SALINITY GRADIENT STUDY OF OKLAHOMA

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PREFACE

This thesis is an extension of a preliminary study by Dr. Roger J. Schoeppel which suggested that the vast tabulation of water resistivity data in oil company files may be more reliable than commonly recognized. His contention is that all recorded water resistivity data should be considered valid instead of arbitrarily eliminating suspected erroneous values, as is current practice. Dr. Schoeppel's inspiration, support, and co-supervision of this work are gratefully acknowledged.

The writer is also grateful to the many individuals and companies who assisted him during the study. Dr. John W. Shelton co-supervised the study and offered valuable suggestions for direction. Drs. Douglas C. Kent and Tommy B. Thompson served on the author's committee and provided helpful criticisms. Dr. Gary Stewart also provided encouragement and helpful comments. Tabulations of data were kindly provided by Mr. Kenneth Kemp with Schlumberger Well Services Company, Mr. B. F. Davis with Skelly Oil Company, Mr. D. H. Winchell with Lone Star Producing Company, and Mr. Arle Collins with the U. S. Department of Interior, Bureau of Mines. The base map was made available by Mr. Roy Davis of the Oklahoma Geological Survey. Assistance in plotting was graciously provided by Cities Service Oil Company, and the writer wishes to especially thank Dr. Richard H. Lassley for this help. Mr. John Roberts with the Oklahoma Geological Survey supplied helpful information concerning Oklahoma petroleum production. Appreciation is also expressed

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CHAPTER I

ABSTRACT

The concentration of dissolved solids in formation water generally increases linearly with depth. The rate of change in salinity with depth was mapped for Oklahoma from tabulated water resistivities of borehole fluid samples. Contour maps were prepared to represent salinity gradients for 3 sets of data: those from reservoirs of all ages, those from Permian and Pennsylvanian reservoirs, and those from pre-Pennsylvanian reservoirs. Data preparation by computer included generation of latitude and longitude coordinates for machine smoothing and plotting; the maps, however, were hand-contoured. A series of computer-drawn conductivity (an approximation of salinity) versus depth plots of the basic data arranged in appropriate stratigraphic intervals complement the salinity gradient maps.

The coincidence of anomalously fresh salinities on the conductivity versus depth plots (scatter plots) with low values of salinity gradient suggests that depth is not a dominant factor in the calculation of linear salinity gradients. All salinity gradient maps show a dominant west-to-east increase in gradients over the northern two-thirds of the state. The more complex patterns in the southern third are consistent with a diverse structural framework. Freshening by meteroic waters is evident in the pre-Pennsylvanian section downdip from the Ozark uplift and on the north side of the Arbuckle uplift. Scatter plots reveal

that this recharge affects Ordovician units to depths of 4,000 ft. The Anadarko and Arkoma basins and part of the Ardmore basin are characterized by abnormally low gradients which indicate relatively fresh water at great depths. A number of salinity gradient highs restricted to Permian-Pennsylvanian units, may reflect greater stratigraphic discontinuity of that section than in pre-Pennsylvanian rocks. These highs may also indicate upward movement of water along fault zones.

Correlation is good between certain salinity features and several large oil and gas accumulations. Areas for potential use of salinity studies include ground water and geothermal resources as well as hydrocarbon exploration and production.

CHAPTER II

INTRODUCTION

Although much study has been made of the composition and movement of hydrocarbons and associated water, relatively little emphasis has been placed on surveying subsurface waters as a complete fluid system. The identification and study of the ion concentrations of subsurface waters are thought to offer important clues to sources, movement, and other subsurface conditions.

Studies of relatively deep ground water are needed for a better understanding of our geothermal energy resources. This information may also be useful in the development of improved exploratory procedures for hydrocarbons. The accurate assessment of reserves for deep fresh water awaits the thorough evaluation of subsurface waters.

This investigation focuses its attention on the vertical and horizontal distribution of water resistivity in subsurface formations of Oklahoma (Fig. 1). Electrical resistivity of underground water is normally a function of the water's salinity, which, in turn, may offer valuable clues in determining present and past water movement and sources.

Water Resistivities

In well logging, the electrical resistivity of formation water (R_w) is its ability to impede the flow of an electric current.

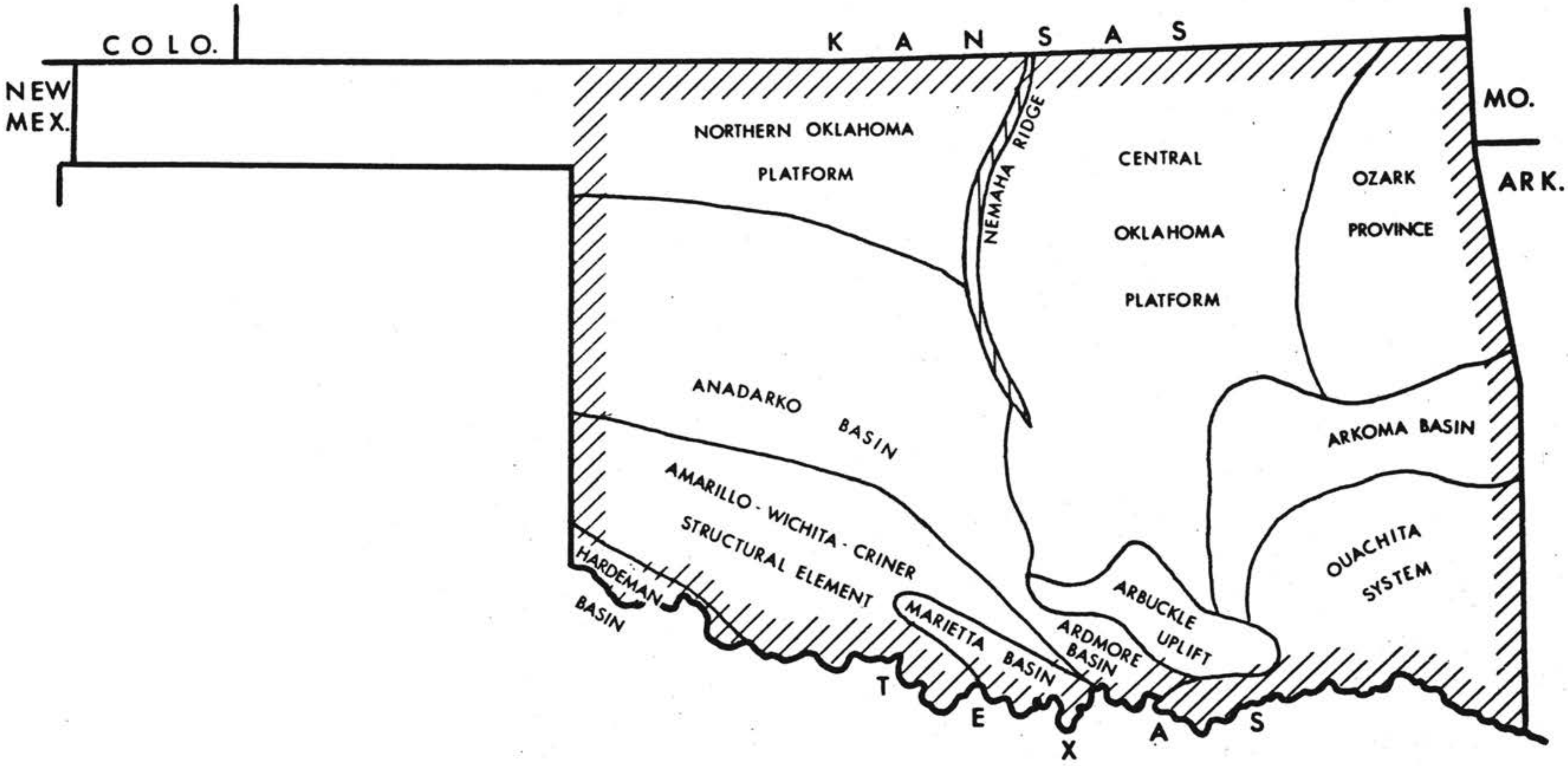

Fig. 1.-Index map showing the area under study and the major structural elements of Oklahoma (after Arbenz, 1956).

Numerical values of water resistivity depend upon 3 principal factors: the type and concentration of dissolved solids, and the temperature. Conductivity ($1/R_w$), or the reciprocal of water resistivity, represents an indirect measure of salinity. At a constant temperature, the range of $1/R_w$ values will be proportional to the range of salinity values.

Water resistivity measurements are obtained primarily by one of 3 methods: (1) by direct measurement of the sample resistivity, (2) by calculation from a water analysis, and (3) by estimation from an electric log. An easy and reliable method of calculating water resistivity from a water analysis has been presented by Dunlap and Hawthorne (1951). (In this study, directly measured resistivities were used in preference to calculated values because of their availability in tabulated form.)

Water resistivity is a parameter which must be known in calculating certain log-derived properties of formations. Among these are the water saturation, which gives an indication of the relative amounts of hydrocarbons and water contained in the pore space, and the formational porosity. They also are used to determine invasion of particular formations by water from casing or cement leaks and to determine the suitability and compatibility of waters to be injected into oil-producing formations to stimulate oil production (Wright _et_ _al_., 1957).

Much effort has been directed toward cataloging laboratory resistivity measurements for reference by formation and location. Although resistivity values of this type have been considered unreliable by many investigators (Ayers _et_ _al_., 1952; Hawkins and Moore, 1956; Jones, 1960), tabulations of these data are thought to be useful sources of information for regional salinity studies.

Salinity Mapping

Several investigations have been conducted in the last 20 years involving various types of salinity or resistivity mapping. Emphasis in these efforts has been oriented chiefly toward the interests of the petroleum industry.

The earliest significant work was by Puzin in 1952, who tabulated R_w values for Oklahoma and mapped them by geologic system to show "equi-resistivity lines." His objective was to provide an aid in the interpretation of electric logs in Oklahoma.

In 1962, Jones showed that mapping R_w values for one formation could be a significant aid in locating stratigraphic traps. He found generally that oil production is associated with pockets of higher salinity, or stagnant, water and postulated that this phenomenon is more common in the Rocky Mountain basins because flushing is enhanced by outcrops of reservoirs in the foothills flanking the basins. Those areas exhibiting higher resistivities are indicative of continued and stronger flushing.

In McNeal's classic study of Permian basin hydrodynamics in 1965, salinity maps of each formation are used to supplement his potentiometric maps. The salinity maps not only serve as control for correction of water densities for local potentiometric surfaces, but also suggest some interesting correlations between anomalous salinities and fault zones.

Hydrologists have also recognized the importance that deep water reserves could play in the future. Kohout (1970), for example, believes that a major reorientation of our thinking regarding saline and deep saline water resources needs to be made. He discusses uses of saline ground water and also includes a map adapted from Feth _et al_. (1965), showing the depth to and quality of the shallowest ground water containing more than 1,000 ppm dissolved solids.

Recent salinity studies have also been reported by a research group of Continental Oil Company. Their investigations show that borehole salinity profiles can help in locating subsurface geologic features as well as temperature and pressure conditions. Specific mapping by Zanier and Timko (1970) and Zanier and Pert (1971) relates initial potentials of oil and gas wells to the ratio of the formation salinity above the producing zone to the salinity of the producing zone itself. Higher ratios correlate very well with higher initial potentials.

The first known effort to undertake the mapping of salinity gradients was that of Klanderud and Schoeppel in 1965. They showed that tabulated water resistivities are useful in determining both vertical and lateral salinity variations. In this initial "engineering" approach to the problem, resistivity gradients were mapped for the Arkoma basin of eastern Oklahoma and western Arkansas. Although no attempts were made to correlate the results with geology, the study is of significance in that it forms the basis for the direction and mapping procedure used in this investigation. The effort is similar to a regional treatment of geothermal gradients reported by Schoeppel and Gilarranz (1966).

Reliability of the Gradient Approach

A steady increase in salinity with depth is supported by a number of workers as the most general salinity-depth relationship (Bredehoeft et al., 1963; White, 1965; Overton and Timko, 1969; Fertl and Timko, 1970b). Two additional studies which show a linear increase of salinity with depth are reported by von Engelhardt and Gaida (1963) and Dickey (1969).

Von Engelhardt and Gaida performed compaction experiments on clay sediments in an attempt to explain the increasing concentrations of salinity with depth that were reported by previous investigators from the Illinois basin, certain areas of Texas, Arkansas, and north Louisiana. Their investigation showed that the membrane filtering property of clays tends to concentrate dissolved solids as water is compacted out of the shale.

The study by Dickey of pore water salinity for several formations in Oklahoma supports the stated salinity-depth relationship. He noted that the trend of the salinity data is to increase linearly with depth in Pennsylvanian Cherokee sandstones (Fig. 2).

It should be cautioned that a linear increase in salinity with depth is not without exception. Many investigators have noted, for example, that salinity decreases in geopressured zones (Dickey, 1969; Overton and Timko, 1969; Fertl and Timko, 1970b). Even in relatively more stable environments, abrupt changes in the slope of the vertical salinity profile may be observed.

This investigation assumes that a linear increase in salinity with depth can be used to characterize salinity data obtained from various geologic formations over large areas. Furthermore, it is contended that any local exceptions to this general relationship would be minimized by regional mapping. Hence, it is expected that maps showing the rate

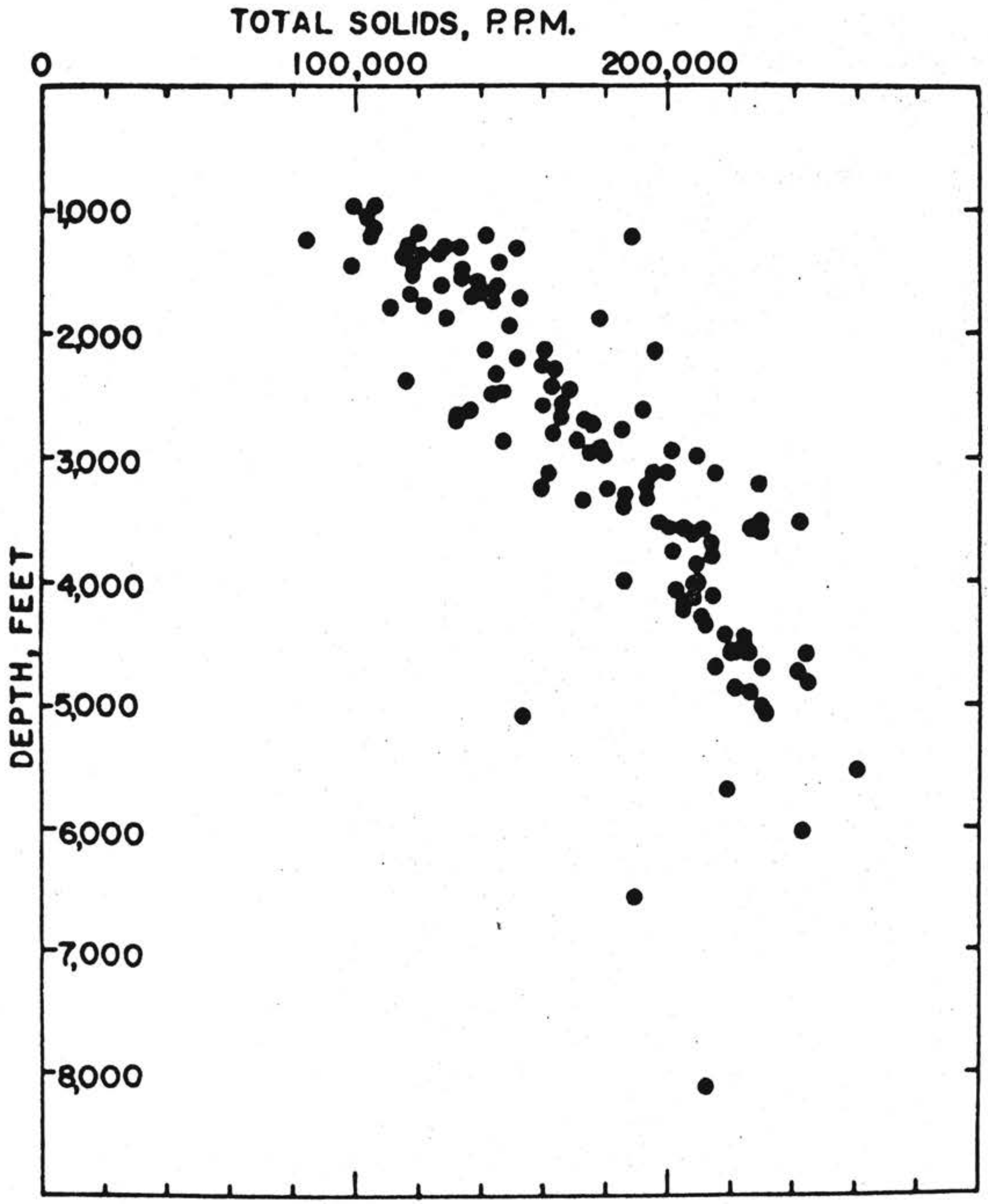

Fig. 2.-Plot of salinity vs. depth for the Pennsylvanian Cherokee Group of Oklahoma (from Dickey, 1969).

of change of salinity with depth, or the salinity gradient, should indicate regional changes in the ion concentrations of subsurface water.

