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entitled Subsurface Geology and Petrology of the Salem
Limestone in Portions of Hamilton, White and Wayne
Counties, Illinois

be accepted as fulfilling this part of the requirements for the degree of Master of Science

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SUBSURFACE GEOLOGY AND PETROGRAPHY
OF THE SALEM LIMESTONE
IN PORTIONS OF
HAMILTON, WHITE, AND WAYNE COUNTIES, ILLINOIS

a thesis submitted to the
Division of Graduate Studies and Research
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

in the Department of Geology
of the College of Arts and Sciences

1986

by

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ABSTRACT

The Salem Limestone (Valmeyeran Series) in Hamilton, White and Wayne Counties, Illinois, consists of up to 500 feet of carbonate rocks. These sediments were deposited in a series of five tidally influenced, shoaling-upwards cycles on a shallow, southwestward-dipping paleoslope. The development of each cycle has been influenced by: 1) the geometry of the basin, 2) syndepositional structures within the basin, and 3) previous cyclic deposits. Each cycle contributed to the infilling of the basin, so that the Salem Limestone as a whole represents one large shallowing-upwards sequence.

Seven lithofacies have been recognized from available cores. They include: 1) Echinodermal-Oolitic Grainstone, 2) Echinodermal-Bryozoan Grainstone, 3) Oolitic Grainstone, 4) Oolitic Packstone, 5) Pelloidal Aggregate Grainstone, 6) Bioclastic Wackestone, and 7) Bioclastic Dolostone. They were deposited in environments ranging from winnowed offshore tidal bars; to normal marine, open platforms; to restricted marine, inter- or back shoal platforms.

The paragenetic sequence of these rocks reflects progressive subsidence. Early marine phreatic cements are present in all lithologies, primarily as isopachous calcite fringes. Moderate burial compacted the rock, causing spalling of these fringes; and also brought the sediments into a mixing zone environment, where dolomitization occurred. In the meteoric phreatic, there was both precipitation of abundant calcite, and development of fenestral porosity. Deep burial resulted in oil emplacement, and the deposition of calcite, anhydrite, and dolomite, all of which may be related to the Mississippi Valley-Type lead-zinc deposits of southern Illinois.

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INTRODUCTION

Purpose of the Study

The Salem Limestone is a middle Mississippian carbonate sequence of the Valmeyeran Series in south central Illinois. It has been examined closely by a number of workers, because of its long standing economic uses as an excellent building stone from Indiana, and an oil producing unit in Illinois and Indiana. As a result of these studies, the Salem's general depositional environment is relatively well known. Most workers report it to be a cyclic, shoaling upwards carbonate sequence deposited in a shallow, warm water epeiric sea.

Subsurface studies of the Salem Limestone are less common than outcrop studies. The relatively deep position of the Salem within the Illinois Basin, and the presence of many productive horizons above it, mean that well control through the Salem has been limited in the past. However, an increase in drilling activity to the Salem of Wayne County, Illinois in the early 1970's has provided some important additional data.

The Salem Limestone in White and Hamilton Counties, Illinois (Fig. 1) has been divided into five shoaling-upwards cycles (Wayne Pryor, 1980). But most Salem oil production (and many new discoveries) are north of Hamilton County, in Wayne and Clay Counties, Illinois (Fig. 2). Thus, the purposes of this study are as follows:

- 1) To trace these five cycles from the relatively non-productive Hamilton County into White and Wayne Counties.
- 2) To compare these mappable units between productive fields and look for patterns or trends in cycle development.

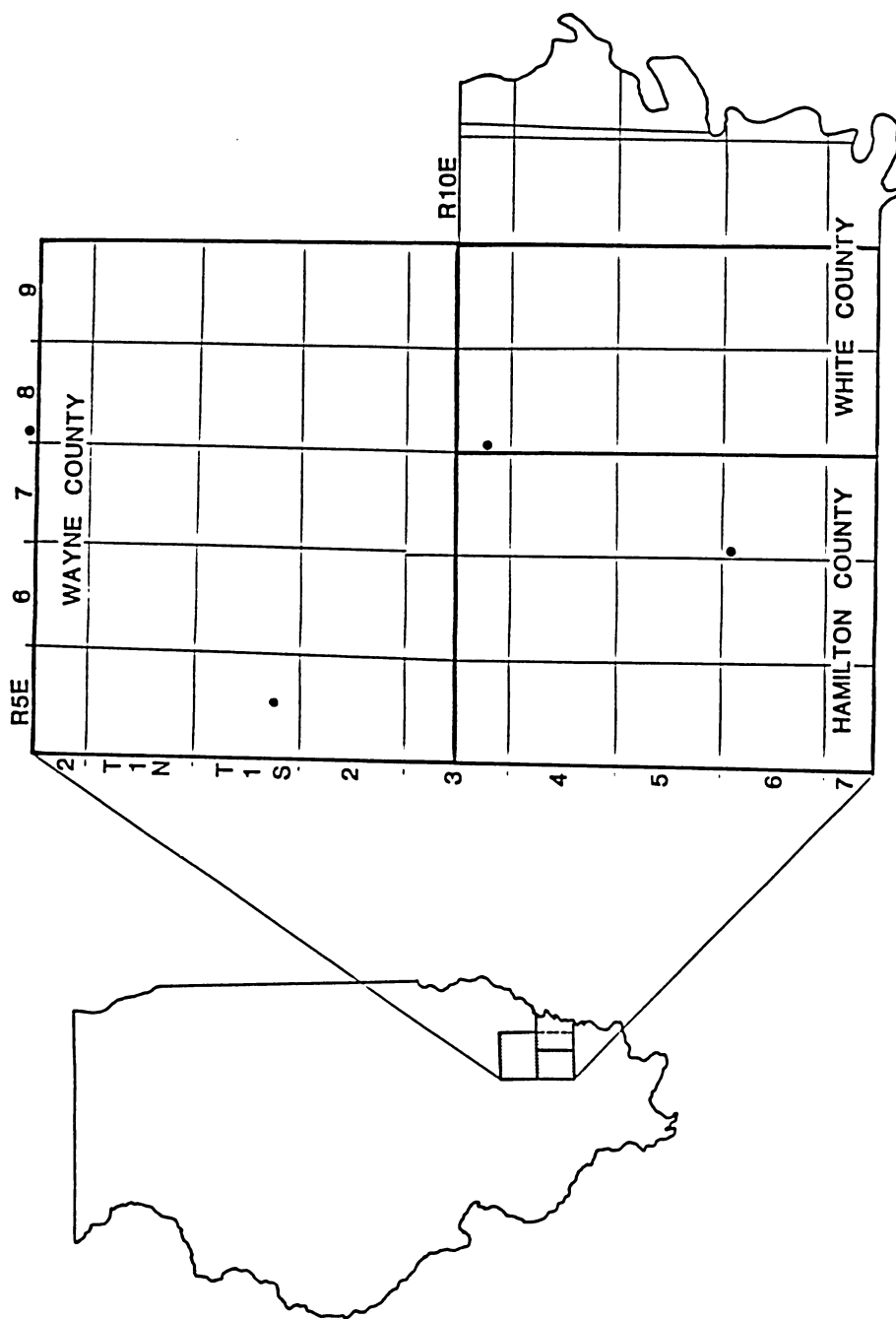
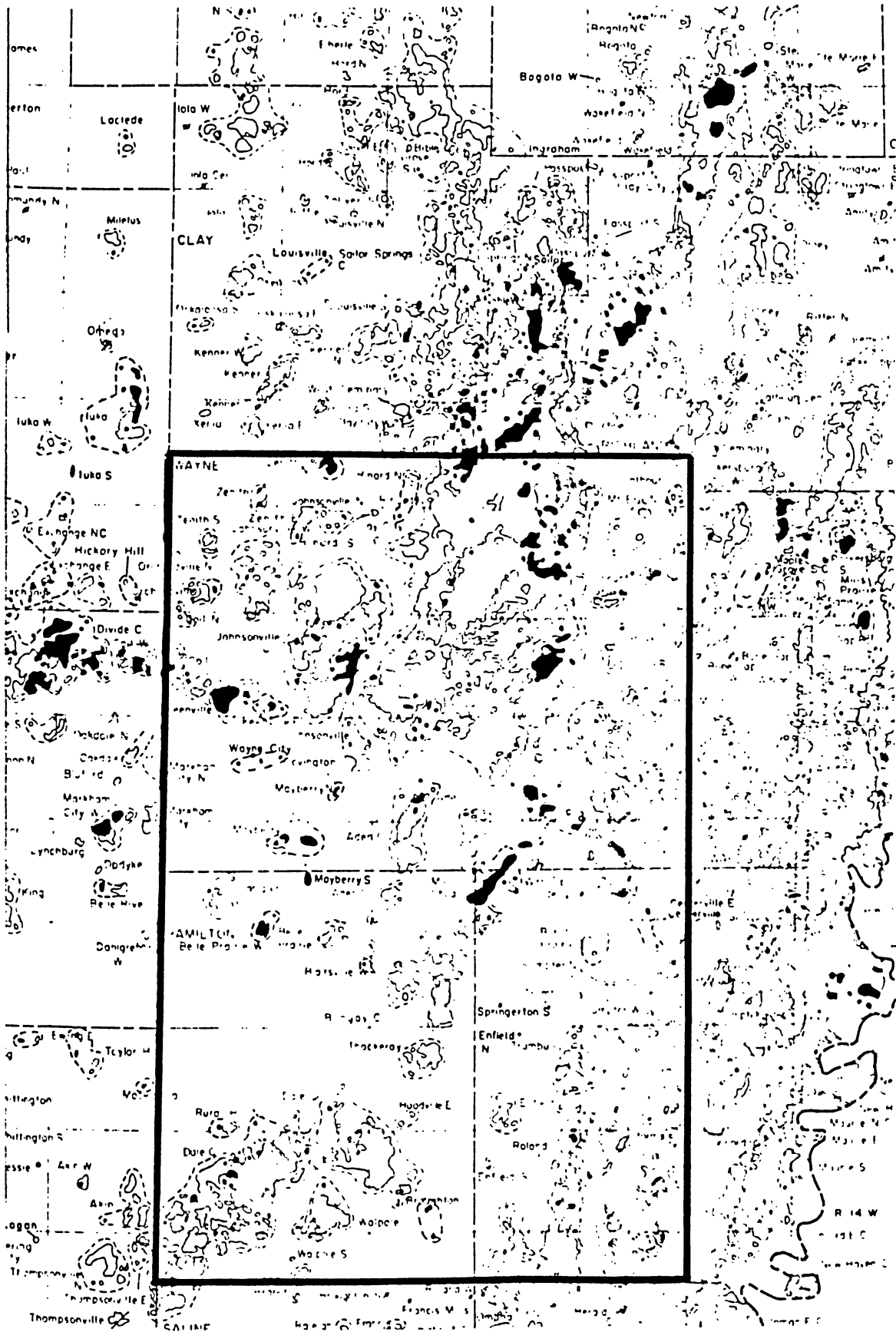


Figure 1. Location of study area, with four dots representing cores used in this study.

Figure 2. Study area, outlined in black, showing increase in oil production towards the north.



- 3) Use core material to examine lithofacies and diagenesis and determine controls on porosity development.
- 4) Fit observed lithofacies and diagenetic products into a depositional model.

Location

The data for this study comes primarily from Hamilton County, with selected data from Wayne and White Counties, Illinois. These counties were chosen to compare data from the center of the Illinois Basin (near Hamilton County) to data from the flank of the Basin (Wayne County).

Stratigraphic Nomenclature

The Salem Limestone was named by Cumings in 1901 for the Indiana building stone quarries in Salem, Washington County, Indiana. Study of the Salem began much earlier, however, when in 1864, Hall described fauna from a location at Spergen Hill, Monroe County, Indiana. The name Spergen Limestone was adopted by the United States Geological Survey in 1938 (Wilmarth, 1938), even though the Cumings name Salem Limestone predated it. The Salem has also been variously called "Bedford Oolitic Limestone" (Hopkins and Siebenthal, 1897) and by the quarry name "Indiana Limestone." The name Salem Limestone has now been accepted by the U.S. Geological Survey.

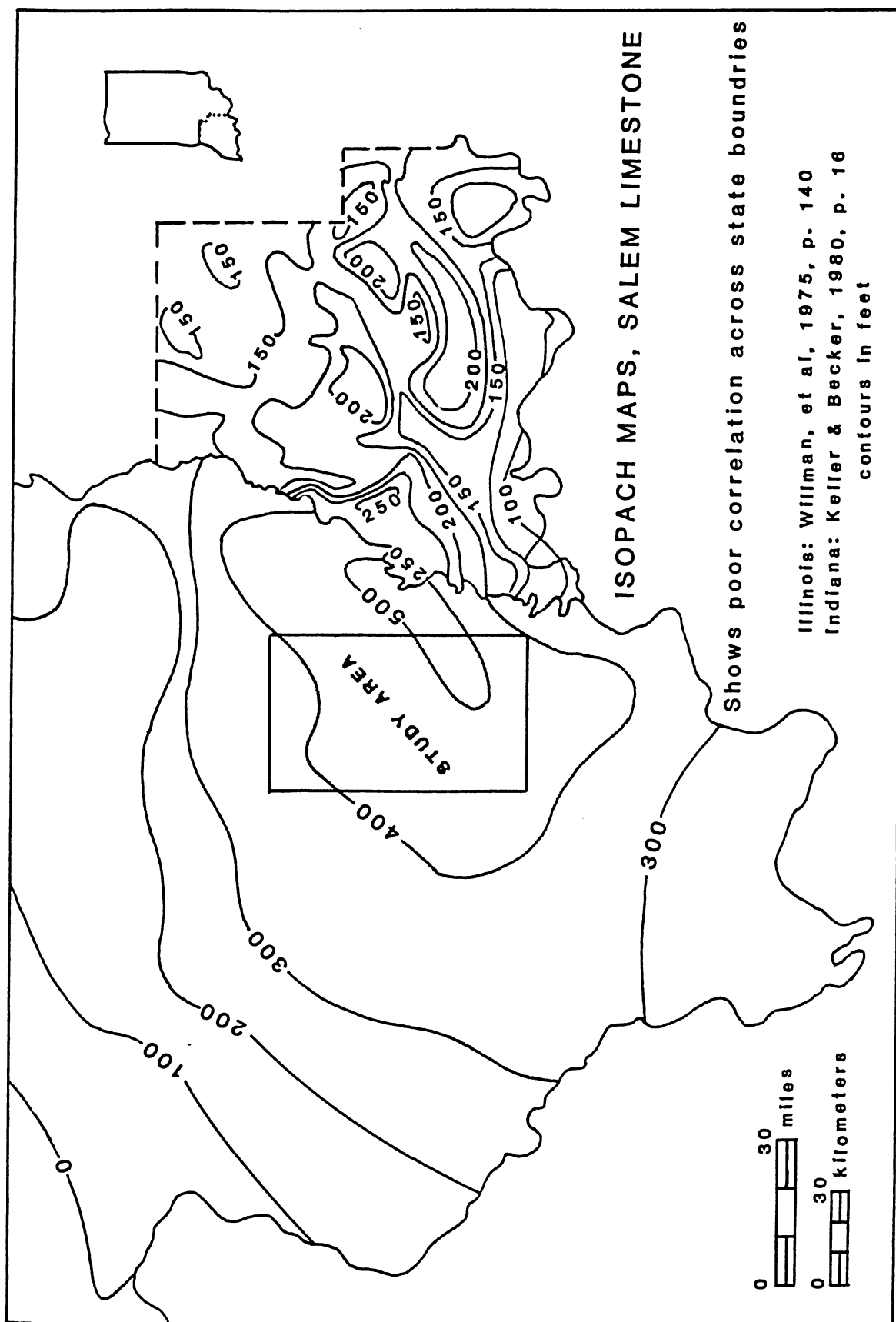
From outcrops in western Illinois, Baxter (1960) divided the Salem into four members. From the oldest, they are the Kidd, Fults, Chalfin, and Rocher members. In southern Indiana and northern Kentucky, Benson (1976) defines instead the Somerset member, present at the base of some Indiana and Kentucky outcrops. None of these members are recognized in the subsurface of south-central Illinois.

Most of the stratigraphic placement problems with the Salem are caused by the transitional nature of both the lower and upper contacts. The base of the Salem is gradational with the Ullin locally, and the upper Salem-St. Louis contact has been shown to be gradational in the study area (Lineback, 1972). In addition, only the lower portion of the Salem (in Hamilton and White Counties) correlates with the Indiana outcrops (Lineback, 1972, p. 18) and the western Illinois outcrops (Lineback, 1970 p.393). These discrepancies in contact correlation continue to cause stratigraphic problems, but are not within the scope of this study. More subsurface correlation needs to be done, especially across the Illinois-Indiana border, as demonstrated by Fig. 3. The standard Illinois stratigraphic classification is shown in Fig. 4.

Basin Setting

The Illinois Basin is presently defined by the Mississippi River Arch and the Kankakee Arch to the north, the Cincinnati Arch to the east, and the Ozark Dome, Pasacola Arch, and Nashville Dome to the south and southwest (Fig. 5). These arches create an oval-shaped, structural basin, with its long axis oriented NNW-SSE. Subsidence of this basin is believed to have begun in the Cambrian and continued intermittently at least through the Pennsylvanian (Willman, et.al., 1975, p. 23). It contains approximately 14,000 feet of Paleozoic rock at the deepest portion of the basin.

During the Mississippian, the basin was open to the south, over what would become the Pasacola Arch at the end of the Paleozoic. This open circulation is reflected by the types of rocks deposited in the three series of the Mississippian. The oldest series, the relatively thin (+/- 100 feet) Kinderhookian, is represented by normal marine



Worthen 1866		Ulrich and Smith 1905		S. Weller 1920		J. M. Weller and Sutton 1940		J. M. Weller et al. 1948		Present classification 1974	
↑		↑		↑		↑		↑		↑	
Chester Group		Chester Group		Lower "Oha" Ls. M.		SE.		FLUORSPIR DIST.		↑	
		Fredonia Ls. M.		Fredonia Ls. M.		Fredonia Ls. M.		Fredonia Ls. M.		Levias Ls. M.	
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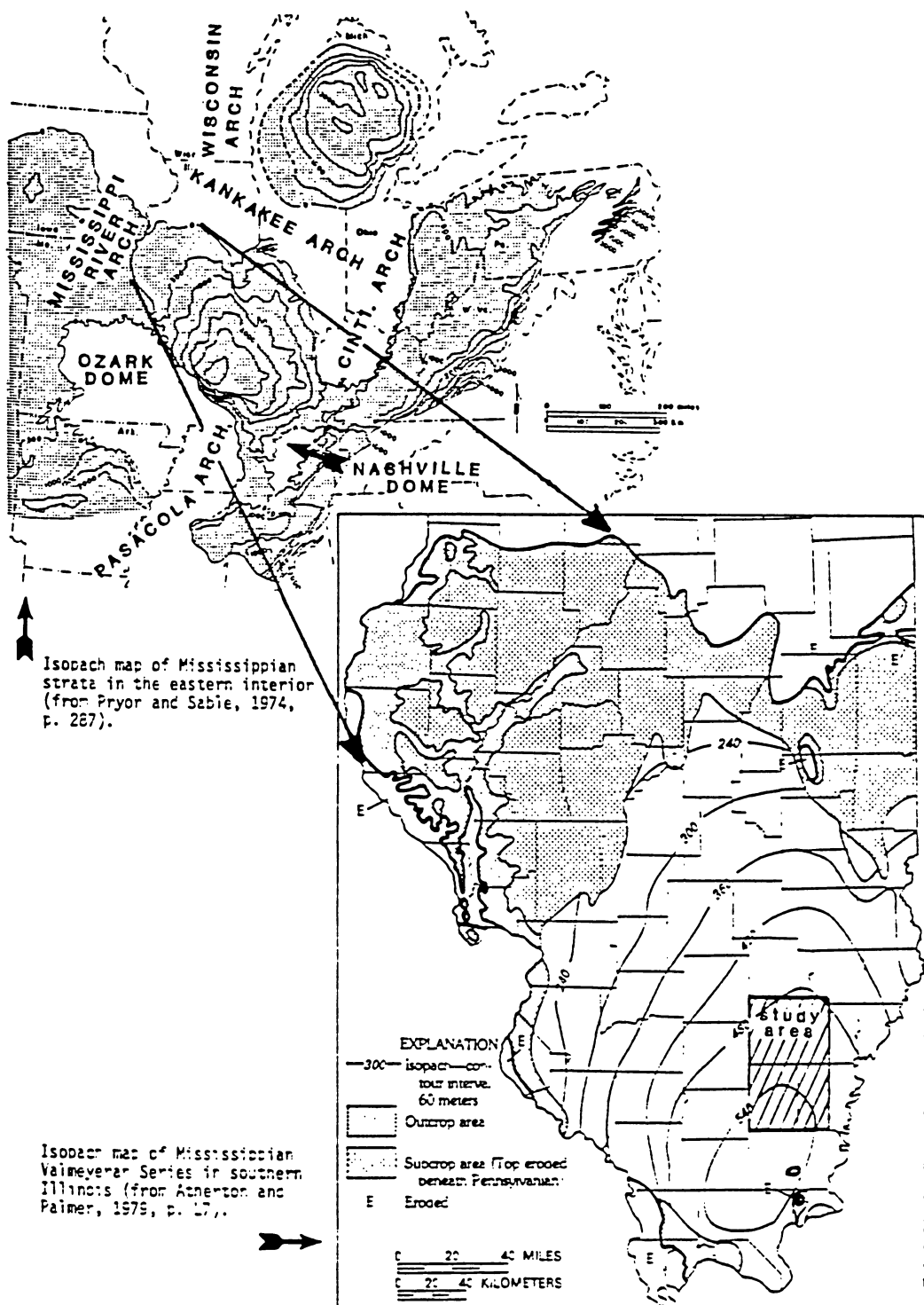


Figure 5. General structure of the Illinois Basin.

shales and limestones and deltaic siltstones; the very thick (up to 1800 feet) Valmeyeran consists of open marine, shoaling upwards carbonate cycles, and siltstone deltas in the southwestern and central-eastern portions of the basin. Finally, the moderately thick (+/- 1200 feet) Chesterian series consists of limestone-sandstone-shale sequences which are transitional to similar Pennsylvanian sequences.

Valmeyeran Series

At the close of Kinderhookian time, the major structural elements were low amplitude, ill-defined uplifts and basins (Pryor and Sable, 1974, p. 288-290). Therefore, the surface presented for Valmeyeran deposition was a south-southeast dipping intracratonic shelf in the northwest portion of the basin, and a west-southwest dipping intracratonic shelf in the eastern portion of the basin. Uplift of a remote landmass to the east was providing sediment to the Michigan River in the northeast (Pryor and Sable, 1974, p. 292); and these sediments were deposited in the Borden Delta of northern Indiana and Illinois. Thus, the early Valmeyeran in Illinois is characterized by units of highly variable thicknesses, due primarily to the depositional pattern of the Borden Delta. In the north, the delta consists of siltstones deposited in water estimated to be 183-305 m deep (Lineback, 1968). These sediments thinned southward into a basin in which a thick unit of siliceous and cherty carbonate was later deposited (the Fort Payne). When stability ensued, infilling exceeded subsidence (Ullin Limestone), so that a surface of relatively low relief resulted. This, then, was the flat, relatively shallow shelf substrate for the Salem Limestone shoaling-upwards cyclic deposits.

Shoaling-Upwards Cycles

Salem Limestone sediments mark the beginning of sedimentation at wave base in the Illinois Basin. Water depth has been estimated to be no more than 10-30 m deep (Cluff and Lineback, 1981, p. 46). At this bathymetric position, sediments were deposited in a series of shoaling-upwards cycles. An understanding of what these cycles are, and how they might have formed, is central to an understanding of the Salem in general.

There are many theories concerning the causes of cyclical sedimentation, but the two main divisions are 1) steady subsidence with variations in sedimentation rate and/or climate, or 2) episodic vertical tectonic movement. The result of either (or a combination of both) is as follows: carbonate is produced on shelves of intermediate depth and moderate-high wave or tide energy. These skeletal-oolitic sediments build oceanward, in the direction of highest energy, and as they build, they are piled up and shaped by the waves or tides creating them. Shoreward of these skeletal-oolite shoals is a lower energy, subtidal shelf or lagoonal zone, where primarily skeletal packstones and grainstones are being deposited. These overlie the oolite shoals in vertical sequence, and are themselves overlain by further shoreward, shallow lagoon or intertidal sediments. This "capping" facies is often represented by wackestones, dolomites, and/or evaporites. This surface, then, is closed to carbonate deposition, and a relative transgression must occur before carbonate production is able to create the shoal phase of the next cycle. This transgression is often described as "rapid" because the sediments representing it are very thin or non-existent. Using a word which connotes speed, such as "rapid", can be misleading.

Thin transgressive deposits could result from several causes. For instance, Wilson (1975, p. 54) points out that transgressions often destroy their own deposits when waves seaward of the shoals migrate across lagoonal deposits. Slower sedimentation rates during a transgression would also leave a thinner record. An important controlling factor, however, on the appearance of these transgressive deposits is the fact that the transgression occurred across an epeiric sea floor. Irwin (1965) estimated that these seas had slopes of less than one foot per mile, which created very shallow, low energy zones hundreds of miles wide. In this setting, even a small change in water depth would cause a relatively large advance landward, and the transgression could actually be "rapid."

This epeiric sea environment not only promotes cyclic deposition, but it controls the distribution of lithofacies to some extent. In general, the sediments tend to be deposited in concentric facies belts which follow bathymetric contours. The sediments are wedge-shaped, thickening seaward, but are locally controlled by topography. Reef trends are absent (Ahr, 1973, p. 221).

Figure 6 diagrams the development of a shoaling-upwards cycle, and shows the resulting facies distribution and characteristic spontaneous potential-resistivity log curve. It is this log signature which Wayne Pryor (1980) used to delineate five shoaling-upwards cycles within the Salem for this study area. These cycles have been named for colors, the oldest cycle being Orange, then Blue, Green, Purple, and finally, Red (Fig. 7). These cycles will be described in more detail in the chapter titled "Subsurface Mapping."

Figure 6. Idealized development of a single shallowing-upwards cycle, and the corresponding SP-resistivity log. Stage one shows ooid shoals developing in a shallow, high energy zone, and building towards the direction of highest energy, which is seaward. Behind the shoal is a lower energy, open marine intertidal lagoon. During stage two, these sediments prograde, with the landward facies capping the seaward facies. Stage three shows that further progradation can bring sabkha sediments into contact with the intertidal lagoon sediments. This surface, then, is closed to carbonate deposition; and a relative transgression occurs across this surface to begin the next shoaling-upwards cycle (after Wilson, 1974, p. 53).

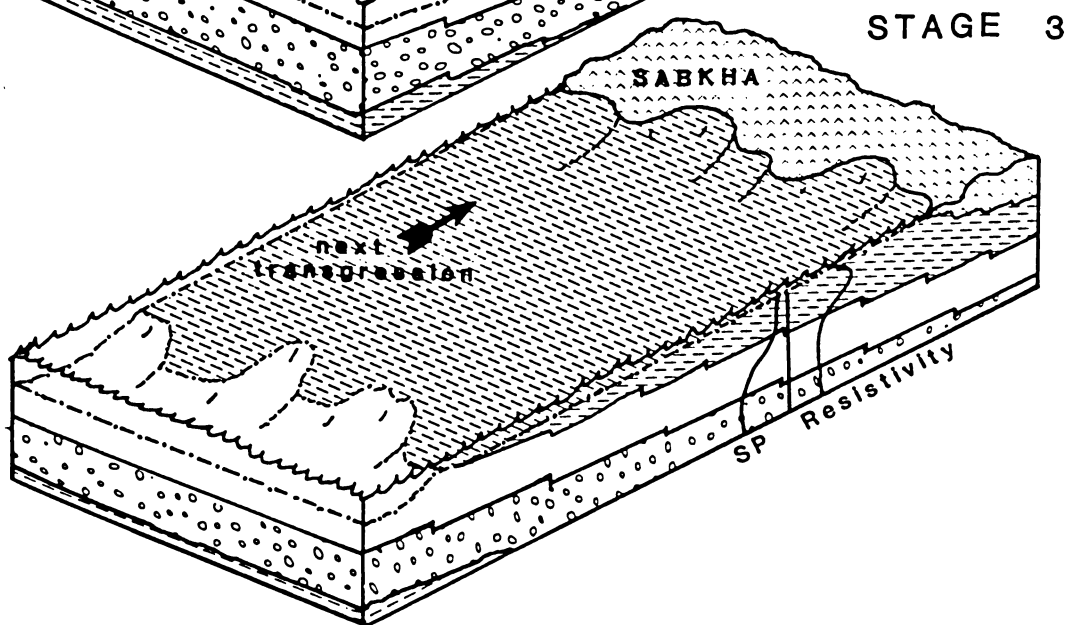
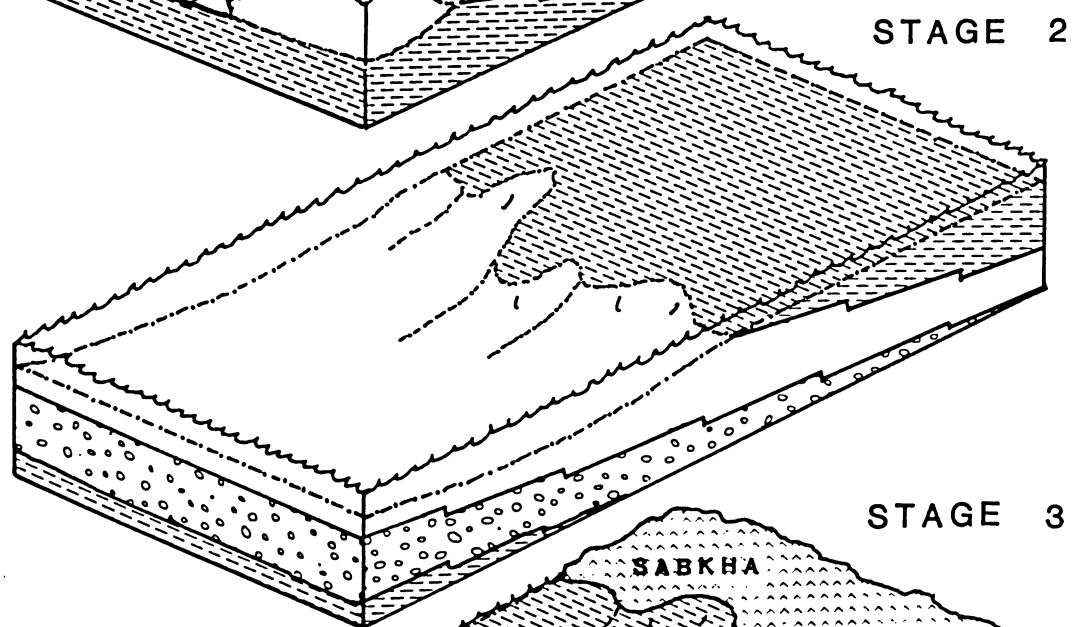
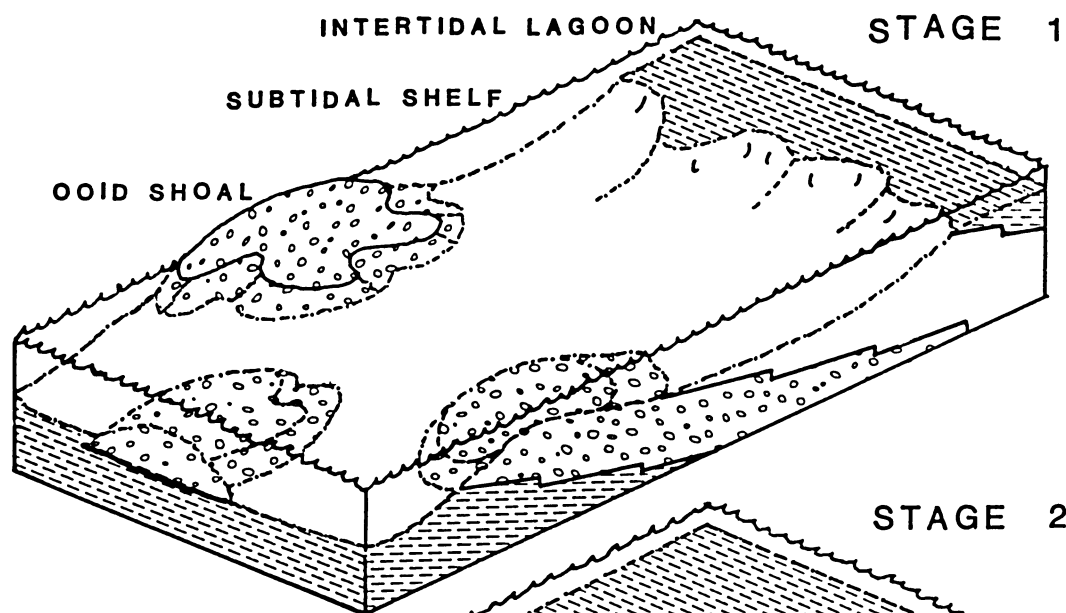
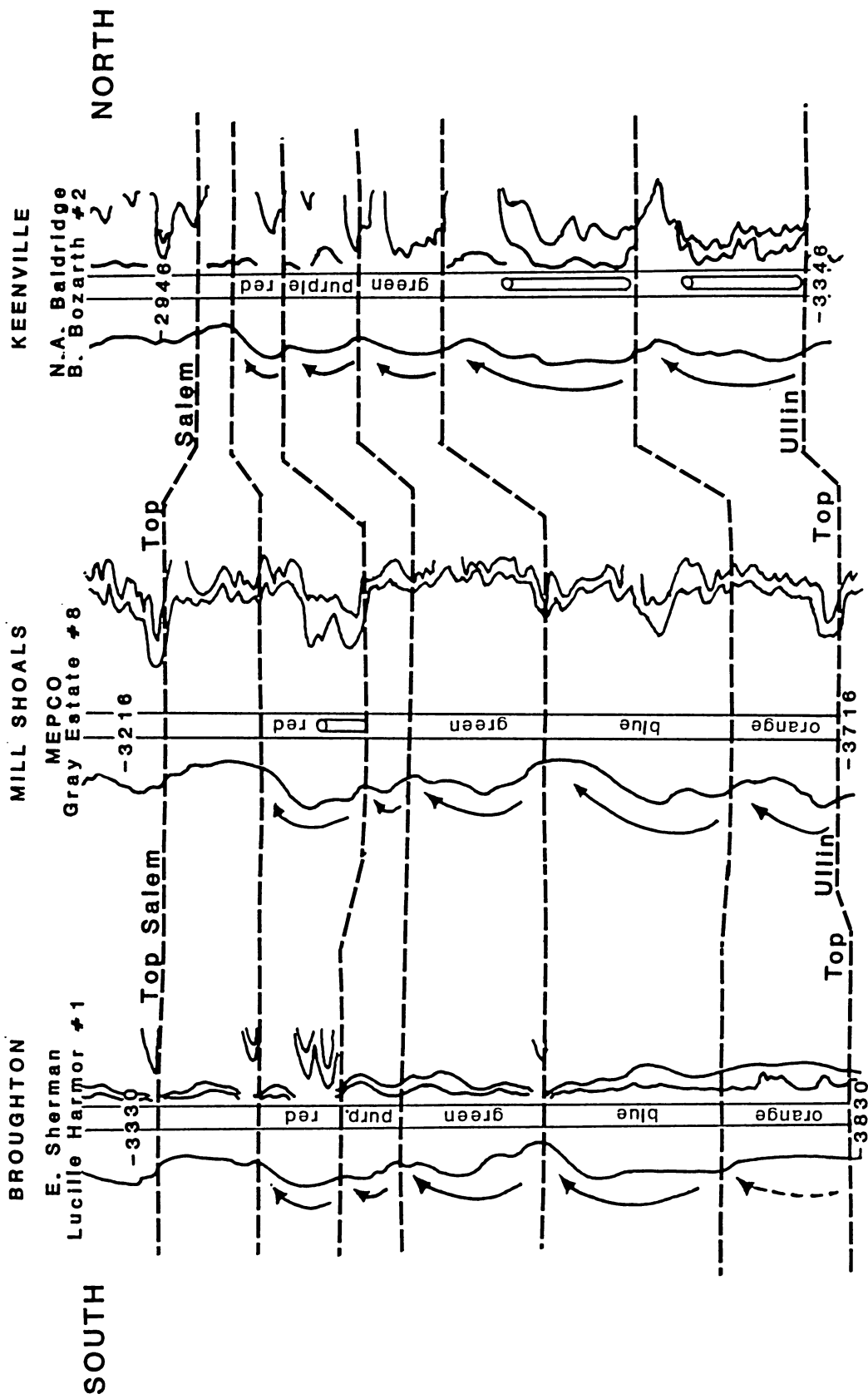


Figure 7. Five shoaling-upwards cycles in the Salem Limestone, and relative positions of cores used in this study. This cross section shows that at the beginning of Salem time, in the south, the water was too deep for ideal cycle development; while in the north, the water was an optimum depth for ideal cycle development. Infilling of the basin occurred with the deposition of each cycle; so that by the end of Salem time, the converse was true. Water was too shallow in the north for ideal cycle development, but was an optimum depth in the south for ideal cycle development. This is described in more detail in the chapter titled "Subsurface Mapping".

FIVE SHOALING-UPWARDS CYCLES in SALEM LIMESTONE



SUBSURFACE MAPPING

Methods

A series of subsurface maps have been generated for the Salem Limestone and its cycles using 417 electric logs obtained from the Oil and Gas Library at the Illinois State Geological Survey, Urbana, Illinois. These logs represent essentially all the Salem penetration in Hamilton County and Range 8 East and Range 9 East in White County; and selected logs from Wayne County. Well locations are found on Fig. 8.

Salem shoaling-upwards cycles in each well were correlated to their nearest neighbors based on an idealized shoaling upwards cycle as described by Cluff and Lineback (1980, p. 50). Figure 9 depicts this idealized cycle and the corresponding spontaneous potential-resistivity curve associated with it. Structure maps of each Salem cycle are based on the top of the low porosity, highly resistive portion which caps each cycle. Net porosity and porosity-isopach ratio maps are based on relative negative SP deflection from a shale baseline.

The sparse well log control within the Hamilton-White-Wayne Counties study area has determined that five field-centered areas should be the foci for subsurface mapping. These areas are shown in Fig. 8. Each area has a set of sixteen maps: a structure map on the top of the Salem, the tops of each of the five cycles, top of the Ullin; and a net porosity map, an isopach map, and net porosity/isopach ratio maps for the three most productive cycles in the Salem, the Red, Blue, and Orange.

The purpose of these maps is four-fold. 1) To demonstrate the continuity and mappability of the Salem cycles; 2) To compare these mappable units between productive fields; 3) To determine if these maps

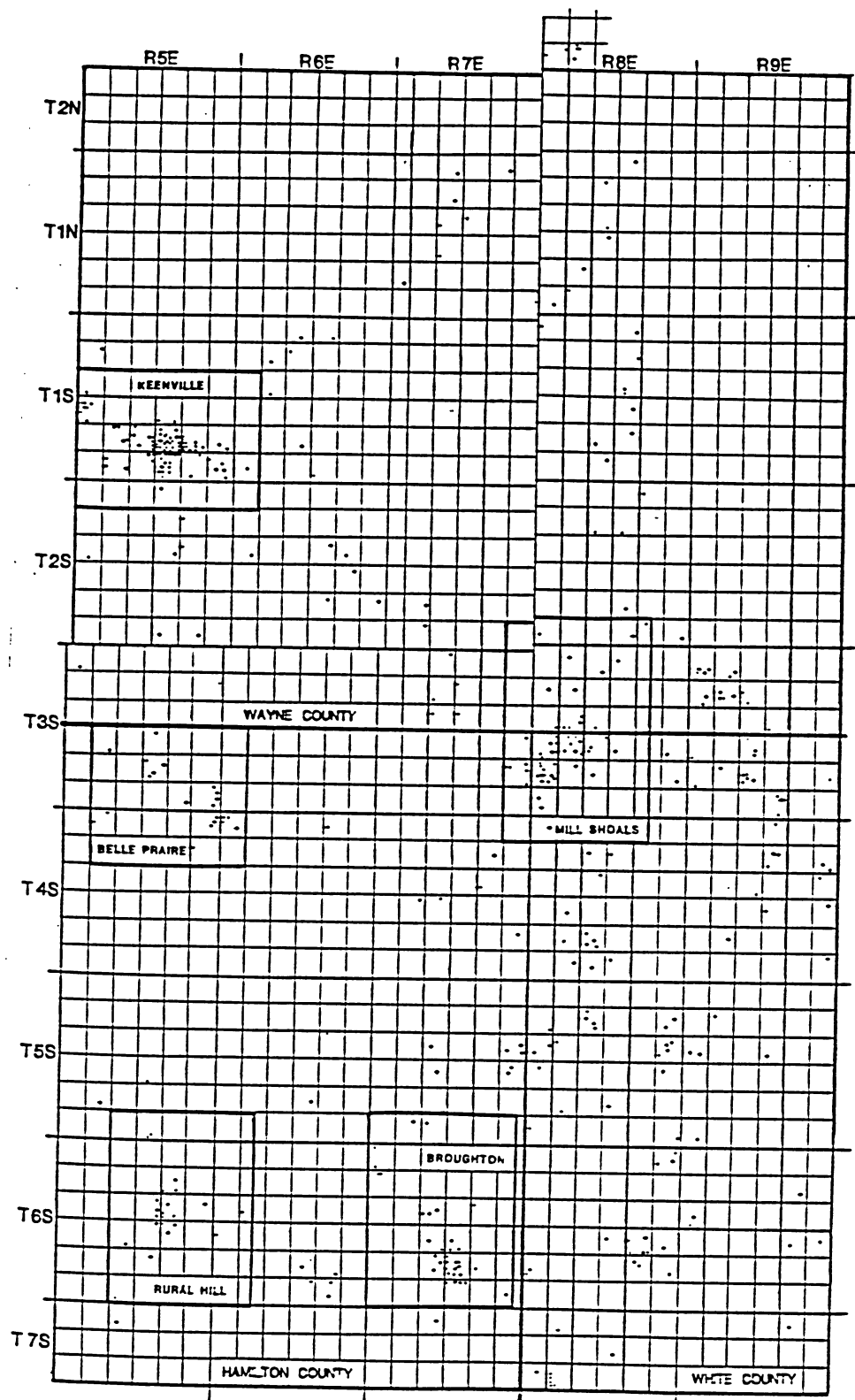


Figure 8. Study area showing well locations and field centered map locations.

IDEALIZED SALEM GRAINSTONE CYCLE

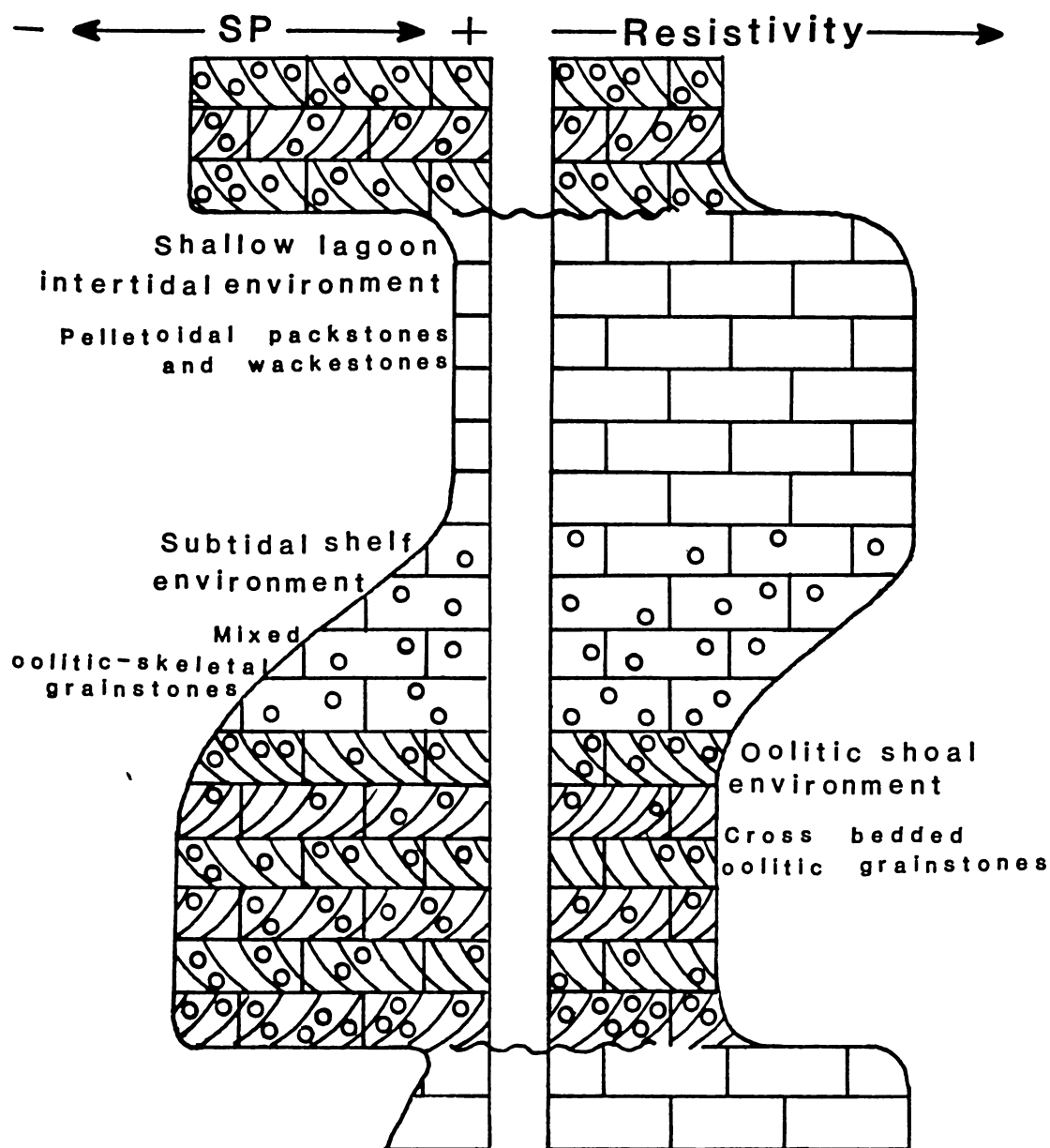


Figure 9. Idealized shoaling-upwards cycle spontaneous potential-resistivity curve, and associated lithologies (after Cluff and Lineback, 1981, p. 50).

show a correlation between structure, isopach, and distribution of porosity; 4) To investigate the relationship between geometries of the mapped cycles and lithology, depositional environment, and preexisting and syndepositional structure.

The electric log correlation methods used in this study to address the problems outlined above have two major limitations. The first is the low-density of well control available for construction of these maps. The second is the effect of diagenesis (cementation, dolomitization, secondary porosity development) on the distribution of porosity within a cycle. Because the shape of the SP curve is, in part, controlled by amount of porosity, diagenesis which affects porosity can influence depositional environment interpretations based on the SP curve. Both of these shortcomings are common problems in subsurface geology. These methods, however, were developed based on sound geological principles, and if the limitations are kept in mind, the methods can produce useful geological models.

Distribution and Geometry of Sediments

Structure maps on top of the Salem (Figs. S₁-S₅) reveal that of the five mapped areas, the Keeneville area is a structural nose; Belle Prairie and Broughton are saddles associated with structural highs and have closure; and Mill Shoals and Rural Hill are small domes in and of themselves. In all five areas, structural elements with closure have elongate axes with a general alignment of approximately N30E. The structural noses and saddles have a general alignment of N60-N70W.

Inspection of logs across the entire three-county area has shown that each of the five Salem cycles is a mappable unit. Some of these

cycles, however, more closely resemble the "ideal" (Fig. 9) than others. The quality of development of these cycles, and their persistence across the study area, can indicate which portion of the basin was at the optimum water depth for cycle development.

The most persistent beds within the Salem are the "tight", highly resistive "mud" facies, which cap each cycle. Of these, two particularly persistent beds are the resistive units which cap the red cycle and the blue cycle. Correspondingly, the two cycles which contain persistent porous intervals in all areas are the red cycle and the blue cycle. Conversely, the orange cycle is best developed to the north (Keeneville, Belle Prairie), but very poorly developed to the south. The green and purple cycles are thin, and irregularly developed, but everywhere present.

These observations seem to indicate a general shallowing of the Illinois Basin during Salem time as follows:

- 1) The Orange (basal) cycle is transitional with underlying Ullin in southern Hamilton and White Counties. Water here was generally too deep for good cycle development, although some development occurred on structural highs (e.g., Broughton). To the north in Wayne County, where the basin was structurally higher, shallower water conditions promoted good Orange cycle development.
- 2) The Blue cycle is well developed everywhere. Possibly the Orange cycle infilled the basin to an optimum depth for construction of shoaling upwards cycles. This good development is the reason that "mud" facies capping the Blue cycle is such an excellent marker bed within the Salem.
- 3) The Green and Purple cycles are relatively thin. This could be be-

cause the basin was so shallow that a very small change in relative sea level caused widespread transgressions and regressions. Alternatively, the water could have just been too shallow for good cycle development, and the results were thin cycles with erratic porosity distribution. The Purple cycle is interesting because it is a coarsening-upward cycle, unlike all the others.

4) The Red cycle is generally well-developed, but its porous zone is a dolomite, not an oolite shoal. This dolomite cycle is an indication that the sediments had built up high enough to be strongly affected by meteoric water as it mixed with marine water. To the north in the Keeneville field, where the basin is structurally higher, the Red cycle is very thin; its porous zone is essentially missing; and some of the rocks show evidence of hardgrounds and erosional surfaces (Cluff and Lineback, 1980, p. 62). Because the Red cycle "mud" facies is so persistent throughout the area, this cycle was probably uniformly shallow.

Overlying the Salem Limestone shallowing-upwards sequence is the St. Louis Limestone, an evaporitic, cherty limestone thought to be of intertidal and supratidal origin (Cluff and Lineback, 1980, p. 65). In fact, the Salem and St. Louis are stratigraphically equivalent just north of Wayne County (Lineback, 1972).

The development of the Salem shallowing-upwards cycles clearly reflects the shallowing of the Illinois Basin during Salem time; but the cycles were also affected by pre-existing topography within the basin. That these structures were pre-existing is shown by two pieces of information. First, the close correspondence between structure maps on the top of the Ullin and on top of the Salem indicate little structural movement during that time period (Figs. U₁-U₅ and S₁-S₅). Second,

isopach maps (Figs. X₁-X₁₅) show that in each area, the mapped cycles thin over these antecedent highs. Sediments were presumably swept off the crests of these highs by greater wave action and deposited on the slopes of the structure. The only exceptions to this are the Red cycle dolomite in Mill Shoals, which is an early diagenetic feature; and the Blue cycle porous zone in Belle Prarie (an oolite shoal?).

Porosity development on the crests of the structures is variable (Figs. Y₁-Y₁₅). If the amount of porosity thickens over the crest, it could be a result of better sorting and ooid development under higher energy conditions. If the amount of porosity thins over the crest, it could be because the sediments themselves are thinning over the crest, or, the higher bathymetric position could have facilitated water movement through the sediment, and caused thorough cementation.

Net porosity-isopach ratio maps (Figs. Z₁-Z₁₅) show whether net feet of porosity is controlled by sediment thickness or by. In general, as the sediments get thinner, the porosity increases, indicating that porosity is not directly correlatable with sediment thickness. Two exceptions, however, are Mill Shoals and Rural Hill (the two domes). In these cases, they do correlate directly. The porosity/thickness ratio becomes smaller off structure in the intershoal area, where wave energy was too low for good ooid development, and the primary sediment deposited was carbonate mud.

Tharp (1983) and Roberts (1984) reported for the McClosky and Spar Mountain, respectively, that the ooid shoals tended to avoid each other in vertical profile, reflecting the effects of syndepositional topography on ooid shoal development. This phenomenon was not noted for the Salem ooid shoals. It is possible that the Salem's localized maps on

pre-existing structure mask the effects of syndepositional structure. Figure 10 is a summary of these thickness and porosity data for each field.

①

isopach
φ
φ/iso.

IDEAL Cross-section through sediments over pre-existing dome.

THIN
THIN
SAME

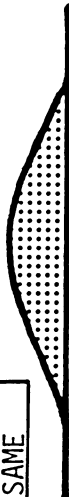


②

isopach
φ
φ/iso.

IDEAL Cross-section through oolite shoal.

THICKEN
THICKEN
SAME



③

isopach
φ
φ/iso.

IDEAL Cross-section through sediments over dome with post-depositional movement.

SAME
SAME
SAME



①

Idealized thickness/porosity data over pre-existing, syndepositional, and post-depositional structures; and their expected map trends over structural crests.

②

Map trends over structure crests for isopach, net porosity, and net porosity-isopach ratio maps of the Salem Limestone. This data indicates most structures were pre-existing.

RED CYCLE BLUE CYCLE ORANGE CYCLE

THINS	THINS	THINS	isopach
THICKENS	THICKENS	THINS	φ
THICKENS	THICKENS	THICKENS	φ/iso.
THICKENS	THINS	THINS	isopach
THICKENS	THINS	THINS	φ
THICKENS	THINS	THINS	φ/iso.
THINS	THINS	THINS	isopach
THINS	THINS	THINS	φ
THINS	THINS	THINS	φ/iso.
THINS	THINS	THICKENS	isopach
THICKENS	THINS	THICKENS	φ
THICKENS	THICKENS	THICKENS	φ/iso.
THINS	THICKENS	THIN	isopach
THICKENS	THICKENS	THICKENS	φ
THICKENS	THICKENS	THICKENS	φ/iso.

Keenville

Mill Shoals

Rural Hill

Broughton

Belle Prairie

Figure 10. Summary of isopach and porosity data, and its relationship to pre- and syndepositional structure for each field.

LITHOLOGY

Cores and samples for this study were obtained from the Core Library at the Illinois State Geological Survey, Champaign, Illinois. Two continuous cores were available: the Fletcher F. Farrar Roy Reed #4, T1S R5E Sec. 27, Wayne County, Illinois (3600 - 3656 feet, blue cycle); and the Moore Engineering and Production Company Gray Estate #8, T3S R8E Sec. 30, White County, Illinois (3805 - 3828 feet, red cycle). Two composite cores were also available: the Union Oil Company of California Henry R. Bissey #5, T2N R8E Sec. 17, Clay County, Illinois (3635 - 3674 feet, orange cycle); and the Texas Company M. Davis #14, T6S R7E Sec. 7, Hamilton County, Illinois (3782 - 3786 feet, blue cycle). Figure 7 shows the relative position of these cores within an idealized electric log signature.

Carbonate rock descriptions appearing in this study utilize an adapted version of Embry and Klovan's (1971) carbonate classification, which is a modification of Dunham's (1962) system. The adaption (shown in Fig. 11) changes Embry and Klovan's mudstone to micstone to avoid confusion with a highly argillaceous rock.

Depositional environment interpretations are based in part on the Standard Facies Belts (SFB) and Standard Microfacies (SMF) of Wilson (1974) (Fig. 12).

These samples have been divided into seven lithofacies, based primarily on lithology and percentage and type of allochems. Computer-generated correlation matrices have helped to confirm the chosen separations between samples and in addition have revealed some relationships between these lithologies and diagenetic products. The lithologies are as follows:

ALLOCHTHONOUS LIMESTONES ORIGINAL COMPONENTS NOT ORGANICALLY BOUND DURING DEPOSITION				AUTOCHTHONOUS LIMESTONES ORIGINAL COMPONENTS ORGANICALLY BOUND DURING DEPOSITION				
LESS THAN 10% > 2mm COMPONENTS		GREATER THAN 10% > 2mm COMPONENTS		BY	BY	BY		
		MATRIX SUPPORTED		> 2mm COMPONENT SUPPORTED		ORGANISMS	ORGANISMS	ORGANISMS
CONTAINS LIME MUD (<.03 mm)						NO LIME MUD	GRAIN SUPPORTED	WHICH
MUD SUPPORTED		LESS THAN 10% GRAINS < .03mm < 2mm		ACT	ENCRUST	BUILD		
GREATER THAN 10% GRAINS				AS	AND	A RIGID		
MIC- STONE	WACKE - STONE	PACK - STONE	GRAIN- STONE	FLOAT- STONE	RUD - STONE	BAFFLE- STONE	BIND- STONE	FRAME- STONE

Figure 11. Carbonate rock classification used in this study. This adaptation of Embry and Klovan's classification (1971) changes mudstone to micstone, to avoid confusion with an argillaceous rock.

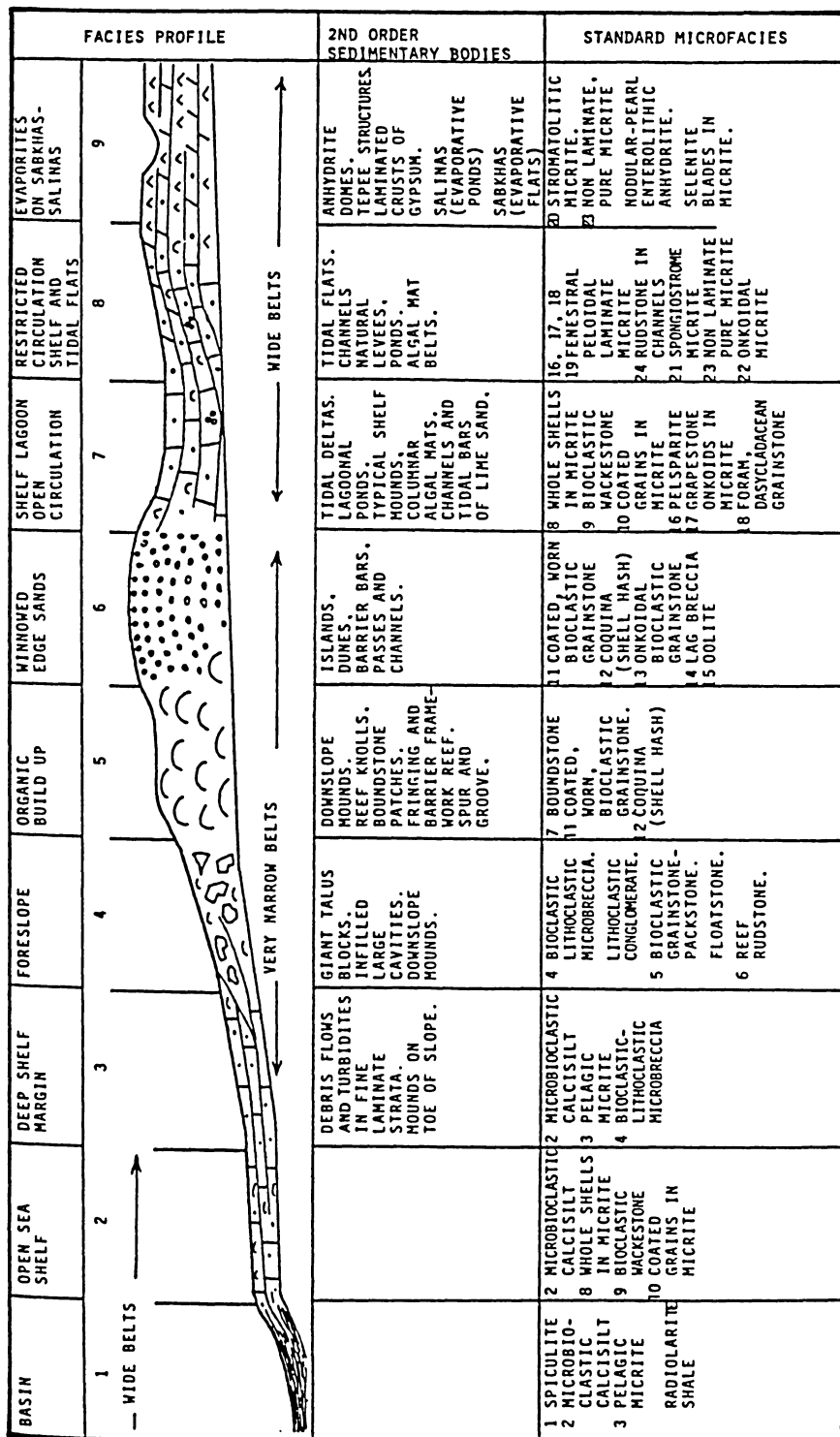


Figure 12. Summary of Wilson's (1974) Standard Facies Belts (SFB) and Standard Microfacies (SfF) (p. 351).

1) Echinodermal-Oolitic Grainstone

Description

This lithofacies (Figs. 13 and 14) is defined by the presence of greater than 15 percent ooids and echinoderm fragments and less than 5 percent micrite. There is often at least 15 percent bryozoa. Minor constituents include Endothyra sp., ostracods, pelecypods, gastropods, brachiopods, and traces of pellets, pelloidal aggregates, grapestone, and intraclasts. Geopetal pellets are present in two samples. Allochems average approximately 64 percent of the rock.

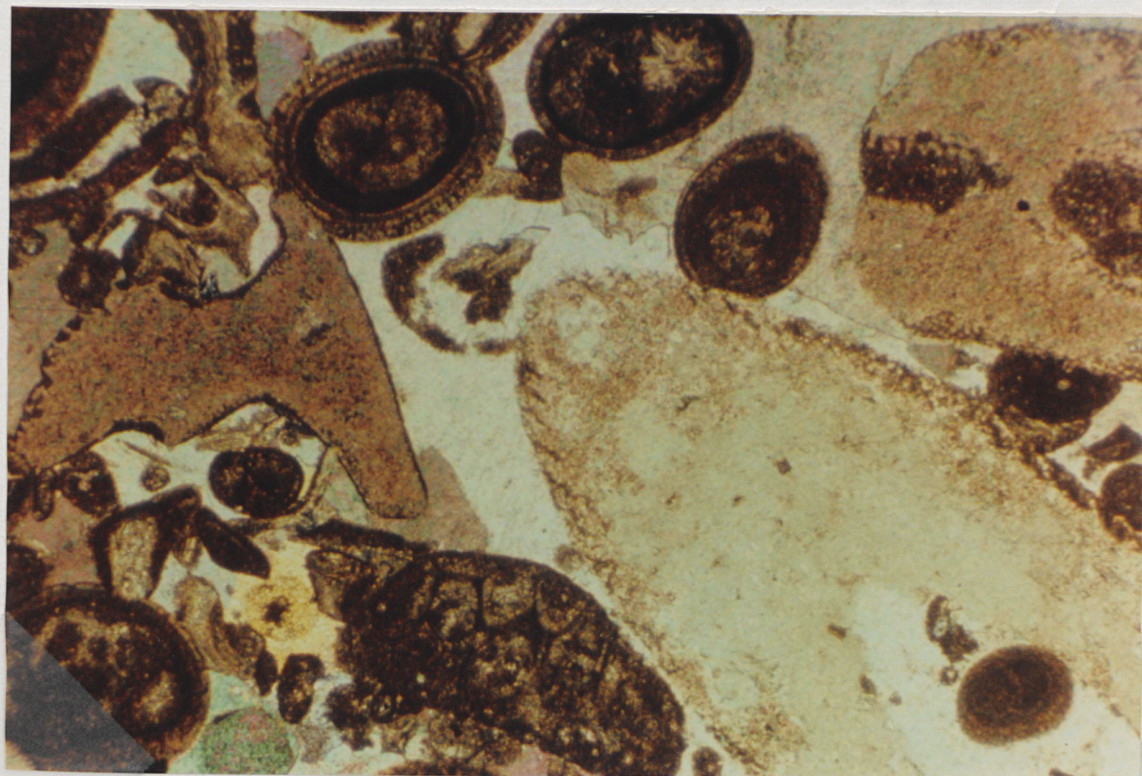
Grain size averages 350 microns; but irregular fossil fragment shapes and the presence of geopetal pellets make sorting poor-moderate. Most grains have micrite rims, and superficial oolitic coatings are common. Packing ranges from high (sutured grain contacts, broken grains, spalled oolitic layers and micrite rims) to low (whole grains and point contacts).

Orthochems average approximately 32 percent of the rock. The most abundant cement type is syntaxial overgrowths, but equant calcite/drusy mosaic calcite are also very important. Isopachous blades are common, but generally only internal to grains. Xenotopic-C dolomite is present in almost all samples, ranging up to 22 percent of orthochems in some places. Trace orthochems include Fe-calcite and silica.

Porosity ranges from 0 to 9 percent, but averages 4 percent. The most common type is primary intergranular, but primary intragranular, oomoldic, moldic, fracture, and fenestral-vuggy are also present. Average pore size is approximately 100 microns, but the fenestrae range up to 3300 microns.

Figure 13. Echinodermal -Oolitic Grainstone (Lithofacies 1), hand sample.

Figure 14. Echinodermal -Oolitic Grainstone (lithofacies 1), thin section. Up is towards top of page.



Stratigraphic Position

This lithofacies constitutes the upper portion of the Orange cycle and is scattered through the Blue cycle, often grading into a more oolitic (#3, below) or more bioclastic (#2, below) lithofacies.

Depositional Environment

The depositional environment of this lithofacies is best characterized by Wilson's SFB 6 and SMF 11. The presence of full and superficial ooids, absence of micrite, light color, and diverse fauna indicate well-oxygenated water with moderate-high wave energy. This lithofacies probably represents a location somewhat to the landward side of the shoal or tidal bar because the abundance of fauna would require a relatively stable substrate for development.

2) Echinodermal-Bryozoan Grainstone

Description

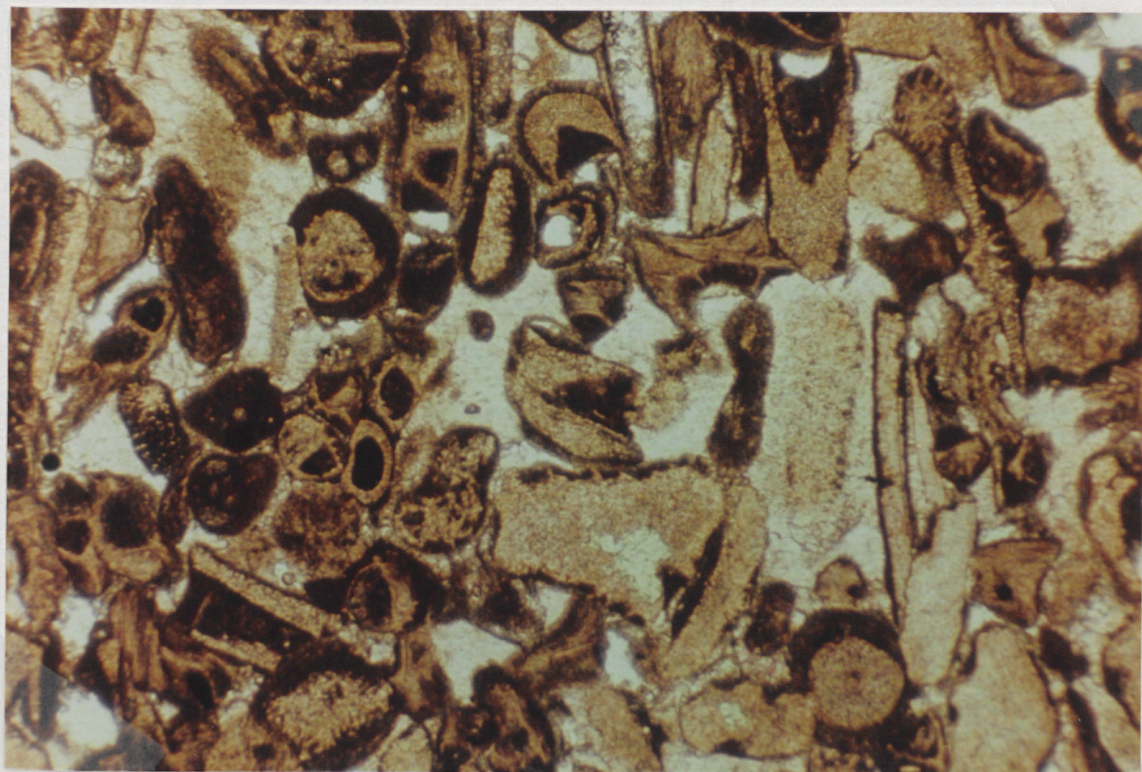
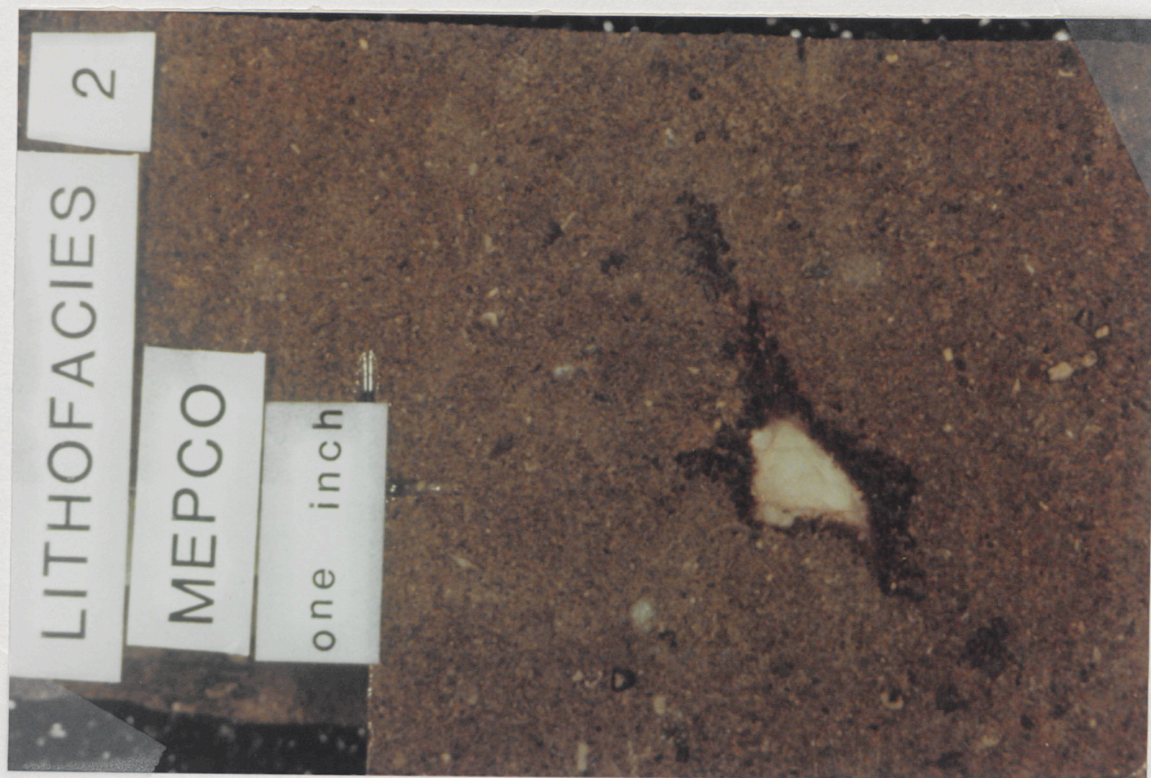
This lithofacies (Figs. 15 and 16) is defined by greater than 15 percent echinoderm and bryozoa fragments and less than 5 percent micrite and ooids. Other allochems include: Endothyra sp., brachiopods, pelecypods, gastropods, ostracods, ooids, grapestone, pellets, pelloidal aggregates, and trilobites. Allochems account for approximately 65 percent of the rock.

