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STRATIGRAPHIC, STRUCTURAL AND GEOMORPHOLOGICAL FACTORS CONTROLLING OIL ACCUMULATION IN UPPER CAMBRIAN STRATA OF CENTRAL OHIO

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STRATIGRAPHIC, STRUCTURAL AND GEOMORPHOLOGICAL FACTORS CONTROLLING OIL ACCUMULATION IN UPPER CAMBRIAN STRATA OF CENTRAL OHIO

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ABSTRACT

STRATIGRAPHIC, STRUCTURAL, AND GEOMORPHOLOGICAL FACTORS CONTROLLING OIL ACCUMULATION IN UPPER CAMBRIAN STRATA OF CENTRAL OHIO

Stratigraphic, structural and paleogeomorphic factors are all interrelated and essential to an understanding of the erratic distribution of oil accumulation in the Cambrian sediments of Morrow County, Ohio.

The Copper Ridge Dolomite is the uppermost formation of the Cambrian in Morrow and Marion counties, Ohio. It is truncated by the Knox unconformity which marks the boundary between the Cambrian and Ordovician. Three alphabetized zones of the Copper Ridge subcrop at the unconformity. Zones E and F consist of sucrosic, porous, vuggy dolomite. Zone F, the stratigraphically highest zone, occurs at the tops of the highest dolomite hills, whereas zone E subcrops on the flanks of the highest hills and caps the lower erosional remnants. Zone D is a fine-textured, non-porous, argillaceous dolomite and has the most extensive subcrop aerial distribution of these three zones. It is confined to the valley floors which separate the numerous hills.

The pre-Knox unconformity structure consisted of a closely-spaced series of southeast-trending anticlines and synclines. Denudation of the structurally "wrinkled" zones of the Copper Ridge Dolomite caused the development of a trellis drainage system. The principal drainage courses were eroded into anticlinal folds, and the divides which separated them are in the synclinal lows. The result is synclinal erosional remnants on which the two highest zones of the Copper Ridge Dolomite are preserved.

The Lower Chazy is the oldest Ordovician formation resting on the Knox unconformity in Marion and Morrow counties. It consists of interbedded shales, siltstones, and argillaceous limestones, all of which were initially deposited in the topographically low areas of the Knox unconformity. This sediment surrounded the highest hills and buried the lower ones. The Lower Chazy, due to the weight of overburden, was differentially compacted. The top of the Middle Chazy is a good lithologic datum of reference. An isopachous map of the interval between this datum and the base of the D zone of the Copper Ridge Dolomite serves to illustrate the trends, widths, and positions of the pre-unconformity structures. Vertical exaggeration of the anticlines and synclines, however, is directly

related to the amount of differential compaction of the Lower Chazy sediments. These effects are eliminated by selecting a bentonite reference datum approximately 450 feet stratigraphically higher than the Lower Chazy reference datum.

Cambrian oil accumulation occurs only in the porous and permeable erosional remnants of zones E and F of the Copper Ridge Dolomite. The Lower Chazy shales are thought to be the principle source rocks of the hydrocarbons. Northwestward lateral migration from these shales caused displacement of the original connate brines of the reservoirs. The regional tilt of the unconformity is to the east. Thus, the erosional remnants were progressively filled with oil in an updip direction, in a manner consistent with Gussow's Principle. Lack of sufficient hydrocarbons and general absence of zones E and F to the west, account for the relative absence of oil pools in Marion County.

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INTRODUCTION

This investigation of Cambro-Ordovician strata of contiguous portions of Marion and Morrow counties, central Ohio, deals with stratigraphic, structural, and geomorphologic factors that controlled oil accumulation. Oil production is from erosional remnants (hills) at the top of the Copper Ridge Dolomite of Late Cambrian age.

Location of Area

The region of detailed study encompasses Claridon and Richland townships, Marion County, and the following townships in Morrow County: Canaan, Cardington, Gilead, and the southern portion of Washington (see Figure 1).

History of Development

Several small pools in Cambrian strata were discovered, produced, and abandoned in several areas in Ohio prior to the discovery of oil in the Cambrian rocks of Morrow County. The first commercial production of Cambrian oil in Ohio was established in 1909 near Tiffin, in Pleasant Township, Seneca County. In 1919 a small oil pool was discovered southwest of Caledonia in Claridon Township, Marion County, from Cambrian erosional remnants.

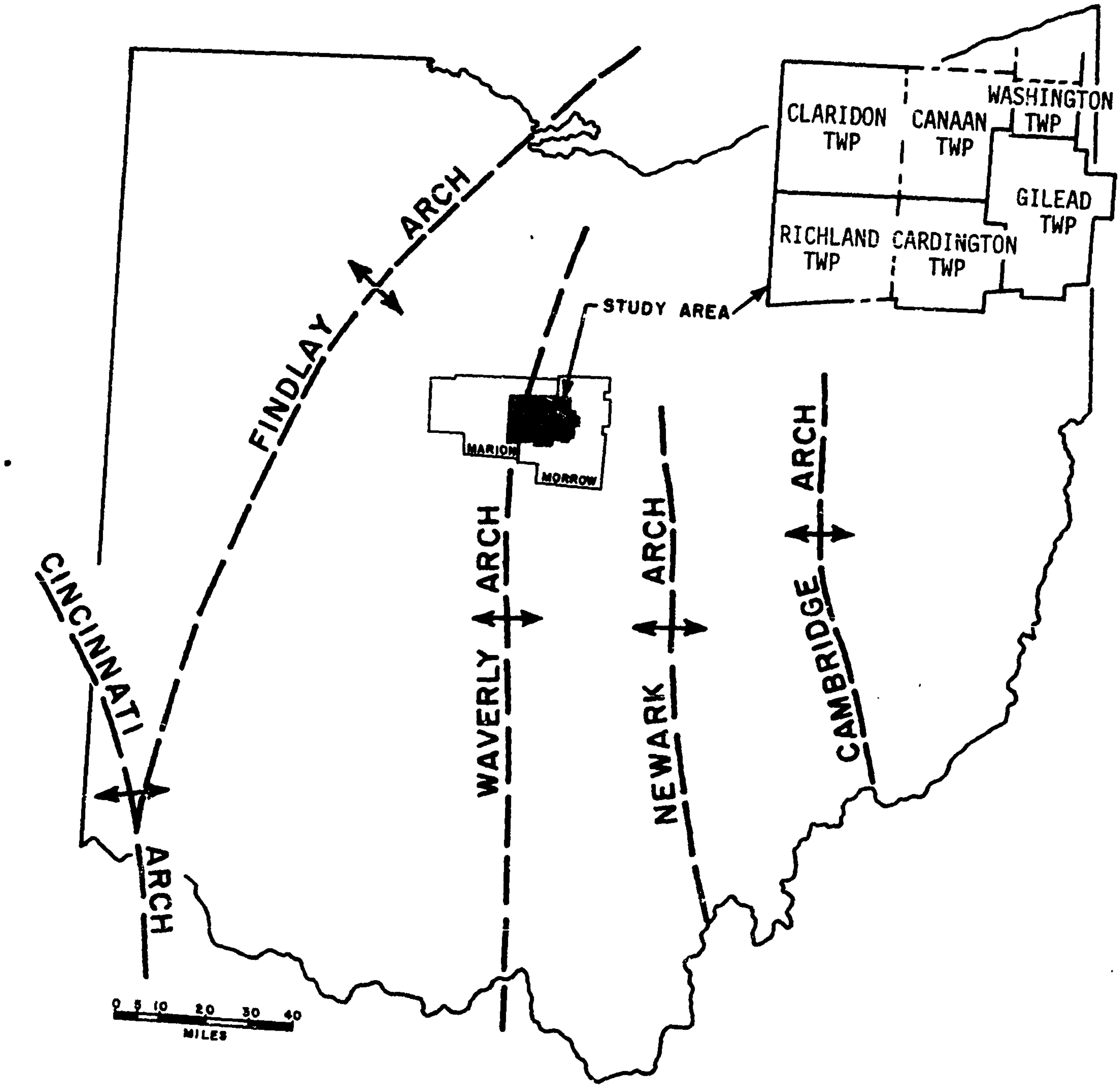

Figure 1. Location map and significant structural axes in Ohio.

Other discoveries were at Pickerington in Violet Township, Fairfield County (1920), the southern outskirts of the city of Newark, in Licking County (1924), and near the town of Tiffin in Clinton Township, Seneca County (1938). Production from these pools was small (initial production ranging from 25-100 barrels of oil per day) and was accompanied by salt water. In 1959, a small oil pool was discovered in Bennington Township, Morrow County. Inasmuch as reserves were limited, only sporadic drilling activity continued in this county until June, 1961.

Intensive drilling activity in Morrow County was precipitated by the discovery of oil in Cambrian erosional remnants below the post-Knox unconformity[1] in June, 1961. The discovery well, Orrie Myers-1, located in C NW NE of Section 33, Canaan Township, Morrow County, was drilled to a depth of 3,174 feet and completed in a 123 foot section of oil-saturated, vuggy dolomite (Copper Ridge), flowing at the rate of 200 barrels of 39° API gravity oil per day through perforations from 2,908 to 3,031 feet. The ultimate recoverable reserves of this discovery well have been estimated as high as 800,000 barrels.

This discovery initiated exploration programs which spread rapidly throughout most of Morrow County and gradually into the surrounding counties. Leasing activity in the area was intensive and bonus prices rose rapidly. From the time of initial discovery in 1961 through the early months in 1964, drilling activity accelerated at such a rapid pace that Ohio conservation laws proved inadequate to cope with the chaotic conditions developing in Morrow County. Spacing regulations requiring that wells be

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[1] The post-Knox, pre-Chazyan unconformity surface is hereafter referred to as the Knox unconformity in this report.

certain distances from each other were lacking, town lot drilling was common, and no effort was made by operators to adopt sensible producing practices. In the town of Cardington, for example, some wells were so closely spaced that the drilling rigs were in close contact. With this close spacing and lack of restrictions governing rate of production, reservoir energy was quickly dissipated and uneconomic oil recoveries resulted.

In March, 1964, the Ohio Division of Mines adopted new conservation rules established by state regulatory officials. Some of the more important rules placed into practice were: 1) all operations must be conducted in such a manner as to prevent the waste of oil or gas in order to conserve oil and gas reserves, and to promote safety; 2) ten-acre spacing is required, with 330 feet as a minimum distance from the boundary of a 10-acre tract and 660 feet from any other well producing from the same reservoir; 3) voluntary pooling is encouraged on tracts smaller than 10 acres; 4) a security bond of not less than $5,000 is required of an operator to assure that all drilling production and plugging requirements are met; and 5) in the interest of safety, no well shall be drilled and operated closer than 100 feet to churches, schools, and public buildings. It wasn't until later that daily allowable requirements were placed on the wells and production records were required by the Ohio Division of Mines.

Geological Problems

Early in the exploration activity in Morrow County it became apparent that the production pattern was erratic. None of the pools were large and this, together with the sporadic distribution of hydrocarbon accumulation in the area, created problems in exploring for additional oil reserves that defied conventional exploration techniques.

Oil geologists quickly recognized that oil accumulation occurs in erosional remnants (hills) immediately below the Knox unconformity. The productive zone occurs almost exclusively in the Copper Ridge Dolomite (Upper Cambrian). Of the hundreds of wells that penetrate the unconformity, no production has been established at depths greater than 150 feet below the erosion surface. At places, hydrocarbons have been encountered in locally fractured and dolomitized zones in the Lowville (Black River Group) and Chazyan Limestones, in the basal portion of the overlying Ordovician.

Geologists recognized the occurrence of oil in buried Cambrian hills; however, it soon became apparent that some of these produce water, rather than oil. Two major problems in establishing Copper Ridge production developed: 1) the reason that some hills are oil-productive while others, of equal topographic relief, are water-bearing; and 2) the absence of oil production from similar erosional remnants to the west of Morrow County, in Marion County.

Exploring for prospective hydrocarbon accumulations in the Copper Ridge Dolomite by surface methods is impractical because of a "blanket" of glacial drift. Early exploration programs were based almost entirely on seismic and gravity techniques until sufficient wells had been drilled to gain adequate data for subsurface geological studies. The gravity meter was utilized as a regional reconnaissance tool to delineate subsurface anomalies; many of these were checked later by seismic means. This method has been used with fair success to predict the location of erosional remnant "highs" (Ferris, 1964, and McCarthy, 1964). The reflection seismograph has been used with greater success in delineating the Cambrian hills at the Knox unconformity (McCarthy, 1964, and Sitler, 1964). Seismic exploration was employed to locate the Copper Ridge anomaly which led to the initial discovery; however, seismic prospecting has not always been successful. Although both geophysical methods have been used extensively in this area it appears that the reflection seismograph (in spite of its limitations) has been more successful in locating buried dolomite hills than has the gravity meter.

Data from mechanical logs, cores, and well cuttings are utilized effectively in establishing subsurface exploration programs after sufficient wells have been completed. These tools may be used to interpret the subsurface stratigraphy in detail and to reconstruct the paleogeomorphology of the pre-Ordovician surface.

Purpose of Investigation

The purpose of this investigation is to reconstruct the geological history of the Cambro-Ordovician sediments in Marion and Morrow counties and to determine factors which control oil accumulation. Detailed subsurface stratigraphy of these sediments must be understood in order to determine the interrelationship among structure, sedimentation, and geomorphology and the part that each plays in controlling oil accumulation. Oil and gas accumulation occurs immediately below the Knox unconformity and this poses several challenging problems, as follows: 1) what was the relationship between pre-Ordovician structure and the paleotopography of the Knox unconformity? 2) what type of drainage pattern was developed on this erosion surface? 3) are porosity and permeability due to diagenesis, fracturing, or weathering, or any combination of these? 4) are hydrocarbons indigenous or have they migrated? 5) what are the likely source beds? 6) why are commercial oil accumulations confined to certain erosional remnants and not to others that are topographically as high (if not higher) that have similar reservoir (porosity and permeability) conditions? 7) what hydrodynamic principles are involved in the accumulation of the hydrocarbons?, and 8) does truncation of porous beds occur at the unconformity or do permeability barriers exist to prevent updip migration of hydrocarbons from Morrow to Marion County?

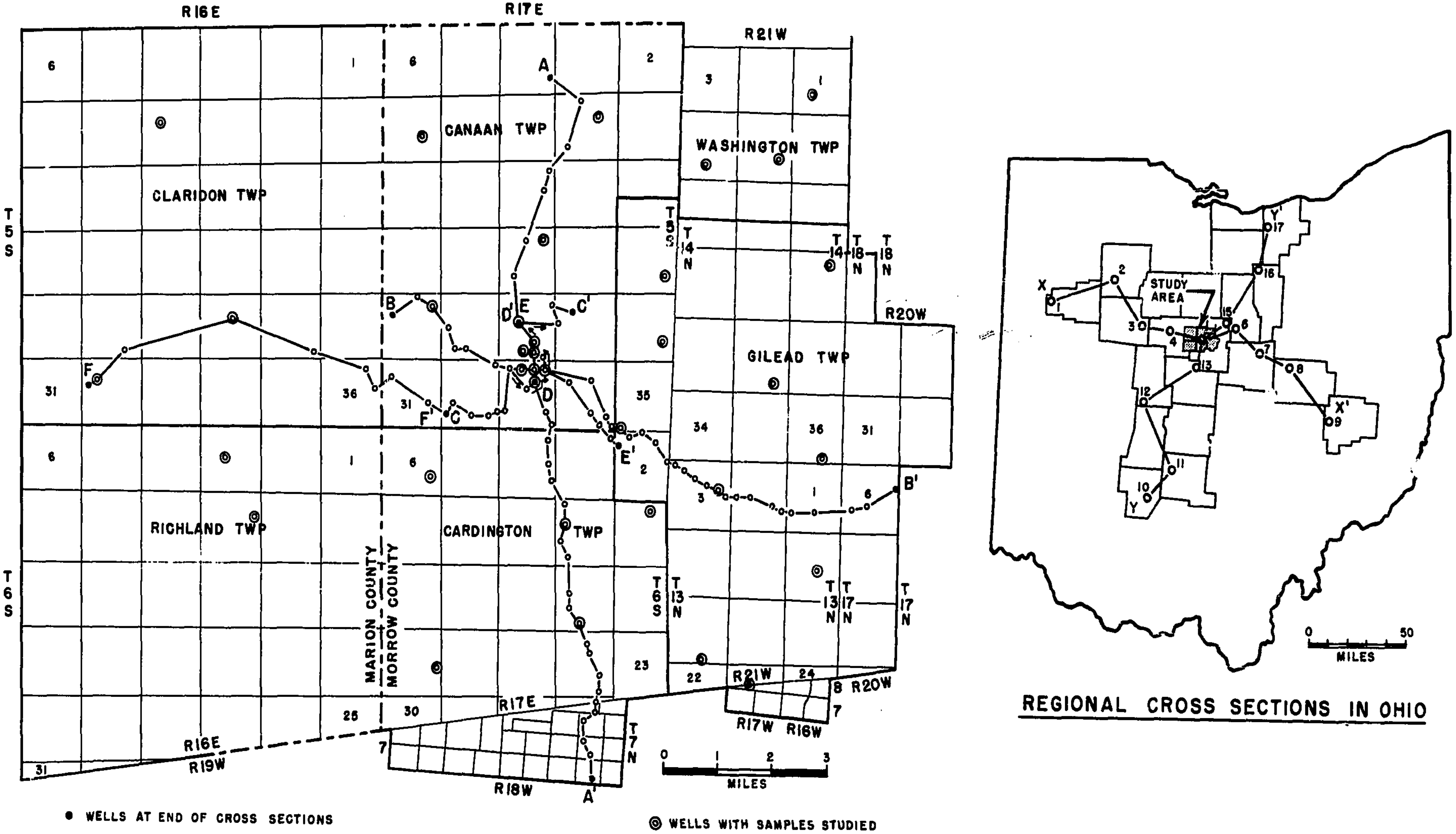
Methods of Investigation

Sample Studies

Well cuttings and cores were studied in this investigation in order to interpret the lithologies indicated on the gamma ray-neutron logs and to establish precision in stratigraphic correlations. Well cuttings from 35 wells and 3 cores were examined. Locations of the wells whose samples were studied are shown on Figure 2. The name of the operator, lease, and location of each well utilized are listed in Appendix A.

Stratigraphic Profiles

Busch (1961) proposed the use of precise stratigraphic correlations based on mechanical logs. These proved indispensible in defining stratigraphic trap prospects. In this investigation approximately 1,000 mechanical logs were studied and correlated. In addition, three cores and cuttings from 35 wells were examined and described in detail. Cross sections illustrating the stratigraphy throughout this region were constructed, using both sea level (structural cross section) and lithologic marker beds (stratigraphic cross section) as datum planes. Location of cross sections used in this study is shown on Figure 2. The name of the operator, lease, and location of each well are listed in Appendix B in the order in which they appear on the cross sections, as shown on Figure 2.



DETAILED CROSS SECTIONS - MARION & MORROW CO'S

REGIONAL CROSS SECTIONS IN OHIO

FIGURE 2

LOCATION OF DETAILED & REGIONAL CROSS SECTIONS IN OHIO

Maps

Isopachous. The use of an isopachous map is of considerable value in reconstructing paleodepositional environments. Busch (1959) demonstrated the significance of isopaching "genetic sequences" of strata as a means of reconstructing the paleotopography of an unconformity at the base of the isopached interval. He stated that, "A genetic sequence is a stratigraphic interval devoid of any significant breaks in sedimentation that may be mapped completely independent of present day structural configuration." The upper boundary of the genetic sequence should be a lithologic time marker or a stratigraphic unit parallel with a geologic time marker and the base is marked by an unconformity (erosion surface). Levorsen (1960) described paleotopography as follows, "The topographic relief or the configuration of the surface of an unconformity at the time it was overlapped, its paleotopography, may be determined by preparing an isopach map of the stratigraphic interval between the unconformity and the next overlying marine horizon that may be used as a plane of reference." In Figure 3B, the interval b, b', and b" between XX' and YY' is the interval that may be isopached to show paleotopography of the unconformity. The paleodrainage pattern developed on an erosion surface and the paleogeomorphological features developed on an erosion surface due to the dissection by stream pattern development were discussed by Andresen (1962) and Martin (1966), respectively. It should be pointed out that the structural attitude and physical characteristics (resistant or nonresistant to erosion) of these rocks subcropping at the erosion surface determine the type of drainage pattern that developed on that surface. In this investigation an isopachous map was constructed, utilizing the interval between the reference

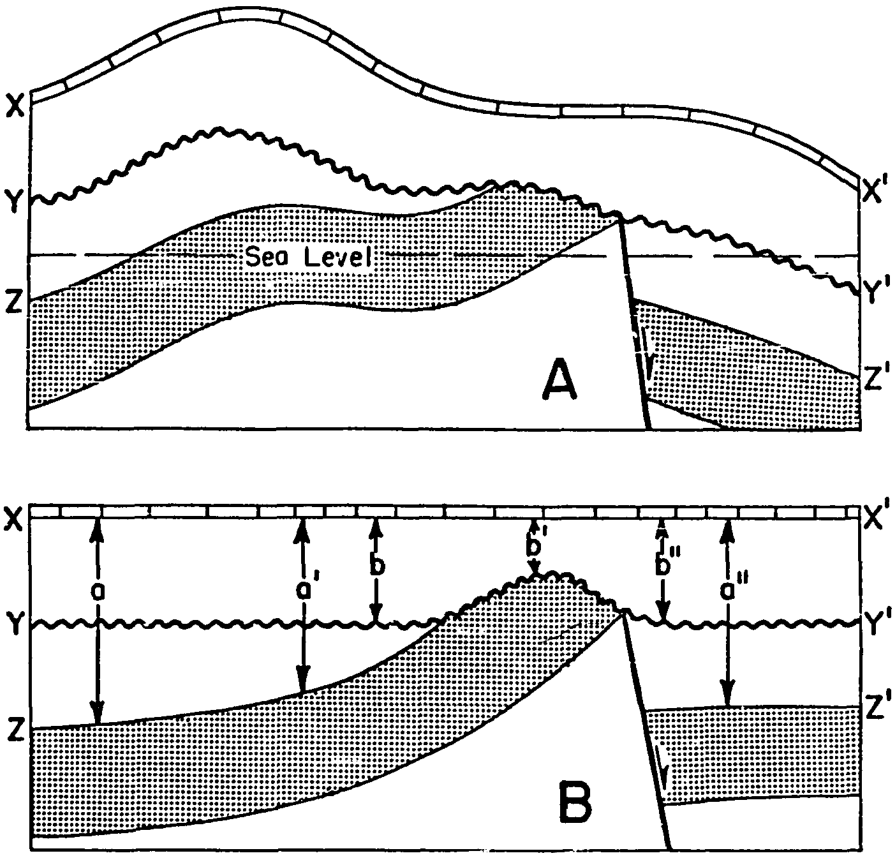


Figure 3. A: Structure section. B: The same section reconstructed into a stratigraphic section. The marine marker formation XX' is straightened out and leveled to serve as a reference line. Section B is hung on XX'. The thicknesses a, a', and a" reflect the structure during B time, and the thicknesses b, b', and b" reflect the topography of surface YY' on which the overlapping formation was deposited. (From PALEOGEOLOGIC MAPS by A. I. Levorsen. W. H. Freeman and Company. Copyright © 1960.)

datum at the top of the Middle Chazy Limestone to the Knox unconformity in order to illustrate the paleotopography of the Cambrian erosion surface.

A second isopachous map was drawn to illustrate the structural attitude of stratigraphic units subcropping at the Knox unconformity. Levorsen (1960) stated, "The paleostructure of the pre-unconformity formation is shown by an isopach map of the interval between the next overlying marine horizon and a formation boundary below the unconformity." In Figure 3B, the interval a, a', and a" between XX' and ZZ' may be isopached to illustrate pre-unconformity structure. Levorsen wrote, "It should be kept in mind that these paleogeologic dips and strikes may be quite different from present day dip and strike of the same formation. The former reflect paleostructure of the area, and while their influence may be seen in the present structure, it is frequently obscured." An isopach map constructed in this manner removes the effects of present day structure and illustrates only pre-unconformity structure. In this investigation an isopach map of the interval between the top of the Middle Chazy Limestone and a horizon within the Copper Ridge Dolomite (base of zone D) was drawn to illustrate pre-Knox unconformity structure.

Structure. In this investigation a structure map on the Knox unconformity was drawn to ascertain the direction and amount of regional tilt and to determine any possible effect which this might have had on localizing accumulation of oil and gas.

Knox unconformity subcrop. Levorsen (1966) says, "A subcrop map is a paleogeologic map in which the overlying formation is still present." In this study a subcrop map at the Knox unconformity was constructed to show the distribution of the formations that lie immediately below this erosion surface. This map is of value in determining the extent to which stratigraphy, structure, and paleogeomorphology have influenced accumulation of oil in the Copper Ridge Dolomite.

STRATIGRAPHY

Introduction

Cambro-Ordovician sediments involved in this study do not crop out in Ohio. Calvert (1962) pointed out that these rocks appear as surface outcrops in the Adirondack region of New York; in the Upper Mississippi River Valley area of Iowa, Minnesota, and Wisconsin; in the Ozark region of southeastern Missouri; and in the Appalachian Valley. The surface stratigraphy has been worked out in detail in each case using local names for individual units. In each locality different criteria for subdivision and correlation purposes are used. Therefore, the problem in Ohio is to determine which of the stratigraphic exposures described in the local regions best fits the subsurface lithologic units found in the state.

The stratigraphic terminology of the Cambro-Ordovician of the Upper Mississippi Valley has been applied by some authors to subsurface strata of the same age in Ohio. Calvert (1962) indicated that there is no precedent for application of Iowa, Minnesota, and Wisconsin terminology to the rocks in Ohio inasmuch as rocks of the Upper Mississippi Valley represent different lithologic facies that commonly indicate a different environment of deposition.

Calvert's study (1962) showed that the general lithologic characteristics of surface outcrops of Cambro-Ordovician rocks in the Appalachian Valley of Virginia and Tennessee are maintained in the subsurface northward into Ohio. He used both surface and subsurface rock samples in reaching these conclusions. Although the formations thin considerably northward and the Cambrian rocks are truncated progressively below the Knox unconformity, their lithologic character indicates that the depositional environments were similar. The stratigraphic nomenclature used in the Appalachian Valley more appropriately fits the Cambro-Ordovician sediments of Ohio than does the nomenclature from areas previously mentioned. In this investigation the stratigraphic nomenclature from the Appalachian Valley (Rose Hill district, Virginia) is used when referring to distinct units as shown on Table 1, a generalized geologic column of Upper Cambrian and Ordovician rocks in Ohio.

Table I is diagrammatic in that it fails to show the significance and magnitude of the Knox unconformity which separates the Lower and Middle Ordovician. In some portions of Ohio the Middle Ordovician rests unconformably upon the Upper Cambrian.

In Morrow County, the Upper Copper Ridge Dolomite (Cambrian) subcrops at the Knox unconformity. There it is overlain by Lower Chazy strata (Middle Ordovician). Numerous erosional remnants of Copper Ridge Dolomite were emergent (as islands) during deposition of Lower Chazy sediments. In these cases the Middle Chazy overlies the erosional remnants, except for occasional dolomite hills which project through both Lower and Middle Chazy rocks and are thus overlain directly by Upper Chazy Limestone.

Regional Stratigraphy

In this investigation only the regional stratigraphy of those Upper Cambrian and Lower and Middle Ordovician strata that are pertinent to the problem in the subsurface of Ohio are summarized. Consideration is

TIME UNITS			LITHOSTRATIGRAPHIC UNITS			
SYSTEM	SERIES	STAGE	SEQUENCE	SUPERGROUP	GROUP	FORMATION
ORDOVICIAN	CINCINNATIAN	RICHMONDIAN	TIPPECANOE	MAQUOKETA		Queenston Shale
		RICHMONDIAN MAYSVILLIAN EDENAN				Reedsville Shale
	CHAMPLAINIAN	MOHAWKIAN		OTTAWA	TRENTON	Trenton Limestone
						Eggleston Limestone
						Moccasin Limestone
					BLACK RIVER	Lowville Limestone
		CHAZYAN			CHAZY	Upper Chazy Limestone
						Middle Chazy Limestone
						Lower Chazy Limestone Shale Dolomite
	CANADIAN		SAUK	KNOX	BEEKMANTOWN	Lambs Chapel Dolomite
						Chepultepec Dolomite
CAMBRIAN	ST. CROIXAN	TREMPEALEAUAN FRANCONIAN			LEE VALLEY	Copper Ridge Dolomite
		DRESBACHIAN				Maynardville Dolomite
						Conasauga Shale

Table 1. Generalized Column of Upper Cambrian and Ordovician Rocks in Ohio

given to the surface outcrops in the Appalachian Valley of Virginia and Tennessee and comparisons of lithology and thickness are made with subsurface stratigraphic equivalents in central Ohio.

Cambrian System

Upper Cambrian formations encompassed by the Sauk Sequence are significant to this study in Morrow County, Ohio. The Sauk Sequence, proposed by Sloss and others (1949), includes strata between the Precambrian (basement complex) and the contact between the St. Peter Sandstone and the underlying Oneota Dolomite. This marks the position of the first major regional unconformity (Knox unconformity) above the basement complex. Those units of the Sauk Sequence discussed in this report make up the Knox Supergroup of Late Cambrian and Early Ordovician age.

The Knox Dolomite was named by Safford (1869) for those Cambro-Ordovician units that are similar lithologically, but overlain and underlain by stratigraphic units that differ distinctly in lithologic character. It can be subdivided into two groups on the basis of lithologic differences. The older units, the Maynardville Dolomite and the Copper Ridge Dolomite (Cambrian) were placed in the Lee Valley Group by Calvert (1962) and the younger formations, the Chepultepec Dolomite and the Lambs Chapel Dolomite (Lower Ordovician) make up the Beekmantown Group described by Brainerd and Seely (1890).

The Lee Valley Group as defined by Calvert (1962) is composed of the Maynardville Dolomite and the Copper Ridge Dolomite. These units are generally pure, partly oolitic, and partly cherty dolomite with local occurrences of thin interbedded limestone. The Lee Valley Group in the type of Hawkins County, Tennessee, is underlain by the shales and thin limestones of the Conasauga Formation and overlain by the sandy and argillaceous beds of the Lower Ordovician Chepultepec Dolomite.

Maynardville Dolomite. The type locality of the Maynardville Limestone is near Maynardville, Union County, Tennessee. It was originally described by Oder (1934). The outcrops which he discussed are no longer accessible due to impounding of water behind the Norris Dam. Oder described the Maynardville Limestone as the limestone and chert-free dolomite between the Nolichucky (Conasauga) Shale and the cherty dolomites of the Knox Group (Copper Ridge Dolomite). Hall and Amick (1934) selected and described another Tennessee section of the Maynardville that was considered the type section for several years, but the type section now utilized was described by Bridge (1956) near Lake Norris at Maynardville, Tennessee. Here Bridge found the Maynardville to be predominantly gray to black calcareous shale at the base, grading upward into gray to blue gray, fine to medium crystalline, argillaceous, sandy, laminated limestone interbedded with gray, calcareous, silty shales. The section grades upward into a gray, finely crystalline, partly oolitic dolomite. Thickness approximates 350 feet.

The Maynardville changes facies northward in surface exposures into a dolomite section in the Appalachian Valley at Rose Hill, Virginia. Miller and Fuller (1954) described the Maynardville as the limestone and dolomites that conformably overlie the Conasauga Shale, although the base of the Maynardville is interbedded gray and black shales with fairly massive beds of limestone which overlie a predominantly shale section. The top of the Maynardville is transitional by interbedding into the Copper Ridge Dolomite, and no clear-cut contact can be drawn between them. At

Rose Hill, Virginia, the lower portion of the Maynardville is a gray, fine-grained, silty, laminated to mottled limestone with gray shale or shaly limestone locally interbedded. The limestone contains chert and oolites are conspicuous. The upper part is light gray to dark gray, fine to medium crystalline, sandy, oolitic, cherty dolomite with scattered gray calcareous shale and shaly limestone partings. The total section measures about 250 feet.

The Maynardville thins northward in subsurface to about 80 feet in Morrow County, Ohio. The entire sequence is dolomitic except near the base, where a gray to black, sandy calcareous shale occurs. The dolomite is light brown to gray, fine to medium grained, sandy, partly oolitic, and cherty with stringers of gray calcareous shale throughout. Because the Maynardville is completely dolomitic in the subsurface of Ohio it is herein referred to as the Maynardville Dolomite.

<u>Copper Ridge Dolomite</u>. Ulrich (1911) proposed the term Copper Ridge for the dolomitic chert which overlies the Maynardville Formation and is overlain conformably by the sandy, argillaceous, partly cherty Chepultepec Dolomite near the Copper Ridge of eastern Tennessee and southeastern Virginia. At this locality, the bulk of the formation is chert; however, throughout most of the outcrop area and in subsurface the Copper Ridge is dolomitic; because of this the name has been changed to the Copper Ridge Dolomite. The type section which Ulrich described is about 1,300 feet thick. In the Appalachian Valley in the Rose Hill District of southwestern Virginia, the Copper Ridge Dolomite measures 850 feet. At nearly all described localities the Copper Ridge is divisible locally and regionally into a lower dark-colored and an upper light-colored member.

The lower dark member of the Copper Ridge Dolomite is characterized by a dominance of dark gray to brown, medium to coarsely crystalline, partly oolitic, very cherty (chert grains gray to white), partly sandy dolomite. Freshly broken pieces of this rock yield a strong petroliferous odor, and it is aptly called "stinkstone".

The upper light member of the Copper Ridge Dolomite is composed of white to light gray to light tan, fine to coarsely crystalline, cherty, oolitic, partly sandy and argillaceous dolomite. It becomes increasingly sandy near the top and scattered rounded white quartz grains are common; however, these are less abundant as in the overlying Chepultepec Dolomite.

Harris (1966), in a report on the Copper Ridge Dolomite in Union and Claiborne counties, northeastern Tennessee, reported that approximately 60% of the Upper Cambrian Copper Ridge Dolomite (average thickness 925 feet) is composed of algal stromatolite structures. These algal stromatolite structures are indicative of a shallow water intertidal depositional environment according to studies by Logan and others (1964). Logan and others reported that modern stromatolites (apparently similar to those in the Copper Ridge Dolomite) are for the most part restricted to intertidal zones. These algal zones are composed of finely to coarsely crystalline dolomite with abundant vugs. Harris suggested that these persistent porous stromatolite zones in the subsurface offer potential sites for accumulation of hydrocarbons.

In the subsurface of Ohio, the Copper Ridge Dolomite (also referred to as the Trempealeau Dolomite) has thinned to approximately 300 feet and can be subdivided readily into lower and upper zones. In central Ohio, the lower and upper zones are composed of similar dolomite except for a marked absence of abundant chert. Oolites were observed only in the upper member; however, only a few wells penetrate the lower member and it is therefore not completely known. At the base of the upper member in central Ohio there is an extremely glauconitic, sandy, argillaceous dolomitic zone.

In the subsurface of Morrow County, the Upper Copper Ridge Dolomite is overlain by the Chazyan Formations which were deposited unconformably upon and around erosional remnants of the Knox unconformity erosional surface. The Ordovician Chepultepec and Lambs Chapel Dolomites have been either eroded away, truncated, or both in this area.

Ordovician System

Only those formations of Early and Middle Ordovician age are discussed in this report. The Lower Ordovician includes two formations, Chepultepec and Lambs Chapel Dolomites. These constitute the uppermost part of the Sauk Sequence which is represented throughout the Appalachian Valley by the Beekmantown Group (upper part of the Knox Dolomite Supergroup).

The Beekmantown Group was named by Brainerd and Seely (1890) in New York where they subdivided the previously designated "Calciferous" of the Champlain Valley, Vermont, into five distinct lithologic units. In this region the upper and lower boundaries of the Beekmantown are questionable because each is marked by unconformity. Ulrich (in Wilmarth, 1938) correlated the Beekmantown Limestone of New York and environs with the Chepultepec Dolomite of Alabama on the basis of lithologic similarity and fossil content. Therefore, it appears reasonable to place the base of the Beekmantown Group at the base of the Chepultepec Dolomite in Alabama and the Appalachian Valley where it conformably overlies the Copper Ridge Dolomite (Lee Valley Group). Regionally the upper boundary of the Beekmantown Group is marked by unconformity (Knox unconformity). Therefore, the Beekmantown Group in the Appalachian Valley is composed of sandy, argillaceous, and partly cherty dolomites of the Chepultepec Dolomite and the Lambs Chapel Dolomite (Longview-Kingsport-Mascot Dolomite, undifferentiated).

All formations comprising the lower part of the Tippecanoe Sequence of Sloss and others (1949) are Middle Ordovician. The Tippecanoe Sequence was designated to include all rocks from the base of the St. Peter Sandstone (Knox unconformity) to the base of the New Albany Shale (the next higher regional unconformity). Formations of the Tippecanoe Sequence discussed in this report comprise the Ottawa Supergroup.

The Ottawa Supergroup was described and named by Swann and Willman (1961) for those stratigraphic units comprising the Champlainian (Chazyan and Mohawkian) of Middle Ordovician age. It is underlain by the rock units of the Canadian (Lower Ordovician) and overlain by those of the Cincinnatian (Late Ordovician). The Ottawa Supergroup can be subdivided into Chazy, Black River and Trenton Groups.

The Chazy Group (Safford and Killebrew, 1900) is composed of the Chazy (Murfreesboro) Limestone which unconformably rests on the Lower Ordovician or Upper Cambrian sediments and is overlain conformably by the lithographic limestones of the Black River Group. Those formations included in the Chazy Group are the Lower Chazy Shale-Limestone-Dolomite, the Middle Chazy Limestone, and the Upper Chazy Limestone.

The Black River Group (Vanuxem, 1842) was defined as the strata between the Trenton Limestone and the Calciferous (Beekmantown). It was redefined by Cushing (1911) to exclude rocks of Chazyan age. Calvert (1962) included the Lowville, Moccasin, and Eggleston Limestones in the Black River Group; the Moccasin and Eggleston are considered Trentonian by some authors.

Chepultepec Dolomite. The type Chepultepec Dolomite was described from exposures near Chepultepec (renamed Allgood), Blount County, Alabama, by Ulrich (1911). The Chepultepec has conformable contacts at base and top. The Copper Ridge-Chepultepec contact is placed at the base of the first dolomitic sandstone or sandy dolomite above the prominent oolitic, cherty dolomites of the Copper Ridge. The upper contact of the Chepultepec is at the boundary between the upper dark, argillaceous, partly silty dolomite and the overlying white and cream-colored dolomite beds of the Lambs Chapel Dolomite. Butts (1926) established the accepted definition of the Chepultepec Dolomite as those formations that rest conformably upon the Copper Ridge Dolomite of Ulrich (1911), Butts (1926), Oder (1934), and Miller and Fuller (1954). Two distinct lithologic members have been recognized in the Chepultepec Dolomite, a lower sandy member and an upper argillaceous member.

The lower sandy member of the Chepultepec Dolomite is composed of interbedded sandy, argillaceous dolomites and dolomitic sandstones. The dolomites are light brown to gray, fine to medium crystalline, argillaceous, and partly cherty with grains of rounded, frosted quartz scattered throughout. The sandstone beds are white, fine- to medium-grained quartz sands with dolomite cement. Numerous gray, green, and brown shale partings are common.

The upper argillaceous member is characterized by dark gray to brown, medium crystalline, argillaceous dolomite with a decrease in chert and sand content. Green calcareous shale partings are common throughout the section.

The Chepultepec Dolomite, which attains an exposed thickness of approximately 1,000 feet in the Rose Hill District in Virginia, thins northward into Ohio to about 180 feet in the subsurface in Fayette County where only the lower member is present. The latter is truncated northward and is absent at the Knox unconformity in Madison County, Ohio. In Morrow County, Ohio, the Chepultepec is absent.

Lambs Chapel Dolomite. Calvert (1962) proposed the name "Lambs Chapel Dolomite" for surface and subsurface units previously referred to as the Longview-Kingsport-Mascot Dolomites. The type section of the Lambs Chapel Dolomite was taken near Lambs Chapel, Lee County, Virginia, where it includes a full exposure of the rocks designated as Longview-Kingsport-Mascot as originally described by Ulrich in Gordon (1924) and by Rodgers (1943), respectively. This section has been described by Miller and Fuller (1954).

The Lambs Chapel overlies the Chepultepec Dolomite. It is composed of white to cream-colored, fine to coarsely crystalline, partly sandy, partly argillaceous dolomite. Traces of white oolitic chert occur locally. Thin green shale partings are common.

In the outcrop the Lambs Chapel is approximately 900 feet thick. The formation is progressively truncated northward in the subsurface and is absent in Lewis County, Kentucky. According to Calvert (1962), the Lambs Chapel probably does not occur in the subsurface of Ohio, unless it is present in the extreme southeastern or southwestern corners of the state.

