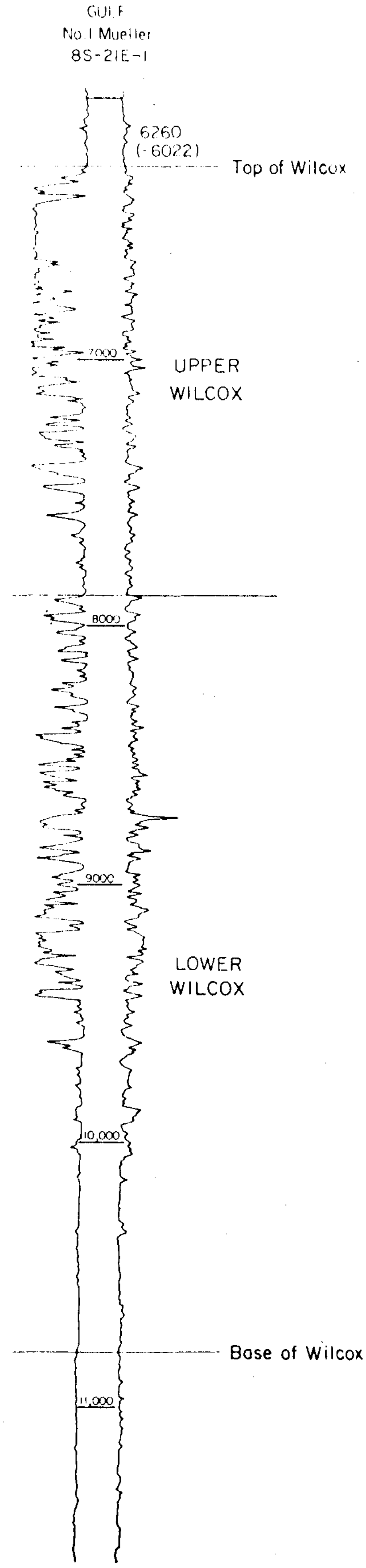

Figure 9. Electrical log showing division of the Wilcox Group into the lower and upper parts, each of which represents a major progradational cycle.

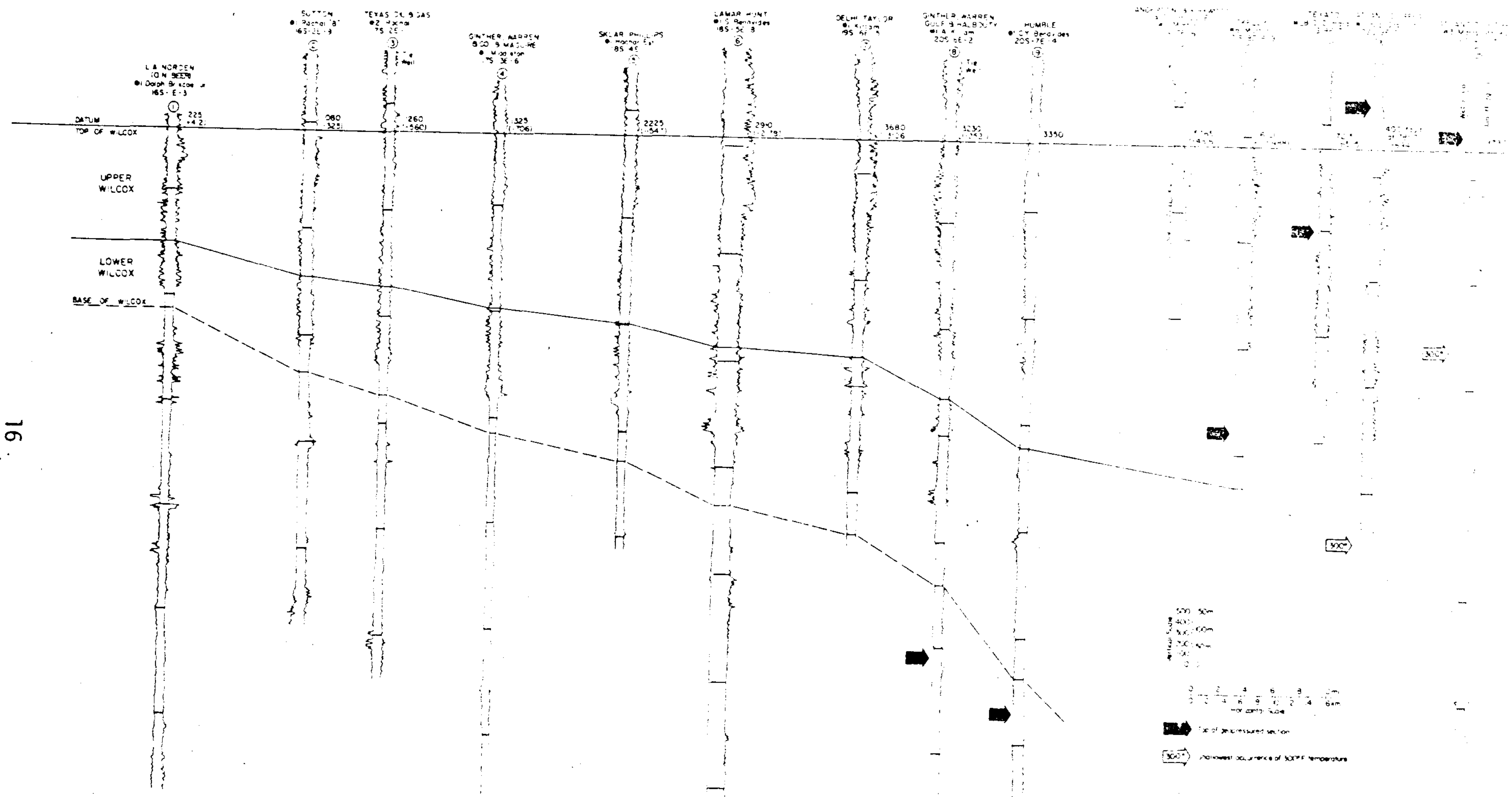

Figure 10. Stratigraphic dip section 1. The locations of this section and those which follow (figs. 11 to 32) are shown in Figure 8. The datum for each section is the top of the Wilcox Group (top of Carrizo Formation in this report) and the transition between the Wilcox and the underlying Midway is shown by the dashed line. The Wilcox Group is divided into lower and upper at the major shale unit. The top of geopressure is shown by the black arrows and the approximate point at which 300°F is reached is shown by the arrows labeled 300°F.

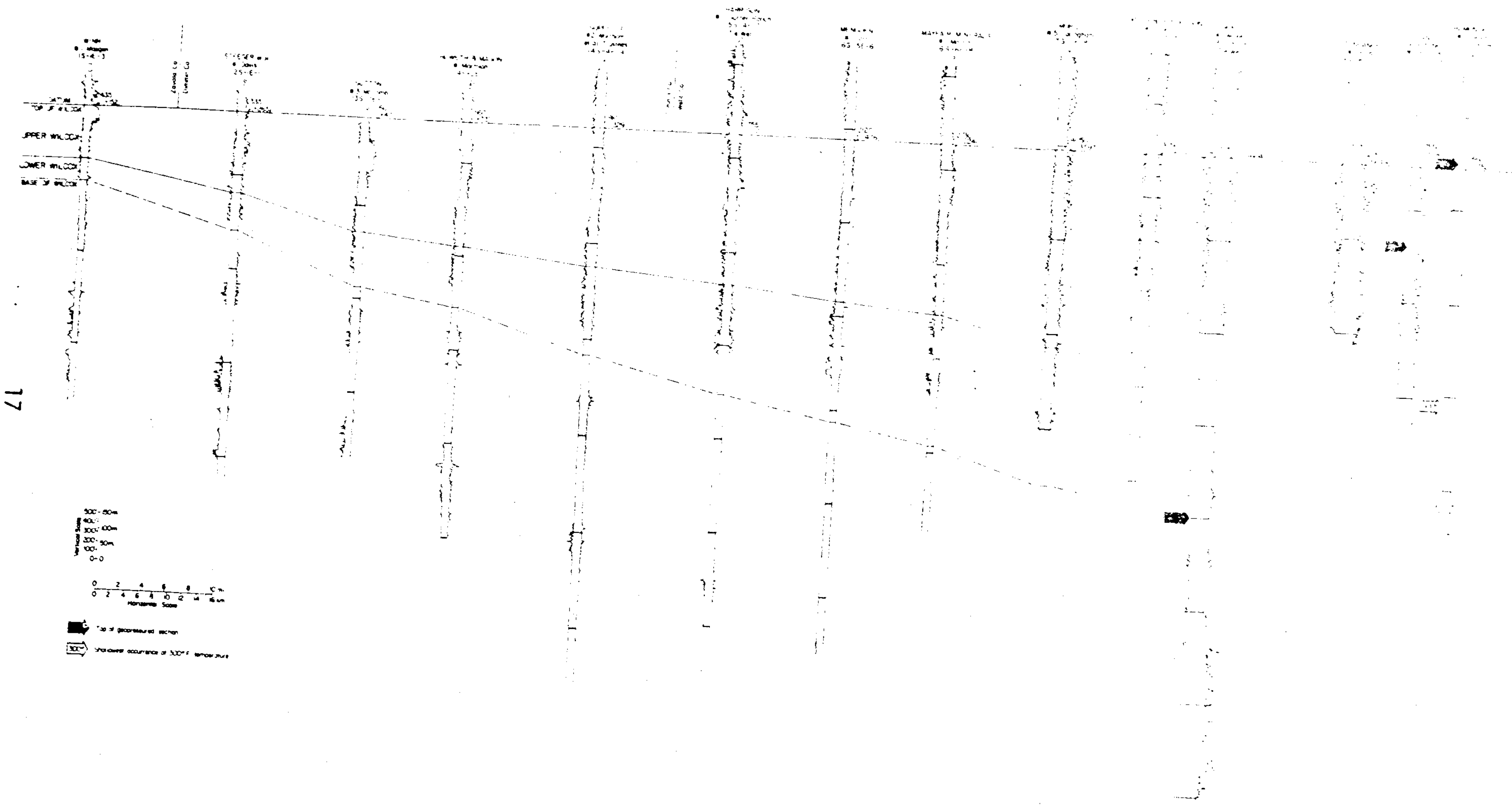

Figure 11. Stratigraphic dip section 2.

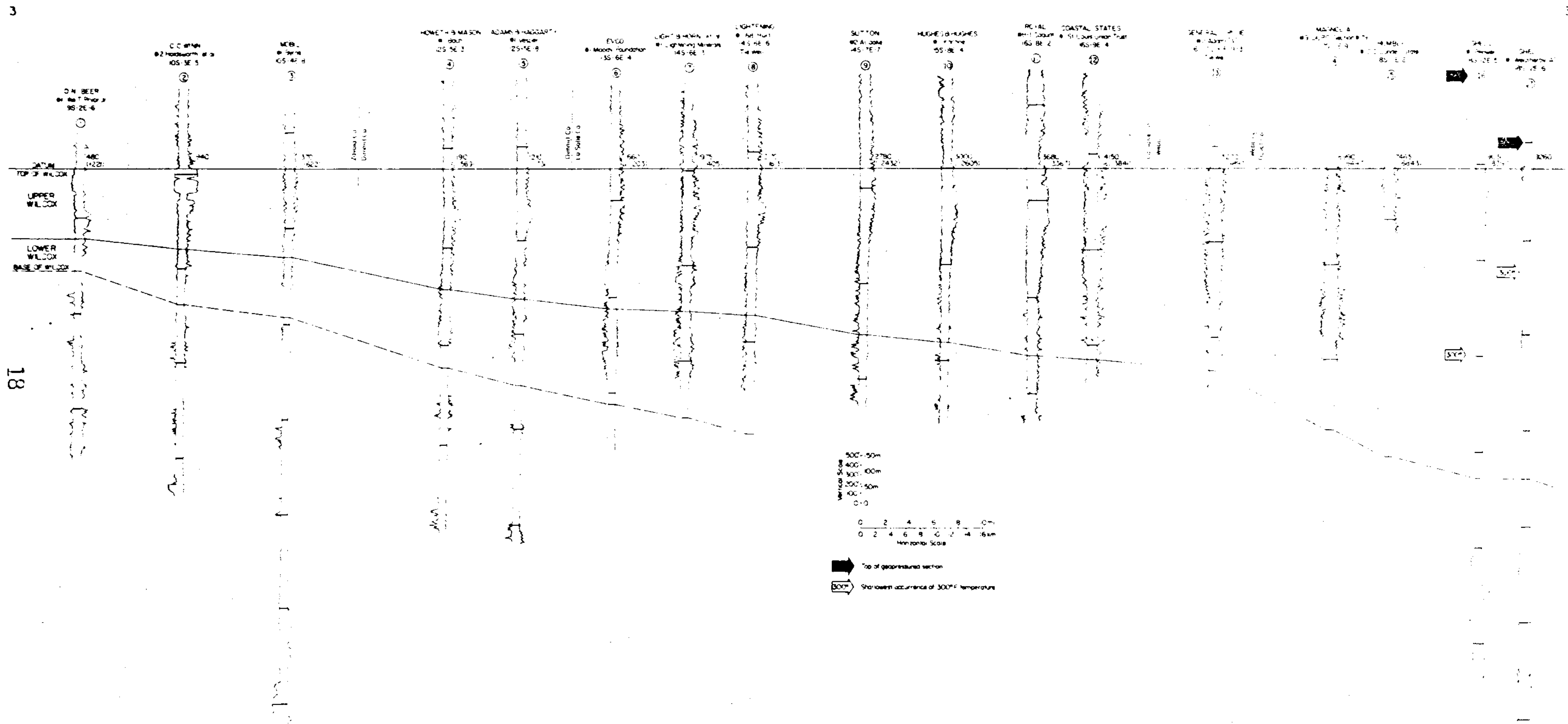

Figure 12. Stratigraphic dip section 3.

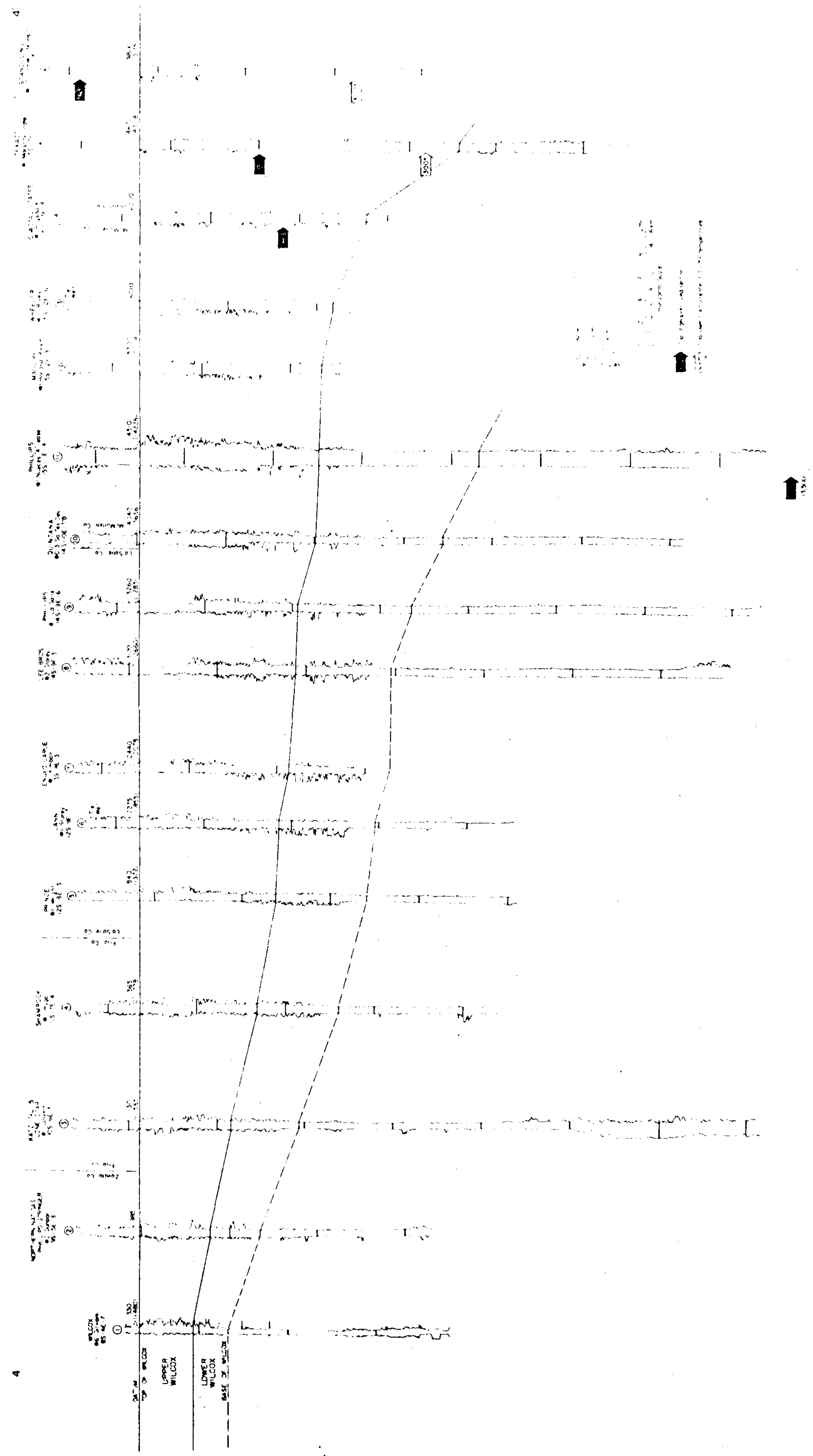

Figure 13. Stratigraphic dip section 4.

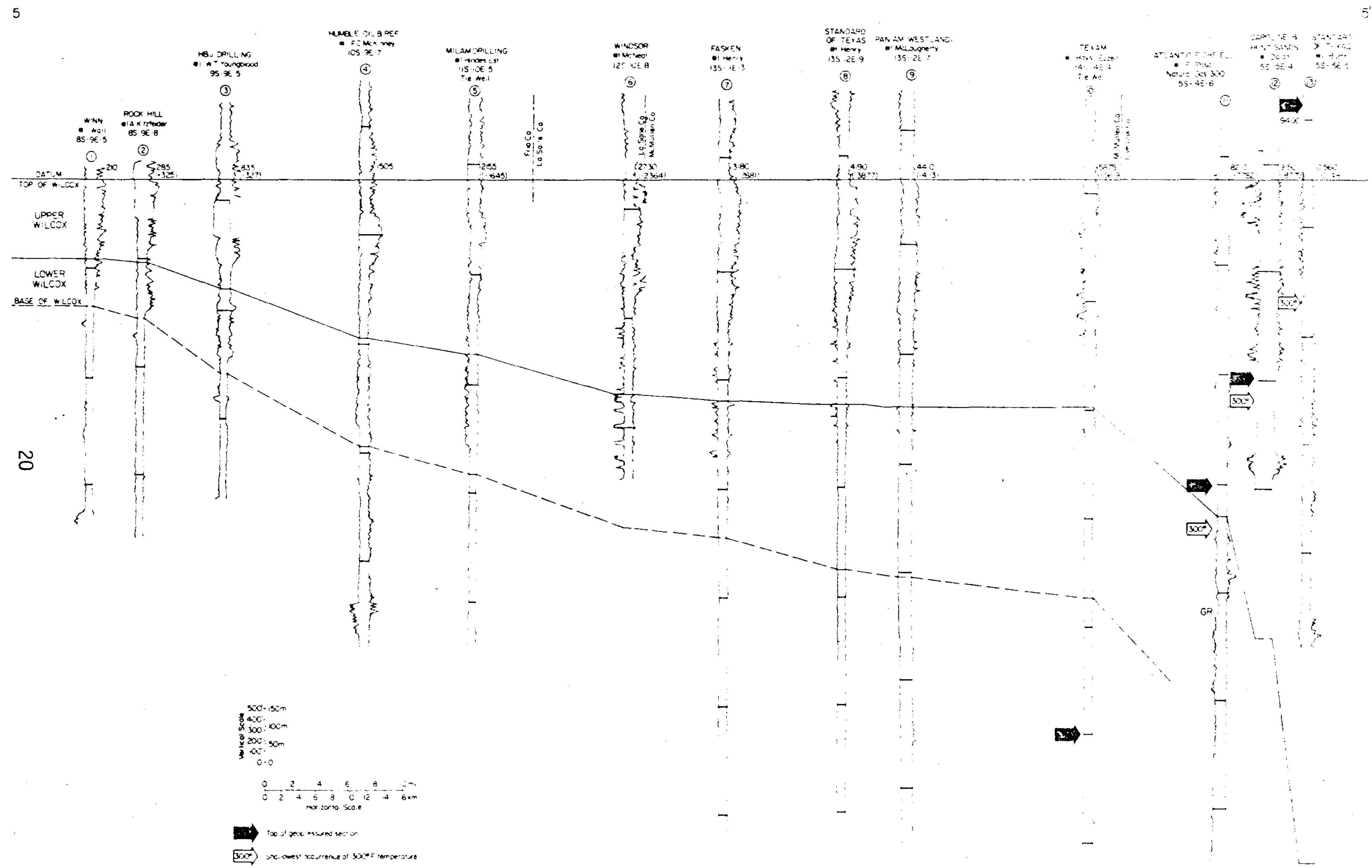

Figure 14. Stratigraphic dip section 5.