Objectives and Scope

The principal objective of this study was to prepare 3 salinity gradient maps of Oklahoma, excluding the Panhandle (Fig. 1). The maps include a composite of data from all ages, a map using only pre-Pennsylvanian data, and a map using only Permian and Pennsylvanian data. All maps were prepared with data adjusted by a computer smoothing technique to reduce the influence of sharply anomalous values and accentuate regional trends.

Plots of conductivity versus depth for each geologic system and both groups of systems described above are included for interpretation of resistivity changes with depth. An attempt is also made to correlate the results with current theories of fluid movement, as well as with other regional or subregional geologic and geophysical features.

CHAPTER III

PREVIOUS INVESTIGATIONS

Of particular interest to this work are studies of topics related to salinity gradients such as, subsurface fluid composition, compaction, diagenesis, ground water movement, pressure and temperature variations, paleogeology, and entrapment of hydrocarbons.

Subsurface Fluid Composition

According to Dickey and Hunt (1971), the most useful system for categorizing underground waters was proposed by Sulin (1946). The Sulin system distinguishes 4 main types of ground water: (1) sulfate-sodium, (2) bicarbonate sodium, (3) chloride-magnesium, and (4) chloride-calcium. The first 2 are characteristic of artesian, hydrodynamic systems. The third is found only in association with evaporitic sequences, and the last is that type commonly associated with oil production. Because the Sulin system separates waters which appear to have different origins, it has been regarded as a "genetic classification" by Russian workers.

In the Rocky Mountain basins, strong hydrodynamic conditions have caused extensive mixing of 2 or more types of waters. However, in plains areas where the hydrodynamic forces are less, the zone of mixing between types (1) and (2) (meteoric) and type (4) is relatively thin. Brines with type (4) characteristics are thought by Russian investigators to occur in "zones of restricted water interchange." Waters of this type are also commonly referred to as connate water. Lane (1908) first proposed the term "connate water" as the altered remains of original sea water trapped when the sediments were deposited. White (1965) included an element of time in redefining it as "'fossil' water that has been out of contact with the atmosphere for at least an appreciable part of a geologic period."

Chemical composition of oil field waters has long been recognized to be strikingly similar in many different parts of the world (de Sitter, 1947; von Engelhardt and Gaida, 1963; Dickey and Hunt, 1971). Practically the only anion present is chloride, with sulfate and bicarbonate being very low in concentration, if present at all. The principal cation is sodium; the calcium:magnesium ratio is commonly between 3 and 5. Perhaps the most interesting of all similarities, though, is the observation that in practically all pre-Tertiary sedimentary basins, oil field waters become saltier with depth (Bredehoeft _et al_., 1963; von Engelhardt and Gaida, 1963; White, 1965; Dickey, 1969; Dickey and Hunt, 1971). Brine concentrations as great as 300,000 ppm of total dissolved solids have been reported from Oklahoma (Wright _et al_., 1957).

Numerous theories have been advanced to explain both the extremely high ionic concentrations of deep brines and their linear increase with depth. Among the suggestions are molecular diffusion from salt beds, gravitational segregation of ions, thermal diffusion, osmosis, and membrane-filtering or so-called "salt-sieving." Membrane-filtering, which presently enjoys the highest credibility, was first proposed by de Sitter (1947) and has since been supported by Berry (1959), Bredehoeft et al. (1963), von Engelhardt and Gaida (1963), McKelvey and Milne (1962), and White (1965). According to White, the theory states that as compaction proceeds in a sedimentary section with considerable montmorillonite and illite content, clay minerals become so closely compacted that anions in water flowing upward are filtered out. Because of their relatively smaller size, adsorbed cations can still continue to move through the membrane, but, this movement causes an electrical "streaming" potential to be generated between the two sides of the membrane. Additional cations are prohibited from passing through the membrane because of the electrical imbalance. This mechanism allows the uncharged water molecules to pass through the membrane in the direction of lower electrical potential, thereby allowing for an increase in the salt concentration on the input side (White, 1965).

As compaction progresses in a sedimentary basin, connate water occupies pore spaces that are continually decreasing in size. The resulting excess pore water must be constantly expelled to relieve the space problem, a circumstance which usually causes a general upward movement of water. According to the theory, a large part of the expelled water will migrate updip, but a significant amount will be filtered through the compacting shales as described above. A slow rate of subsidence results in a normally compacted sequence with salt concentrations decreasing toward the surface. However, if the filtration rate is exceeded by the rate of burial, some of the weight of the overburden has to be supported by the pore water and the result is abnormal fluid pressures. With the addition of the adsorbed water released from clay minerals undergoing diagenetic changes, these abnormally pressured zones also exhibit unusually low dissolved solids content compared to the horizons above and possibly below. Some degree of upward filtration must slowly be continuing, however, as evidenced by observed pressure gradients. It is interesting to note that Dickey (1969) attributes the linear increase of dissolved solids concentration with increasing depth to be characteristic of "pre-Tertiary sediments in undisturbed areas all over the world." The fact that it is not characteristic in Cenozoic sediments indicates that processes of compaction and membrane filtration are not yet complete.

Bredehoeft _et_ _al_. (1963) proposed a modification of de Sitter's principle regarding the source of the filtered fluid. They theorized that meteoric water migrating downdip from the outcrops of an aquifer and then filtering upward in the center of the basin can result in the observed increase in concentration with depth. They state that hydrostatic pressure of the meteoric water on the flanks of the basin provides the driving force for a continual flow of water downdip into the center of the basin and then vertically through confining strata serving as semi-permeable membranes.

Diagenesis

The process of diagenesis can best be viewed by looking at active sedimentary basins. Considerable work has been recently done on Gulf Coast sediments relating interstitial fluids and diagenesis (Myers and van Siclen, 1964; Powers, 1967; Burst, 1969).

As sediments are deposited and subsequently subjected to a steadily increasing overburden weight, they undergo changes principally due to the effects of increasing pressure and temperature. At the time of deposition, Gulf Coast marine clay sediments contain approximately

70-80% water by volume. Burst (1969) has found that this water is expelled from the sediment in 3 separate stages. During the first few thousand ft of burial, water content is reduced to about 30% (about 20-25% interlayer water and 5-10% residual pore water) in response to overburden pressure. The second stage of dehydration is theorized to be primarily dependent upon thermal effects, occurring between temperatures of 182° and 232°, and involves the release of intracrystalline bound water from clay minerals undergoing changes. Thus, depending on the geothermal regime of an area, second stage dehydration could occur at depths anywhere between 4,000 and 16,000 ft. Third stage dehydration of the last monolayer of water from clay platelets occurs very slowly and at depths too great to be of much interest to the petroleum industry.

The second stage is considered the most important to oil migration, because it involves the displacement of water in volumes 10-15% of the compacted bulk volume of sediment and occurs at depths where hydrocarbon components are most likely to migrate. According to Burst, this is a volume significant enough to redistribute any mobile subsurface component, thereby segregating by migration various commercially exploitable fluid concentrations.

De Sitter (1947) considered compaction to take place in 2 stages. He theorized that the second stage occurred when the permeability was reduced to the point where clays as semi-permeable membranes would restrict ion movement. In a multilayered sand-shale sequence, this mechanism would have the effect of retaining the greatest ion concentrations toward the bottom of the sequence. Sandstones would be flushed by water filtering upward from the underlying massive shales. It is interesting to note that Dickey and Hunt (1971) suggest that oil accumulations occur where large amounts of water have passed through what they call a "capillary filter," which is apparently analagous to a semi-permeable clay membrane. A significant conclusion of Burst's study is that the mean depth of hydrocarbon production statistically occurs about 1,500 to 2,000 ft above the average depth of the second stage dehydration. These observations could indicate some connection between hydrocarbon accumulation and ion concentration.

As noted by Burst, hydrocarbon migration is dependent upon the movement of relatively large volumes of water, which, in turn, is apparently dependent upon a high montmorillonite content in the compacting sediments. Powers (1967) suggests that illite and kaolinite clays rich in organic materials may be expected to compact to oil shales rather than to serve as source rocks. According to this theory, the best source rock for petroleum is a montmorillonitic organic clay.

Regional Flow Studies

Although many authors regard the regional flow of fluids in a compacting basin to be upward in the center, several investigators have included detailed salinity studies in their evaluations of regional hydrodynamics and have found quite unexpected flow patterns to exist. A study of particular interest is the dissertation by Berry (1959) on the hydrodynamics and geochemistry of the San Juan basin of northwestern New Mexico. Berry's potentiometric studies reveal that flow in Cretaceous aquifers of the basin is not only directed toward the lowest outcrop outlets to the northwest, but also "basinwards" in and around the "Inner Basin." Salinities in the same aquifers show an abrupt increase coincident with the location of the potentiometric lows. Also, the absolute potentiometric surface elevations fall below the lowest Cretaceous outcrop. These conditions suggested to Berry the presence of an osmotic hydrodynamic system in addition to the gravitational flow system.

To explain his findings, Berry hypothesized that highly saline waters from solution of the Todilto evaporitic sequence entered the Jurassic Entrada sandstone and related units (below the Cretaceous aquifers) and were trapped within the "Inner Basin" due to a density contrast. Osmotic pressures then developed between the Entrada and the fresher waters of the Cretaceous Dakota Group via the intervening claystone in the Brushy Basin Member of the Morrison Formation which acted as a semi-permeable membrane. The Dakota potentiometric surface was correspondingly lowered and water salinity in the Dakota increased as ions were filtered by the underlying clay membrane. Potentiometric surfaces of overlying aquifers in shale sequences were subsequently lowered in the same manner. Berry suggests that as salt water is lost from the Entrada by outflow from the osmotic system, the Todilto evaporites supply additional dissolved solids to perpetuate flow. He estimates that these conditions have existed for 20 million years and could continue for another 5 million years.

In a very similar study conducted on the Paradox basin, Hanshaw and Hill (1968) found unusually high salinities and potentiometric surfaces in the Upper Paleozoic units bordering the San Juan basin. They suggest that these units may be the receptors of highly saline waters which are being forced out of the Entrada by the San Juan basin's osmotic system.

The osmotic principle has also been called upon by Breeze (1971) to explain otherwise mysterious abnormal to subnormal pressures in Pennsylvanian Morrowan sandstones of northwestern Oklahoma. Breeze found that shale resistivity, shale compaction, geothermal gradients, and salinity variations all indicate that the Morrow should be geopressured. However, his potentiometric map shows geopressures only in west and west-central Oklahoma, with pressures decreasing northwestward to normal and subnormal levels. Furthermore, on the basis of X-ray diffraction analyses of clays representative of each pressure environment, Breeze concluded that diagenesis of clays could not have contributed significantly to the pressures. He attributes the geopressures to compaction phenomena and suggests that the normally and subnormally pressured areas were once geopressured. Due to a favorable stratigraphic environment, an osmotic system then developed that allowed the lowering of pressures to the observed levels.

Osmosis may in time be proved to be a dominant flow characteristic of the Anadarko basin. However, because Breeze's study was confined to a limited stratigraphic sequence and several unexplained features still exist, such as anomalously fresh water in the Morrow without significant clay diagenesis, it is difficult to support Breeze's conclusion as a partial basis for interpretation of this study.

In contrast to the suggested downward flow in the San Juan "Inner Basin," the apparent flow direction in the inner part of most normally compacting basins is upward. The ion concentration theories of de Sitter (1947), Bredehoeft _et al_. (1963), von Engelhardt and Gaida (1963), and White (1965) all involve upward filtration of expelled waters as the means of concentrating dissolved solids. However, it is quite probable that both mechanisms for concentration of dissolved solids and regional subsurface fluid flow are in fact valid. The extent to which they interact, however, has been given little attention except for one publication by Jones (1969) on the hydrodynamics of Gulf Coast geopressures. Jones hypothesized that due to compartmentalization by growth faulting of rapidly deposited deltaic, inner neritic, and middle neritic sands and clays, avenues of exit for fluids expelled by compaction were closed. The resulting rapid rise in the fluid pressure was accompanied by a proportional rise in filtration of fluid through the overlying clays. However, as filtration caused dilution of brines in the overlying hydrostatic aquifer system, osmotic forces opposing the escape of water from the geopressured zone soon equalled the outward pressure and flow ceased.

Also according to Jones' hypothesis, cessation of the upward flow of water greatly checked the rate of upward heat flow by convective heat transfer and overheating of geopressured reservoirs began. Increased temperatures enhanced the dehydration of montmorillonite clays and their alteration to illite, with the accompanying release of intracrystalline water as pore water. This additional pore water was then forced into adjacent aquifers, raising their fluid pressure and decreasing their salinities. Jones (1968) states that hydrodynamic forces responsible for subsurface fluid movement in the Gulf Coast area are due to gravity, temperature, chemical changes, molecular and ionic phenomena, and perhaps spontaneous electrical currents.

Factors Related to the Salinity Gradient

Although many authors have documented the linear increase in salinity with depth, it must be cautioned that this is merely a general relationship, and deviations should be expected. Moreover, such deviations have been observed to be more frequent and more severe in basins where subsidence is still active and compactive processes are incomplete. In fact, salinity-depth relationships are so disturbed in many parts of the Gulf Coast that numerous investigators have reported that no apparent relationship exists (Timm and Maricell, 1953; Myers and van Siclen, 1964; Jones, 1968; Dickey, 1969). In relatively more stable regions, however, changes in the salinity gradient with depth have been found to be extremely valuable for recognizing and evaluating subsurface geologic features as well as denoting zones of abnormal pressure and temperature.

Pressure Variations

Several factors have been recognized as resulting in the development and maintenance of geopressures. Conditions usually responsible are rapid, deep burial of marine sand-shale sequences with low sand-shale ratios. Discontinuous sand bodies and/or compartmentalization by faulting serve to prevent the normal upward escape of excess pore fluid during burial, and the result is increased reservoir pressures. Also involved may be the addition of intracrystalline bound water as free pore water from swelling clays undergoing diagenesis as previously noted. Powers (1967) indicates that abnormal pressures may easily be caused by the volume increase associated with the release of the last few layers of bound water during clay alteration.