Chazy Limestone. The Chazy Limestone was named and described by Emmons (1842) from an exposure near the town of Chazy, in Clinton County, New York. The description of the Chazy Limestone section of New York more closely fits that of the Appalachian Valley section than does the Tennessee section described by Safford and Killebrew (1900). Safford and Killebrew named the equivalent units the Murfreesboro Limestone for the section they described near Murfreesboro, Rutherford County, in western Tennessee. This 70 foot section is characterized by light blue, heavy-bedded, mostly cherty limestone, exposed in the Nashville basin, where it overlies the Knox unconformity. However, it is certain that the Chazy Limestone sequence of the Rose Hill District, Virginia, and the subsurface of Ohio more closely fit the lithologic character and stratigraphic position of the Murfreesboro Limestone of Butts (1940) in the Appalachian Valley. This section is similar to the 150 foot section of cherty, argillaceous limestone called the Chazy Limestone in New York. Therefore, the term Chazy Limestone is used in this report rather than Murfreesboro. The Chazy (Murfreesboro) Limestone described by Butts (1940) in the Appalachian Valley and the section described by Miller and Fuller (1954) in the Rose Hill District, Virginia, can be both readily subdivided into three distinct units which rest unconformably on the Beekmantown Dolomites and occur below the Black River Limestones. These three members are referred to as the Lower Chazy Shale-Limestone-Dolomite, the Middle Chazy Limestone, and the Upper Chazy Limestone.

Lower Chazy Shale-Limestone-Dolomite. The Lower Chazy Shale-Limestone-Dolomite formation of the Chazy Limestone overlies the Knox unconformity.

The Lower Chazy Limestone ranges in thickness from zero to approximately 120 feet in subsurface. It was deposited in the valleys and low areas surrounding the dolomite hills. Consequently, it is thickest in the valleys, thins gradually over the lower hills, and is absent over the higher hills. The Lower Chazy Shale-Limestone-Dolomite formation has a maximum thickness of approximately 65 feet in the Morrow County, Ohio, region.

Lithologically the Lower Chazy varies considerably from place to place, both locally and regionally. Generally in the outcrop of the Appalachian Valley the base is marked by a conglomerate composed of subangular dolomite pebbles in gray, argillaceous, dolomite matrix with numerous partings and stringers of green to black, glauconitic, pyritized and calcareous shale. Also present in the conglomerate are scattered, rounded, frosted quartz grains and sand lenses. Above the basal conglomerate, the Lower Chazy is composed of interbedded limestones and shales. The limestones are gray to brownish, finely crystalline to lithographic, argillaceous, and sandy. The shales are green to black, glauconitic, sandy, dolomitic, and commonly contain traces of pyrite. A few scattered, thin beds of white to gray to brown, dense to finely crystalline, argillaceous dolomites are present near the base above the basal conglomerate.

In Morrow County, Ohio, the lithology is similar, although the basal conglomerate zone is not readily recognizable in well cuttings. However, the basic lithology of interbedded dense, argillaceous, sandy limestones and green to black, glauconitic, sandy calcareous shales make up most of the lower member with a few dolomite stringers present locally.

In the subsurface of Ohio the Lower Chazy Shale-Limestone-Dolomite formation has been referred to frequently as the Glenwood, but in this report it is referred to as the Lower Chazy Shale-Limestone-Dolomite or simply the Lower Chazy.

Middle Chazy Limestone. The middle division of the Chazy Group is conformable with the Lower Chazy Limestone. Where the Lower Chazy does not cover the higher hills of the erosion surface, the Middle Chazy is in unconformable contact with the Copper Ridge Dolomite. At places where the dolomite hills were extremely high, the Middle Chazy did not cover the tops of these hills, being absent over the crest and occurring only around the flanks. Generally, the thickness of the Middle Chazy Limestone in the Appalachian Valley in the outcrop is about 50 to 120 feet; in a few instances it is much thinner, or absent, over the higher hills.

The Middle Chazy Limestone is composed principally of gray to tan to white lithographic limestone containing scattered calcite crystals called "birdseyes".

In the subsurface to the north in Ohio, the Middle Chazy Limestone maintains consistent lithologic character and has a maximum thickness of 50 to 55 feet. Locally in Morrow County, above some of the erosional remnants, the Middle Chazy Limestone becomes a dolomitic limestone or a dolomite close to the base. This zone has porosity and permeability and occasionally produces oil.

Upper Chazy Limestone. The Upper Chazy Limestone lies conformably upon the Middle Chazy Limestone. In a few cases the base rests unconformably on highs of the erosion surface that project through the

Lower and Middle Chazy members. The Upper Chazy Limestone is about 40 to 120 feet thick in the Appalachian Valley.

The lithology of this member consists of gray to brown, dense, argillaceous, partly dolomitic, chert-bearing limestones interbedded with green to gray to black, calcareous, and silty shales.

In the subsurface of Ohio, the Upper Chazy is approximately 50 feet thick and maintains lithologic consistency.

Lowville Limestone. The name Lowville Limestone was applied to the "Birdseye Limestone" by Clarke and Schuchert (1889), the type locality being near Lowville in Lewis County, New York. They also described what they thought to be the Lowville Limestone in Tennessee. However, this section in the Appalachian Valley was later subdivided into Mosheim Limestone (Ulrich, 1911, near Mosheim Station, Tennessee), Lenoir Limestone (Safford and Killebrew, 1876, near Lenoir Station, Tennessee), and Lowville Limestone (restricted). The Mosheim and Lenoir were subsequently assigned to the Chazyan. The remaining dense to lithographic limestones are herein considered as Lowville. The Lowville Limestone conformably overlies the Upper Chazy Limestone.

At the surface in the Appalachian Valley, the Lowville Limestone is about 780 feet thick. It consists of light brown to tan to gray lithographic limestone with few beds of birdseye limestones, highly argillaceous limestones, and bentonitic shale partings locally. Traces of oolites, chert, and dolomite have been found in the subsurface as well as on the surface.

Northward in the subsurface, the Lowville Limestone thins to about 300 to 350 feet in central Ohio. The lithologic content is consistent with that of the surface exposures. Regionally in the subsurface of central Ohio (Morrow County), a 10 foot section of highly argillaceous limestone occurs about 50 feet above the base of the Lowville. This serves as a reliable lithologic marker bed on the gamma ray-neutron logs.

Moccasin Limestone. Campbell (1894) named the Moccasin Limestone for exposures near Gate City, in Scott County, Virginia. This locality is near the Rose Hill District of the Appalachian Valley (40 miles) which has a better section with upper and lower boundaries that are easily recognizable. The base of the 280 foot section of Moccasin Limestone is marked by the thin shaly or silty zone above the lithographic limestones of the Lowville. The top is marked by the base of the lowermost silty, bentonitic zone of the overlying Eggleston Limestone.

The Moccasin consists of tan to white, lithographic limestone that is argillaceous at the base and grades upward into a white, lithographic limestone with scattered calcite crystals, and traces of pyrite and bentonite. In the subsurface of Morrow County, Ohio, the Moccasin thins to about 100 feet.

Eggleston Limestone. The Eggleston Limestone, named for exposures near Eggleston, Giles County, Virginia, by Mathews (1934), includes strata lying conformably above the Moccasin Limestone and below the overlying Trenton Limestone.

In the outcrop in Virginia, the Eggleston consists of dark tan to brown, fine-grained, thick- and thin-bedded, argillaceous limestone containing several thin beds and a few thick beds of bentonite. These bentonite beds are traceable at the surface from locality to locality.

In the subsurface of central Ohio, this limestone unit retains its lithologic character and the bentonites, although less well-developed.

It is readily recognizable and serves as excellent lithologic time markers for subsurface mapping of genetic sequences. Locally, in a few wells, the bentonitic zones are hard to find. The thickness of the Eggleston in central Ohio is about 50 feet.

Trenton Limestone. The 100-foot section of light gray, crystalline, fossiliferous limestone that crops out near Trenton Falls in Oneida County, New York, was named the Trenton Limestone by Vanuxem (1938). The upper boundary of the Trenton Limestone is marked at the base of the overlying black, calcareous shales (called the Utica Shale in New York), whereas the Trenton is underlain by the limestones of the Black River Group in New York.

In the Appalachian Valley, the Trenton Limestone is overlain by the Reedsville Shale and underlain by the Eggleston Limestone. All boundaries appear conformable. The limestone in the Appalachian Valley is 550 feet thick. The lithologic character is similar to that at the type section in New York and consists of gray, medium crystalline, fossiliferous, cherty, partly argillaceous limestone; a few gray shale partings occur throughout the section.

In the subsurface in Morrow County, Ohio, the Trenton Limestone is conformable with the underlying Eggleston Limestone and is overlain by the black, silty, calcareous Eden Shale. The Trenton is about 50 to 60 feet thick in the subsurface of central Ohio.

Cambro-Ordovician Boundary Problem

The Cambro-Ordovician boundary in the Valley and Ridge Province and over much of the eastern United States presents a problem that does not confront stratigraphers in the subsurface of Morrow and adjacent counties, Ohio. In the Morrow County area the Chazy Limestones of Ordovician age (dated by paleontology in various outcrop sections by Emmons, 1842; Vanuxem, 1842; Safford, 1851; Butts, 1940; and Miller and Fuller, 1954, among others) unconformably overlie the Copper Ridge Dolomite, the latter having been dated by paleontology by Ulrich (1911), Butts (1940), and Miller and Fuller (1954), and others, as Upper Cambrian. This boundary is called the post-Knox unconformity. It is of considerable magnitude in the subsurface of Ohio and actually extends over the eastern, central, and southern portions of the United States. This hiatus has been called the post-Knox, post-Arbuckle, and post-Ellenberger unconformity. It is the first widespread (major erosional surface) stratigraphic break above the basement complex that occurs throughout eastern United States and other parts of the world, as stated by Bushback (1961) and Patterson (1961). This break in stratigraphy is the result of one of the longest erosional periods of the Paleozoic.

In the outcrop the Maynardville Limestone and Copper Ridge Dolomite of the Appalachian Valley have been placed in the Upper Cambrian (Miller and Fuller, 1954). The overlying Chepultepec and Lambs Chapel Dolomites (Longview-Kingsport-Mascot Dolomites, undifferentiated) are assigned to the Lower Ordovician. The Chazy, Lowville, Moccasin, Eggleston, and Trenton Limestones are assigned to the Middle Ordovician (see Table 1). The Knox unconformity marks the boundary between Lambs Chapel Dolomite and the Chazy Limestone.

As Calvert (1962) emphasized, the significance and magnitude of the Knox unconformity has not been properly evaluated. The local relief of the erosion surface in Virginia, as well as in some areas in the subsurface northward in Ohio, is as much as 400 feet (Miller and Fuller, 1954). This amount of relief represents a hiatus of several million years.

Many workers have been troubled with the position of the Cambrian-Ordovician boundary. Evidence presented in this text on the lithologic characteristics of the Upper Cambrian and Lower and Middle Ordovician rocks suggests that stratigraphically the Knox unconformity might be the most practical place to establish the boundary between the Cambrian and Ordovician rocks. The rocks below the unconformity are predominantly dolomites, whereas the rocks deposited upon the erosion surface are predominantly limestones. This strongly suggests a change in depositional environment or, if not, there would have been ample time for dolomitization of the rocks below the Knox unconformity (if not primary dolomites) to occur before the limestones were deposited. However, this argument is not valid. If rocks below the unconformity are secondary dolomites, there would have been ample time for dolomitization before the deposition of the limestones regardless of their age.

Fossil evidence clearly indicates that the Chepultepec and the Lambs Chapel Dolomites are Early Ordovician in age. The fossil record illustrates a significant change in fossil assemblages between the Copper Ridge Dolomite and the Chepultepec Dolomite as shown by Ulrich (1911), Butts (1940), and Miller and Fuller (1954). Ulrich (1911), Schuchert (1924), and Dunbar (1949) have shown that those fossil assemblages in the rocks below the Knox unconformity and those overlying the erosion surface are distinctly different. However, this change in fossil assemblages should be expected because of the duration of time consumed by emergence, regional tilting, possible folding, erosion (truncation), and resubmergence of the area.

The boundary between the Cambrian and Ordovician is conformable at most places. In the light of the above observations it appears that the Knox unconformity truly marks the boundary between the Lower and Middle Ordovician.

Origin of Knox Dolomites

Many investigators have concluded that the Upper Cambrian and Lower Ordovician dolomites of the Knox Supergroup are primary dolomites. Others have proposed that these formations are replacement dolomites. The origin of thick sequences of stratigraphic dolomite that grade laterally into limestone creates many problems. Many stratigraphers have concluded from field relationships that the dolomite facies formed closer to ancient shorelines than did the laterally equivalent limestone facies (Dixon, 1907; Van Tuyl, 1918; Hatch et al., 1938; Cloud and Barnes, 1948; Rittenhouse, 1949; Fairbridge, 1957; and Brinkmann, 1960). They postulate that the limestones were deposited where the water was colder and deeper. Evidence of silica in the non-dolomitic limestone facies (Chilingar, 1953) suggests a lower alkalinity, favoring precipitation of calcium salts, but not of magnesium (Chilingar, 1953, 1956c). This seems to be exactly the opposite of the situation reported by Cooper (1956) relative to the Knox Dolomites. These dolomites are moderately siliceous (2.5 to 12%) whereas the equivalent limestones are low in silica content. Cooper used these observations to demonstrate that the Knox Dolomites did not originate by replacement of limestones. It seems impractical if not impossible to change limestones into dolomite because of differences in silica content of the two rock types. Therefore, Cooper concluded that this was significant evidence to assume that the dolomites were primary, as were the limestone facies further removed from the ancient shoreline.

The stratigraphic relationships of the Knox Supergroup and equivalent limestone facies across the outcrop belts in the southern Appalachians illustrate the interrelationships of the depositional environment of these carbonate facies (Cooper, 1945 and 1956; and Dunbar and Rodgers, 1957). The Knox Supergroup, which includes in ascending order the Maynardville (Dolomite) Limestone, the Copper Ridge, the Chepultepec, and the Lambs Chapel Dolomites (Longview-Kingsport-Mascot Dolomites, undifferentiated) crop out in the northwestern outcrop belts, and their limestone equivalents, the Conococheague and Jonesboro Limestones, crop out in the southeastern outcrop belts. If the above-mentioned generalization about dolomite forming closer to ancient shorelines than contemporary limestones is valid, it would appear that there was a northwestern source of magnesium-rich waters and near-shore environments to the north where the dolomites occur and normal carbonate deposition to the south. Cooper (1956) assembled chemical data on these Cambro-Ordovician carbonate rocks that further corroborates this interpretation. He stated that this sequence of dolomites is primary dolomite deposited from sea waters that contain dissolved $Mg(HCO_3)_2$, which under the proper environmental conditions of salinity, temperature, pressure, and alkalinity will replace calcium as the precipitating base. Dunbar and Rodgers (1957) indicate that the Knox Dolomites were of primary origin. Yet others have considered the possibility of penecontemporaneous replacement origin of the dolomites from limestones dolomitized before lithification.

In the present investigation detailed study of the Copper Ridge Dolomite suggests that it is not a primary dolomite. From the well cuttings and thin sections the dolomite has a sucrosic texture, consisting of granular, coarse grained (euhedral and subhedral) crystal sizes ranging from 5 microns (not common) to more than 100 microns (average 25-50 microns), with vuggy porosity. Sucrosic dolomites generally are not considered primary dolomites (Hohlt, 1948; Fairbridge, 1957). A study of the sucrosic dolomites of the Mississippian Charles Formation by Parker (1956) and Edi (1958) reveals varying degrees of dolomitization. The nature of the porosity and the characteristics of sucrosic dolomite have been described fully by Waldschmidt et al. (1956) and Murray (1960). These authors have concluded that sucrosic dolomites are replacement dolomites.

Primary dolomites have been described by numerous workers, but nearly all primary or penecontemporaneous dolomites described to date were deposited as fine-grained dolomite muds (1 to 5 microns) in low-energy supertidal environments (Wells, 1962; Shinn, 1964; Deffeyes et al., 1965; Illing et al., 1965; and Kinsman, 1965). Coarse-grained primary dolomites have not been described from recent sediments.

Dolomitization of the sucrosic dolomites of the Copper Ridge is so complete that it is extremely difficult to find relic fabrics of the original limestone in well cuttings. However, from examination of core slabs and thin sections of the Copper Ridge Dolomite, the relic fabric of the parent rock was observed, thus proving that the Copper Ridge is a replacement (secondary) dolomite. The parent limestone rock type was predominantly a fossiliferous calcarenite with occasional fine-grained lime mud layers scattered throughout the section. The fossiliferous relic fabric is mostly that of algal structural remains. These are not the layered algal mat material, but remains of algal stromatolite structures. Numerous workers have described algal mat and stromatolite structures from recent sediments (Black, 1933; Young, 1935; Ginsburg et al., 1954; Ginsburg, 1957 and 1960; Rezak, 1957; Logan et al., 1964; and Roehl, 1967). Harris (1966) described algal stromatolite remains throughout the entire section of the Copper Ridge Dolomite in Union and Claiborne counties in Tennessee. Other fossil fabrics were observed, the most common of which were fragments of brachipod shells. Because there have been no discoveries of primary dolomite fossil remains of these types defined to date, there is no reason to expect that these organic fabrics (algae, brachipods) found in the Copper Ridge were composed originally of anything but aragonite or calcite. Oolites are present in some layers and quartz grains are scattered throughout most of the section.

The deposition of the parent rock of the Copper Ridge Dolomite was close to a low-energy, intertidal, mud flat environment. Calcarenite deposition probably was in shallow water somewhat removed from this intertidal area where fossiliferous debris, oolites, and quartz grains were concentrated by higher energies.

There is no evidence from observed thin section data to date the time of dolomitization. Because the Copper Ridge Dolomite is the only formation that was studied in thin section, it is not known whether the other Knox Dolomites are replacements. However, from the facts available in the literature on the fossil content in these formations it appears that these rocks were deposited as limestones and later replaced by dolomite. Whether dolomitization occurred during diagenesis (penecontemporaneous dolomitization) or after diagenesis and lithification (replacement) is not clear. However, the time of the dolomitization probably occurred before the deposition of the overlying formations which are predominantly limestones. If this is true, dolomitization occurred during the early Ordovician.

Cambro-Ordovician Stratigraphic Relationships of Central Ohio

In central Ohio the Chazy Limestone was deposited upon the Knox unconformity surface. The Chepultepec and Lambs Chapel Dolomites had been eroded from the area, exposing the Copper Ridge Dolomite at the erosion surface. Figure 4 includes two regional stratigraphic cross sections, hung from the top of the Middle Chazy Limestone, and extending across Ohio. These illustrate the truncation of beds at the erosion surface. The position of these regional cross sections is shown on Figure 2.

In Figure 4, cross section X-X' (data taken from cross section published by Calvert, 1965) shows the regional stratigraphy of the Upper Cambrian and Lower and Middle Ordovician from west to east across central Ohio. The Chepultepec Dolomite is present to the east and west but is absent in central Ohio, thus demonstrating the existence of a structural high in pre-Chazy time. This structural high is called the Waverly arch (Woodward, 1961), the trend and magnitude of which are shown on Figure 8. The presence of the relatively thick truncated sections of the Chepultepec on the flanks of the Waverly arch leaves little doubt that it was deposited originally over the entire state. Further to the east and southeast, as mentioned by Calvert (1962), the Lambs Chapel Dolomite may subcrop at the Knox unconformity surface.

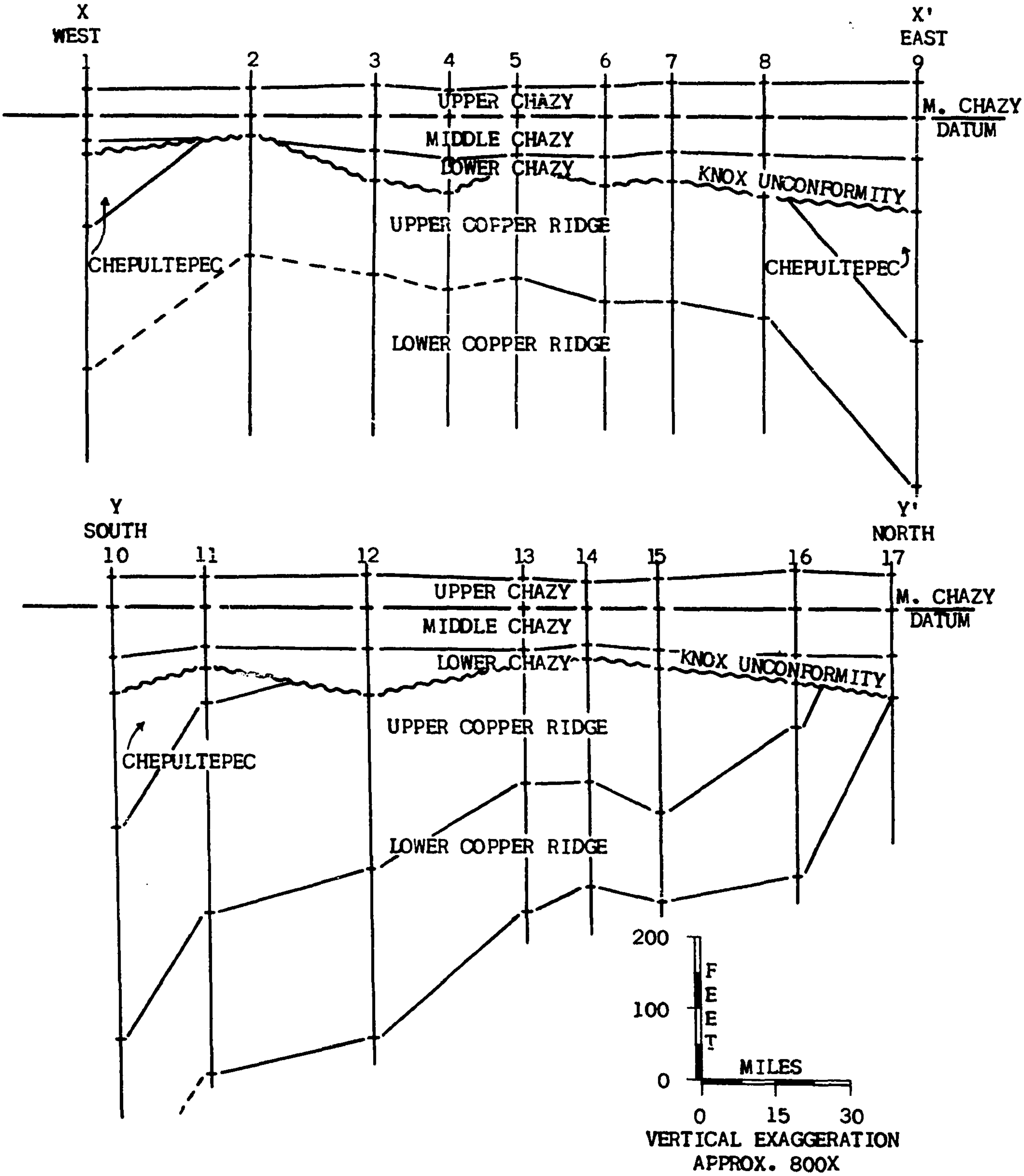


Figure 4. Regional Cross Sections of Upper Cambrian and Lower Ordovician rocks in Ohio showing significance of Knox Unconformity. Data from Calvert, 1964 and 1965. (See Figure 2 for location of the cross sections.)

The Lower Chazy is absent to the west over the erosional remnant high on the Knox unconformity. The size and scale of the cross section greatly exaggerates the size of the erosional remnant due to the spacing of wells. However, in the local study (in western Morrow County and eastern Marion County) these erosional remnants are numerous and the Lower Chazy was deposited in the valleys and lowlands surrounding these highs. The lower hills were covered by Lower Chazy sediments and the higher dolomite hills were not covered by sediments until Middle (and Late) Chazy time.

Cross section Y-Y' (data from Calvert, 1964) illustrates the regional stratigraphy of the Cambro-Ordovician sediments from south to north through central Ohio. This cross section shows the progressive truncation of the Chepultepec Dolomite, the Upper Copper Ridge Dolomite, and the Lower Copper Ridge Dolomite from south to north respectively. The truncation of the above-mentioned formations probably was caused by the rise of the Waverly arch as indicated on cross section X-X'. These formations undoubtedly extended much further to the north when deposited. The Lambs Chapel Dolomite does not subcrop in the southern part of Ohio, as indicated by the cross section of Calvert (1962).

Figure 5, subcrop map on the Knox unconformity (modified from Calvert, 1965) shows the subcrop of the Upper Cambrian formations in Ohio. Although this map is generalized, the subcrop of the various formations is based on all available data at the time the map was drawn. This map shows the progressive truncation of the Chepultepec and the Upper and Lower Copper Ridge Dolomites regionally throughout Ohio. These subcrop patterns are consistent with the regional cross sections X-X' and Y-Y' in Figure 4.

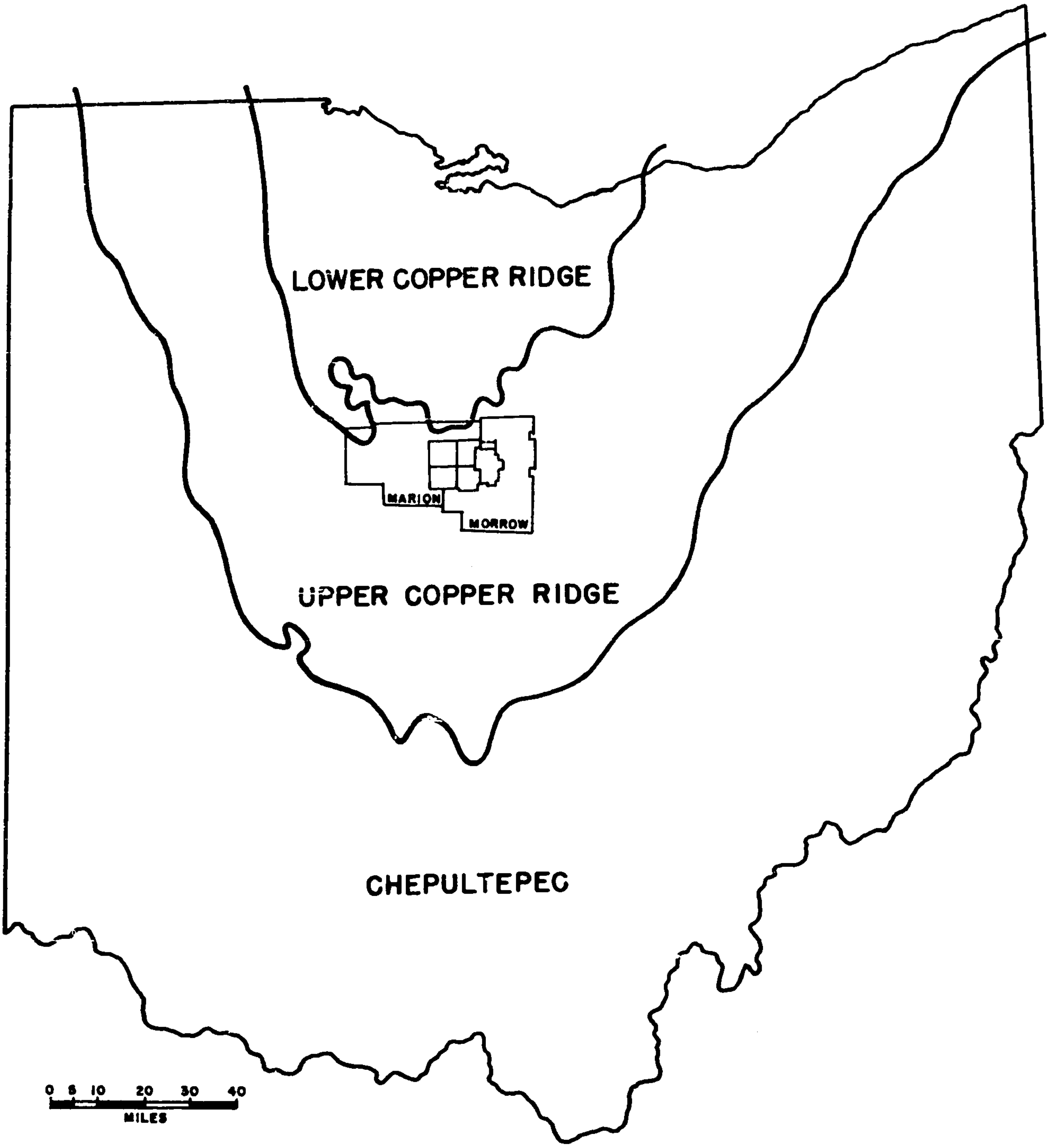


Figure 5. Knox Unconformity Subcrop Map of Ohio, showing location of study area. (Modified from Calvert, 1965).

Local Stratigraphy

In the subsurface of Marion and Morrow Counties, lithologies of the formational units are almost identical with their counterparts in the outcrop of the Appalachian Valley in Virginia and Tennessee. Because of this lithologic consistency over a distance of several hundred miles, it may be assumed that the physical and chemical conditions of their depositional environments were similar. These formations are considerably thinner in the subsurface. The Lambs Chapel and the Chepultepec Dolomites, which occur below the Knox unconformity in other parts of the state, are absent in Morrow County and north-central Ohio (see Figure 5). The Copper Ridge Dolomite subcrops at the Knox unconformity in the region where the Beekmantown Group is absent. The ancient Knox topographic surface, characterized by numerous erosional remnants scattered over the highly eroded terrain, is carved in the Copper Ridge Dolomite. The existence and trends of the dolomite hills that project above the erosion surface are directly related to pre-erosion structural conditions. The paleo-drainage pattern likewise was structurally controlled. Many of these erosional remnants had a paleotopographic relief of 100-150 feet and their tops remained emergent during the deposition of the Lower Chazy Shale-Limestone-Dolomite and in some cases during Middle Chazy deposition.

The Lower Chazy is made up of interbedded shales and limestones, shales comprising at least 50 to 60 percent of the section. Because of its high argillaceous content and variable thickness, the Lower Chazy was susceptible to differential compaction, once an overburden was deposited. Thus, the Middle and Upper Chazy, and to a lesser extent, the still higher Lowville sediments, exhibit a draping effect over the buried hills of the

Copper Ridge. The net result of the differential compaction within the Lower Chazy is best demonstrated by the Middle Chazy Limestone. Differential compaction of this shaly section was simultaneous with deposition of the overburden. Thus, the depositional interface was not a flat surface, but, rather, a subdued replica of the unconformity surface. Differential rate of sedimentation gradually filled the low areas. At a bentonite marker bed in the base of the Eggleston Limestone, about 450 feet above the Knox unconformity, compensatory deposition in the low areas has virtually eliminated the effects of differential compaction. At the top of the Trenton Limestone (50 to 75 feet higher in the section), practically all of the draping effect due to differential compaction of the Lower Chazy is gone.

Sample and Core Studies

Samples and cores from 35 wells in Marion and Morrow counties were studied in detail to determine the lithologic characteristics of the stratigraphic units. The locations of wells from which cuttings and cores were studied are shown on Figure 2. There are no wells in the study area with a complete stratigraphic section. Wells exhibiting a thick Copper Ridge Dolomite section generally have little Lower Chazy Shale-Limestone-Dolomite because these wells were drilled into the erosional remnants. Conversely, where the Copper Ridge section is thin, the Lower Chazy is typically well-developed. The thickness of the Lower Chazy depends upon whether the well is in a valley (thickest section) or on the flank of a dolomite high (thinner section). Sampled wells are distributed throughout the entire area of detailed study in order to detect any lateral changes that might occur within individual stratigraphic units. Finally, in and around the Denmark Pool (Sections 28 and 33 in Canaan Township, Morrow County) samples were studied in nearly every well in order to get a better understanding of the lithologic characteristics of the Copper Ridge Dolomite (reservoir rock) from a productive area.

Figures 6 and 7 are representative logs from Morrow County illustrating important stratigraphic units involved in this investigation. The discovery well, Orrie Myers-1, (Figure 6) is in Section 33 in Canaan Township, and illustrates one of the thickest Copper Ridge sections because it was drilled into one of the highest erosional remnants. The Lower Chazy and most of the Middle Chazy are absent. A well drilled into a topographic low (Hines Norton-1, Section 33, Canaan Township), illustrates thick Lower Chazy and Middle Chazy sections above the Copper Ridge (see Figure 7).

In the area of investigation the Copper Ridge is divisable into six lithologic zones which can be identified and correlated on the gamma ray-sonic logs. These zones have been designated from base up as A, B, C, D, E, and F. Zone A (Figure 7) is the upper part of the Lower Copper Ridge Dolomite of the Appalachian Valley of Virginia. Less than 10 percent of the wells penetrated the Copper Ridge into zone A. The other zones, B through F (Figures 6 and 7) are all part of the Upper Copper Ridge Dolomite. In the study area only zones D, E, and F subcrop at the Knox unconformity.

Zone A, the upper part of the Lower Copper Ridge Dolomite, is composed of dark gray to brown, fine to coarse crystalline, argillaceous, sandy dolomite with a minor amount of chert; porosity is generally poor.

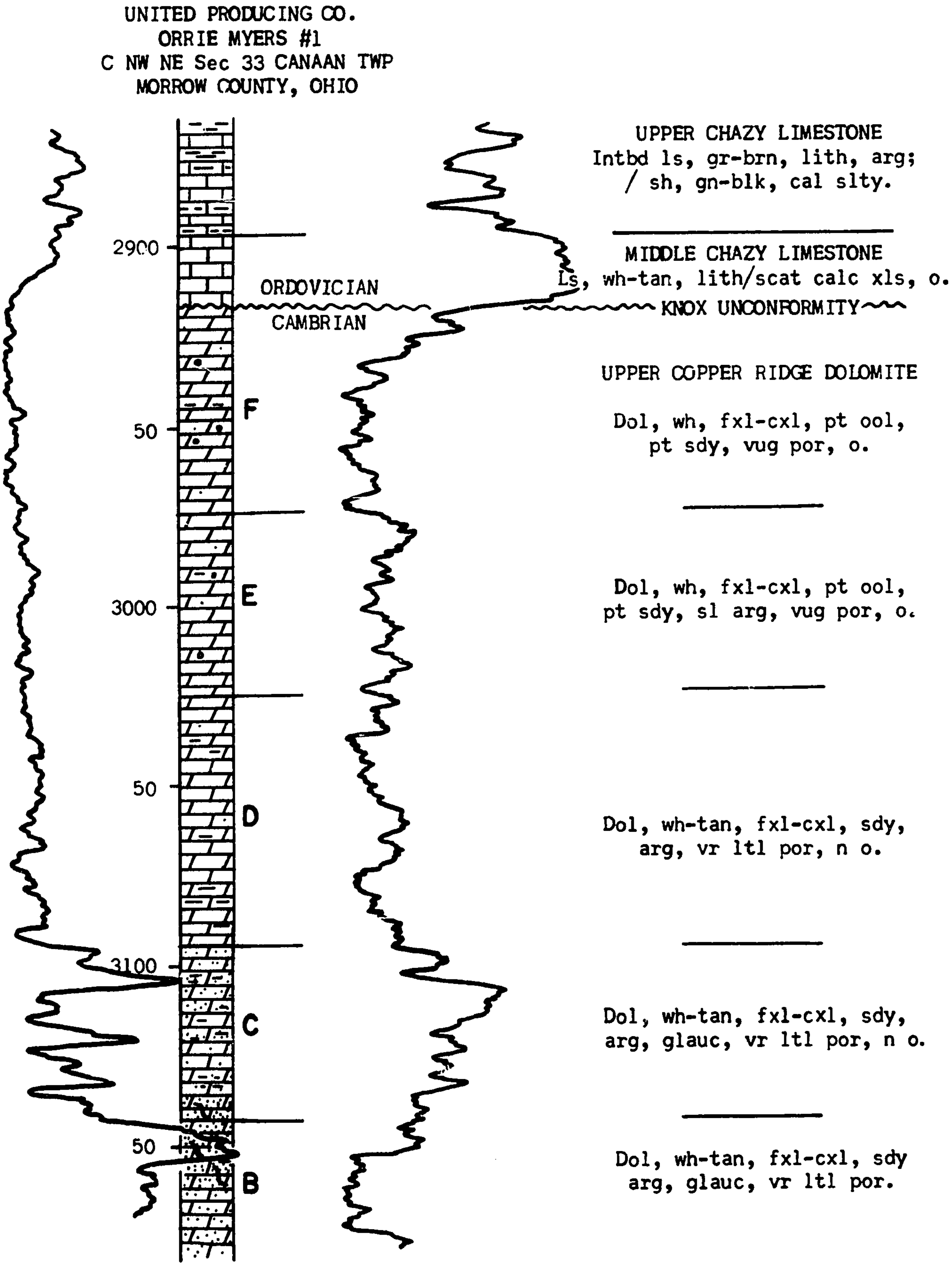


FIGURE 6. Type log of Upper Cambrian - Lower and Middle Ordovician, showing sample descriptions and alphabetized zones of the Upper Copper Ridge Dolomite.

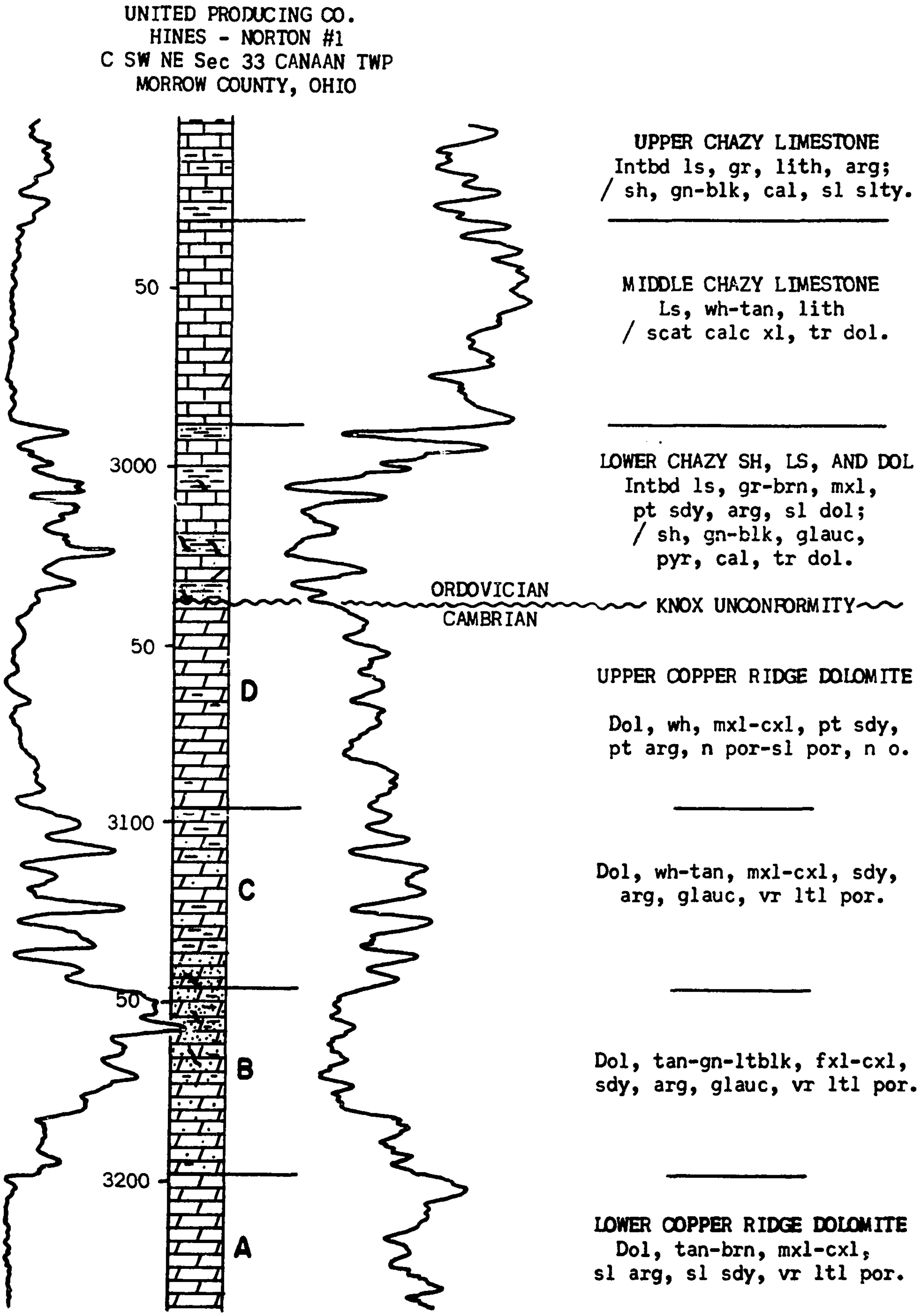


FIGURE 7. Type log of Upper Cambrian - Lower and Middle Ordovician, showing sample descriptions and alphabetized zones of the Upper Copper Ridge Dolomite.

Zones B and C (zone B is not to be confused with the "B Zone" of Calvert, 1964 and 1965) are the lower zones of the Upper Copper Ridge Dolomite. They consist of white to tan to greenish brown, fine to coarsely crystalline, glauconitic, sandy, argillaceous dolomite with little porosity. B is more glauconitic and sandy than C. Each zone is about 50 feet thick.

Zone D consists of white, fine- to coarse-grained, partly sandy, argillaceous dolomite. The porosity in zone D is higher than that of zones A, B, and C. It is about 70 feet thick and subcrops in the topographically low areas and extends to the top of some of the lower erosional remnants. Although this zone subcrops at the Knox unconformity and was subjected to a prolonged period of weathering and leaching, it exhibits a lower order of porosity than the two overlying stratigraphic units (E and F).

Zones E and F consist of white, granular, medium to coarsely grained, partly oolitic, partly sandy, slightly argillaceous dolomite. These sucrosic dolomites have well-developed vuggy porosity. Zone E is approximately 50 feet thick. Zone F includes all of the section to the top of the Copper Ridge Dolomite and ranges in thickness up to 110 feet. Zone E subcrops around the flanks of many of the higher dolomite hills and caps some of the smaller erosional remnants. Zone F subcrops only at the top of the highest dolomite hills.

