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Petrology and Petroleum Geology of the Meramecian (Upper Mississippian) Warsaw Formation, Kiowa and Comanche Counties, Kansas

by

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Matthew E. Wilson

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Advisory Committee:

Chairman

For the Department

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ABSTRACT

The Meramecian (Late Mississippian) Warsaw Formation is an important oil and gas reservoir in Kiowa and Comanche counties, Kansas. Hydrocarbon production in the Warsaw is limited to where the Warsaw is truncated by the regional pre-Pennsylvanian unconformity. Porosity in the Warsaw is not, however, related to proximity to the unconformity. Shales of the Desmoinesian (Middle Pennsylvanian) Cherokee Group, which directly overlie the Warsaw at the subcrop, form more effective seals to hydrocarbons than does the Salem Limestone which overlies the Warsaw downdip.

Whether lithofacies or structure controls distribution of Warsaw production is the most significant problem for exploration within the subcrop trend. Depositional control on distribution of porosity was diminished through occlusion of interparticle porosity in grain-supported rocks by calcite cementation or even reversed through creation of intercrystalline and moldic porosity in mud-supported rocks by dolomitization and dissolution. The upper Warsaw is more permeable than the lower Warsaw. Lateral variation of lithofacies, such as the transition into the non-productive, argillaceous Cowley facies of the Warsaw, is important in exploration on a regional scale, but not on the scale of individual

oil fields. Structure is the major control on distribution of oil and gas fields within the subcrop.

Structural traps within the Mississippian were created by warping before deposition of the Cherokee Group, which thins over positive features on the top of the Mississippian. Reactivation of anticlines created closure on units at least as young as the Late Pennsylvanian Lansing Group, allowing Mississippian exploration prospects to be mapped using shallower Pennsylvanian horizons.

ACKNOWLEDGEMENTS

This thesis is dedicated to Barbara Frisz Wilson, whose faith and hard work made everything possible.

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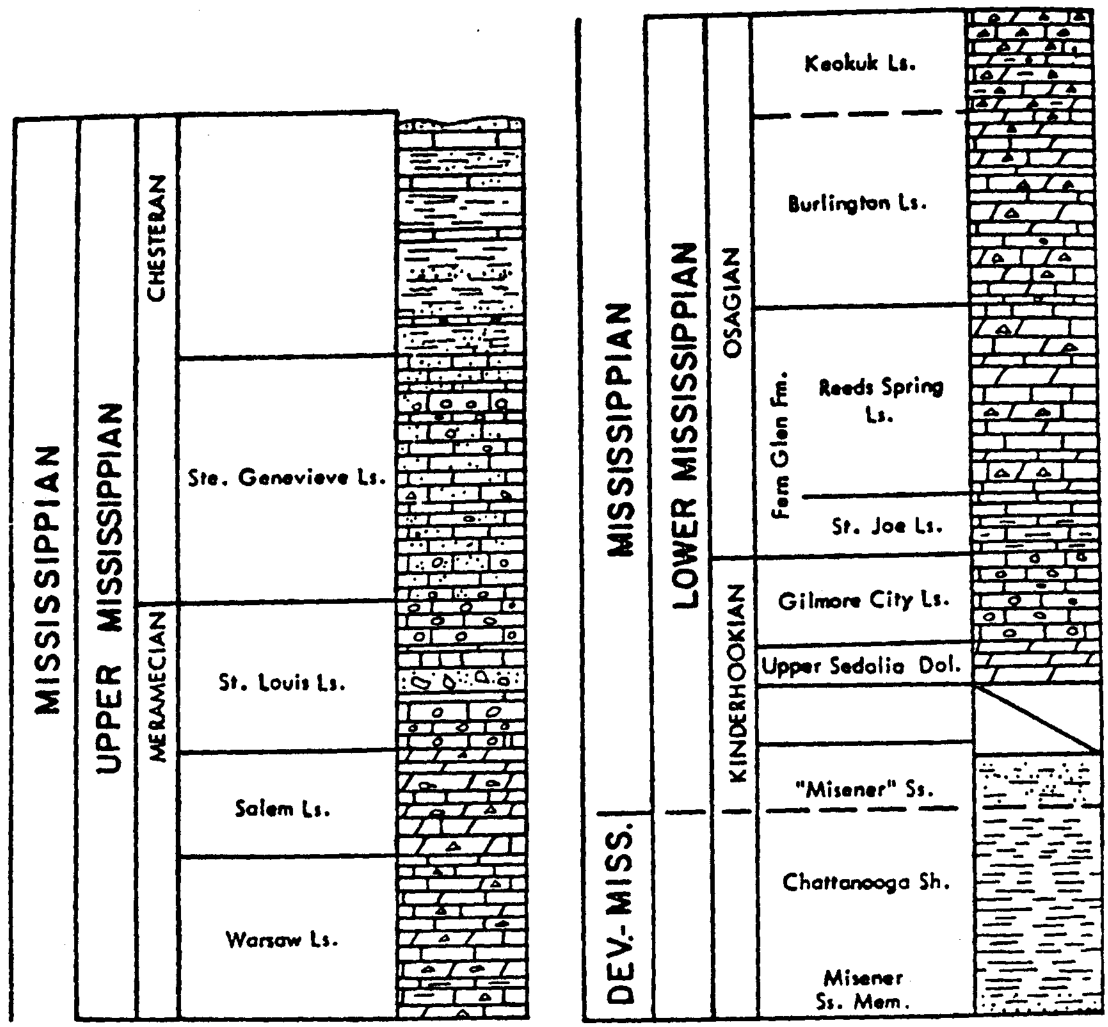
INTRODUCTION

The Warsaw Formation of Meramecian age (Late Mississippian) (Fig. 1) is an important petroleum reservoir in western Kansas. Oil and gas accumulations in the Warsaw are distributed along the subcrop of the Warsaw beneath the pre-Pennsylvanian unconformity (Figs. 2 and 3). Recognition of controls on hydrocarbon accumulation, whether horizontal variation in lithofacies or minor structures within the subcrop trend, is important in choosing exploration strategies. If lithofacies control distribution of reservoirs, it is necessary to map favorable lithofacies. If hydrocarbon traps are structural, isopachous and structural contour maps are tools for exploration.

Analyses of lithofacies are necessary to determine the type of depositional and diagenetic textures of the reservoir rock and to characterize the Warsaw for lithostratigraphic correlation using cores. Inconsistent definitions of the Warsaw among oil companies operating in western Kansas, however, have prevented definition of a mappable lithostratigraphic unit. Cross sections of geophysical well logs presented in this report document a typical log signature of the Warsaw that is correlative throughout Kiowa and Comanche counties. Consistent lithostratigraphic and geophysical correlation provide

Fig. 1.- Mississippian stratigraphy of western Kansas (from Goebel, 1968). Cowley facies is not shown due to uncertainty of stratigraphic position.



MISSISSIPPIAN
UPPER MISSISSIPPIAN
CHESTERAN
MERAMECIAN
Ste. Genevieve Ls.
St. Louis Ls.
Salem Ls.
Warsaw Ls.
MISSISSIPPIAN
DEV.-MISS.
LOWER MISSISSIPPIAN
OSAGIAN
KINDERHOOKIAN
Fern Glen Fm.
Keokuk Ls.
Burlington Ls.
Reeds Spring Ls.
St. Joe Ls.
Gilmore City Ls.
Upper Sedalia Dol.
"Misener" Ss.
Chattanooga Sh.
Misener Ss. Mem.

Fig. 2.- Location of study area. Also indicated is Bindley field, which produces from the Warsaw and is the subject of a study by Ebanks, et al. (1977).

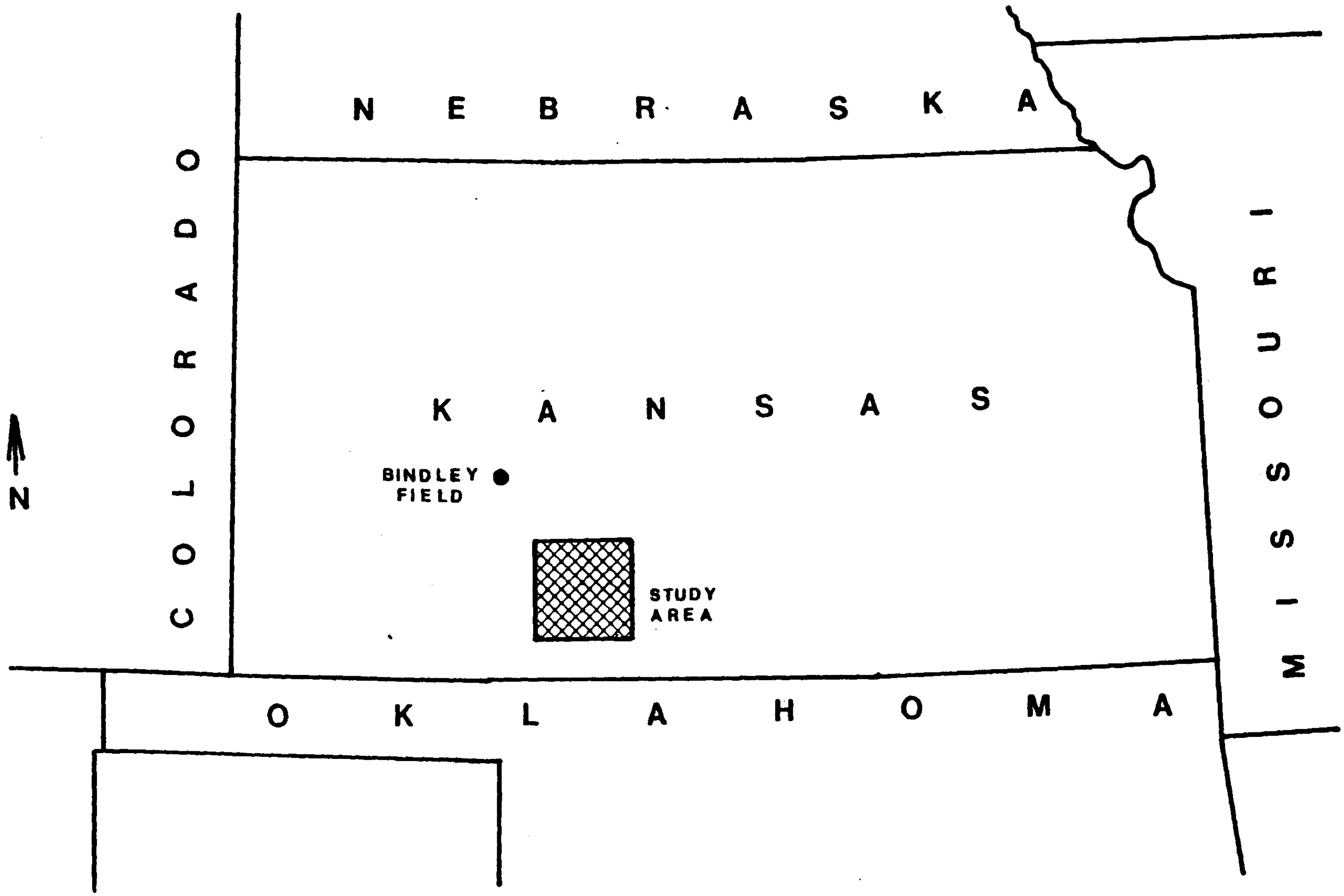
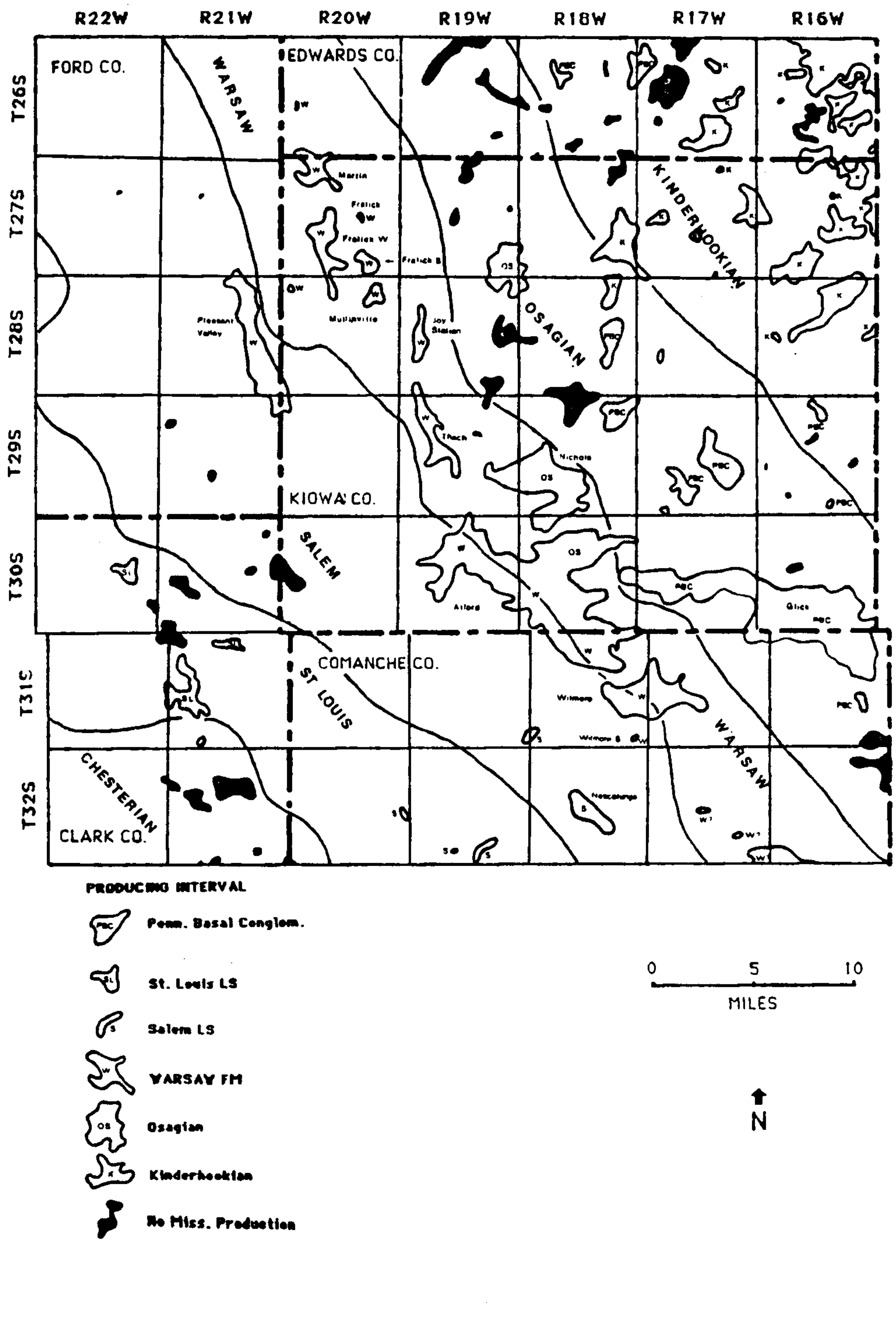

NEBRASKA
COLORADO
KANSAS
MISSOURI
OKLAHOMA
N
BINDLEY FIELD
STUDY AREA

Fig. 3.- Mississippian subcrop (modified from Merriam, 1963) superimposed on map of oil and gas fields in study area (modified from Paul, et al., 1982). Note coincidence of Warsaw reservoirs with Warsaw subcrop.



R22W
R21W
R20W
R19W
R18W
R17W
R16W
T26S
T27S
T28S
T29S
T30S
T31S
T32S
FORD CO.
EDWARDS CO.
KIOWA CO.
COMANCHE CO.
CLARK CO.
WARSAW
KINDERHOOKIAN
OSAGIAN
SALEM
ST LOUIS
CHESTERIAN
WARSAW
PRODUCING INTERVAL
Penn. Basal Conglom.
St. Louis LS
Salem LS
WARSAW FM
Osagian
Kinderhookian
No Miss. Production
0
5
10
MILES
N

the framework necessary for future biostratigraphic studies and for studying variations in lithology and their effect on reservoir distribution.

PREVIOUS STUDIES

Early work on the Mississippian of western Kansas was on a regional scale. Lee (1940) outlined basic stratigraphy, and several authors, including Lee (1953), Maher (1946, 1947), Edson (1947), Collins (1947), and Lane (1978), produced regional cross-sections. The Liberal Geological Society (1956) published a cross-section from Comanche County, Kansas to Baca County, Colorado. Clair (1948) studied lithostratigraphy of the Mississippian of western Kansas. Maher and Collins (1949) investigated pre-Pennsylvanian geology of southwestern Kansas, southeastern Colorado and the Oklahoma Panhandle. Veroda (1959) and Beebe (1959) studied regional stratigraphy of the Hugoton Embayment. Thomas (1982) studied the Cowley facies in Barber County using cores and electric logs. Hiestand (1938) reported on insoluble residues in Mississippian rocks of central Kansas. Goebel (1966) refined the lithostratigraphy and biostratigraphy of western Kansas.

Biostratigraphic studies include work on conodonts by Thompson and Goebel (1969), Selk and Ciriaks (1968), Klapper (1971), and Lane (1978). Works on foraminifers include Girty (1940), Lee (1940,1953), Zeller (1950), and Nodine-Zeller (1972). Girty (1940) also studied pollen and megafossils. Lee (1940) discusssed pollen as well.

Open-file analyses of conodonts from the Mull Matkin #1 well and of megafossils from the Anadarko #1 Boisseau B well by the Kansas Geological Survey are on file at the survey.

Several reports on Mississippian stratigraphy cover local areas in the Oklahoma Panhandle. Barby (1958) examined Upper Mississippian strata in Beaver County, Oklahoma. Thornton (1965) worked to the east in Alfalfa and parts of Woods and Grant counties, Oklahoma.

Studies of Mississippian oil fields in Kansas are numerous, but few involve detailed petrography. Kansas Oil and Gas Fields (Kansas Geol. Soc., 1959, 1965) contains short descriptions of traps, reservoirs, and economics of Mississippian oil and gas fields (Table 1). Most analyses contain structural and isopachous maps and cross-sections.

Some oil field studies of other producing intervals include useful information such as the structural contour map of the pre-Pennsylvanian unconformity in Clark County, Kansas and Harper and Woods Counties, Oklahoma by Manhard and Busch (1974). Robinson et al (1985) contains data on trace elements and isotopes from the St. Louis Limestone in the core from the Mesa Moore #2-29 well.

Detailed studies of Mississippian oil fields include a study of the North Buffalo field in Harper County,

Table 1.- Brief studies of Mississippian oil and gas fields in Western Kansas from Kansas Oil and Gas Fields, (vol. 2 and vol. 4, Kansas Geological Society, 1959 and 1965, respectively).

FIELD	PRODUCING INTERVAL(S)	COUNTY	GEOLOGISTS	vol.
Alameda	Lansing-Kansas City, Miss., Viola, Simpson	Kingman	C. R. King	4
Albion and Albion North	Kansas City, Miss. Conglom., and Viola	Reno	M. O. Oros	4
Bull Creek	Residual Osage	Rice	W. J. Wright	4
Damme and Finnup	Marm., Morrow., and St. Louis	Finney	R.L. Schmidlapp	2
Donald	Osagian	Barber	T. Elster	4
Eubank	LKC, Cherokee, Marm., Morrow., Chesteran, and Ste. Genevieve	Haskell	L. B. Fugitt and R. D. Wilkinson	2
Gove	LKC, Osagian	Gove	M. F. Bear	2
Glick	Residual Osage	Kiowa	R. M. Euwer	4
Hallet	Salem-Warsaw	Hodgeman	D. L. Beene	4
Hanston-Oppy	Marm., Osagian	Hodgeman	B. L. Ingold	4
Hockett	Chest., Morrow.	Meade	R. D. Wilkinson	2
Liberal SE	Mississippian	Seward	R.C. Strohmeyer	2
Lippoldt	Warsaw	Hodgeman	G. F. Stewart	4
Lundgren and Lundgren S	Salem	Gove	R. C. Marion	2
L. T. P.	Chrke, Warsaw	Ness	R. J. Harris	4

FIELD	PRODUCING INTERVALS(S)	COUNTY	GEOLOGISTS	vol.
McKinney	Chesteran and Morrowan	Meade and Clark	J. J. Jamieson	2
Nescatunga	Salem-Warsaw and Viola	Comanche	W. M. Capps	4
Nichols	Osagian	Kiowa	G. R. Curtis	2
Novinger	Marmaton and Chesteran	Meade	C. A. Renfroe	2
Nunn	Lansing-Kansas City, Marmaton, Cherokee, Miss.	Finney	R.A. Aukermann	2
Pleasant Prairie	LKC, Marmaton, Morrowan and St. Louis	Haskell, Finney, and Kearny	R. E. Roby	2
Sawlog Creek South East	Osagian	Hodgeman	G. W. Zorger	4
Schaben	Osagian	Ness	P. L. Hilpman	4
Shallow Water	Marmaton and St. Louis	Scott	R.A. Aukermann	2
Stairett	Warsaw ?	Hodgeman	R. M. Lineham	4
Stevens	Morrow., Chest.	Meade	W. R. Fennel	2
Wieland, Wieland North, Wieland West	Cherokee, Residual Osage, and Warsaw	Hodgeman	B. R. Stinson	4
Wil	LKC, Residual Kinderhookian	Edwards	G. A. McCaleb and J. Wheeler	4

Oklahoma, by Kornfield (1959). Glick field (Euwer 1963, 1964, 1965, 1968; and Duran, 1960), in Kiowa and Comanche counties, lies within residual chert overlying the Osagian. Bennett (1960) and Fugitt and Wilkinson (1959) described Eubank field, which produces from Chesteran and Ste. Genevieve rocks. Ball (1966) emphasized the importance of mapping lithofacies of the St. Louis Limestone in a study of Pleasant Prairie field.

The Kansas Geological Society (1959) has published several maps and a cross-section of the area around the Aldrich and Arnold fields in Ness County. Bindley Field in Hodgeman County (Ebanks et al, 1977) is most pertinent to this investigation because of similarities in structure with fields in the study area and location along the trend of the Warsaw subcrop. Descriptions of lithofacies, structure, and petroleum geology of Bindley Field provide a valuable basis for comparisons and contrasts to the fields in Comanche, Ford and Kiowa counties.

METHODS

Thirteen cores from Clark, Comanche, Ford, and Kiowa counties, that include portions of the Warsaw, Keokuk-Burlington, Salem, and St. Louis, were slabbed and described (Table 2, Fig. 4). Approximately 195 thin sections were prepared and stained with potassium ferricyanide (positive for ferrous iron) and Alizarin Red-S (positive for calcium carbonate) by the method of Evamy (1969). Thin sections were described for depositional texture (Dunham, 1962), cement (Folk, 1965), and porosity (Choquette and Pray, 1970).

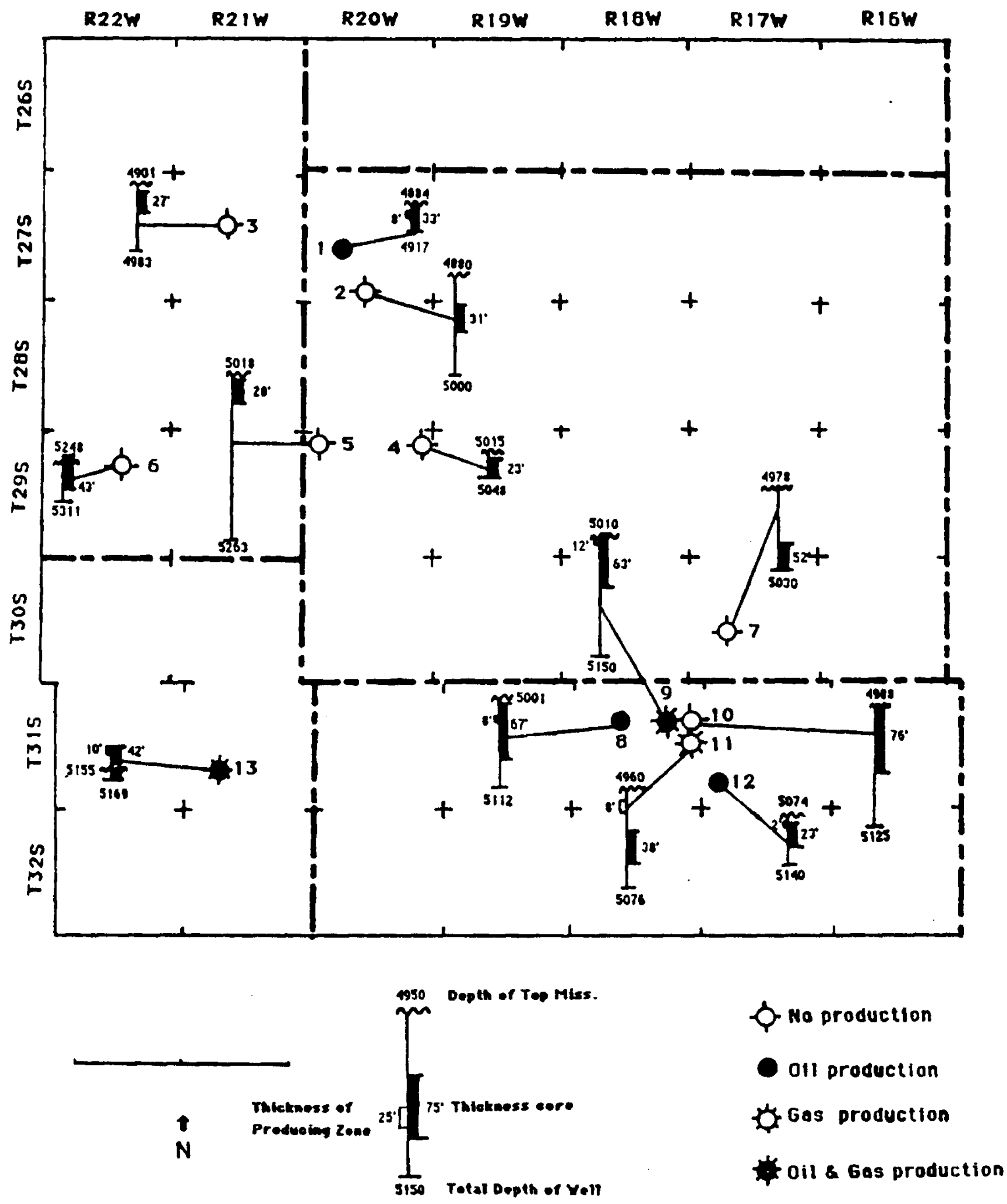
Analyses of permeability, porosity, and oil and water saturation from some of the cores are available from the Kansas Geological Survey. Additional core analyses were made available by Mull Drilling Company of Wichita, Kansas. Data from drill-stem tests were obtained from the scout-ticket file at the Kansas Geological Survey.

An isopachous map of the Warsaw (Fig. 15), a structural contour of the top of the Mississippian (Fig. 6), and six cross sections covering the study area (Plates 1-5; Fig. 21) were produced from 300 geophysical logs obtained from the Kansas Geological Survey. Structural contour maps and isopachous maps of overlying units were made for selected areas around reservoirs.

Table 2.- Cores used in this study. All are in the collection of the Kansas Geological Survey. Numbers in left column locate well in Fig. 4.

	Location	Operator	Lease Name	Date	Interval Cored
1	C-NW-SE 20-27S-20W	Mull Drilling	1Brensing G	1965	upper Warsaw 4874-4907
2	C-SE-NW 33-27S-20W	Anadarko	1 Brensing A	1965	upper Warsaw 4910-4940
3	C-NE-NW 16-27S-21W	Mull Drilling	1 Matkin	1963	lower Salem 4904-4931
4	C-SW-SW 1-29S-20W	Mull Drilling	1 Alford A	1964	mid Warsaw 5021-5041
5	NW-NW-SE 6-29S-20W	T.X.O	1 Manke	1976	lower Salem 5068-5090
6	C-SW-NE 10-29S-22W	Sam Gary	10-7 Hoener	1981	Salem 5241-4284
7	C-SW 20-30S-17W	Cities Service	1 Booth B	1966	Osagian 5025-5055
8	C-NW-NW 30-31S-17W	Anadarko	1 Burkhall A	1974	mid Warsaw 5077-5101
9	C-NW-NE 9-31S-18W	Graham- Michaelis	3-9 Uhl	1972	Warsaw 5017-5068
10	C-NW-SE 11-31S-18W	Anadarko	1 Boisseau B	1971	Warsaw 5007-5071
11	C-NE-SW 12-31S-18W	Cities Service	1 Clark B	1967	Warsaw 4990-5064
12	C-NE-SW 13-31S-18W	Cities Service	1 Pyle A	1967	mid Warsaw 5010-5048
13	NE-NW-NW 29-31S-21W	Mesa	2-29 Moore	1983	St. Louis 5155-5169

Fig. 4.- Location of cores in study area. Spot locations, lease names, operators, spud dates, and intervals cored are given in Table 2.



R22W
R21W
R20W
R19W
R18W
R17W
R16W
T26S
T27S
T28S
T29S
T30S
T31S
T32S
4950 Depth of Top Miss.
Thickness of Producing Zone
25'
75' Thickness core
5150 Total Depth of Well
N
No production
Oil production
Gas production
Oil & Gas production

Logs through the entire Warsaw and the Keokuk-Burlington are necessary to establish a consistent lithostratigraphic definition of the Warsaw. Units within the Mississippian can be accurately identified only in context with adjacent units.