The variety of problems that arise from drilling into geopressured zones has prompted the development of several geophysical techniques to identify and estimate high pressures. The theory of the techniques is based upon observations that geopressured zones are characterized by an increase in the shale conductivity and geothermal gradient and a change in the rate of increase of the shale porosity. They also exhibit a decrease from the normal shale density and a decrease in both the sandstone and shale interstitial fluid concentrations (Schmidt, 1971). Many of these factors are closely monitored during drilling of wells where geopressured zones are known or suspected (Fertl and Timko, 1970a).

Due to the effects of ion filtration by shales and/or generation of fresh water from clay diagenesis, there is a very notable freshening of geopressured zones affecting as much as 1,000 ft of the overlying sediments.

Changes in the Geothermal Gradient

Much research in the last five years has been directed toward the understanding and evaluation of geothermal gradients. Schoeppel and Gilarranz (1966) are due primary credit for renewed emphasis in this area by pointing out the usefulness of temperatures recorded on well log headings and the significance of regional geothermal gradient studies. Not only has this realization prompted a concentrated effort to compile regional geothermal gradient maps that had previously been regarded as unfeasible, but it has also renewed interest in evaluation of those factors responsible for both vertical and lateral variations in the geothermal gradient.

One of the more significant observations is an abrupt increase in the geothermal gradient accompanying the transition into a geopressured zone. Factors cited as responsible for this increase include the loss of convective heat transfer as enumerated earlier from Jones (1969) and the reduction in thermal conductivity. In addition, Jones reports that the thermal conductivity of the mineral grains of sediments is generally 4 to 5 times greater than that of water. For this reason, the thermal conductivity of a shale will vary inversely with its porosity. Thus, abnormally pressured sections, with their high water content, will actually act as effective thermal insulators or barriers to normal heat flow upward through the section. Jones has reported geothermal gradients in the shales overlying geopressured zones in the Gulf Coast as high as 6°F/100 ft.

Recent compilation of temperature data by George (1970) has led to the following conclusions regarding additional geothermal gradient variations:

(1) In geologically young, thick sand and shale sequences, such as in the Gulf Coast area, an increase in temperature above normal for that area indicates a pressure above normal.

(2) If the pressure is normal in all porous zones, a change in gradient indicates a change in rock type or a change in porosity and/or permeability within the same rock type.

(3) Moving ground water appears to have much more effect on the gradient than thermal conductivity or even heat convection--except in special cases such as salt plugs and very thick zones with very high porosity and good continuous vertical permeability.

(4) Subsurface temperatures change very slowly except under the influence of moving ground water.

(5) A zone of continuous porosity and permeability which exhibits a gradient below normal indicates that water has moved down from a shallower depth.

(6) A zone of continuous porosity and permeability that exhibits a gradient above normal indicates that water has moved up from depths greater than normal.

(7) A block that has been uplifted and eroded should exhibit a higher than normal gradient.

(8) A block that has moved down by faulting should exhibit a lower than normal gradient.

(9) A porous zone below an angular unconformity will be cooler than normal because of freshening of meteoric waters during erosion.

Additional correlations include the observation by Kissin and Kazintsev (1962) that certain oil and gas fields of the Cis-Caucasus region of Russia are characterized by a rapid increase in temperature with depth. They speculate that the cause may be due to geologic structure, differences in the thermal conductivity, and the effect of subsurface waters.

A change in the geothermal gradient will not directly influence salinities, but in most cases, the factors which cause the change in geothermal gradients will also cause changes in salinity gradients. A good example that has already been noted is the relation between geopressures, temperatures, and salinities. Examples to follow include many of those features itemized by George in his appraisal of the value of temperature as an indicator of other subsurface features.

Structural and Stratigraphic Features

A research group of Continental Oil Company has recently determined that for cases where the salinity of formation waters is in equilibrium between sandstones and adjacent shales, the areas are normally compacted and are characterized by an exponential increase in water salinity with depth (Overton and Timko, 1969; Zanier, 1969; Fertl and Timko, 1970b; Fertl and Timko, 1971). Based upon this observation, they noted that the product of water salinity and shale porosity is a constant and called the concept the "salinity principle." In such cases, water salinity increases as porosity of shale is reduced in response to compaction. Thus, where porosity is normal, that is where it decreases exponentially with depth, a plot of depth versus the logarithm of water salinity yields a straight line. The slope of this line is called the compaction coefficient and has been found by Zanier (1969) to be predictable for any geologic age. Deviations from this normal trend are attributed to irregularities in compaction and/or in response to tectonic forces. For the purposes of this study, a linear salinity-depth relationship is considered to be a first approximation of actual conditions, regardless of whether the actual relationship is logarithmic or linear.

Overton and Timko (1969) and Fertl and Timko (1970b) have used the mud filtrate resistivity temperature and the water salinity determined from the SP log in clean sands to plot a logarithm of salinity versus depth profile of boreholes. From these profiles, they state the following conclusions:

(1) An exponential salinity increase with depth indicates a

normally compacted area (straight line on depth versus logarithm of salinity plot).

(2) A supernormal increase indicates overcompaction.

(3) A gradually changing subnormal salinity increase indicates stress relief by faulting.

(4) A rapidly changing subnormal salinity indicates high pressure.

(5) A rapidly increasing (returning to normal) salinity in an overpressured environment indicates a permeable sand of significant extent.

(6) A sudden reduction or increase in salinity may indicate an unconformity.

Further application of the "salinity principle" by Zanier and Pert (1971) and Zanier and Timko (1970) has also been made to evaluate reservoir performance. They found that in lenticular sandstones of the Pennsylvanian Morrowan trend, higher initial potential wells are unmistakably associated with the fresher portions of sandstone bodies, which exhibit salinities relatively higher than overlying or underlying sediments. Techniques for predicting the initial potential based on salinities are thought by these workers to be at least equal to methods using log-calculated water saturation and porosities in determining performance of a reservoir. It is also suggested that salinity changes can be of help in determining the geometry of the sand body.

Hydrocarbon Occurrence

Prospecting for hydrocarbons should include the compilation of all available subsurface data that could possibly indicate if petroleum was generated by source rocks and the ascertation of whether it is likely to accumulate in commercial quantities. Until recently, salinities of formation waters were not extensively used in the search for hydrocarbons. Recent research indicates that accumulation of hydrocarbons in many cases is similar, or closely related, to the mechanism that concentrates dissolved solids. In any case, a careful study of salinities can be extremely valuable in determining the general history of regional flow in a basin, as well as establishing guidelines for deducing the present flow patterns and recognizing certain subsurface features.

The work of Burst (1969) has shown that the geothermal gradient plays a significant role in hydrocarbon generation and migration. Burst predicts that "most future discoveries of liquid hydrocarbons probably will be from a 2,000 ft temperature-dependent interval extending a thousand ft above and below what has been designated as the top of the second stage interlayer-water dehydration level." This level is temperature-dependent and can be determined directly from geothermal gradient maps. As noted earlier, geothermal variations have been shown to be dependent upon many of the same factors that control salinity variations.

Since Hubbert's classic paper on the hydrodynamic entrapment of hydrocarbons in 1953, much attention has been focused on the role of differential pressures as a trapping mechanism. For example, McNeal (1961) studied the hydrodynamics of the Bisti Field, New Mexico; Myers (1968) investigated differential pressures in the Gulf Coast; and a series of papers have been published by the Petroleum Research Corporation (Hill *et al.*, 1961; Treckman *et al.*, 1962). These studies are representative of the rather recent appreciation of the role of subsurface pressure in oil and gas exploration. The relationship of differential pressures to salinities suggests that salinities, too, might be an important exploratory tool.

Probably the most significant studies with respect to exploration are the ones by Jones (1960, 1962) of Rocky Mountain petroleum traps. He delineated areas where flushing had occurred from water resistivities of a particular formation and showed that hydrocarbon traps, on the other hand, are untouched by such flushing. Jones' study has proved to be of value in areas where gravitational hydrodynamics are of primary importance, but opportunity remains for the application of salinity data to the understanding of more subtle hydrodynamic conditions.

CHAPTER IV

METHODOLOGY

Data Procurement

Source

As previously mentioned, formation water salinity data are available from 3 sources: the SP log, chemical analyses, or direct lab measurement. Data used in this study were obtained almost exclusively from laboratory resistivity measurements published by the U. S. Bureau of Mines (Wright *et al.*, 1957) and the API (no date). Supplementary data were supplied by several operators in Oklahoma. (A copy of the data is available upon request from Dr. R. J. Schoeppel.)

Items of information essential for each data point include the well location, the R_w value, the depth at which the water sample was taken, and the temperature at which the resistivity was measured. Many available resistivity values had to be rejected because of insufficient well location or depth information. Nevertheless, 2,749 resistivity measurements were completed and used in the study. All resistivities with complete supplementary information were used without reservation. Excluding uplift areas such as the Ozark, Arbuckle, Wichita, and Ouachita mountains, approximate coverage is two data points per township. The geologic age of the sampled reservoir is known in most cases, enabling their mapping and evaluation according to geologic age (see Table I).

TABLE I

STRATIGRAPHIC DISTRIBUTION OF DATA USED IN THE STUDY

Geologic Age	No. of Resistivity Values	
Permian		87
Pennsylvanian		1510
Virgilian	202	
Missourian	491	
Desmoinesian and Atokan	669	
Morrowan	20	
*Springeran	128	
Mississippian		104
Devonian-Silurian		208
Ordovician		804
Mohawkian	769	
Canadian	35	

*In this compilation, Springeran is included as a series of the Pennsylvanian system although it is commonly regarded as part of the Mississippian system.

Quality

Water analyses of formation fluids have been considered by several investigators to be of questionable validity (Ayers et al., 1952; Hawkins and Moore, 1956; Jones, 1960). Samples can be contaminated by condensation, from casing and cement leaks, invasion of drilling mud filtrate, and the drilling mud itself. Because of these possibilities, the most questionable values are those from drill-stem tests whereas the most accurate are believed to be those collected at the wellhead of producing wells. Jones (1960) estimates that 80% of all Wyoming wildcat drill-stem test water samples are strongly contaminated and recommends that electric logs be used to determine water resistivities.

It should be pointed out that although the data used in this study are not error free, they have been carefully selected and reported as representative of a particular horizon in a local area. Concerning the quality of data published by the Bureau of Mines, for example, Dickey (1969) reports that "their analyses are highly controlled technically, and are usually complete and reliable."

Data Processing

This investigation was assisted by the use of automatic data processing techniques in sorting, calculating, averaging, and plotting the voluminous data. Not only was computer processing useful in data compilation for preparation of the salinity gradient maps, but also in the preparation of conductivity ($1/R_w$) versus depth plots for various geologic ages. Since conductivity is directly proportional to salinity, these graphs may be considered as salinity-depth plots.

Sorting

Data were compiled without regard to geographical distribution in order to test the validity of the supposition that recorded water resistivity data are more reliable than generally considered. However, since a reasonable sized grid system had to be selected for regional mapping, it was decided to numerically average local values by quarter-townships as illustrated in Figure 3. Each quarter represents a 3 mi by 3 mi grid with the average value of the data for that area plotted in its center. The location (1, 28, 51) shows how the data were automatically plotted.

Calculation of Salinity Gradients

Because the resistivity of a water sample with a constant concentration of dissolved solids varies with temperature, a datum of 80° F was chosen as standard. All R_w values not measured at this temperature were corrected by computer during processing, using correction equations given by Schlumberger (1969).

Based on the assumption that the salinity increase of formation water with depth is linear, a salinity gradient was computed for each data point by dividing the conductivity ($1/R_w$) by the depth of the sample. All gradients within an area of 1/4 township were then averaged to produce the value that was plotted for that location (Fig. 3).

Smoothing

A simple data reduction process was employed as a part of computer processing in an attempt to eliminate the influence of harshly anomalous points. This process produces at each point for which data exists a new smoothed gradient based on both an original value and the influence of nearby points. The routine is designed to allow the closer

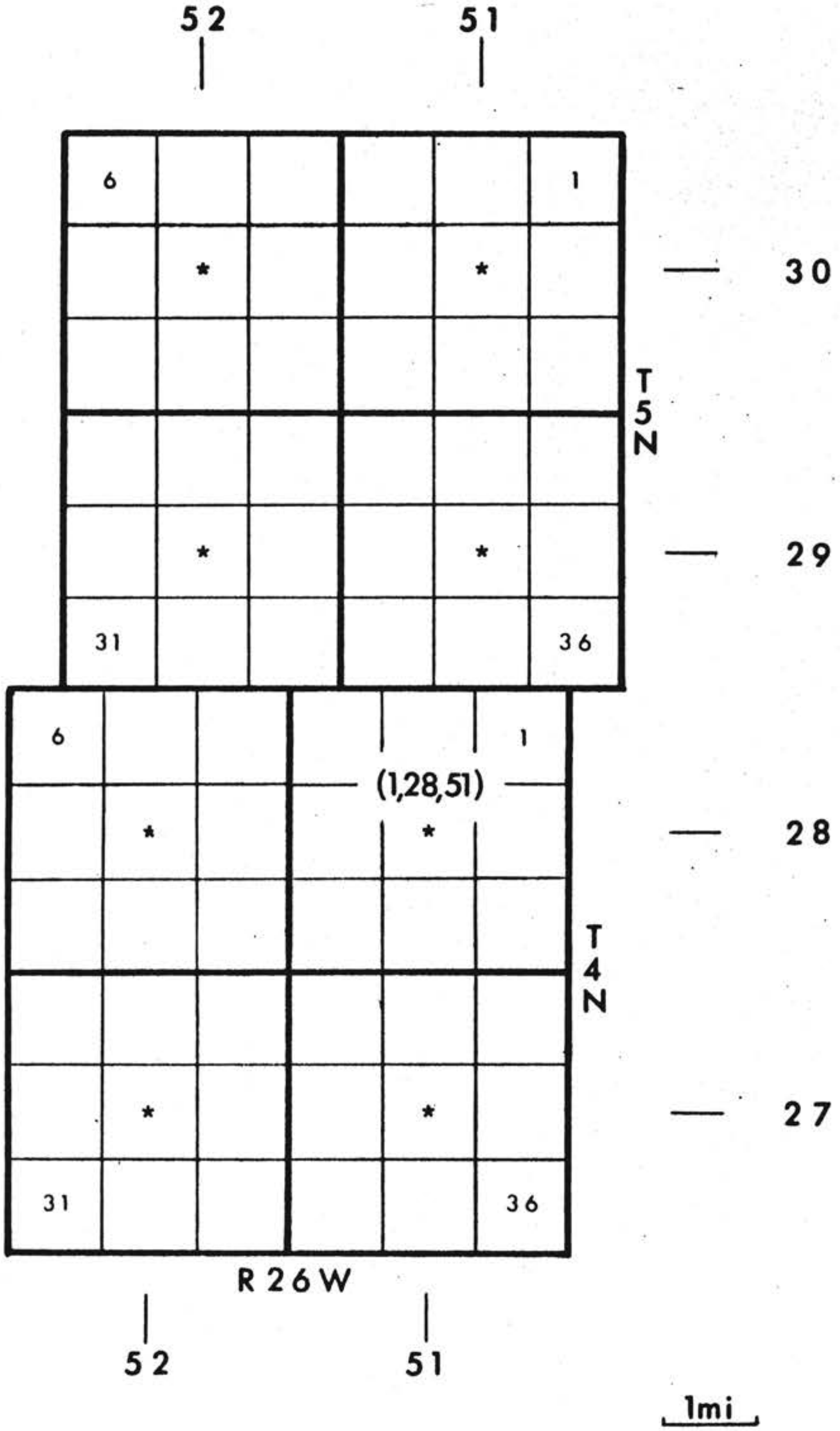

Fig. 3.-Diagram showing grid locations of plotted points with respect to General Land Office system.

surrounding points more influence in the averaging procedure than those farther away. If a sufficient number of closely surrounding points were not present in an initial search, the search area was incremented as needed to include a predetermined minimum number. It is hoped that anomalously high or low values, inconsistent with surrounding data trends, are realistically adjusted for meaningful regional mapping.