The porosity variations within the Copper Ridge Dolomite are important. The highest porosity (vuggy porosity) was found in zones E and F. Zones D, E, and F were exposed to weathering and leaching at the surface for an extended period of time. In zone D the porosity is not nearly as high as in zones E or F, but this is expected because E and F are found at the tops of the erosional remnants or on the higher flanks and D is only exposed in the valleys. Zones A, B, and C do not have high porosity, probably because of the lack of subaerial exposure in the area. The lithologic character of the zones D, E, and F might have played a large role in the amount of porosity developed. Zones E and F were the only zones where oolites were observed. In general, these zones are much cleaner (pure dolomite) than the underlying zones which have varying amounts of argillaceous material. Zones E and F are not as massive as zone D. These factors, lithology and bedding characteristics, together with the different topographic positions in which zones D, E, and F were exposed to weathering and leaching, could account for the vuggy porosity in E and F, whereas D is much less porous.

In general, the Copper Ridge Dolomite in the subsurface of Ohio differs from that exposed at the outcrop, in that there is little or no chert in the Ohio section whereas chert is common throughout the exposed sections. Few fossils or fossil fragments were observed in the Copper Ridge well cuttings and cores. Questionable fossil fragments with algal-like structures were observed in a core in zone B. Harris (1966) reported algal stromatolites in the Copper Ridge Dolomite in surface outcrops in Tennessee.

The Knox unconformity is a sharp boundary between the white, porous, crystalline dolomite of the Copper Ridge and the greenish and blackish, glauconitic, sandy shales and thin, gray carbonates of the Lower Chazy.

The Lower Chazy formation represents a transgressive sequence that was deposited in an erratic pattern in the valleys which separated the numerous dolomite erosional remnants. It is composed of interbedded shales, limestones, and thin dolomite beds. At the outcrop (in Virginia) the base is marked by a thin conglomeratic zone. This zone may be present in the subsurface of Ohio, but it is difficult to identify from well cuttings. The basal zone in the subsurface ranges from a highly argillaceous, sandy, glauconitic dolomitic conglomerate to a dolomitic, glauconitic, sandy shale. Interbedded with and slightly above the basal shales and/or dolomite conglomerates of the Lower Chazy are thin, gray to brown, sandy, argillaceous dolomite beds and thin beds of limestone that are gray to brown, finely crystalline to lithographic. The latter beds are sandy and glauconitic. The middle and upper parts of the Lower Chazy contain thick shaly sequences with thin interbedded limestones. These shales are green to black, glauconitic, calcareous, and sandy with occasional traces of pyrite. The thin limestones consist of white to gray to brown, dense to finely crystalline, sandy, argillaceous and slightly dolomitic limestone.

Maximum thickness of the Lower Chazy in the study area is about 65 feet. This formation is composed of at least 60 percent greenish-black, glauconitic shales and is a highly compactable stratigraphic unit.

The Middle Chazy Limestone rests conformably upon the Lower Chazy and is unconformable at the base only where Copper Ridge Dolomite hills project through the Lower Chazy. It is 50 feet thick and consists of white to tan, lithographic, partly argillaceous limestone with a few calcite crystals (birdseyes) scattered throughout. In some local areas dolomite replacement occurs near the base of the limestone.

The Chazy and Copper Ridge formations can be identified readily on the gamma ray-sonic logs. In addition, most of the zones within the Copper Ridge Dolomite can be identified readily from the logs. In general, the Copper Ridge Dolomite has a low order of gamma-ray radiation. The Lower Chazy formation has a fairly high gamma-ray radiation, as compared to the Middle Chazy, the latter of which is similar to the Copper Ridge Dolomite in radioactive intensity.

Detailed Stratigraphic Profiles

Numerous cross sections were constructed for the purpose of determining the stratigraphic relationships of Cambrian and Ordovician formations. Plate I, stratigraphic cross section A-A', is a detailed profile beginning in the northern part of north central Canaan Township (Section 4) and extending southward through Canaan and Cardington townships to lot 11 in southern Cardington Township (Figure 2). A second regional cross section, Plate II, stratigraphic profile B-B', begins in the western part of southern Canaan Township (Section 30) and extends eastward through Canaan and Gilead townships to Section 6 in eastern Gilead Township. These regional cross sections intersect at the discovery well, the Orrie Myers-1, in Section 33 in Canaan Township. Each section consists of more than 30 wells and together the several sections form a framework into which all other wells have been correlated.

The top of the Middle Chazy was used as the datum of reference on these two profiles in order to remove the effects of post-depositional regional tilt. In so doing, however, the pre-unconformity structure of the Copper Ridge was distorted (accentuated) due to differential compaction of the Lower Chazy.

Zones D, E, and F of the Upper Copper Ridge Dolomite subcrop at the Knox unconformity throughout the entire area, as shown on cross sections A-A' and B-B'. It may be noted that zone F appears only as a cap on the highest erosional remnants in such wells as 2861, 10, and 1554 on cross section A-A', and wells 10, 155, 248, 275, and 152 from west to east on profile B-B'. On profile A-A' zone E caps the erosional remnant in well 2459, and in section B-B' in wells 2720, 189, 424, and 1562. Zone E subcrops on the flanks of erosional remnants as illustrated in wells 1631, 16, 1951, 1384, and 555 on cross section A-A' and wells 12 and 96 on profile B-B'. Zone D subcrops around the flanks of the higher erosional remnants and in the valleys surrounding the hills. In a few cases zone D caps some very low erosional remnants.

The sediments overlying the Middle Chazy exhibit a minor amount of thinning directly above the highest hills of the Copper Ridge. More rapid sedimentation of the post-Lower Chazy sediments over these low areas practically eliminated the effects of differential compaction by the time 450 feet of overburden had been deposited. Examples of local depositional thinning of the overburden sediments may be noted in wells 2681 and 10 on cross section A-A' and wells 10, 155, 248, 275, and 152 on profile B-B'.

STRUCTURE

Introduction

Four principal north-trending structural axes are present in the state of Ohio, as shown on Figure 1. The trend and position of the Cincinnati-Findlay arch are in the western portion of the state. In all probability this was an incipient low arch in Cambro-Ordovician time and did not achieve its present structural prominence until Late Paleozoic time. The Waverly, Newark, and Cambridge arches are in central and eastern Ohio. None of these achieved the ultimate structural or regional significance of the Cincinnati arch. In fact, the Waverly and Newark arches are of such low structural relief that selective isopaching is the only means by which they can be recognized. It should be noted that the area of investigation in Morrow County directly overlies the Waverly arch (Figure 8).

Regional Structure

The regional structural development in Ohio can be ascertained from studies made by Cohee (1948) in Michigan and environs; Fettke (1948) in Virginia and Tennessee; Freeman (1953) in Kentucky and vicinity; Shearrow (1957) in Ohio; Woodward (1961) in Ohio and vicinity; and Calvert (1962, 1963, 1964, 1965) from Ohio and adjacent states. Using data from these references, it is apparent that there were several episodes of tectonic activity in Ohio.

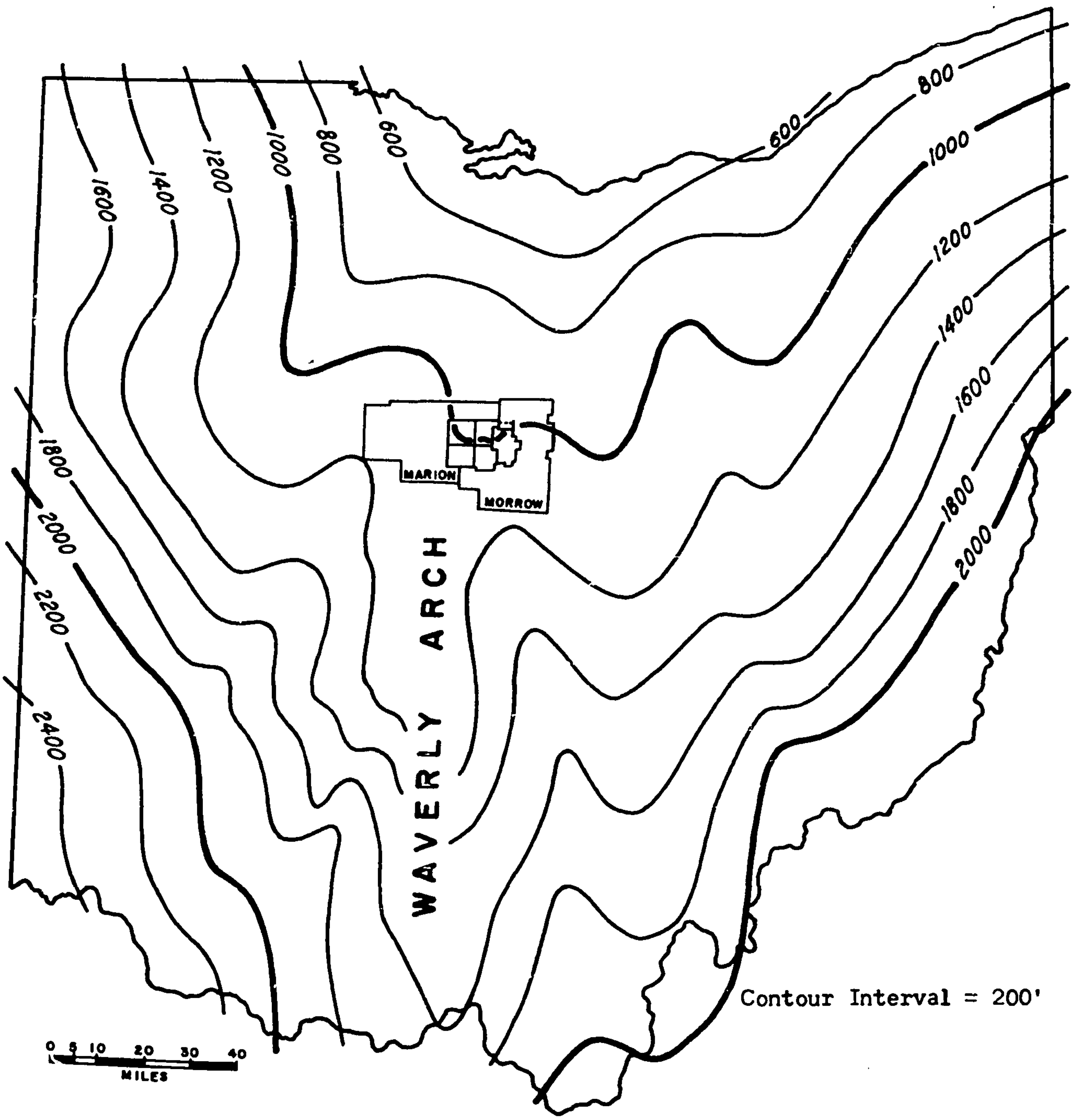


Figure 8. Isopachous Map of the Sauk Sequence* in Ohio, showing location of the study area. (From Calvert, 1963).

*(Knox Unconformity to Precambrian)

Pre-Ordovician Structure

Cambrian structural development in Ohio is illustrated in Figure 8 by an isopachous map of the Sauk Sequence (from the basement complex to the Knox unconformity) (Calvert, 1963). This sequence thins along a north-south axis in central Ohio indicating that a positive area, older than the Cincinnati arch, existed during the Cambrian. Woodward (1961) named this buried structure the Waverly arch. It originated during Middle Cambrian, but active structural uplift did not occur until Early Ordovician at which time Beekmantown rocks and several hundred feet of Lee Valley (Copper Ridge Dolomite) were stripped from its summit. In eastern Ohio, two additional significant Cambrian structural axes can be inferred from this isopachous map. These arches, the Newark arch and the Cambridge arch (from west to east, respectively) are probably younger and less prominent than the Waverly arch. Their growth was apparently complete prior to the deposition of Middle Ordovician sediments.

Thickening of the Sauk Sequence to the southwest of the Waverly arch indicates that the Cincinnati arch was not present in Cambrian time. A similar rate of thickening to the southeast of the Waverly arch suggests that the Appalachian basin was subsiding slowly at this time.

Ordovician and Post-Ordovician Structure

The present structural configuration of the Knox unconformity is shown on Figure 9 (Calvert, 1965). Generally, the regional strike is north-south and the dip is about 50 feet per mile to the east.

It is generally agreed that this regional tilt to the east is due to either apparent growth of the Cincinnati arch in western Ohio or more probably to subsidence of the southeastern portion of the Appalachian

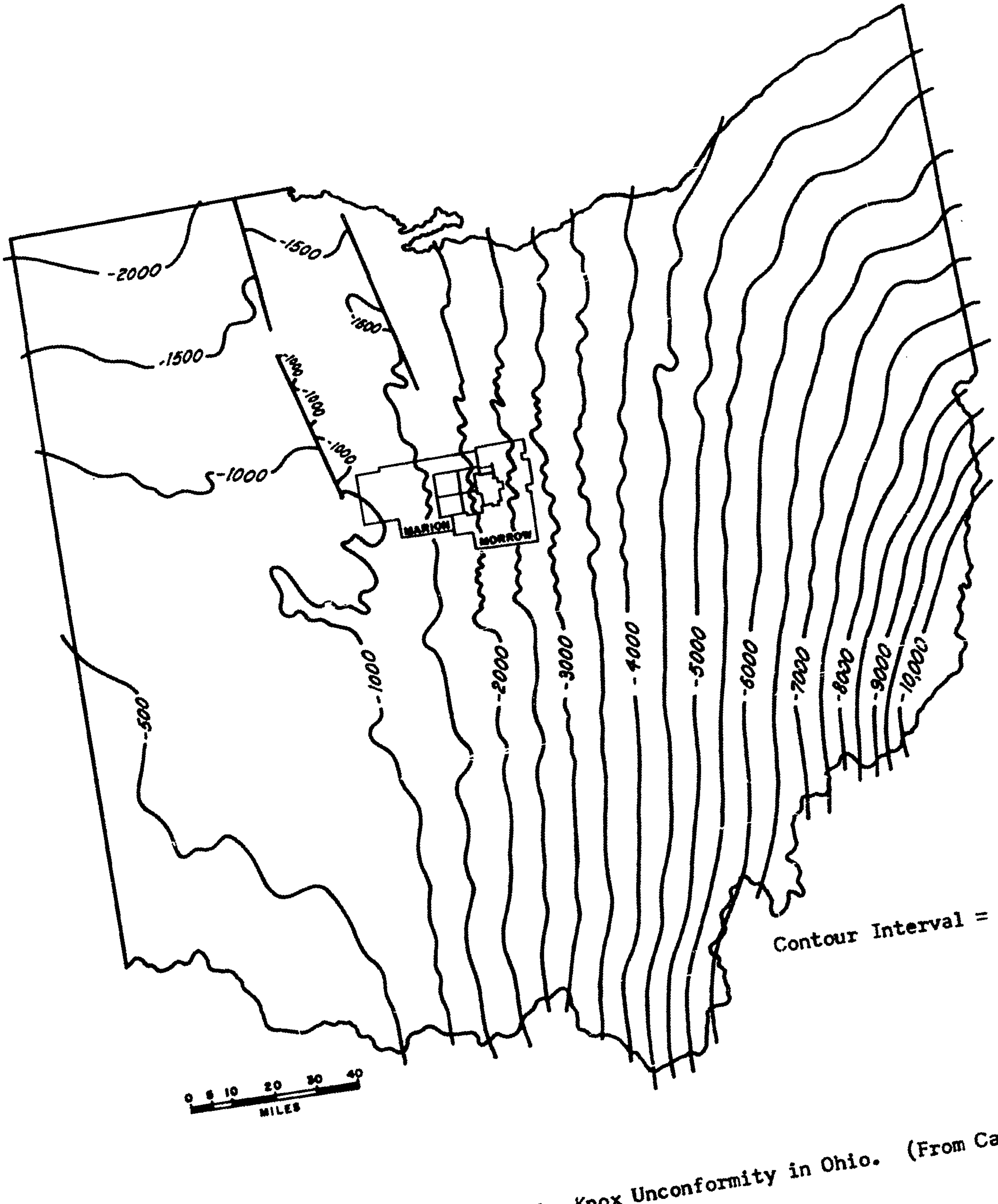


Figure 9. Structure Map of the Knox Unconformity in Ohio. (From Calvert, 1965).

basin. The position of the Cincinnati arch of north-central Kentucky extends northwards into southwestern Ohio and, thence, northwestward into east-central Indiana.

There has been some controversy over the position, extent, and significance of the Cincinnati arch in Ohio. Orton (1888) and Phinney (1891) concluded that it is a figment of geologic imagination in western Ohio. Carmen and Stout (1934) considered the Cincinnati arch the dominant structural feature in western Ohio. They demonstrated that it extends northward from Tennessee and Kentucky into southwestern Ohio where it divides into two branches. One segment continues northeastward where it connects with the Findlay arch of north-central Ohio (Figure 1). The second branch extends northwestward across northern Indiana where it is known as the Kankakee arch. Wilson and Sterns (1963) show the Cincinnati arch extending northward and connecting with the Findlay arch, in accord with the findings of Carmen and Stout. However, Lockett (1947), Green (1957), Woodward (1961), and Shearrow (1966) all agree that the Cincinnati arch does not connect with the Findlay arch. They indicate that it is present only in the southwestern corner of Ohio. These men further indicate by the use of structure maps that the Cincinnati arch extends northwest into eastern Indiana and not northeast into Ohio. This implies a slight sag between the Cincinnati arch and the southern plunging Findlay arch in western Ohio. It is the writer's opinion that the data and illustrations of Carmen and Stout on the position and extent of the Cincinnati arch are the most reliable. Wilson and Sterns (1963) as well as Calvert (1964) are in complete agreement with Carmen and Stout. Further evidence, used to substantiate this conclusion, can be found in the outcrop pattern of the Ordovician and Silurian rocks on the geologic map of the state of Ohio, which indicates that the Findlay arch and the Cincinnati arch are connected.

There is some question about the origin of the Cincinnati arch. Some believe it to be a compressional structure, but the majority agree that the region of the Cincinnati arch appears structurally level and essentially undisturbed. Therefore, this structural high "grew" at the expense of subsidence of the bordering areas to the east, north, and west. The subsidence of the Appalachian, Michigan, and Illinois basins was not shared by the broad central platform area of the Cincinnati arch which remained tectonically stable. The general regional north-south strike and gentle eastward dip, as illustrated on Figure 9, are related to the subsidence of the Appalachian basin rather than to uplift of the Cincinnati-Findlay arch complex. The hingeline separating the Cincinnati-Findlay arch complex of western Ohio from the Appalachian basin in eastern and southeastern Ohio (Owens, 1967) occurs about 30 miles west of the axis of the buried Waverly arch (Figure 1).

Local Structure

The influence of the regional structure in Morrow County and environs can be seen by the general north-south strike and eastward dip of the rocks above and below the Knox erosion surface. Below this unconformity numerous small anticlines and synclines are completely masked by the effects of Late Paleozoic regional tectonics as demonstrated by a structure map with a contour interval of 500 feet (see Figure 9). The eastward regional dip is superimposed over the pre-unconformity structure.

Knox Unconformity Structure

A structure map of the Knox unconformity surface was constructed, using a contour interval of 20 feet, to illustrate the present structural configuration of the erosion surface (subcrop of Copper Ridge Dolomite) in northwestern Morrow County and environs. Numerous structural trends which coincide with erosional remnant "hills" and valleys are apparent throughout the investigated area.

Regional strike is north-south and the dip is to the east. The most conspicuous features are the southeastward-trending "hills" and "valleys", shown in Plate III. The higher elevations occur along the western boundary of the map, where they are between 1,800 and 1,900 feet below sea level. The Knox erosion surface slopes gently towards the eastern edge of the map where the elevations are 2,300 feet below sea level. Therefore, the slope of the Knox unconformity surface from west to east is approximately 500 feet in 9 miles or one-half degree per mile. The terrain of the erosion surface is not flat, as illustrated by the rough and irregular topography.

The geometric configuration and distribution pattern of the erosion remnant "highs" and valley areas of the Knox unconformity is genetically related to the pre-unconformity structure. These hills originated because of differential weathering and erosion of the Copper Ridge Dolomite while it was subaerially exposed. The magnitude of the hills is directly related to the pre-Knox unconformity structure, which, in turn, controlled the development and distribution of the drainage system that dissected this dolomite terrain. Within the drainage system there were many divides above the base level of the streams. These erosional remnants are aligned along a northwest-southeast trend throughout the entire area. Their size and geometric configuration is directly related to the size of pre-unconformity structures.

The slopes between the valleys and hills are much steeper and more irregular than the gentle regional tilt to the east. The slopes of the hills vary from less than one degree to seven or eight degrees. A conspicuous erosional remnant occurs in Section 33, Canaan Township. The slope from the top of this remnant to the adjacent valley floor between the discovery well (topographically the highest well in Section 33) and the well immediately to the south is five degrees. Although these figures do not sound extremely high, they serve to illustrate the irregularity of the Knox unconformity surface, an undulating terrain covered with numerous northwest-southeast-trending erosional remnants between low-lying valley floors.

The map of the Knox unconformity clearly illustrates the true magnitude of the erosional remnants even though the effects of present structure have not been removed. A paleotopographic map (Plate VIII) was drawn to show the topography and drainage pattern that existed on the Knox unconformity before Late Paleozoic tilting. Such a map shows the true shape and distribution pattern of erosional remnants but exaggerates their respective heights.

Pre-Knox Unconformity Structure

It is probable that the geometric configuration and distribution of the erosional remnants beneath the Knox unconformity are genetically related to both pre-unconformity structure and rock lithology.

The break in stratigraphy at the Knox unconformity suggests ample time for deformation and erosion during the hiatus.

In mapping the pre-unconformity structure of the Copper Ridge Dolomite the effects of regional strike and dip must be removed. The paleostructure of the pre-unconformity formations was reconstructed (as shown on Figure 3) by isopaching the stratigraphic interval between the base of zone D in the Copper Ridge Dolomite and the top of the Middle Chazy Limestone (see Figures 6 and 7).

Where there is a stratigraphic unit between the surface of an unconformity and a marine horizon at the top of the isopached interval that is capable of significant differential compaction during diagenesis, the upper surface will not maintain its essentially horizontal depositional attitude. With this mapping technique the upper boundary is restored to its approximate depositional attitude and the pre-unconformity structures are exaggerated by the amount of differential compaction that occurred within the isopached interval.

The isopached interval shown on Figures 6 and 7 includes the Lower Chazy Shale-Limestone-Dolomite formation that was deposited with an erratic distribution pattern in the valleys and on the flanks (occasionally over the tops) of the erosional remnants. The erratic distribution pattern and irregularity in thickness are due to physical conditions (rough terrain on the Knox unconformity surface) within the depositional environment. These variations in thickness and the shaly composition of the Lower Chazy favored differential compaction during diagenesis and lithification. As a result there are compaction-formed anticlines in the sediments overlying the erosional remnants. This draping effect is greatest in the formations immediately overlying the Lower Chazy, gradually diminishes, and finally disappears, upward. This is accomplished by compensatory deposition over areas of maximum differential compaction. The upper Ordovician and Lower Silurian sediments probably exhibit uniform stratigraphic thickness in the restricted area of study and diverge systemmatically to the east, thus, obliterating all effects of differential compaction in the Lower Chazy.

Nevin and Sherrill (1929) gave two examples of differential compaction. The first occurs where sediments composed of homogenous beds of considerable lateral extent are deposited on a flat, or nearly flat, surface; the only effects of gravitational compaction would be a decrease in porosity, a decrease in thickness, and an increase in density. No structures would develop because the attitude of the beds will not change. This case applies only to the compensatory fill deposited over the Lower Chazy. However, in the second case, the sediments may be deposited on a surface of considerable relief, or may vary in character and thickness laterally, with differential compaction resulting. When sedimentation occurs on an erosion surface (presumably a surface of consolidated rocks) which exhibits local relief, the sediments deposited in the valleys and around the flanks undergo differential compaction. If sedimentation continued until the hills were buried, then the sediments that were deposited above the peaks of the hills would be compacted, as in the first case. If the top of one of these overlying beds were a marker horizon, it would have been deposited originally as a nearly flat horizon. As more deposition covered the area it would act as overburden and result in compaction of the sediments between the depositional interface and the consolidated rocks at the base of the sequence. Differential compaction would then occur in the materials deposited in and around the hills that project above the erosion surface, with maximum effect where the sediments are thickest. The marker bed also would undergo compaction but it would be, as in the first case, where the compaction is uniform. However, because the beds below were differentially compacted, the marker bed would be draped over the buried hill. Continued compaction would occur throughout the section due to added overburden and this would result in an increase in folding and closure of all horizons above the buried hill. Athy (1934) and Conybeare (1967) show similar results in studies of compaction and local structure "focalized" over buried terrains. The situation existing in Morrow County and environs is similar to those described above.

Many geologists have studied the effects of compaction of sediments during rock diagenesis. The lithologic characteristics of the Lower Chazy make it particularly susceptible to differential compaction. It is composed of more than 60% shales. The nature of the depositional surface on which the Lower Chazy was deposited also must be considered. These sediments have undergone differential compaction because of their composition. The amount of differential compaction is directly related to the thickness of the deposit and to its aerial extent.

Athy (1930) and Hedberg (1936) derived basic graphs relating variations in porosity of mudstones (shales) with depth. The curves show that the original porosity of unconsolidated shales may be as high as 80 percent, but generally is in the range of 50 to 60 percent. These figures are similar to the data presented by Nevin (1949), Emery and Rittenberg (1952), Weller (1959), Meade (1966), and Muller (1967). Water-deposited muds and clays are consolidated chiefly by compaction. Muller (1967), Athy (1930), and Hedberg (1936) indicate that the driving off of original pore water due to the action of overburden creates pressures which are effective only until the grains are driven together and the water is removed. However, the pore spaces among the grains are so minute in clays and muds that there is little free circulation of water once the grains come together. Compression, therefore, is the active factor in reducing the porosity of such sediments, and its effectiveness depends largely on the ease with which the connate water escapes. The maximum compaction occurs during the early stages of diagenesis when porosity may drop from 60 or 80 percent to 20 percent. Muller (1967) stated, "The porosity decreases continually with increasing depth of burial; very rapidly down to about 500 meters (1,500 feet) and more slowly below that depth. Only grain size, clay-mineral composition and temperature play an important role in porosity reduction below a depth of about 500 meters. At this depth the clay mud becomes a mudstone (or shale if fissile) with a porosity of about 30 percent; the total volume of the sediment having decreased by about 50 percent." The conclusions derived from graphs prepared by Athy and Hedberg are similar to those of Muller.

The amount of porosity lost during compaction of clays and shales is directly related to the amount of water removed from the sediment after burial. The reduction in sediment volume is caused chiefly by reduction in porosity, which is the equivalent of a reduction in water content. Burst (1969) observed that the water removed initially during compaction in diagenesis is caused by the weight of the overburden. The pore water (connate water) is first driven out of the pore spaces separating the grains. This removal is the most significant portion of the dehydration process. The removal of pore water by compaction during diagenesis reduces the water content to about 30% (5-10% residual pore water and 20-25% interlayer water) and is usually completed in the first few thousand feet of burial. After this point, water in the interlayer position in clay minerals is removed not by compression but by movement of water into the minute pore system by increase in temperature with depth. Finally, water may be removed from the clay lattice as sediment temperature increases. Of course, a great amount of time is essential in all stages.

Another factor involved in the compaction of mud and shale is the rearrangement of the grains in the development of closer packing. Soft clay minerals are squeezed into the interstices among the more resistant grains, which further reduces the porosity until the mud is lithified.

Draping effects of the Middle Chazy that are related to differential compaction of the Lower Chazy are illustrated on Plate IV, cross section C-C'. The northeast-southwest trend of this duplicated cross section is normal to the long axes of the hills and valleys.

Structural cross section C-C' (Plate IV) is hung from sea level and illustrates the attitude of the strata as they are today. A series of anticlines and synclines are observable within the Copper Ridge Dolomite. The angle of dip on the limbs of these structures is less than one degree. Wells which demonstrate these anticlinal structures are numbered 37, 17, 20, and 2593. Synclinal structures are depicted by well numbers

579, 2741, 10, 2844, and 2286. None of these structures are of large magnitude. The wells used in the cross section may or may not be on the axes of these several structures, and in many cases they are actually on the flanks. Wharton (1964) originally reported that the Denmark Pool (Sections 28 and 33, Canaan Township) was on the flank of a syncline.

The top of the Middle Chazy Limestone is the reference datum of stratigraphic cross section C-C' (Plate IV). The amplitudes of the Copper Ridge structures are greater in this cross section than those noted in the structural cross section. This accentuation is caused by the differential compaction of the Lower Chazy. In essence, flattening of the upper boundary of the Middle Chazy has distorted the structural configuration below the Knox unconformity. The mechanics of this are simple. For example, if the upper boundary of the Middle Chazy Limestone in well numbers 2741, 10, and 2844 (wells drilled into synclines) were adjusted from the position on the structure section to a horizontal plane, as on the stratigraphic profile, there would not be much raising or lowering of the datum. However, if well numbers 17 and 11 (wells that penetrated anticlinal structures) were so adjusted, they would have to be raised considerably more than the wells that penetrate synclines. In doing this the distortion results are equal to the amount of compaction of the Lower Chazy.

It is for the same reason that the topographic relief of the Knox unconformity is distorted on stratigraphic cross section C-C'. Structural cross section C-C', however, simulates the true amount of topographic relief on this erosion surface, except for the fact that no horizontal scale was used in drawing the profile.

Anticlines and synclines of the Copper Ridge are shown on cross sections C-C'. The anticlinal areas are structurally high and topographically low, whereas the synclinal areas are structurally low and topographically high, thus exhibiting topographic inversion. Except for vertical exaggeration, the amplitude of the structures on the structural profile C-C' are as they appear in the subsurface of Morrow County. They consist of simple crustal warps; their structural attitudes not being in accordance with those of the overlying strata of the Ordovician.

Plate V is a pre-unconformity structure map of the stratigraphic interval between the top of the Middle Chazy Limestone and the bottom of zone D of the Copper Ridge Dolomite. Numerous Copper Ridge anticlines and synclines extend across the area in a northwest-southeast direction. The synclines are represented by the thickest isopached intervals and anticlines by the thinner values.

The axes of synclinal structures shown on Plate V coincide with topographic highs on the Knox unconformity shown on Plate III. This inverted topography is substantiated further by referring to cross sections C-C'.

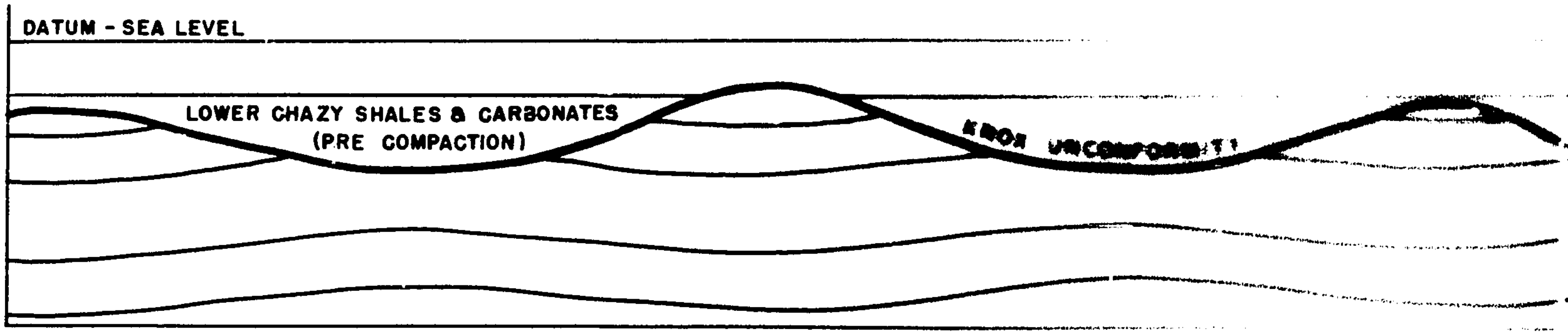
It has been recognized that differential compaction of the Lower Chazy produces an apparent vertical distortion of the amplitude of the Copper Ridge anticlines and synclines. By such differential compaction it is theoretically possible to "create" anticlines and synclines in the subjacent strata. This possibility can be evaluated by isopaching a thicker interval above the unconformity in which the effects of differential compaction are eliminated by compensatory fill.

Stratigraphic cross section D-D' (Plate VI) was drawn through seven wells shown on cross sections C-C' to illustrate factually the effects of differential compaction on the overlying strata and the pre-unconformity structures. The reference datum is a prominent bed of bentonite at the base of the Eggleston Limestone, approximately 450 feet above the Knox unconformity. In this illustration the amplitude of the Copper Ridge structures is subdued about 50 percent, but the structures are still apparent. The comparatively uniform thicknesses of the Eggleston and Trenton formations at the top of the section (Plate VI) indicate that compensatory deposition within the 450 feet of section overlying the unconformity has almost completely masked the effects of differential compaction within the Lower Chazy.

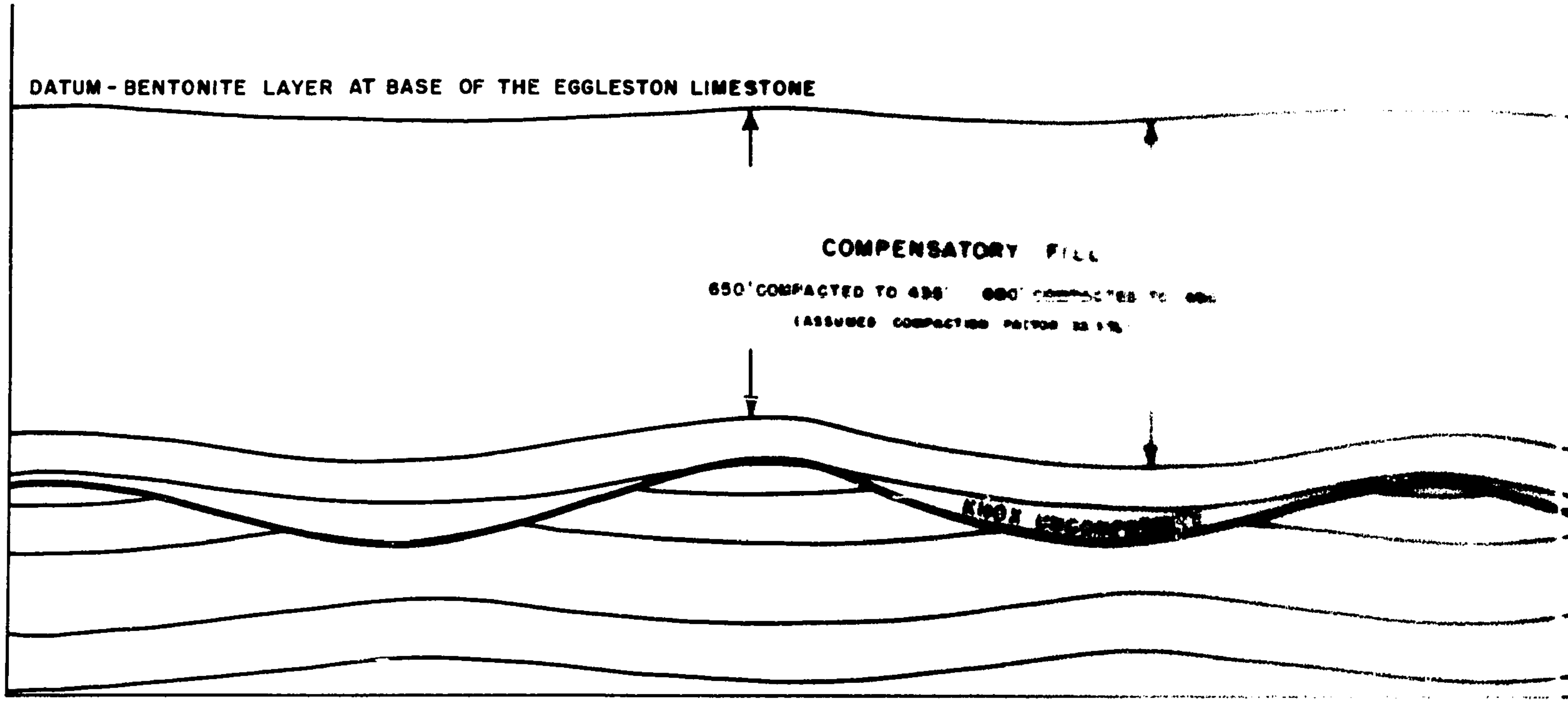
Plate VII, a pre-Knox unconformity structure map, was constructed by isopaching the interval from the base of the bentonite in the Eggleston Limestone to the base of zone D of the Copper Ridge Dolomite. This map is of a nine-section area in southern Canaan and northern Cardington townships. The anticlinal and synclinal structural axes are in the same position as shown on Plate V; however, the amplitude of the structures is greatly reduced.

Figure 10 is a series of hypothetical cross sections illustrating the effects of differential compaction within the Lower Chazy.

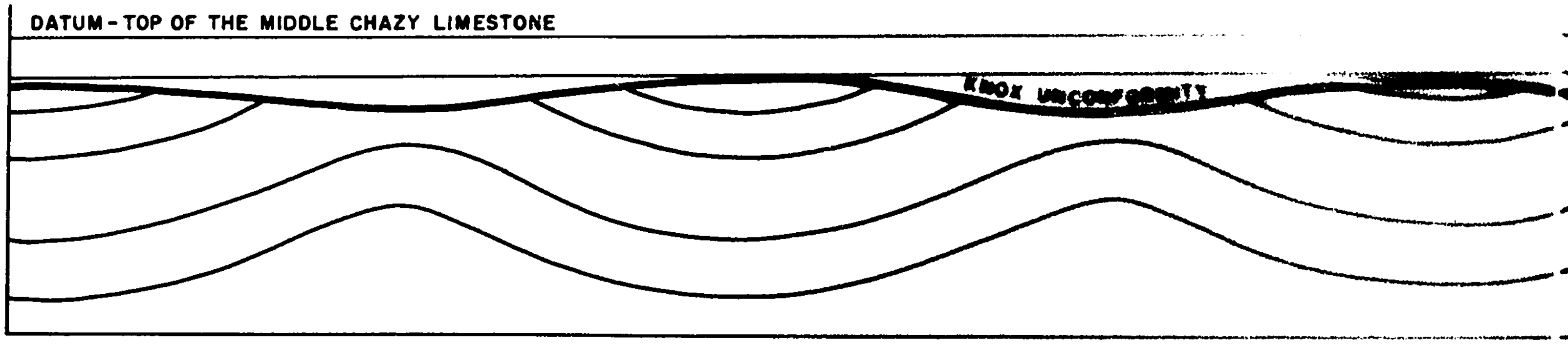
In Diagram A the attitudes of the strata above and below the Knox unconformity are shown approximately as they existed in immediate post-Middle Chazy time. The Copper Ridge Dolomite subcropping at the Knox unconformity was lithified but the Lower and Middle Chazy sediments were not. The pre-unconformity structure and the Knox erosion surface are shown as they were at the beginning of Late Chazy time.



