OKLAHOMA GEOLOGICAL SURVEY

CARL C. BRANSON, *Director*

BULLETIN 102

Permian Salt and Associated Evaporites in the Anadarko Basin of the Western Oklahoma-Texas Panhandle Region

by
Louise Jordan and David L. Vosburg

The University of Oklahoma

Norman

1963

FOREWORD

Rock salt is a valuable resource but is difficult to find because it is dissolved in most drilling processes. The present report proves the presence of three large layered bodies of rock salt beneath the surface of western counties of Oklahoma. The known reserves are sufficient to supply world demand for many years. The bedded salt is in one instance 400 feet thick, and all of it is at depths which are practical for production.

Rock salt is used as processed salt for such things as cattle salt and is important in chemical industry as a source of sodium and chlorine. Chambers are developed in rock-salt layers for the storage of liquefied petroleum gases and other materials.

The facts presented in this book should stimulate greater use of this important mineral and encourage further development of industry in the area.

—CARL C. BRANSON

CONTENTS

ILLUSTRATIONS

FIGURES

PLATES

TABLES

PERMIAN SALT AND ASSOCIATED EVAPORITES IN THE ANADARKO BASIN OF THE WESTERN OKLAHOMA-TEXAS PANHANDLE REGION

LOUISE JORDAN AND DAVID L. VOSBURG*

ABSTRACT

Permian salt and associated evaporites within a 20,000-square-mile region in western Oklahoma and the Texas Panhandle are Leonardian and Guadalupean, and possibly Ochoan, in age. This report is concerned chiefly with the subsurface geology of the three principal evaporite sequences, each of which is 300 to 1,000 feet thick and consists mainly of rock salt and salty shale interbedded with anhydrite. These evaporite sequences contain all the rock salt known in Oklahoma. The evaporites occur with red clastic sediments in a sequence 4,000 feet thick, embracing all strata from the base of the Wellington Formation to the top of the Dog Creek Shale. Four stratigraphic sections accompanying the report illustrate the distribution and facies relationships of these beds. The youngest evaporites of the region—relatively thin anhydrite beds in the Cloud Chief Formation, of possible Ochoan age—are not considered herein.

The evaporites are classed in ascending order as Wellington, Cimarron, and Beckham. Wellington and Cimarron evaporite units known in the subsurface of Kansas are here extended and mapped into Oklahoma and the Texas Panhandle. The term "Beckham evaporites" is a new term that includes (ascending) the Flowerpot salt (new), Blaine anhydrite, and Yelton salt (new). Each evaporite sequence is widely distributed, occurring as eastward-thinning tongues or wedges within the framework of Permian clastic sediments. Together the evaporites have a maximum thickness of 2,500 feet. The evaporite strata, excluding clastics, consist of halite (about 80 percent), anhydrite, and thin beds of dolomite (less than 5 percent). No po-

---

* University of Rhode Island, Kingston, R. I.

tassium salts were found or were indicated by investigations for the present study.

The oldest halite-anhydrite sequence in Oklahoma, called the Wellington evaporites, is of Leonardian age and normally ranges in thickness from 1,000 to 1,300 feet. It is divided into a lower anhydrite-salt unit, a shale unit, and an upper anhydrite unit. The salt in the upper part of the lower unit is equivalent to the Hutchinson Salt of Kansas. Depth to the salt in the Wellington ranges from 800 feet in northwest-central Oklahoma (Grant County) to 3,900 feet near Elk City in Beckham County. Over an area of approximately 16,500 square miles the average aggregate thickness of salt strata in the Wellington is 225 feet.

Above the Wellington are the Hennessey shales, which are overlain by the Cimarron evaporites. The Cimarron evaporites consist of lower and upper salt units separated by the Cimarron anhydrite and have a maximum thickness of 1,000 feet. The lower salt and Cimarron anhydrite are especially persistent, and the anhydrite is a valuable structural datum. Total thickness of Cimarron salt strata over 13,000 square miles of western Oklahoma is generally 500 feet, and the depth range is between 215 and 2,420 feet. The lower salt unit is noteworthy because it locally consists of massive salt more than 400 feet thick, and thus is probably the thickest salt in Oklahoma.

Red shales above the Cimarron are classed as Flowerpot-Hennessey. They are overlain by the Beckham evaporites (Guadalupean), the youngest salt-bearing strata of western Oklahoma and the eastern part of the Texas Panhandle. The middle unit of the Beckham sequence is the well-known Blaine anhydrite, 150 feet thick, which crops out extensively in western Oklahoma and occurs so persistently in subsurface that it is a valuable stratigraphic datum. Salt beds directly below and directly above the Blaine, respectively called Flowerpot and Yelton, have much less geographic distribution, yet each attains a thickness in excess of 250 feet. The Flowerpot salt has an average thickness of 200 feet and a maximum thickness of 625 feet (including salty shale). It occurs over more than 7,000 square miles of western Oklahoma and is found at depths as shallow as 30 feet in northern Oklahoma, and as deep as 1,655 feet in southwestern Oklahoma in the area north of the Wichita Mountains. The Yelton salt occurs chiefly in Beckham and Washita Counties, Oklahoma, and in Wheeler County, Texas, at depths of 390 to 1,285 feet. Much of the Yelton sequence is massive rock salt, reaching a maximum thickness of 287 feet in the eastern part of Beckham County.

Included in the report are maps showing distribution, thickness, and depth from surface of the principal salt beds.

As outlined by structural mapping at the base of the Blaine anhydrite and of the Wellington evaporites, the major structural feature of the region is the Anadarko syncline. It trends west and northwest across much of western Oklahoma into the Texas Panhandle, its axis following a line just north of the Wichita Mountains. Permian strata on the south limb dip as much as 250 feet per mile, whereas on the north limb they dip 9 to 40 feet, or an average of 20 feet, per mile.

With the exception of the Yelton salt, which occurs in the axial part of the syncline, the Permian evaporites bear no obvious relationship to major structure. Multiple rather than single salt basins were developed for any given sequence, and the maximum salt thickness for one stratigraphic unit does not coincide structurally or geographically with the maximum thicknesses of the other evaporites.

Salt reserves in western Oklahoma are estimated to be more than 21 million million (21,000,000,000,000) short tons. Although much of the salt is thick and nearly pure, the reserves are virtually unexploited. Within the area studied, a small amount of salt is produced from brine wells in the Upper Cimarron salt in Beckham County, and some of the salt beds are used for underground storage of liquefied petroleum gases. Four salt caverns are currently being used, one each in a salt bed of the Blaine anhydrite (Beckham County), in the Flowerpot salt (Beaver County), in the lower Cimarron salt (Beaver County), and in the Lower salt-anhydrite unit of the Wellington (Grant County). Total storage capacity of these facilities is nearly 250,000 barrels.

Future uses of the salt probably will include expanded production for livestock and human consumption, and for such chemical purposes as the production of chlorine, caustic soda, and soda ash. Additional underground storage facilities for liquefied petroleum gases are currently being made in Permian salt beds of Oklahoma. Similar caverns might be made for the underground storage of natural gas, or possibly for the storage of low-intensity radioactive waste materials. A knowledge of the distribution and thickness of salt beds also is useful in the interpretation of seismic data obtained in the exploration for petroleum.

INTRODUCTION

General statement—The Permian basin of the south-central United States contains thick evaporites within a region of more than 100,000 square miles, extending from southeastern New Mexico and West Texas across the Texas Panhandle and western Oklahoma into Kansas (Ham, 1960, fig. 2, p. 140).

The present study is a subsurface investigation of the evaporites of the Permian basin that occur in western Oklahoma and the eastern part of the Texas Panhandle (fig. 1). This area embraces 20,000 square miles and lies wholly within the Anadarko basin, as originally recognized by Gould (1924, p. 324). It is bounded on the south by the Wichita Mountains in Oklahoma and, in Texas, by the

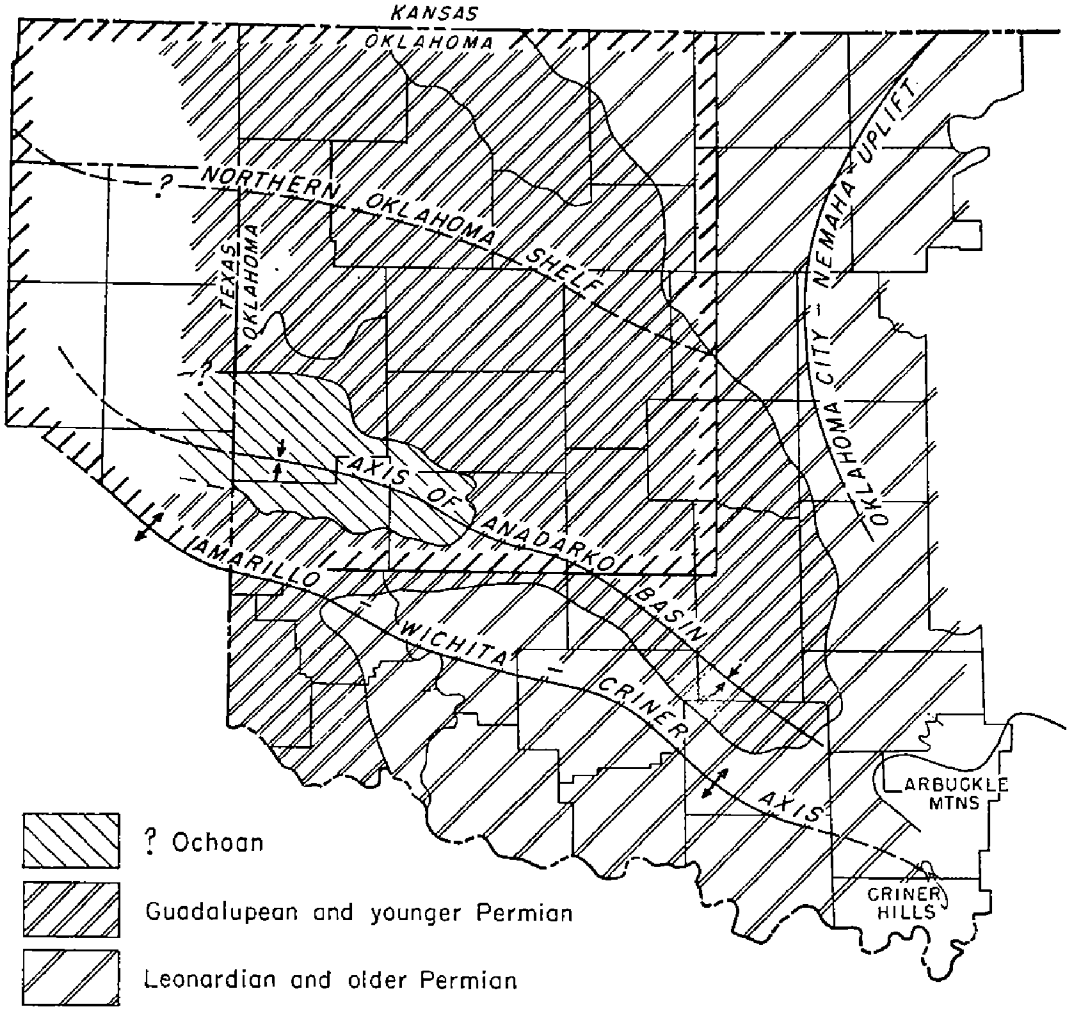

Figure 1. Index map showing geologic framework of area investigated.

buried Amarillo uplift. Permian evaporites continue westward and southward across the Amarillo uplift, and northward into Kansas, but they are not considered in this report. The northern element of the Anadarko basin has been called the Northern Oklahoma shelf by Arbenz (1956). Structural contouring for the present report shows that Permian beds define the Northern Oklahoma shelf quite poorly, however, as the north limb of the Anadarko basin over most of its area has homoclinal dip.

Permian strata of the Anadarko basin (fig. 2) range in age from Wolfcampian (Early Permian) through Leonardian and Guadalupean ("Middle" Permian) and possibly into the Ochoan (Late Permian). Beds of Wolfcampian age in this area contain no definite evaporites. In subsurface they are mostly marine carbonates and shales, whereas in outcrops of central Oklahoma they are red shales and sandstones. Above the Wolfcampian are four major evaporite units. The two earlier units are widely distributed in subsurface, but grade toward the outcrop into red sandstones and shales that are locally interbedded with lacustrine deposits. The upper two units are represented by evaporites both in subsurface and on the outcrop.

The oldest evaporites are in the basal Leonardian Wellington Formation. They are succeeded upward by the Cimarron evaporites and Beckham evaporites, of Leonardian and Guadalupean ages. Each evaporite unit consists mainly of salt and anhydrite. Combined thickness of the Wellington, Cimarron, and Beckham evaporites is 2,500 feet, and these units occur in a Permian sequence having a thickness of 4,000 feet. In a general way the evaporites occur as wedging tongues that increase in thickness down dip to the west, away from the eastern land areas and shore lines.

The uppermost evaporites, consisting of massive beds and lenses of gypsum and anhydrite in the Cloud Chief Formation, possibly of Ochoan age, have not been investigated for this report.

As interpreted from well logs and a few locally available cores, the evaporite units consist of halite, anhydrite, dolomite, and shale. Halite clearly predominates and occurs in as much as 2,000 feet of strata, some of it almost pure rock salt 1,000 feet thick. In the remaining evaporite strata anhydrite is the dominant rock and is associated with shale and thin beds of dolomite.

The evaporites are everywhere characterized by NaCl, $CaSO_4$, and carbonates, and in no part of the investigated area have potash salts been recognized.

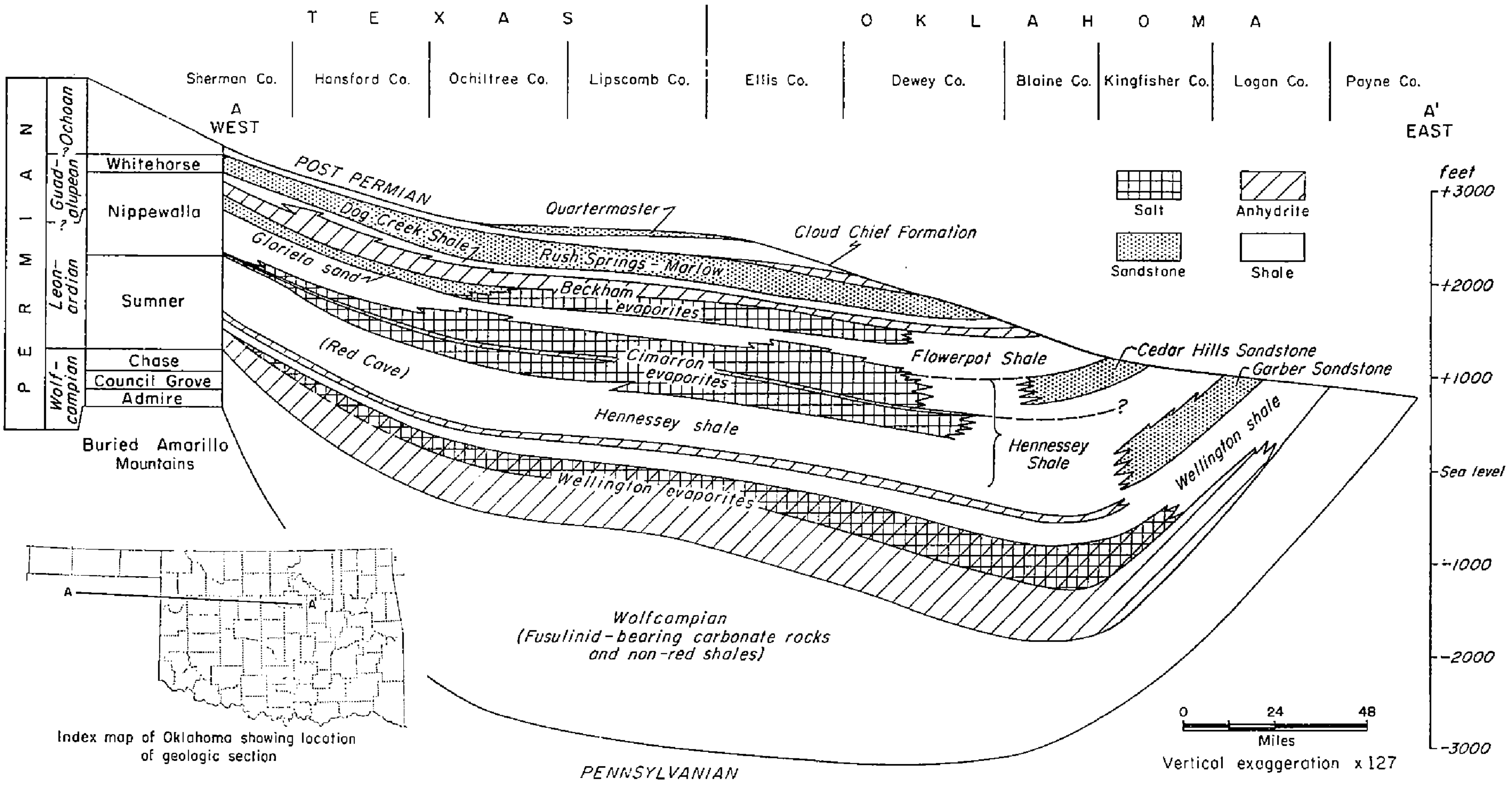

Figure 2. Generalized geologic structure section of Permian strata in western Oklahoma and Texas Panhandle.

Previous investigations—Early reports on the Permian redbeds of Oklahoma were devoted to the mapping and correlation of surface units. Geologists who participated in the work include Greene (1920, 1926), Gould (1924, 1926), Aurin and others (1926), Gould and others (1926, 1927), Gouin (1927, 1928), Becker (1927, 1930), Evans (1928, 1931), Clifton (1930), Brown (1937), Green (1936, 1937), and Norton (1937). More detailed recent mapping of Permian strata in western Oklahoma, including evaporites at the surface, is that done by Scott and Ham (1957) in the Carter area, mostly in the southeastern part of Beckham County; Myers (1959) in Harper County; and Fay (1962) in Blaine County.

Papers relating to evaporite chemistry, mineralogy, and commercial exploitation of evaporites are included in the references. The alteration relationships between gypsum and anhydrite have been discussed by Hill (1937), Posnjak (1938), and Scruton (1953). General works dealing with the conditions and mechanics of evaporite deposition include a discussion of cyclic phenomena (Hills, 1942), lithologic associations of evaporites (Krumbein, 1951) and a classification of brackish waters related to climate (Hedgpeth, 1951). Smith (1942) compiled analytic data on the waters of Oklahoma. Lang (1957) compiled an exhaustive bibliography of salt in the United States.

Moore (1951, 1954) and Widess (1952) reported the effects of subsurface salt deposits on the interpretation of seismic records. Lishman (1961) discussed the identification of salt from unfocused electrical resistivity logs.

Subsurface investigations in the early years, previous to the discovery and use of electrical logging, were limited by the relatively few holes drilled for oil in western Oklahoma. Information was obtained from rock cuttings or from logs made by drillers. Evaporites including salt are shown on cross sections or are mentioned by Greene (1926), Clifton (1926b), Freie (1930), Six (1930), Rogatz (1935), Mohr (1939), and Norton (1939). Adkison (1960) prepared a subsurface cross section from Kansas southward to south-central Oklahoma in which he made a detailed study of the rocks in 19 wells.

Ham and Jordan (1961) established a tentative standard section for the shallow subsurface Permian section in western Oklahoma. Jordan (1959-1962) wrote several brief papers on the occurrence of salt in the subsurface of western Oklahoma and on the storage of liquefied petroleum gas in salt beds. Ward (1961a, 1961b) and

Ward and Leonard (1961) discussed the pollution of ground water and streams by salt springs in western Oklahoma, giving solution of shallow salt beds by circulating ground water as the chief cause of pollution.

Present investigation—Subsurface evaporites of the Anadarko basin have long been recognized, but no regional study of these beds has been previously attempted. Although the petroleum industry has caused several thousand wells to be drilled through these rocks, the character, thickness, and distribution of the evaporites have been largely ignored because oil and gas have not been found in the Anadarko basin in beds younger than Wolfcampian, except locally in the Panhandle field of Texas.

The present study has originated from a need for regional stratigraphic interpretations and a preliminary evaluation of salt resources. It has been stimulated by recently developed underground storage facilities in salt for liquefied petroleum gas in Oklahoma through which much new information from cores, caliper logs, and sonic logs has been made available. In addition to the probability that new storage areas for liquefied petroleum gas will be required in the near future, it is also probable that salt for chemical and industrial uses will be produced from the enormous reserves of the region. There is also the possibility that radioactive waste may be put into underground storage in salt beds of the Anadarko basin. Finally a better understanding of the evaporite beds resulting from this study will assist in solving seismic velocity problems encountered in petroleum exploration.

Basic information for the present investigation has been obtained mostly from electrical and gamma-ray-neutron logs. More precise information is obtainable from cores, caliper logs, and sonic logs, and these have been used as primary control in the few areas where they are available. Essential lithologic interpretations from the above data were used in constructing the subsurface cross sections, thickness maps, and structure maps, subject to confirmation by coring. Well cuttings have been used only to a slight extent because most cuttings through the evaporite strata have not been saved by operating companies, and further the available samples are not reliable because the soluble salt is dissolved during drilling. The reliability of cuttings for determination of lithology is further reduced by the drilling techniques, such as large bit size and natural drilling mud, normally employed in drilling the Permian strata down to the top of the marine carbonates assigned to the Wolfcampian. The distinction between salt and anhydrite is possible with a considerable degree of confidence wherever the combination of focused resistivity and gamma-ray surveys is available in conjunction with sonic and/or caliper (section gauge) logs.

The investigation was undertaken in 1959 by Vosburg under the direction of Jordan to fulfill the requirement for the Doctor of Philosophy degree in geology at The University of Oklahoma. At that time Porter E. Ward, geologist in the Ground Water Branch of the U. S. Geological Survey, was engaged in a study of near-surface salt deposits for the U. S. Public Health Service. Most of the data were collected with the cooperation of Mr. Ward and with the assistance of T. L. Rowland during the summer of 1959. Active search for information was completed in January, 1960. Some more recent data acquired from cores and pertinent logs of holes drilled to investigate possible storage sites have been incorporated. Compilation of data was greatly expedited by the cooperation and generous assistance of the oil industry, which is gratefully acknowledged. Eileen Krall and Marion E. Clark drafted the cross sections and text-figures under the direction of Roy D. Davis, who drafted the maps. Critical evaluation of the manuscript by William E. Ham and Kenneth S. Johnson of the Oklahoma Geological Survey has been a major contribution to the successful completion of the project.