REGIONAL GEOLOGY

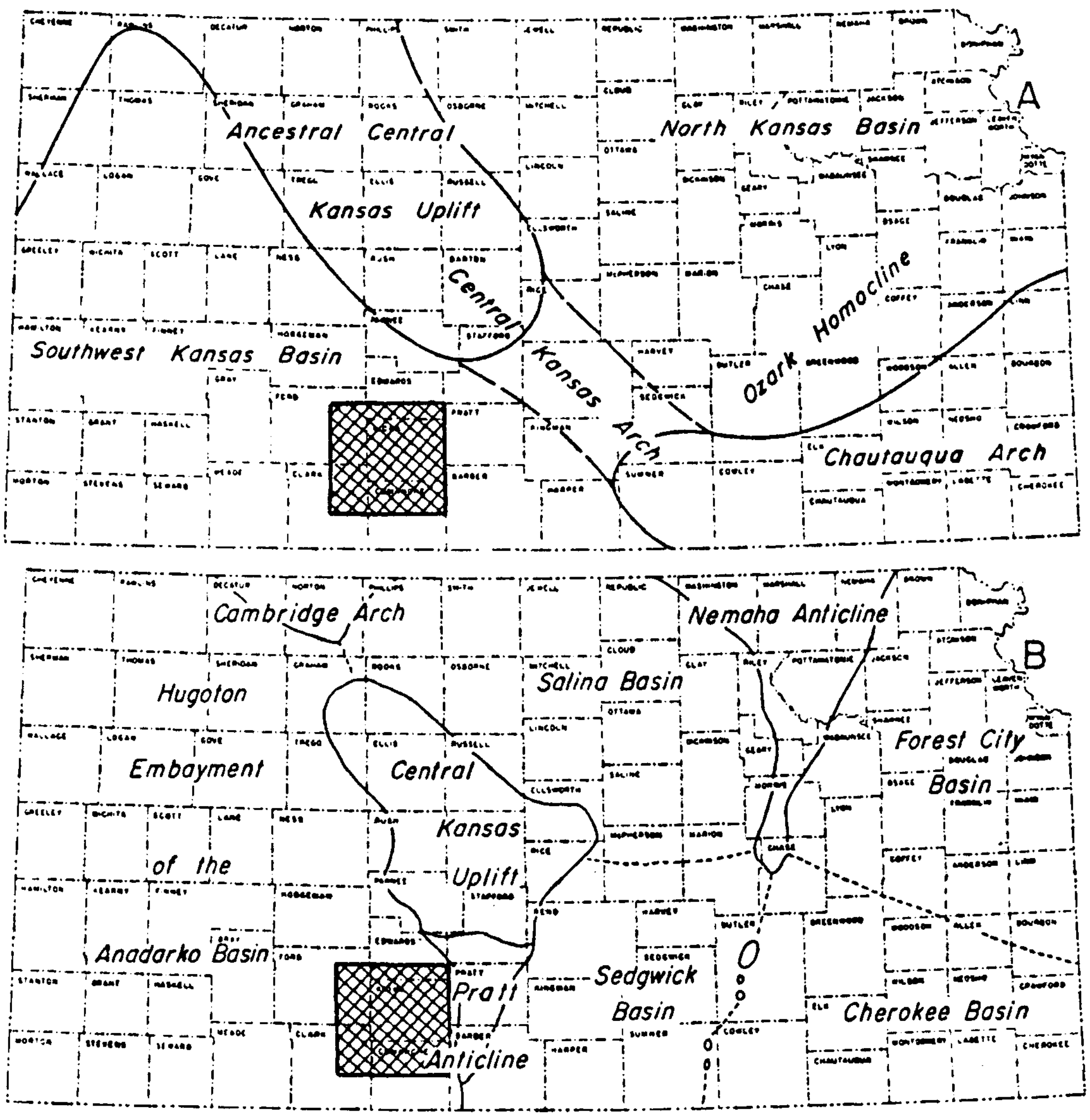
Pre-Mississippian Structure

Mississippian rocks in the study area unconformably overlie the Middle Ordovician Viola Limestone. During Mississippian time, the Ancestral Central Kansas uplift (Fig. 5), north of the study area, either was a positive feature or did not subside as much as the Southwest Kansas basin during deposition of the Warsaw (Merriam, 1963). The Warsaw decreases in thickness towards the uplift, but it probably extended over the entire Ancestral Central Kansas uplift; it was later removed by pre-Pennsylvanian erosion (Goebel, 1968).

Post-Mississippian Structure

Mississippian rocks in the study area dip to the southwest away from the Central Kansas uplift, and westward away from the Pratt anticline. Toward the Central Kansas uplift successively older Mississippian units are truncated by the pre-Pennsylvanian unconformity. The pre-Pennsylvanian unconformity truncates Chesterian rocks in the southwestern part of the study area and Kinderhookian rocks in northeastern Kiowa County. Superimposed on this regional structure are local structures ranging in size from approximately

Fig. 5.- A. Pre-Mississippian structure in Kansas; B. Post-Mississippian structure (from Merriam, 1963). Study area indicated by shading.


A
Ancestral Central
Kansas Uplift
North Kansas Basin
Central Kansas Arch
Ozark Homocline
Southwest Kansas Basin
Chautauqua Arch
B
Cambridge Arch
Nemaha Anticline
Hugoton
Embayment
of the
Anadarko Basin
Salina Basin
Central
Kansas
Uplift
Forest City
Basin
Sedgwick
Basin
Pratt
Anticline
Cherokee Basin

one section (1 square mile) to a township (36 square miles) (Fig. 6). Detailed structural contour maps of northwestern Kiowa County reveal five positive features in one township alone (Figs. 8-14).

Most wells in the study area penetrate less than 100 feet into Mississippian rocks, so the most practicable datum in mapping structure is the top of the Mississippian System. Because of the sparsity of well control on the base of the Mississippian and lower units and the difficulty of correlating horizons within the Mississippian, structure beneath the pre-Pennsylvanian unconformity is only vaguely defined.

Structure in units overlying the Mississippian is well defined. Structural contour maps of several horizons within Desmoinesian (Middle Pennsylvanian) and Missourian (Late Pennsylvanian) units (Figs. 8-14) reveal that, in general, structural closure in these rocks is less than closure on the top of the Mississippian (Table 3, Fig. 7), but still adequate to reflect structures in the Mississippian. Increase of closure downward is common in many structures in the Midcontinent (Powers, 1925; Clark, 1932; Merriam, 1963. The Cherokee Group (Desmoinesian), mainly limestone with interbedded shale in the study area, has structural relief and thins over underlying structures (Figs. 9 and 10). The Lansing-

Fig. 6.- Structural contour of top of Mississippian. Only wells in which top was picked are shown.

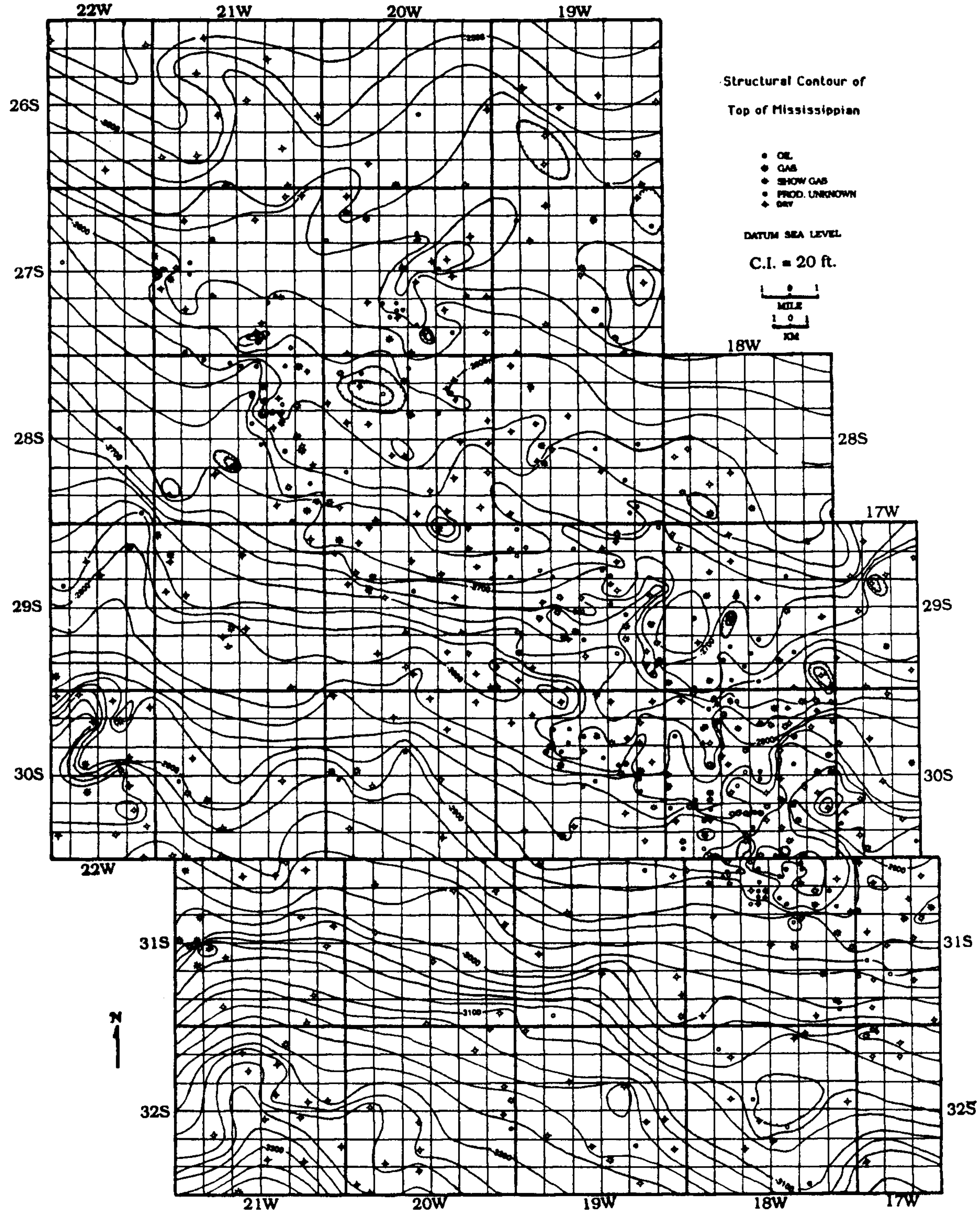

Structural Contour of
Top of Mississippian
OIL
GAS
SHOW GAS
PROD. UNKNOWN
DRY
DATUM SEA LEVEL
C.I. = 20 ft.
MILE
KM
22W
21W
20W
19W
18W
17W
26S
27S
28S
29S
30S
31S
32S
N

Fig. 7.- Pennsylvanian horizons used in structural-contour and isopachous maps: 1) base of Fort Scott Limestone (used as an approximation of the top of Cherokee Group); 2) base of Kansas City Group; 3) base of Hushpuckney Shale Member of the Swope Limestone; and 4) top of the Lansing Group.

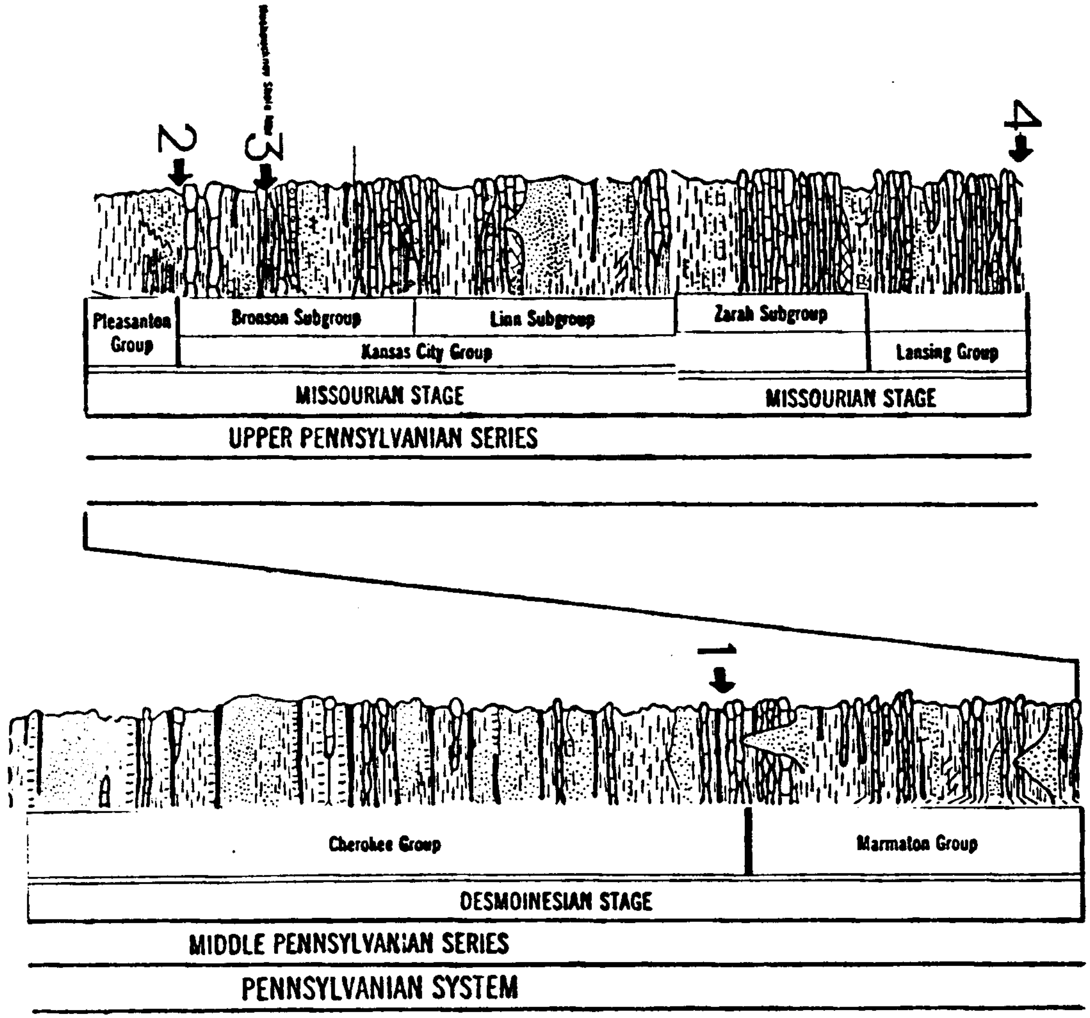

2
3
4
Pleasanton Group
Bronson Subgroup
Linn Subgroup
Kansas City Group
Zarah Subgroup
Lansing Group
MISSOURIAN STAGE
MISSOURIAN STAGE
UPPER PENNSYLVANIAN SERIES
1
Cherokee Group
Marmaton Group
DESMOINESIAN STAGE
MIDDLE PENNSYLVANIAN SERIES
PENNSYLVANIAN SYSTEM

Table 3.- Structural closure on reservoirs in northwestern Kiowa County. The Cherokee Group is Desmoinesian (Middle Pennsylvanian); the Kansas City Group, the Hushpuckney Shale Member of the Swope Limestone, and the Lansing Group are all Missourian (Late Pennsylvanian). Amount of thinning is derived from isopachous maps, which were made only for Cherokee and Lansing-Kansas City Groups. Net closure is the sum of closure and thinning. Data are in feet.

Structural Closure on Selected Reservoirs

Fralick	**Closure**	**Thinning**	**Net Closure**
Lansing-Kansas City	30	0	30
Hushpuckney	30	-	-
Base Kansas City	30	-	-
Cherokee	30	10	40
Mississippian	40	-	-

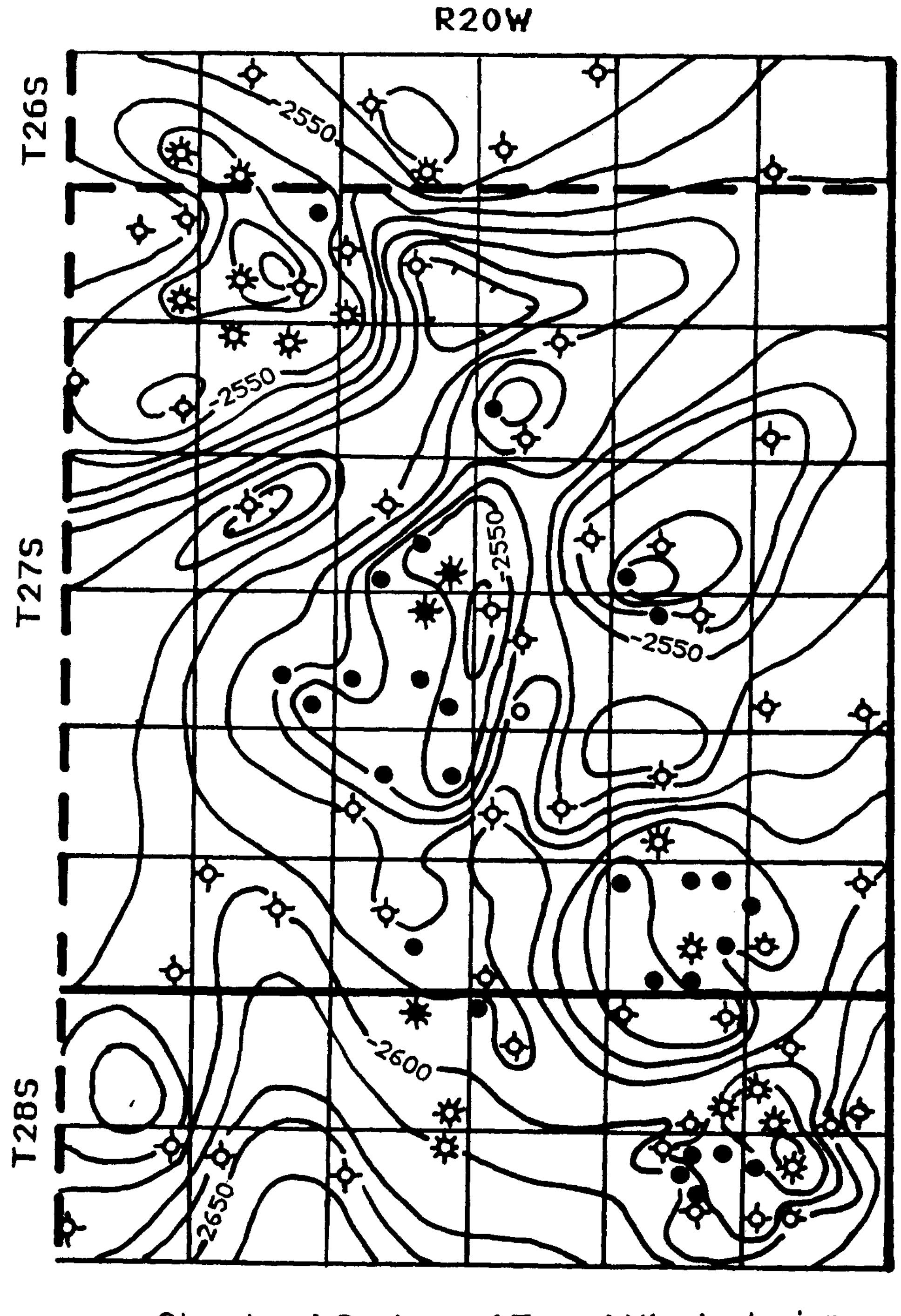
Fralick South	**Closure**	**Thinning**	**Net Closure**
Lansing-Kansas City	0	20	20
Hushpuckney	20	-	-
Base Kansas City	10	-	-
Cherokee	10	10	20
Mississppian	20	-	-

Fralick West	**Closure**	**Thinning**	**Net Closure**
Lansing-Kansas City	20	10	30
Hushpuckney	20	-	-
Base Kansas City	30	-	-
Cherokee	20	10	30
Mississippian	30	-	-

Martin	**Closure**	**Thinning**	**Net Closure**
Lansing-Kansas City	20	10	30
Hushpuckney	30	-	-
Base Kansas City	10	-	-
Cherokee	10	10	20
Mississippian	40	-	-

Mullinville	**Closure**	**Thinning**	**Net Closure**
Lansing-Kansas City	20	10	30
Hushpuckney	10	-	-
Base Kansas City	10	-	-
Cherokee	0	30	30
Mississippian	30	-	-

Fig. 8.- Structural contour of top of Mississippian System in northwestern Kiowa County. Note coincidence of hydrocarbon production with positive features. Only wells in which tops were picked are shown. Elevations are feet below sea level.



Structural Contour of Top of Mississippian

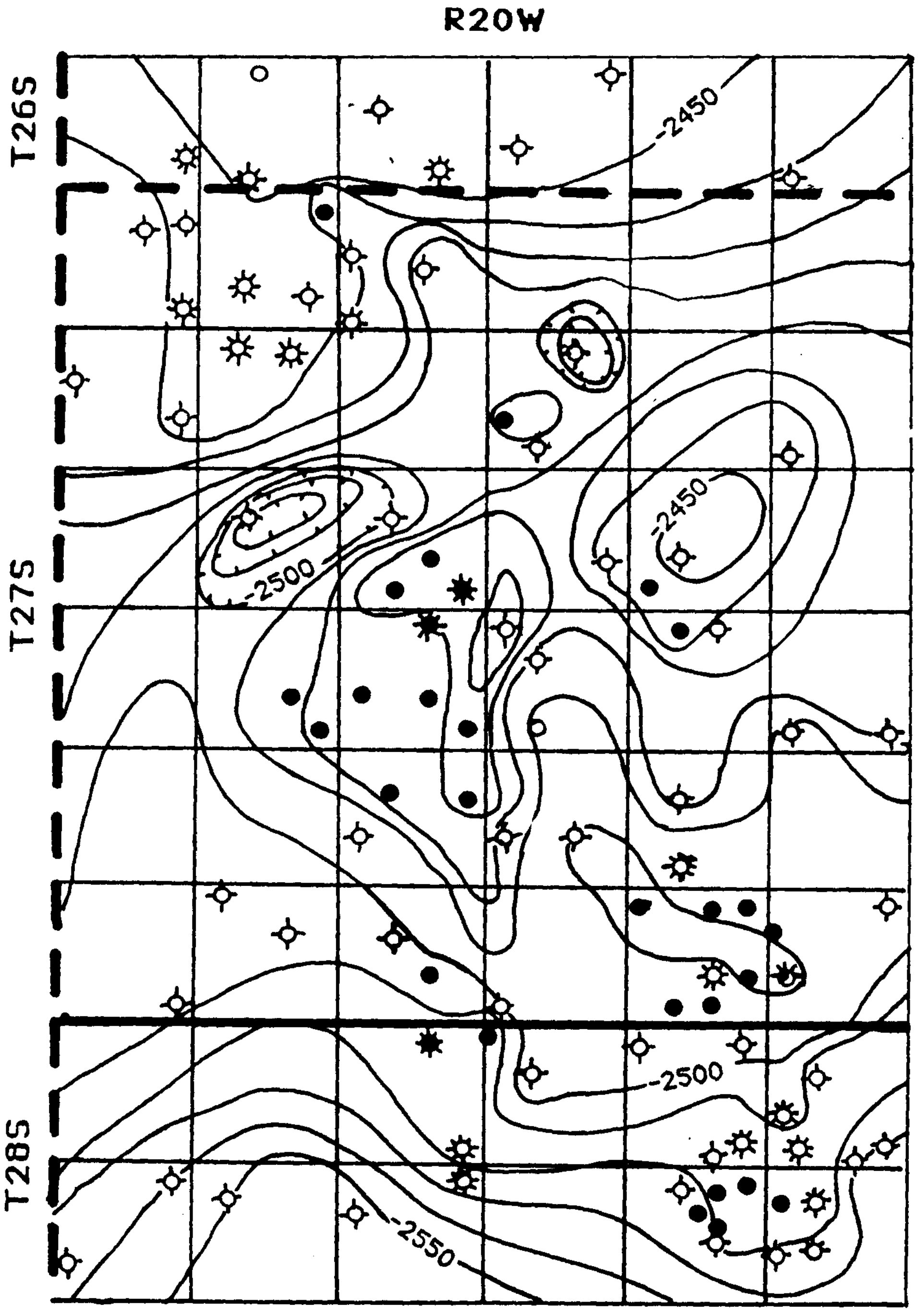
N

C. I. 10'

0 1

MILES

Fig. 9.- Structural contour of top of Cherokee Group (Desmoinesian, Middle Pennsylvanian). Datum is sea level.



.Structural Contour of Top of Cherokee Group

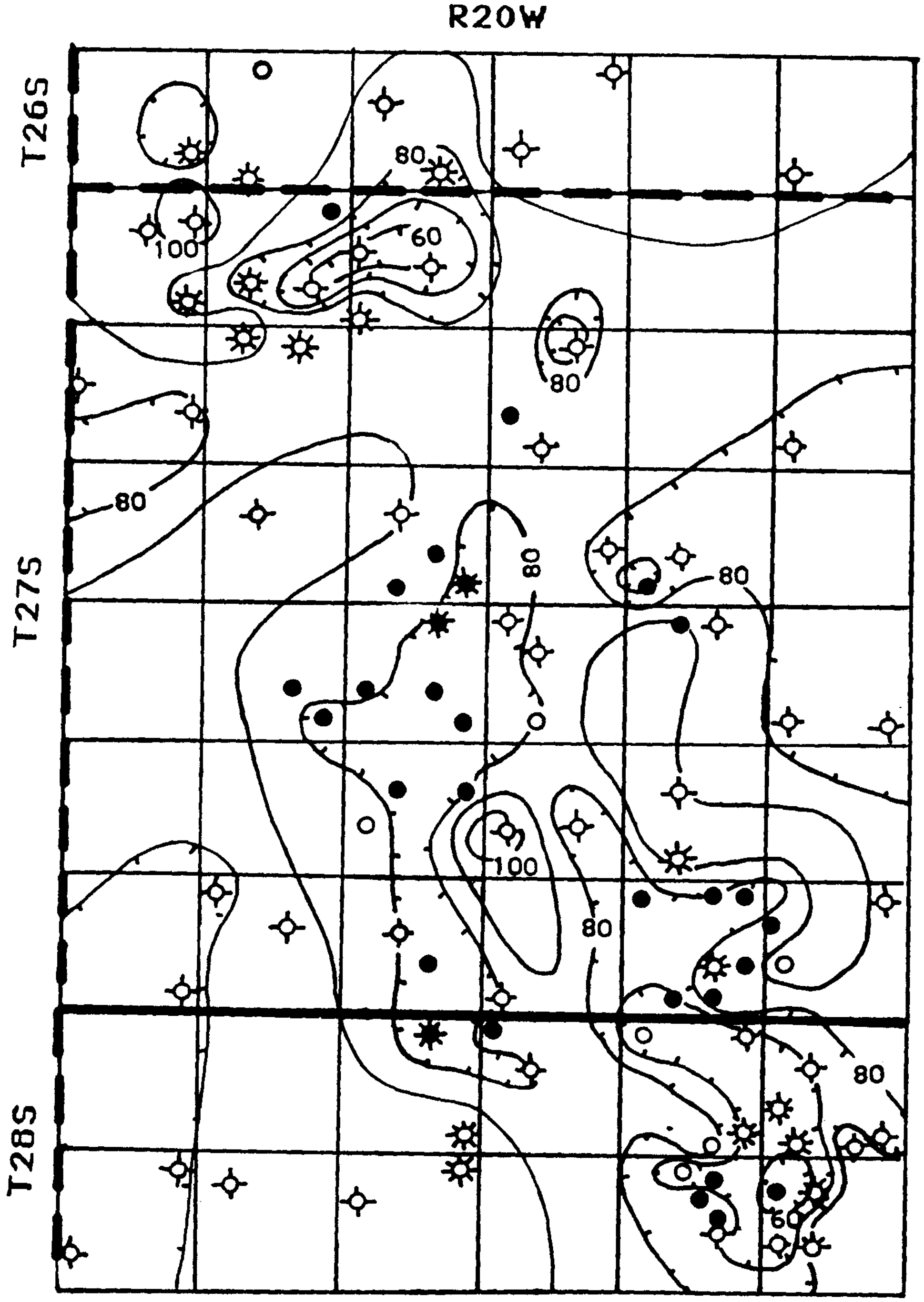
N

C. I. 10'

0 1

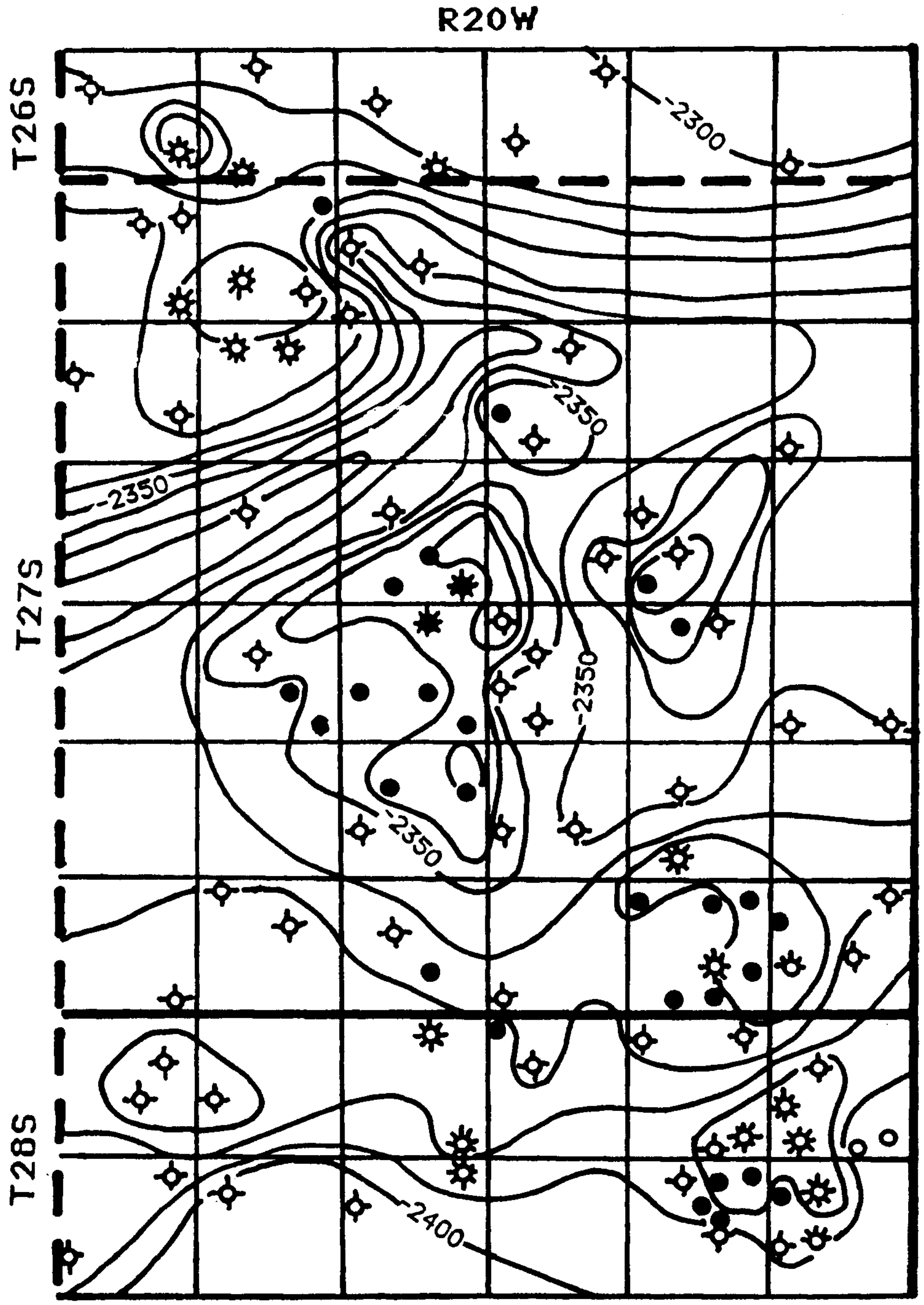
MILES

Fig. 10.- Isopachous map of Cherokee Group. Note thinning over areas of positive relief on top of Mississippian (Fig. 8).



Isopachous Map of Cherokee Group

Fig. 11.- Structural contour of base of Kansas City Group (Missourrian, Late Pennsylvanian). Datum is sea level.