Plotting and Contouring

Plotting was done on a 30-inch drum plotter by Cities Service Oil Company. However, to avoid radical smoothing by machine contouring packages, all maps were hand-contoured.

Data Presentation

The number of parameters collected for each data point presents several totally different possibilities for data analysis. Two of these, salinity-depth plots and salinity gradient maps, were employed in this investigation.

Scatter Plots

The geologic age recorded for each individual point enables concentration on one or several particular age groups. Salinity-depth plots were drawn by computer for each of 10 age combinations. They were also plotted for 2 combinations of ages, pre-Pennsylvanian and Permian-Pennsylvanian. These plots will be subsequently referred to as "scatter plots" because of their shotgun pattern in appearance.

Salinity Gradient Maps

Procedures and techniques in preparing maps of salinity gradients are essentially the same as those for any contour map. All of the data collected was used in the preparation of a composite map. In addition, an attempt has been made to evaluate stratigraphic influences by dividing the complete data bank between the Pennsylvanian and Mississippian Systems. These 2 sets of data have been used to construct 2 other salinity gradient maps (Permian-Pennsylvanian and pre-Pennsylvanian).

The scale for each map is 1:750,000, which permits easy reference to published maps of Oklahoma for comparison with geological and geophysical features and parameters.

CHAPTER V

PRESENTATION OF DATA AND INTERPRETATION

Scatter plots of conductivity versus depth are presented for reservoirs of the following ages: Permian; Pennsylvanian Virgilian, Missourian, Desmoinesian and Atokan, Morrowan, and Springeran; Mississippian; Devonian-Silurian; and Ordovician Mohawkian and Canadian. Although the Springeran has been classified by some investigators as Mississippian in age it is considered Pennsylvanian in this report. Lithologic units within it show more similarity to the dominantly clastic beds of the Permian and Pennsylvanian than to the older carbonate-sandstone sequences. Two groupings, Permian-Pennsylvanian and pre-Pennsylvanian, are also presented to show the distribution of salinity-depth data used to prepare the two corresponding salinity gradient maps. A composite salinity gradient map was prepared from all data used in the study.

Scatter Plots

The scatter plots presented show the general distribution of points, range of depths and salinities, relative number of points, and an estimation of the general depth to petroleum production for each stratigraphic interval represented. These plots can not be used reliably to evaluate the function of how salinity increases with depth. In order to do this, points would have to be plotted for each age at one specific locality. Unfortunately, this type of data control is unknown to the writer.

Permian

Salinities reported for Permian reservoirs (Fig. 4) reflect the presence of extensive evaporitic deposits resulting in high salinities at relatively shallow depths. General depths of reported values range from 1,000 to 3,000 ft, with the greatest reported depth at about 6,500 ft.

Pennsylvanian

Pennsylvanian reservoirs are the source of the greatest number of data points for any one geologic system. The Virgilian plot (Fig. 5) reflects no anomalously fresh values, whereas the Missourian (Fig. 6), Desmoinesian and Atokan (Fig. 7), Morrowan (Fig. 8), and Springeran (Fig. 9) all show some abnormally fresh water which could be due to geopressures or some other salinity reducing mechanism. A check of the input data shows that the large group of anomalously fresh points on the Missourian plot were reported from the eastern half of Beckham County near the trough of the Anadarko basin. Other scattered abnormally fresh salinities in the Missourian and other Pennsylvanian reservoirs were found to occur consistently throughout the Anadarko and Arkoma basins and in the deeper parts of the Ardmore basin. Normal salinities as seen on the Morrowan plot are present in Okfuskee County in east-central Oklahoma, while the abnormally fresh values are reported from west-central and northwestern counties included in the Anadarko basin.

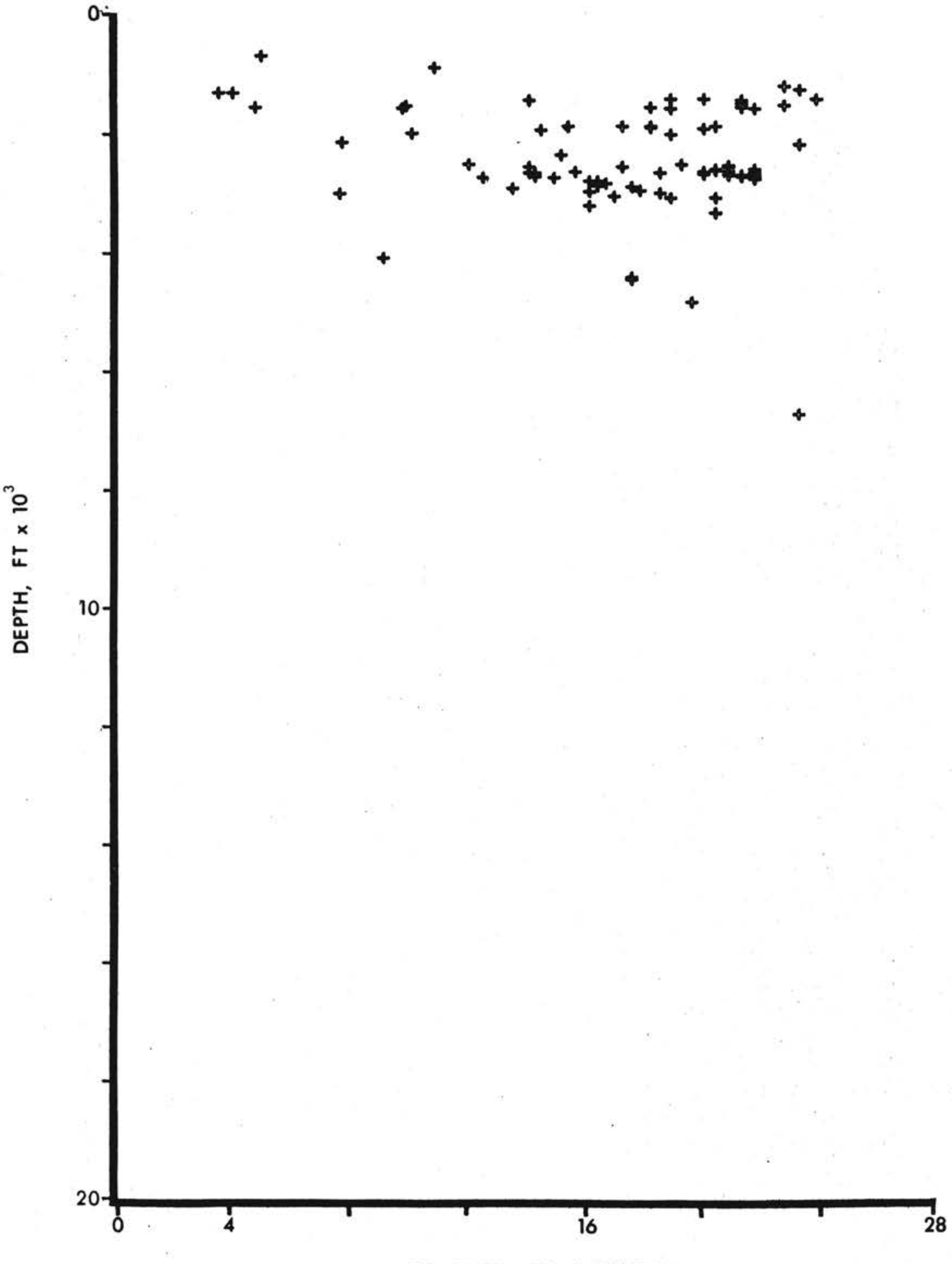

Fig. 4.-Plot of conductivity vs. depth for Permian reservoirs.

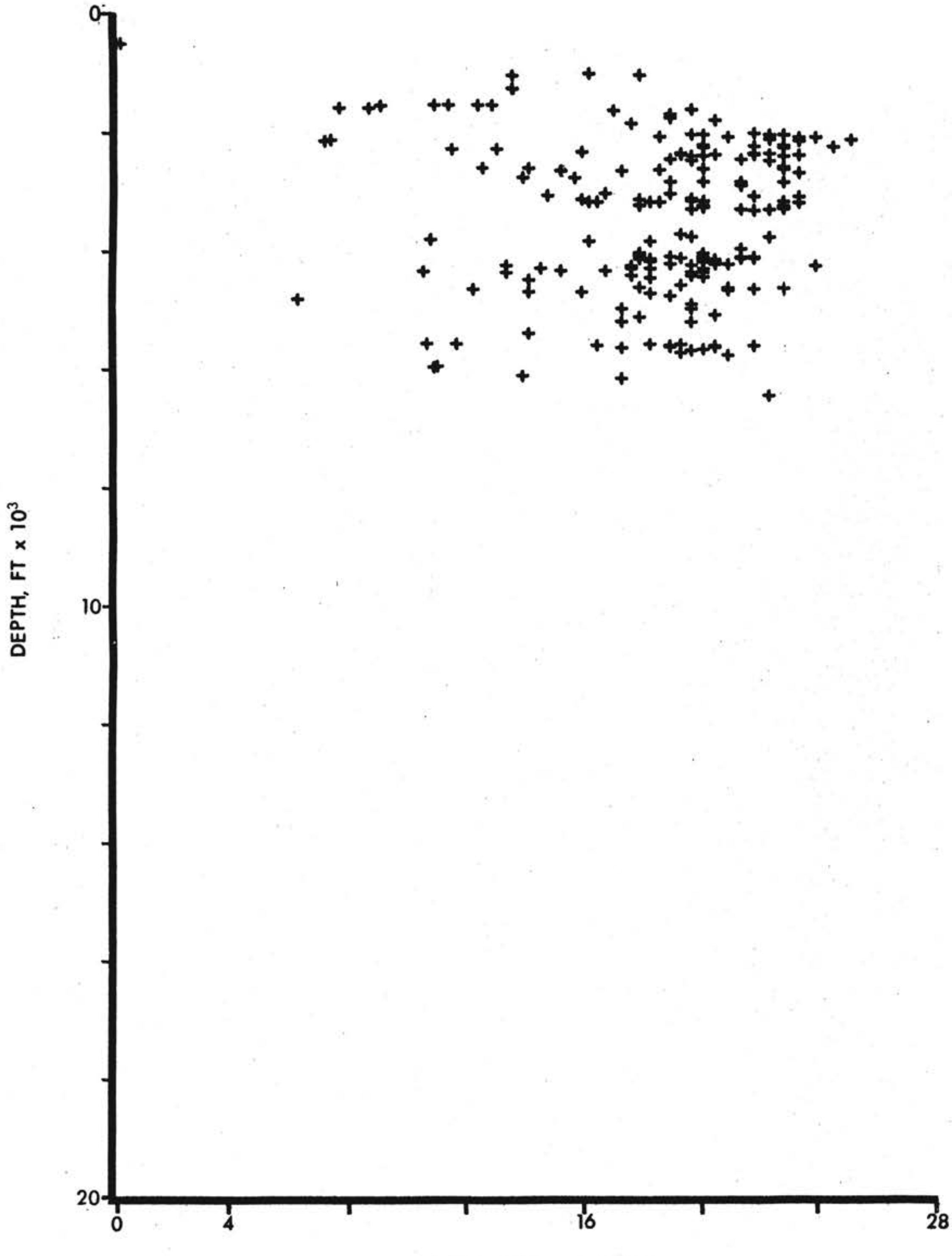

Fig. 5.-Plot of conductivity vs. depth for Pennsylvanian Virgilian reservoirs.

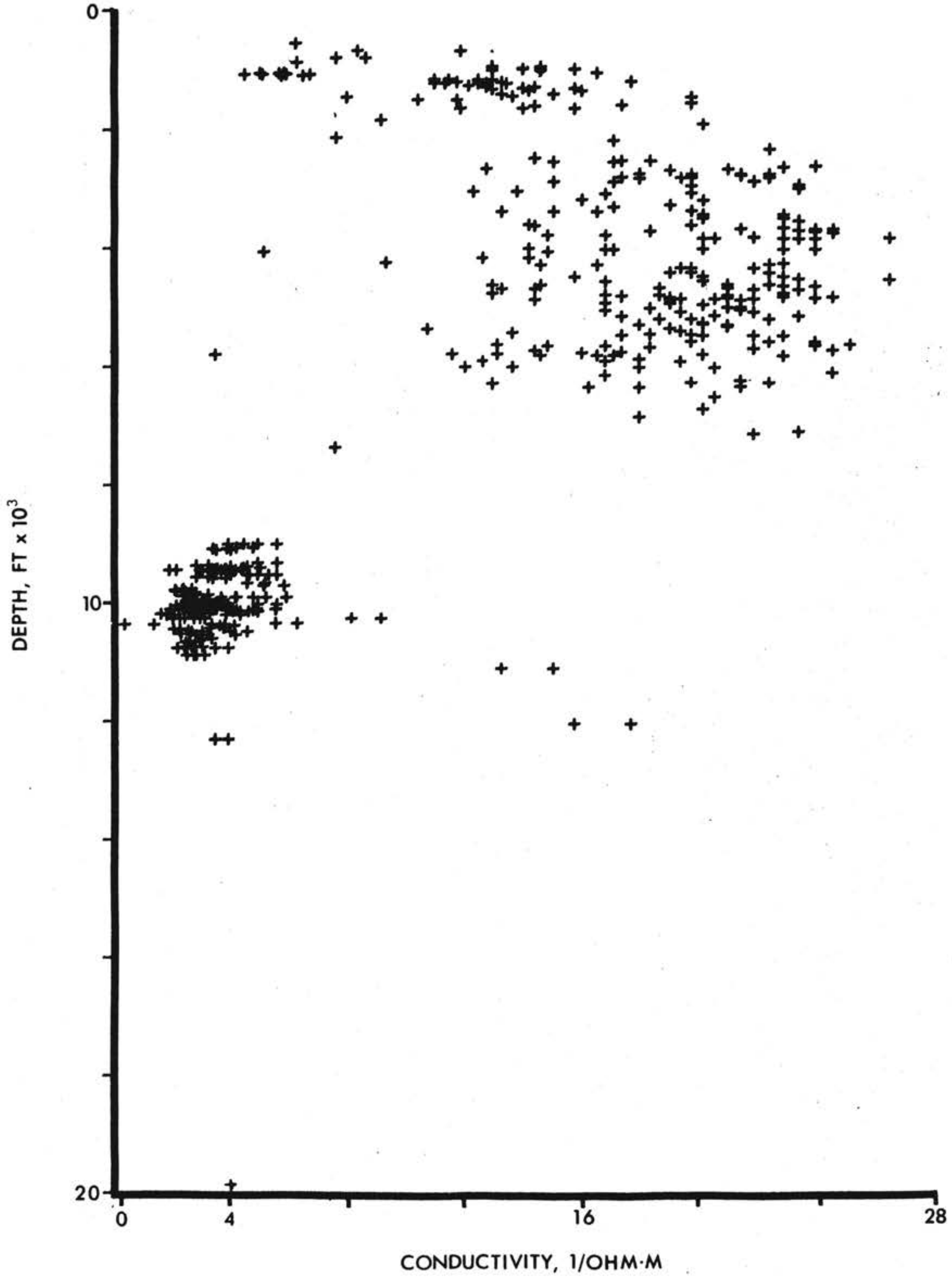

Fig. 6.-Plot of conductivity vs. depth for Pennsylvanian Missourian reservoirs.