STRATIGRAPHY

INTRODUCTION

Permian rocks of Leonardian and Guadalupean ages are exposed over a wide area in central and western Oklahoma, dipping gently west and southwest into the Anadarko basin. Three sequences of evaporite deposits, separated by shales, are present in the subsurface. The evaporite units and the intervening shales are, in ascending order: Wellington evaporites, Hennessey shales, Cimarron evaporites, Flowerpot-Hennessey shales, and Beckham evaporites (pl. I). Subdivisions have been made on the basis of rock type and electrical log characteristics. Composite thickness of these strata ranges from approximately 2,500 feet in western Beaver County, to 3,900 feet in north-central Beckham County, Oklahoma.

The nomenclature used in this report is informal. The relationship to present accepted usage is shown, in so far as it is known, both on the surface and in the subsurface (fig. 3). The area covered and the amount of control information available in many localities make this a preliminary report subject to revision as more complete data come to hand. As the exact stratigraphic position of most of these units has not been clearly established in relation to surface nomenclature, it seems desirable to use informal terms which can be modified easily, should more detailed investigations indicate that modification is needed.

WELLINGTON EVAPORITES

Nomenclature and stratigraphic relations—The term "Wellington evaporites" as used herein is essentially synonymous with the term "Wellington Formation" as commonly understood and used in the subsurface. The Wellington is underlain throughout most of the area by marine carbonates of Wolfcampian age, but around the Amarillo-Wichita Mountains axis the underlying beds are clastic debris assigned to the Pontotoc Group or its equivalents. The Wellington is overlain by clastics, which in the east are called Garber Sandstone and in the central part of the area are called Hennessey Shale. In the Texas Panhandle the overlying beds are called "Red Cave." The top of the gray shale overlying the uppermost occur-

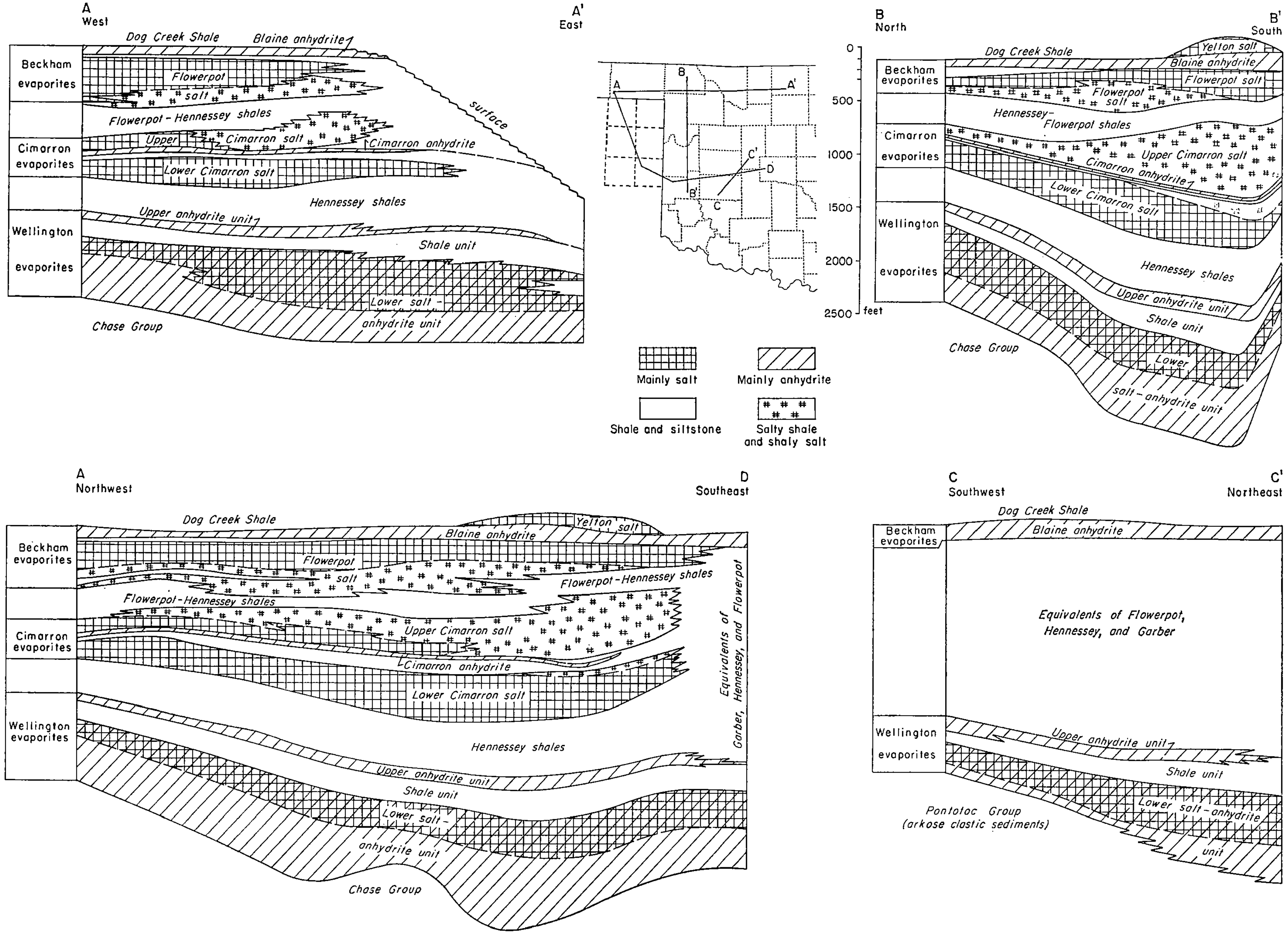

Plate I. Schematic diagrams and index map of the geologic cross sections presented in this report, showing gross lithology of major units (principally evaporites separated by fine clastics) and their relationship to each other and to the surface. Datum is base of Blaine anhydrite.

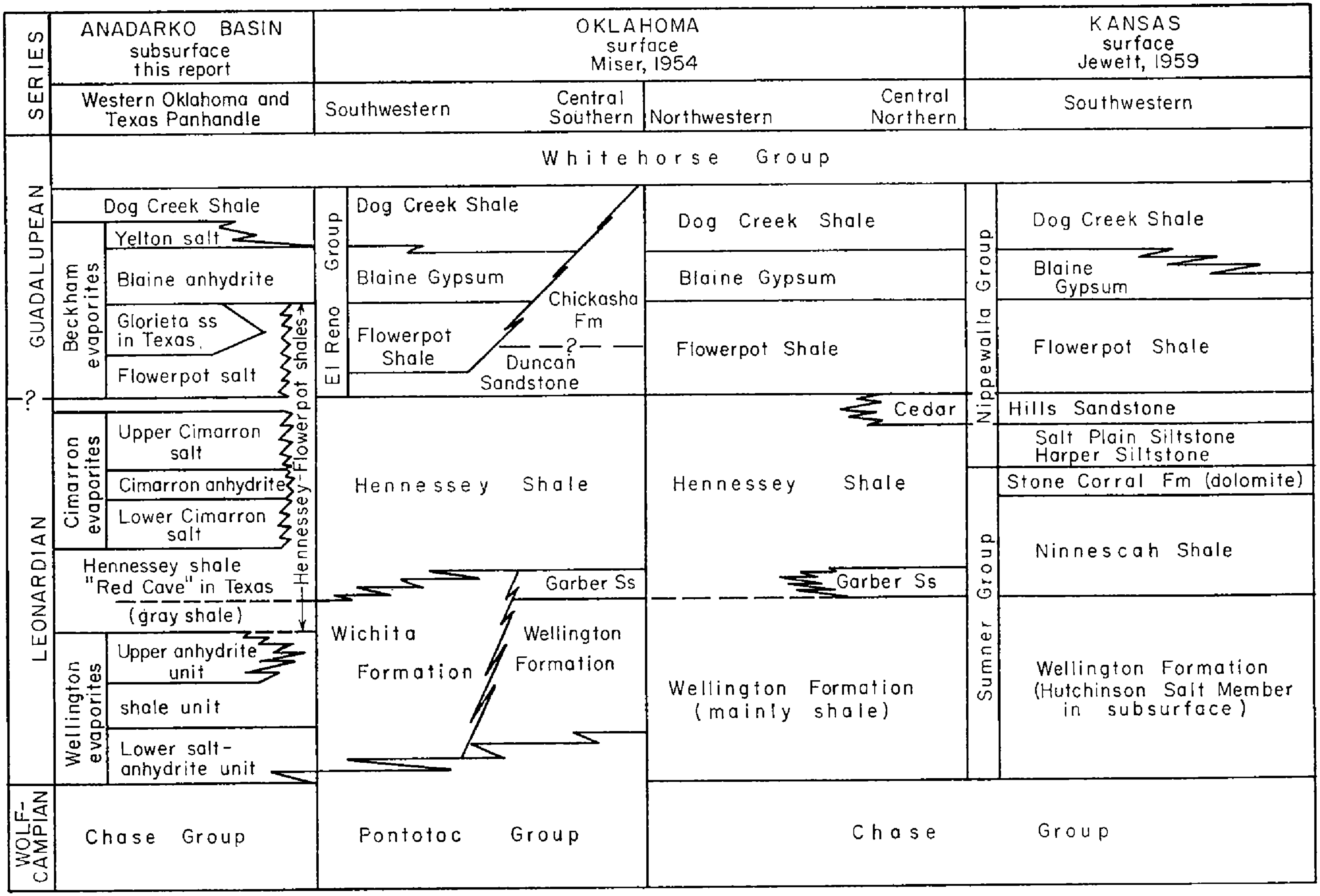

Figure 3. Stratigraphic nomenclature of Permian strata dealt with in this report, showing probable relationship between surface and subsurface units.

rence of anhydrite or dolomite cannot be readily established in the subsurface and is therefore not included as part of the Wellington evaporites, even though these gray shale beds are assigned to the Wellington Formation of surface nomenclature. The base of the Wellington Formation is considered to be at the top of the Herington Limestone. In the subsurface, the base of the Wellington evaporites is established at the base of those beds that can be easily identified as anhydrite by the charcteristics shown on electrical or radioactivity logs (fig. 4).

Distribution—The Wellington Formation crops out along a line striking north and extending from Kansas southward through Oklahoma to the Arbuckle Mountains. Equivalent strata extend around the western end of the mountains and southward into Texas (Miser, 1954). Along the outcrop in central Oklahoma, the formation is mostly shale and sandstone, dipping gently west and southwest. In subsurface the formation consists predominantly of evaporites. They are recognized in all parts of the mapped area except along the northern flank of the Wichita Mountains in T. 8 N.

Thickness—Across the northern part of the area the Wellington evaporites range in thickness from 820 feet in Beaver County, to 1,110 feet in Woodward County. Farther east, in Grant County, the thickness is 860 feet, but only the lowermost 675 feet contains clearly recognizable evaporites (pl. II, cross section A-A′). In the southeastern part of the area, on the south flank of the Anadarko basin, the thickness is 475 feet near the Wichita Mountains (sec. 8, T. 8 N., R. 18 W.). Here the lower part of the Wellington evaporite section grades into beds assigned to the Pontotoc Group. The Pontotoc conglomerates, sandstones, and shales are progressively lower in the section northward and eastward and grade slowly into evaporites so that in sec. 36, T. 14 N., R. 13 W., the evaporites are 1,160 feet thick, the lower salt-anhydrite unit being 830 feet thick (pl. II, cross section C-C′).

A north-south section (pl. II, cross section B-B′) shows 950 feet of Wellington evaporites in northern Harper County, a maximum of 1,300 feet in north-central Beckham County, and 740 feet in central Beckham County.

The Wellington evaporites thicken southward from Beaver County, Oklahoma, into the Panhandle of Texas (pl. II, cross section A-D). In central Ochiltree County, Texas, well 11 penetrated 980 feet of evaporites which are 1,170 feet thick in eastern Roberts County, Texas (well 13). Southeast of well 13 the section remains nearly

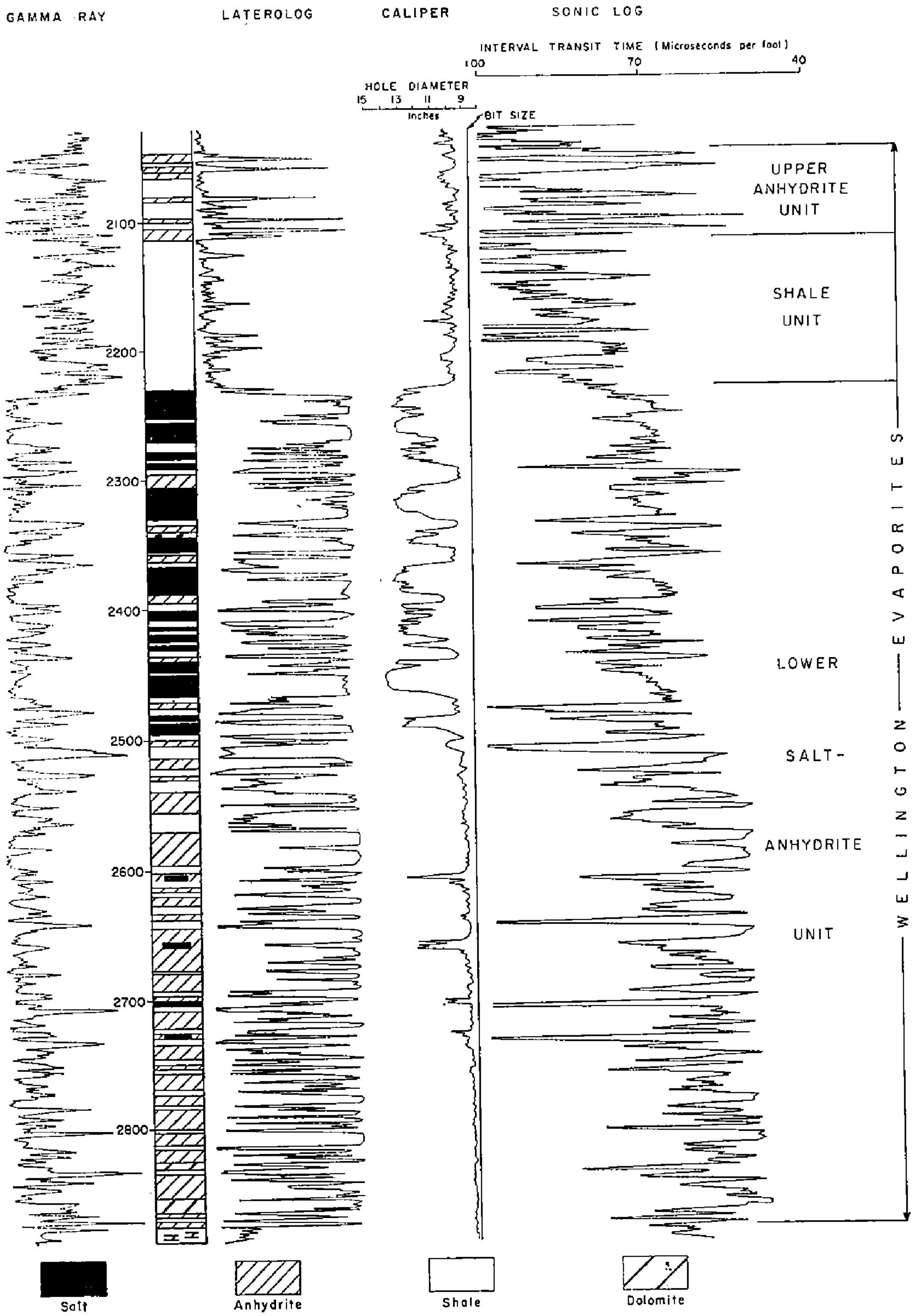

Figure 4. Subdivisions of the Wellington evaporites as shown by lithologic, gamma-ray, laterolog, caliper, and sonic logs of Gulf-Warren's SWD-1 Mocane Plant, sec. 18, T. 5 N., R. 25 ECM., Beaver County, Oklahoma, showing mainly salt in the upper half of the Lower salt-anhydrite unit.

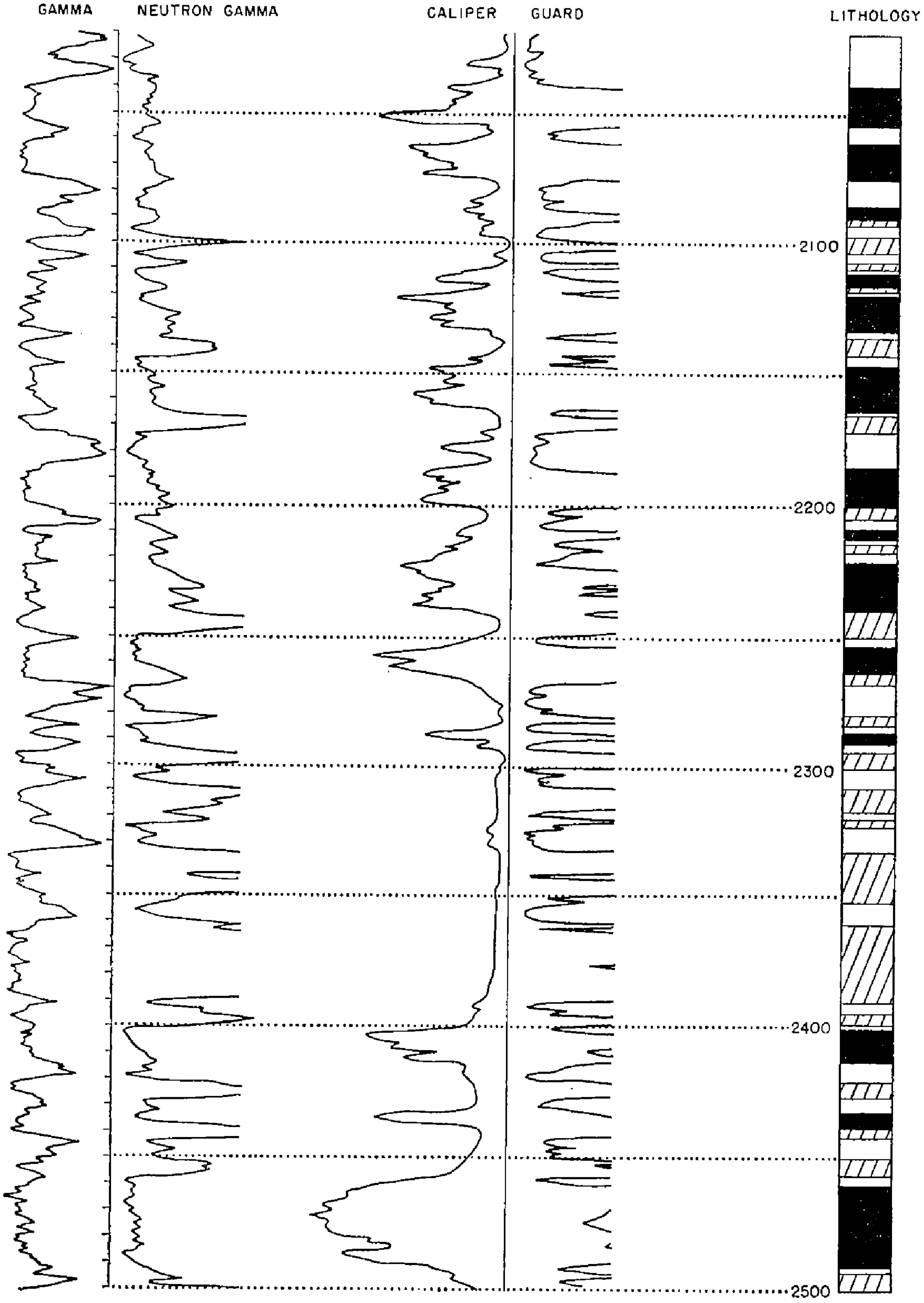

Figure 5. Salt strata in the upper part of the Lower salt-anhydrite unit of the Wellington evaporites, as shown by logs of the Cities Service 1 Dunnaway "B," sec. 9, T. 26 N., R. 25 W., Harper County, Oklahoma (from Jordan, 1960, p. 27). In the lithologic column, blank areas are shale, solid black is salt, and diagonal ruling is anhydrite.

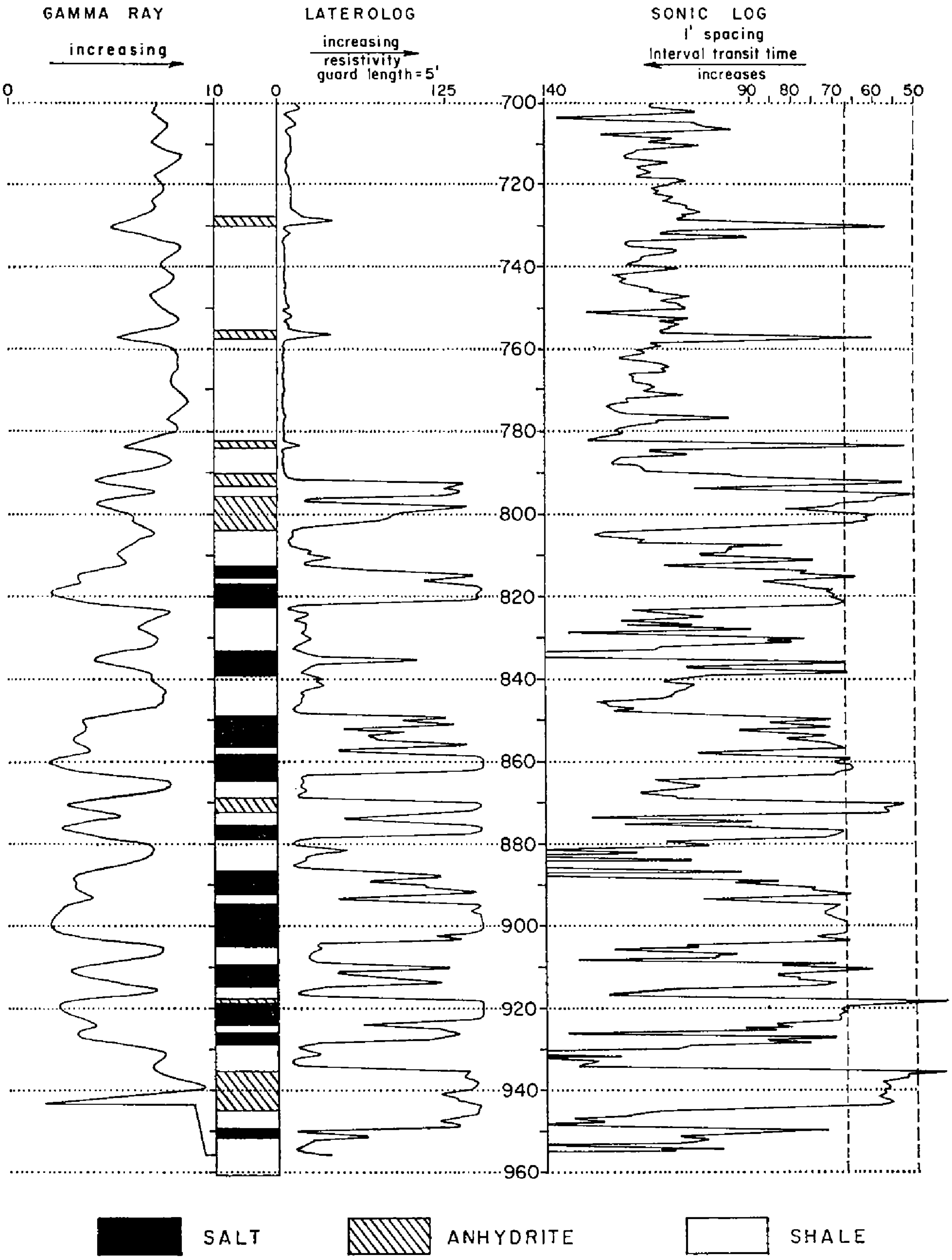

Figure 6. Salt strata in the Lower salt-anhydrite unit of the Wellington evaporites, as shown by logs of the Continental Oil Company test hole, sec. 32, T. 27 N., R. 5 W., Grant County, Oklahoma (from Jordan, 1961c, p. 273). Top of unit at 790 feet.

constant, having a thickness of 1,190 feet in east-central Wheeler County, Texas (well 15).