A. PRESENT DAY POST-KNOX TOPOGRAPHY & PRE-KNOX STRUCTURE

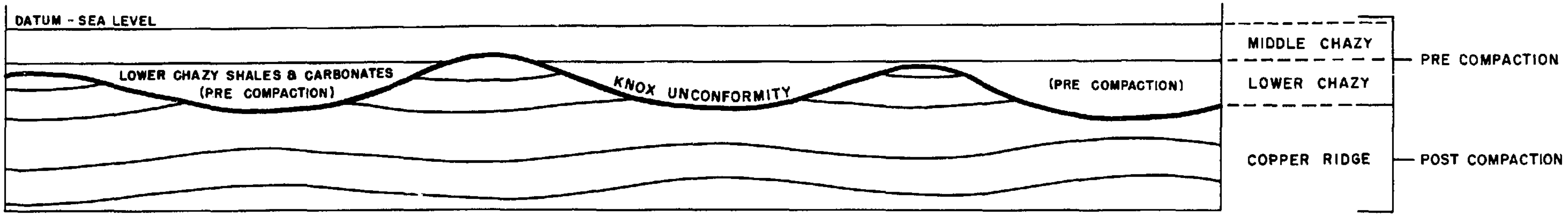


B. PRESENT DAY POST-KNOX TOPOGRAPHY & PRE-KNOX STRUCTURE

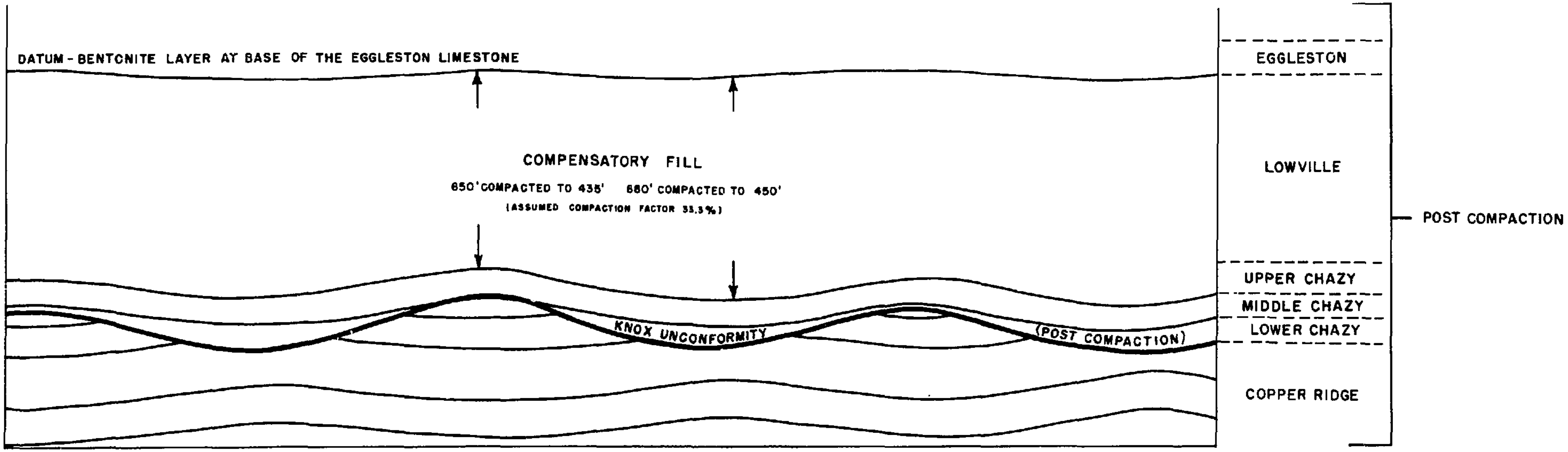


C. SUBDUED POST-KNOX TOPOGRAPHY & ACCENTUATED PRE-KNOX STRUCTURE

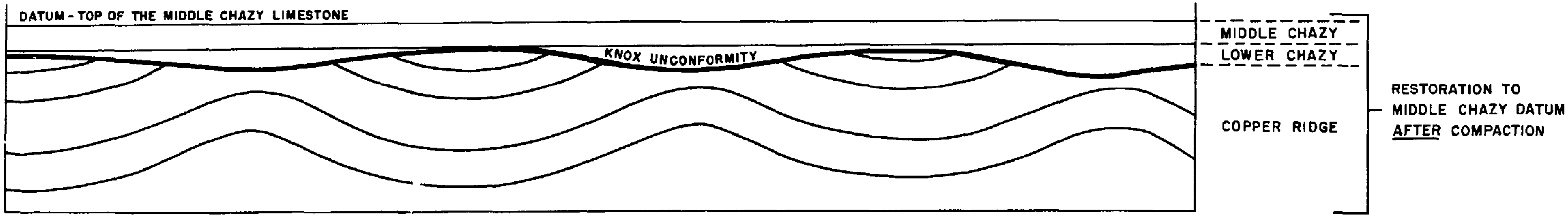
FIGURE 10. EFFECTS OF DIFFERENTIAL COMPACTION ON



A. PRESENT DAY POST-KNOX TOPOGRAPHY & PRE-KNOX STRUCTURE



B. PRESENT DAY POST-KNOX TOPOGRAPHY & PRE-KNOX STRUCTURE



C. SUBDUED POST-KNOX TOPOGRAPHY & ACCENTUATED PRE-KNOX STRUCTURE

FIGURE 10. EFFECTS OF DIFFERENTIAL COMPACTION ON ISOPACHOUS MAPPING

The structural attitude of the Copper Ridge Dolomite and the topographic relief of the Knox unconformity of Diagram B are the same as in Diagram A. The reference datum in Diagram B is a persistent bed of bentonite occurring approximately 450 feet above the Knox unconformity. Differential compaction of the Lower Chazy has caused a draping effect in these strata overlying the hills on the Knox erosion surface. Draped anticlines are in juxtaposition overlying buried synclinal erosional remnants of the Copper Ridge Dolomite.

In Diagram C the Middle Chazy reference datum has been used. In so doing, the post-Knox topography is subdued and the structures of the Copper Ridge Dolomite are amplified.

The origin of these Copper Ridge structures is not known. Walters (1958) suggested that Arbuckle structures in central Kansas were due to draping of these sediments over buried Pre-Cambrian hills. Such an explanation will not apply to the Copper Ridge structures, because there is no apparent thinning of the uneroded stratigraphic units over the anticlines. It is more likely that these minor upwarps were developed in response to compressive stresses associated with the uplift of the Waverly arch.

PALEOGEOMORPHOLOGY

Introduction

The morphology of buried erosional landscapes must be worked out in connection with subsurface studies of unconformity surfaces. Particular emphasis commonly is placed on the application of modern geomorphological concepts in determining the patterns of the ancient drainage systems. Controlling factors such as composition and relative resistance of strata, structures, faults, joints, etc. that pre-determine the particular type of drainage pattern must be taken into account.

A geological analysis of the nature of buried hills on an erosion surface is possible only through a thorough familiarity with the science of geomorphology. Martin (1964) stated, "Buried hills were shaped by the effect of erosion (primarily running water) upon a landscape; their final shape depends on the interaction between these erosional forces and the underlying geology."

McKee (1963) and Martin (1966) show the importance of differential compaction of sediments above a buried landscape. Such compaction tends to conceal or accentuate structures lying beneath the erosion surface. The amount of differential compaction can be only estimated, but its effects can be overcome by isopaching a thicker interval in which the compensatory fill has wiped them out. This holds true only as long as it is reasonably certain that the interval represents a time of continuous deposition.

In this investigation, it is obvious that paleogeomorphology is important. The Knox erosion surface is marked by numerous erosional remnants. By using modern geomorphological principles, it is possible to extrapolate a drainage system and its interfluves (buried hills) in an area that has been abundantly drilled.

Relationships of Stratigraphy and Structure to Paleotopography

The paleotopography of the Knox unconformity landscape at the time of burial can be reconstructed by constructing an isopachous map of the formation or formations overlying the unconformity. Such a map represents a cast of the topographic relief or configuration of the surface at the time it was overlapped. Thin or thick isopachous intervals represent casts of highs and lows, respectively, of the erosion surface.

The importance of the lithologic character of the strata overlying the unconformity has been shown earlier in the text. Differential compaction tends to subdue the topography of the erosion landscape when the sediments are restored to their original depositional (horizontal) attitude. Differential compaction of the Lower Chazy and compensatory deposition within the overlying strata are illustrated in Plates IV and VI. The interval mapped in this investigation to show the paleotopography of the Knox unconformity is between the erosion surface (top of Copper Ridge Dolomite) and the top of the Middle Chazy Limestone. The restoration of the top of the Middle Chazy Limestone to a horizontal surface caused the topography to be subdued considerably, as shown on the stratigraphic section C-C' (as compared to the structure section C-C'), Plate

IV, and on the diagrammatic cross sections of Figure 10. On Plate III, a combination of structural and topographic configuration of the Knox unconformity is illustrated. In order to reconstruct the paleotopography of the Knox unconformity without the present regional structural tilt, an isopachous map of the Middle and Lower Chazy strata was constructed (Plate VIII). The geographic extent of the hills and valleys of the landscape are truly reflected but the vertical amplitude of these features is subdued because of Lower Chazy differential compaction. The hills and valleys of the erosion surface trend in a northwest-southeast direction. The cause of this lineation was the trellis drainage pattern that developed on the surface. Such drainage patterns are related genetically to the lithology and structure of the underlying strata.

The conspicuous northwest-southeast-trending ridges are remnants of pre-Knox unconformity structures. The topographic highs are synclines and resulted from stream erosion inverting the topographic relief. The Copper Ridge anticlines were breached and eroded by the southeast-trending drainage courses, leaving the intervening structurally low areas as erosional remnants.

The trellis drainage pattern that was developed on the Knox unconformity is illustrated in Plate VIII. Several consequent streams flowed diagonally to the northwest-southeast ridges. For example, one consequent stream that flowed through this region from north to south extended through the center of Canaan and Cardington townships. Numerous subsequent streams flowed parallel with the ridges. Along these subsequent valleys many tributaries, (obsequent streams), flowed down the scarp slopes of the synclinal ridges.

In general the drainage in this region is to the south and southeast. Apparently these streams flowed toward an ancient shoreline which was to the south or southeast.

Because of the lithologic similarity of zones E and F of the Copper Ridge Dolomite, it is not likely that topographic inversion occurred during the weathering and erosion of these units. It is probable that denudation of the anticlinal and synclinal "wrinkled" surface was initiated within the Chepultepec Dolomite (or even the Lambs Chapel Dolomite). These formations are known to contain numerous resistant sandy zones which could have served as a cap rock formation. The inverted surface was lowered into the underlying Copper Ridge Dolomite zones.

There are numerous examples of folded areas where the trellis drainage is present. The Jura Mountains of Switzerland are an excellent example of an area composed of anticlinal ridges and synclinal valleys in which relief and structure correspond. These mountains are ideally suited for the analysis of drainage and relief because of their youthful stage and because of their simple structures. The Jura folds are open and are composed of a single, massive, resistant capping layer underlain by great thicknesses of distinctly weak rocks. Other examples of trellis drainage occur in the Appalachian Mountain folded belt; however, it is more complex. The Alps, the Carpathians, the Atlas, and the Ouachitas also are examples of fold mountain regions.

The Malone Mountains of western Texas demonstrate how completely the process of erosion can bring about inversion of relief. Synclinal ridges are the rule, not the exception. This area is probably much like the area that existed in central Ohio. The strata are dipping at considerably higher angles in Texas than in Ohio, but the terrain is similar. In the Malone Mountains all the anticlines are breached and the drainage is confined to the anticlinal valleys and to the flanks of the synclinal ridges.

The inversion of relief in intact open folds is shown on Figure 11. Folds of this type are present at the Knox erosion surface. The upper diagram illustrates an early stage of development in which the anticlinal hills are being breached by stream erosion. The majority of the valleys are in the synclinal troughs. The lower diagram shows inversion of relief. The anticlines are breached and the sites of the former anticlinal arches have now become anticlinal valleys, and conversely, the synclinal troughs have become synclinal mountains. The drainage has shifted from the synclines to the anticlines and is well integrated.

Zones E and F of the Copper Ridge Dolomite occur at the tops of the synclinal ridges and zone D is present in the valley floors of the breached anticlines, as shown on Figure 12 (which is a schematic block diagram of the Knox erosion surface).

Calvert (personal communication) has suggested that the topographically low areas of the Knox unconformity represent a buried karst topography. He cites an example in central Kansas, described by Walters (1946), in which the Arbuckle Limestone was exposed to prolonged weathering and erosion and, as a result, developed a paleokarst topography with many sinkholes and solution valleys.

Where carbonate rocks are uplifted and exposed to weathering for a prolonged period of time karst topography sometimes develops. Subterranean channels may be opened up in regions underlain by thick sequences

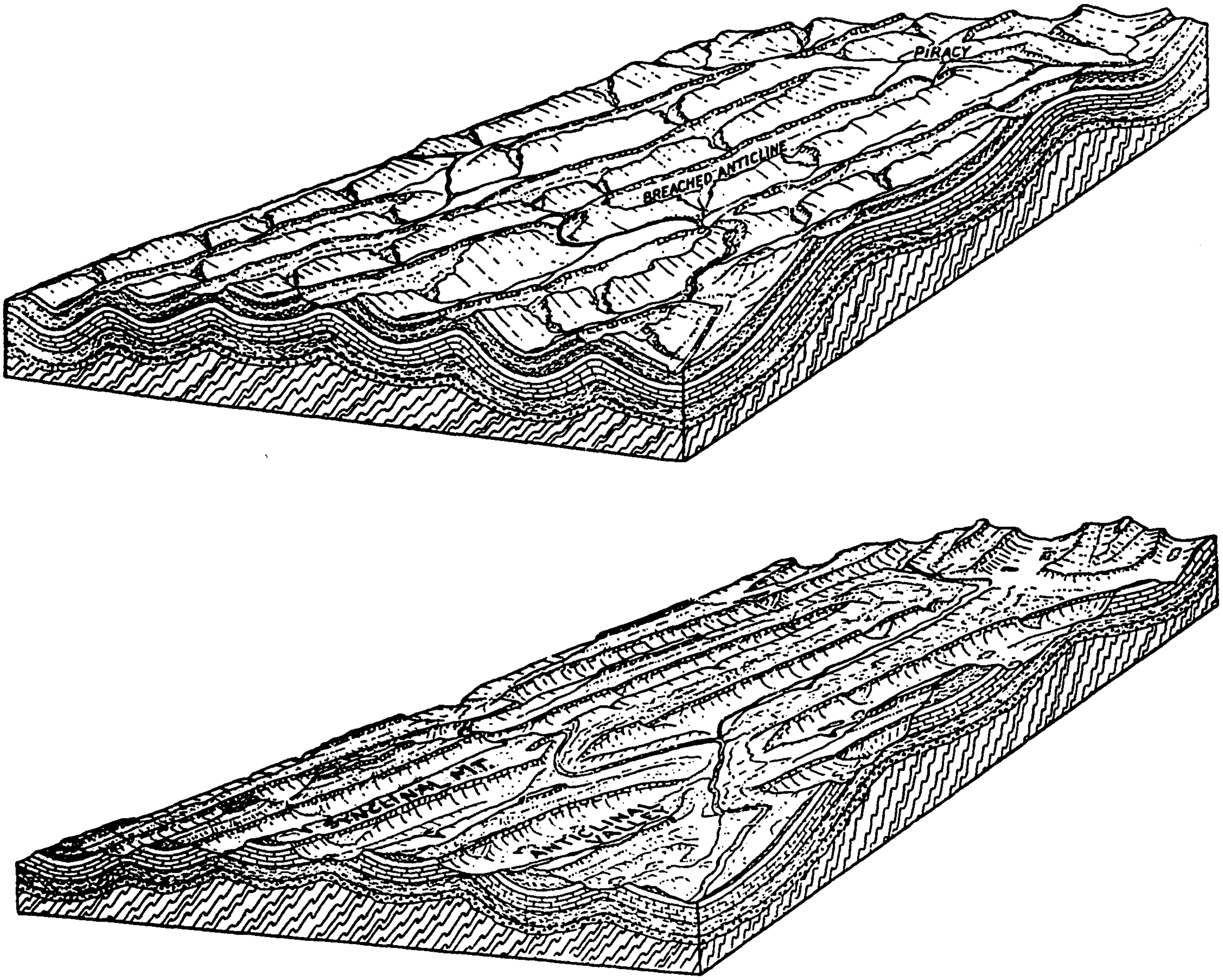


Figure 11. Inversion of topography by drainage development on intact open folds. Upper diagram illustrates headward erosion by subsequent streams breaching the anticlines. General drainage is from streams in the breached anticlines into the subsequent drainage in the synclinal valleys to the master transverse stream. Lower diagram shows synclinal mountains and anticlinal valleys. Subsequent drainage is through breach anticlinal valleys into the transverse stream. Stream adjustment to structure is complete and all drainage is integrated. (Drawn by Donald Rockwell and Thomas Chisnell in GEOMORPHOLOGY by O. D. von Engeln. The Macmillan Company. Copyright 1942, Fourth printing 1953.)

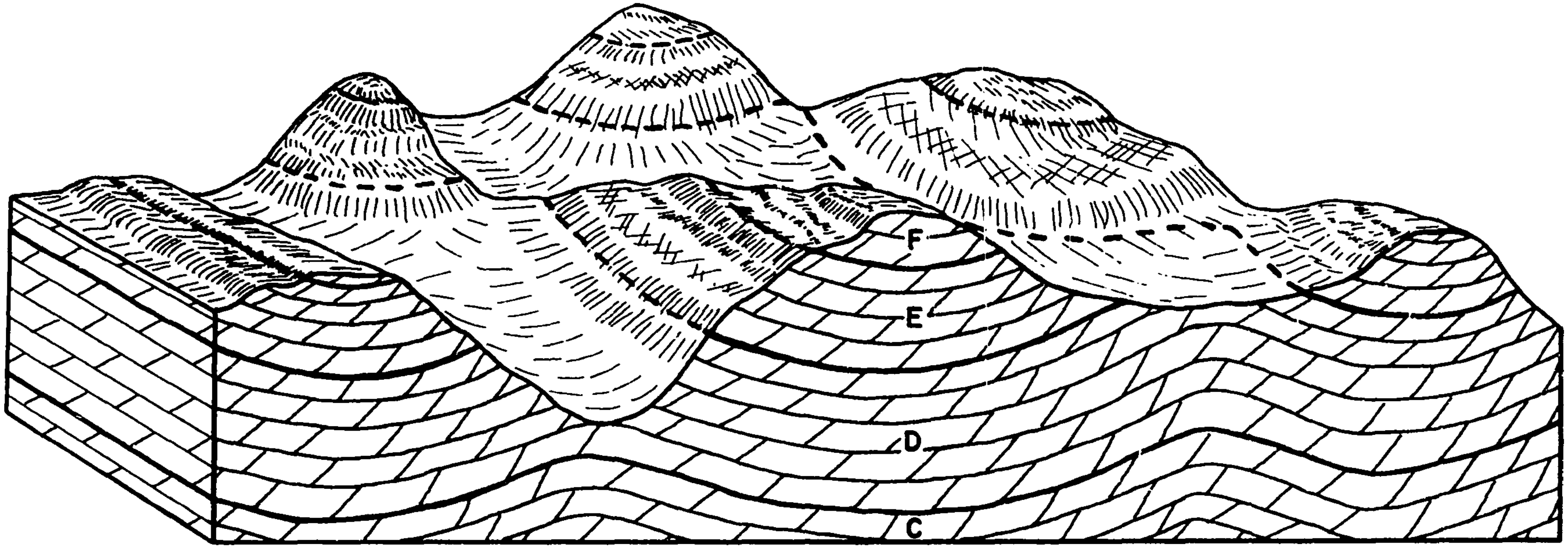


Figure 12. Schematic block diagram showing the topography on the Knox erosion surface (Knox Unconformity). The region illustrates topographic inversion to synclinal ridges and anticlinal valleys. Copper Ridge Dolomite zonation is shown in vertical profile. The subcrop patterns of zones D, E, and F of the Copper Ridge Dolomite are shown as they appear at the erosion surface.

of carbonates. Channels are developed along joints and fractures and along bedding planes by the percolating ground water. Valley development by normal weathering and stream erosion ceases because the water is infiltrating the ground. Only major streams that have originated outside the carbonate area are able to persist in open-surface channels.

Excellent examples of karst topography occur in southern Indiana and central-northern Kentucky; north of the Adriatic Sea, in Yugoslavia; in central Florida; northern Yucatan; and Barbados and Puerto Rico in the West Indies.

The possibility of karst topography was considered in this study; however, evidence in favor of a buried karst topography was not substantiated. The sample and core studies offer no evidence of interformational breccias within the Copper Ridge Dolomite. In a core sample of zone B (from Clear Creek Township in Ashland County, Ohio) there is a dense unsorted, flat-pebble conglomerate-breccia zone. These flat pebbles consist of broken algal stromatolites of variable sizes. They occur as suspended particles within a tidal flat mud. This corresponds to zone B of the Copper Ridge of this report which, on the basis of gamma ray-neutron logs can be correlated readily for considerable distances. An accumulation of material that collapsed into sinkholes or solution channels would not occur in all wells at the same relative stratigraphic position. The wide range of sizes of the stromatolite chips and their random orientation indicate that they were deposited in a high-energy, supratidal environment under conditions of rapid burial. Roehl (1967) illustrated similar interformational flat pebble conglomerate zones in the Stony Mountain (Ordovician) and Interlake (Silurian) formations of the Willeston basin.

HYDROCARBON ACCUMULATION

Introduction

Known hydrocarbon accumulations in Marion and Morrow counties are confined to the Cambro-Ordovician portion of the sedimentary section. The majority of the production is confined to the Copper Ridge Dolomite, at depths no greater than 150 feet below the Knox unconformity. Other hydrocarbon accumulations occur in localized areas surrounding buried Copper Ridge hills, where secondary dolomitization and fracturing have taken place. This latter accumulation involves the Chazy and the lower Lowville Limestones.

Throughout this investigation different techniques were used to reconstruct the geological history of the stratigraphy, structure, and geomorphology in an effort to find a factor or set of factors that controlled the accumulation of the hydrocarbons. Particular effort was made to establish a set of parameters that would explain both productive wells and dry holes. Such an understanding is considered essential to further exploratory and development drilling in this area.

Controlling Influence of Stratigraphy, Structure and Paleogeomorphology

The factors that control the accumulation of hydrocarbons are stratigraphy, structure, and paleogeomorphology. Each of these factors has been discussed individually and it is apparent that each is genetically related to the other two.

The reservoir rock is the Copper Ridge Dolomite that subcrops at the Knox unconformity. The effects of prolonged subaerial erosion at the unconformity surface were of great importance, particularly in this case, because the reservoir rocks are dolomites which are generally soluble. The upper zones were readily subjected to weathering by percolating meteoric waters and subsequently the more soluble parts dissolved, so that high porosity and permeability developed. Thus, porosity and permeability in the Copper Ridge Dolomite were genetically related to lithology. On the basis of sample and core studies, zones E and F are known to have high porosity (vuggy), whereas zone D (which also subcrops at the Knox erosion surface) has little porosity.

Zones E and F are composed of white to tan sucrosic dolomite. The grains are fine to coarsely crystalline, randomly orientated, euhedral to anhedral in shape, partially interlocking and mutually interferring. Scattered throughout zones E and F are white to colorless, fine to medium quartz grains, a few scattered oolites and several green to gray glauconitic shale partings. A few fossil fragments were seen on thin sections, and a single core sample contained algal stromatolite fragments. The porosity and permeability of zones E and F appear to be genetically related to the dolomitization of the parent rock and to the leaching and weathering at the erosion surface by percolating groundwater. Types of porosity observed in the thin sections are intercrystalline pore spaces, vugs, and fracture pore spaces. The amount of porosity in the Copper Ridge Dolomite is neither reduced nor destroyed as a result of either cementation or other diagenetic effects.

Sucrosic dolomite porosity is the result of replacement of calcite by dolomite. The porosity and permeability that are developed in these replacement dolomites were strongly influenced by the composition of the original carbonate sediments and the degree to which the rock has been replaced by sucrose dolomite (Harbaugh, 1967).

Murray (1930) recognized what he considered to be selective leaching at an unconformity by meteoric waters where dissolution of calcite from a dolomitic limestone caused the origin of dolomite porosity. The porosity and permeability of a sucrosic dolomite is commonly intercrystalline pore space that develops as the grains grow during dolomitization (the Copper Ridge Dolomite is over 80 percent dolomite). Murray (1960) stated that as dolomitization occurs within a rock with an initial dolomitization of less than 50 percent, the porosity generally decreases because the dolomite is growing from solutions percolating through it and from material dissolved within the parent rock. If the dolomite content is above 50 percent, the porosity increases. Values approximating as much as 30 percent have been noted where the rock was initially 80 to 90 percent dolomite.

Murray (1960) and Powers (1962) have shown that there are times during dolomitization of limestones when the porosity developed is not the result of the replacement of calcite with dolomite. The porosity is formed instead by dissolution of the calcium carbonate. Similar conditions could exist in the Copper Ridge Dolomite, forming the large vugs that are prominent in zones E and F.

Large vugs in sucrosic dolomites are the result of dissolution of large patches of calcite during dolomitization. As the area is dissolved, the growth of dolomite rhombs develops the interlocking framework that holds open the pore structures. The resulting pore geometry and porosity will be vugs between the interlocking dolomite grains, or vugs plus intercrystalline porosity, if mutually interferring dolomite rhombs hold open the framework of the rock.

Bathurst (1958) demonstrated how porosity may be destroyed by cementation in conjunction with dolomitization (replacement). Pore space could be destroyed by cementing material growing into the pore spaces. He demonstrated that cement grows into intergranular pore spaces, and is commonly optically continuous with the particles of the rock on which it is growing. Cementation of this type is not apparent in zones E and F of the Copper Ridge Dolomite.

The fact that erosion attacks the higher areas more readily could explain the greater porosity and permeability in zones E and F, which cap the ridges of the erosion surface. Zone D, which subcrops in the valleys around the flanks of the erosional remnants, is not porous and permeable even though it was exposed to similar leaching and weathering conditions as were zones E and F. Zone D is characterized by white to tan, finely to coarsely crystalline, sandy, argillaceous dolomite. In general, it appears that the lack of porosity may be due to the higher amount of clay within this zone. Also, the grain size in zone D is, on the average, much smaller than in zones E and F. No cores of zone D were available; therefore, it is not possible to determine if this zone once had porosity that was subsequently destroyed by cementation from circulating solutions. It is important, however, to note that this zone lacks the porosity and permeability found in zones E and F.

The subaerial distribution of D, E, and F is shown on Plate IX. It represents a paleogeologic map at the horizon of the Knox unconformity, just prior to the deposition of the Lower and Middle Chazy formations of the Middle Ordovician. Elongate patches (trending northwest-southeast) of zones E and F are abundantly apparent. Zone F, the youngest portion of the Upper Copper Ridge, occurs at the tops of the higher erosional remnants. The boundary between zone F and the underlying zone E occurs on the flanks of the dolomite hills. Zone E subcrops around the flanks of the higher hills and caps many of the lower erosional remnants. Zone D caps only the low hills and characteristically subcrops in the valleys surrounding the hills and ridges. The relative position of the occurrence of these zones is genetically related to the pre-Knox unconformity structure and the topography that developed by erosion of these various zones during subaerial exposure. Their relative positions are illustrated on the block diagram of the breached anticlines shown on Figure 12.

Zones E and F occur over the axes of synclines and are structurally low but topographically high in this area. The anticlinal axes, on the other hand, were breached by the drainage development on the erosion surface, resulting in a topographic inversion.

The occurrence and production of hydrocarbons in the area of investigation are confined primarily to zones E and F. There are no known instances of oil production, or shows, from zone D. These facts are illustrated on structural cross sections C-C' (Plate IV). The oil-saturated zones are stippled to illustrate the stratigraphic confinement of the hydrocarbons to zones E and F.

Structural cross section C-C' (see Figure 2 for location) was drawn perpendicular to the trend of the northwest-southeast aligned ridges. A comparison of the various ridges shows that hydrocarbons occur only in zones E and F, but the thickness of the oil columns in the individual ridges varies from ridge to ridge depending on the amount of relief at the Knox erosion surface. The hydrocarbons have migrated up the regional dip to the west through these ridges. For example, the base of the oil-saturated zone in wells 10 and 2844 is lower than in well 2741 to the southwest and well 2286 to the northeast. Similarly throughout the entire area as well as on this cross section, the oil-saturated zones in the various structurally controlled ridges appear to be adjusted to their own inherent conditions of stratigraphy, structure, and geomorphology.

Structure cross section E-E' (Plate X) (see Figure 2 for location), which is parallel to the trend of the ridges (northwest-southeast), illustrates the relationship of the oil-saturated zone to the structure and stratigraphy along a longitudinal section through a ridge. Those zones to the southeast are the lowest (oil confined only to zones E and F) and each successive remnant to the northwest is slightly updip. As one erosional remnant filled to the spillpoint, the oil migrated along the unconformity surface to the next remnant updip which contained the porous and permeable reservoir rocks (zones E and/or F).

Sitler (1964) prepared a map that shows the updip limit of the oil production in the Copper Ridge Dolomite from the drilling records and data available in 1964. This limit is approximately north-south through the western portion of Canaan and Cardington townships.

Further exploration has moved the line to the west, but there have been only one or two producing wells in Marion County. Extensive exploration programs and drilling turned up numerous erosional remnants in Marion County with sufficient closure, but no hydrocarbons. The present production limit is approximately the Marion County-Morrow County boundary line. One reason for the lack of production from the Copper Ridge Dolomite in Marion County is shown on stratigraphic cross section F-F' (Plate XI). Zones E and F are eroded away throughout this area. There are numerous erosional remnants, but they are capped by zone D which lacks porosity and permeability. On the cross section only one well in Marion County (well number 8) has zones E and F. Salt water was found in these zones in this well.

Figure 13 illustrates dolomitization of the lower part of the Middle Chazy Limestone. This dolomitization is unpredictable except that it occasionally occurs over erosional remnants of the Copper Ridge Dolomite. This dolomite zone in the Middle Chazy and one well in the Lowville represent the only productive horizons in the portion of Morrow County studied herein other than the Copper Ridge Dolomite. Chazy Limestones are shown on the subcrop map (Plate IX) and marked "Omc Dol".

The dolomitic zone that sometimes occurs at the base of the Middle Chazy may be identified by the higher porosity shown by a decrease in intensity on the neutron curve. This dolomite zone is shown on Figure 13 in the Payne No. 1 well. On cross sections C-C' and E-E', wells 2286 and 70, respectively, have thick sections of oil-saturated dolomite in the Middle Chazy. In Sections 17, 18, and 19 of Canaan Township the majority of production comes from the Middle

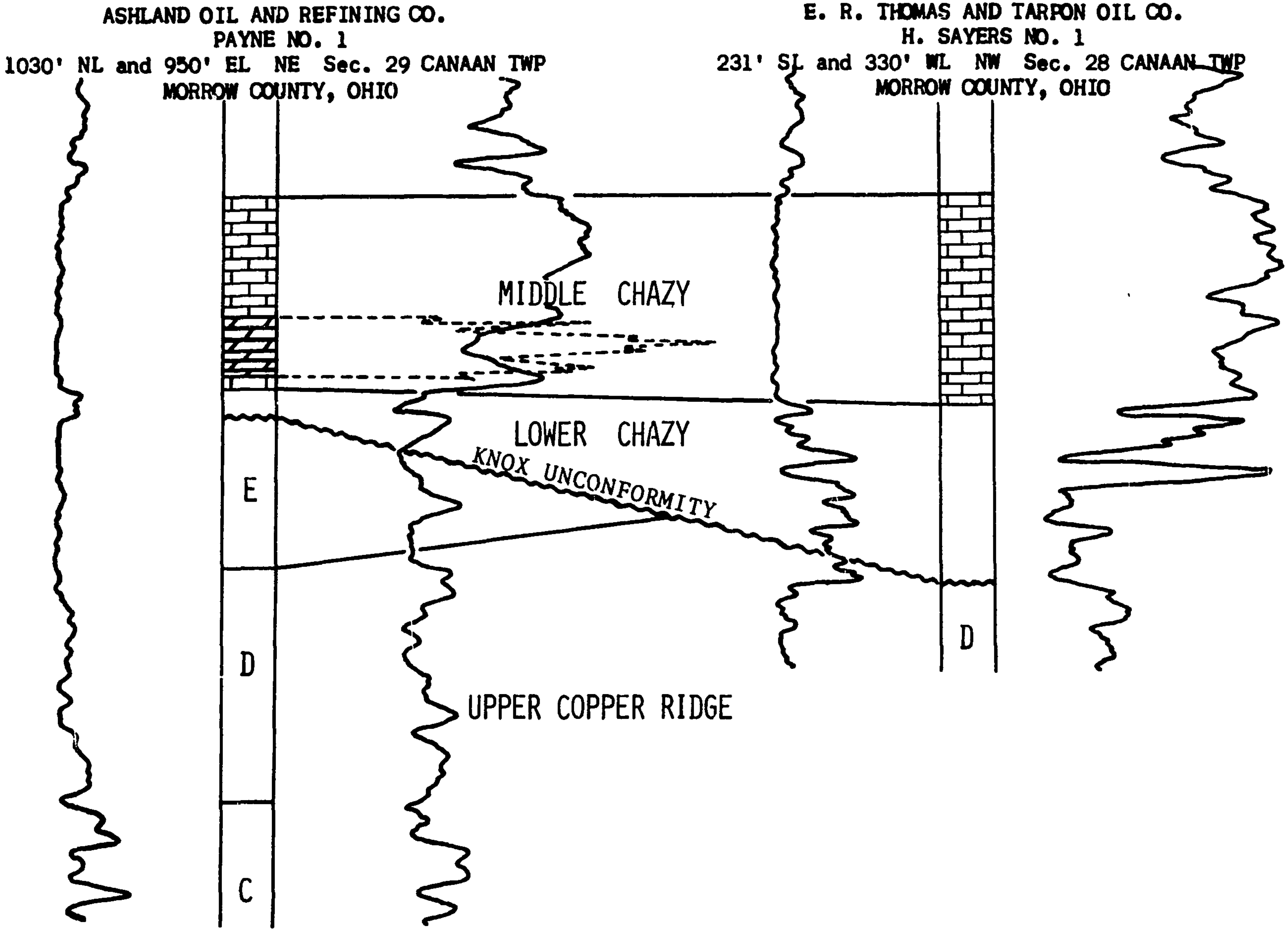


Figure 13. Dolomite zone within the Middle Chazy Limestone.

Chazy. Well 120 in Section 34 of Canaan Township, the offset to well 70 mentioned above, is dolomitized some 300 feet upsection into the Lowville Limestone. This well produced only for a short period of time from a zone high in the Lowville formation.

Origin and Migration of Hydrocarbons

Wherever the reservoir rock is composed of organic material such as limestone, there is the possibility of indigenous oil; however, the formation of the hydrocarbons in situ has been ruled out in this case. Although there is abundant evidence that the original rock type of the Copper Ridge Dolomite was a fossiliferous (algal stromatolite) calcarenite, the accumulation of hydrocarbons within the Copper Ridge Dolomite during the period of subaerial exposure (hiatus of the Knox unconformity) seems unlikely. Such hydrocarbons would have migrated to the surface and escaped into the atmosphere before the deposition of the Chazy sediments.

The shaly Lower Chazy which was deposited in the valleys of the erosion surface is more likely to have been the source of the hydrocarbons. These black and green shales probably contained considerable organic matter from which hydrocarbons could have developed. The Lower Chazy sediments formed an effective seal over the underlying Copper Ridge Dolomite reservoir rocks. Therefore, any hydrocarbons generated within the Lower Chazy would be forced laterally along bedding planes until an intersection with the surface of the unconformity was reached. There the hydrocarbons would either enter the porous and permeable Copper Ridge Dolomite reservoir rock (if intersection occurred at zone E or F) or migrate along the unconformity surface in an updip direction until zones E or F were encountered. The oil within the porous and permeable reservoir rock would migrate to the highest possible position within the reservoir (the top of the erosional remnant) and displace the interstitial fluids present (connate water and meteoric water). Petroleum globules tend to aggregate in the larger pore spaces (vugs and intergranular pore spaces) of the reservoir, the water-wet caprock serving as a natural filter. The hydrocarbon droplets and globules move to the top of the reservoir and do not have sufficient buoyancy pressure to overcome the capillary pressure of the water occupying the pores of the overlying caprock. Therefore, the Lower Chazy could serve as both source rock and caprock.

The nature of differential entrapment of hydrocarbons along with water in the erosional remnants on the Knox erosion surface suggests a situation similar to that of differential entrapment proposed by Gussow (1953). Gussow's Principle provides the following explanation for the so-called anomalous occurrences of oil and gas in contiguous reservoirs: some apparently good structures (filled with salt water) are associated with similar structures where oil and gas are produced. Gussow's Principle explains why gas fields may occur in a downdip position and produce little or no oil, whereas structures in an updip direction produce oil with little or no gas, and others still further updip are water-bearing.

There are no known gas pools, or gas caps on oil pools, within the study area. The oil pools do, however, contain some dissolved gas. The presence of oil in the erosional remnants in Morrow County and of water in similar erosional remnants updip in Marion County suggests a situation similar to the conditions described by Gussow. If there is any gas in the Copper Ridge of central Ohio it should occur in erosional remnants downdip (southeast) of the study area.

Gussow based the principle of differential entrapment on the assumption that oil and gas migrate over great distances, and further assumed that adequate source beds were located in a downdip or basinward direction. This investigation seems to indicate that the source beds were not far removed from the reservoir rocks. In the basinward direction (southeast), the Lower Chazy thickens gradually to about 90 feet, in Adams County. It is the writer's opinion that long-distance migration, as suggested by Gussow, is not applicable in this case. The intermittant positioning and erratic extent of the reservoir rocks would not provide a continuous pathway for long-distance migration. Such "carrier" beds are essential for long-distance migration, as originally described by Rich (1931).

The updip limit of oil production occurs along the Marion-Morrow County contiguous boundary. West of this line erosional remnants on the Knox unconformity generally are water-filled. Two reasons for the paucity of oil accumulation in an updip westward position are: 1) inadequate supply of oil from source rocks of limited geographic extent and thickness, and, 2) most of the Copper Ridge hills to the west, in Marion County, are composed of the non-reservoir zone D type of lithology. The limited nature of the source rock is further supported by the fact that the Lower Chazy becomes less shaly to the west and grades into the St. Peter Sandstone. The Lower Chazy shale zone is genetically related to the St. Peter Sandstone, which overlies the Knox unconformity throughout west-central Ohio as well as most of Michigan, all of Illinois and

Indiana, and parts of Kentucky, Missouri, Iowa, Nebraska, Minnesota and Wisconsin. The eastern limit of the St. Peter Sandstone is shown by Dapples (1955) on a map showing the aerial distribution of the St. Peter Sandstone and the Simpson Group. This limit lies immediately to the west of the Waverly arch shown on Figure 1. Because the St. Peter Sandstone marks a change in depositional environments, the intermediate zone between it and the Lower Chazy shales in the Marion County area may have lacked the essential qualities for the development of source rock characteristics such as developed in the Lower Chazy further removed to the east in Morrow County and environs.

As shown on Plate X, hydrocarbon accumulations in successive traps along a ridge are filled to the spillpoint and drain into the next higher reservoir facies. In this instance there are numerous interconnected erosional remnants with closure in an updip direction, to the west, but there was an inadequate supply of oil to displace the water occupying the hills to the west.

The hydrocarbons in the dolomitized zone in the Middle Chazy (Figure 13) are either derived from the Lower Chazy source beds or might have leaked from the Copper Ridge reservoirs. Most of the occurrences of secondary dolomite in the Middle Chazy are in contact with these erosional remnants. In either case, the oil occupies fractures and intergranular pore spaces within the Middle Chazy. Such production from these occurrences is generally low; however, this zone could produce as long as oil could migrate from the Copper Ridge reservoir below.

CONCLUSIONS

Cambro-Ordovician formations under investigation do not crop out in Ohio. Those Cambro-Ordovician sediments that crop out in the Appalachian Valley in Virginia and Tennessee maintain their lithologic character into the subsurface of Ohio more closely than do those that outcrop in the Adirondack region of New York; in the upper Mississippi Valley in Iowa, Minnesota, and Wisconsin; or in the Ozark region of southeastern Missouri. From the outcrop in the Appalachian Valley northward into the subsurface of Ohio the formations thin considerably and are progressively truncated below the Knox unconformity.

During Late Cambrian and Early Ordovician, uplift along the Waverly arch (extends north-south through central Ohio) was accompanied and followed by truncation and erosion of the beds exposed at the surface.

In Morrow County and environs the Knox unconformity represents the boundary between the Cambrian and Ordovician sediments. The Copper Ridge Dolomite (Upper Cambrian) subcrops at the unconformity and is overlain by the Lower Chazy Shale-Limestone-Dolomite (Middle Ordovician).

The Copper Ridge Dolomite can be subdivided into zones based on lithologic characteristics, porosity (and permeability), and gamma ray-neutron log characteristics. The Copper Ridge Dolomite (and possibly the other dolomites of the Knox Supergroup) is interpreted as a replacement dolomite from fossiliferous, oolitic calcarenite. Whether the dolomitization occurred before or after the limestones were lithified is questionable, but dolomitization was probably complete by the time the Lower Chazy shales and limestones were deposited.

Lithologically, the Lower Chazy is a calcareous, greenish-black shale that was deposited in the valleys around the flanks of the erosional remnants on the Knox unconformity surface. The irregular distribution, erratic thickness and shaly composition of the Lower Chazy resulted in differential compaction as this unit was subjected to the weight of the overburden.

Draped anticlines occur in the sediments above the Lower Chazy as a result of the differential compaction. The effects of this differential compaction, however, were offset by compensatory fill in the depressed areas by the time 450 feet of overburden had been deposited.

Structurally, Morrow County is on the east flank of the Cincinnati arch and the west flank of the Appalachian geosyncline. The present regional strike is approximately north-south and the dip is about 50 feet per mile to the east and southeast.

A detailed structure map of the Knox unconformity in the study area shows an irregular surface marked by erosional remnants and intervening valleys aligned in a northwest-southeast direction.

The ridges on this erosion surface are remnants of pre-Knox unconformity synclinal highs. The topographically low areas (paleodrainage courses) occur in breached anticlines of the underlying Copper Ridge Dolomite. There is, thus, an inverted topography on the Knox unconformity.

Differential compaction within the Lower Chazy shale sequence caused distortion of pre-unconformity paleostructures. The isopachous map constructed to show paleotopography (thickness from the top of the Middle Chazy to the Knox unconformity) presents a greatly subdued picture, whereas the isopachous map illustrating the paleostructure (thickness from the top of the Middle Chazy to the base of zone D in the Copper Ridge) caused an accentuation of the Copper Ridge structures.

Hydrocarbon accumulations are genetically related to the lithology, stratigraphy, structure and paleogeomorphology of the sediments above and below the Knox unconformity.

Oil production occurs primarily in the Copper Ridge Dolomite, and to a much lesser extent, in the Black River Group (Lowville Limestone) and the Chazy limestones.

Production from the Copper Ridge Dolomite was no deeper than 150 feet below the Knox unconformity. It is restricted to zones E and F, which are stratigraphically the highest zones of the Copper Ridge Dolomite, the zones that cap the tops of the erosional remnants. Porosity and permeability in these zones were partially the result of dolomitization and leaching by meteoric waters while the Copper Ridge Dolomite was subaerially exposed. Zone D, which underlies these porous and permeable zones, does not have much porosity and permeability. If such ever did exist it could have been lost by precipitation of dolomite in the pores and pore throats as percolating solutions of calcium and magnesium carbonate moved downward through the rock.

The source of the hydrocarbons is probably the overlying Lower Chazy. The oil was forced along the bedding planes, during compaction, until they intersected an erosional remnant that was porous and permeable, in which the oil could accumulate. These hydrocarbons probably were generated from within the immediate area. Long-distance migration does not appear likely. Blanket-like carrier beds do not exist. Instead, porous reservoir beds are erratically distributed. The source bed in the local area was probably the cap rock (Lower Chazy) which acted as a permeability barrier after compaction was complete.