Structural Contour of Base of Kansas City Group

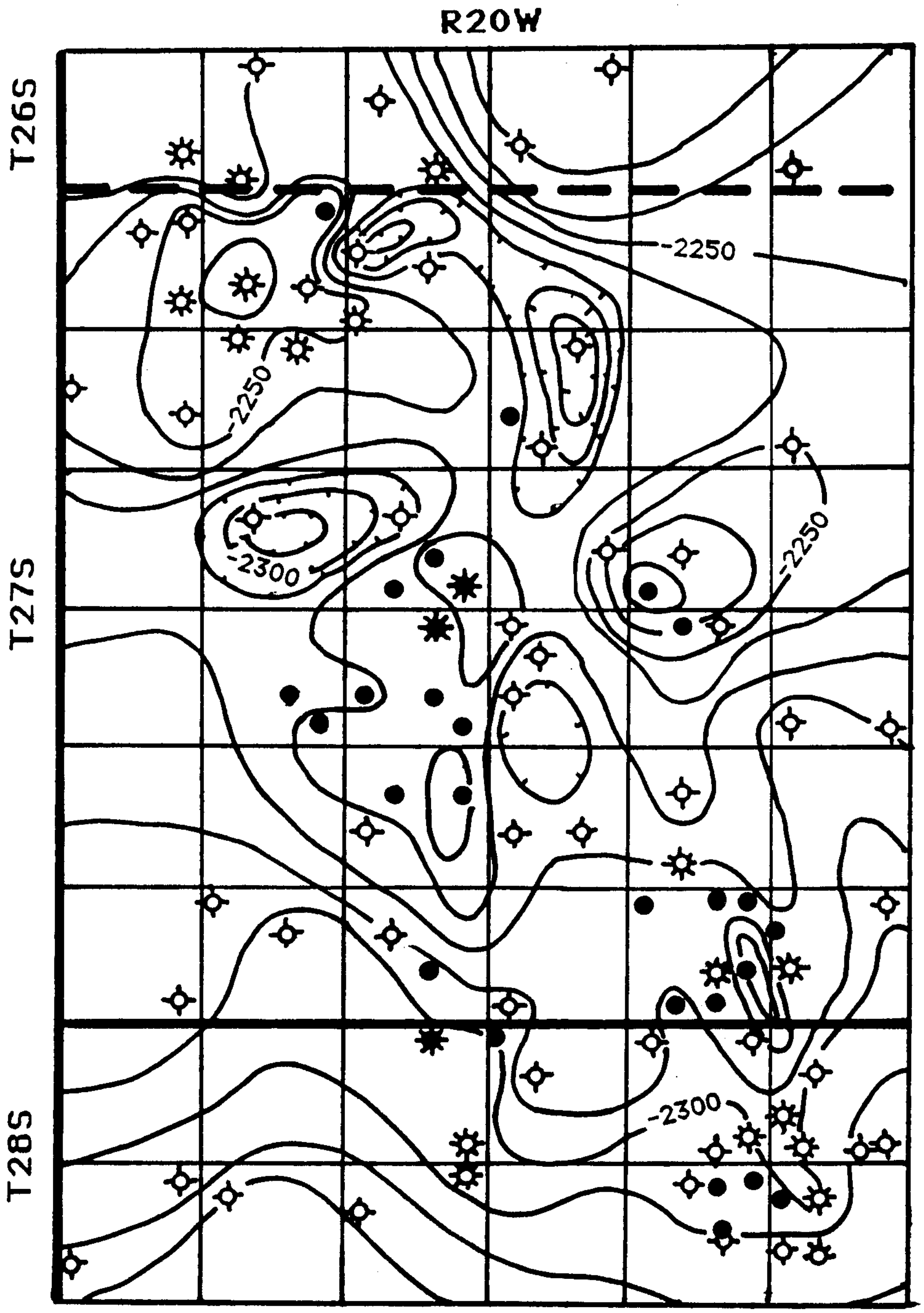
N

C. I. 10'

0 1

MILES

Fig. 12.- Structural contour of base of Hushpuckney Shale Member of the Swope Limestone (Missourian, Late Pennsylvanian). Datum is sea level.



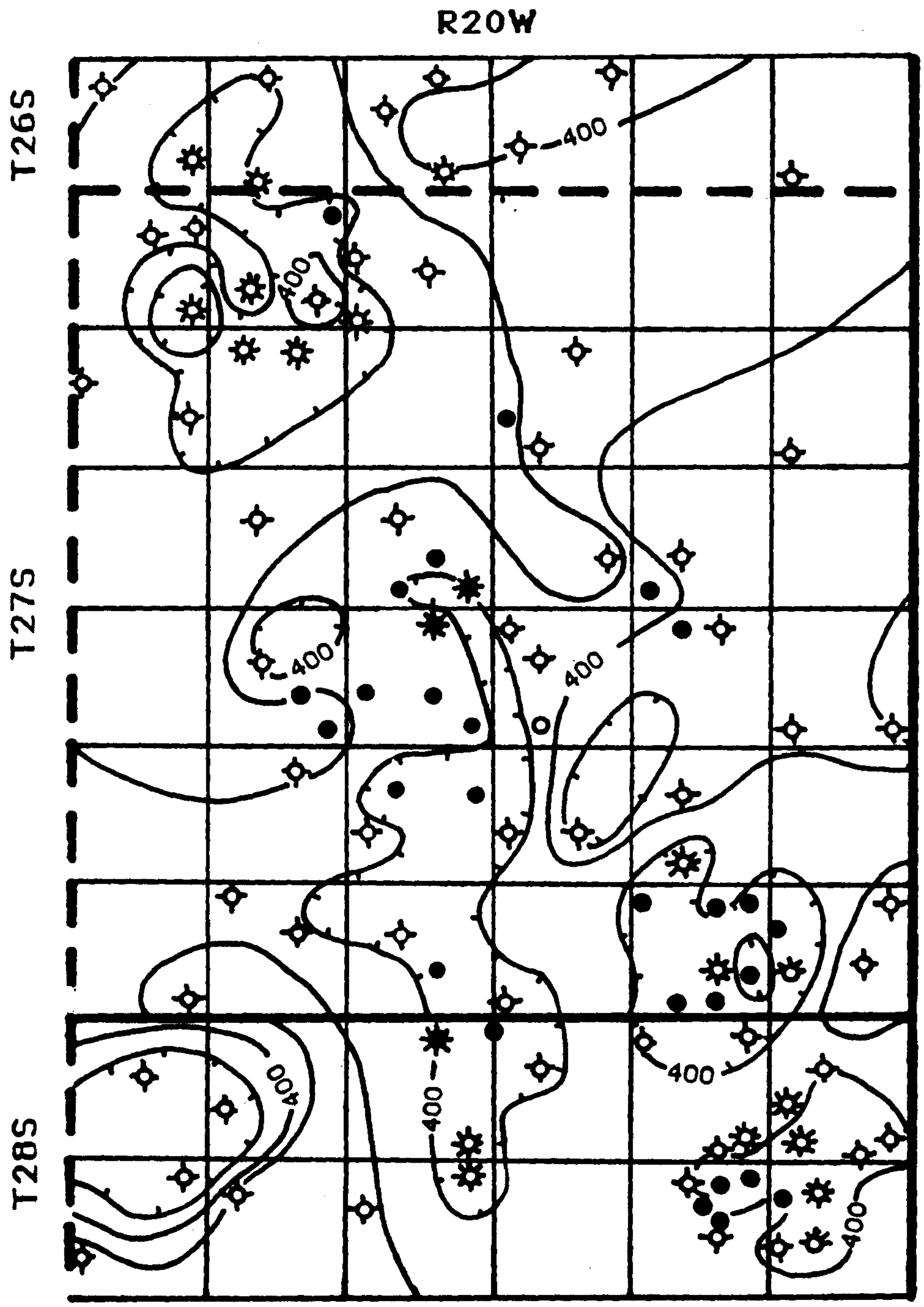
Structural Contour of Base of Hushpuckney Shale

N C. I. 10' 0 1 MILES

Kansas City groups (Missourian) also thin over most structures (Fig. 13) and have structural relief (Fig. 14) comparable to that of the Cherokee Group. In most cases thinning of the Pennsylvanian units accounts for the closure being less than that on the top of the Mississippian system. Clark (1932) described this property for other structures in the Midcontinent.

The regional angular unconformity attests to regional uplift between Late Mississippian (late Chesteran) or Early Pennsylvanian (Morrowan). Powers (1925) noted periodic rejuvenation of small uplifts in the Midcontinent. Thinning in the Cherokee Group (Desmoinesian) coincident with structure shows that the Cherokee was deposited over topographic highs, either structural uplift of pre-Pennsylvanian units or erosional topography resulting from uplift. Structural closure on the top of the Cherokee Group is no greater than closure on the top of the Lansing-Kansas City groups, thus there was no intervening period of rejuvenation. Structural closure on the Lansing-Kansas City groups shows that further warping took place at some later time. The Pennsylvanian and Permian periods were a time of widespread subsidence across the northern Midcontinent, therefore, structural highs probably grew by subsiding less than adjoining areas (Merriam, 1963). Detailed

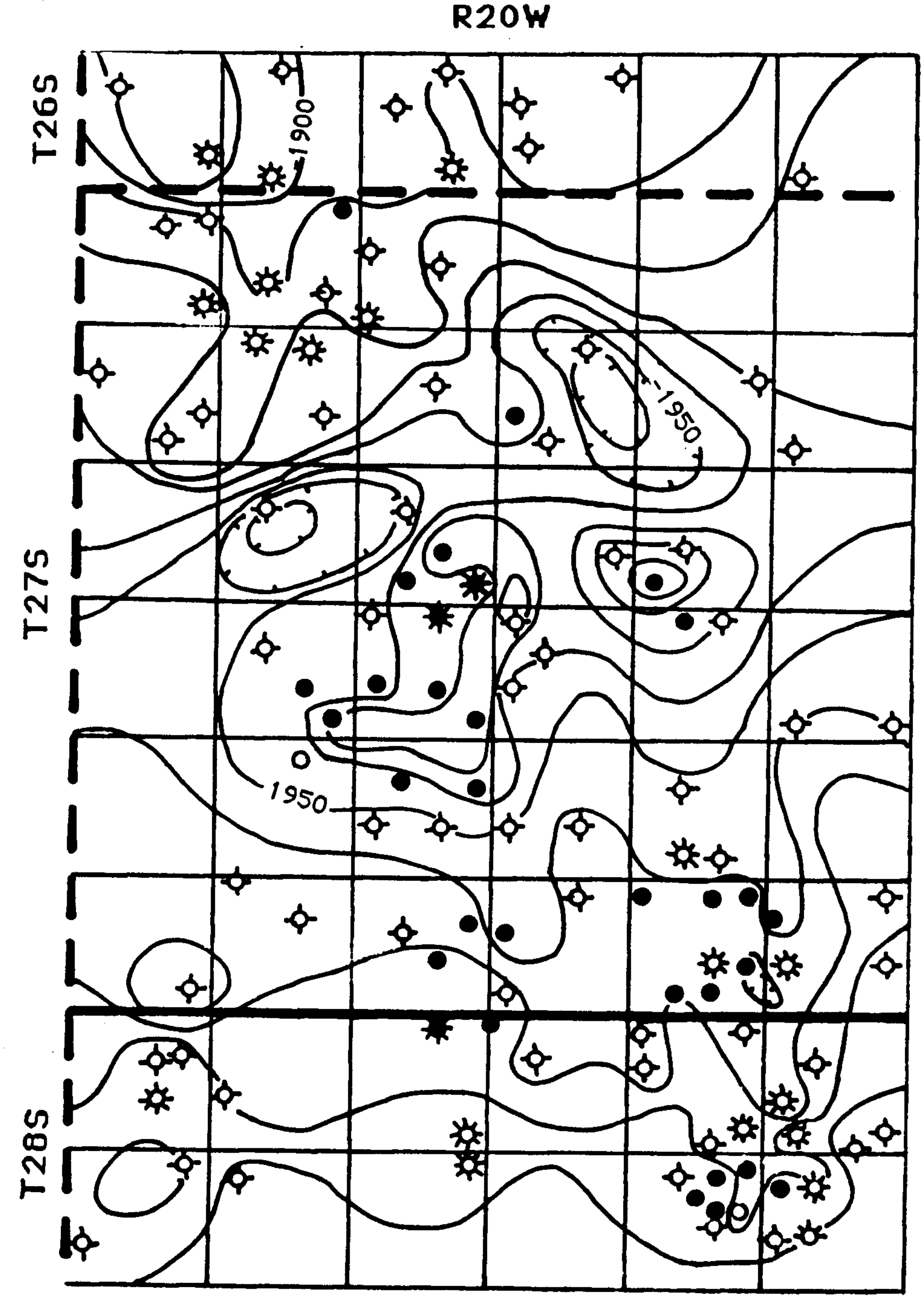
Fig. 13.- Isopachous map of Lansing-Kansas City (Missourian, Late Pennsylvanian) groups. Note thinning over positive areas of underlying units.



Isopachous Map of Lansing-Kansas City Groups

N C. I. 10' 0 1 MILES

Fig. 14.- Structural contour of top of Lansing Group (Missourian, Late Pennsylvanian). Note coincidence of positive areas on Lansing Group with positive areas on Mississippian (Fig. 8). Datum is sea level.



Structural Contour of Top of Lansing Group

N

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geophysical well-logs (20ft/in) of Permian units do not exist, preventing construction of accurate structural maps of these units to determine the minimum age of deformation.

Mississippian Stratigraphy

The Mississippian System of western Kansas is divided into Kinderhookian, Osagian, Meramecian, and Chesteran stages (Fig. 1). Thin, sandy, red and green shale, which separates the Viola from Mississippian carbonates may be Kinderhookian in age (Goebel, 1966). The Kinderhookian Sedalia Dolomite is not recognized in the study area (Goebel, 1968). The Kinderhookian Gilmore City Limestone, which consists of shaly, slightly cherty dolomitic limestone and oolitic limestone, is present only in the northwestern part of the study area where it is up to 120 feet thick (Goebel, 1966).

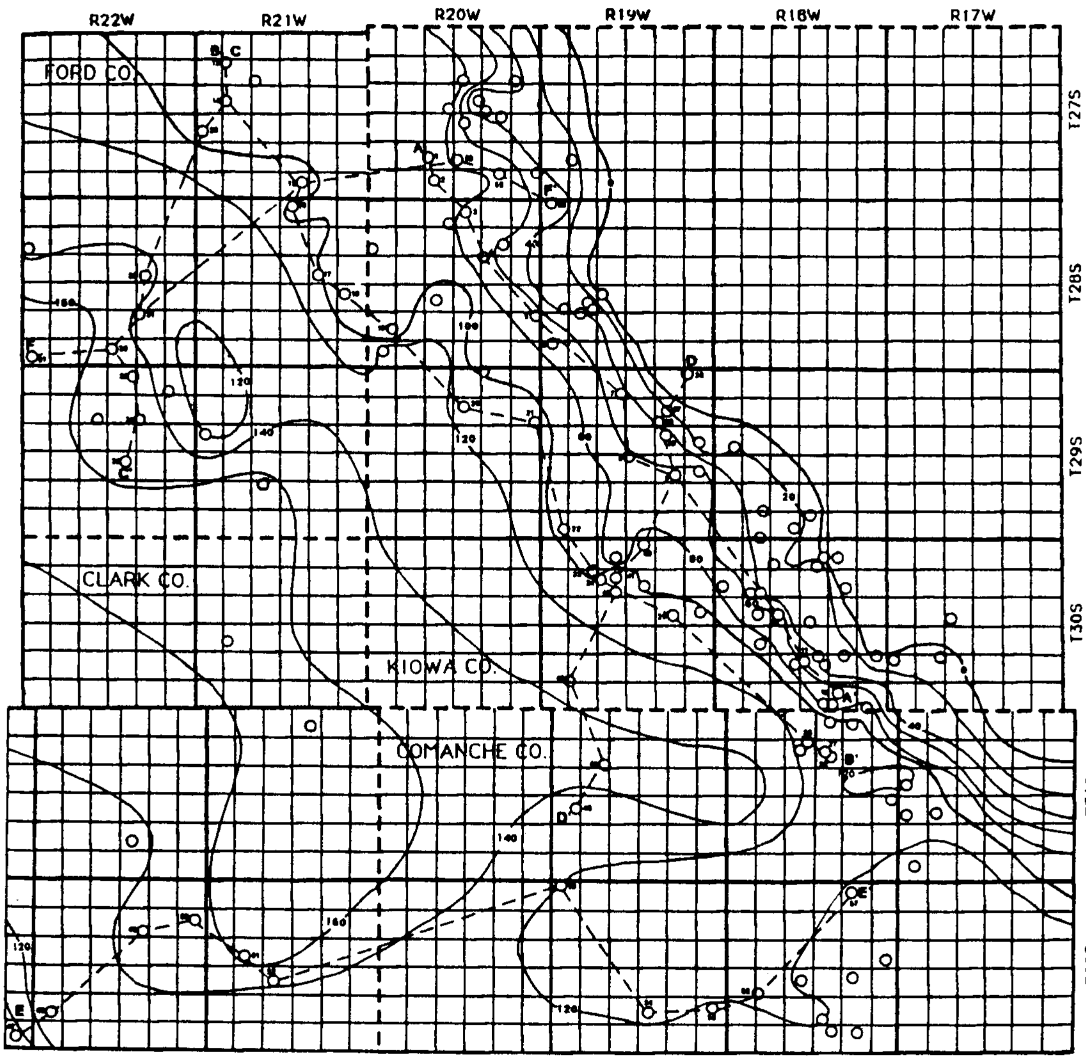
Southeast of the study area rocks of Osagian and possibly Meramecian age are represented by the Cowley facies, which consists of shaly, silty, dolomite with abundant, dark gray, opaque, fossiliferous chert (Lee, 1940). Lee (1953) showed that the Cowley is a lateral equivalent of the Osagian Fern Glen and Keokuk-Burlington, but thought it conformably overlain by the Warsaw. Thompson and Goebel (1969), however, expanded the Cowley to include Meramecian rocks. Conodonts from a core of the Cowley facies in Harper County, east of the study area, indicate late Meramecian age (Thompson and Goebel, 1969).

The Osagian Fern Glen Formation is a very shaly, cherty, limy dolomite up to 80 feet thick that is present only in the southern part of the study area (Goebel, 1968). The Osagian Keokuk-Burlington is an argillaceous, very cherty dolomite grading upward into slightly argillaceous, very cherty spiculitic dolomite and limy dolomite. Thickness varies from an erosional edge in the northeast to 80 feet in the northwestern part of the study area and up to 350 feet thick in Clark County. Chert nodules in the Keokuk-Burlington are black, gray, and white, fossiliferous or non-fossiliferous and in some cases are surrounded by a white, diffuse rim of chert, which envelopes dolomite. Where the Osagian is truncated by the pre-Pennsylvanian unconformity, dolomite is leached from the diffuse rims of chert nodules, leaving a porous residue of chert called tripolitic chert. Partially silicified anhydrite is a minor constituent of chert nodules.

In the northern part of the study area the upper Keokuk-Burlington is a non-argillaceous, cherty dolomitic limestone, easily recognized on neutron and density logs by convergence of neutron porosity and density porosity curves (e.g., Sam Gary Seacat #26-4, Plate 3). This layer aids in distinguishing the more argillaceous and dolomitic lower Keokuk-Burlington from the lower Warsaw, which is also argillaceous, dolomitic, and cherty. In eastern Comanche County, where the Keokuk-Burlington grades into the cherty and argillaceous Cowley Facies, distinction between the lower Warsaw and the Keokuk-Burlington diminishes. An east-west cross-section across Comanche County (Plate 5) shows that the contact between the Warsaw and the Keokuk-Burlington can be correlated eastward into the transition to the Cowley facies.

The Warsaw Formation is the basal formation of the Meramecian Stage. Lithofacies and diagenetic history of the Warsaw are described in detail in the following sections. Thickness of complete Warsaw varies from 90 ft in northwestern Kiowa County to 170 ft in Clark and Comanche counties (Fig. 15). The base of the Warsaw is very argillaceous, but disseminated clay content decreases upward through the lower Warsaw, and clay is present only in thin beds of calcareous shale in the upper Warsaw. The lower Warsaw is characterized by argillaceous, very cherty, dolomitized lime mudstone, containing scattered anhydrite nodules partially replaced by chert. This grades upward into cherty, dolomitized

Fig. 15.- Isopachous map of Warsaw Formation. Only logged wells containing entire Warsaw are shown. Numbers next to wells refer to cross sections (plates 1-5; cross section F-F′ is Fig. 21).



Cross-section indices

C. I. 20'

Isopachous Map
of Warsaw Fm.

miles
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packstone containing echinoderm fragments. Chert in the lower Warsaw is similar to that in the Keokuk-Burlington, typically dark gray to white, semi-translucent, spiculitic, dense chert surrounded by a diffuse rim of white chert which envelopes crystals of ferroan dolomite.

The upper Warsaw is characterized by slightly cherty echinoderm-bryozoan dolopackstone interbedded with stylolitic echinoderm-bryozoan grainstone. Beds of glauconitic, porous, bryozoan-bearing dolomitic wackestone and dolomitic packstone are common. Beds of calcareous shale containing minor amounts of chert and silicified anhydrite are also present. In Hodgeman County, north of Ford County, the Warsaw is thinner, more dolomitic, and contains more moldic porosity (Ebanks et al, 1977).

The Salem Limestone is distinguished from the Warsaw on geophysical logs by decreased gamma-ray count, indicating lower clay content, and by decreased neutron-porosity values relative to density-porosity, representing decreased dolomite content. The contact is placed at the base of the first pure limestone bed approximately 20 feet thick. Conodonts from the Mull Matkin #1 well in Ford County verify that the lower part of the lithostratigraphic unit described as Salem in this report is biostratigraphically equivalent to the Salem

Limestone at the type locality in Indiana (Goebel, 1968).

The Salem is mostly grainstone with some dolomitic packstone; both contain echinoderms, ramose and fenestrate bryozoans, common brachiopods, rare gastropods, trilobites, and ostracodes. Foraminifers are rare in the lower Salem and are usually detectable only in thin section. Nevertheless, presence of Endothyrid foraminifers is a distinguishing characteristic of the Salem (Goebel, 1968).

Vertical solution channels and fractures filled with green clay are abundant. Stylolites are abundant; local swarms are associated with chert nodules.

The Salem-St. Louis contact is indistinct on geophysical logs, because both formations consist of thick beds of pure limestone with a few thin beds of dolomitic limestone. The St. Louis can generally be recognized by oolitic grains in well-cuttings, although the upper Salem may contain minor beds of oolite. Oolitic coatings tend to be thin, but ooids are pervasive and indiscriminate as to type of skeletal nucleii in both the Salem and St. Louis.

Abundant echinoderms, fenestrate and ramose bryozoans, common brachiopods, and few gastropods, trilobites, bivalves, ostracodes, and endothyrid foraminifers comprise the St. Louis skeletal grains.

Some echinoderms and brachiopods are partially silicified, but nodular or bedded chert is not common. Stylolites are fairly common. Goebel (1968) mentions bedded anhydrite and shale in the St. Louis in the Hugoton Embayment, but neither were encountered in the Moore #2-29 core from Clark County. A 40 foot-thick shale in what is either the St. Louis or the Salem is penetrated by the Rupp #11-1B well in Ford County (Plate 3).

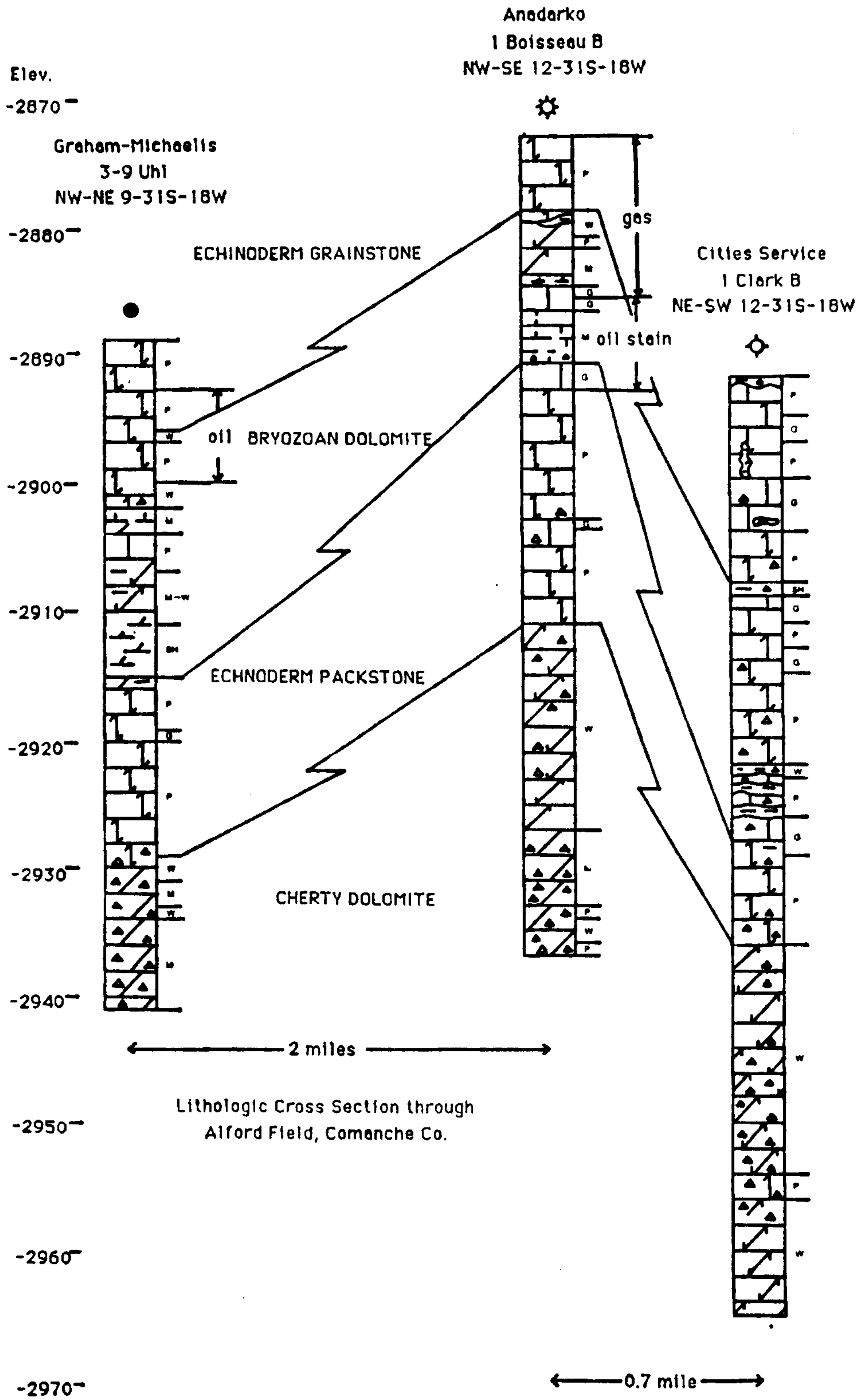
WARSAW LITHOLOGIES AND DIAGENESIS

Lithofacies

Cores of the Warsaw from (northern Comanche County) contain four lithofacies (Figs. 16 and 17). Cores from northern part of the study area (northwestern Kiowa County) are incomplete, because only the upper two lithofacies were cored (Fig. 18). The four lithofacies are: 1) cherty dolomite; 2) echinoderm packstone; 3) bryozoan dolomite; and 4) echinoderm grainstone (Table 4). These designations denote distinguishing characteristics of each lithofacies; they do not necessarily represent the most abundant components, as those may be non-diagnostic. Poor quality of geophysical well-logs for cored intervals prevents definition of diagnostic log signatures for each facies, although shale beds in the bryozoan dolomite may be distinctive. Greater dolomite content in the cherty dolomite and bryozoan dolomite in comparison to the echinoderm packstone and echinoderm grainstone should be distinguishable in neutron and density logs.

The lowermost and thickest unit, the cherty dolomite lithofacies, consists of argillaceous, dolomitic, spiculitic wackestone and dolomitic mudstone that grade upward into cherty-echinoderm dolopackstone. Nearly all

Fig. 16.- Lithofacies of Warsaw from cores from southern part of Alford field, northern Comanche County. Depositional textures are indicated by G = grainstone; P = packstone; W = wackestone; M = mudstone. Elevations are feet below sea level.



Lithologic Cross Section through
Alford Field, Comanche Co.

Fig. 17.- Lithofacies from Wilmore field, northern Comanche County. Depositional texture indicated by G = grainstone, P = packstone, W = wackestone, M = mudstone. Elevations are feet below sea level.

Lithologic Cross Section through Wilmore Field, Comanche Co.

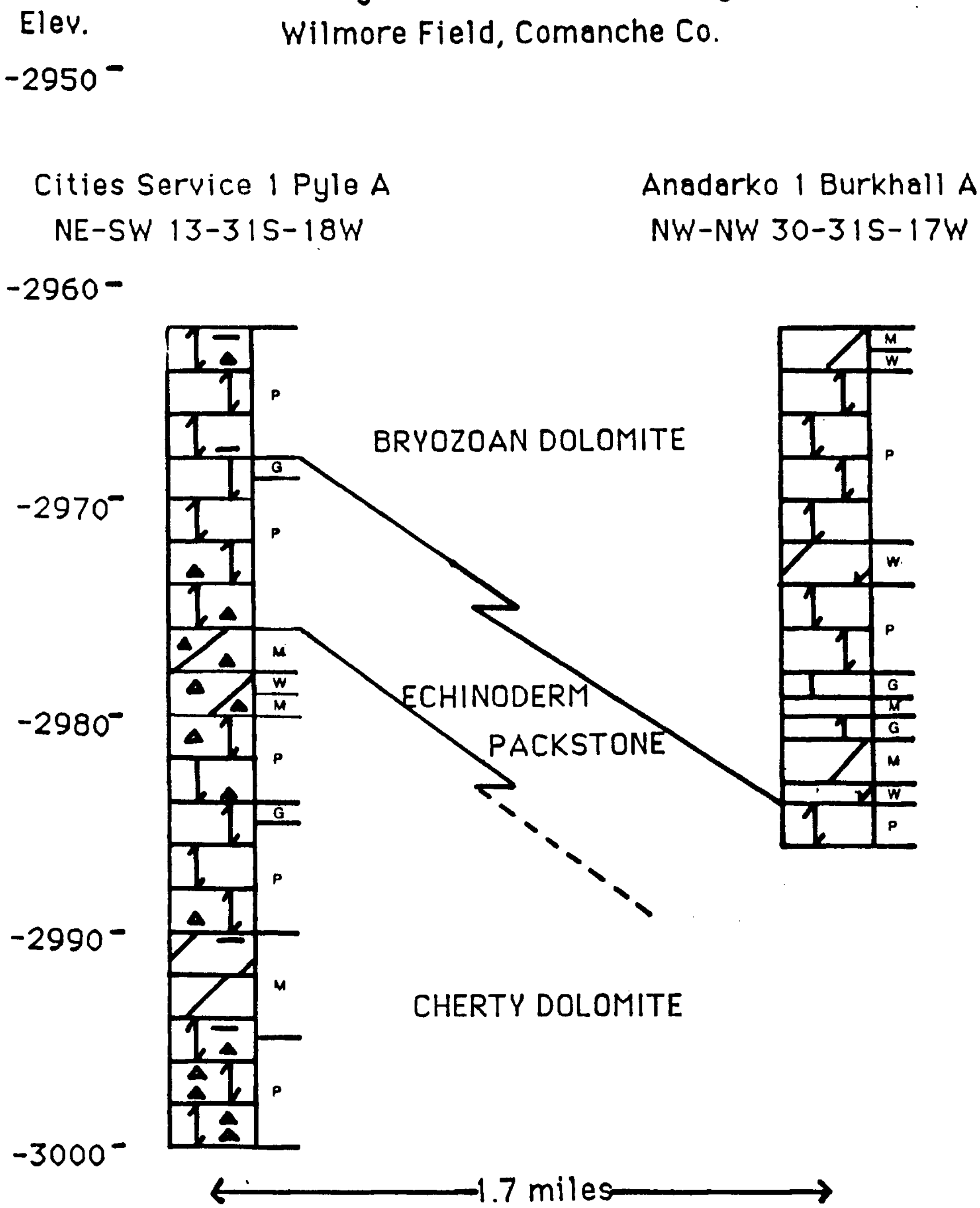
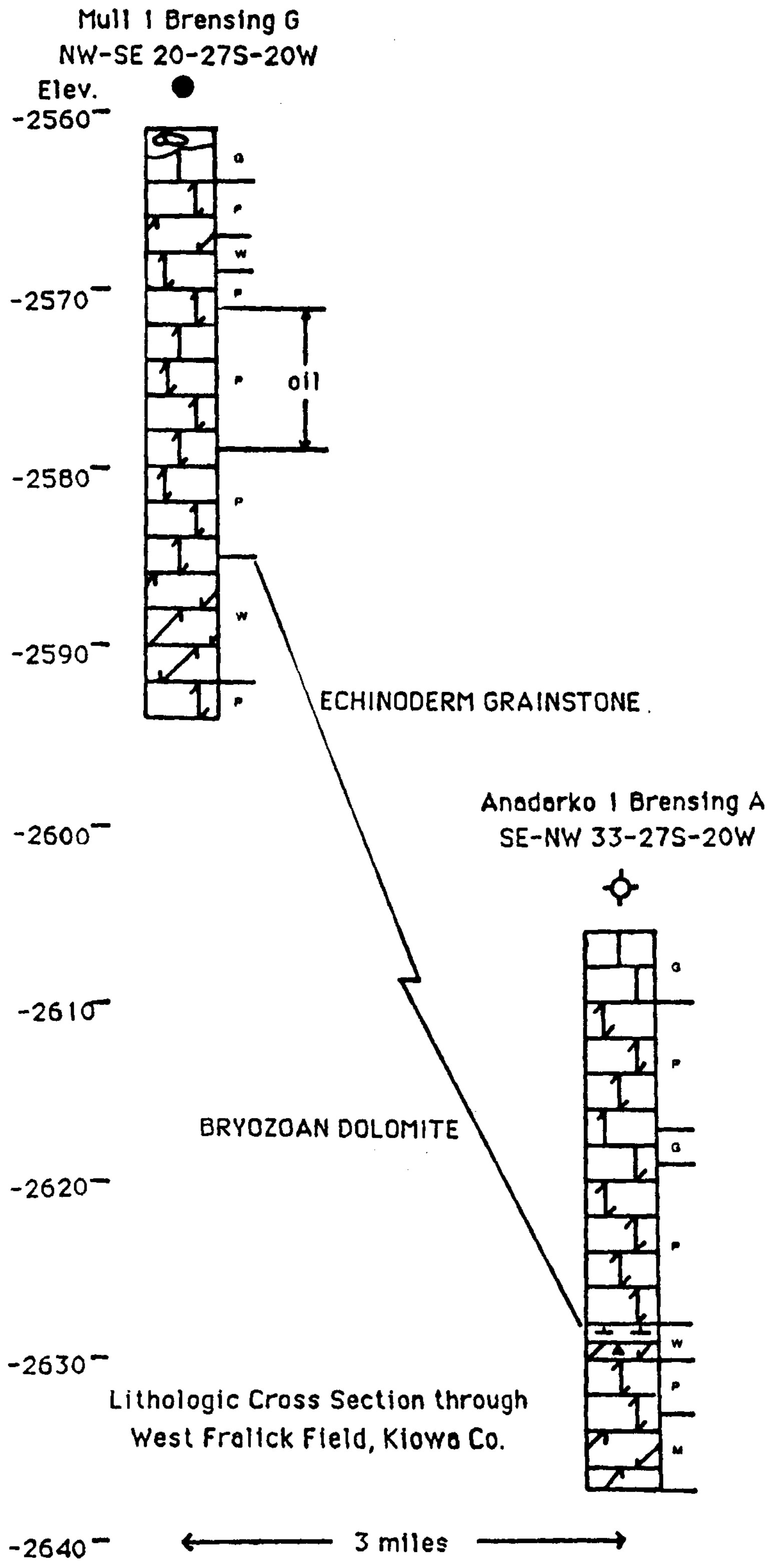


Fig. 18.- Lithofacies from West Fralick field, northwestern Kiowa County. Depositional texture indicated by G = grainstone, P = packstone, W = wackestone, M = mudstone. Elevations are feet below sea level.