Subdivisions—The Wellington evaporites are easily divisible into three units. These units are designated the Lower salt-anhydrite unit, Shale unit, and Upper anhydrite unit (ascending order). The Lower salt-anhydrite unit might also be subdivided into a "salt unit" above, and "lower anhydrite" below.

Lower Salt-Anhydrite Unit

Nomenclature and stratigraphic relations—The base of the Lower salt-anhydrite unit is placed at the base of beds that can be identified as anhydrite by the characteristics shown by electrical logs and is coincident with the base of the Wellington evaporites as previously defined. The top of the unit, called the "Main anhydrite" by many subsurface geologists, appears on electrical logs as an abrupt resistivity increase (figs. 4-6) from a shale value and can be recognized in the subsurface over large areas of the Midcontinent region. At many places this resistivity change from shale to evaporites is indicative of salt rather than anhydrite.

Distribution—The Lower salt-anhydrite unit can be recognized throughout the area, except along the extreme southern edge near the Wichita Mountains where the entire unit grades into clastic rocks assigned to the Pontotoc Group.

Character and thickness—Over most of the region the unit consists mainly of evaporites—anhydrites and salt—that are interbedded with shale and dolomite. In thickness these strata range from 570 feet to 920 feet. Approximately the lower half of the unit normally consists of anhydrite and shale, whereas the upper half contains beds of rock salt as well. Part or all of these salt-bearing strata are equivalent stratigraphically to the Hutchinson Salt Member of the Wellington Formation in Kansas.

The evaporite unit as a whole is remarkably uniform in character throughout the region, except in the southeast (pl. I), where most of the evaporites grade into shale, and in the area south of the basin axis, where these beds grade by change of facies (beginning at the base) into coarse clastics of the Pontotoc Group around the flanks of the Wichita Mountains. Slight thinning at a uniform rate takes place northward from the axis of the Anadarko basin (pl. II, cross section B-B′). Section A-A′ (pl. II) shows a range in thickness along the northern shelf area from 570 feet in southwestern Beaver County to 860 feet in northern Woodward County, gradually thinning from this point eastward to 675 feet in Grant County. The salt-bearing section in Grant County (pl. II, cross section A-A′, well 10) is 250 feet below the top of the unit. The beds above the salt are mostly shale with thin anhydrite stringers, which are thicker and more numerous in the upper hundred feet.

Southward from Beaver County, Oklahoma (pl. II, cross section A-D), the unit thickens to 690 feet in Ochiltree County, Texas, and to 830 feet in southeastern Roberts County, Texas. The thickening continues southeastward and the unit reaches a maximum of 920 feet in Wheeler County, Texas, in the axis of the basin. Other wells within the axial portion of the basin show a thickness ranging from 800 to 900 feet, but the maximum possible thickness may be much greater locally.

Except for the gradation of the evaporites into clastic sediments near the Wichita Mountains as noted above, the two-fold division of the lower Wellington into a lower anhydrite and an upper salt is regionally persistent. The lower half is normally anhydrite and shale. Anhydrite beds, generally up to 30 feet thick, make up about half of this sequence. From Beckham County westward into the Texas Panhandle, however, the normal anhydrites become increasingly dolomitic, so that in the lowermost 200 feet of the Wellington approximately 80 percent is dolomite interstratified with thin beds of shale and anhydrite. At a few places the shale and anhydrite beds are more than ten feet thick. This dolomite is called the Hollenberg Dolomite in the subsurface of the Texas Panhandle. Discontinuous beds of salt and salty shale, ten feet or less thick, are contained locally in the Hollenberg Dolomite.

Salt—That part of the Lower salt-anhydrite unit which contains salt is illustrated in figure 4. The logs shown are from the Gulf-Warren salt-water-disposal well (sec. 18, T. 5 N., R. 25 ECM.) used for disposal of salt water during the construction of their underground storage cavity. The salt-bearing section from 2,230 to 2,490 feet is 260 feet thick. Approximately 55 percent of the rocks of this interval is salt, 26 percent is anhydrite and dolomite, and the remaining 19 percent is shale.

A similar section of salt-bearing Wellington evaporites in Harper County is illustrated in figure 5. This illustration shows about 450 feet of strata containing an estimated 42 percent salt, 30 percent anhydrite, and 28 percent shale.

The salt strata of the Lower salt-anhydrite unit in sec. 6, T. 22 N., R. 22 W., Woodward County, are 565 feet thick and contain 37 percent salt, 34 percent anhydrite, and 29 percent shale.

Another much thinner section of salt strata present in sec. 32, T. 27 N., R. 5 W., Grant County, is shown in figure 6. A section 138 feet thick occurs from a depth of 812 to 950 feet. Salt con-

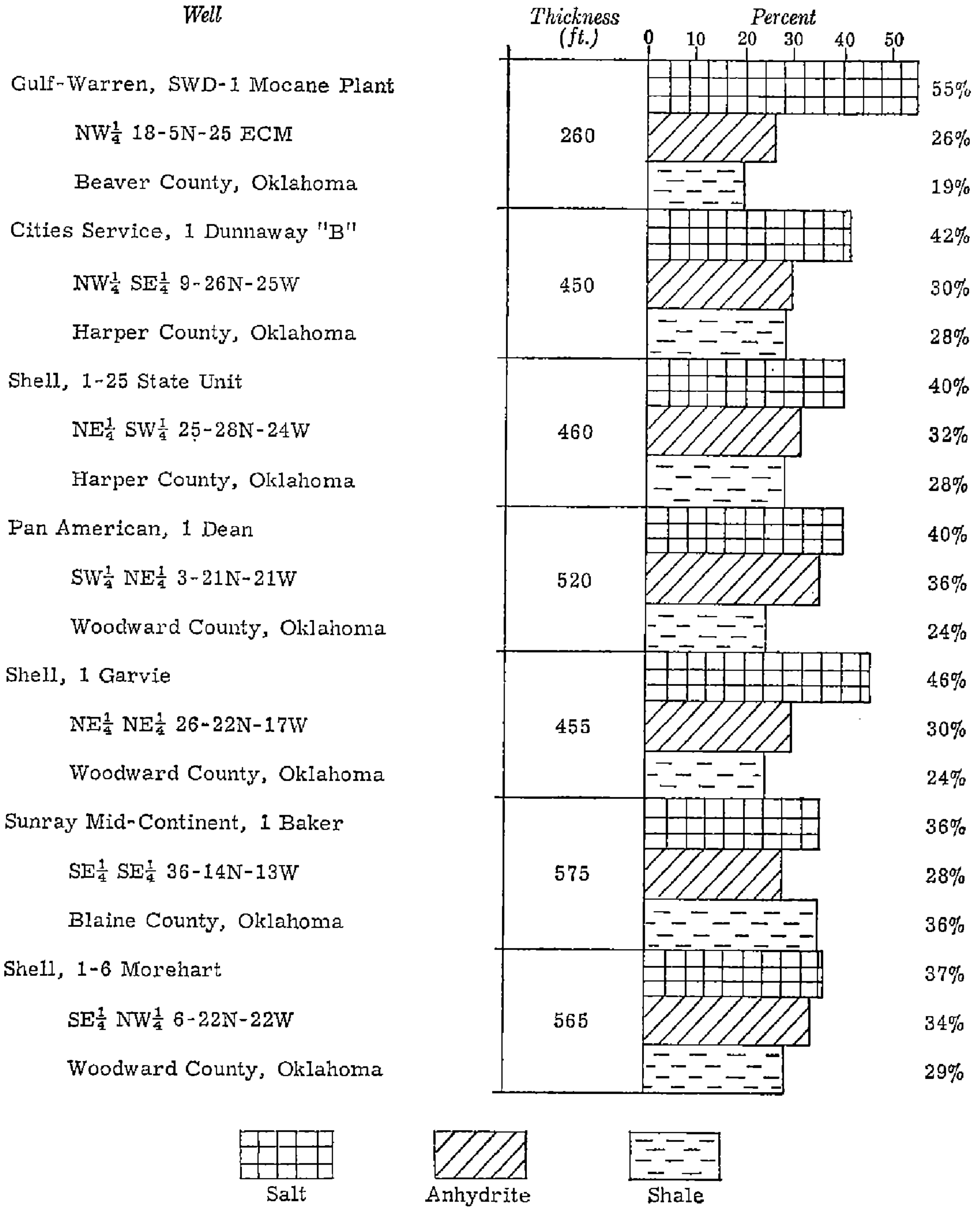

Figure 7. Chart showing the thicknesses of the salt-bearing section of the Wellington evaporites in representative wells. Histograms indicate the percentage of salt, anhydrite, and shale calculated from sonic or caliper logs.

stitutes 49 percent of the thickness, shale 46 percent, and anhydrite 5 percent.

The upper half of the Lower salt-anhydrite unit contains the salt-bearing beds assigned to the Wellington evaporites. Part or all of these salt-bearing strata are equivalent stratigraphically to the Hutchinson Salt Member of the Wellington Formation in Kansas. The salt normally represents 40 to 50 percent of the salt-bearing sequence, anhydrite and shale representing the remainder (fig. 7). Toward the eastern edge of the area, the shale is equal in amount (36 percent) to the anhydrite. Westward, anhydrite beds are more numerous and thicken at the expense of the shales.

In the southern part of the area, the thickness and number of salt strata within the presumed salt-bearing section of the Lower salt-anhydrite unit are unknown. The most southerly well in which beds could be identified as salt layers is the Sunray Mid-Continent 1 Baker, sec. 36, T. 14 N., R. 13 W. In the entire area west and south of this well, no definitive electrical surveys of wells for separation of salt and anhydrite were obtained.

Shale Unit

Nomenclature and stratigraphic relations—The base of the middle shale unit of the Wellington evaporites is marked on electrical logs by a resistivity increase at the top of the Lower salt-anhydrite unit. The selection of the top of the unit is somewhat arbitrary, but is made at the base of a zone in which the anhydrite beds are markedly more evident than the extremely thin beds of anhydrite and dolomite within the Shale unit itself. The top can be recognized and correlated locally as a time-stratigraphic level, but time-stratigraphic correlation is not possible on a regional basis.

Distribution—This middle unit of the Wellington evaporites has been recognized everywhere within the area, but on both the eastern and western edges of the area recognition is locally difficult.

Character and thickness—Beds of gray, gray-green, and mottled maroon-green shales predominate, although the sequence is broken by thin stringers of anhydrite and dolomite, which may be found in samples and appear as low resistivity peaks on electrical logs. The peaks are negative in character where the thickness of the anhydrite or dolomite stringer is appreciably less than the electrode spacing, and are absent if the thickness is equal to spacing.

The Shale unit has a uniform thickness of about 200 to 250 feet throughout most of the area. As much as 330 feet of strata is present (pl. II, cross section B-B′) in the axis of the Anadarko basin, owing to the addition of beds near the base of the unit. A slight increase in thickness is present in the southeastern part of the area. This increase is due to the gradation into shale of some of the upper beds of the Lower salt-anhydrite unit, and also to the absence of some of the anhydrite beds near the base of the overlying Upper anhydrite unit (pl. II, cross section C-C′).

The thin anhydrite and dolomite beds, generally present, increase in thickness and number westward. As a result, separation of the Upper anhydrite unit and the Shale unit is locally arbitrary.

Upper Anhydrite Unit

Nomenclature and stratigraphic relations—The base of the Upper anhydrite unit is established at the base of a zone of anhydrite and shale overlying the Shale unit, marked by an abrupt decrease in the amount of anhydrite. The top of the Upper anhydrite unit marks the top of the Wellington evaporites. The abrupt increase in resistivity at the top of this unit is a striking feature on electrical logs in this part of the Permian sequence, and it marks the uppermost anhydrite or dolomite. Normally the unit is overlain by not more than 50 feet of gray shale, which is included in the Wellington Formation of the surface. The top of the unit has been referred to by many subsurface geologists of Oklahoma as the "First Anhydrite," or "Upper Anhydrite." The upper beds of this anhydrite unit are called the "Panhandle lime" in the subsurface of the Texas Panhandle.

Distribution—The Upper anhydrite unit is present everywhere except in the extreme eastern and southeastern parts of the region. In these areas the unit is difficult to recognize and is projected by correlation from the west.

Character and thickness—The Upper anhydrite unit of the Wellington evaporites consists of interbedded anhydrite, dolomite, and gray shale. At few places does the unit contain more than 30 percent anhydrite and dolomite, and it normally contains less than 20 percent. Eastward the unit thins by loss of anhydrite and dolomite beds. As indicated by electrical logs, the unit is absent in western Caddo and Blaine Counties. To the north some evidence of its presence is recognizable as far east as western Garfield and Major Counties (pl. II, cross sections A-A′ and A-D).

The thickness of the Upper anhydrite unit normally ranges from slightly less than 100 feet up to 150 feet. Even thicker sections, as much as 250 feet, are present within the deeper parts of the Anadarko basin (pl. II, cross section A-D). The thinner sections are in the extreme eastern and southeastern parts of the area (pl. II, cross sections A-A′, A-D, and C-C′) where thin anhydrite and dolomite beds grade to shale both at the top and at the base of the unit.

HENNESSEY SHALES

Nomenclature and stratigraphic relations—The term "Hennessey shales," as used herein, includes all beds lying above the uppermost thin anhydrite or dolomite assigned to the Wellington evaporites and below the lowermost bed of salt assigned to the overlying Lower Cimarron salt. This is the normal relationship over most of the region, but toward the eastern margin, where the Cimarron salts are missing, the Hennessey shales are in contact with the overlying Flowerpot Shale. The contact between the Flowerpot Shale above and the Hennessey Shale below cannot be established in the subsurface from electrical logs. Where the Hennessey and Flowerpot shales are in contact they have been designated the Flowerpot-Hennessey shales. In this region it is probable that all strata referred to as Cimarron evaporites are wholly or largely equivalent to the Hennessey Shale.

A thin section of gray, mottled gray-green and red or maroon shale directly overlies the Upper anhydrite unit of the Wellington evaporites. These beds, characterized by the presence of gray shale, are normally assigned to the Wellington Formation of the surface. The top of this zone has been called "Base of the Red" in the subsurface by Aurin (1917), Clifton (1926a, 1926b), and others.

Above this gray zone are red and red-green shales called "Red Cave" in the subsurface of the Panhandle of Texas. These beds are considered to be equivalent to some part of the Garber Sandstone and Hennessey Shale which crop out five to thirty miles east of the mapped area in central Oklahoma. Stratigraphically these beds have been distinguished from the gray shales of the Wellington Formation below on the basis of surface mapping and to some extent by study of subsurface samples. The character recorded by electrical logging techniques shows no significant difference between red, green, and gray shale. For this reason, the gray shales of the Wellington Formation are considered and illustrated (pl. II) as part of the Hennessey shales.

Distribution—Hennessey shales are present in all parts of the mapped area. They can be recognized everywhere in the subsurface except along the eastern margin where the Cimarron evaporites, as shown by electrical logs, are absent. As indicated in figure 3, the Cimarron evaporites are probably equivalent to the upper part of the Hennessey shales. The stratigraphic position of the Cimarron evaporites is not clearly established, because the contact between the Hennessey and Flowerpot shales cannot be determined in the subsurface.

Character and thickness—As mentioned above, these beds are a mixture of red and red-green shales except for a thin zone of gray shale (assigned to the Wellington Formation on the surface) at the base. Locally, thin stringers of anhydrite or dolomite appear as resistivity peaks on electrical logs. In the Panhandle field of Texas some commercial oil and gas is produced from thin sandstones or siltstones within the unit. These wells require some type of fracturing treatment for commercial production.

In the area investigated the thickness of the Hennessey shale unit in its normal development ranges from 270 feet to 705 feet. In a general way the thinner sections are in northern Oklahoma and the thicker sections are in that part of the Anadarko basin lying just north of the Wichita Mountains. In northern Oklahoma the thickness ranges from a minimum of 270 feet in central Beaver County, to a maximum of 500 feet in southwestern Woods County. The average thickness in the northern part of the area is approximately 400 feet (pl. II, cross section A-A′). The average thickness is similar in the northern Texas Panhandle (pl. II, cross section A-D), thickening to 550 feet in the axis of the Anadarko basin just west of the Oklahoma-Texas boundary (T. 11 N.) in Wheeler County, Texas. Thicknesses in Oklahoma reach a maximum of 705 feet (pl. II, cross section A-D, well 18) in northeastern Beckham County. East of central Washita County, the Hennessey and Flowerpot shales cannot be separated. Here the Cimarron evaporites, which normally serve to divide this thick shale sequence (pl. II, cross section C-C′), are absent. A similar absence of the Cimarron evaporites east of central Alfalfa County makes these beds inseparable.

CIMARRON EVAPORITES

Nomenclature and stratigraphic relations—The term "Cimarron evaporites" is here proposed for the subsurface sequence of salt and anhydrite which occurs between the Wellington and Beckham evaporites. As here used, the Cimarron evaporites consist of an upper and lower unit of salt separated by a middle unit of anhydrite, and these divisions are termed Lower Cimarron salt, Cimarron anhydrite, and Upper Cimarron salt (fig. 8). The name is taken from the middle anhydrite, a subsurface unit widely used and called Cimarron anhydrite in the Texas and Oklahoma Panhandles and in Kansas many years before it was traced into the outcrops of the Stone Corral Dolomite in central Kansas (Norton, 1939, p. 1777). The Cimarron anhydrite is a highly useful bed in subsurface because over a wide area it is the only marker in a thick sequence of red shales and sandstone below the Blaine and above the Wellington. The name probably originated from its position in the lower part of the Cimarron series, as the term was used by Cragin (1896).

In Oklahoma, the evaporites grade updip, eastward, into outcropping red shales and sandstones. The best correlation indicates that the Cimarron evaporites, in their full development, are equivalent to the middle and upper parts of the Hennessey Shale, including the Cedar Hills Sandstone Member (fig. 3). The lower part of the Hennessey Shale of the outcrop persists in subsurface, and everywhere underlies the Cimarron evaporites. Above the upper salt, at the top of the evaporite sequence, is the Flowerpot Shale.

Distribution—The Cimarron evaporites underlie all but the eastern and southeastern parts of the area (pl. III, map D). The limit is shown on map D as a line parallel to the Wichita Mountains, trending northeast across the northwestern corner of Washita County to southern Blaine County, and there swinging northward to central Alfalfa County, Oklahoma, and eastern Barber County (R. 11 W.), Kansas. Over most of the area both salt units are present, but the Upper Cimarron salt is absent in most of Harper, Woods, and Alfalfa Counties at the north and in southwestern Major County. The lower salt unit does not extend into the eastern parts of Custer and Dewey Counties. Where the Upper Cimarron salt is absent, the overlying shales are assigned a Hennessey age.

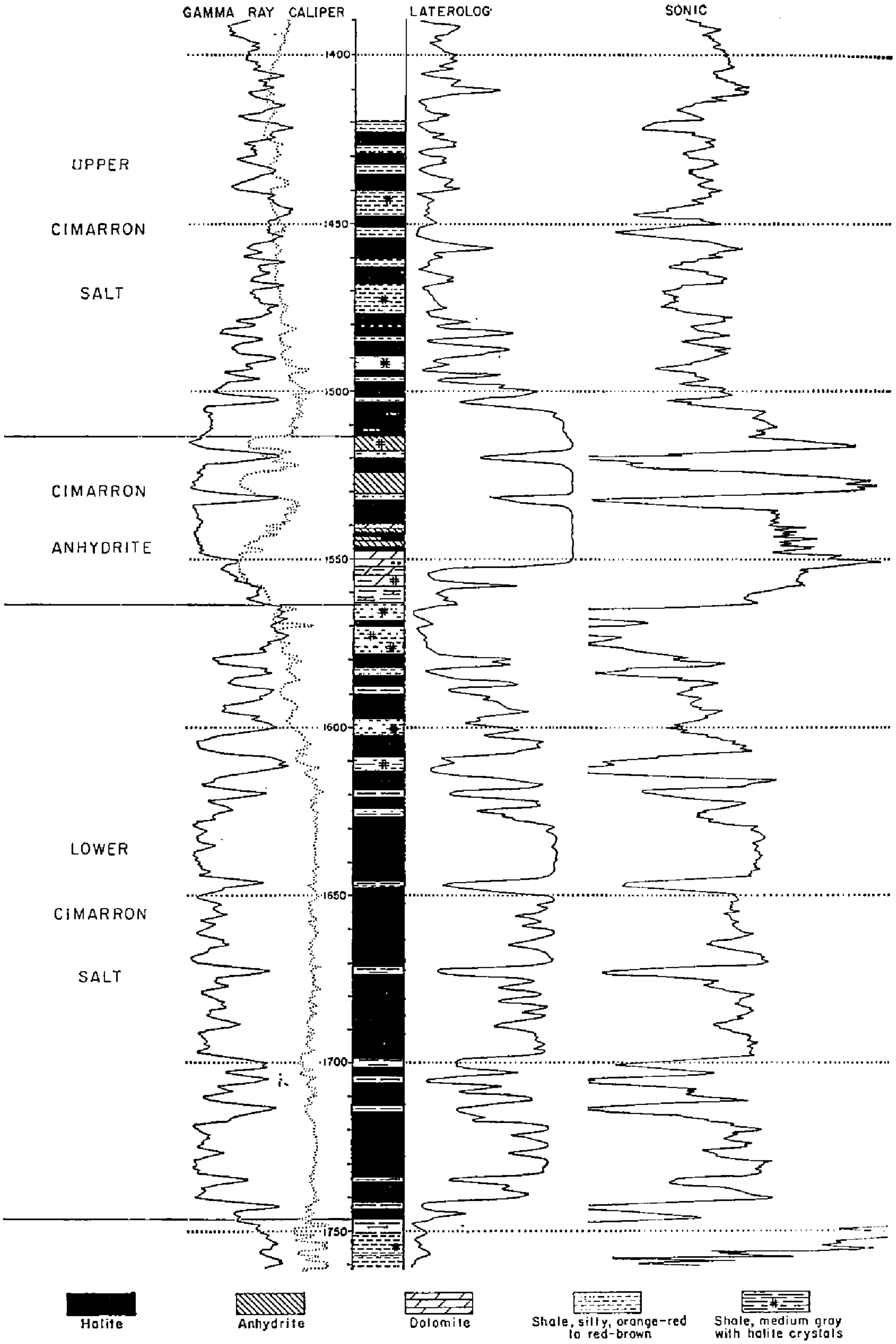

Figure 8. Cimarron evaporites, consisting of Upper Cimarron salt, Cimarron anhydrite, and Lower Cimarron salt in the Gulf-Warren SWD-1 Mocane Plant, sec. 18, T. 5 N., R. 25 ECM., Beaver County, Oklahoma, as shown by gamma-ray, caliper, laterolog, and sonic logs, and continuous cores (from Jordan, 1962a, p. 25). Top of Cimarron evaporites is at 1,330 feet.