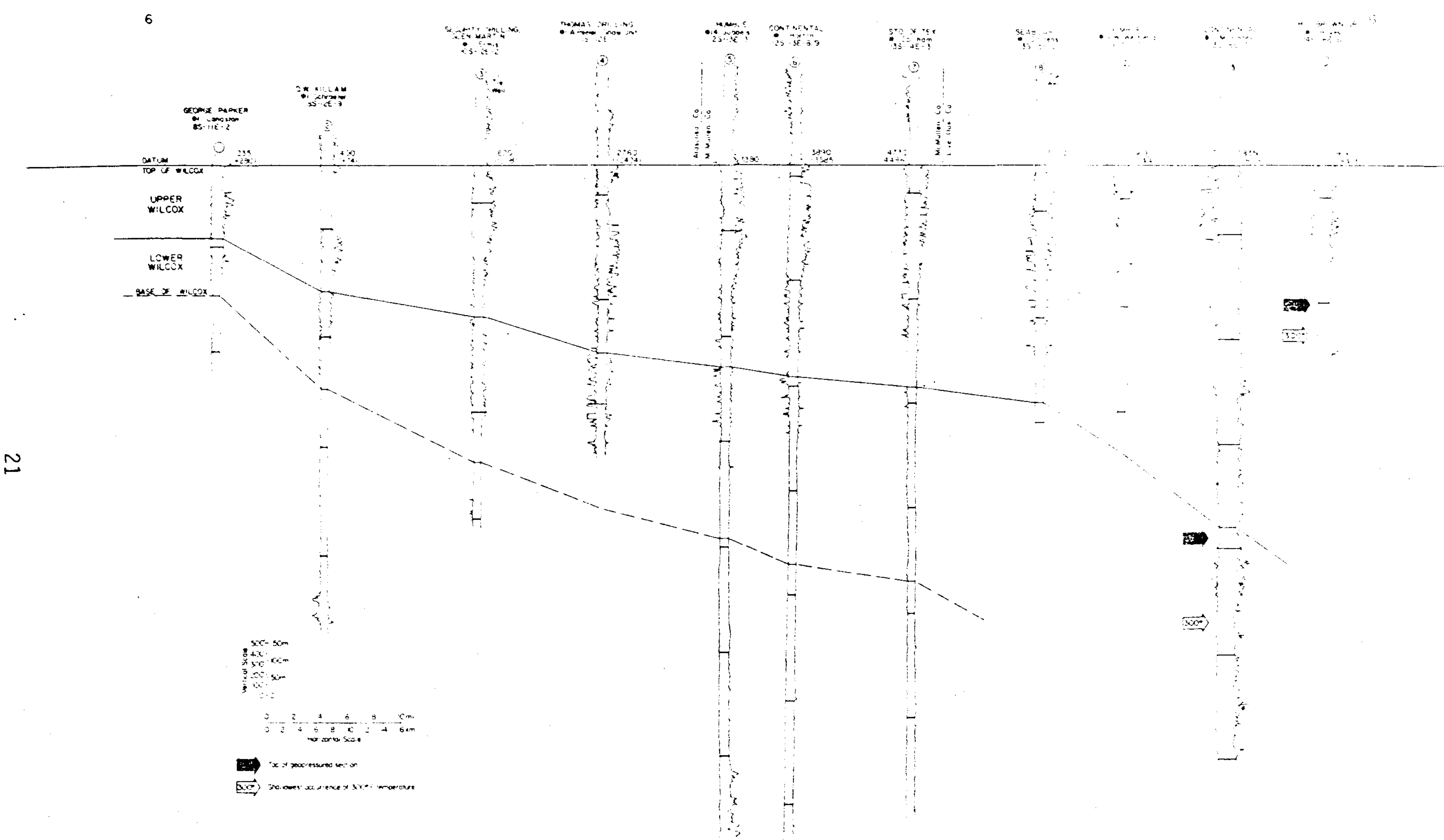

Figure 15. Stratigraphic dip section 6.

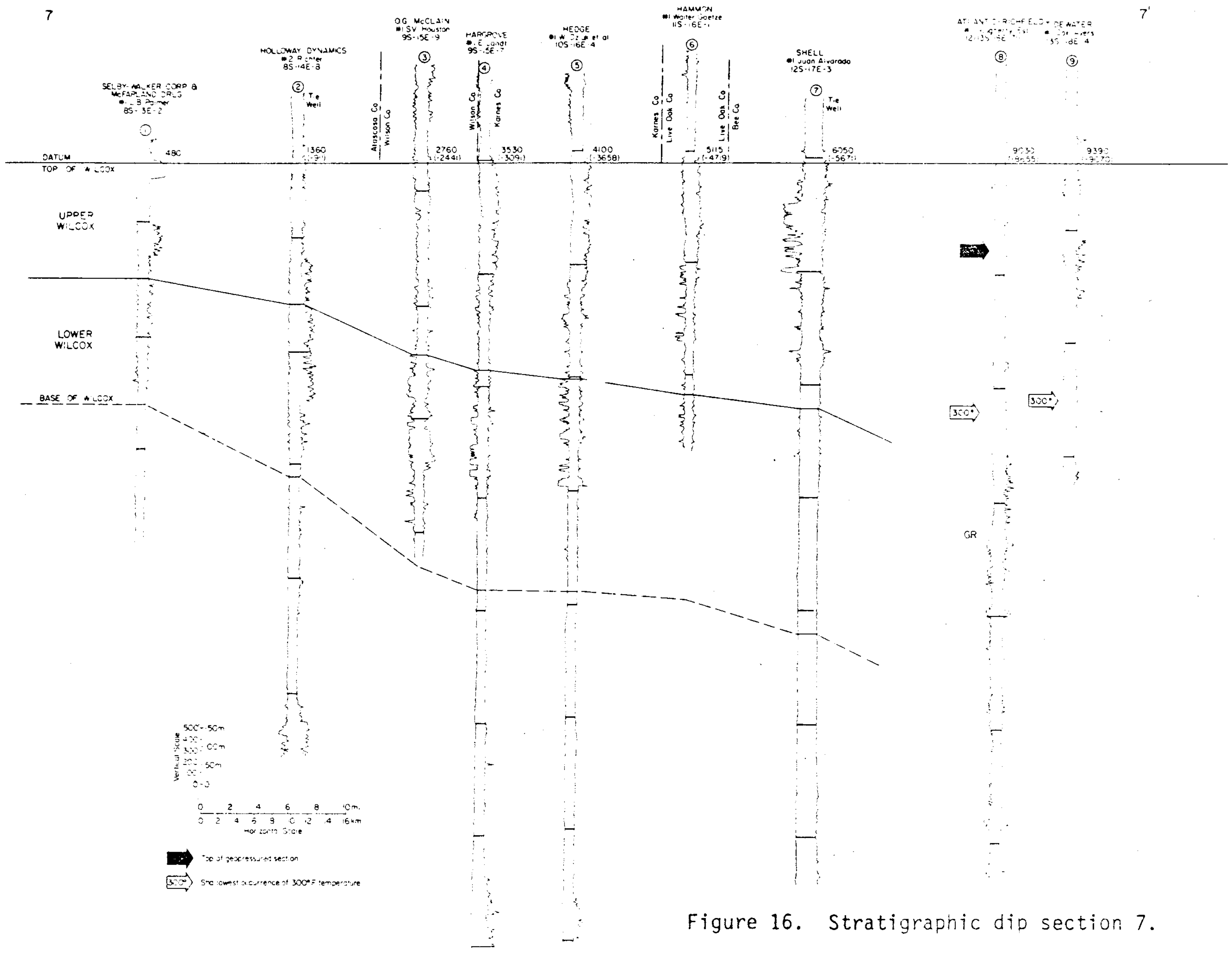

Figure 16. Stratigraphic dip section 7.

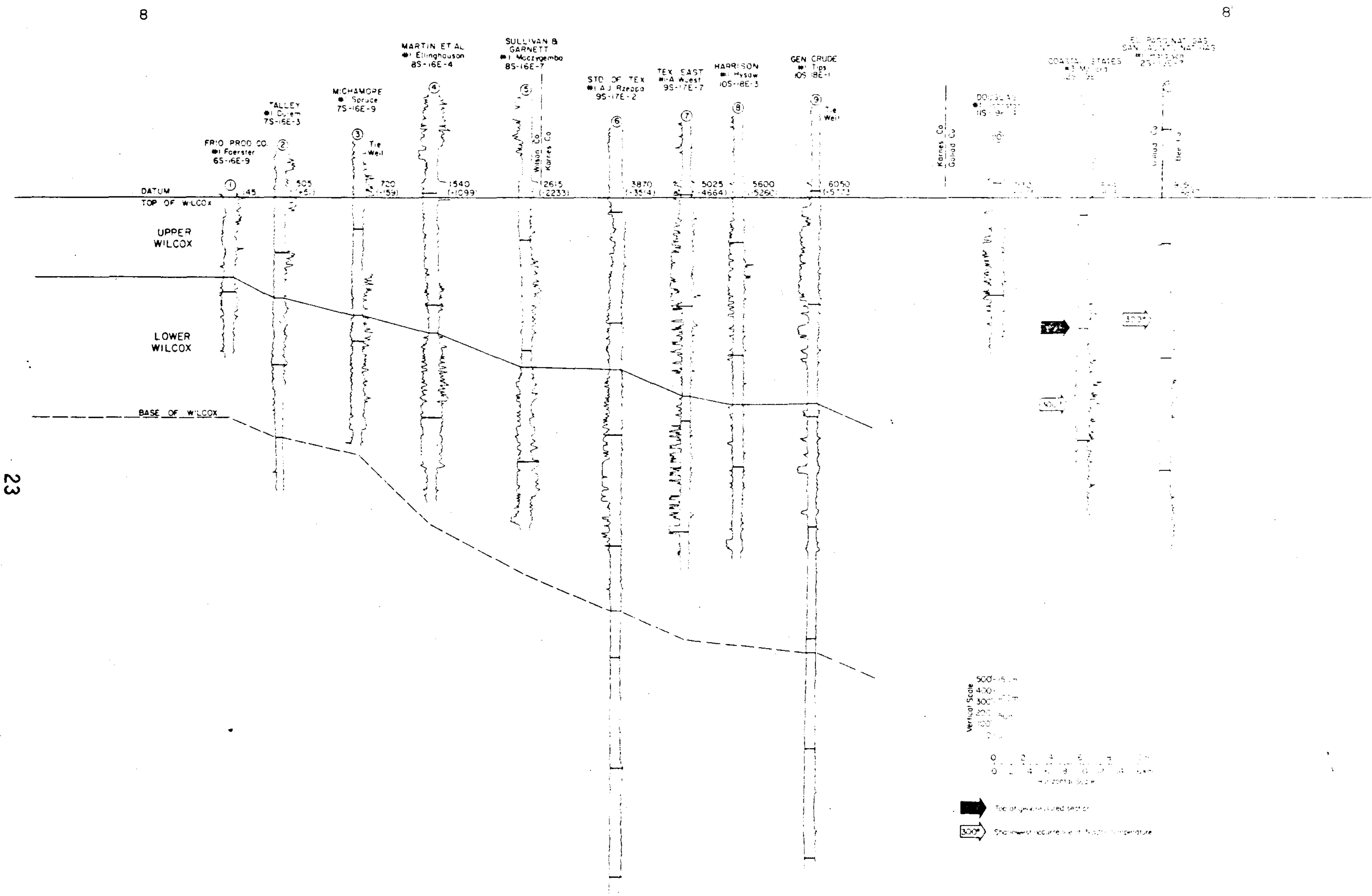

Figure 17. Stratigraphic dip section 8.

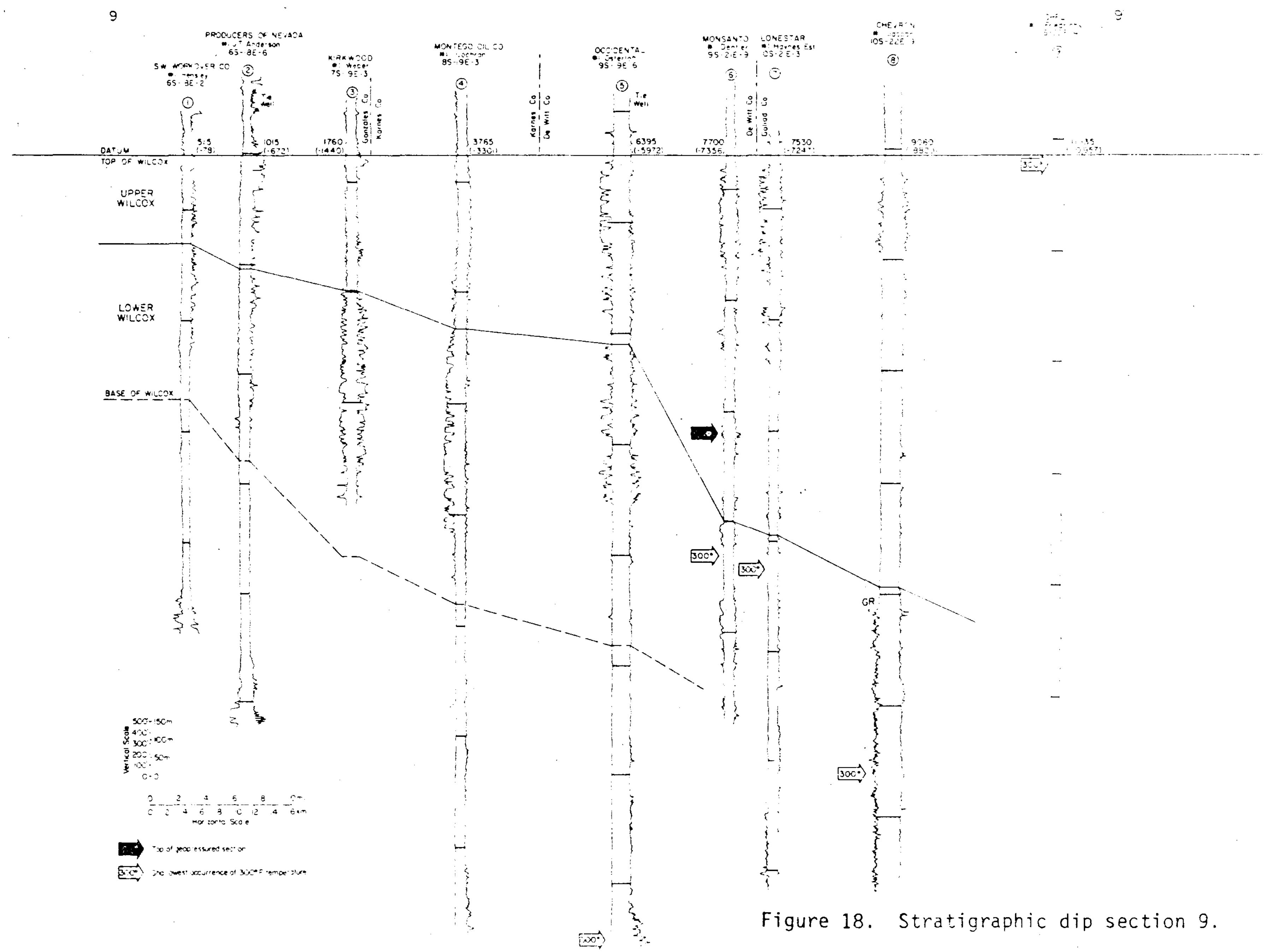

Figure 18. Stratigraphic dip section 9.

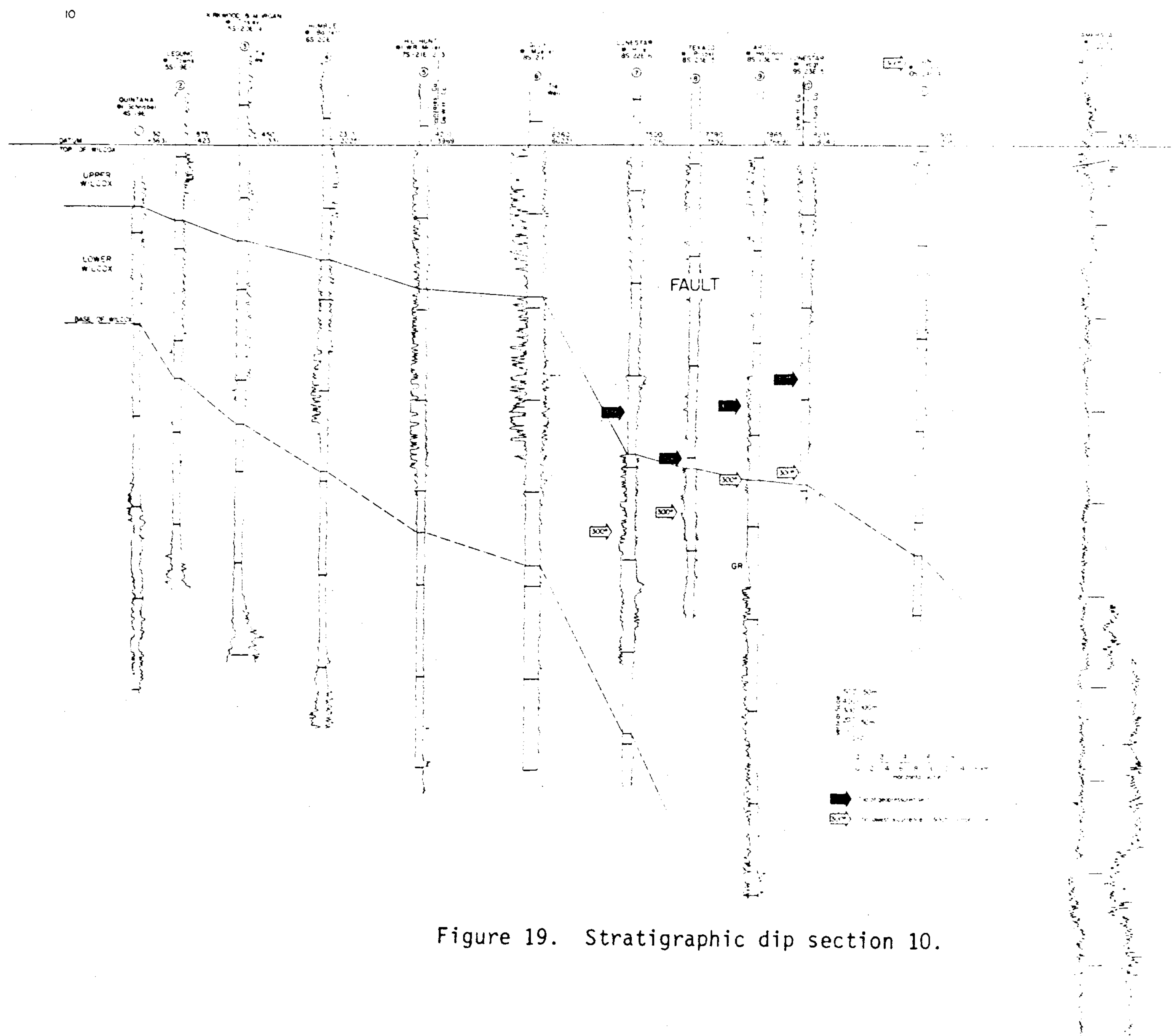

Figure 19. Stratigraphic dip section 10.

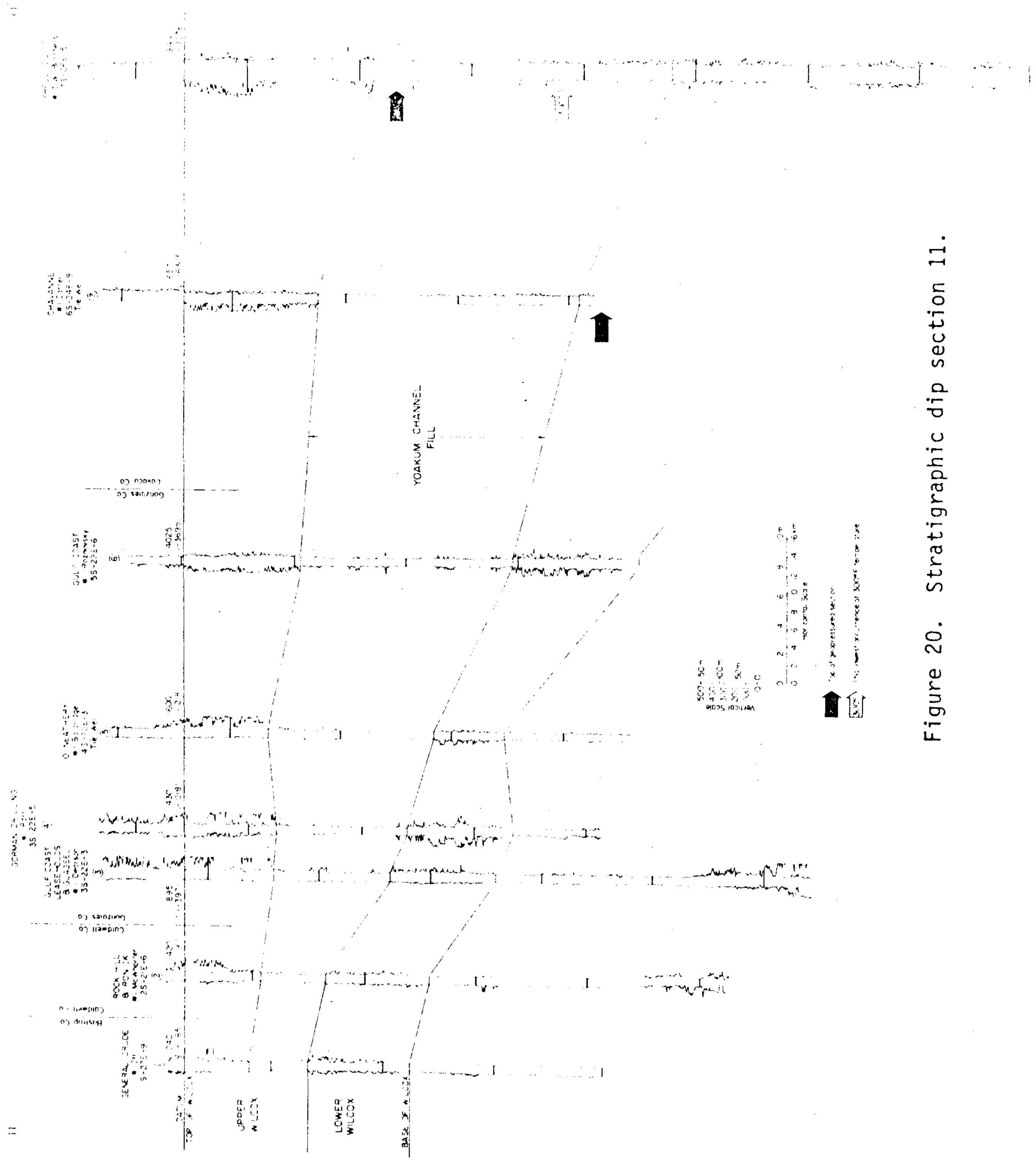

Figure 20. Stratigraphic dip section 11.