Grain size averages approximately 300 microns, but sorting in this lithology is poor. Most grains have micrite rims. Packing ranges from high (broken grains, stylolites, sutured grain contacts) to low (grains "floating" in cement). Low angle cross bedding is present in some samples.

Orthochemical constituents account for approximately 31 percent of the rock. The most abundant cement type is syntaxial overgrowths.

Figure 15. Echinodermal-Bryzoan Grainstone (Lithofacies 2), hand sample.

Figure 16. Echinodermal-Bryzoan Grainstone (lithofacies 2), thin section. Up is towards top of page.



Equant calcite and drusy mosaic are significant porosity reducers. Isopachous blades and fibers are well-developed in a majority of samples. All samples have Xenotopic-C dolomite, and anhydrite and silica are common.

Porosity ranges from 0 to 12 percent, but averages approximately 4 percent. The most common type of porosity is primary intergranular, but there is some moldic and oomoldic porosity. Average pore size is approximately 100 microns, with a range up to 1350 microns.

Sratigraphic Position

This lithofacies is found intercalated with bioclastic dolostone (#7, below) in the upper portion of the Red porous cycle and intercalated with bioclastic dolostones in the lower portion of the Orange porous cycle. In the Blue cycle, it grades into (above and below) oolitic echinodermal grainstones (#1).

Depositional Environment

This lithofacies most closely fits Wilson's SFB 7 and SMF 11. General lack of ooids excludes a tidal shoal environment; however, coated grains, absence of micrite, and a few cross beds indicates some moderate amount of wave or tide energy. Fauna is a somewhat restricted marine assemblage. Relatively well-developed marine isopachous cement may indicate that this lithofacies remained under marine water influence longer than shoal-related facies such as the oolitic-echinodermal grainstone (#1), and the oolitic grainstone (#3, below). Its close association with bioclastic dolostones (#7) may also be an indication of a slightly restricted depositional environment.

3) Oolitic Grainstone

Description

The oolitic grainstone lithofacies (Figs. 17 and 18) is defined by the presence of greater than 45 percent ooids and less than 5 percent micrite. The most common bioclasts are echinoderm fragments, but also present in small amounts are bryozoa, Endothyra sp., pelecypods, and gastropods. Pellets, pelloidal aggregates, and grapestone are also present. These allochems account for 68 percent of the rock.

Sorting in this lithofacies varies from well-sorted to poorly-sorted. Average grain size is approximately 350 microns. Packing ranges from very low (floating grains) to very high (spalled ooids, stylolites); and this range of packing can be seen in the space of an inch. These sediments are commonly crossbedded.

Orthochemical constituents account for approximately 28 percent of the rock. The most common cements are equant calcite and drusy mosaic. Isopachous blades and isopachous fibrous cements are quite well-developed in some samples. Xenotopic-C dolomite is present in all samples; with Fe-calcite, Fe-dolomite, anhydrite, and silica being less common. "Dead oil" appears in pores of several samples.

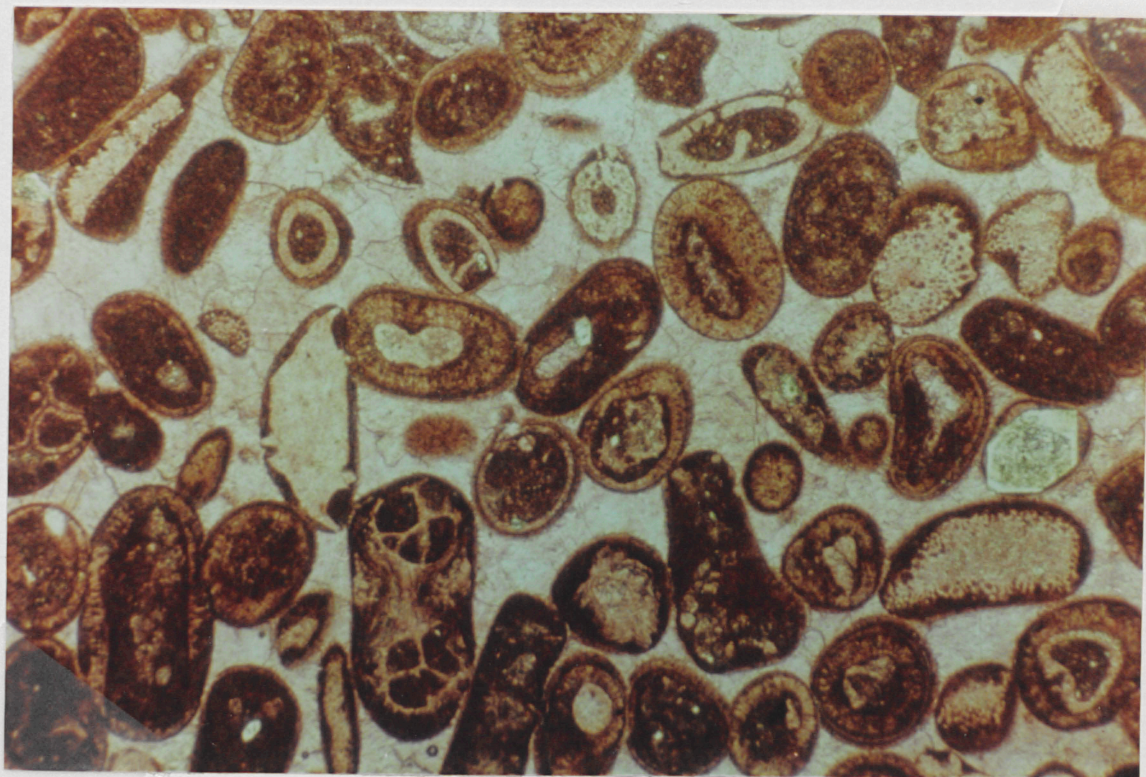
Porosity in this lithofacies ranges from 0 to 9 percent, but averages about 4 percent. The most abundant porosity type is secondary moldic or vuggy, and some of these pores reach 1 cm in length. Also present is primary intergranular (probably enhanced), fracture, and oomoldic porosity.

Stratigraphic Position

The oolitic grainstone lithofacies is found throughout the Blue cycle porous zone, interfingering with and grading into other litho-

Figure 17. Oolitic Grainstone (Lithofacies 3), hand sample.

Figure 18. Oolitic Grainstone (Lithofacies 3), thin section. Up is towards top of page.



facies, most often oolitic-echinodermal grainstones (#1) and echinodermal-bryozoa grainstones (#2). There is only one example of this lithofacies from the Orange cycle porous zone.

Depositional Environment

The oolitic grainstone lithofacies is best characterized by Wilson's SFB 6 and SMF 15, a marine shoal lime sand. A Sedimentation Seminar (1966) showed that crossbed directions within the Salem are bipolar, indicating a tidal influence on a shallow marine shelf. In addition, the SW-NE orientation of porous zones within the Salem (striking perpendicular to paleoshoreline) is also a good indication of a tidally influenced environment. Similar conclusions were reached by the Sedimentation Seminar (1966), Choquette and Steinen (1980), Roberts (1984), Tharp (1983), Off (1963), and Ball (1967).

4) Oolitic Packstone

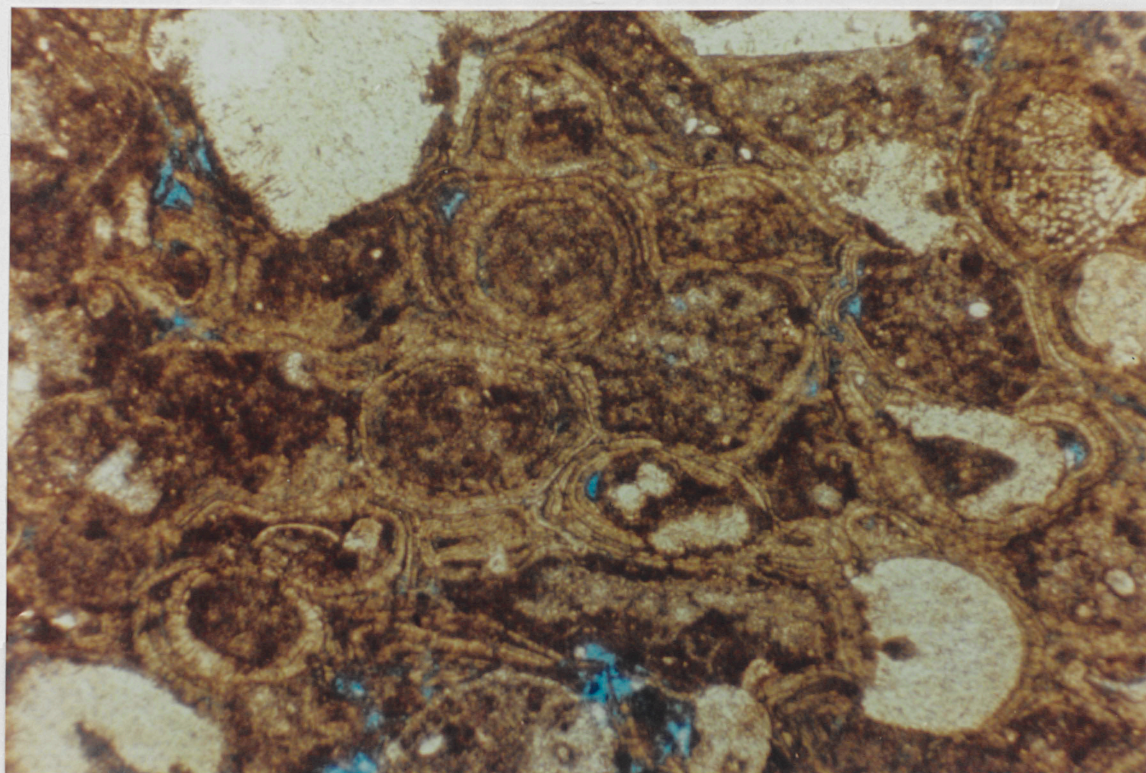
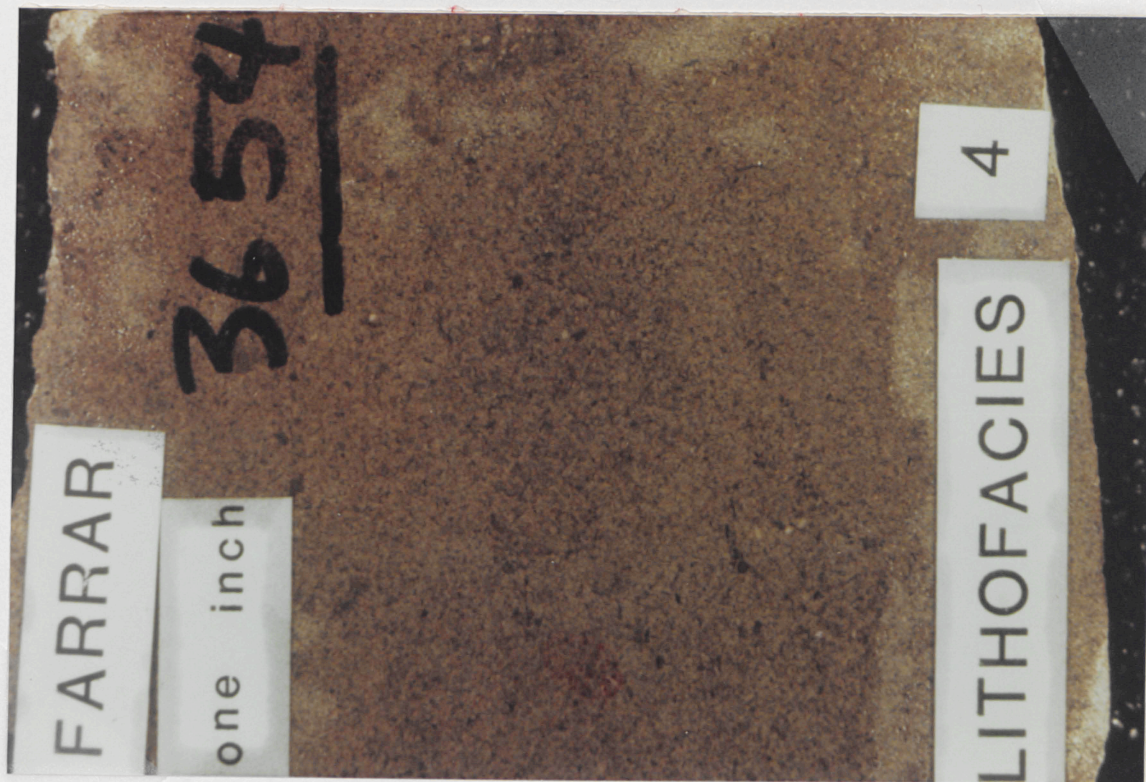
Description

This lithofacies (Figs. 19 and 20) is defined by the presence of greater than 45 percent ooids and greater than 5 percent micrite. Allochems account for approximately 78 percent of the rock; and of this, ooids are the most common allochem. Fauna include echinoderms and bryozoa, with small amounts of Endothyra sp., brachiopods, grapestone, and pelloidal aggregates.

Grains average approximately 350 microns, but sorting is poor, and grain size ranges from 30 microns to 2100 microns. The texture of this lithofacies is very unusual. These ooids have radial cortices composed of fibrous crystals. Very high packing caused "plastic" deformation of ooids, so that the oolitic coatings are of very uneven thickness around the nucleus, and the ooids became interlocked without sutured contacts.

Figure 19. Oolitic Packstone (Lithofacies 4), hand sample.

Figure 20. Oolitic Packstone (Lithofacies 4), thin section. Up is towards top of page.



After compaction, these compressed ooid coatings were preferentially dolomitized.

This interlocking texture leaves little room for orthochemical constituents -- they make up approximately 20 percent of the rock. Of that 20 percent, micrite constitutes approximately 11-15 percent. The remainder consists of syntaxial overgrowths, drusy mosaic and equant calcite, and isopachous bladed and fibrous cements internal to grains.

Porosity in the oolitic packstone lithofacies averages from 2 to 3 percent and is enhanced primary intergranular.

Stratigraphic Position

This facies is very rare, and is restricted to the lower portion of the Blue cycle porous zone.

Depositional Environment

The allochemical constituents of this lithofacies seem to represent deposition on an active marine shoal. High packing occurred very early during diagenesis; and was then followed by selective dolomitization of the ooid cortices and the micrite component of the matrix. The presence of abundant micrite does not fit the marine shoal model, and it may be diagenetic.

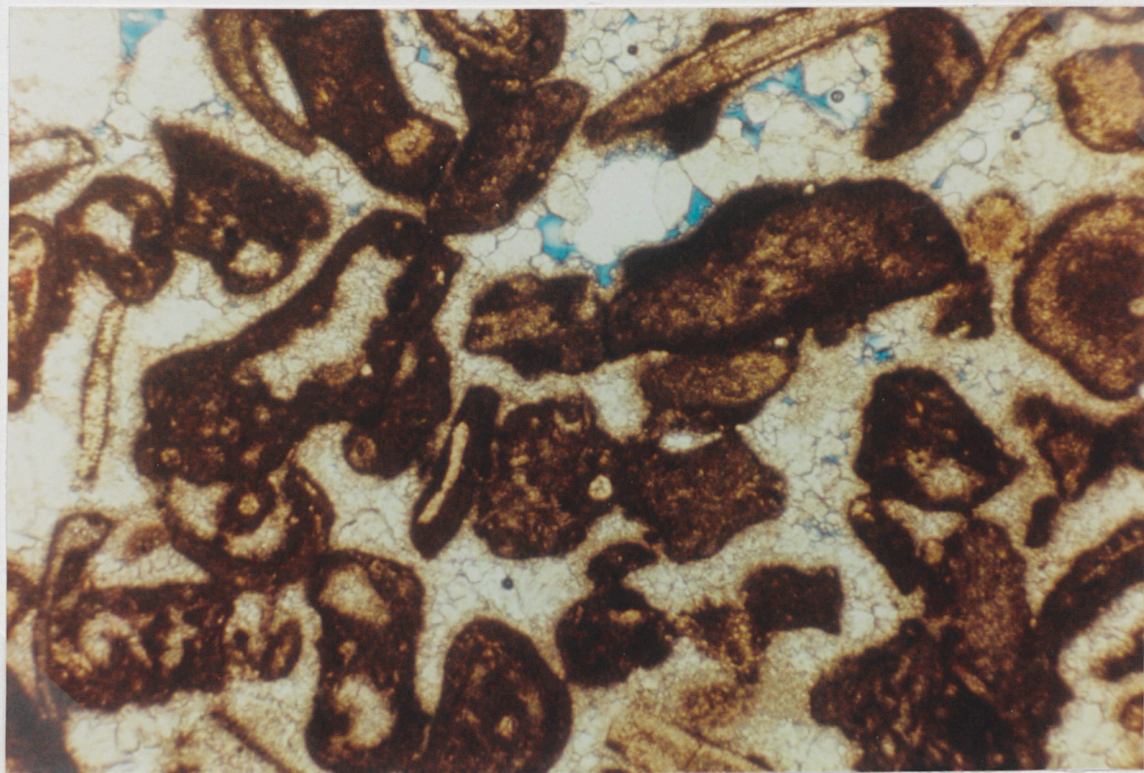
5) Pellobidal Aggregate Grainstone

Description

This lithofacies (Figs. 21 and 22) is defined by the presence of greater than 30 percent pellobidal aggregates, or "Bahamite" particles as defined by Beales (1958). Allochems account for 55 percent of the rock. Of this, the only significant fossil fragments are echinoderms. Also present in small amounts are bryozoa, Endothyra sp., ostracods, gastro-

Figure 21. Pelloidal Aggregate Grainstone (lithofacies 5), hand sample.

Figure 22. Pelloidal Aggregate Grainstone (lithofacies 5), thin section. Up toward top of page.



pods, and trilobites. Calcspheres and grapestone are common. Also present are a small number of superficial ooids, intraclasts, and geopetal silt.

Average grain size is approximately 350 microns, but some samples exhibit grading. Packing in this lithofacies is very low; shown by "floating" grains and what appears to be original fenestral pore space, now filled with calcite.

Orthochemical constituents account for approximately 43 percent of the rock. The most abundant cement types are equant calcite/drusy mosaic. Isopachous bladed and fibrous cements are very well developed. Syntaxial overgrowths, anhydrite, and Xenotopic-C dolomite are present in small amounts. Micrite constitutes approximately 5 percent of the orthochemicals.

Porosity averages approximately 2 percent and is mostly primary intergranular with a small amount of primary intercrystalline and secondary moldic.

Stratigraphic Position

The pelloidal-aggregate lithofacies in these samples is only found at the top of the Blue cycle porous zone, overlying the oolitic grainstone lithofacies (#3). As mentioned earlier, the resistive portion of the Blue cycle is very persistent throughout the study area. Because the Salem Limestone pelloidal aggregate lithofacies is found at the transition between the porous and resistive portions of the Blue cycle, the pelloidal aggregate could be widespread throughout the study area as well.

Depositional Environment

This lithofacies is characterized by Wilson's SFB 7 and SMF 16-17

(an open marine platform or shelf lagoon); and it appears to contain grains equivalent to the Bahamite type particle described by Beales (1958). Similarities between Bahamites and the Salem pelloidal-aggregate lithofacies include:

- Pelloidal "lumps" with calcispheres scattered throughout,
- A fenestral fabric with calcite filling fenestrules,
- A remarkable lack of compaction,
- The generally non-porous nature,
- A relative lack of skeletal grains,
- The presence of interstitial anhydrite,
- The lack of cross bedding,
- The relative absence of ooids,
- Lateral gradation into oolitic crinoidal calcarenites and crinoidal calcirudites,
- The uniformity of the lithofacies over wide areas.

Beales (1958, p. 1868) reports that these Bahamite sediments form in shallow, slightly restricted water, with lower water turbulence than on the shoal proper. This environment is identical to one in which grapestone form, hence their close association. In addition, grapestone formed from an oolitic grainstone facies, which explains the vertical gradation into the oolitic grainstone lithofacies of the Blue cycle (Winland and Mathews, 1974, p. 927). Benson (1976) recorded the presence of pelloidal aggregates in southern Indiana and central and eastern Kentucky. He concluded (p. 93) that this lithofacies formed in a high subtidal to low intertidal, quiet water environment; and that the presence of calcispheres indicates a water depth of 3-5 meters (10-15 feet).

6) Bioclastic Wackestone

Description

This lithofacies is defined by the presence of less than 50 percent fossil fragments, and micrite which is greater than 50 percent of orthochemical components (Figs. 23 and 24). Allochems average approximately 26 percent of the rock, and of these, echinoderm fragments are the most abundant. Also present in small amounts are: bryozoa, brachiopods, Endothyra, ooids, pelecypods, trilobites, and coral.

The average grain size is approximately 200 microns, but sorting is very poor. Packing ranges from low (grains floating in micrite matrix; delicate, unbroken bryozoa fronds) to medium (a few broken grains, differential compaction of pellets inside and outside of grains) to high (many stylolites and some broken grains). This lithofacies has been thoroughly burrowed.

Orthochemical constituents account for approximately 73 percent of the rock. Of these, micrite averages about 75 percent of the orthochems. Common cements include syntaxial overgrowths, drusy mosaic-equant calcite, isopachous blades, silica (both replacement of single grains and wholesale replacement of rock) and pyrite. Porosity is found only in trace amounts.

Stratigraphic Position

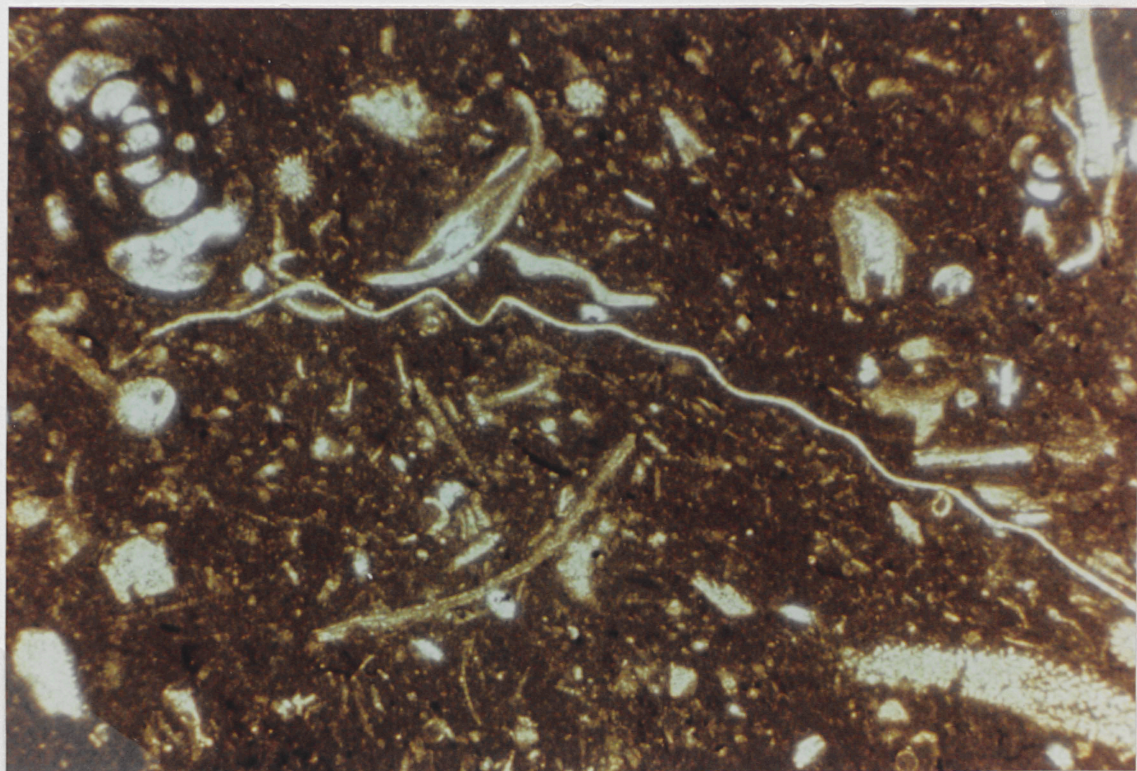
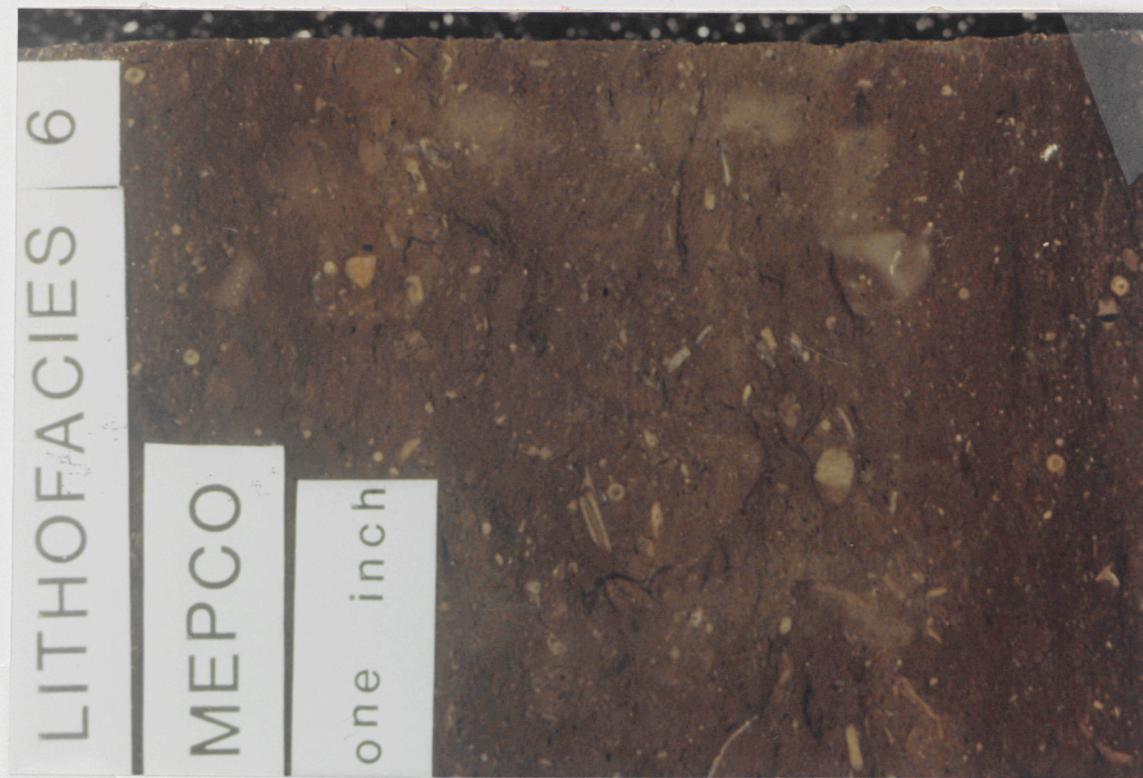
Examples of the bioclastic wackestone lithofacies are found at the base of the Red cycle porous zone (or, alternatively, the top of the resistive cap of the Purple cycle). These grade upwards into packstones and finally the dolostone of the Red cycle porous zone.

Depositional Environment

This lithofacies is best represented by Wilson's SFB 7 and SMF 9, a

Figure 23. Bioclastic Wackestone (Lithofacies 6), hand sample.

Figure 24. Bioclastic Wackestone (Lithofacies 6), thin section.
Up is towards top of page.



marine shelf or lagoon with open circulation. It was probably deposited just below wave base in water a few tens of meters deep (Wilson, 1975, p. 25). Thorough burrowing has completely destroyed any original bedding.

7) Bioclastic Dolostone

Description

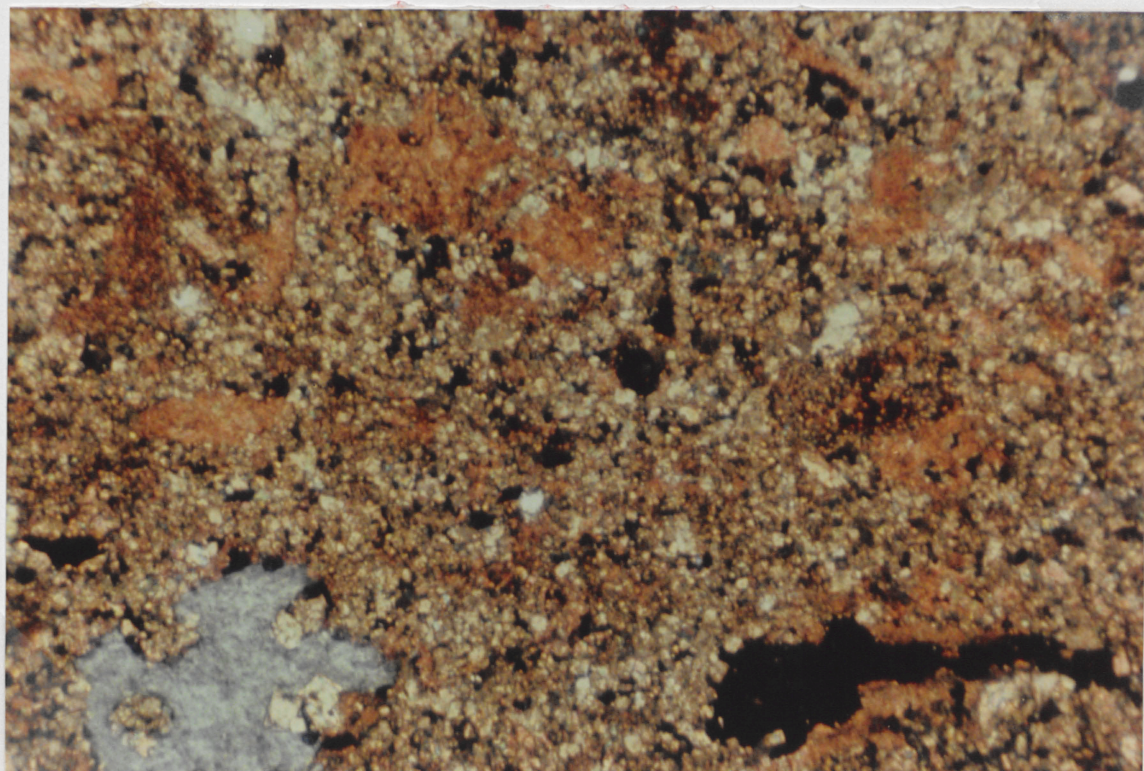
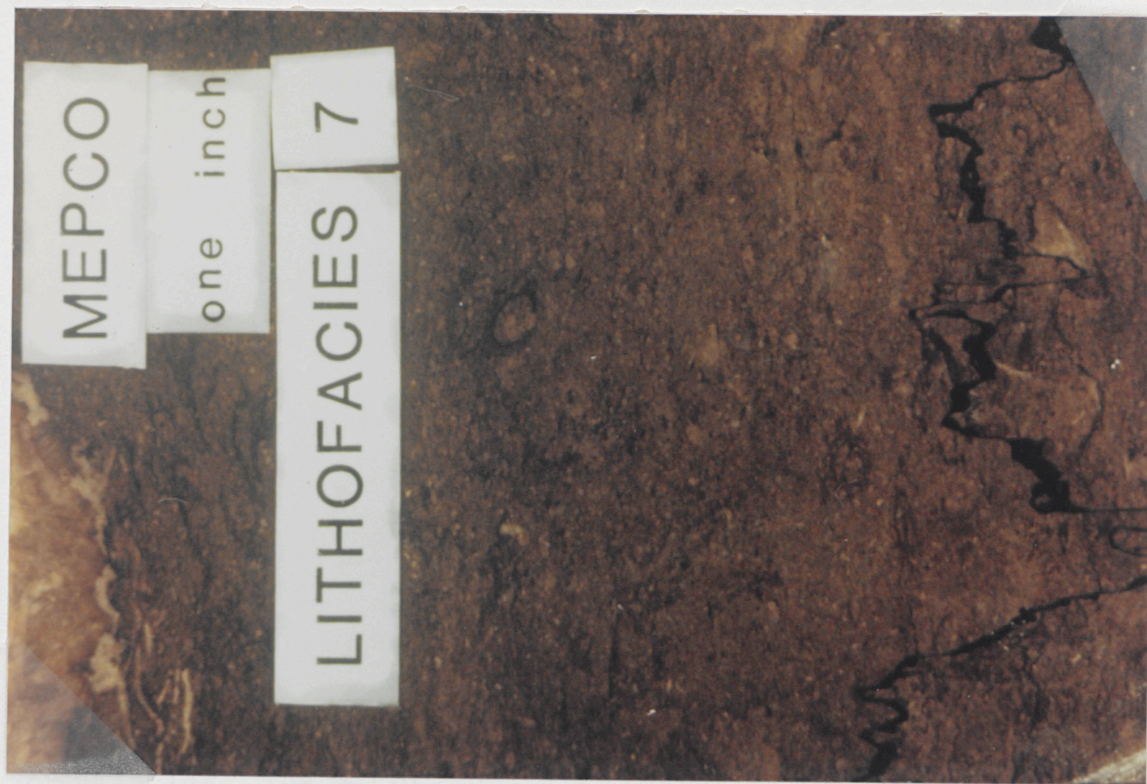
This lithofacies (Figs. 25 and 26) is defined by greater than 50 percent (of orthochems) Idiopathic-E dolomite and greater than 20 percent (of allochems) fossil fragments. Allochemical components average approximately 40 percent of the rock. The most abundant fossil fragment appears to be echinoderms, but that could be misleading if echinoderms are more resistant to complete dolomitization than other particles. Other allochems present in small amounts include: bryozoa, brachiopods, ostracods, Endothyra sp., coral, ooids, quartz grains, calcispheres, and trilobites.

Grains average approximately 240 microns, but sorting is poor, and the grain size range is 5700 microns to 14 microns. Packing is ubiquitously high, with a few large stylolites, many smaller stylolites, and many sutured grain contacts. This lithofacies has been completely burrowed; some burrows are vertical.

Orthochems comprise approximately 58 percent of the rock. The most important by far is Idiopathic-E dolomite. This dolomite consists of clear, non-ferroan rhombs, averaging 20 microns in diameter; but reaching up to 60 microns when near stylolites. Other minor orthochems include: equant calcite-drusy mosaic, syntaxial overgrowths, isopachous blades, anhydrite, Xenotopic-C dolomite, Xenotopic-P dolomite, quartz,

Figure 25. Bioclastic Dolostone (Lithofacies 7), hand sample.

Figure 26. Bioclastic Dolostone (Lithofacies 7), thin section.
Up is towards top of page.



and pyrite.

Visible porosity averages about 2 percent, and ranges up to 6 percent.

Stratigraphic Position

The bioclastic dolostone lithofacies makes up most of the Red cycle porous zone, where it overlies bioclastic wackestones (#6) and interfingers with and underlies echinoderm-bryozoan grainstone (#2). The bioclastic dolostone is also found at the base of the Orange cycle porous zone, where it also interfingers with echinoderm-bryozoan grainstones (#2).

Depositional Environment

Dolomitization has destroyed much of the original character of this lithofacies. The relic fauna are similar to the echinoderm-bryozoa grainstones (#2) and the relic burrows are similar to bioclastic wackestones (#6). Because the dolostone is closely associated in vertical sequence with both lithofacies, it seems likely that the bioclastic dolostone was originally an echinoderm-bryozoa grainstone facies (#2) or a bioclastic wackestone facies (#6). Once these sediments were deposited, the environment may have shifted to an intertidal setting where mixing or refluxing zone waters were available for dolomitization.

PETROGRAPHY

Methods

Cores available for this study span 122 feet of the three most productive zones in the Salem: the porous portions of the Red, Blue, and Orange cycles. Of this, the Red cycle core (23 feet) and the Blue cycle core (56 feet) are continuous. The Orange cycle core is represented by thin sections every foot for 39 feet. The remaining four feet are biscuits from the Blue cycle.

The two continuous cores, the Red cycle (Gray Estate) and Blue cycle (Roy Reed), were slabbed and described at intervals of 1 inch and 2 inches, respectively. Each interval was measured for grain size average and range, packing, percent porosity, and largest and average pore size. These descriptions comprise Appendix A. Eighty-three thin sections were prepared from all four cores. Each thin section was stained with a solution of Alizarin Red S and potassium ferricyanide as described by Dickson (1966, 1980). Thirty-nine of the samples were impregnated with blue epoxy before thin sectioning. Sixty-eight thin sections were point counted, using 200 counts per slide: 100 counts for percentage of orthochems, allochems, and pore space; and 100 counts for percentage of cement types.

Twenty-six thin sections were polished to three microns and examined using a Nuclide ELM-2B Cold Cathode Luminoscope to determine relative Mn^{++}/Fe^{++} composition in cements.

Lithologic Components

Faunal Allochems

Echinoderms: Echinoderms are the most abundant fossil fragment in the

Salem, averaging approximately 19 percent of allochems. Echinoderm fragments display many forms, including columnals, plates, and spines. They are present in every lithology, and are generally host to large syntaxial overgrowths. Some Salem echinoderm fragments also have micritic rinds, minor silica/chert replacement, and minor Xenotopic-P dolomite replacement.

Bryozoa: Bryozoa rank second to echinoderms as the most common fossil fragment, comprising approximately 11 percent of allochems. Like echinoderms, bryozoans appear in every lithology, and there appears to be a consistent ratio between the two (also reported by Benson, 1976, p.73). Bryozoa fragments take a range of forms, from delicate fenestrate fronds preserved in wackestones, to thick-walled robust zooecia as nucleii to ooids, to completely micritized, dendritic forms. The bryozoa, as a whole, are very susceptible to micritization. Some fenestrate varieties are host to very well-developed isopachous cements, which occlude intraparticle pore space.

Foraminifera: Foraminifera are a comparatively minor, yet very important, component of Salem fauna in southeast Illinois. In this study area, the foraminifera (primarily Endothyra sp.) are distributed throughout all lithologies, yet average less than five percent of the rock, and only range to 15 percent. This is in contrast with the Salem in Indiana, where workers saw so many spherical grains in hand sample, they called the rock an oolite, when in fact all the grains were Endothyra. In this study area, Endothyra sp. are always completely micritized. Their multichambered tests, however, are often left unfilled by later generations of pore filling cements, so they are important

contributors to primary, intragranular pore space.

Corals: Rugose corals are a very minor faunal element, but are interesting because they are restricted to two lithofacies, the wackestone and dolostone facies. The coralites are small (approximately 1 cm diameter), round to oval in shape, and appear in clusters -- they may be colonial. Commonly, anhydrite is found in the coralline intraparticle pore space when none is found elsewhere.

Ostracods: Ostracods are minor faunal constituents, always less than three percent of the rock, but present in all lithologies. They appear as whole, articulated fossils, commonly filled with sparry, equant calcite; and as disarticulated valves, which are good hosts for isopachous bladed cements.

Molluscs: Bivalve pelecypods and gastropods each average about one to two percent. Bivalves are thin-walled, the walls usually marked by just a micrite rim surrounding a recrystallized shell. Silica replacement cement is common. Disarticulated bivalve shells with a thick rind of micrite are a common intraclast. Because these bivalves were originally aragonite, they are now significant contributors to secondary moldic porosity.

Gastropods have thick, micritized walls, with the internal chambers generally filled with isopachous blades and equant calcite. There are a few high-spined species.

Brachiopods: Brachiopod fragments are ubiquitous, yet minor, comprising less than four percent. There are both impunctate and pseudopunctate varieties, and spines are very common. Some fragments are quite large.

Like bivalve pelecypods, brachiopod fragments surrounded by micrite are a common intraclast.

Trilobites: Trilobite fragments are the least common faunal element, most often in trace concentrations. They are slightly more common in relatively restricted lithologies, such as the wackestone and dolostone.

Calcspheres: Calcspheres are small calcite circles which often display pseudouniaxial cross extinction. They have been reported by several authors to look like, and possibly be, the reproductive cysts of dasycladacian alge. In the Salem Limestone, calcspheres are strongly associated with pelloidal aggregates (see below), which may also have been bound together by alge.

Detrital Allochems

Ooids: Ooids are spherical to subspherical sand-sized carbonate grains consisting of a detrital nucleus surrounded by a cortex of tangentially or radially oriented crystals. These crystals generally surround the nucleus in a series of rings, and can range from a superficial coating of one or two layers to well over 50 percent of the ooid diameter. Two basic morphologies of ooid cortex are known: 1) those with crystals arranged radially with respect to the nucleus; and 2) those with crystals arranged tangentially to the nucleus. Some ooids have rings of each type.

After years of field and laboratory work, ooids remain largely an enigma, and multiple theories exist for almost every aspect of their formation, original mineralogy, and diagenesis.

Ooids are a relatively major constituent of most Salem lithologies, averaging approximately 11 percent of the allochemical components, when

present. Salem ooids consist of nuclei of many types, most often echinoderms, bryozoa, and brachiopods.

The cortex of Salem ooids display the range of morphologies: radial, tangential, and combinations of both. It is unclear whether this reflects original mineralogy (radial = calcite, tangential = aragonite) or water energy (radial = low energy, tangential = high energy). In some lithologies, several ooids are cemented together and then additional oolitic layers deposited around the clast.

Despite differing theories, there is a set of chemical conditions necessary for the inorganic precipitation of calcium carbonate, and these conditions help to define an environment where precipitation is likely. Ooids from modern shallow marine carbonate platforms form when warm water temperatures cause a loss of CO_2 and a rise in salinity. The resulting rise in the ion activity product, $a_{\text{Ca}^{2+}} \times a_{\text{CO}_3^{2-}}$ (Simon, 1981, p. 330), initiates CaCO_3 precipitation. This system works best when there is a mixing of open marine and restricted marine waters, with a relative topographic high in between to create the higher energy needed for ooid formation. Salem lithologies represent conditions identical to those above, so this is a likely mechanism for Salem ooid formation.

Pelloidal aggregates: Pelloidal aggregates are a minor, yet important detrital constituent of the Salem, and are equivalent to the "Bahamites" described by Beales (1958). In thin section, they appear as highly irregularly-shaped, completely micritized "lumps" (Fig. 27). In some samples, individual pellets comprise the "lumps" and in others, the pelloidal component is indistinguishable. Both types often contain calcispheres. Pelloidal aggregates show strong associations with grape-

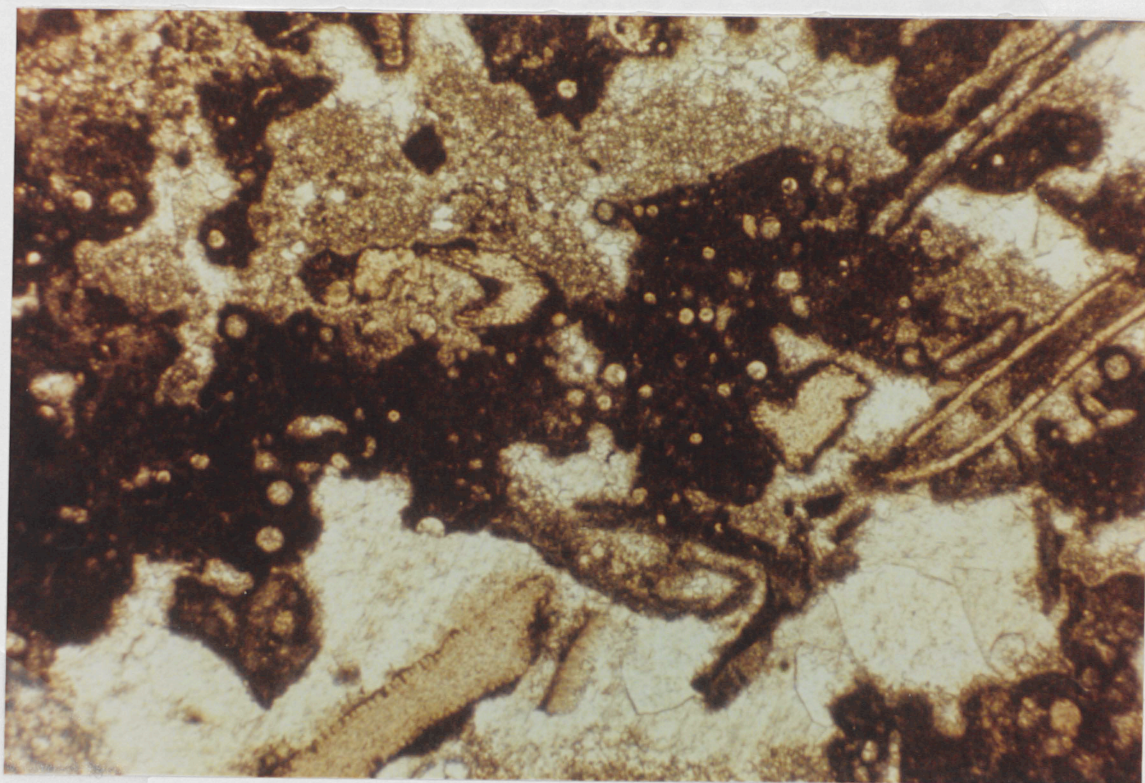


Figure 27. Pelloidal aggregates, equivalent to Beales (1958) Bahamites. Also present in photo are associated calcispheres and geopetal silt.

stone and intraclasts. The most striking feature of rocks composed of these grains is their fenestral, uncompacted texture. Pelloidal aggregates comprise their own lithofacies, and are present in small amounts in all grainstone lithofacies. Pelloidal aggregates, however, are not found in the dolostone facies. This absence could be an artifact of preservation during dolomitization.

Grapestone: Grapestones in the Salem are carbonate sand grains bound together by micrite. Often, the grapestones themselves have oolitic coats around them. There are many varieties: those with many small fossil shards surrounded by micrite with a round shape; those with two or three larger fossil fragments, like echinoderms or bryozoa, with micrite surrounding them irregularly; and those grapestones composed of ooids, with the surrounding micrite taking a botryoidal form. There is even a large grapestone composed of grapestone clasts (Fig. 28).

In the Salem, grapestone seem to have a close association with pelloidal aggregates and intraclasts. Bathurst (1971, p. 318-319) reports that whereas ooids form where a shoal bottom leads to stronger tidal currents, grapestones form in less turbulent water, where they are bound by the subtidal algal mat and are stationary for long periods of time. The environment where this process is most favored is on warm, shallow banks, in water that is only a few centimeters deep at low tide, and is locally exposed. Pelloidal aggregates and intraclasts form in this kind of environment as well, and the close association of the three provides a good environmental indicator.

Geopetal Silt: Geopetal silt in the Salem is sediment consisting of silt-sized calcite grains often mixed with pellets, but never containing

fossil fragments (Fig. 29). In some places, pellets comprise all the geopetal textured sediment, which can comprise up to 38 percent of allochems present. Geopetal silt occurs in two cores, and is restricted to the grainstone lithofacies. When present, the silt rests on the upper surfaces of all grains, and fills the bottoms of all former primary cavities. It generally rests on an isopachous fringe cement. In appearance, it is equivalent to the "vadose silt" described by Dunham (1963), but in environmental interpretation, it may not be equivalent. Discussion of the origin of geopetal silt will be found in the diagenesis section.

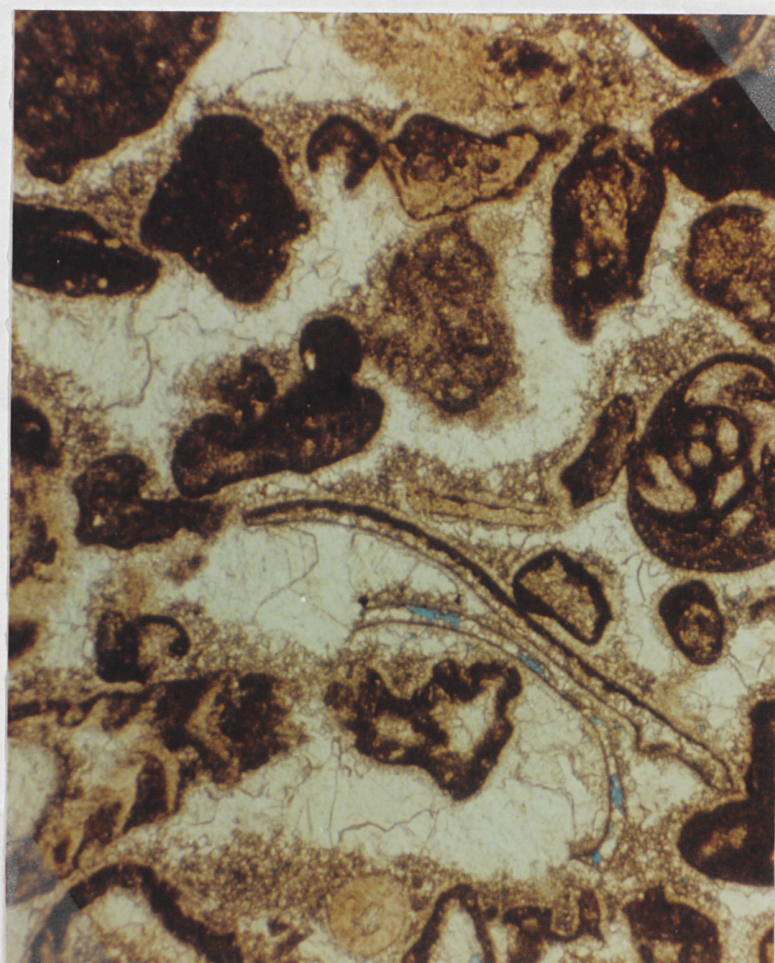
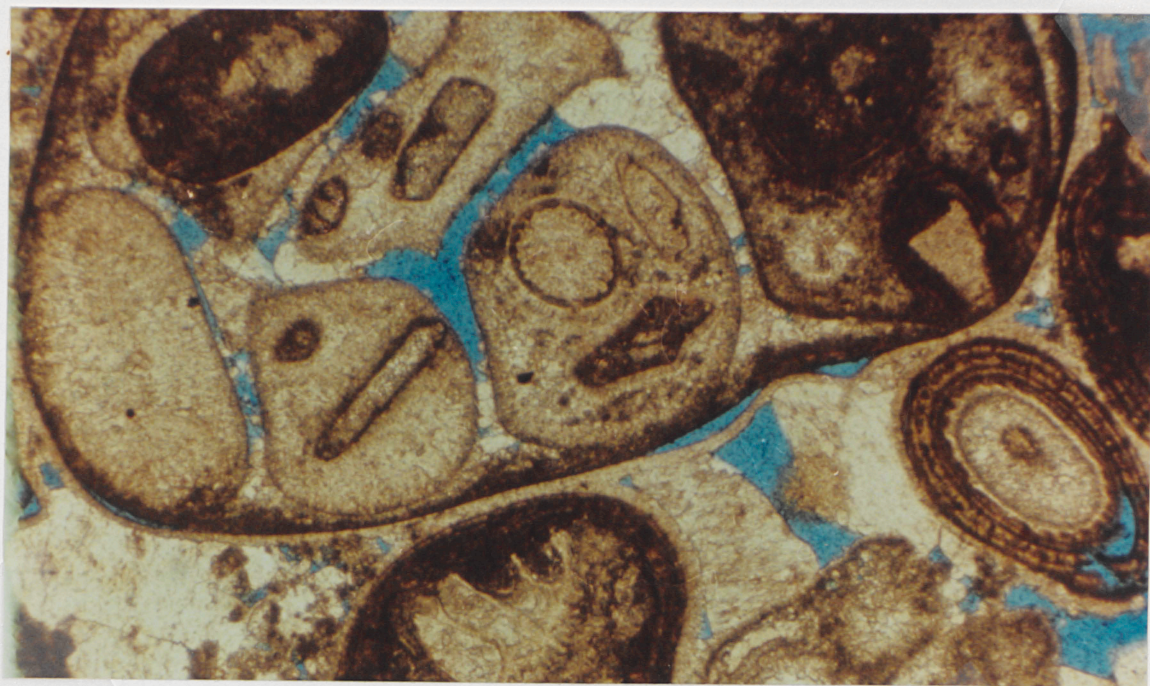
Peloids-Pellets: The terms peloids and pellets are applied to spherical-ovoid grains entirely composed of micrite. "Peloids" implies no specific size or origin, whereas "pellets" implies a fecal origin, with the size controlled by the size of the animal.

Salem peloids fall into two categories: those which are round or irregular in shape, have an original size of approximately 300 microns, and are clearly micritized ooids or fossil fragments; and those with a subrounded or ovoid shape, an average size of 90 microns, and are probably fecal pellets. It is this second group which commonly display a geopetal texture.

Intraclasts: These particles are fragments of partially lithified carbonate sediment, eroded within the general area of deposition, and incorporated within new sediment (Blatt et. al., 1972, p. 422). In the Salem, they are differentiated from peloids by the presence of a large fossil fragment which is surrounded by micrite, from ooids by the lack of radial or concentric structure, and from grapestone because there is only one grain, not several, with micrite bound to it.

Figure 28. Grapestone composed of grapestone clasts; and surrounded by isopachous calcite fringe. Porosity in blue.

Figure 29. Geopetal silt, resting on upper surfaces of grains. It is sandwiched between isopachous calcite and equant calcite. It is nearly identical to vadose silt, described by Dunham (1963). Porosity in blue.



Quartz: Quartz grains in these rocks are less than two percent of allochems, average 35 microns (coarse silt), and are monocrystalline. Scattered grains are ubiquitous throughout all lithologies.

Micrite: Microcrystalline (less than four microns) lime mud is a comparatively minor constituent of the Salem samples used for this study. Because of ubiquitous micritization of fossil fragments and ooids, and abundance of pellets and pelloidal-aggregates, micrite could be derived from mechanical abrasion of these, and other, grains.

Orthochems

Isopachous bladed and fibrous calcite: Isopachous bladed and fibrous calcite forms fringes around and within framework grains. Largest fibrous cements have dimensions of 6 microns by 92 microns; largest blades have dimensions of 62 microns by 186 microns. Both are always non-ferroan. There is a direct, inverse relationship between numbers of echinoderm fragments (and therefore syntaxial overgrowth cements) and development of isopachous bladed and fibrous cements. Therefore, isopachous bladed and fibrous cements are best developed in oolitic and pelloidal grainstones. In echinodermal lithofacies, the major growth of isopachous cements is internal to fossil fragments. These cements are non-luminescent.

Syntaxial overgrowths: Echinoderm grains are composed of a single calcite crystal, which creates a good substrate for rapid nucleation and growth of calcite cement in optical continuity with the original grain. Because echinoderms are the most abundant fossil fragment in all lithologies, syntaxial overgrowths are probably the most significant diagenetic product and porosity reducer in the Salem Limestone. Syntaxial

overgrowths observed here were always non-ferroan, and always non-luminescent.

Equant calcite: Pore-filling, equant calcite takes several forms in the Salem. 1) Drusy mosaic calcite crystals coarsen toward pore centers, and the cement is generally intraparticle. It usually rests on isopachous cements and is always non-ferroan and non-luminescent. 2) Equant blocky cement does not coarsen toward pore centers and is found in interparticle pore space. It is very difficult to distinguish this cement from syntaxial overgrowths (viewed from an orientation which blocks the fossil fragment). Indeed, this cement may be primarily syntaxial overgrowths. It is non-ferroan and non-luminescent. 3) Late euhedral calcite grows into pore space and ends in scalenohedral terminations. It can have very fine ferroan bands toward the terminations and under cathodoluminescence grades gradually from non-luminescent to very dull with thin, dull band(s) to dull at tip of crystal.

Dolomite: Dolomite also displays many textures, and is classified here according to the system of Gregg and Sibley (1984, p. 913) (Fig. 30). 1) Idiotopic-E dolomite in the Salem is the common "sucrosic" dolomite texture -- all dolomite crystals are small (19 microns), euhedral rhombs. The rock is crystal-supported, with either porosity or another mineral in the inter-crystalline area. This texture is found in trace amounts in other lithologies but comprises more than 50 percent of the dolostone lithology. Idiotopic-E dolomite replaces almost all components, both depositional and diagenetic, at some locale in the Salem, so timing is equivocal. It is always non-ferroan and non-luminescent. 2) Idiotopic-S dolomites are subhedral-anhedral crystals with straight

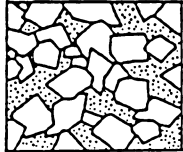
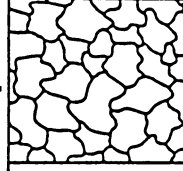
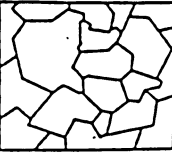
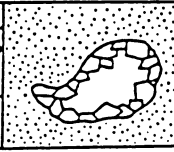
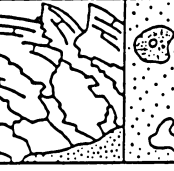
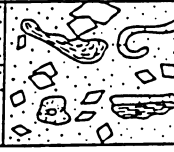
Idiotopic Dolomite- Rhombic shaped euhedral to subhedral crystals.	Xenotopic Dolomite- Nonrhombic, usually anhedral crystals.
 Idiotopic-E (Euhedral), almost all dolomite crystals are euhedral rhombs; crystal-supported with intercrystalline area filled by another mineral or porous (as in sucrose texture).	 Xenotopic-A (Anhedral), tightly packed anhedral dolomite crystals with mostly curved, lobate, serrated, indistinct or otherwise irregular intercrystalline boundaries. Preserved crystal-face junctions are rare and crystals often have undulatory extinction in cross-polarized light.
 Idiotopic-S (Subhedral), subhedral to anhedral dolomite crystals with low porosity and/or low, intercrystalline matrix; straight, compromise boundaries are common and many of the crystals have preserved crystal-face junctions.	 Xenotopic-C (Cement)- pore lining saddle-shaped or baroque dolomite crystals characterized by scimitarlike terminations, when observed in thin section, and sweeping extinction in cross-polarized light.
 Idiotopic-C (Cement), euhedral dolomite crystals lining large pores and vugs or surrounding patches of another mineral such as gypsum or calcite.	 Xenotopic-P (Porphyrotopic), single anhedral dolomite crystals or patches of anhedral dolomite crystals floating in a limestone matrix. The dolomite crystals usually have undulatory extinction in cross-polarized light.
 Idiotopic-P (Porphyrotopic), euhedral dolomite crystals floating in a limestone matrix. The crystals are matrix-supported rather than crystal-supported.	

Figure 30. Dolomite textural classification used in this study (from Gregg and Sibley, 1984, p. 913).

compromise boundaries and a high percentage of enfacial junctions. Within the study area, these dolomites are a small percentage of the represented dolomite textures. They are generally adjacent to, or within, a major stylolite or area of high compaction. They are non-ferroan and non-luminescent. 3) Idiopathic-C crystals are euhedral and are found in these rocks surrounding patches of anhydrite. These are non-ferroan and non-luminescent. 4) Idiopathic-P crystals are isolated, matrix-supported rhombs, seen here rarely within vadose silt. They are non-ferroan and non-luminescent. 5) Xenotopic-C dolomite is a pore-filling cement. Its baroque, or saddle-shaped, crystals are very distinctive, characterized by large crystal size, strongly sweeping extinction, and abundant fluid inclusions. Even though this cement is a relatively minor allochemical constituent, it is a major contributor to reduced porosity and permeability because it selectively fills pore space completely with large crystals. It is almost always non-ferroan (only one ferroan example) and is always non-luminescent. 6) Xenotopic-P texture is defined as single anhedral dolomite crystals replacing precursor carbonates. In the case here, the crystals are generally replacing echinoderm fragments (some of which had already been replaced by silica) and anhydrite. These replacive crystals have little or no undulatory extinction, are non-ferroan, and are non-luminescent.

Silica: Diagenetic silica takes three forms in these rocks. The first is replacement of fossil fragments. This silica is white in color and sometimes euhedral. The second is chalcedonic silica. This texture replaces both fossil fragments and matrix. In one sample (M3826, lithofacies #8), chalcedony is replacing the rock in several "waves", boun-

ded by stylolites. These could be silicified burrows. Chalcedony is usually yellow, sometimes white, and always anhedral. The third texture is zebraic chalcedony (length slow) (Fig. 31). This is characterized by radial fibrous crystal habit with fibers alternating light and dark under polarized light. This occurs as pore fillings in trace amounts. Folk and Pittman (1971) described the association of zebraic chalcedony with evaporite minerals, but here it is probably only associated with a pre-existing pore.

Anhydrite: Anhydrite in the Salem displays two crystal habits. The first type is pore-filling anhydrite, which is most often found interior to coral fragments but is also present as fracture-fillings. This anhydrite generally displays replacive textures around the borders, and in hand sample has euhedral crystal boundaries. Some euhedral anhydrite is brown, indicating hydrocarbon inclusions. In these cases, the anhydrite is clearly replacive, but it is not clear whether this began as a void-filling cement and extended outward, or whether it is completely replacive. The second type is nodular anhydrite. These irregular and eye-shaped nodules are sometimes clustered in "beds," which have replaced carbonate grains and matrix. These never contain hydrocarbon inclusions. In either case, there is no draping of sediment around nodules, and there are no pseudomorphs after gypsum.

Porosity

Porosity in Salem thin sections is quite variable in amount (0 to 30 percent), size (20 microns to 1 cm), and type. It is classified here according to Choquette and Pray (1970) (Fig. 32), with recognition of secondary porosity based, in part, on criteria outlined by Schmidt et.

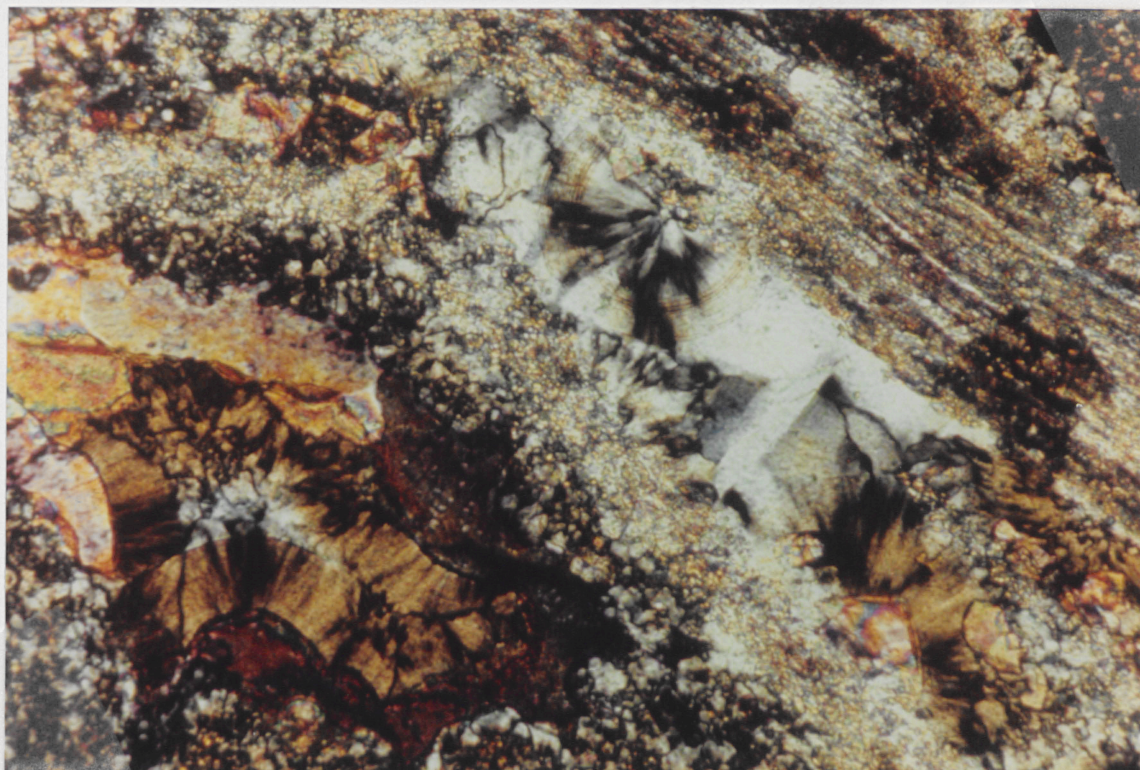


Figure 31. Zebraic chalcedony. In the Salem, this probably represents a pore filling texture.

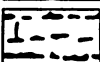
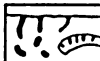
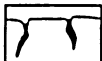
BASIC POROSITY TYPES										
FABRIC SELECTIVE			NOT FABRIC SELECTIVE							
	INTERPARTICLE	BP		FRACTURE	FR					
	INTRAPARTICLE	WP		CHANNEL *	CH					
	INTERCRYSTAL	BC		VUG *	VUG					
	MOLDIC	MO		CAVERN *	CV					
	FENESTRAL	FE	*Cavern applies to man-sized or larger pores of channel or vug shapes							
	SHELTER	SH								
	GROWTH-FRAMEWORK	GF								
FABRIC SELECTIVE OR NOT										
	BRECCIA BR		BORING BO		BURROW BU					
					SHRINKAGE SK					
MODIFYING TERMS										
GENETIC MODIFIERS				SIZE * MODIFIERS						
PROCESS		DIRECTION OR STAGE		CLASSES						
SOLUTION	s	ENLARGED	x	MEGAPORE	mg	large	lmg	256		
CEMENTATION	c	REDUCED	r			small	smg	32		
INTERNAL SEDIMENT	i	FILLED	f	MESOPORE	ms	large	lms	1/2		
						small	sms	1/16		
				MICROPORE	mc					
Genetic modifiers are combined as follows:				Use size prefixes with basic porosity types: mesovug msVUG small mesomold smsMO microminterparticle mncBP						
Genetic modifiers are combined as follows:				*For regular-shaped pores smaller than cavern size.						
Genetic modifiers are combined as follows:				†Measures refer to average pore diameter of a single pore or the range in size of a pore assemblage. For tubular pores use average cross-section. For platy pores use width and note shape.						
Genetic modifiers are combined as follows:				ABUNDANCE MODIFIERS						
Genetic modifiers are combined as follows:				percent porosity (15%)						
Genetic modifiers are combined as follows:				or						
Genetic modifiers are combined as follows:				ratio of porosity types (1:2)						
Genetic modifiers are combined as follows:				or						
Genetic modifiers are combined as follows:				ratio and percent (1:2) (15%)						

Figure 32. Classification of porosity types used in this study.
(from Choquette and Pray, 1970, p. 224).

al (1977). Porosity types include the following:

Interparticle (includes primary, reduced, and enhanced): Interparticle is the most common porosity type in the Salem Limestone, ranging up to 750 microns. It is almost always reduced by one or more generations of cement. In fact, the amount of interparticle porosity bears an inverse relationship to the number of echinoderm fragments (and therefore to syntaxial cements). In lithologies where cementation was inhibited by micrite, such as packstones and wackestones, primary interparticle porosity may be solution enhanced.

Intraparticle (includes primary, reduced): Intraparticle porosity is present in many lithologies, yet forms only a minor percentage of total porosity. It is almost always present with Endothyra grains, but is also present within fenestrate bryozoa, ostracods, and whole brachiopods. It has generally been reduced by one or more generations of cement.

Moldic (includes oomoldic, skelomoldic): Moldic porosity is present in grainstone and dolostone lithologies but does not constitute a large percentage of porosity. In ooids, the dissolution responsible for formation of this porosity results in the removal of nuclei and/or the selective removal of certain rings within the cortex, both of which were probably originally aragonite.