Character and thickness—Salt is the dominant rock in the Cimarron evaporites. Within the salt is the thin persistent anhydrite-dolomite unit termed the Cimarron anhydrite. Immediately below the Cimarron anhydrite is a thin silty shale separating the anhydrite from the Lower Cimarron salt below. The salt above the Cimarron anhydrite (Upper Cimarron salt) contains a high percentage of shale, whereas the Lower Cimarron salt is relatively pure. Each salt unit locally contains a minor amount of anhydrite in the form of thin discontinuous stringers.

The maximum thickness of the Cimarron evaporites is in Beckham and Roger Mills Counties, Oklahoma, and in the Texas Panhandle at the corner common to Wheeler, Gray, Roberts, and Hemphill Counties (pl. III, map D), where the salt-bearing strata are more than 1,000 feet thick. In those areas of most dense control it can be shown that the Cimarron evaporite thickness varies directly with the thickness of salt. The area of thinnest Cimarron which contains both Upper and Lower Cimarron salts occurs in northwestern Beaver County, where the unit is 200 feet thick. Similar thin areas are present to the north and northeast, but here only one or the other of the salt units is normally present (pl. III, map D). In general, most of the variation in the thickness of the Cimarron evaporites occurs in the Upper Cimarron salt, whereas the Lower Cimarron salt displays a general thickening trend into the Anadarko basin (pl. II). Depth to top of salt beds ranges from a minimum of 215 feet in the northeast to a maximum of 2,420 feet southwest of Elk City (pl III, map D).

Subdivisions—The Cimarron evaporites are divided in subsurface into three units (fig. 8). The lowermost unit, Lower Cimarron salt, lies directly above Hennessey shales. The middle unit is the Cimarron anhydrite, which separates the Lower Cimarron salt from the uppermost unit or Upper Cimarron salt.

Lower Cimarron Salt

Nomenclature and stratigraphic relations—Kulstad (1959, p. 241) mentioned "Cimarron salts" in the Hugoton embayment, but the term "Lower Cimarron salt" was first used in the literature by Jordan (1962a, p. 25) in discussing the liquefied-petroleum-gas storage in the Mocane area, Beaver County, Oklahoma. The Lower Cimarron salt lies directly above the Hennessey shales and is separated from the overlying Cimarron anhydrite in most places by a thin silty shale.

Distribution—The geographic extent of the Lower Cimarron salt is shown on plate III, map D. The southeastern and eastern limits extend along a line through western Washita County, across west-central Custer County and east-central Dewey County. From east-central Dewey County, the trend swings northeastward across Major County, into the southwestern part of Alfalfa County. The boundary turns northward and extends through central Alfalfa County, trending northwest through T. 29 N., R. 12 W., into Kansas.

Character and thickness—The Lower Cimarron salt is 170 feet thick in southwestern Beaver County and thickens gradually into the Anadarko basin, reaching a maximum of about 450 feet in northeast-central Wheeler County, Texas, and about 435 feet in northern Beckham and southern Roger Mills Counties, Oklahoma (pl II, cross section A-D). A Cimarron evaporite section (fig. 8) is shown by logs of the Gulf-Warren salt-water-disposal well in SE¼ SW¼ SE¼ NW¼ sec. 18, T. 5 N., R. 25 ECM., Beaver County. Jordan (1962a, p. 23) gave the following description of the Lower Cimarron salt from continuous cores taken from this well:

> The formation [Cimarron anhydrite] is underlain by 280 feet of halite with relatively few interbeds of reddish-brown or greenish-gray shale. Much of the salt is colorless and coarse crystalline, but at places the clay between crystals gives a gray appearance in contrast to the reddish-brown appearance of the salt above the Cimarron anhydrite. Orange-red fibrous halite occurs as veins in shale in both sections.

Estimations based upon the logs shown in figure 8 indicate that the Lower Cimarron salt is 78 percent halite and 22 percent shale. Anhydrite beds are absent.

Another log (fig. 9) from the Cities Service 1 Dunnaway "B", NW¼ SE¼ sec. 9, T. 26 N., R. 25 W., Harper County, Oklahoma, shows only the Lower Cimarron salt. The top of the salt is at a depth of 1,246 feet and its thickness is 230 feet. Estimated proportions are 69 percent salt and 31 percent shale.

In the northern part of the area the Lower Cimarron salt reaches a maximum thickness of 440 feet in Harper County, Oklahoma. It thins gradually eastward, becoming more shaly, and loses its identity in western Alfalfa County (pl. II, cross section A-A′). South of Harper County, the section is approximately 435 feet thick in the axis of the Anadarko basin in southern Roger Mills and northern

Beckham Counties (pl. II, cross section B-B′). Similar thick sections are found north of the Amarillo uplift in Wheeler County and southeastern Roberts County, Texas (pl. II, cross section A-D). Northward the unit thins to approximately 200 feet in northern Lipscomb and Ochiltree Counties, Texas, and to approximately 170 feet in southwestern Beaver County, Oklahoma.

Shale above the Lower Cimarron salt—At most places in the area, a thin zone of silty shale immediately overlies the uppermost salt stratum of the Lower Cimarron salt and is beneath the lowermost bed called Cimarron anhydrite (pl. I). These beds are orange red,

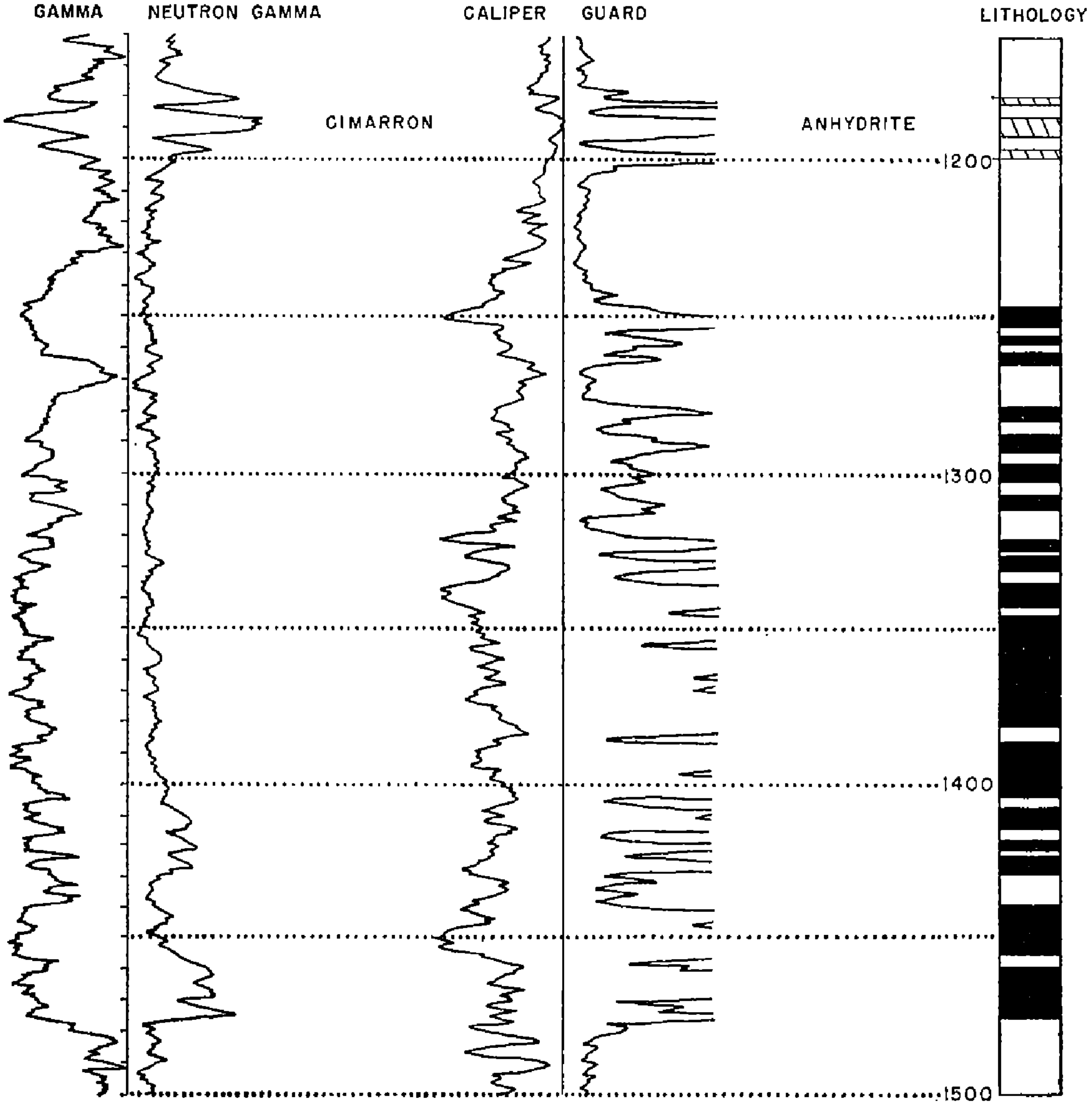

Figure 9. Cimarron anhydrite and Lower Cimarron salt as shown by logs of the Cities Service 1 Dunnaway "B," sec. 9, T. 26 N., R. 25 W., Harper County, Oklahoma (from Jordan, 1960, p. 25). In the lithologic column, solid black is salt, blank areas are shale, and diagonal ruling is anhydrite.

red, or reddish brown and gray. Locally coarse siltstone to very fine sandstone is present. The upper part contains thin discontinuous stringers of dolomite, dolomitic anhydrite, and anhydrite. The thickness is generally less than 50 feet.

Cimarron Anhydrite

Nomenclature and stratigraphic relations—The Cimarron anhydrite for many years has been a useful stratigraphic marker in the subsurface. This unit is considered (Lee and Merriam, 1954, p. 3) equivalent to the Stone Corral Formation of the surface, which, in Kansas, is above the Ninnescah Shale and below the Harper Siltstone (Jewett, 1959). The correlation of the subsurface "Cimarron anhydrite" with the Stone Corral at its type locality in Kansas was established in 1929 by W. L. Ainsworth (Norton, 1939, p. 1777). The unit does not crop out in Oklahoma, but can be traced into the subsurface Stone Corral of Kansas. The Cimarron anhydrite of the subsurface lies above the Lower Cimarron salt and below the Upper Cimarron salt.

Distribution—Examination of various types of logs shows the Cimarron anhydrite to be best developed in northwestern Oklahoma. Here, the typical section produces three resistivity peaks on electrical logs. These can be traced from western Beaver County, as far east as eastern Woodward and west-central Woods Counties (pl. II, cross section A-A′, wells 1-5). Southward from Beaver County, Oklahoma (pl. II, cross section A-D, wells 11-15), the resistivity character can be traced across the Panhandle of Texas into eastern Wheeler County, Texas. South from Harper County, Oklahoma (pl. II, cross section B-B′, wells 22-24), thinner beds with high resistivity persist only as far as central Ellis County. To the south and east the unit loses its distinctive character, and the resistivity peaks disappear one at a time. The stratigraphic position of the Cimarron anhydrite can be traced as a zone of indistinct character by subsurface correlation almost to the Wichita Mountains. To the east the zone is indistinct beyond western Alfalfa, eastern Dewey, and central Custer Counties, Oklahoma (pl. II).

Character and thickness—The average total thickness of the Cimarron anhydrite, which consists of anhydrite, salt, and dolomite, is approximately 40 feet. As much as 80 feet has been found locally, the increase being due largely to the presence of salt beds between the beds of anhydrite and dolomite. Some sample logs in the Panhandle of Texas show more than 150 feet of Cimarron anhydrite, and this thickness includes anhydrite beds which are probably equivalent to Lower Cimarron salt beds elsewhere.

Logs from the Gulf-Warren salt-water-disposal well at the Mocane Plant, SE¼ SW¼ SE¼ NW¼ sec. 18, T. 5 N., R. 25 ECM., Beaver County, are shown in figure 8. Jordan (1962a, p. 23) described the Cimarron anhydrite from continuous cores taken from this well as follows:

> It [Cimarron anhydrite] consists of two beds each of anhydrite near the top and dolomite at the base, each pair of beds being separated by halite and minor amounts of reddish-brown shale.... The upper medium-crystalline anhydrite contains crystals of halite, whereas the lower bed is very fine crystalline and banded. The halite strata are colorless and coarse crystalline, except for a two-foot section immediately below the upper anhydrite, which contains clear fibrous halite with a faint pink coloration. Halite just above the medium-gray very fine-crystalline dolomite is clear, colorless, and coarse crystalline. Part of the dolomite is finely oölitic.

The Cimarron anhydrite in the Gulf-Warren well is 50 feet thick. At this locality the Cimarron anhydrite contains beds of anhydrite and salt and a bed of dolomite at the base. Thirty miles to the southeast, the Cities Service 1 Dunnaway "B", NW¼ SE¼ sec. 9, T. 26 N., R. 25 W., Harper County, contains Cimarron anhydrite as three beds of anhydrite probably associated with dolomite and separated by shale (fig. 9). The section is 20 feet thick and occurs at a depth of 1,178 to 1,198 feet.

Upper Cimarron Salt

Nomenclature and stratigraphic relations—The term "Upper Cimarron salt" was first used in the literature by Jordan (1962a, p. 25, fig. 1). Using logs of the Gulf-Warren well, Jordan illustrated the electric-log characteristics of most of these beds (fig. 8, top of unit not shown). The base of the Upper Cimarron salt rests at this locality upon the uppermost bed of the Cimarron anhydrite, but overlies shales of the anhydrite zone where the anhydrite is missing. The top of the salt zone is difficult to establish in some areas because the beds become more shaly upward (pl. II). The top of the salt is placed at the base of the thickest nonsalty shale sequence above the Cimarron anhydrite and below the base of the Blaine anhydrite. This criterion, although not completely satisfactory, was found to be the most practical and workable. At places in the Texas Panhandle and in western Oklahoma, almost the entire sequence between the Cimarron anhydrite and the Blaine anhydrite contains salt (pl. II, cross section B-B′, well 27; cross section A-D, well 14). Commercial sample logs from wells in this western area show a zone of thin fine-grained siltstones and sandstones lying in approximately the same stratigraphic position as the nonsalty shales to the east. The base of this sandy zone marks the top of the Upper Cimarron salt where that salt is present.

Distribution—The extent of the Upper Cimarron salt is shown on Plate III, map D. It is present in the mapped area of the Texas and Oklahoma Panhandles, in Ellis, Woodward, Roger Mills, and Beckham Counties and in the western part of Dewey County, but is absent in most of Harper, Woods, and Alfalfa Counties in the north, and in much of Major, Blaine, and Washita Counties to the east and south.

Character and thickness—Jordan (1962a, p. 23) gave the following brief description from continuous cores (fig. 8) taken from Gulf-Warren's salt-water-disposal well at the Mocane Plant, SE¼ SW¼ SE¼ NW¼ sec. 18, T. 5 N., R. 25 ECM., Beaver County, Oklahoma:

> A 184-foot section of interbedded and intermingled coarse-crystalline halite and reddish-brown shale, from 1,330 to 1,514 feet, rests upon the Cimarron anhydrite. For the most part the halite contains clay that imparts an overall dull reddish-brown appearance.

Approximately one-third of the 184-foot section contains beds, one to three feet thick, which are primarily salt. The remainder of the section is primarily shale and salty shale. This section is typical of Beaver County (pl. II, wells 1, 2), and of the Texas Panhandle (pl. II, wells 11-15). Elsewhere, primarily salty shale is present in the section. The percentage of salt found within the salt-bearing section decreases as the unit thickens eastward. The thickening of the unit is due not to greater salt deposition but to greater deposition of shale.

FLOWERPOT SHALE AND FLOWERPOT-HENNESSEY SHALES

The Flowerpot Shale is a surface term, referring to shale and siltstone strata lying below the Blaine Formation and above the Cedar Hills Sandstone or Duncan Sandstone (figs. 2, 3). As this sequence is traced into the subsurface, the underlying clastic beds disappear, so that Flowerpot Shale is in contact with Hennessey Shale. This contact cannot be traced with confidence in the subsurface; thus the stratigraphic position of these strata in terms of surface nomenclature is obscure, and for purposes of this report the beds are referred to as the Flowerpot-Hennessey shales (pl. I).

The nonsalty strata above the Upper Cimarron salt and below the lowermost beds of Flowerpot salt are a facies of the salt-bearing section. As mentioned above, establishment of the nonsalty unit to separate Cimarron salt from Flowerpot salt is arbitrary at some places. In the Panhandle of Texas, a sandy zone represents the dividing strata, whereas over most of the mapped area, the zone of nonsalty shale separates the Upper Cimarron salt from Flowerpot salt. The relationship of this nonsalty unit to units of surface nomenclature is obscure. These beds are probably equivalent in most places to the upper part of the Hennessey Shale. However, the overlying Flowerpot salt is thin in some places, and the unit could be equivalent to the Flowerpot Shale.

Around the edges of the Anadarko basin, local clastic units are recognized on the surface. These include the Cedar Hills Sandstone in the northeast and the Duncan-Chickasha Formations in the south. Shale beds equivalent to these clastic units may be present within the interval referred to here as Flowerpot-Hennessey shales, which separate the Upper Cimarron salt below from the Flowerpot salt above.

The Flowerpot-Hennessey shales reach a maximum thickness of 400 feet in the north and northwestern parts of the area (pl. II, cross sections A-A′, A-D, and B-B′). South of Beaver County, Oklahoma, in central and southern Ochiltree County, Texas, as little as 100 feet is present. Within the axis of the Anadarko basin, thicknesses from 200 to 300 feet are present. Eastward, the unit loses its identity as the salt-bearing sections grade to shale (pl. I).

Where the salt is absent the section is represented by a sequence of red shales and red fine-grained siltstone broken by thin stringers of anhydrite and dolomite. Locally, this section contains beds of fine-grained red silty sandstone and reddish-brown, maroon, and green shales. The sequence extends from the uppermost anhydrite bed of the Wellington evaporites upward to the base of the Blaine anhydrite, or to the surface if the Blaine beds are absent. Where the Lower Cimarron salt, Upper Cimarron salt, and Flowerpot salt are missing, the thickness of clastic strata from the top of the Wellington evaporites to the base of the Blaine anhydrite is approximately 2,100 feet.

Mappable clastic units, such as Garber Sandstone and others mentioned previously, have been traced into the subsurface, from their areas of outcrop around the edges of the Anadarko basin, by the use of samples and electrical logs. The correlation of these clastic facies has normally been limited to local areas and has been of questionable success on a regional basis. Adkison (1960) correlated samples from rotary drilling along with electrical logs from Caddo County, Oklahoma, to Barber County, Kansas. He illustrated the sandy clastic units, then correlated them with dashed lines for limited distances and at many places combined them with other units, using compound names.

BECKHAM EVAPORITES

Nomenclature and stratigraphic relations—The term "Beckham evaporites" is here proposed for that subsurface sequence of salt and anhydrite which occurs next above the Cimarron evaporites and is overlain by the Dog Creek Shale. The name is taken from Beckham County, Oklahoma, where the maximum thickness of 700 feet is attained. As in the case of the Cimarron evaporites, the Beckham evaporites consist of an upper and a lower unit of salt separated by a medial unit of anhydrite (pl. II, wells 15-18; fig. 13), and these divisions are named Flowerpot salt, Blaine anhydrite, and Yelton salt (ascending order). Both the Flowerpot salt and the Blaine anhydrite are widely present within the Anadarko basin and occur also beyond it to the southwest, but the Yelton salt is localized in the axial part of the basin, just north of the Wichita-Amarillo uplift. The Blaine anyhdrite is especially persistent in subsurface as well as on the outcrop, and the base of this unit is a valuable datum that has been used for all cross sections in this report.

Distribution—The complete section of Beckham evaporites is present in the south-central part of the area, in Beckham and Washita Counties, Oklahoma, and in part of Wheeler County, Texas. Beyond this area, the salt above the Blaine anhydrite, herein named the Yelton salt, is missing (pl. III, map E). The Blaine anhydrite can be recognized in subsurface everywhere between its two lines of outcrop on the northeastern and southern margins of the Anadarko basin, except in the extreme southeastern part of the area. The Flowerpot salt is present generally in the area west of R. 18 W., except for the area between the Canadian and Cimarron Rivers, where the eastern limit is approximately R. 23 W. (pl. III, map C).

Character and thickness—The Beckham evaporites consist mostly of salt, salty shale, and anhydrite. Locally in the west some sandstone is present within or immediately below the Blaine anhydrite. Minor amounts of nonsalty shale are present within the Flowerpot salt.

In the northern part of the area, where the Yelton salt is absent, the thickness of the Beckham evaporites is from 170 feet in Woodward County to 580 feet in Harper County. In Beckham County, Oklahoma, and Wheeler County, Texas, where all units of the Beckham evaporites are present, the thickness reaches a maximum of 700 feet.

Subdivisions—The Beckham evaporites consist, in ascending order, of the Flowerpot salt, Blaine anhydrite, and Yelton salt. These units can readily be established from electrical and radioactive logs.