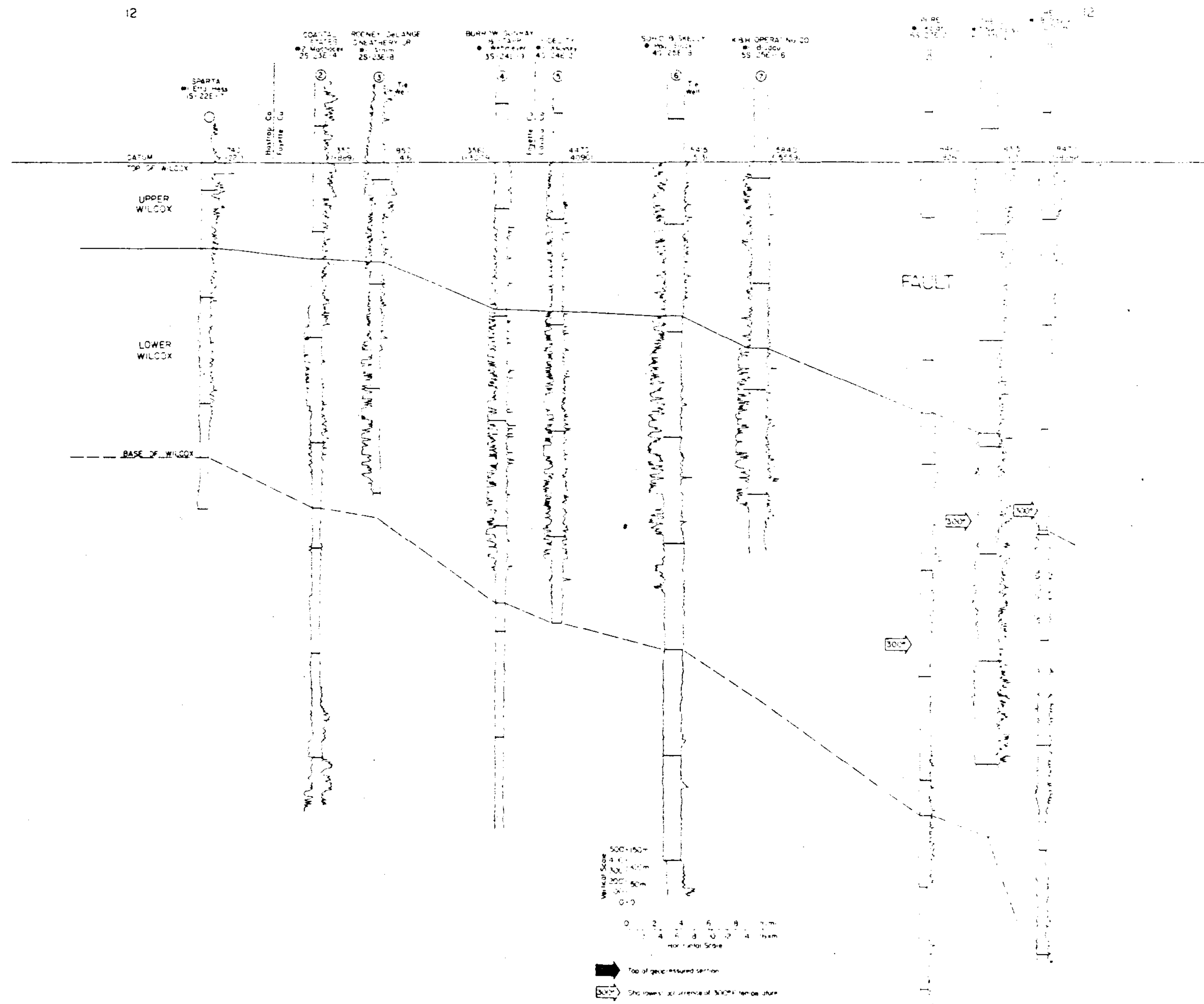

Figure 21. Stratigraphic dip section 12.

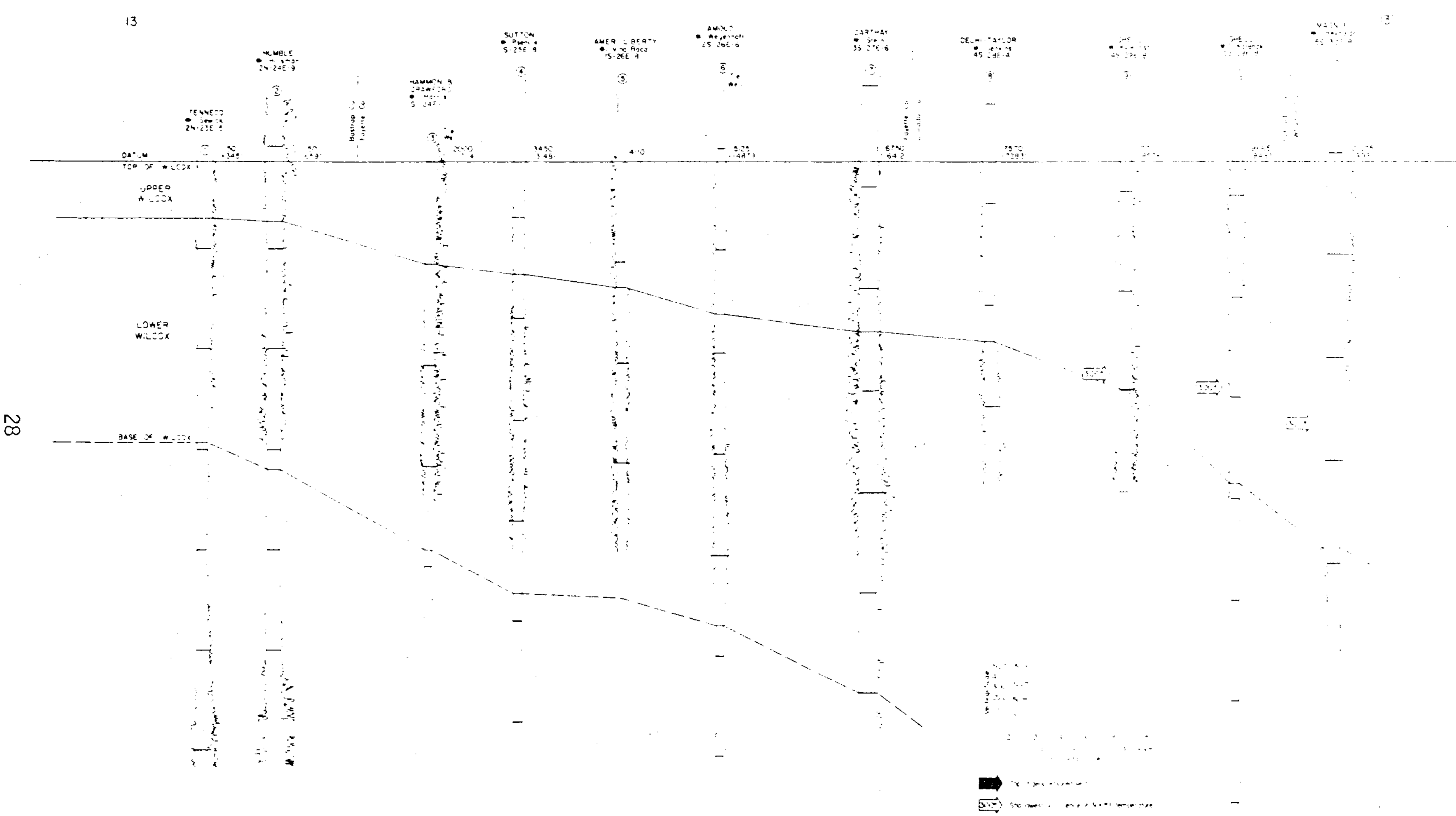

Figure 22. Stratigraphic dip section 13.

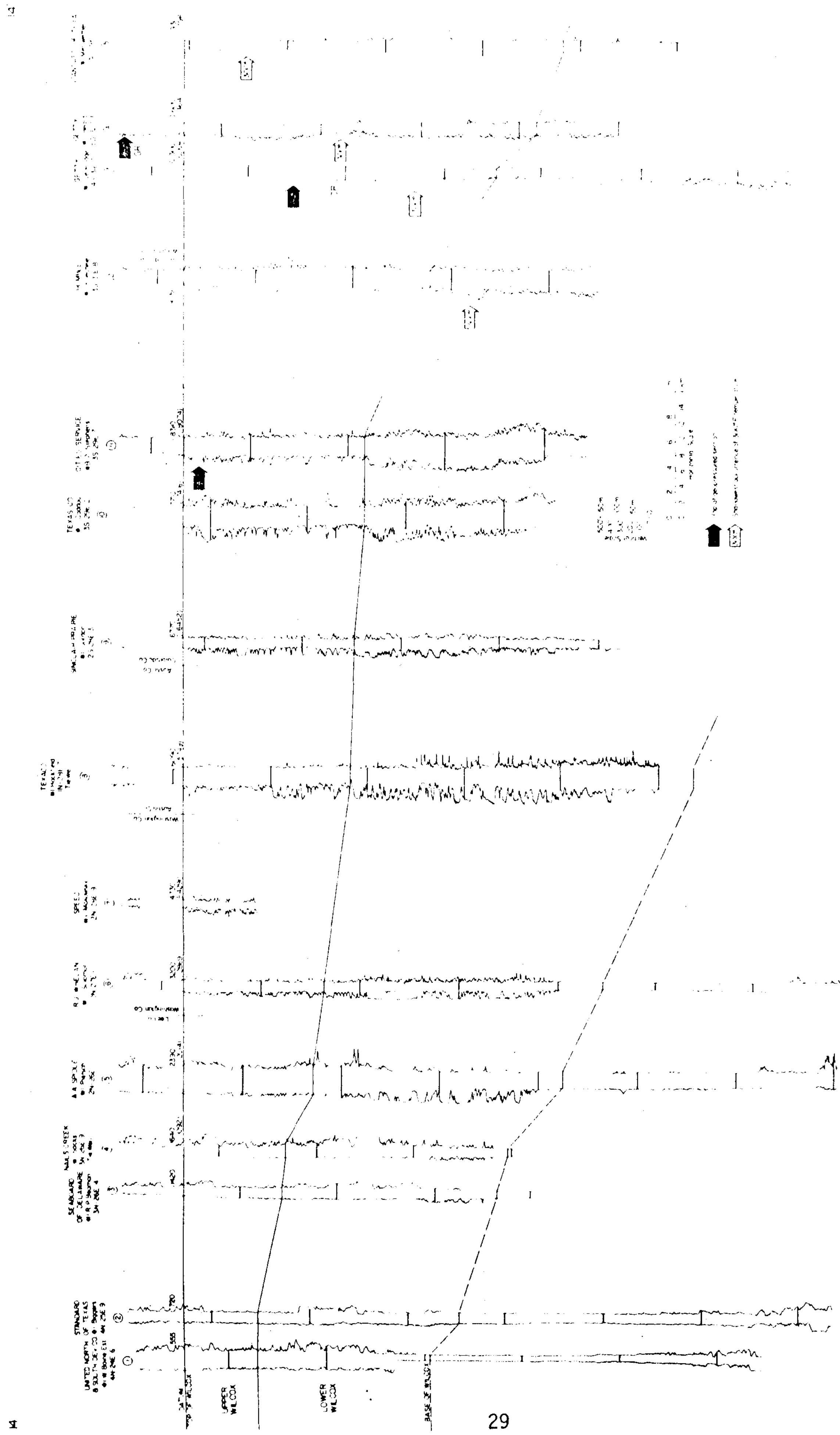

Figure 23. Stratigraphic dip section 14.

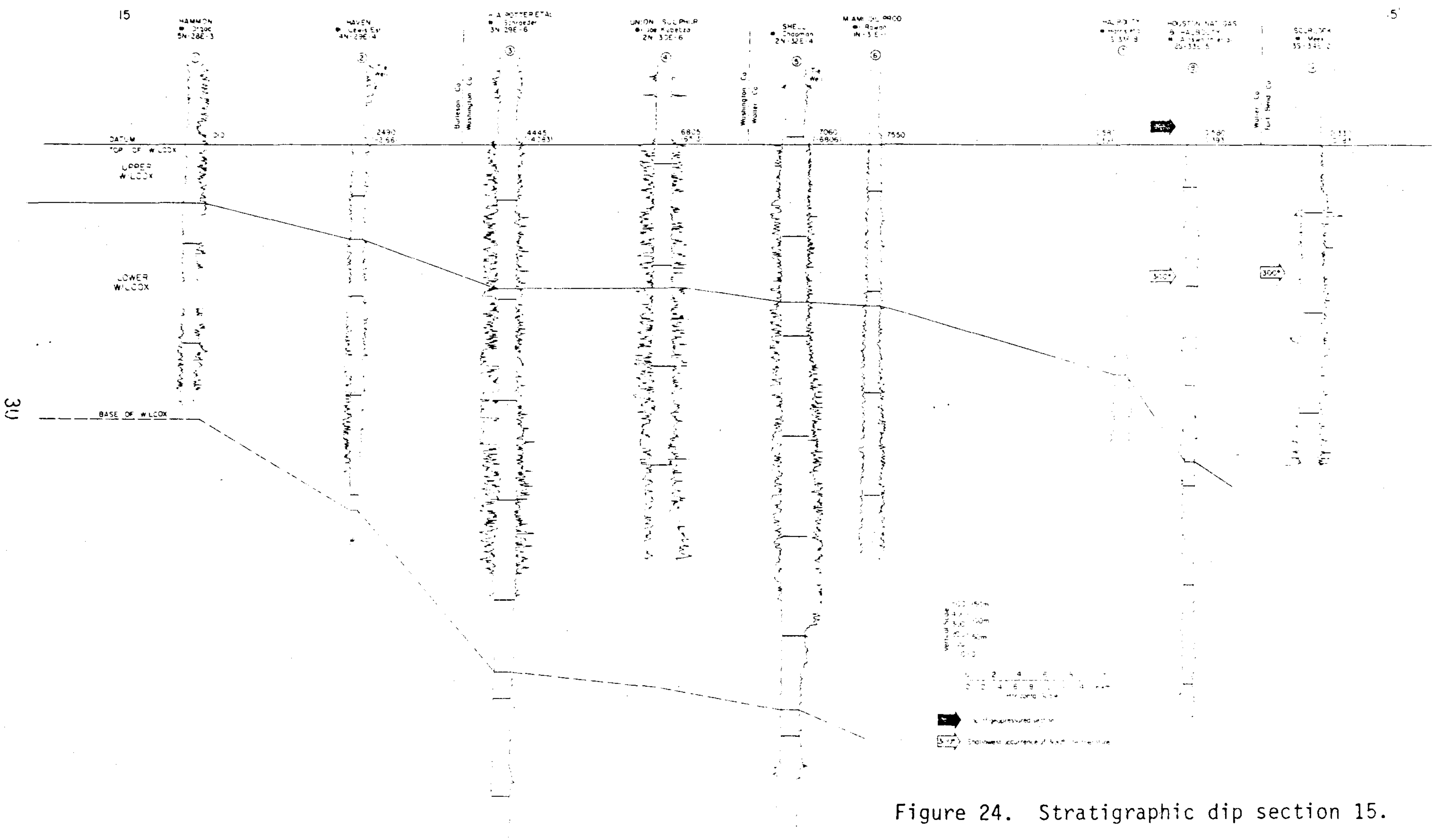

Figure 24. Stratigraphic dip section 15.

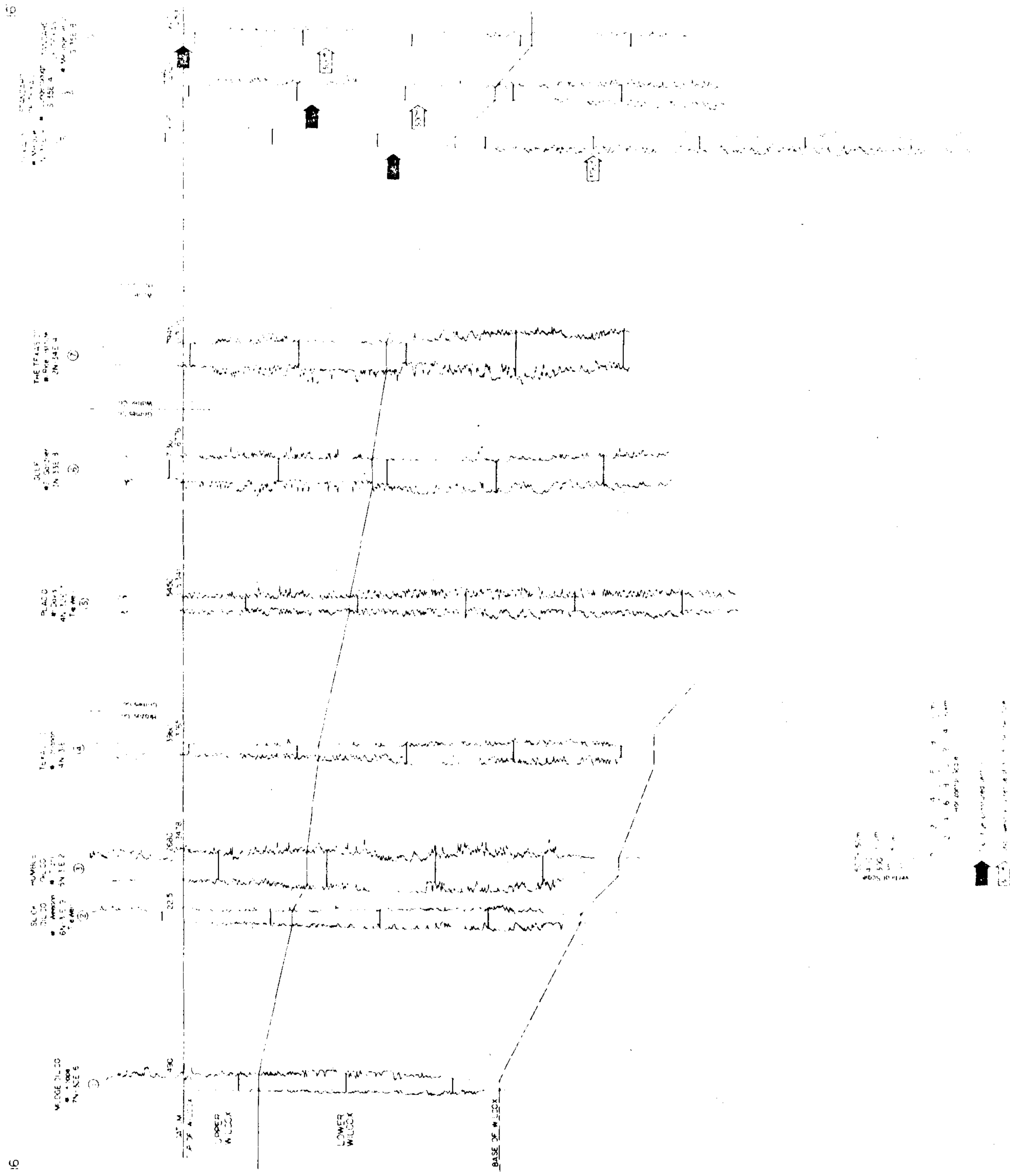

Figure 25. Stratigraphic dip section 16.