Moldic porosity development within fossil fragments is always related to dissolution of bivalve mollusc shells. Generally, only a micritic envelope remains to show the shape of the original shell, and the internal porosity is reduced by calcite cement.

Intercrystalline: Two varieties of this type of porosity exist in Salem samples. The most common is intercrystalline porosity formed between Idiomatic-E dolomite rhombs. Average pore size is 19 microns, and porosity ranges from 0 to 6 percent in the dolostone facies. The second type of intercrystalline porosity is created by separations between cleavage planes in large anhydrite crystals and Xenotopic-C dolomite crystals. Although rare, these intercrystalline pores can range to sizes greater than 10 mm, and could increase permeability much the same as microfractures do.

Fenestral-vuggy: Fenestral porosity is a very important type of porosity, especially within the Blue cycle in Wayne County. In this cycle, the fenestrae are spherical to irregular in shape, averaging 2 mm and ranging to greater than 1 cm. Individual fenestra occur in subparallel or indistinct bands, and fenestrae as a whole occur in bands and patches (Fig. 33). As described by Choquette and Pray (1970, p. 246), these fenestra are much larger than surrounding interparticle pore space, and their margins are made of many smaller grains. In some Salem fenestra, scalenohedral calcite crystals can be seen projecting into the void space with the unaided eye.

Fracture: Trace amounts of fracture porosity are present in almost every lithotype. Although their volume is small, they may contribute significantly to the permeability of the rock.

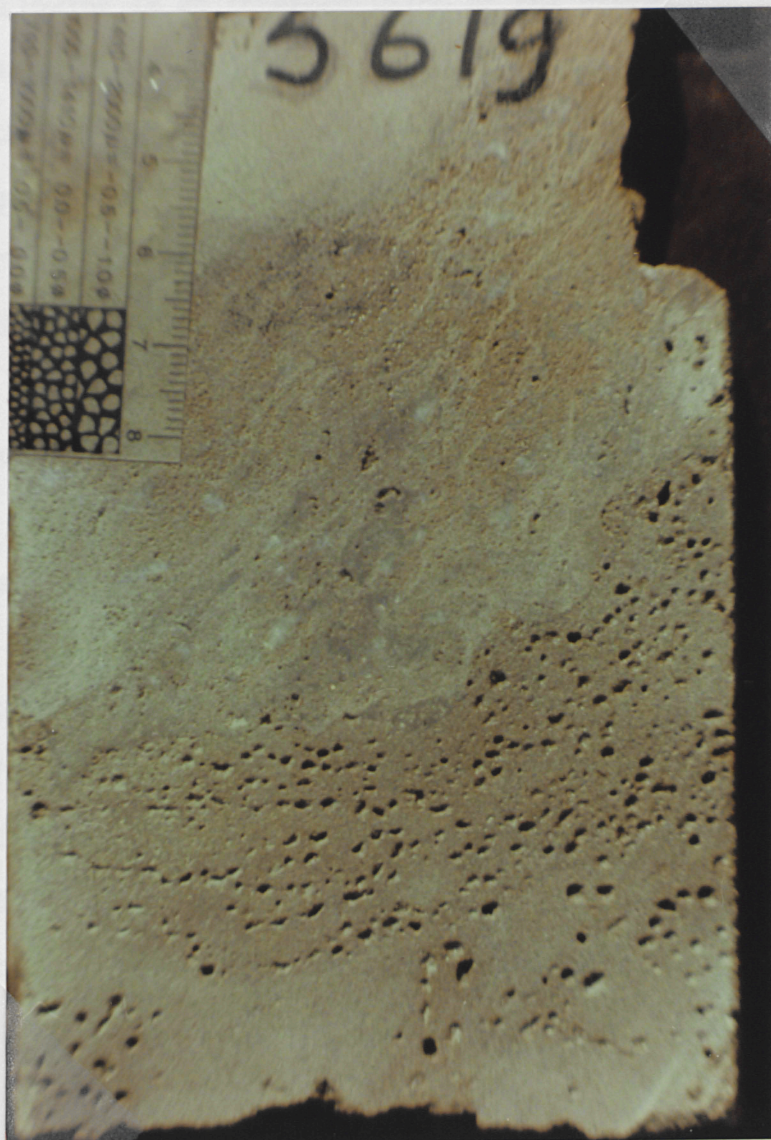


Figure 33. Fenestral porosity of the Salem Limestone blue cycle. This hand sample shows general alignment of pores. Fenestral porosity in thin section appears in Figure 40.

DIAGENESIS

The cyclic, prograding depositional style of the Salem Limestone insured that the sediments (deposited in a marine environment) moved through the "predictable diagenetic pathways" described by Longman (1980). Following is an interpretation of the diagenetic history of the Salem determined from cross-cutting relationships and textural evidence. A summary diagram of this history appears in Fig. 34.

Marine Phreatic

All orthochems in the Salem were deposited within a marine environment, and diagenesis began immediately under the same conditions. Three changes in the sediment took place in the marine phreatic. The most widespread change occurred in stagnant marine pore waters and resulted in thorough micritization of most grains, and micrite envelopes on many others. Algae may have helped to promote micritization, as well as the binding of grapestone at or near the sediment-water interface in slightly agitated waters. In the active marine phreatic, where water was being forced through the sediment by waves, tides, or currents, isopachous fibrous or bladed cements were deposited around grains. The crystal habit of these cements reflects original mineralogy, but without strontium or stable isotope compositions, it is extremely difficult to recognize whether cements were originally fibrous aragonite or fibrous Mg-calcite. In Salem lithologies, isopachous cements are best developed in grainstone lithologies where initial porosities were high, and proximity to shoals provided the vertical obstructions important for water movement. Surprisingly, good isopachous cement development is also found in the pelloidal aggregate lithofacies. The characteristically uncompacted, fenestral nature of this lithofacies may have encouraged

Figure 34. Paragenetic sequence observed in the Salem Limestone in this study. Time after deposition of grains increases towards the right.

→

MARINE PHREATIC	MIXING ZONE	METEORIC PHREATIC	VADOSE	MODERATE BURIAL	DEEP BURIAL
	GRAPESTONE CEMENT				
	MICRITIZATION				
	CALCITE DRUSE				
		Moderate compaction			
		Silica replacement			
		Selective dolomite			
		Geopetal silt	?		
			Calcite druse		
			Equant calcite		
			Drusy mosaic		
			Syntaxial overgrowth		
			Idiotopic-e dolomite		
			Dissolution		
			Late calcite		
				Anhydrite	
				Xenotopic-c dolomite	
				Oil emplacement	
				Major stylolite	
PARAGENETIC SEQUENCE OBSERVED IN SALEM LIMESTONE					

isopachous cement growth.

Primary porosity is generally preserved in the marine phreatic. Salem oolites with unusually good isopachous calcite cement development can show significant porosity reduction (Fig. 35), but this type of occlusion is volumetrically small.

One effective method of porosity reduction in the marine phreatic was early compaction. Ooids with good radial fibrous development were deformed early, resulting in lamella that were plastically deformed between grains. These radial lamella were later preferentially dolomitized (discussed in detail below). Choquette and Steinen (1980, p. 187) observed a similar feature in the Ste. Genevieve Limestone. They determined that compaction predated dolomitization based on the known incompatibility (both chemical and physical) of dolomites. Apparently, dolomitization "freezes" earlier compaction fabrics. Compaction definitely postdated isopachous blade development, shown by broken grains with no blade growth on the fractured surface (Fig. 36).

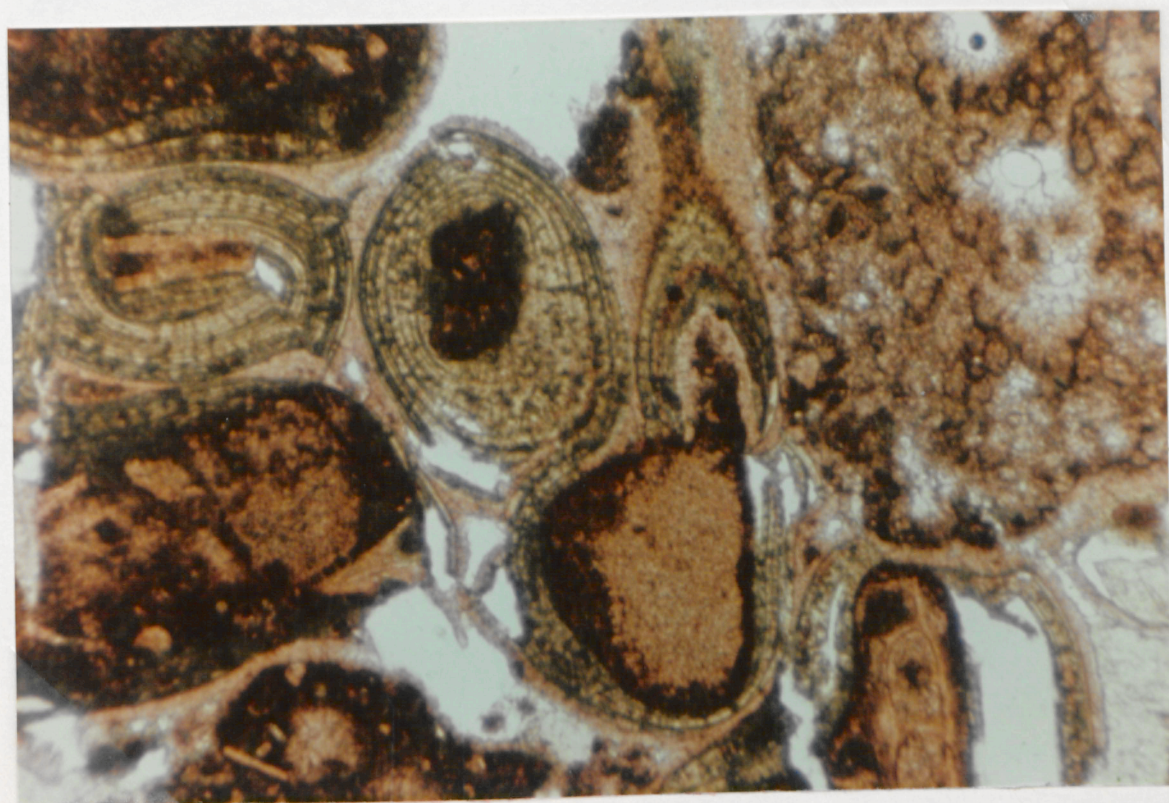
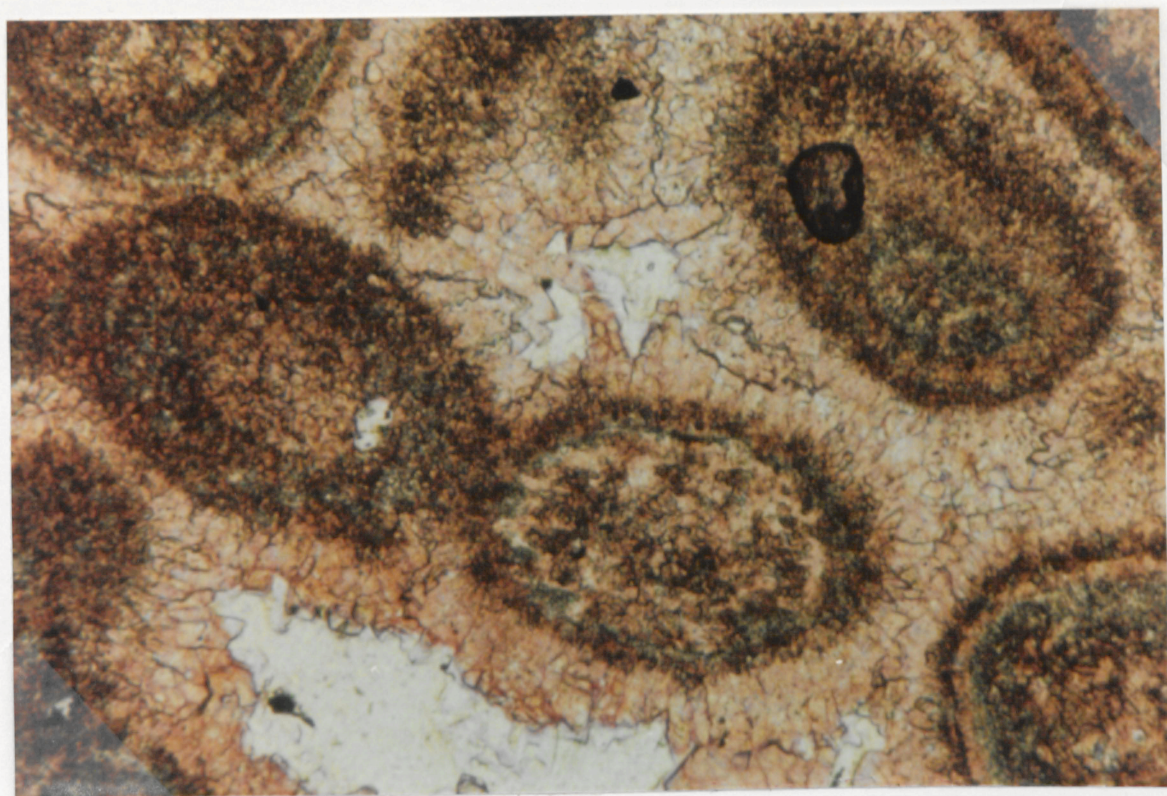
Mixing Zone

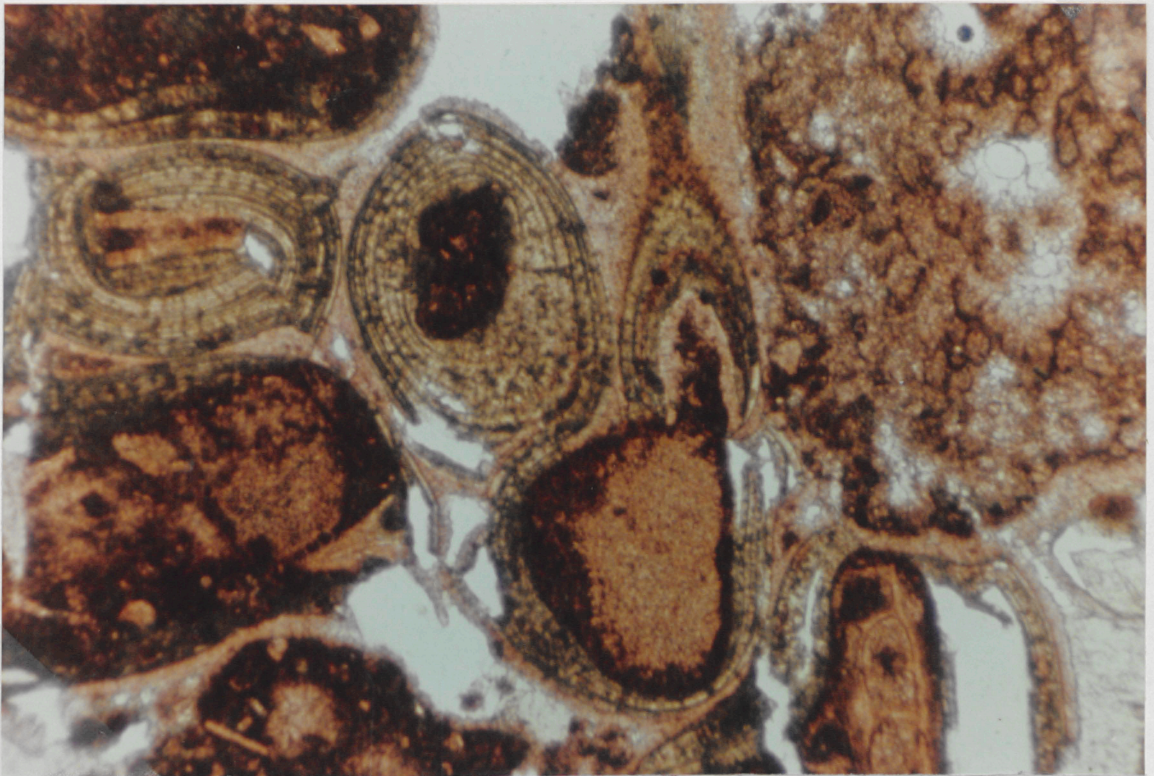
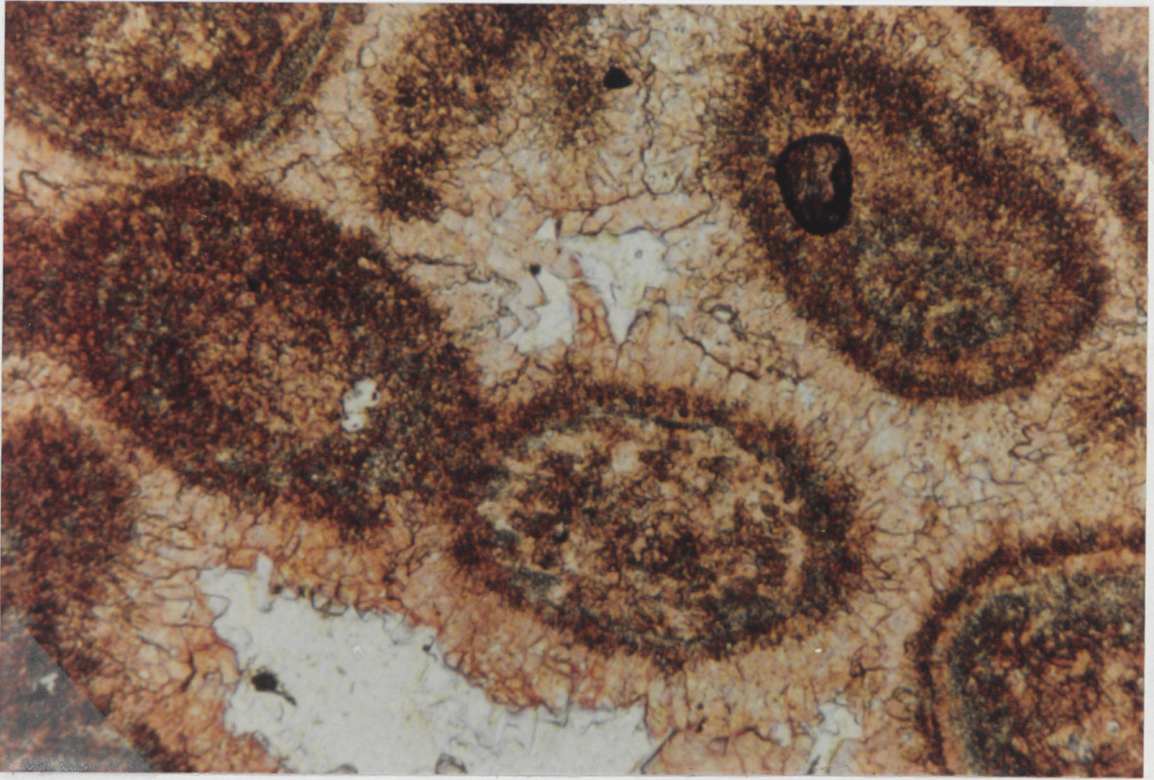
During progradation of Salem sediments, a meteoric or fresh water lens moved across previously deposited sediments, and mixed this with pre-existing marine pore fluids. Diagenetic products from this mixing environment are equivocal, both in the chemistry of their formation and in their timing.

An early diagenetic product in the mixing zone is silica, in the form of 1) selective replacement of fossil fragments; 2) chalcedonic replacement of entire rock; and 3) zebraic, pore-filling chalcedony. The selective silicification of fossil fragments suggests that the decay of organics created a micro-environment with a relatively low pH and was

Figure 35. Isopachous calcite blades surrounding micritized ooids and occluding primary porosity (white).

Figure 36. Timing of compaction revealed by broken isopachous fringes, and broken grain surfaces without isopachous blade development.





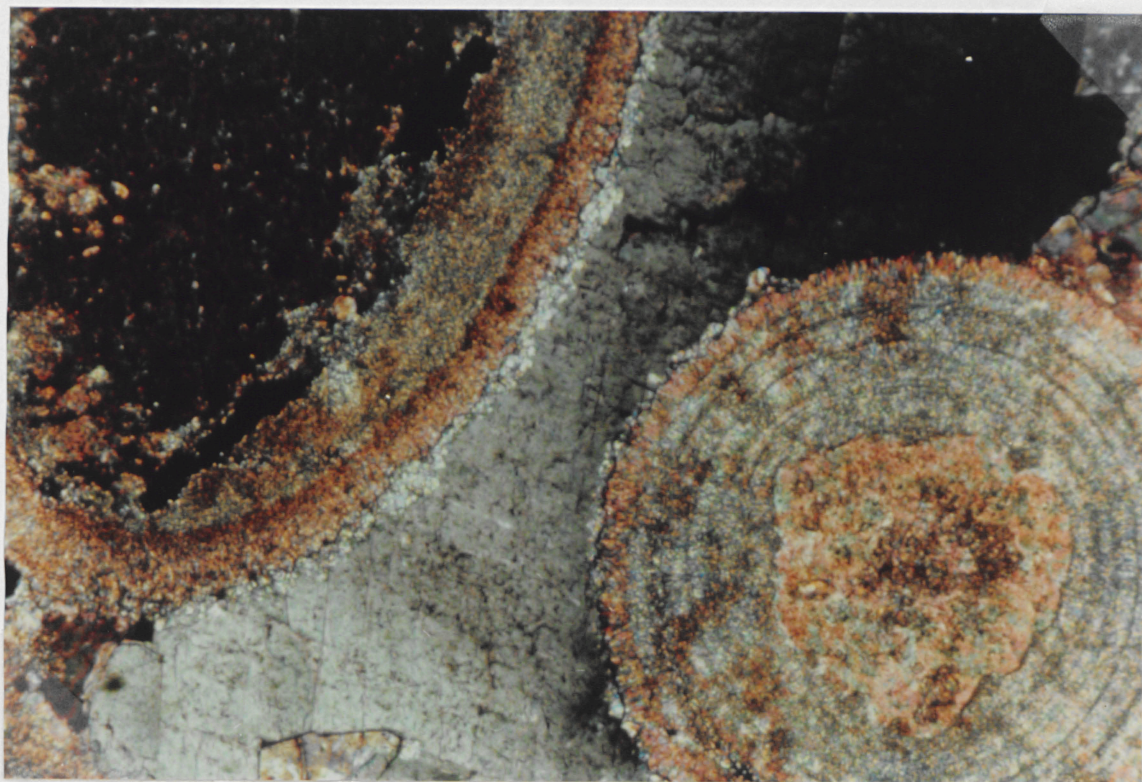


Figure 37. Selective dolomitization on a single ooid. Calcite nucleus (pink), dolomitized lamellae (white), final calcite lamella. The ooids are cemented by xenotopic-C dolomite.

will precipitate dolomite (Badiozamani, 1973; Folk and Land, 1975). This is accomplished very easily in the mixing zone. Choquette and Steinen (1980) were the first to propose this mixing zone model for dolomites in the Ste. Genevieve Limestone of the Illinois Basin. They postulated that a meteoric water lens, formed by exposed oolite shoals, initiated dolomitization in underlying mudstones and wackestones. Then, as progradation continued, meteoric water from an upland source continued the dolomitization process on previously formed dolomite nuclei.

It is not possible here to repeat Choquette and Steinen's isotope and strontium work for the Salem Limestone. There are, however, some important similarities between Ste. Genevieve and Salem dolomites which may indicate similar modes of dolomite formation. They are:

- 1) The basin setting and the depositional environment, which are essentially identical; and the resulting fauna and lithofacies, which are very similar.
- 2) The presence of early, selective dolomitization.
- 3) The limpid, well-formed dolomite rhombs making up the dolostone.
- 4) The absence of contemporaneous evaporites (important because mixing zone waters should be strongly undersaturated with respect to evaporites (Longman, 1981, p. 129). Anhydrite in the Salem is a late diagenetic feature).
- 5) The thickening of dolomite facies over paleohighs (in Salem, the Mill Shoals Red cycle porous zone).

The major problem with this interpretation for the Salem is that the Salem dolomites do not appear to directly underlie sandy calcarenites or oolites as they do in the Ste. Genevieve. It is possible that the initial dolomitization under an oolite shoal (proposed by Choquette

and Steinen) was not important in this instance, but meteoric recharge from an upland source was; and the location of dolomites was controlled by porosity development over pre-existing highs which allowed mixing to occur easily.

Idiotopic-E dolomitization of echinodermal-bryozoan packstone and wackestone lithofacies reduced initial porosities of approximately 20-30 percent to porosities of approximately 10 percent. These dolomites are now good reservoir rocks in several locations.

Meteoric Phreatic

Continued progradation of Salem sediments removed them further from marine influence and filled available pore space with meteoric water. Under these conditions, vuggy porosity developed, and abundant calcite cements were precipitated, changing the character of the Salem sediments drastically.

The meteoric phreatic has been subdivided into five characteristic divisions, based on dissolved CaCO_3 content of the water (Longman, 1981, p. 98). The Salem appears to have been influenced by two or three of these five; the zone of solution (of aragonite, or aragonite/calcite); and the zone of calcite precipitation.

Oomoldic and vuggy porosity developed in the zone of solution. Oomoldic porosity could be related to variations in magnesium content of the ooids; or, to dissolution of originally aragonite ooids (Sandberg, 1975, p. 524). Vuggy porosity was created by dissolution of a grain or mineral which created 1) very round, 1500 micron sized pores, which are "bedded" (Fig. 33); and 2) irregular-shaped vugs or fenestrae up to 1 cm in length. These vugs are timed as meteoric phreatic because they are lined with isopachous, bladed calcite cements from the active

meteoric phreatic environment, and therefore date vug development just prior to them.

In the CaCO_3 -saturated, active meteoric phreatic zone (as described by Longman, 1981), calcite nucleated on the abundant echinoderm fragments present in most lithofacies. If there were no micrite envelopes surrounding the grains, isopachous calcite blades and large, sometimes poikilotopic, syntaxial overgrowths developed. Large crystals of equant calcite, which do not coarsen toward the center of original pores, are also common. This may indicate that pore fluids were not moving rapidly through the system, which enhanced the tendency of calcite to attach to single crystals rather than nucleate on a multi-crystalline substrate. Drusy mosaic calcite cement (coarsening toward pore centers) is most commonly found within fossil fragments, and simply reflects competition between growing crystals for space (Bathurst, 1975, p. 428).

Overall, porosity and permeability were substantially reduced during cementation in the meteoric phreatic.

Vadose

It is equivocal whether Salem sediments were exposed to a vadose diagenetic environment. The depositional model certainly allows for prograding bioclastic-oid shoals to build above the water table; but direct evidence is not conclusive.

From the cores available for this study, the presence of geopetal silt ("vadose silt") is the only link with a possible vadose environment. Vadose silt was first described by Dunham (1969a) for a Permian carbonate buildup in New Mexico. Salem geopetal silts have many of the same characteristics Dunham chose to define this internal sediment. Similarities are:

- 1) They are equigranular, small (approximately 10-20 microns) crystals, which are very well sorted and have no skeletal material.
- 2) They are geopetal.
- 3) They always overlie an early calcite cement (isopachous blades) and are overlain by a later calcite cement (syntaxial overgrowths or equant calcite).

Differences with Dunham's vadose silt are important, though. They are:

- 1) Geopetal silt in Salem appears to only fill primary voids, not primary and secondary, as do Dunham's.
- 2) Micro-crossbedding within the silt is not apparent, as it is in silts described by Dunham.

It is these final two characteristics which the Salem does not share with Dunham's vadose silt which are critical to his vadose origin for the sediment. Also, the Salem geopetal silts are overlain by syntaxial overgrowths. This means that the overgrowths would not have precipitated in the meteoric phreatic environment on the "way up" (from marine exposure to meteoric exposure), they would have precipitated on the "way down" to burial. It seems unlikely that these echinoderm-rich sediments would have resisted syntaxial overgrowths for that length of time.

Although the geopetal silts in the Salem look strikingly like those of Dunham, there is not a strong case for a vadose environment of origin. The fact that the silts were found "sandwiched" between two meteoric phreatic cements more clearly dates them as developing during meteoric phreatic exposure. Subaerial exposure, and even hardgrounds and omission surfaces, have been reported for the Salem Limestone in

this area (Cluff and Lineback, 1981, p. 62), but none of these features were noted during the course of this study.

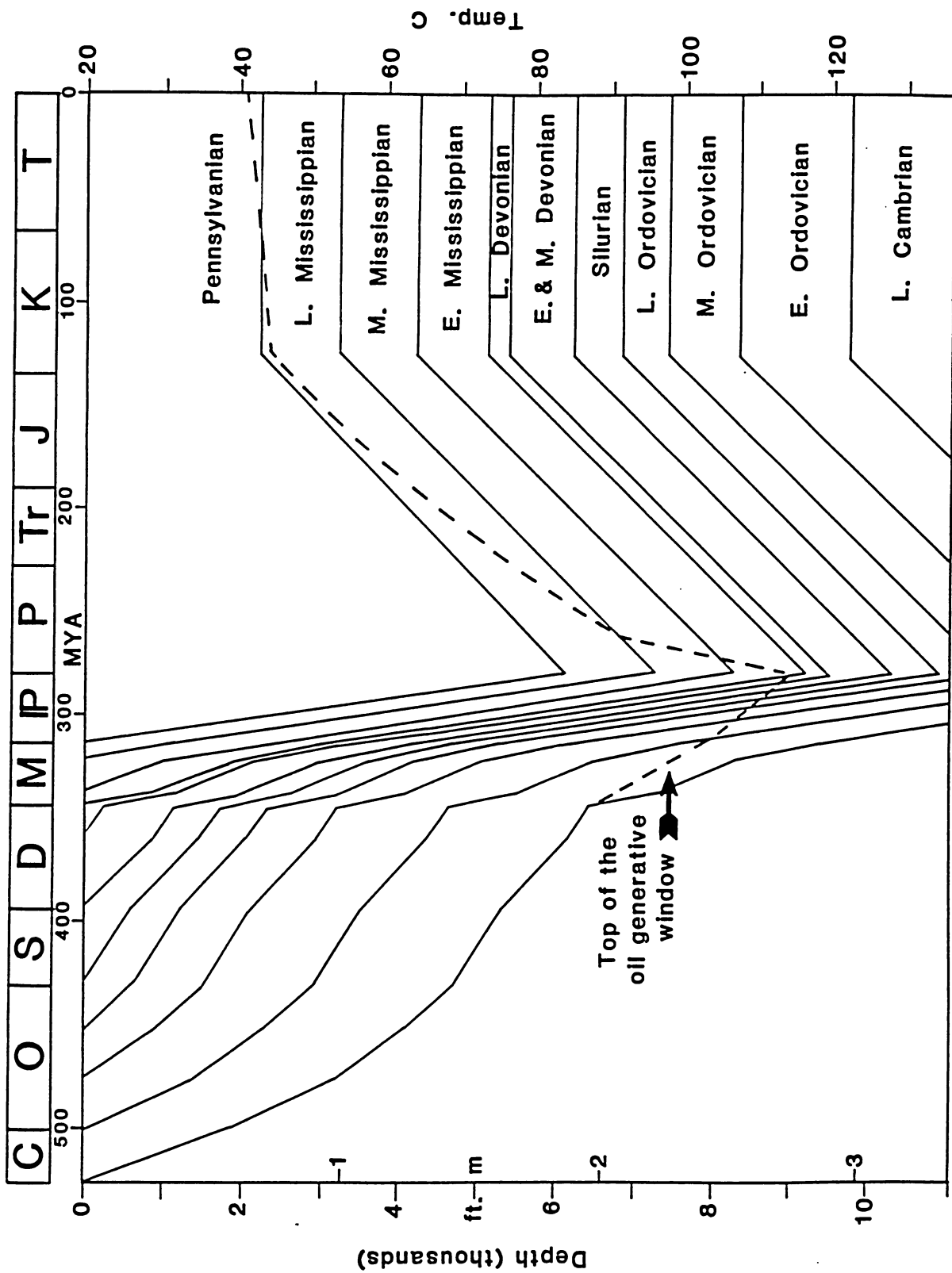
Burial Diagenesis

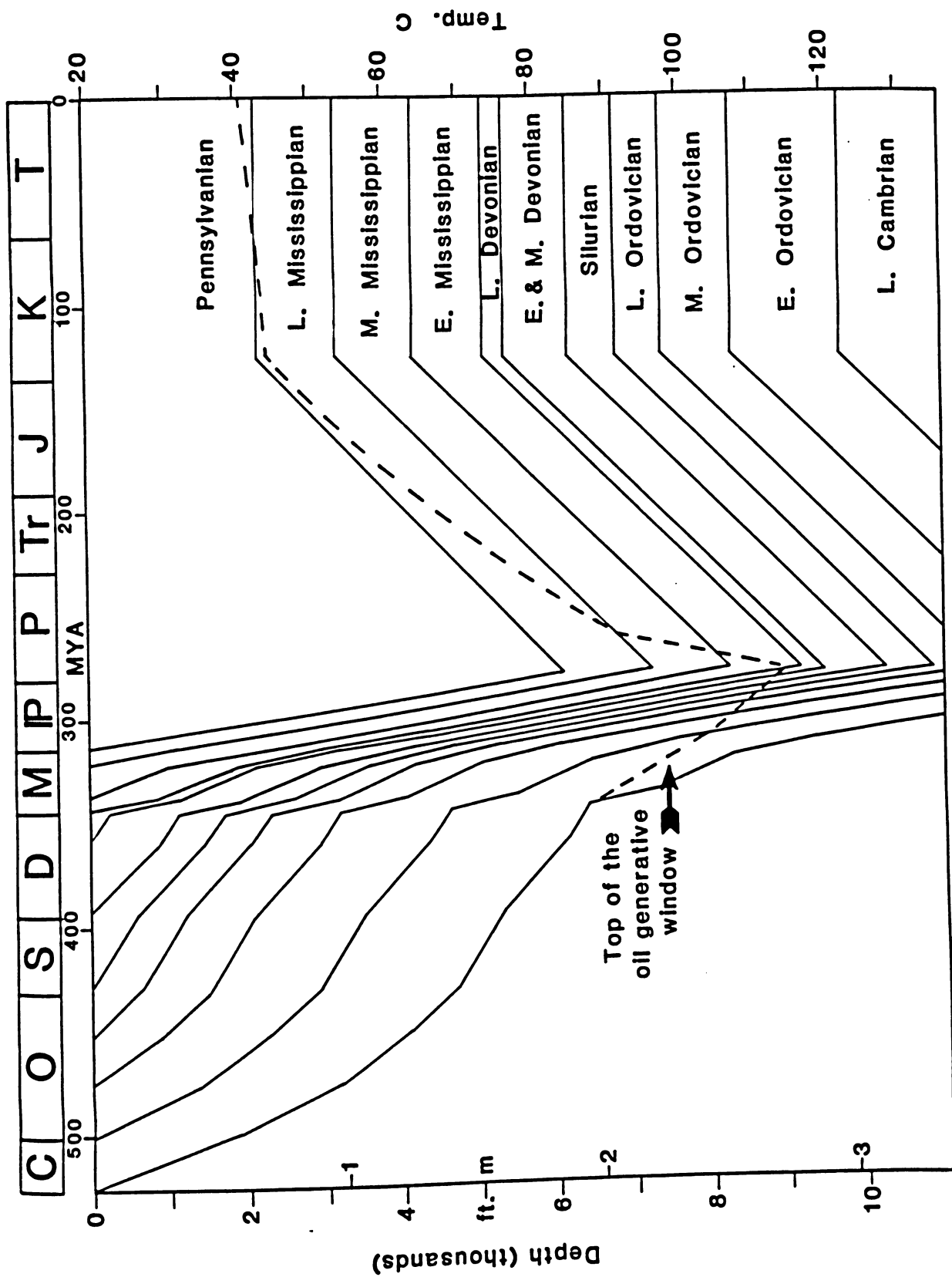
Salem sediments were progressively buried until sometime before the late Cretaceous (Willman, 1975, p. 27). Prior to that erosional event, the Salem was buried under approximately 2379-2684 meters (7800-8800 feet) of sediment. Figure 38 depicts a burial history curve for the Salem Limestone and shows that the formation entered the oil window in approximately early Permian time.

Burial diagenesis products in Salem rocks are not volumetrically important, but they are important permeability and porosity reducers, because they are strongly related to existing porosity.

Late euhedral calcite is the first of the burial cements; and its late timing is based on texture, luminescence, and paragenetic sequence. This calcite appears as large scalenohedral crystals projecting into secondary vugs. It occasionally has very faint ferroan bands near the terminus; and in the generally non-luminescent Salem cements, it is the one cement which goes from very dull luminescence near the pore wall to dull or subzoned dull luminescence at the tip of the crystal. This variation in luminescence indicates a trend from oxidizing pore waters (very dull cements) to reducing pore waters (subzoned dull cements), probably resulting from progressive burial of the sediments. In the paragenetic sequence, it overgrows, and therefore postdates, isopachous blades from the meteoric phreatic. It is always surrounded by, and therefore predates anhydrite and Xenotopic-C dolomite.

Anhydrite in the Salem is a burial diagenetic cement, apparently without a gypsum precursor. Gypsum is the stable phase at or near sur-





face conditions, suggesting that the anhydrite is not from an evaporitic environment. One piece of textural evidence to support this conclusion is that there are no pseudomorphs after gypsum. It is possible that with burial, continued replacement of gypsum by anhydrite caused the pseudomorphs to lose their shape with time (Kinsman, 1969, p. 834); but associated evaporitic environment sedimentary structures, such as algal mats, dessication cracks, or teepees, are absent. In addition, the fact that there is not a large amount of anhydrite confined to a particular lithofacies or bed (Chowns,et.al., 1974, p. 893) excludes the presence of an evaporitic environment. Rather, the anhydrite appears as widely disseminated patches or nodules throughout the Salem.

Additional textural evidence comes from the anhydrite's position in the cement paragenetic sequence. It is a late cement and cuts across isopachous calcite blades, sucrosic dolomite, and fills vugs into which the late euhedral calcite crystals had been growing. It commonly replaces bioclastic and ooid grains, probably by simultaneous dissolution and precipitation, as seen by in situ bioclastic inclusions in a relic pattern (Murray, 1964, p. 520-21). Of particular interest is the fact that some Salem anhydrite is brown, caused by the presence of hydrocarbon inclusions. This times the emplacement of anhydrite within the oil window, beginning in early Permian time. Thomas and Glaister (1960, p. 579) report very similar anhydrites in cyclic Meramecian carbonates in southwest Saskatchewan. They observed that anhydrite was found at porosity and permeability breaks within the rock; which suggested that emplacement was controlled by a salt-filtration mechanism acting on sulfate-rich circulating brines. An investigation of the Salem Limestone in Illinois led Cluff and Lineback (1981, p. 17) to a similar

late-stage brine origin for anhydrite.

Saline, subsurface brines are the source for another volumetrically small, yet ubiquitous, cement within the Salem -- Xenotopic-C dolomites. This dolomite (also called baroque, saddle-shaped, and sparry), with its characteristically large crystal size, fills only pre-existing pore space in all lithotypes. It cuts across all other cements except anhydrite, with which it intergrows and replaces.

Xenotopic-C dolomites show a recurring association with epigenetic sulfide mineralization, sulfate-bearing carbonates, and hydrocarbon reservoirs (Radke and Mathis, 1980, p. 1159), similar to the association for the Salem. These dolomites are reported to be deposited from saline, heated (50°C-130°C), subsurface brines by many authors (Radke and Mathis, 1980, p.1159; Gregg and Sibley, 1984, p.908; Choquette, 1971, p. 340-345; Grover and Read, 1983, p. 1298). This corresponds to the stability field for anhydrite precipitation (minimum 42°C-58°C, Murray, 1964, p. 513-14; Hardie, 1967, p. 185) as well. Indeed, these dolomites have been reported elsewhere to contain hydrocarbon inclusions, just as the anhydrite does in the Salem (Longman, 1981, p. 115-116); so precipitation of the two minerals may be penecontemporaneous and be timed after early Permian.

Although there are important questions concerning the kinetics of dolomite formation, burial conditions may be better able to satisfy the requirements needed for dolomite formation, such as:

- 1) Rapid reaction rates, caused by increased temperature.
- 2) Hydration of Mg^{+2} for incorporation into the solid carbonate lattice, caused by increased temperature.
- 3) High permeabilities, satisfied instead by more rapid reaction rates.

4) Chemical stability, maintained by subsurface flow (Mattes and Mountjoy, 1980, p. 260).

5) Lower critical roughening temperature for crystal faces because of substitution of Fe and Ca into lattice (Gregg and Sibley, 1984, p. 925).

There is a strong possibility that Xenotopic-C dolomitization in the Salem Limestone is related to the Mississippi Valley-Type mineralization in southern Illinois. Xenotopic-C dolomitization has been related to emplacement of Mississippi Valley-type deposits by many authors. Choquette (1971, p. 340-345), in particular, related coarse ferroan dolomite within the Ste. Genevieve in Lawrence County, Illinois, to the Mississippi Valley-type deposits at Cave-in-Rock, Illinois. The temperature of depositing fluids at Cave-in-Rock (100°C-150°C) matches the proposed temperature of formation of Salem Xenotopic-C dolomite, and the age of mineralization at Cave-in-Rock (Permian-Upper Cretaceous) (Grogen and Bradbury, 1967, p. 379) also matches the proposed age of anhydrite-dolomite-hydrocarbon emplacement for the Salem. Unlike the Ste. Genevieve ferroan dolomite, the Salem Xenotopic-C dolomite is non-ferroan. This also agrees well with Mississippi Valley-Type deposits, which are generally non-ferroan.

The relationship between Salem Limestone diagenesis, hydrocarbon emplacement, and Mississippi Valley-Type deposits is interesting, and important. Further investigations combining the studies of Mississippi Valley-type deposits and hydrocarbon emplacement may lead to increased efficiency in exploration in both areas.

As mentioned above, hydrocarbon emplacement may have been penecontemporaneous with anhydrite and Xenotopic-C dolomite precipitation, and it also postdated anhydrite cements, shown by oil in anhydrite cleavage

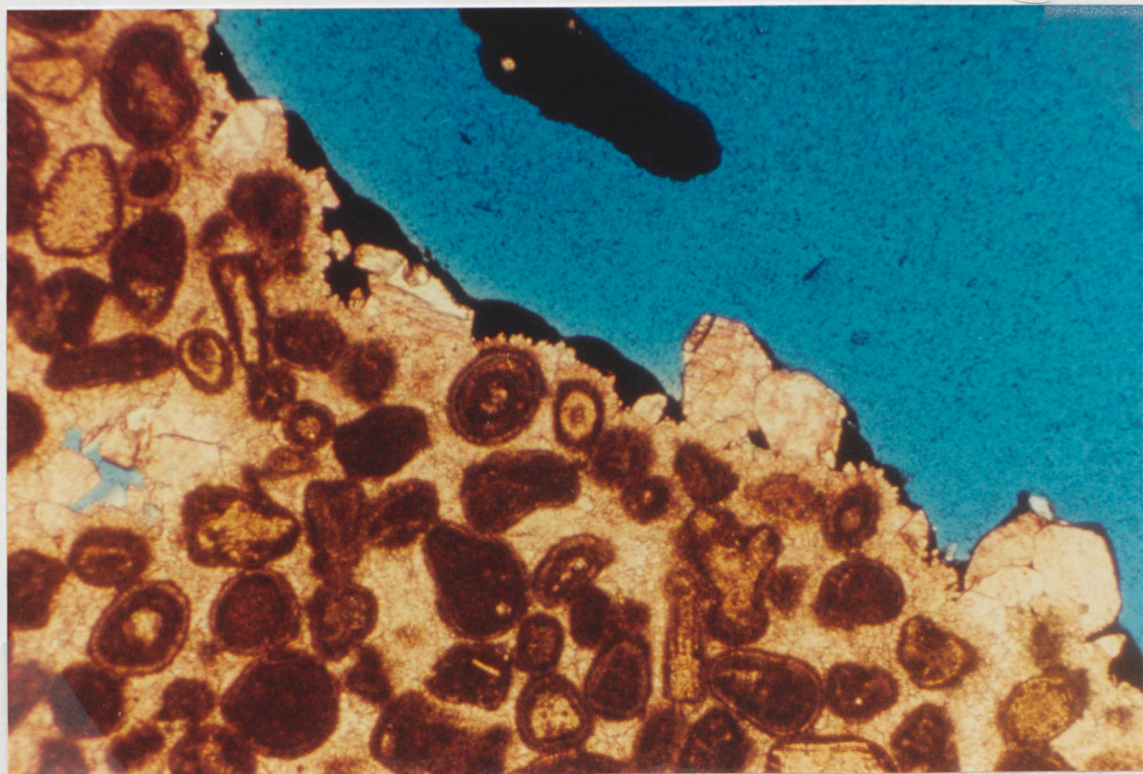
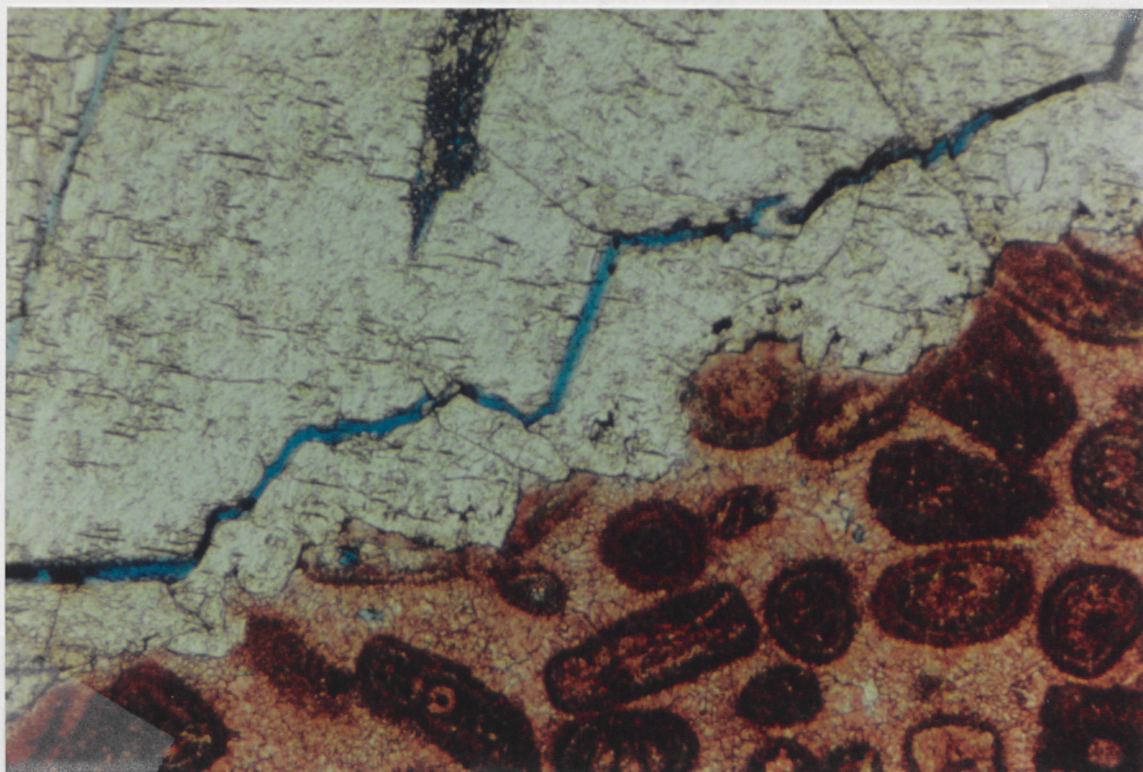
fractures (Fig. 39). "Dead" oil remains in some large pores in the oolitic grainstone lithofacies (#6), and appears to have prevented further cementation in those pores (Fig. 40).

Stylolites are certainly a burial diagenetic feature in Salem rocks. They cut all cements; but their relationship with hydrocarbon emplacement is not clear. The stylolites can be quite large, some with amplitudes over two inches. Associated with the insoluble residue along the stylolite is Idiotopic-S dolomitization.

Although the diagenetic sequence is probably more complicated than presented here, the major events have been recorded as the paragenetic sequence. The sequence seen in these Salem rocks reveals steady subsidence as cyclic sediments prograded again and again over the Salem sediments. In summary: secondary dissolution is an early diagenetic feature; most primary porosity was occluded during meteoric phreatic diagenesis; and late diagenetic products reduced permeability and are related to hydrocarbon emplacement.

Figure 39. Anhydrite replacing ooids and isopachous calcite cement. Fracture in anhydrite (blue) contains residual oil.

Figure 40. Fenestral pore. Pore walls lined with scalenohedral calcite crystals. Residual oil (black) coats the cement.



DEPOSITIONAL MODEL

Shoaling-upwards cycles in carbonate sequences are very common, and occur in several different environments. Wilson (1974, p. 282) has outlined three basic types of carbonate cycles: oolite or grainstone cycles, lime mud cycles, and platform interior cycles; and has defined depositional environments for each. Comparison of characteristics between Wilson's cycles and Salem cycles can give valuable insight into the depositional environment of the Salem.

Following is a summary of characteristics from each of Wilson's shoaling-upwards cycle types.

1) Ooid-Grainstone Cycles

- a) Common in Jurassic and early Carboniferous strata.
- b) Generally occur on portions of wide shelves marginal to basins. The prominent grainstone member must result from progradation of the shelf margin environment (SFB 6).
- c) Ooids and coated, non-bioclastic grainstones dominate. The well-formed ooids are, by analogy with Holocene sediments, indicative of strong and regular tidal currents.
- d) Cycles may grade upward and shelfward to a restricted marine facies; or a surface of non-deposition (lag) may overlie the grainstone.
- e) When restricted marine facies do occur at the top of a cycle, they tend to be thick-bedded lagoonal muds rather than thin-bedded intertidal/sabkha deposits.
- f) Reefs are absent from seaward margin of shelves. A reef would restrict tidal currents too much for ooid formation.
- g) Crinoidal limestone is important on seaward side of shelf.

h) Cycles commonly constitute part of megasequence which shoals upward; the cycles multiply and so become thinner and more restricted in character vertically in the section.

2) Lime Mud-Sabkha Cycles

a) Tend to occur on wide shelves and across shallow intracratonic basins, particularly where far removed from major shelf margins.

b) Micritic texture generally throughout. The only common packstones or grainstones are found in channels or levees.

c) Earliest beds are open or partly restricted marine. Latest part is always a tidal flat sequence.

d) Sharp lithologic contact occurs at the top, but there is no evidence of downcutting channels or much intense action of meteoric water.

e) Dolomitization of such cyclic sequences common.

f) These cycles may be facies equivalent to ooid grainstone cycles which lie on the seaward exterior of wide shelves; the micritic facies is more shoreward.

3) Platform Cycle with Intense Diagenesis

a) Dolomitization common.

b) Large scale development of shrinkage pores, fenestral fabric, or birdseye developed in pelloidal or homogeneous lime mudstones.

c) Prism cracks and teepees formed through several meters of sediment. Sheet cracks parallel to bedding, oblique zebra cracks, and neptunian dikes.

d) Cycle capped by red soil and caliche horizons; breccias, pelloidal fabrics with reverse grading; onkoids.

Comparison between observed Salem cycle characteristics and Wilson's (1974) generalized cycle characteristics shows unequivocal agreement between the Salem and Wilson's Ooid-Grainstone cycle. Near the top of Salem, during the generally restricted time of the basin, there might have been some gradation into Wilson's Lime Mud-Sabkha Cycle as well. Wilson interprets the Ooid-Grainstone Cycle as resulting from tidal influence on a regressive wide shelf marginal to a basin. Because of the striking similarity with Wilson, the Salem appears to have formed under the same conditions. Two other pieces of evidence support this model.

1) A cross-bed study done by the Sedimentation Seminar (1966) on the Salem in Indiana shows a marked bimodal distribution of current directions. The primary mode points downslope (southwest) and the secondary mode points upslope (northeast). The Seminar interpreted these cross-beds to be the result of ebb and flow tidal currents on a shallow marine shelf.

2) Geometries of oolite bodies in this study tend to have an elongate axis with a general alignment of N30E. Tharp (1983, p. 19) reports N50E for Ste. Genevieve oolite bodies, and Roberts (1984, p. 114) reports N40E for Spar Mountain oolite bodies. These NE-SW trends of elongation perpendicular to the paleoshoreline suggest the back-and-forth water energy generated by tidal currents. Indeed, the geometries of these oolite bodies match closely the description of tidal bar belts by Off (1963), and Ball (1967). In addition, the mixing of open marine and restricted water fauna seen in Salem lithofacies could indicate back-and-forth currents as well. In summary, the Salem appears to have been deposited on a shallow marine shelf in an epeiric sea. Carbonate pro-

duction, coupled with relative sea level rises across an epi-
iric sea, created a series of shoaling-upwards cycles which progressively filled in the basin. These cycles were shaped by strong tidal current energy during deposition.

This depositional setting results in a characteristic suite of rocks, many of which are present in the Salem cores used for this study. The oolitic packstone and grainstone lithofacies (#4, 3 respectively) represent the shoal portion of the cycle. These are always overlain by open platform echinodermal-oolitic grainstones (#1), echinodermal-bryozoan grainstones (#2) or the more restricted pelloid aggregate grainstone (#5). Progradation brought these normal marine sediments into contact with meteoric water, and early dolomitization occurred (lithofacies #7), probably controlled primarily by porosity of the sediments. Diagenesis of these lithofacies is also characteristic of this depositional model. Marine cements reflect the depositional environment; meteoric cements and porosity are the result of progradation away from marine influence; and deep burial cements were deposited after the rock had been buried by succeeding cycles.

Figures 41 and 42 are summary diagrams incorporating many of the above ideas into a series of block diagrams.

The most important practical use for this model of the Salem Limestone history is in exploration for hydrocarbons. Aspects of this study which may enhance exploration include:

- 1) Proven mappability of the five Salem cycles, which provides a basis for detailed reservoir mapping, accuracy in predicting position of cycle of interest, and a base for comparison between cycles.
- 2) Determination that location of well in basin will determine which

Figure 41. Distribution of Salem lithofacies in cross section, and their relationship to Wilson's (1974) Standard Facies Belts (SFB) and Standard Microfacies (SMF). Relative positions of cores examined in this study shown with respect to Salem lithofacies.

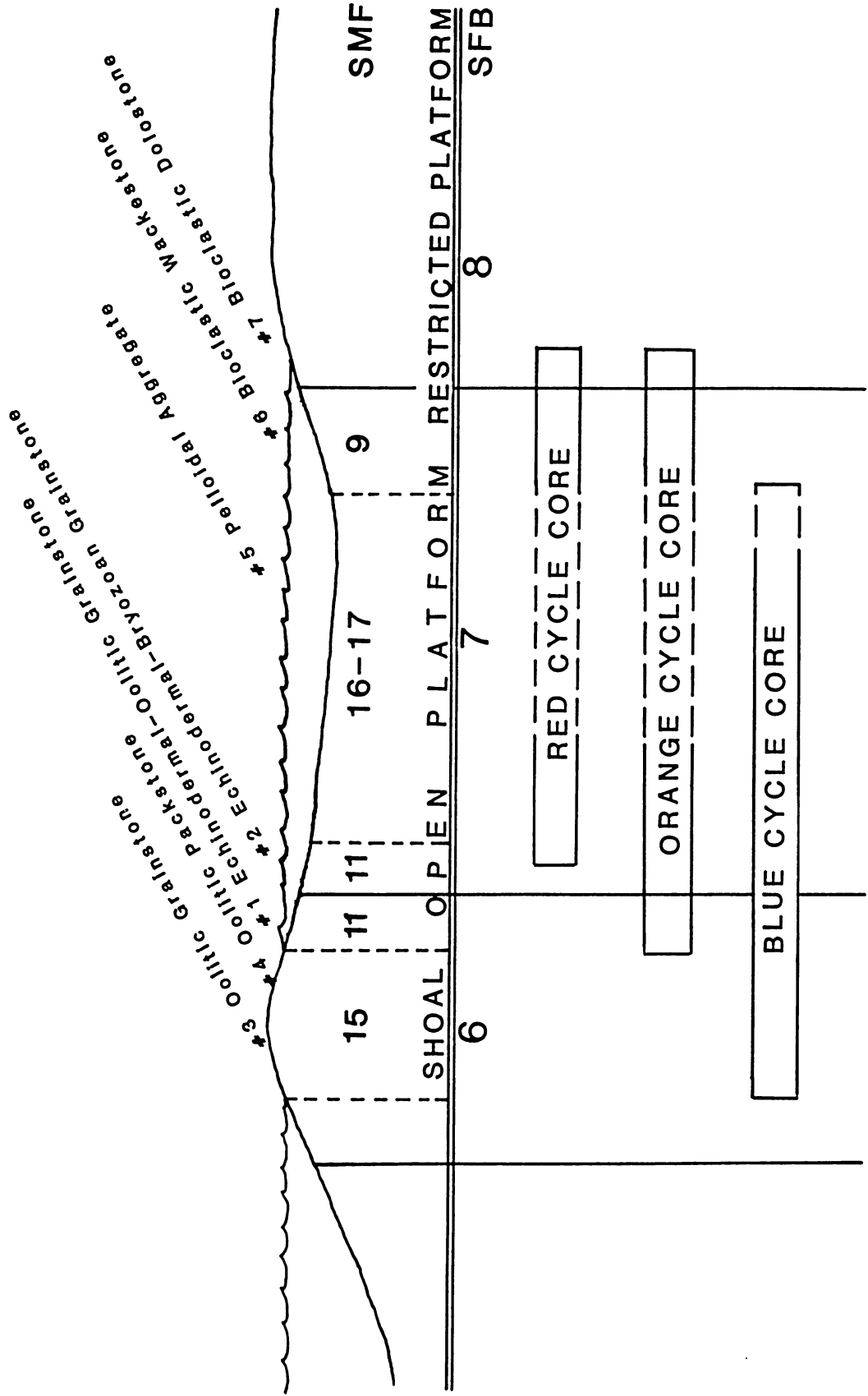
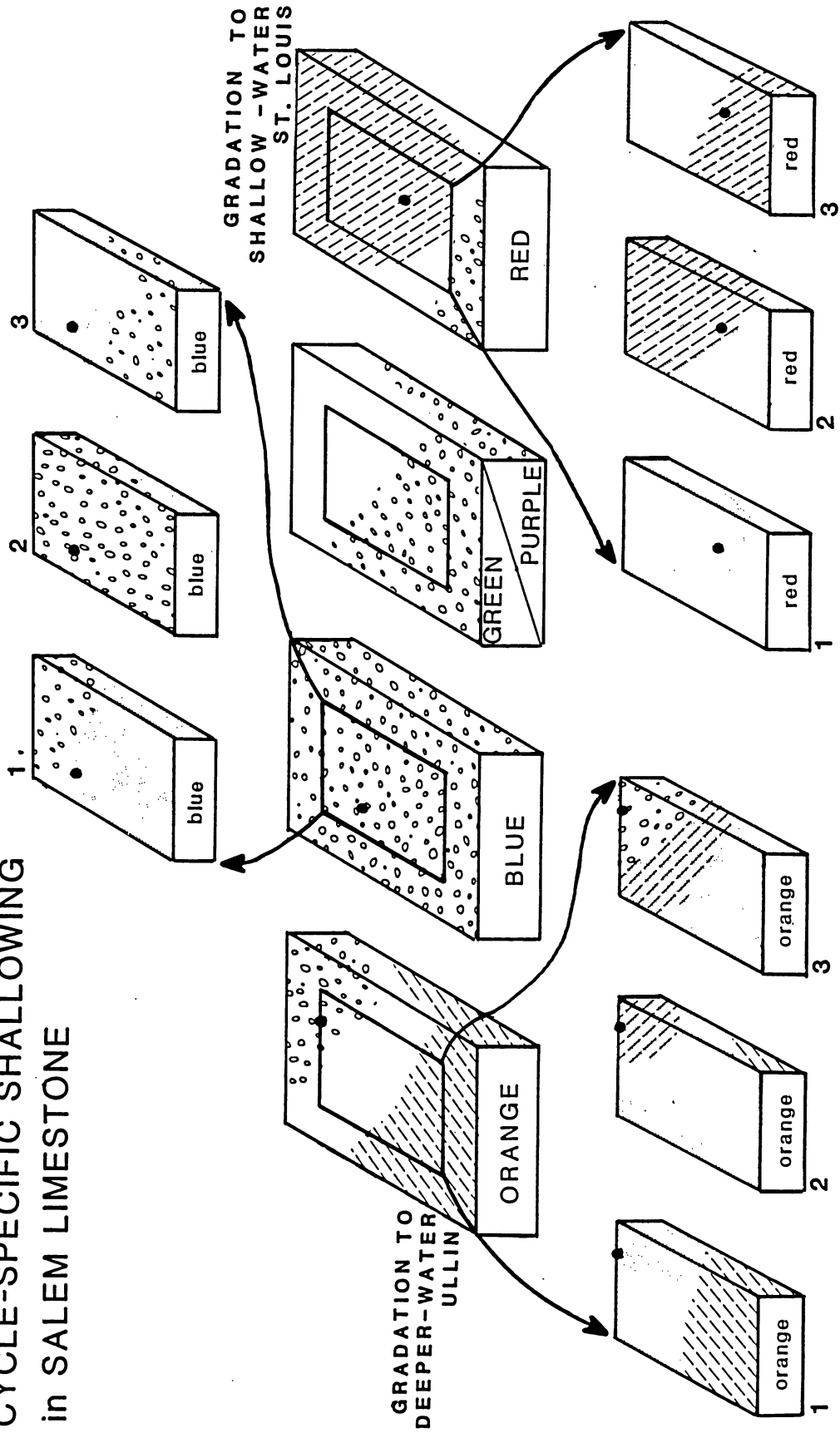


Figure 42. This series of block diagrams depicts progressive shallowing throughout the five cycles in the Salem Limestone (large blocks in center). In addition, each individual cycle is comprised of a shallowing-upwards sequence, represented by the stylized prograding sediments in the small block diagrams.

GENERAL SHALLOWING and CYCLE-SPECIFIC SHALLOWING in SALEM LIMESTONE



cycles will be best developed (e.g., center of basin - uppermost Salem; margins of basin - lower-middle Salem)>

3) Consideration that dolomite reservoirs are controlled by presence of primary porosity, just as oolite reservoirs are; so they should be explored for in a similar manner.

4) Recognition that to maximize reservoir thickness, oolite shoals should be drilled slightly off crest of the structure; dolomites should be drilled on the crest of the structure.

CONCLUSIONS

1. The Salem Limestone in Hamilton, White, and Wayne Counties, Illinois, consists of at least five shoaling upward cycles which can be mapped throughout the study area.
2. Thickness, development, and lithologic components of these cycles demonstrate a cycle-specific shallowing of the water northward and a shallowing of the water in general from the onset of Salem time through the beginning of St. Louis time.
3. Individual cycles tend to thin over pre-existing highs, thicken on the flanks of the structures, and thin in the inter-structure areas (with the exception of dolomite facies).
4. From available cores, the Salem displays seven different lithofacies, as follows: 1) Echinodermal-Oolitic Grainstone, 2) Echinodermal-Bryozoan Grainstone, 3) Oolitic Grainstone, 4) Oolitic Packstone, 5) Pelloidal Aggregate Grainstone, 6) Bioclastic Wackestone, 7) Bioclastic Dolostone.
5. Orthochemical constituents reflect relatively steady subsidence of marine-deposited grains. Vuggy and oomoldic porosity was produced in the solution zone of the meteoric phreatic; and abundant equant calcite and syntaxial overgrowths were deposited in the precipitation zone of the meteoric phreatic. Late porosity and permeability-reducing anhydrite and dolomite may be related to the Cave-in-Rock Mississippi Valley type lead-zinc deposits.