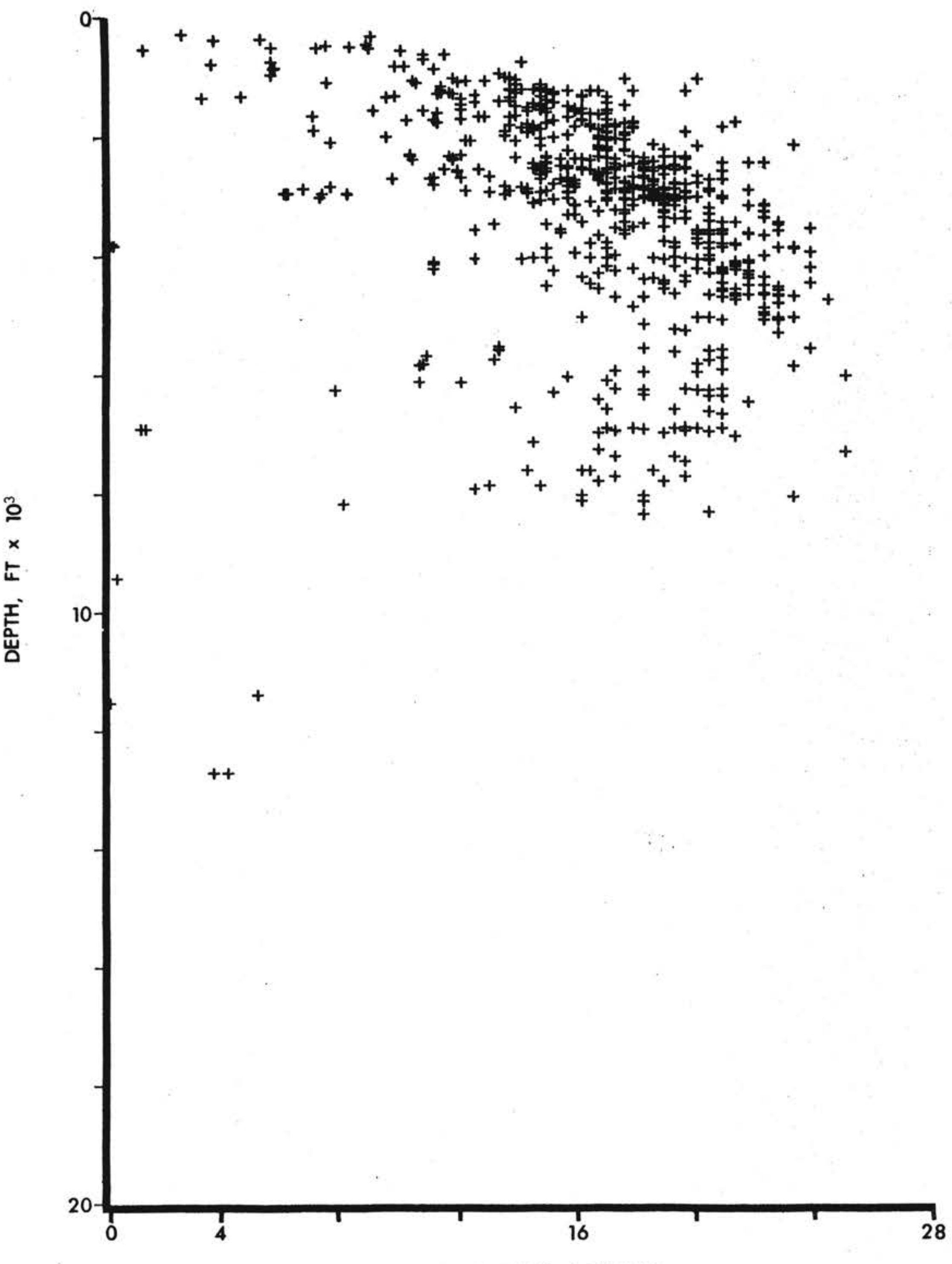

Fig. 7.-Plot of conductivity vs. depth for Pennsylvanian Desmoinesian and Atokan reservoirs.

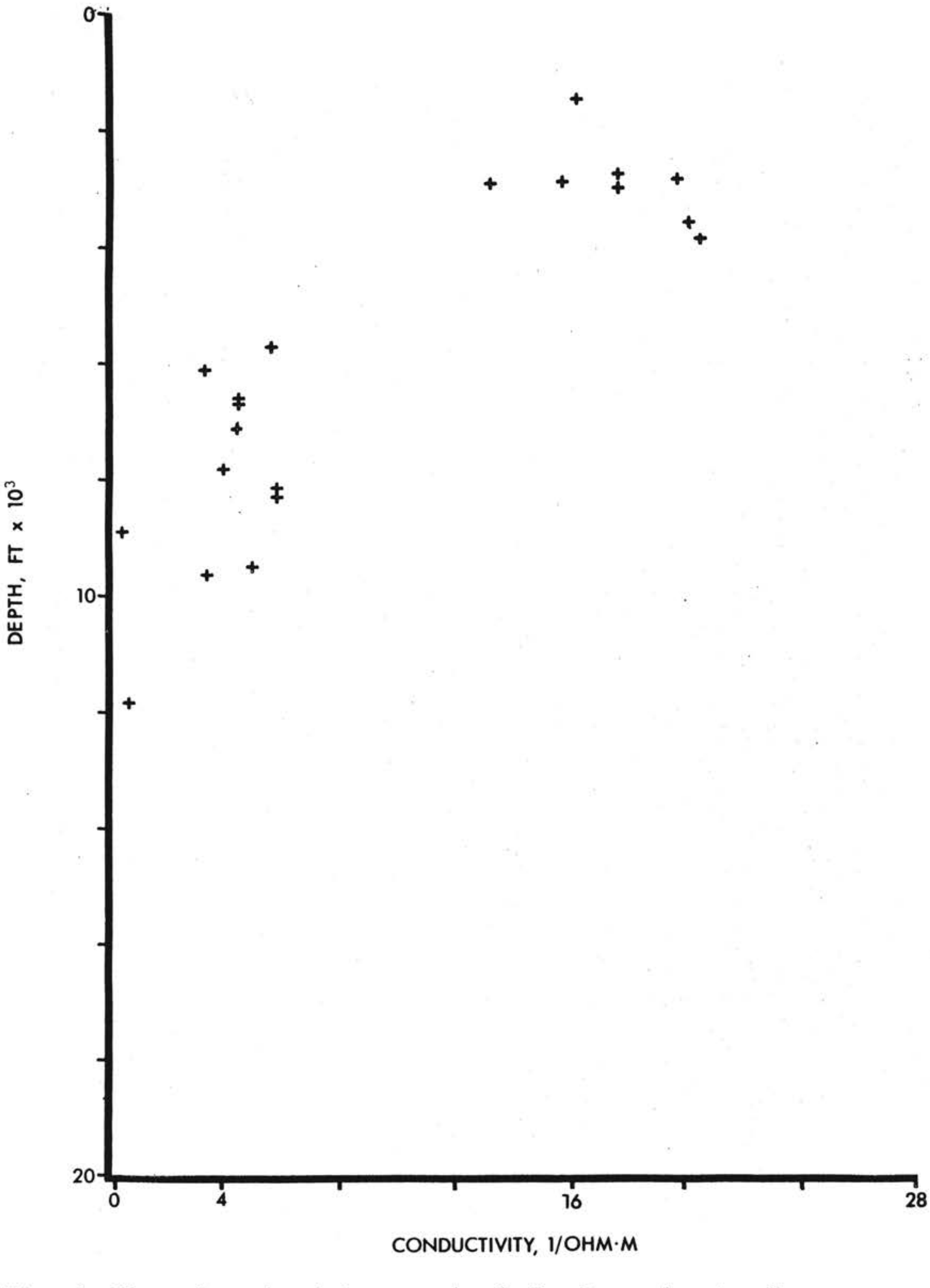

Fig. 8.-Plot of conductivity vs. depth for Pennsylvanian Morrowan reservoirs.

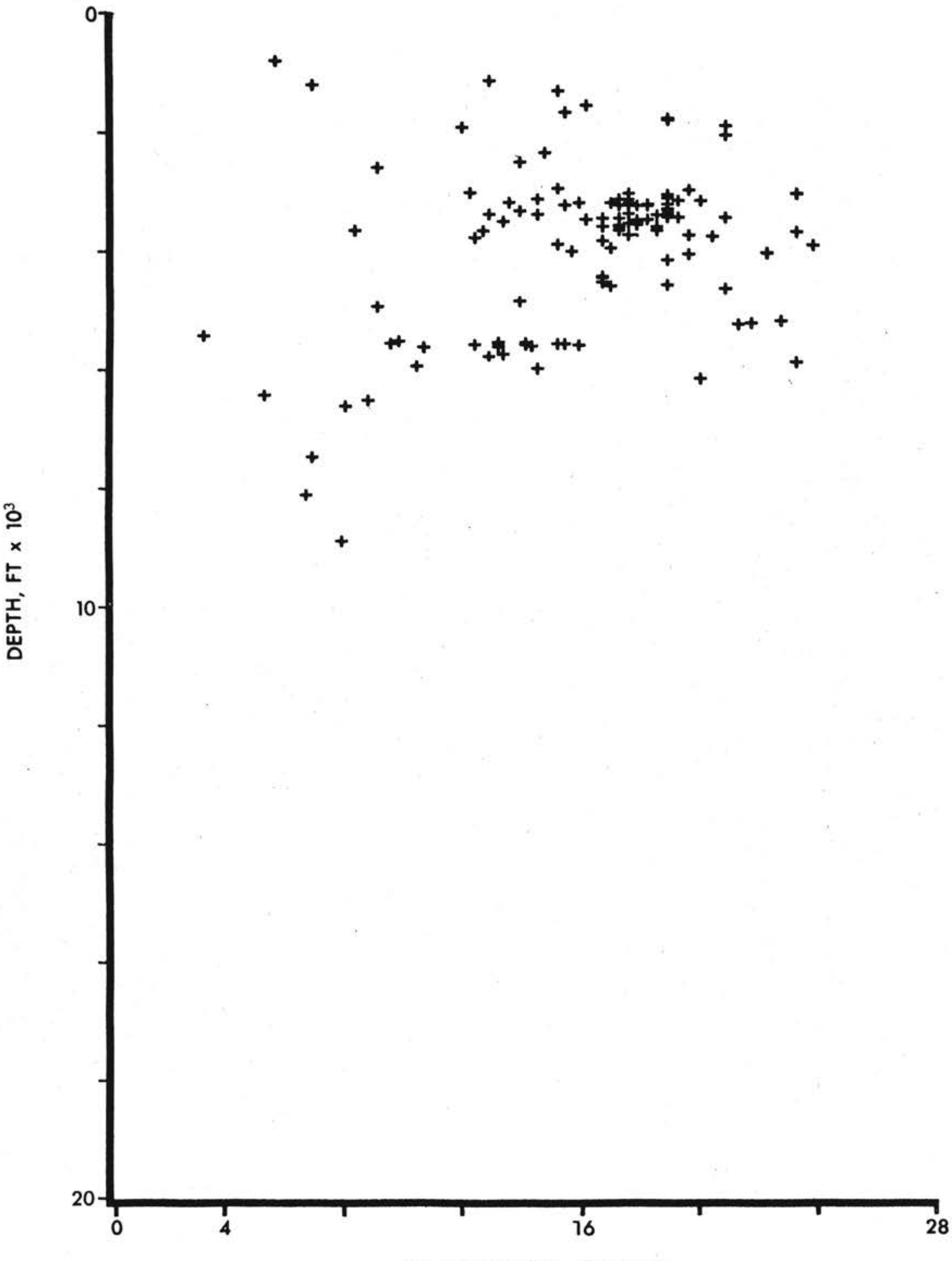

Fig. 9.-Plot of conductivity vs. depth for Pennsylvanian Springeran reservoirs.

Sampling depths range from about 2,000 to 6,000 ft for the Virgilian, 1,000 to 11,000 ft for the Missourian, 1,000 to 8,000 ft for the Desmoinesian and Atokan, 3,000 to 10,000 ft for the Morrowan, and 2,000 to 6,000 ft for the Springeran. Assuming that the majority of values were reported from petroleum producing wells, these figures may be regarded as the approximate depth of significant petroleum occurrence.

Mississippian

Data included from Mississippian units generally show normal salinities (Fig. 10), even at one reported depth of 15,219 ft in Grant County. However, several anomalous values at intermediate depths of 6,000 to 8,000 ft are located in Major, Woodward, and Harper counties of northwestern Oklahoma. Sampling depths in the Mississippian generally range from 2,000 to 7,000 ft.

Devonian and Silurian

The plot for Devonian and Silurian reservoirs (primarily of the Hunton Group) (Fig. 11) represent resistivities from two general depths, 4,000 to 5,000 ft in east-central Oklahoma and around 7,000 ft in Cleveland, Oklahoma, and Canadian counties. Abnormally fresh water occurs at scattered locations in these areas. The one relatively fresh point at 14,310 ft is located in Dewey County of western Oklahoma.

Ordovician

A group of unusually fresh water samples from depths between 1,000 and 4,000 ft are present in the data for Ordovician Mohawkian reservoirs (primarily of the Simpson Group and Viola Formation) (Fig. 12). Most

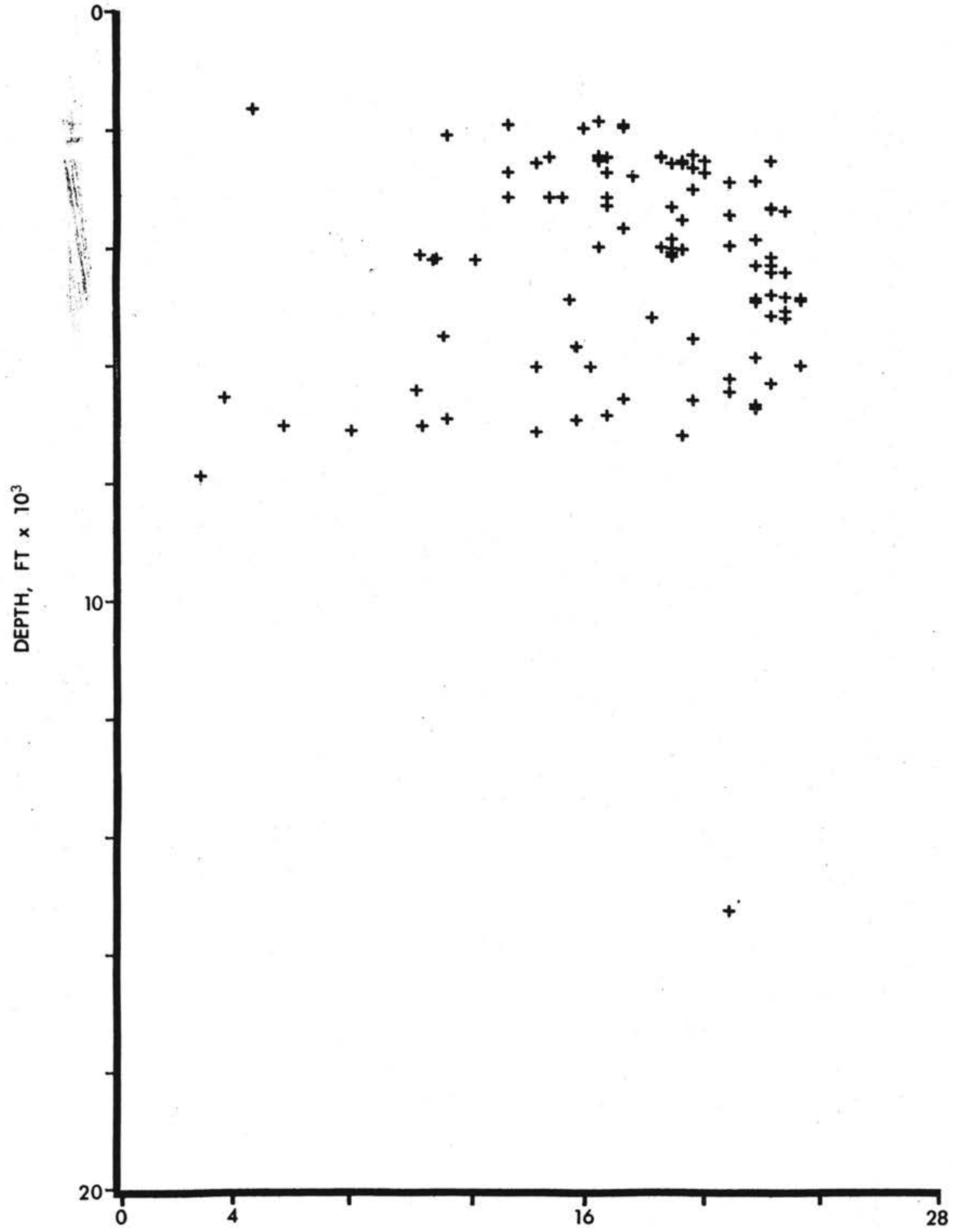

Fig. 10.-Plot of conductivity vs. depth for Mississippian reservoirs.