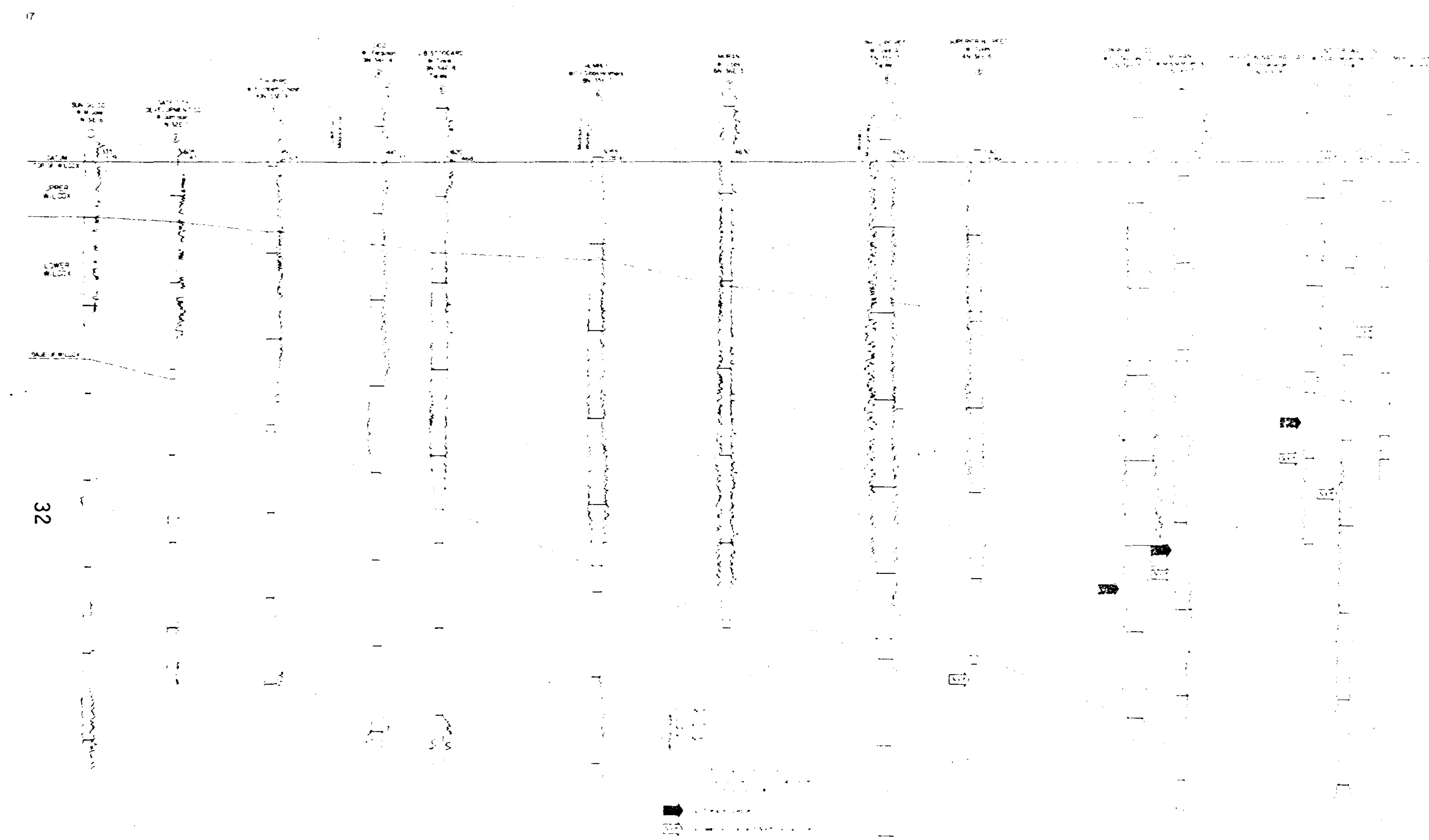

Figure 26. Stratigraphic dip section 17.

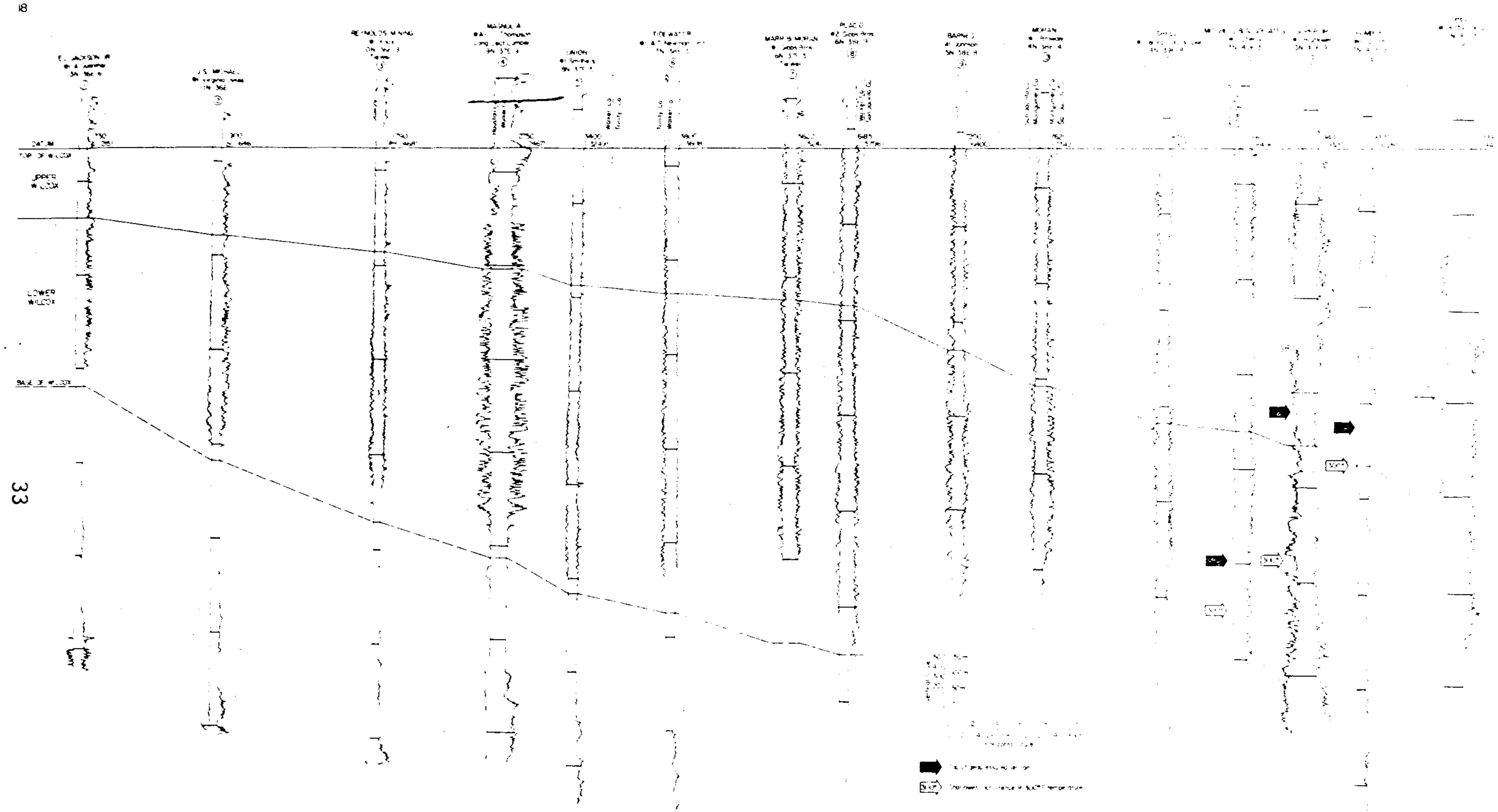

Figure 27. Stratigraphic dip section 18.

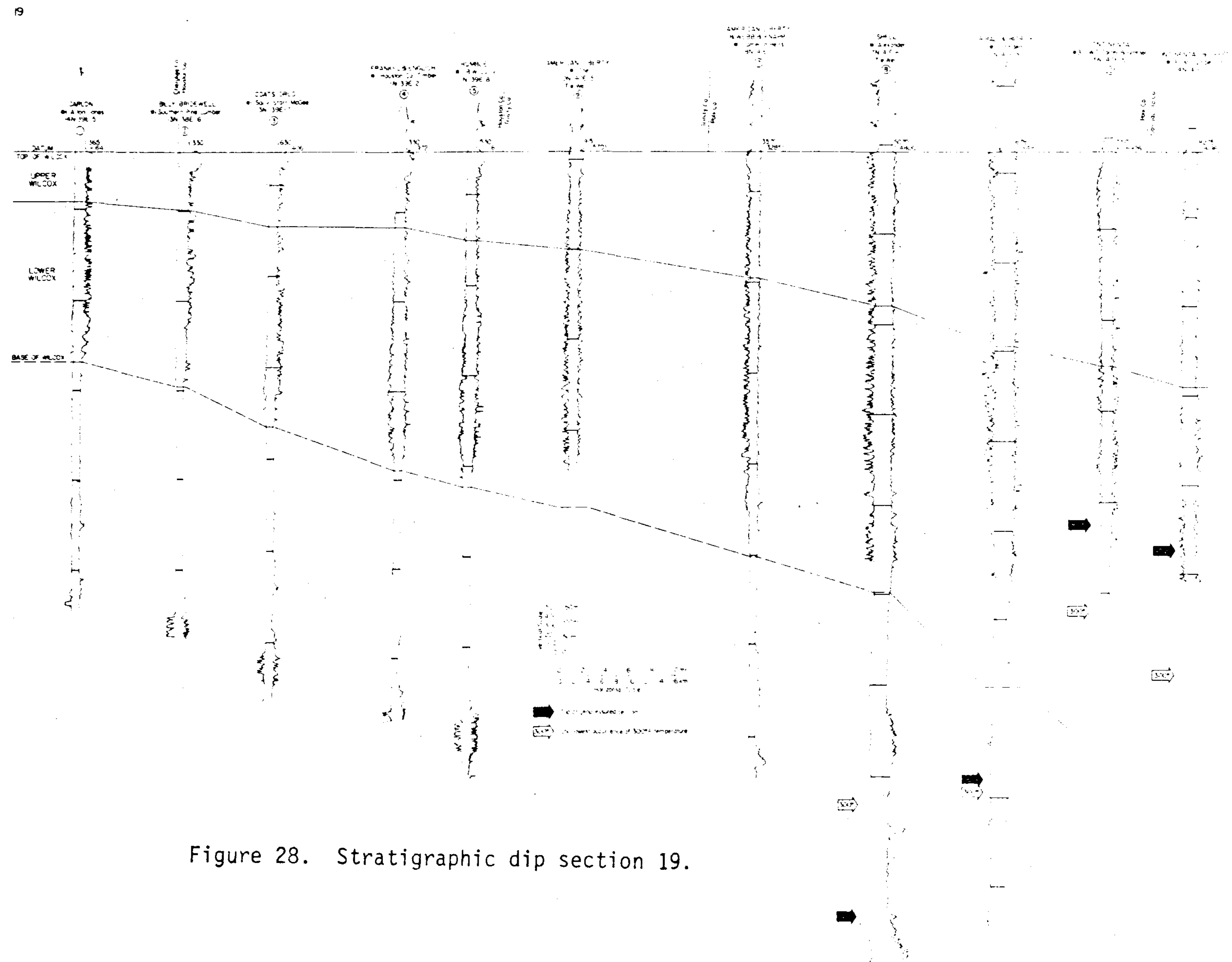

Figure 28. Stratigraphic dip section 19.

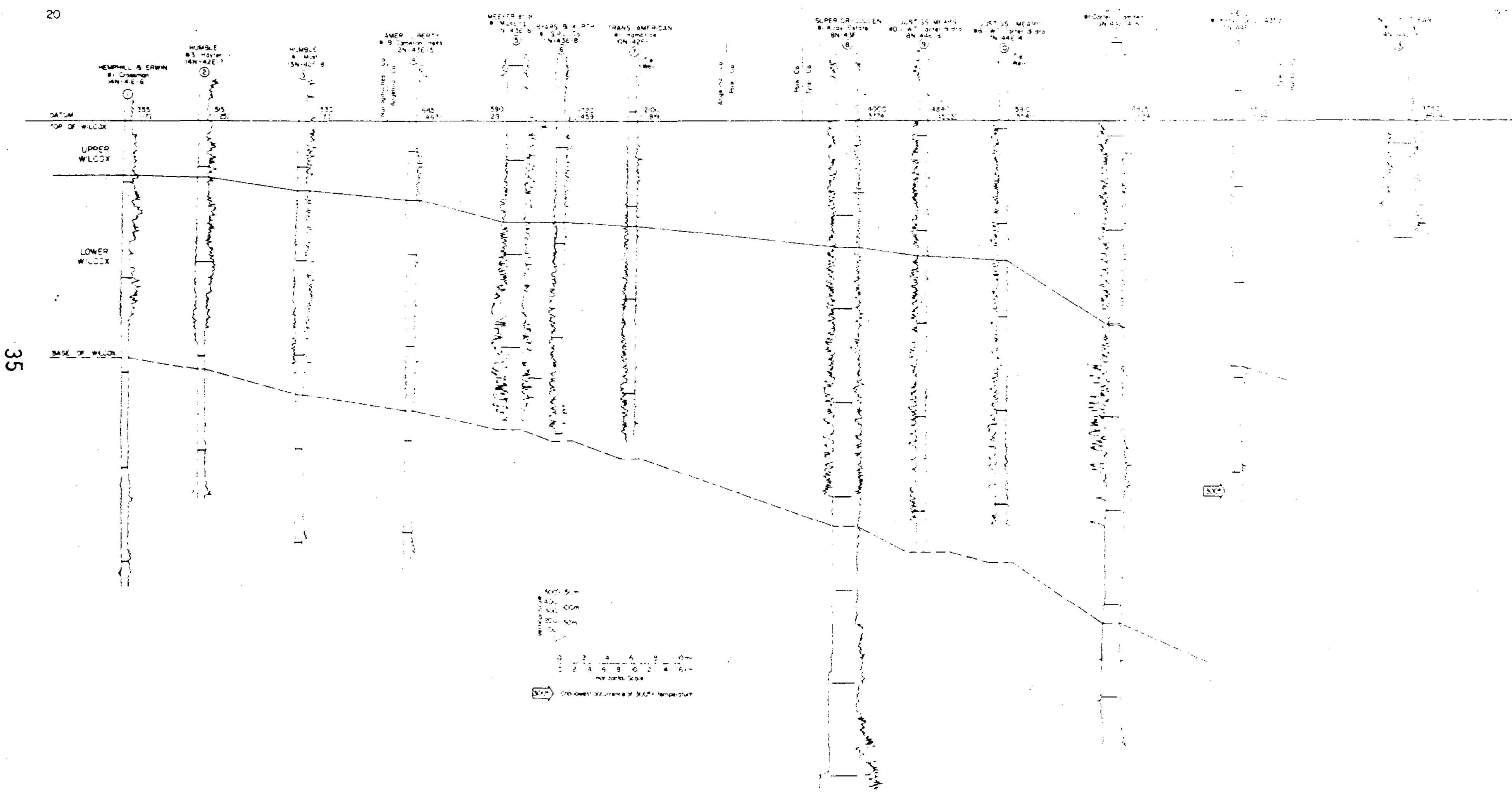

Figure 29. Stratigraphic dip section 20.

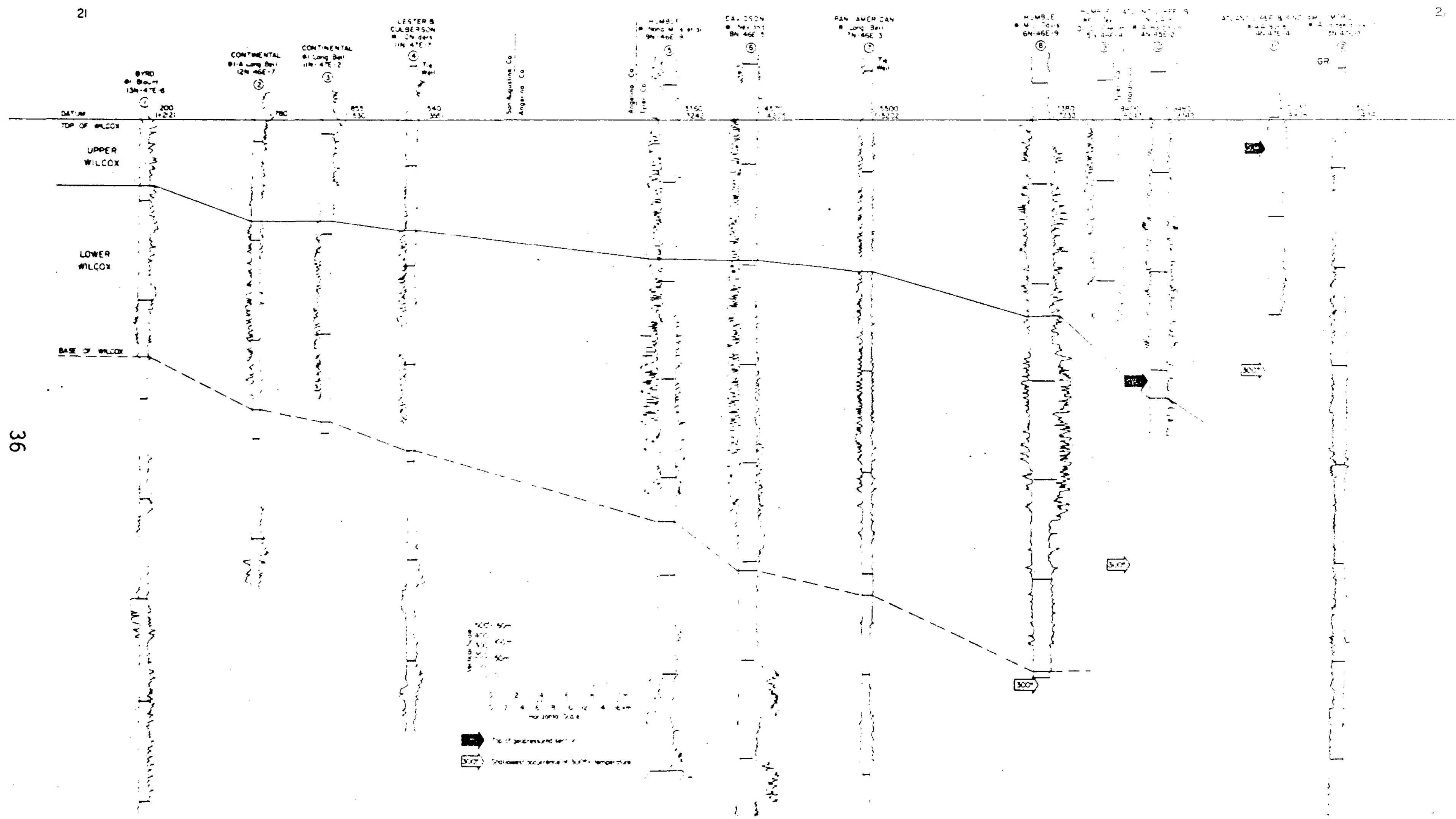

Figure 30. Stratigraphic dip section 21.

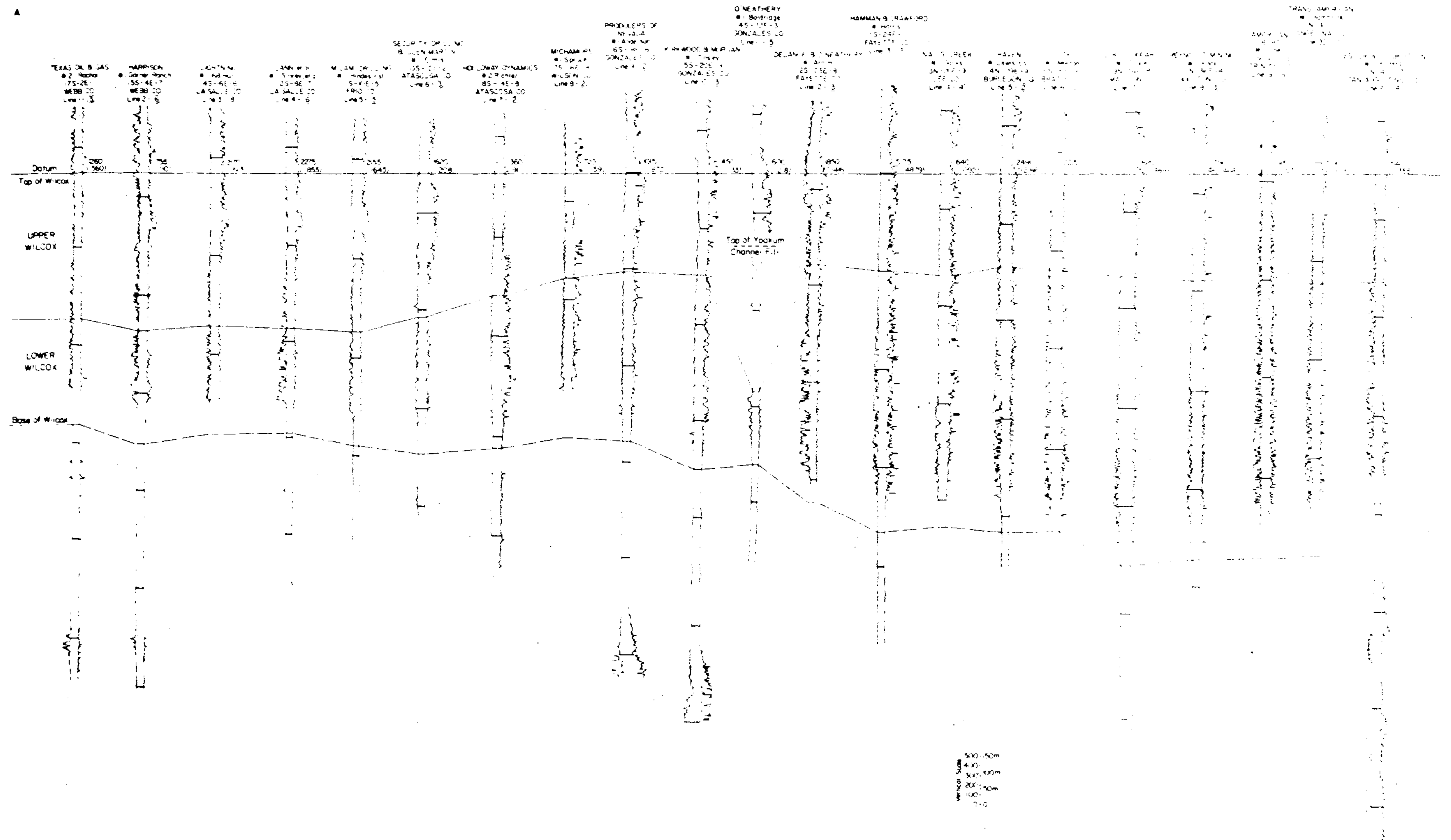

Figure 31. Stratigraphic strike section A.