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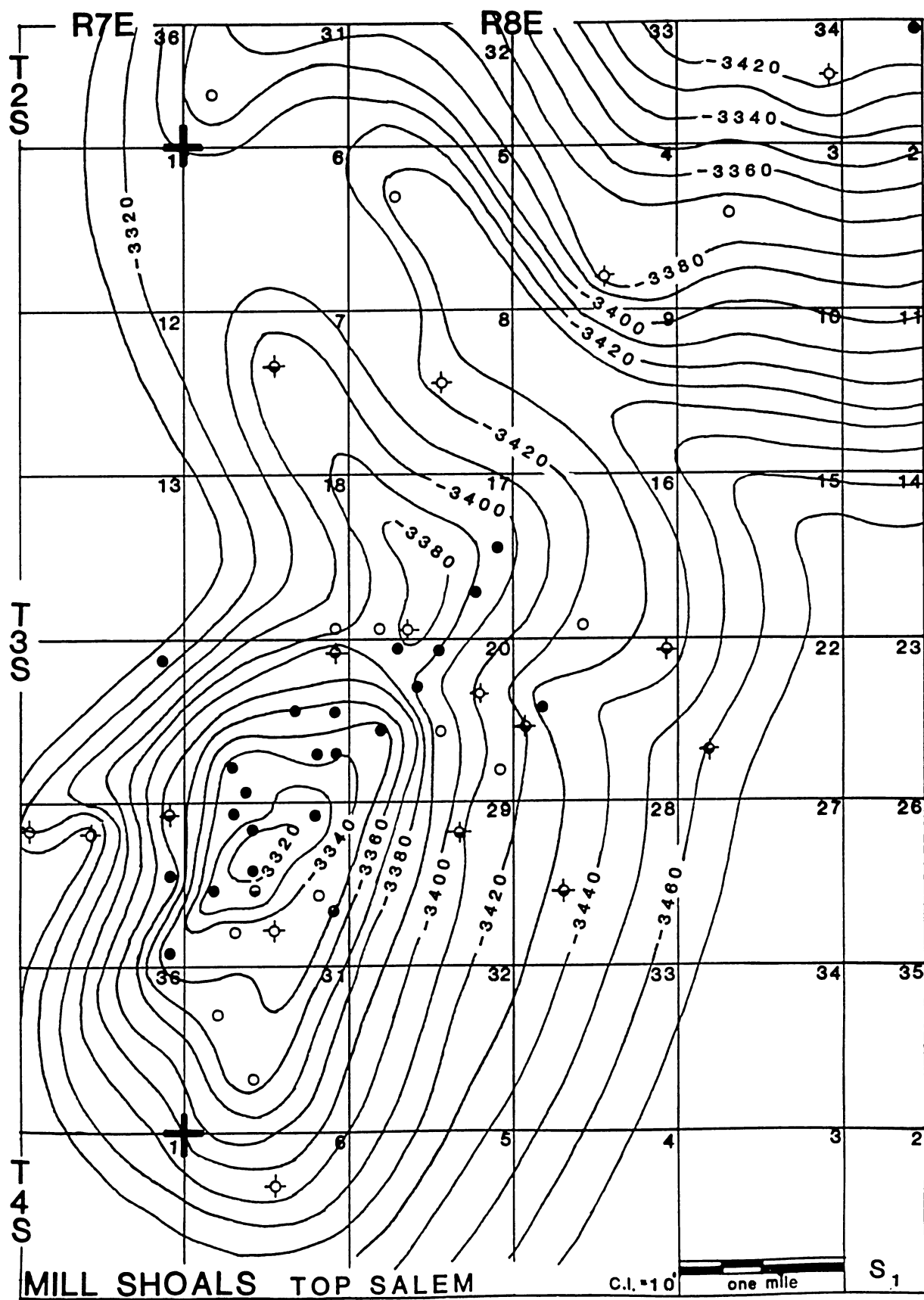
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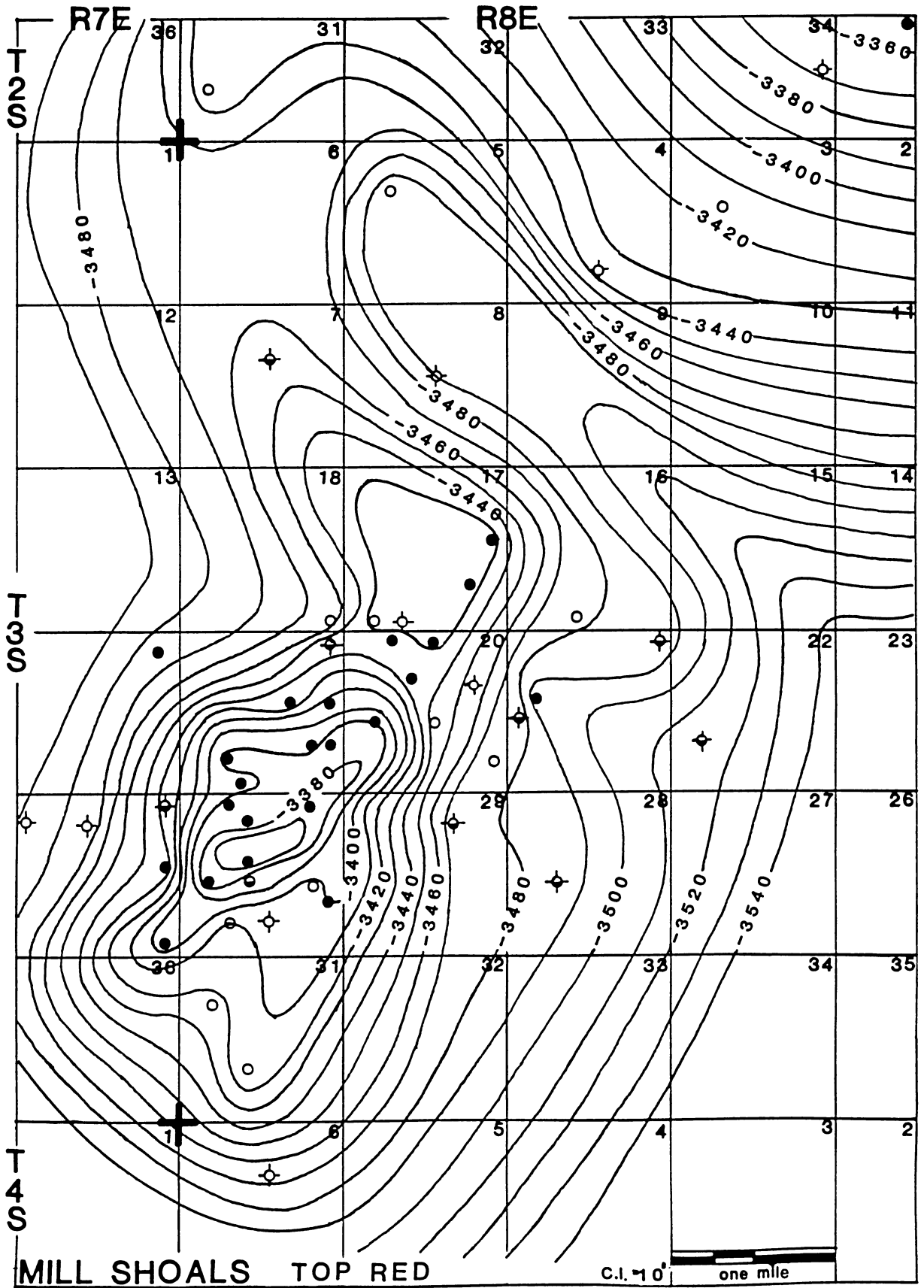
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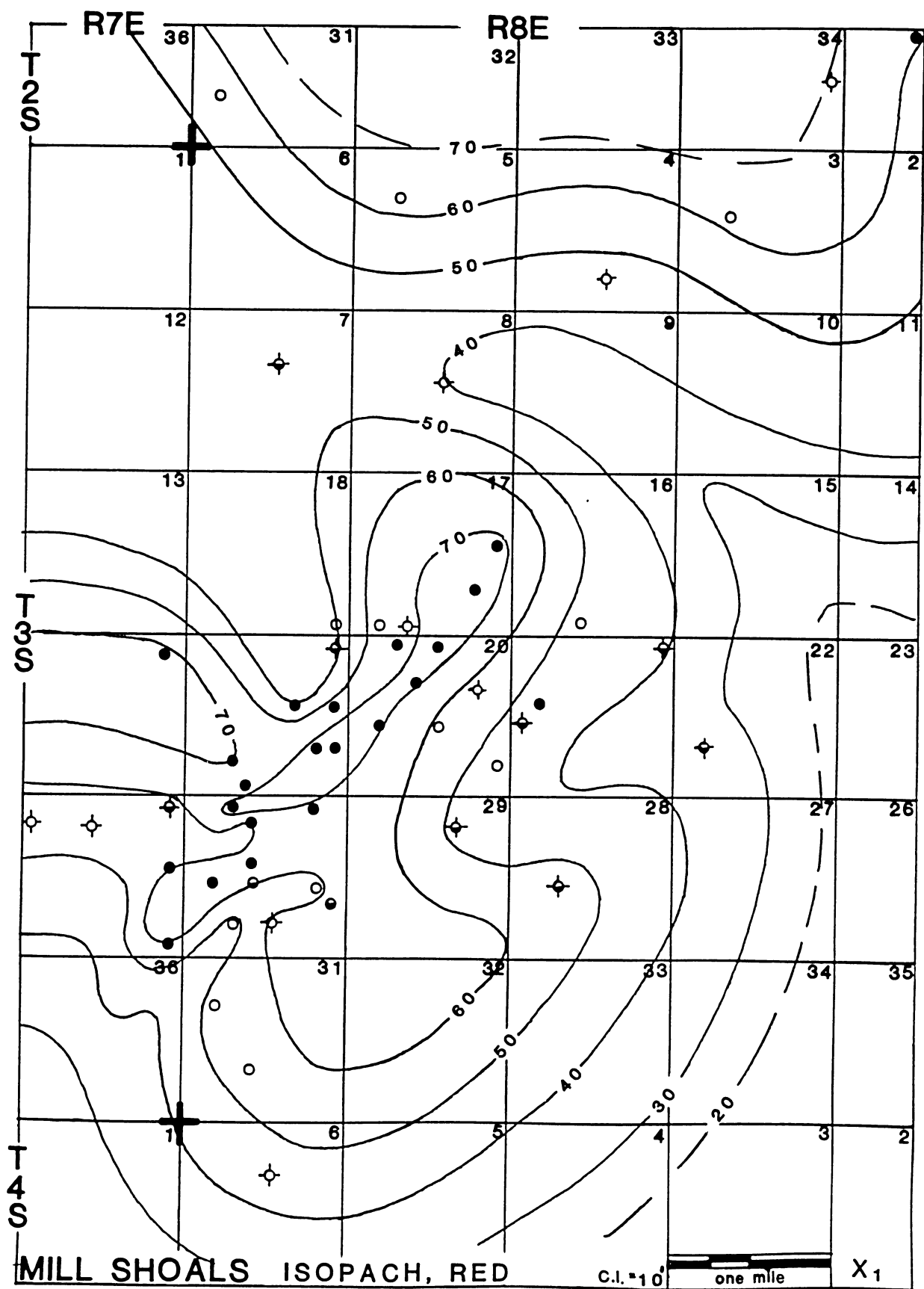
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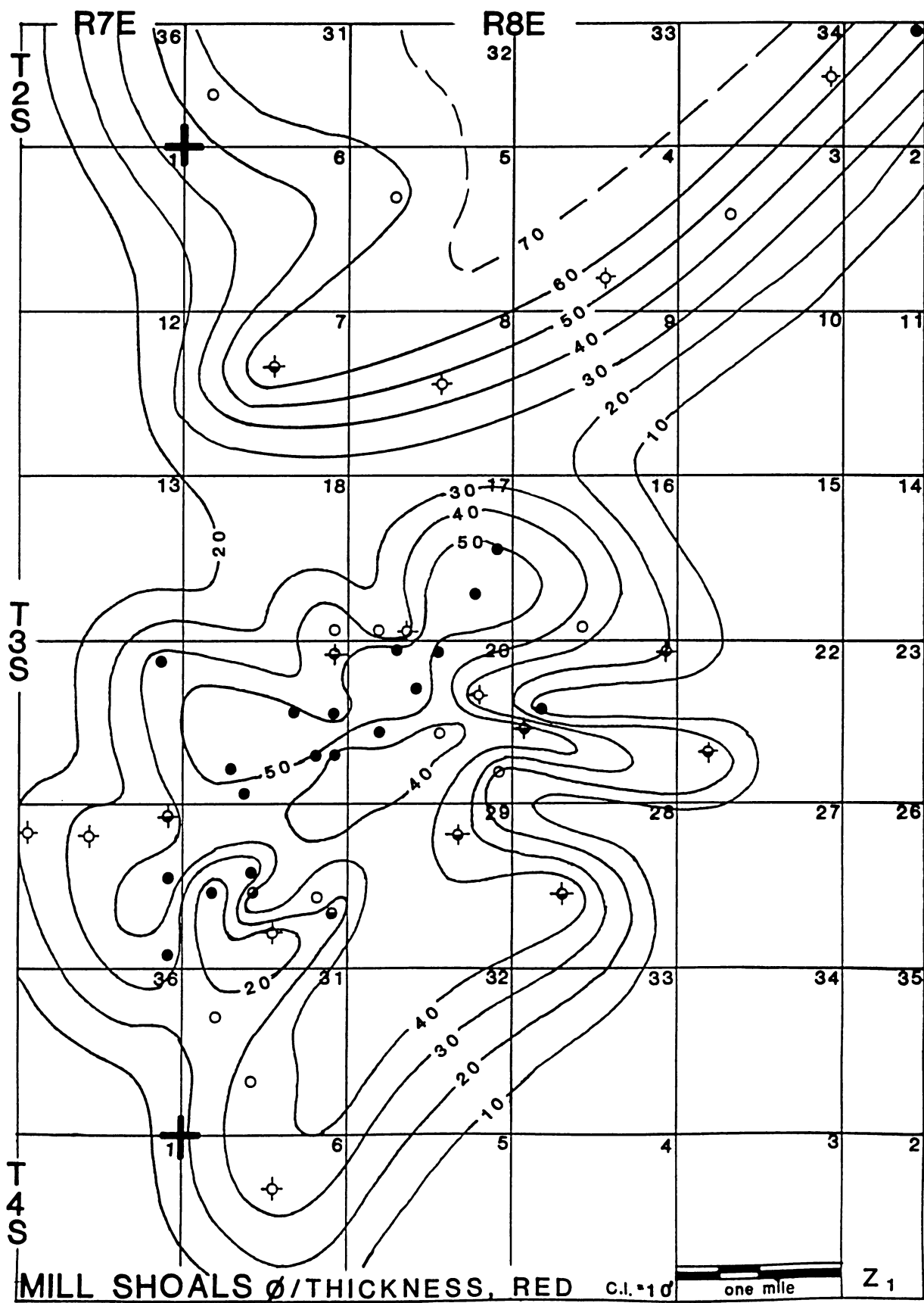
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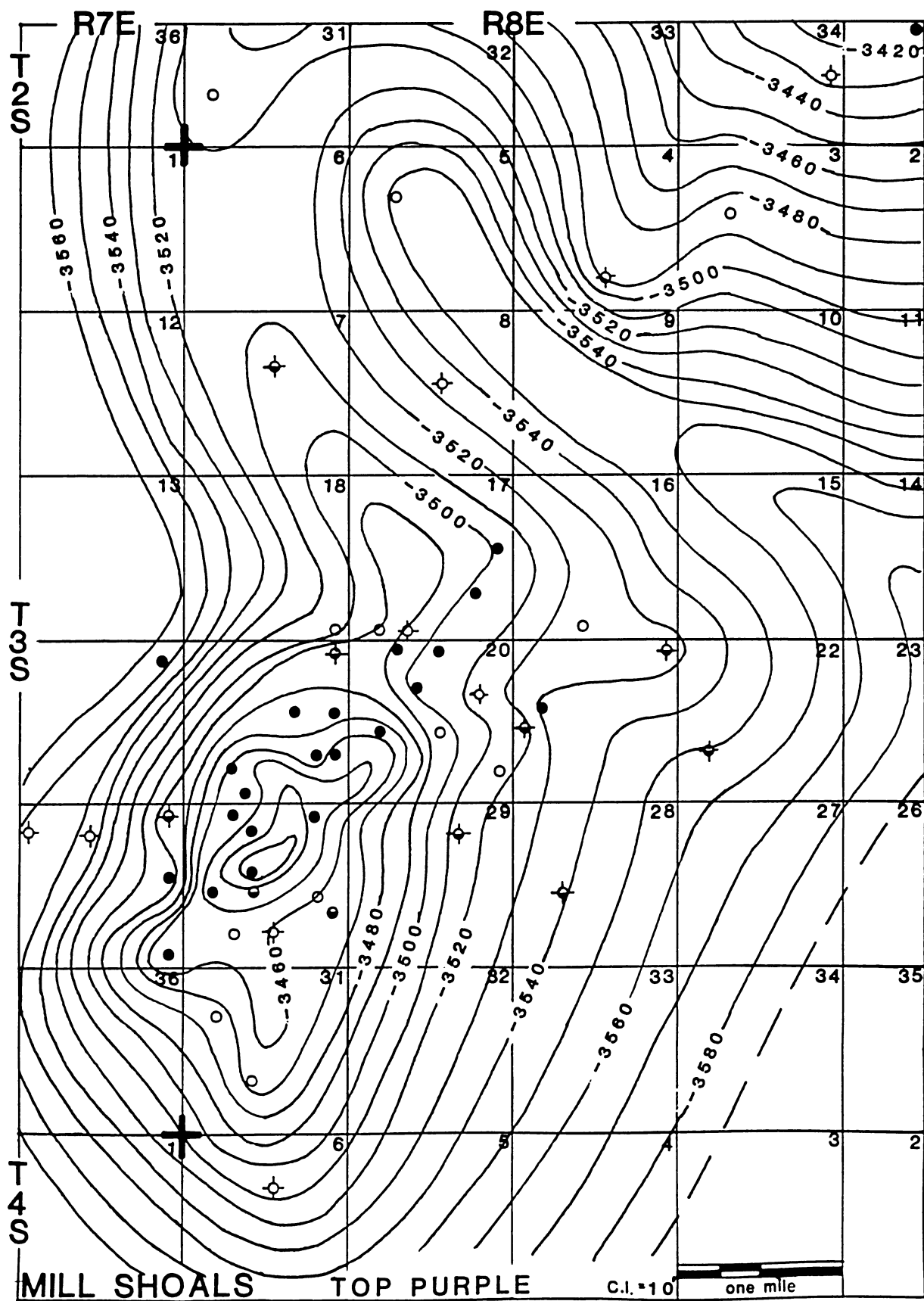
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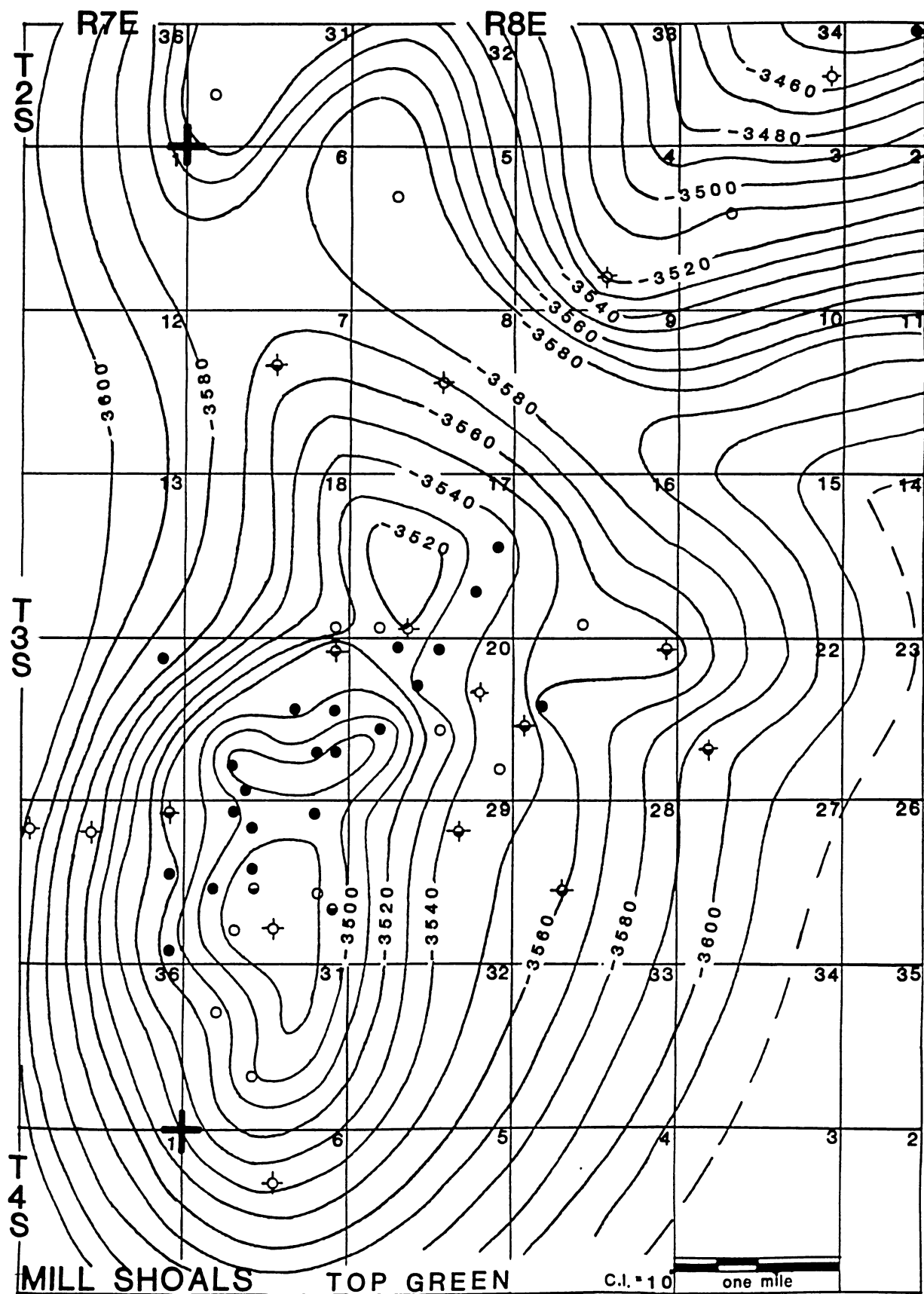