Flowerpot Salt

Nomenclature and stratigraphic relations—The term "Flowerpot salt" refers to beds of salt and salty shale which occupy the stratigraphic position of the Flowerpot Shale as defined on the surface. This unit was clearly illustrated by Greene (1926, p. 13) as lying immediately below the Blaine Gypsum, but Greene applied no name. Locally the salt may represent beds older than Flowerpot Shale, but this age assignment has not been definitely established. The salt is underlain by shales and siltstones of Flowerpot or Flowerpot-Hennessey age. Overlying the Flowerpot salt is the Blaine anhydrite.

Distribution—The known extent of the Flowerpot salt is shown on plate III, map C. The unit is generally present in the western half of the area. In the south, the Flowerpot salt is present as far east as eastern Custer County, whereas in the north it extends eastward as far as western Woods County. In the central part of the area the Flowerpot salt is absent in all but the northern part of Woodward County and parts of eastern Ellis County. In Beaver and Harper Counties, the salt is locally absent (pl. III, map D).

Character and thickness—The Flowerpot salt normally consists of salty shale near the base and of relatively pure salt near the top. Locally in Harper and Ellis Counties, as much as 100 feet of nonsalty shale lies below the base of the Blaine anhydrite and above the purer salt beds (pl. II, cross section B-B′). In southern Ellis County two salt zones are present (pl. II, cross section B-B′, well 26), sep-

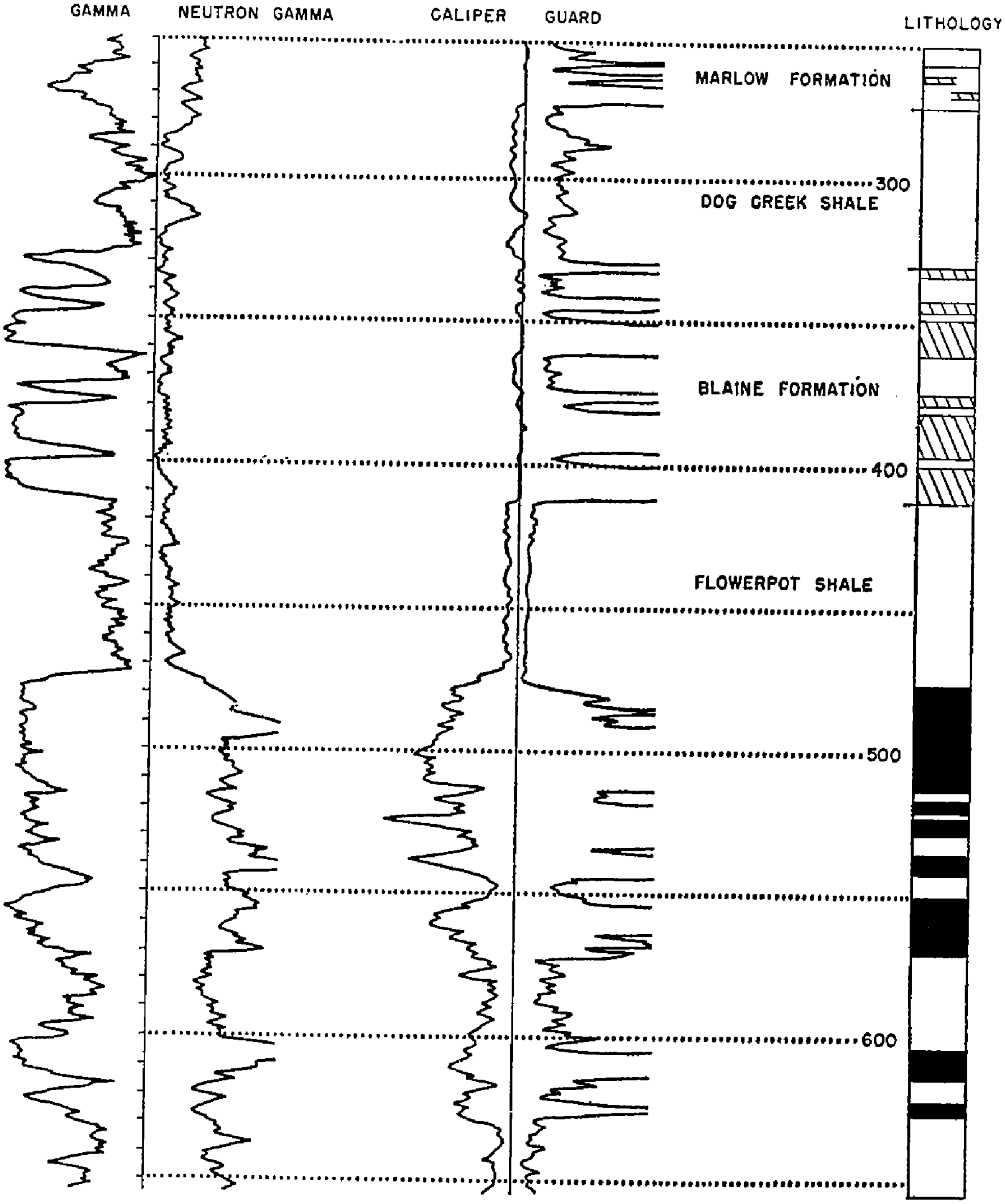

Figure 10. Gypsum strata in the Blaine Formation (Blaine anhydrite of this report) and salt beds in the Flowerpot Shale (Flowerpot salt of this report) of the Beckham evaporites, as shown by logs of the Cities Service 1 Dunnaway "B," sec. 9, T. 26 N., R. 25 W., Harper County, Oklahoma (from Jordan, 1960, p. 24). In the lithologic column, solid black is salt, blank areas are shale, and diagonal ruling is gypsum.

arated by salty shale. Directly below the Blaine anhydrite in the Panhandle of Texas is a thin sandstone, at most places less than 20 feet thick. This bed has been recognized only in Texas, where it is recorded on sample logs as the Glorieta Sandstone.

The thickness of the Flowerpot salt is variable throughout the area (pl. III, map C). Locally, in the Texas Panhandle and north-central Beaver County, Oklahoma, the thickness is more than 500 feet. Less than four miles east of this thick Flowerpot salt section in Beaver County, the salt is absent, having been removed by solution as suggested by the 300-400 feet decrease in elevation of the overlying Blaine (pl. III, map A). The average thickness of the Flowerpot salt is 200 to 250 feet, except near the edges of the area, as shown on plate III, map C.

Logs (fig. 10) of the Flowerpot section in the Cities Service 1 Dunnaway "B" in NW¼ SE¼ sec. 9, T. 26 N., R. 25 W., Harper County, show 60 feet of Flowerpot Shale immediately below the Blaine anhydrite. Beneath this shale a 150-foot section contains salt, the upper 95 feet being 81 percent salt.

Another section showing Flowerpot salt (fig. 11), from the Texaco Inc. et al. 1 Lehman, liquefied-petroleum-gas storage well in SW¼ SE¼ sec. 30, T. 1 N., R. 20 ECM., Beaver County, is illustrated by the gamma-ray log of the Blaine anhydrite and Flowerpot salt section. The following description of the cored section (Jordan, 1961a, p. 34) was obtained from geologist L. E. Case.

> Gray shale occurs both above the basal anhydrite [Blaine anhydrite] stratum and in the underlying Flowerpot. A six-inch bed of fine-grained gray sandstone is noted at 780 feet within the Blaine anhydrite. A similar thickness of siltstone and sandstone is present in the 26 feet of Flowerpot shale which overlies the salt. Relatively pure pink salt occurs from 866 to 888 feet and from 894 to 1,030 feet, but some beds of shale, none more than two inches thick, are present. The lowermost 68 feet of section contains salt with a shale content ranging from 10 to 60 percent.

The Flowerpot salt is abnormally thick in east-central Custer County (fig. 12). Figure 12 shows the laterolog and gamma-ray log of the Gulf Oil Corp. 1 Burgtorf in SE¼ NW¼ sec. 6, T. 13 N., R. 15 W. The well has 625 feet of section below the Blaine anhydrite which is interpreted as salt and salty shale, although no sonic or caliper logs are available, and other supplementary control is lacking. This interpretation, confirmed by E. W. Sengel of Schlumberger Well Surveying Corp., is compatible with the section as it

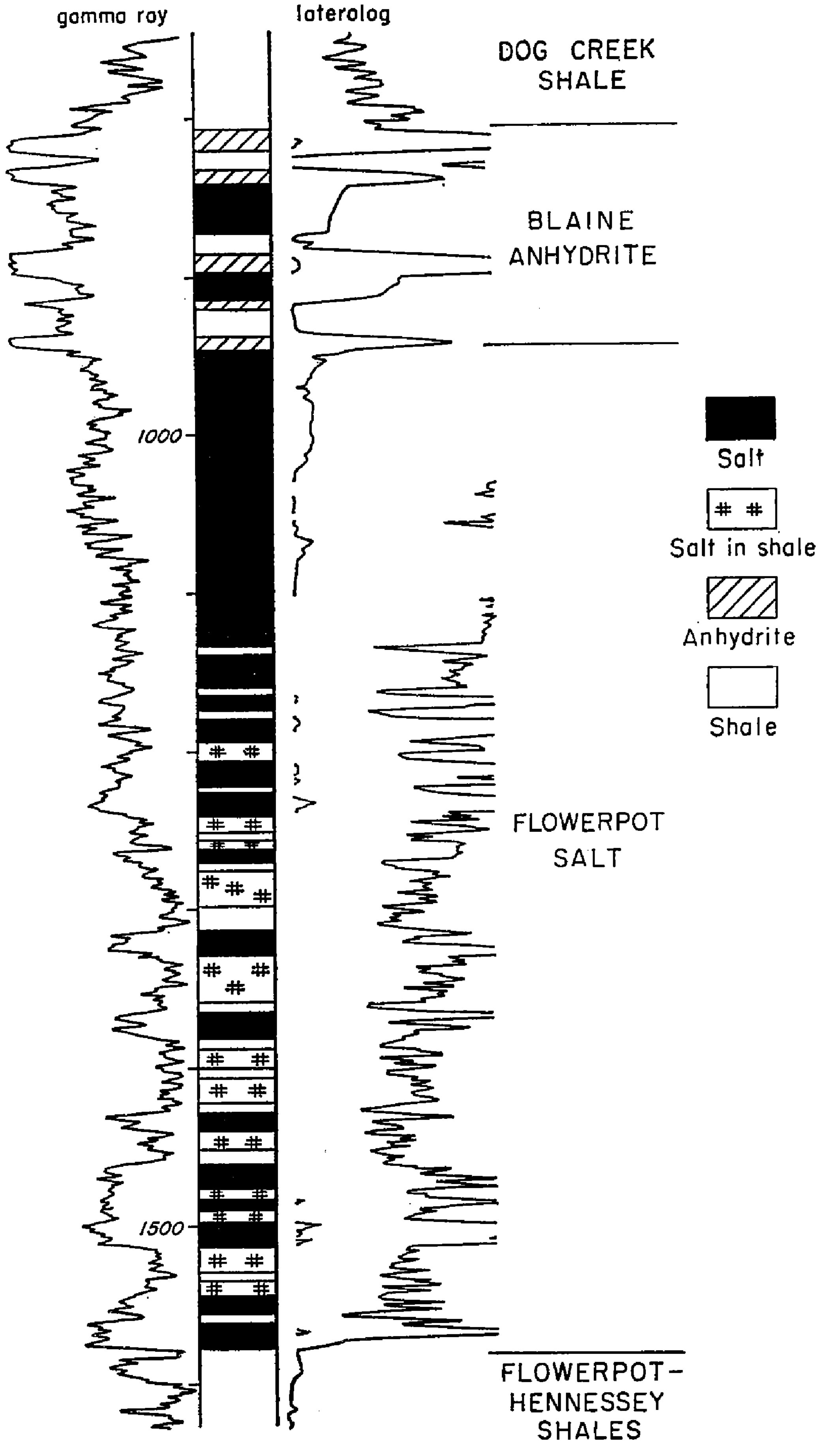

Figure 12. Blaine anhydrite and Flowerpot salt of the Beckham evaporites, as interpreted from logs of the Gulf Oil Corporation 1 Burgtorf, sec. 6, T. 13 N., R. 15 W., Custer County, Oklahoma, showing 625 feet of salt-bearing section.

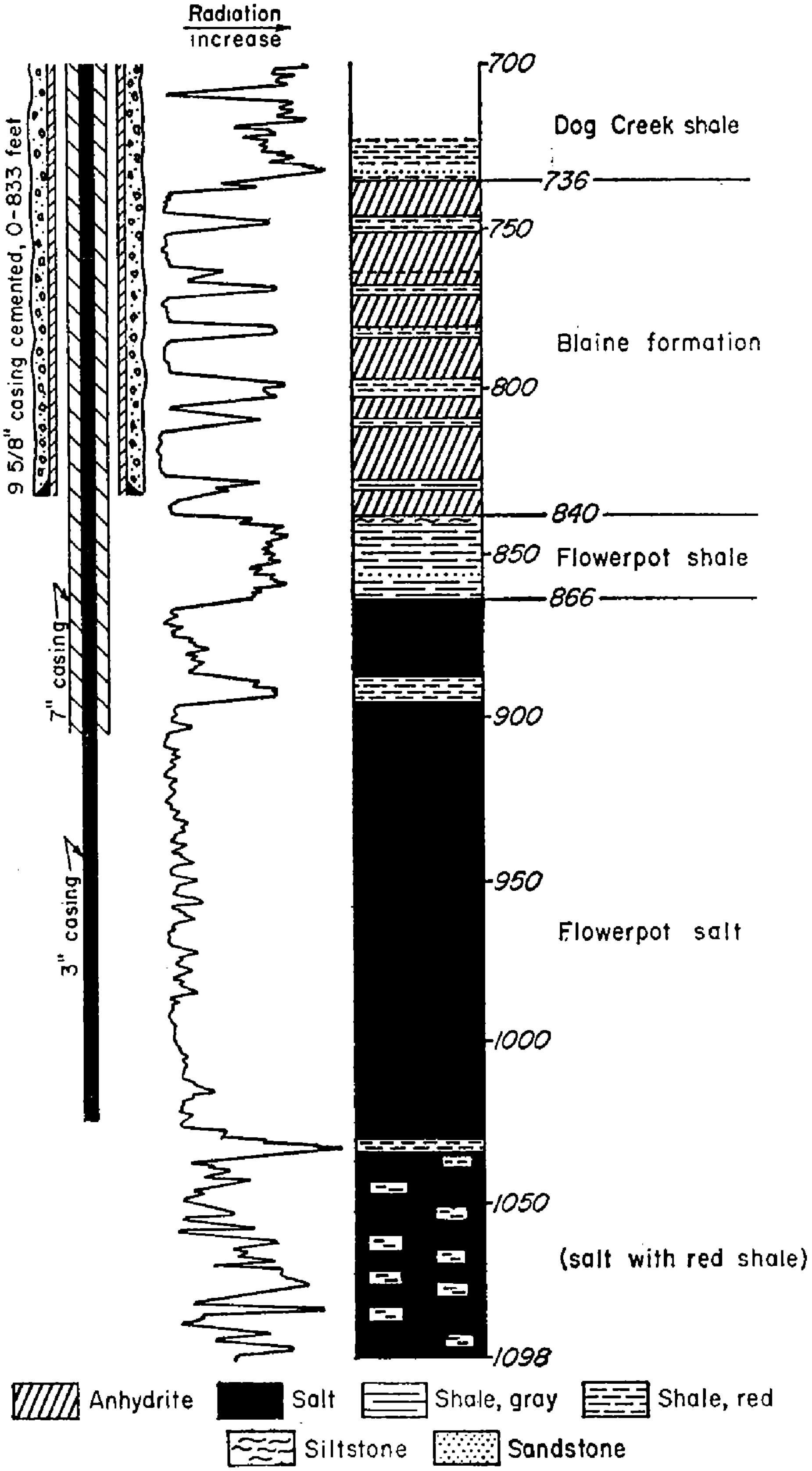

Figure 11. Blaine anhydrite and Flowerpot salt of the Beckham evaporites, as shown by logs of the Texaco Inc. et al. 1 Lehman, LPG-storage well, sec. 30, T. 1 N., R. 20 ECM., in southwestern Beaver County, Oklahoma (from Jordan, 1961a, p. 35). At left is the casing program used in the construction of the LPG-storage facility.

is understood. Similar thickness of salt might be found elsewhere in the Anadarko basin in those areas where information is lacking.

Flowerpot salt is present within 30 feet of the surface at the Big Salt Plain (T. 27 N., R. 19 W.) on the Cimarron River between Woods and Woodward Counties (Ward, 1961b, p. 275). The discovery of near-surface salt came as the result of shallow core drilling by the U. S. Army Corps of Engineers. Salt was encountered from 30 to 175 feet below the surface in 19 test holes. Ward stated that none of the holes penetrated all of the salt, but gave the following description of the salt-bearing zone:

> The upper part of the 91-foot zone contains more shale than salt, but 80 percent or more of the lower 57 feet is salt. Most of the salt is bedded crystalline halite, but a minor amount occurs as a fibrous material filling vertical and near-vertical cracks in the shale. A considerable part of the halite is colorless, but much of it contains included shale and clay that impart an overall dull reddish-brown appearance. The shale beds of the Flowerpot are silty, gypsiferous, and blocky. Generally they are reddish-brown but may be mottled or interbedded with greenish-gray beds. The formation is characterized by intersecting veins of colorless or orange-red selenite. Some gypsum occurs in the Flowerpot as thin impure beds, and some occurs as nodules.

Blaine Anhydrite

Nomenclature and stratigraphic relations—The subsurface term "Blaine anhydrite" as used in this report is essentially synonymous with the Blaine Formation of surface usage. Along the northeastern margin of the Anadarko basin, as well as in the adjoining outcrop belt that extends from Blaine County to Woodward County, the Blaine consists of interbedded anhydrite (or gypsum), dolomite, and shale generally 100 feet thick (Myers, 1959, p. 32-33; Fay, 1962, p. 30; Fay, 1962, personal communication). This area contains the outcrops of the type locality in Blaine County.

In all other parts of the Anadarko basin, and in fact over most of the region, the Blaine contains additional anhydrite beds at the top, building up the evaporites generally to a thickness of at least 150 feet. This more common sequence is considered strictly equivalent to the Blaine Formation as the outcrops are classified in southwestern Oklahoma (Scott and Ham, 1957, p. 16-20; Ham, 1960; Johnson, K. S., 1962, personal communication), and because these beds are so closely related that they cannot be separated into two or more groups, they are here treated as a single unit. Thus according to the present interpretation the thicker sections of the Blaine anhydrite contain evaporite beds at the top which are not present at the type locality, these additional upper evaporites being represented at the type locality by fine clastic sediments in the lower part of the Dog Creek Shale.

The Dog Creek Shale lies above the Blaine in all outcrop exposures and in nearly all the subsurface of the Anadarko basin. Yelton salt, in part a facies of the Dog Creek Shale, occurs above the Blaine anhydrite in Beckham and Washita Counties, Oklahoma, and in Wheeler County, Texas. Below the Blaine is the Flowerpot Shale or nearly pure halite of the Flowerpot salt.

Distribution—As stated above, the Blaine anhydrite is present in the subsurface between the lines of outcrops shown on the Geologic Map of Oklahoma (Miser, 1954). To the southeast the Blaine anhydrite is absent in the subsurface as well as on the surface. Cross section c — c′ represents a southeastern line of wells in which Blaine anhydrite can be easily recognized. The anhydrite beds may be traced about 25 miles farther southeast of the line of section c — c′, into central Caddo County, where they pass into beds recognized as Chickasha Formation (K. S. Johnson, 1962, oral communication).

Character and thickness—The Blaine Formation has been described from surface exposures at numerous localities by many geologists. As a general summary the formation in the eastern outcrop belt, principally in Blaine, Major, Woodward, Harper, and Woods Counties, is about 100 feet thick, whereas in the outcrop belt on the south flank of the Anadarko basin, chiefly in Washita, Kiowa, and Beckham Counties, the Blaine Formation is normally 150 feet thick. The greater thickness on the southwest results mainly from addition of beds at the top. In both outcrop regions the Blaine consists of gypsum beds interstratified with shale, together with thin beds of dolomite.

Because of its widespread distribution and continuity, the Blaine has been extensively used as a datum for surface and subsurface mapping. Some uncertainty exists regarding the terminology and correlation of individual members and beds within the formation, but discussion of these problems is beyond the scope of this report.

In subsurface the Blaine normally consists of anhydrite and shale, and for the purposes of this report it is referred to as the Blaine anhydrite. It ranges in thickness from 80 to 250 feet, and contains in its thicker sections some beds of nearly pure rock salt.

In the shallow subsurface of Harper, Beaver, Woodward, Ellis, and Dewey Counties it is 80 to 100 feet thick and is much like the strata of the eastern outcrop belt. Gamma-ray logs from the Cities Service 1 Dunnaway "B" in Harper County (fig. 10) show six gypsum beds, none less than four feet thick, interstratified with shale, and the section recognized as Blaine is 82 feet thick. The Texaco Inc. et al. 1 Lehman liquefied-petroleum-gas storage well (fig. 11) in Beaver County contains 104 feet of Blaine anhydrite. Jordan (1961a, p. 34) gave the following description of cores from this well as described by geologost L. E. Case:

> The Blaine Formation from 736 to 840 feet consists of seven anhydrite beds, none less than five feet thick. Red-brown shale is present between the upper six anhydrite beds. Gray shale occurs . . . above the basal anhydrite stratum. . . . A six-inch bed of fine-grained gray sandstone is noted at 780 feet.

Toward the axial part of the Anadarko basin the Blaine increases in thickness to 150 feet. Most of the increase results from the addition of anhydrite beds at the top of the Blaine, these evaporite beds having graded from shales in the lower part of the overlying Dog Creek Formation. A thickness of approximately 150 feet is maintained in subsurface through Roger Mills County, the southern part of Custer County, and the eastern part of Washita County, into the surface outcrops of Beckham County and the southern part of Washita County. The Blaine is 166 feet thick in the Gulf 1 Sprowls, NW¼ NW¼ sec. 28, T. 13 N., R. 23 W., Roger Mills County, wherein the stratigraphic and lithologic sequence is entirely similar to that of the southern outcrop belt.

Within the Anadarko basin the maximum thickness of the Blaine ranges between 200 and 250 feet and is found in a depositional trough centering in northern Beckham County and western Washita County, Oklahoma, and in the adjoining parts of Wheeler County, Texas. This locus coincides approximately with the shallow structural axis of the Anadarko basin (fig. 14). The increased thickness results principally from the addition of salt beds, especially within the upper anhydrite strata, that correlate with the Van Vacter Gypsum of the outcrop, and salt beds that lie directly above the Collingsworth Gypsum of outcrop nomenclature. The Blaine anhydrite is 243 feet thick in the Shell 1 Yelton of Beckham County and consists of interstratified beds of anhydrite, salt, and shale (fig.