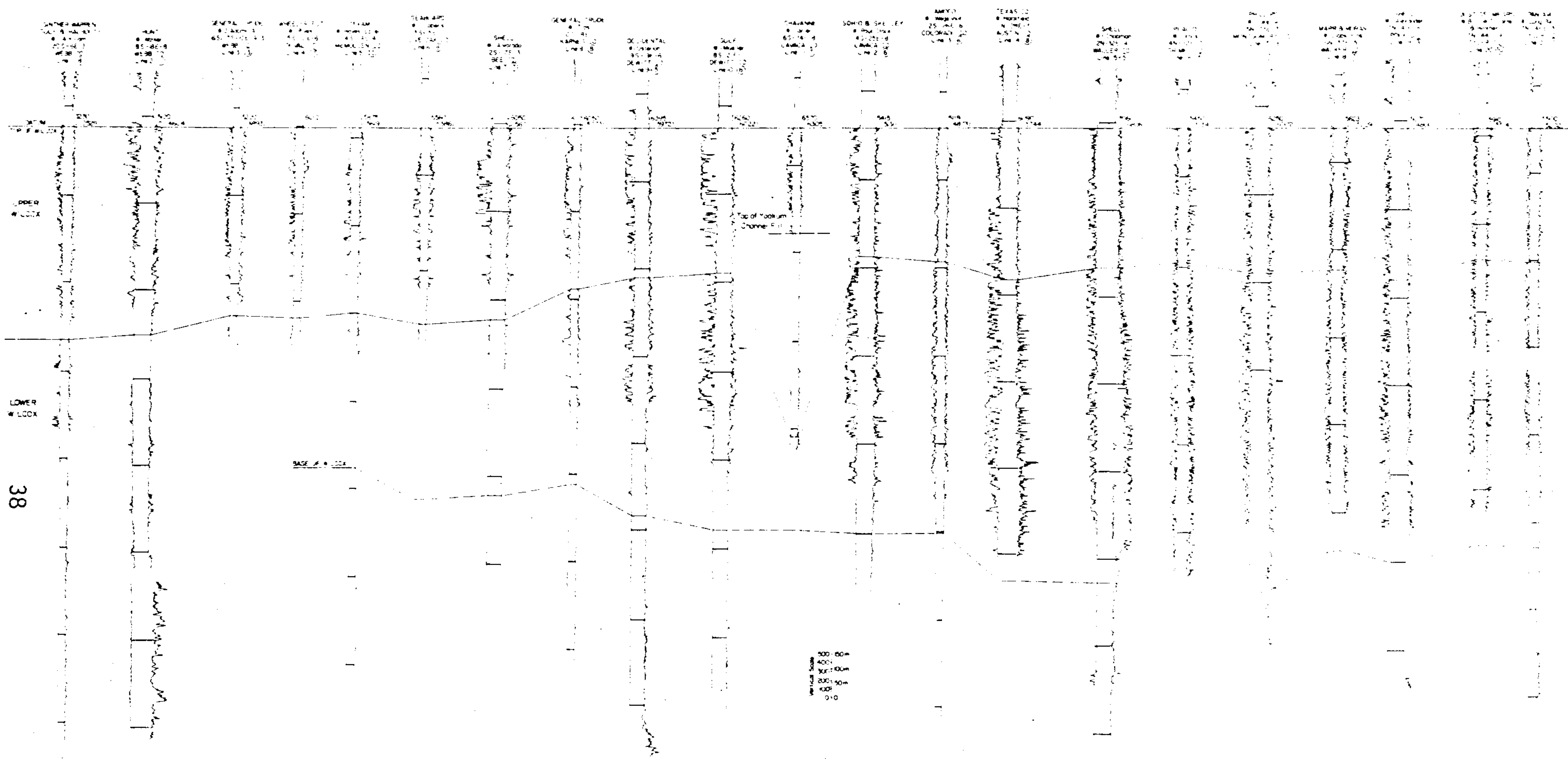

Figure 32. Stratigraphic strike section B.

LOWER WILCOX SANDSTONE DISTRIBUTION

Net-sandstone and sandstone-percent maps outline a high-sandstone trend which is broad and lobate along the Upper and Middle Texas Gulf Coast and narrow and straight along the Lower Texas Gulf Coast.

Sandstone-distribution maps of the lower Wilcox (figs. 33 and 34) are based on the control provided by the wells on the stratigraphic dip sections prepared during this study and by maps previously prepared by the Bureau of Economic Geology as part of an extensive study of the lower Wilcox (Fisher and McGowen, 1967). These maps show a high-sandstone trend, subparallel to the present-day Gulf Coast, which is broad along the Upper and Middle Texas Gulf Coast (up to 80 miles wide) and narrow along the Lower Texas Gulf Coast (approximately 20 miles wide). Sandstone thicknesses range from a maximum of greater than 2,000 feet to the north to slightly more than 400 feet to the south.

Along the northern two-thirds of the trend, both the net-sandstone and sandstone-percent maps (figs. 33 and 34) show a very lobate pattern on the gulfward side of the broad sandstone trend (from De Witt County on the south to Sabine County on the north); this lobate pattern is very similar to that illustrated by Fisher and McGowen (1967) who interpreted it as representing deposition by a high-constructive delta system (the Rockdale Delta System). The southernmost delta lobe, the Guadalupe Delta of Fisher and McGowen, was subsequently cut by a large erosional feature named the Yoakum Channel by Hoyt (1959). Fisher and McGowen believed the Yoakum Channel may have been cut by turbidity currents which resulted from the movement of deltaic sediments down depositional slope. In the axis of the channel the entire lower Wilcox high-sandstone section has been removed and replaced by the dominantly shale section of the lower part of the upper Wilcox (figs. 22 and 23).

South from De Witt County, the net-sandstone and sandstone-percent maps show a marked contrast from the broad, lobate trend to the north to the narrow, straight trend to the south. This strike-dominanted trend was considered by Fisher and McGowen (1967) as having been deposited as strandplain and barrier-bar depositional systems and was named the San Marcos Strandplain and Cotulla Barrier Bar Systems.

The emphasis of this study is on the downdip-most sandstone units where reservoirs with potential for production of 300°F geothermal water occur; here, the configuration of the sandstone lobes on the net-sandstone map conforms very closely with that published by Fisher and McGowen (1967). Updip, on the other hand, the well control used in this study is sparser than that used by Fisher and McGowen; thus, the net-sandstone maps are somewhat different.

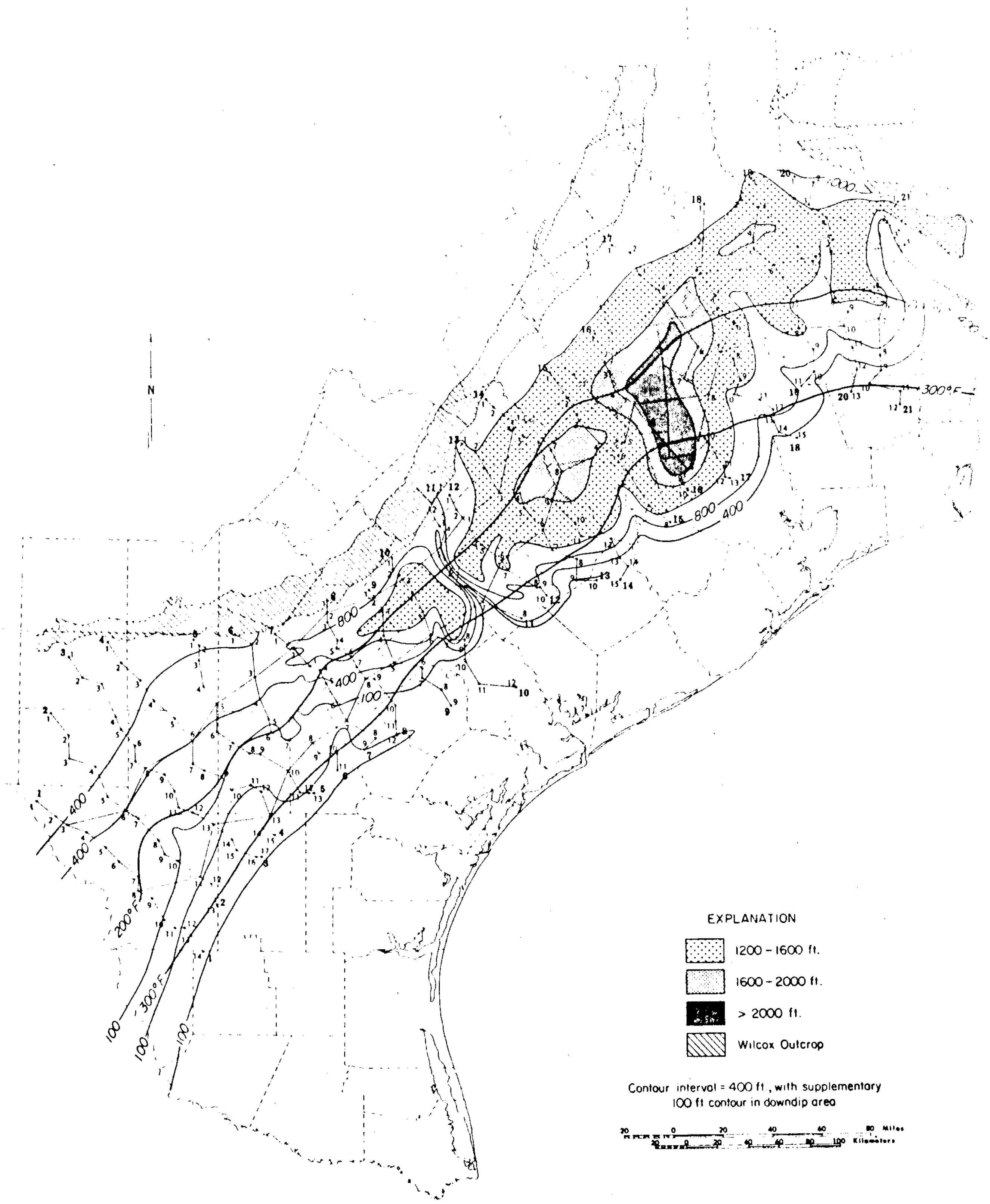

Figure 33. Net sandstone - lower Wilcox.

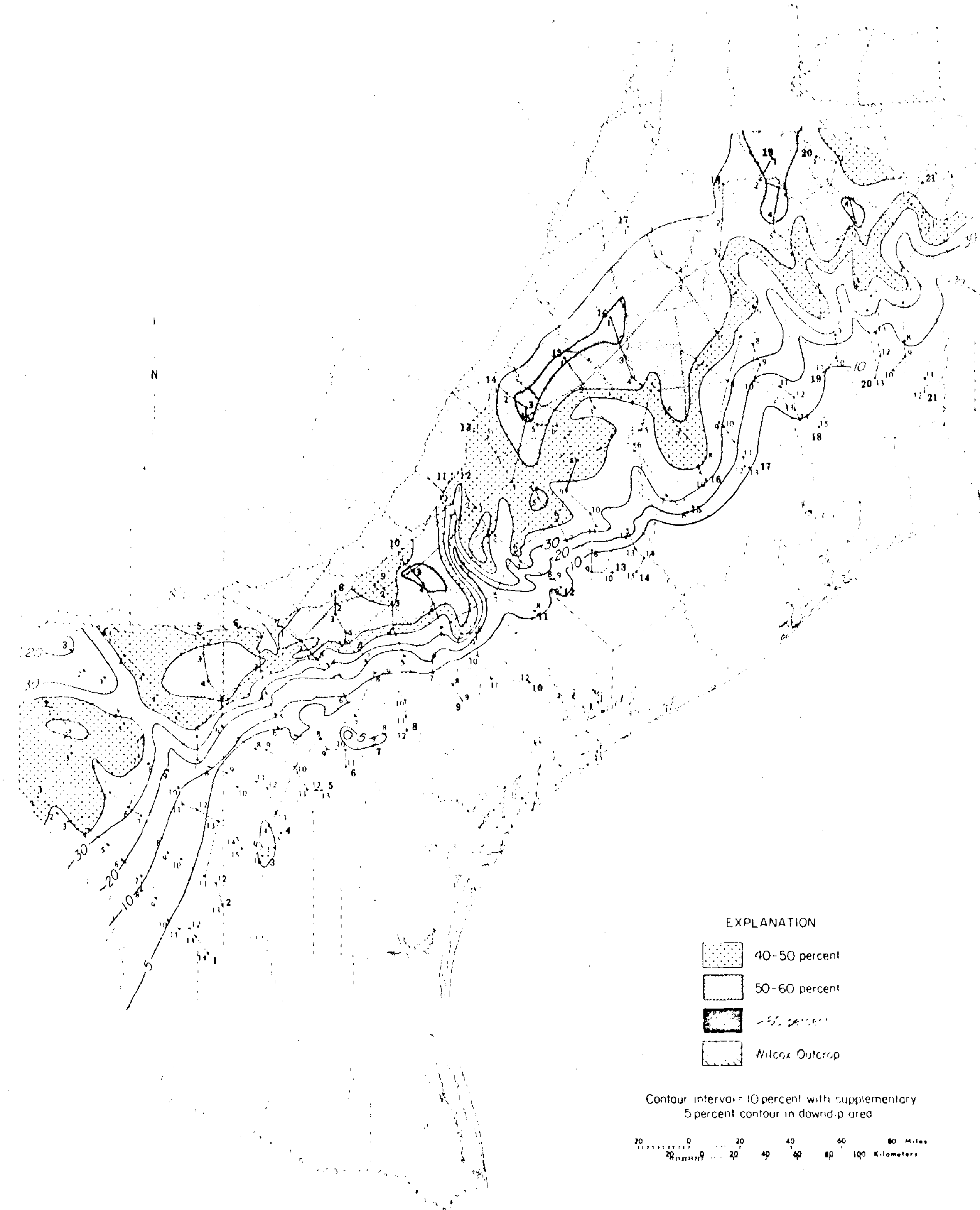

Figure 34. Sandstone percentage - lower Wilcox.

UPPER WILCOX SANDSTONE DISTRIBUTION

The high-sandstone trend, as defined by the net-sandstone and sandstone-percent maps, is broad to the south along the Lower Texas Gulf Coast, is slightly narrower to the north along the Middle Texas Gulf Coast, and broader again along the Upper Texas Gulf Coast.

The sandstone-distribution maps of the upper Wilcox (figs. 35 and 36) shows the trend to be broad (80 miles wide) both to the south along the Lower Texas Gulf Coast and to the north along the Upper Texas Gulf Coast and to be narrow (40 miles wide) in the central part along the Middle Texas Gulf Coast. The net-sandstone and sand percentage values are larger along the Lower and Upper Texas Gulf Coast and smaller along the Middle.

The dip-oriented lobate pattern typical of the lower Wilcox is not present on the upper Wilcox net-sandstone or sandstone-percent maps (figs. 35 and 36). In contrast, the upper Wilcox sandstone distribution maps show major sandstone bodies oriented at a slightly oblique angle to depositional strike. These upper Wilcox sandstones were interpreted by Fisher (1969) to have been deposited as strandplains of a high-destructive delta system. The net-sandstone map (fig. 35) shows the tendency for the sandstone bodies to be oriented at a low angle to strike but does not show the very digitate downdip edge illustrated by Fisher (1969, fig. 66). The differences between these two maps are attributed to differences in well control and to differences in criteria used in picking upper Wilcox. Only the deeper wells that penetrated both the upper and lower Wilcox were used in this study whereas Fisher used many of the shallow wells as well. In addition, the upper Wilcox of this study includes both the upper and middle Wilcox of Fisher, thus resulting in the inclusion of units from a much thicker section than considered by Fisher (1969). Thinner mapping units commonly show better definition of the original depositional patterns.

In the Upper Wilcox the Yoakum Channel appears only on the sandstone-percent map (fig. 36) because the thick channel fill included in the upper Wilcox is dominantly shale, thus lowering significantly the sandstone percentage. The net-sandstone map (fig. 35), in contrast, does not show the channel because the normal upper Wilcox sandstone section was deposited across the already filled Yoakum Channel.

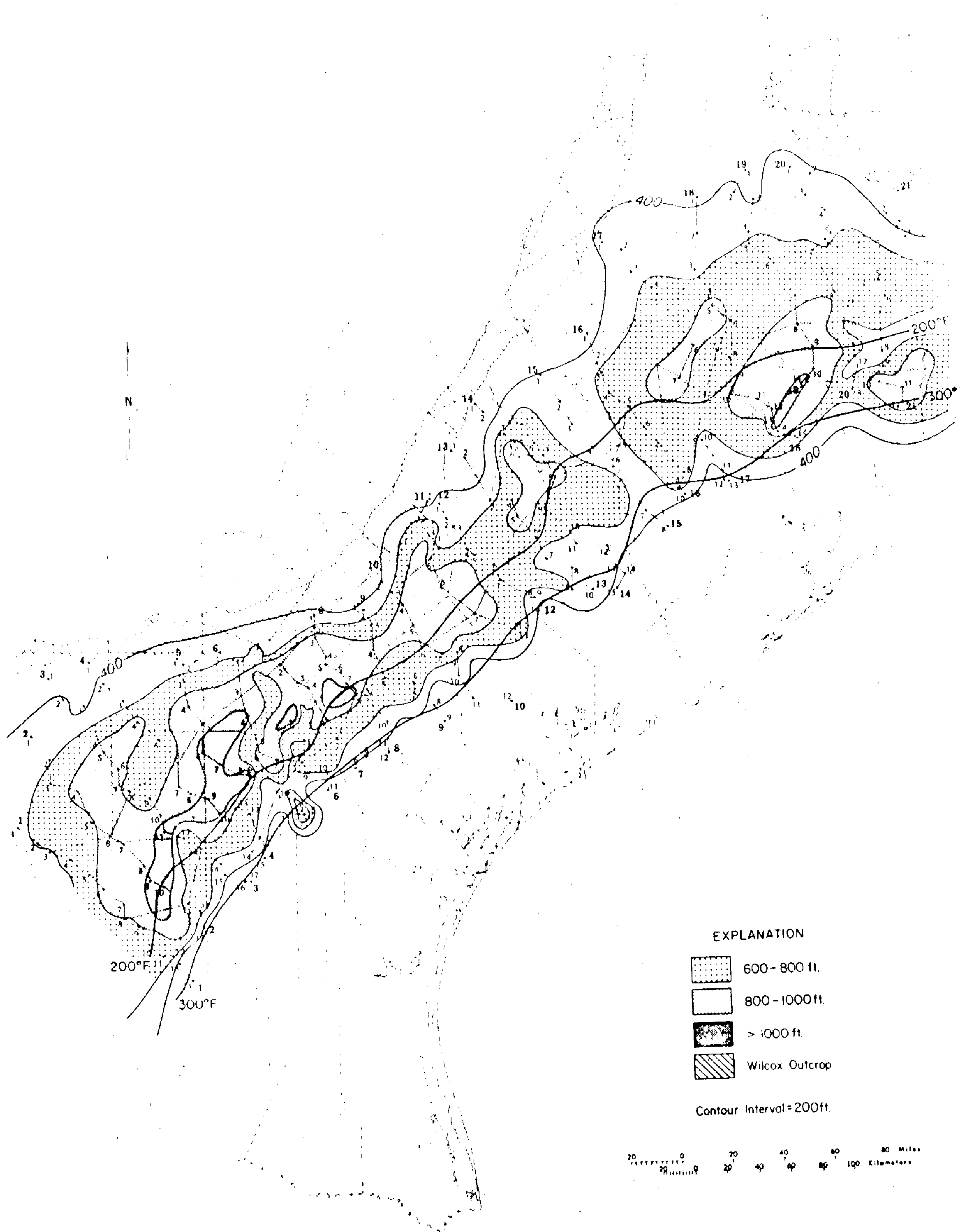

Figure 35. Net sandstone - upper Wilcox.

Figure 36. Sandstone percentage - upper Wilcox.

FORMATION PRESSURES

The top of geopressure, determined from resistivity logs, sonic logs, and drilling mud weights, occurs at depths of 8,000 to 10,000 feet in areas where the Wilcox is dominantly shale and at depths of 11,000 to 13,000 feet where the Wilcox is dominantly sandstone.

Knowledge of the first occurrence of geopressures and the pressure depth profile in a geologic section is valuable for improving drilling and completion techniques and for making reserve estimates and performance predictions. Information obtained about geopressures before drilling permits the use of minimum safe mud weights; helps prevent lost circulation, blowouts, gas cutting, wall sticking, and heaving shales; and assists in the selection of proper casing, casing seats, and wellhead equipment. Hence the well can be drilled faster at reduced costs. In exploration, the identification of geopressure tops in regional control wells permits contour mapping that helps define favorable sandstone ratio environments and establishes probable depths at which subsequent wells will encounter geopressured formations.

The map of depth to top of geopressure in the Wilcox Group (fig. 37) reflects the configuration of the net-sandstone maps. The top of geopressure is relatively shallow, less than 9,000 feet below sea level, downdip of the main-sandstone depocenter; in contrast, top of geopressure occurs deeper than 13,000 feet in areas of major deltaic lobes, such as northern Harris County where the contours form salients in the downdip direction and conform to the lobate sandstone patterns.

Fluid pressure in shales is determined by using data from both resistivity and sonic logs. A reliable tool for detecting and evaluating geopressured formations is the short normal curve or amplified short normal curve of the electrical log. This resistivity method (Hottmann and Johnson, 1965) relies on the observation that shale resistivity R_{sh} increases with depth as the porosity and water content of shales decreases under conditions of normal compaction. Geopressured shales depart from the normal trend and lower values of R_{sh} are recorded because of the increased porosity and water content of the geopressured shales. The amount of divergence of R_{sh} from the established normal compaction trend is a measure of the pore fluid pressure in the shale and also in adjacent sandstones. Normal procedure for detecting geopressures involves a semilog plot with R_{sh} plotted on the logarithmic scale and depth on the linear scale (fig. 38). A cap rock with higher than normal resistivity is frequently observed above the top of geopressure. The transition zone from hydropressured to geopressured conditions may be sharp and definitive (fig. 38) or gradual and somewhat equivocal.