Lithologic Cross Section through West Fralick Field, Kiowa Co.

Table 4.- Description of lithofacies.

DESCRIPTION OF LITHOFACIES	ALLOCHEMS
4. **ECHINODERM GRAINSTONE:** echinoderm-bryozoan grainstone and dolopackstone.	Abundant: echinoderms, ramose and fenstrate bryozoans; common: brachiopods; rare: gastropods, ostracodes, trilobites, and foraminifers.
3. **BRYOZOAN DOLOMITE:** Glauconitic, echinoderm-bryozoan dolowackestone and dolopackestone; minor spiculitic dolomudstone, lime grainstone, calcareous shale, and argillaceous dolomudstone.	Abundant: echinoderms, fenestrate bryozoans; common: ramose bryozoans, brachiopods; minor-to-rare: sponge spicules; rare: gastropods and ostracodes.
2. **ECHINODERM PACKSTONE:** Slighty cherty, echinoderm-bryozoan dolopackstone with minor beds of grainstone and a few thin layers of shale.	Abundant: echinoderms, ramose bryozoans; Abundant-to-common: fenestrate bryozoans; common-to-abundant: brachiopods; rare: trilobites and gastropods.
1. **CHERTY DOLOMITE:** Cherty, argillaceous, spiculitic dolowackestone and dolomudstone grading upward into cherty echinoderm dolopackstone.	Abundant: echinoderms; common: fenestrate and ramose bryozoans, and sponge spicules.

interparticle space in the dolopackstone is filled with dolomitic matrix. Important aspects of this lithofacies are sponge spicules, abundant chert, and partially silicified anhydrite. Black, gray, and white fossiliferous chert nodules in this lithofacies are commonly surrounded by diffuse rims of chert, closely resembling chert described by Ebanks, et al. (1977, p. 320). Amount of grain-supported rocks increases toward the southeast, as does the chert abundance. Ramose bryozoans are more abundant than fenestrate bryozoans, especially near the top of the lithofacies. Thickness of the cherty-dolomite lithofacies varies from 30 to 60 feet in northern Comanche County to approximately 30 to 80 feet in northwestern Kiowa County.

The second unit, the echinoderm-packstone lithofacies, comprises slightly cherty, dolomitic echinoderm-bryozoan packstone with minor beds of grainstone and a few thin layers of shale. Dominant skeletal particles are echinoderms and ramose bryozoans, but in a few samples fenestrate bryozoans are dominant. Brachiopods are common to abundant; trilobites and gastropods are rare. High-amplitude stylolites are present. In contrast to packstones of the cherty-dolomite lithofacies, interparticle areas in packstones of the echinoderm-packstone lithofacies are more commonly occluded by calcite cement than by dolomitic matrix. Thickness of this lithofacies decreases northward from 10 t0 20 feet in northern Comanche County to approximately 5 to 15 feet in northwestern Kiowa County.

The bryozoan-dolomite lithofacies is complex because of large areal and vertical variations of clay content, fauna, and depositional fabric. This lithofacies consists of glauconitic, dolomitic wackestone and packstone containing abundant fenestrate bryozoans and echinoderms, common ramose bryozoans and brachiopods, and minor to rare sponge spicules, gastropods, and ostracodes. Spicule-bearing dolomite and echinoderm-bryozoan grainstone are present in lesser amounts. Clay is present both in discrete layers of calcareous shale and in argillaceous dolomite. This lithofacies contains more grain-supported fabric and fewer discrete beds of shale to the south, although disseminated glauconite increases. The major compositional difference between the packstones in this lithofacies and the echinoderm-packstone and echinoderm-grainstone lithofacies is the greater abundance of fenestrate bryozoans compared to ramose bryozoans. In some cases fenestrate bryozoans are more abundant than echinoderms. Molds of fenestrate bryozoans, sponge spicules, and, in rare cases, echinoderms are present. This lithofacies contains minor amounts of silicified brachiopods and other skeletal grains, and nodular, white and black, fossiliferous chert with diffuse white rims containing dolomite crystals. Nodular anhydrite at the base of the lithofacies are formed of vertical laths similar to those described by Ebanks, et al. (1977, p. 320). They are partially replaced by silica. The bryozoan-dolomite lithofacies varies from 10 to 25 feet thick.

The uppermost fourth lithofacies, echinoderm grainstone, contains echinoderm-bryozoan grainstone and dolopackstone with minor chert. Ramose bryozoans are again more abundant than fenestrate bryozoans. Brachiopods are common to abundant. Minor constituents are gastropods, ostracodes, trilobites, and foraminifers.

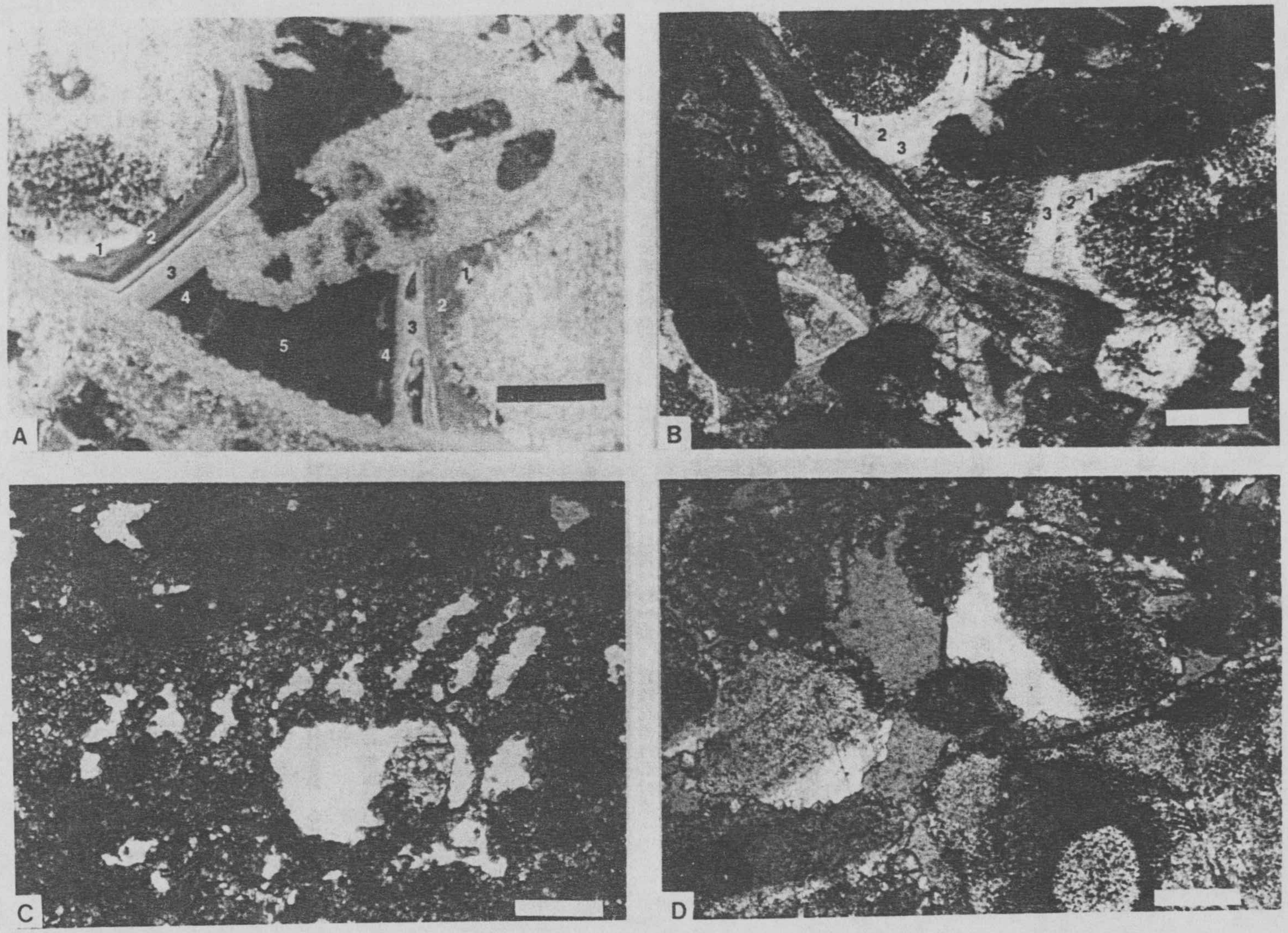
In-situ brecciation, vertical and horizontal solution channels filled with green clay, and narrow fractures are common, probably because all available samples from the study area are truncated by the pre-Pennsylvanian unconformity. The echinoderm-grainstone lithofacies varies in thickness from 10 to 30 feet thick.

Only the echinoderm-grainstone lithofacies and the top of the bryozoan-dolomite lithofacies were cored in northwestern Kiowa County. The bryozoan dolomite differs slightly from its equivalents in northern Comanche County in being less cherty and argillaceous and containing more ramose bryozoans than fenestrate bryozoans.

Calcite Cement

Staining for calcite and iron reveals up to five zones of cement (Fig. 19B). The first generation is non-ferroan calcite developed as syntaxial overgrowths (Bathurst, 1975; rim cement of Lucia, 1962) on echinoderm fragments, as small, bladed crystals on echinoderms, brachiopods and ramose bryozoans, or as equant cement reducing molds of aragonitic skeletal grains. This generation is bright under cathodoluminescence (Fig. 19A, indicating a high Mn/Fe ratio or significant Mn in the absence of Fe (Frank, et al., 1982). It is overlain by internal sediment in very few samples. The second generation of cement is slightly ferroan calcite, which is dull under cathodoluminescence, indicating a low Mn/Fe ratio. Cements are typically equant but are locally bladed, especially on brachiopods and bryozoans and, rarely, on echinoderms. The third generation of cement is equant, and in most cases, low in iron content. This generation is generally luminescent, but contains subzones of dull calcite. The fourth generation is equant, ferroan calcite which is dull under cathodoluminescence. In some grainstones the third and fourth zones are merged into multiple, thin subzones of

Fig. 19.- A) Calcite cement zones in grainstone from echinoderm-packstone lithofacies in Cities Service #1 Clark B core under cathodoluminescence (scale bar equals 0.25 mm). B) Same view in plane light (scale bar equals 0.25 mm). C) Mold of fenestrate bryozoan from bryozoan-dolomite lithofacies in Anadarko #1 Brensing A core (scale bar equals 0.5 mm). D) Interparticle (BP) porosity in dolopackstone from echinoderm-grainstone lithofacies in Mull #1 Brensing G core (scale bar equals 0.5 mm).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alternately dull, ferroan and brightly luminescent non-ferroan cement. In one case nine subzones are present. The fifth zone is highly ferroan, nonluminescent calcite that occludes remaining interparticle pore space in most grainstones. Highly ferroan calcite which fills molds of sponge spicules may be equivalent to zone five, but may represent a separate generation of cement which post-dates chertification.

Abundance, zonation, and types of cement vary with fabric, types of allochems, and to lesser degrees, with lithofacies and geographic location. Calcite cement is best developed in grainstone and least developed in dolomitic wackestone and dolomitic mudstone. Most dolomitic packstones have fewer zones of calcite cement than grainstones. Dolomitic packstones rarely have more than three zones, and some packstones, especially those in the cherty-dolomite lithofacies, have no visible calcite cement (Table 5). Typical grainstones and packstones in the bryozoan-dolomite lithofacies only have two, or rarely three, generations of cement, whereas grain-supported rocks in the echinoderm-packstone and the echinoderm-grainstone lithofacies typically have three to five generations. Dolomitic packstones in northwestern Kiowa County contain one generation of cement, which is luminescent non-ferroan calcite. This

Table 5.- Number of calcite cement zones in each lithofacies. North refers to rocks from Anadarko #1 Brensing A and Mull #1 Brensing G. South refers to cores from northern Comanche County. Where only 1 generation is present, it is almost always without exception the first zone. Where two are present, they are zones one and two. Where three are present, they are zones one, two and three, etc.

LITHOFACIES	Number of calcite cement zones			
	grainstone	packstone	wackestone	mudstone
Echinoderm Grainstone	1-3 (North) 3-5 (South)	1-2 (North) 3-5 (South)	0-1	0
Bryozoan Dolomite	2-3	1-3	0-2(North) 0 (South)	0
Echinoderm Packstone	2-5	2-4	N/A	N/A
Cherty Dolomite	2	0-2	0-2	0

differs from the packstones in northern Comanche County that commonly have three generations of cement.

Dolomitic wackestones commonly lack visible calcite cement, but a generation of luminescent, non-ferroan calcite is locally followed by ferroan calcite. Some dolomitic mudstones contain echinoderms with partially dolomitized overgrowths of non-ferroan calcite, but most lack visible calcite cement.

Dolomite

Matrix in Mississippian rocks in this area consists entirely of dolomite rhombs typically ranging in size from 15 to 150 micrometers. Most rhombs have cloudy nuclei with clearer rims. Dolomite crystals commonly penetrate from matrix into grains and cement, but rarely entirely replace skeletal grains. Exceptions are fenestrate bryozoans that have been pseudomorphically replaced by minute dolomite crystals in some highly dolomitized rocks. Although the average size of dolomite crystals in matrix-supported rocks does not differ significantly from that in grain-supported rocks, maximum size of dolomite crystals is greater in matrix-supported rocks. Typical maximum size of dolomite crystals in grain-supported rocks is 130 micrometers; in matrix-supported rocks it is 100 micrometers.

Dolomite is ferroan only in the outer rims of larger dolomite rhombs. A dark, opaque substance that Ebanks, et al. (1977) described as bitumen fills interparticle pores. Chert envelopes dolomite crystals in a few cases or, in rare instances, replaces them.

Geophysical well logs reveal that the amount of dolomitization in the Warsaw does not vary significantly in relation to the pre-Pennsylvanian unconformity, i. e., the Warsaw is not more dolomitic where it is truncated by the unconformity than where it is overlain by Mississippian rocks. Minor geographic variation in size of dolomite crystals is evident. Dolomite crystals vary from 15 to 100 micrometers in northern Comanche County and from 20 to 170 micrometers in northwestern Kiowa County. Average size also increases from approximately 60 micrometers in the south to approximately 30 micrometers in the north.

Ferroan saddle dolomite is present as cement in large molds of skeletal fragments and in highly dolomitized rocks. Saddle dolomite also replaces anhydrite or fills voids left by partially dissolved anhydrite. Chert partially replaces baroque dolomite in rare instances, particularly in voids after anhydrite.

Chert

Nodular chert and fabric-selective silicification are present in the Warsaw. The most commmon form of nodular chert is white, gray, and black fossiliferous chert with diffuse white rims (Fig. 20C). Chert is more common in the lower part of the Warsaw, especially in zones with abundant sponge spicules. Skeletal grains and cements in fossiliferous chert nodules are completely replaced by microquartz (less than 10 micrometers), except for the centers of some echinoderm fragments. Similar textures were observed by Meyers (1977) in Mississippian rocks from New Mexico. The rims of chert nodules typically envelop instead of replace ferroan calcite cement, dolomite, and echinoderms (Fig. 20D). Ironically, echinoderms outside the nodules are more commonly silicified than other skeletal grains. Meyers, in contrast, observed that echinoderms were the least commonly silicified skeletal grains. In some cases brachiopods are replaced by spherules of lenght-slow chalcedony up to 100 micrometers in diameter.

Anhydrite

Both spherulitic and lenticular anhydrite are common, but nearly all have been at least partially replaced by chert. Spherical nodules of anhydrite, found

Fig. 20.- A) Euhedral quartz replacing fibrous anhydrite in cherty-dolomite lithofacies from Anadarko 1 Boisseau B core. Note anhydrite inclusions in quartz (scale bar equals 0.5 mm). B) Chalcedony psuedomorphically replacing fibrous anhydrite (scale bar equals 0.5 mm). C) Fossiliferous chert from echinoderm-packstone lithofacies in Graham-Michaelis Uhl #3-9 core. D) Chert replacing anhydrite from cherty-dolomite lithofacies in Graham-Michaelis Uhl #3-9 core. Note diffuse rim of white chert.

in the cherty-dolomite lithofacies of the Warsaw, are typically completely replaced by quartz, microquartz (less than 10 micrometers), and spherules of length-slow chalcedony. Some chalcedony pseudomorphically replaces anhydrite needles (Fig. 20B).

Vertically elongate nodules of anhydrite pseudomorphically replaced by chert, are present in the bryozoan dolomite lithofacies. Varieties of silica present in these nodules include mosaics of quartz and microquartz, euhedral quartz (Fig. 20A), and spherules of length-slow chalcedony. All quartz varieties locally contain lath-shaped inclusions of anhydrite up to 20 micrometers long.

Porosity and Permeability

Dominant porosity types in the Warsaw are intercrystalline (BC, Choquette and Pray, 1970), moldic (MO; Fig. 19C), and interparticle (BP; Fig. 19D). Despite partial occlusion of porosity by cement in grainstones, they average 11.6% (Table 6). Rhombs of dolomite occupy some of the interparticle space in dolomitic packstones, but interparticle and intercrystalline porosity combine for an average of 9.7%. Average permeability, however, is only 0.13 md. Average porosity in packstone in the northern part of the study area is 14%, but only 9% in

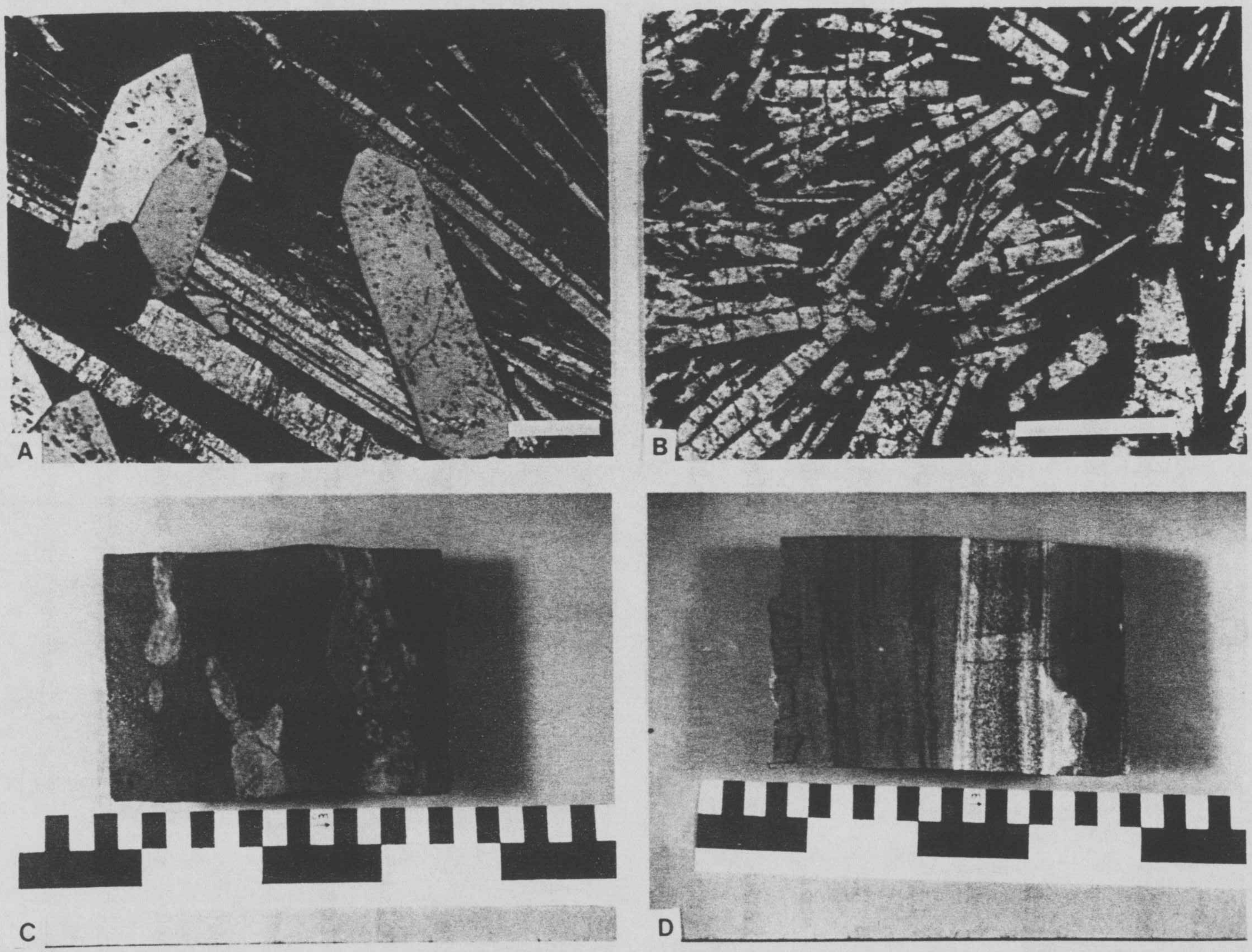
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Table 6.- Average porosities (percent) and average (logarithmic) permeabilities (millidarcies) of textural categories. Averages from the north are from the Mull #1 Brensing G core. Averages from the south are from the Anadarko #1 Burkhall A and #1 Boisseau B cores, and the Cities Service #1 Pyle A core. N/A = analysis not available.

Texture	Porosity North	South	Overall
Grainstone	N/A	12	12
Packstone	14	8.7	9.7
Wackestone	14	12	13
Mudstone	N/A	15	15

Texture	Permeability North	South	Overall
Grainstone	N/A	0.13	0.13
Packstone	0.81	14	1.8
Wackestone	2.8	11	5.3
Mudstone	N/A	3.9	3.9

the southern part. Permeability varies from a logarithmic average of 0.8 md in the south to 14 md in the north. Horizontal permeability is typically twice as great as vertical permeability except where open fractures are present.

Dolomitic wackestone and dolomitic mudstone have average porosities of 13% and 15%, respectively (Table 7). Porosity in matrix-supported rocks includes intercrystalline porosity and molds of sponge spicules, fenestrate bryozoans (few) (Fig. 19C), and echinoderms (rare). Average permeability in matrix-supported rocks is 2.8 md in the north and 11 md in the south.

Porosity and permeability vary more with texture and dolomite content than with lithofacies, but in general, the bryozoan dolomite and echinoderm grainstone lithofacies are more porous and permeable than the lower two lithofacies (Table 7). The greater porosity in the echinoderm-grainstone lithofacies compared to the porosity in echinoderm-packstone lithofacies is surprising considering the similarity between the two lithofacies. This is explained by packstones in the echinoderm-grainstone ltihofacies having higher porosity than packstones in the echinoderm-packstone lithofacies.

Table 7.- Average porosity (percent) and logarithmic average of permeability (millidarcies) of each lithofacies. Averages from north are from the Mull #1 Brensing G core and those from the south are from the Anadarko #1 Burkhall A and #1 Boisseau B cores and the Cities Service #1 Pyle A core. N/A = No analysis available. N/P = Texture not present.

Lithofacies	Average Porosity				
	Grainstone	Packstone	Wackestone	Mudstone	Overall
Echinoderm Grainstone	N/A	14	16	N/P	14
Bryozoan Dolomite	N/A	7.0	14	18	11
Echinoderm Packstone	12	8.6	N/P	N/P	9.3
Cherty Dolomite	8.3	8.4	3.5	12	10

Lithofacies	Average Permeability				
	Grainstone	Packstone	Wackestone	Mudstone	Overall
Echinoderm Grainstone	N/A	19	17	N/P	18
Bryozoan Dolomite	N/A	3.1	4.9	0.10	3.3
Echinoderm Packstone	0.30	0.91	N/P	N/P	0.88
Cherty Dolomite	0.10	0.18	2.2	11	0.27

DEPOSITIONAL ENVIRONMENTS

On a regional scale the depositional environments of the Warsaw are comparable to Lane's (1978) carbonate shelf in the Osagian, which extended from eastern Colorado to Missouri. The shelf comprises inner shelf, main shelf, and shelf margin. Inner shelf is characterized by thin, dolomitized, grain-supported carbonates adjacent to the subaerially exposed Transcontinental arch. Main shelf was further seaward (south) and is characterized by thicker, less dolomitized, grain-supported carbonates. The shelf margin forms a narrow seaward edge of the main shelf and is characterized by argillaceous, cherty, lime wackestones or mudstones.

The geographic distributions of the three divisions described by Lane roughly coincide with three regional facies of the Warsaw. The Warsaw in Hodgeman County, as described by Ebanks, et al. (1977) has been more extensively dolomitized than in the study area, and represents the dolomitized inner-shelf facies. The Warsaw in the study area corresponds to the less dolomitic main shelf. Argillaceous, cherty, dolomitic wackestones of the Cowley facies represent the shelf margin.

The higher clay content of the Warsaw distinguishes it from the overlying and underlying units, as in the very shaly type section of the Warsaw in Illinois. The source of terrigenous clastics in Kansas was probably the Transcontinental arch. Abundance of matrix-supported rocks and matrix-rich packstones in the cherty-dolomite lithofacies suggests a low-energy environment of deposition. Skeletal grains in this lithofacies are sparse and low in diversity, suggesting severe environmental conditions (Boucot and Carney, 1981), such as hypersalinity or periodic exposuure. Nodular anhydrite (Ebanks et al., 1977, p. 319), may indicate either a supratidal environment (Kerr and Thomson, 1963) or an evaporitic lagoonal environment (Sarg, 1981; Dean et al., 1975). Beds containing echinoderms, which are stenohaline beasts (Breimer and Lane, 1987), indicate that normal marine conditions alternated with hypersaline conditions; the generally low energy appears to rule out transportation into an area of hypersalinity. Sponge spicules are found in the same intervals as anhydrite nodules; they, too, are unlikely to have been transported.

The echinoderm-packstone lithofacies and the echinoderm-grainstone lithofacies contain diverse minor constituents, suggestive of a normal-marine environment. Greater abundance of grain-supported rocks and of primary porosity in packstones of the echinoderm-grainstone lithofacies indicates that it may have been deposited in an environment of higher energy than the echinoderm-packstone lithofacies. These lithofacies were probably deposited in a subtidal, open-shelf environment.

The bryozoan-dolomite lithofacies is the most complex lithofacies; it contains matrix-supported and grain-supported rocks interbedded with green calcareous shale and argillaceous dolostone. The presence of vertically elongate anhydrite nodules (Ebanks, et al., 1977, p. 320) may indicate supratidal conditions. Modern analogs could be vertically oriented gypsum crystals exposed in sabkhas of Qatar (Illing et al, 1965) and Abu Dhabi (Butler, 1969). Anhydrite nodules and the lack of skeletal grains in the calcareous shale also suggest restricted conditions. Turbid water alone should not have been enough to exclude crinoids, because inadunate crinoids could have survived in a clay-rich environment (Breimer and Lane, 1978). Diverse fauna in the grain-supported rocks suggests that normal-marine conditions prevailed periodically during deposition of this lithofacies.

DIAGENETIC HISTORY

Calcite Cementation

Distribution of cement is influenced by fabric, geographic location, and, to a lesser degree, lithofacies. Cement is best developed, in terms of number of zones and volume, in grain-supported rocks and least developed in matrix-supported rocks, probably due to lower early porosity and permeability in matrix-supported rocks.

Packstones in the cherty-dolomite lithofacies rarely have calcite cement, perhaps because of greater volume of matrix compared to packstones in other lithofacies. Grain-supported rocks of the bryozoan-dolomite lithofacies have less cement than those of the echinoderm-packstone and echinoderm-grainstone lithofacies. This may be due to the lower permeability of surrounding argillaceous, matrix-supported rocks in the bryozoan-dolomite lithofacies, especially before dolomitization enhanced permeability.

Grain-supported rocks in the echinoderm-grainstone lithofacies contain a greater number of cement zones in the southern part of the study area, which may account for the greater porosity in packstones in the north.