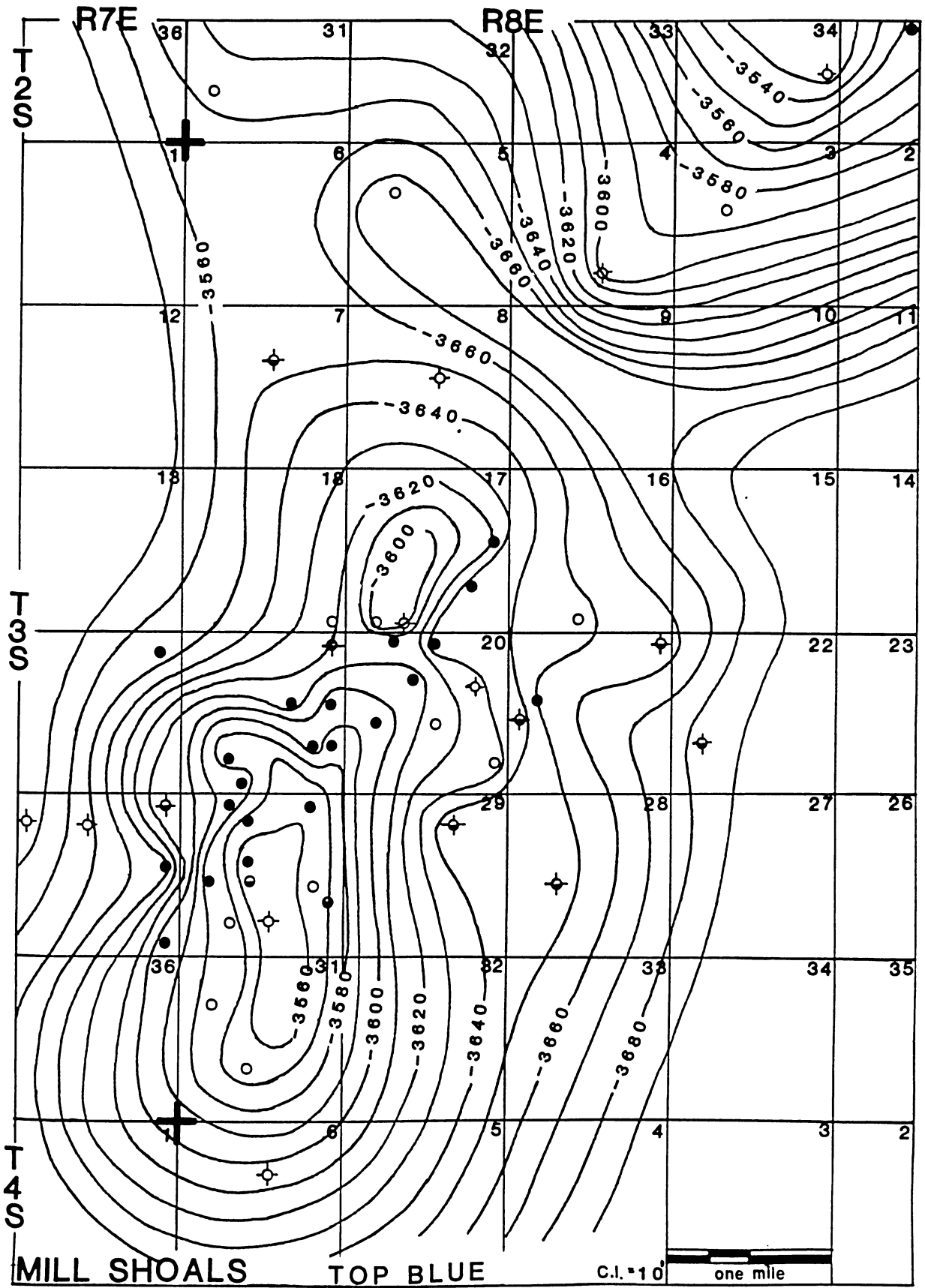


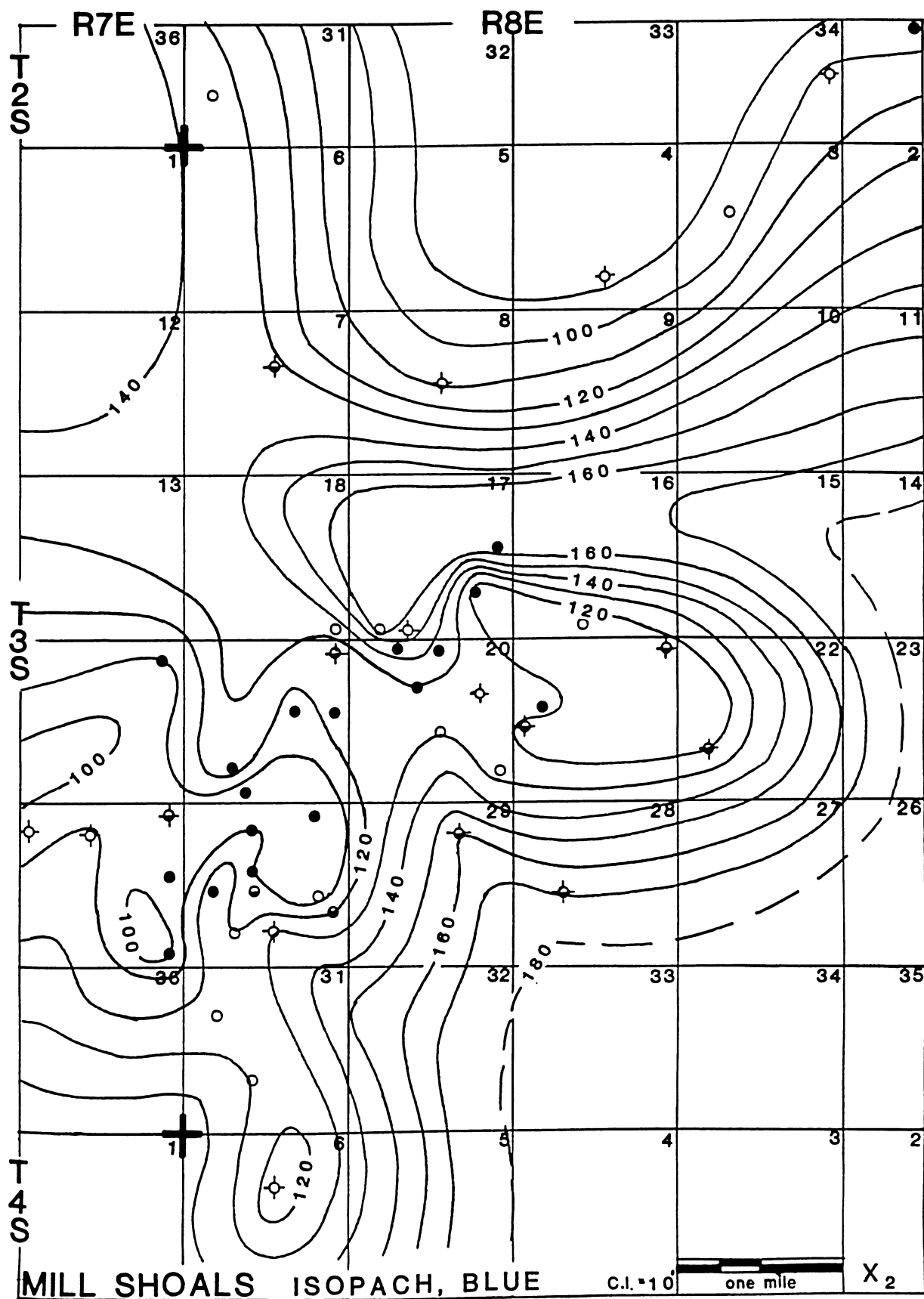


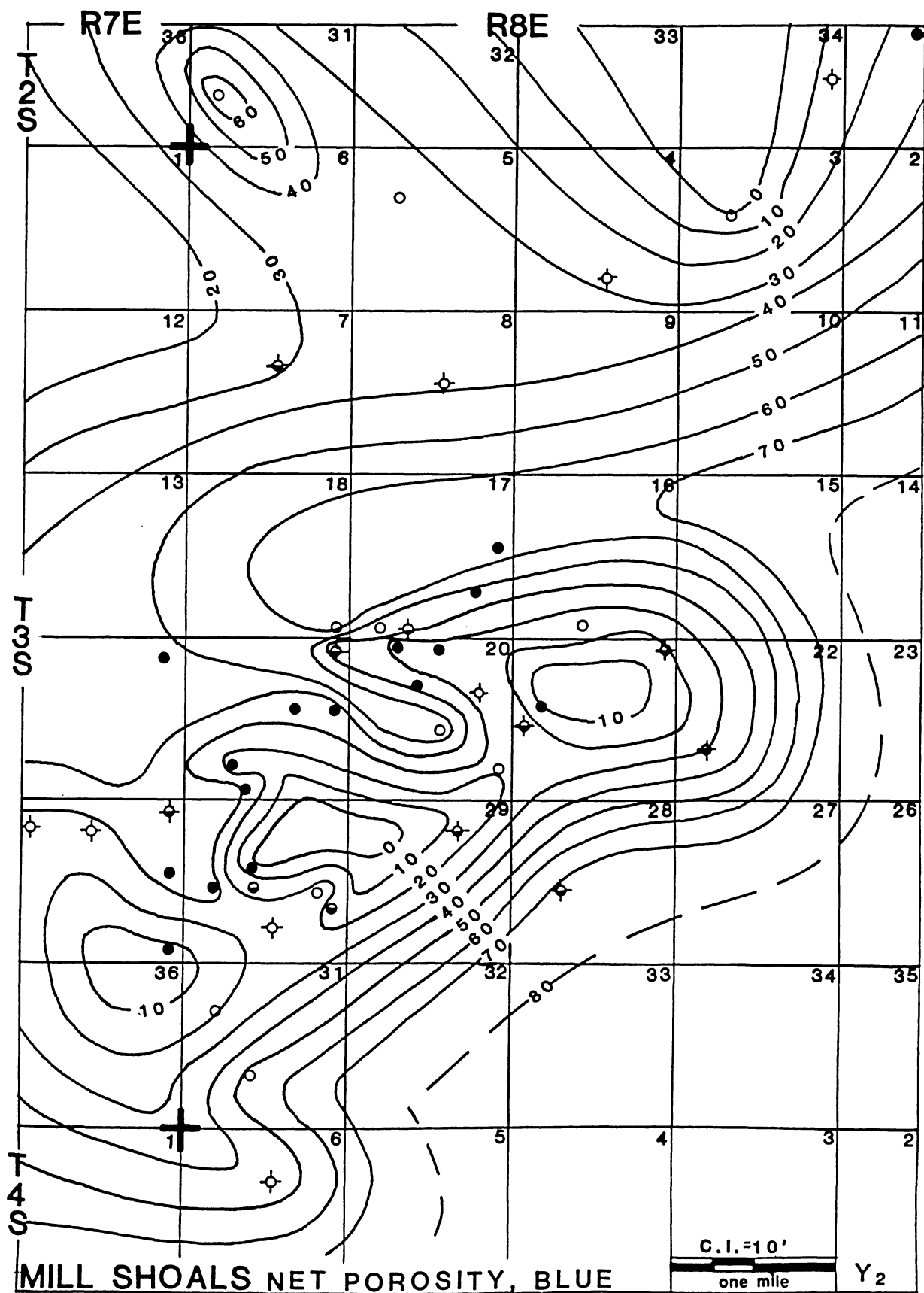


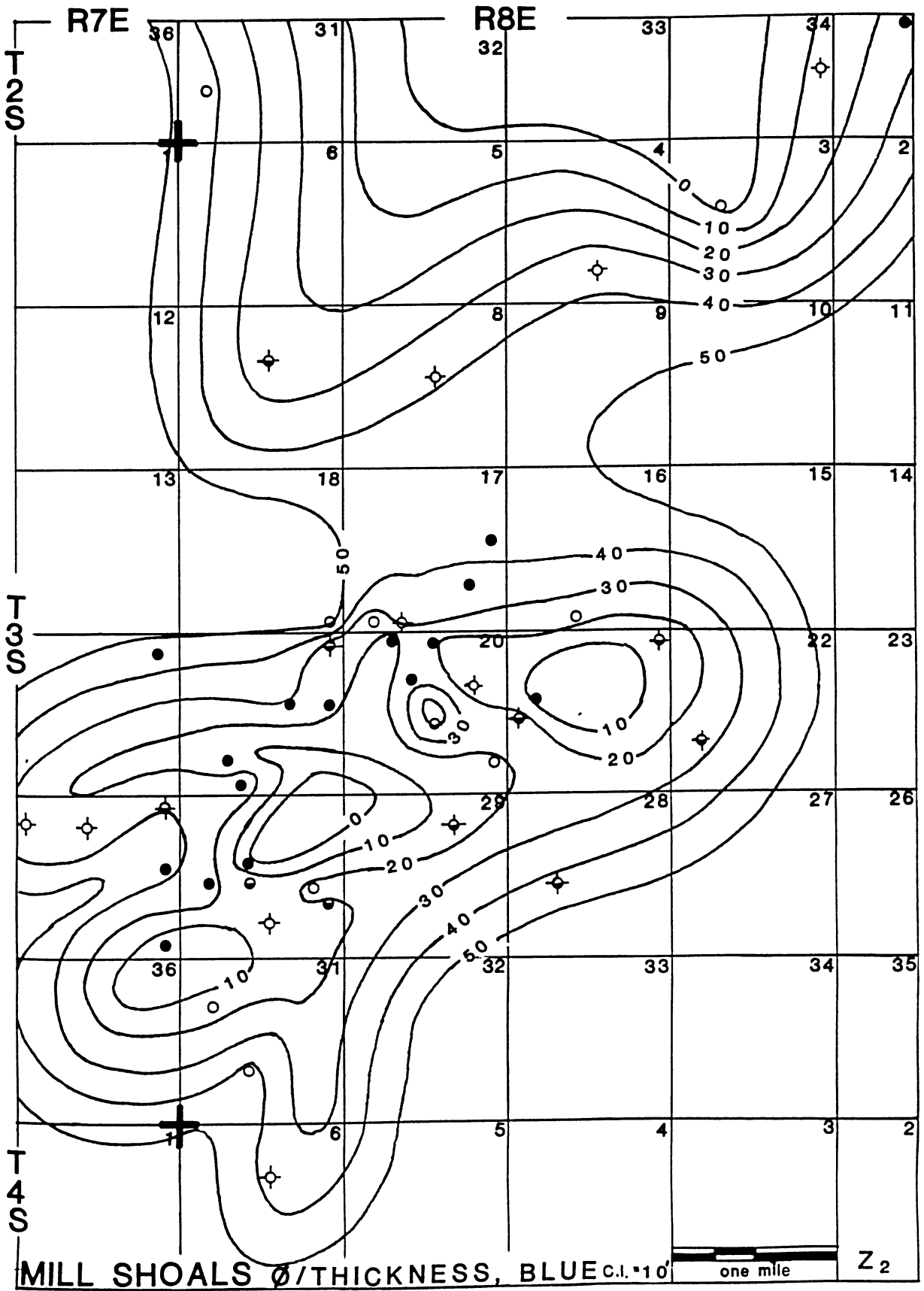


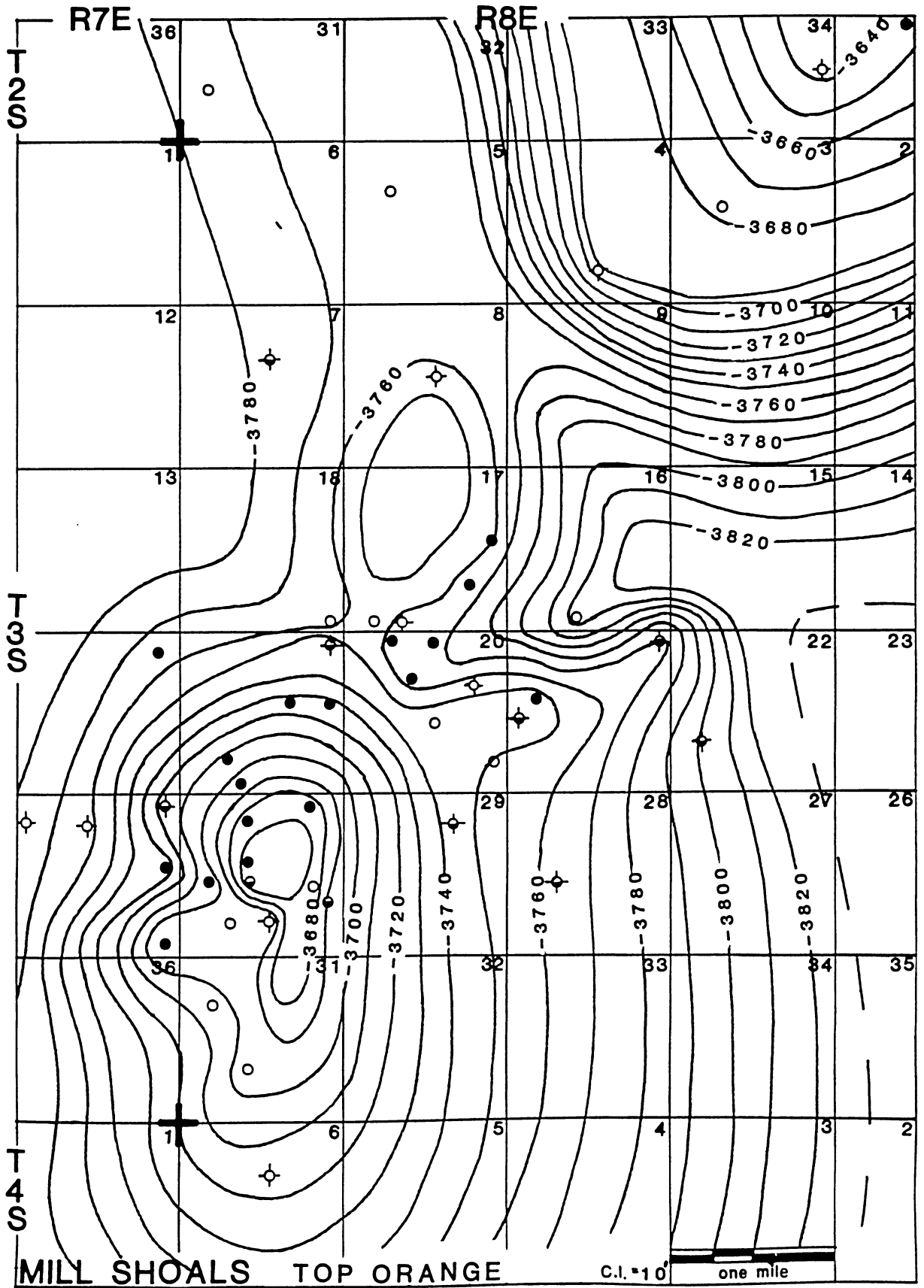


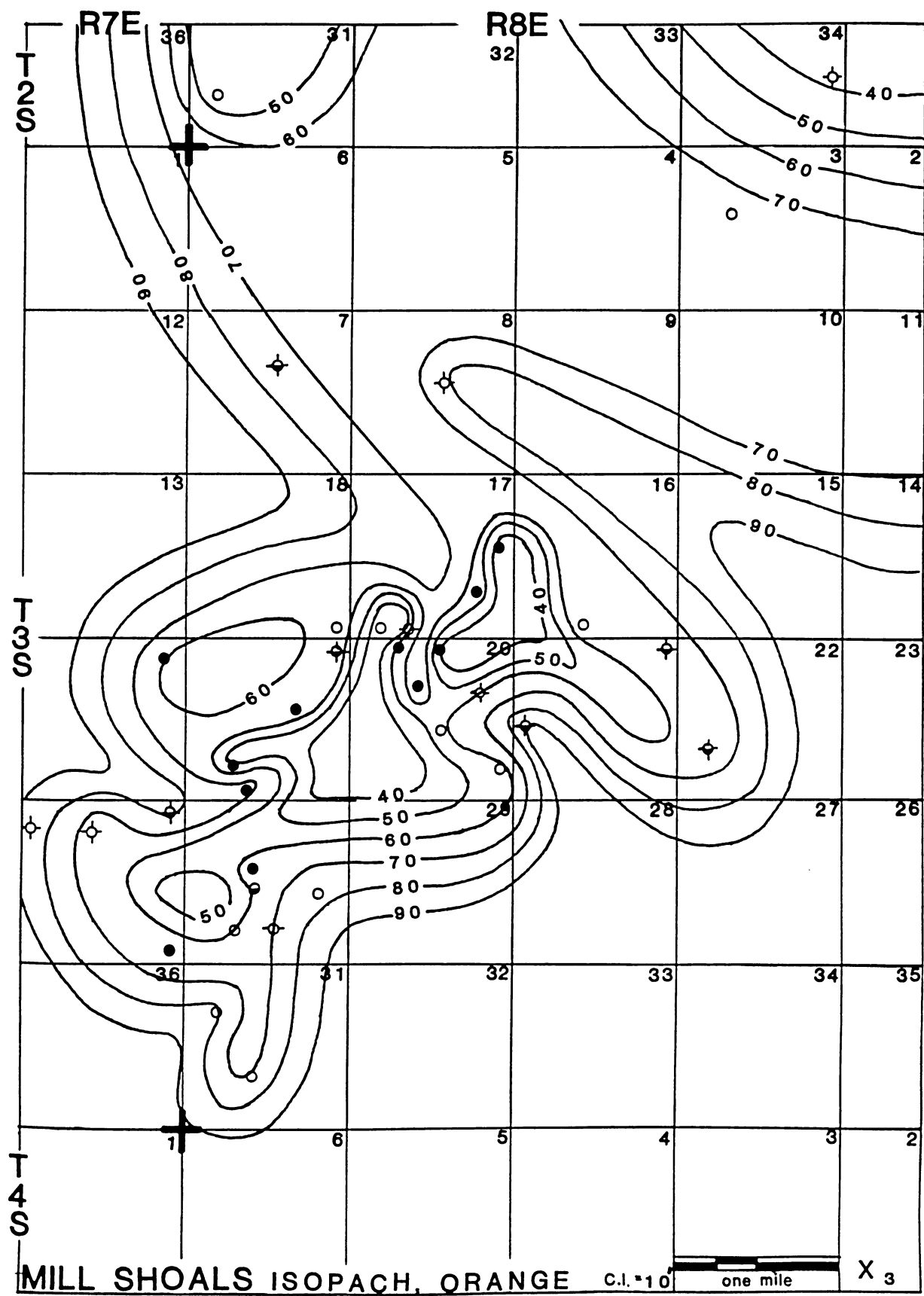


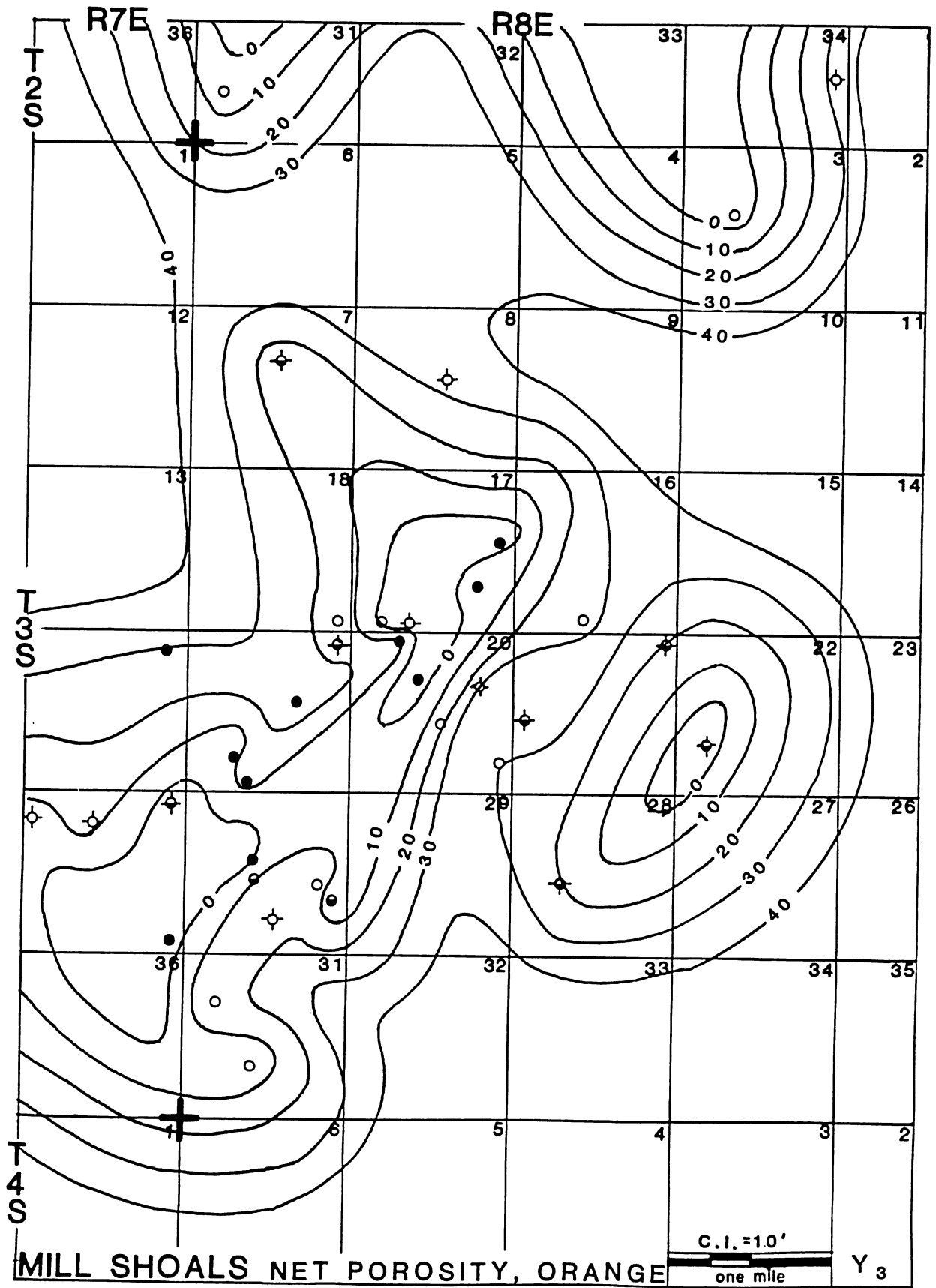


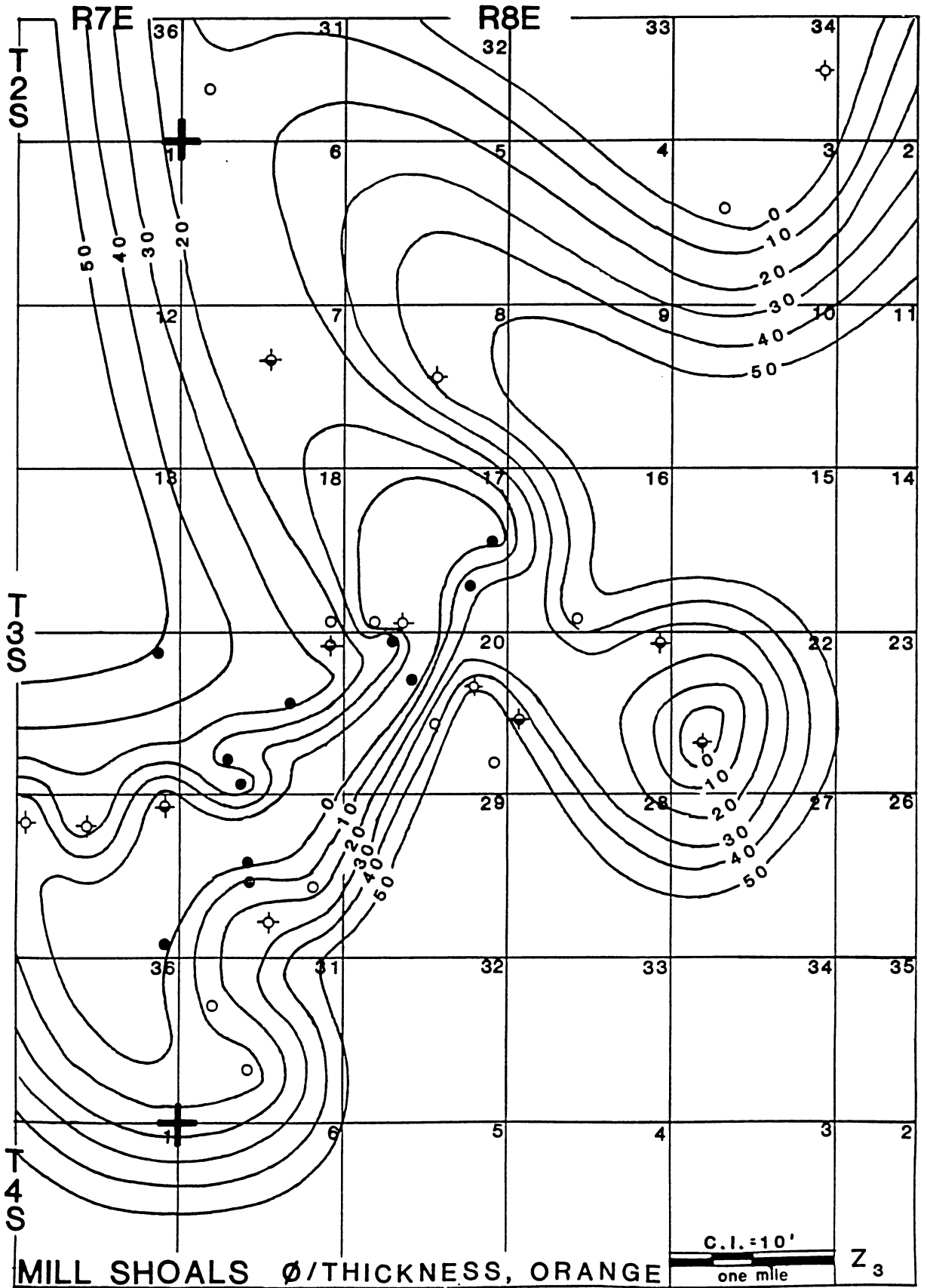


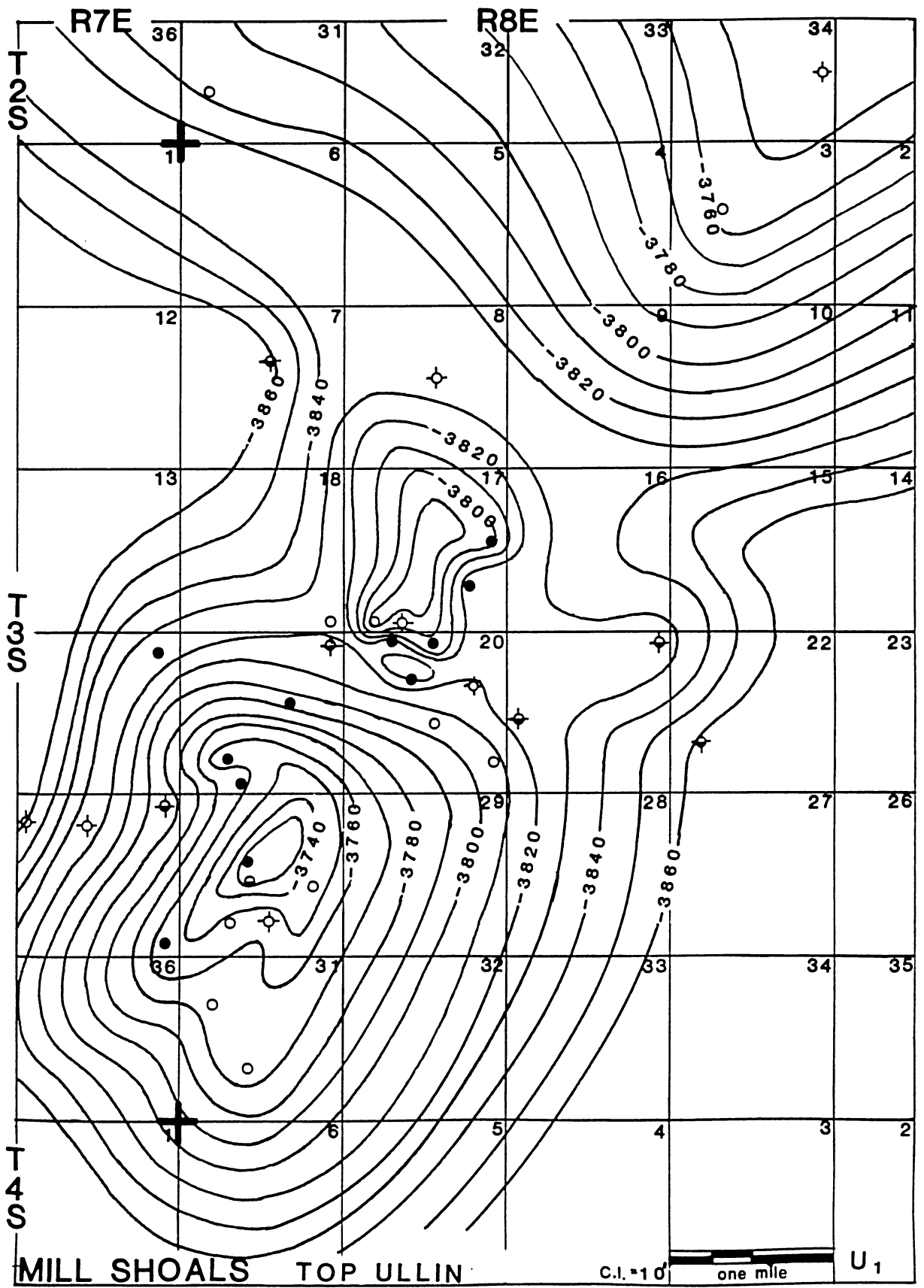


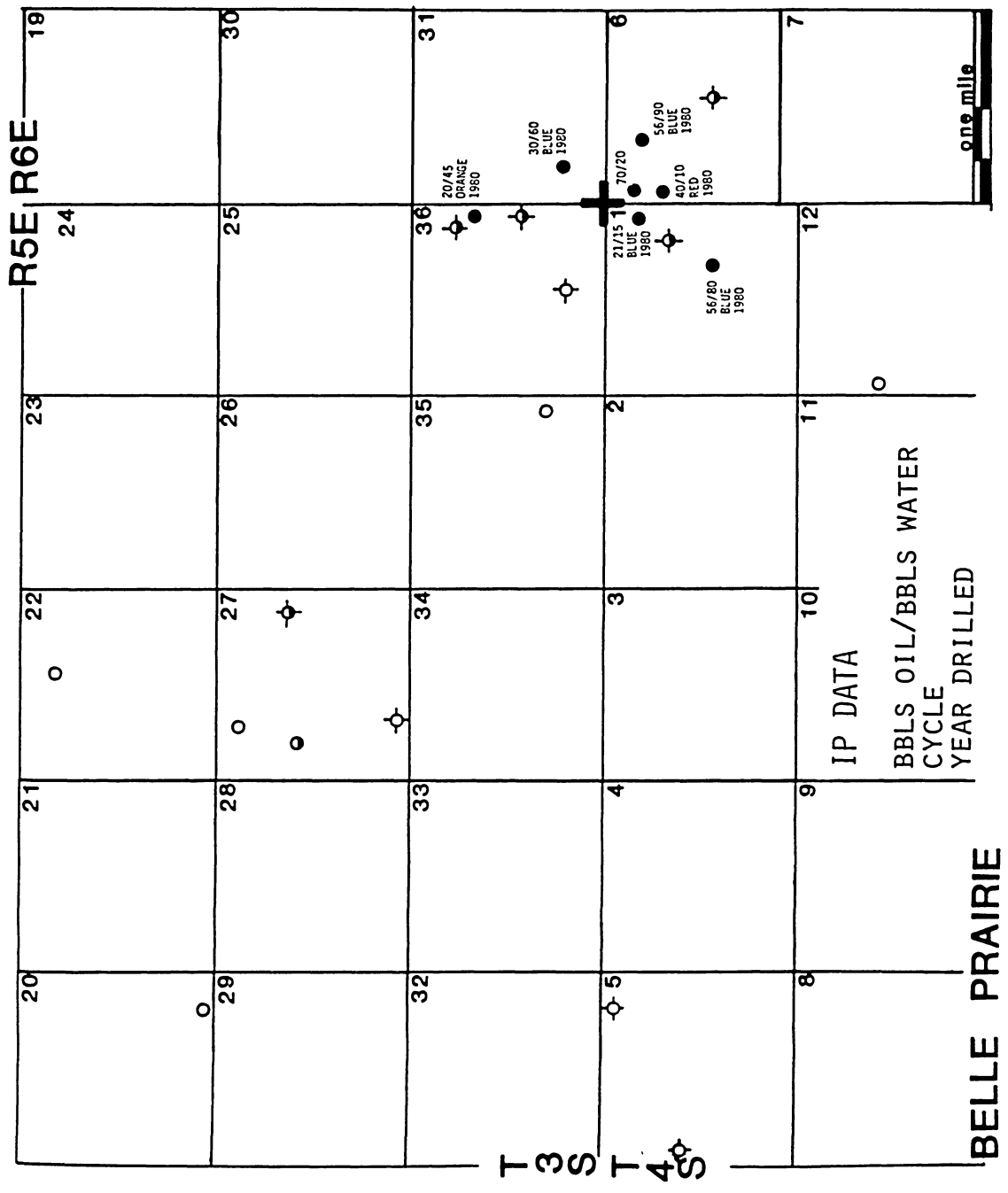


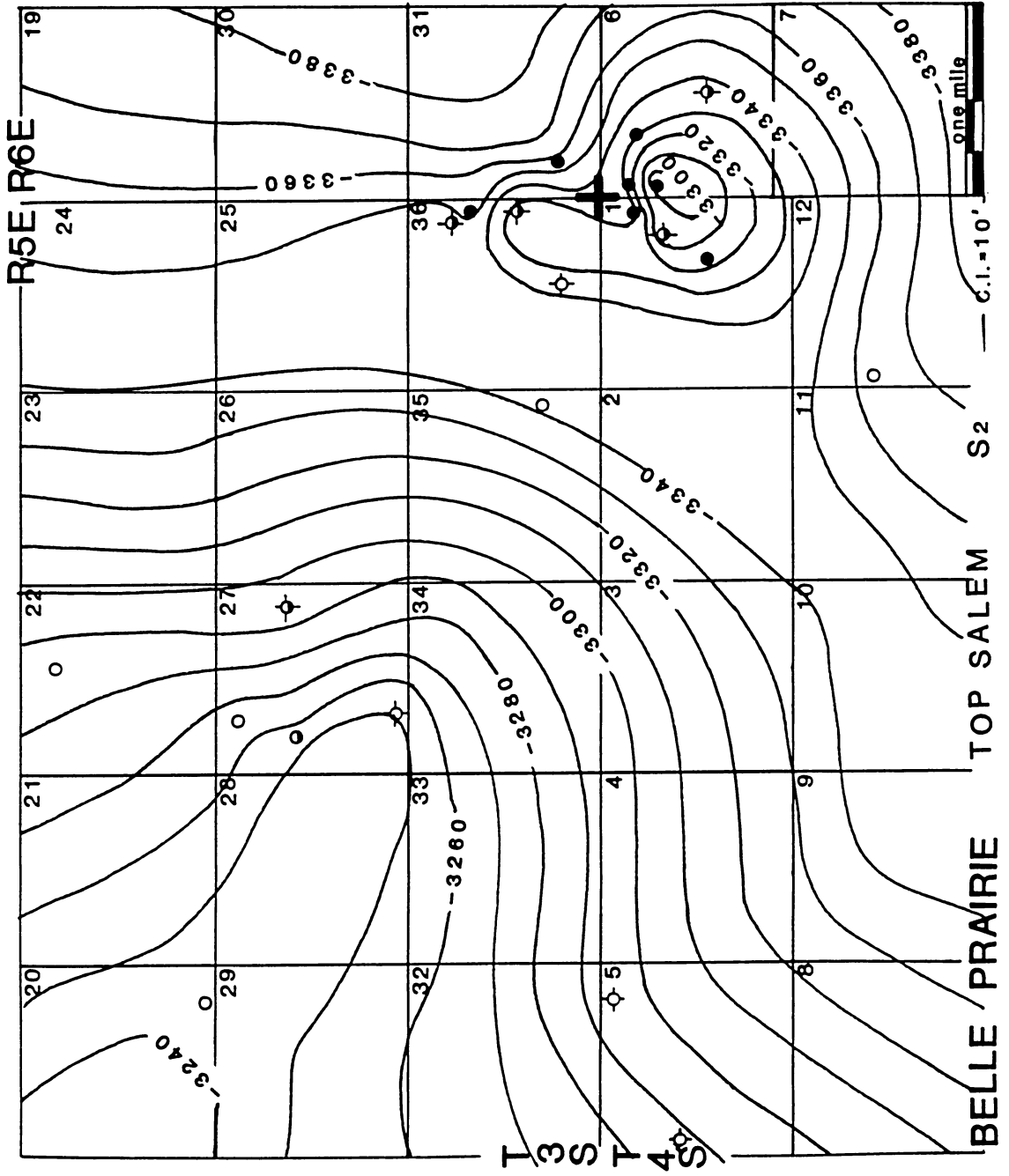


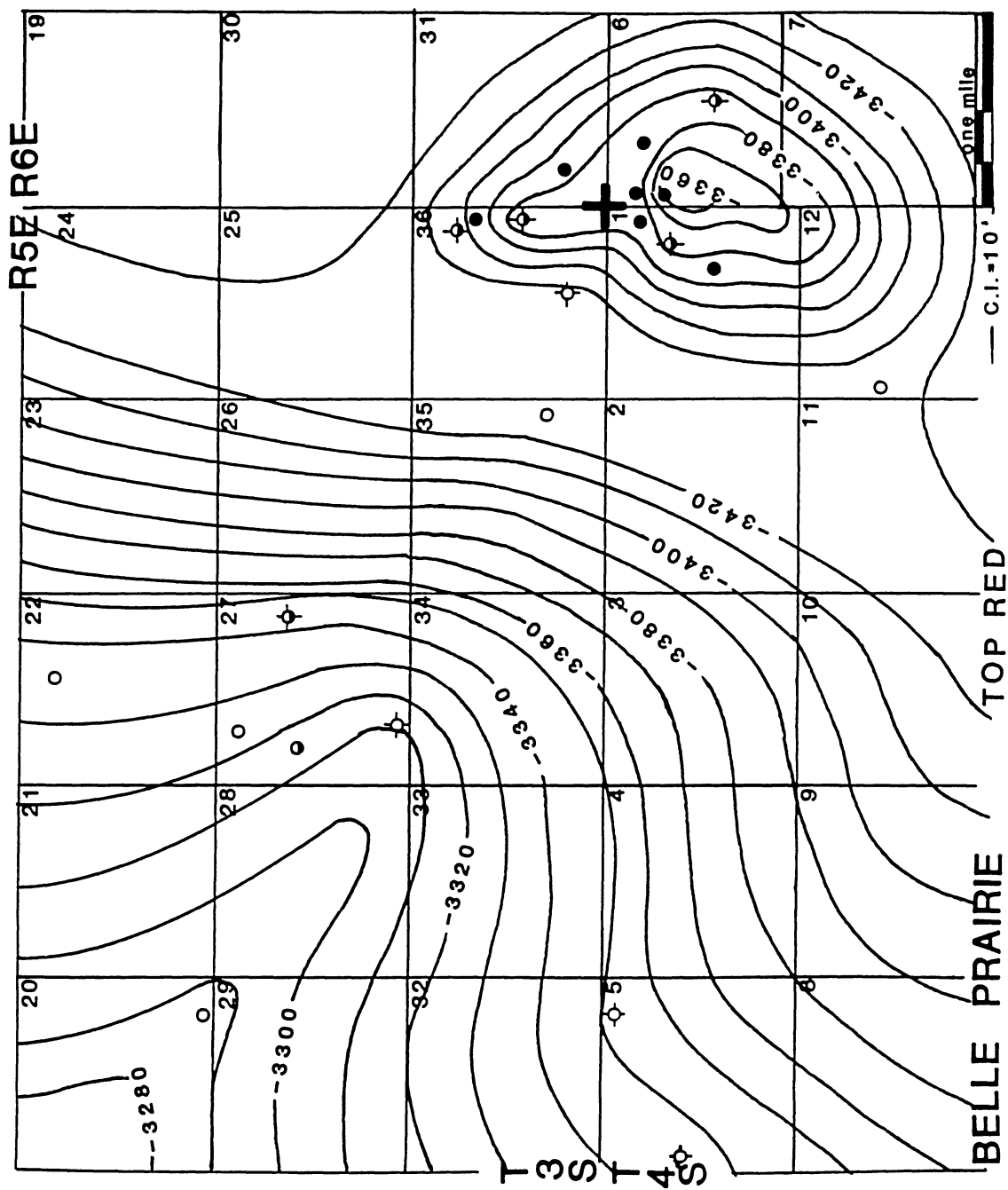


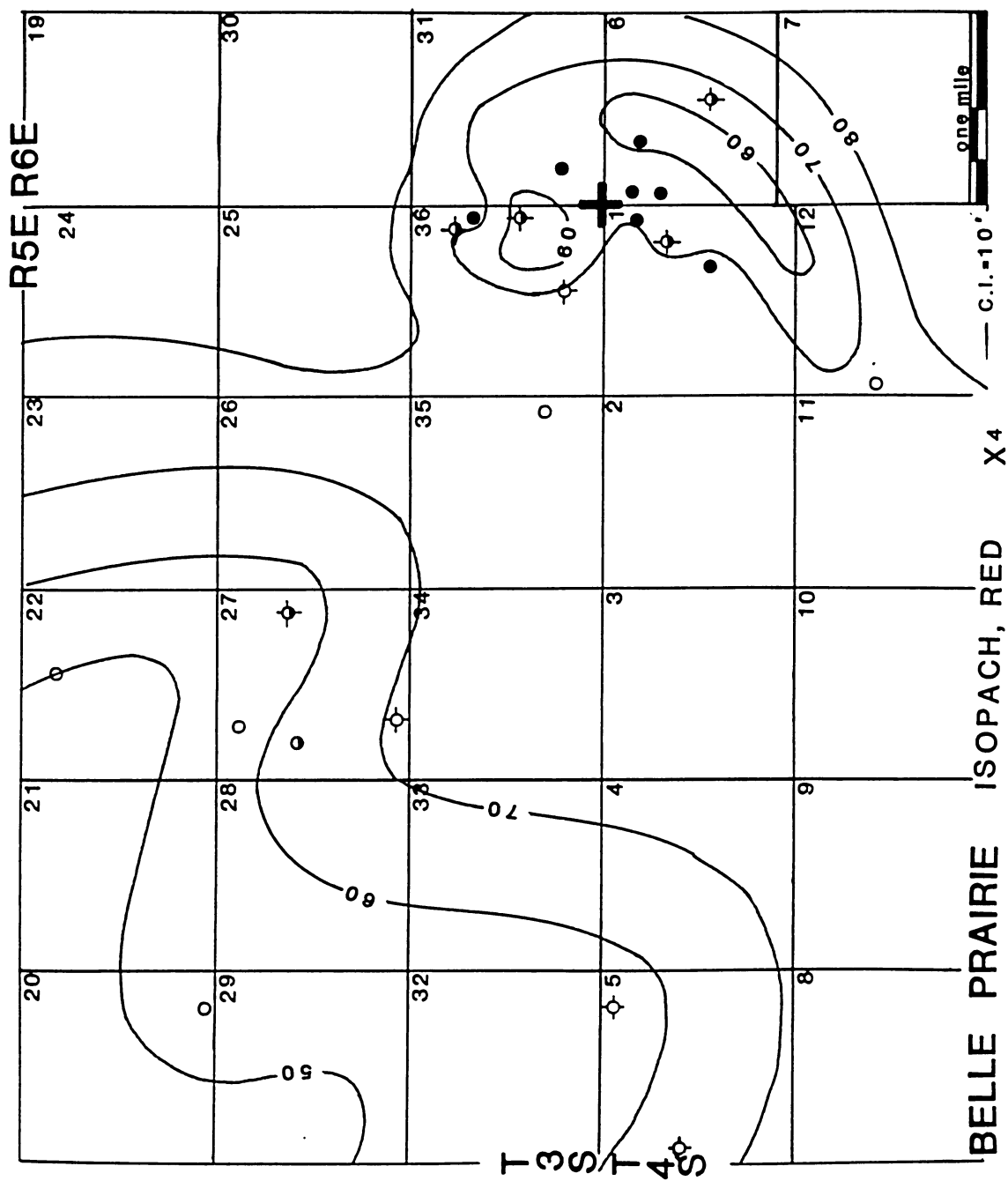


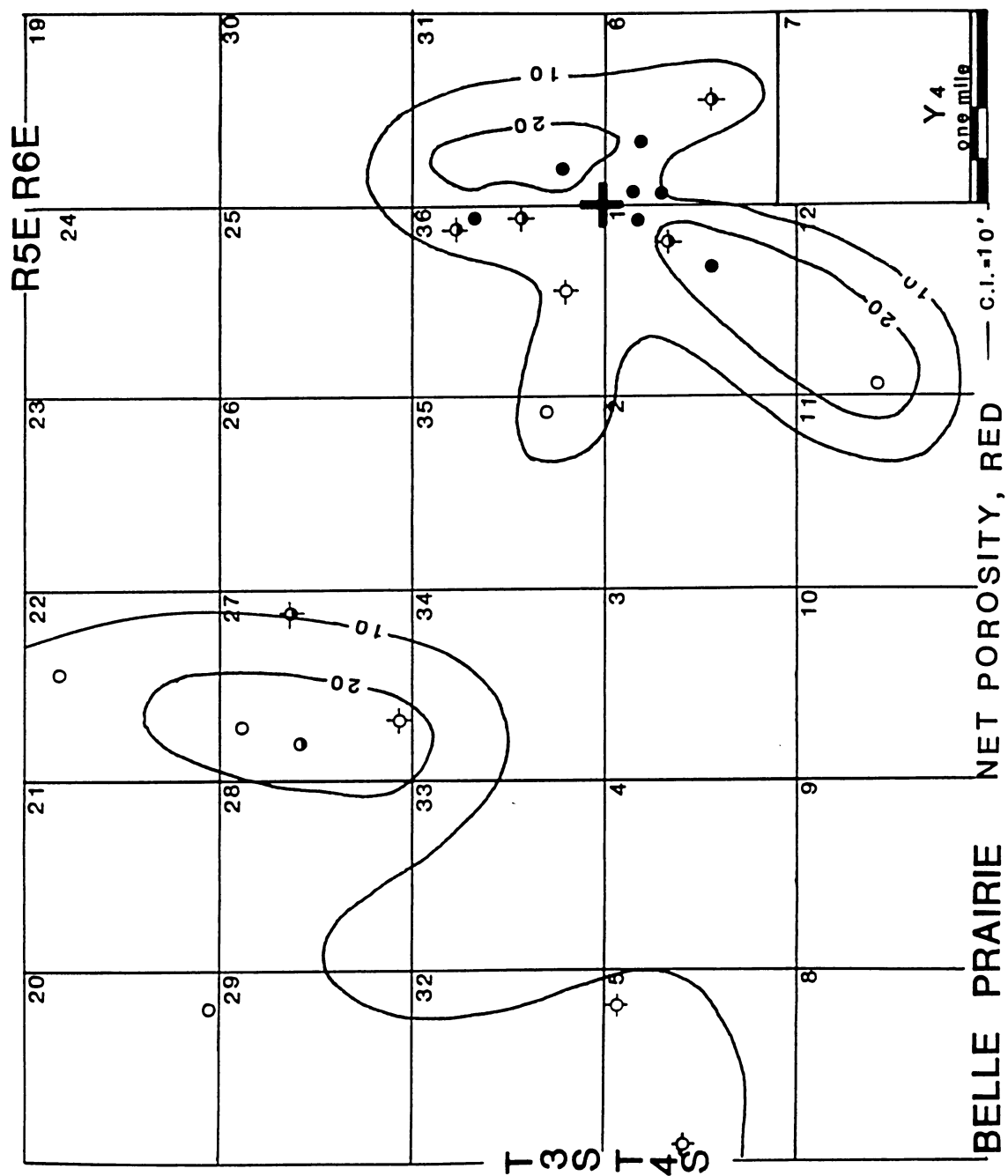




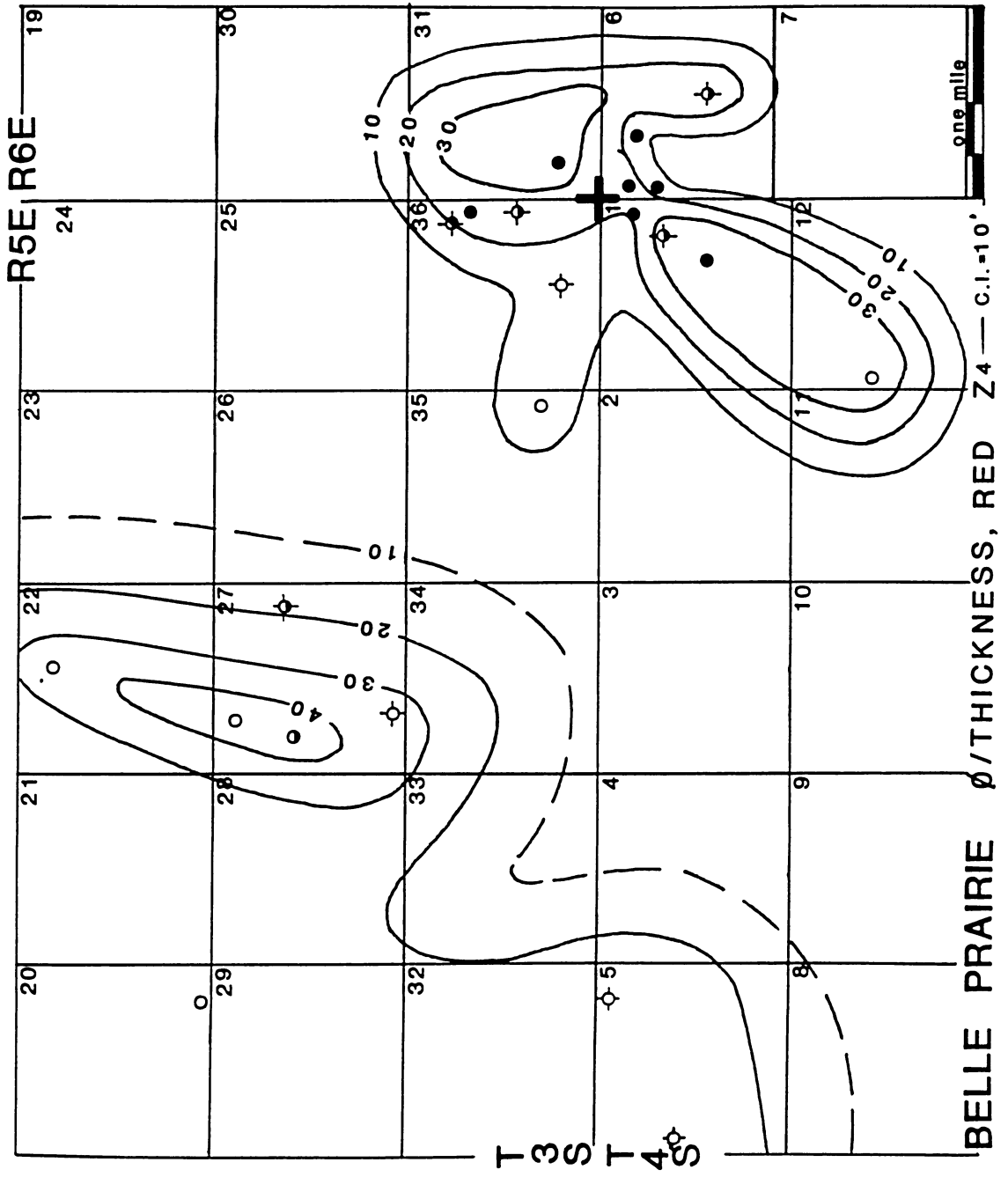


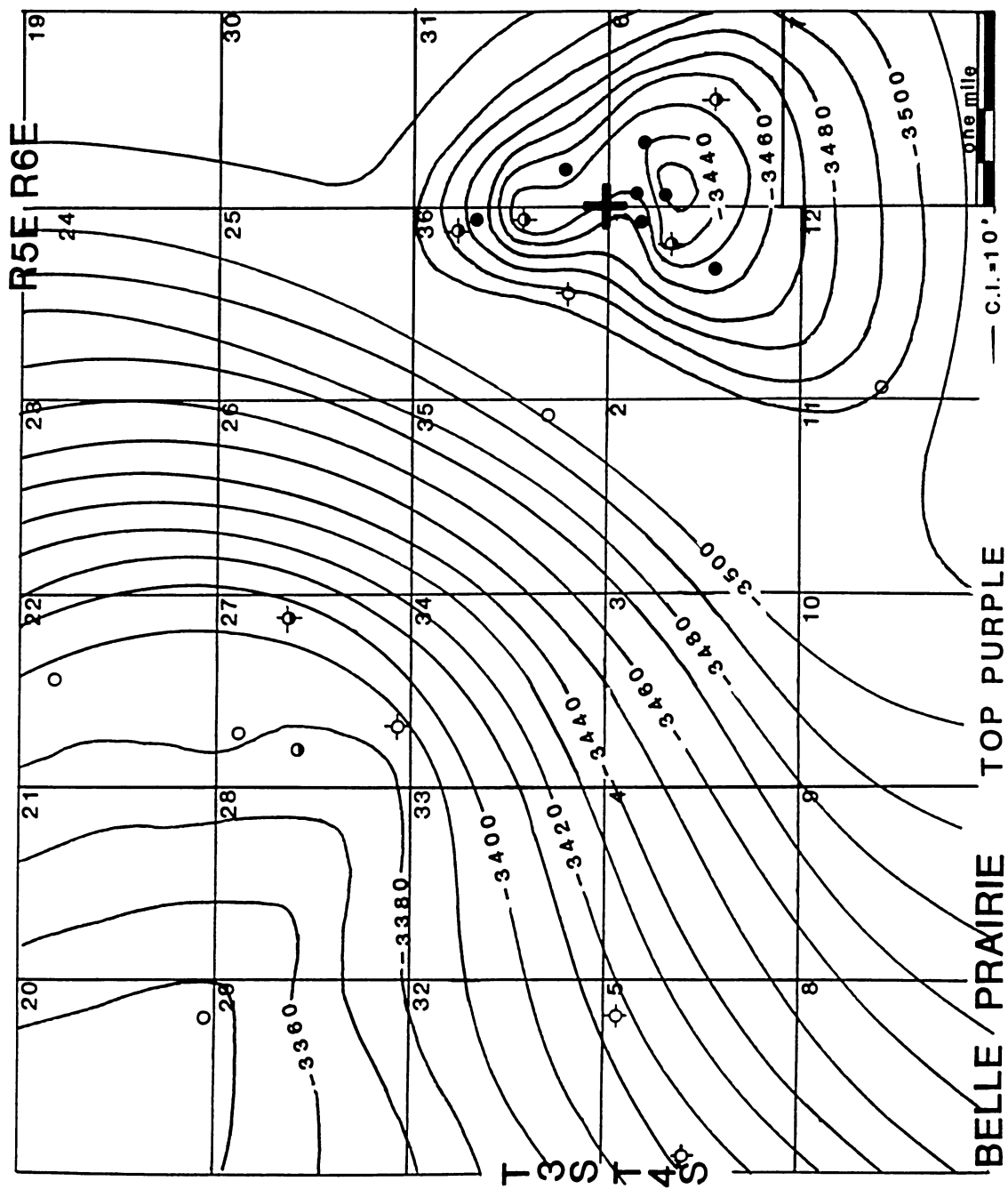


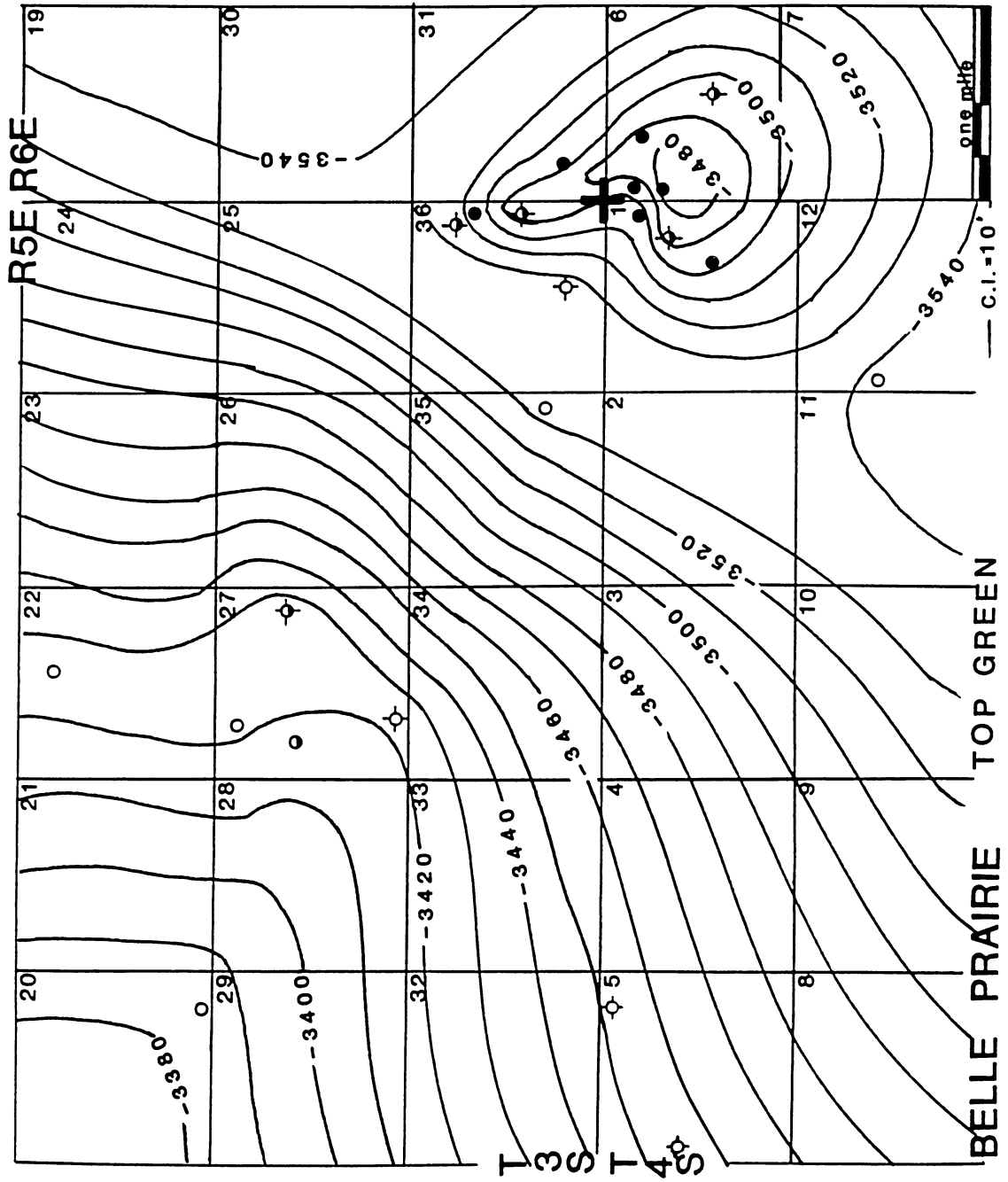


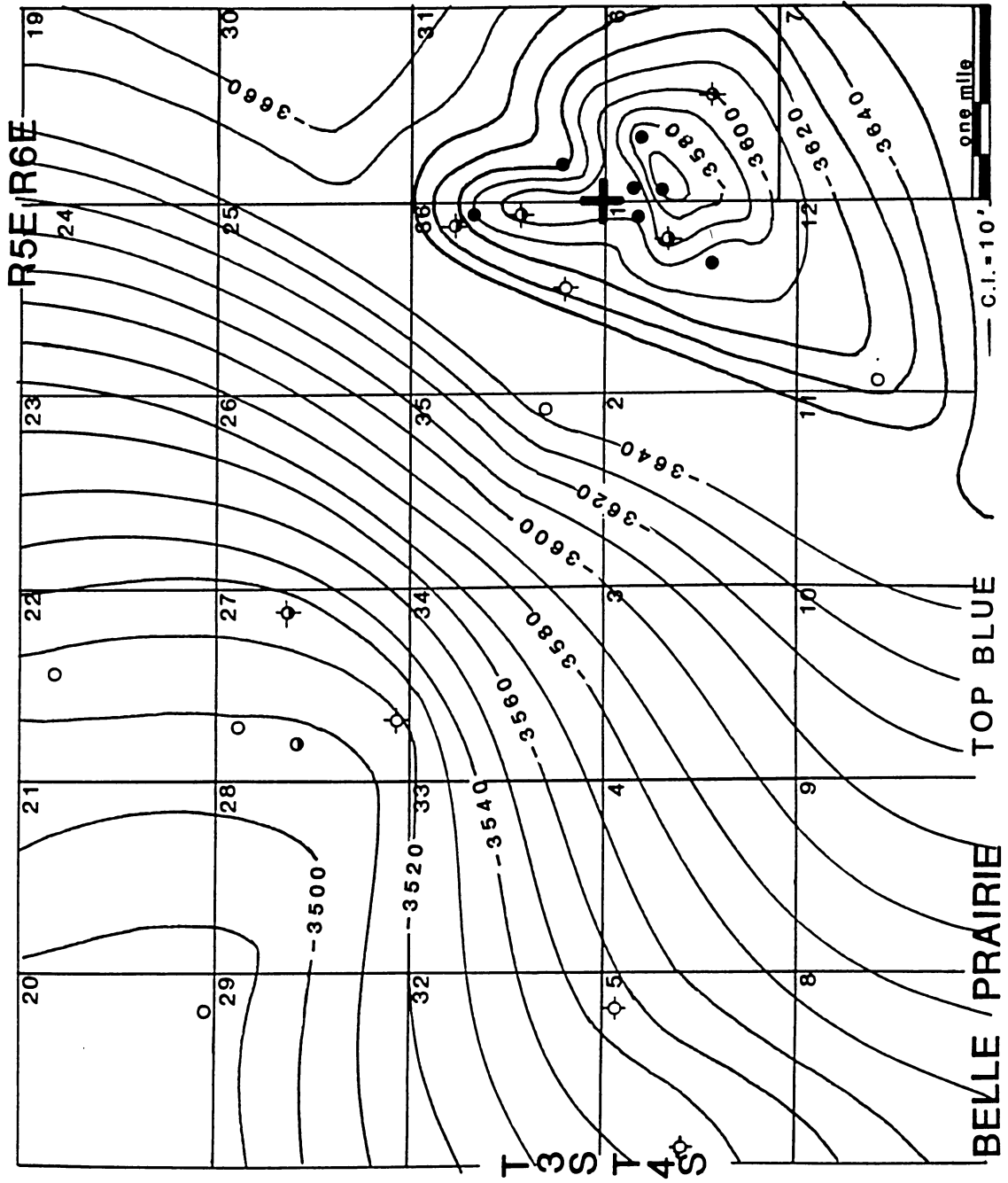


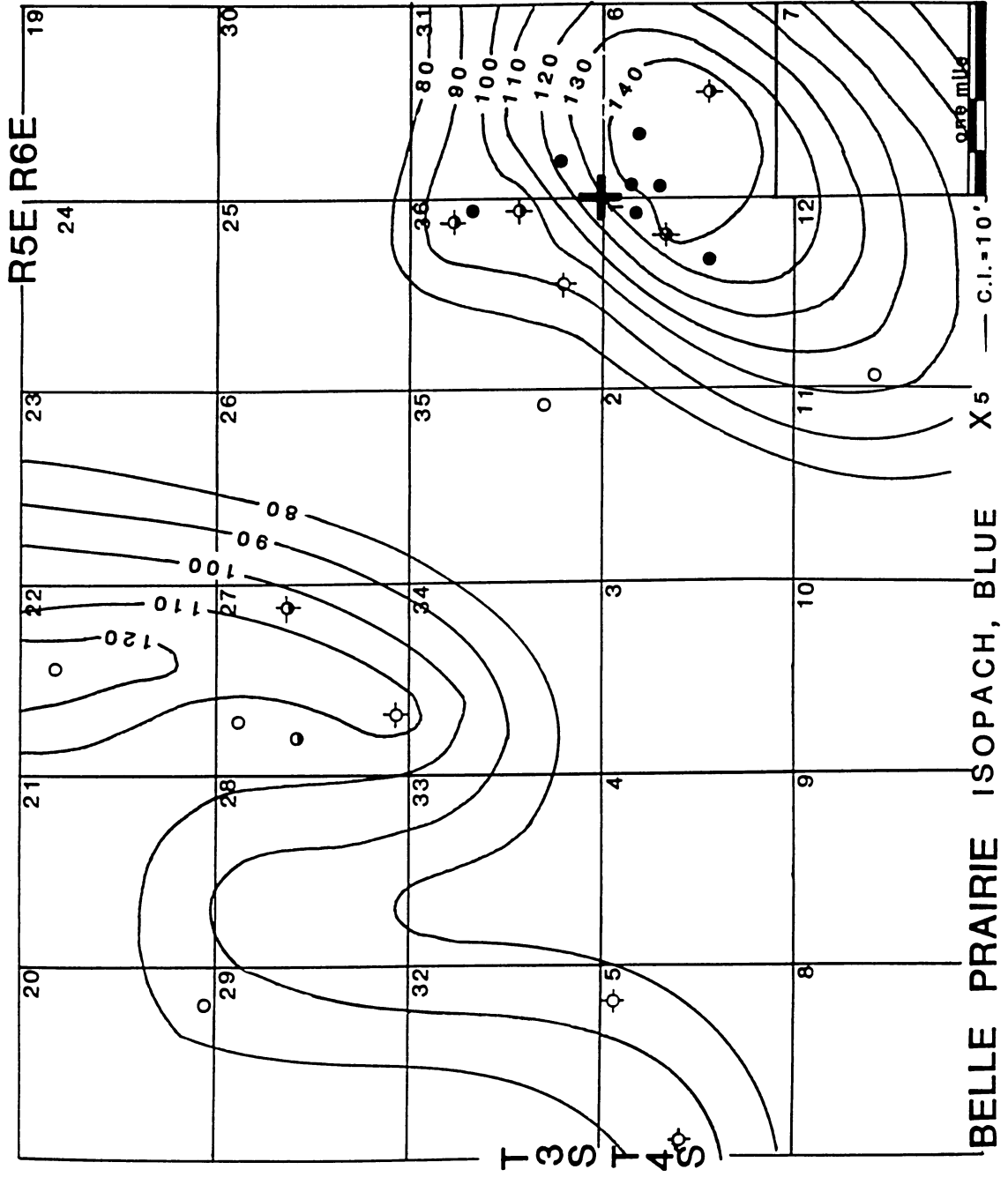
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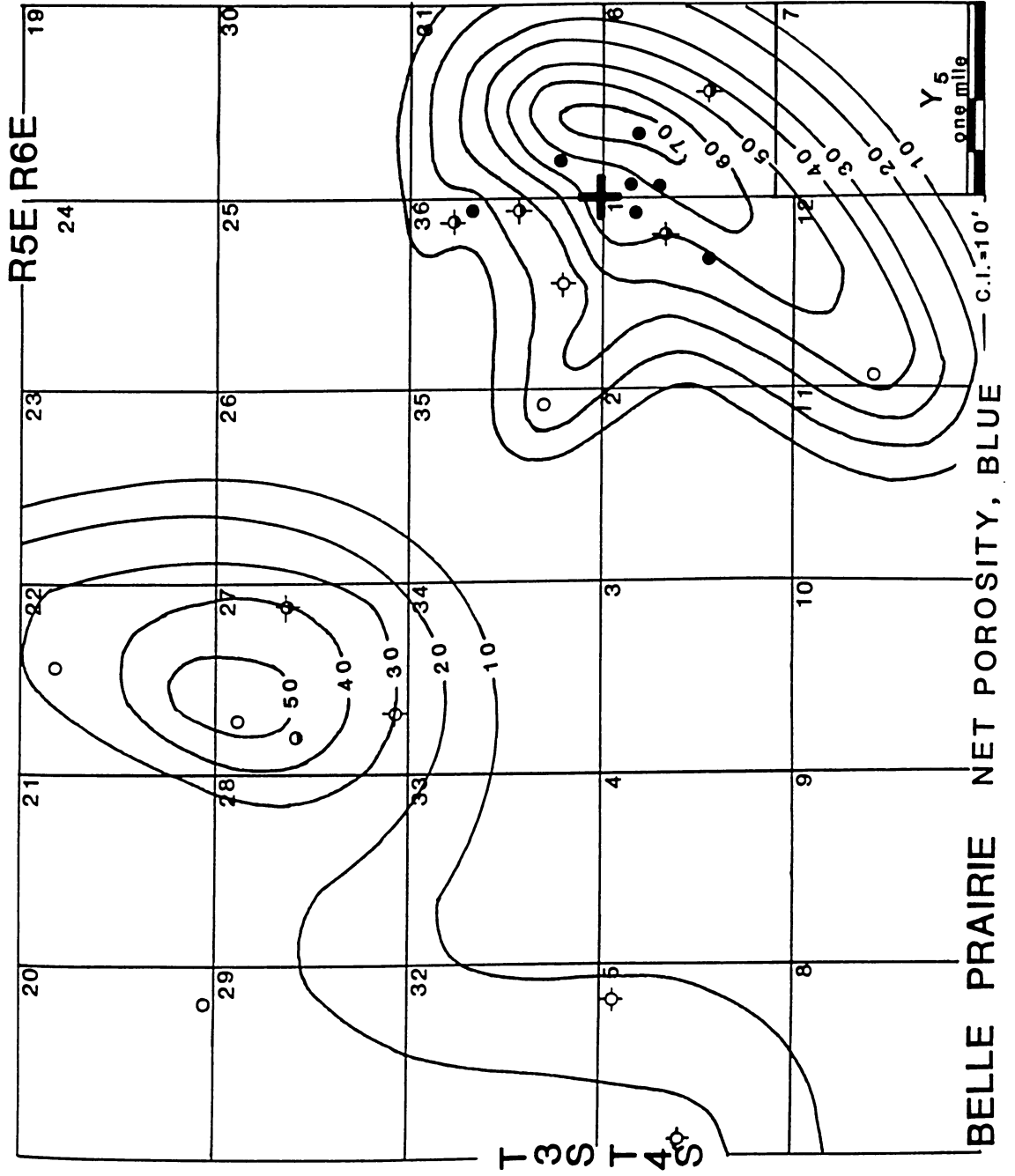