Sonic logs are probably more reliable than electrical logs for locating and evaluating geopressures. When the shale transit time Δt_{sh} is plotted on semilog paper versus depth (fig. 39), a normal compaction trend line is established and the geopressure top is located at the depth where the plotted data for Δt_{sh} depart from the normal trend.

Top of geopressure contour lines for the Wilcox (fig. 37) were drawn from data determined primarily by analysis of resistivity logs. Supplementary data from sonic and gamma-ray logs were also used. For example, top of geopressure for the Superior Oil Company, #1 T. J. Hightower and Humble Oil and Refining Company, B. E. Quinn #B-1, Liberty

County, Texas is marked by the arrows at about 12,200 feet in the geologic section (fig. 27). A plot of the logarithm of R_{sh} versus depth for these two wells show departures from the normal shale compaction trend that are identified as top of geopressure (fig. 40). It is important to pick only thick high-quality shales to establish the trend line. For example, an effort was made to select shales that were at least 10 to 30 feet thick and to avoid silty, limey, and washed-out shales. Resistivity data for shales at depths less than 4,000 or 5,000 feet were disregarded because these shallow formations contain fresh water with high resistivity values that cannot be used to establish the compaction trend. Discontinuities observed in the trend line may be caused by an abrupt change in lithology or differences in the geologic age with consequent drastic changes in shale properties. A major change in bit size may also affect resistivity values. Bentonitic shales and shales located near salt masses should be avoided because these have low resistivity (high salinity) which may falsely indicate higher than normal pressures. The presence of gas-cut mud and muds containing additives to combat lost circulation may also contribute to spurious resistivity data.

In using well logs for detecting geopressures, the quality of the logs should be considered because logging tools can malfunction in deep holes where temperatures and pressures exceed the safe rating specifications of the logging instruments. Mud weight versus depth recorded on resistivity plots (fig. 40) provides a first approximation of the location of the transition zone. Although mud weights alone are inaccurate and can be misleading for picking geopressure tops, a mud weight of 12 to 13 lbs/gal (0.623 to 0.675 psi/foot) is used to first approximate the depth of the transition zone in the Wilcox when the quality of well-log data is questionable. Depth to geopressure top can then be adjusted after correlations with suitable logs and pressure data from nearby wells. Mud weights are not recommended for quantitative evaluation of geopressure. Detailed analytical procedures for quantitatively determining the geopressure profile are available (Hottmann and Johnson, 1965; Pirson, 1970; Fertl, 1976), but these methods were not deemed necessary for this regional study.

At depths less than 8,000 to 10,000 feet in the Wilcox, fluid pressure gradients are commonly below or slightly above hydropressure level. Below 10,000 feet, however, most of the gas and oil producing reservoirs are geopressured and the gradient increases with depth. Bottom-hole shut-in pressures (BHSIP) from drill-stem tests in the De Witt County area clearly show that most geopressured formations first occur between depths of 9,000 and 10,000 feet (fig. 41); generally, gradients increase with depth to a maximum of about 0.85 psi per foot. Limited BHSIP data for the area including Live Oak, Duval, Webb, and Zapata Counties indicate that geopressures in the Wilcox reservoir occur at depths between 7,700 and 12,000 feet and gradients are less than 0.90 psi per foot (fig. 42). Similar data for deep wells in the Harris County Area show that geopressures in the Wilcox lie between 10,000 and 15,300 feet and gradients range up to 0.87 psi per foot (fig. 43).

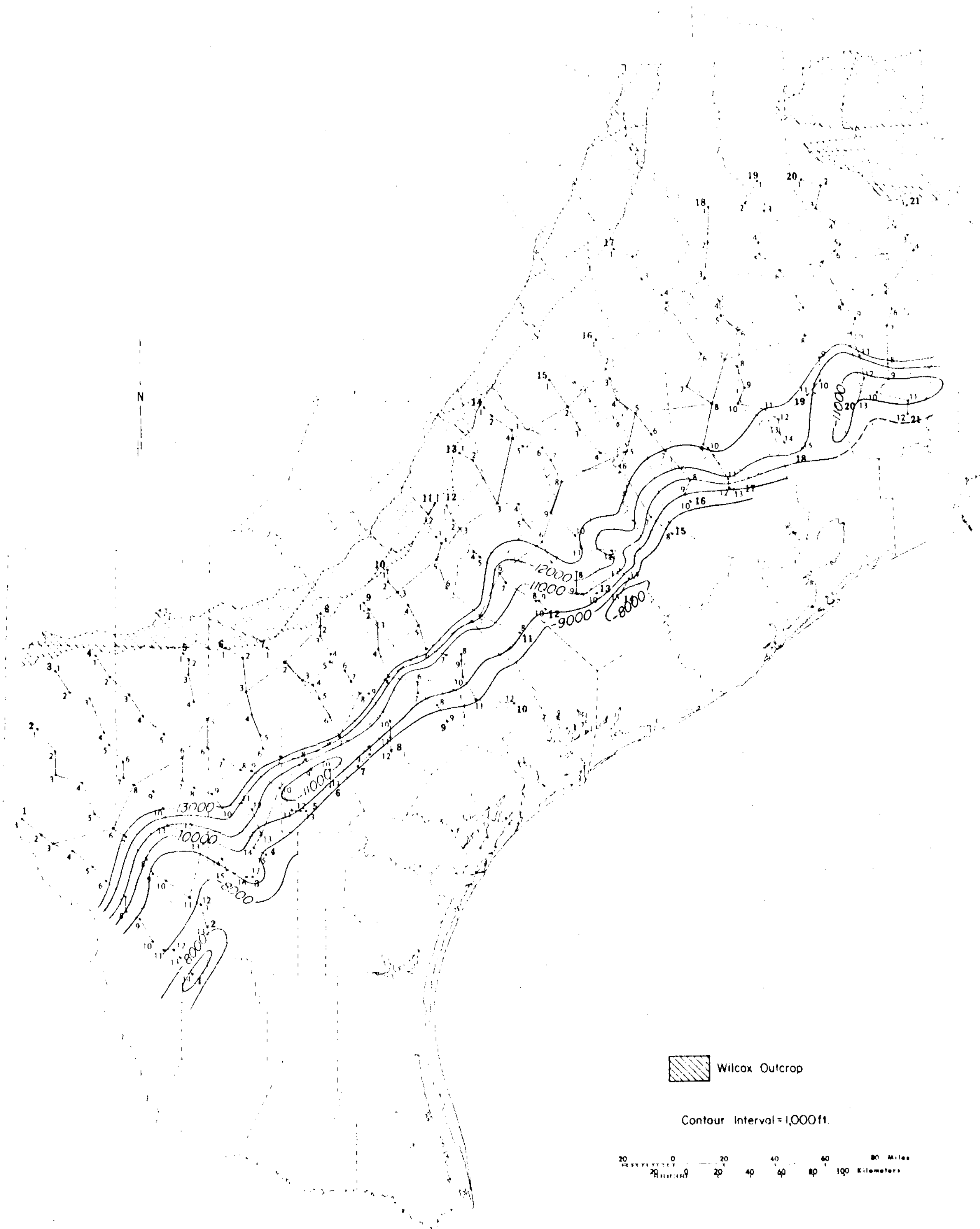

Figure 37. Top of geopressure within the Wilcox Group, Texas Gulf Coast.

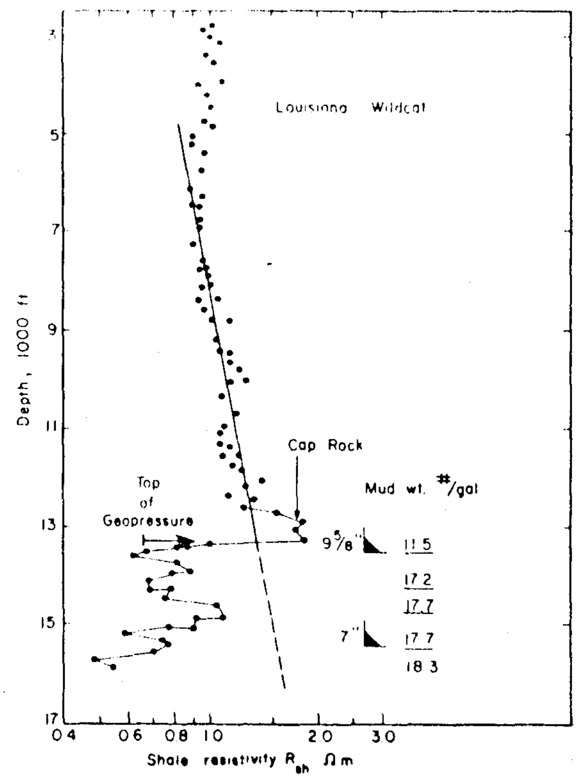

Figure 38. Shale resistivity plot for a Gulf Coast well (after Fertl, 1976).

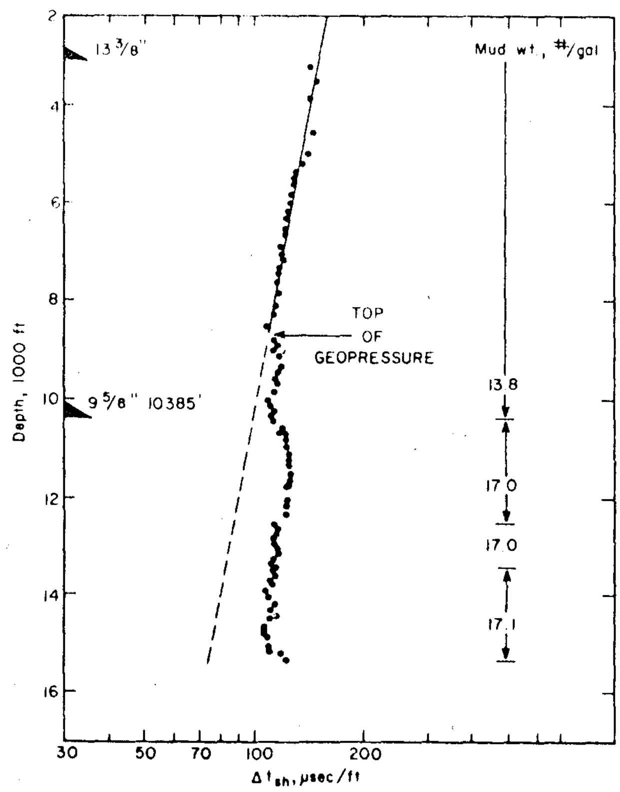

Figure 39. Shale transit time for a Gulf Coast well (after Fertl, 1976).

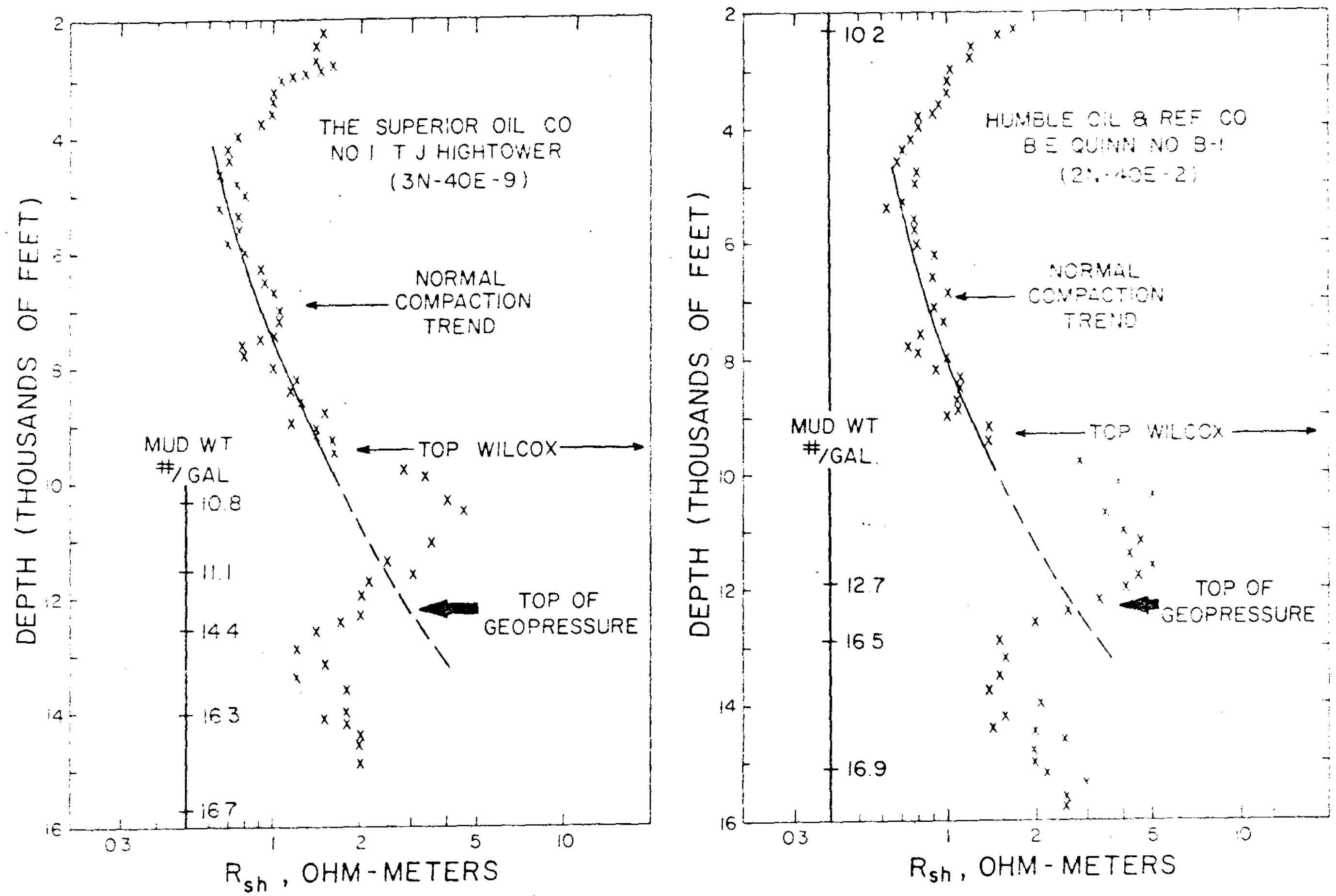

Figure 40. Shale resistivity versus depth plots show tops of geopressure for two wells about 10 miles apart, Liberty County, Texas.

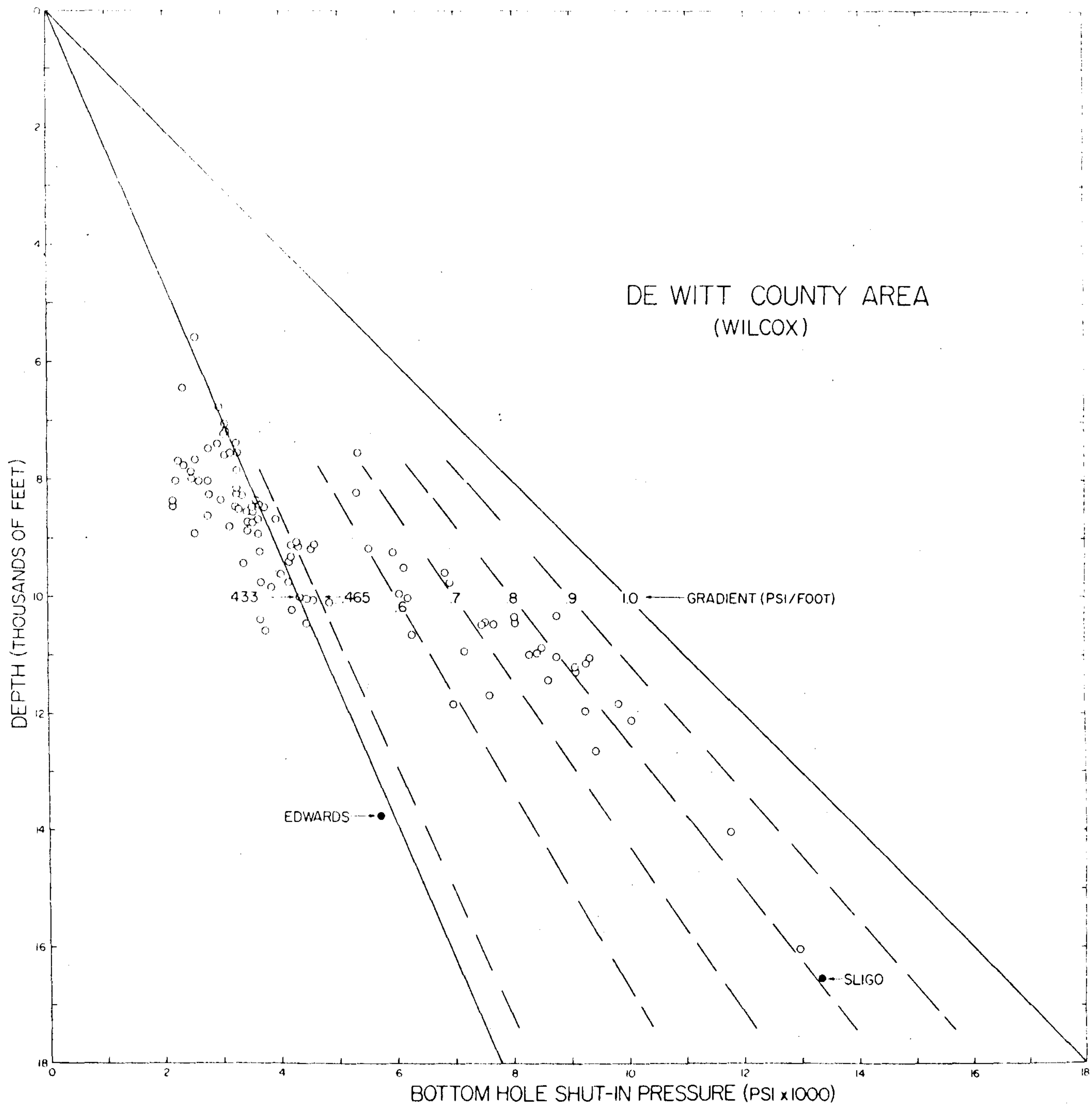

Figure 41. Bottom-hole shut-in pressure versus depth plot for the De Witt County area.

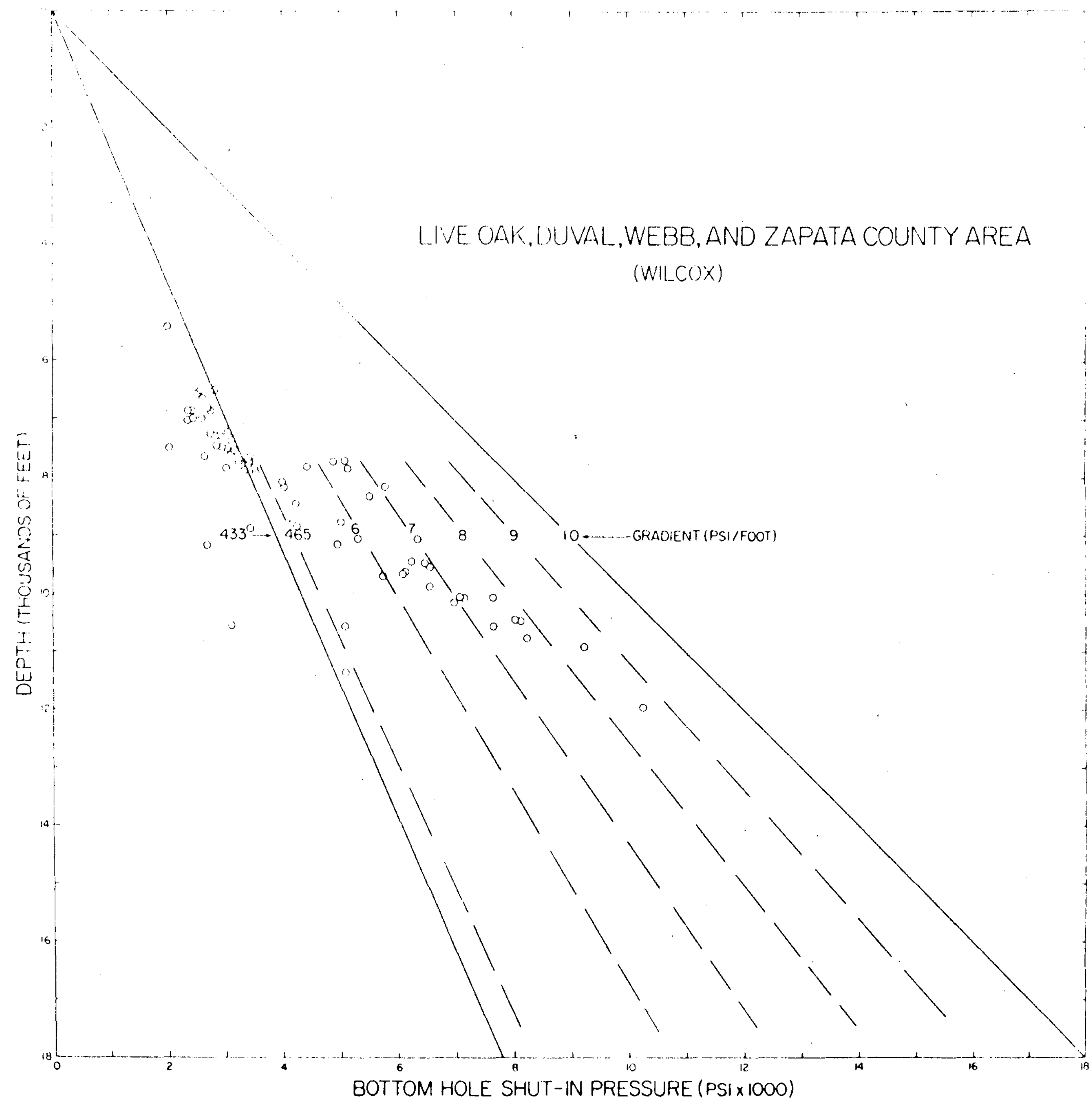

Figure 42. Bottom-hole shut-in pressure versus depth plot for the area including Live Oak, McMullen, Duval, Webb, and Zapata Counties.