Hydrocarbons within a ridge appear to migrate from closure to closure in a regionally updip direction after the lower reservoir is filled to its spillpoint. Adjacent ridges also are paths along which hydrocarbons have migrated, but these bear no relationship to hydrocarbons in other ridges.

Lack of hydrocarbon accumulation in Marion County and in parts of the western edge of Morrow County suggests an inadequate supply of oil to fill all of the more regionally updip erosional remnants. In Marion County salt water production from reservoir rocks is common. The fact that water appears in structures (closures) updip from oil production can be explained by Gussow's Principle. Also, in Marion County, zones E and F (the producing zones within the Copper Ridge in Morrow County) are generally absent over the erosional remnants. Therefore, this area lacks reservoir rocks over most of the erosional remnant highs.

Other hydrocarbon accumulations and production occur from localized areas of fractured and dolomitized zones in the Black River (Lowville Limestone) and the Chazy Limestones. In these cases the oil migrates upward from the source rock or from the Copper Ridge reservoirs below the unconformity (where the Lower Chazy is absent over an erosional remnant) into the overlying fractured and dolomite zones.

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APPENDICES

APPENDIX A

List of wells with cores or samples studied. See Figure 2 for the location of these wells.

Wells with cores studied:

Ohio Drilling Permit Number	Operator, Lease, and Location
11	United Producing Company, Inc. Orrie Myers #1 660' EL 660' NL NE Sec. 33 Canaan Twp. Morrow Co.
12	United Producing Company, Inc. Orrie Myers #3 1980' WL 660' NL NW Sec. 23 Canaan Twp. Morrow Co.
80	Comanche Oil, Inc. Brinkman #2 737' NL 672' WL NW Sec. 2W Gilead Twp. Morrow Co.

Wells with well cuttings studied:

Ohio Drilling Permit Number	Operator, Lease, and Location
	Claridon Township, Marion County
8	United Producing Company, Inc. Mitchell #1 660' SL 660' WL NE Sec. 27
66	United Producing Company, Inc. Francis Gruber #2 1079' WL 1126' SL NW Sec. 32
84	Frank Adkins Paul Showers No. 1 541' EL 712' SL NW Sec. 9

Appendix A, continued

Richland Township, Marion County

15 The Clinton Oil Company M. and A. Stose #1
660' SL 660' EL NE Sec. 10

67 John Adams W. and M. J. Jevas No. 1
490' EL 242' SL NE Sec. 3

Canaan Township, Morrow County

10 United Producing Company, Inc. Orrie Myers #1
1980' EL 660' NL NE Sec. 33

11 United Producing Company, Inc. Orrie Myers #2
660' EL 660' NL NE Sec. 33

12 United Producing Company, Inc. Orrie Myers #3
1980' WL 660' NL NW Sec. 33

15 United Producing Company, Inc. Bush-Levering #1
2025' EL 620' SL SE Sec. 28

16 United Producing Company, Inc. Hall-Levering #1
660' NL 660' WL SE Sec. 28

17 United Producing Company, Inc. Hines-Norton #1
660' SL 660' WL NE Sec. 33

20 United Producing Company, Inc. Ault-Hall #1
660' SL 660' EL NW Sec. 28

22 United Producing Company, Inc. Brade~ #1
660' SL 660' EL SW Sec. 28

49 Wood Rider, Inc. E. T. Snyder #A-1
660' NL 660' EL NE Sec. 30

2022 Ashland Oil and Refining Company Pangborn #1
1633' NL 1685' EL NE Sec. 10

2313 Hodson Ohio Oil Company H. McKinstry No. 1
700' NL 760' WL SE Sec. 7

2642 Hoagland Drilling Company Force No. 1
758' NL 1550' EL NE Sec. 21

Cardington Township, Morrow County

27 D. J. Houchins Drilling Company and Shore Oil Company
A. P. Smith #1
660' SL 660' WL NW Sec. 10

Appendix A, continued

Cardington Township, Morrow County, continued

31	United Producing Company, Inc. Linder #1 660' EL 1980' SL SE Sec. 6
64	Jerry Moore and El Paso Drilling Co. W. B. Hess No. 1 1980' EL 660' NL NE Sec. 11
501	Ashland Oil and Refining Company C. J. Ruehrmund #1 2100' SL 330' EL SE Sec. 19
1406	Ashland Oil and Refining Company Dennis #1 330' SL 1620' WL SW Sec. 15

Gilead Township, Morrow County

104	Comanche Oil, Inc. Williams-Shaw Unit #1 1973' El 600' SL SE Sec. 26-E
113	Comanche Oil, Inc. R. Newsom #1 571' SL 796' EL NE Sec. 3
155	Algonquin Petroleum Company E. Brinkman #1 250' SL 300' WL SW Sec. 35
338	Jerry Moore, Inc. Walton #2 150' SL 1250' WL SW Sec. 15-S
1009	Hurtt Drilling Company Ghent #1 1620' SL 300' WL NE Sec. 24-N
1475	Ashland Oil and Refining Company M. Anthony #4 1500' SL 990' EL SE Sec. 26-W
1813	Ashland Oil and Refining Company W. Long #1 1154' SL 700' EL SE Sec. 23-W
2131	Griffith Production H. G. Curran #1 230' SL 78' EL SW Sec. 36
2520	Buckeye Oil and Gas Owen and Mary Holt #1 2325' NL 855' EL NW Sec. 23-S
2663	Keener Oil Company F. and R. Loren No. 2 236' NL 183' EL SW Sec. 12

Washington Township, Morrow County

2059	Ashland Oil and Refining Company H. J. Kunze #1 1370' SL 410' EL SW Sec. 10-S

Appendix A, continued

Washington Township, Morrow County, continued

2581 Southern Triangle Oil Company, Ray Farrar and Joe Young Co., Inc.
C. Smotherman No. 1
563' NL 1657' EL SE Sec. 11-S

2904 Clark Oil and Refining Corporation H. M. and Helen Cover #1
230' NL 1450' WL SW Sec. 1-S

APPENDIX B

The wells included on the stratigraphic and structural cross sections that appear in this report are listed below. The location of the wells on each profile section is shown on Figure 2. The wells used on these cross sections are identified by the Ohio Drilling Permit Number which appears above each well on the various sections. The wells are listed in order of positioning on the profile section by the permit number; the operator, the lease name, and the location are given.

STRATIGRAPHIC CROSS SECTION A-A'

Ohio Drilling Permit Number	Operator, Lease, and Location
83	John Adams G. Cochran #1 1980' SL 660' EL SE Sec. 4 Canaan Twp. Morrow Co.
1563	Hobson Oil Company F. & V. Furniss #1 330' NL 700' EL NW Sec. 10 Canaan Twp. Morrow Co.
1598	Great Lakes Drilling Company M. L. McCullough #1 990' SL 1120' WL SW Sec. 10 Canaan Twp. Morrow Co.
1631	Ideal Drilling Company Lester Bending #1 426' NL 281' EL NE Sec. 16 Canaan Twp. Morrow Co.
2861	E. R. Thomas L. G. Bending #1 770' SL 1550' EL NE Sec. 16 Canaan Twp. Morrow Co.
2545	Mansfield Oil & Development Company, Incorporated Paul & Opal Force #1 985' NL 345' EL NW Sec. 21 Canaan Twp. Morrow Co.
75	Ashland Oil and Refining Company L. Linder #1 750' SL 750' WL SW Sec. 21 Canaan Twp. Morrow Co.
20	United Producing Company, Inc. Ault-Hall #1 660' SL 660' EL NW Sec. 28 Canaan Twp. Morrow Co.
16	United Producing Company, Inc. Hall-Levering #1 660' NL 660' WL SE Sec. 28 Canaan Twp. Morrow Co.
15	United Producing Company, Inc. Bush-Levering #1 2025' EL 620' SL SE Sec. 28 Canaan Twp. Morrow Co.
10	United Producing Company, Inc. Orrie Myers #1 1980' EL 660' NL NE Sec. 33 Canaan Twp. Morrow Co.
17	United Producing Company, Inc. Hines-Norton #1 660' SL 660' WL NE Sec. 33 Canaan Twp. Morrow Co.
2510	Mansfield Oil and Development Company E. & I. Fissell No. 2 915' SL 1036' EL SE Sec. 33 Canaan Twp. Morrow Co.
2459	Mansfield Oil and Development Company E. & I. Fissell No. 1 230' SL 230' EL SE Sec. 33 Canaan Twp. Morrow Co.

Stratigraphic Cross Section A-A', continued

19	United Producing Company, Inc. Clinger #1 660' NL 660' EL NE Sec. 4 Cardington Twp. Morrow Co.
625	Ashland Oil and Refining Company H. & M. Lee #1 478' SL 654' EL NE Sec. 4 Cardington Twp. Morrow Co.
1504	Ashland Oil and Refining Company Lee & Lee #1 1320' SL 200' EL SE Sec. 4 Cardington Twp. Morrow Co.
1951	Bill Allen Associates A. M. Smith #1 249' NL 713' WL NW Sec. 10 Cardington Twp. Morrow Co.
27	D. J. Houchins Drilling Company and Shure Oil Company A. P. Smith #1 660' SL 660' WL NW Sec. 10 Cardington Twp. Morrow Co.
2434	Pilgrim Oil and Gas Company Judith Long #3 509' NL 385' WL SW Sec. 10 Cardington Twp. Morrow Co.
2377	Pilgrim Oil and Gas Company Judith Long #2 685' SL 633' WL SW Sec. 10 Cardington Twp. Morrow Co.
1384	Ashland Oil and Refining Company Walter Long #2 360' NL 1000' WL SW Sec. 15 Cardington Twp. Morrow Co.
649	Ashland Oil and Refining Company Walter Long #1 1620' SL 1040' NL SW Sec. 15 Cardington Twp. Morrow Co.
1406	Ashland Oil and Refining Company L. Dennis #1 330' SL 1620' WL SW Sec. 15 Cardington Twp. Morrow Co.
1358	Ashland Oil and Refining Company M. Mack #3 810' NL 2480' EL NE Sec. 22 Cardington Twp. Morrow Co.
1554	Ashland Oil and Refining Company V. G. Ullom #5 1108' SL 2375' EL NE Sec. 22 Cardington Twp. Morrow Co.
555	Perry Fulk R. & E. Baker #2 495' NL 995' EL SE Sec. 22 Cardington Twp. Morrow Co.
641	Charles McGrew R. Partlow #1 1836' NL 1400' EL SE Sec. 22 Cardington Twp. Morrow Co.
404	Donald E. Davis J. Arndt #1 115' NL 1405' EL NE Sec. 27 Cardington Twp. Morrow Co.
666	Herb Neyhouse C. Bunnell #1 450' SL 130' EL Lot 8 Cardington Twp. Morrow Co.

Stratigraphic Cross Section A-A', continued

712	M and D Inc. E. & H. Kirkpatrick #1 356' NL 335' WL Lot 9 Cardington Twp. Morrow Co.
668	Perry Fulk and Daniel L. Schwetz L. & M. McClintock 555' NL 323' WL Lot 10 Cardington Twp. Morrow Co.
1367	Burgin Production Company Vocational Agr. Assoc. #1 600' SL 1000' WL Lot 10 Cardington Twp. Morrow Co.
1584	Obie Shaw M. & M. Berry #1 545' SL 790' WL Lot 11 Cardington Twp. Morrow Co.

STRATIGRAPHIC CROSS SECTION B-B'

Ohio Drilling Permit Number	Operator, Lease, and Location
2503	Otter Creek Exploration Company Ward Crum No. 1 807' WL 1570' SL NW Sec. 30 Canaan Twp. Morrow Co.
2164	Hanson Oil Properties E. & S. Snyder #1 330' NL 230' EL NW Sec. 30 Canaan Twp. Morrow Co.
49	Wood Rider, Inc. E. T. Snyder #A-1 660' NL 660' EL NE Sec. 30 Canaan Twp. Morrow Co.
2522	Ashland Oil and Refining Company Kramer No. 1 351' NL 389' WL SW Sec. 29 Canaan Twp. Morrow Co.
2720	Ashland Oil and Refining Company Kramer Unit No. 1 680' SL 1550' WL SW Sec. 29 Canaan Twp. Morrow Co.
189	Ashland Oil and Refining Company Sellars #1 750' SL 2250' WL SW Sec. 27 Canaan Twp. Morrow Co.
2141	Carter Development Company J. Pfeifer #1 230' NL 230' EL NE Sec. 32 Canaan Twp. Morrow Co.
37	Graytex Drilling Company Brader #1 660' NL 660' WL NW Sec. 33 Canaan Twp. Morrow Co.
12	United Producing Company, Inc. Orrie Myers #3 1980' WL 660' NL NW Sec. 33 Canaan Twp. Morrow Co.
10	United Producing Company, Inc. Orrie Myers #1 1980' EL 660' NL NE Sec. 33 Canaan Twp. Morrow Co.
11	United Producing Company, Inc. Orrie Myers #2 660' NL 660' EL NE Sec. 33 Canaan Twp. Morrow Co.
96	Ashland Oil and Refining Company Nixon-Bush #1 2000' NL 2305' EL NE Sec. 34 Canaan Twp. Morrow Co.
2038	Ashland Oil and Refining Company Whitney #3 1090' SL 790' EL SE Sec. 34 Canaan Twp. Morrow Co.
548	Perry Fulk Olds #1 300' SL 50' WL SE Sec. 34 Canaan Twp. Morrow Co.
155	Algonquin Petroleum Company E. Brinkman #1 300' WL 250' SL SW Sec. 35W Gilead Twp. Morrow Co.

Stratigraphic Cross Section B-B', continued

249	Comanche Oil, Inc. E. Brinkman C-5 1150' W 70' NL NW Sec. 2W Gilead Twp. Morrow Co.
248	Comanche Oil, Inc. E. Brinkman #4 600' EL 70' NL NW Sec. 2W Gilead Twp. Morrow Co.
337	Jerry Moore, Inc. and Kin-Ark Oil Company Barbara Scott B-2 610' NL 350' WL NE Sec. 2W Gilead Twp. Morrow Co.
325	Jerry Moore, Inc. and Kin-Ark Oil Company P. Thomas #3 1200' NL 460' EL NE Sec. 2W Gilead Twp. Morrow Co.
275	Jerry Moore, Inc. and Kin-Ark Oil Company P. Thomas #2 1076' SL 78' EL NE Sec. 2W Gilead Twp. Morrow Co.
280	Jerry Moore, Inc. and Kin-Ark Oil Company N. Kincade #1 97' NL 91' WL NW Sec. 3 Gilead Twp. Morrow Co.
135	Tad Weed and Associates N. Kincade #1 710' WL 375' NL NW Sec. 3 Gilead Twp. Morrow Co.
182	Petrotech Corporation E. Snyder #1 1341' WL 1691' SL NW Sec. 3 Gilead Twp. Morrow Co.
424	K. D. Brown and R. O. Leighton Grayer-Spencer #1 1420' NL 350' EL NW Sec. 3 Gilead Twp. Morrow Co.
398	Walter Duncan Hospital Unit #1 820' SL 1200' WL NE Sec. 3 Gilead Twp. Morrow Co.
113	Comanche Oil Inc. R. Newson #1 571' SL 796' EL NE Sec. 3 Gilead Twp. Morrow Co.
491	Dale Kirkconnell R. Gandee #2 182' SL 423' EL NE Sec. 3 Gilead Twp. Morrow Co.
1143	Thurlow Weed Farm Bureau Co-op. #2 100' SL 100' WL NW Sec. 2E Gilead Twp. Morrow Co.
1933	Louis M. Lottie Keernan-Edgell #2 21' SL 1135' WL NW Sec. 2E Gilead Twp. Morrow Co.
300	Southern Triangle Oil Company and Jenkins Engineering Company Fairgrounds #2 750' NL 1150' WL SE Sec. 2E Gilead Twp. Morrow Co.
152	Robert E. Semmler D. Claypool #1 1650' SL 660' EL SE Sec. 2E Gilead Twp. Morrow Co.

Stratigraphic Cross Section B-B', continued

433	Kin-Ark Oil Company	R. McKirgen #1	1240' SL 135' WL SW Sec. 1 Gilead Twp. Morrow Co.
1836	Bill Allen Associates	R. McKirgen No. 1	1289' NL 430' EL WS Sec. 1 Gilead Twp. Morrow Co.
323	Hobson Oil Company	S. & V. Hobson #1	1185' NL 520' WL SW Sec. 6 Gilead Twp. Morrow Co.
1562	Hobson Oil Company	S. & V. Hobson #2	890' NL 832' EL SW Sec. 6 Gilead Twp. Morrow Co.
2895	Wenner Petroleum Corporation	Shipman No. 1	728' SL 84' EL NE Sec. 6 Gilead Twp. Morrow Co.

STRATIGRAPHIC AND STRUCTURE CROSS SECTIONS C-C'

Ohio Drilling Permit Number	Operator, Lease, and Location
2722	Ashland Oil and Refining Company Pfeifer-Bailey Unit No. 1 230' WL 1242' SL SW Sec. 32 Canaan Twp. Morrow Co.
2754	Hoagland Drilling Company W. S. Belt #1 433' NL 1090' WL SW Sec. 32 Canaan Twp. Morrow Co.
2218	Ashland Oil and Refining Company W. Parker No. 1 1387' SL 90' EL SW Sec. 32 Canaan Twp. Morrow Co.
2561	Hadson Ohio Oil Company W. E. Ashbaugh No. 1 750' SL 1150' EL SW Sec. 32 Canaan Twp. Morrow Co.
2588	Hadson Ohio Oil Company W. E. Ashbaugh No. 2 1420' SL 400' EL SE Sec. 32 Canaan Twp. Morrow Co.
579	Ashland Oil and Refining Company Hess #1 575' SL 375' WL SW Sec. 33 Canaan Twp. Morrow Co.
37	Graytex Drilling Company Brader #1 660' NL 660' WL NW Sec. 33 Canaan Twp. Morrow Co.
2741	Ashland Oil and Refining Company Hines-Norton Unit No. 2 379' SL 2540' EL NW Sec. 33 Canaan Twp. Morrow Co.
17	United Producing Company, Inc. Hines-Norton #1 660' SL 660' WL NE Sec. 33 Canaan Twp. Morrow Co.
10	United Producing Company, Inc. Orrie Myers #1 1980' EL 660' NL NE Sec. 33 Canaan Twp. Morrow Co.
11	United Producing Company, Inc. Orrie Myers #2 660' NL 660' EL NE Sec. 33 Canaan Twp. Morrow Co.
2844	Ashland Oil and Refining Company Myers Unit #4 340' SL 1470' EL SE Sec. 28 Canaan Twp. Morrow Co.
15	United Producing Company, Inc. Bush-Levering #1 2025' EL 620' SL SE Sec. 28 Canaan Twp. Morrow Co.
16	United Producing Company, Inc. Hall-Levering #1 660' NL 660" WL SE Sec. 28 Canaan Twp. Morrow Co.
20	United Producing Company, Inc. Ault-Hall #1 660' SL 660' EL NW Sec. 28 Canaan Twp. Morrow Co.

Stratigraphic and Structure Cross Sections C-C', continued

2286	Ashland Oil and Refining Company Heffley No. 1 1850' SL 250' WL SW Sec. 27 Canaan Twp. Morrow Co.
2593	General Oil Company of Ohio Albert Rhoades, Et Al No. 1 969' SL 231' EL NE Sec. 28 Canaan Twp. Morrow Co.
2367	General Oil of Ohio, Incorporated Loffer-Nance-Gruber #1 315' SL 1630' WL NW Sec. 27 Canaan Twp. Morrow Co.

STRATIGRAPHIC CROSS SECTION D-D'

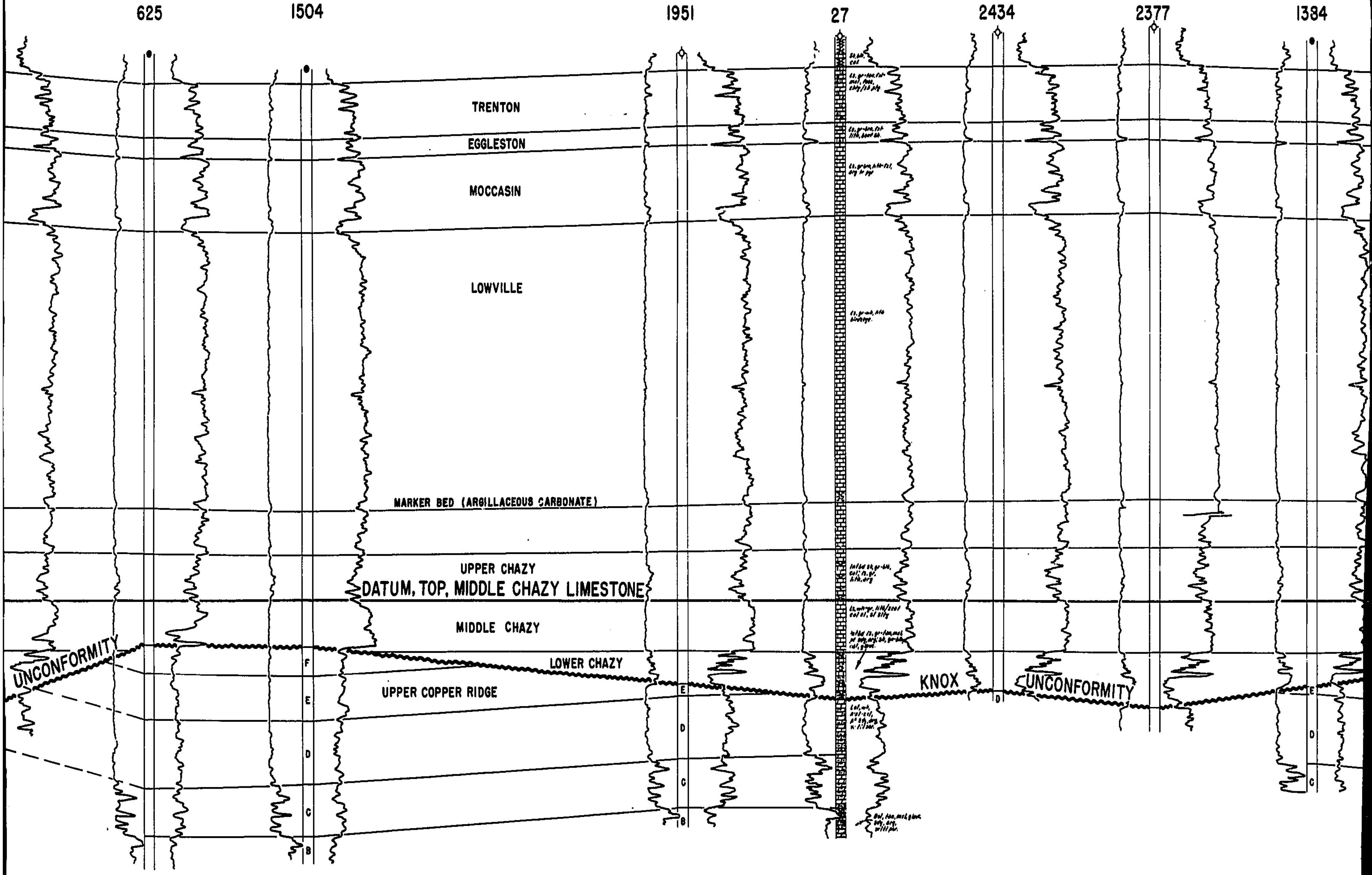
Ohio Drilling Permit Number	Operator, Lease, and Location
17	United Producing Company, Inc. Hines-Norton #1 660' SL 660' WL NE Sec. 33 Canaan Twp. Morrow Co.
10	United Producing Company, Inc. Orrie Myers #1 1980' EL 660' NL NE Sec. 33 Canaan Twp. Morrow Co.
11	United Producing Company, Inc. Orrie Myers #2 660' NL 660' EL NE Sec. 33 Canaan Twp. Morrow Co.
2844	Ashland Oil and Refining Company Myers Unit #4 340' SL 1470' EL SE Sec. 28 Canaan Twp. Morrow Co.
15	United Producing Company, Inc. Bush-Levering #1 2025' EL 620' SL SE Sec. 28 Canaan Twp. Morrow Co.
16	United Producing Company, Inc. Hall-Levering #1 660' NL 660' WL SE Sec. 28 Canaan Twp. Morrow Co.
20	United Producing Company, Inc. Ault-Hall #1 660' SL 660' EL NW Sec. 28 Canaan Twp. Morrow Co.

STRUCTURE CROSS SECTION E-E'

Ohio Drilling Permit Number	Operator, Lease, and Location
20	United Producing Company, Inc. Ault-Hall #1 660' SL 660' EL NW Sec. 28 Canaan Twp. Morrow Co.
16	United Producing Company, Inc. Hall-Levering #1 660' NL 660' WL SE Sec. 28 Canaan Twp. Morrow Co.
15	United Producing Company, Inc. Bush-Levering #1 2025' EL 620' SL SE Sec. 28 Canaan Twp. Morrow Co.
2844	Ashland Oil and Refining Company Myers Unit #4 340' SL 1470' EL SE Sec. 28 Canaan Twp. Morrow Co.
11	United Producing Company, Inc. Orrie Myers #2 660' NL 660' EL NE Sec. 33 Canaan Twp. Morrow Co.
2992	Ray Farrar and Joe Young Oil Company E. & M. Hinds #1 1096' SL 995' WL NW Sec. 34 Canaan Twp. Morrow Co.
1545	Ashland Oil and Refining Company R. & M. Bush #2 1650' SL 330' WL SE Sec. 34 Canaan Twp. Morrow Co.
70	Ashland Oil and Refining Company Whitney-Jolly-Olds #1 680' SL 1220' EL SE Sec. 34 Canaan Twp. Morrow Co.
669	Perry Fulk Oil Company H. & W. Click #1 416' NL 88' EL NE Sec. 3 Cardington Twp. Morrow Co.
80	Comanche Oil Company, Inc. E. Brinkman #2 737' NL 672' WL NW Sec. 2W Gilead Twp. Morrow Co.

STRATIGRAPHIC CROSS SECTION F-F'

Ohio Drilling Permit Number	Operator, Lease, and Location
49	Midland Drilling Company F. L. Gruber #1 703' SL 425' WL NW Sec. 32 Claridon Twp. Marion Co.
66	Midland Drilling Company F. L. Gruber #2 1126' SL 1079' WL NW Sec. 32 Claridon Twp. Marion Co.
75	Comanche Oil Company W. J. Schwaderer #1 432' SL 1050' WL SE Sec. 29 Claridon Twp. Marion Co.
8	United Producing Company, Inc. Mitchell #1 660' SL 660' WL NE Sec. 27 Claridon Twp. Marion Co.
81	Texaco Inc. R. L. Retterer #1 330' SL 330' EL SE Sec. 26 Claridon Twp. Marion Co.
19	Wood Rider Inc. H. Ault #2 1371' SL 1231' EL NE Sec. 36 Claridon Twp. Marion Co.
22	George Schoonmaker H. Ault #1 50' SL 50' EL NE Sec. 36 Claridon Twp. Marion Co.
55	Wood Rider Inc. Roscoe Archballe #1 660' SL 660' WL NW Sec. 31 Canaan Twp. Morrow Co.
2552	Hanson Oil Properties M. & W. Bailey No. 1 880' SL 1500' WL SE Sec. 31 Canaan Twp. Morrow Co.
2722	Ashland Oil and Refining Company Pfeifer-Bailey Unit No. 1 230' WL 1242' SL SW Sec. 32 Canaan Twp. Morrow Co.


625
1504
1951
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2434
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1384
TRENTON
EGGLESTON
MOCCASIN
LOWVILLE
MARKER BED (ARGILLACEOUS CARBONATE)
UPPER CHAZY
DATUM, TOP, MIDDLE CHAZY LIMESTONE
MIDDLE CHAZY
LOWER CHAZY
UNCONFORMITY
UPPER COPPER RIDGE
KNOX
UNCONFORMITY
F
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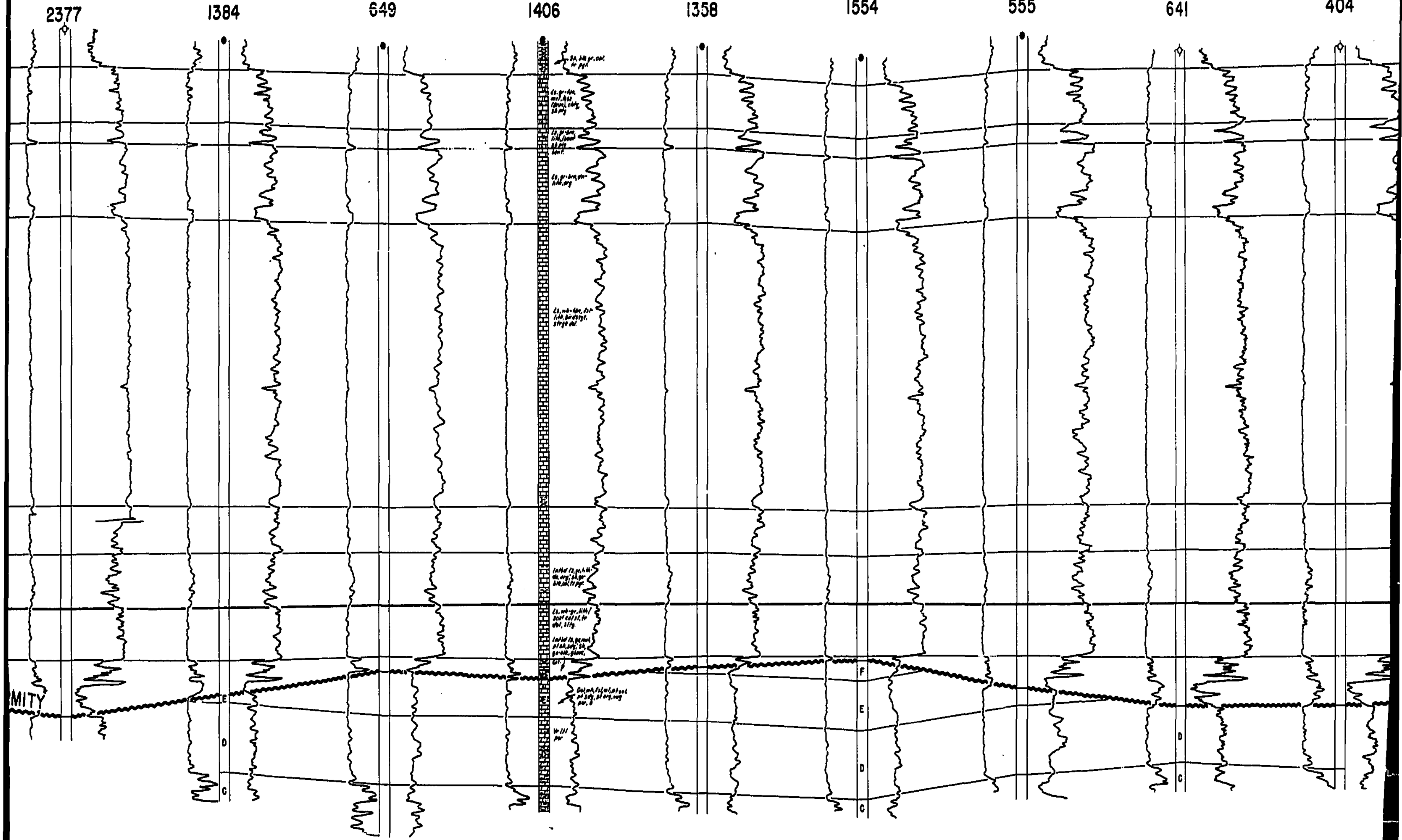
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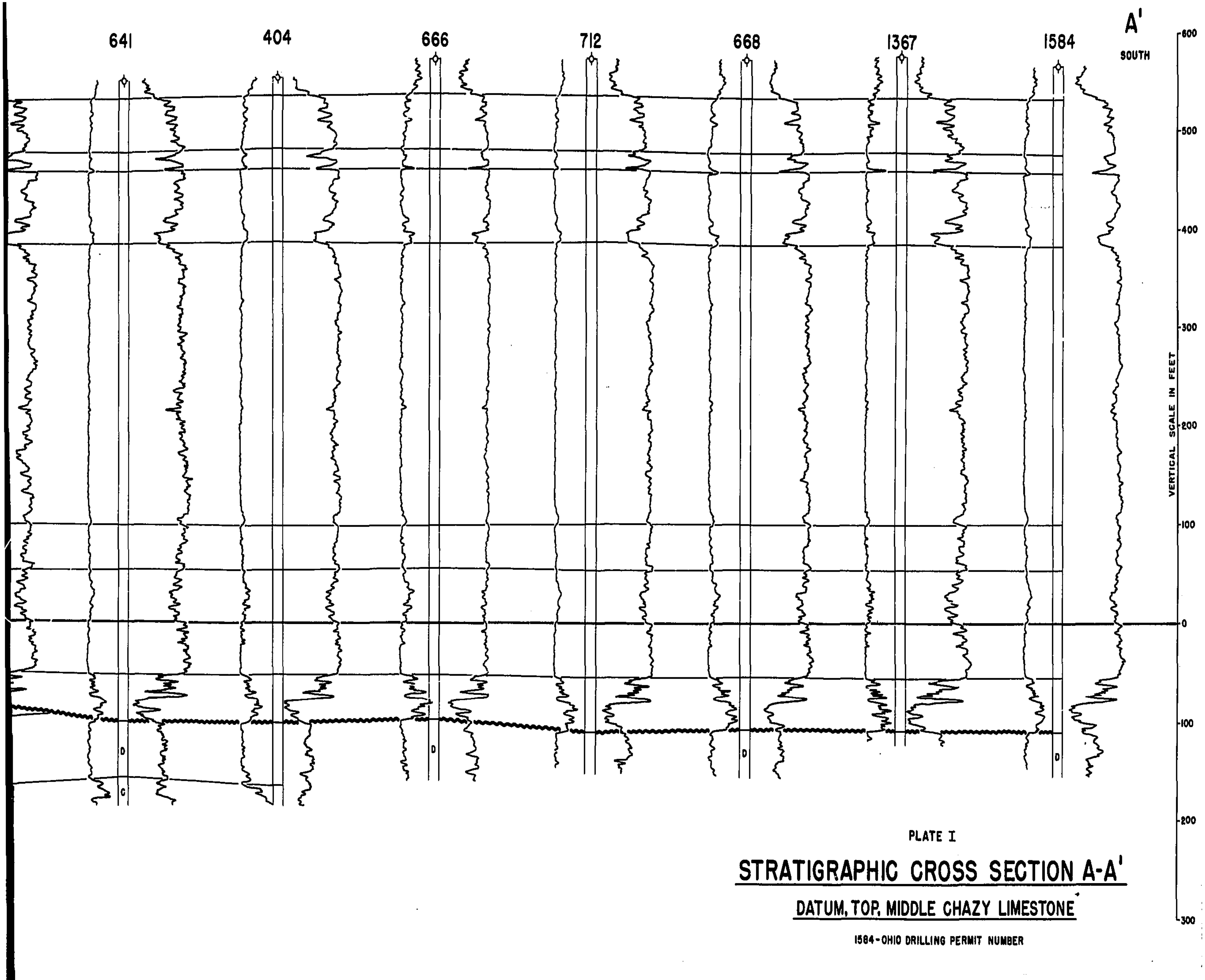
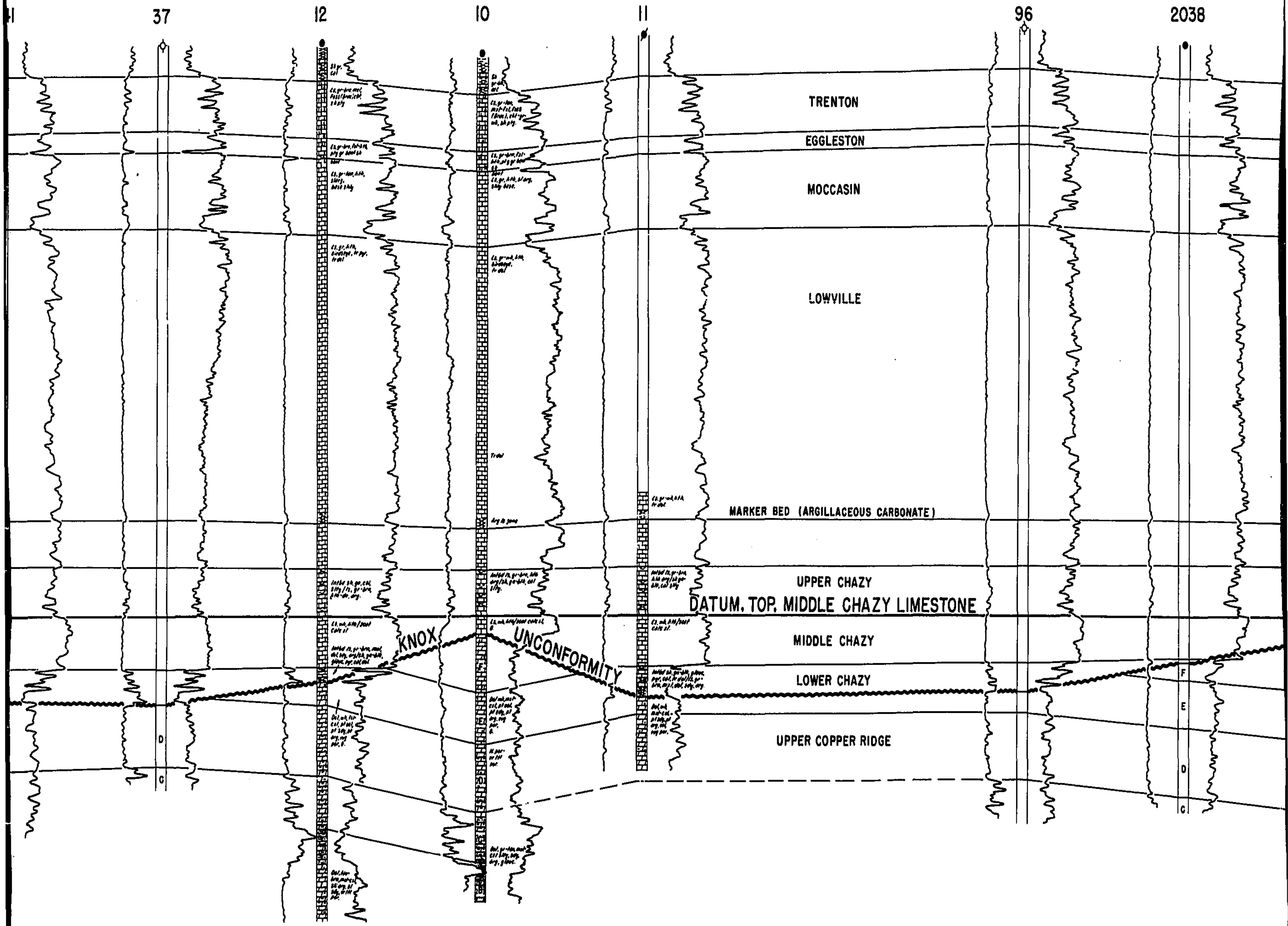


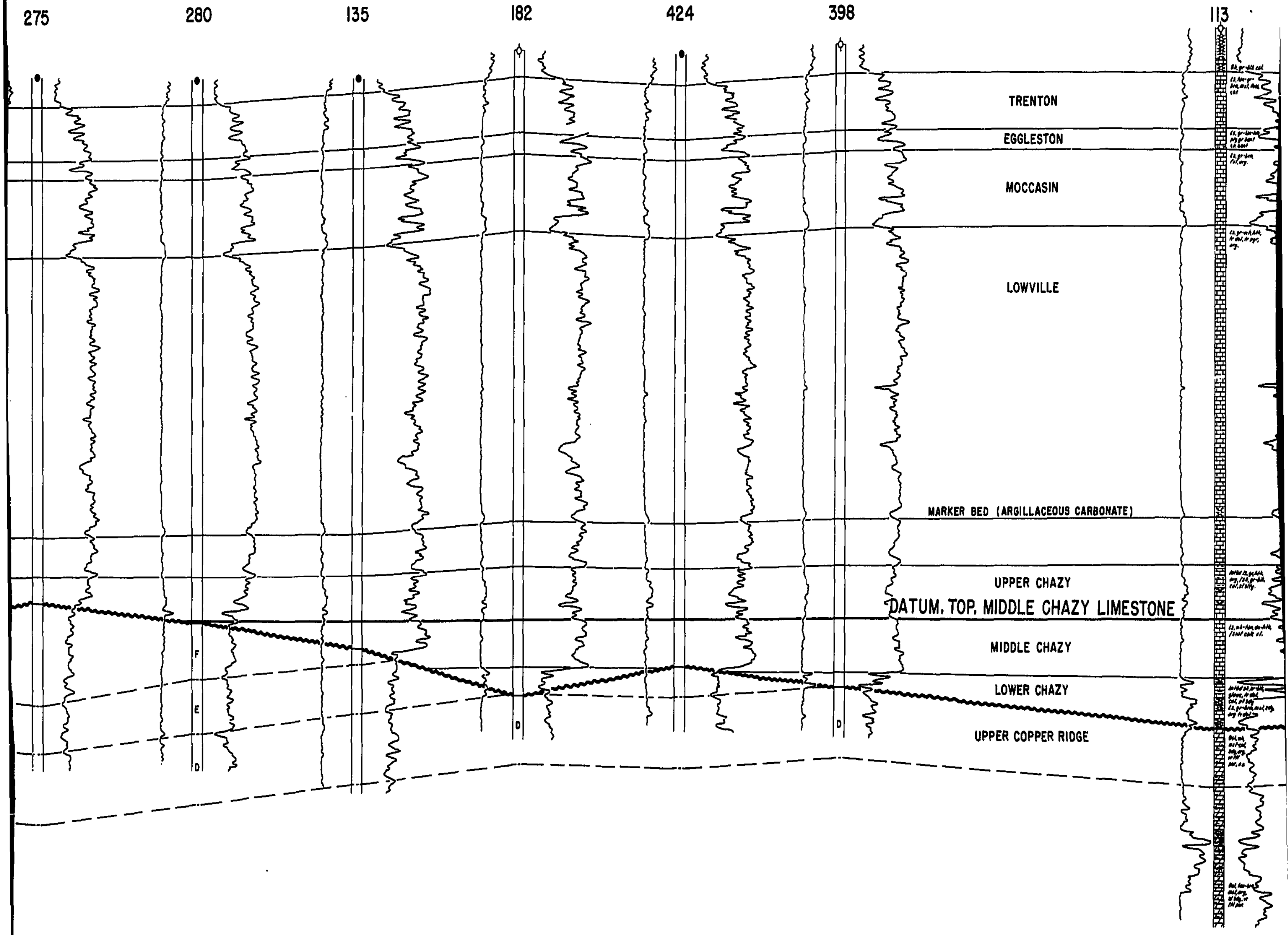
PLATE I

STRATIGRAPHIC CROSS SECTION A-A'