Conditions of cement precipitation are conjectural from petrology alone without isotopic or other data, but options are narrowed by staining and cathodoluminescence. The first generation of cement does not contain iron, suggesting oxidizing or slightly reducing conditions, perhaps in the vadose or shallow phreatic zones (Evamy, 1969). A high Mn/Fe ratio or significant Mn in the absence of iron is indicated by bright luminescence (Frank, et al., 1982). Brightly luminescent calcite may have precipitated under a broad range of oxidizing conditions or under conditions which reduce manganese but not iron (Frank, et al., 1982). Luminescent calcite may also precipitate under highly reducing conditions in which iron is precipitated as FeS_2. No pyrite was found in association with any cement zones. Dissolution of aragonitic molluscan fragments followed precipitation of the first generation of calcite cement. Dissolution suggests meteoric water (Land et al., 1967). The second generation of cement is dully luminescent, indicating a low Mn/Fe ratio, and is slightly ferroan. This generation precipitated under reducing conditions, which may be caused by burial, but also may form within a shallow phreatic lens. The third generation of cement is non-ferroan, as indicated by staining, and has significant Mn as indicated by bright luminescence, suggesting slightly reducing conditions in a shallow phreatic environment. The fourth and fifth generations have low Mn/Fe ratios and are progressively more ferroan. This trend reflects increasingly reducing conditions, possibly caused by increasing burial depth.

Only ferrous iron (Fe^{+2}) can enter the calcite lattice. In normal marine water and meteoric water, both of which are usually oxidizing (Baas-Becking et al., 1960), the stable species of iron is ferric iron (Fe^{+3}), or, more precisely, metastable ferric hydroxide, which is very insoluble, and therefore in very low concentration (Garrels and Christ, 1965).

Negative Eh (reducing conditions) is necessary for the precipitation ferroan carbonate (Garrels and Christ, 1965). Reducing conditions can form in environments with abundant decaying organic matter or in environments isolated from the atmosphere, such as deep burial or with negligible groundwater flow at intermediate depths.

Alternating zones of non-ferroan and slightly ferroan calcite suggest that the first three or four generations of cement were precipitated before significant burial, allowing variations in regional groundwater flow to alter Eh. Meyers and Lohmann (1985) evoke changing patterns of groundwater flow, caused by changes in sea level, to explain variations in abundance of iron and other trace elements as well as isotopic composition.

The last phase of calcite cement, highly ferroan calcite, was probably precipitated during deep burial, although reducing conditions can exist in a shallow phreatic zone. Oldershaw and Scoffin (1967), Walls et al. (1974), Wong and Oldershaw (1981), Walls and Burrowes (1985), and Meyers and Lohmann (1985) all describe ferroan cement precipitated under deep burial conditions as indicated by depletion of ^{18}O, that is, higher temperatures of crystal growth.

Dolomitization

Dolomitization in the Warsaw has largely spared allochems, suggesting that dolomite has selectively replaced lime-mud matrix, as described by Lucia (1962). Preferential dolomitization of finer grained sediments may be due to the greater abundance of nucleation sites or the mineralogical susceptibility of lime mud, which is typically composed of metastable aragonite and Mg-calcite (Murray and Lucia, 1967).

Dolomite crystals impinge on both cement and skeletal grains. Moldic pores in highly dolomitized rocks, which probably formed during or after dolomitization, contain no calcite cement, even though these rocks are highly permeable. Nevertheless these observations only suggest that cementation preceded dolomitization.

Cloudy centers, common in the dolomite of the Warsaw, are common in sucrosic dolomites (Sibley and Gregg, 1987). Sibley (1980) ascribed cloudy centers to nucleation from fluids near calcite saturation (probably marine water) and clear rims precipitated from fluids undersaturated with respect to calcite. Abundant inclusions might also be indicative of replacement dolomite. The clear rims were probably precipitated from dilute, shallow-subsurface water, which causes slow precipitation and thus favors formation of clear crystals (Folk and Land, 1975; Morrow, 1982).

Anhydrite nodules and the lower diversity of faunal types in parts of the cherty-dolomite and bryozoan-dolomite lithofacies, suggest that the these lithofacies were deposited either in an evaporative lagoon (Sarg, 1981) or a supratidal environment (Illing, et al., 1965). A supratidal environment would be conducive to sabkha dolomitization, as described by Illing et al (1965). No strong evidence for a supratidal environment, however, such as crinkled laminae or rip-up clasts, was noted.

Although dolomitization is common beneath regional unconformities (Sonnenfeld, 1964), the Warsaw shows no variation in dolomitization with proximity to the pre-

Pennsylvanian unconformity.

Chertification

The most significant aspect of chert in the Warsaw is the association of chert with abundant siliceous-sponge spicules, suggesting a source of amorphous silica. Bio-genic silica (opal-A) is amorphous (Siever, 1962) with a higher solubility than cristobalitic opal (opal-CT). It therefore dissolves to form solutions super-saturated with respect to opal-CT (Kastner, et al., 1977). Interstitial water in marine sediments is commonly supersaturated with opal-CT, but undersaturated with respect to amorphous silica (Hurd, 1973). Most non-thermal, deep subsurface waters are supersaturated with respect to quartz and undersaturated with respect to amorphous silica (White, 1965).

Quartz rarely precipitates from solutions supersaturated with respect to both quartz and opal-CT (Williams and Crerar, 1985). Nucleation rates for cristobalite may be much higher than nucleation rates for quartz, in light of the reluctance of quartz to precipitate at low temperature (Williams and Crerar, 1985). Therefore, chert in the Warsaw probably precipitated as opal-CT and recrystallized to form chalcedonic quartz, microquartz, and quartz.

Length-slow chalcedony, the most abundant variety of silica in the Warsaw, replaced carbonate shells, calcite cement, and evaporite crystals or nodules. Length-slow chalcedony may have recrystallized rapidly in the presence of sulfate-rich brines with moderate concentrations of silica (Folk and Pittman, 1971). Microquartz, defined as quartz with crystal size less than 10 micrometers, probably recrystallized slowly in a solution with low silica concentration. Crystal size of microquartz increases with time (Williams and Crerar, 1985).

Chert replaces non-ferroan and slightly ferroan calcite cements, but envelopes highly ferroan calcite cement. Molds of sponge spicules are filled with highly ferroan calcite. Dissolution of spicules, the ostensible source of silica, may have preceded precipitation of highly ferroan calcite, but pore water has negligible storage capacity for silica. More likely, ferroan calcite replaced sponge spicules. Dolomite crystals enveloped and, in some cases,replaced by chert, indicate that chertification followed dolomitization.

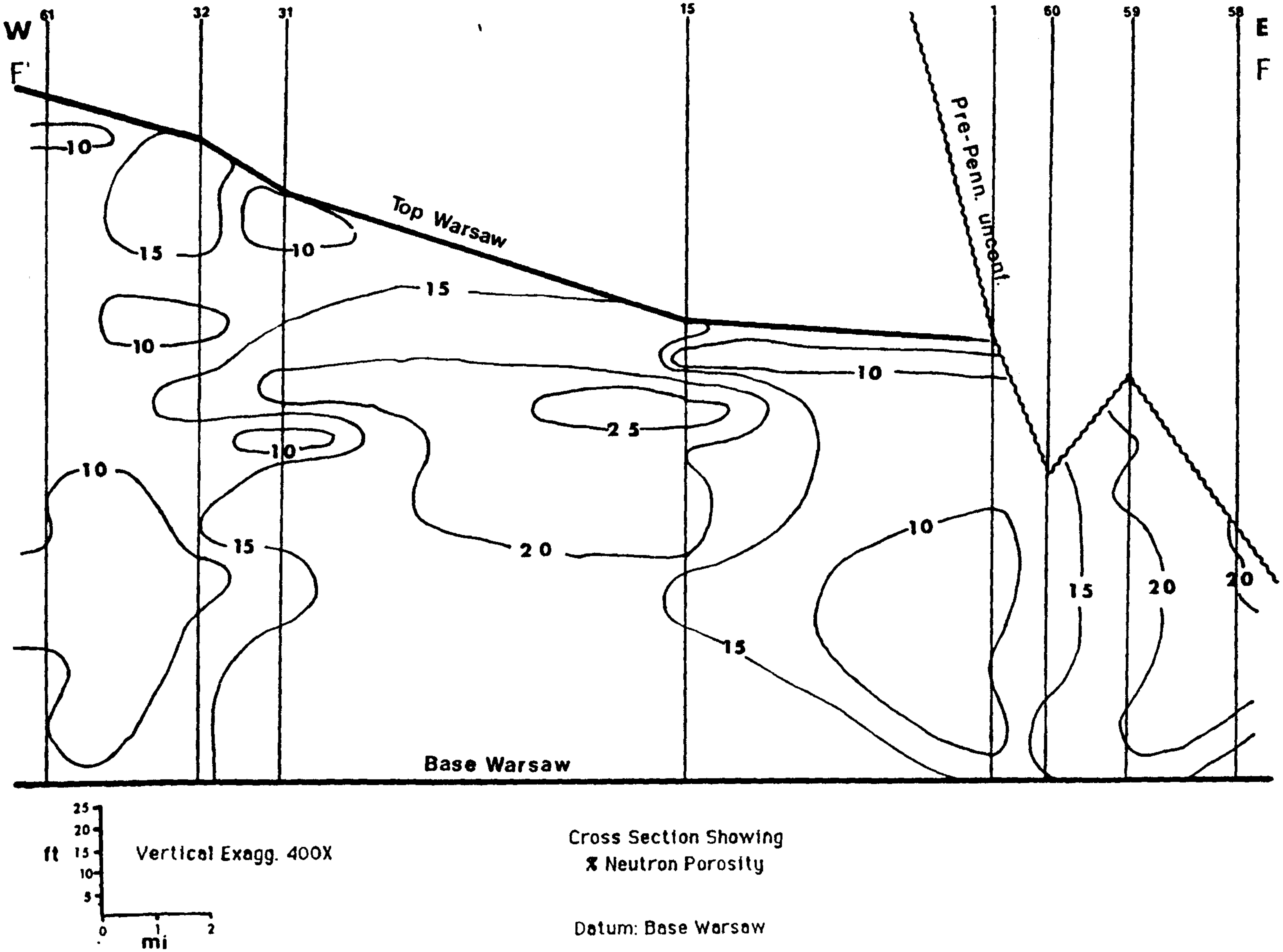
PETROLEUM GEOLOGY

Most oil and gas fields in the study area coincide with structural highs on the top of the Mississippian. Closure on these uplifts are reflected in units at least as young as the Pennsylvainian Lansing Group, allowing identification of Mississippian traps by mapping of shallower units.

Coincidence of Warsaw hydrocarbon production with the Warsaw subcrop (Fig. 3) suggests either: 1) seals are lacking in Mississippian rocks overlying the Warsaw, 2) the pre-Pennsylvanian unconformity may have been the migration route for hydrocarbons, or 3) porosity and permeability were developed where the Warsaw is truncated by the unconformity. A dip cross section (Fig. 21) shows, however, that neutron-porosity values vary from less than 10% to greater than 25%, but show no correlation with proximity to the unconformity. This appears to rule out porosity enhancement by dissolution benath the unconformity during the Late Mississippian-Early Pennsylvanian hiatus.

Type and quality of reservoir rock in the subcrop varies regionally. In the inner-shelf rocks of the Warsaw in Hodgeman and Ness counties, dolomitized, matrix-supported rocks are productive, whereas porosity in grain-supported is almost completely occluded by

Fig. 21.- Dip cross section of Warsaw porosity. Note lack of influence of unconformity on porosity. Warsaw rocks in wells on left are overlain by younger Mississippian rocks, whereas Warsaw is truncated by the pre-Pennsylvanian unconformity on right. Datum: base of Warsaw.



Cross Section Showing
% Neutron Porosity

Datum: Base Warsaw

cement (Ebanks, et al., 1977). In main-shelf rocks of the study area both dolomitized, matrix-supported rocks and grain-supported rocks are productive. The southeastern limit of the productive trend roughly coincides with the transition into shelf-margin rocks, represented by the argillaceous Cowley facies.

Oil and gas production is greater in the upper Warsaw than the lower Warsaw. The basal cherty-dolomite lithofacies has sporadic slight oil stains and the echinoderm-packstone lithofacies has minor oil stains, the upper two lithofacies in most cases have slight to heavy oil stain, probably reflecting the greater permeability in the upper two lithofacies. The Graham-Michaelis Uhl #3-9 well in the southern part of the Alford field in northern Comanche County produces oil from the upper part of the bryozoan-dolomite lithofacies and the lower part of the echinoderm-grainstone lithofacies. In the nearby Anadarko Boisseau B #1 well, oil production is from the lower part of the bryozoan-dolomite lithofacies and gas is produced from the upper part of that lithofacies and from the echinoderm-grainstone lithofacies.

In the Fralick West field in northwestern Kiowa County, oil production is mainly from the lower part of the echinoderm- grainstone lithofacies, although heavy oil stain is present throughout this lithofacies and the top of the bryozoan-dolomite lithofacies in the Mull Brensing G #1 well. The same lithofacies in the Mull Brensing A #1 well, which is two miles away, are approximately 40 feet lower in elevation, but do not produce oil or gas, again indicating that accumulation of hydrocarbons is more dependent on structure than lithofacies.

Average oil saturation was calculated for the Cities Service Pyle A #1 well using the following equation (Doveton, 1982, p.29):

$$S_o = 1 - (R_w/phi^2 R_t)^{1/2}$$

where S_o is the fraction of porosity saturated with oil, phi is the porosity derived from a sonic log, and R_t is the resistivity in ohms/meter derived from a deep induction log. R_w, resistivity of formation brine, is assumed to be 0.4 ohms/meter, a value typically used by logging engineers for the Warsaw in the study area, as indicated on geophysical well logs. Porosity values are necessary for calculation of oil saturation. The average porosities of the cherty-dolomite and echinoderm-packstone lithofacies derived from plugs taken every foot from cores are 10.0% and 10.4%, respectively, and those derived from the sonic log are 11% and 10%, respectively.

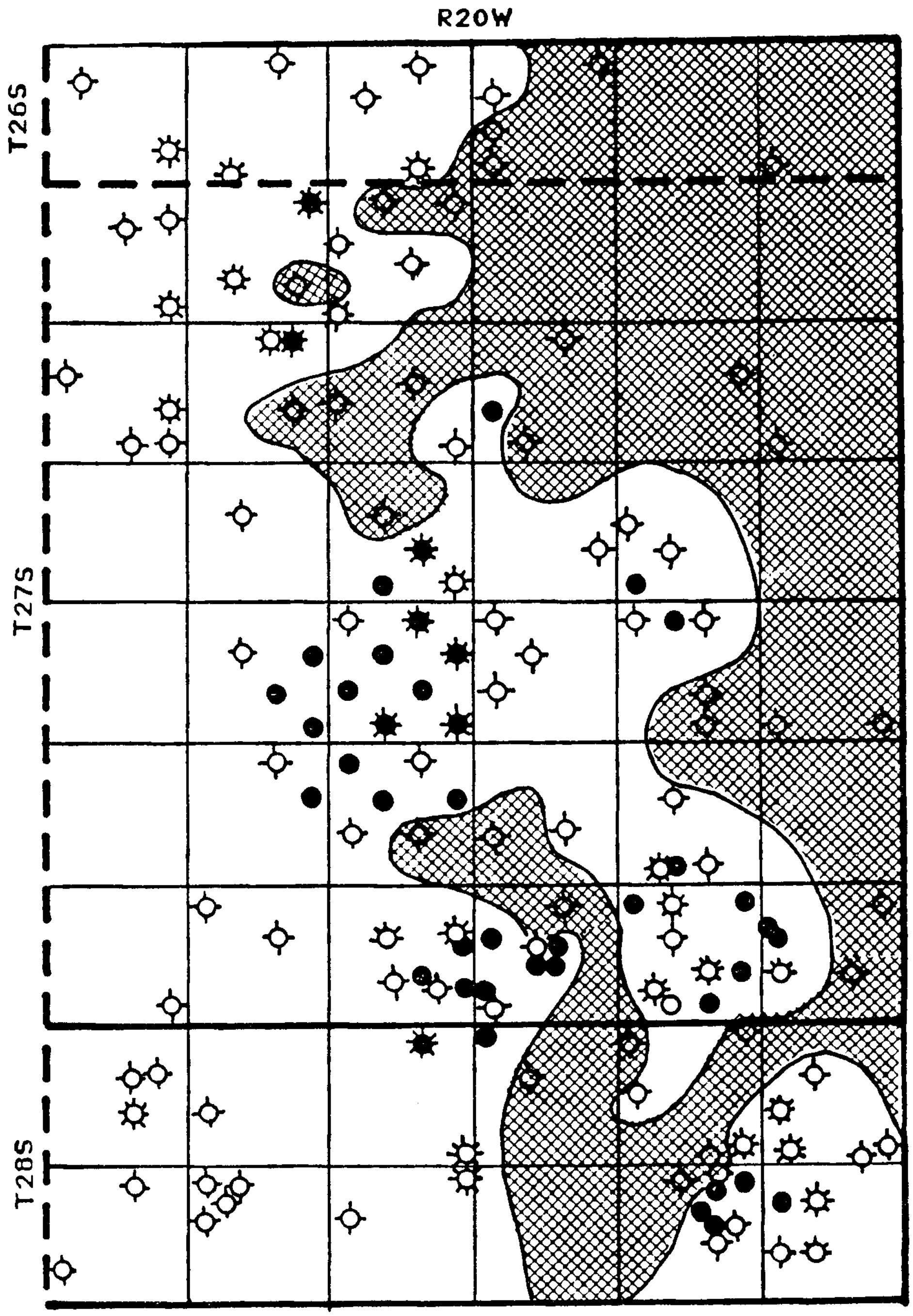
Therefore, log values for porosity in the bryozoan-dolomite lithofacies (21%) and the echinoderm-grainstone lithofacies (18%) can be assumed to be adequate for calculation of oil saturation, although these lithofacies were not cored in this well.

Average oil saturation of the cherty-dolomite lithofacies was 24% and that the echinoderm-packstone lithofacies was 48%. The bryozoan-dolomite lithofacies had highly variable oil saturation. The lower, argillaceous part had 37% saturation and the upper part had 55% saturation. The echinoderm-grainstone lithofacies had the highest hydrocarbon saturation at 81%.

Although permeability data for the complete Warsaw is not available from a single well, generalizations can be made by making a composite section from several wells. In the Pyle #1 A well the logarithmic average of permeability of the cherty-dolomite lithofacies is 0.27 md , and that of the echinoderm-packstone lithofacies is 1.1 md. The average permeability of the bryozoan-dolomite lithofacies in the #1 Burkhall A core is 1.2 md, and is 5.4 md in the Brensing G #1 well. The average permeability of the echinoderm-grainstone lithofacies in the Brensing G #1 well is 18 md.

A map of the results of drill-stem tests of the Warsaw in northwestern Kiowa County shows fluid (oil,

Fig. 22.- Results of drill-stem tests on the Warsaw formation in northwestern Kiowa County. Recovery of only drilling mud indicates low permeability in the interval tested. Recovery of formation fluids indicate not only porosity but also measurable permeability. The upper Warsaw is eroded from the eastern part of this area, indicating that the lower Warsaw is less permeable than the upper Warsaw.



Results of Drill Stem Tests
of Warsaw Formation

gas, or brine) production in the western part of township 27S R20W, but only drilling mud production, meaning very little formation fluid, in the eastern part (Fig. 22). Production of mud in a drill-stem test is an indication of low permeability in the interval being tested. The upper Warsaw is eroded from the eastern part of township 27S R20W but is present in the western part, confirming that the lower Warsaw is less permeable than the upper Warsaw (Table 7).

SUMMARY AND CONCLUSIONS

1. The Warsaw Formation can be divided into four lithofacies. The lowermost and thickest unit, the cherty-dolomite lithofacies, comprises cherty, dolomitic, spiculitic, echinoderm mudstones, wackestones, and packstones with minor silicified anhydrite nodules. The overlying echinoderm-packstone lithofacies contains dolomitic packstones and minor grainstones that contain bryozoans and echinoderms. The bryozoan-dolomite lithofacies, the most complex lithofacies, encompasses dolomitic bryozoan-echinoderm packstones and wackestones; dolomitic, spiculitic wackestones; and green, calcareous shale that contains anhydrite nodules. The echinoderm-grainstone lithofacies is similar to the echinoderm-packstone lithofacies; it includes dolomitic packstones and grainstones that contain echinoderms and bryozoans.

2. Cementation followed a general trend towards more ferroan calcite in the later generations, probably due to an increase in burial depth. Calcite cementation is more complete in the southern part than in the northern part of the study area, perhaps accounting for the greater porosity in packstones in north.

3. Spatial association of sponge-spicules molds with chert suggests that spicules were the source of silica. Highly ferroan calcite cement fills molds of sponge

spicules, but chert also envelopes ferroan calcite. Therefore, chertification may have been simultaneous with the formation of highly ferroan calcite, or ferroan calcite precipitated both before and after chertification.

4. Warping took place after Mississippian deposition and before deposition of the Early Pennsylvanian Cherokee Group. Structures were rejuvenated at some time after deposition of the Middle Pennsylvanian Lansing Group. Mississippian structural traps can thus be mapped using shallower Pennsylvanian horizons.

5. Correlations of geophysical and lithologic logs show that the lower Warsaw and the Keokuk-Burlington Formation become increasingly argillaceous and cherty to the southeast, perhaps representing a transition into the Cowley facies, which marks the southeastern limit of Warsaw production.

6. The upper Warsaw is more porous and permeable than the lower Warsaw, due both to the greater preservation of primary porosity and the development of bryomoldic porosity, especially in the upper part. Depositional texture, and to a lesser degree lithofacies, control permeability and porosity. Permeability and porosity is greater in mud-supported than in grain supported rocks. Porosity and permeability of packstones is greater in the

echinoderm-grainstone lithofacies than in other lithofacies. Porosity values from sonic logs are equivalent to values from core analyses and can be used in place of core analyses.

7. Oil and gas accumulation is controlled primarily by structure with only slight influence by lithofacies. This differs from the lithostratigraphic trap of Bindley field in Hodgeman County described by Ebanks, et al. (1977). Nearly all reservoirs in the Warsaw lie directly beneath the pre-Pennsylvanian unconformity, but porosity is not greater where the Warsaw is truncated by the unconformity. Shales of the Desmoinesian Cherokee Group form better seals than Mississippian rocks which overlie the Warsaw downdip.

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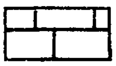
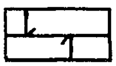
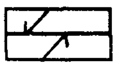
Appendix A: Core Descriptions

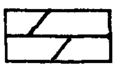
Explanation

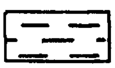
LITHOLOGY

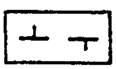
 Limestone

 Dolomitic Limestone

 Limy dolomite

 Dolomite

 Shale

 Calcareous Shale

 Stylolite

 Chert

 Missing interval

MISCELLANEOUS

ANH Anhydrite
(in diagenesis column)

TS Thin Section
(in depth column)

FOSSILS

Echinoderm
Ramose bryozoan
Fenestrate bryozoan
Brachiopod
Sponge spicule
Trilobite
Gastropod
Foraminifer

ab Abundant
c Common
m Minor
f Few
r Rare

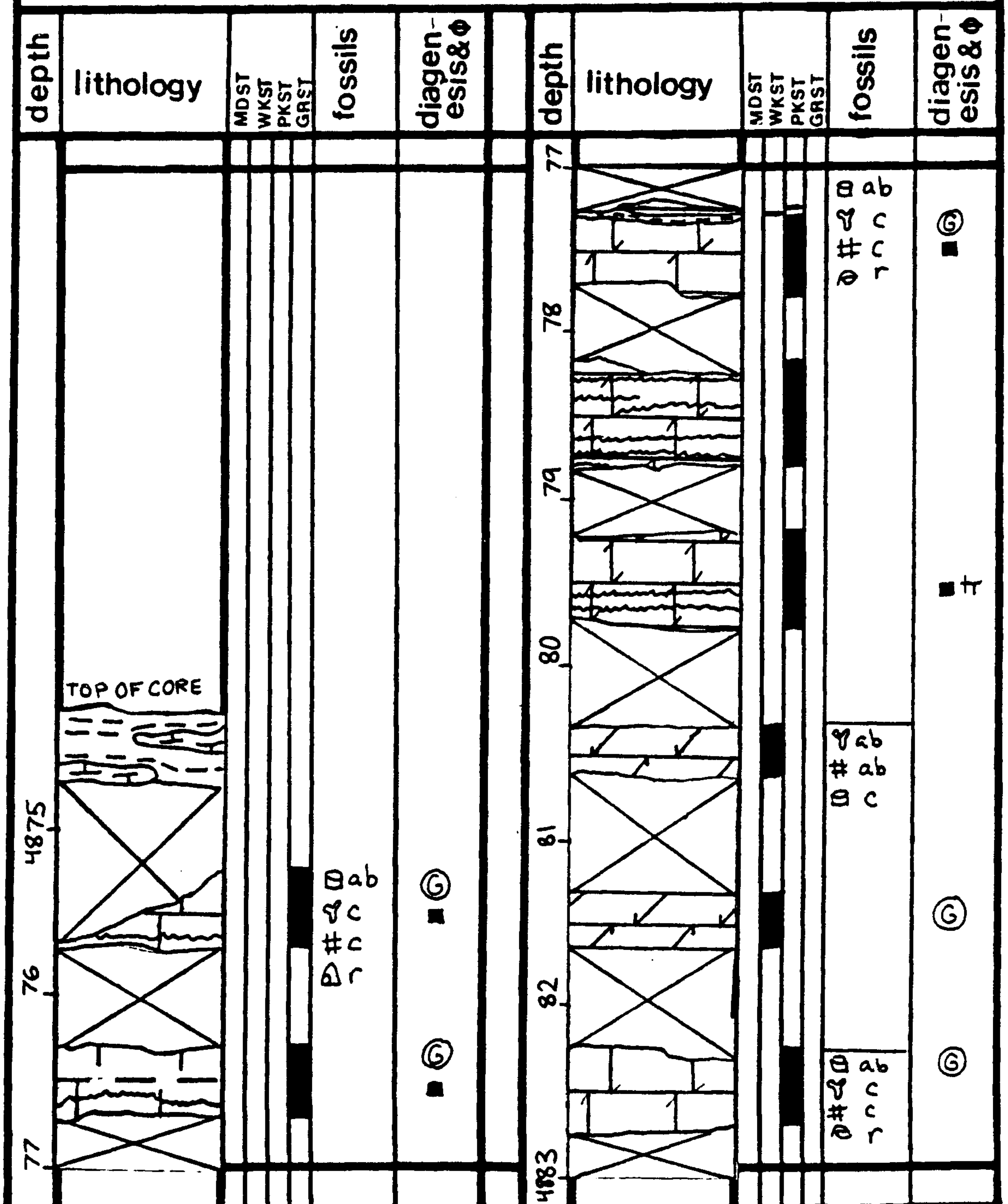
POROSITY

BC Intercrystalline
BP Interparticle
FR Fracture
MO Moldic
VUG Vuggy
WP Intraparticle

DIAGENESIS

Glauconite
Pyrite

Mull Drilling #1 Brensing G   KB 2313
C-NW-SE 20-T27S-R20W   Interval: 4874-4907



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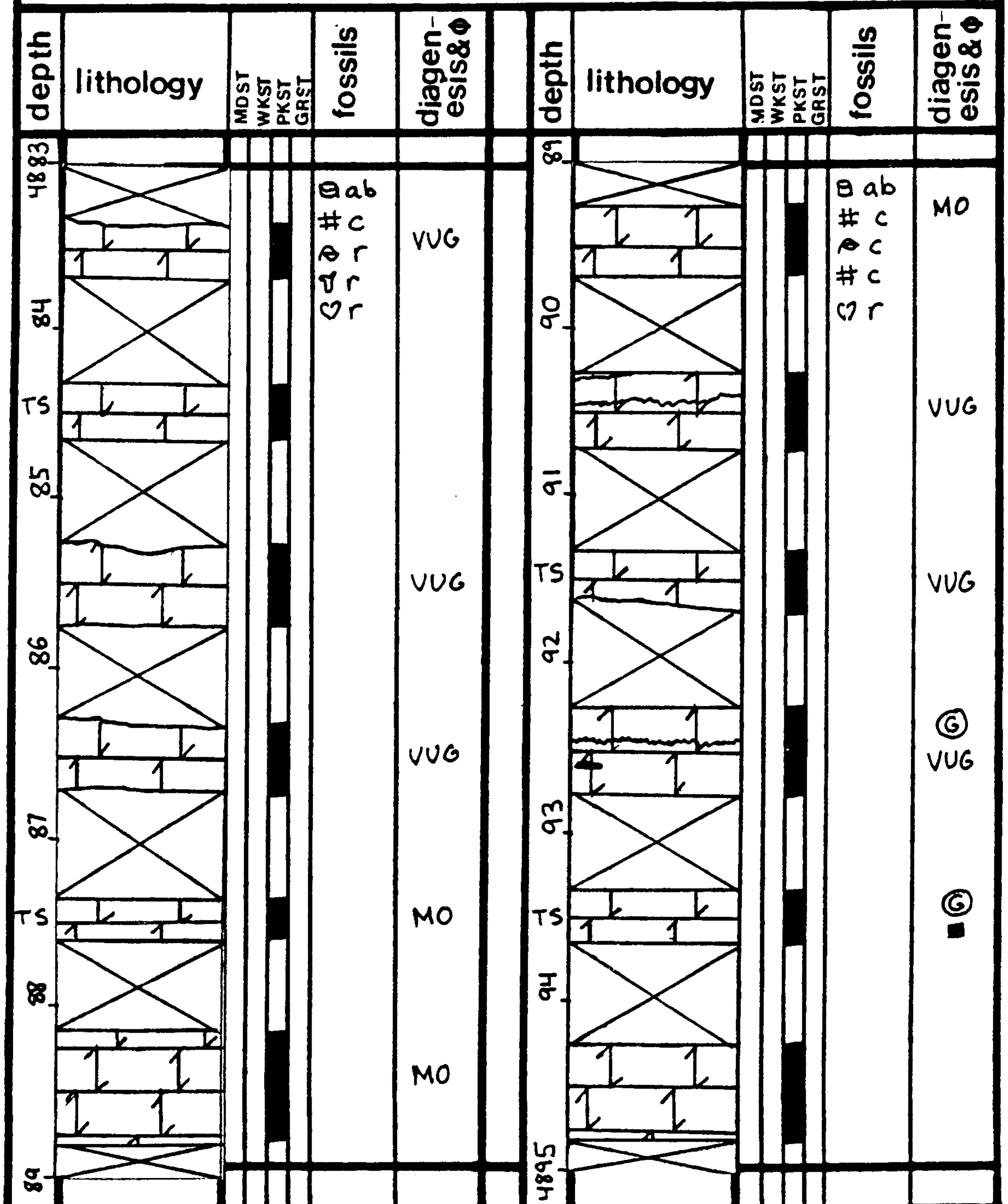