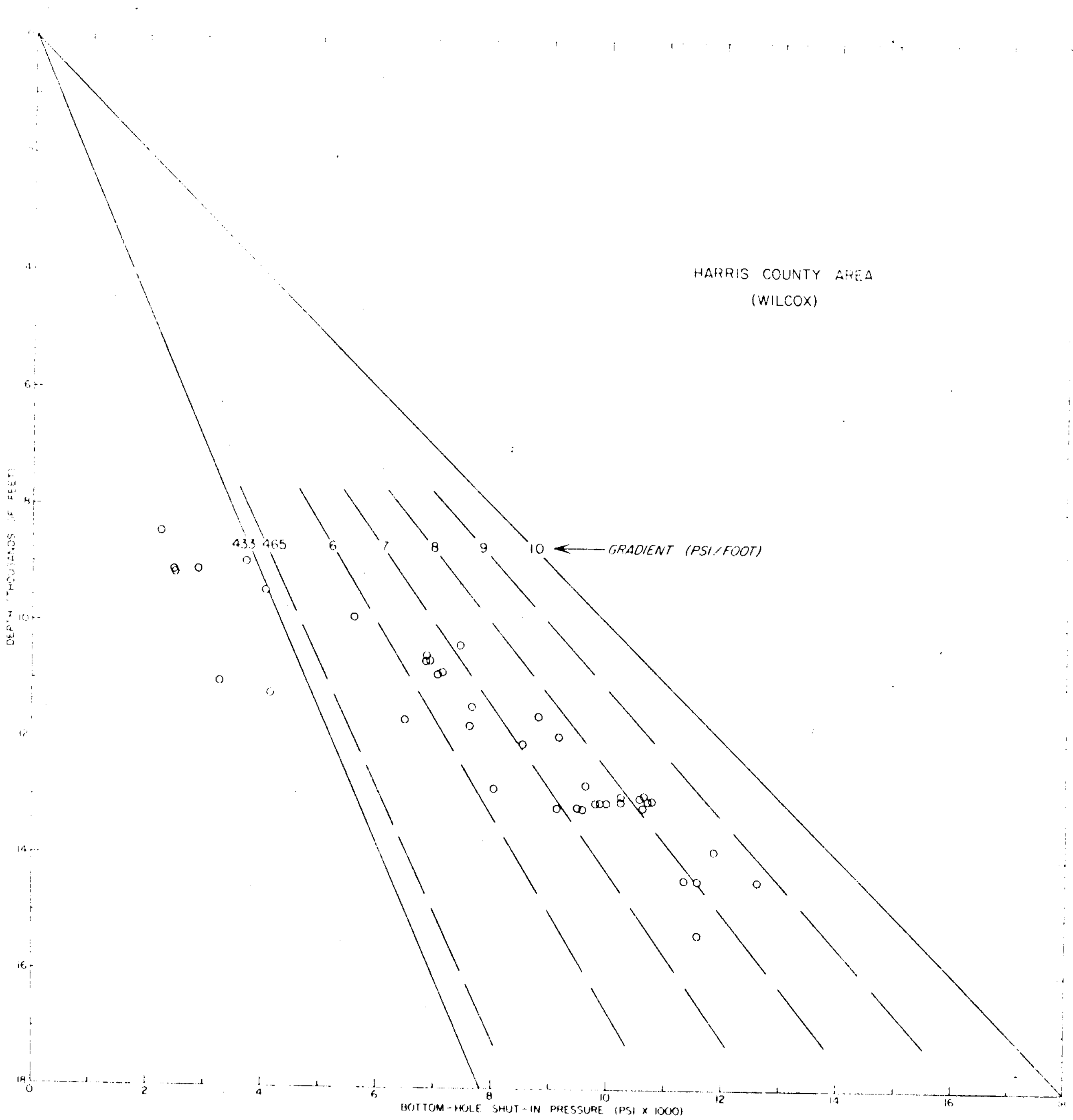

Figure 43. Bottom-hole shut-in pressure versus depth plot for the Harris County area.

FORMATION TEMPERATURES

In the geopressure zone the geothermal gradient reaches as high as 2.7°F per 100 feet, resulting in the occurrence of the 300°F isotherm as shallow as at 10,850 feet in depth.

Formation temperatures have been recorded in this report primarily to serve as a tool to delineate thick sandstone reservoirs with temperatures greater than 300°F. However, subsurface temperature also must be known in order to determine the amount of methane dissolved in the water (Bebout, Loucks, and Gregory, in press). Temperature plays a major role in sandstone, shale, and hydrocarbon diagenesis (Galloway, 1974) which, in turn, control porosity, permeability, and elastic properties of the reservoir rocks. The role of temperature in stimulating diagenetic conversions of clay minerals and dewatering of clay-rich sediments in the Gulf Coast subsurface enivronment is well documented (Burst, 1959, 1969). Alterations in permeability, porosity, and elastic properties caused by changes in temperature have a substantial influence on the bulk volume, pore-fluid volume, and fluid deliverability of reservoirs. Heat effects on elastic properties, in particular, may have an impact on the interpretation of seismic and well-log data that are used for finding, producing, and evaluating geothermal reservoirs.

The point at which 300°F occurs in the Wilcox is indicated where possible on all wells on the stratigraphic sections (figs. 10-32). From these sections the updip-most occurrence of sandstone in the Wilcox with temperatures higher than 300°F is available and has been plotted on the net sandstone maps of lower and upper Wilcox (figs. 44 and 45). Minimum thickness of sandstone penetrated by deep wells with temperatures higher than 300°F are shown, gulfward of the 300°F isotherm.

The average geothermal gradient of the Wilcox is not linear with depth but goes through a 3-stage change of slope that differs for shallow, medium, and deep formations. Generally, gradients increase and higher temperatures occur shallower toward the southwest part of the Wilcox trend (table 1). Gradients are moderate (1.4 to 1.9°F per 100 feet) at depths less than about 9,000 feet in shallow formations that generally lie above the Wilcox. Gradients are highest (2.1 to 2.7°F per 100 feet) from about 9,000 to 14,000 feet and are lowest (1.2 to 1.5°F per 100 feet) in the lower Wilcox from 14,000 to 19,000 feet.

Harris County Area

This area includes parts of Harris, Liberty, Austin, and Colorado Counties and portions of adjacent counties (fig. 46). The geothermal gradient in the upper Wilcox is about 2.1°F per 100 feet in the depth interval 8,300 to 14,000 feet. The lower Wilcox from 14,000 to 18,000 feet has a gradient of about 1.2°F per 100 feet. Formations above the Wilcox (0 to 10,000 feet) have a geothermal gradient of about 1.4°F per 100 feet. A subsurface temperature of 300°F occurs at 13,050 feet below sea level.

De Witt County Area

This area includes portions of DeWitt, Karnes, Goliad, Victoria, and Lavaca Counties (fig. 47). The geothermal gradient in the upper

Wilcox (7,400 to 14,000 feet) is about 2.6°F per 100 feet. A gradient of 1.2°F per 100 feet occurs in the lower Wilcox at depths between 14,000 and about 19,000 feet. Shallow formations above the Wilcox (0 to 8,600 feet) have a geothermal gradient of about 1.5°F per 100 feet. A temperature of 300°F occurs at a depth of 11,700 feet.

Area Including Portions of Live Oak, McMullen, Duval, Webb, and Zapata Counties

Geothermal gradients in this southwestern part of the Wilcox trend (fig. 48) range from 1.9°F per 100 feet for formations above the Wilcox (0 to 9,700 feet) to 2.7°F per 100 feet for the upper Wilcox (6,800 to 14,000 feet) to 1.5°F per 100 feet in the lower Wilcox (14,000 to 16,000 feet). A temperature of 300°F occurs at a depth of 10,850 feet.

Temperature data used to obtain gradients (figs. 46, 47, and 48) were taken from well logs and corrected to approximate thermal equilibrium by the empirical relation developed by Kehle (1971).

$$T_E = T_L - 8.819 \times 10^{-12} D^3 - 2.143 \times 10^{-8} D^2 + 4.375 \times 10^{-3} D - 1.018 \quad (1)$$

where

T_E = equilibrium temperature, $^{\circ}$F

T_L = bottom-hole temperature from well logs, $^{\circ}$F, and

D = depth, feet.

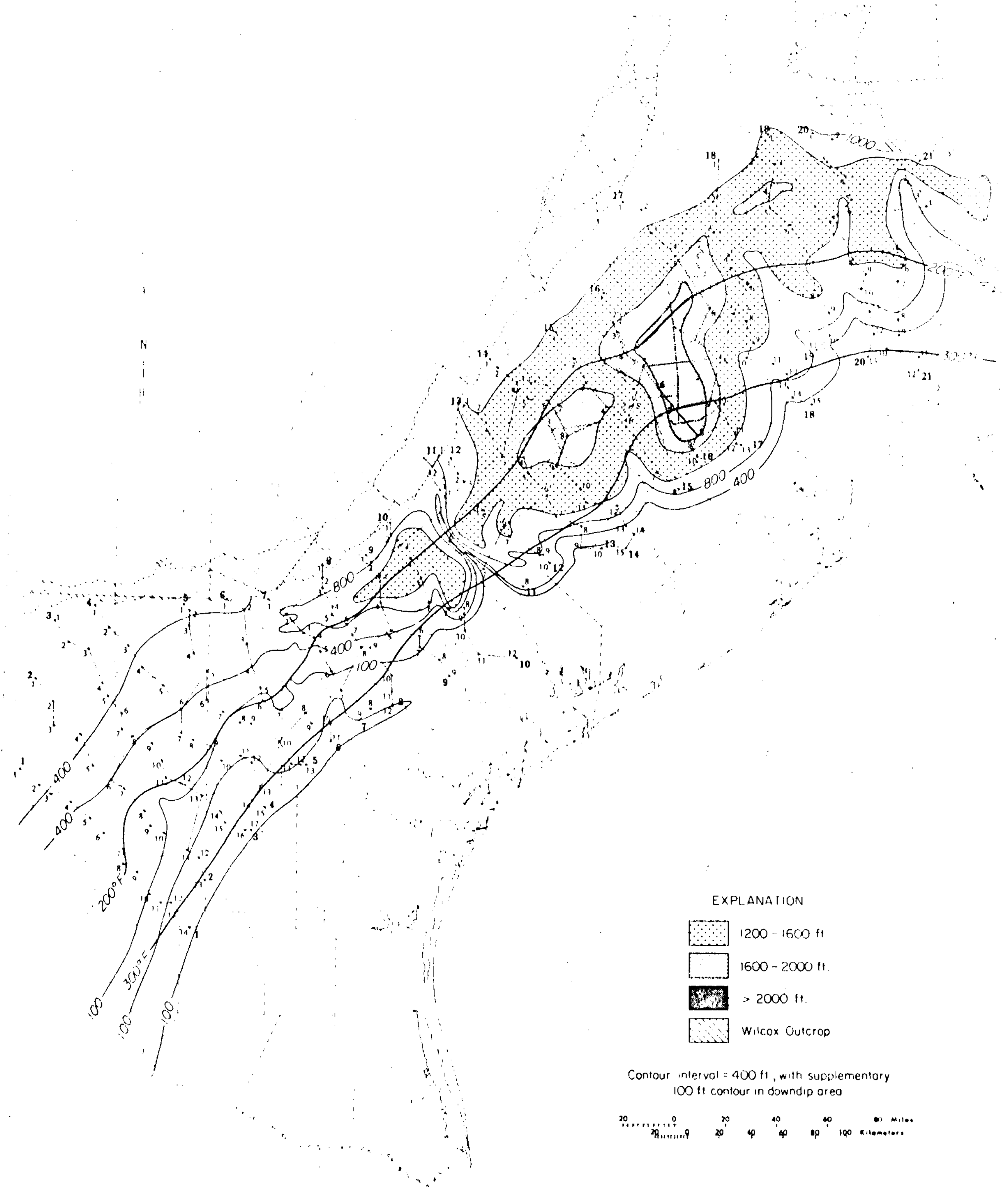

Figure 44. Net sandstone of the lower Wilcox with the 200 and 300°F isotherms.

Figure 45. Net sandstone of the upper Wilcox with the 200 and 300°F isotherms.

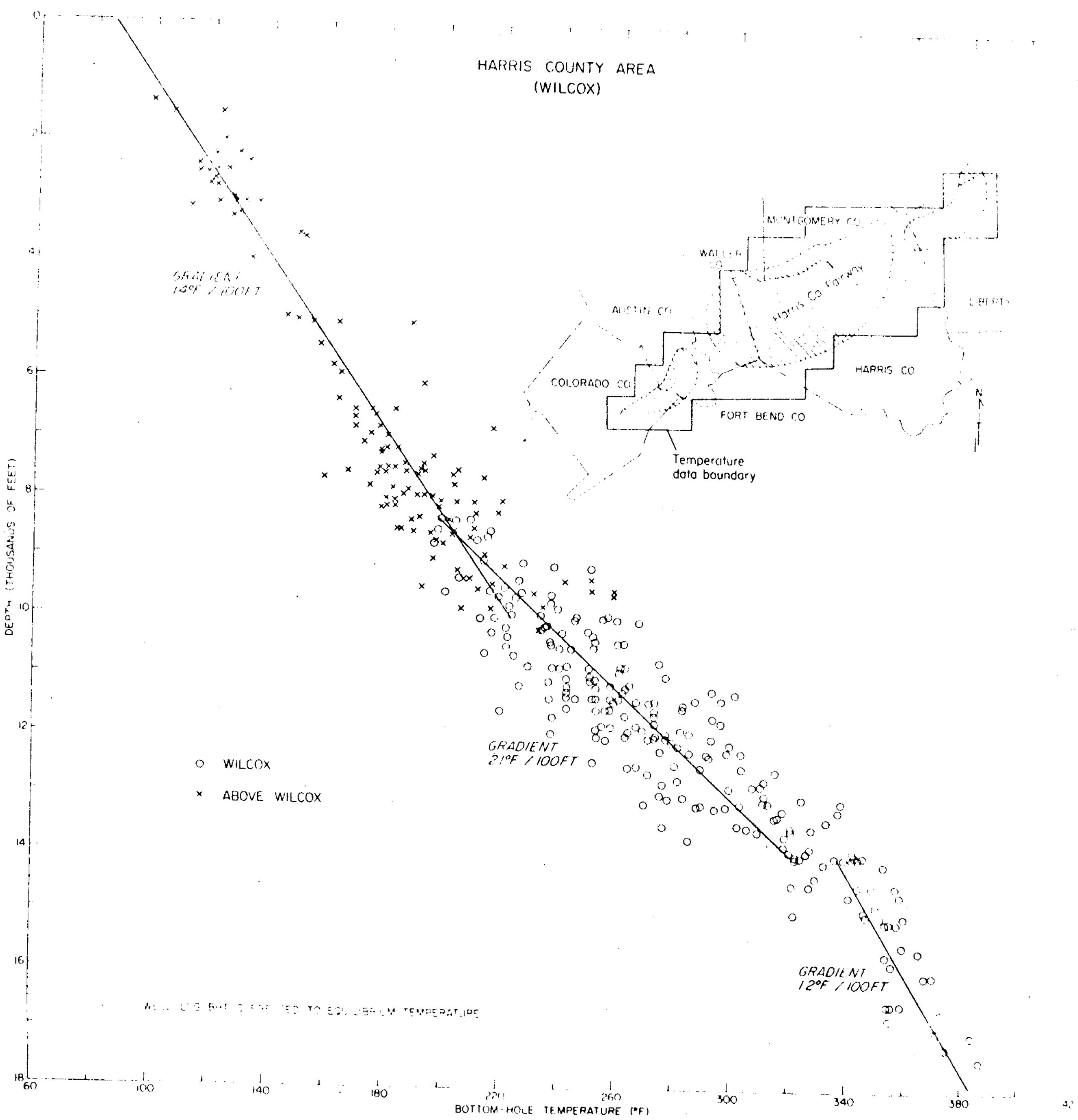

Figure 46. Temperature-versus-depth plot and geothermal gradients for the Harris County area.

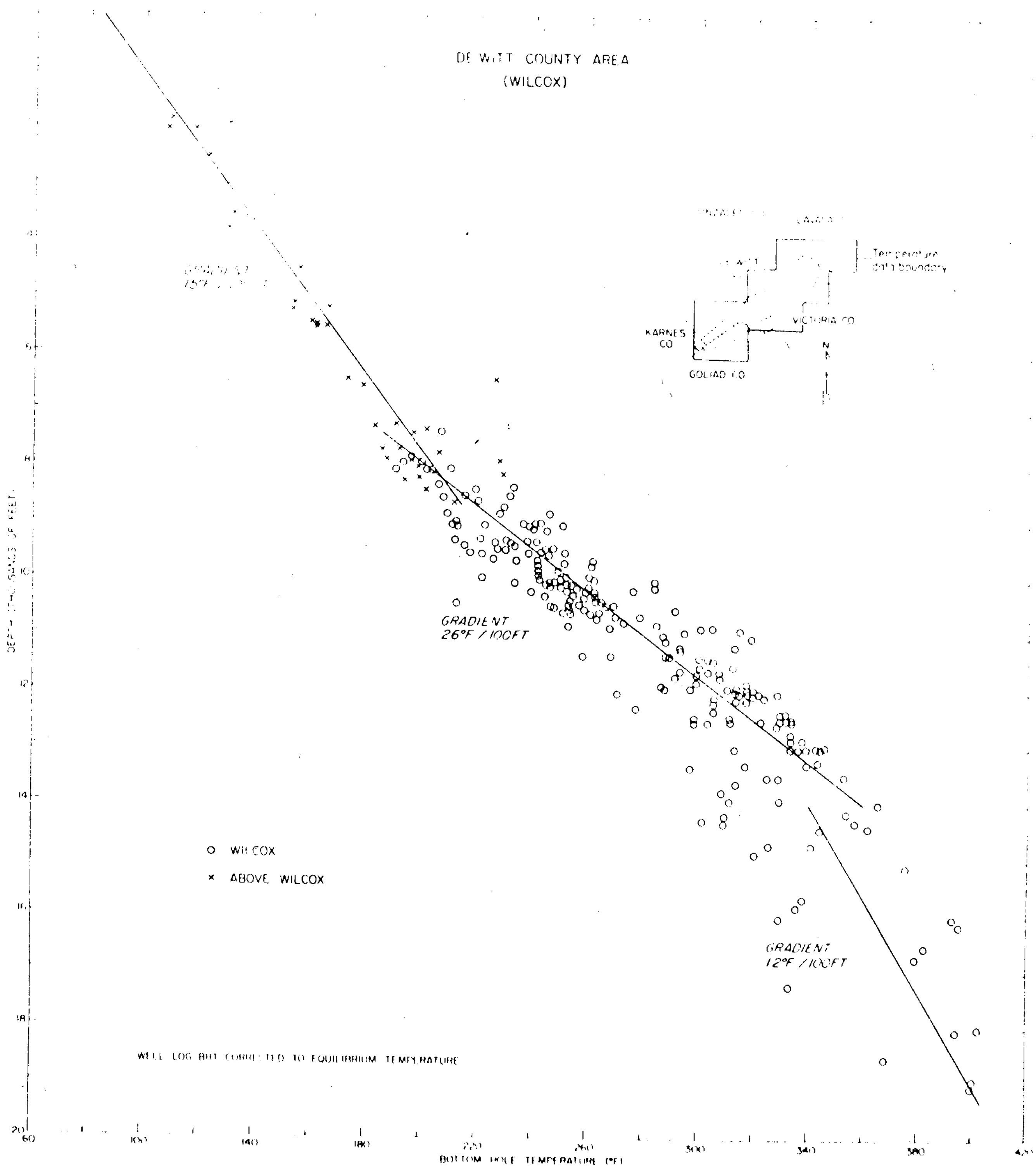

Figure 47. Temperature-versus-depth plot and geothermal gradients for the De Witt County area.