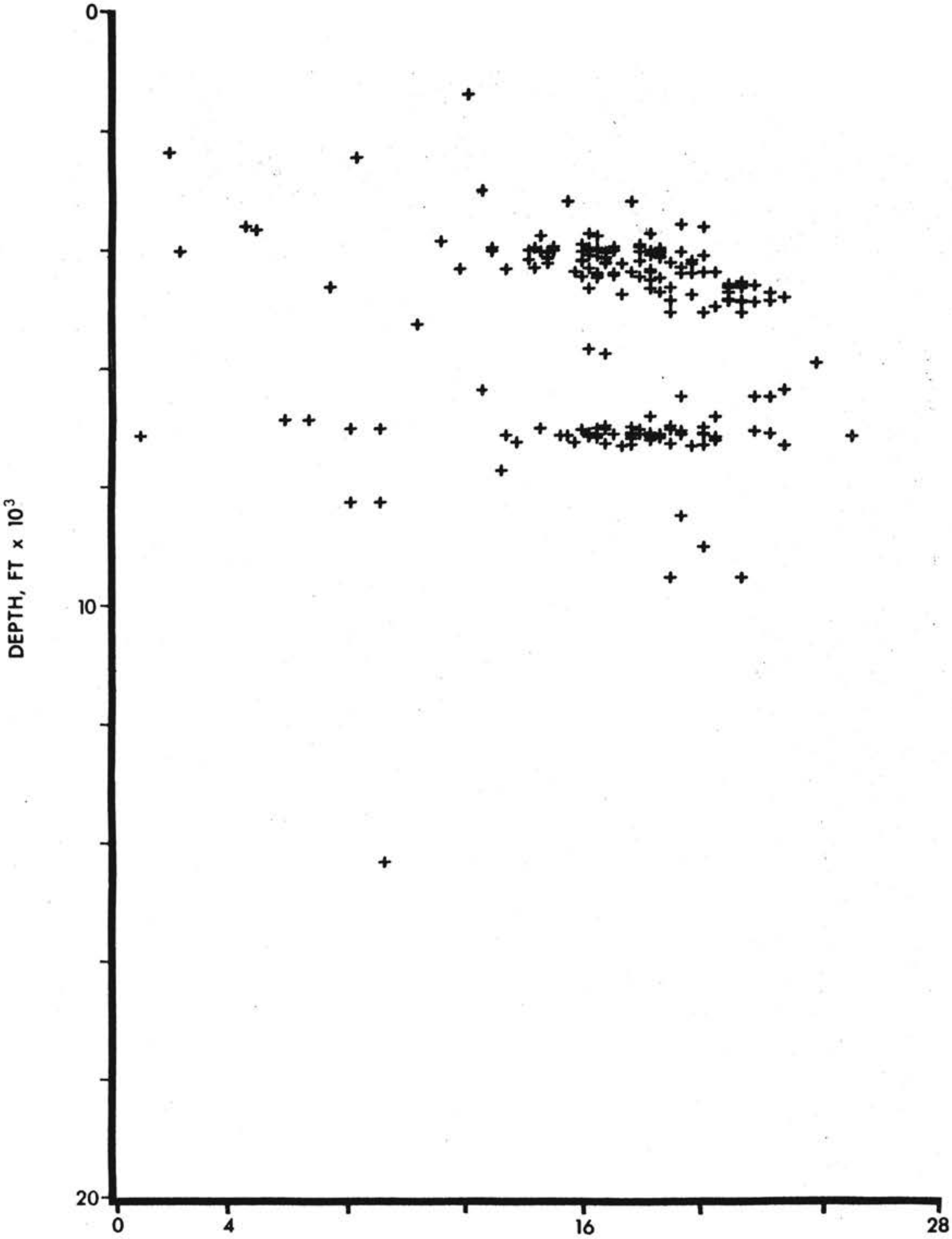

Fig. 11.-Plot of conductivity vs. depth for Devonian and Silurian reservoirs.

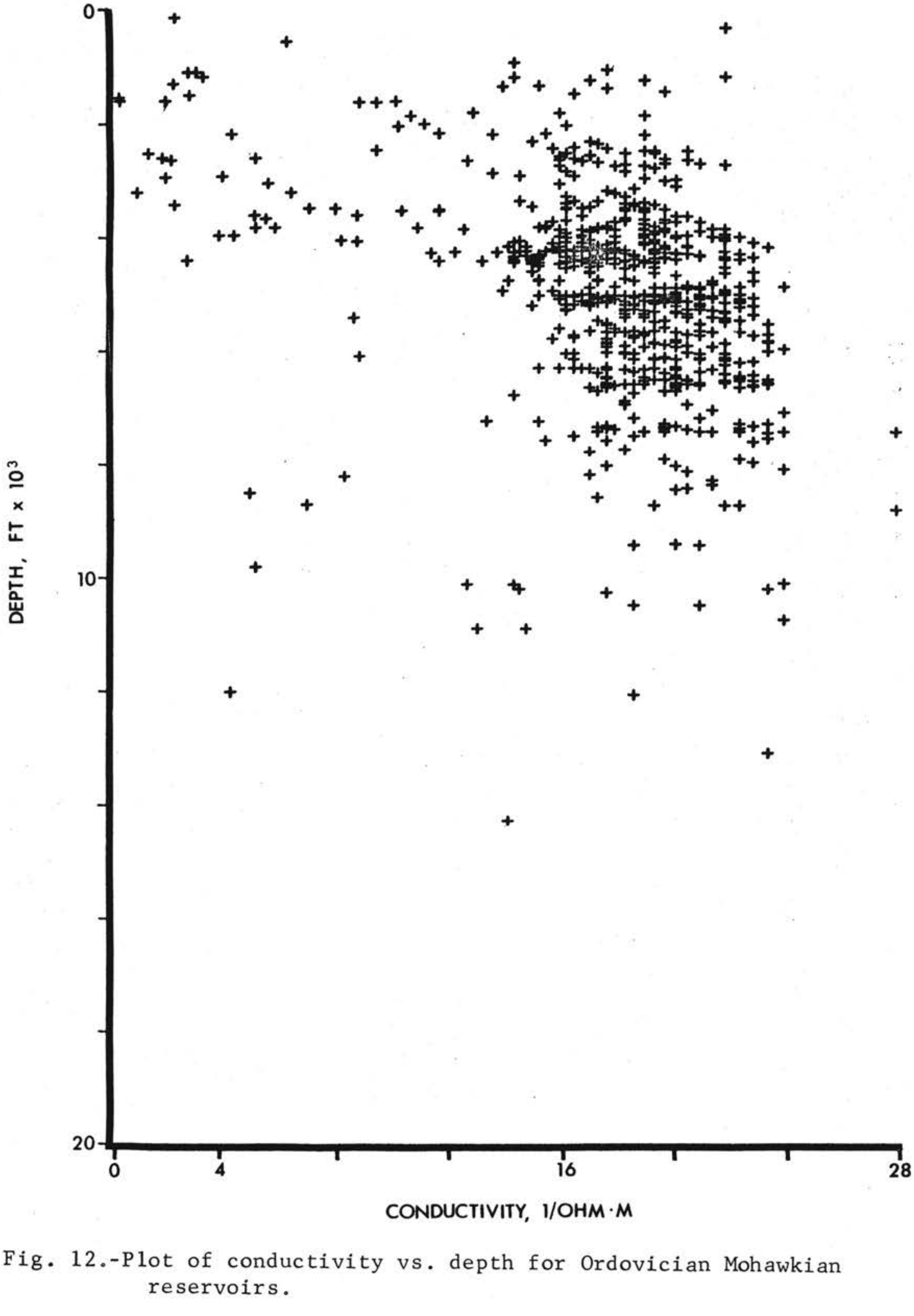

Fig. 12.-Plot of conductivity vs. depth for Ordovician Mohawkian reservoirs.

of these data are reported from Murray and Garvin counties, just north of the Arbuckle uplift, and are thought to result from the effects of meteoric recharge of units that crop out on the uplift. The remainder of this group, located in Nowata County of northeastern Oklahoma apparently reflect recharge effects of the Ozark uplift.

Abnormally fresh values from about 8,000 and 10,000 ft are located in one of the deeper parts of the Ardmore basin south of the Arbuckle uplift. The majority of control points for the Mohawkian range in depth from 3,000 to 8,000 ft and cover a large area of central Oklahoma.

One seemingly anomalous salinity from the Ordovician Canadian (primarily of the Arbuckle Group) plot (Fig. 13) can be explained by noting that it is from the Arbuckle Formation in the Arkoma basin, where geopressures in the overlying or possibly underlying section or recharge effects from the Ozark uplift may account for this anomaly.

Permian-Pennsylvanian and Pre-Pennsylvanian

Combinations of the individual plots were grouped as Permian-Pennsylvanian (Fig. 14) and pre-Pennsylvanian (Fig. 15) to show the distribution of points available for preparation of the respective salinity gradient maps. These figures show the general depths of sampling and the control density, but salinity trends are less apparent than in the individual plots.

The wide distribution of data as seen from the scatter plots is the basis for previous investigators questioning the validity of this type of data. However, explanations presented thus far and results to be noted from the salinity gradient maps suggest significant utility of these data.

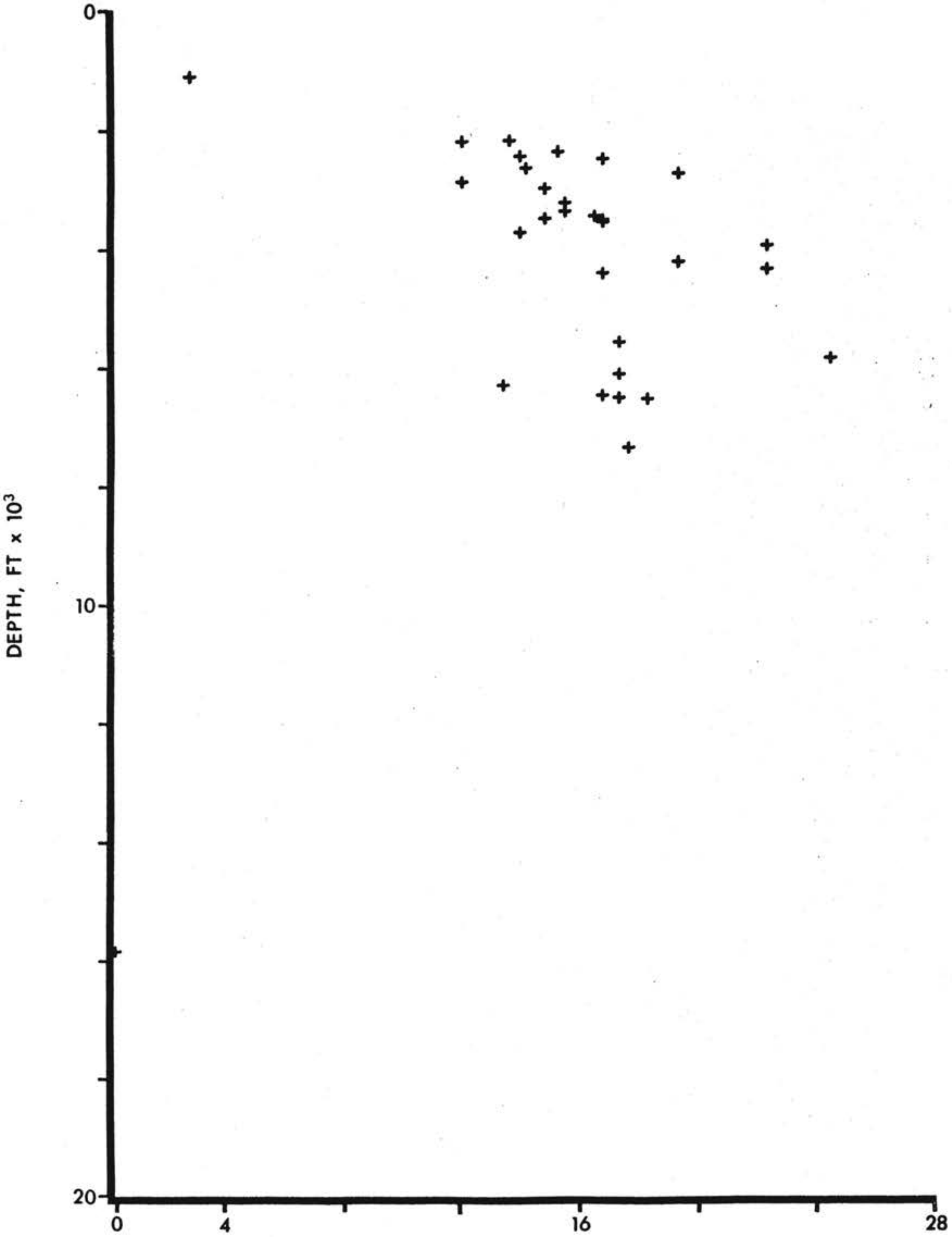

Fig. 13.-Plot of conductivity vs. depth for Ordovician Canadian reservoirs.