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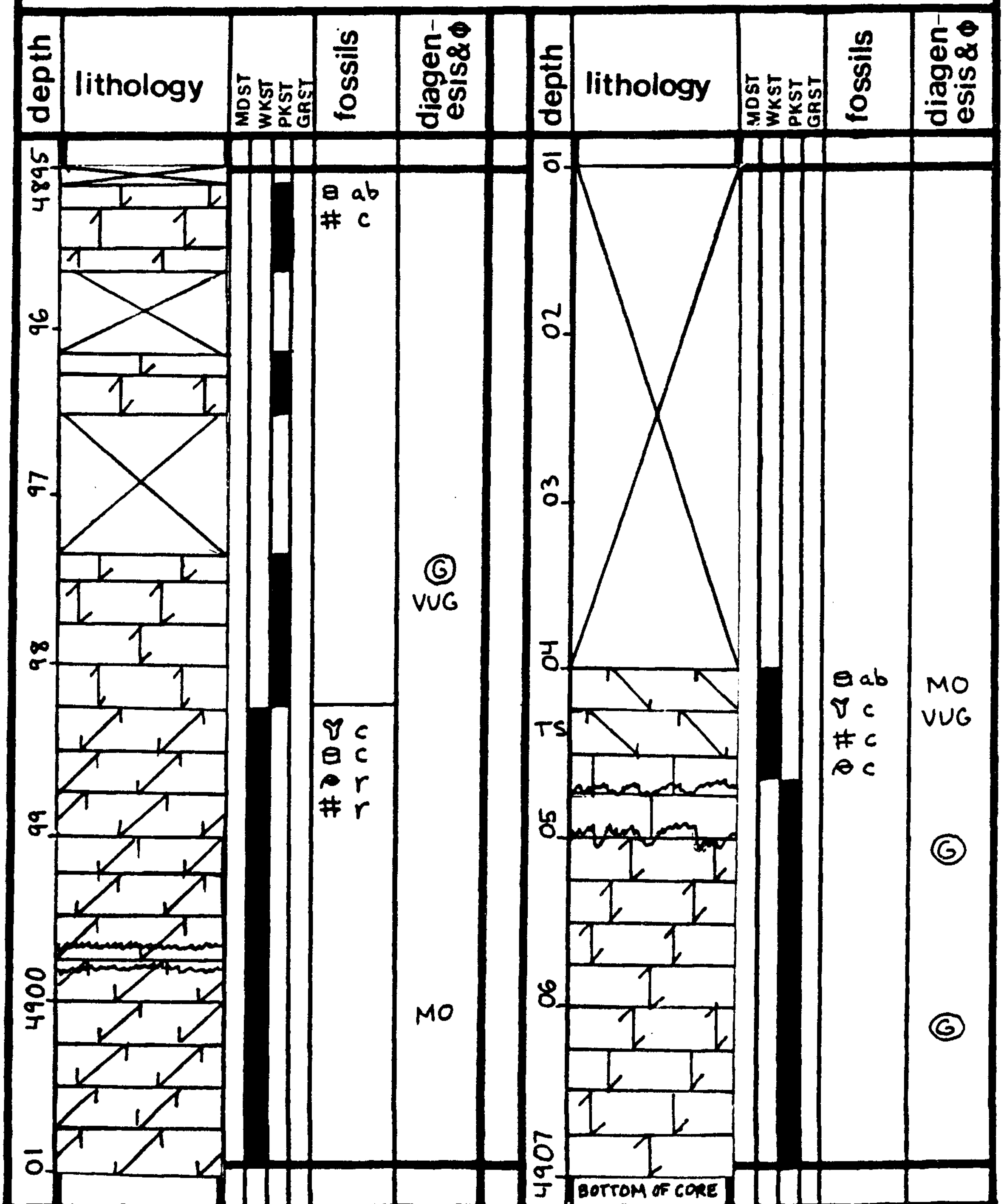
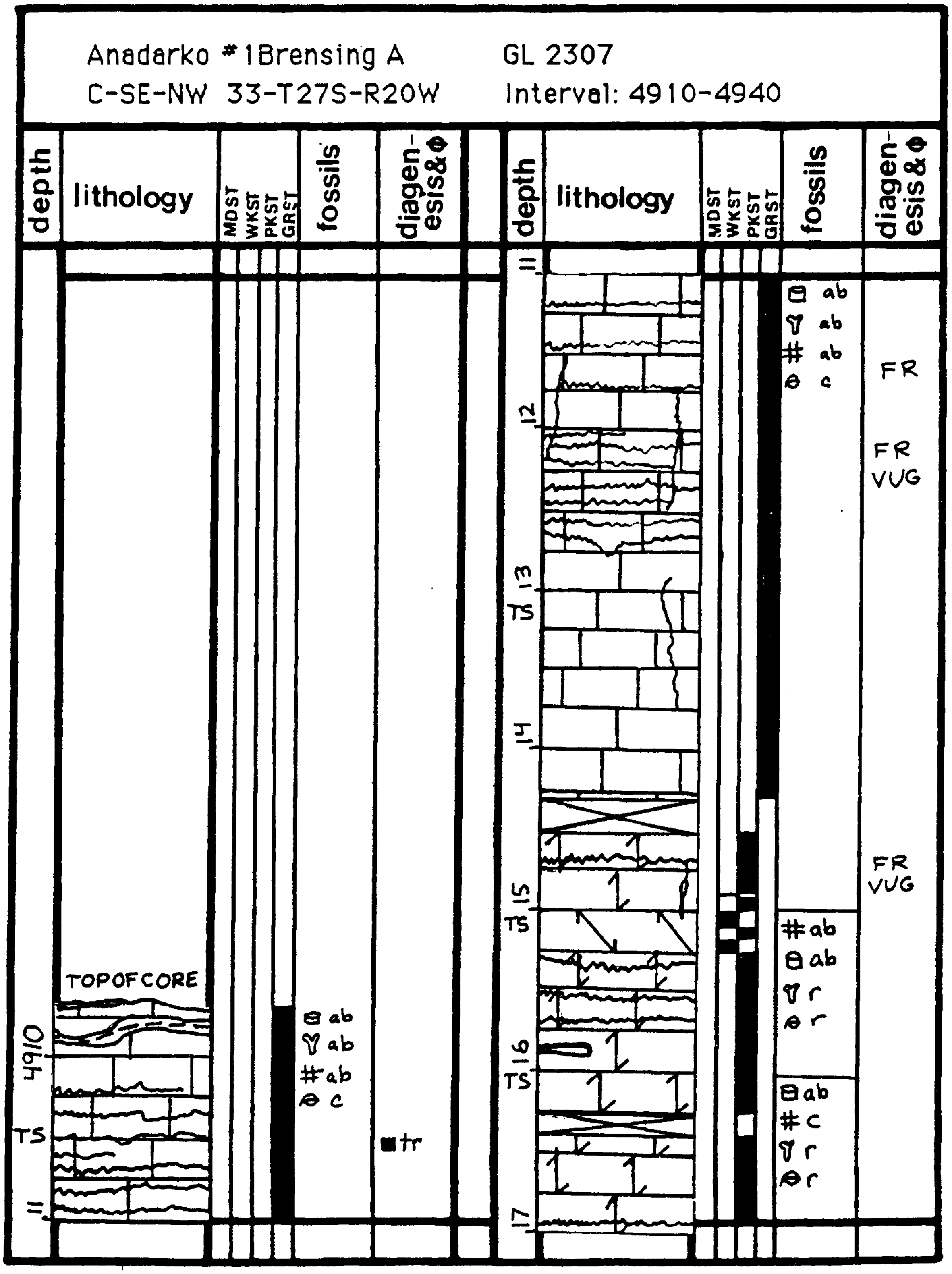
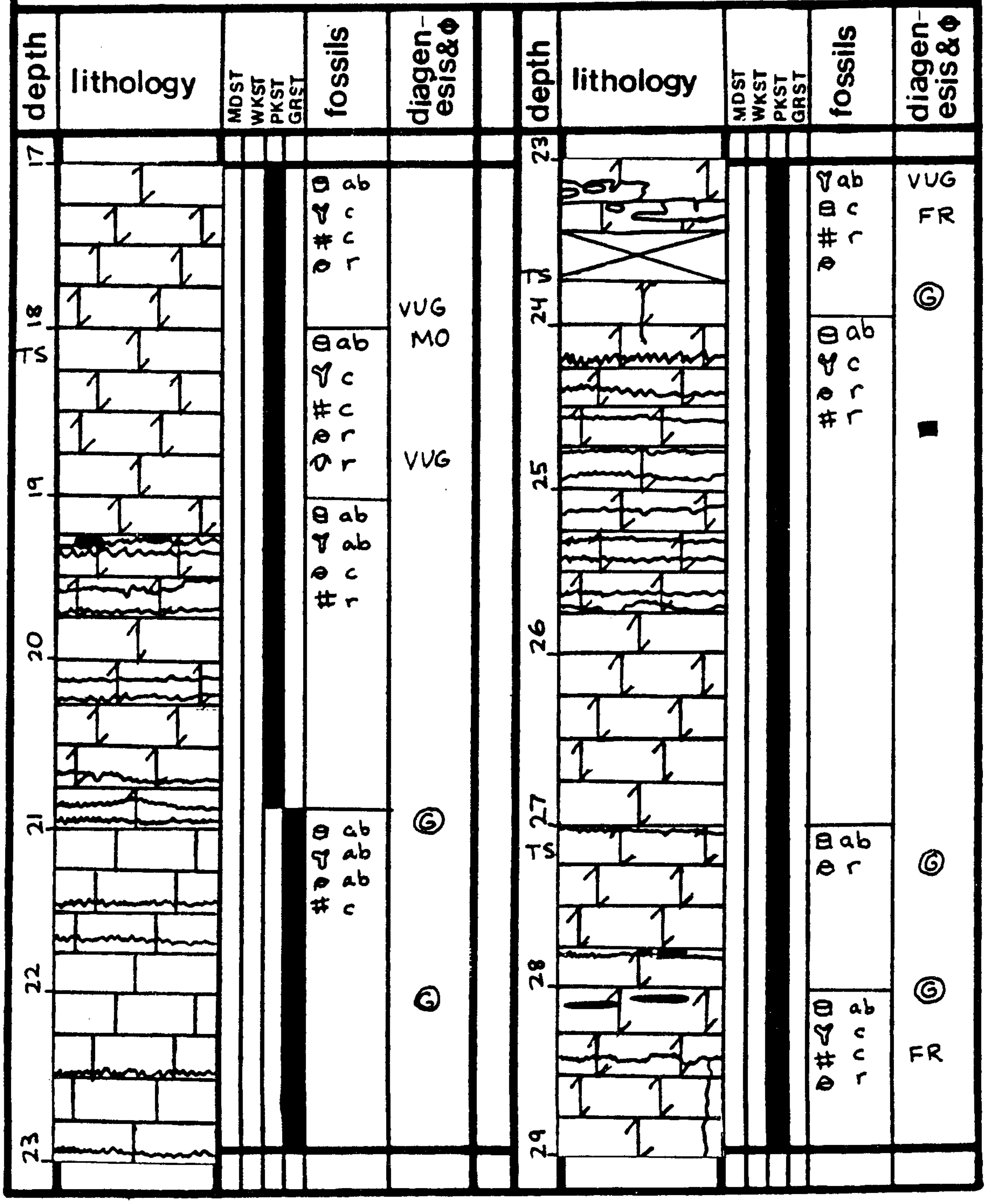



Anadarko #1Brensing A
GL 2307
C-SE-NW 33-T27S-R20W
Interval: 4910-4940
depth
lithology
MDST WKST PKST GRST
fossils
diagen-esis&Φ
TOPOFCORE
4910
TS
11
ab
ab
#ab
c
tr
12
13
TS
14
15
TS
16
TS
17
ab
ab
ab
c
FR
FR
VUG
FR
VUG
#ab
ab
r
r
ab
#c
r
r

Anadarko #1Brensing A GL 2307

C-SE-NW 33-T27S-R20W Interval: 4910-4940



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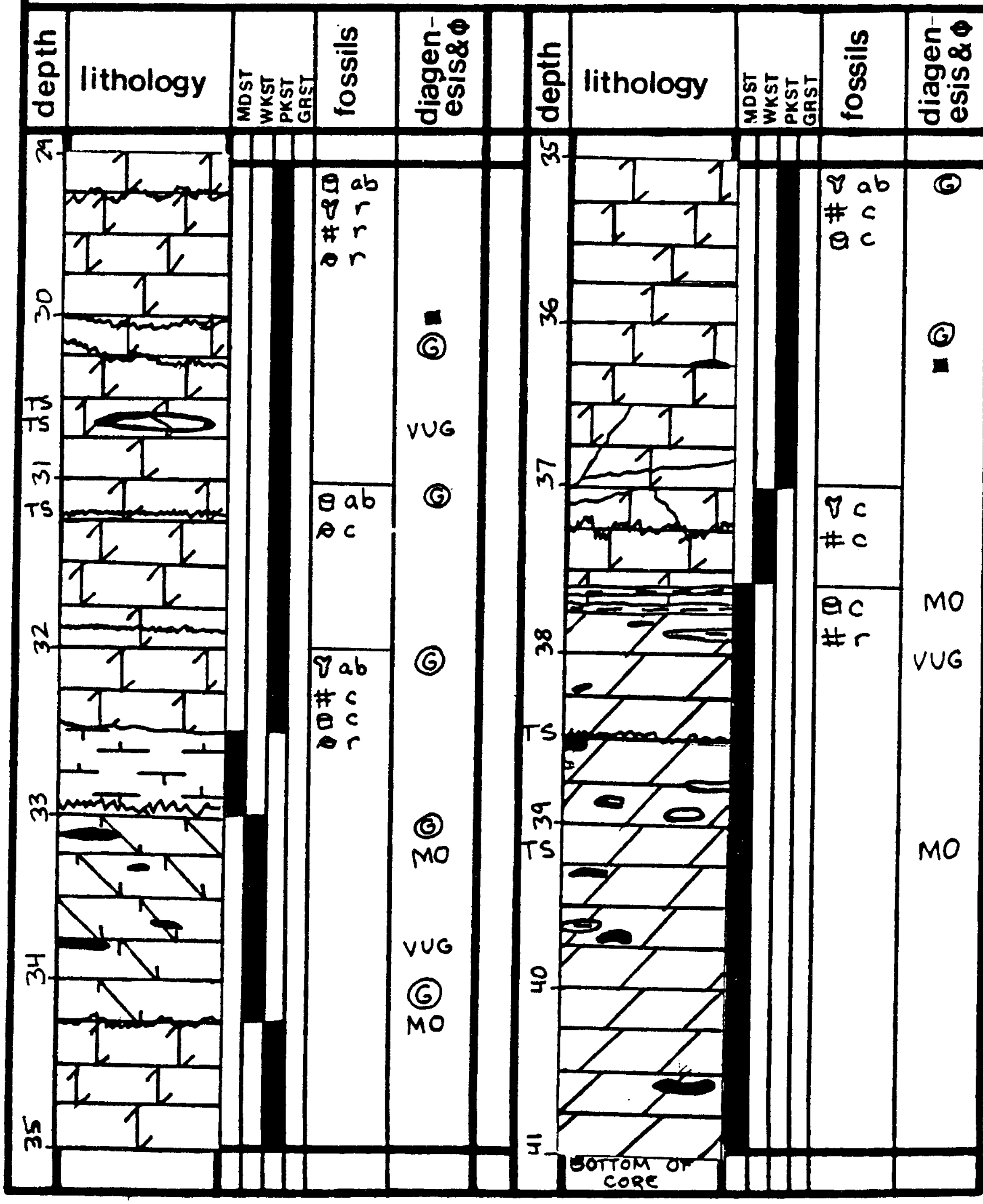

Anadarko #1 Burkhall A GL2115

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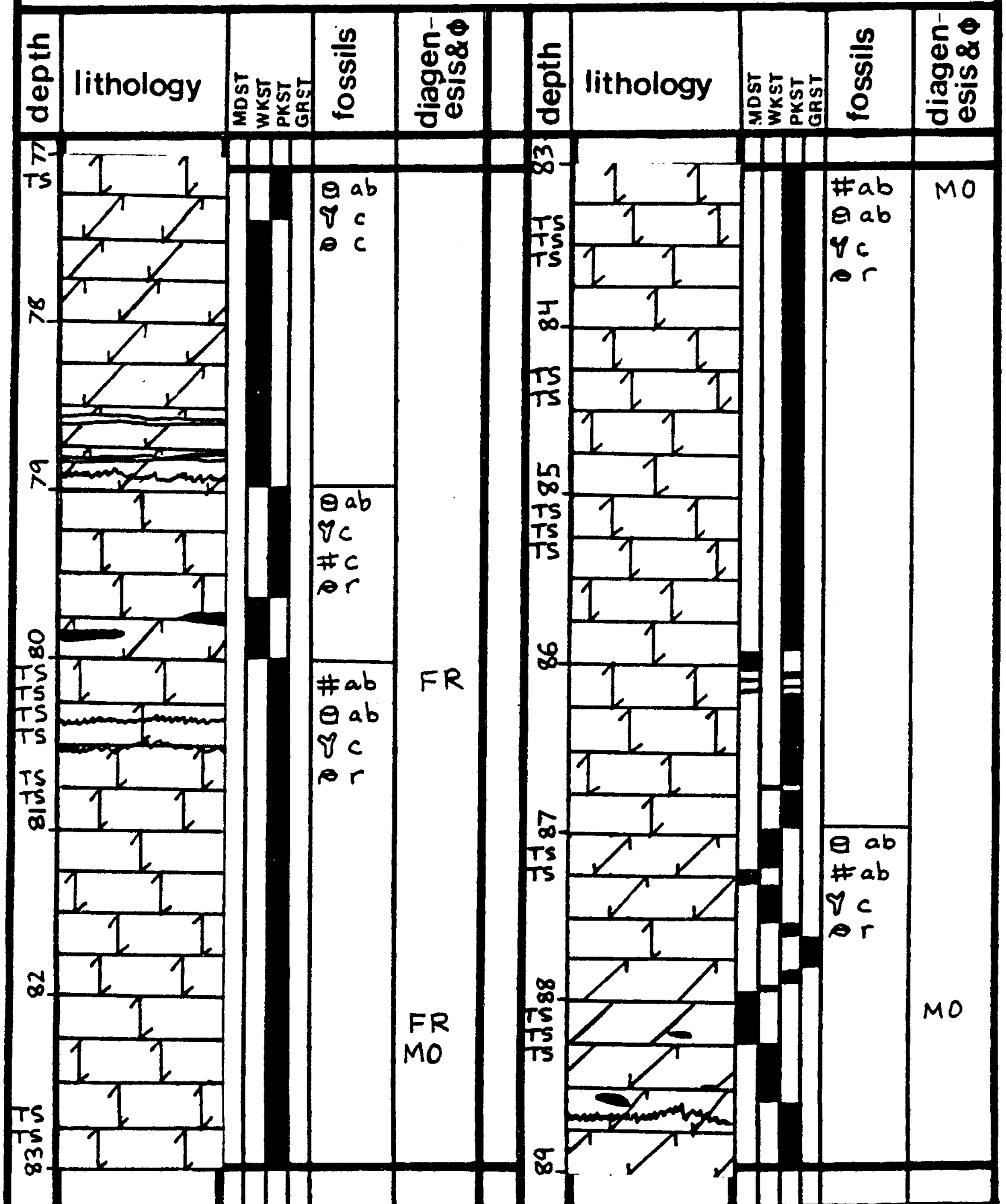

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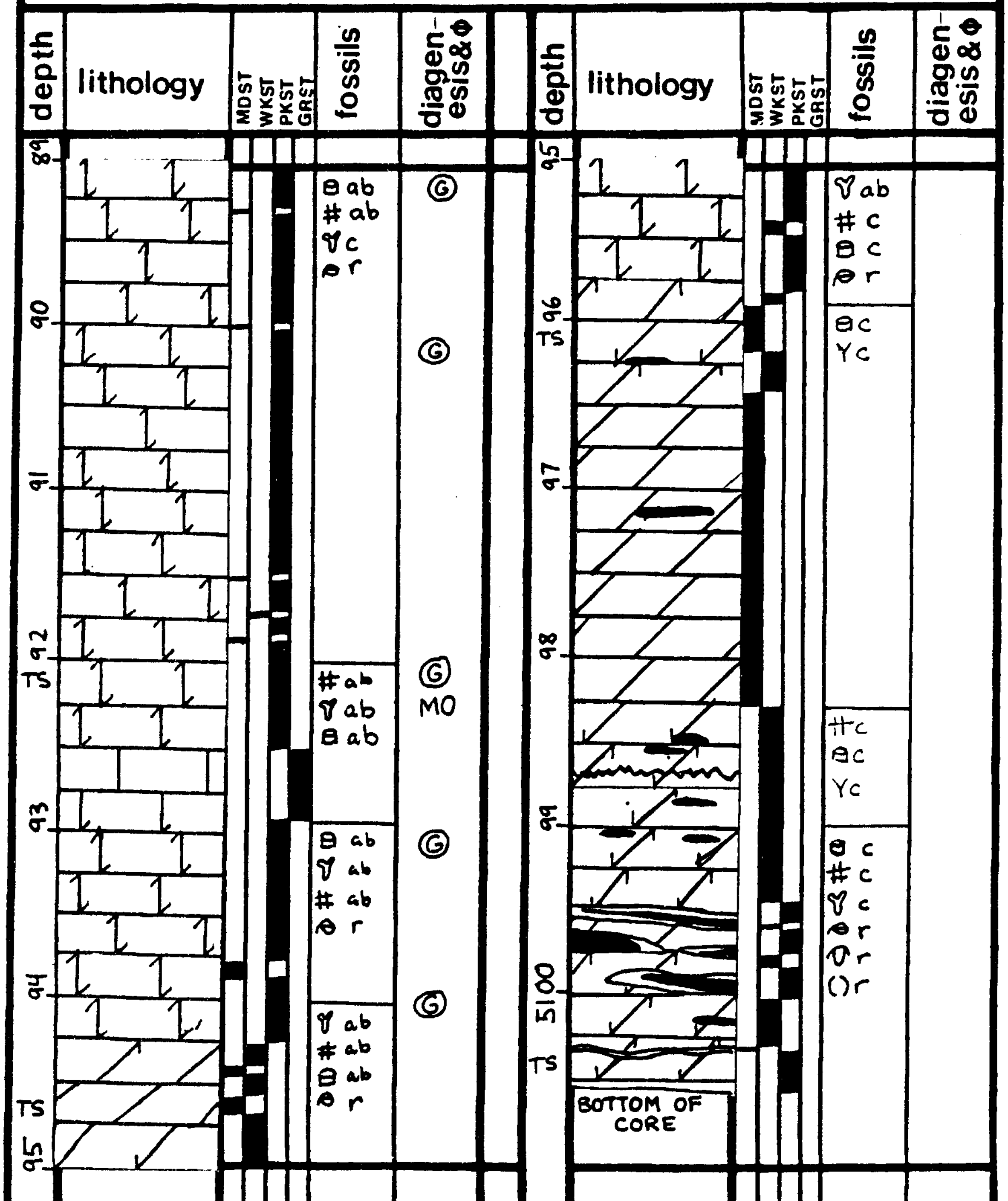
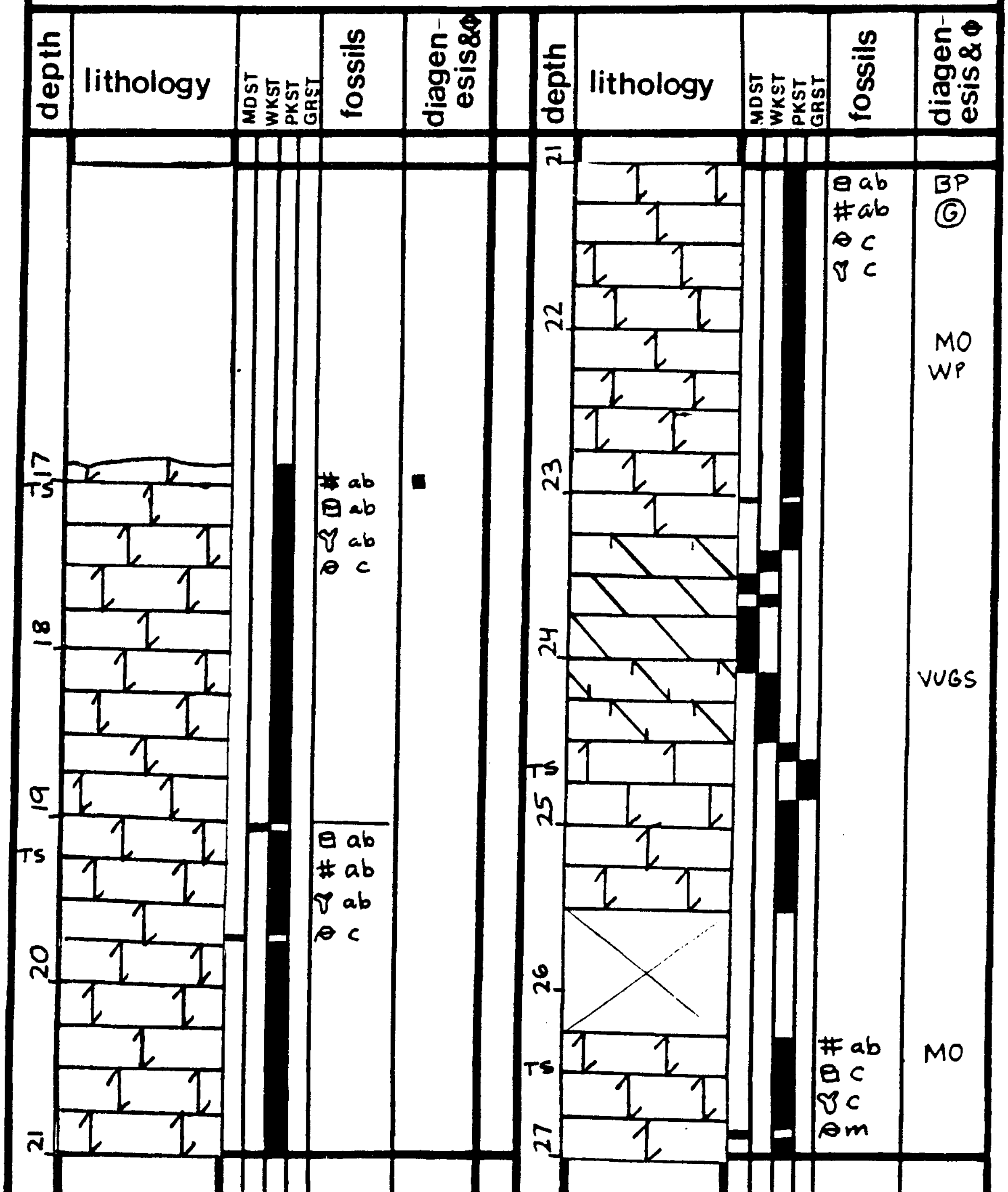


Graham-Michaelis #3-9 Uhl   KB 2128

C-NW-NE 9-T31S-R18W   Interval: 5017-5068



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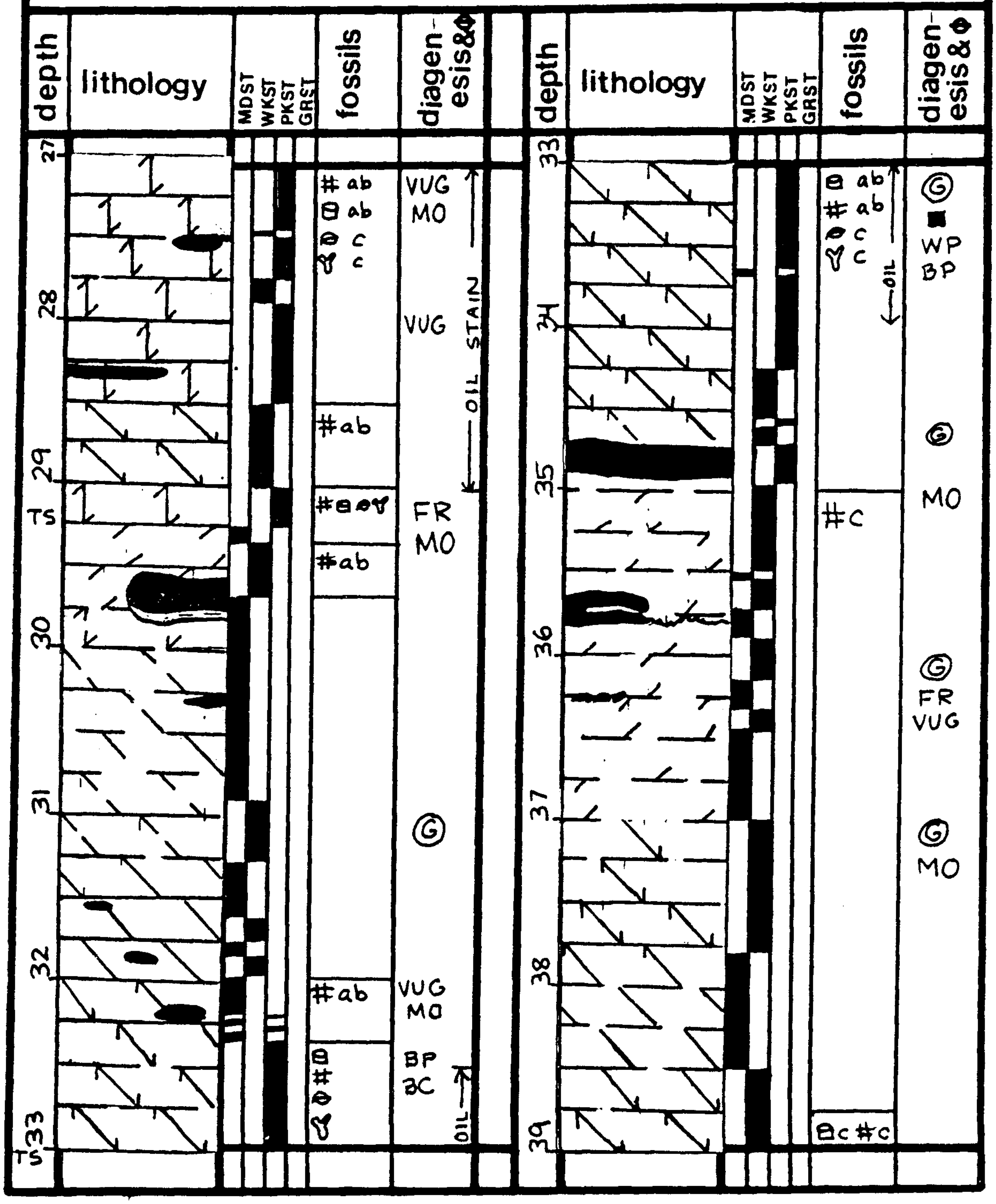
C-NW-NE 9-T31S-R18W   Interval: 5017-5068