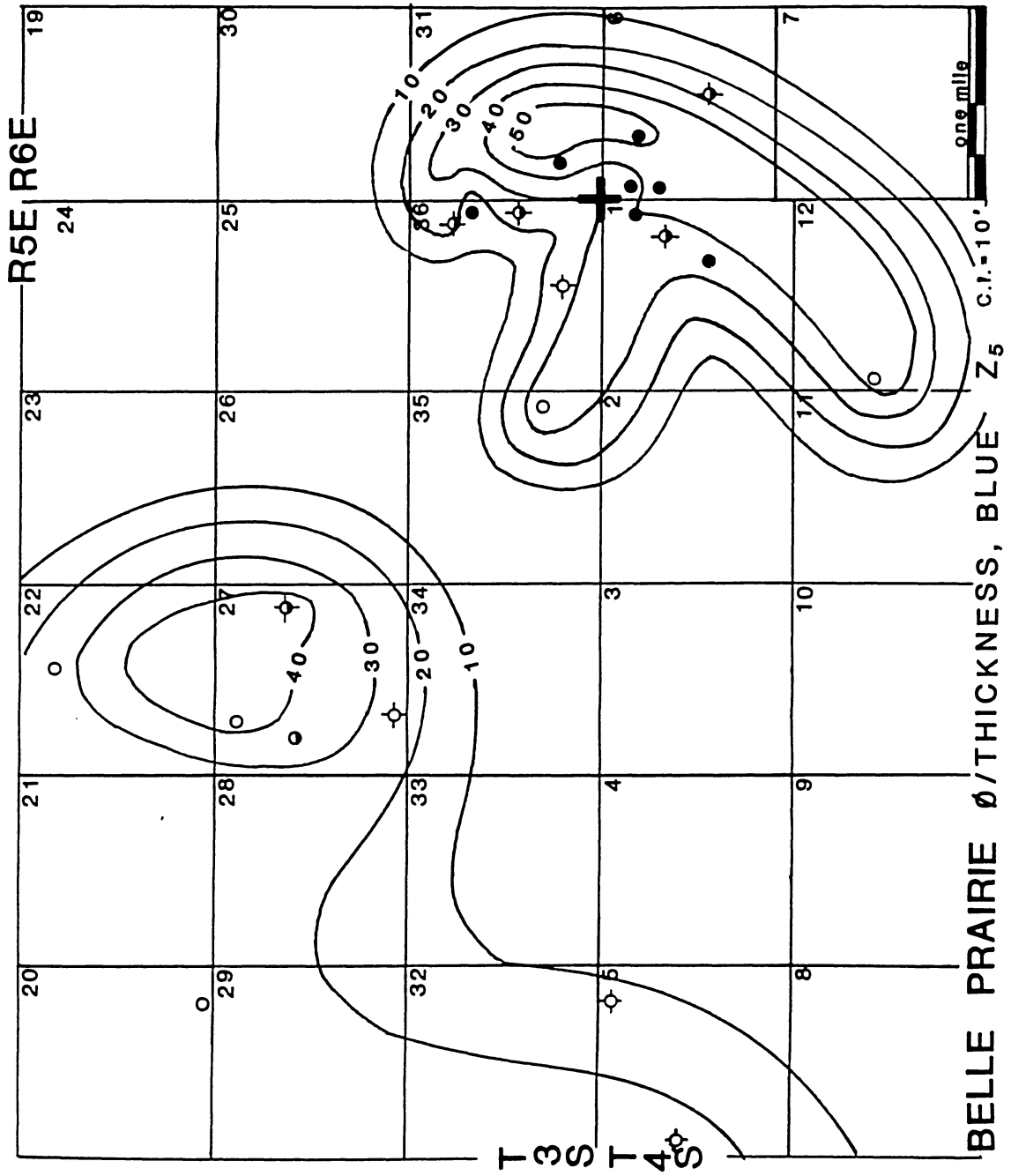


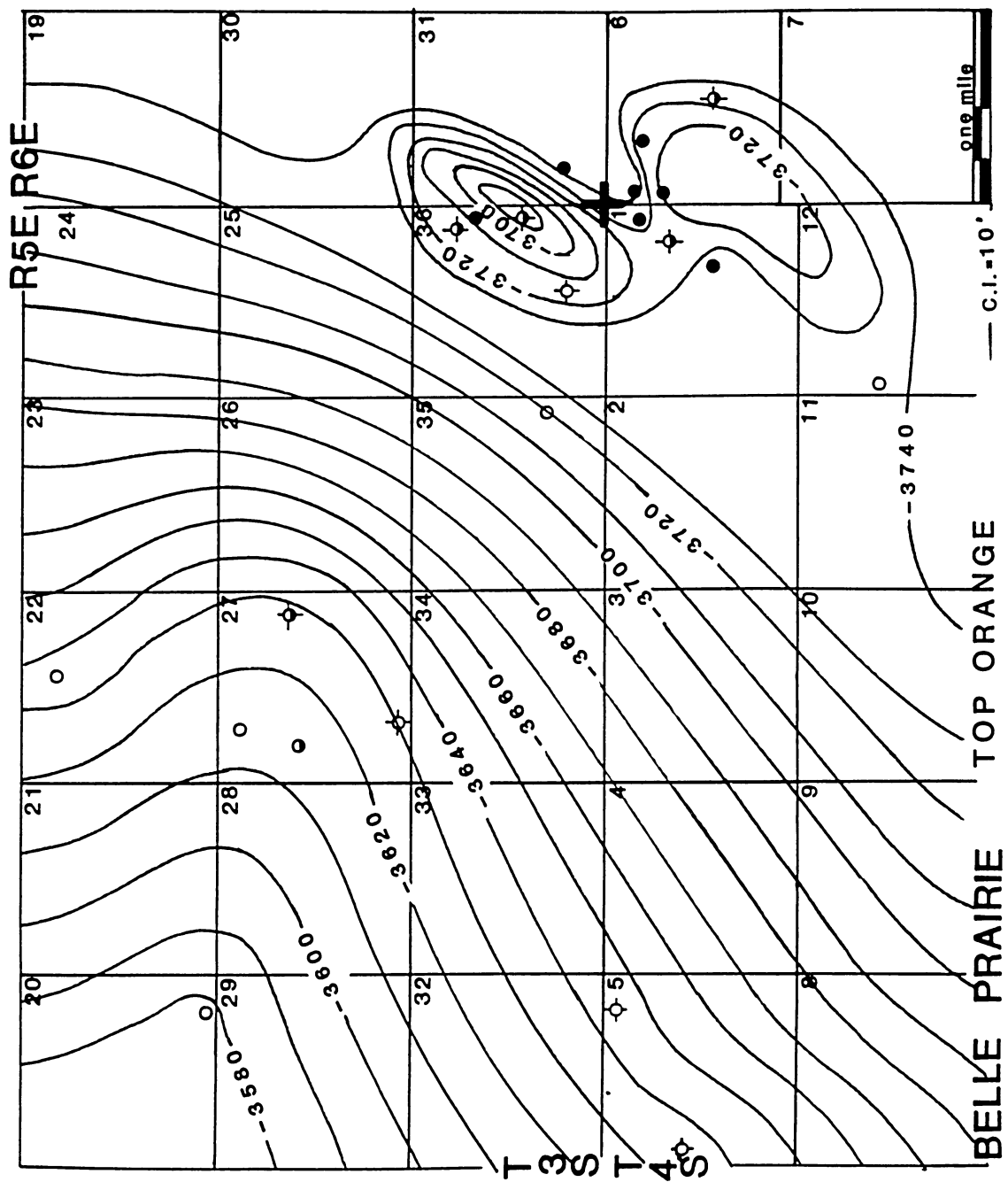


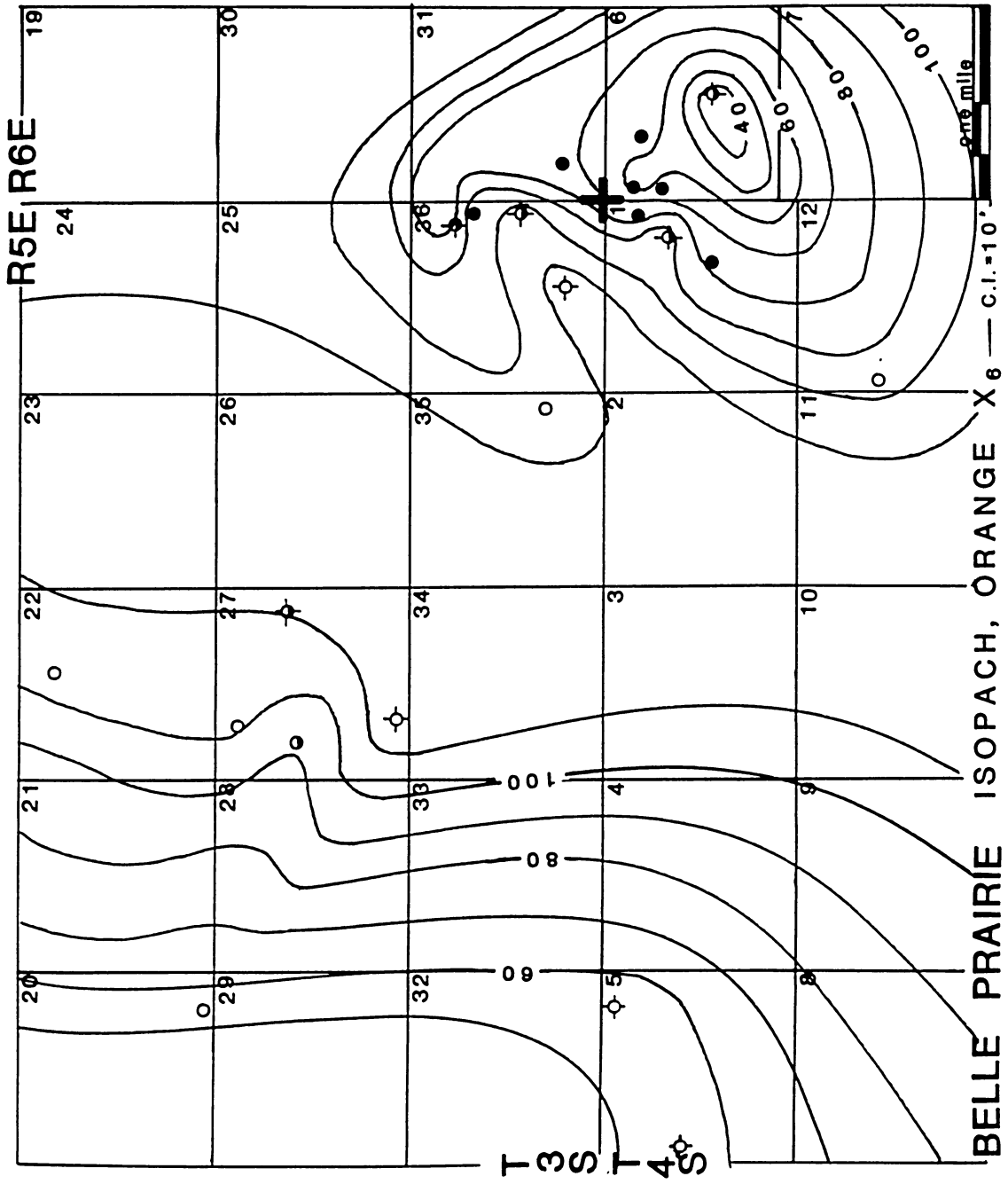


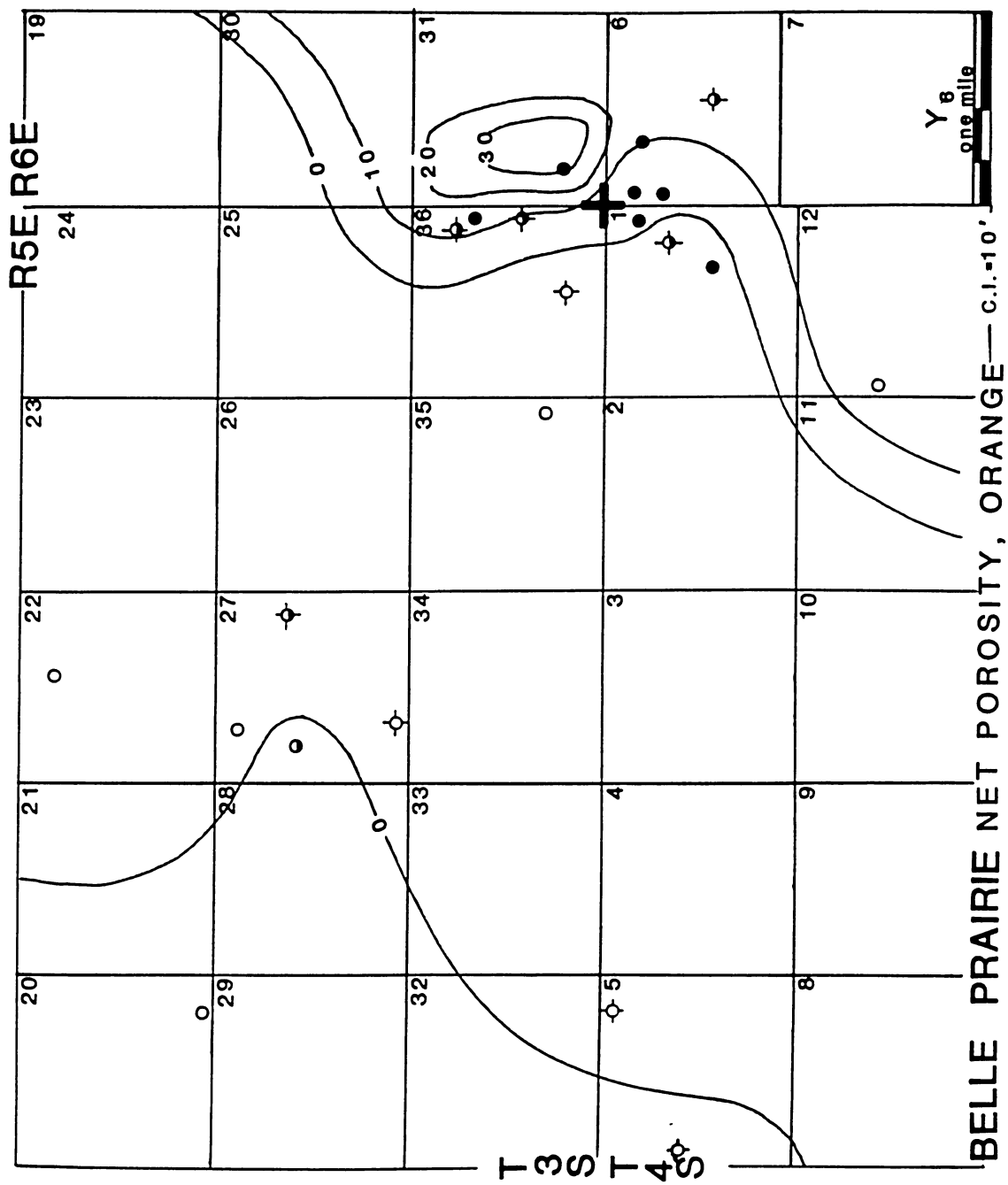


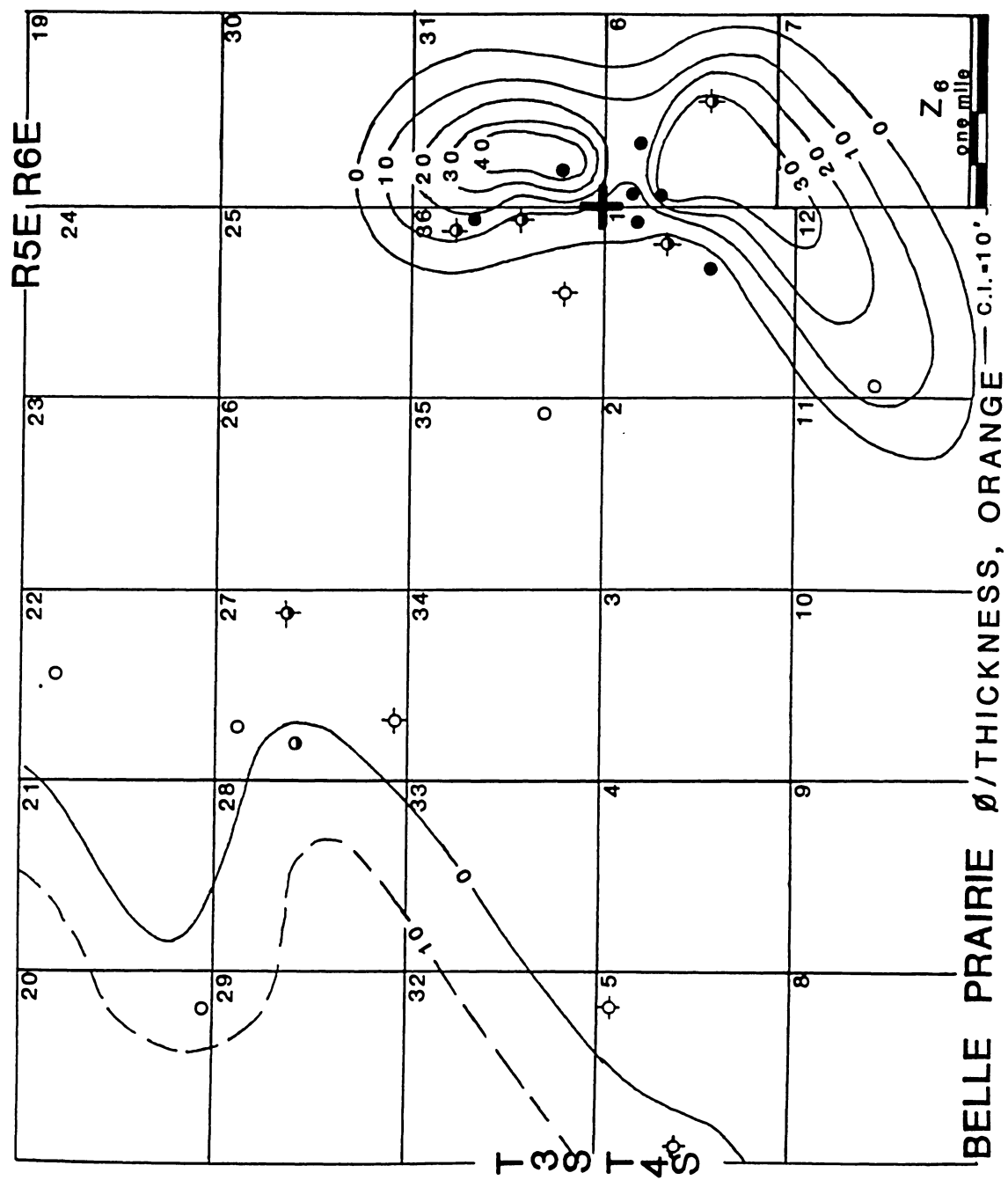


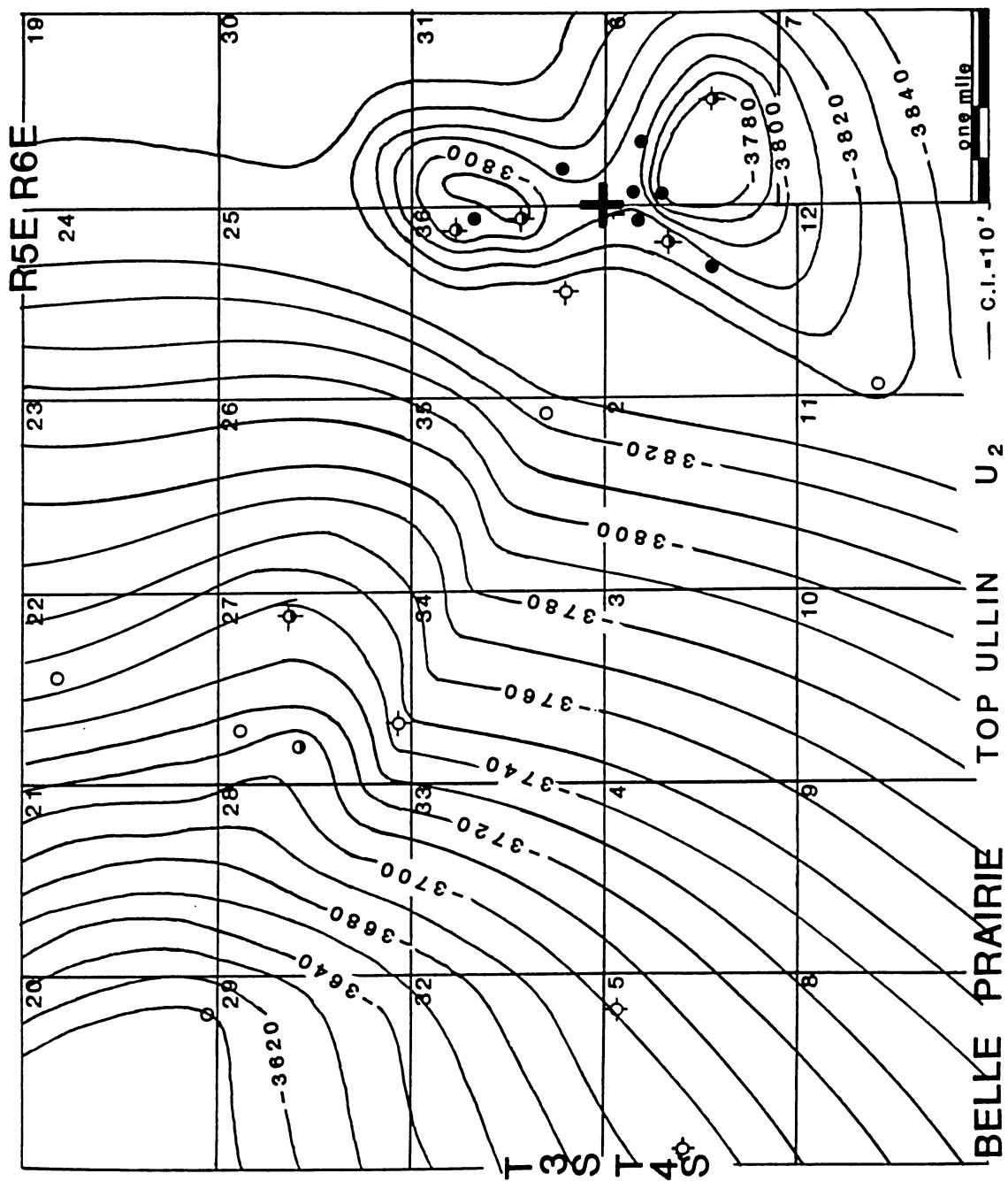


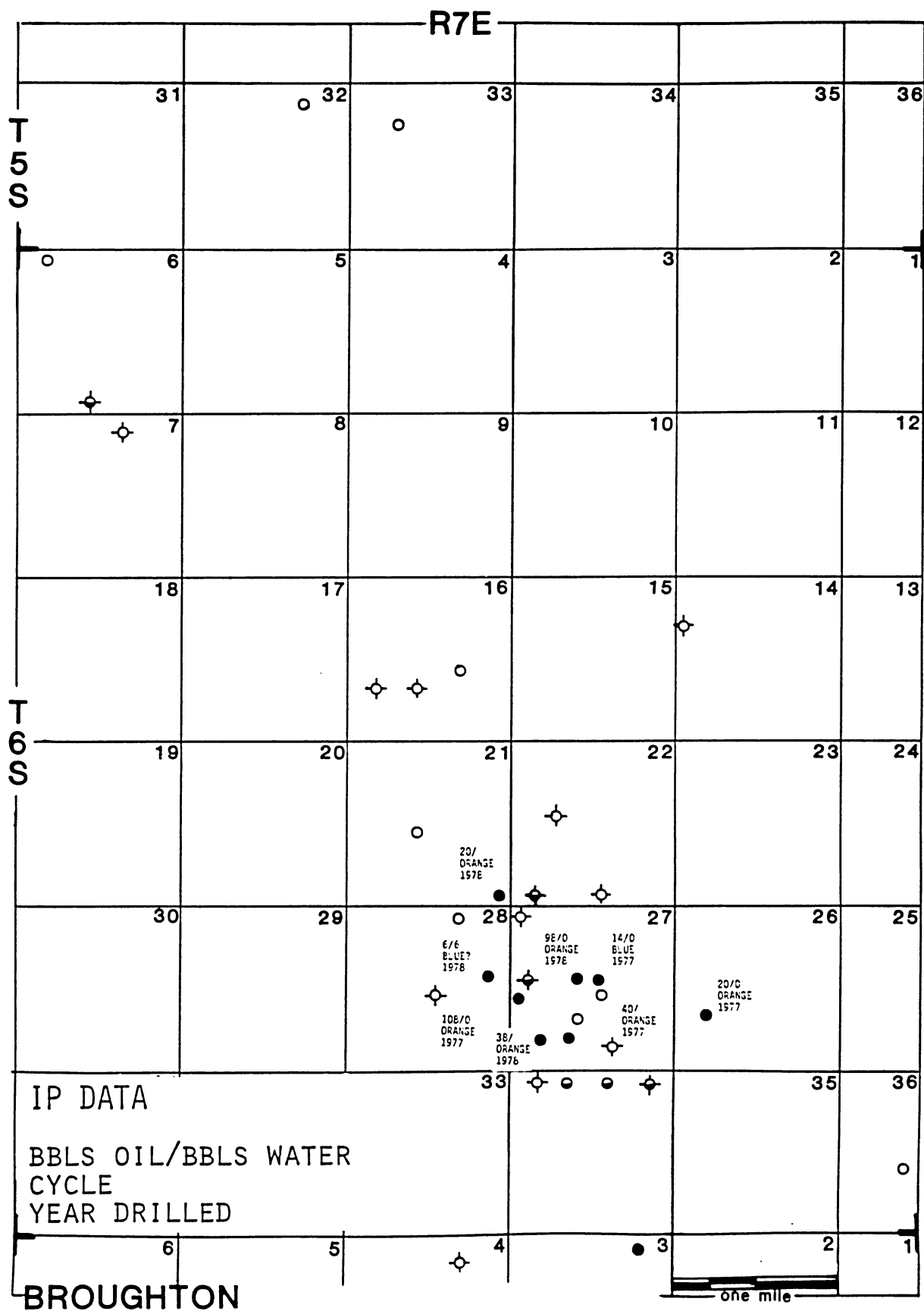


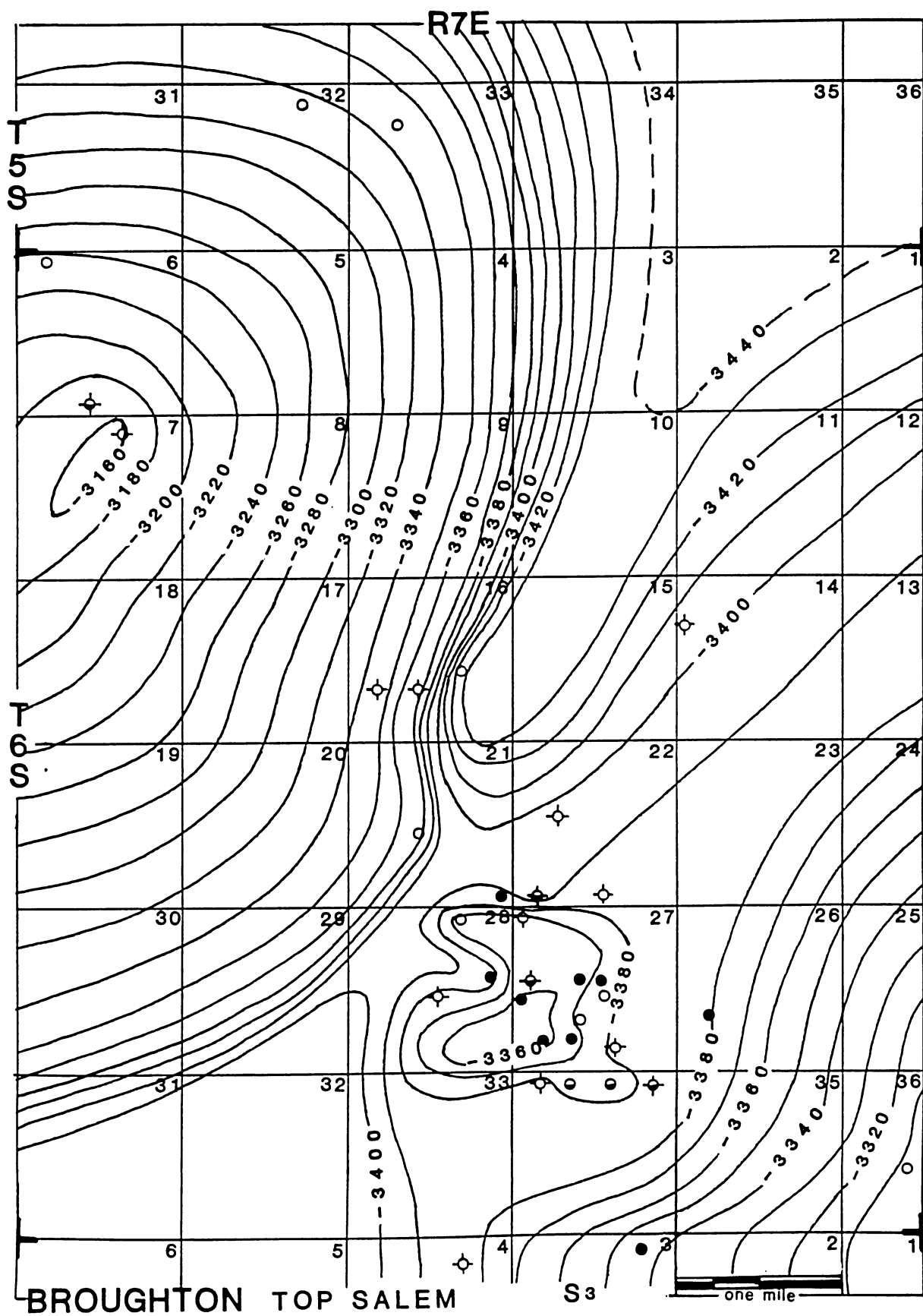


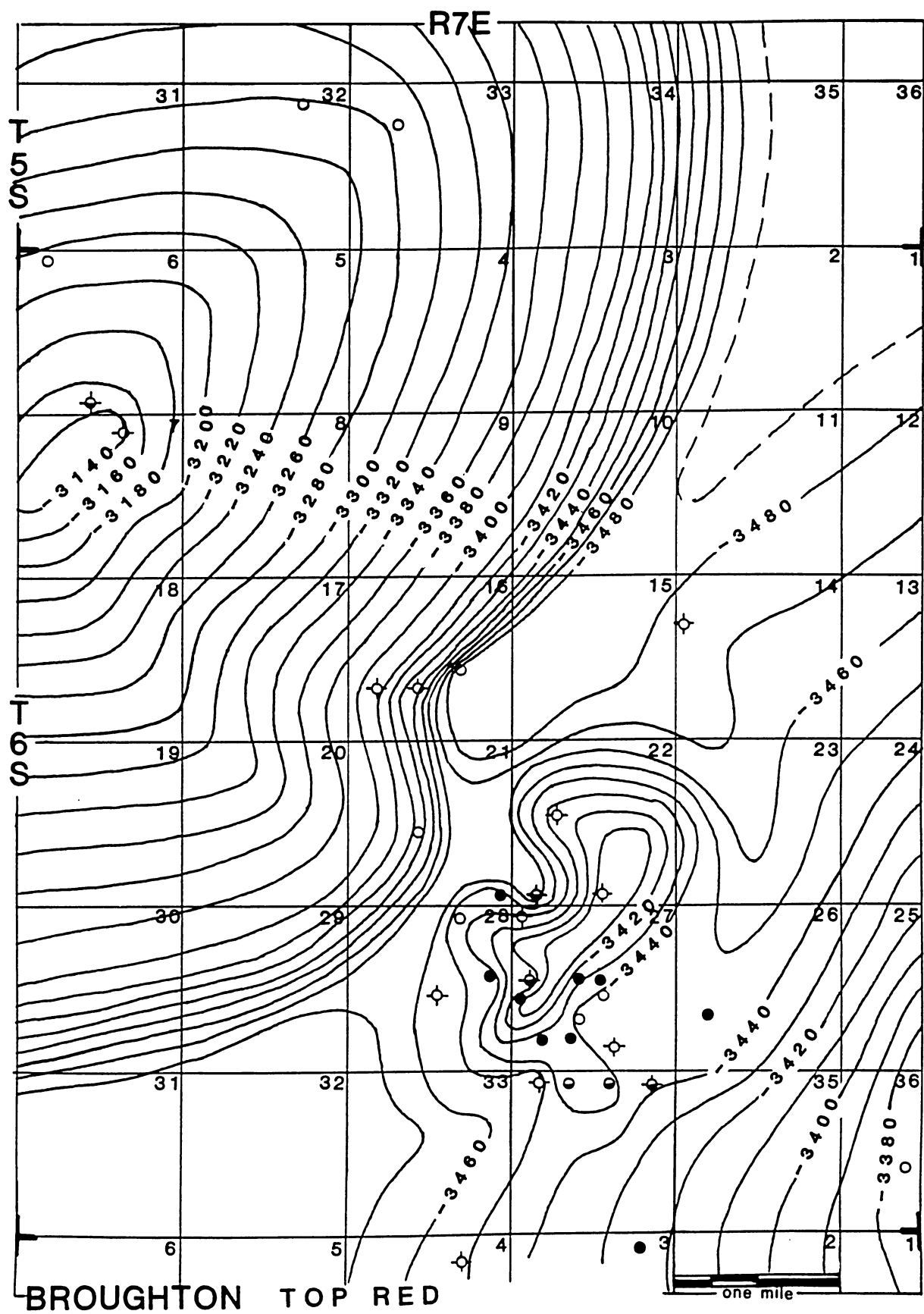


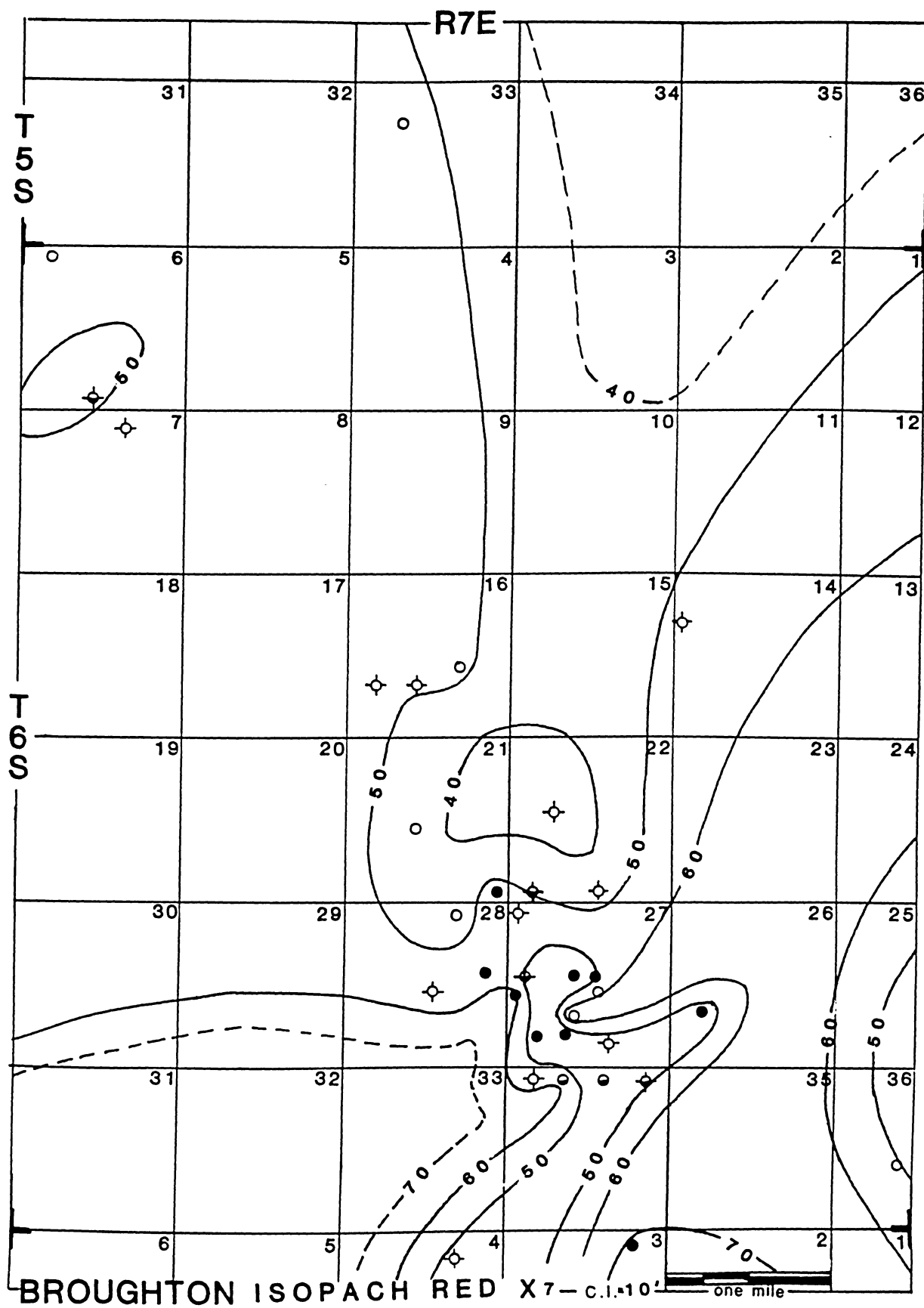


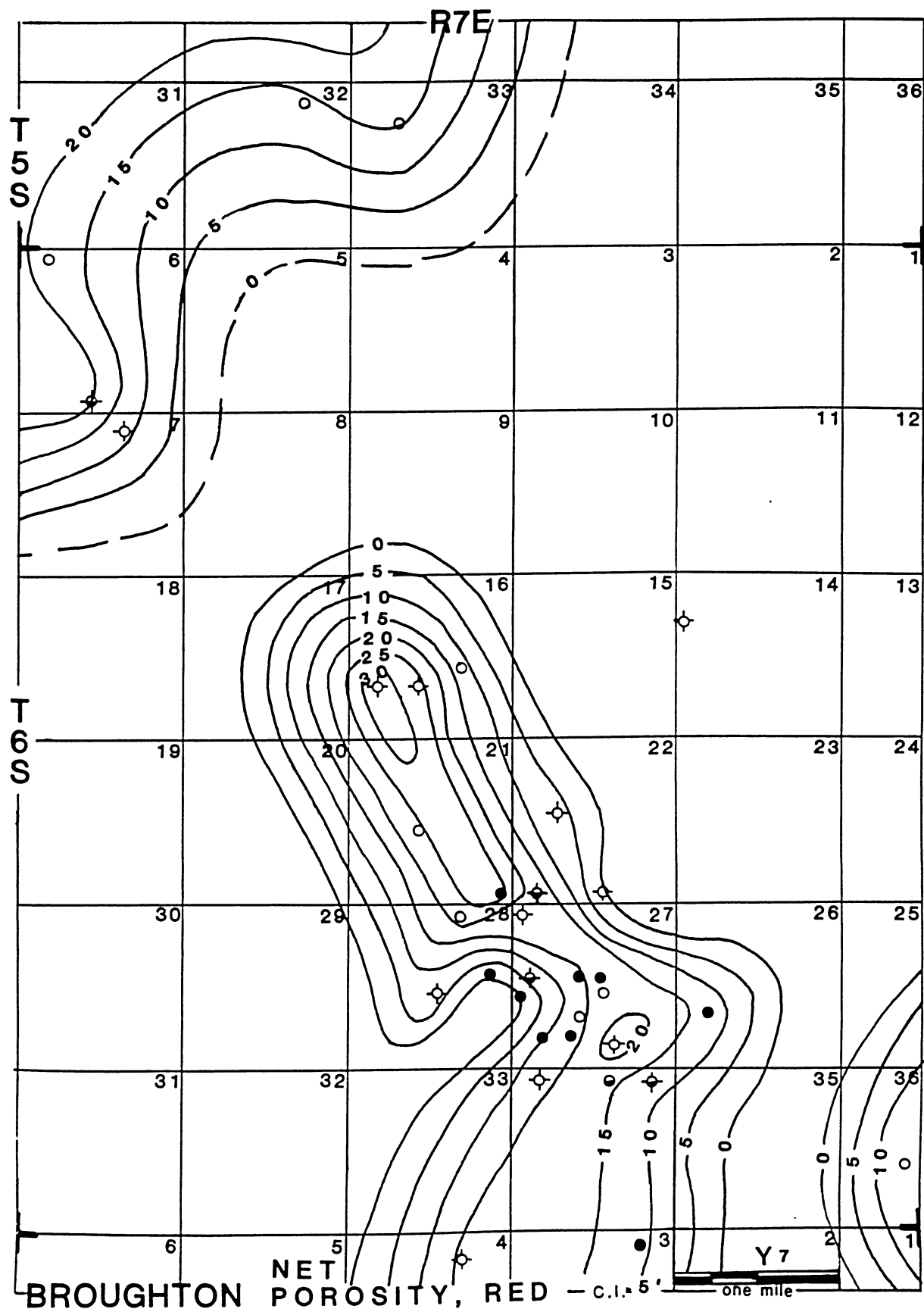


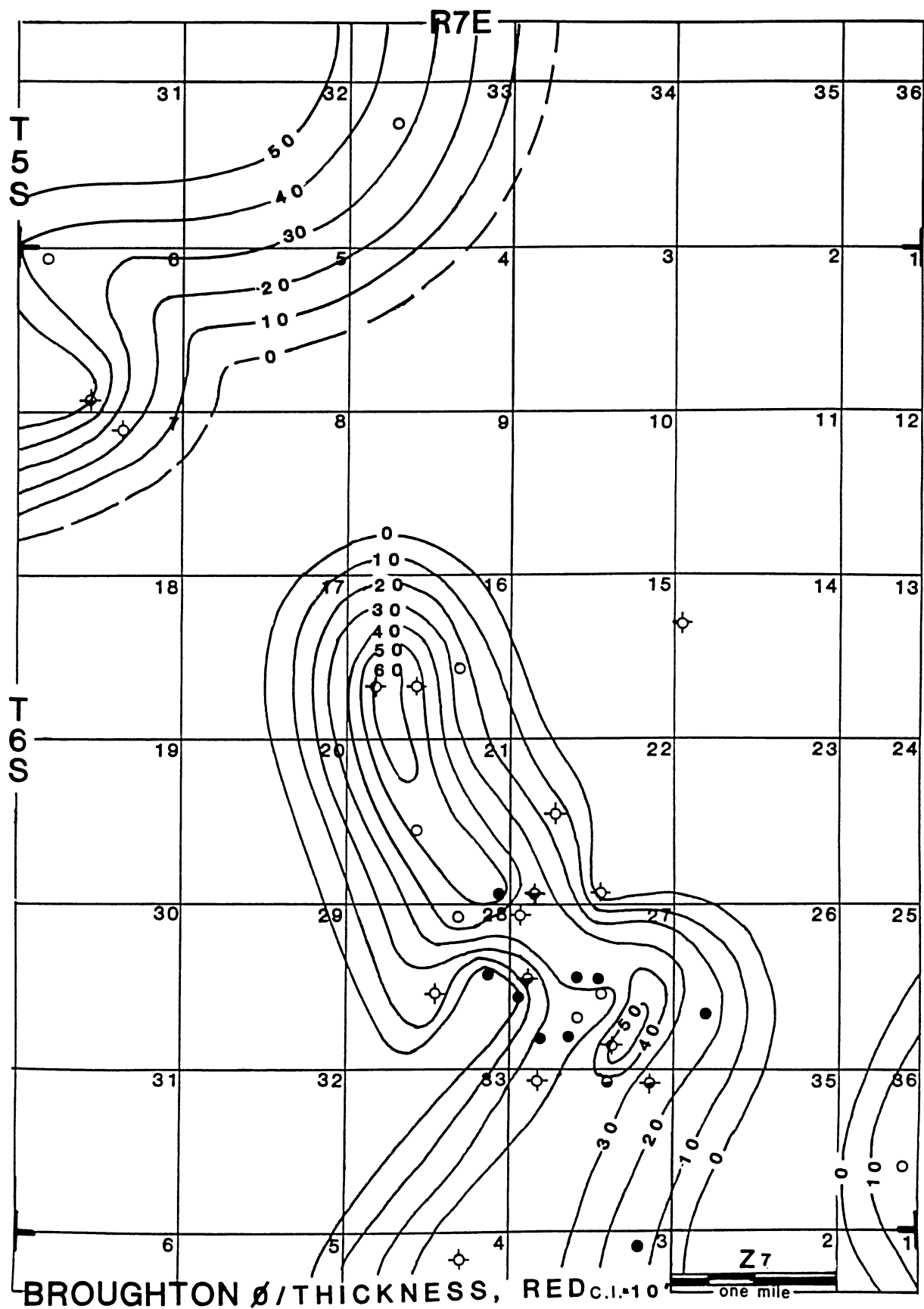


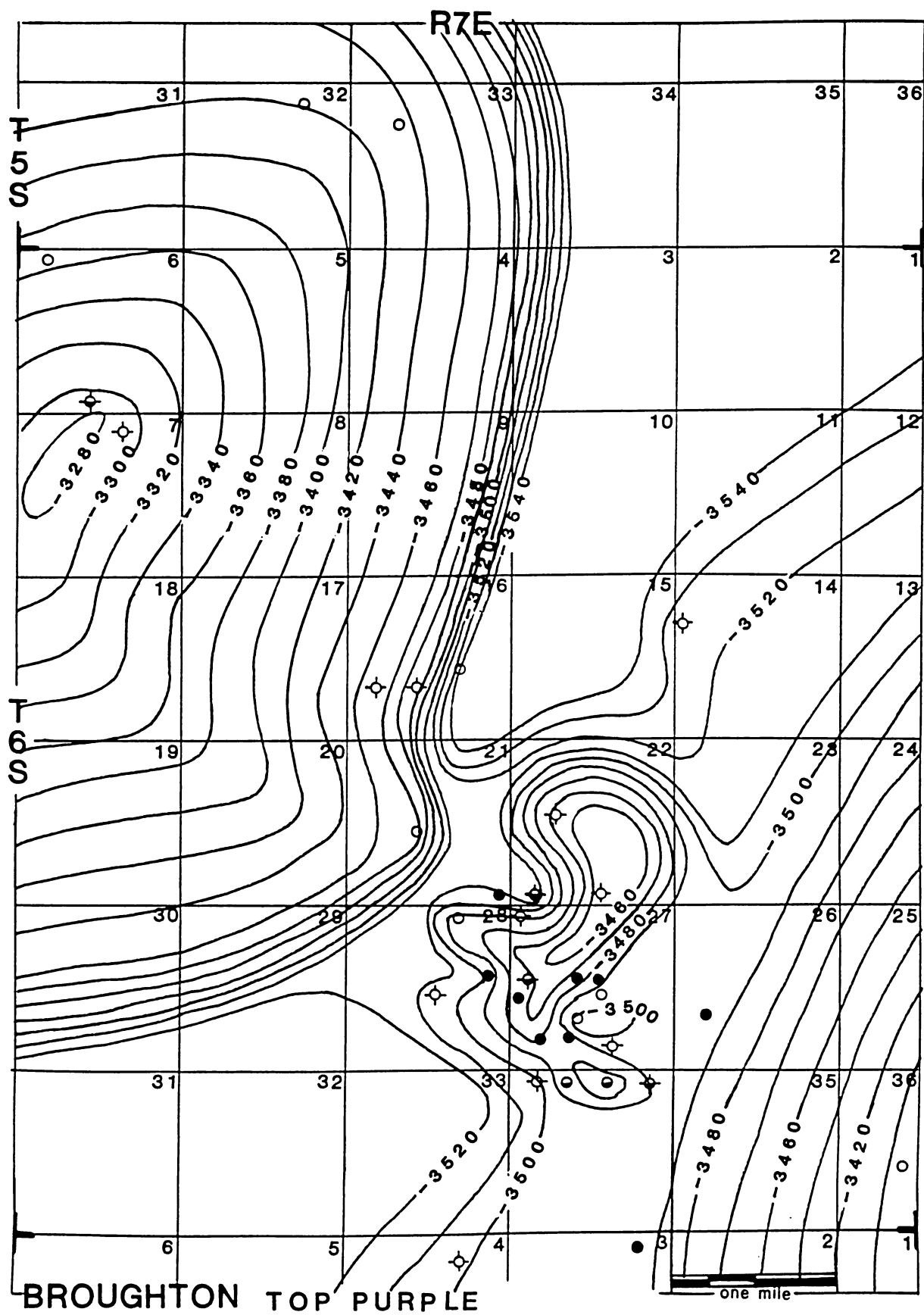


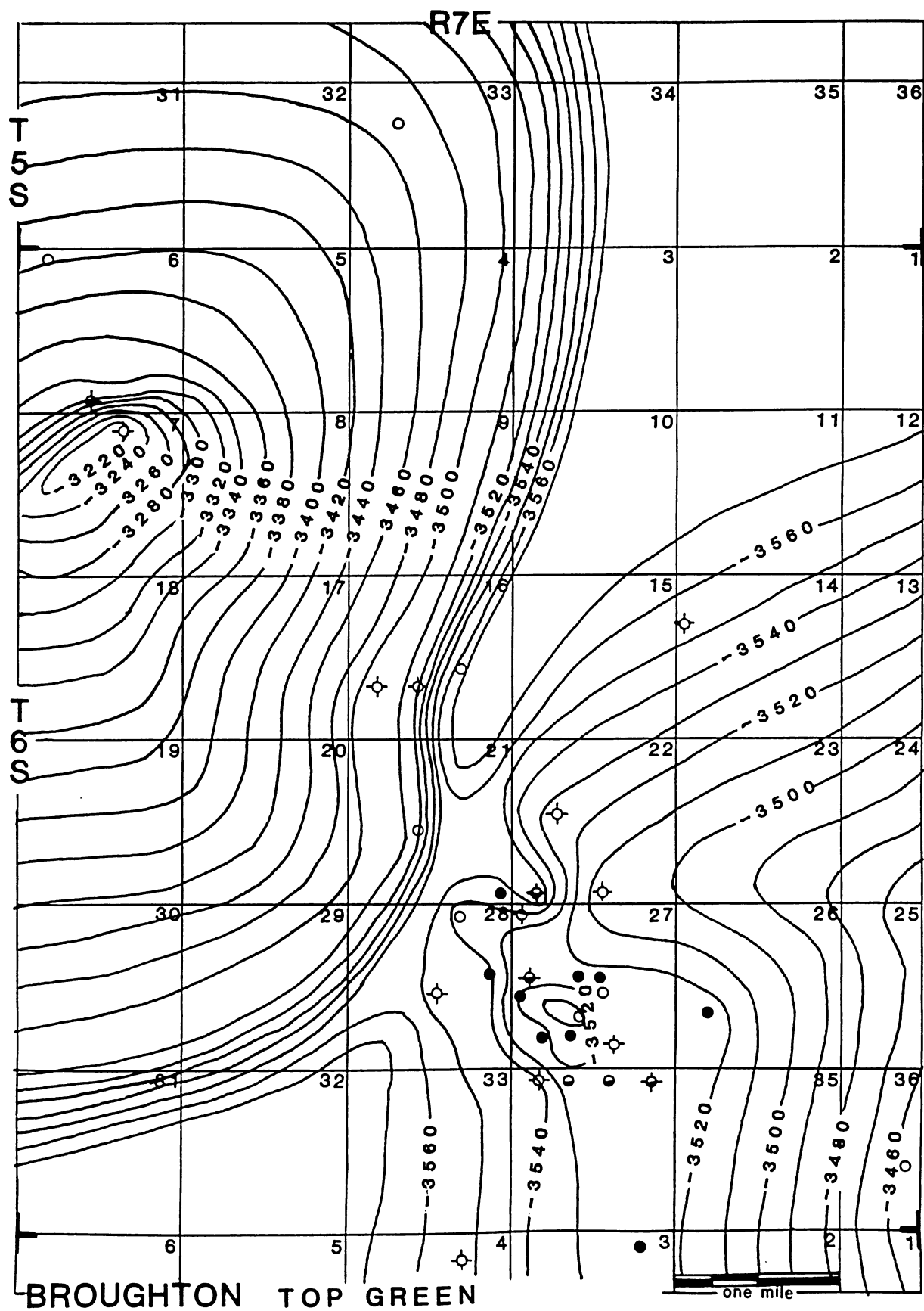


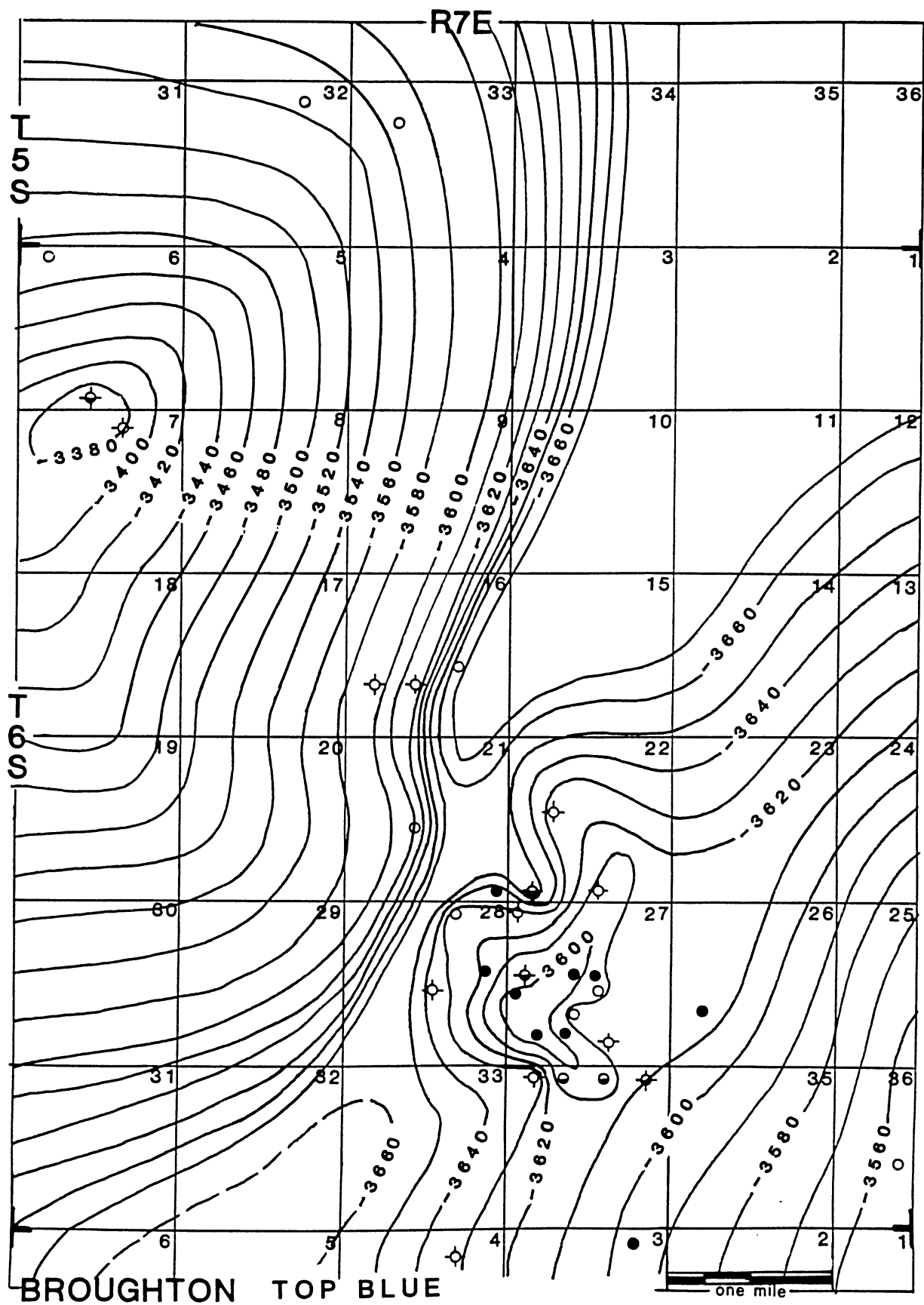


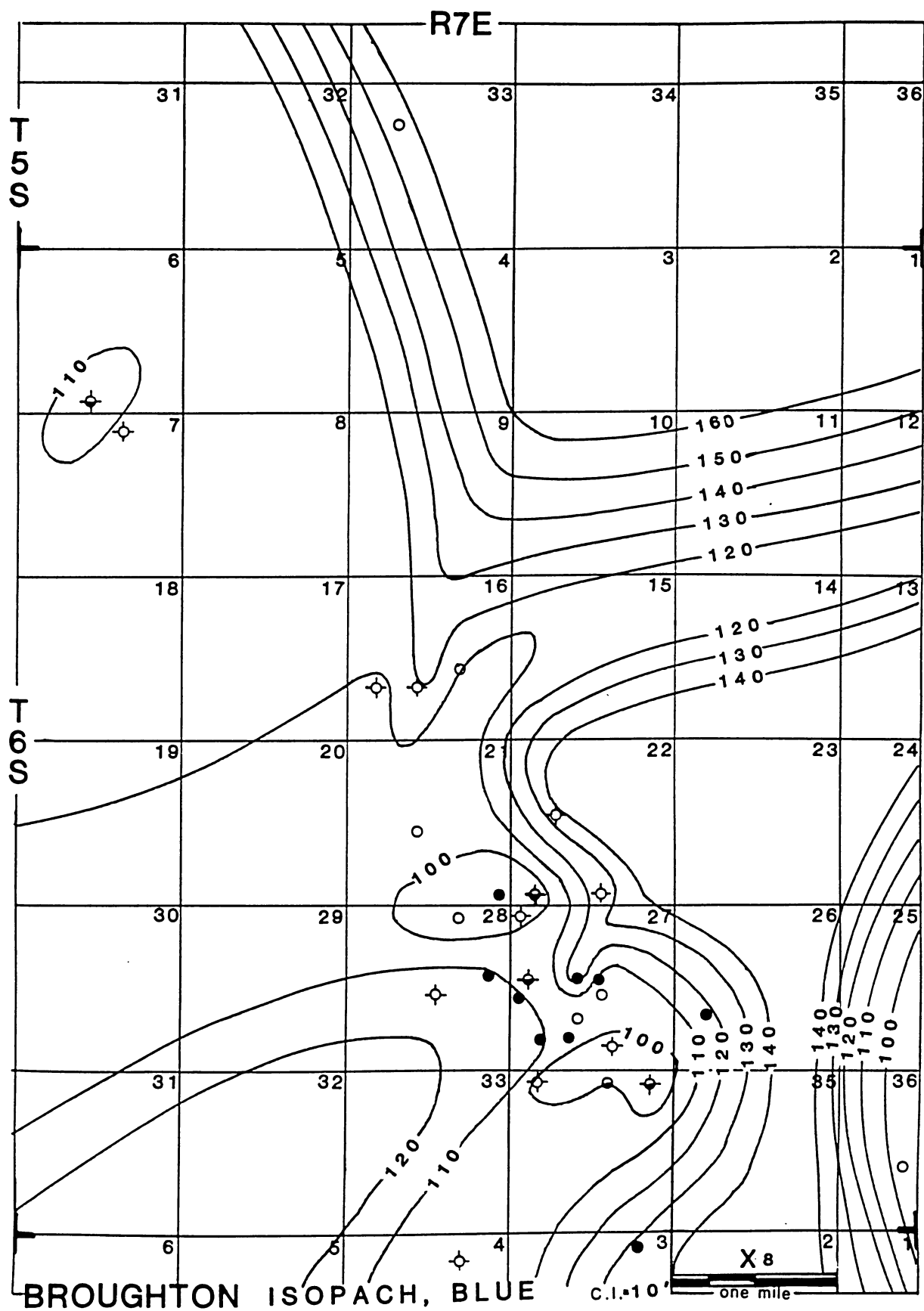


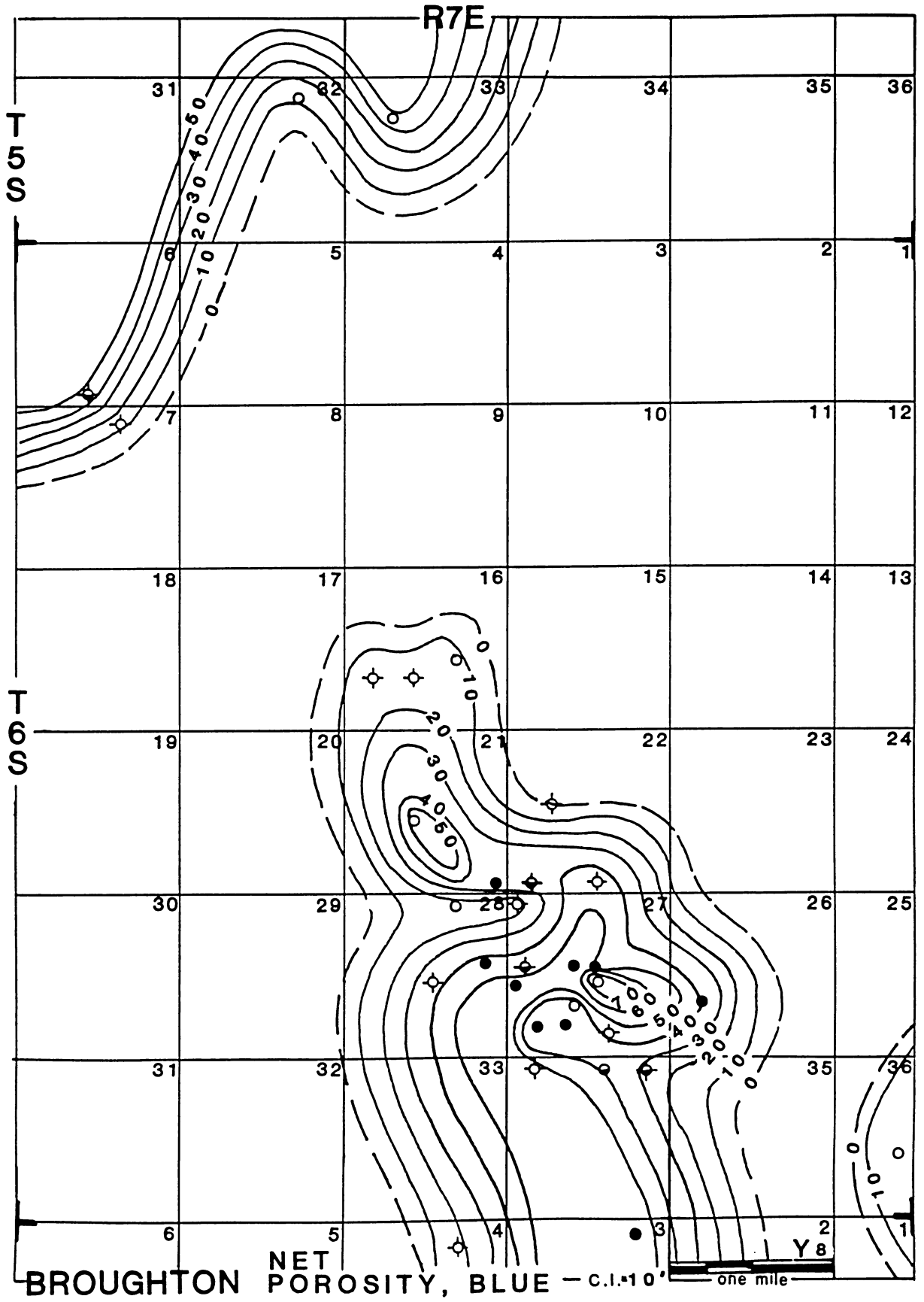


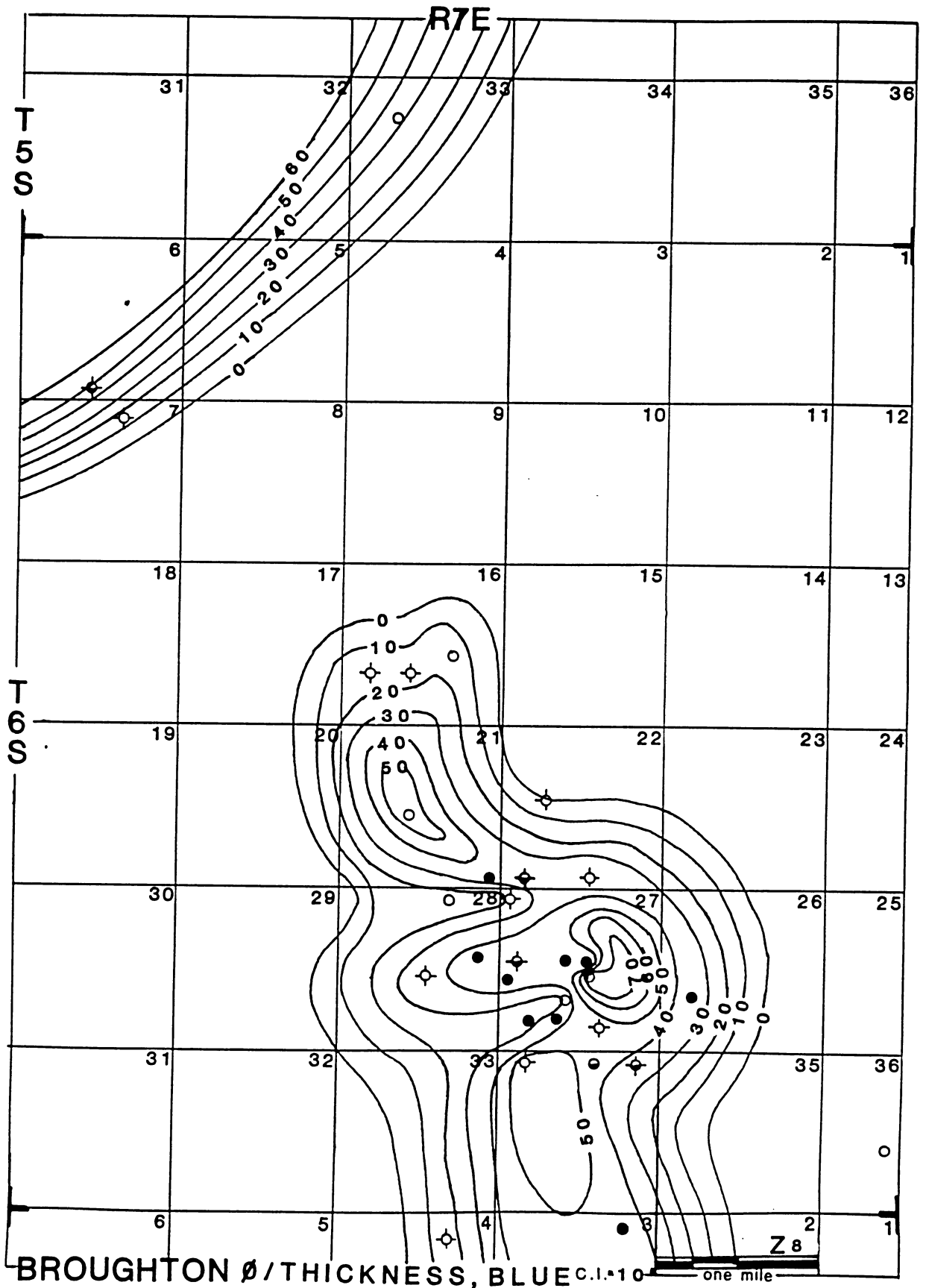


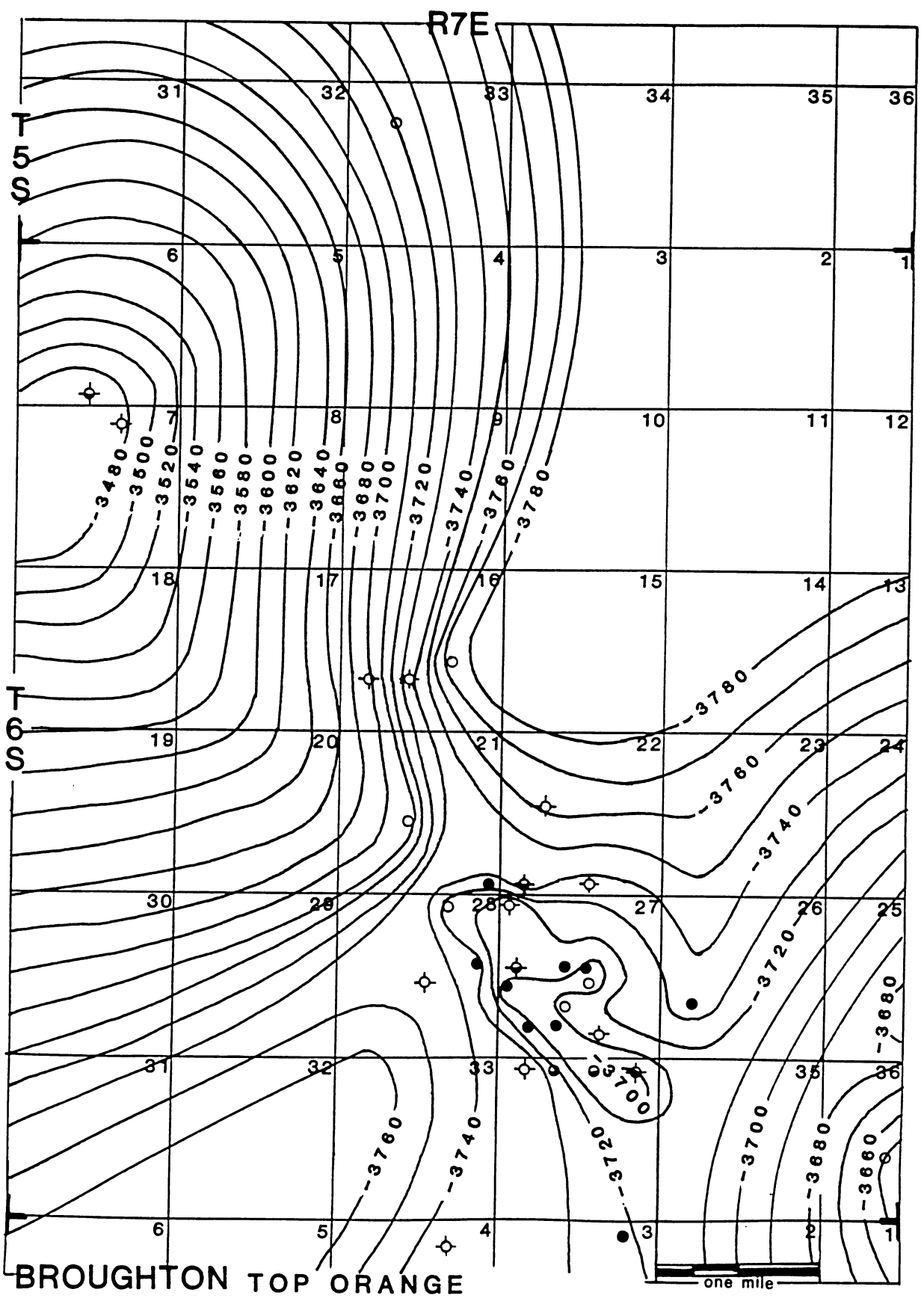


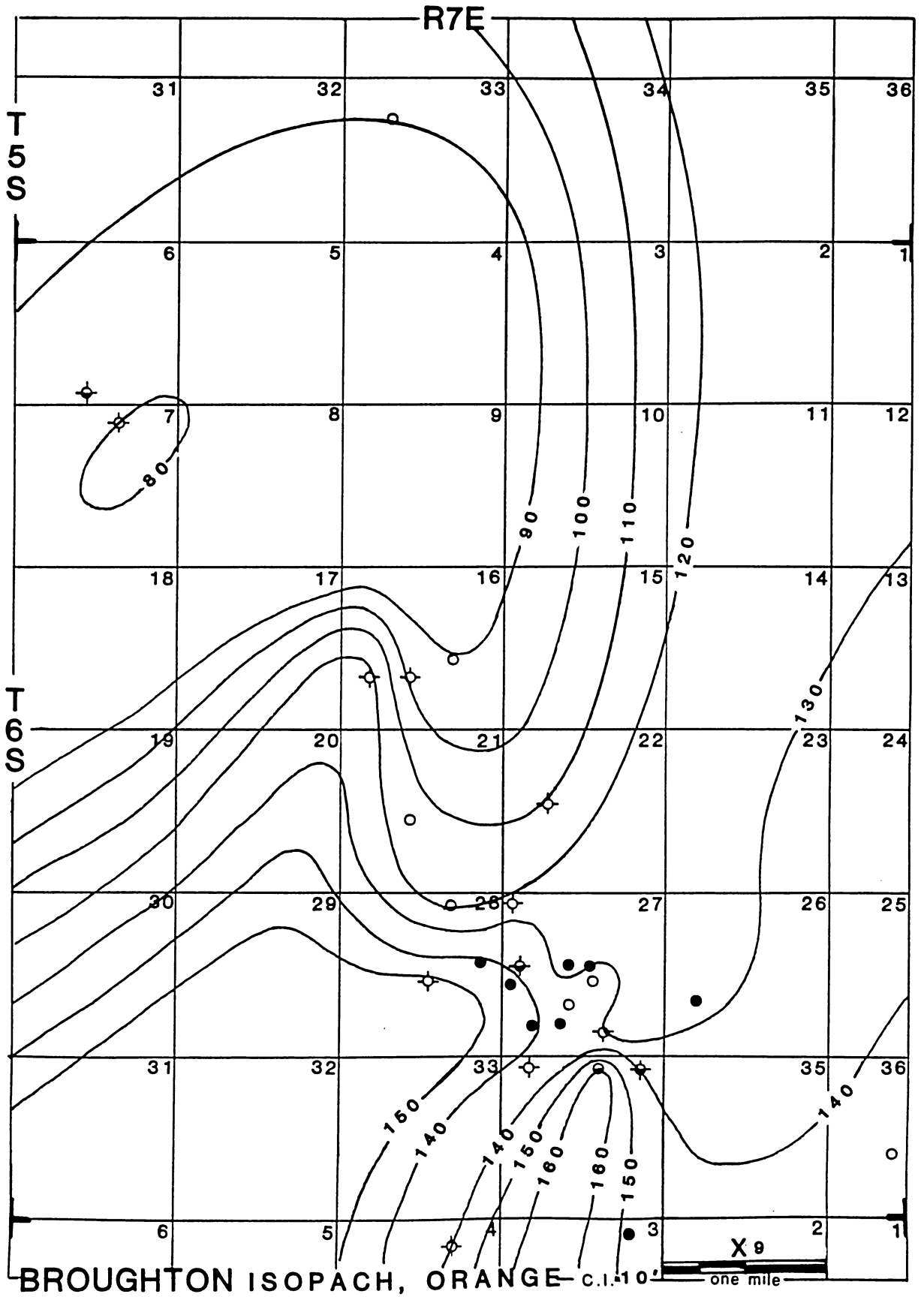


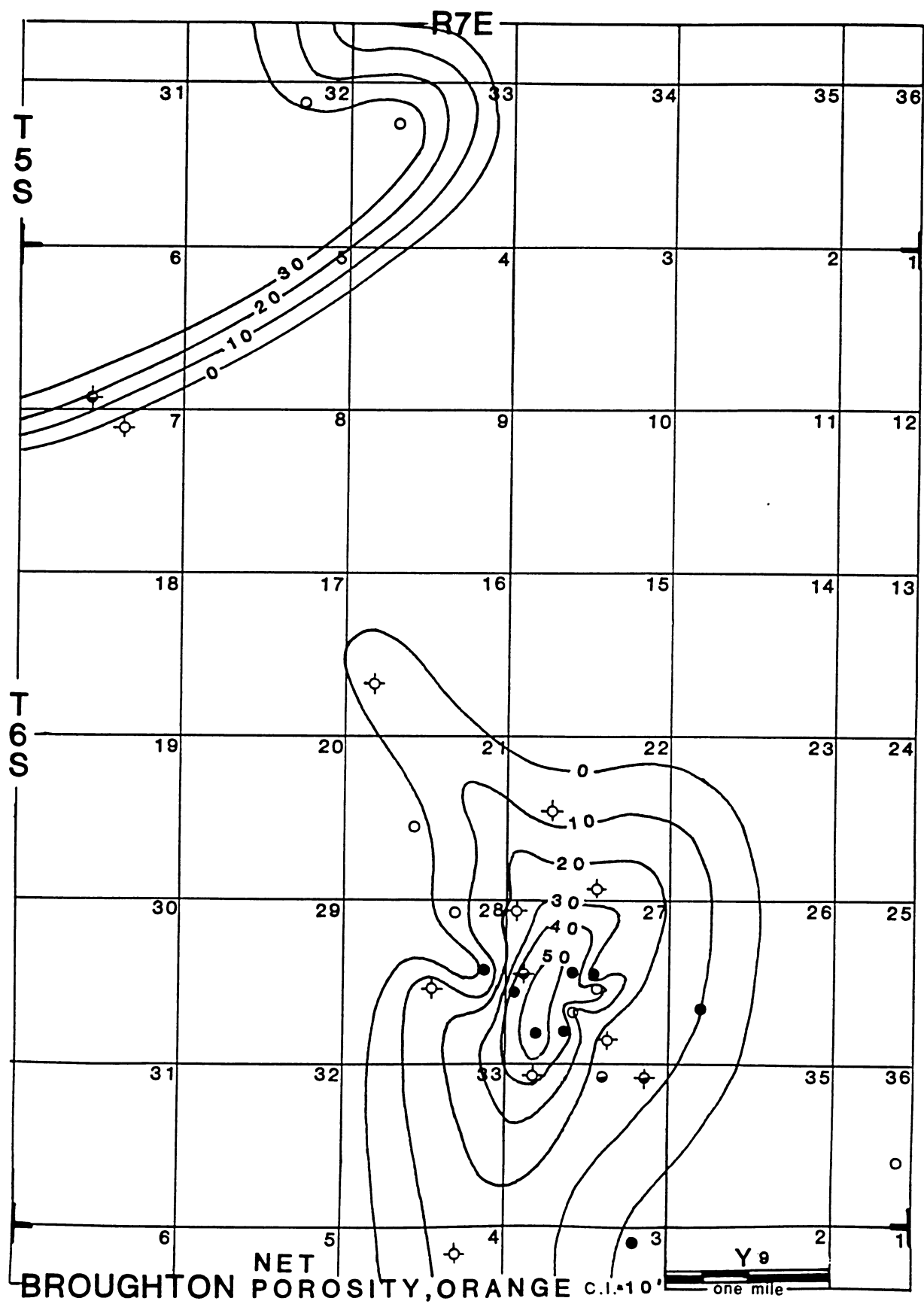


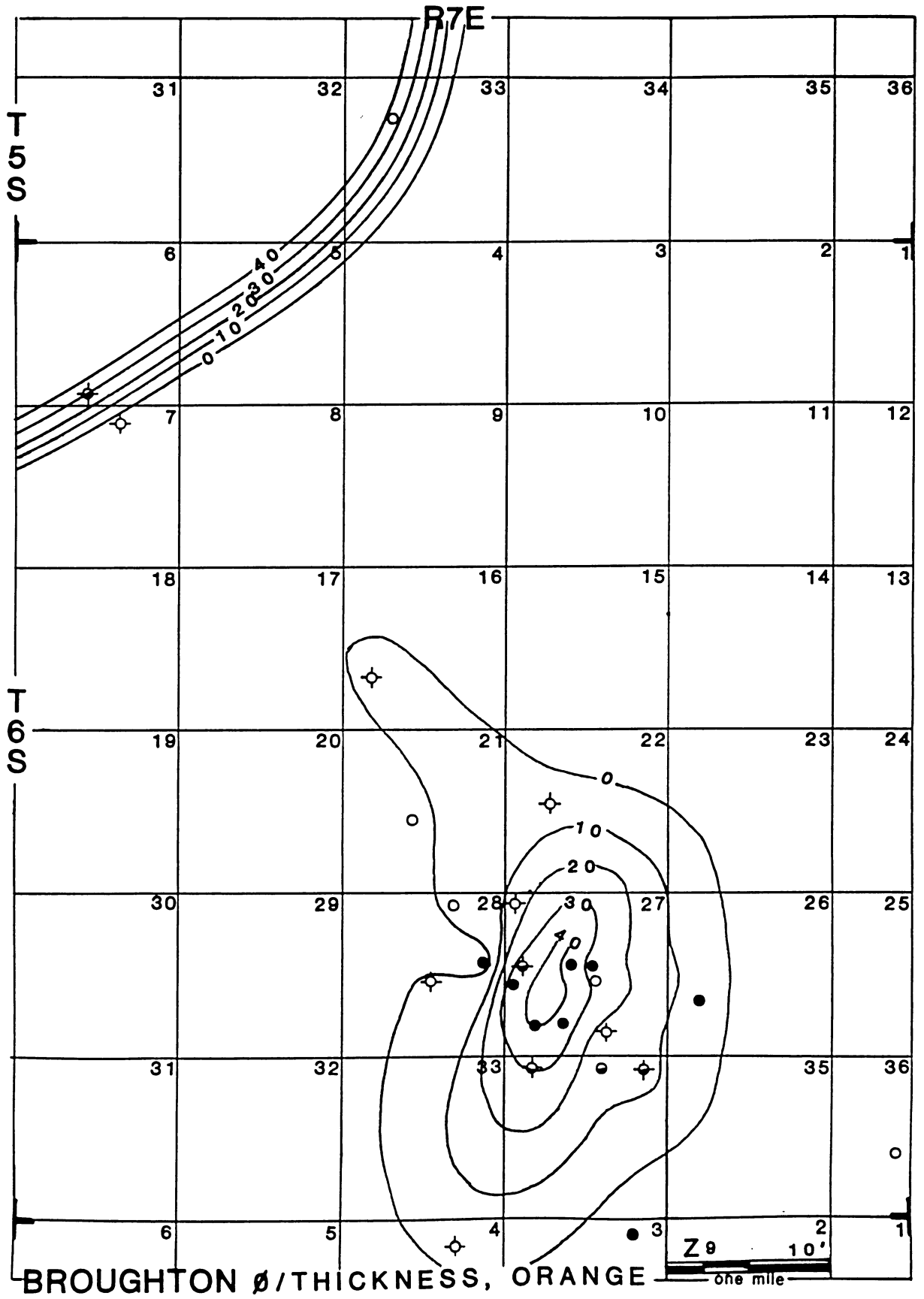


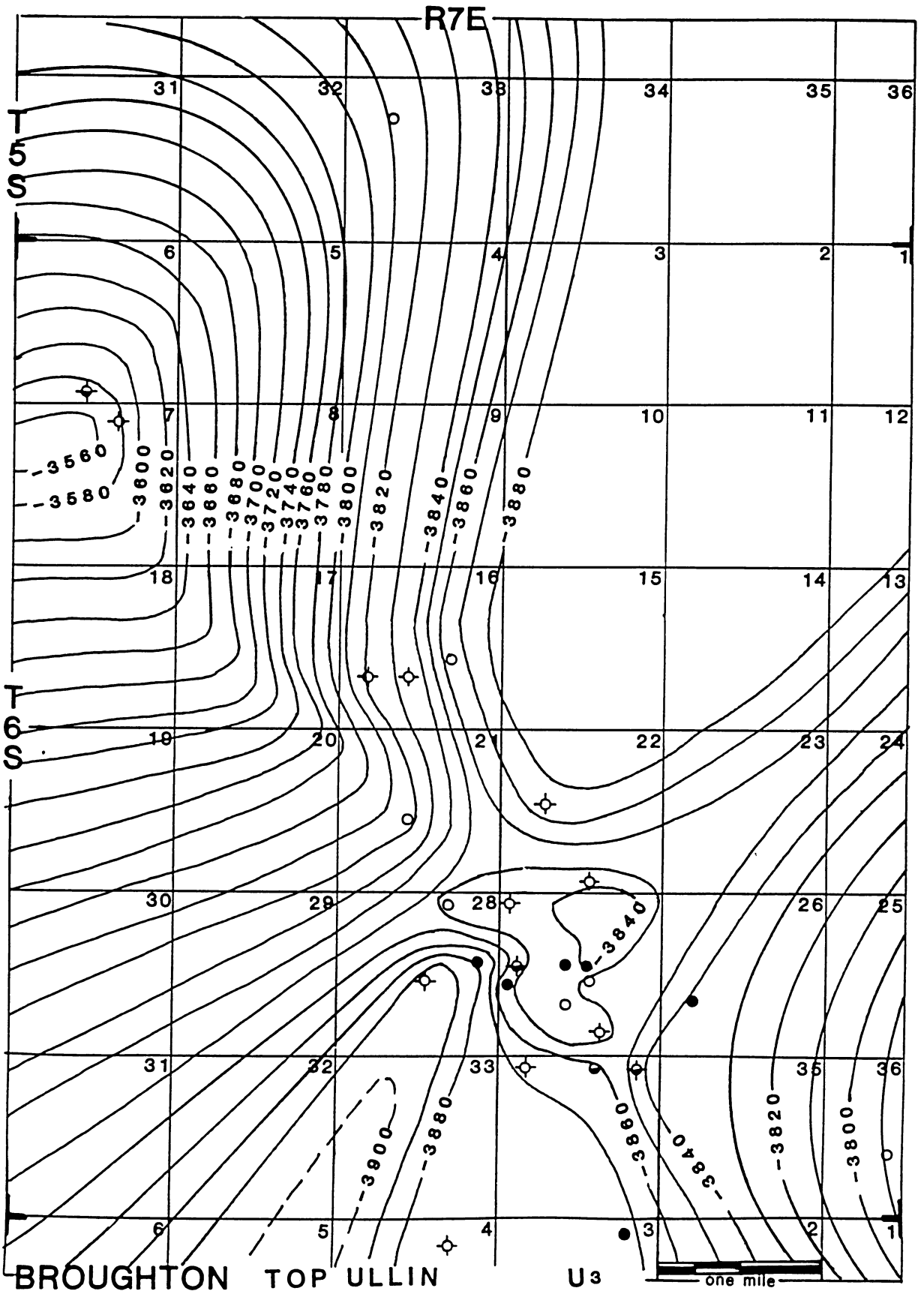


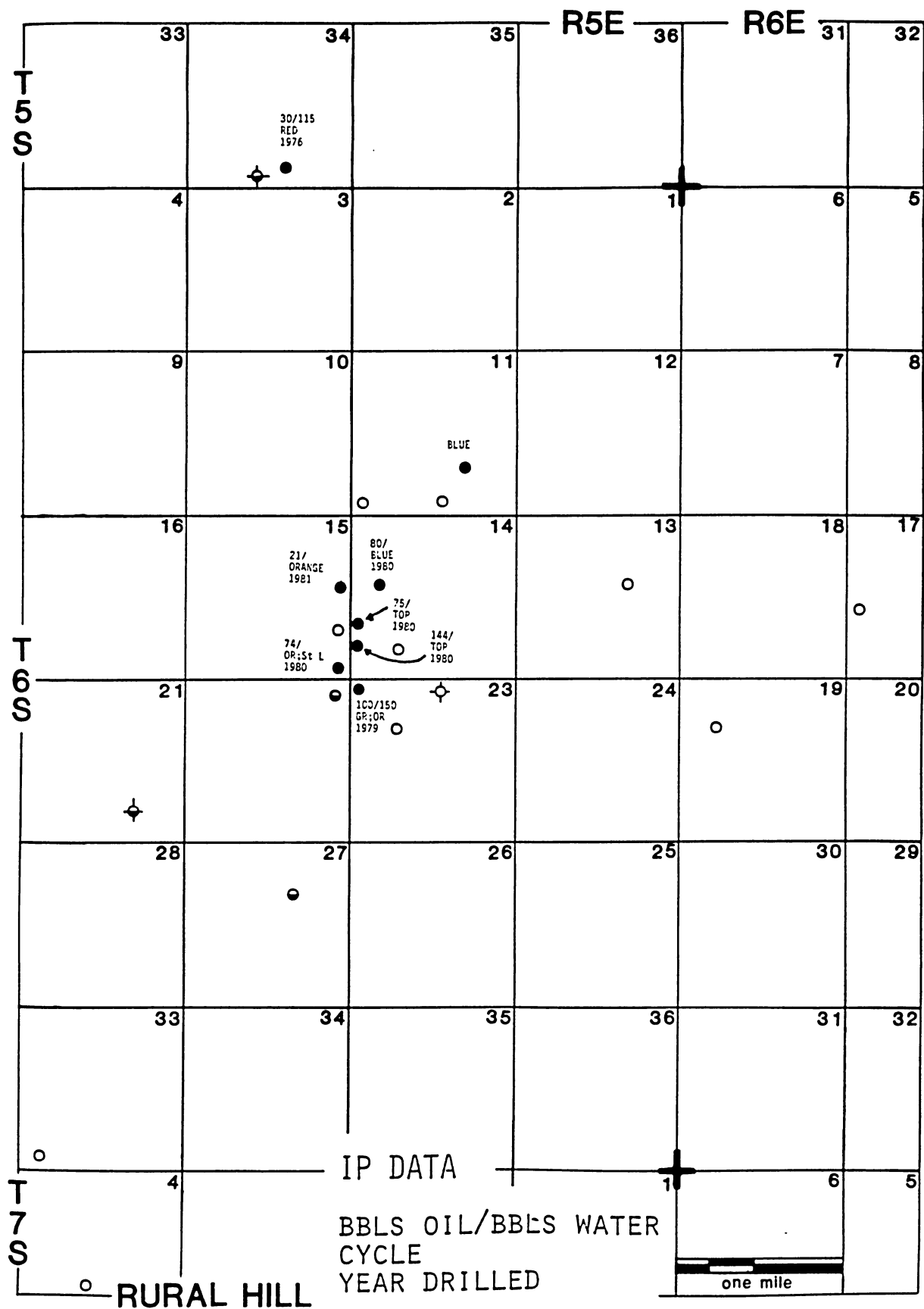


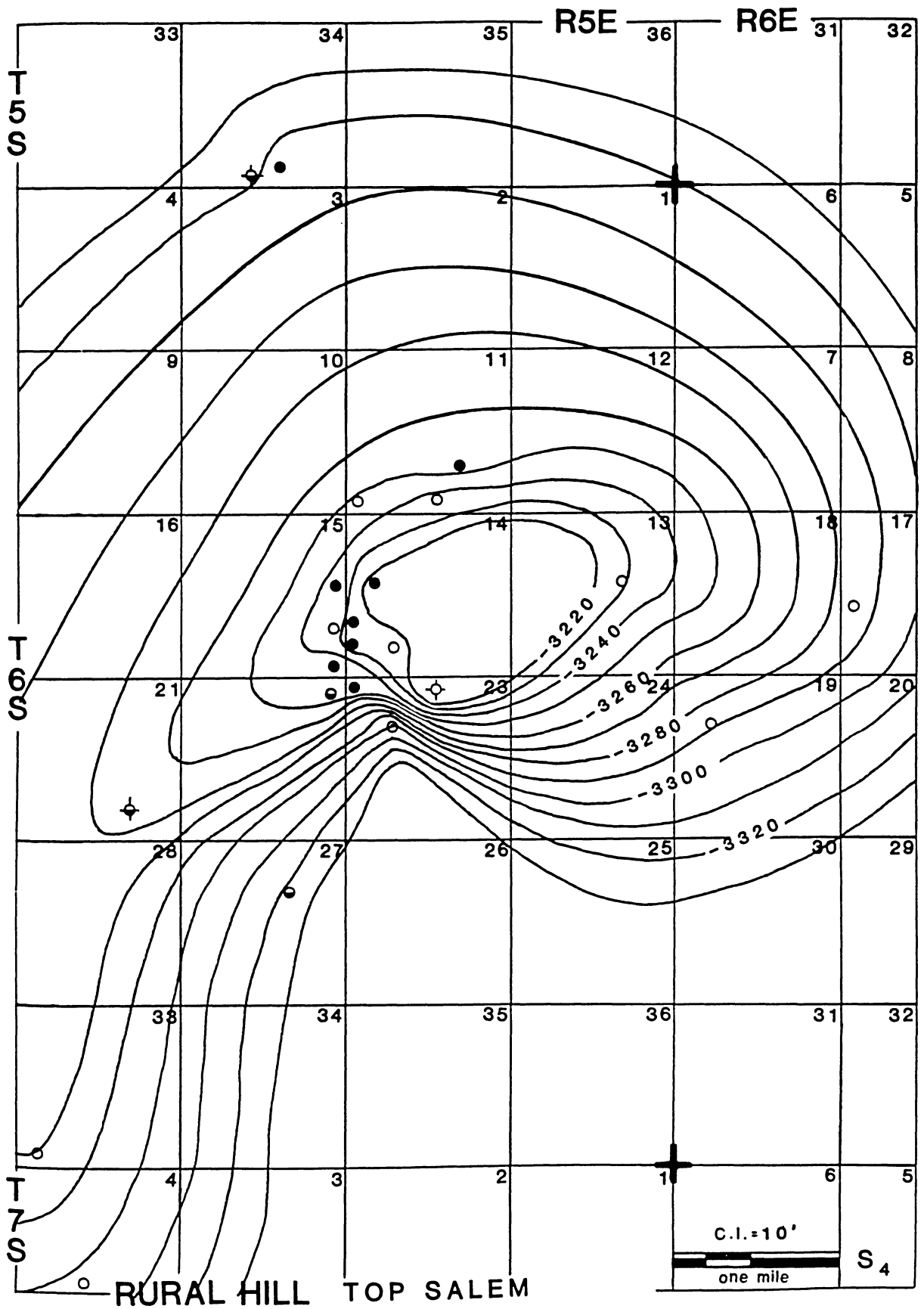


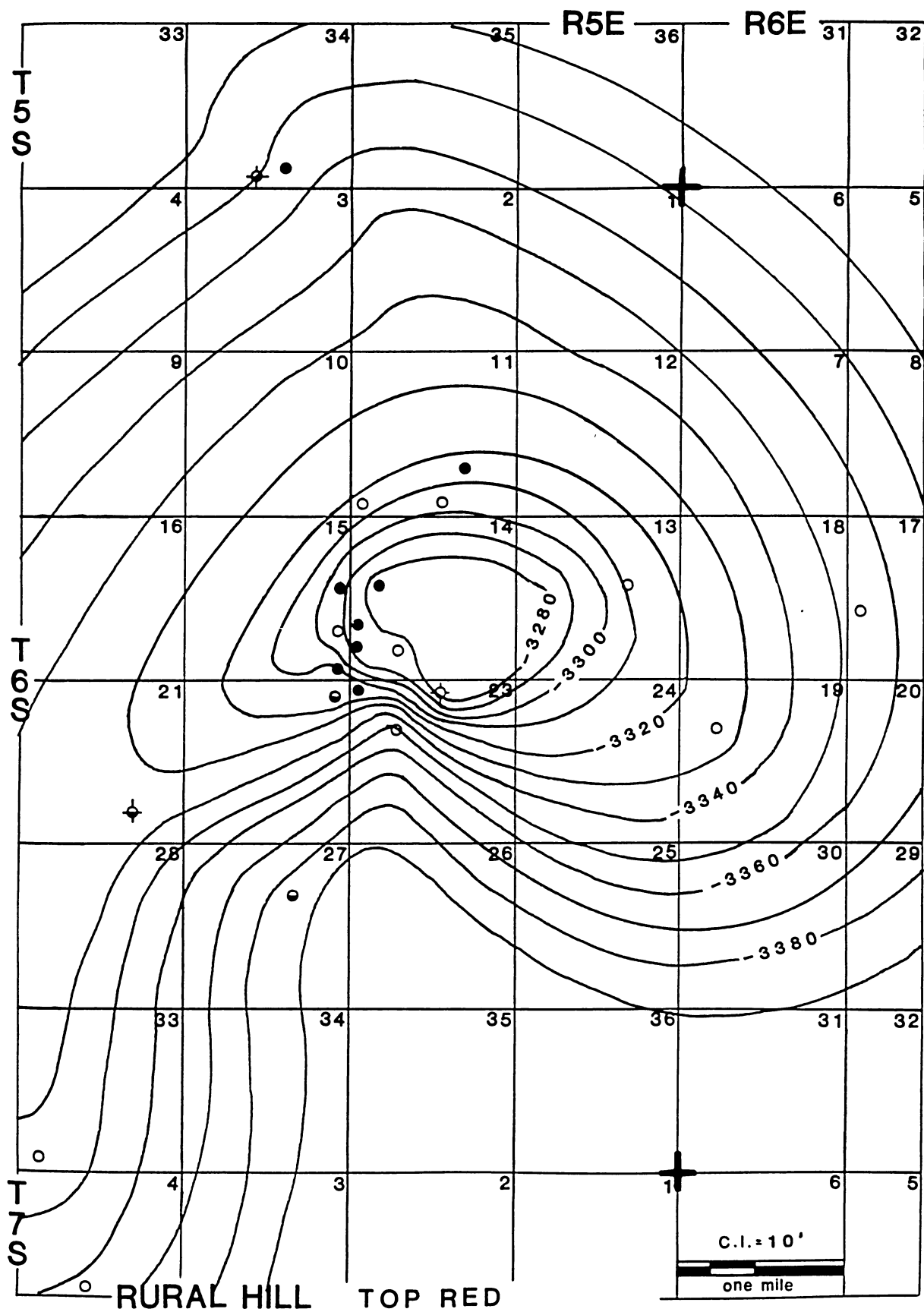


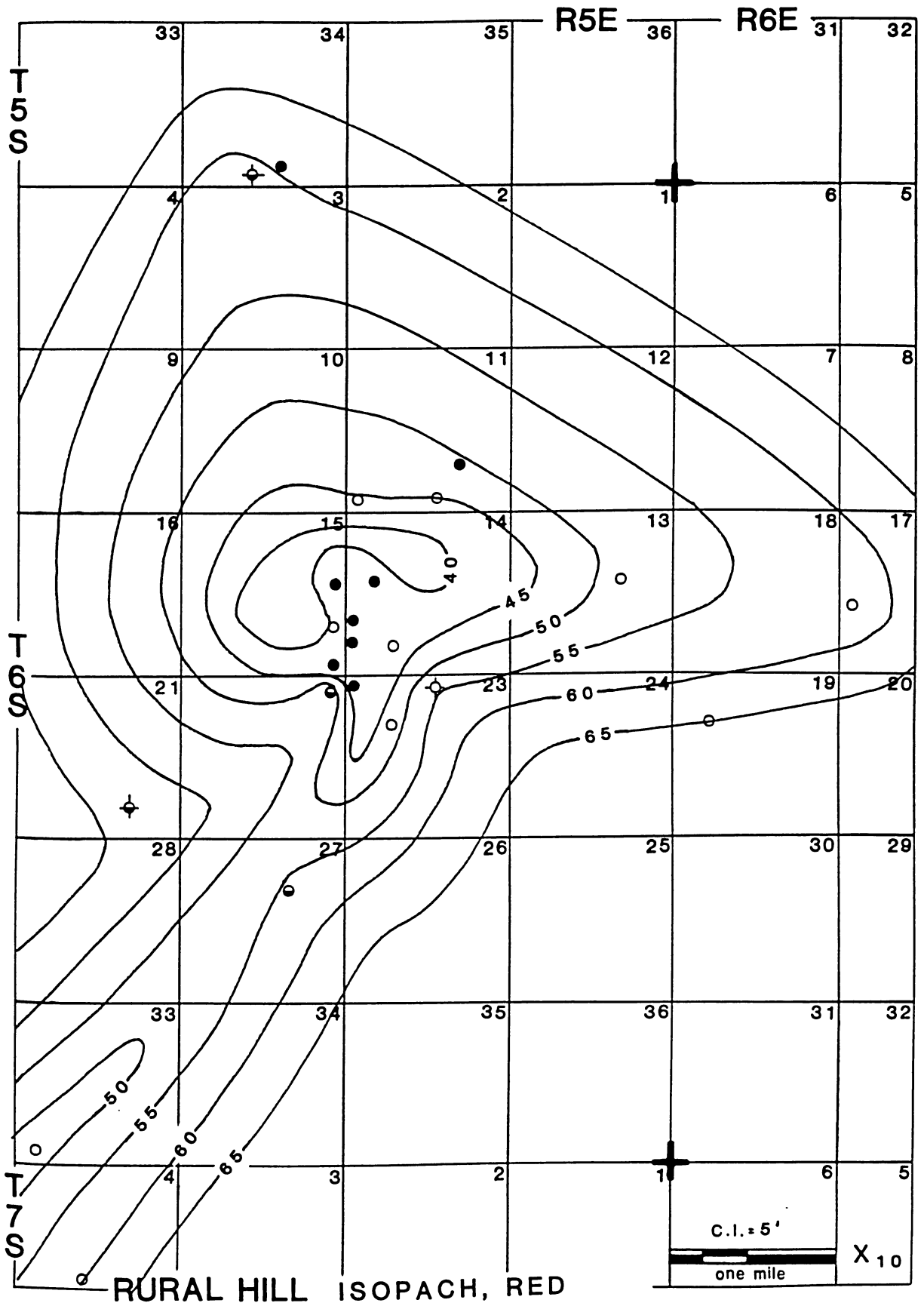


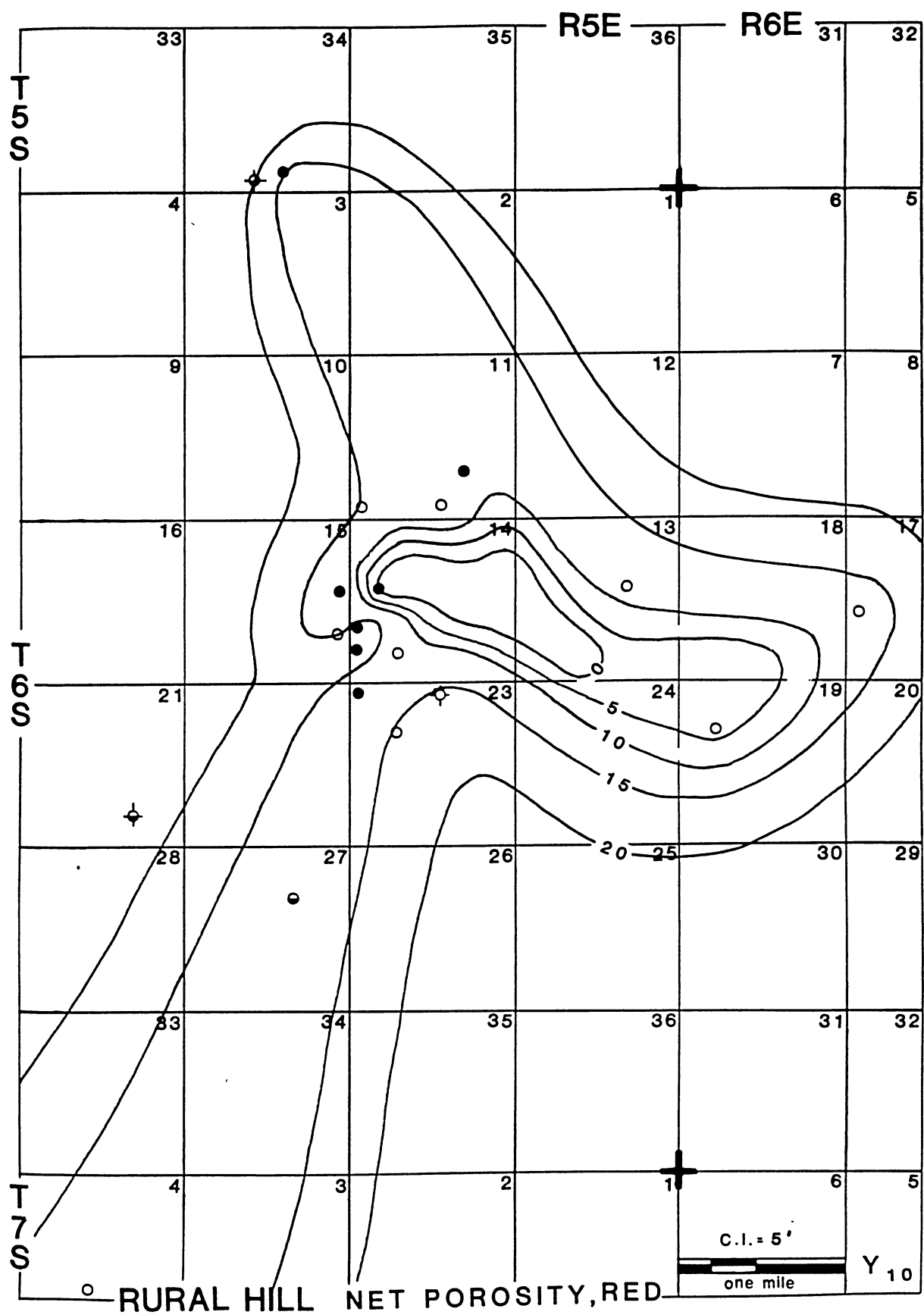


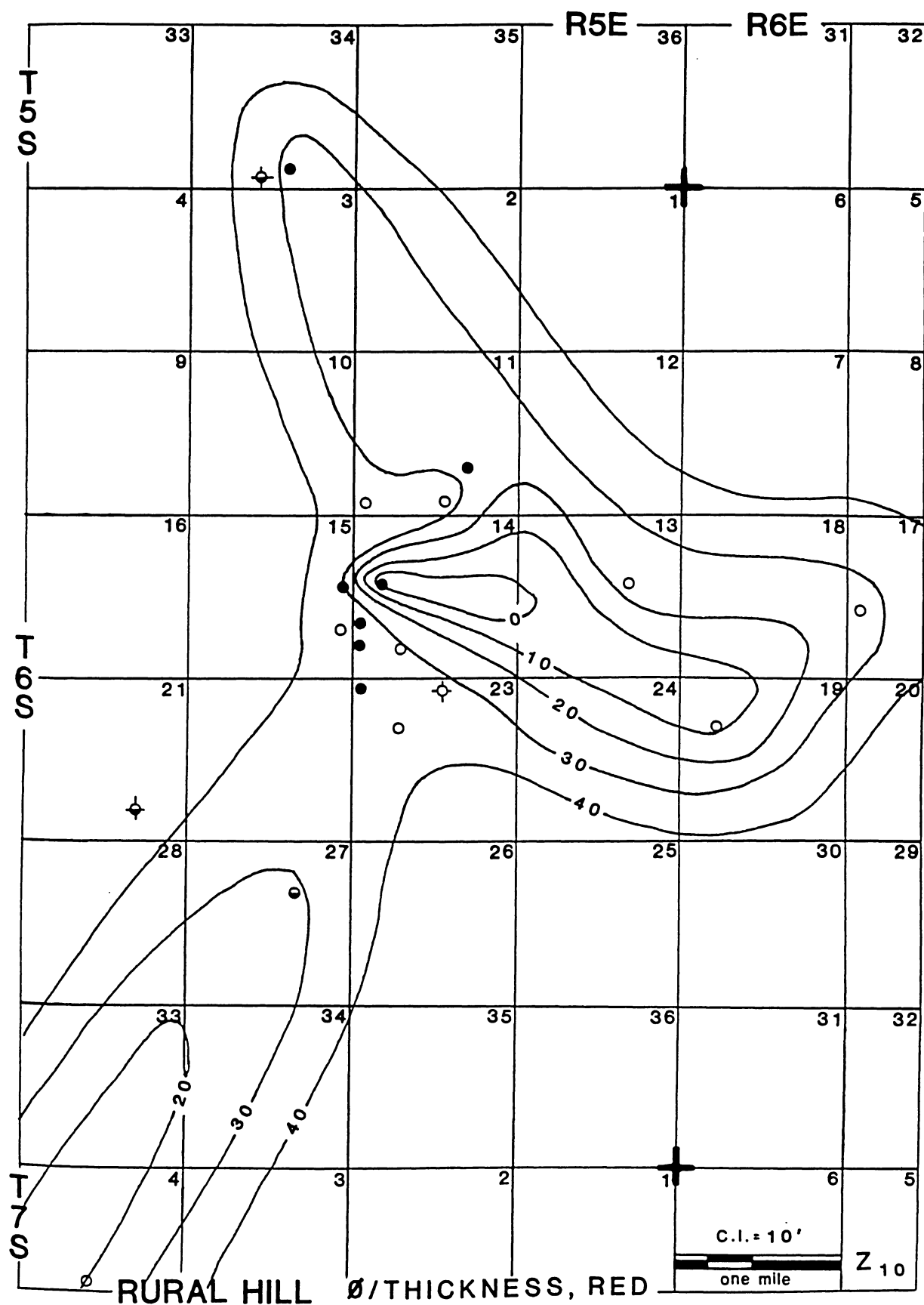


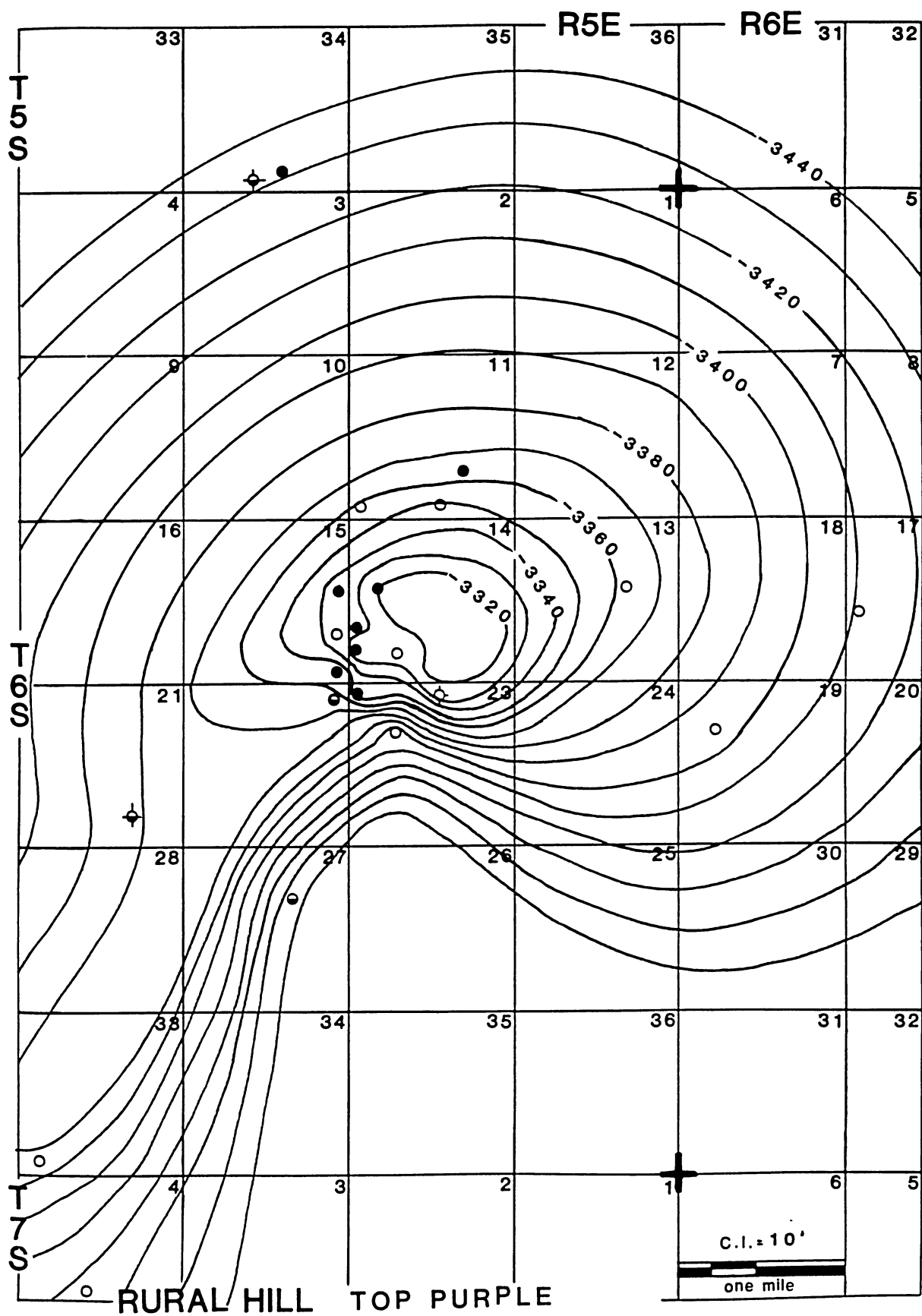


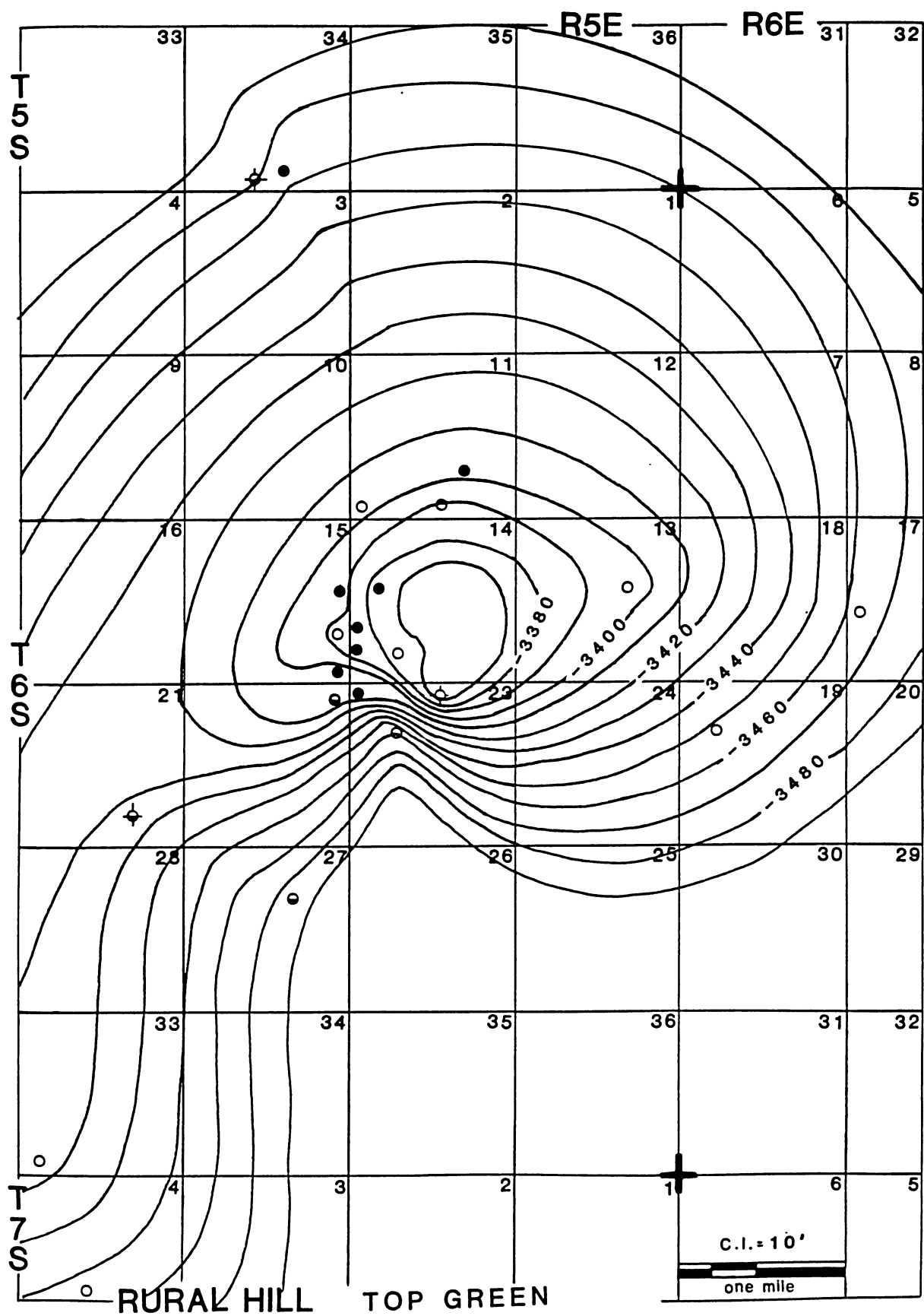


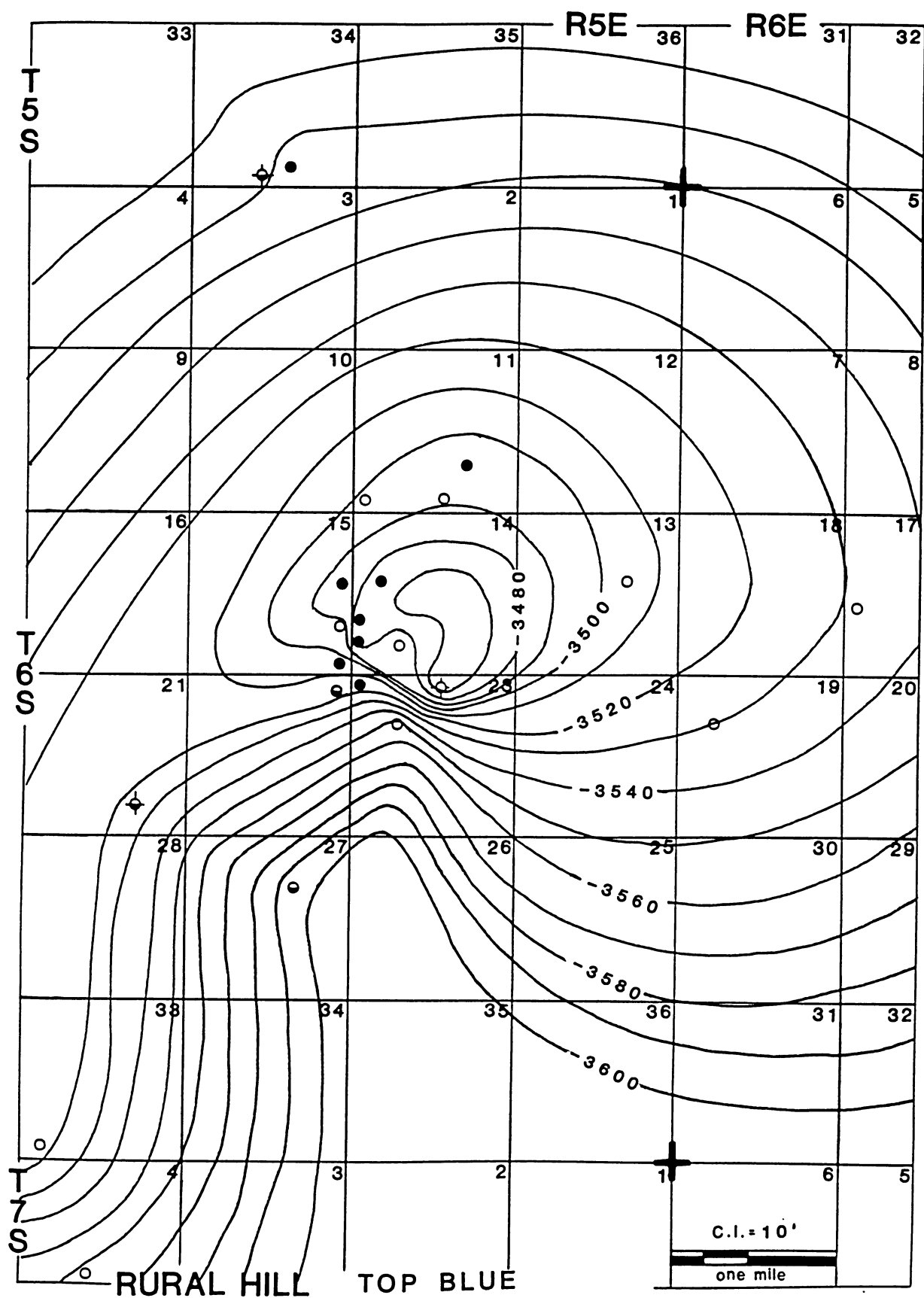


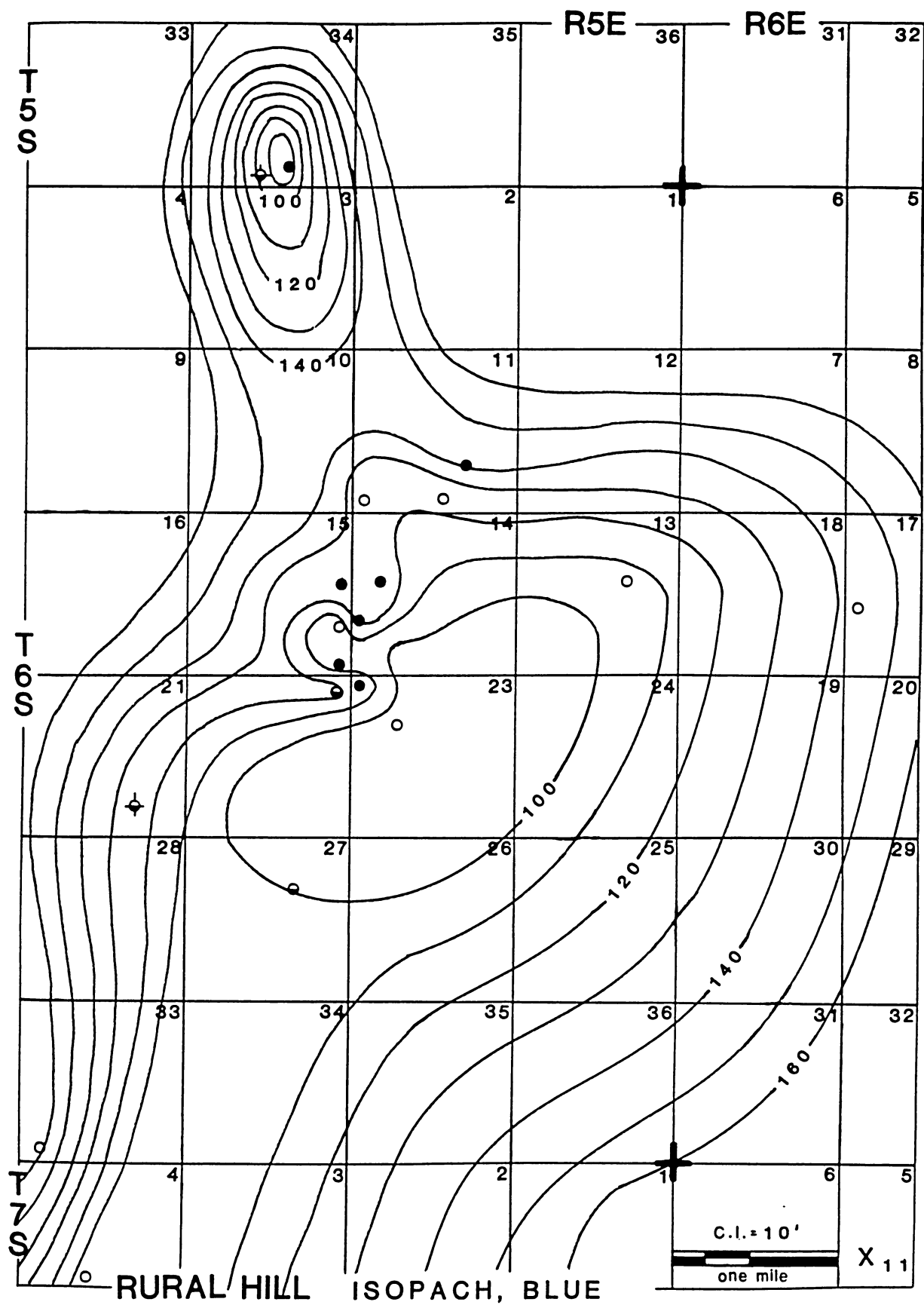


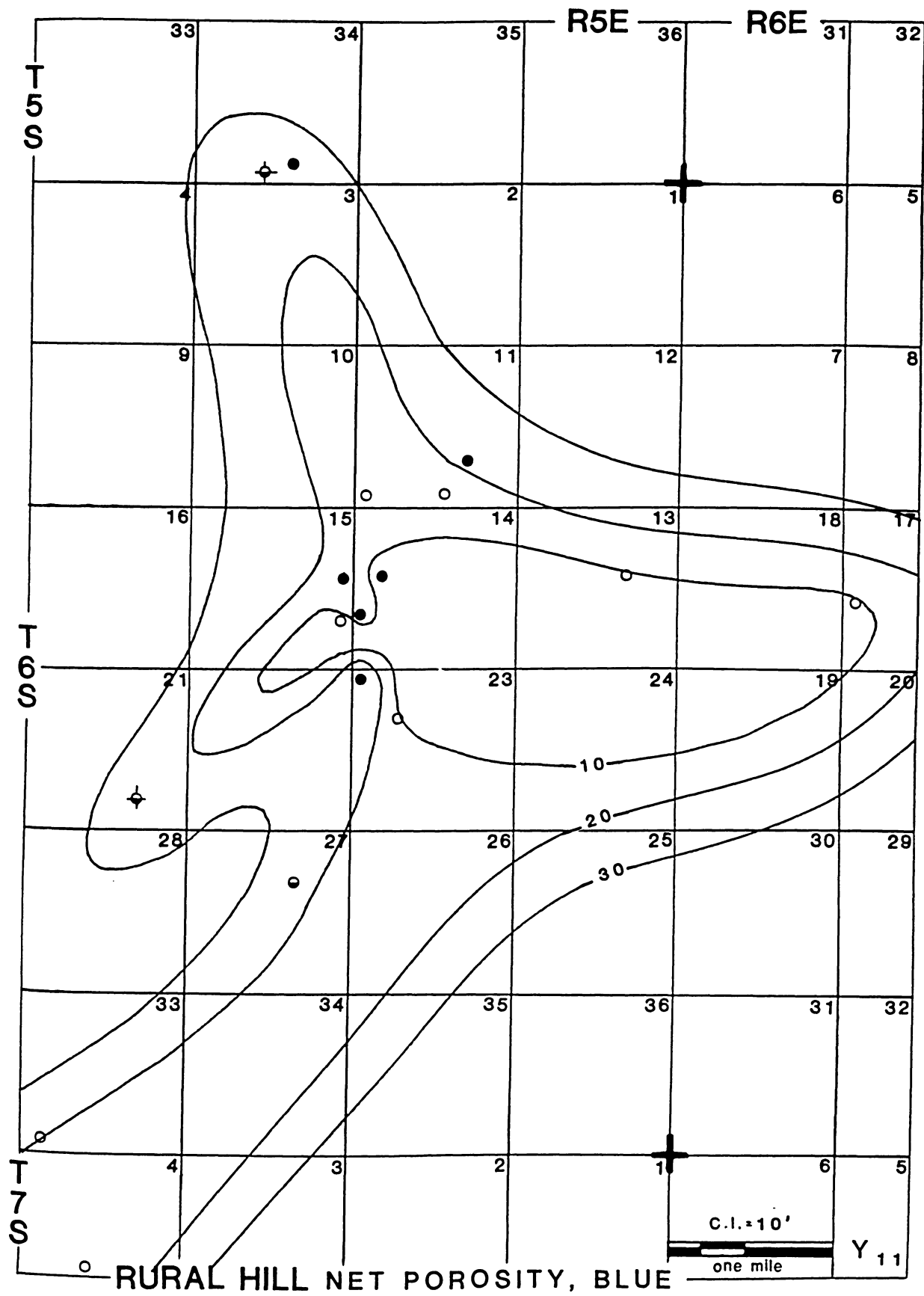


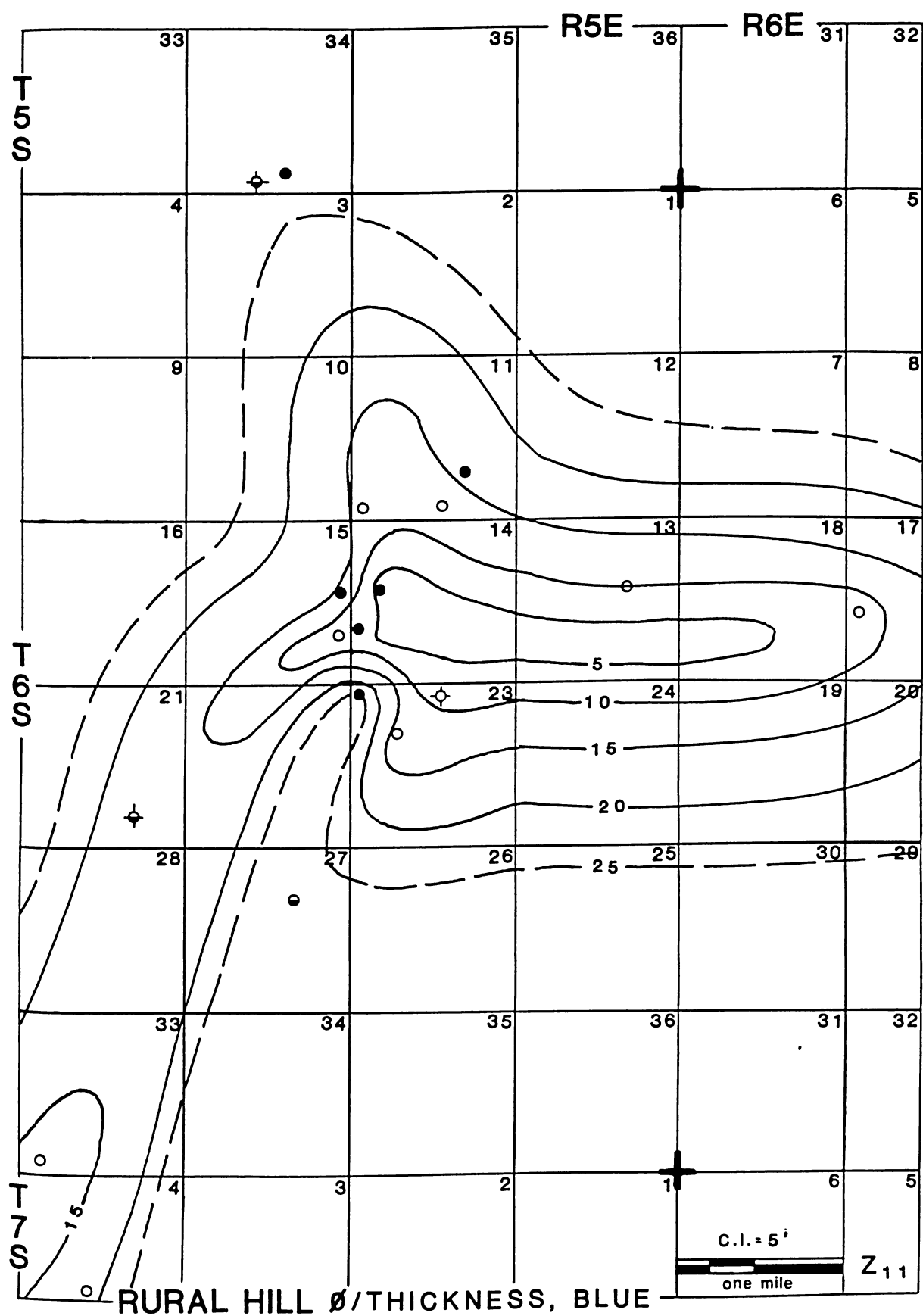


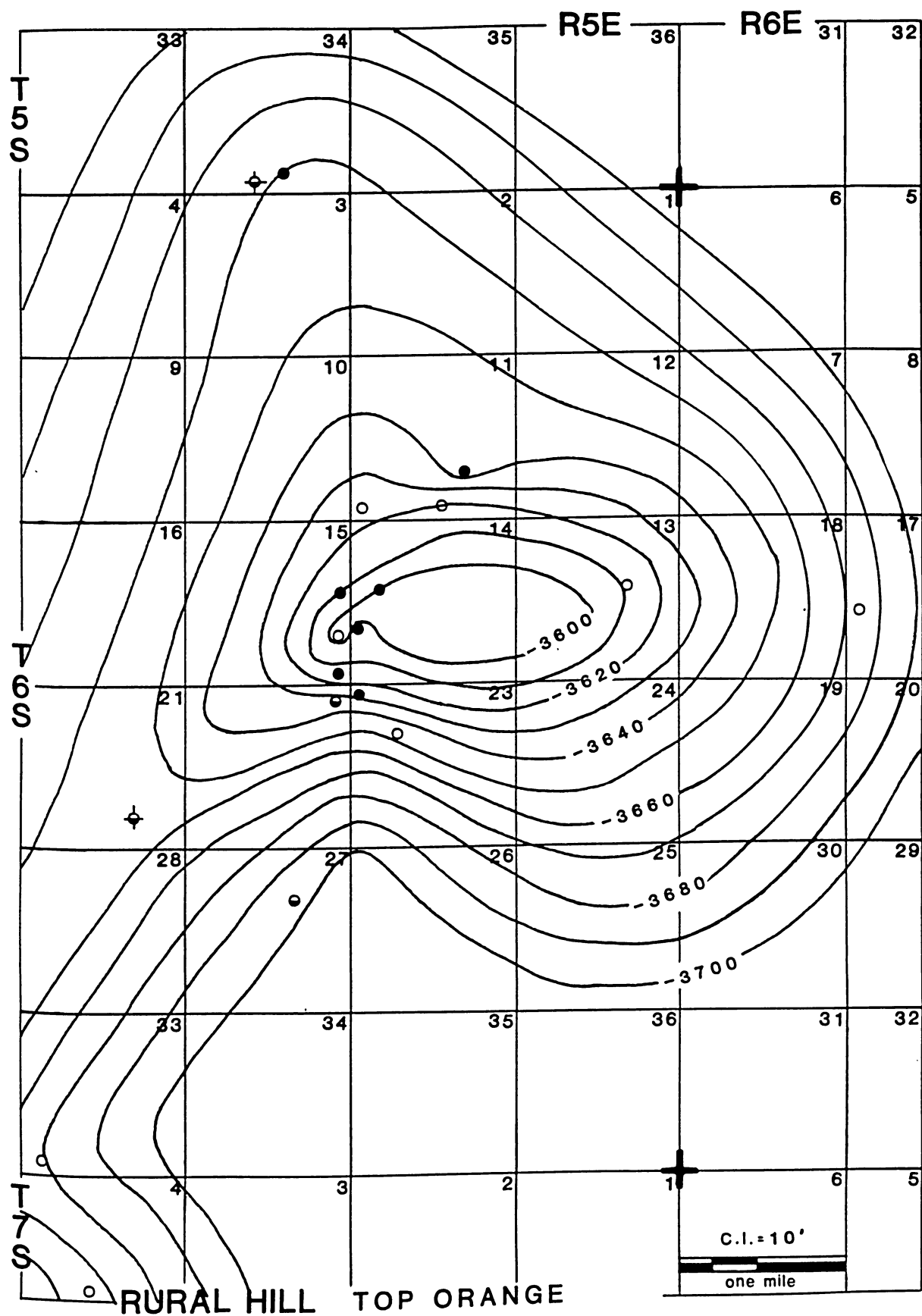


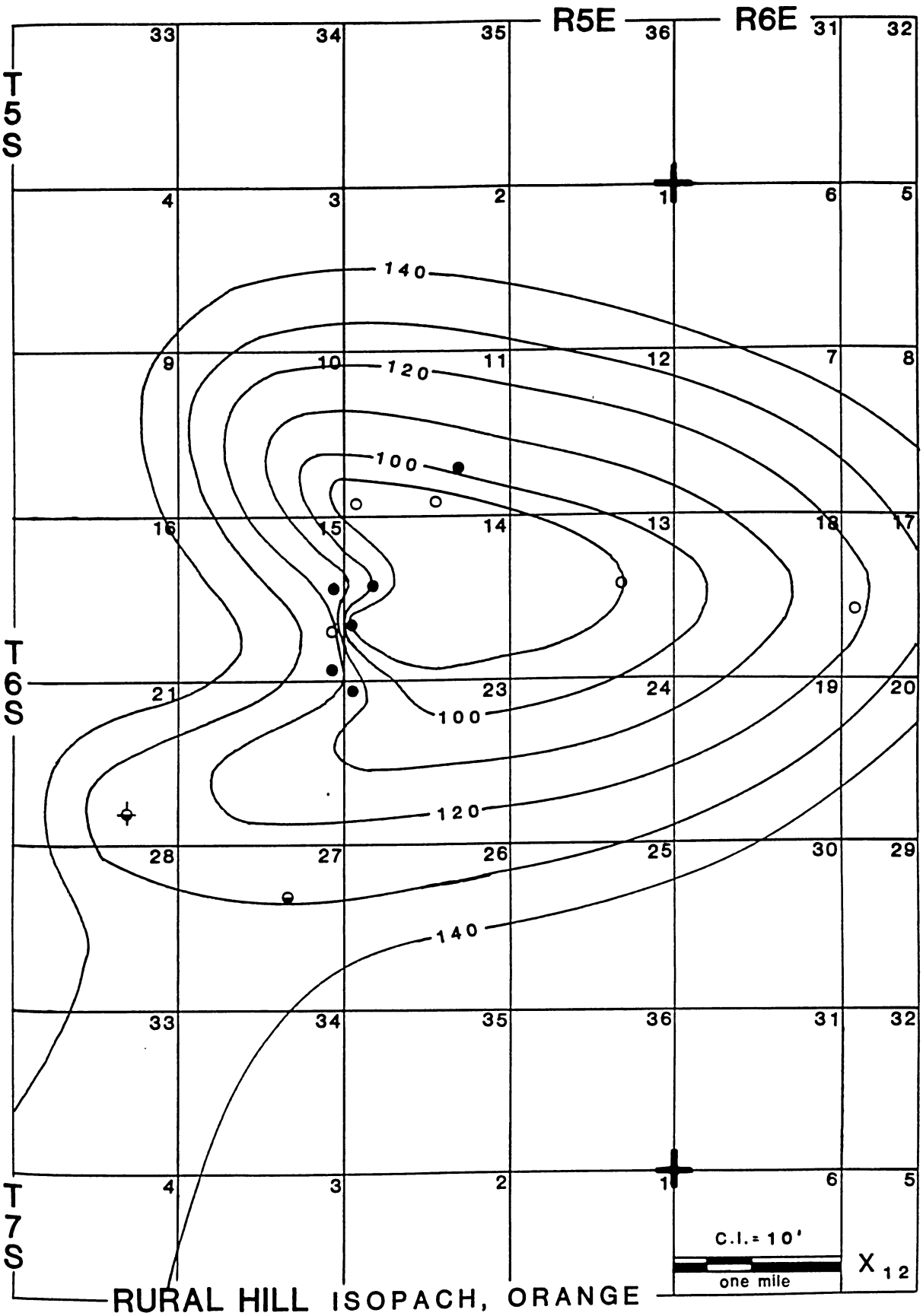


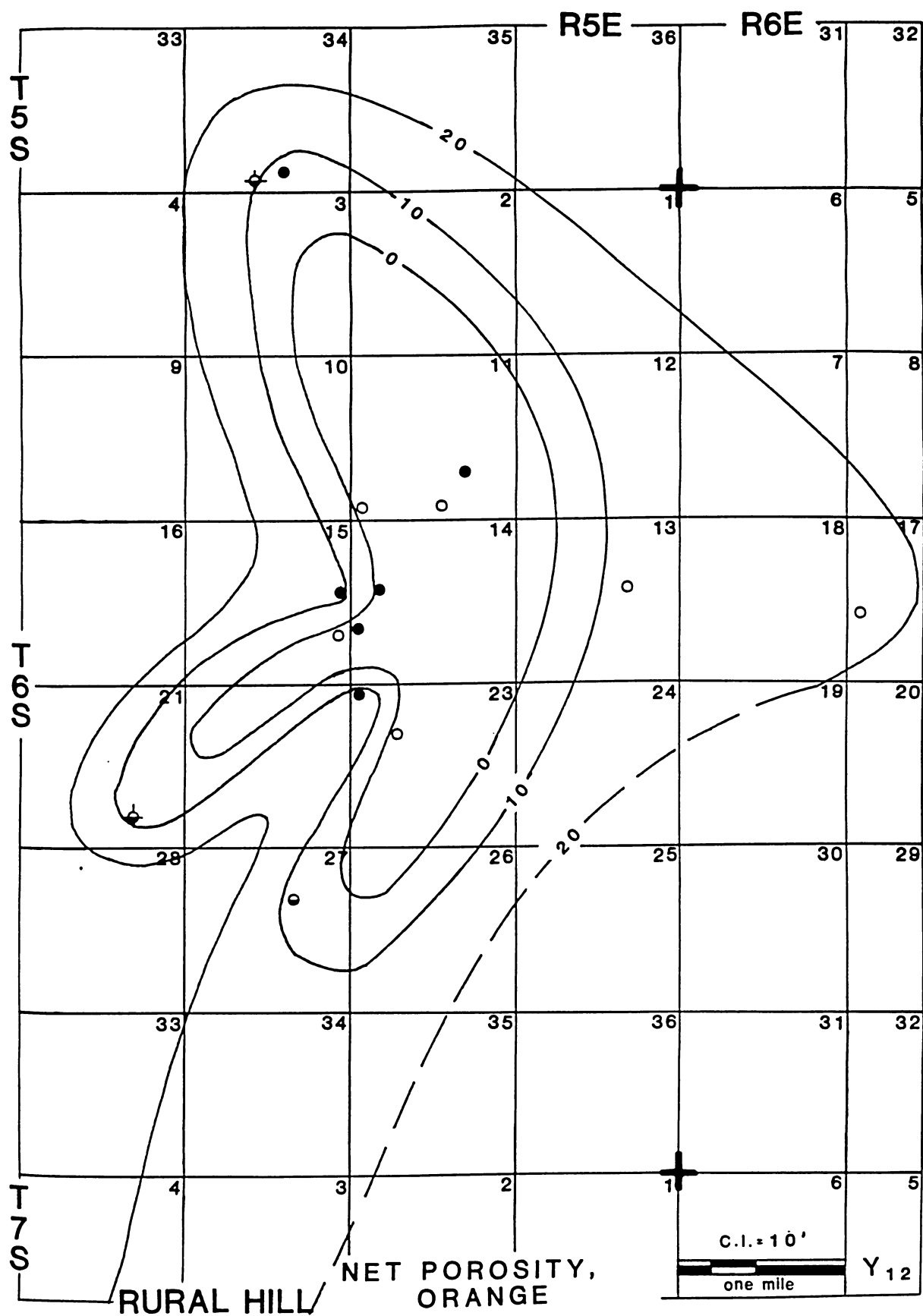


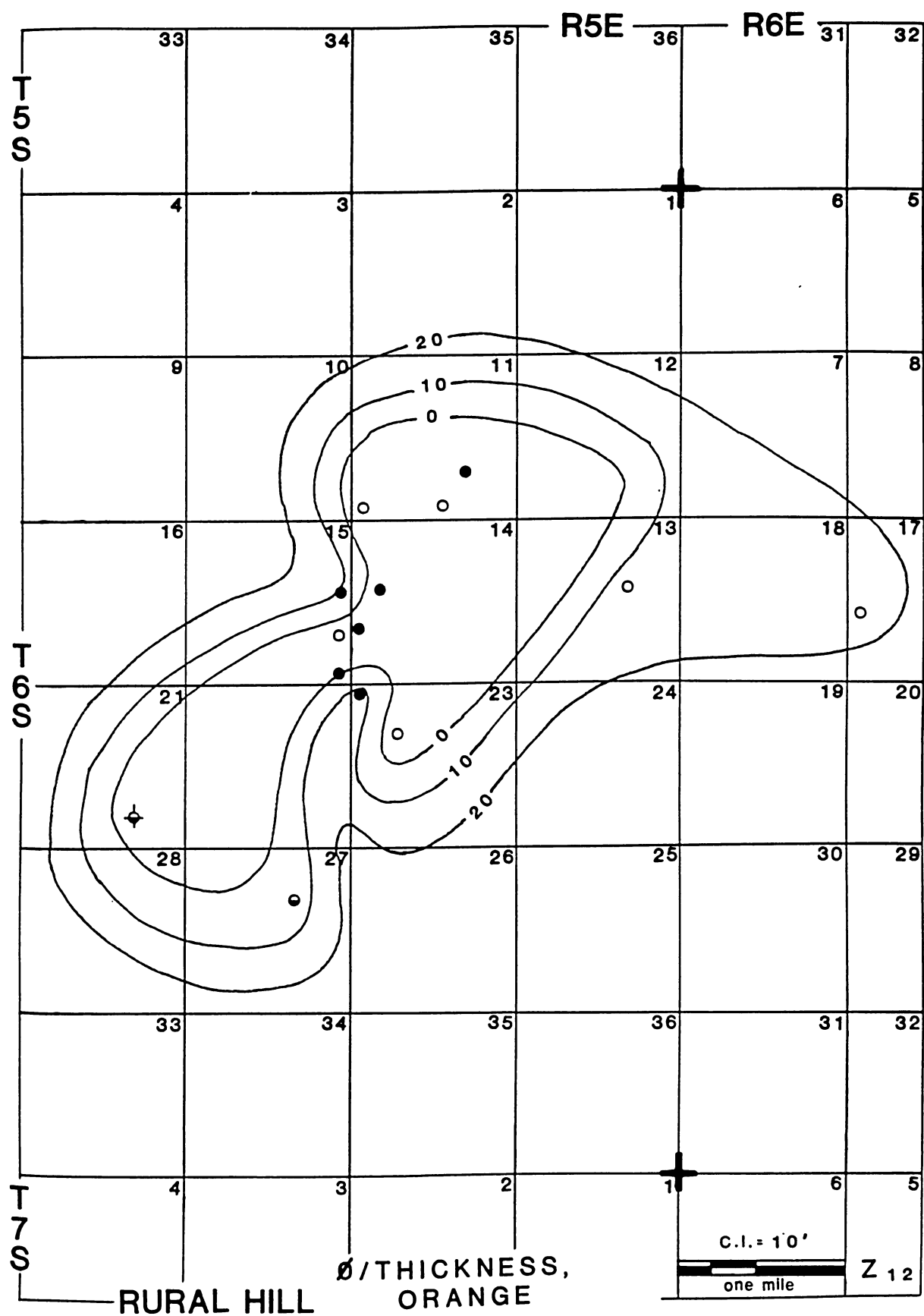


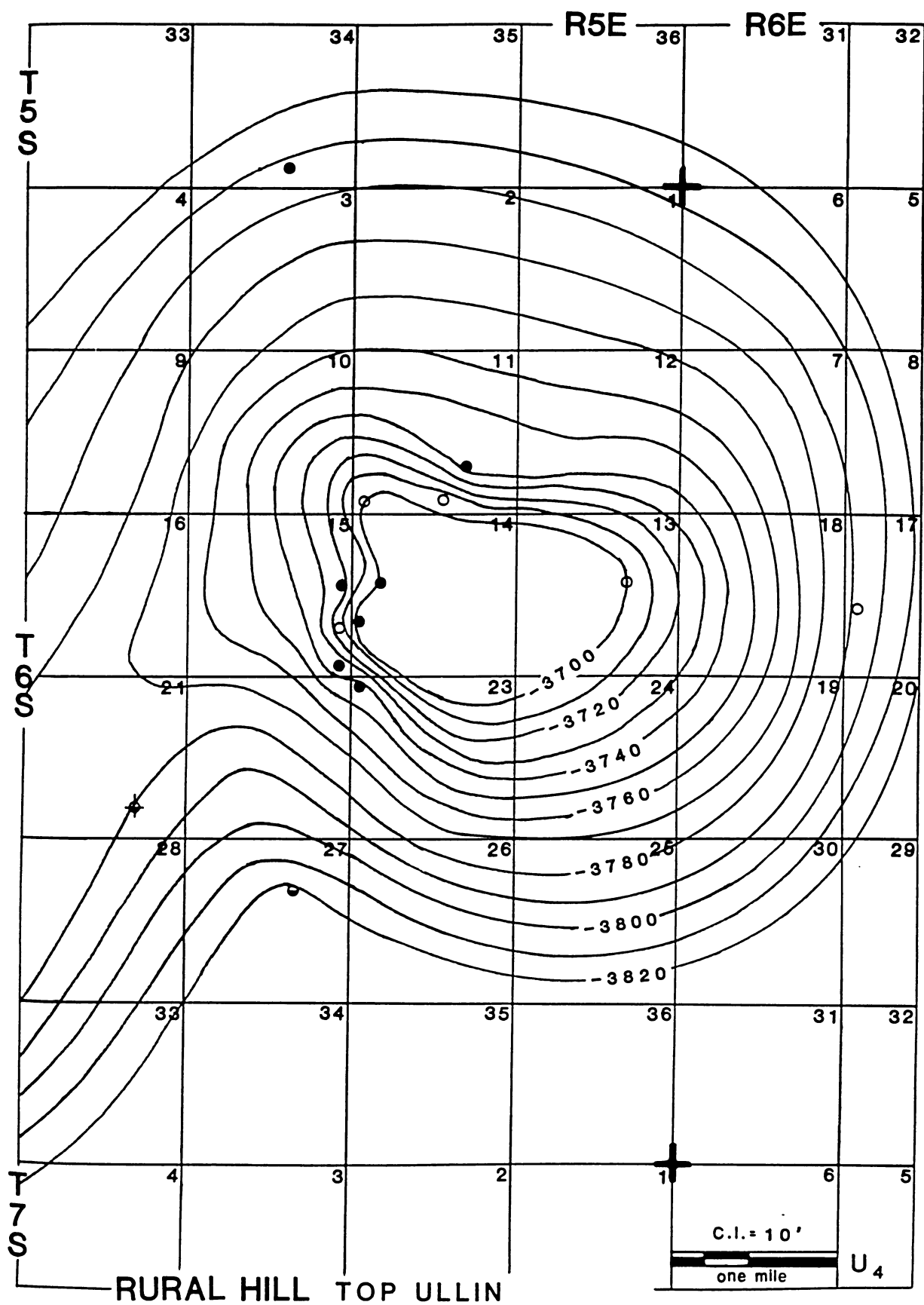


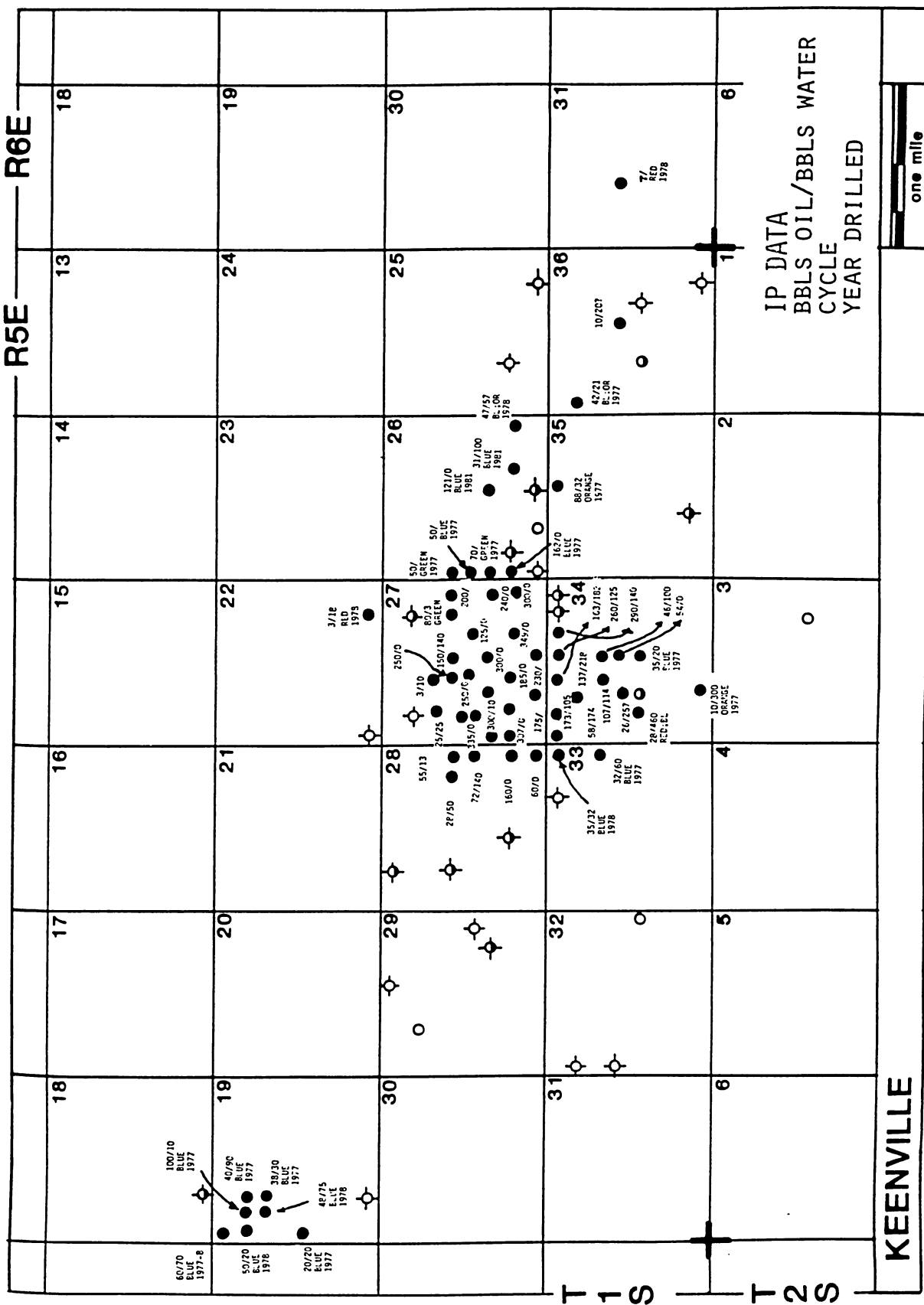


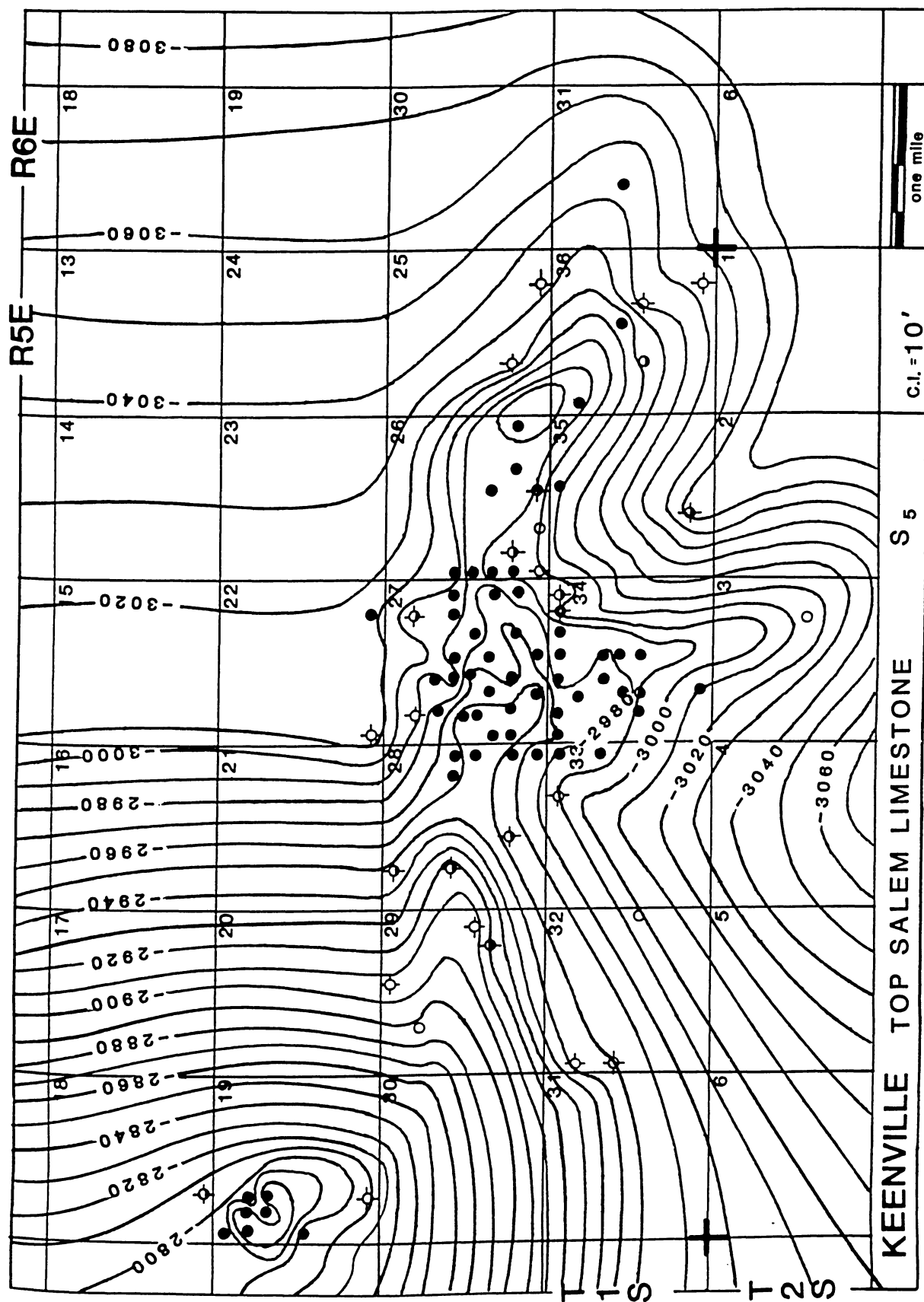


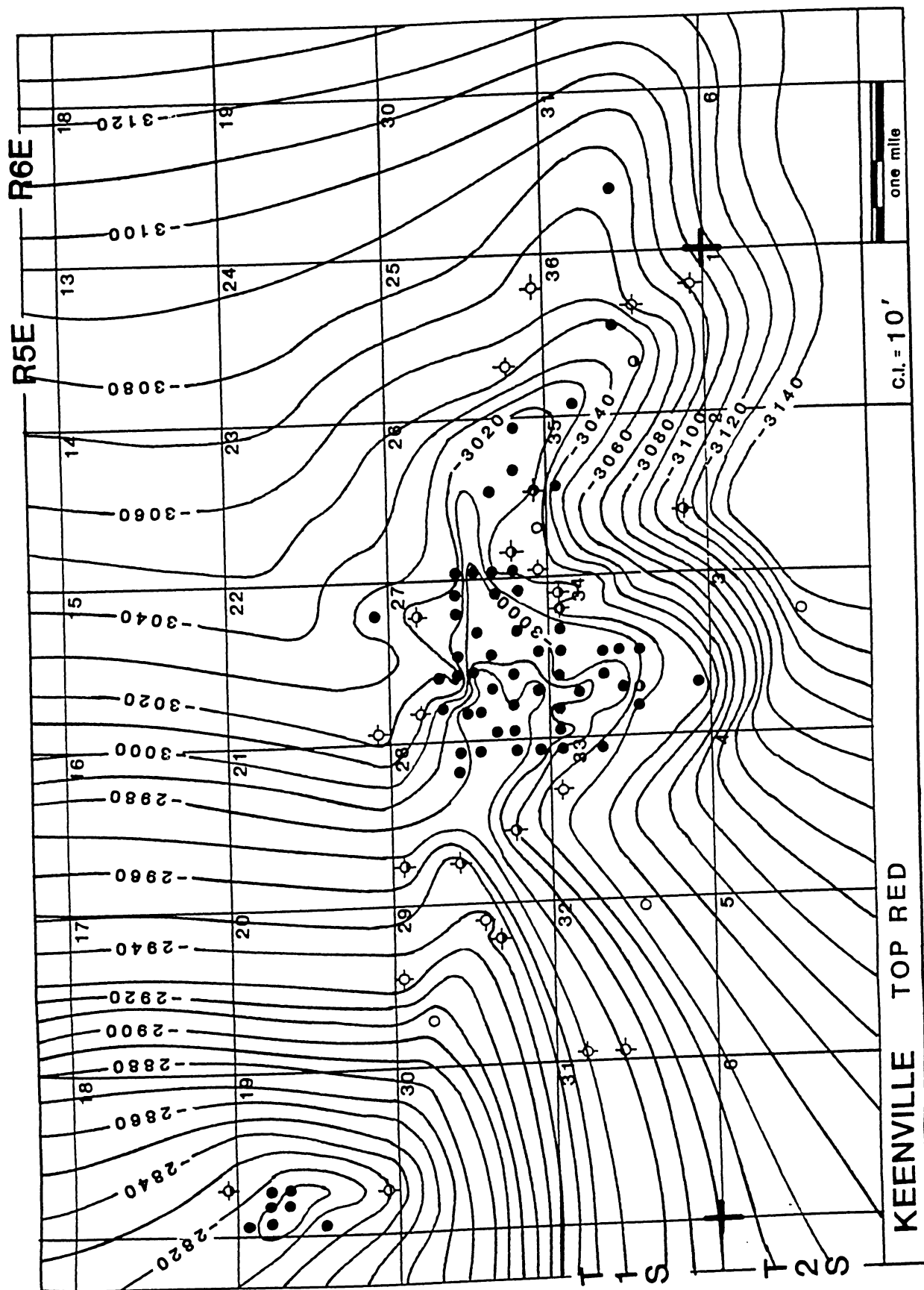


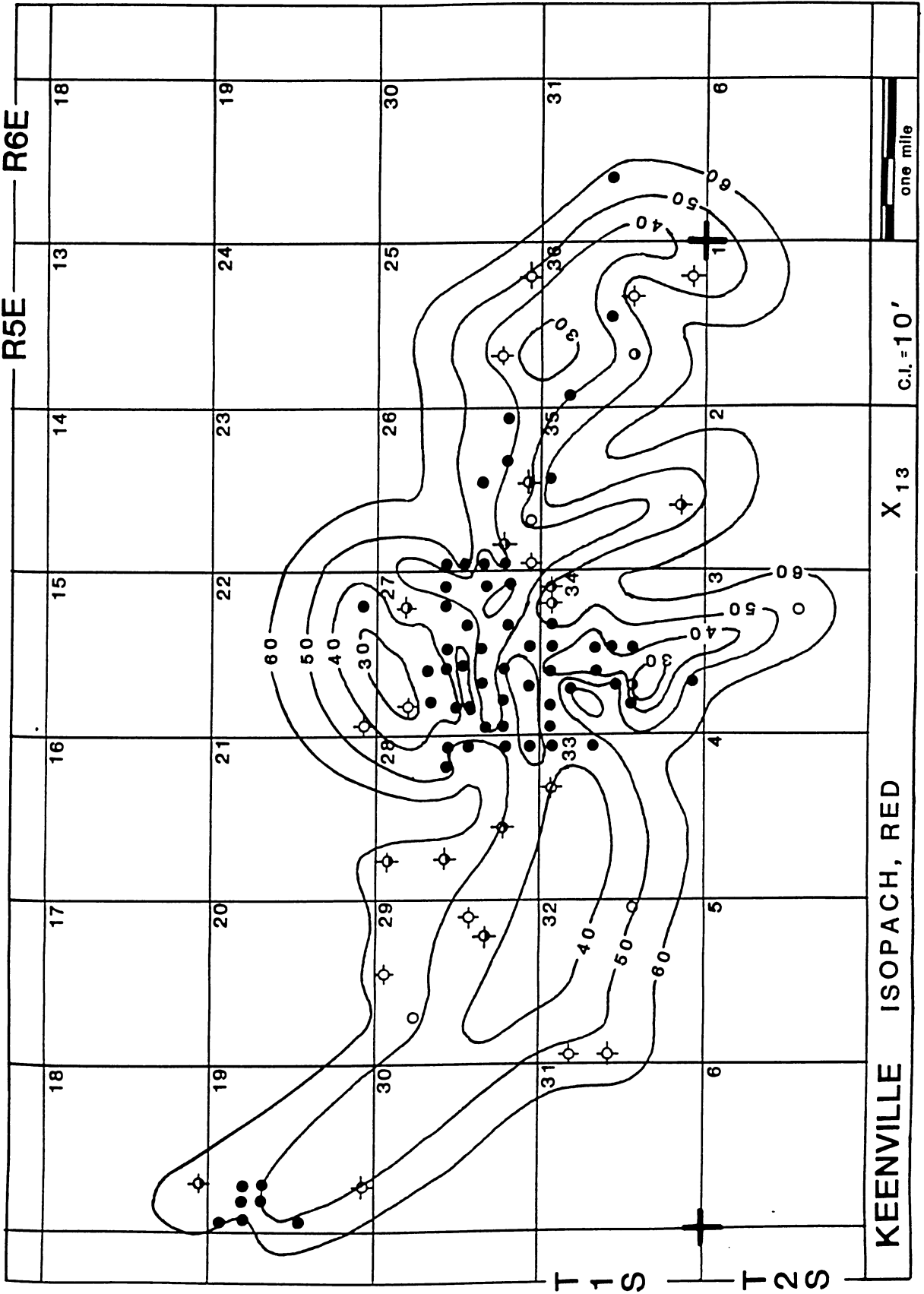


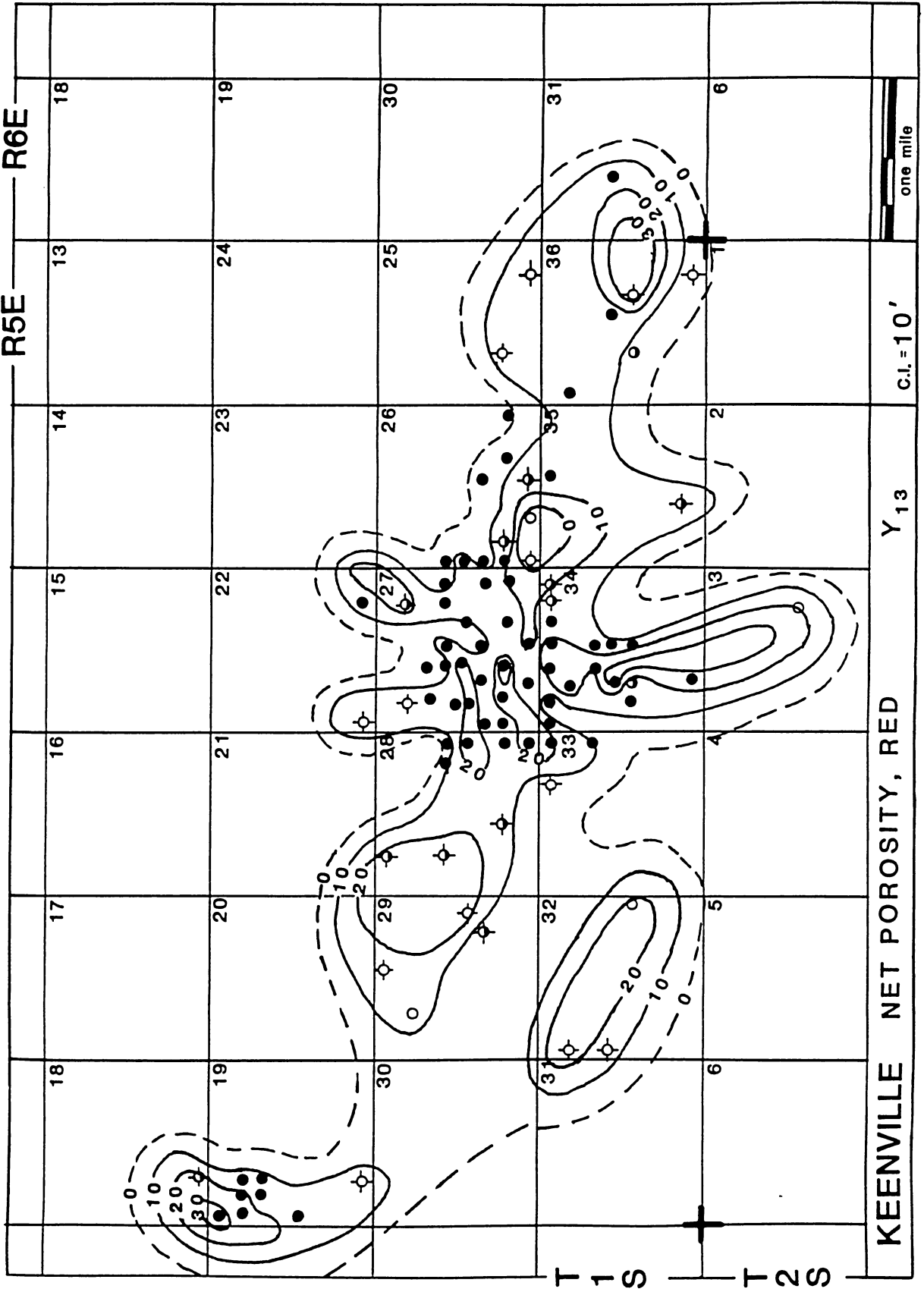


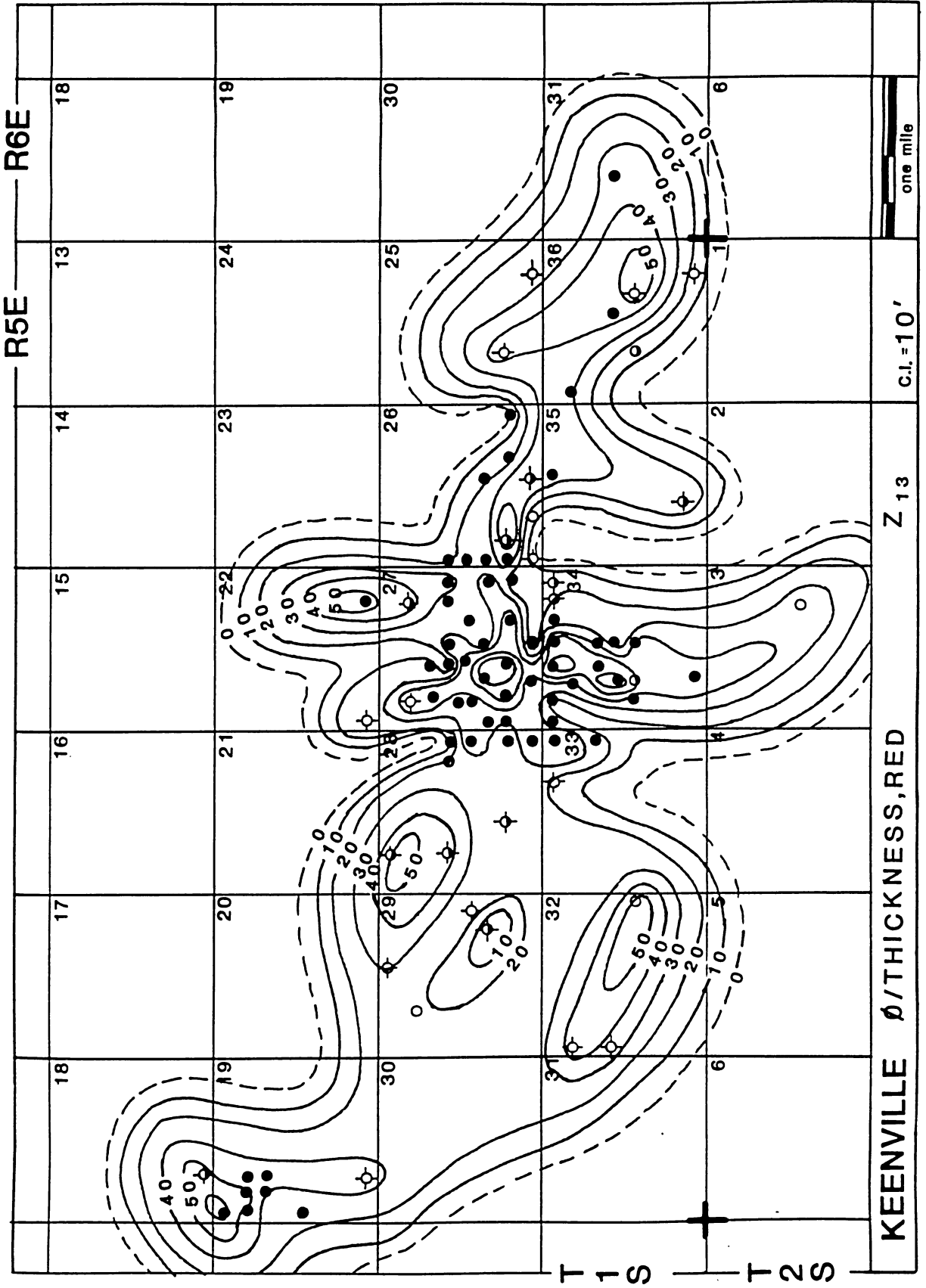


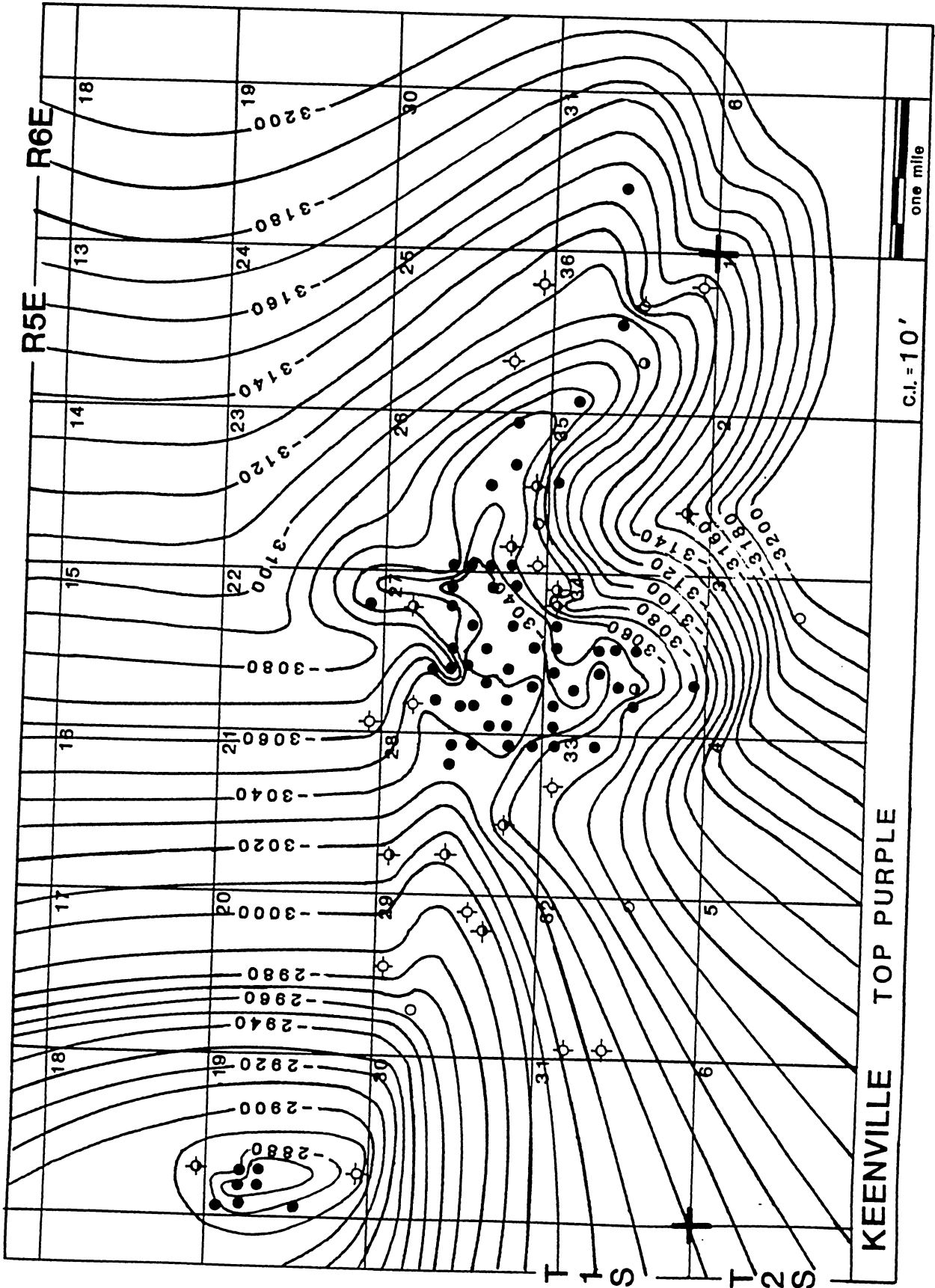


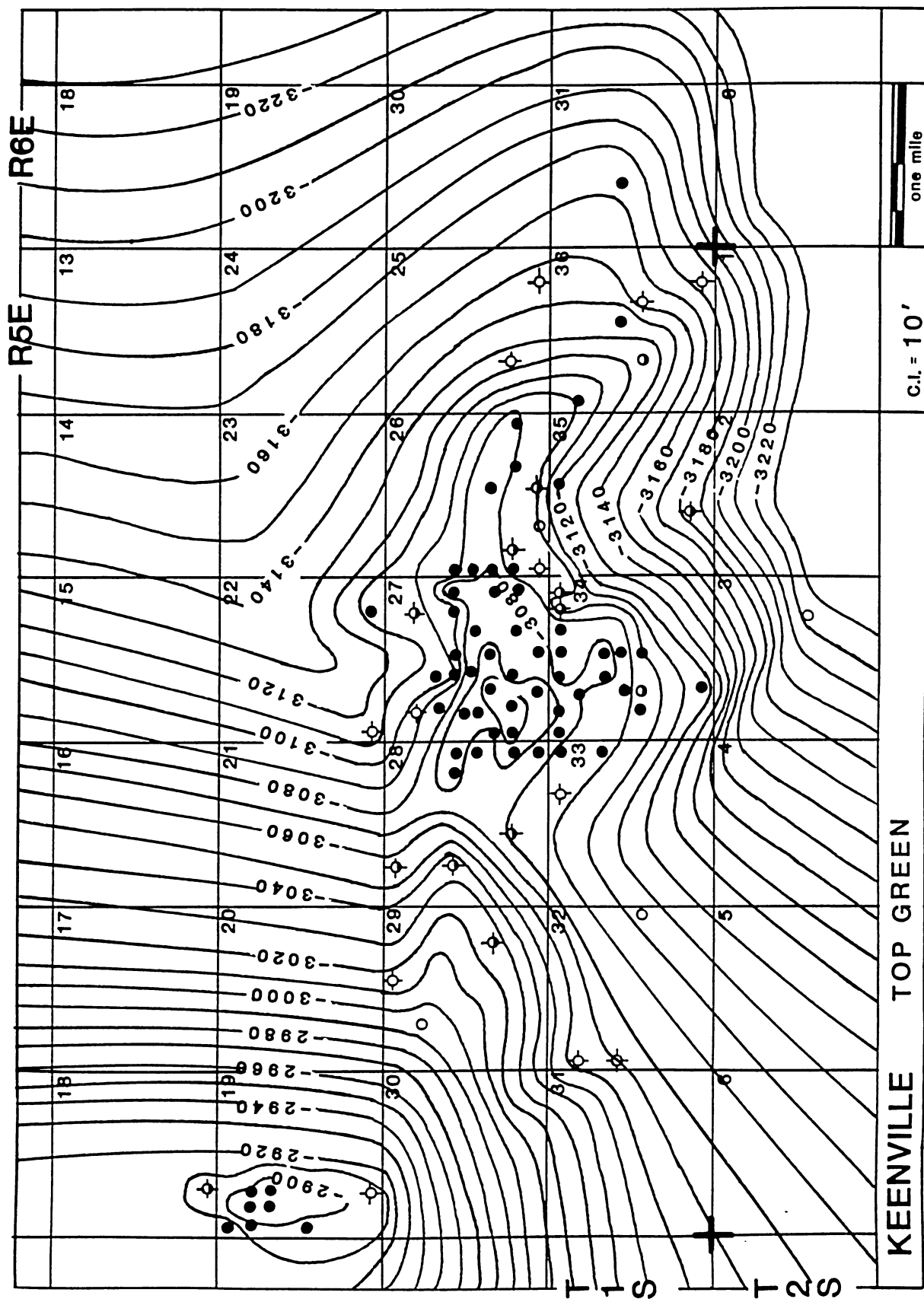


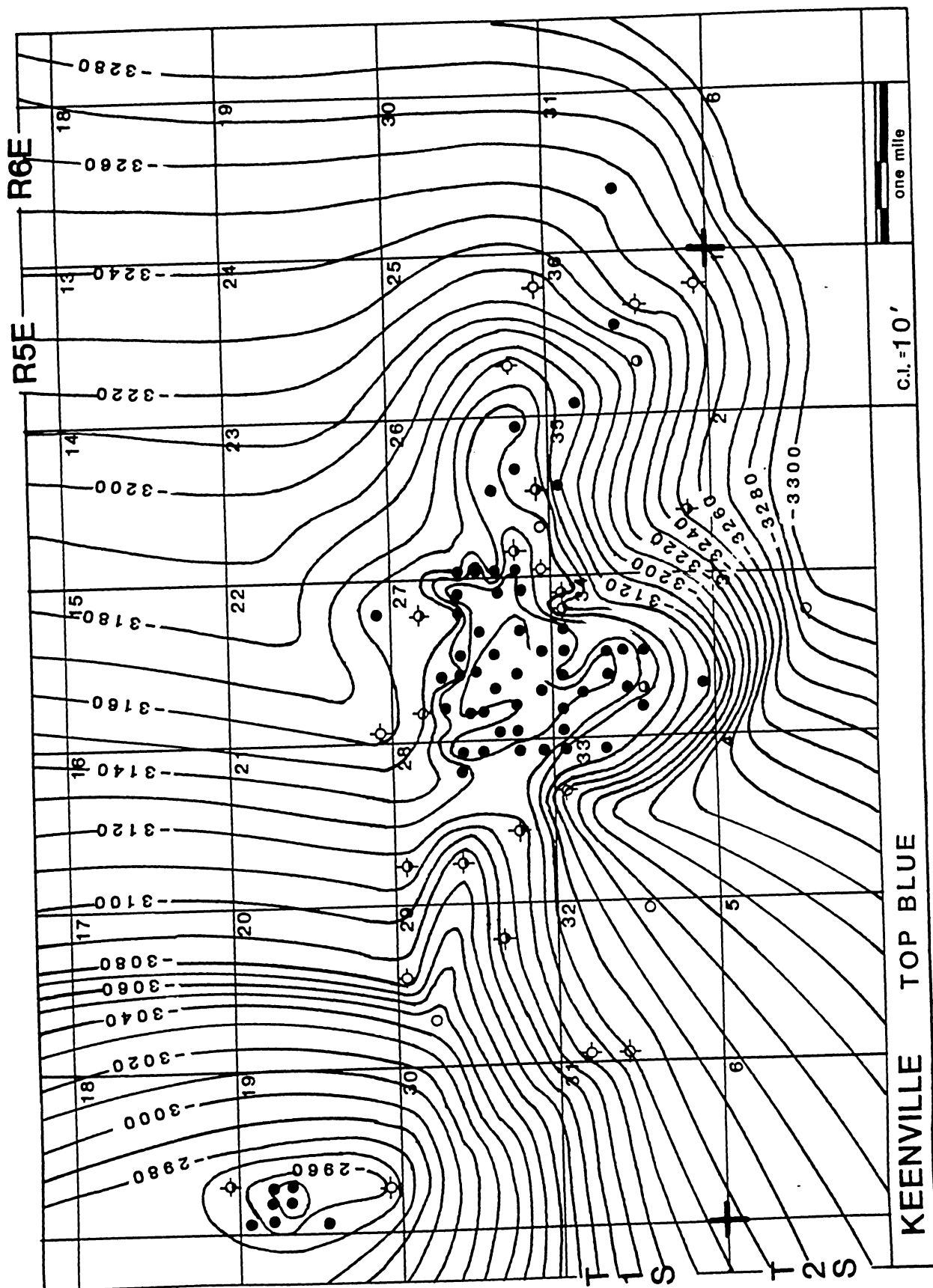


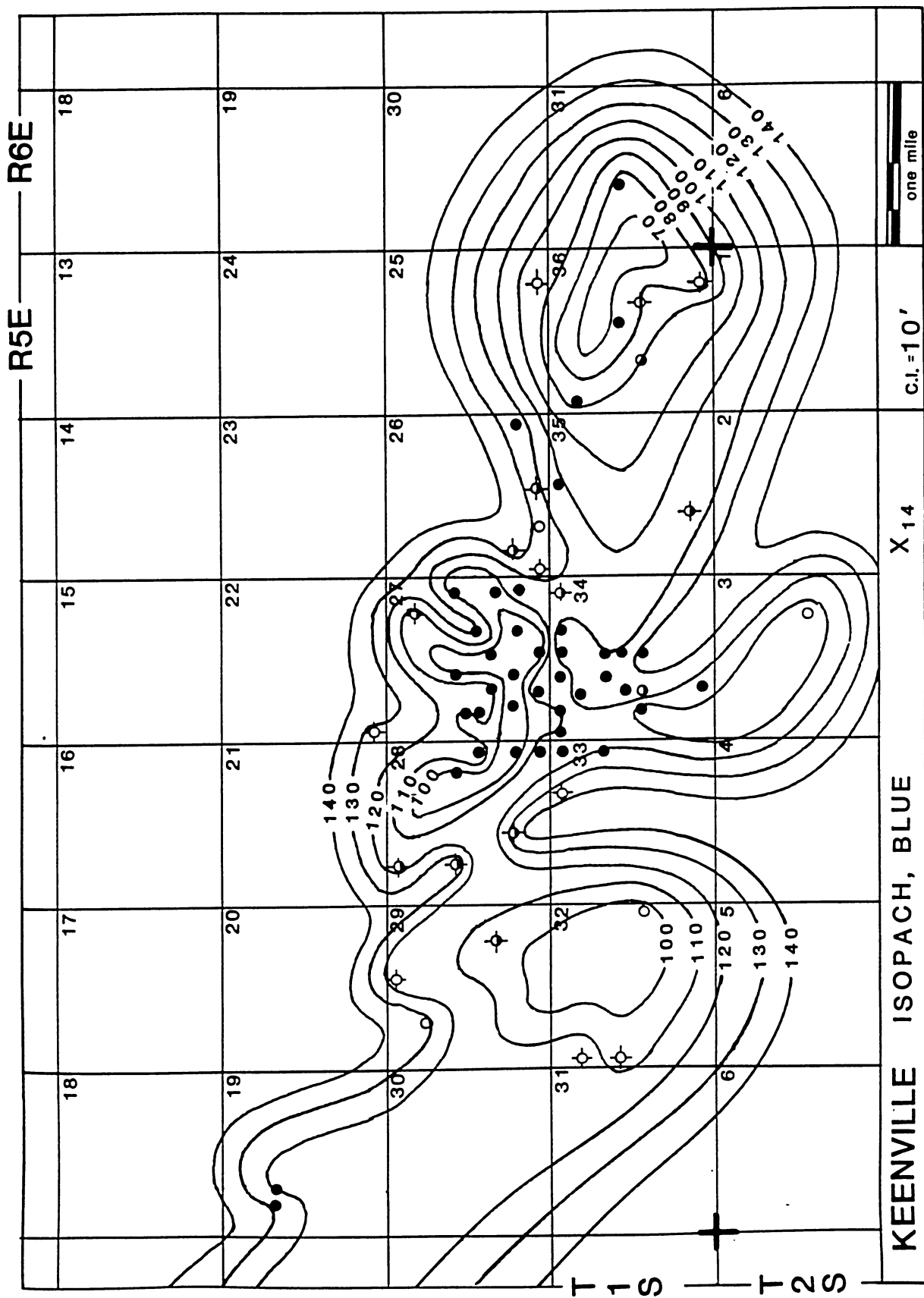


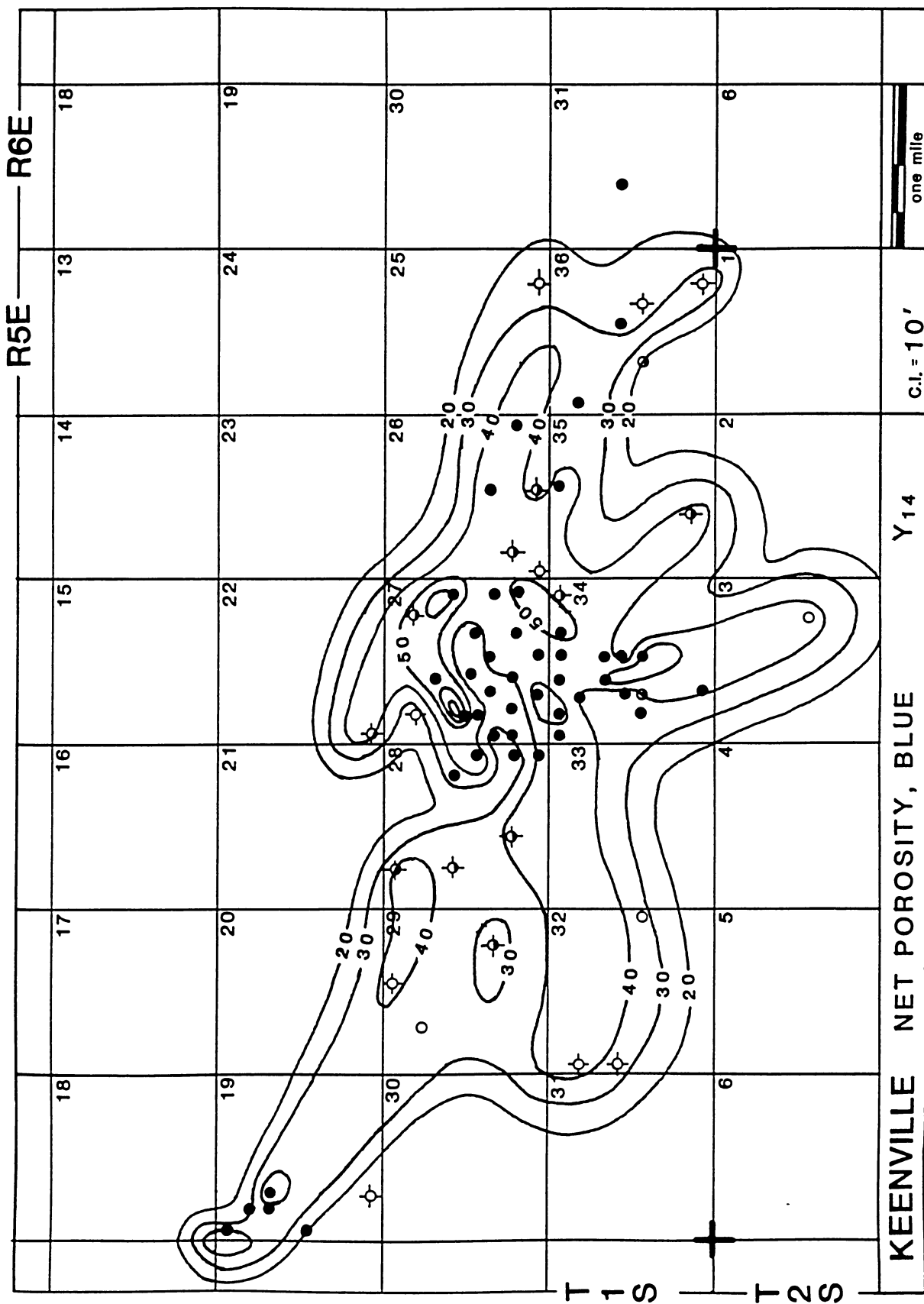


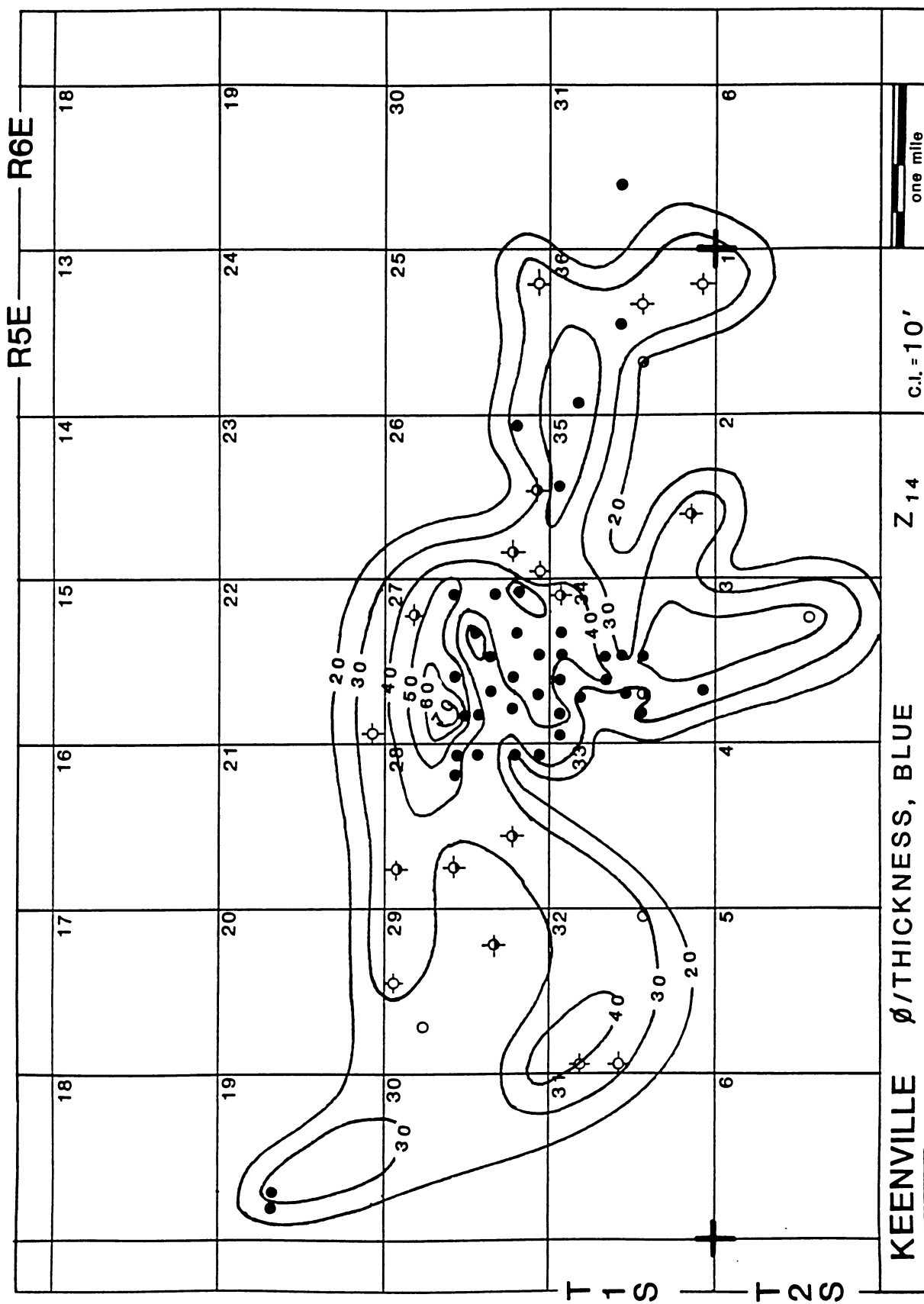