13). In this well the Blaine is overlain by a thick sequence of Yelton salt and is underlain by the Flowerpot salt.

Yelton Salt

The Yelton salt, the youngest of the Beckham evaporites, is underlain by the Blaine anhydrite and is overlain by Dog Creek Shale (upper part). It was recognized and figured (Ham and Jordan, 1961, p. 7) from the Shell Yelton liquefied-petroleum-gas 1 well in NE¼ SW¼ SE¼ sec. 15, T. 10 N., R. 21 W., in the Elk City field, Beckham County, Oklahoma. Results of the present investigation show that the salt has regional distribution as a stratigraphic unit. It is here named the Yelton salt, the name being taken from the Yelton well in Beckham County. In the type well (fig. 13) it is 215 feet thick and occurs at a depth of 1,125 to 1,340 feet. Cores and logs of the Yelton salt in the well show that the salt section contains 20 to 25 percent interbedded shale. This sequence was described by Jordan (1959, p. 32, 34) as consisting of coarse-crystalline salt with thin interbeds of brown and gray-green shale.

That the Yelton salt is a salt facies of shale beds in the lower part of the Dog Creek Formation is shown by correlation of wells along the axis of the Anadarko basin from Wheeler County, Texas, across Beckham and Washita Counties into Caddo County, Oklahoma (K. S. Johnson, 1962, oral communication).

The thickness of the Yelton salt (pl. III, map E) reaches a maximum of 287 feet on the southwest edge of the Elk City field in Beckham County, Oklahoma, and 275 feet in eastern Wheeler County, Texas. These two areas appear to be local areas of rapid deposition. If deposition was uniform throughout the area, then these thick areas may have subsided locally, preserving more salt than is normally present. Depth to the top of the salt beds ranges from 390 to 920 feet in Wheeler County, Texas, and from 665 to 1,285 feet in the Elk City area.

The Yelton salt has been recognized only in the deeper parts of the Anadarko basin (pl. III, map E). Mapping of its distribution is based solely upon interpretations of electrical logs, as no cores, caliper logs, or sonic logs are available for localities outside the Elk City field area. The northeastern limit mapped probably approximates the actual limit, but western and northwestern limits are not firmly established owing to the absence of log information from the few wells drilled. Solution of salt probably limits the present areal distribution at places.

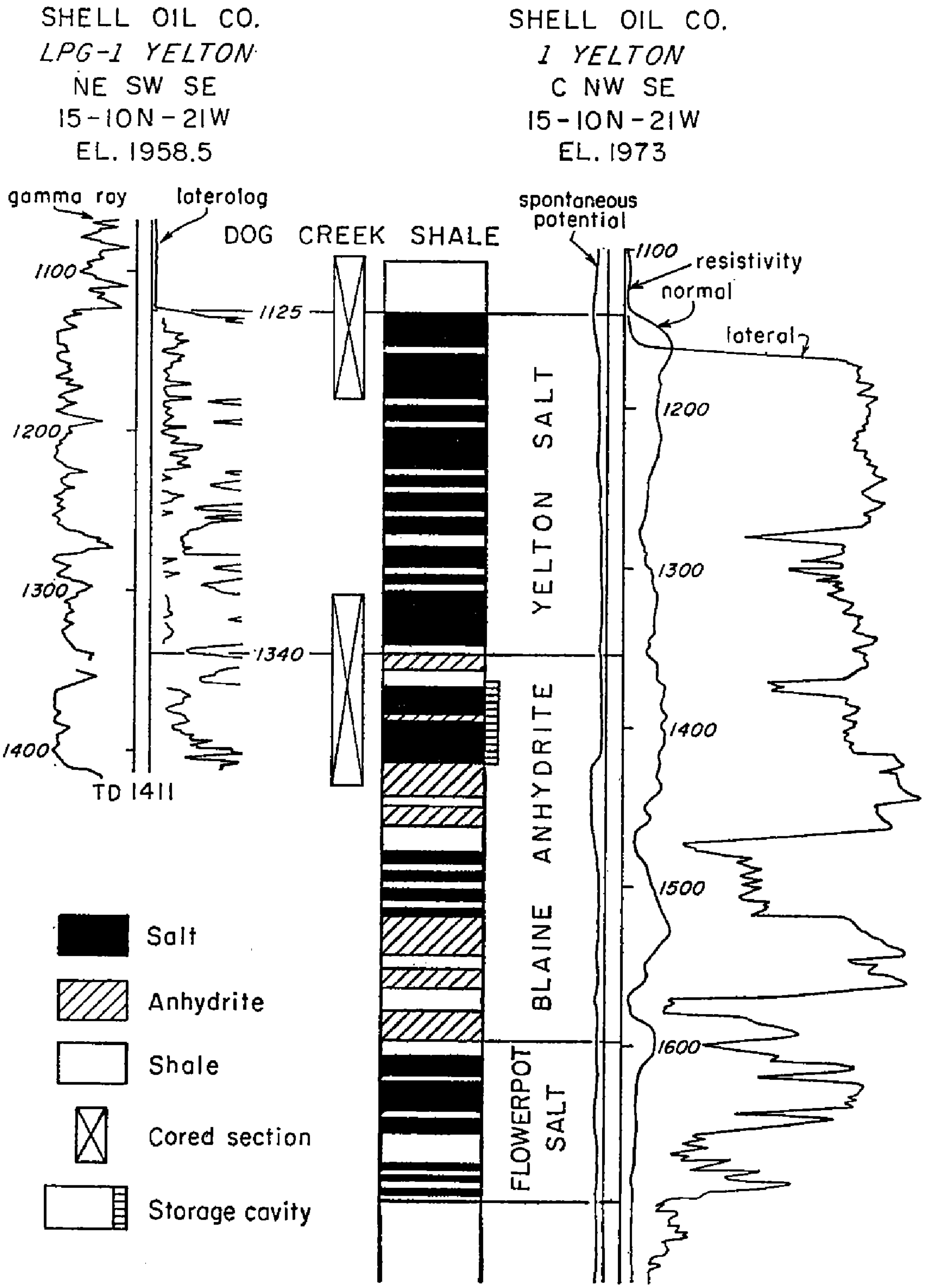

Figure 13. Type section of Yelton salt of the Beckham evaporites underlain by Blaine anhydrite, shown by logs of wells drilled on the Yelton lease, Elk City field, Beckham County, Oklahoma.

STRUCTURE

General Statement

Howell (1922) referred to the Anadarko basin as "Washita Syncline." Gould (1924, p. 323-324) formally proposed the name "Anadarko Basin" as follows:

> . . . The distinguishing structural feature of the entire area [southwestern Oklahoma] is a large synclinal basin, the axis of which extends southeast-northwest across the area discussed. The southeastern end or head of this basin, as it is now understood, is located in northeastern Stephens County, a few miles northwest of the west end of the Arbuckle Mountains. From this point the axis of the basin is known to extend northwest for a distance of about 150 miles, until it appears to lose its identity, in the area occupied by the Quartermaster formation in northern Beckham and southern Roger Mills County. It is possible, however, that later investigations may show that this structural trough continues across the state line into the Panhandle of Texas, paralleling the buried granite ridge [Amarillo mountains] which is now believed to be the northwestern projection of the Arbuckle-Wichita Mountain axis.
>
> Toward the axis of the Anadarko Basin, the rocks dip from both sides, the dips on the south side in the vicinity of the Wichita Mountains being steeper than on the north side. The same redbed formations are exposed in the same sequence on both sides of the basin. For this srtuctural feature the name "Anadarko Basin" is proposed . . .

The general concept outlined by Gould in the quotation above remains with little major change. The basin axis does extend parallel to the Amarillo mountains as Gould suspected, although the mountain axis to the south of the basin is now thought to consist of the Amarillo-Wichita-Criner Hills axis, rather than a Wichita-Arbuckle Mountains axis.

The major structural features are shown on figure 1. East of the area is the Oklahoma City-Nemaha uplift, a subsurface feature which had little or no effect on the Permian sediments to the west. The Arbuckle Mountains lie to the southeast, and during Permian time they were probably covered by fine clastics. The Amarillo-Wichita-Criner Hills axis dominates the southern and southwestern parts of the area shown on figure 1. Immediately north of the mountain axis is the axis of the Anadarko basin.

STRUCTURE AT BASE OF WELLINGTON EVAPORITES

Plate III, map B, shows structure as drawn at the base of the Wellington evaporites. The axis of the Anadarko basin is well defined and trends eastward through southern Oklahoma in Tps. 10, 11 N., but near the Oklahoma-Texas line its axis swings northwest and continues across Wheeler County, Texas. The basin is terminated indistinctly in Roberts County, Texas. Two axial depressions are present in Oklahoma. The deeper is centered near Elk City, and the other is in northern Caddo County. Validity of this interpretation is mitigated, however, in the southernmost area by the fact that the base of the Wellington is drawn across a line of facies changes, and therefore its contours do not accurately portray its structural configuration.

Local nosing is present in southern Blaine County, northern Woodward County, south-central Ellis County, and most of Harper County.

On the south flank of the Anadarko basin the dip is northward, on the order of 236 feet per mile, or about 2.5 degrees. The north and much larger limb of the basin dips much more gently southward, toward the basin axis. In Alfalfa County, the strike is northwest, the beds dipping gently to the southwest at approximately 19 feet per mile. Across Woods County, the strike is generally east and the dip is south at about 16 feet per mile. The strike in Beaver County, Oklahoma, and the northern Panhandle of Texas is northeast and the dip is southeast at 20 feet per mile. In northeastern Hemphill County, Texas, and southwestern Ellis County, Oklahoma, the dip increases to about 37 feet per mile. Except for a local depression in T. 15 N., R. 16 W., in northern Custer County, Oklahoma, this is the only part of the area having any appreciable increase in southward dip toward the basin axis.

STRUCTURE AT BASE OF BLAINE ANHYDRITE

Plate III, map A, shows the structure at the base of the Blaine anhydrite. The axial part of the Anadarko basin is well outlined and the deepest area is centered in western Washita County, T. 10 N., R. 19 W. Compared to the structure at the base of the Wellington evaporites, the deepest part of the basin has shifted slightly to the east. The axis has the same general configuration as that shown at the base of the Wellington evaporites, but, throughout its length, is slightly farther south. In Oklahoma, south of T. 17 N., the configuration is regular, although the dips on the north flank of the basin are steeper (38 feet per mile) than are those at the base of the Wellington horizon. The south flank has a dip of 170 feet per mile, which is considerably less than the dip at the base of the Wellington evaporites. North of T. 17 N., the dips are only about 9 feet per mile, and the contours form irregular noses and local structures, both anticlinal or domal and depressional.

The development of local structures, in terms of relief, increases westward into the Texas Panhandle and has the highest relief and most complex configuration in northern Beaver County, Oklahoma. These local structures, shown on map A (pl. III), do not reflect the structural attitude of the rocks found below the Blaine anhydrite.

The attitude of the Cimarron anhydrite, 600 to 1,200 feet below the Blaine anhydrite, shows little direct relationship to structure of the Blaine anhydrite. Figure 14 shows the Blaine-Cimarron section in two wells less than one mile apart in sec. 17, T. 5 N., R. 26 ECM. Well 1 at the south (left) is the Cleary Petroleum, Inc. 1 Albert, 125 feet north of the center of SE¼ SE¼ (elevation: 2,594 feet). Well 2 at the north (right) is the Ammco Tools, Inc. 1 Davis in NE¼ NE¼ NE¼ (elevation: 2,563 feet). The base of the Cimarron anhydrite is used as a datum to show that the two wells can be readily correlated below 1,000 feet. Well 2 is 13 feet lower at the base of the Cimarron but is 257 feet lower at the base of the Blaine anhydrite. Salt is absent in the 200-foot section immediately below the Blaine in well 2, whereas a 330-foot massive section of Flowerpot salt lies immediately below the Blaine in well 1. The lower altitude of the base of the Blaine in well 2 is due to the removal of most of the salt in the section. At places in this area, the Blaine anhydrite may be absent or represented by a thinner section than that shown in figure 14, and it is believed that this is caused by solution of gypsum. A comparison of Blaine structure (pl. III, map A) and thickness of Flowerpot salt (pl. III, map C) in the northwest quarter of Beaver County shows that the place where the Blaine dips steeply to the northwest is the limit of the Flowerpot salt.

Apparent depressions in the Blaine thus have originated locally through solution of salt between the Blaine and Cimarron anhydrites. The complexity of this solution phenomenon is shown only in those areas where control points are closely spaced. This is indicated by

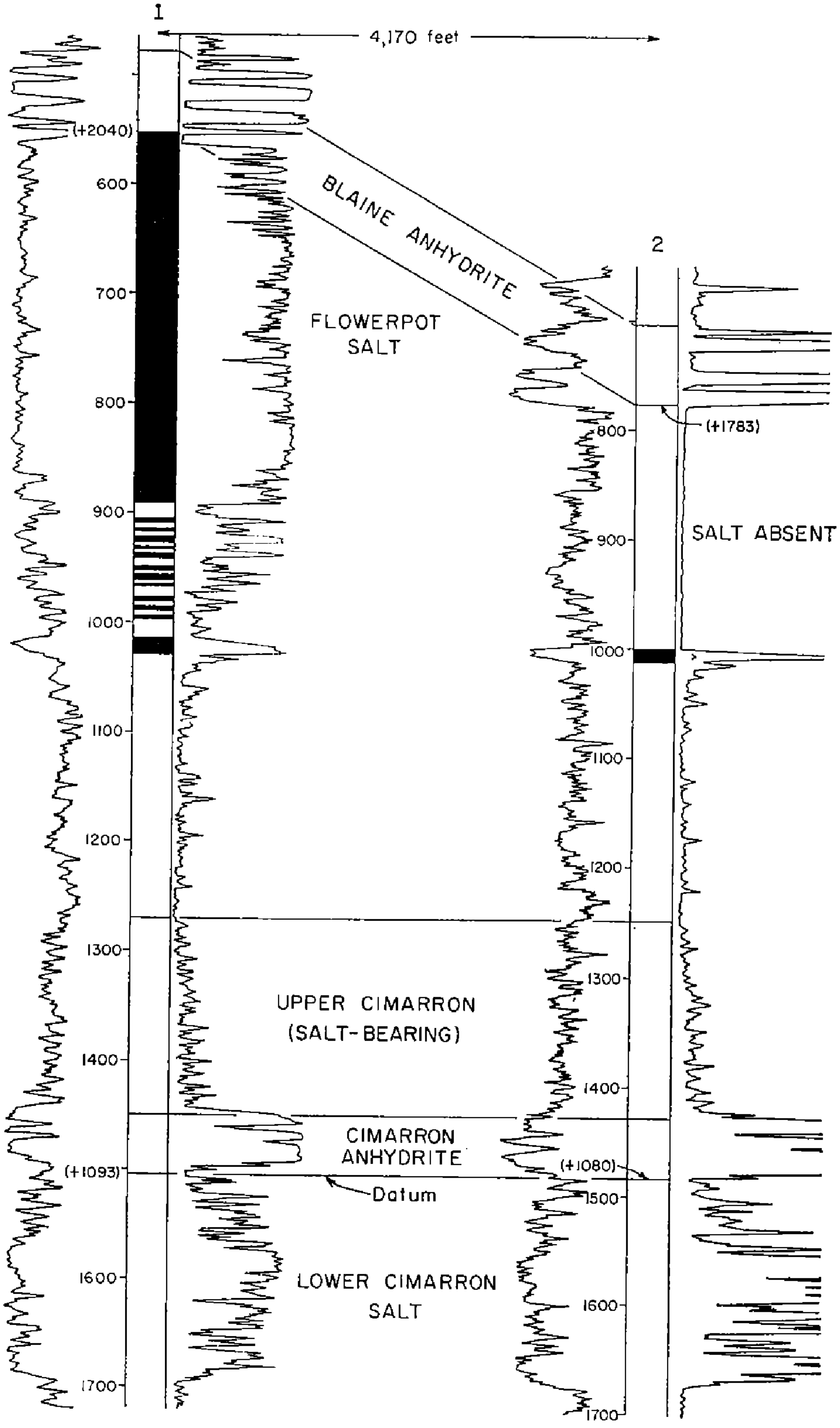

Figure 14. Gamma-ray and laterolog surveys of two wells in sec. 17, T. 5 N., R. 26 ECM., showing a 257-foot lower altitude at the base of the Blaine anhydrite in well 2 where Flowerpot salt has been removed by solution. Structurally, the base of the Cimarron anhydrite differs by only 13 feet in the two wells.

comparison of the pattern in Beaver County, where control is the best, with the Texas Panhandle, where control (mostly commercial sample logs) is relatively closely spaced, and finally with Roger Mills and Custer Counties, Oklahoma, where control is widely spaced. If uniform densely spaced control points were present throughout the area mapped, the karstlike pattern would probably be demonstrable over all but the deeper parts of the Anadarko basin, and in those areas where Upper Cimarron and Flowerpot salts are absent. Exceptions to the expected sinkhole pattern might occur under two conditions: first, if the underlying salt beds were not subjected to solution, perhaps because of saturated brines or great depth of burial; and second, if solution had removed essentially all the salt. In the latter case, the

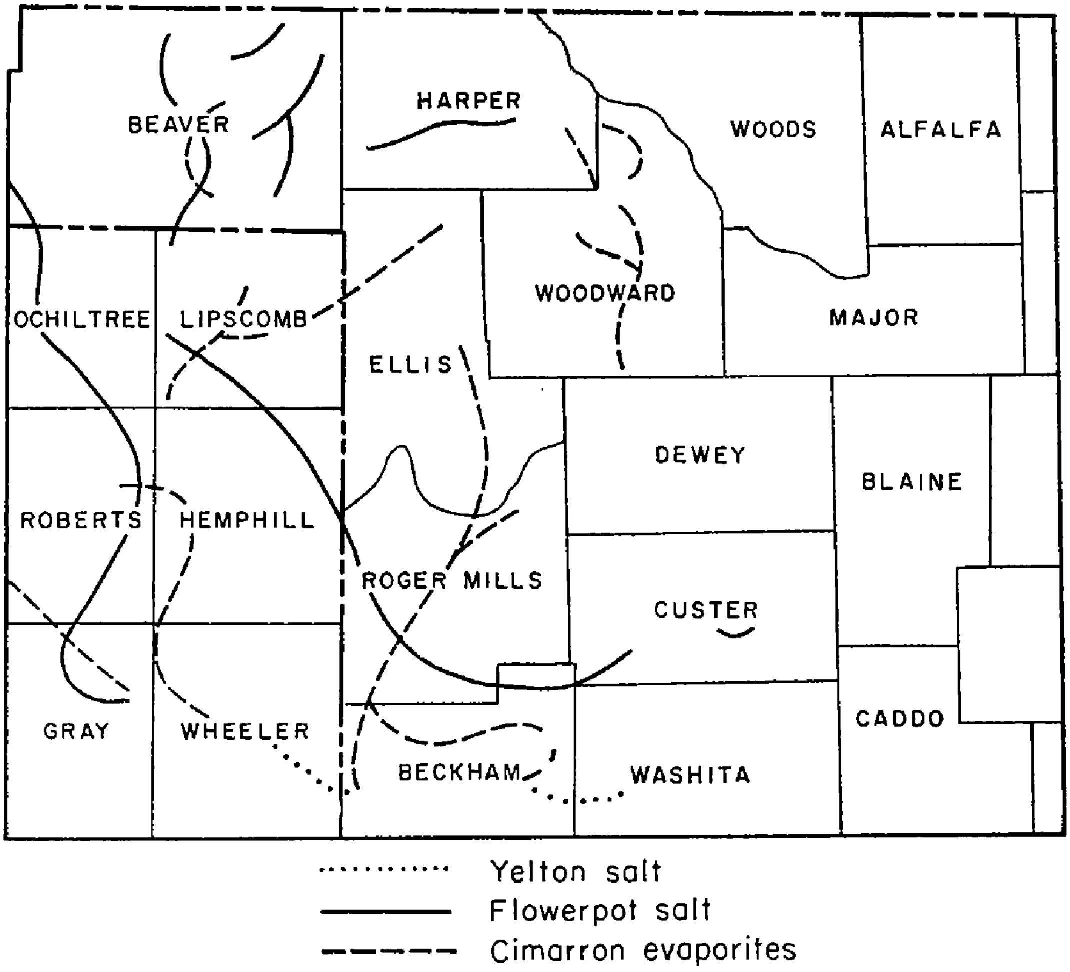

Figure 15. Lines of local maximum thickness of Yelton salt, Flowerpot salt, and Cimarron evaporites, showing lack of development of a well-defined salt basin at any particular time, and the change in position of salt maxima through time.

Blaine anhydrite would subside and the amount of subsidence would be approximately equal to the average total thickness of the salt removed. Surface investigations have shown karst topography to be present at several localities and in various stages of development in western Oklahoma (Fay, 1958; Myers, 1960, 1962b). Similar topography is believed to have been present in the recent geologic past (Myers, 1962a).

RELATION OF SALT TO STRUCTURE

With the exception of the Yelton salt, deposition of salt in the Anadarko basin generally has no relationship to regional structure. In figure 15 the axes of areas of maximum thickness of Yelton salt, Flowerpot salt, and Cimarron evaporites are shown. The Yelton salt lies approximately along the structural axis of the basin as contoured at the base of the Blaine (pl. III, map A). The axes of the Flowerpot and Cimarron are randomly distributed and show no development of a single well-defined salt basin for either unit, and the salt maxima do not coincide from one unit to the next through time. With more control data and a detailed understanding of the part erosion and/or solution has played in the distribution of salt within the Anadarko basin, some relationship between salt thickness and structure may become evident.

SALT RESOURCES

INTRODUCTION

The term "salt" or "rock salt" implies the mineral halite and a chemical composition of sodium chloride, NaCl. The best information to date, available from cores taken from each of the major salt beds in western Oklahoma, shows that halite is widely distributed and is the only chloride mineral. Halite is undoubtedly the dominant mineral in all the salt units referred to in this report, yet the slight possibility remains that potassium salts such as sylvite and polyhalite may be locally present.