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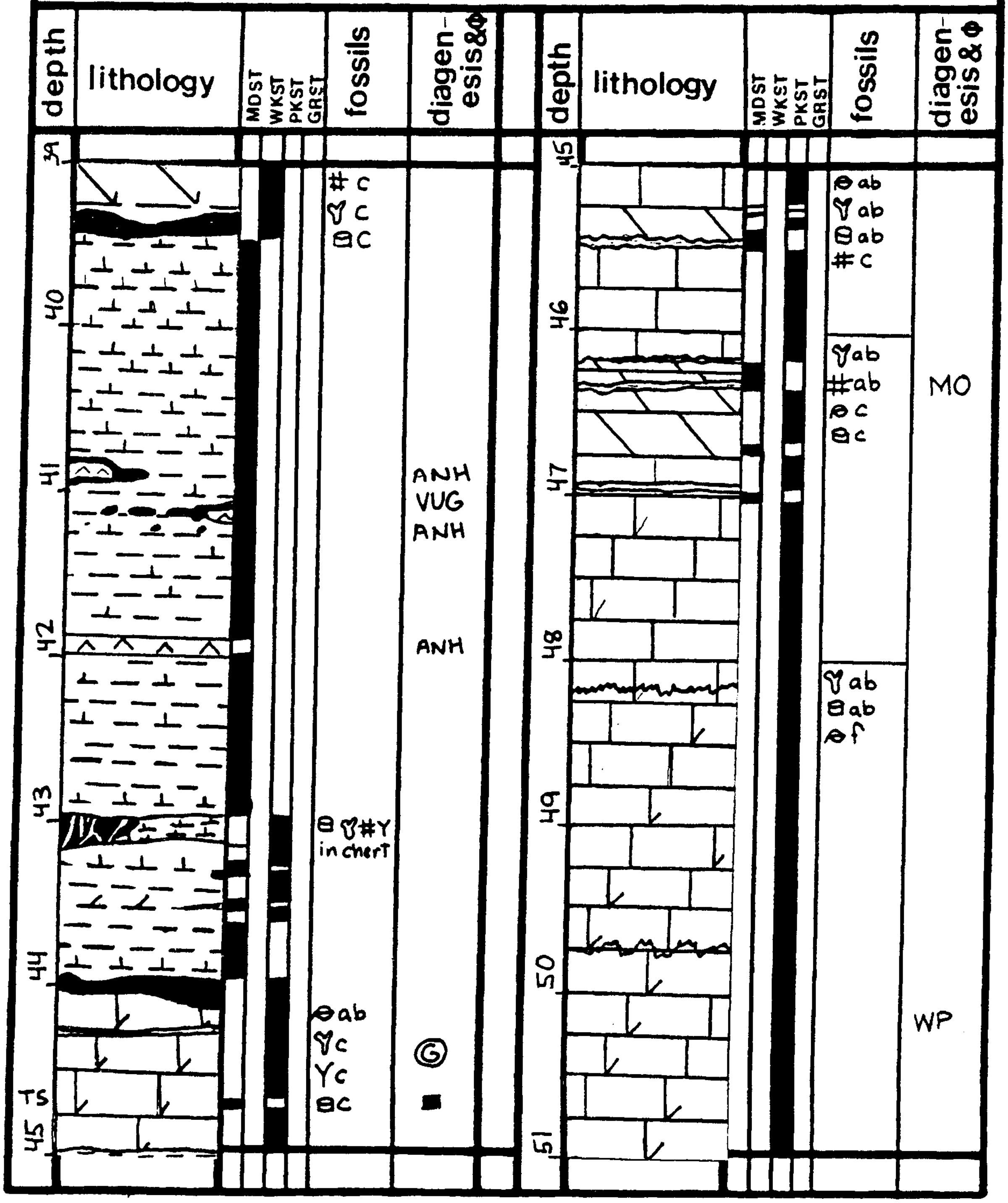
C-NW-NE 9-T31S-R18W   Interval: 5017-5068



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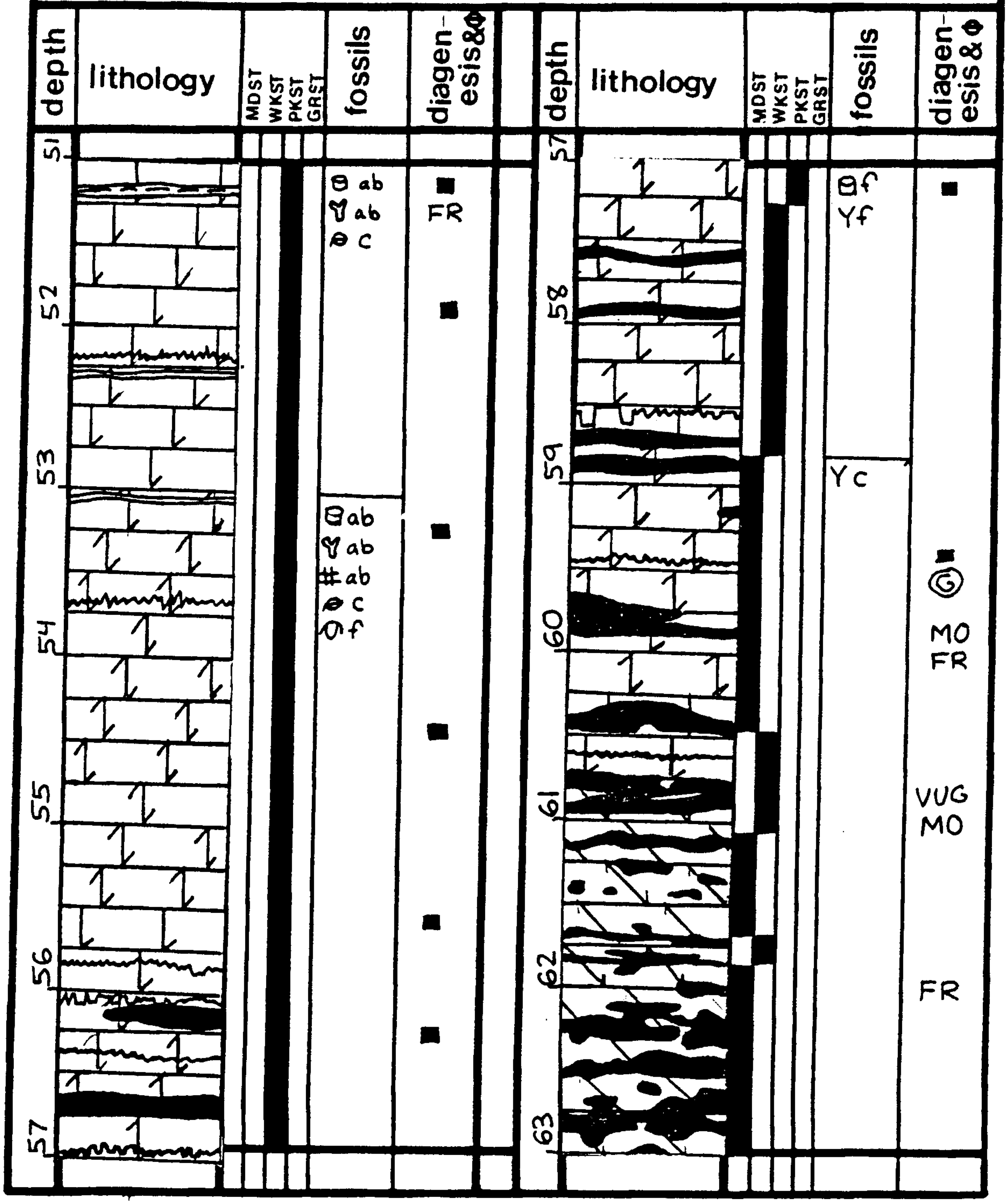

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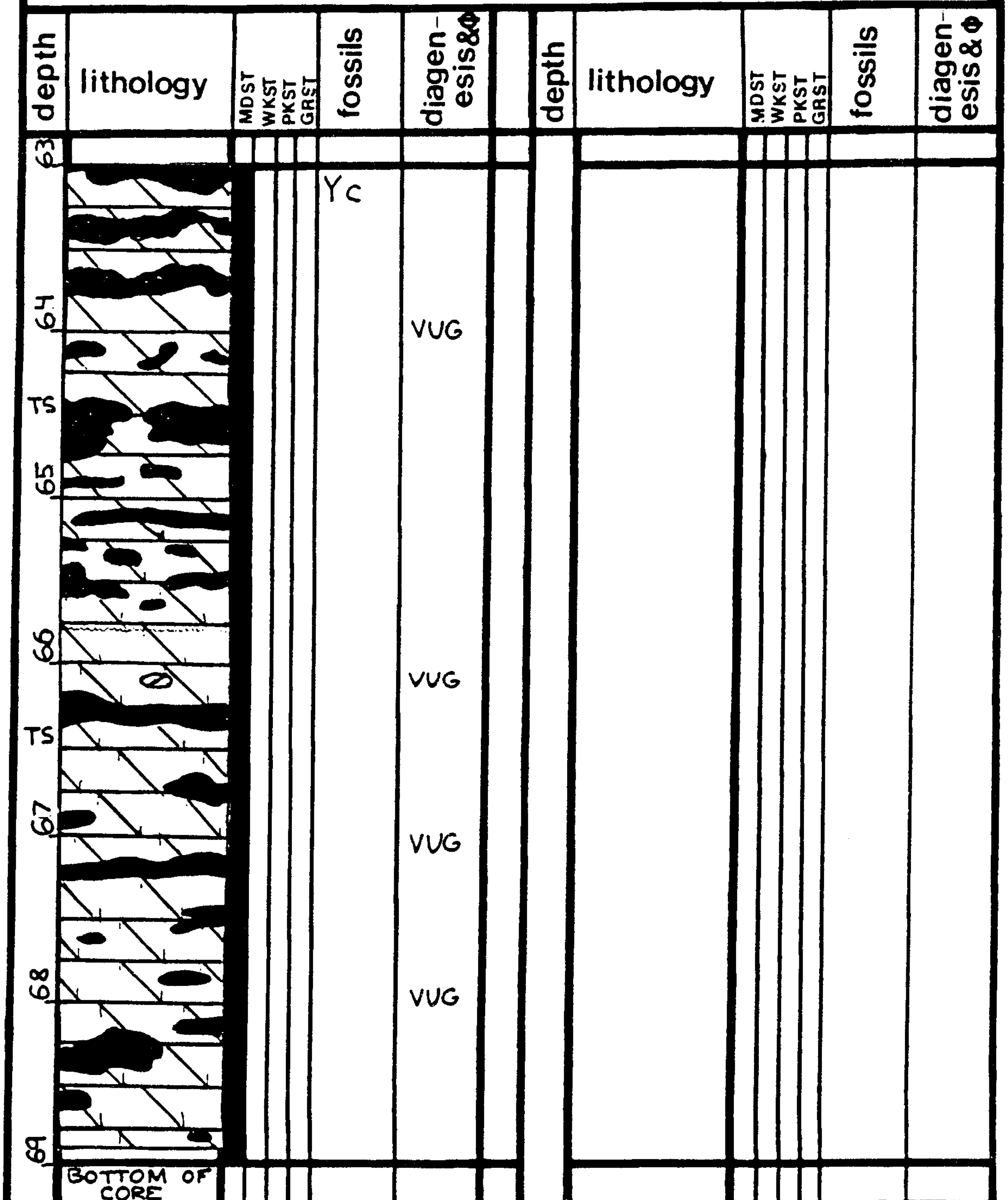
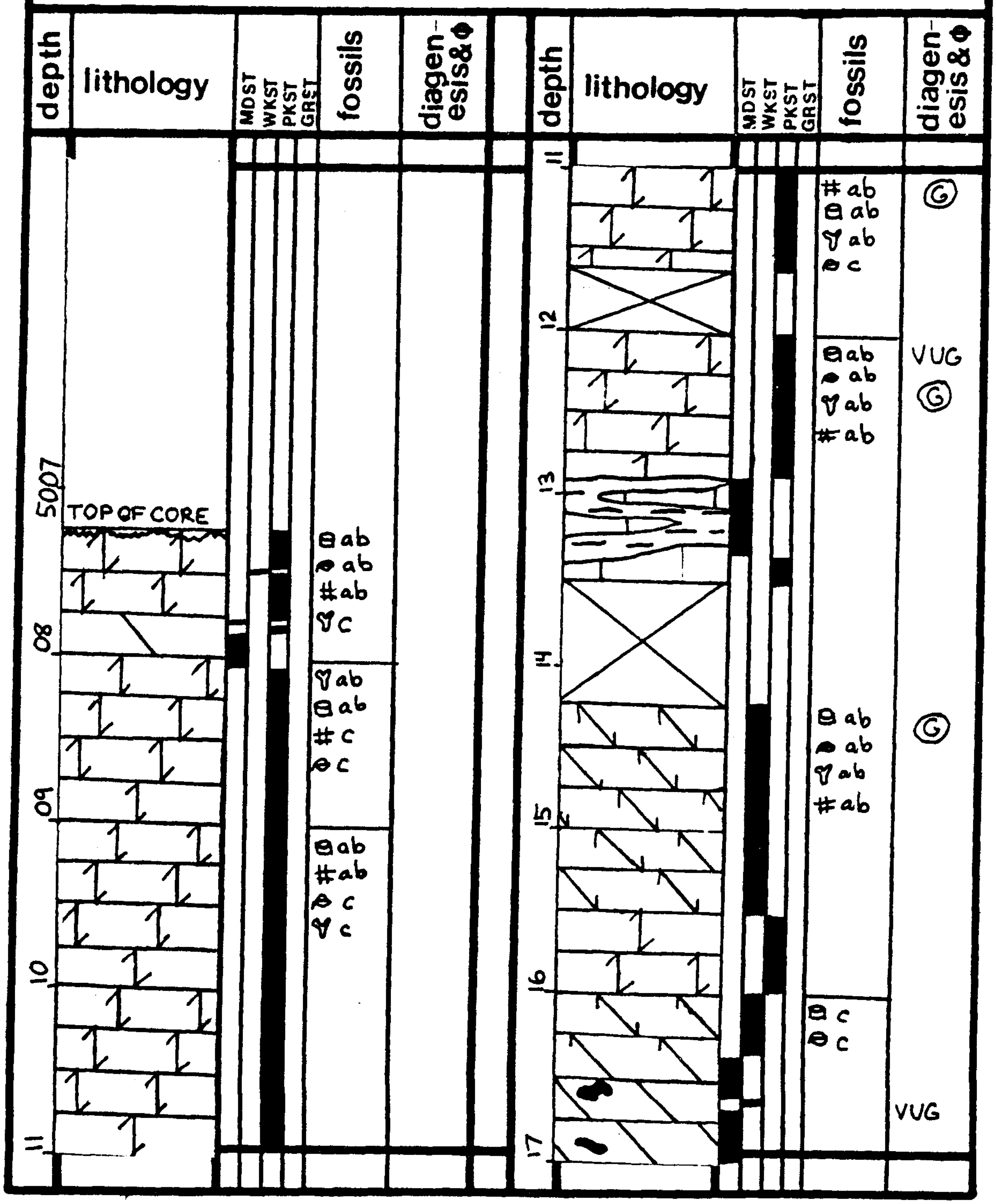


Anadarko #1 Boisseau B GL 2134

C-NW-SE 11-T31S-R18W Interval: 5007-5071



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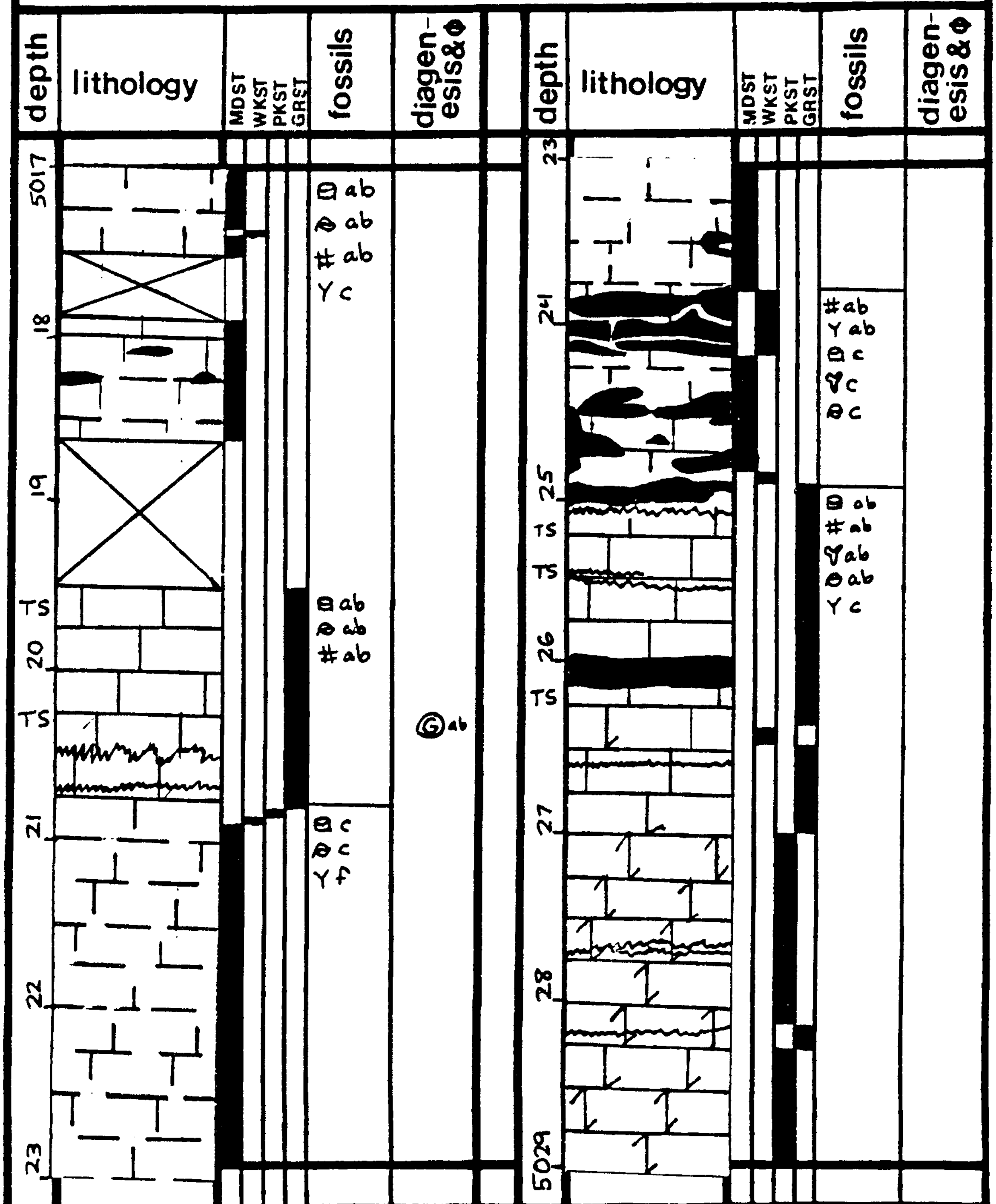

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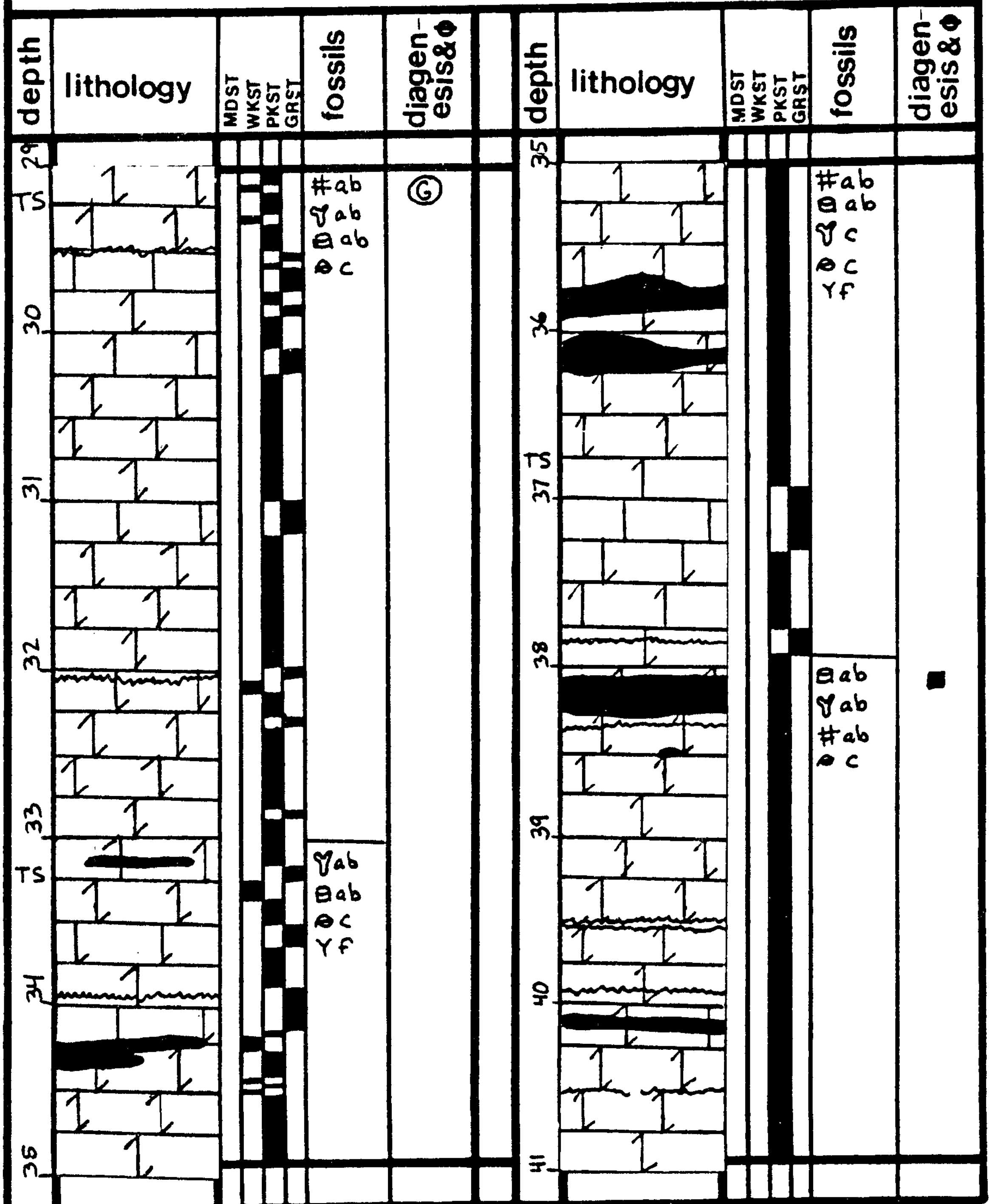

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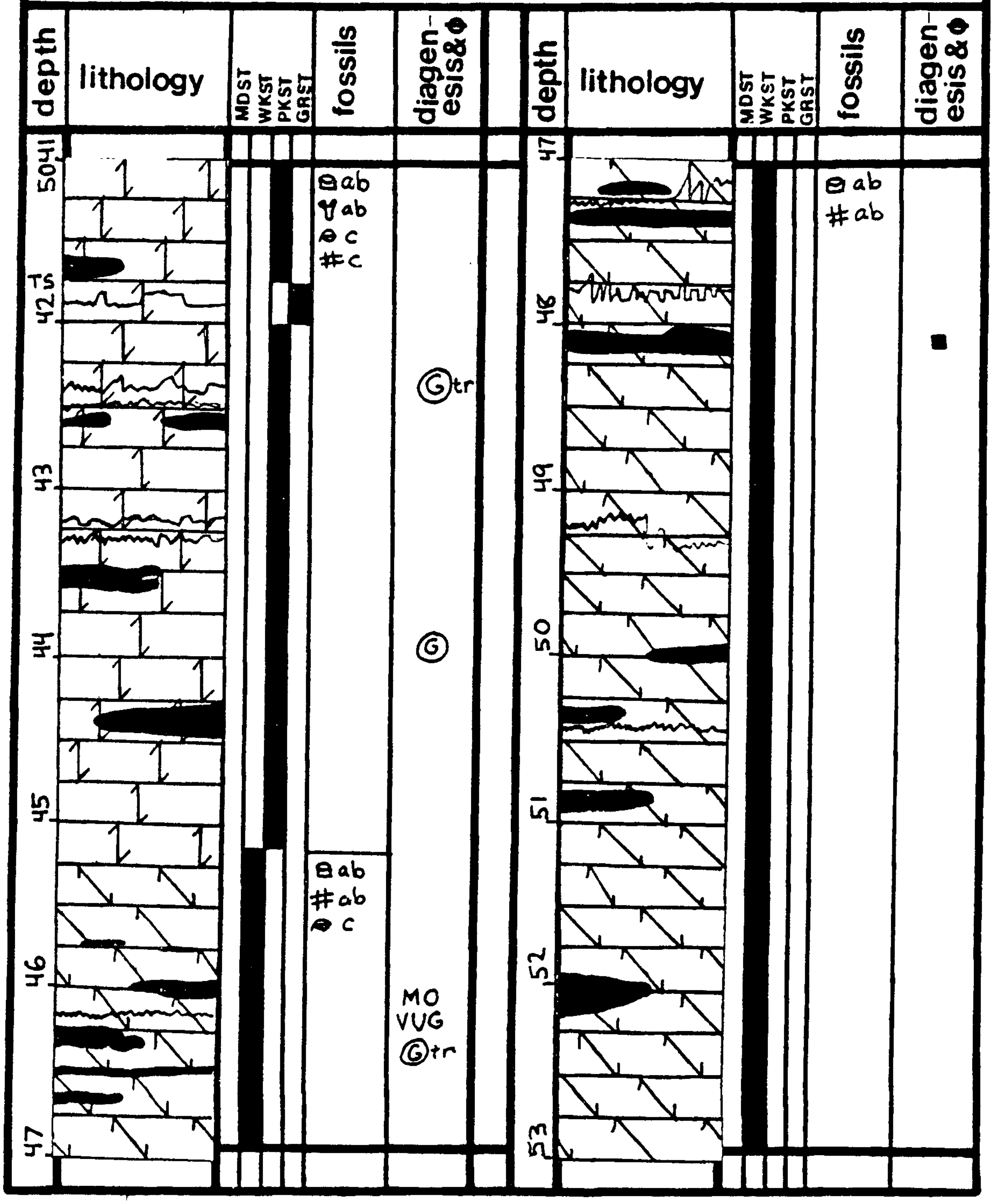

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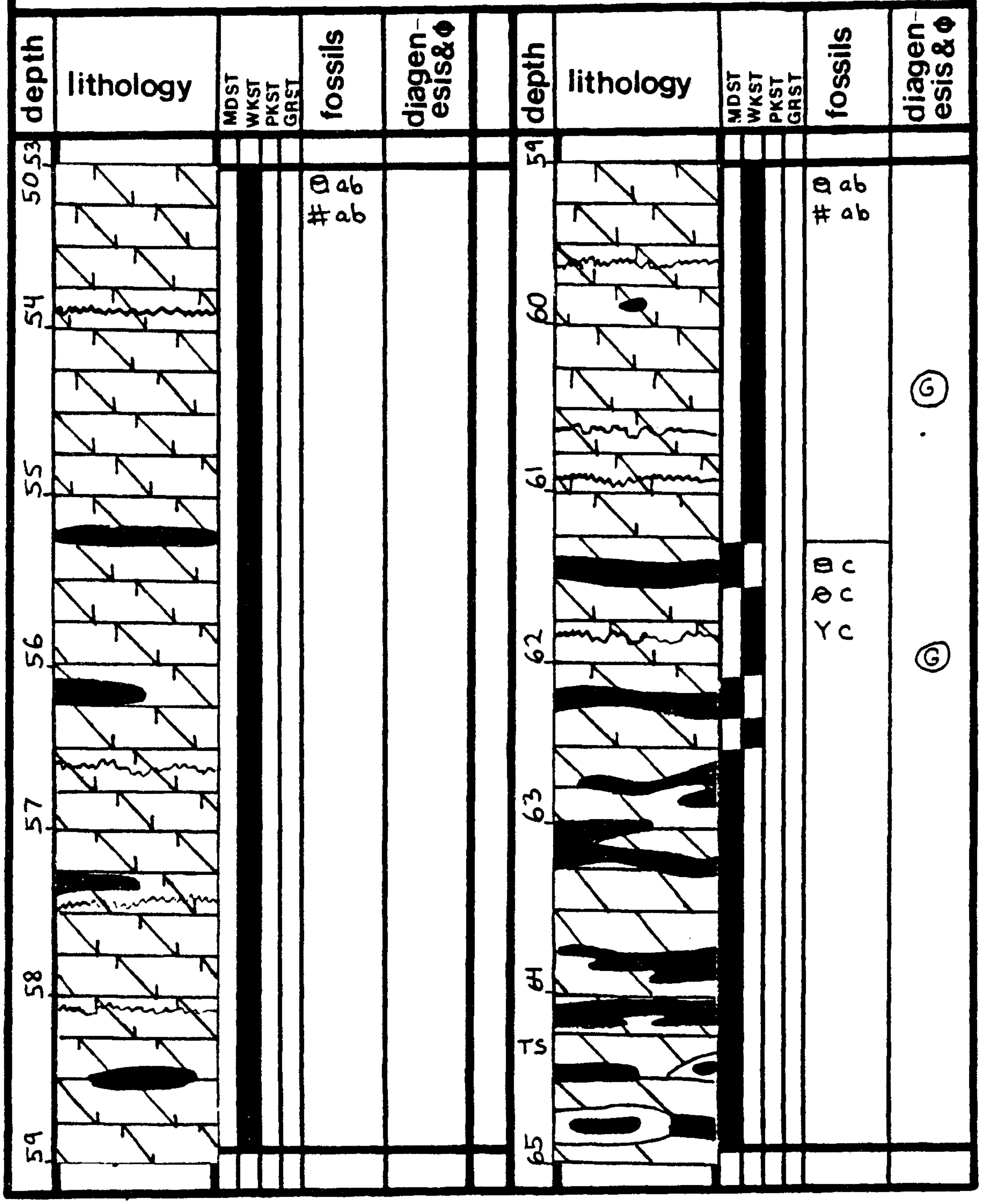

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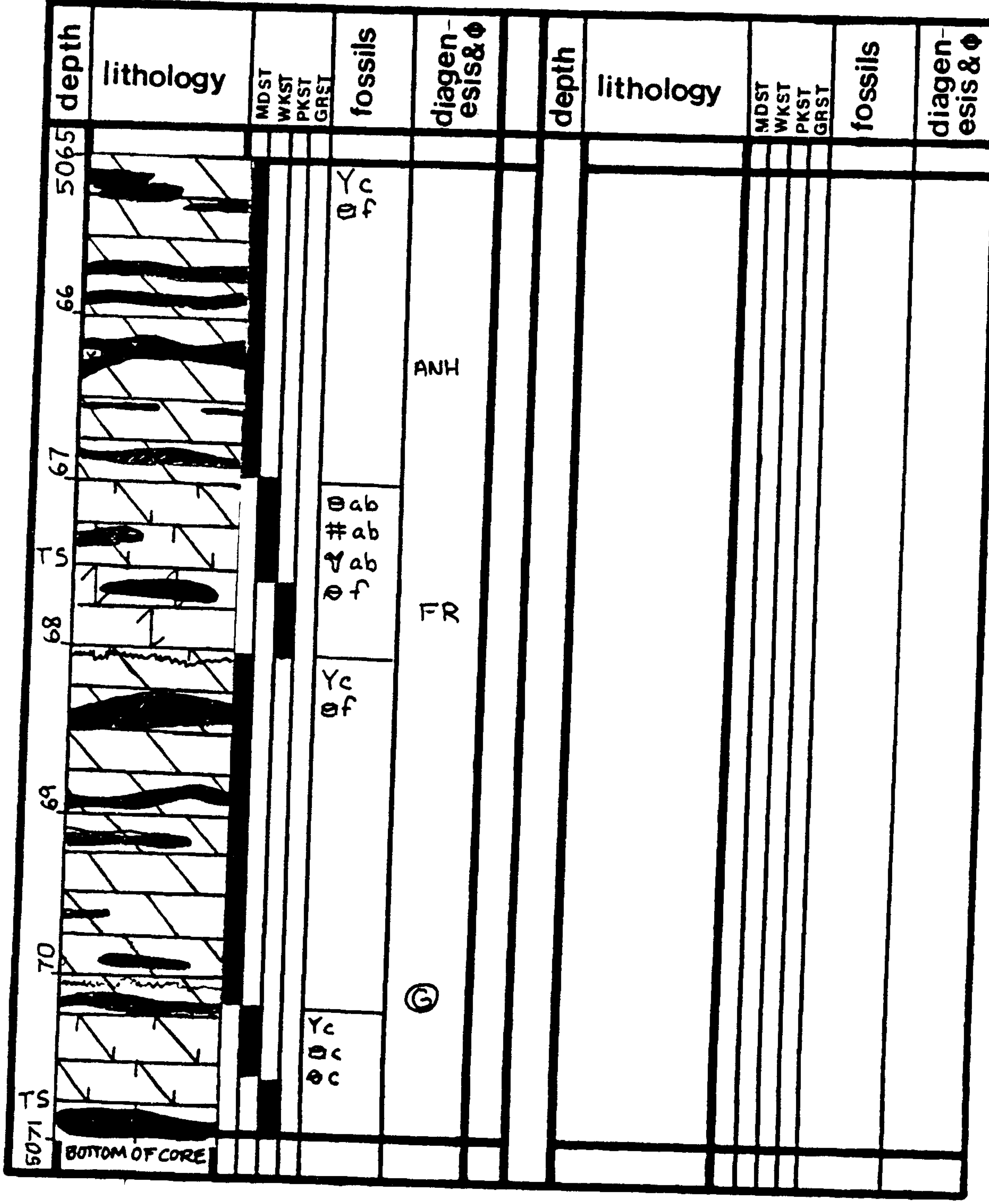