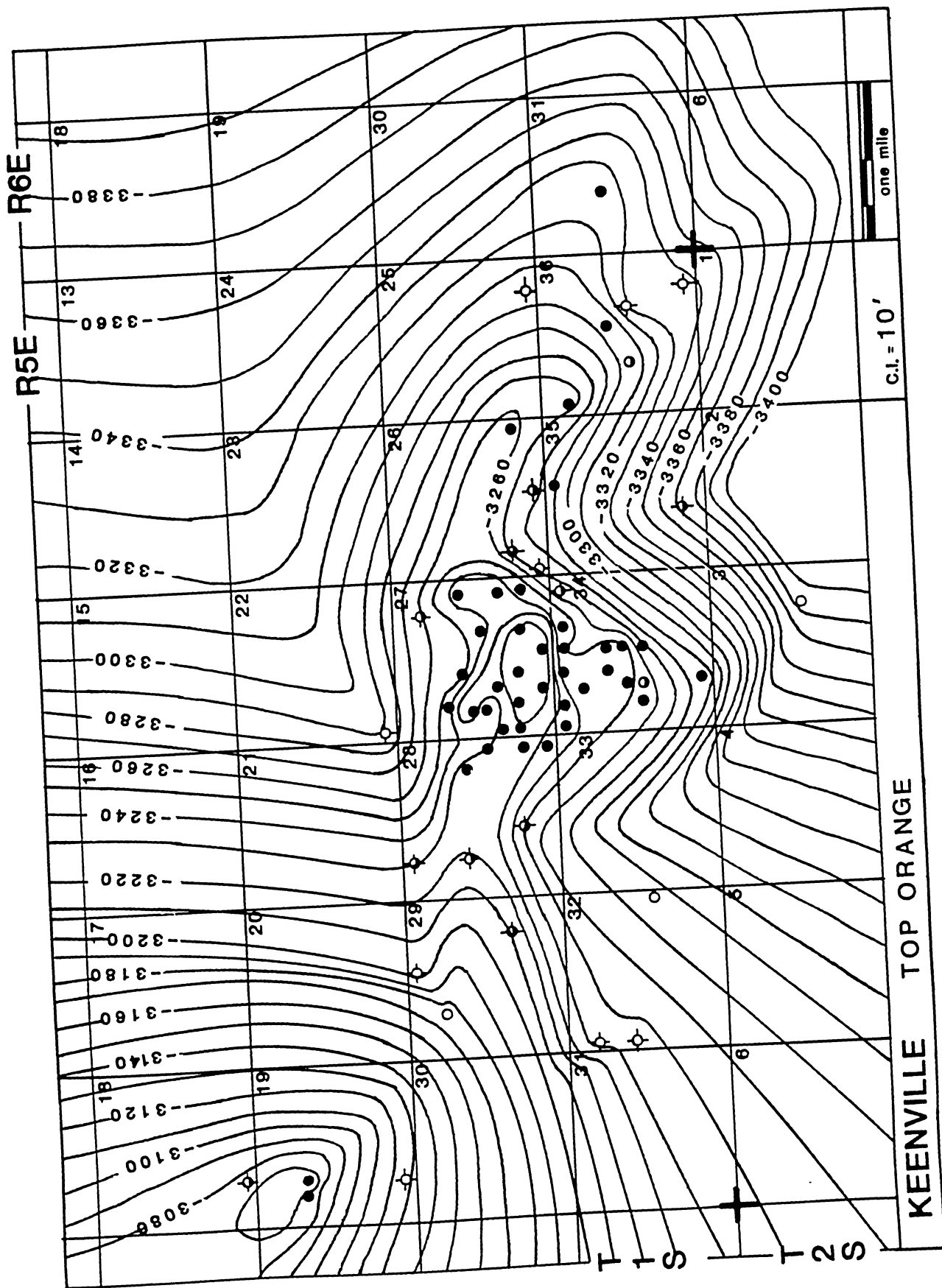


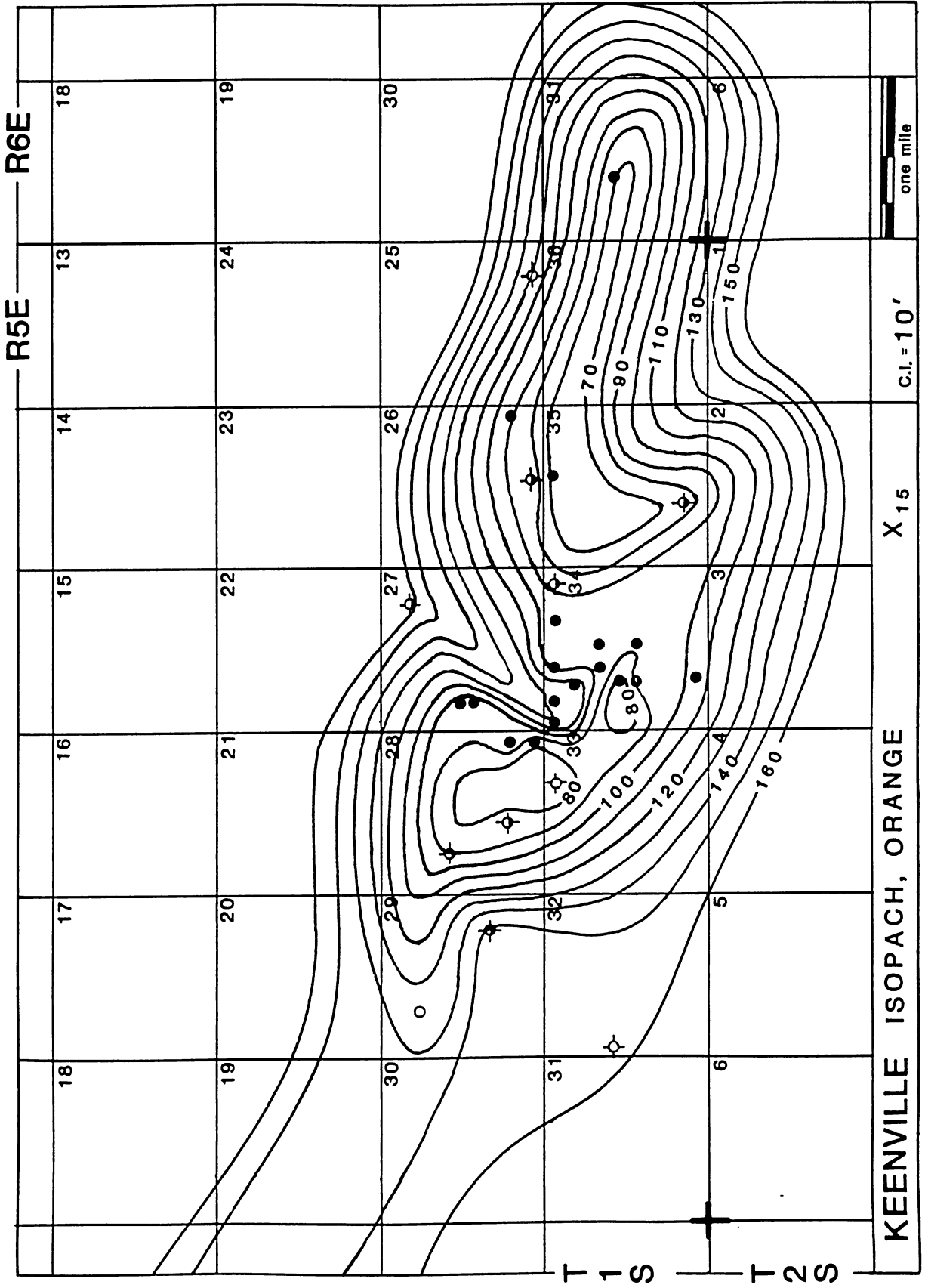


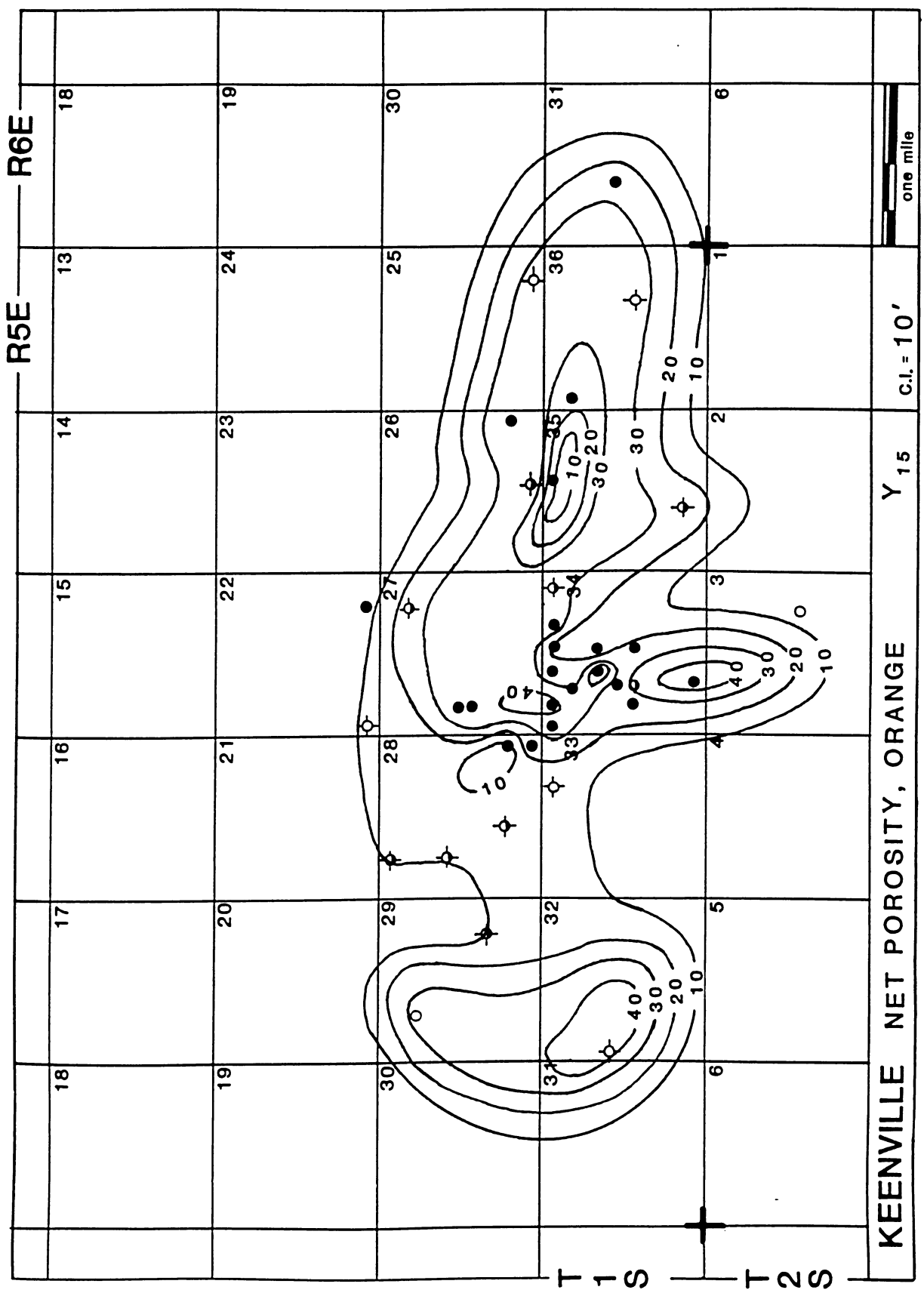


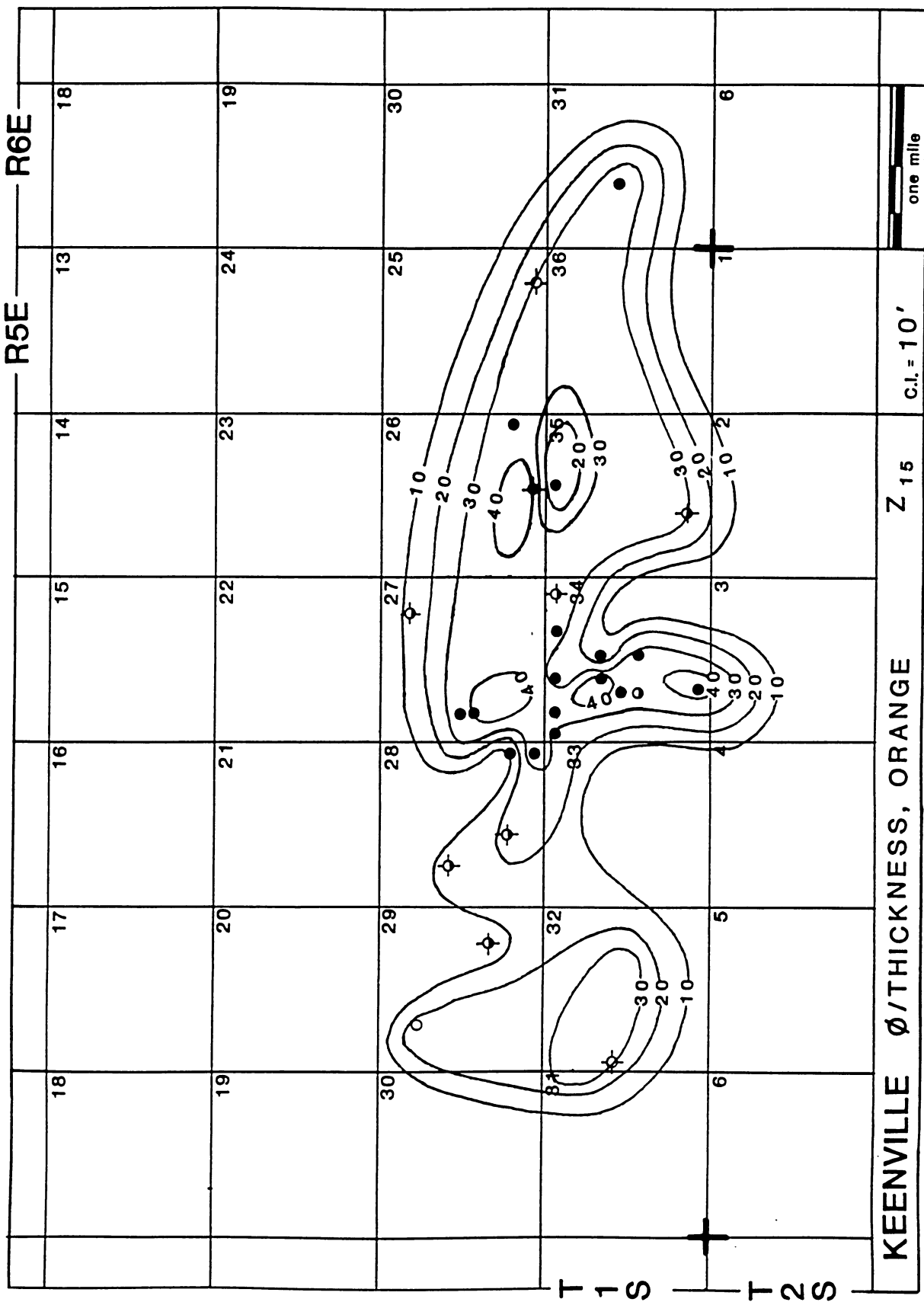


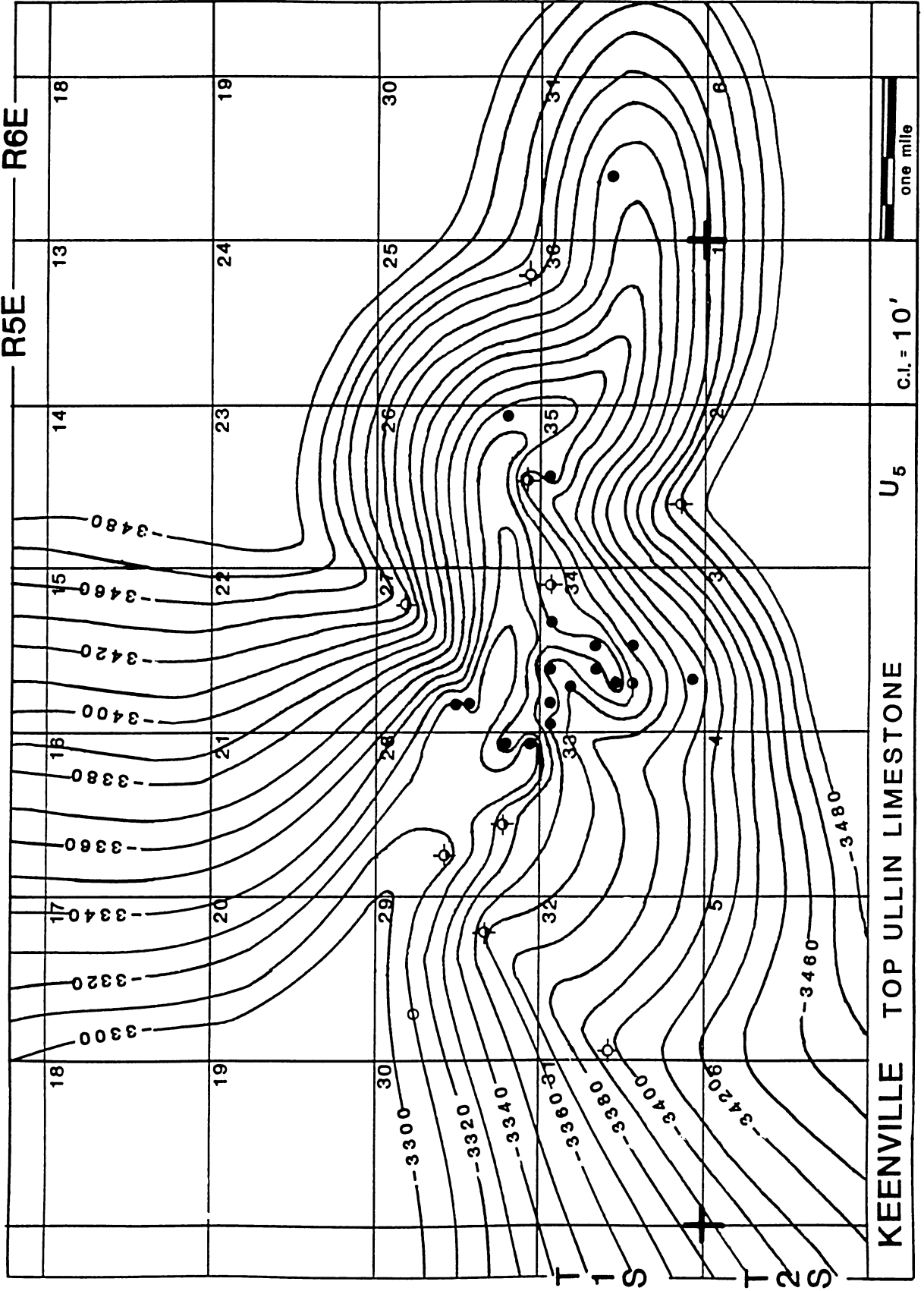












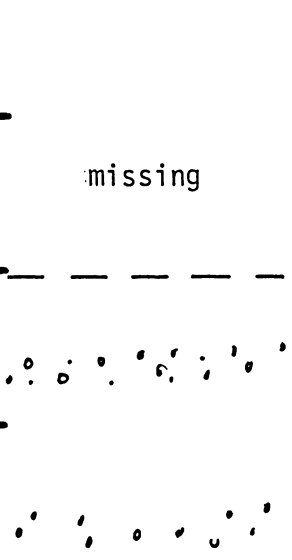
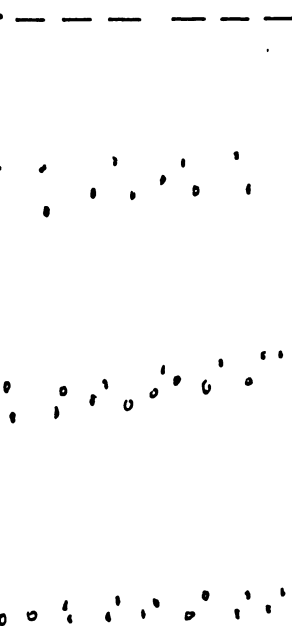
Core descriptions of:

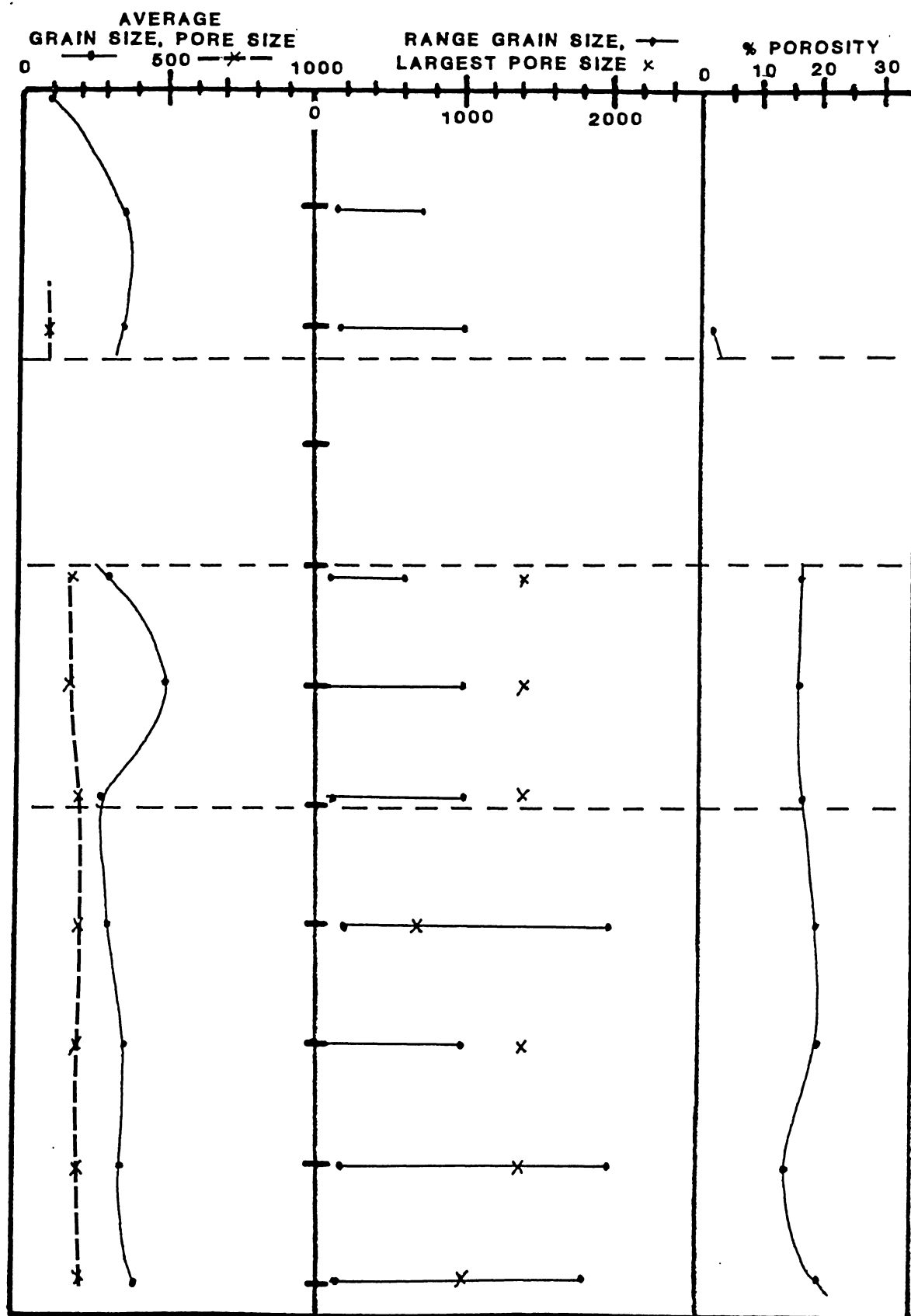
- | | |
|---|--------------|
| 1) Fletcher F. Farrar
Roy Reed #4 T1S R5E Sec. 27
Wayne County, Illinois | 3600 - 3656' |
| 2) Moore Engineering and Production Company
Gray Estate #8 T3S R8E Sec. 30
White County, Illinois | 3805 - 3828' |

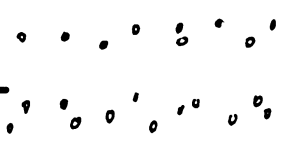
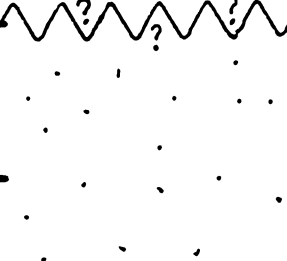
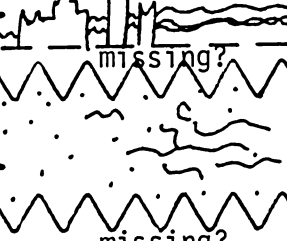
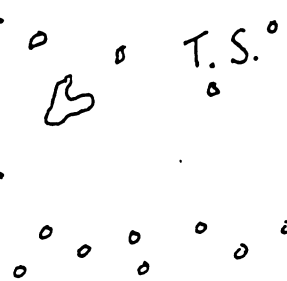
Packing: low=floating grains or point contacts
 medium=planar contacts between grains
 high=sutured, embayed, or broken grains

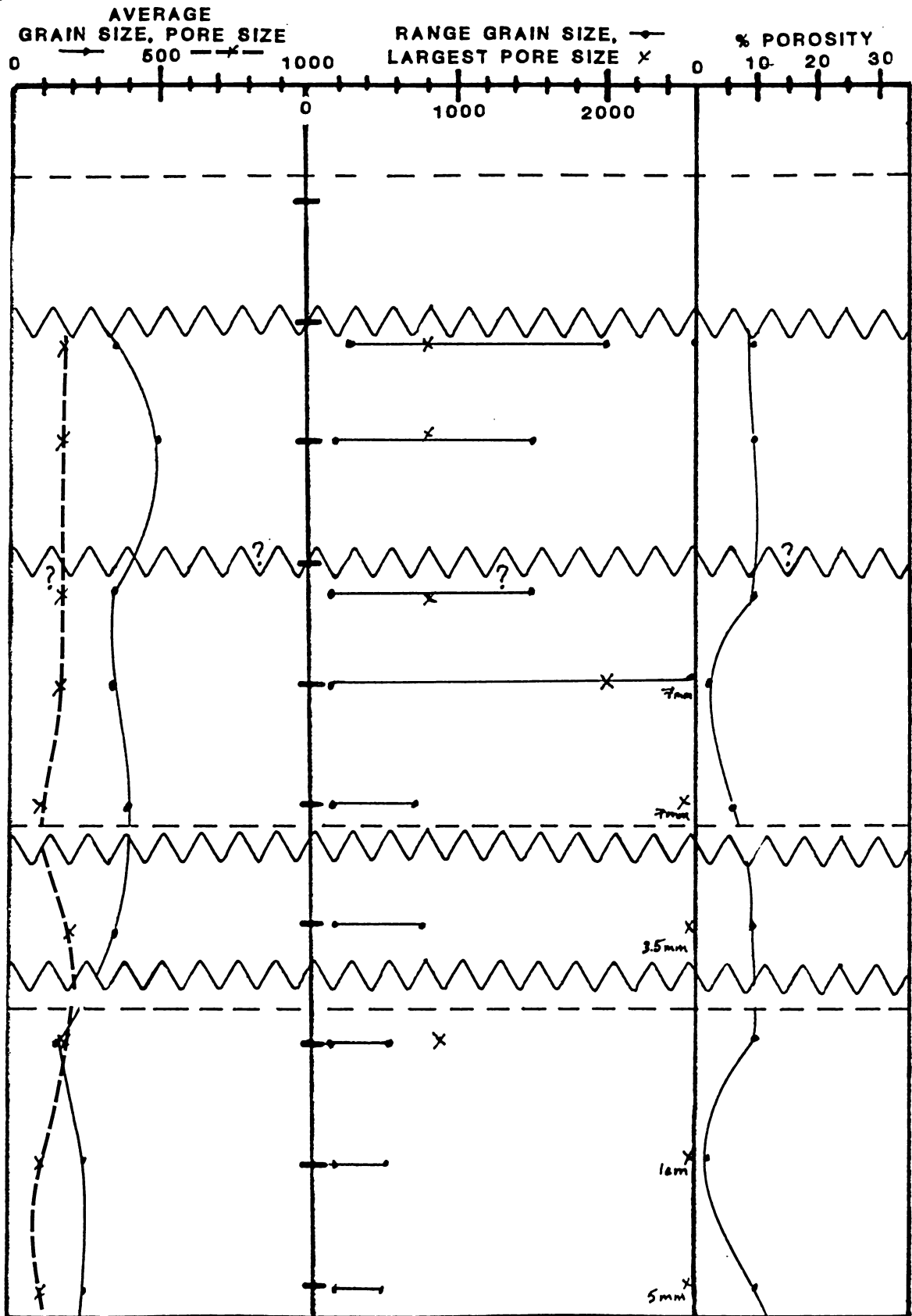
Average and range grain size and pore size scales in microns.

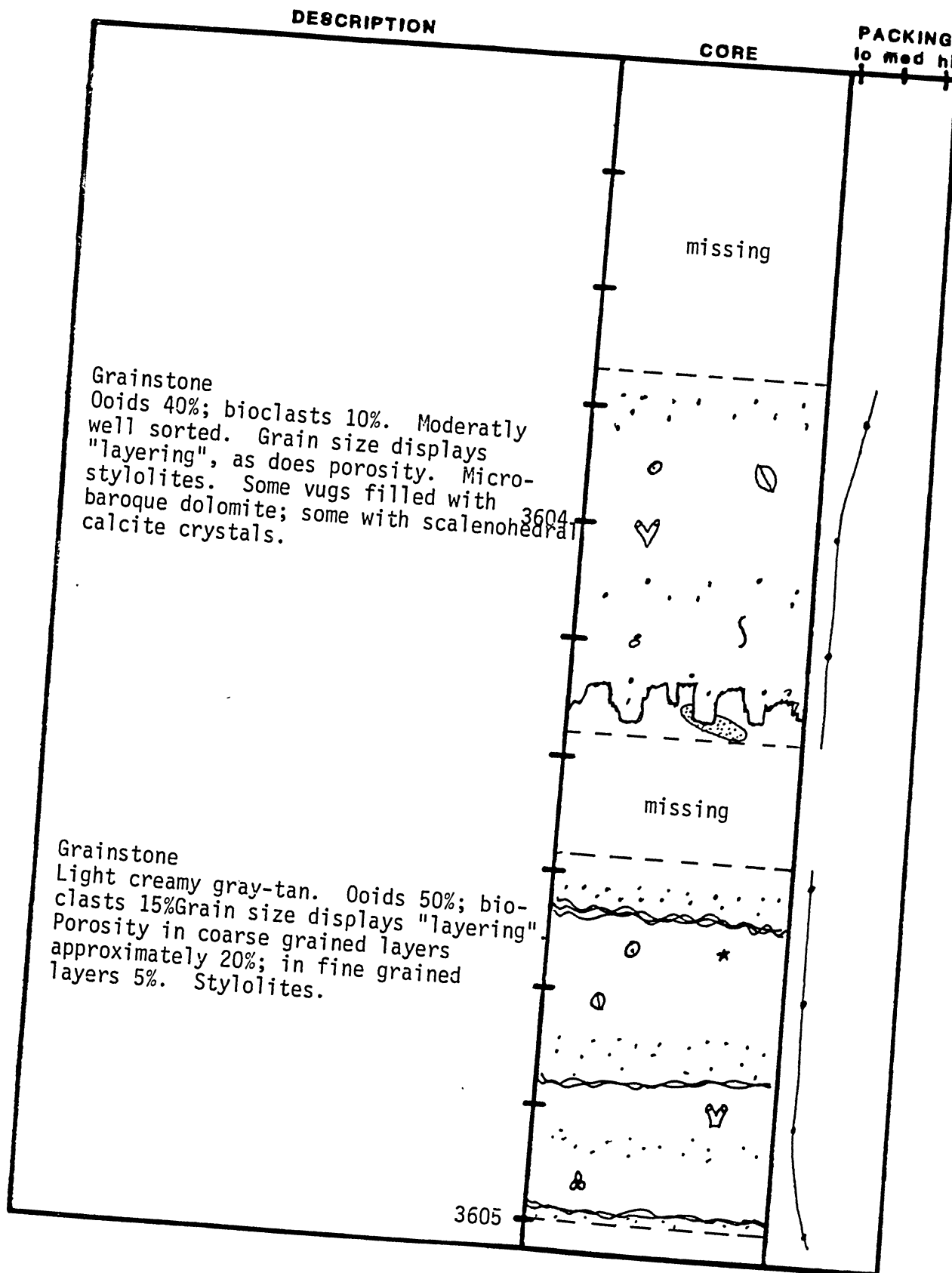
	top/bottom piece of core depth known		ooids
	top/bottom piece of core depth unknown		echinoderms
	location of thin section		<u>Endothyra</u> sp.
	pores		mollusks
	sparry calcite		fenestrate bryozoa
	stylolite		brachiopods
	burrows		bivalves
	grapestone		branching bryozoa
	anhydrite		rugose corals

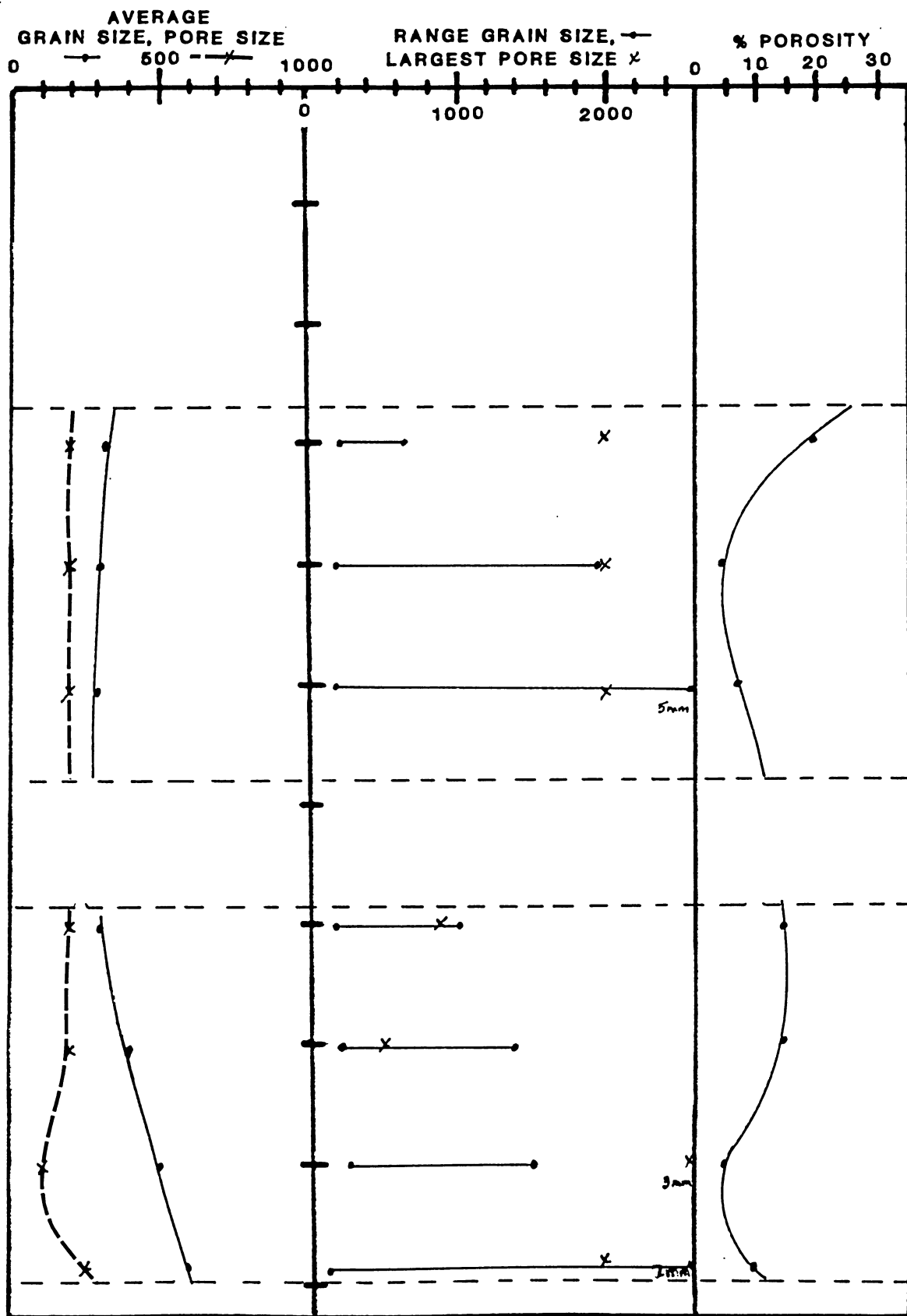
FARRAR DESCRIPTION	CORE	PACKING to med hi
Grainstone-Packstone Light creamy gray-tan. Ooids-50%; bioclasts 20%; other, 30%. Well sorted. Whole brachiopod filled with geopetal silt and calcite spar. Spar filled fracture at top; cream colored silt found below this fracture. Primary porosity is calcite cement reduced.	3600 	
Grainstone Light gray. Ooids 50-60%; bioclasts 10%. Grain size appears "sorted" into "layers". More porosity in layers with larger grain size. Some pore filling sparry calcite, but not much cement in general.	missing 	
Grainstone. Ooids 30%; bioclasts 20%. Light creamy gray-tan. Well sorted ooids. Existing pores lined with druse and scalenohedral calcite. Occluded pores filled with sparry calcite.	3601 	



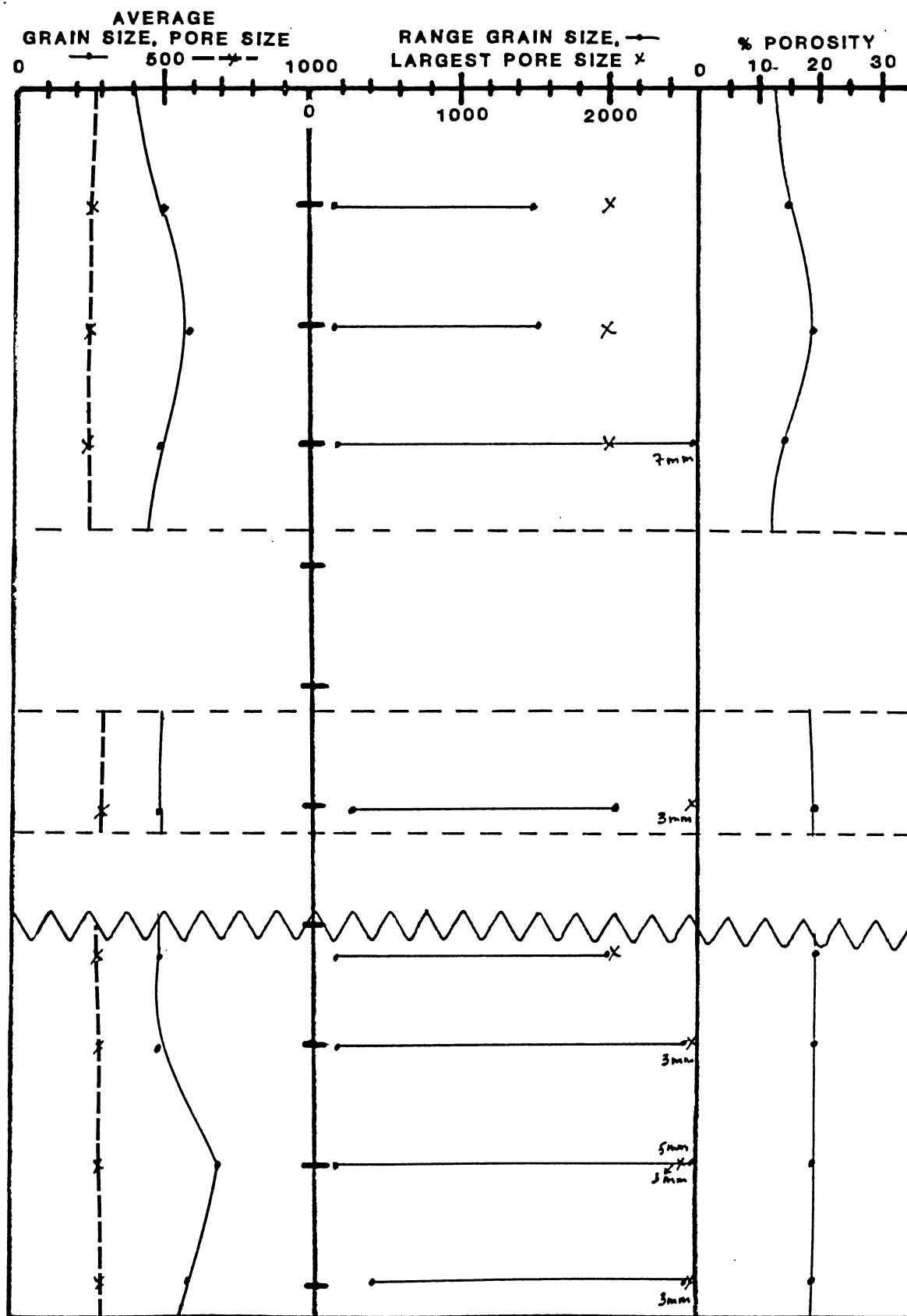
DESCRIPTION	CORE	PACKING lo med hi