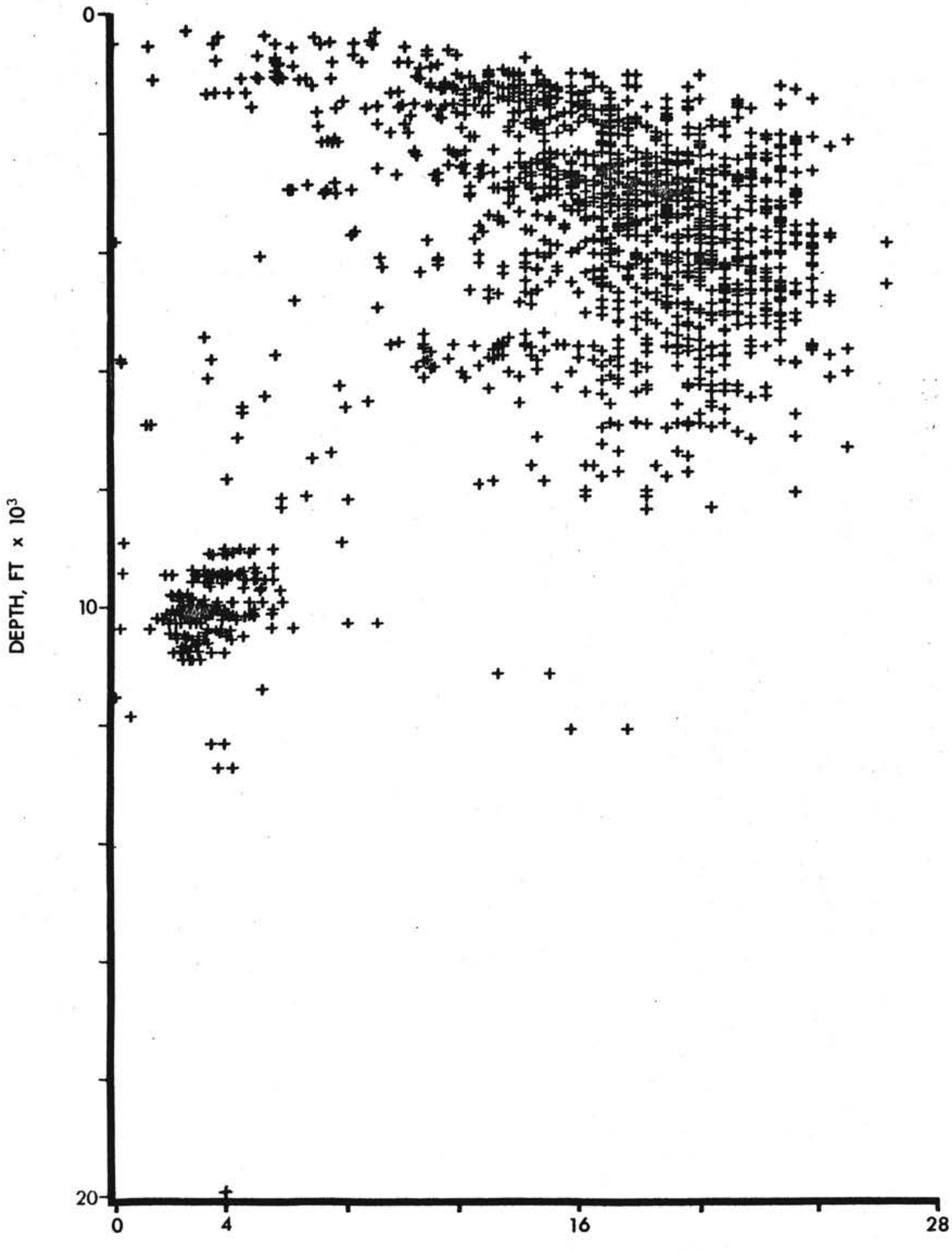

Fig. 14.-Plot of conductivity vs. depth for Permian and Pennsylvanian reservoirs.

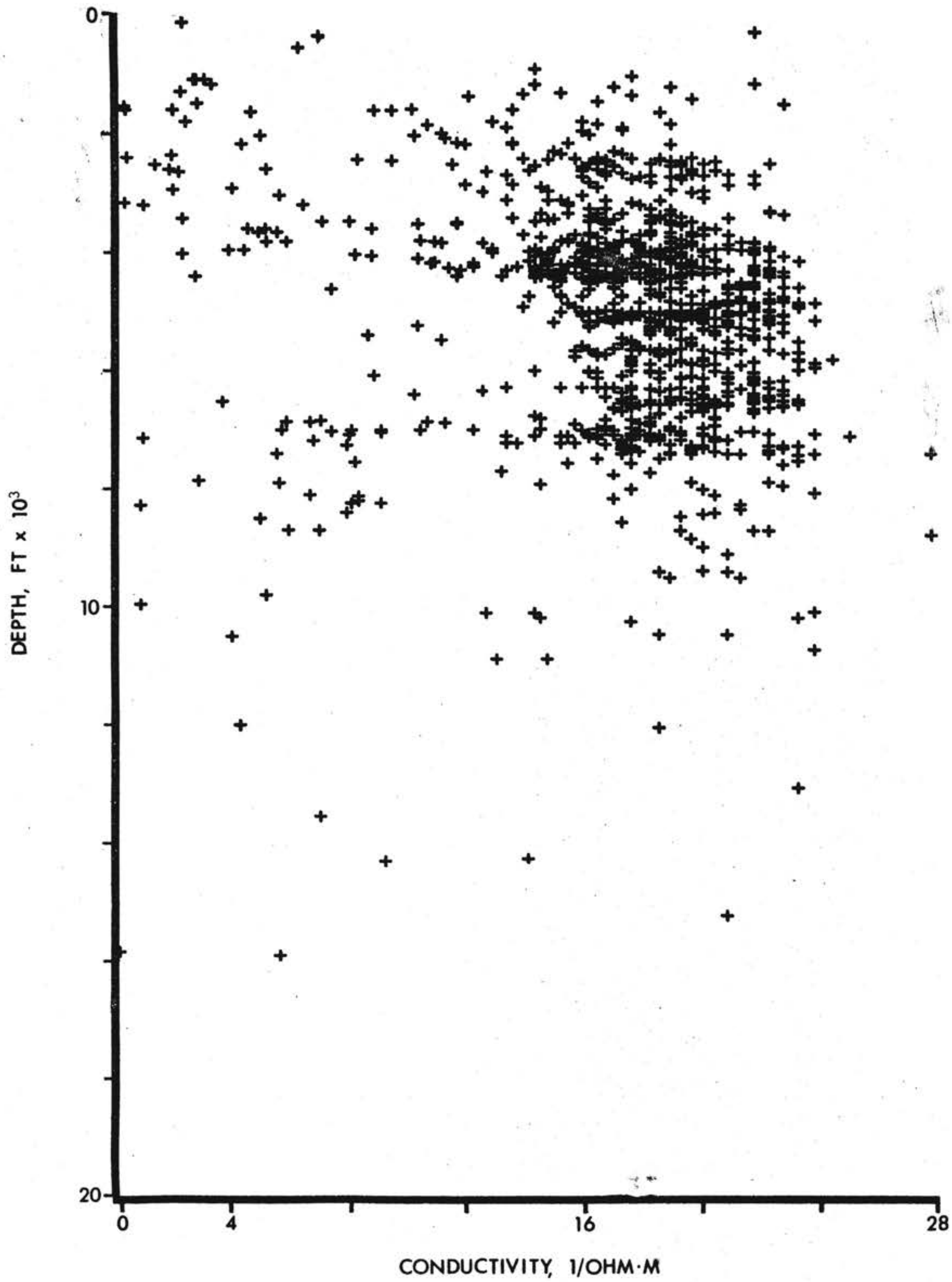

Fig. 15.-Plot of conductivity vs. depth for pre-Pennsylvanian reservoirs.

Salinity Gradient Maps

The general trend in all maps is for the salinity gradient to decrease with increasing depth to basement, a characteristic which could indicate a disproportionate influence of depth in the calculation of gradient values. Where depth is the dominating factor, the gradient is approximately inversely proportional to the depth of sampling. However, in spite of any limitation imposed by the nature of the data and corresponding assumption of a linear gradient, the maps are thought to represent a first approximation to salinity variations over the general area of study.

Composite

General features delineated by the composite salinity gradient map (Fig. 16) are dominated by an overall west-to-east increase in gradients across the northern half to two-thirds of the state. A large area of very low gradients exists in western, west-central, and northwestern Oklahoma. Gradients generally increase eastward from this low to maximum values in the northeastern part of the state. Local exceptions are generally higher than normal trends, with the exception of a relatively low gradient in central Kay County and a one-point low to the south in northern Noble County. Prominent high salinity gradients based on more than one point for the northern two-thirds of Oklahoma include those in the following counties: Alfalfa, northern Grant, eastern Garfield and western Noble, southern Kay, and northern Noble, southwestern Okmulgee and northeastern Okfuskee, and eastern Lincoln and southwestern Creek.

Prominently low salinity gradients in the southern third of the state are present in eastern Latimer, eastern Haskell, and northern LeFlore counties; western Pittsburg and southeastern Hughes counties; Coal County; eastern Garvin, western Pontotoc, and northern Murray counties; southern Johnston and northern Marshall counties; southwestern McClain, northwestern Garvin, and eastern Grady counties; and northern and western Stephens County. Significantly high gradients are located in western Latimer and eastern Pittsburg counties; southwestern Pittsburg and northern Atoka counties; western Hughes and northeastern Pontotoc counties; southwestern Grady and northeastern Comanche counties; Jefferson and Cotton counties; and around the remaining periphery of the Wichita uplift in southwestern Oklahoma.

Permian-Pennsylvanian

No notable changes from trends shown in the composite are apparent on the Permian-Pennsylvanian salinity gradient map (Fig. 17) for the northern two-thirds of the state. However, in the southern third, there are several differences. The two areas of low gradients in Coal County and in eastern Garvin, western Pontotoc, and northern Murray counties on the composite map are less prominent on the Permian-Pennsylvanian map. Two other lows (southwestern McClain, northwestern Garvin, and eastern Grady counties and southern Johnston and northern Marshall counties) which are absent or less significant, may reflect in part the stratigraphic distribution of data.

Pre-Pennsylvanian

The anomalies which show deviation from the general west-to-east increase in salinity gradients on the composite map are conspicuously absent from western, northwestern, central, and north-central Oklahoma on the pre-Pennsylvanian map (Fig. 18). In addition, a reversal from the regional trend shown by the composite map is present in northeastern Oklahoma, where values decrease eastward from an area of high gradients through Osage, eastern Pawnee, Creek, Okmulgee, and possibly McIntosh and southern Muskogee counties. This trend roughly parallels the outcrop pattern on the southwestern flank of the Ozark uplift.

In the southern third of the study area, the high gradients in western Latimer and eastern Pittsburg counties can not be confirmed because of lack of data; the high in southwestern Hughes and northeastern Pontotoc counties is significantly reduced and shifted southwestward. Composite lows which are not present on the pre-Pennsylvanian map include those in western Pittsburg and southeastern Hughes counties and in western Stephens County. The composite low just north of the Arbuckle uplift (in eastern Garvin, western Pontotoc, and northern Murray counties) is significantly stronger where only pre-Pennsylvanian data is considered.

Summary of Map Features

From study of the maps, the following summarization can be made:

(1) The general trend on all three maps is for salinity gradients to increase from west to east.

(2) A pre-Pennsylvanian belt of low gradients parallels the pre-Pennsylvanian outcrop on the Ozark uplift.

(3) An area of high gradients separates the large western area and the smaller eastern belt of low gradients and also parallels the outcrop pattern on the southwestern flank of

the Ozark uplift.

(4) An area of low gradients is present north of the Arbuckle uplift and is most prominent in pre-Pennsylvanian units.

(5) Low gradients in both the Arkoma and Anadarko basins are well expressed on all three maps.

(6) The low gradient area in the southern part of the Ardmore basin is present only in pre-Pennsylvanian data.

(7) The low in Coal County is pre-Pennsylvanian.

(8) The low in western Pittsburg and southeastern Hughes counties is Permian-Pennsylvanian only.

(9) Practically all of the local anomalies with higher than normal gradients are expressed only in Permian-Pennsylvanian units, with the notable exception of the high in southwestern Okmulgee and northeastern Okfuskee counties which is expressed on all three maps.

CHAPTER VI

CORRELATIONS

Many of the anomalies and trends shown on the salinity gradient maps correlate well with certain geologic and geophysical features of the state. In certain areas, however, where the local geology is very complicated, such as the area surrounding the Arbuckle Mountains, geologic correlations are difficult to make from regional maps.

Geologic Correlations

Hydrodynamics

Influent meteoric waters forced to significant depths downdip from outcrops are apparently responsible for 2 of the observed salinity gradient lows; namely, the areas just north of the Arbuckles on all maps and the belt bordering the northeastern quarter of the state on the pre-Pennsylvanian map. Gravitational hydrodynamics is strongly influenced by present topography in that both the Arbuckle anticline and the southwestern flank of the Ozark dome are topographic highs.

Hubbert (1953) attributes the hydrodynamic tilting westward of oil-water interfaces in the Pennsylvanian Wheeler, Layton, and Bartlesville sandstones of the Cushing field to water flowing westward under a hydrostatic head from the Ozark uplift. This condition is probably too subtle to be reflected on the Permian-Pennsylvanian salinity gradient map

(Fig. 17). However, the pre-Pennsylvanian map indicates that the Cushing field is near the maximum values along the gradient high which separates areas of fresher waters on the east and west-to-southwest (Fig. 18). Pre-Pennsylvanian units to the east of this high would be expected to exhibit tilted oil-water interfaces or flushed traps. Hydrodynamic tile of the interface or flushing might also be expected for pre-Pennsylvanian units north of the Arbuckle uplift (Fig. 18).

Comparison was also made between the salinity gradient maps and the maps of Hart (1966), showing the depth to the fresh-salt water interface in southern Oklahoma. Several areas are present where a shallow interface corresponds to a high gradient, and where a deep interface corresponds to a low gradient. The best fit occurs in eastern Lincoln and southwestern Creek counties, where the base of the fresh water is as much as 400 ft higher than in surrounding areas. This corresponds to a prominent salinity gradient high is present on the Permian-Pennsylvanian map (Fig. 17).

Tectonic and Structural Framework

The general tectonic framework of Oklahoma (Fig. 1) is reflected quite well by all the salinity gradient maps. The deepest parts of the Anadarko, Ardmore, and Arkoma basins correspond very closely to areas of low salinity gradients. From the Anadarko basin, gradients increase eastward across the Central Oklahoma platform, northward across the Northern Oklahoma platform, and abruptly southward onto the Amarillo-Wichita-Criner uplift. Likewise, salinity gradient contours in part of the Arkoma basin parallel the basinal configuration and increase sharply toward a gradient "plateau" in the Ouachita belt and more gradually northward toward the Ozark uplift. An unexplained gradient high, present in eastern Pittsburg and western Latimer counties, trends perpendicular to the gradient low.

Several specific correlations to the structural framework are based on a comparison of the salinity gradient maps to paleogeologic maps (Jordan, 1962; Tarr _et_ _al_., 1965) and the tectonic map (Arbenz, 1956). An area of locally high gradients and complex gradient patterns is present on both the composite and Permian-Pennsylvanian maps in the northwestern part of the Central Oklahoma platform (in eastern Garfield, Noble, Kay and western Osage counties). This area corresponds rather well to various uplifts associated with, or located near, the Nemaha Ridge. It is suggested that these anomalies reflect the possible structural influence on salinities--either by the direct influence of fault zones or by controlling stratigraphic variations and thus restricting water flow.

Another salinity feature that coincides with certain structural features is the narrow area of high salinities, paralleling the Ozark uplift in northeastern Oklahoma in pre-Pennsylvanian units (Fig. 18). Comparison with the pre-Pennsylvanian geologic map indicates that the Cushing-Cleveland structural trend is aligned with the gradient high. This structural high may act as a barrier separating fresher waters to the east (off the Ozark uplift) from those to the west.

The salinity gradient highs in southwestern Hughes and northeastern Pontotoc counties and in southwestern Okmulgee and northeastern Okfuskee counties form a trend parallel to both the Pennsylvanian outcrop and the trend of en echelon faults in that area.

Regional Stratigraphy

A striking characteristic of the pre-Pennsylvanian map is that it lacks the variety of local highs, or salinity increases, shown particularly well by the composite and Permian-Pennsylvanian maps in much of the northern two-thirds of the state. Permian beds are known to contain evaporitic sequences which are thought to have contributed to the high salinities. Also, another aspect of regional stratigraphy is thought to be reflected in the pre-Pennsylvanian and Permian-Pennsylvanian maps. The rather uniform pattern of the former indicates a general continuity of rock type and permeability whereas anomalies in the Permian-Pennsylvanian units may reflect variations in rock type, interval thickness, and permeability. Areas with low salinity gradients that contain a thick stratigraphic section are the Anadarko, Arkoma, and Ardmore basins. Geopressures are documented in parts of these three basins.

Location of a salinity gradient high in the Permian-Pennsylvanian map of Alfalfa County coincides with the location of the Great Salt Plains. Consequently, it is likely that some influence of the Permian evaporites is reflected in the observed anomaly.