DATUM, TOP, MIDDLE CHAZY LIMESTONE

1584-OHIO DRILLING PERMIT NUMBER


41
37
12
10
11
96
2038
TRENTON
EGGLESTON
MOCCASIN
LOWVILLE
MARKER BED (ARGILLACEOUS CARBONATE)
UPPER CHAZY
DATUM, TOP, MIDDLE CHAZY LIMESTONE
MIDDLE CHAZY
KNOX UNCONFORMITY
LOWER CHAZY
UPPER COPPER RIDGE
D
C
F
E
D
C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182
424
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EGGLESTON
MOCCASIN
LOWVILLE
MARKER BED (ARGILLACEOUS CARBONATE)
UPPER CHAZY
DATUM, TOP, MIDDLE CHAZY LIMESTONE
MIDDLE CHAZY
LOWER CHAZY
UPPER COPPER RIDGE
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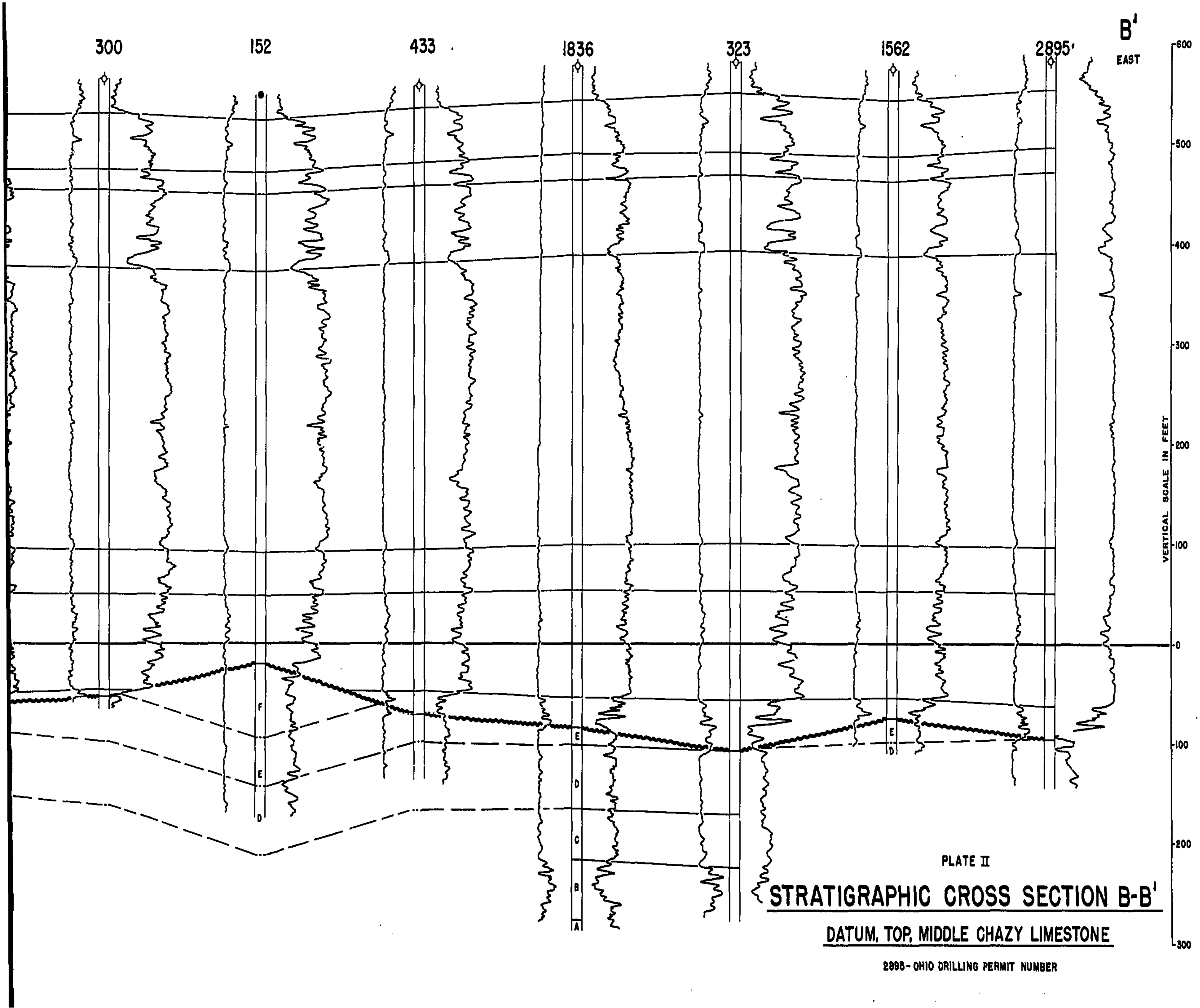
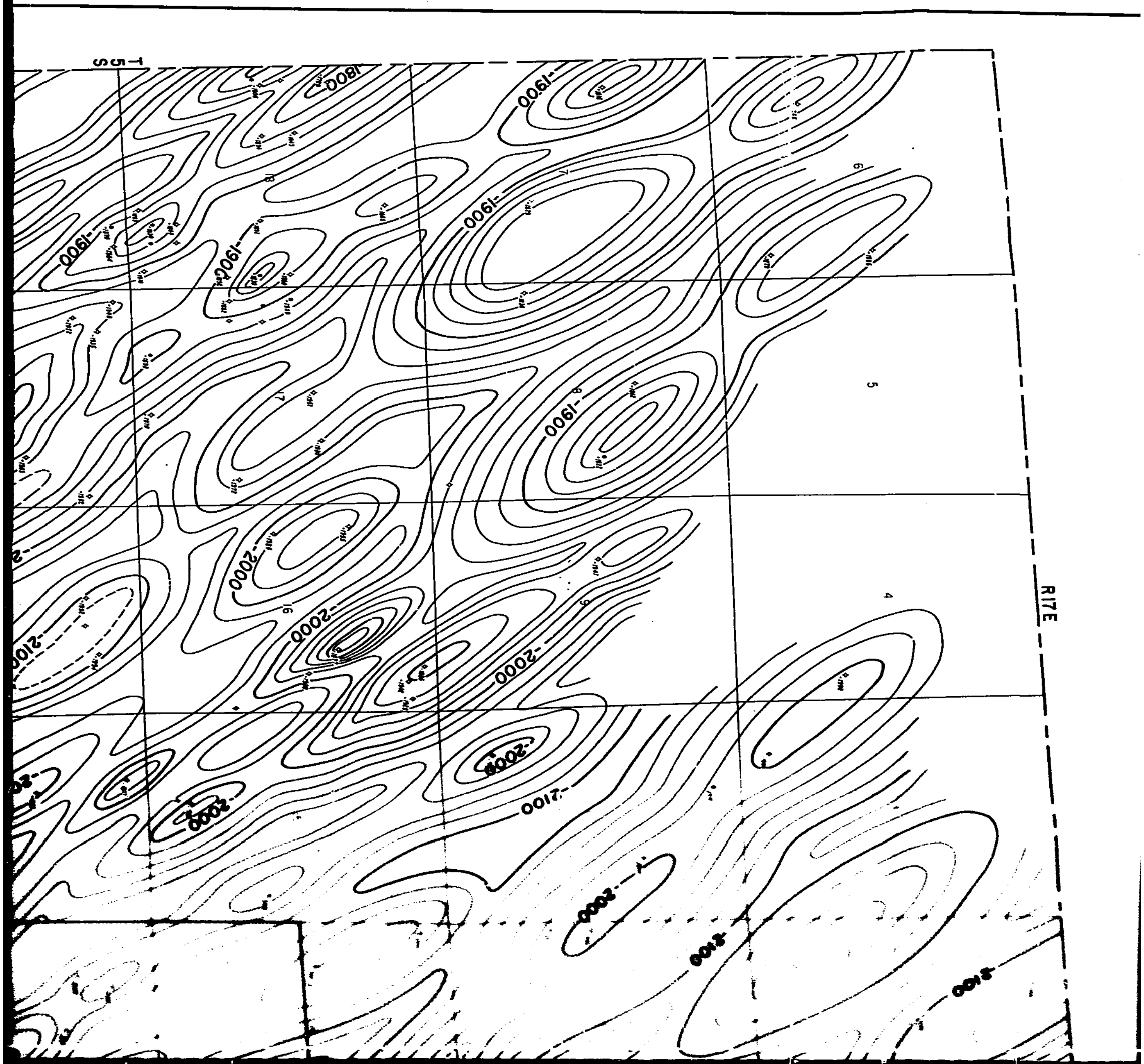


PLATE II

STRATIGRAPHIC CROSS SECTION B-B'

DATUM, TOP, MIDDLE CHAZY LIMESTONE

2895 - OHIO DRILLING PERMIT NUMBER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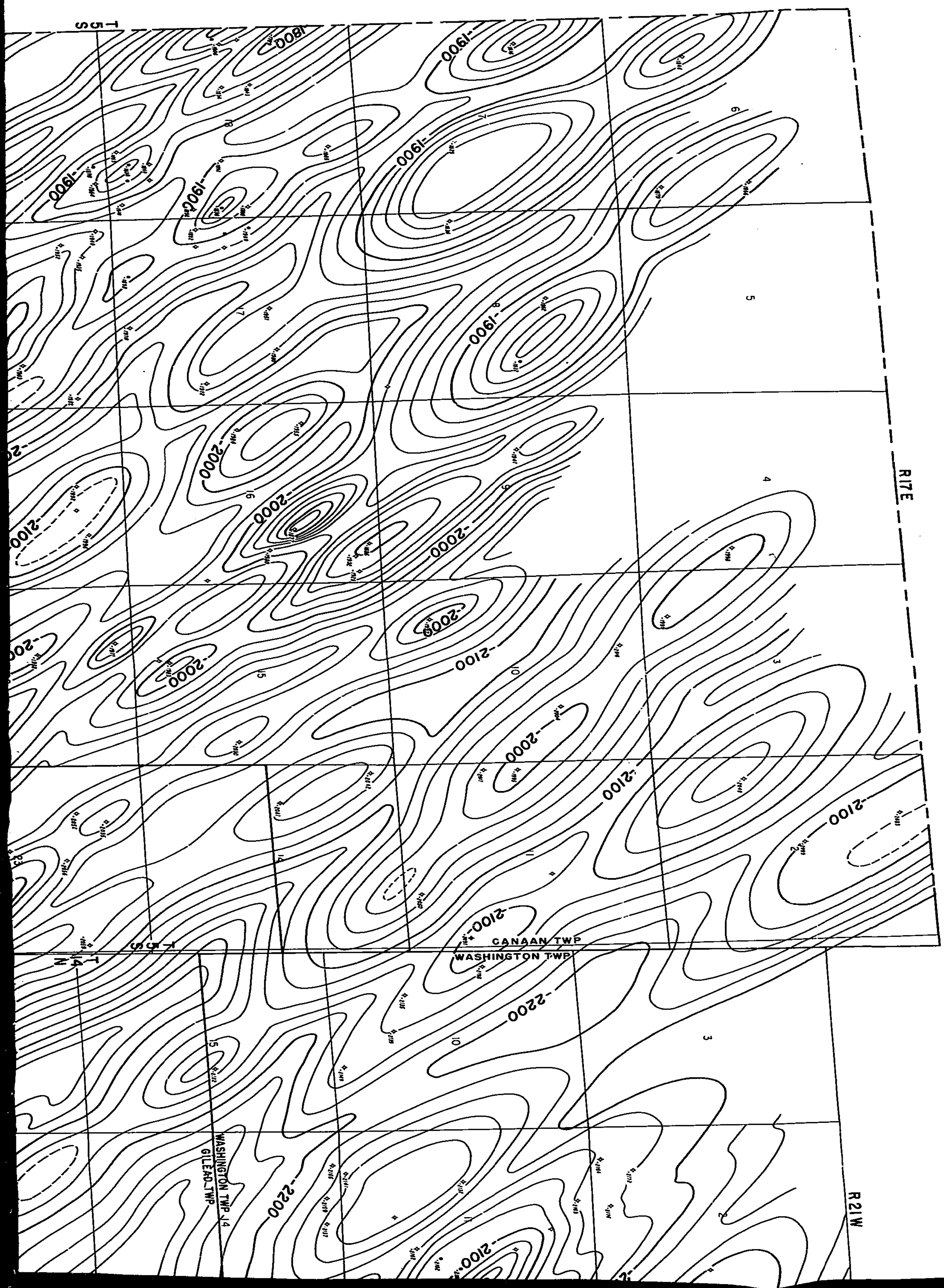
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T 4 N
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R21W
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WASHINGTON TWP
WASHINGTON TWP
GILEAD TWP
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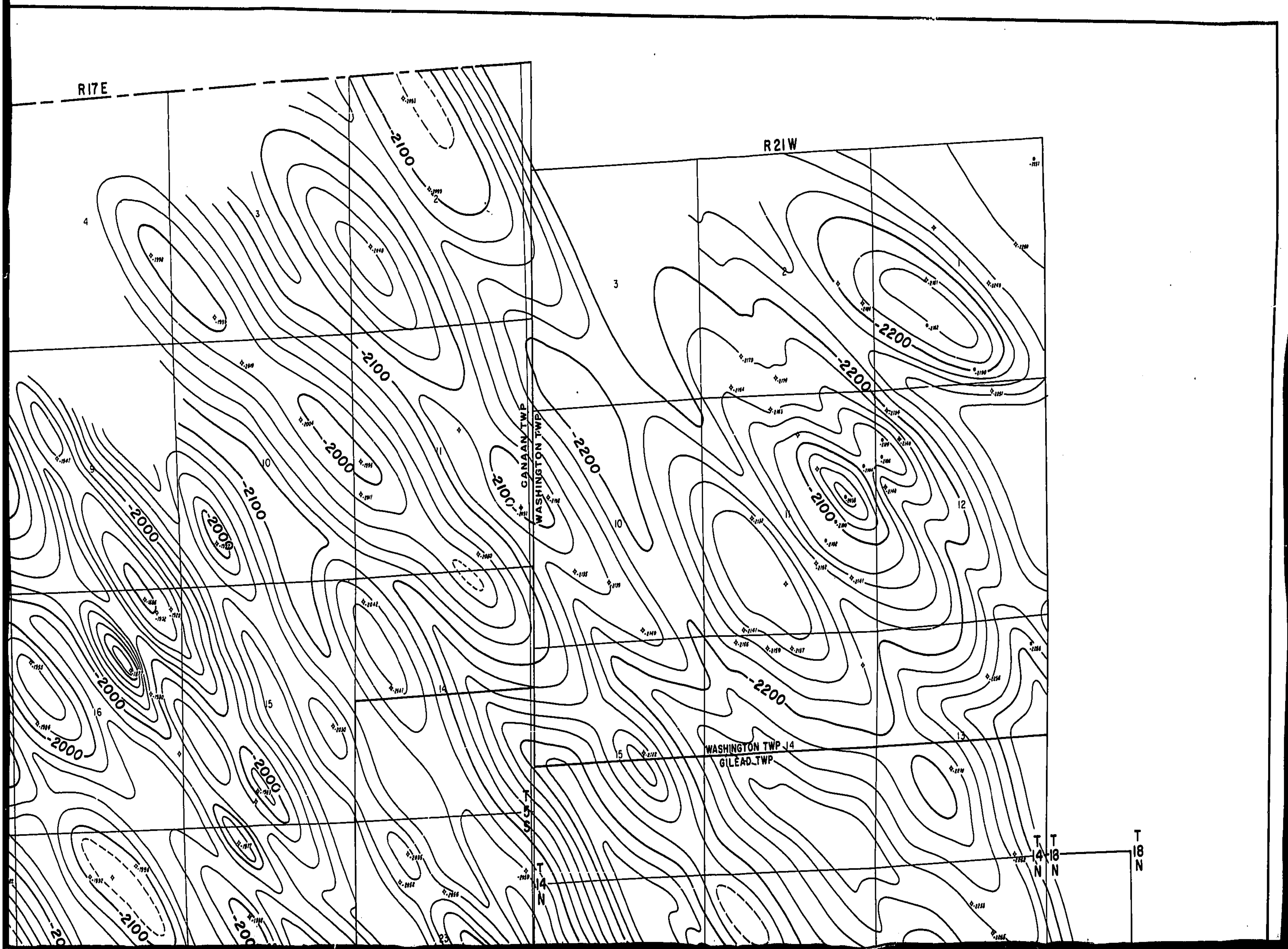
2100
2200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R21W
CANAAN TWP
WASHINGTON TWP
WASHINGTON TWP 14
GILEAD TWP
T 5 S
T 14 N
T 14 N
T 18 N
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-2100
-2000
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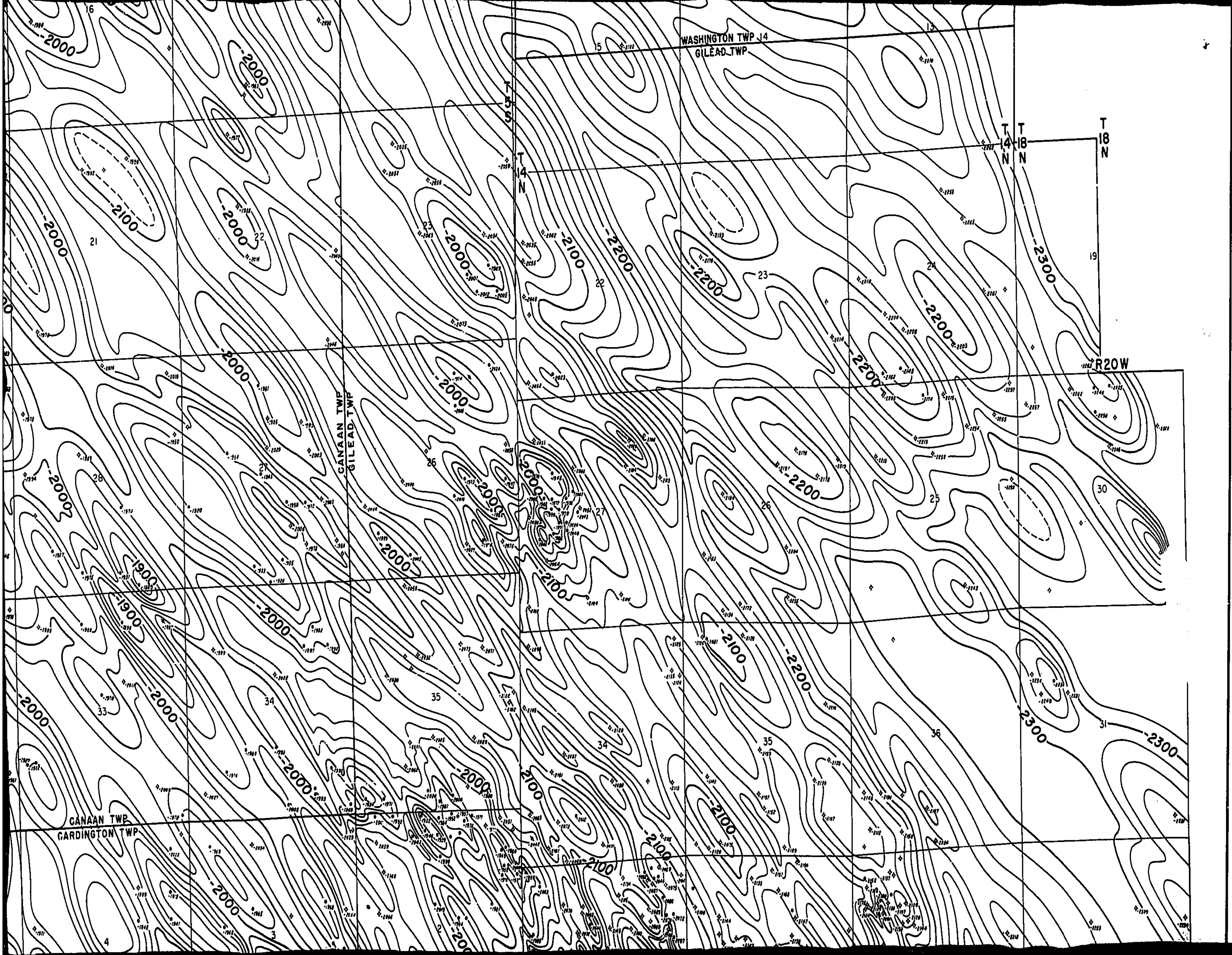
WASHINGTON TWP 14
GILEAD TWP
CANAAN TWP
GILEAD TWP
CANAAN TWP
CARDINGTON TWP
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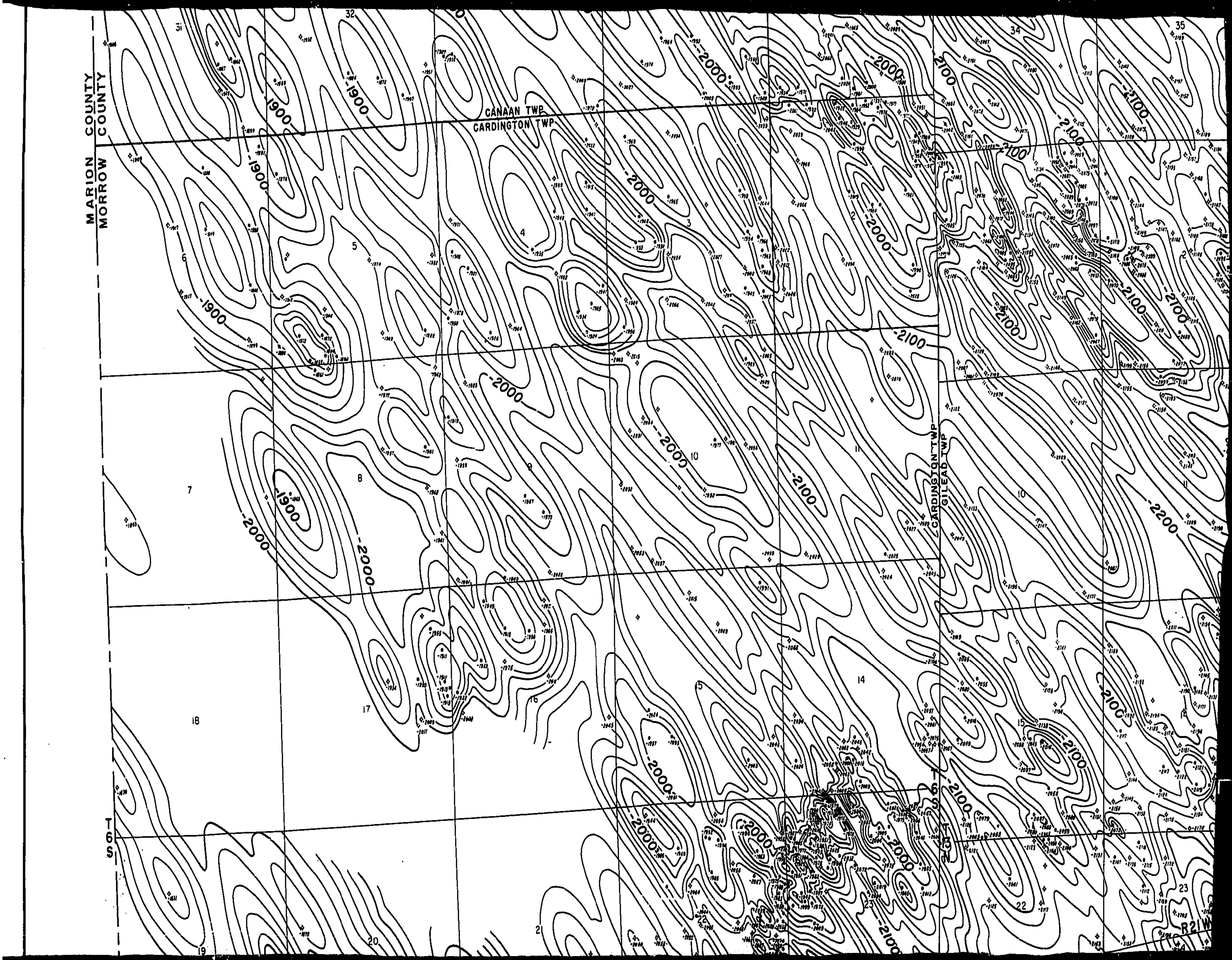
MARION COUNTY
MORROW COUNTY
CANAAN TWP
CARDINGTON TWP
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GILEAD TWP
T6S
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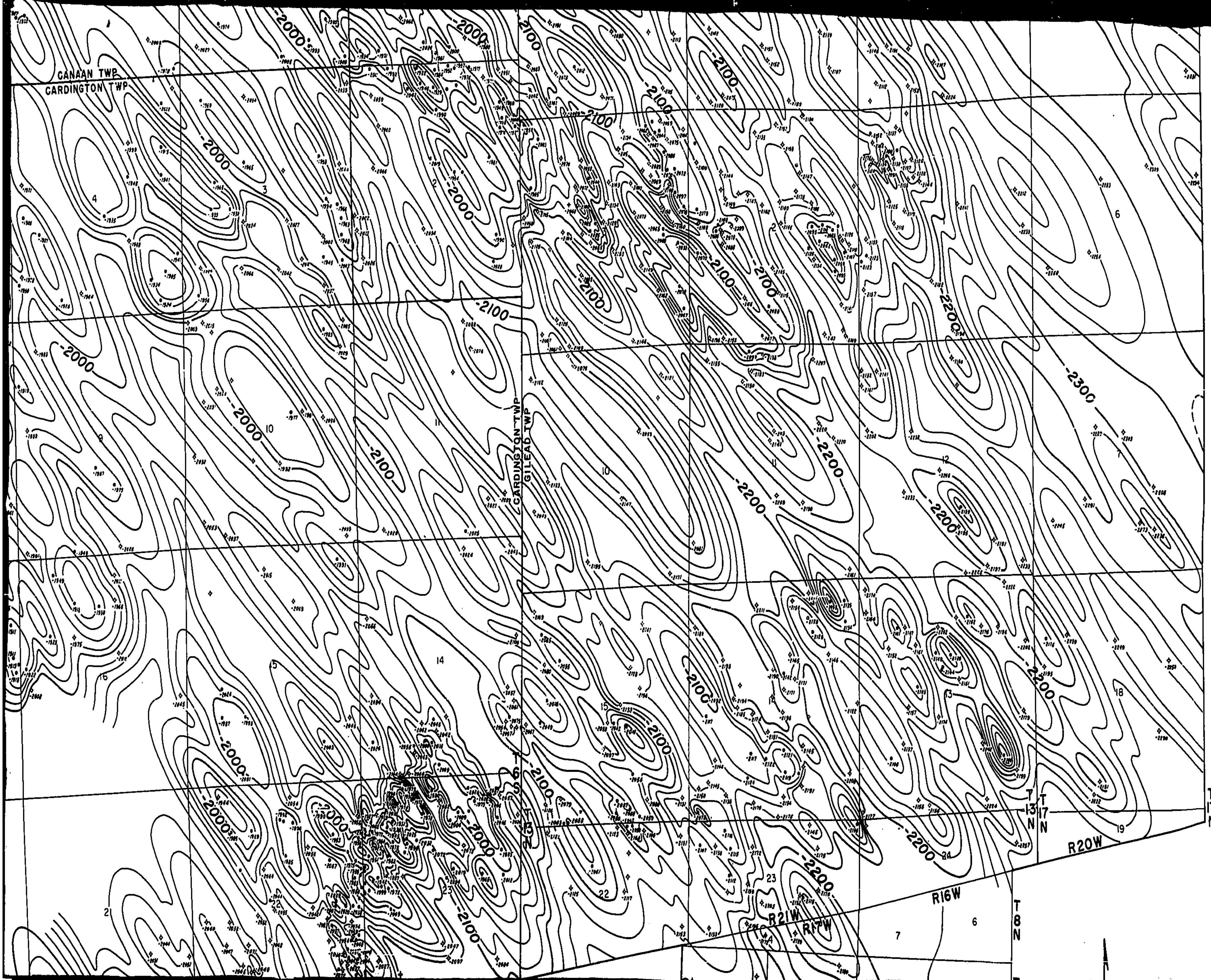
CANAAN TWP
CARDINGTON TWP
CARDINGTON TWP
GILEAD TWP
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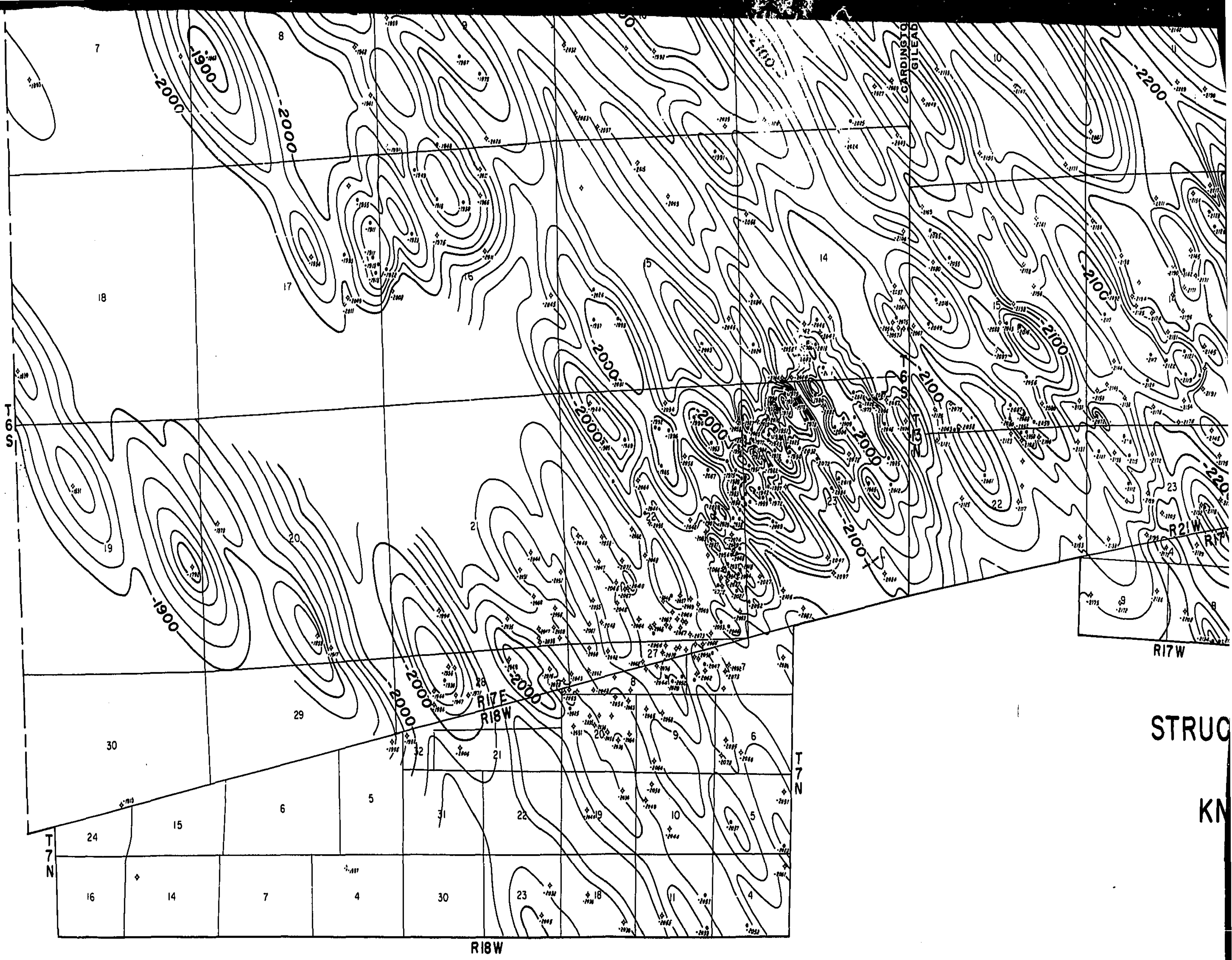
R17W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CARDINGTON
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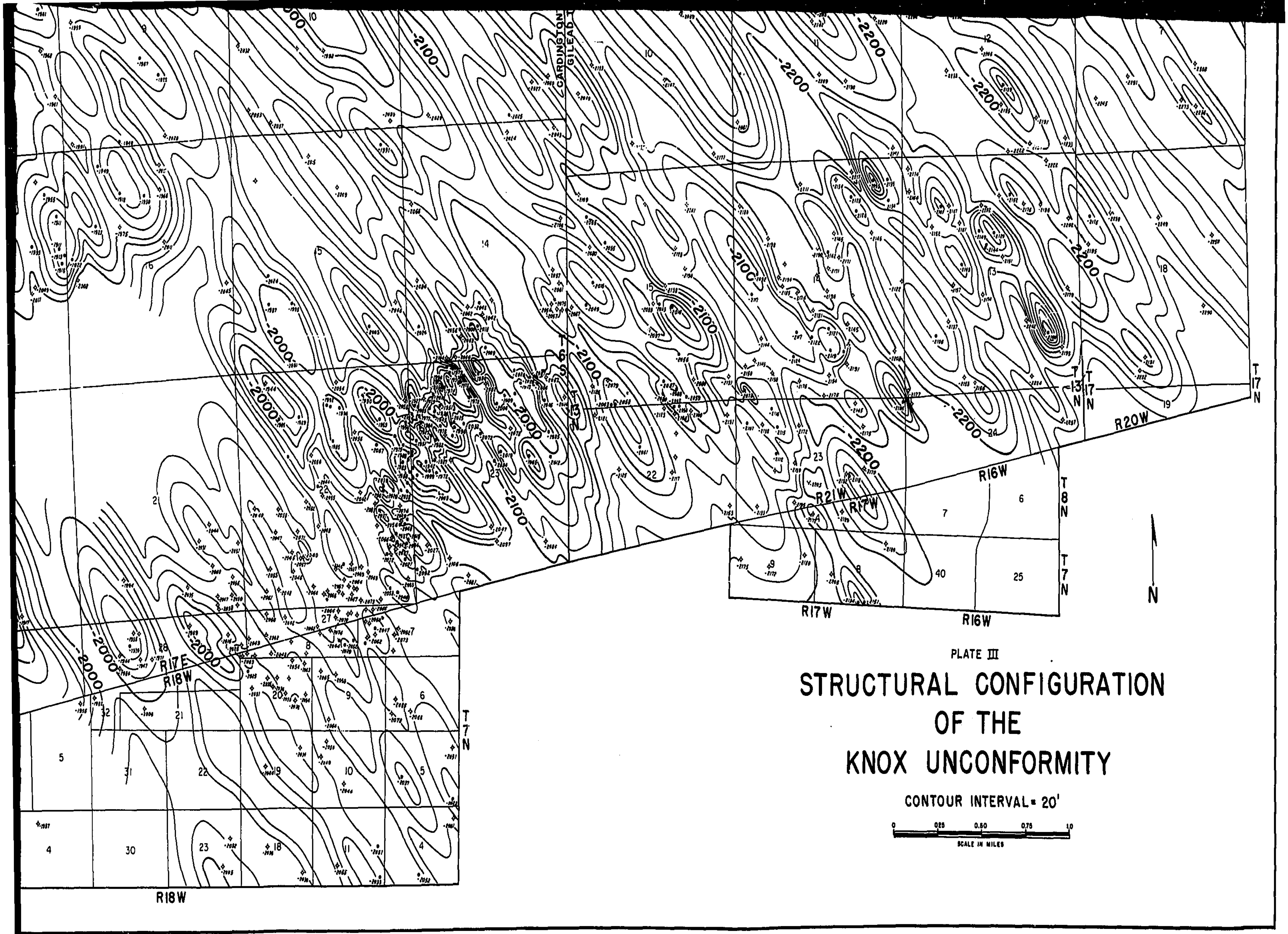


PLATE III

STRUCTURAL CONFIGURATION OF THE KNOX UNCONFORMITY

CONTOUR INTERVAL = 20'

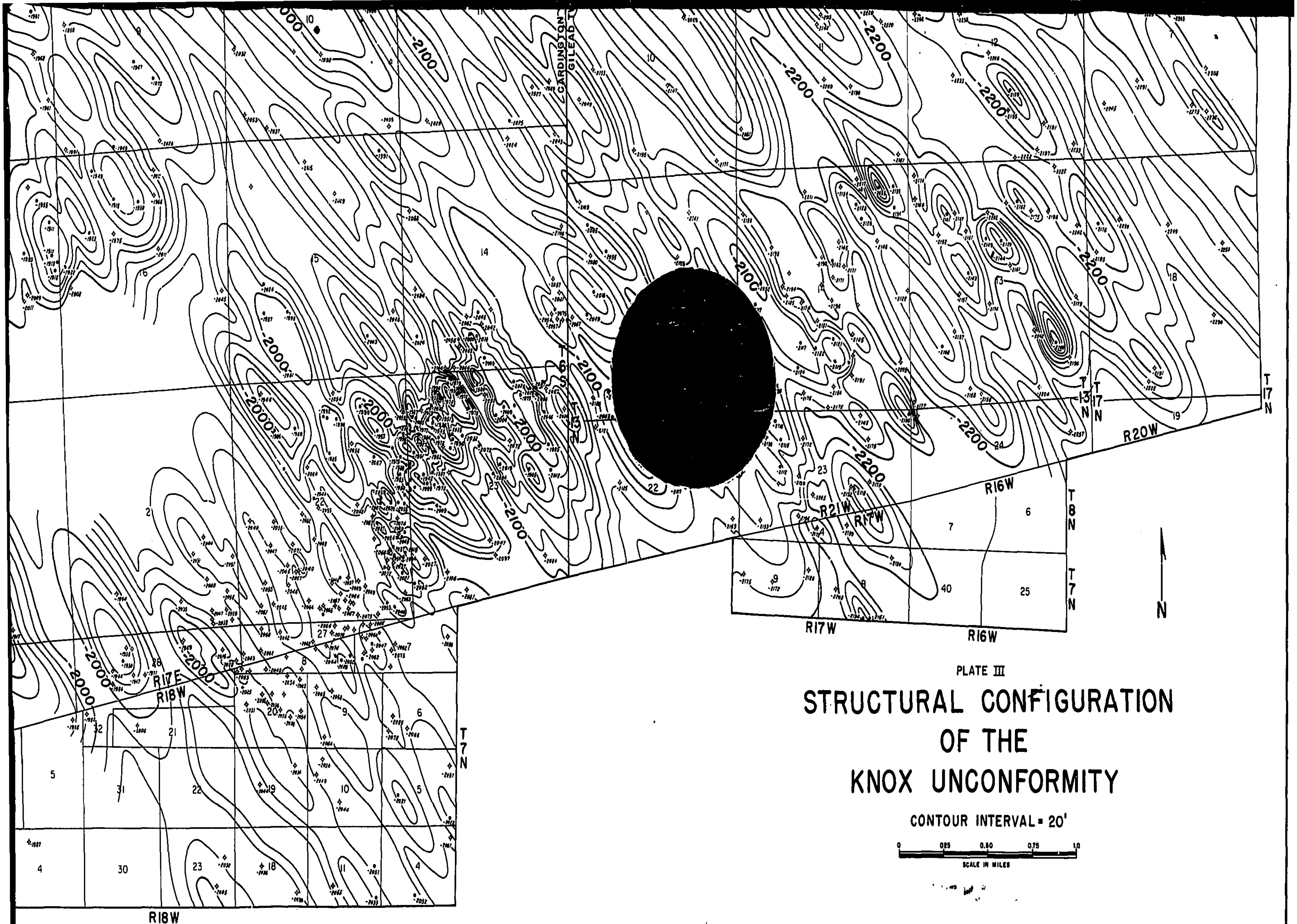
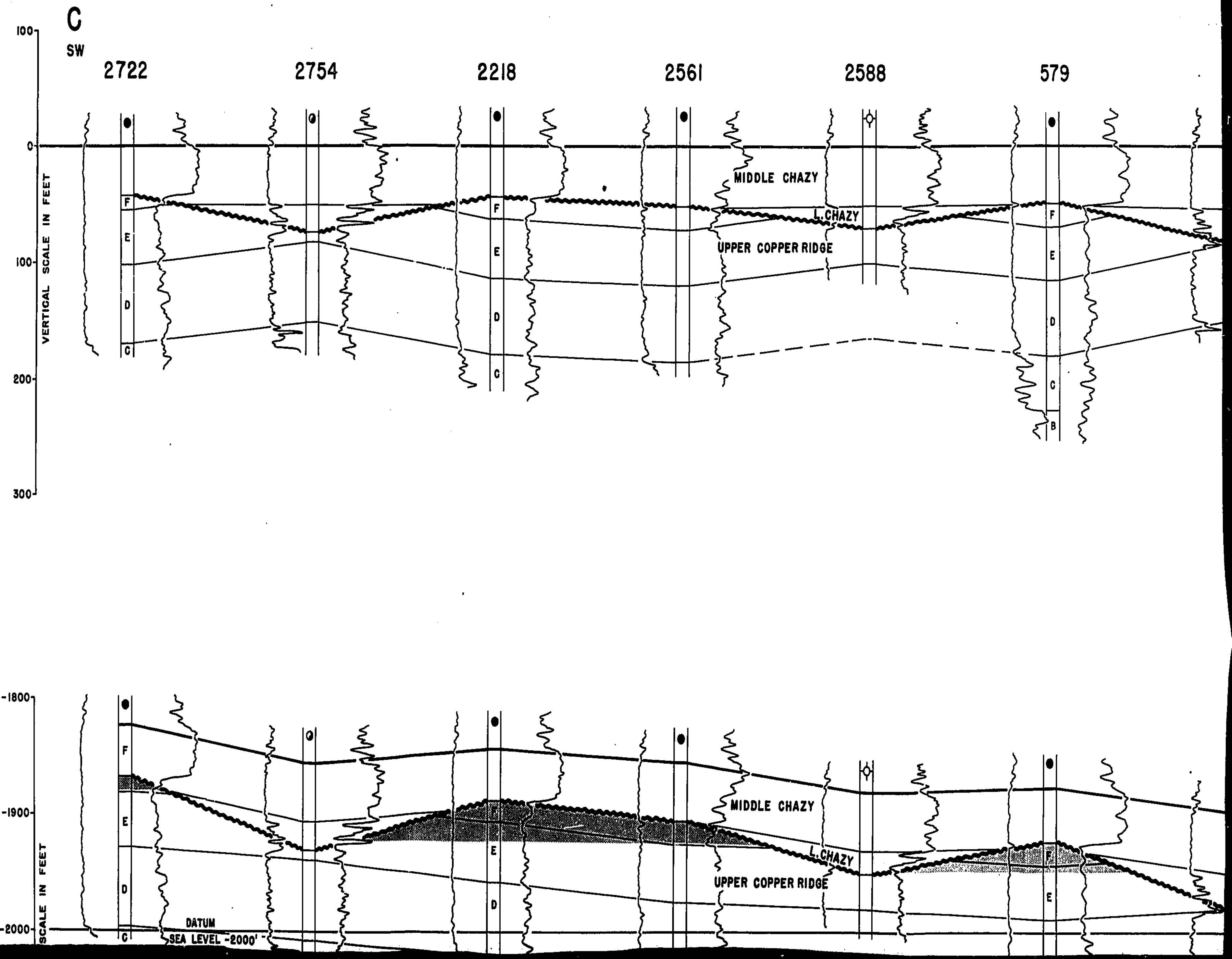