Salt cores have been obtained mainly by oil companies to evaluate the feasibility of underground storage caverns for liquefied-petroleum gases, but a few shallow cores have been obtained by Federal agencies investigating salt springs and salt contamination in fresh-water streams (Ward, 1961). The localities and units cored are the shallow Flowerpot salt in Woods and Woodward Counties, Wellington salt from Grant County, Flowerpot and Cimarron salt from Beaver County, and Yelton salt in Beckham County. Geologists from the Oklahoma Geological Survey have examined all the cores that were not destroyed, confirming that halite is present and that it makes up at least 80 percent of most salt layers. The most complete information is from continuous cores taken through approximately 300 feet of the Cimarron evaporites in Beaver County (fig. 8). These cores were carefully sampled and analyzed chemically in the geochemical laboratory of the geological survey. Composite samples of salt beds 20 to 25 feet thick, from depths of 1,490 to 1,738 feet, showed a range of sodium chloride content from 91.8 to 94.8 percent. The remaining constituents are anhydrite and some shale.

In areas where cores are not available, reasonable inferences can be made from a study of various types of electrical logs, and it can be generally inferred that salt beds of substantial thickness and moderate to high purity are present over wide areas in the Yelton, Flowerpot, Cimarron, and Wellington evaporites. These salt beds are potentially valuable for large-scale economic use in western Oklahoma.

General Uses of Salt

Salt is one of the more versatile of all nonmetallic mineral commodities. It is produced in large tonnages and serves a wide variety of uses. In 1961 salt sold or used by producers in the United States totaled 25,707,000 short tons with a value of $160,223,000, or an average value of $6.23 per ton. The major use (10 million tons, or 39 percent) was the production of chlorine and caustic soda, both widely used as chemical raw materials. The next major use (5.7 million tons) was for the production of soda ash or sodium carbonate, which is an essential ingredient in the manufacture of glass. The third largest use (9 percent) was for snow and ice removal from highways. Finally, salt is widely sold for human consumption and as a supplemental feed for livestock, and on a small scale it enters many chemical and industrial processes and is used in a wide variety of common consumer goods (MacMillan and Schreck, 1962, p. 1050, table 7).

In addition, underground salt layers are now extensively used for storage of petroleum products. A cavern is formed by dissolving the salt, and the cavern serves as an underground room. These caverns are used by the petroleum industry to store (1) liquids such as gasoline, fuel oil, or crude oil, (2) liquefied petroleum gases (LPG) which include low-pressure liquids such as butane or propane, and (3) high-pressure volatiles such as ethylene. The use of such cavities for natural gas, coke-oven gas, or such purified gases as oxygen or hydrogen is only commencing as compared to liquid-state storage. Other gaseous, volatile, and toxic materials vital to our modern industrial civilization in large quantity might be placed in this type of underground storage, as it is by far the least expensive storage method. Techniques which are under development to create wider use of such storage include the (1) insertion of inert material between the stored substance and the water-brine section of the cavity and (2) lining of the cavity with inert materials. Both of these techniques are to make solution-cavity storage more widely usable for specific materials which dissolve salt, react with it, or have some affinity with water and brine. Methods of forming larger cavities by means of fracture-connection are being used and tested, and they perhaps will result in vast savings. Testing has been and is being conducted by the U. S. Atomic Energy Commission to determine whether radioactive waste products can be safely stored in salt mines (Boegly and others, 1960;

Bradshaw and others, 1962; Empson, 1962; Reynolds and Gloyna, 1960; Struxness and others, 1960). If rock salt proves to be a satisfactory container, solution cavities similar to those used in the petroleum industry might prove to be cheaper and more practical than salt mines. During the 1950's the use of dissolved-salt cavities became increasingly widespread in the petroleum industry. In the four-year period 1958-1962, underground-storage capacity created by mining or by solution processes in salt domes and salt layers increased nearly 100 percent, to 85,465,000 barrels (42 gal). Mined facilities normally in rock other than salt account for only 7,567,000 barrels, so that by far the greater storage capacity is in salt domes or salt layers. Storage in salt layers amounts to 30,532,000 barrels, or 36 percent of the storage volume. Of approximately 254 cavities that have been created in salt layers, the largest number (126) are in Texas, which also has the greatest capacity (15.8 million bbls). Kansas ranks second in number of caverns (85) and capacity (10.6 million barrels). Of the remaining 43 cavities, four have been constructed in Oklahoma, and the others are in New Mexico, Michigan, New York, Ohio, Montana, North Dakota, and Utah (Bizal, 1962).

Salt reserves in western Oklahoma amount to more than 22 million million short tons (table 1) indicating a major source of salt for future exploitation. Salt layers of sufficient thickness at six stratigraphic levels and, at depths ranging from near surface to about 3,000 feet, have the essential requirements to provide suitable and safe underground storage.

PRODUCTION AND USE OF SALT AND SALT LAYERS IN OKLAHOMA

The first commercial production of salt in Oklahoma was by Indians who collected salt from various salt springs for purposes of barter. As early as 1850, at Salina in the Cherokee Nation, the Cherokees exploited salt springs and even drilled shallow wells to increase the flow of brine (Ham, 1958b, p. 86). Before the Civil War, salt was produced by Jesse Chisholm from springs at the Blaine County Salt Plain (Ward, 1961a, p. 82) along Salt Creek below the escarpment formed by the Blaine Gypsum. The source of salt at this locality is undoubtedly the Flowerpot salt, although this unit has not been mapped (pl. III, map c) east of central Dewey County because shallow subsurface control is not available.

The earliest records available on salt production in Oklahoma are for the year 1900, when 6,861 barrels of salt, or 960 short tons, were produced with a market value of $6,136 (Ham, 1958b, p. 86). In the last ten years production of salt in Oklahoma has not exceeded 10,000 tons in any one year, and the average annual production was about 6,300 tons. In 1961, production amounted to only 3,000 tons with a value of $19,000, yet shipment of evaporated salt and rock salt to the State was 76,000 tons.

Present-day salt production is obtained from three localities in Oklahoma (McDougal and Grandone, 1961, p. 283). Natural salt incrustations are scraped up from the Big Salt Plain of the Cimarron River near Edith in Woods County, and salt is recovered by solar evaporation of spring waters introduced into shallow earthern pans in Salton Gulch on Elm Fork of the Red River in Harmon County (Ward, 1961a). Salt from both places is sold without further treatment.

The largest plant is two miles southwest of Sayre in Beckham County, where fresh water is pumped into an underground salt bed, 38 feet thick, and recovered as saturated brine (Johnson, 1963). The brine is evaporated in tanks, using natural gas as fuel. Originally salt brine was obtained from one well drilled to a depth of 1,518 feet in the Upper Cimarron salt of Permian age. Eight years after the completion of the first well, a second hole was drilled 310 feet southwest of the first hole, and brine was produced from it in the same manner as from the original hole. Three years later the solution cavities of the two wells joined, and currently fresh water is pumped into one well and the brine is recovered from the other. From 1934 to January 1, 1958, cumulative production of salt from this plant was 190,414 short tons. The salt is used primarily as stockfeed and as a recharger of water softeners. Some brine is sold to be used in salt-based drilling fluids (Johnson, 1963).

In Oklahoma, four underground storage caverns for liquefied petroleum gas (LPG or LP-gas) with a total capacity of 158,300 barrels have been created in Permian salt layers at four localities. The solution of salt to form three additional cavities in order to increase underground-storage capacity was commenced in December 1962 at one locality (Mocane plant, Beaver County).

In 1953, Shell Oil Company constructed by the solution process the first underground cavity in Oklahoma at the Elk City field, Beckham County, in a salt layer of the Blaine anhydrite (Formation) at a depth of 1,360 to 1,411 feet (Saye, 1956, Jordan, 1959). Capacity of the cavern used to store propane is 15,000 barrels. The evaporite section of the storage hole is shown in figure 13 of this report.

The second underground solution cavity was made in 1959 by Texaco Inc., in the Camrick district, an oil and gas area in the southwest corner of Beaver County in the Oklahoma Panhandle. The 33,000-barrel cavern was formed for storage of propane below 833 feet in the Flowerpot salt. Casing was set in the lower part of the Blaine anhydrite (Jordan, 1961a). Figure 11 of this report illustrates the salt and anhydrite section of the storage hole.

In July 1962, Warren Petroleum Corp., at their Mocane plant in north-central Beaver County, completed their first solution cavern in a 168-foot section of Lower Cimarron salt at a depth below 1,579 feet where casing was set (Jordan, 1962a). In January 1963, they completed the drilling of three additional holes, 300 to 750 feet distant from the first hole, and the process of washing-out salt is now progressing. If these caverns are similar in size to the original one, the capacity of underground storage for LP-gas at this site will be approximately 150,000 barrels. The evaporite section in which these cavities are being formed is illustrated in figure 8. The storage hole is 1,000 feet east of the salt-water disposal well (SWD) and is at the same elevation.

Early in 1961, Continental Oil Co. investigated subsurface salt layers by test drilling in the Wellington Formation (fig. 6) near Medford in central Grant County (Jordan, 1961c). After the feasibility of a storage facility was determined, a second hole was drilled 400 feet north of the test. The two holes were fracture-connected in a salt layer at a depth of about 900 feet. Fresh water was then injected into one well and saturated brine discharged from the other, creating an underground cavity with a capacity of 150,000 barrels for storage of butane.

OCCURRENCE AND RESERVES OF SALT IN WESTERN OKLAHOMA

Rock salt weighs 135 pounds per cubic foot, or 1.88 million short tons per square mile-foot. Based upon the data of plates II and III, it is estimated that a total of 22 million million short tons of salt is present in western Oklahoma (table 1). Present production is less than 10,000 short tons per year. Reserves in each of the four salt-bearing units are discussed below.

Wellington Salt

Available information directly related to the salt in the Wellington evaporites is tabulated in figure 7. Examples of the electric-log characteristics in the salt-bearing section of the Wellington are given in figures 4, 5, and 6. The estimated salt reserves in the Wellington evaporites are 6.5 million million (6.5×10^{12}) short tons (table 1).

The salt-bearing strata in the Wellington evaporites range in thickness from 260 feet in Beaver County, to 575 feet in Blaine County (fig. 7). Thicker sections of evaporites are present within the axis of the Anadarko basin, but definitive information as to salt content is not available. The percentage of salt ranges from 36 percent to 55 percent within the salt-bearing strata. The uppermost two-thirds of it contains as much as 80 percent bedded salt, and some of these beds are 50 feet thick. The top of the Wellington salt is 2,475 feet below the surface in southwestern Beaver County, and is approximately 2,100 feet below the surface across most of Beaver and Harper Counties. As a result of erosion and regional dip, north and east of the surface outcrop of the Blaine Gypsum the Wellington salt lies nearer the surface, so that in Grant County the top of the Wellington salt is 812 feet beneath the surface (fig. 6). East of Grant County, the Wellington salt is assumed to be closer to the surface, as it is in Kansas where the salt is extracted (by underground mining and solution) from depths ranging between 600 and 1,000 feet. To the south, the top of the Wellington salt-bearing section is 3,010 feet below the surface in Blaine County; 3,440 feet deep in central Washita County, within the axis of the Anadarko basin; and 2,820 feet deep on the south flank of the basin in southwestern Washita County (pl. II, cross section c — c′). The depth to the top of the Wellington salt in the Texas Panhandle is 2,750 feet in southeast-central Ochiltree County, 2,935 feet in eastern Roberts County, 3,640 feet in western Wheeler County, and 3,765 feet in eastern Wheeler County, near the Oklahoma-Texas boundary. The maximum depth to the top of the Wellington salt is 3,810 feet in northeastern Beckham County, Oklahoma. However, in the southern part of the area of this report, the amount of salt strata in the Wellington is unknown because suitable electrical surveys or cores are not available.

TABLE 1—PRINCIPAL SALT RESERVES IN PERMIAN STRATA OF WESTERN OKLAHOMA

STRATIGRAPHIC UNIT	AREAL EXTENT (sq. mi.)	AVERAGE THICKNESS* (ft.)	DEPTH RANGE (ft.)	SALT RESERVES (million million short tons)	FAVORABLE AREAS
Yelton salt (generally massive salt)	400	150	550 to 1,275	0.113	Eastern Beckham County
Flowerpot salt (upper half massive salt; lower half salty shale)	7,300	200	38 to 1,700	2.75	Beaver and Harper Counties
Cimarron salts (upper half salty shale; lower half massive salt)	13,100	500	310 to 2,150	12.3	Western parts of Major, Beckham and Roger Mills Counties
Wellington salts (massive salt interbedded with anhydrite and shale)	15,500	225	800 to 3,900	6.5	Beaver eastward to Grant County
			Total	21.66	

---

* Approximate aggregate thickness of salt beds as estimated from focused resistivity, caliper, and sonic logs.

Production of salt by the solution method is possible throughout the Anadarko basin, except near the southern edge where granite wash or other clastics are commonly present in the Wellington. Construction of solution caverns for storage should be most successful in the northwestern part of the region because of the greater purity and massiveness of the anhydrite and dolomite beds which would roof or cap the washed-out caverns. The successful establishment of a storage cavern in Grant County (Jordan, 1961c) indicates that storage caverns are practical even where thick anhydrite beds are absent.

Cimarron Salts

The thickness of Cimarron salts is shown on plate III, map D. The upper figures given on the map indicate depths from the surface to the top of the salt-bearing sequence. The lower figures show the thickness of the salt-bearing strata, not thickness of the salt beds themselves. The contours are drawn with a contour interval of 50 feet, except on the south flank of the Anadarko basin where the contour interval is 100 feet. The contour lines represent lines of equal thickness of salt-bearing strata.

The estimated salt reserves in the Cimarron evaporites of Oklahoma are 12.3 million million (12.3×10^{12}) short tons (table 1), based upon data from the thickness map (pl. III, map D) and the cross sections (pl. II). This salt unit contains almost twice the total salt reserves of any other salt unit discussed in this report, although the purity of the Upper Cimarron salt is in many places less than the average for all of the salt-bearing units.

The electrical log characteristics of the Cimarron salts are shown on figures 8 and 9. These illustrations, along with cross sections A — A′, A — D, and B — B′ shown on plate II, indicate that the Lower Cimarron salt is more pure than the Upper Cimarron salt, and that the lower zone contains more massive salt beds, some as much as 50 feet thick. The best development of the Cimarron salts is in the northwestern part of the area. In Beaver County, at the Gulf-Warren Mocane plant (sec. 18, T. 5 N., R. 25 ECM.), the top of the Upper Cimarron salt is 1,422 feet below the surface, and the salt extends downward to a depth of 1,528 feet, at which depth it is in contact with the top of the Cimarron anhydrite. This locality has the best development of the Upper Cimarron salt found in the area mapped. The salt-bearing section is approximately 50 percent salt, whereas the remaining 50 percent is shale and salty shale.

The top of the Lower Cimarron salt in the Mocane well (fig. 8), is 1,563 feet below the surface. The top of the massive salt bed occurs at a depth of 1,578 feet, and the base of the salt zone is at 1,746 feet. The massive salt-bearing section (168 feet thick) is 75 percent massive salt and 25 percent shale and salty shale. The Lower Cimarron salt consists of almost 90 percent salt in the lowermost 120 feet of the massive salt zone.

Where both the Upper and Lower Cimarron salts are present, they are mapped as a single unit (pl. III, map D). Map D and the cross sections showing the separation of Upper and Lower Cimarron salts (pl. II) indicate the more desirable areas for salt production to be Beaver, Harper, and Ellis Counties, and the western parts of Woods and Woodward Counties.

Flowerpot Salt

Thickness and known areal extent of the Flowerpot salt are shown on map C, plate III. The upper figure shows depth from the surface to the top of the Flowerpot salt, and the lower figure shows thickness of the salt-bearing strata. The contour lines represent equal thickness of salt-bearing strata, and the contour interval is 50 feet.

Flowerpot salt reserves are estimated from the thickness map (pl. III, map C) and the cross sections (pl. II). The reserves are 2.75 million million (2.75×10^{12}) short tons (table 1).

The electric-log characteristics of the Flowerpot salt are shown on figures 10, 11, and 12. The regional stratigraphic relationships are presented on plate II, cross sections A — D, A — A′, and B — B′. Throughout most of the area underlain by Flowerpot salt, the upper part of the salt-bearing strata contains massive salt beds, whereas the lower part is salty shale and thin beds of salt.

Northwest-central Beaver County contains more than 500 feet of Flowerpot salt within 400 to 600 feet of the surface. No cores are available from wells in this area, but comparison of the logs in this area with logs (fig. 11) of the Texaco Inc. et al. 1 Lehman, liquefied-petroleum-gas storage well in sec. 30, T. 1 N., R. 20 ECM., indicates that northwest-central Beaver County is a favorable area for commercial development of salt and for storage cavities. In Beaver County, extreme caution must be exercised because the Flowerpot salt is absent in some places (pl. III, map C). Within less than one mile east of the Mocane well (sec. 18, T. 5 N., R. 25 ECM.), the

Flowerpot salt is absent. In the Lehman well, the salt is 866 feet below the surface and extends downward to a depth of 1,098 feet. The section from 895 feet to 1,030 feet is massive almost pure salt.

The Flowerpot salt reaches 400 feet in thickness in the southwestern part of Harper County, and although the purity (fig. 10) is less than that found in Beaver County, the depth to salt (450 feet average), the stratigraphic position (below capping Blaine anhydrite), and the geographic locale (Laverne gas district) make Harper County a desirable site for storage cavities in salt.

Around the Big Salt Plain of the Cimarron River in T. 27 N., R. 19 W., cores of pure salt have been recovered within 30 feet of the surface (Ward, 1961b, p. 275). This locality is near the present eastward limit of Flowerpot salt (pl. III, map c), and was considered by Ward (1961b, p. 277) to be near the actual depositional margin. In general, the thickness of the salt-bearing section is less than 200 feet, but approximately 10 miles to the southwest the thickness reaches 350 feet. Although the purity of the salt around the Big Salt Plain is not high throughout the salt-bearing section, enough pure salt layers are present at extremely shallow depths to make this area a favorable prospect for salt production.

In the southern half of the mapped area the average depth to the Flowerpot salt is 1,000 feet, and the thickness is in most places less than 300 feet. Two notable exceptions are present. In northern Gray and west-central Wheeler Counties, Texas, in the axis of the Anadarko basin, the thickness of the Flowerpot salt reaches 500 feet, with the top of the salt zone about 1,200 feet below the surface. No information is available as to the purity or character of the salt in this area. The second exception (discussed in the section on stratigraphy) is the Gulf 1 Burgtorf well in sec. 6, T. 13 N., R. 15 W., Custer County. The log on this well (fig. 12) shows a section, 625 feet thick, which is interpreted as bearing salt, located immediately below the Blaine anhydrite. The upper part of this section, from 945 feet (immediately below the Blaine anhydrite) to 1,130 feet, appears to be massive relatively pure salt; the remaining 440 feet lower in the section is broken by numerous beds of shale and salty shale, each unit from 5 to 40 feet thick. The nearest control well, approximately 10 miles northwest in T. 15 N., R. 16 W., contains only 95 feet of Flowerpot salt.

Yelton Salt

The thickness, depth to salt, and presently known limits of the Yelton salt are shown on plate III, map E. The estimated Yelton salt reserves in Oklahoma are 113 billion (113×10^9) short tons (table 1).

The Yelton salt at the type locality is relatively pure, with only minor beds of shale. Based on estimates from the interpretation of the logs presented in figure 13, the Yelton section is 75-80 percent salt and 20-25 percent shale. Unfortunately, the complete Yelton section was not cored in the Shell Oil Company's storage hole and the cores were not available for chemical analysis.

Thick development of the Yelton salt occurs in two separate areas. In southeast-central Wheeler County, Texas, the maximum thickness is 275 feet. The top of the salt-bearing section is 500 feet below the surface. Information is meager, but it is here considered that the salt-bearing section at this locality contains a high percentage of shale. In Oklahoma, the thickest development of Yelton salt is in the eastward-trending synclinal area located south and southwest of the Elk City field. Here 287 feet of salt-bearing strata is present, the top of which is 1,020 feet below the surface. It probably is similar in character to the section at the type locality in the nearby Elk City field. The storage facility at the Yelton location is in a salt bed within the Blaine anhydrite, although much thicker salt is present in the overlying Yelton section.

ROLE OF SALT BEDS IN THE EXPLORATION FOR PETROLEUM

Widess (1952) and Moore (1951) discussed the problems caused in the seismic exploration of the Anadarko basin by the presence of salt in the subsurface. Basically, salt has a much higher seismic velocity (faster wave propagation, or lower transit time) than has shale. The cross sections of this report (pl. II) show that, generally, the salt units occur in stratigraphic positions which are occupied by shale elsewhere. If the presence of thick subsurface salt deposits is not taken into consideration, anomalous phantom structures may be mapped. The seismic-velocity problem is further complicated by the fact that solution or nondeposition has produced an erratic pattern in terms of salt thickness, making interpretation of seismic reflections extremely difficult and risky without adequate knowledge of the salt. A partial solution to the seismic-velocity problem has been to establish transit-time control, with the use of specially cored holes or drilling oil wells as shot points to find the "up hole" travel time. If the holes used for transit-time control were cored with oil-base mud or saturated brine and various types of electrical logs were run, the recorded travel times could be confidently interpreted in terms of rock type, thickness, and depth. Sonic and density logs of proper quality run to the surface would also give such data in an evaporite section. Comparison of the logs run in these holes with the logs of other wells drilled in the area would indicate, at the very least, where the subsurface section had changed sufficiently to require another carefully controlled test hole to reestablish an accurate transit time for the interpretation of seismic records. The use of velocity logs to obtain average velocities is a great help in resolving the transit-time problem. The use of expanding velocity profiles to obtain velocity information is absolutely necessary in all areas having salt and evaporites in the geologic section. The erratic patterns of salt thickness and solution cavities also cause many extraneous events on seismic records which result in deterioration of the reliability of the data.

Knowledge of the thickness and depths of salt strata in the geologic section are needed not only for the early seismic surveys before location of an oil or gas test, but also during the drilling of the hole. Engineers use the information to plan a mud program for drilling wells because desired mud characteristics are radically altered by solution of salt into the drilling fluid. Casing programs can be more effectively planned if the presence of salt is known and considered. Salt strata are cased off to prevent further contamination of the mud. The characteristics of salt shown on some types of electrical logs are similar to those of anhydrite so that, where salt is suspected, appropriate log types should be obtained to avoid the possibility of using a salt layer as a casing seat. Where relatively thin beds of anhydrite and salt are in contact with rocks of low resistivity, a combination of gamma-ray and focussed resistivity logs along with sonic and caliper logs is definitive.

SELECTED REFERENCES

Adams, J. E., 1939, Standard Permian sections of North America: Amer. Assoc. Petroleum Geologists, Bull., vol. 23, p. 1673-1681.

Adkison, W. L., 1960, Subsurface cross section of Paleozoic rocks from Barber County, Kansas, to Caddo County, Oklahoma: U. S. Geol. Survey, Oil and Gas Inv., Chart OC 61, 2 sheets.