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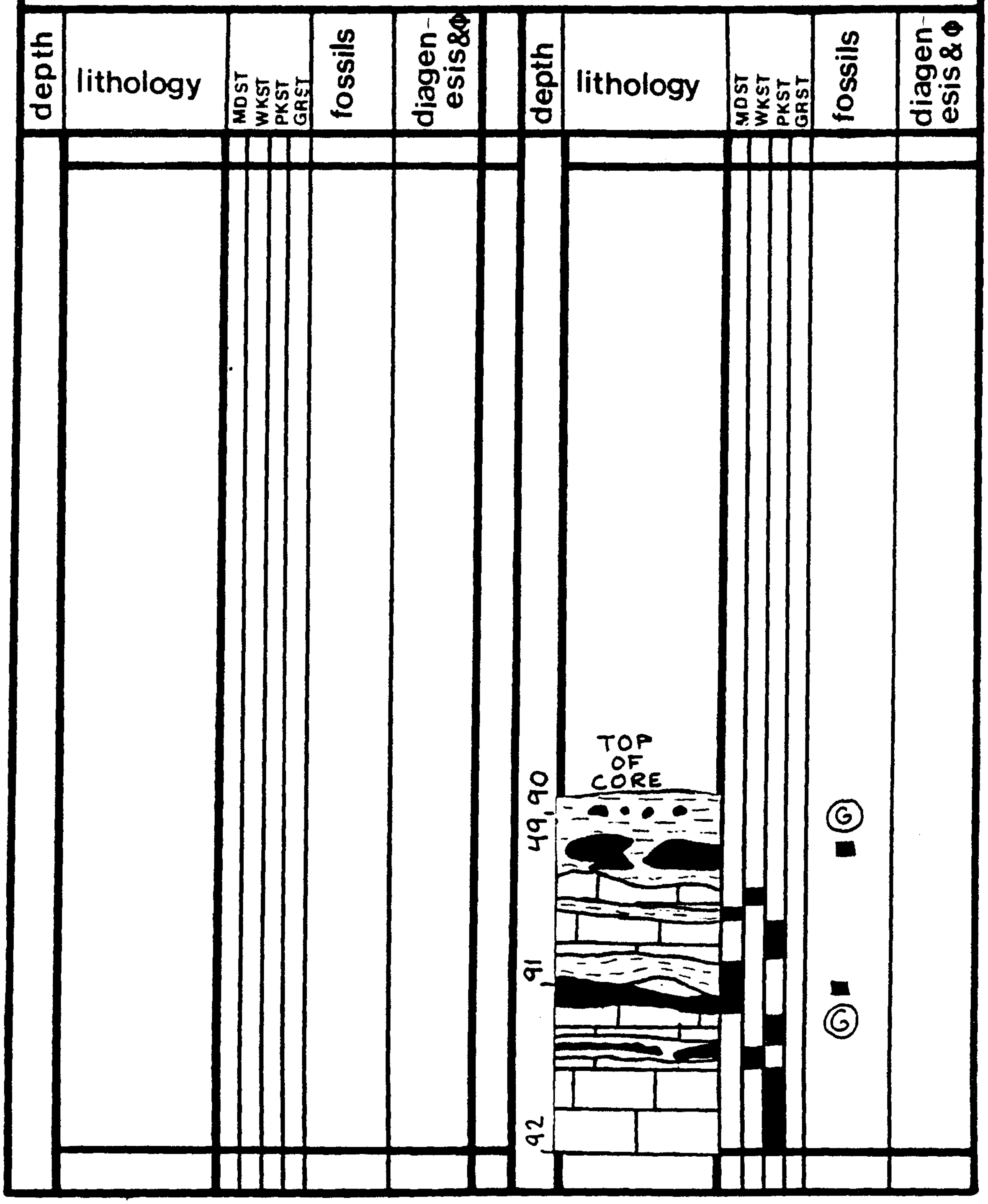

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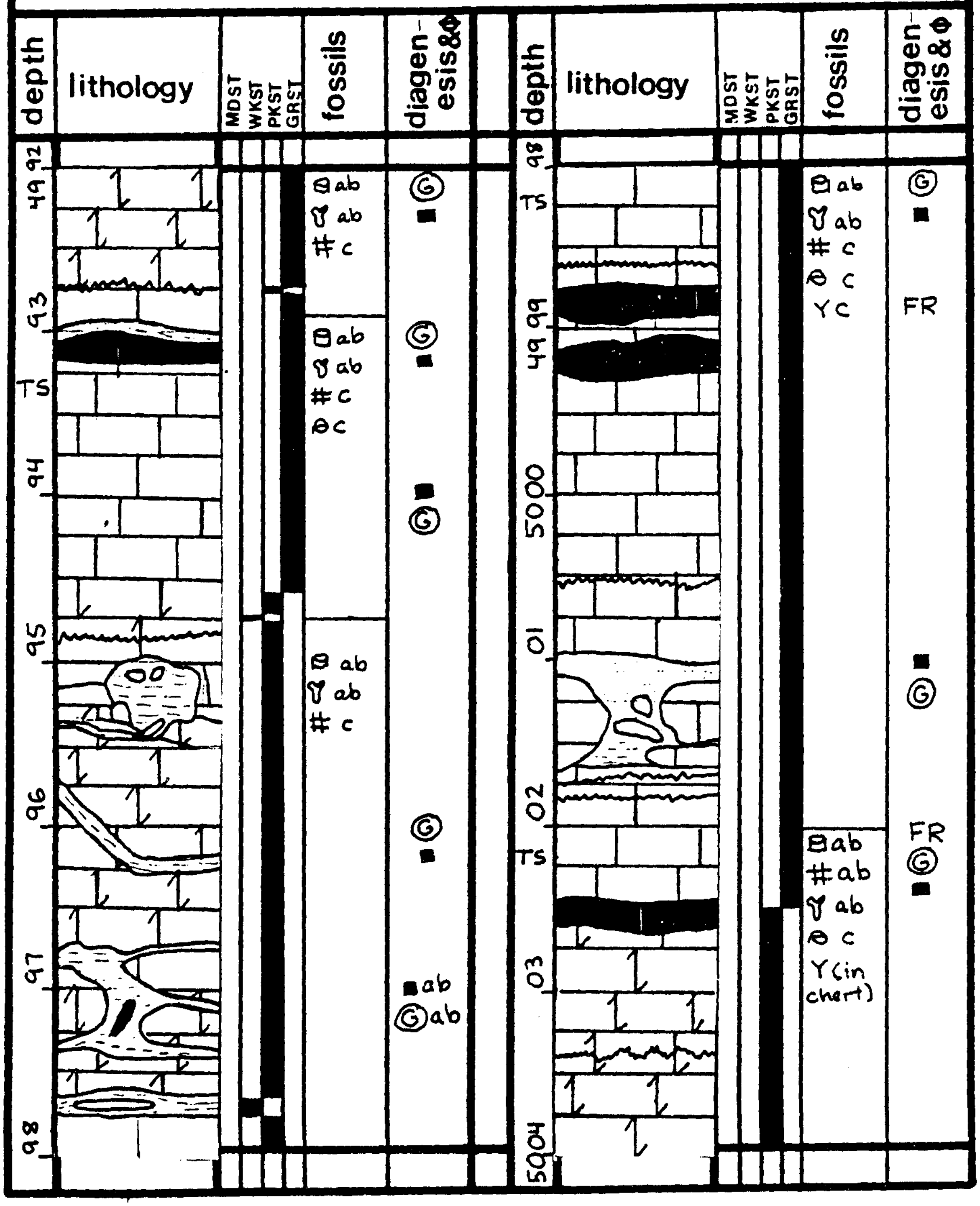

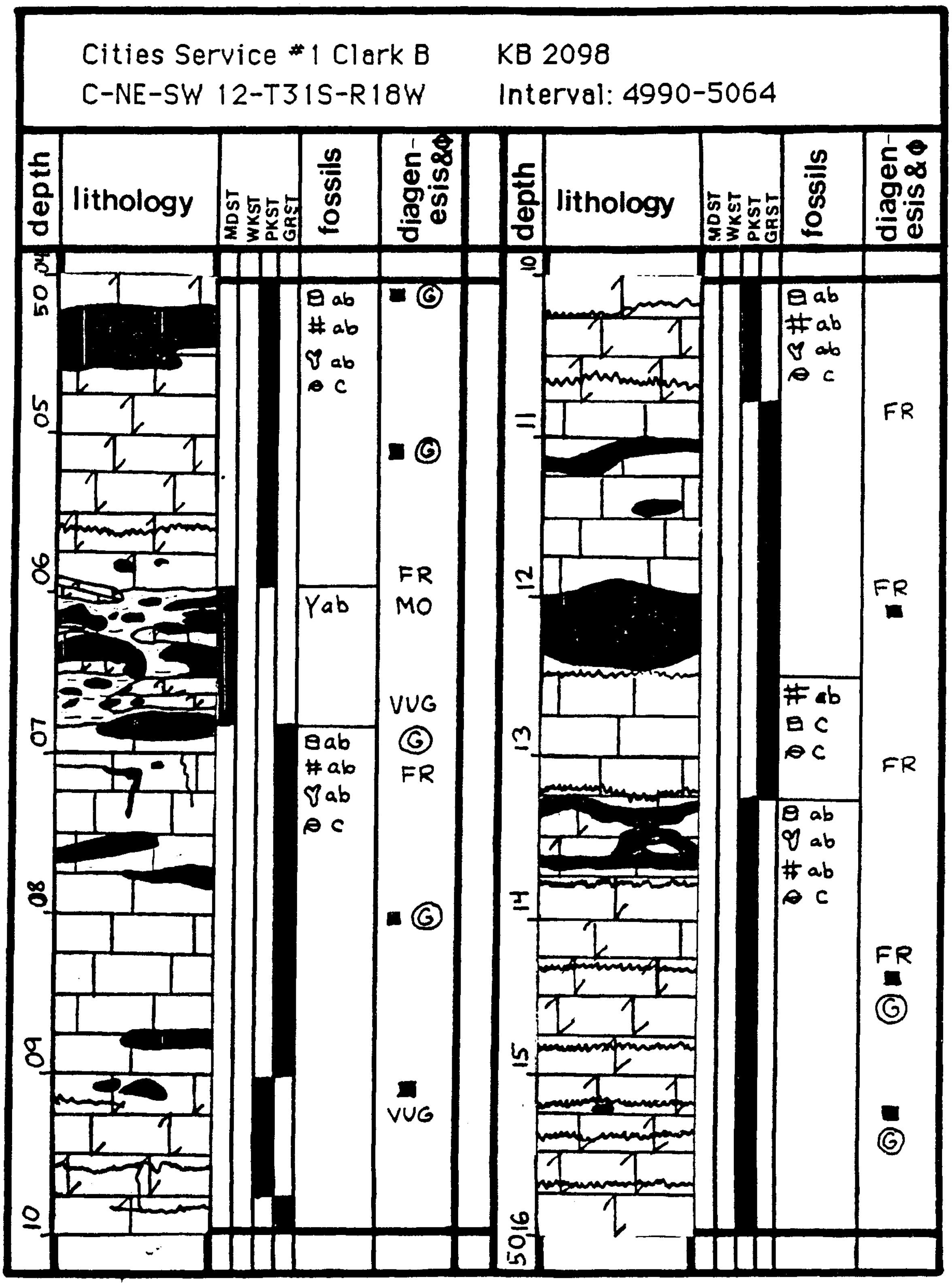

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KB 2098
C-NE-SW 12-T31S-R18W
Interval: 4990-5064
depth
lithology
MDST
WKST
PKST
GRST
fossils
diagen-esis&Φ
50 04
05
06
07
08
09
10
11
12
13
14
15
5016
ab
ab
ab
c
Yab
FR
MO
VUG
FR
VUG

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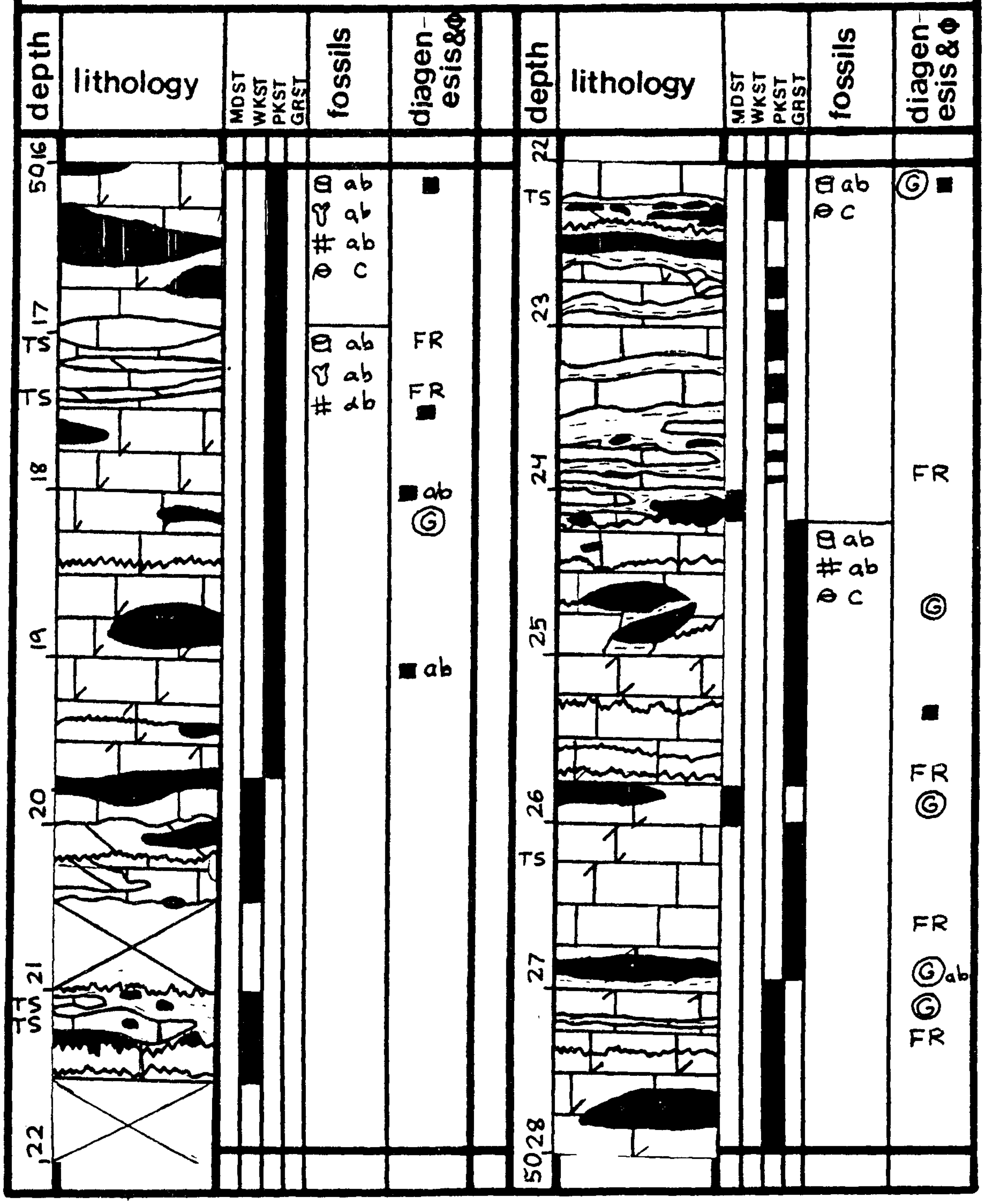
C-NE-SW 12-T31S-R18W Interval: 4990-5064



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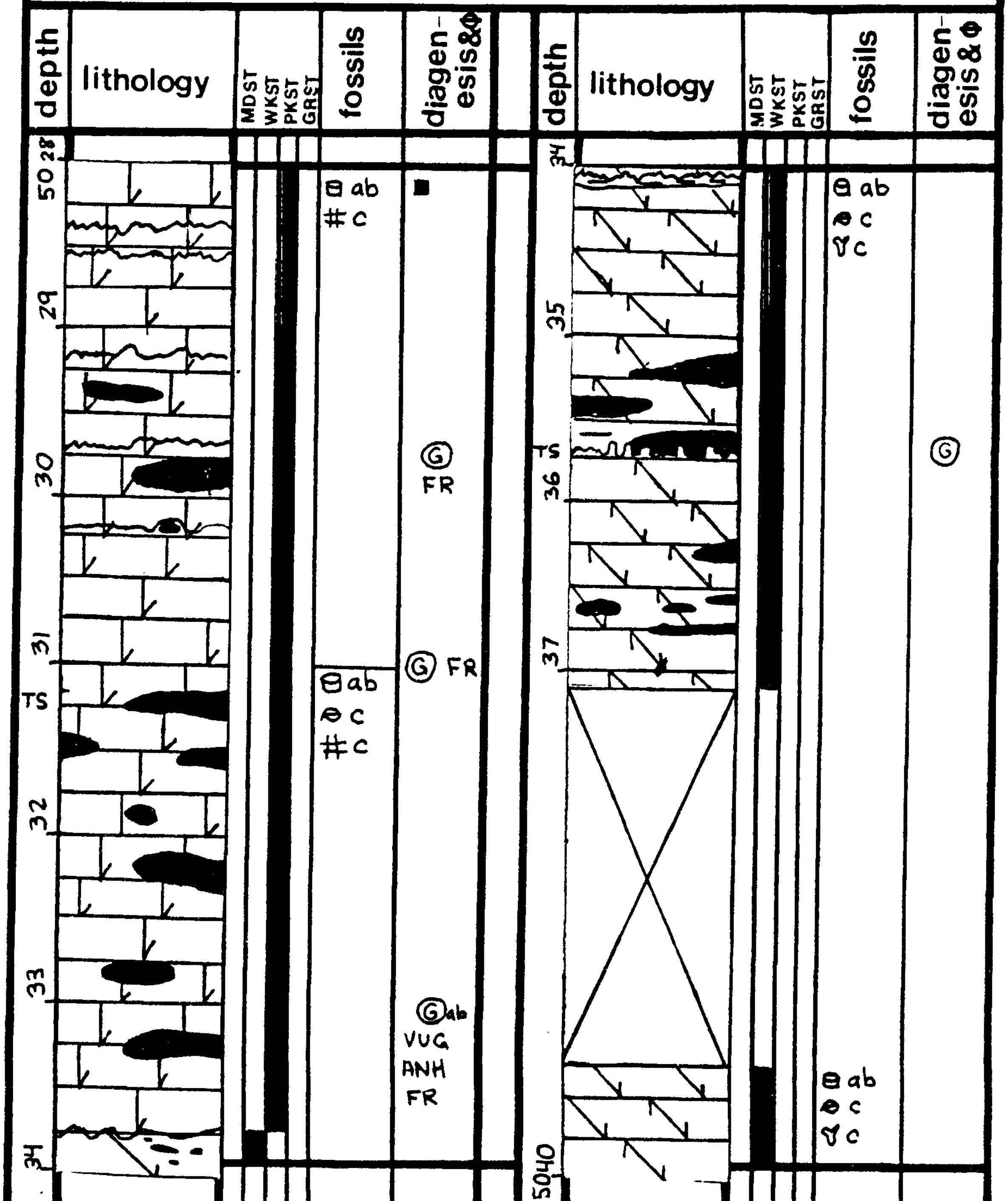

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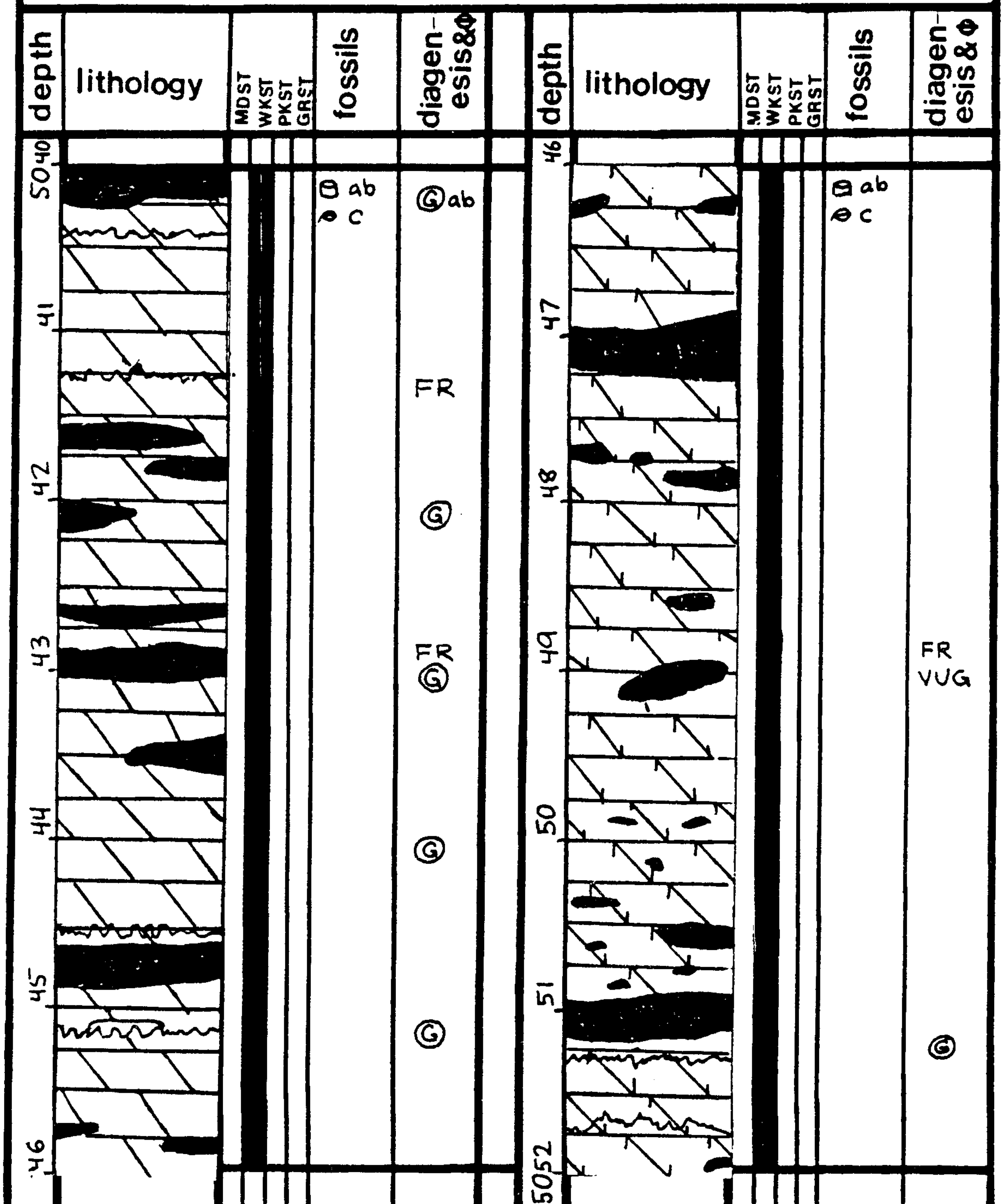

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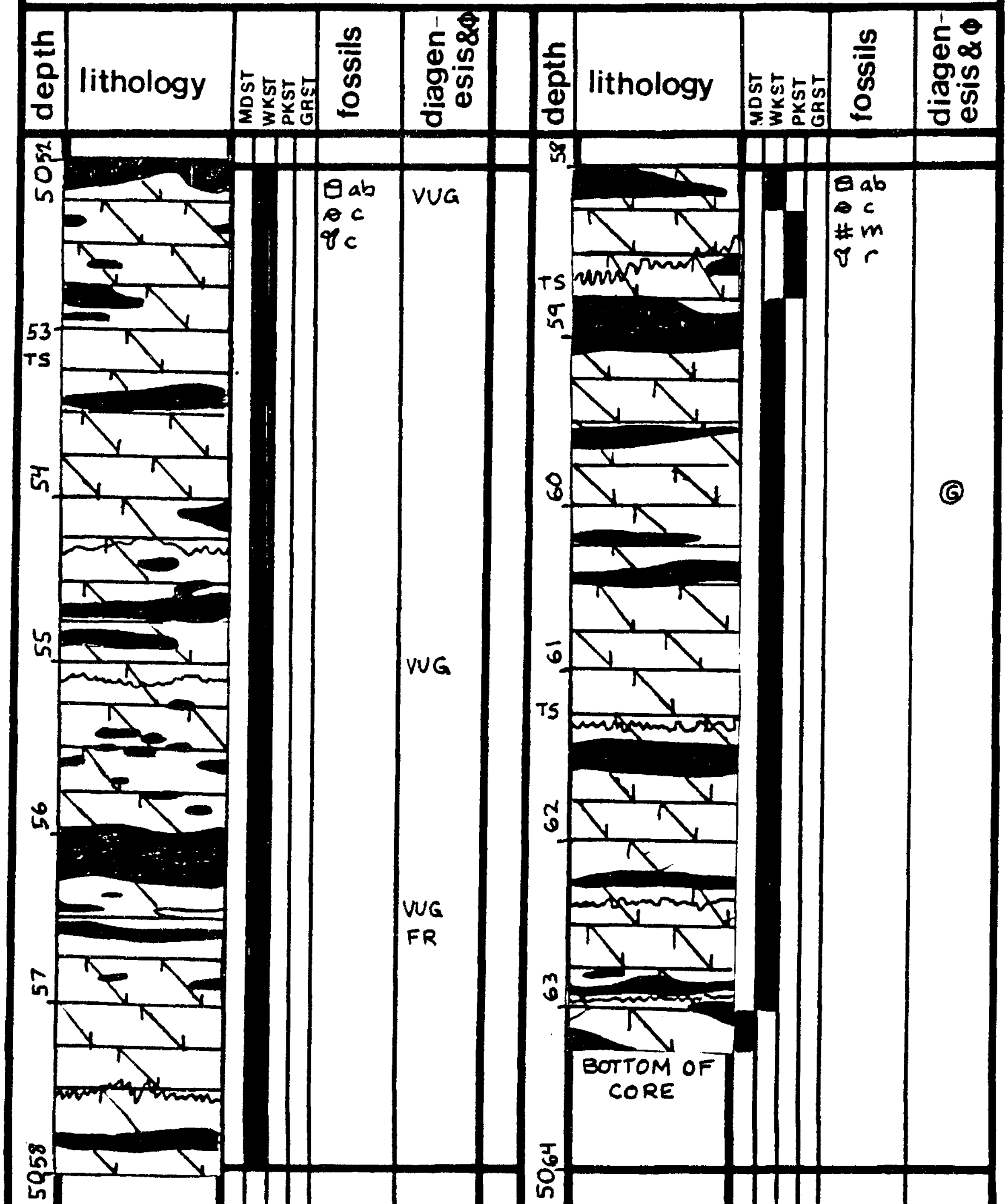

Appendix B: Thin Section List

Mull Drilling #1 Brensing G
C-NW-SE 20-27S-20W

G76	G93
G80	G96
G84	G4900
G87	G4904
G89	G4904B
G91	G4907

Anadarko #1 Brensing A
C-NE-NW 33-27S-20W

A4910-2	A23-3
A4910-2B	A24-3
A13-1	A27-1
A15	A30-2a
A16	A30-2c
A4916B	A31
A18	A33
A22-1	A38-2
A23-1	A40-2

Mull Drilling #1 Matkin
C-NE-NW 16-27S-21W

MT4907-2	MT4915	MT4924
MT4909	MT4917	MT4926-1
MT4909-1	MT4919	MT4928 (1x2)
MT4912-2	MT4922	MT4931

Mull Drilling #1 Alford A
C-SW-SW 1-29S-20W

AL23	AL36
AL23a	AL36a
AL23b	AL36b

T.X.O. #1 Manke
NW-NW-SE 6-29S-20W

M66	M77-2i
M67-1i	M78-2i
M67-1	M81-1i
M69-4	M81-1
M71-3	M83-1
M73-1	M87-1
M73-1i	M90-1

Sam Gary #10-7 Hoener
C-SW-NE 10-29S-22W

H5241-1	H5265
H5245-2	H5270-1
H5249-2	H5275-2
H5255-2	H5280-1
H5260-3	

Thin Section list continued

Anadarko #1 Burkhall A
C-NW-NW 30-31S-17W

BA5077-1	BA84-2
BA80-2	BA85-1i
BA80-2b	BA85-1
BA80-2c	BA85-1ib
BA80-2i	BA87-1
BA80-4	BA87-1b
BA80-4i	BA87-1c
BA82-2	BA88-1
BA82-3	BA88-1b
BA82-3i	BA88-1i
BA83-2	BA92-1
BA83-2b	BA94-5
BA83-2i	BA5096-1
BA84-2	BA5100-3

Graham-Michaelis #3-9 Uhl
C-NW-NE 9-31S-18W

U17	U44a
U5017b	U5044b
U19-2	U45-4
U24-2	U45-4b
U29	U64
U33-2	U66-2

Anadarko #1 Boisseau B
C-NW-SE 11-31S-18W

B50007	B5025b
B5015	B5026
B5015b	B5026b
B5015c	B5029
B5019-	B5033
B5019+	B5037-2
B5020	B5041
B5020b	B5046
B5025-	B5064
B5025	B5071

Cities Service #1 Clark B
C-NE-SW 12-31S-18W

C4993	C5021
C4993b	C5022
C4998	C5031
C5006	C5035
C5007	C5045
C5009	C5053
C16/17	C58-3
C5017	C5061

Thin section list continued
Cities Service #1 Pyle A
C-NE-SW 13-31S-18W

P11-2	P32-3
P14-1	P35-2
P16	P39-1
P20	P42-5
P24-3	P42-5b
P27-1	P42-5c
P28-2a	P45-2
P28-2b	P47-3
P28-2c	

Mesa #2-29 Moore
NE-NW-NW 29-31S-21W

MO 59-3
MO 62-2
MO 67-1