PLATE III

STRUCTURAL CONFIGURATION OF THE KNOX UNCONFORMITY

CONTOUR INTERVAL = 20'


C
SW
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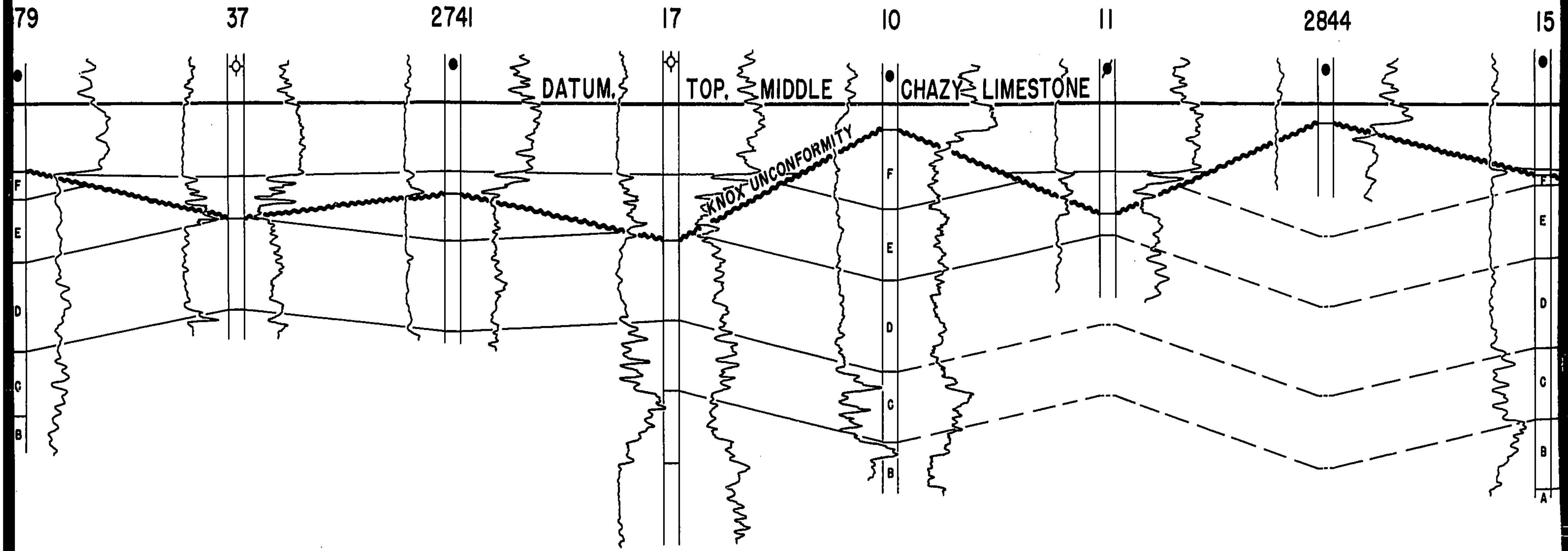
2754
2218
2561
2588
579
100
0
100
200
300
VERTICAL SCALE IN FEET
MIDDLE CHAZY
L. CHAZY
UPPER COPPER RIDGE
F
E
D
C
B
-1800
-1900
-2000
SCALE IN FEET
DATUM
SEA LEVEL -2000'


79
37
2741
17
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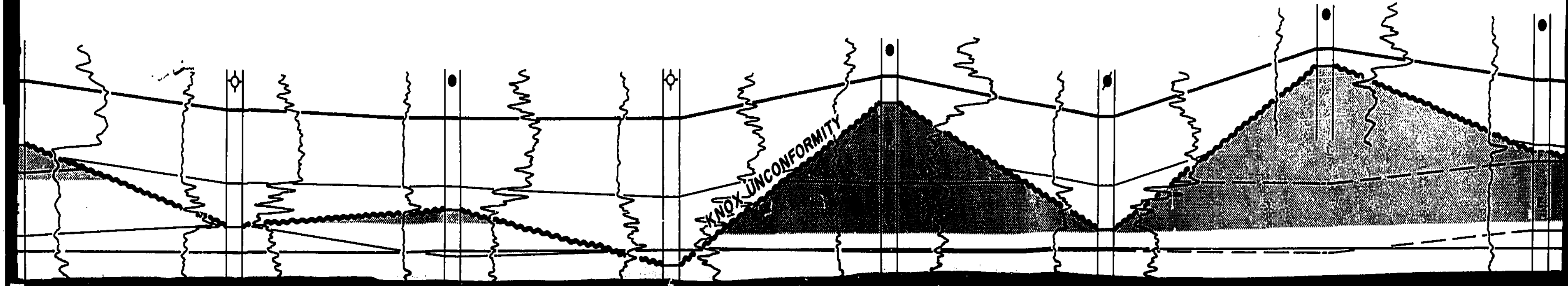
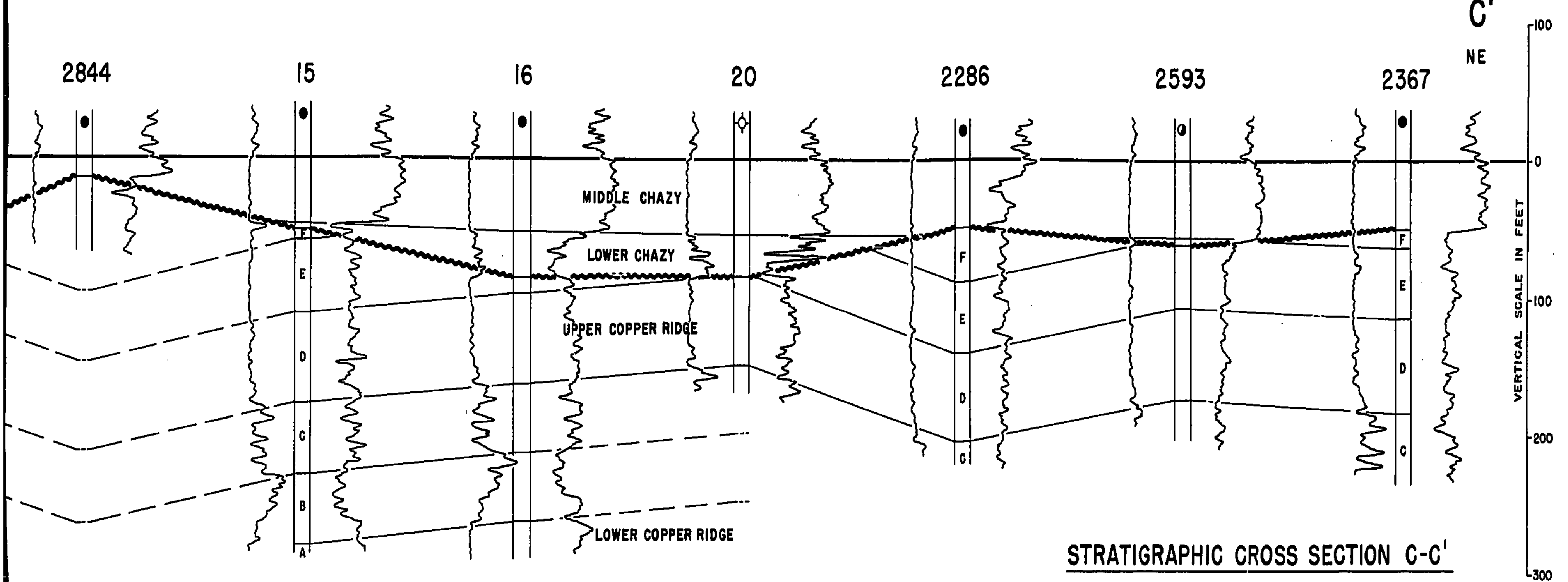
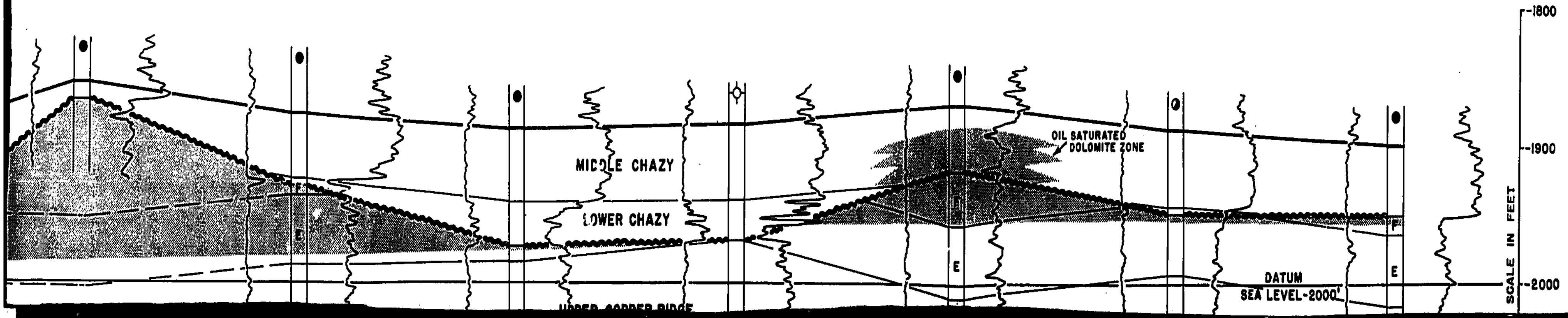
2844
15
DATUM. TOP, MIDDLE CHAZY LIMESTONE
KNOX UNCONFORMITY
F
E
D
C
B
A

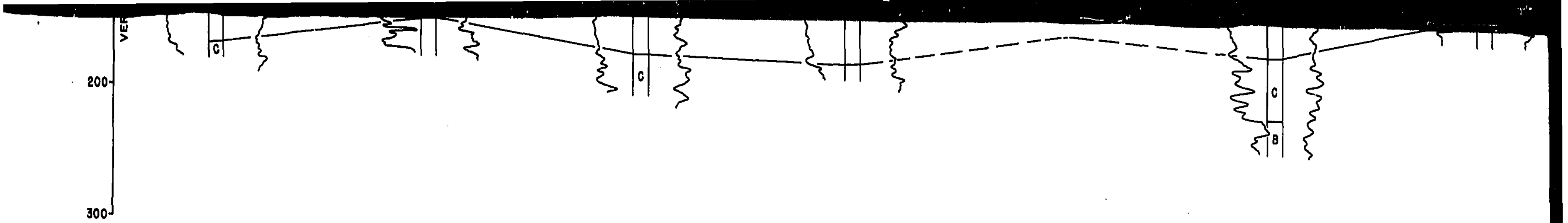

KNOX UNCONFORMITY

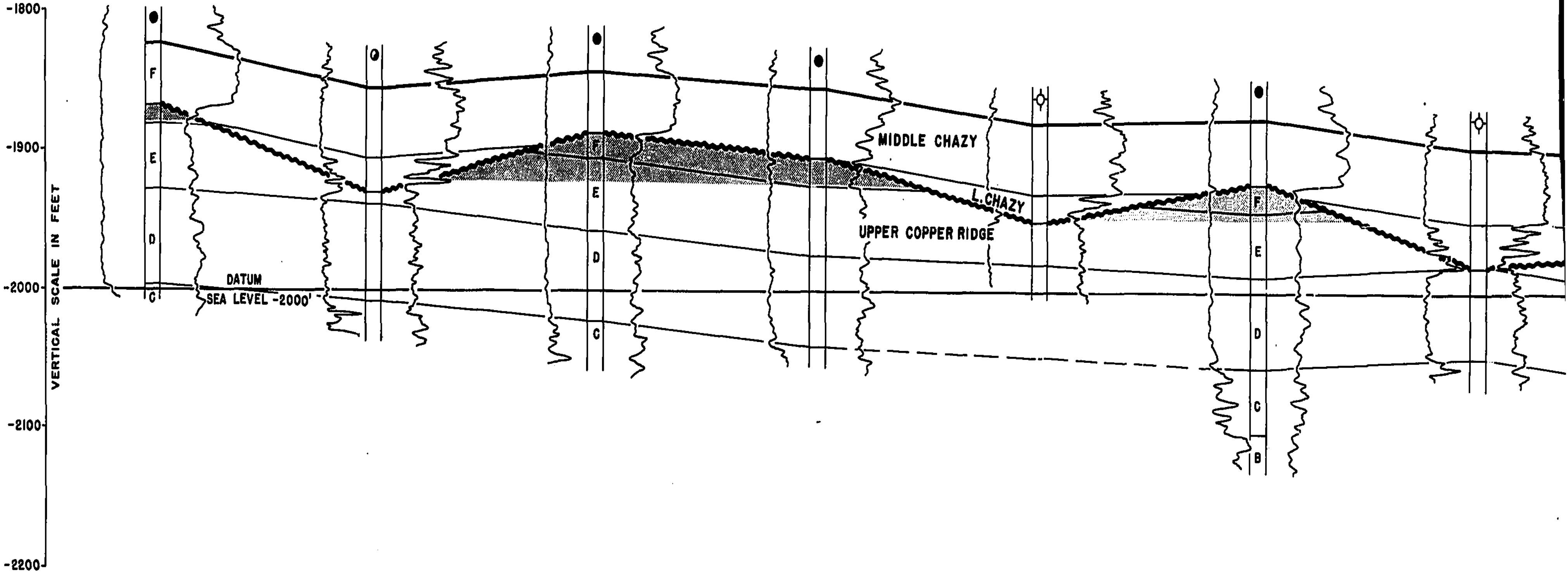


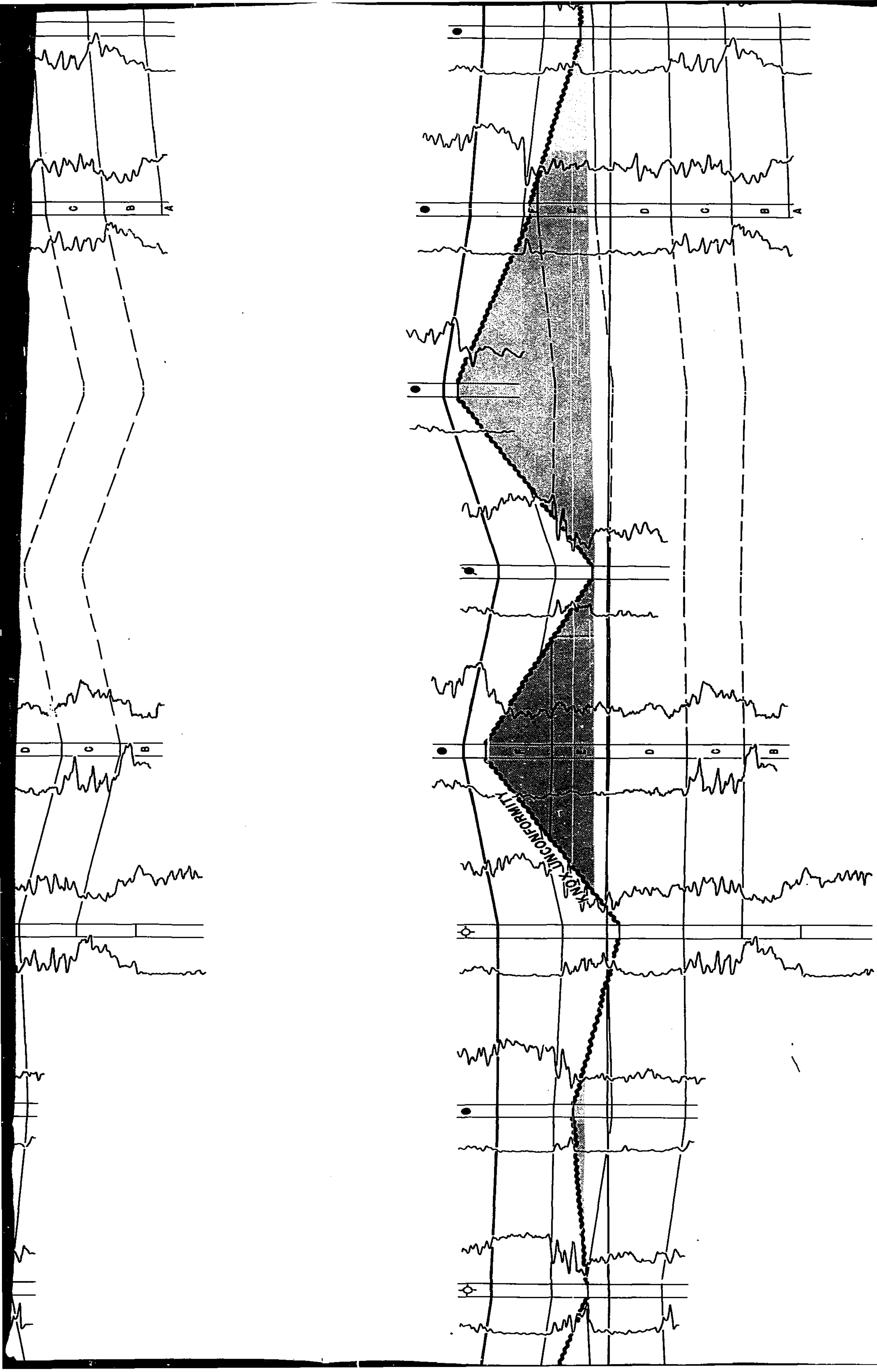
STRATIGRAPHIC CROSS SECTION C-C'

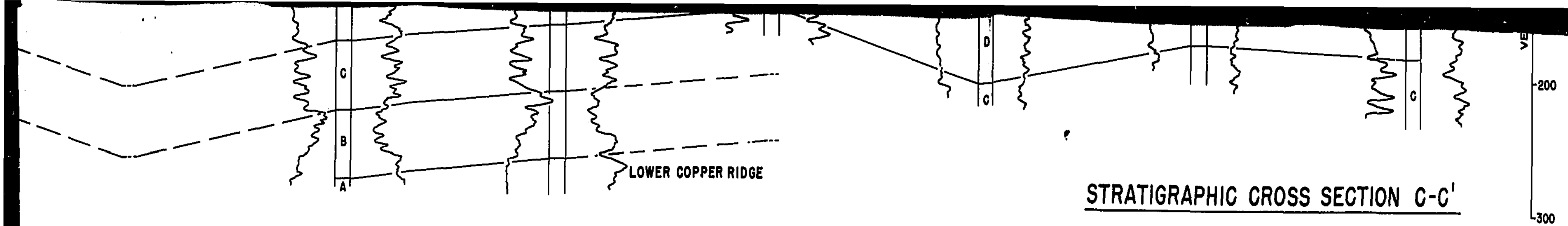
DATUM, TOP, MIDDLE CHAZY LIMESTONE




VER
200
300
C
C
C
B


-1800
-1900
-2000
-2100
-2200
VERTICAL SCALE IN FEET
F
E
D
C
DATUM
SEA LEVEL -2000'
F
E
D
C
MIDDLE CHAZY
L. CHAZY
UPPER COPPER RIDGE
F
E
D
C
B


KNOX UNCONFORMITY
A
B
C
D
E
F



STRATIGRAPHIC CROSS SECTION C-C'

DATUM, TOP, MIDDLE CHAZY LIMESTONE

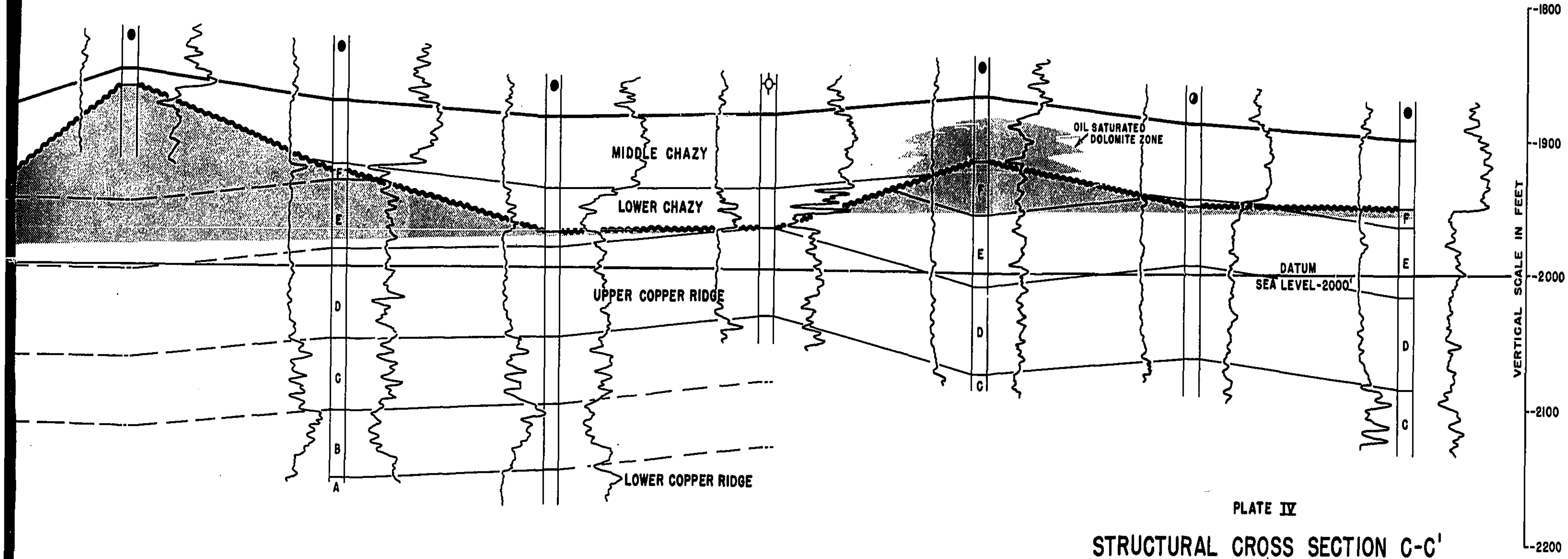


PLATE IV

STRUCTURAL CROSS SECTION C-C'

DATUM SEA LEVEL-2000'

▨ OIL SATURATED ZONE

2367 - OHIO DRILLING PERMIT NUMBER

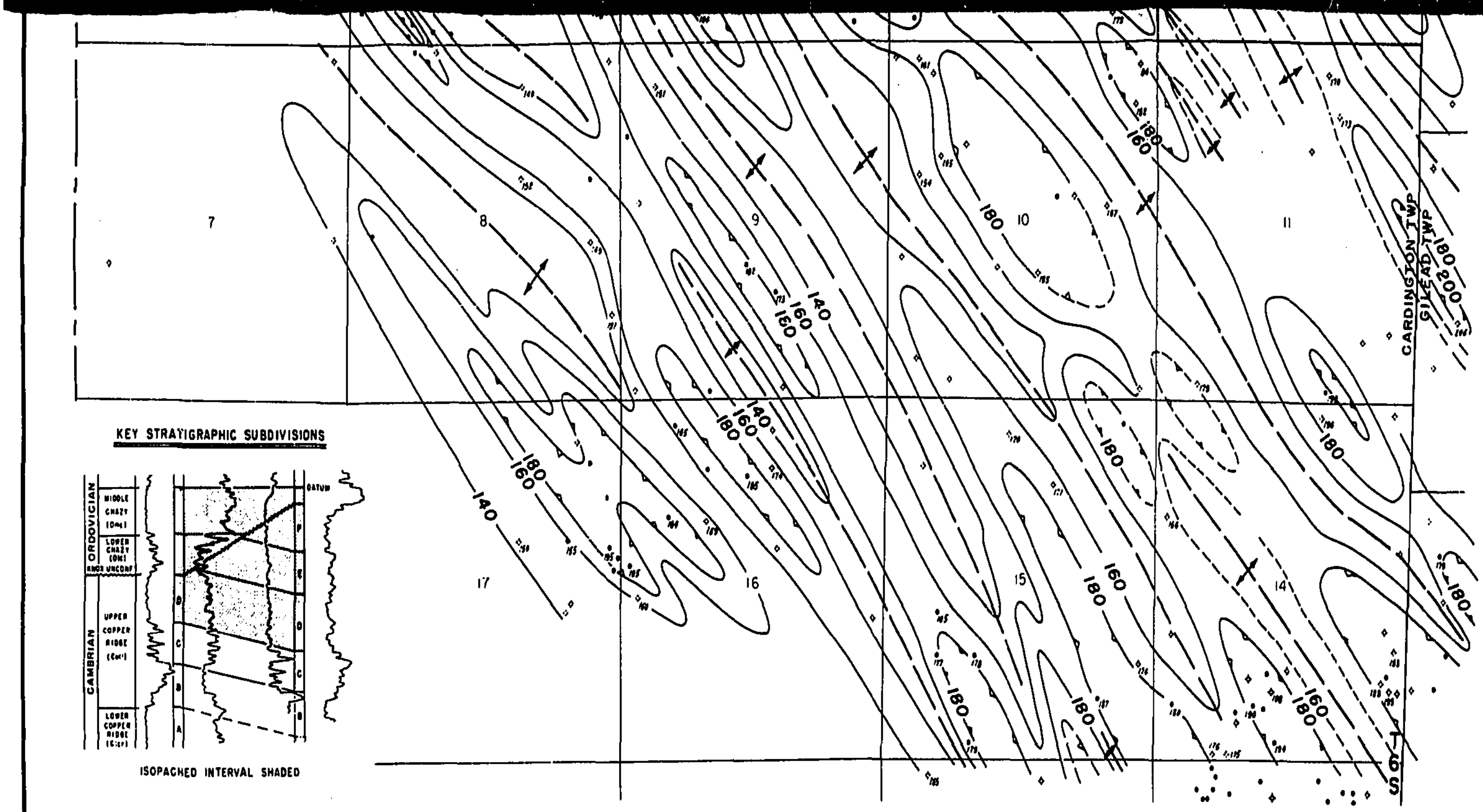


PLATE V

PRE-KNOX UNCONFORMITY STRUCTURE MAP

(ISOPACHOUS MAP FROM TOP OF MIDDLE CHAZY TO BASE OF ZONE D IN COPPER RIDGE)

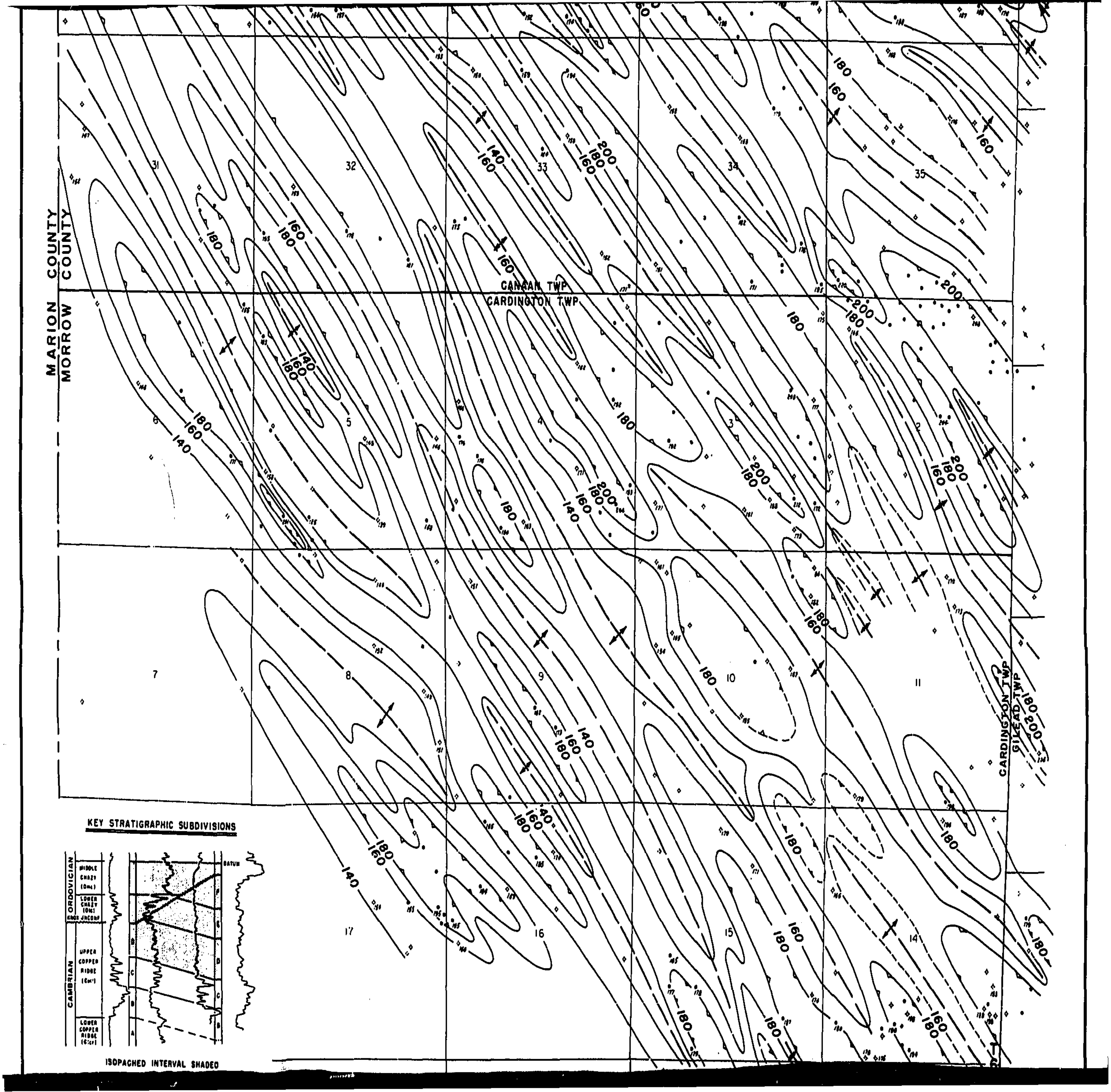
CONTOUR INTERVAL = 20'

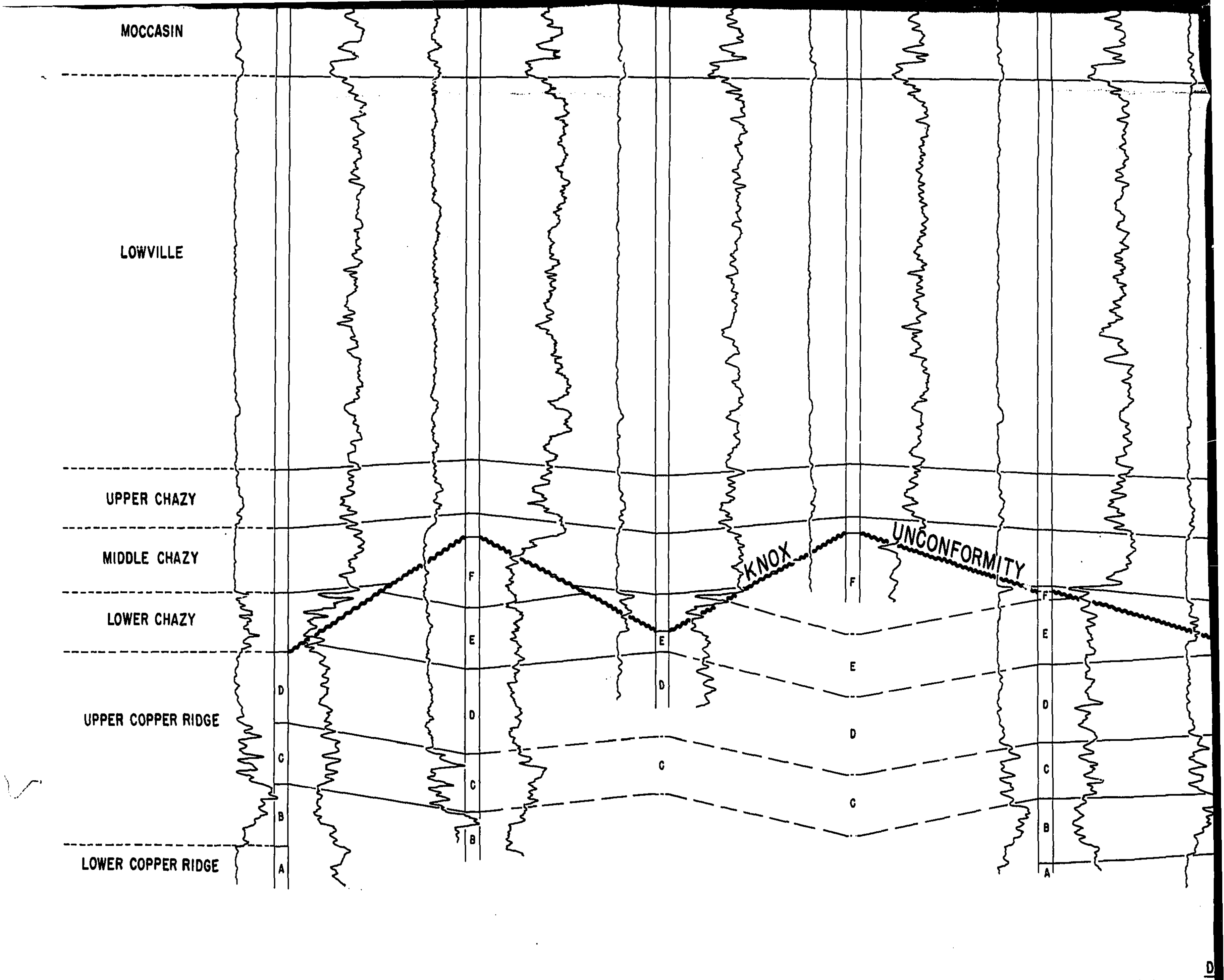
0 0.25 0.50 0.75 1.0
SCALE IN MILES

180 - THICKNESS IN FEET
(TOP OF MIDDLE CHAZY
TO BASE OF ZONE D
IN COPPER RIDGE)

ANTICLINAL AXIS

SYNCLINAL AREA


MARION COUNTY
MORROW COUNTY
CANAAN TWP
CARDINGTON TWP
CARDINGTON TWP
GILEAD TWP
31
32
33
34
35
6
5
4
3
2
7
8
9
10
11
17
16
15
14
140
160
180
200
KEY STRATIGRAPHIC SUBDIVISIONS
ORDOVICIAN
CAMBRIAN
MIDDLE CHAZY (Omc)
LOWER CHAZY (Olc)
KNOX UNCONF
UPPER COPPER RIDGE (Єcr)
LOWER COPPER RIDGE (Єlcr)
DATUM
A
B
C
D
E
F
ISOPACHED INTERVAL SHADED


MOCCASIN
LOWVILLE
UPPER CHAZY
MIDDLE CHAZY
LOWER CHAZY
UPPER COPPER RIDGE
LOWER COPPER RIDGE
KNOX
UNCONFORMITY
D
C
B
A
F
E
D
C
B
E
D
C
F
E
D
C
F
E
D
C
B
A
D

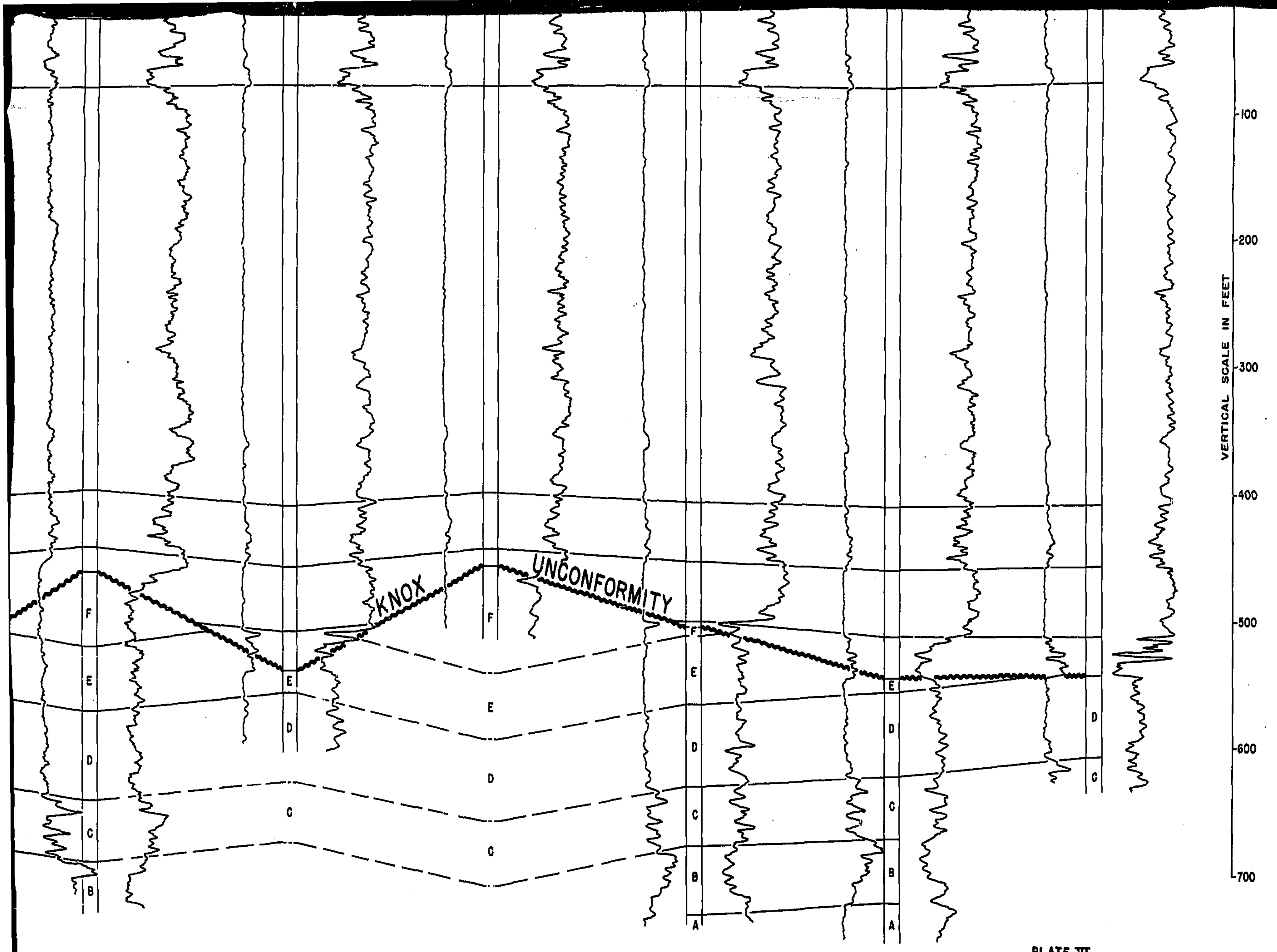
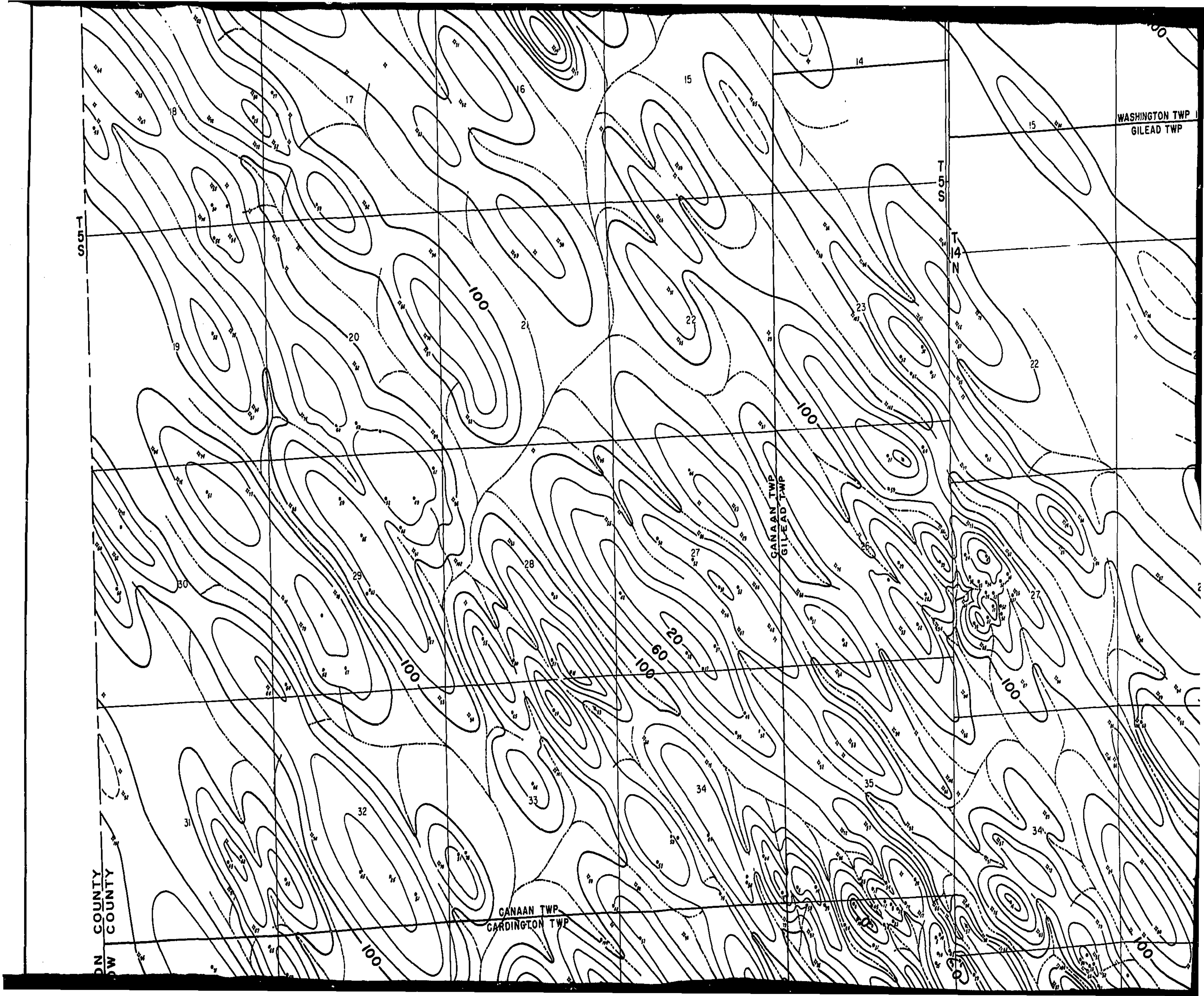