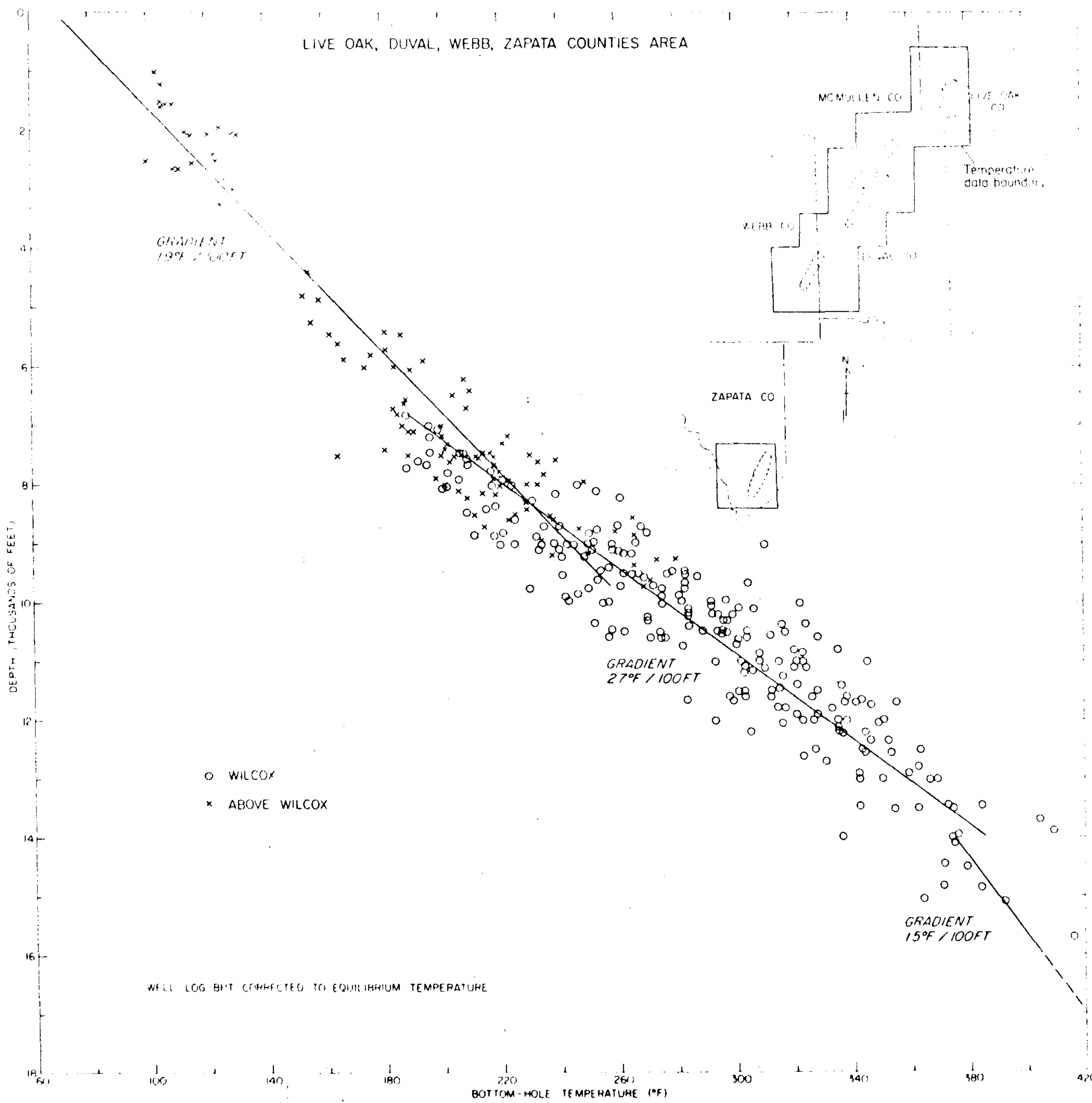

Figure 48. Temperature-versus-depth plot and geothermal gradients for the area including Live Oak, McMullen, Duval, Webb, and Zapata Counties.

GEOTHERMAL FAIRWAYS

Eight geothermal fairways have been identified as having thick sandstone units with subsurface temperatures higher than 300°F.

Geothermal fairways are areas in which thick sandstone sections have subsurface temperatures in excess of 300°F. These fairways are readily identified by superimposing the corrected 300°F isotherm on the net-sandstone maps (figs. 44 and 45). Fairways occur downdip of this isotherm. Eight Wilcox geothermal fairways have been recognized in this way (fig. 49); two of the fairways occur in the upper Wilcox (Live Oak and Webb) and the remaining six, in the lower Wilcox (Liberty, Harris, Colorado, De Witt, and Zapata. The fairways range in areal extent from more than 1,000 to less than 50 square miles and contain total net sandstone varying from 3,600 to less than 300 feet (table 2). The top of geopressure occurs at depths between 9,000 to 13,300 feet and the 300°F temperature, at depths of 10,200 to 13,800 feet. In all fairways, except Zapata, the individual sandstone beds range in thickness from 10 to 60 feet; in the Zapata Fairway individual beds appear to be as thick as 150 feet. Typical electrical logs from wells in these fairways are shown on Figures 50 to 57.

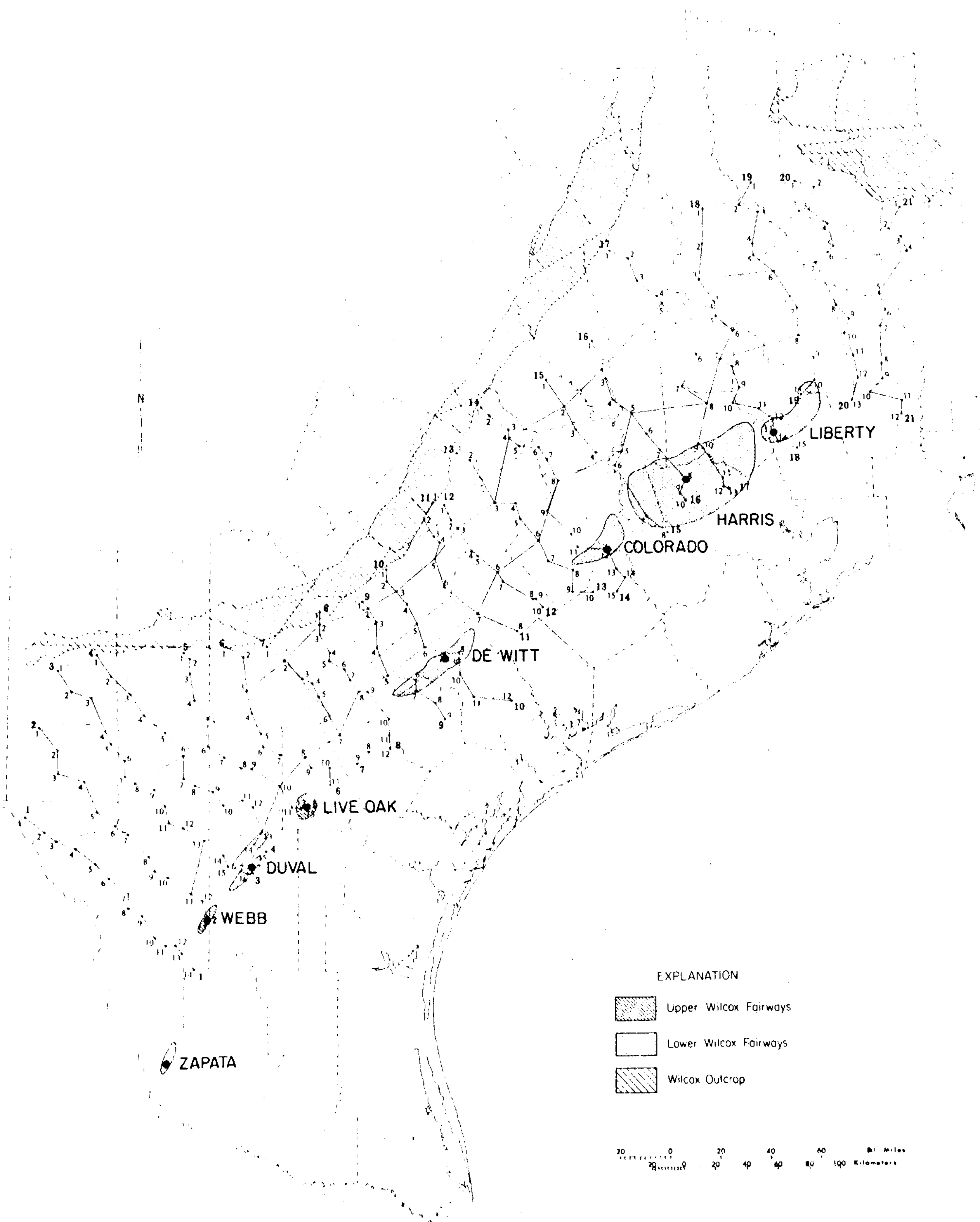

Figure 49. Wilcox geothermal fairways. Well logs representing each of these fairways are shown on Figures 50 to 57. Dots show locations of representative well logs.

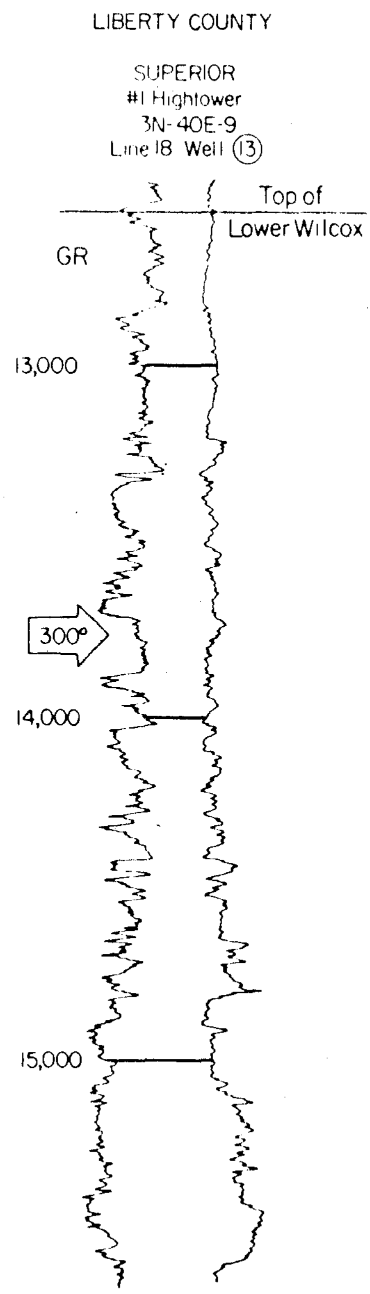

Figure 50. Representative well log from the Liberty Fairway.

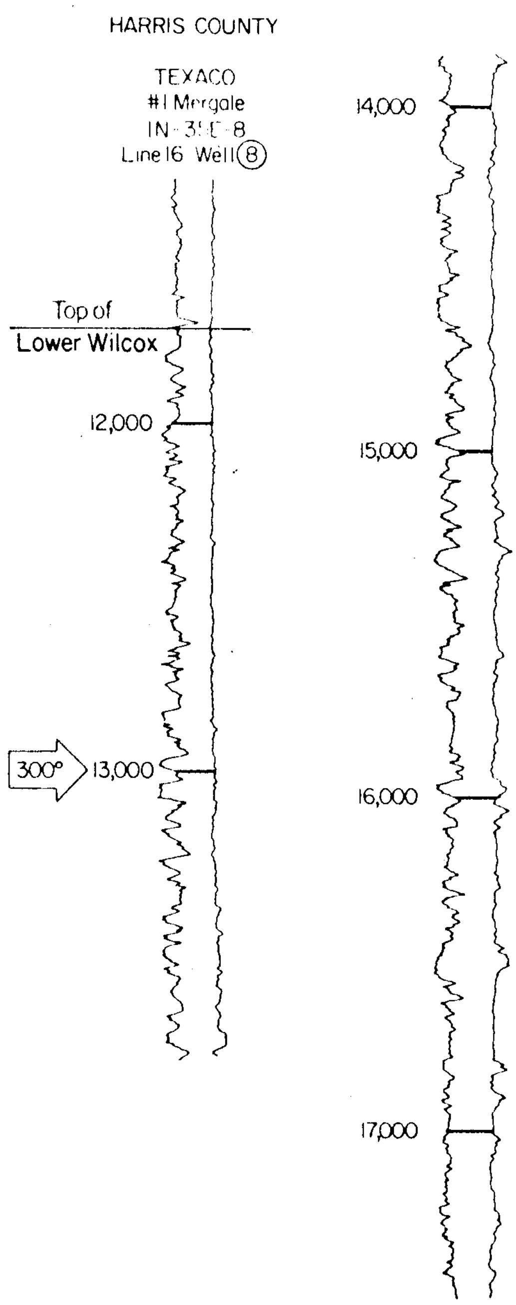

Figure 51. Representative well log from the Harris Fairway.

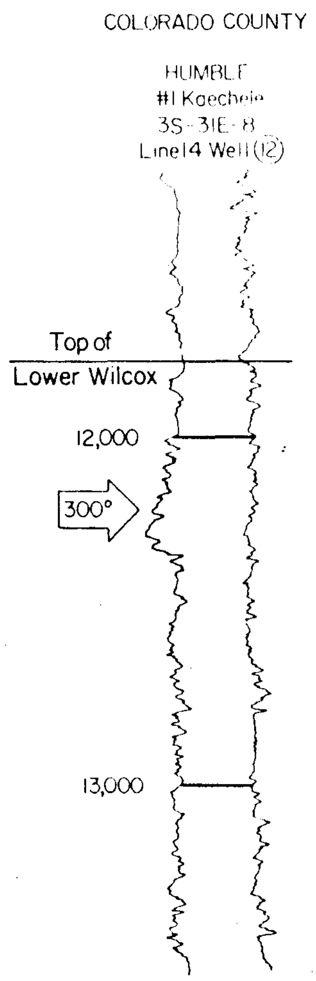

Figure 52. Representative well log from the Colorado Fairway.

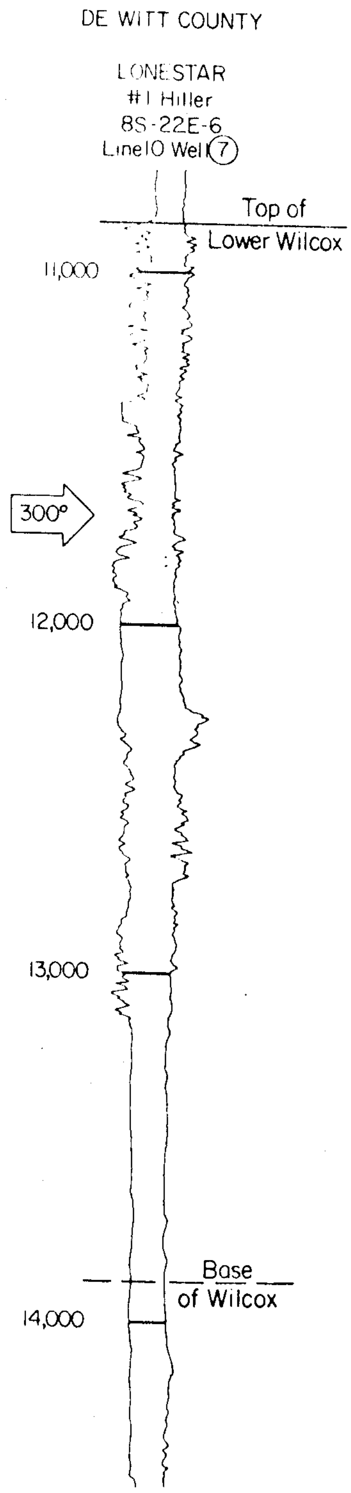

Figure 53. Representative well log from the DeWitt Fairway.

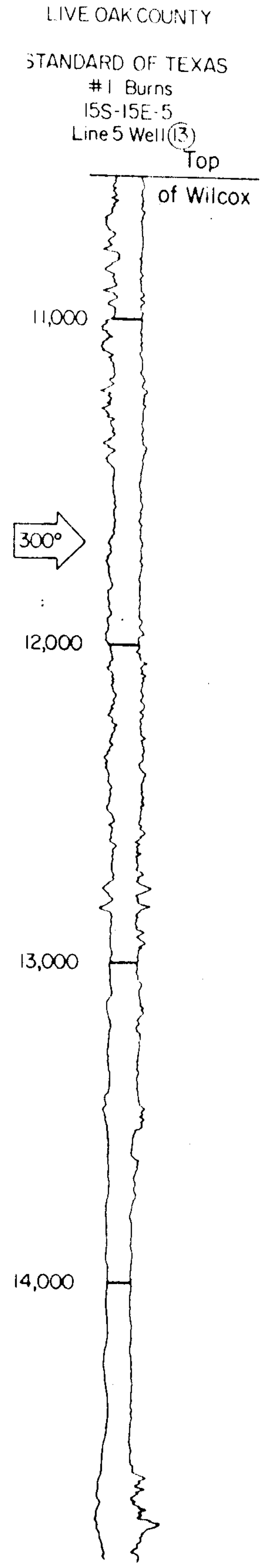

Figure 54. Representative well log from the Live Oak Fairway.

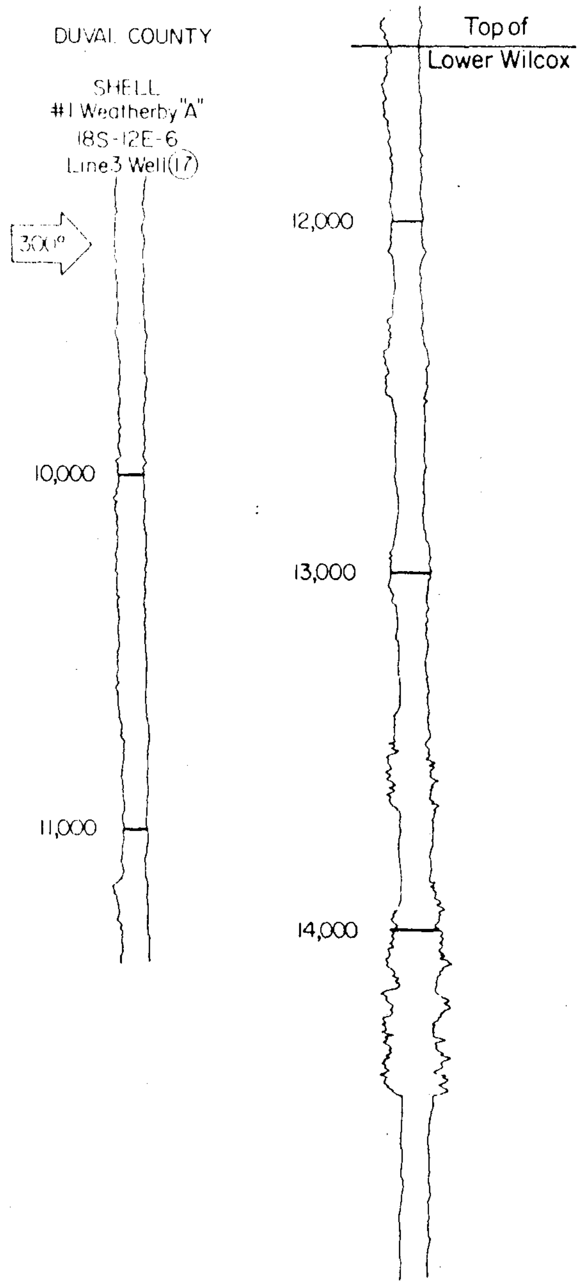

Figure 55. Representative well log from the Duval Fairway.

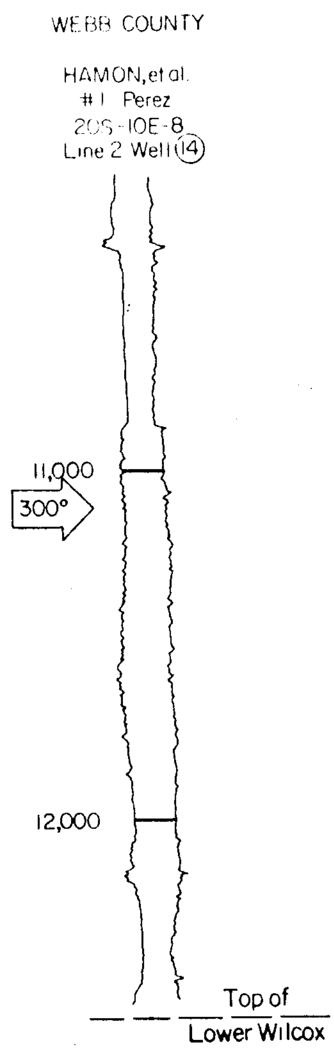

Figure 56. Representative well log from the Webb Fairwav.

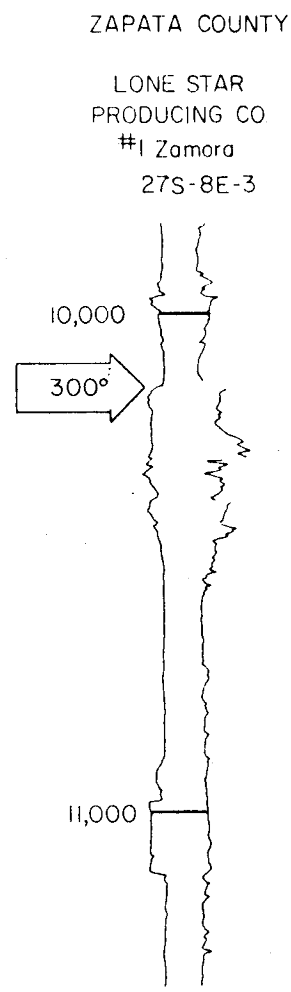

Figure 57. Representative well log from the Zapata Fairway.

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Geomap Company, Houston, Texas, gave us permission to publish the location of faults in the Wilcox from their Gulf Coast mapping service.

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Table 1. Geotherma Gradients of the Wilcox Group,

Texas Gulf Coast

	Harris Co. Area	De Witt Co. Area	Area of Live Oak, McMullen, Duval, Webb, and Zapata Counties
Geothermal Gradients			
Above Wilcox (0-9,000 ft)	1.4	1.5	1.9
Upper Wilcox (9,000-14,000 ft)	2.1	2.6	2.7
Lower Wilcox (below 14,000 ft)	1.2	1.2	1.5
Subsurface Temperatures and Depths			
250^{o}F	10,700	9,800	9,000
300^{o}F	13,050	11,700	10,850
350^{o}F	15,100	14,900	12,700

Table 2. Wilcox Geothermal Fairways

Name	Typical Electrical Log	Number of Wells	Areal Extent (mi^2)	Sandstone Thickness		Depth to	
				Total (ft)	Individual Beds (ft)	300°F (ft)	Top of Geopressure (ft)
Zapata	fig. 57	1	48	340	20-150	10,200	
Webb	fig. 56	1	48	400	10-20	10,800	8,700
Duval	fig. 55	2	140	400	10-50	11,000	9,000-10,000
Live Oak	fig. 54	2	75	240	10-40	11,300	9,400
De Witt	fig. 53	6	280	700	10-50	10,500-19,900	10,100-10,700
Colorado	fig. 52	2	200	850	10-20	12,300	11,400
Harris	fig. 51	11	1,375	3,600	10-60	11,000-13,500	11,100-13,300
Liberty	fig. 50	1	200	460	10-60	12,500-13,800	12,300

*U.S. GOVERNMENT PRINTING OFFICE: 1978-740-306/4277. Region 4.