Arbenz, J. K., 1956, Tectonic map of Oklahoma: Okla. Geol. Survey, Map GM-3.

Aurin, F. L., 1917, Geology of the redbeds of Oklahoma: Okla. Geol. Survey, Bull. 30, 66 p.

Aurin, F. L., Officer, H. G., and **Gould, C. N.,** 1926, The subdivision of the Enid formation: Amer. Assoc. Petroleum Geologists, Bull., vol. 10, p. 786-799.

Bado, J. T., and **Jordan, Louise,** 1962, Petroleum geology of Blaine County, *in* Geology and mineral resources of Blaine County, Oklahoma: Okla. Geol. Survey, Bull. 89, p. 152-188.

Baker, C. L., 1929a, Depositional history of the red beds and saline residues of the Texas Permian: Texas, Univ., Bull. 2901, p. 9-72.

__________ 1929b, Discussion of Permian symposium: Amer. Assoc. Petroleum Geologists, Bull., vol. 13, p. 1057-1063.

__________ 1929c, Nonarid genesis of American red beds: Pan-Amer. Geologist, vol. 52, p. 343-354.

Bartlett, Z. W., 1946, Salt and sulphur resources of Texas: Texas Acad. Science, Trans., vol. 29, p. 186-191.

Bartram, J. G., and **Roark, Louis,** 1921, The Healdton field, Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 5, p. 469-471.

Bass, N. W., 1926, Structure and limits of the Kansas salt beds: Kans., State Geol. Survey, Bull. 11, p. 90-95.

Bauer, C. M., 1926, Oil and gas fields of the Texas Panhandle: Amer. Assoc. Petroleum Geologists, Bull., vol. 10, p. 733-746.

Beams, R. J., 1952, Geology of the Elk City field: World Oil, vol. 134, no. 1 (Jan.), p. 67-72.

Becker, C. M., 1927, Geology of Caddo and Grady Counties, *in* Oil and gas in Oklahoma: Okla. Geol. Survey, Bull. 40-I, 18 p., *also in* Bull. 40, vol. 2, p. 105-118 (1930).

__________ 1930, Structure and stratigraphy of southwestern Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 14, p. 37-56.

Bizal, Robert, 1960, New storage caverns hike capacity by 15%: Oil and Gas Jour., vol. 60, no. 44 (Oct. 29), p. 130-135.

Boegly, W. J., Jr., and others, 1960, Disposal for radioactive wastes in natural salt-field experiments: Purdue Univ., Eng. Bull., Ext. Ser. 106, p. 577-590.

Bowdish, F. W., 1951, Beneficiation of Kansas number four salt, *in* 1951 reports of studies: Kans., State Geol. Survey, Bull. 90, pt. 8, p. 192-218.

Bradshaw, R. L., and others, 1962, Storage of high-level packaged solid waste in rock salt, *in* Ground disposal of radioactive wastes: TID-7628, p. 477-489, issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

Branson, C. C., 1960, Proposed American standard of early Permian rocks, a century-old controversy: Okla. Geol. Survey, Okla. Geology Notes, vol. 20, p. 229-235.

Branson, E. B., 1915, Origin of thick gypsum and salt deposits: Geol. Soc. America, Bull., vol. 26, p. 231-242.

Brown, O. E., 1937a, *in* Discussions at Permian conference at Norman, Oklahoma, May 8, 1937: Amer. Assoc. Petroleum Geologists, Bull., vol. 21, p. 1561, 1565-1567, 1571.

__________ 1937b, Unconformity at base of Whitehorse formation, Oklahoma: Amer. Assoc. Petroleum Geologists, vol. 21, p. 1534-1556.

Burton, G. E., 1921, Relation of the base of the red beds to the oil pools in a portion of southern Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 5, p. 173-177.

Burwell, A. L., 1955, An investigation of industrial possibilities of Oklahoma gypsum and anhydrite: Okla. Geol. Survey, Mineral Rept. 29, 21 p.

Clifton, R. L., 1926a, Stratigraphy of the Whitehorse sandstone: Oil and Gas. Jour., vol. 25, no. 2 (June 3), p. 70-74.

__________ 1926b, Woods, Alfalfa, Harper, Major, Woodward, and Ellis Counties, *in* Oil and gas in Oklahoma: Okla. Geol. Survey, Bull. 40-A, 20 p., *also in* Bull. 40, vol. 2, p. 1-20 (1930).

__________ 1930, Permian structure and stratigraphy of northwestern Oklahoma and adjacent areas: Amer. Assoc. Petroleum Geologists, Bull., vol. 14, p. 161-173.

Cragin, F. W., 1896a, The Permian system of Kansas: Colo. College Studies, vol. 6, p. 1-48.

__________ 1896b, The Cimarron Series of Kansas: Colo. College Studies, vol. 6, p. 53-54.

Cunningham, W. A., 1935, The potassium sulphate mineral polyhalite in Texas: Texas, Univ., Bull. 3401, p. 833-867.

Curtis, N. M., Jr., and **Ham, W. E.,** 1957, Physiographic map of Oklahoma: Okla. Geol. Survey, Educ. Series Map 4.

Darton, N. H., 1920, Permian salt deposits of south-central United States: U. S. Geol. Survey, Bull. 715-M, p. 205-230.

Decker, LaVerne, 1927, Structural trends in southern Oklahoma: Okla. Geol. Survey, Bull. 40-P, 9 p., *also in* Bull. 40, vol. 1, p. 69-77 (1928).

Dott, R. H., ed., 1937a, Discussions at Permian conference, Norman, Oklahoma, May 8, 1937: Amer. Assoc. Petroleum Geologists, Bull., vol. 21, p. 1559-1572.

__________ 1937b, Bibliography of Permian of Oklahoma, Kansas, and Texas: Amer. Assoc. Petroleum Geologists, Bull., vol. 21, p. 1573-1574.

Empson, F. M., 1962, Storage of low-level packaged solids in a salt mine, *in* Ground disposal of radioactive wastes: TID-7628, p. 469-476, issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

Evans, Noel, 1928, Stratigraphy of Weatherford area, Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 12, p. 705-714.

__________ 1931, Stratigraphy of Permian beds of northwestern Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 15, p. 405-440.

Fay, R. O., 1958, A recent sink hole in central Blaine County, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 18, p. 58-64.

__________ 1962, Stratigraphy and general geology of Blaine County, *in*

Geology and mineral resources of Blaine County, Oklahoma: Okla. Geol. Survey, Bull. 89, p. 12-99, 194-247.

Freie, A. J., Sedimentation in the Anadarko basin: Okla. Geol. Survey, Bull. 48, 80 p.

Frye, J. C., and **Schoff, S. L.,** 1942, Deep-seated solution in the Meade basin and vicinity, Kansas and Oklahoma: Amer. Geophys. Union, Trans., p. 35-39.

Gouin, Frank, 1927, The geology of Beckham County, Oklahoma: Okla. Geol. Survey, Bull. 40-M, 17 p., *also in* Bull. 40, vol. 2, p. 165-177 (1930).

―――――― 1928, Geology of Comanche County, Oklahoma: Okla. Geol. Survey, Bull. 40-DD, 25 p., *also in* Bull. 40, vol. 2, 203-223 (1930).

―――――― 1947, Southern Oklahoma oil: Oil Weekly, vol. 126, no. 4, June 23, p. 34-42.

Gould, C. N., 1901, The Oklahoma salt plains: Kans. Acad. Science, Trans., vol. 17, p. 181-184.

―――――― 1902, General geology of Oklahoma: Okla., Terr., Dept. Geology Nat. History, 2nd Bienn. Rept., p. 17-137.

―――――― 1905, Geology and water resources of Oklahoma: U. S. Geol. Survey, Water-supply and Irrigation Paper 148, 178 p.

―――――― 1906, Geology and water resources of the eastern portion of the Panhandle of Texas: U. S. Geol. Survey, Water-supply and Irrigation Paper 154.

―――――― 1908, Salt, *in* Preliminary report on the mineral resources of Oklahoma: Okla. Geol. Survey, Bull. 1, p. 26-40.

―――――― 1910, Salt, *in* Brief chapters on Oklahoma's mineral resources: Okla. Geol. Survey, Bull. 6, p. 69-71.

―――――― 1911, Brief statement of the geological history of Oklahoma: Okla. Geol. Survey, Circ. 2, 13 p.

―――――― 1924, A new classification of the Permian redbeds of southwestern Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 8, p. 322-341.

―――――― 1926a, The correlation of the Permian of Kansas, Oklahoma, and northern Texas: Amer. Assoc. Petroleum Geologists, Bull., vol. 10, p. 144-153.

―――――― 1926b, Our present knowledge of the Permian of the Great Plains: Jour. Geology, vol. 34, p. 415-421.

―――――― 1927a, Gypsum and salt: My Oklahoma, vol. 1, no. 8, p. 22, 50, 55.

―――――― 1927b, Stratigraphy and areal geology, *in* The upper Paleozoic rocks of Oklahoma: Okla. Geol. Survey, Bull. 41, p. 5-21; 45-47.

Gould, C. N. and **Decker, C. E.,** 1925, Index to the stratigraphy of Oklahoma: Okla. Geol. Survey, Bull. 35, 115 p.

Gould, C. N., and **Lewis, F. E.,** 1926, The Permian of western Oklahoma and the Panhandle of Texas: Okla. Geol. Survey, Circ. 13, 29 p.

Gould, C. N., and **Lonsdale, J. T.,** 1926, Geology of Beaver County, Oklahoma: Okla. Geol. Survey, Bull. 38, 71 p.

Gould, C, N., and **Willis, Robin,** 1927, Tentative correlation of the Permian formations of the southern Great Plains: Geol. Soc. America, Bull., vol. 38, p. 431-442.

Green, D. A., 1936, Permian and Pennsylvanian sediments exposed in central and west-central Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 20, p. 1454-1476.

———— 1937, Major divisions of Permian in Oklahoma and southern Kansas: Amer. Assoc. Petroleum Geologists, Bull., vol. 21, p. 1515-1533, correction, vol. 22, p. 110, 1938.

Greene, F. C., 1920, Oklahoma's stratigraphic problem [the redbeds]: Oil and Gas Jour., vol. 18, no. 49 (May 7), p. 54, 56.

———— 1926, Subsurface stratigraphy of western Oklahoma, *in* Oil and Gas in Oklahoma: Okla. Geol. Survey, Bull. 40-D, 14 p., *also in* Bull. 40, vol. 1, p. 41-48 (1928).

Ham, W. E., 1955, Regional stratigraphy and structure of the Arbuckle Mountains: Okla. Geol. Survey, Guidebook 3, pt. 2, p. 29-61.

———— 1958a, Stratigraphy of the Blaine Formation in Beckham County, Oklahoma: Okla. Acad. Science, Proc., vol. 38, p. 88-93.

———— 1958b, Coal, metals, and nonmetals in Oklahoma, *in* Fifty years' progress; Semi-centennial report of the director [of the Oklahoma Geological Survey] to the governor: Norman, Okla. Geol. Survey, p. 63-104.

———— 1960, Middle Permian evaporites in southwestern Oklahoma: Internat. Geol. Congress, 21st, Copenhagen 1960, Rept., pt. 12, p. 138-151.

———— 1962, Economic geology and petrology of gypsum and anhydrite in Blaine County, *in* Geology and mineral resources of Blaine County, Oklahoma: Okla. Geol. Survey, Bull. 89, p. 100-151.

Ham, W. E., and **Curtis, N. M., Jr.,** 1958, Gypsum in the Weatherford-Clinton district, Oklahoma: Okla. Geol. Survey, Mineral Rept. 35, 32 p.

Ham, W. E., and **Jordan, Louise,** 1961, A Permian stratigraphic section in west-central Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 4-9.

Hedgpeth, J. E., 1951, The classification of estuarine and brackish waters and the hydrogeographic climate, *in* Report of the committee on a treatise on marine ecology and paleoecology, 1950-1951, No. 11: Washington, Natl. Research Council, p. 49-56.

Hill, A. E., 1937, The transition temperature of gypsum to anhydrite: Amer. Chemical Soc., Jour., vol. 59, pt. 2, p. 2242-2244.

Hills, J. M., 1942, Rhythm of Permian seas, a paleogeologic study: Amer. Assoc. Petroleum Geologists, Bull., vol. 26, p. 217-255.

Howell, J. V., 1922, Some structural factors in the accumulation of oil in southwestern Oklahoma: Econ. Geology, vol. 17, p. 15-33.

Jewett, J. M., 1959, Graphic column and classification of rocks in Kansas: Kans., State Geol. Survey, stratigraphic chart.

Johnson, K. S., 1963, Brine-well production of Permian salt at Sayre, Beckham County, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 23, p. 83-93.

Jordan, Louise, 1959, Underground storage in salt, Elk City field: Okla. Geol. Survey, Okla. Geology Notes, vol. 19, p. 32-34.

———— 1960, Permian salt beds in Laverne gas area, Harper County, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 20, p. 23-28.

———— 1961a, LPG storage in Flowerpot salt, Beaver County, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 34-35.

———— 1961b, Underground LPG storage in Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 95-96.

———— 1961c, Salt in Wellington Formation, Grant County, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 272-274.

———— 1962a, LPG storage in Cimarron salt, Beaver County, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 22, p. 23-26.

———— 1962b, Statistics of Oklahoma's petroleum industry, 1961: Okla. Geol. Survey, Okla. Geology Notes, vol. 22, p. 124-130.

Kaufmann, D. W., ed., 1960, Sodium chloride, the production and properties of salt and brine: Amer. Chem. Soc., Mon. 145, New York, Reinhold Publ. Corp.

Krumbein, W. C., 1948, Lithofacies maps and regional sedimentary-stratigraphic analysis: Amer. Assoc. Petroleum Geologists, Bull., vol. 32, p. 1909-1924.

———— 1951, Occurrence and lithic associations of evaporites in the United States: Jour. Sed. Petrology, vol. 21, p. 63-81.

Krumbein, W. C., and **Libby, W. G.**, 1957, Application of moments to vertical variability maps of stratigraphic units: Amer. Assoc. Petroleum Geologists, Bull., vol. 41, p. 197-212.

Kulstad, R. O., 1959, Thickness and salt percentage of the Hutchinson Salt, *in* A symposium on geophysics in Kansas: Kans., State Geol. Survey, Bull. 137, p. 241-247.

Lang, W. B., 1957, Annotated bibliography and index map of salt deposits in the United States (to June 1956): U. S. Geol. Survey, Bull. 1019-J, p. iii, 715-753.

Lee, Wallace, and **Merriam, D. F.**, 1954, Preliminary study of the structure of western Kansas: Kans., State Geol. Survey, Oil and Gas Inv., no. 11, 23 p.

Lishman, J. R., 1961, Salt bed identification from unfocused resistivity logs: Geophysics, vol. 26, p. 320-341.

MacMillan, R. T., and **Schreck, V. R.**, 1962, Salt: U. S. Bur. Mines, Minerals Yearbook 1961, vol. 1, p. 1047-1060.

Maddox, G. C., 1950, Stratigraphy and oil possibilities of the marine Permian and Pennsylvanian in northwestern Oklahoma [abs.]: Amer. Assoc. Petroleum Geologists, Bull., vol. 34, p. 620.

McDougal, P. B., and **Grandone, Peter**, 1961, The mineral industry of Oklahoma in 1960: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 282-285.

Miser, H. D., 1954, Geologic map of Oklahoma: Okla. Geol. Survey and U. S. Geol. Survey.

Mohr, C. L., 1939, Subsurface cross section of Permian from Texas to Nebraska: Amer. Assoc. Petroleum Geologists, Bull., vol. 23, p. 1694-1711.

Moore, D. F., 1951, Geology of the Permian salt in the western Anadarko basin, Kansas-Oklahoma: Oil and Gas Jour., vol. 50, no. 29 (Nov. 22), p. 84, 86 (abstract of the Soc. of Exploration Geologists).

———— 1954, Permian salt problem—western Kansas, *in* Oliphant, C. W., ed., Examples of geological and geophysical cooperation in petroleum exploration, a symposium: Geophys. Soc. Tulsa [Okla.], Proc., vol. 2, p. 34-37.

Muir, J. L., 1934, Anhydrite-gypsum problem in Blaine formation, Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 18, p. 1297-1312.

Myers, A. J., 1959, Geology of Harper County, Oklahoma: Okla. Geol. Survey, Bull. 80, 108 p.

———— 1960, An area of gypsum karst topography in Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 20, p. 10-14.

———— 1962a, A fossil sinkhole: Okla. Geol. Survey, Okla. Geology Notes, vol. 22, p. 13-15.

———— 1962b, Young sinkholes: Okla. Geol. Survey, Okla. Geology

Notes, vol. 22, p. 174.

Newland, D. H., 1921, Geology of gypsum and anhydrite: Econ. Geology, vol. 16, p. 393-404.

Nicholson, J. H., 1960, Geology of the Texas Panhandle, *in* Aspects of the geology of Texas, a symposium: Texas, Univ., Bur. Econ. Geology, Publ. 6017, p. 51-64.

Norton, G. H., 1937, Lower red beds of Kansas: Amer. Assoc. Petroleum Geologists, Bull., vol. 21, p. 1557-1558.

——— 1939, Permian red beds of Kansas: Amer. Assoc. Petroleum Geologists, Bull., vol. 23, p. 1751-1819.

Phalen, W. C., 1919, Salt resources of the United States: U. S. Geol. Survey, Bull. 669, 284 p.

——— 1949, Salt, *in* Dolbear, S. H., and Bowles, Oliver, eds., Industrial minerals and rocks, 2nd. ed.: New York, Amer. Inst. Mining Metal. Engineers, p. 807-843.

Pierce, W. G., and **Rich, E. I.,** 1962, Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials: U. S. Geol. Survey, Bull. 1148, 91 p.

Posnjak, Eugen, 1938, The system $CaSO_4$—H_2O: Amer. Jour. Science, vol. 235A, p. 247-272.

Reynolds, T. D., and **Gloyna, E. F.,** 1960, Reactor fuel waste disposal project, permeability of rock salt and creep of underground salt cavities: TID-12383, 121 p., issued by U. S. Atomic Energy Comm., Tech. Inf. Service, Oak Ridge, Tenn.

Rogatz, Henry, 1935, Geology of Texas Panhandle oil and gas field: Amer. Assoc. Petroleum Geologists, Bull., vol. 19, p. 1089-1109.

——— 1939, Geology of Texas Panhandle oil and gas field: Amer. Assoc. Petroleum Geologists, Bull., vol. 23, p. 983-1053.

Sawyer, R. W., 1924, Areal geology of a part of southwestern Oklahoma: Amer. Assoc. Petroleum Geologists, Bull., vol. 8, p. 312-321.

——— 1929, Kiowa and Washita Counties, *in* Oil and gas in Oklahoma: Okla. Geol. Survey, Bull. 40-HH, 15 p., *also in* Bull. 40, vol. 2, p. 311-321 (1930).

Saye, J. E., 1956, Shell Oil Company underground storage in Elk City field, *in* Underground storage of liquid petroleum hydrocarbons in the United States: Research and Coord. Comm., Interstate Oil Compact Commission, p. 74-78.

Schoff, S. L., 1950, Ground water in the Cherokee area, Alfalfa County, Oklahoma: Okla. Geol. Survey, Mineral Rept. 21, 18 p.

Scott, G. L., Jr., and **Ham, W. E.,** 1957, Geology and gypsum resources of the Carter area, Oklahoma: Okla. Geol. Survey, Circ. 42, 64 p.

Scruton, P. C., 1953, Deposition of evaporites: Amer. Assoc. Petroleum Geologists, Bull., vol. 37, p. 2498-2512.

Sherwin, R. S., 1903, Notes on the theories of origin of gypsum deposits: Kans. Acad. Science, Trans., vol. 18, p. 85-88.

Six, R. L., 1930, Blaine, Dewey, Custer, and Roger Mills Counties, *in* Oil and gas in Oklahoma: Okla. Geol. Survey, Bull., 40-UU, 53 p., *also in* Bull. 40, vol. 2, p. 383-431 (1930).

Smith, O. M., 1942, The chemical analysis of the waters of Oklahoma: Okla. Agr. and Mech. College, Engr. Exp. Sta., Pub. 52, 394 p.

Snider, L. C., 1913, The gypsum and salt of Oklahoma: Okla. Geol. Survey, Bull. 11, 214 p.

Struxness, E. G., and others, 1960, Disposal in salt formations, *in* Health physics division annual progress report: ORNL-2994, p. 95-128, issued by Oak Ridge National Laboratory, Oak Ridge, Tenn.

Suffel, G. G., 1930, Dolomites of western Oklahoma: Okla. Geol. Survey, Bull. 49, 155 p.

Swineford, A. M., 1955, Petrography of upper Permian rocks in south-central Kansas: Kans., State Geol. Survey, Bull. 111, 179 p.

Tomlinson, C. W., 1916, The origin of red beds: a study of the conditions of origin of the Permo-Carboniferous and Triassic red beds of the western United States: Jour. Geology, vol. 24, p. 153-179, 238-253.

__________ 1940, Classification of Permian rocks: Amer. Assoc. Petroleum Geologists, Bull., vol. 24, p. 337-358.

Tulsa Geological Society, 1951, Mid-Continent region—Anadarko basin: Amer. Assoc. Petroleum Geologists, Bull., vol. 35, p. 336-343.

United States Bureau of Mines, 1960, Minerals Yearbook: vol. 1, p. 935-947.

Ward, P. E., 1961a, Salt springs in Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 82-85.

__________ 1961b, Shallow halite deposits in northern Woodward and southern Woods Counties, Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, vol. 21, p. 275-277.

Ward, P. E., and **Leonard, A. R.,** 1961, Hypothetical circulation of ground water around salt springs in western Oklahoma, Texas, and Kansas: U. S. Geol. Survey, Prof. Paper 424-D, p. 150-151.

Waterschoot van der Gracht, W. A. J. M. van, 1926, Source rocks of petroleum developed in a salt sequence, illustrated in particular by conditions in the West Texas-Oklahoma-Kansas salt basin: Unpublished manuscript read before the 11th annual meeting of the Amer. Assoc. Petroleum Geologists, Dallas, Texas.

Widess, M. B., 1952, Salt solution, a seismic velocity problem in western Anadarko basin, Kansas-Oklahoma-Texas: Geophysics, vol. 17, p. 481-504.

Wilder, F. A., 1923, Gypsum; its occurrence, origin, technology, and uses, *in* Annual reports, 1917 and 1918, with accompanying papers: Iowa Geol. Survey, vol. 28, p. 47-537.

Wilson, R. A., 1927, Paleogeography, *in* The upper Paleozoic rocks of Oklahoma: Okla. Geol. Survey, Bull. 41, p. 22-66.

INDEX

(**Boldface** indicates main references)