PLATE VI

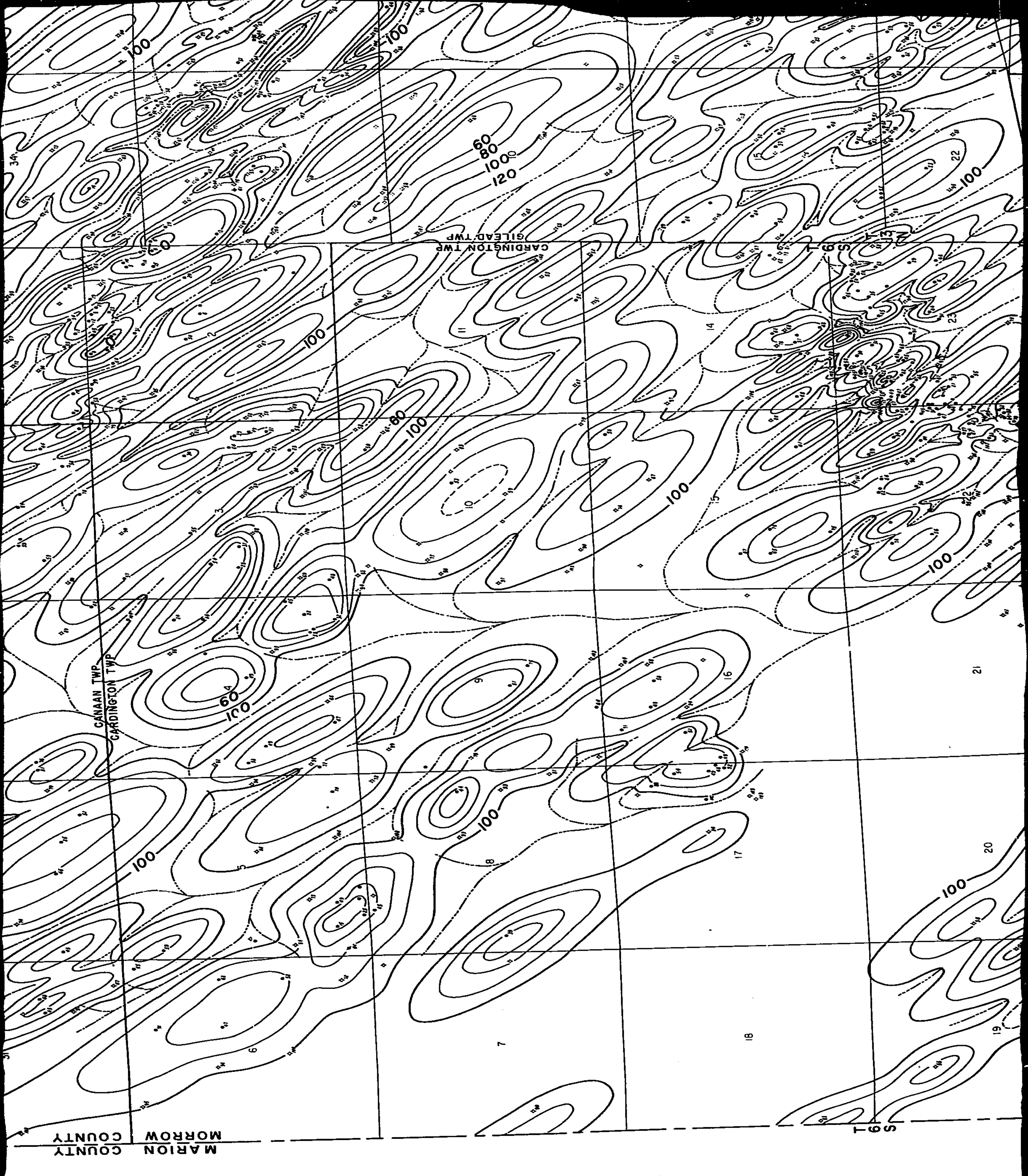
STRATIGRAPHIC CROSS SECTION D-D'

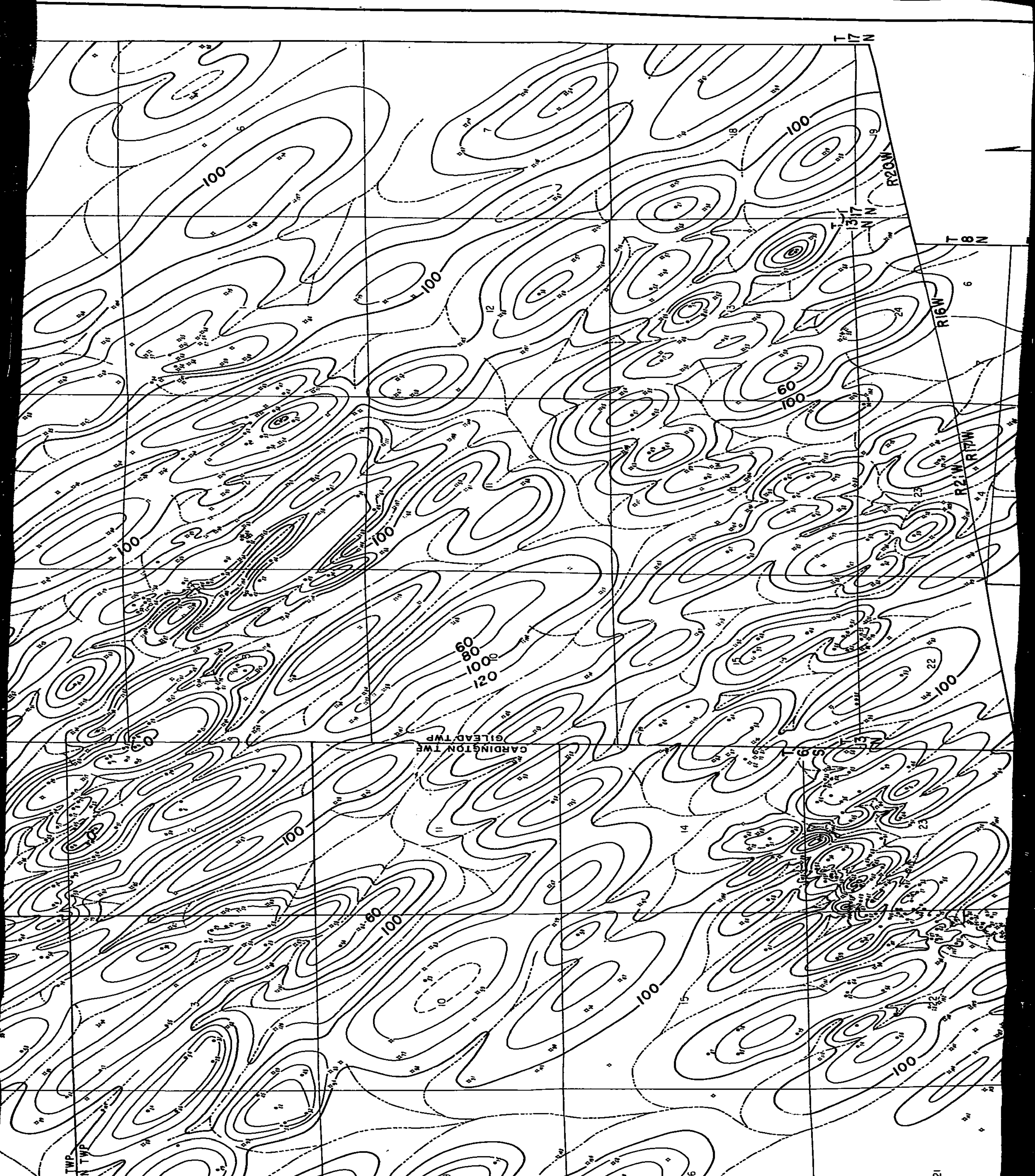
DATUM AT BASE OF BENTONITE IN EGGLESTON LIMESTONE

20-OHIO DRILLING PERMIT NUMBER

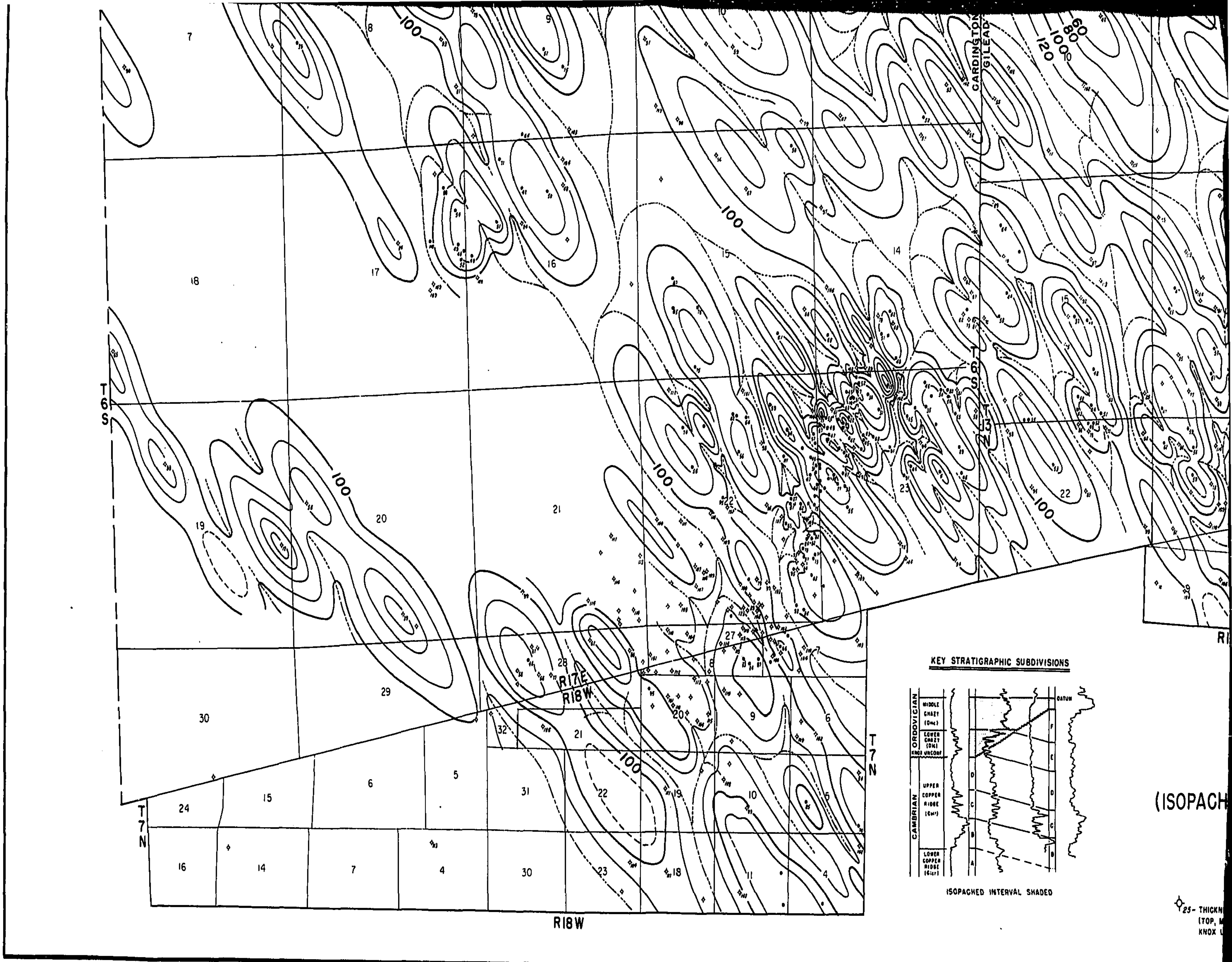

WASHINGTON TWP
GILEAD TWP
CANAAN TWP
GILEAD TWP
CANAAN TWP
CARDINGTON TWP
T 5 S
T 5 S
T 14 N
COUNTY
COUNTY
14
15
16
17
18
15
19
20
21
22
23
22
30
29
28
27
26
27
31
32
33
34
35
34
100
100
100
100
100
100
100
20
60


WASHINGTON TWP 14
GILEAD TWP
T 5 S
T 14 N
T 14 N
T 18 N
T 18 N
R20W
CANAAN TWP
GILEAD TWP
CANAAN TWP
CARDINGTON TWP
16
15
15
13
21
22
23
22
23
24
19
28
27
26
27
26
25
30
33
34
35
34
35
36
31
3
2
1
6
20
60
100
100
100
100
40
60
80
100
120
100
100
100
20


GILEAD TWP
CARDINGTON TWP
CANAAN TWP
CARDINGTON TWP
MORROW COUNTY
MARION COUNTY
T 6 S
60
80
100
120
2
3
4
5
6
7
8
9
10
11
14
15
16
17
18
19
20
21
22
23



T 17 N
R20W
T 13|17 N N
T 8 N
R16W
R21W R17W
100
60
80
120
GILEAD TWP
CARDINGTON TWP
T 6 S
T 13 N
CANAAN TWP
RDINGTON TWP


GARDINGTON
GILEAD
100
120
100
80
60
T6S
T13N
T7N
R17E
R18W
KEY STRATIGRAPHIC SUBDIVISIONS
ORDOVICIAN
MIDDLE CHAZY (Omc)
LOWER CHAZY (Olc)
KNOX UNCONF
CAMBRIAN
UPPER COPPER RIDGE (Cur)
LOWER COPPER RIDGE (Clcr)
DATUM
A
B
C
D
E
F
ISOPACHED INTERVAL SHADED
(ISOPACH
25- THICKN
(TOP, M
KNOX U

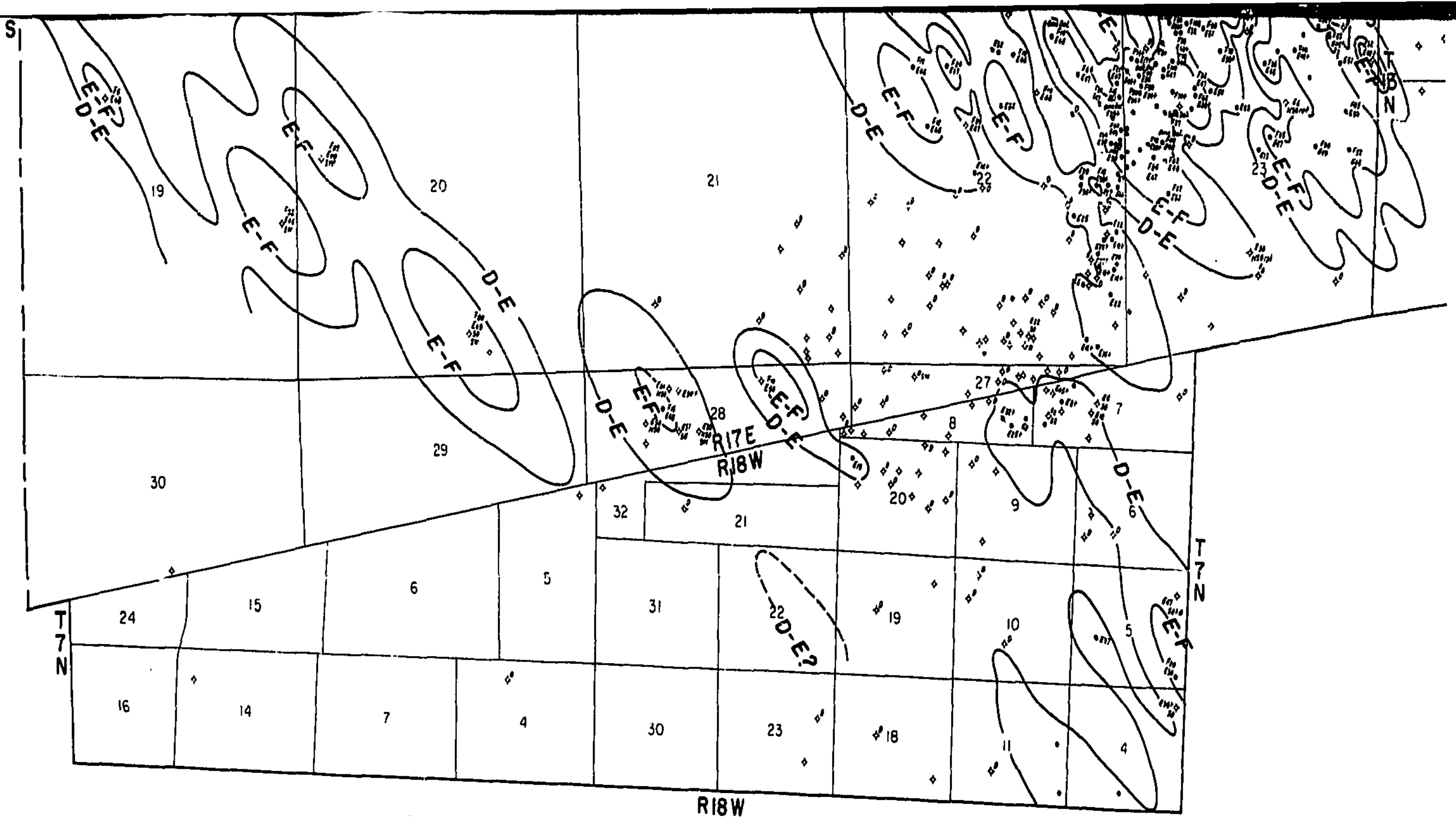


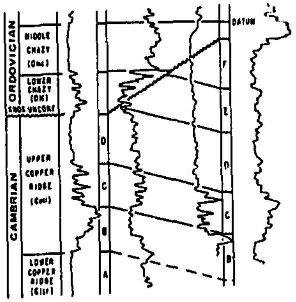
PLATE IX

KNOX UNCONFORMITY SUBCROP MAP

(ZONES D, E, AND F IN UPPER COPPER RIDGE DOLOMITE)

0 0.25 0.50 0.75 1.0
SCALE IN MILES

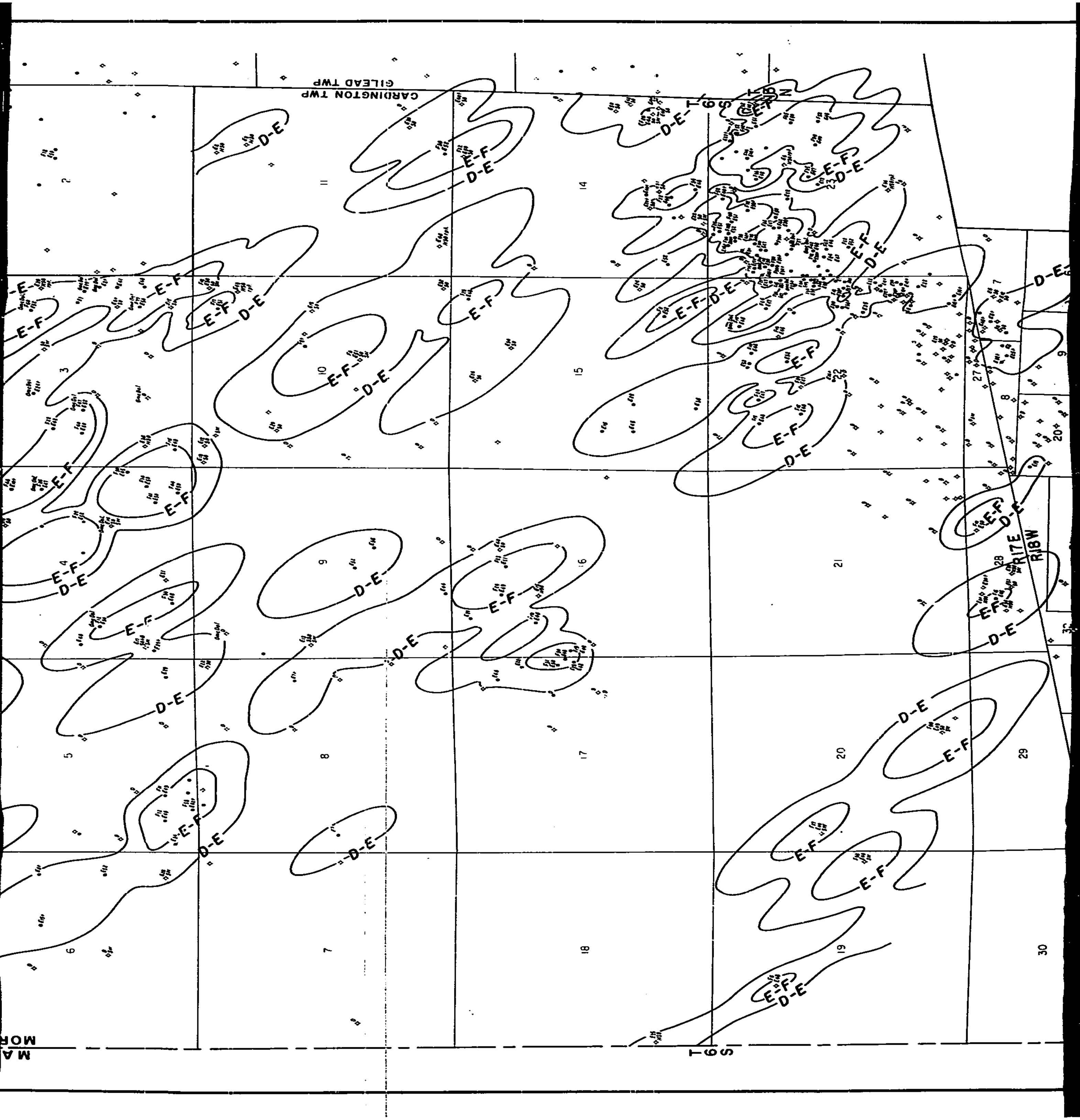
KEY STRATIGRAPHIC SUBDIVISIONS



LEGEND

D-E — CONTACT BETWEEN ZONES D AND E
E-F — CONTACT BETWEEN ZONES E AND F

Omc Dol. — MIDDLE CHAZY DOLOMITE ZONE
F_{20} — ZONE F - 20 FEET THICK
E_{50} — ZONE E - 50 FEET THICK
D — ZONE D
SO — OIL SHOW
NSO rpt. — NO SHOW OF OIL REPORTED
VSSO — VERY SLIGHT SHOW OF OIL
SW — SALT WATER


GILEAD TWP
CARDINGTON TWP
T6S
T18N
R17E
R18W
D-E
E-F
2
3
4
5
6
7
8
9
10
11
14
15
16
17
18
19
20
21
22
23
27
28
29
30
MA
MOR

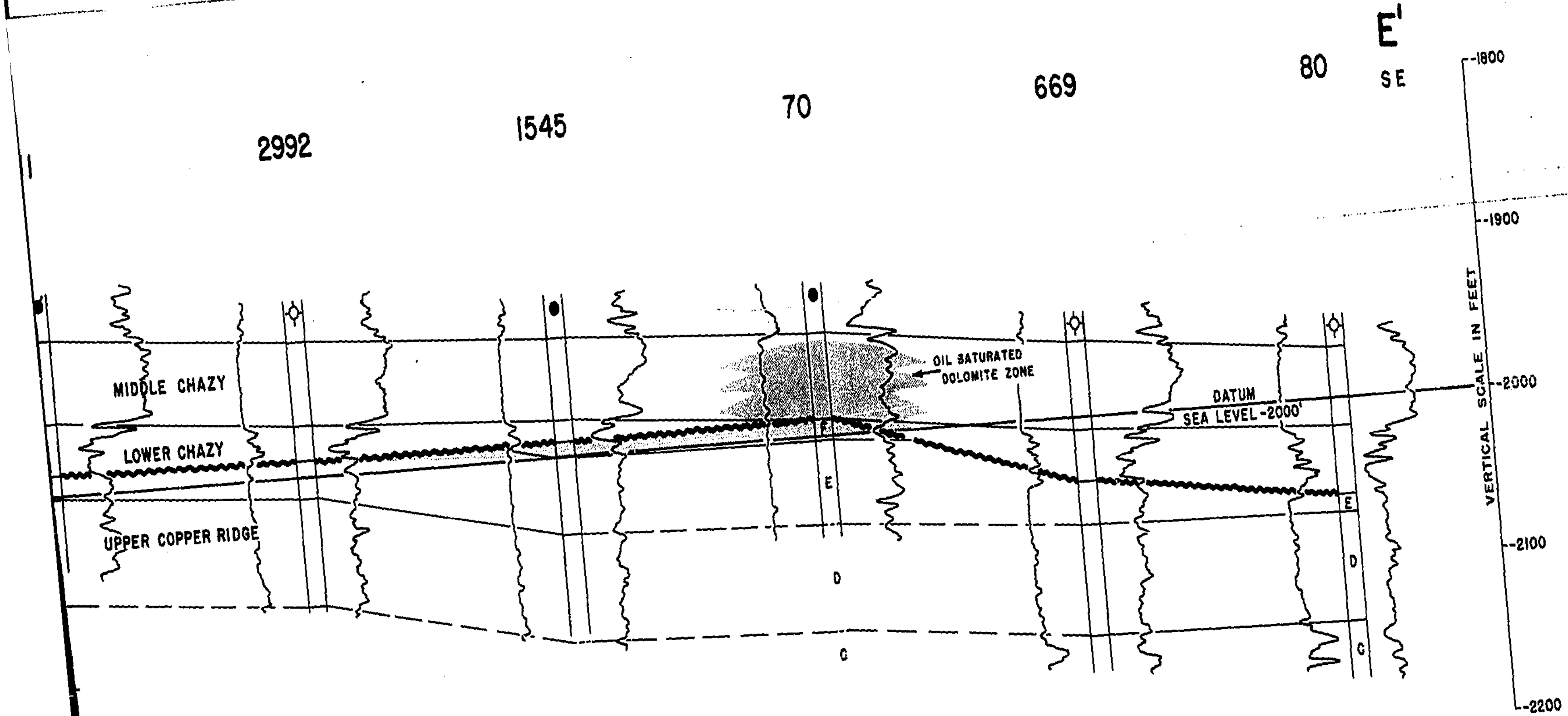


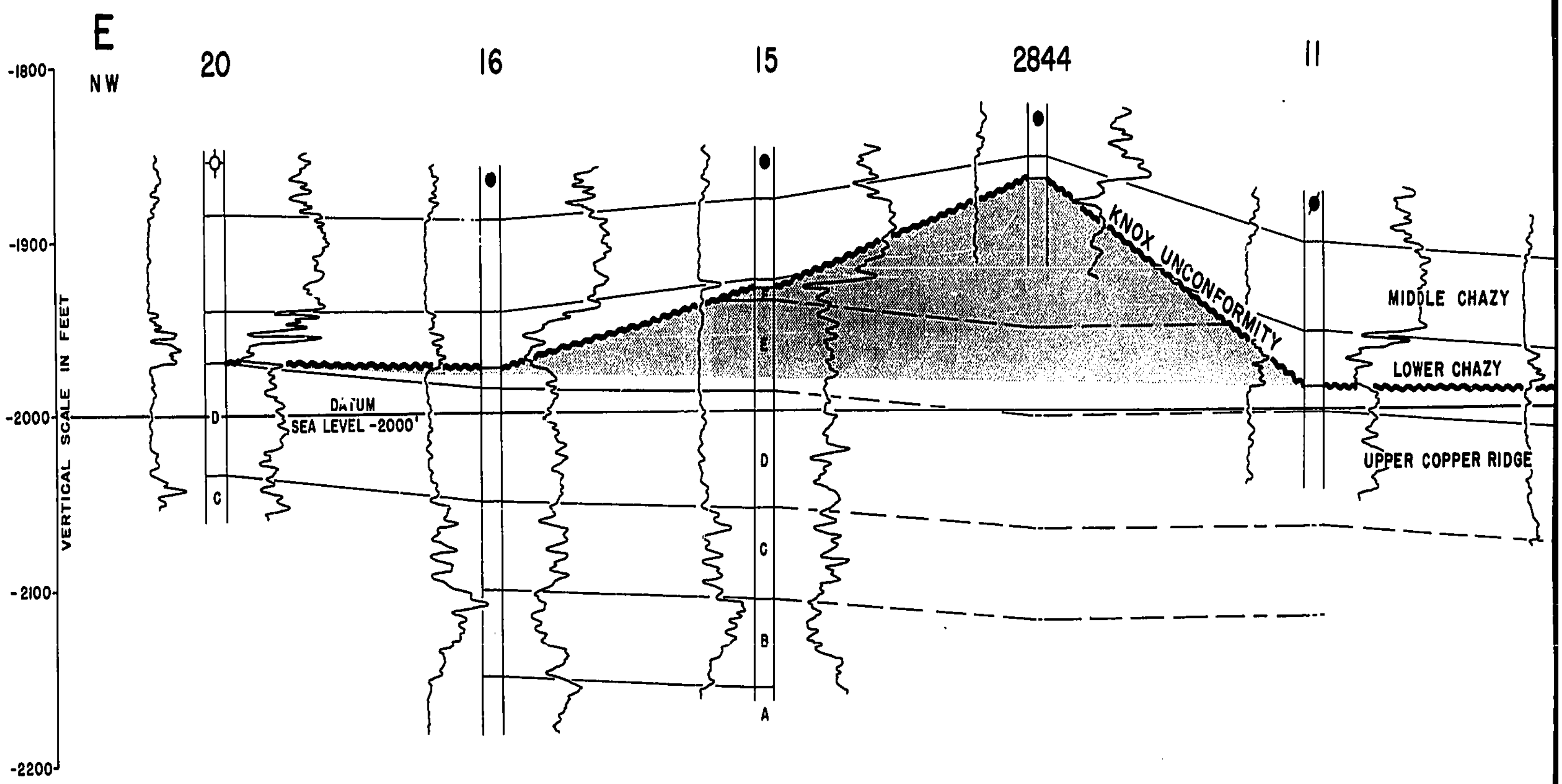
PLATE X

STRUCTURAL CROSS SECTION E-E'

DATUM SEA LEVEL-2000'

▨ OIL SATURATED ZONE

80-OHIO DRILLING PERMIT NUMBER


E
NW
20
16
15
2844
11
-1800
-1900
-2000
-2100
-2200
VERTICAL SCALE IN FEET
KNOX UNCONFORMITY
MIDDLE CHAZY
LOWER CHAZY
UPPER COPPER RIDGE
DATUM
SEA LEVEL -2000'
D
C
E
D
C
B
A

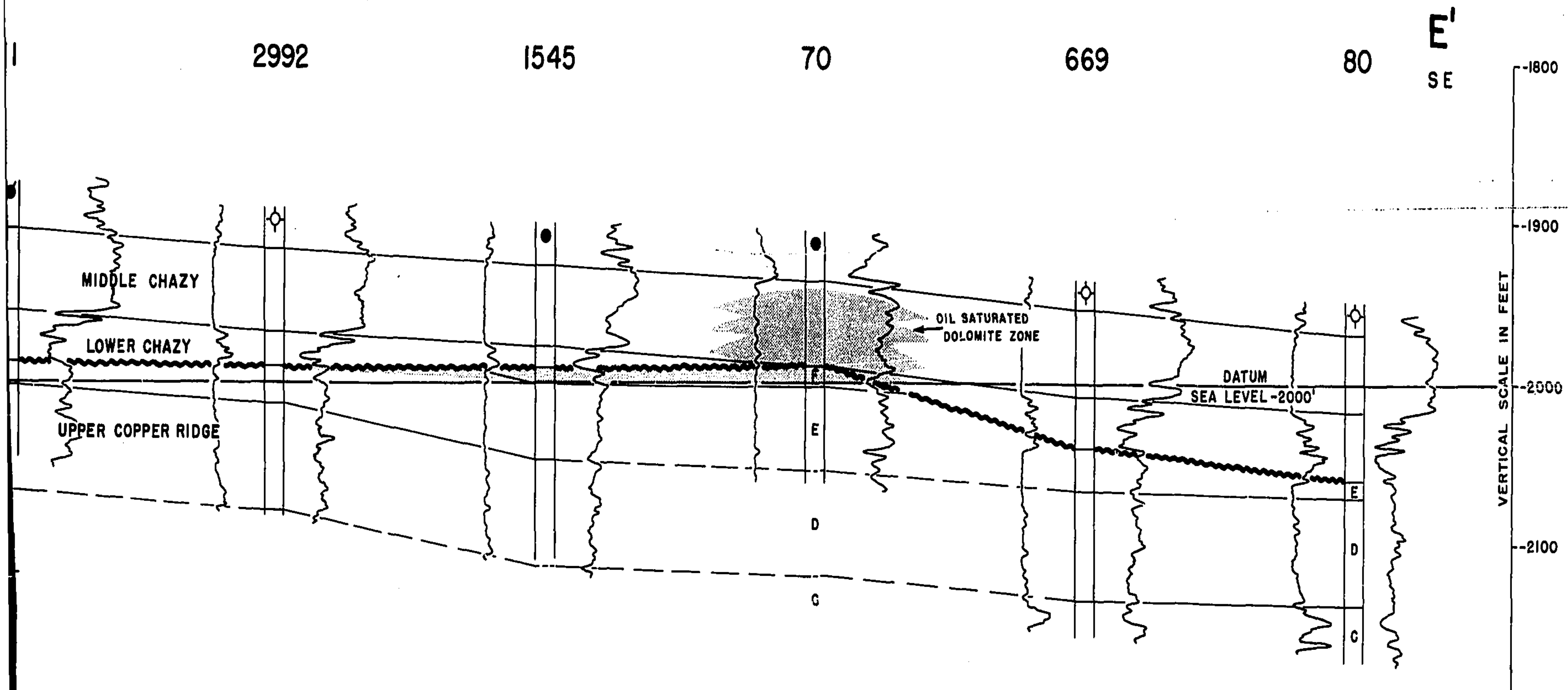


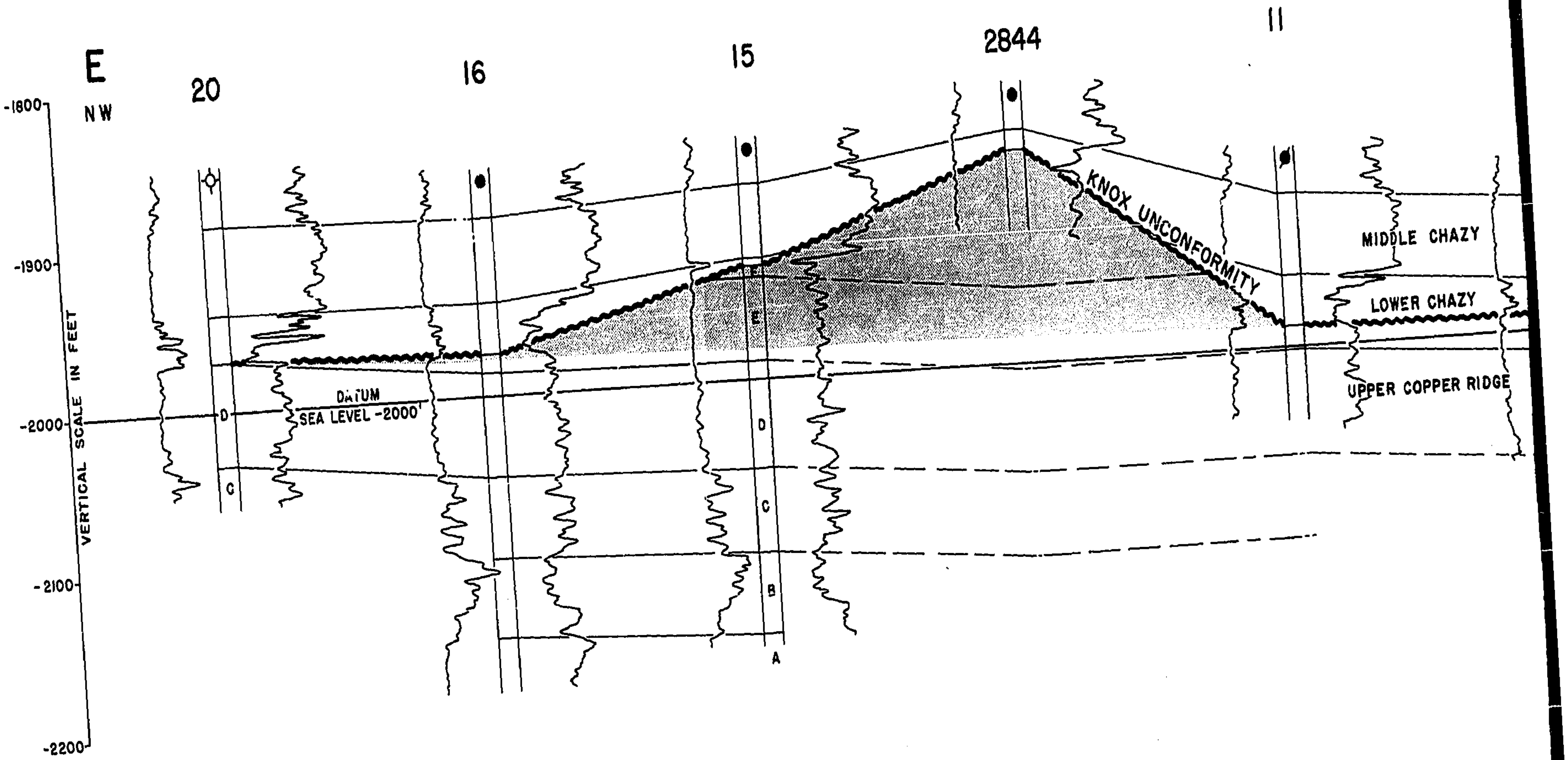
PLATE X

STRUCTURAL CROSS SECTION E-E'

DATUM SEA LEVEL - 2000'

▨ OIL SATURATED ZONE

80 - OHIO DRILLING PERMIT NUMBER


E
NW
20
16
15
2844
11
-1800
-1900
-2000
-2100
-2200
VERTICAL SCALE IN FEET
DATUM
SEA LEVEL -2000'
KNOX UNCONFORMITY
MIDDLE CHAZY
LOWER CHAZY
UPPER COPPER RIDGE
D
C
E
D
C
B
A