Hydrocarbon Occurrence

Several characteristic salinity features have been noted to correspond with oil or gas fields, based on a map of oil and gas fields of Oklahoma by Jordan _et al_. (1966). All features of interest are referred to the pre-Pennsylvanian and/or the Permian-Pennsylvanian map. An effort was made to consider only the significant fields, based on geographic size and production history, in the correlation. More detailed study will be required to make specific correlations, but it is thought that salinity studies are validated in part by relation of several fields to obvious salinity anomalies.

With respect to the Permian-Pennsylvanian salinity gradient map the Tatums and Sholem-Alechem fields in northwestern Carter and eastern Stephens counties are located in an area that is characterized by a sharp increase in salinity gradients to the southwest. It is possible that the cause of the salinity gradient increase is also the mechanism that accounts for oil accumulation. In the same general area, the Carter-Knox field of southeastern Grady and northeastern Stephens counties trends northwest-southeast and coincides with a local salinity high. A large part of the production from the Carter-Knox field is from Permian reservoirs.

To the north, the huge Oklahoma City field of south-central Oklahoma County lies in the same area as a subtle Permian-Pennsylvanian salinity gradient high. Salinities in that area and immediately to the south show the most abrupt transition within a 50 mi radius. However, production data indicate that best producers are pre-Pennsylvanian reservoirs. The Dilworth field of northwestern Kay County coincides roughly with a significant salinity high. It has a greater area of production than fields to the east and southeast where a salinity low is present.

A salinity gradient high in southwestern Harper County corresponds to the eastern part of the Nocane-Laverne gas area. Another possible correlation to gas occurrence is that of the salinity high in western Latimer and eastern Pittsburg counties, which encloses the Wilburton gas field of western Latimer County.

Comparison to the pre-Pennsylvanian salinity gradient map reveals 3 areas of particular interest. The linear area of high salinity gradients in northeastern Oklahoma not only coincides with the Cushing-Cleveland structural trend but also correlates with the large Cushing oil field of western Creek County. Although most of the production in this area is from Pennsylvanian sandstones, it may be that fluid movement through deeper units has contributed to petroleum accumulation. It should be noted, also, that there is a general arcuate trend of dense production coincident with the general trend of the high salinity anomaly through Osage, Creek, eastern Tulsa, and Okmulgee counties.

Another major oil field of Oklahoma, the Golden Trend field of northwestern Garvin County, trends northwest-southeast and corresponds quite well with the trend of pre-Pennsylvanian salinity gradients which increase at a moderate rate toward the southeast. The sharper than normal changes in salinity gradients may indicate permeability variations. Major petroleum production is from both Pennsylvanian and pre-Pennsylvanian units (Damon, 1970).

The area of low salinity gradients north of the Arbuckle exhibits insignificant petroleum production, which would be expected from the theory that the low salinities are due to a strong hydrodynamic flow from outcrops to the south. A significantly strong influent will have the effect of flushing hydrocarbons downdip.

Geophysical Correlations

Magnetic

Correlation to magnetic data is based upon the Vertical-Intensity

Magnetic Map of Oklahoma by Jones and Lyons (1964). The area of most obvious correlation is the northwestern quarter of the Central Oklahoma platform (eastern Garfield, Noble, Kay, western Pawnee, and western Osage counties). This area is characterized by a complexity of magnetic highs and lows and corresponds to a general area of salinity gradient complexities in both the composite and Permian-Pennsylvanian maps.

Gravity

Comparison to the Bouguer Gravity-Anomaly Map of Oklahoma by Lyons (1964) reveals two correlatable areas. The sharp change in gradients north of the negative gravity anomaly of the Ouachita system parallels salinity gradient trends of the composite and Permian-Pennsylvanian maps. Also, gravity data show a large positive anomaly centered in Osage County with a slight north-south elongation. Muehlberger *et al.* (1967) suggests that the source of the anomaly must be below the basement surface. Nevertheless, a local Permian-Pennsylvanian high and the pre-Pennsylvanian trend of high gradients corresponds at least in part to the gravity anomaly.

Geothermal

The most obvious correlation between salinity gradients and geothermal gradients (Schoeppel and Gilarranz, 1966) is in the Arkoma basin. The eastern half of an east-west trend of higher than normal geothermal gradients across east-central Oklahoma coincides with the low salinity gradient anomaly in that basin.

CHAPTER VII

CONCLUSIONS

Regional studies of water salinity gradients can be useful in the analysis of fluid movement, tectonic features, stratigraphic framework, and occurrences of oil and gas. Specific conclusions from this study are listed in the following summary:

(1) Regional stratigraphic continuity of separate intervals can be determined from the distribution and incidence of salinity gradient anomalies.

(2) Most local anomalies are salinity gradient highs--possibly indicating movement of water upward through fault zones or significant changes in permeability.

(3) Areas of significant meteoric recharge are reflected as low salinity gradients which increase away from the source.

(4) The presence of regionally low gradients in areas of thick sediments indicate abnormally fresh water at great depths.

(5) The influence of evaporitic deposits may be identified in areas of thin sediments from relatively high salinity gradients.

(6) Several local salinity gradient anomalies coincide with certain oil and gas fields.

(7) A large arcuate belt of petroleum production, corresponding to an area in northeastern Oklahoma of relatively high

salinity gradients in pre-Pennsylvanian units, suggests the value of salinities in determining the mechanism for such a concentration.

(8) Abnormally high temperatures should be expected in areas of very deep, relatively fresh water. Geothermal data from the Arkoma basin substantiates this relationship.

Salinity data, based on petrophysical estimates, are thought to represent a valuable tool for the explorationist. Salinity data are already available in petroleum industry files and could also be used to locate deep fresh water reserves for future use where the economics permit. This type of data might also assist the continuing investigation of shallow water reserves. Coupled with the detection of corresponding geothermal "hot spots," salinity studies might be valuable in the location of hydrothermal energy sources. On a broader scale, salinity gradient maps may be of considerable aid in deducing regional subsurface flow patterns and as an indication of regional subsurface geochemical environments.

There undoubtedly remains a variety of possible interpretations and correlations from the data presented in this study. Also, further data processing and mapping might lead to more specific applications of economic value.

Specific investigations that probably would increase our knowledge of subsurface fluids are the determination of vertical salinity profiles, their geographic variations, and the mapping of salinities in detailed geologic units.

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VITA

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Buckner, D. H — 1972

Fig. 18

PRE-PENNSYLVANIAN
SALINITY GRADIENT MAP OF OKLAHOMA

By

Duane H. Buckner

1972

Scale 1 : 750,000

0 10 20 30 40 Miles

CONTOUR INTERVAL

10 × 10^4/OHM M FT

50 × 10^4/OHM M FT
for values greater than 100

EXPLANATION

▨ Outcrop of pre-Pennsylvanian Paleozoic sedimentary rocks

▨ Outcrop of Precambrian - Cambrian basement rocks

● Points of Data Control

Base map from Oklahoma Geological Survey

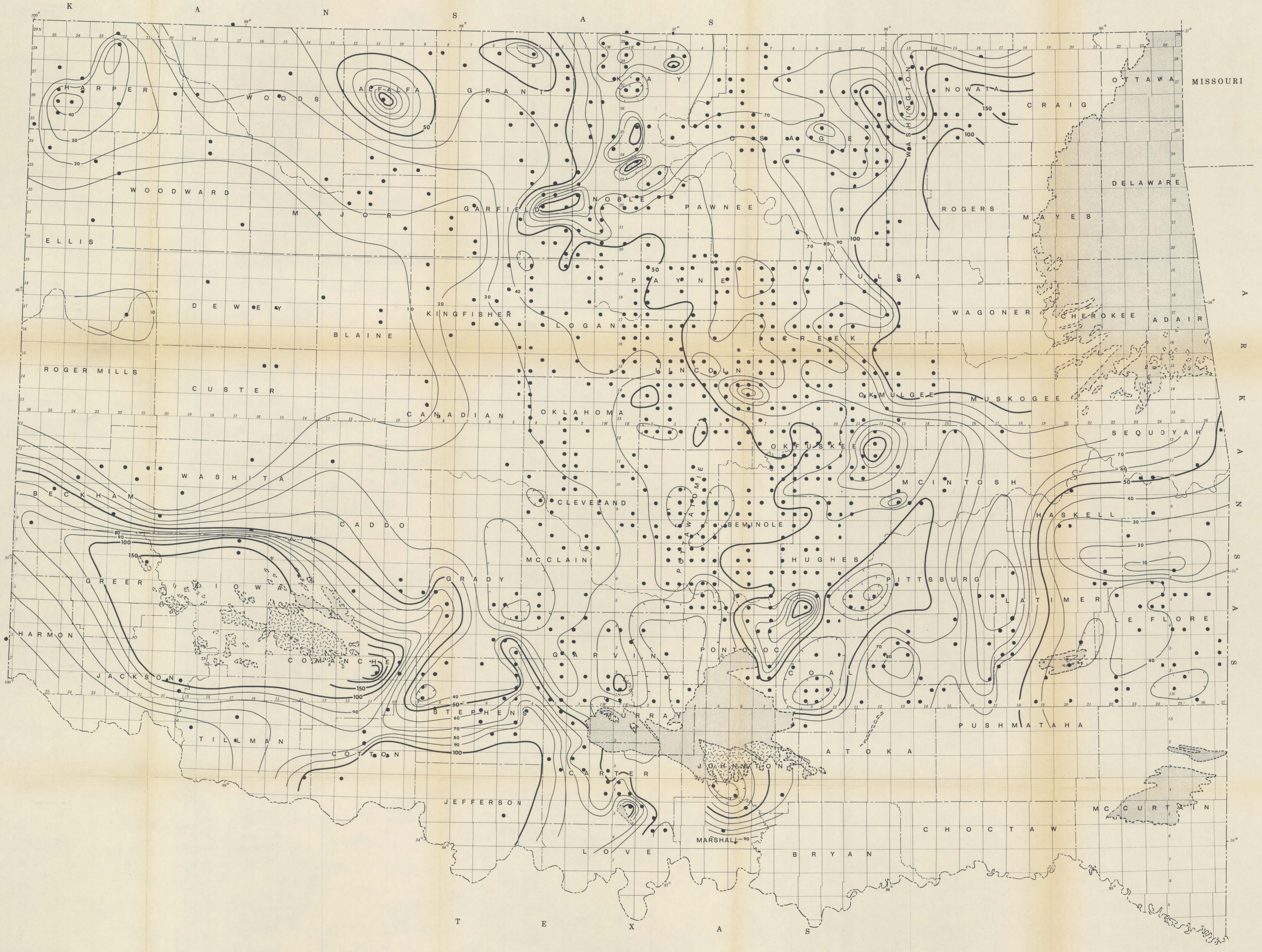

Fig. 16

COMPOSITE

SALINITY GRADIENT MAP OF OKLAHOMA

By

Duane H. Buckner

1972

Scale 1 : 750,000

0 10 20 30 40 Miles

CONTOUR INTERVAL

10 × 10^4/OHM M·FT

50 × 10^4/OHM M·FT
for values greater than 100

EXPLANATION

▨

Outcrop of pre-Pennsylvanian Paleozoic sedimentary rocks

▒

Outcrop of Precambrian - Cambrian basement rocks

●

Points of Data Control

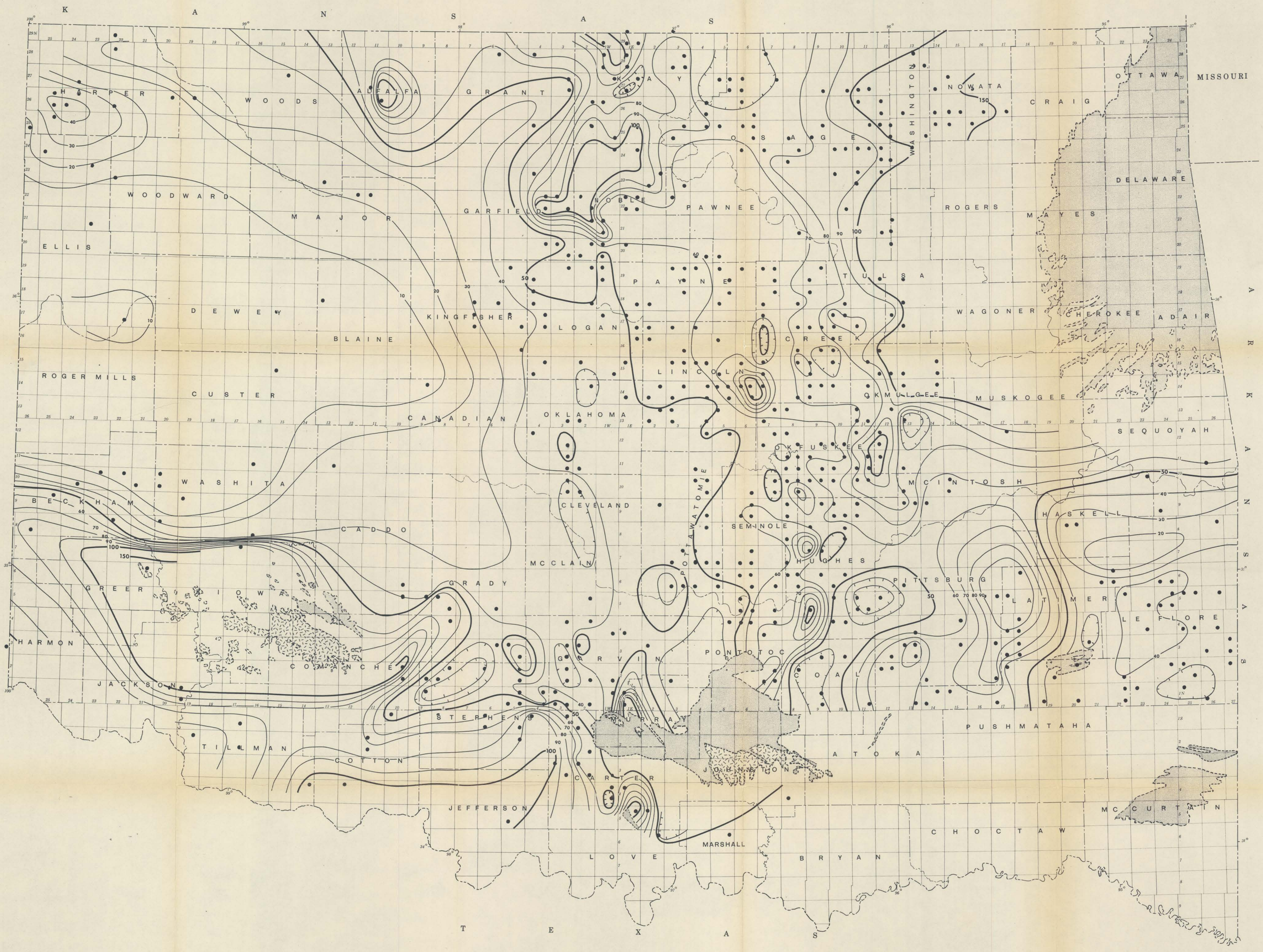

Fig. 17

PERMIAN - PENNSYLVANIAN

SALINITY GRADIENT MAP OF OKLAHOMA

By

Duane H. Buckner

1972

Fig 17

Scale 1:750,000

0 10 20 30 40 Miles

CONTOUR INTERVAL

10 × 10^4/OHM·M·FT

50 × 10^4/OHM·M·FT
for values greater than 100

EXPLANATION

▨ Outcrop of pre-Pennsylvanian Paleozoic sedimentary rocks

▨ Outcrop of Precambrian - Cambrian basement rocks

● Points of Data Control

Base map from Oklahoma Geological Survey