Grainstone. Light creamy gray-tan. Ooids 40-50%; bioclasts 20-30%. Grains size-sorted into "layers". Some broken grains. Some lime mud? Primary porosity reduced by sparry calcite.	missing? 3602 	
Grainstone. Light creamy gray-tan. Ooids 40-50%; bioclasts 20-30%. Grains size-sorted into "layers". Some broken grains. Some lime mud? Primary porosity reduced by sparry calcite.		
Grainstone Ooids 40%; bioclasts 5%. Grain size larger at top of piece, smaller towards bottom. Also better cemented towards bottom. Pore size increases downwards, however. Vugs at bottom have large scalenohedral calcite crystals.	 T.S.	
Grainstone Ooids 30%; bioclasts 20%. Porosity concentrated into "layers". Anhydrite in vugs. Small stylolites.	 missing?	
Grainstone Ooids 50%; bioclasts 1%. Very well sorted, and cemented with sparry calcite. Vugs up to 1/2 inch, lined with scaleno- hedral calcite crystals. Some vugs fil- led with baroque dolomite.	3603  T.S.	

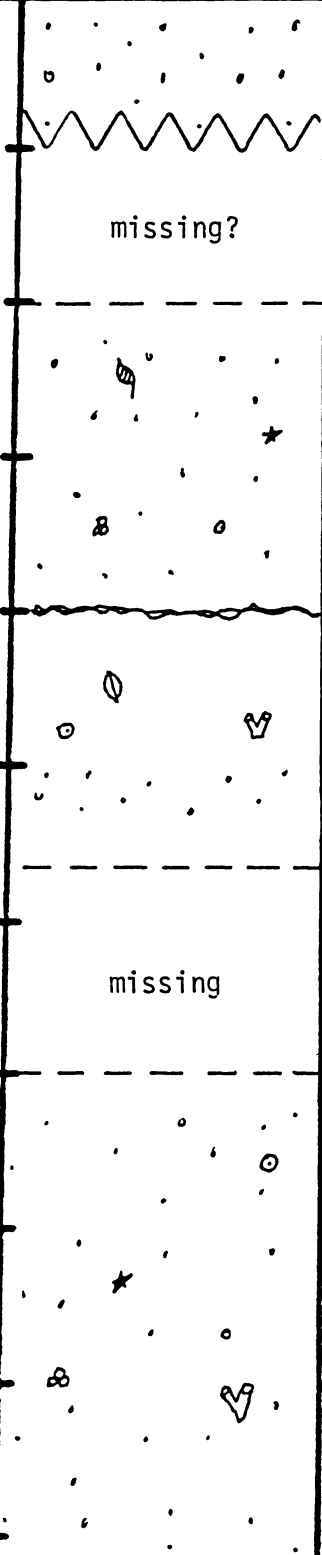


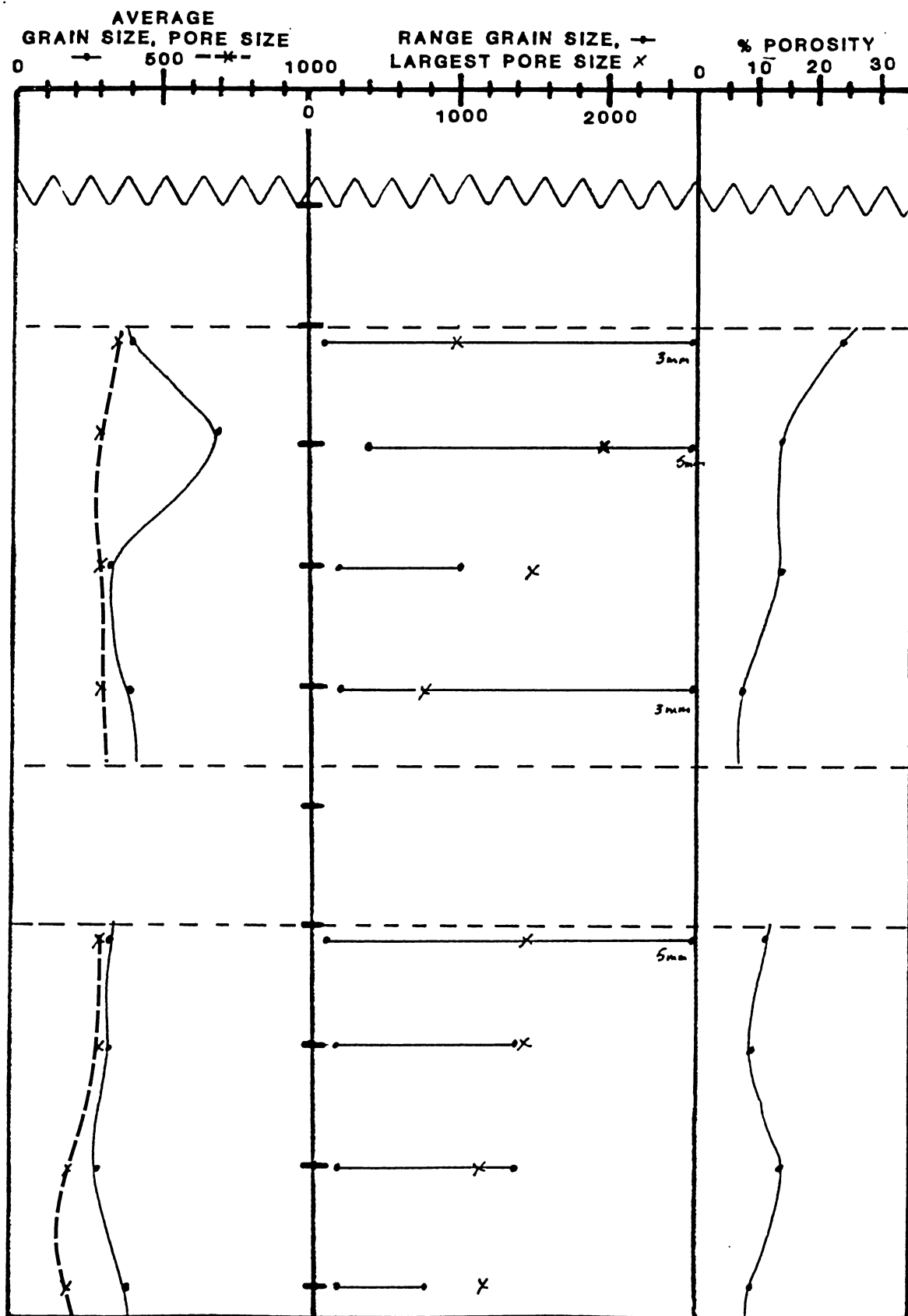


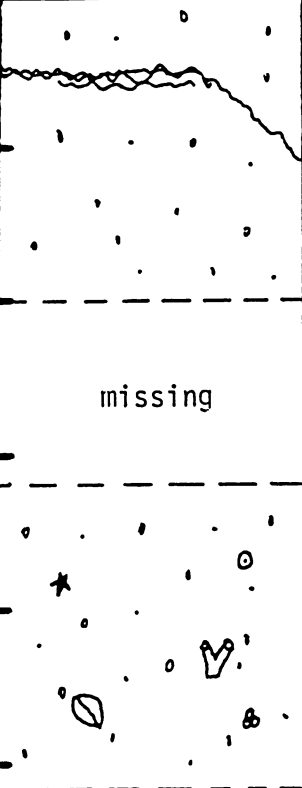


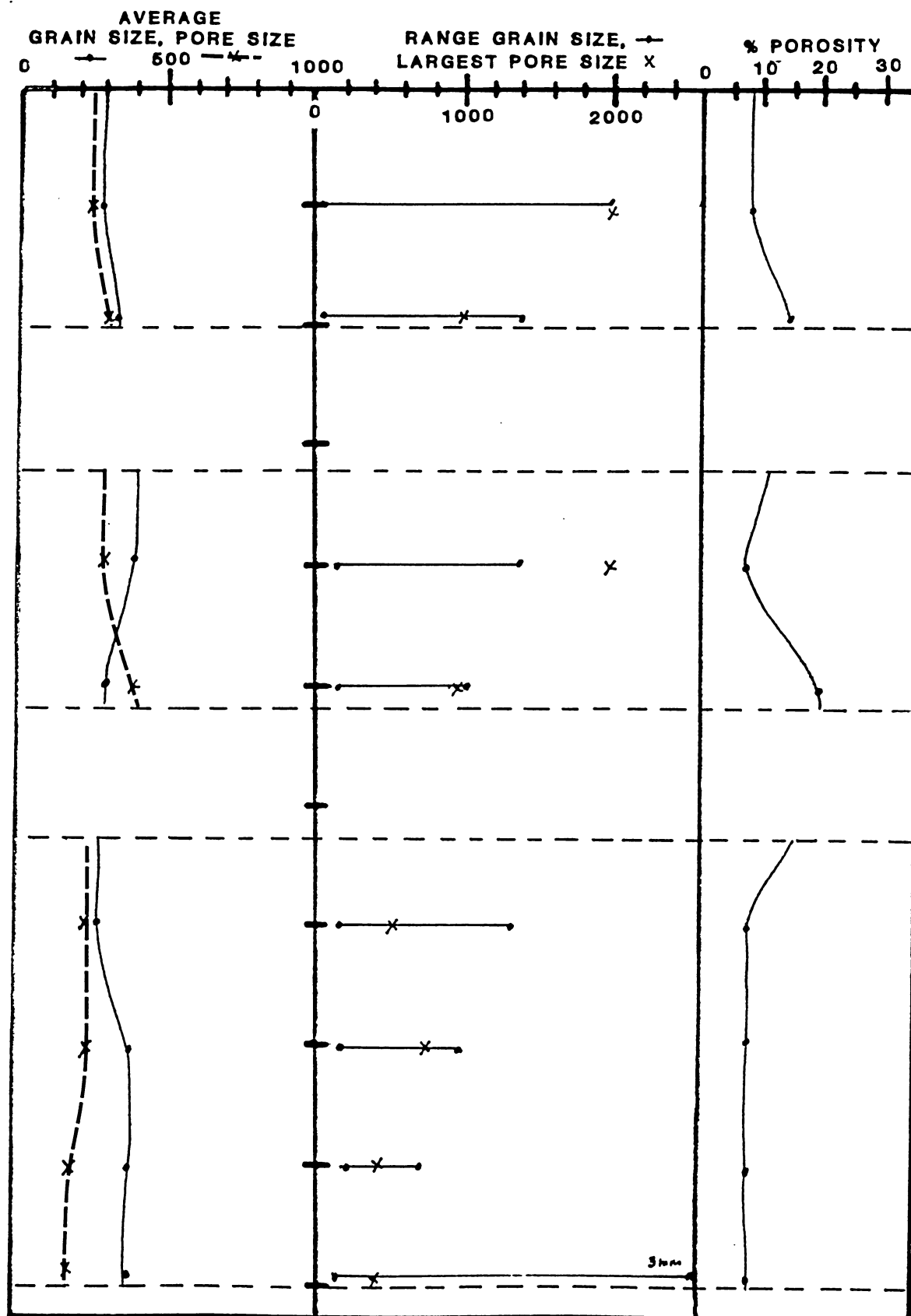
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 40%; bioclasts 15%. Well sorted, in "layers". Larger grain sized layers more porous, with vugs up to 2cm. Some are dissolved mollusk valves. Pores lined with scalenohedral calcite crystals. Small grain size layers tightly cemented with calcite.	3605	
		missing
Grainstone Ooids 25%; bioclasts 20%. Moderately well sorted. Vugs from dissolved mollusk valves.	3606	
		missing?
Grainstone Ooids 30%; bioclasts 15%. Moderately well sorted. Abundant <u>Endothyra</u> and echinoderm fragments. Some vugs are mollusk-shaped. Large vugs at top filled with baroque dolomite		

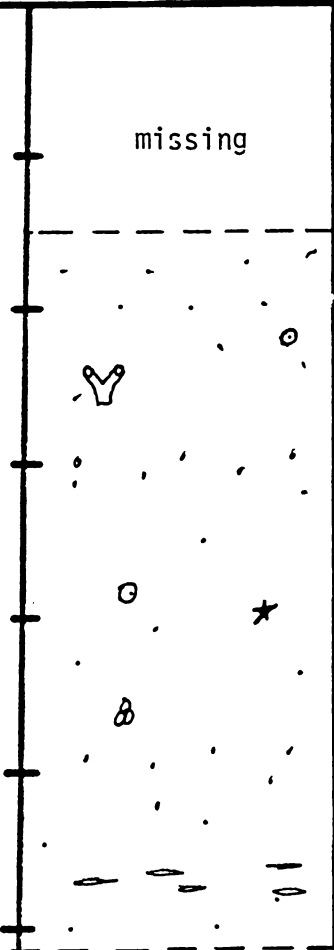
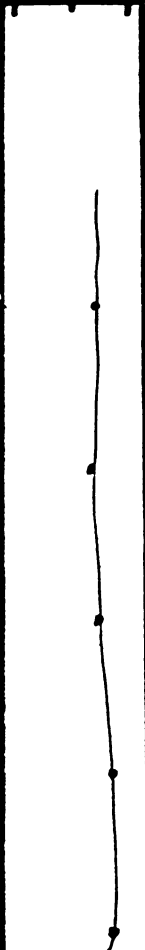
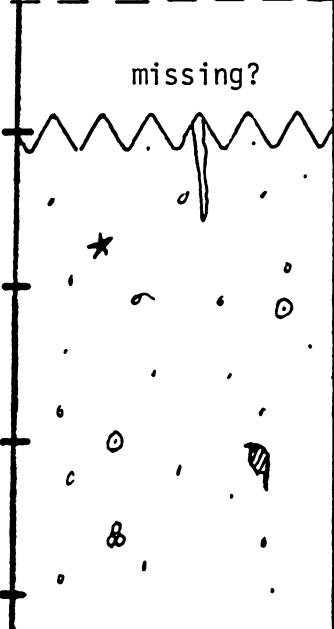
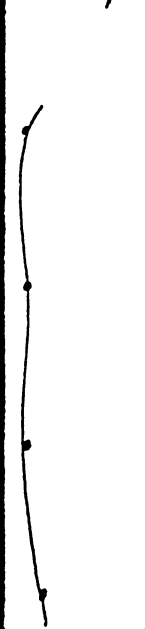


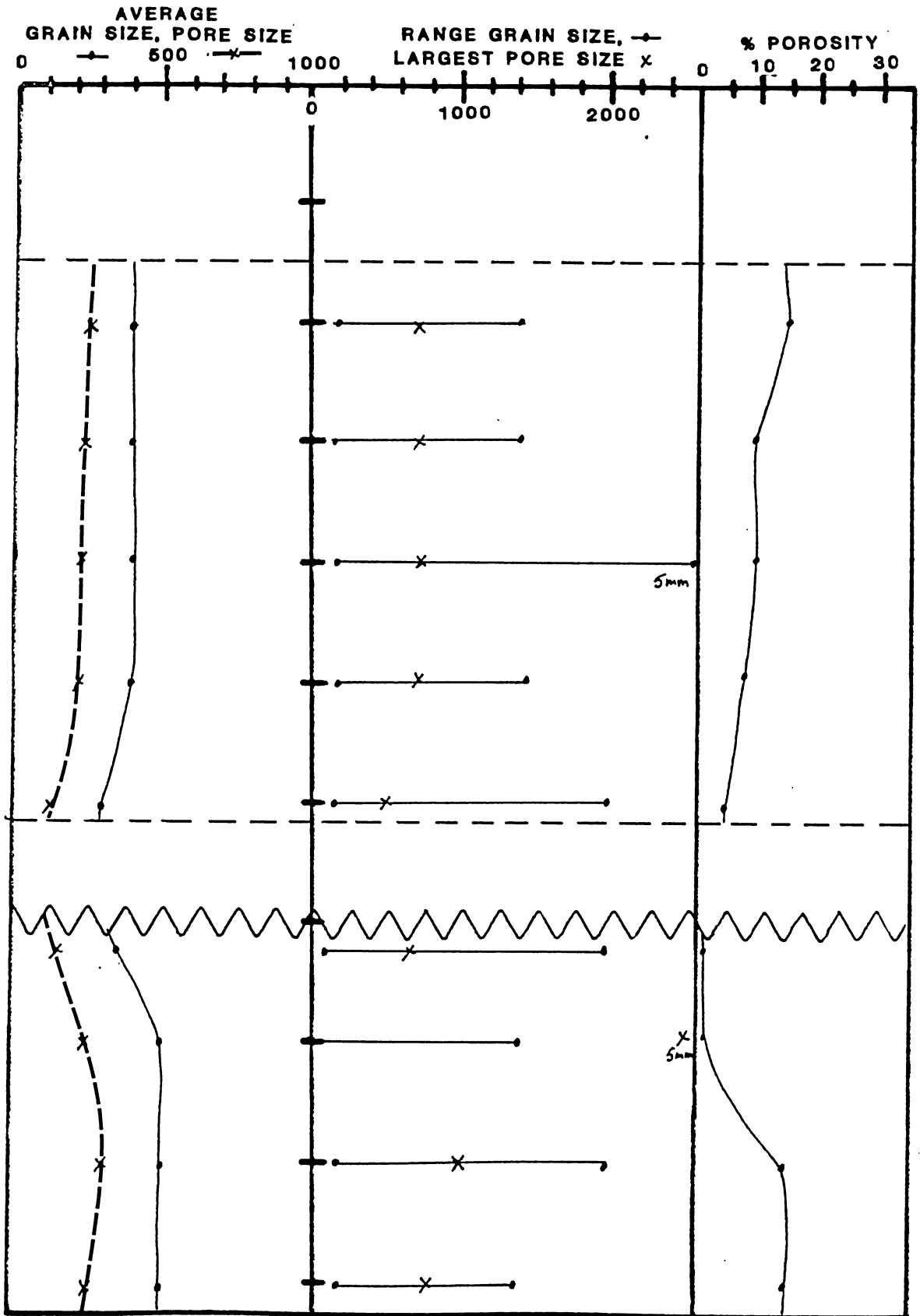
DESCRIPTION	CORE	PACKING to med hi
Grainstone Ooids 30%; bioclasts 15%. Stylolite at 3607'2"; grain size small and well sorted below, and large and well sorted above stylolite. Porosity scattered randomly throughout.	3607 	
Grainstone Ooids 35-40%; bioclasts 10%. Relatively fine grained and well sorted. Porosity scattered randomly	3608	

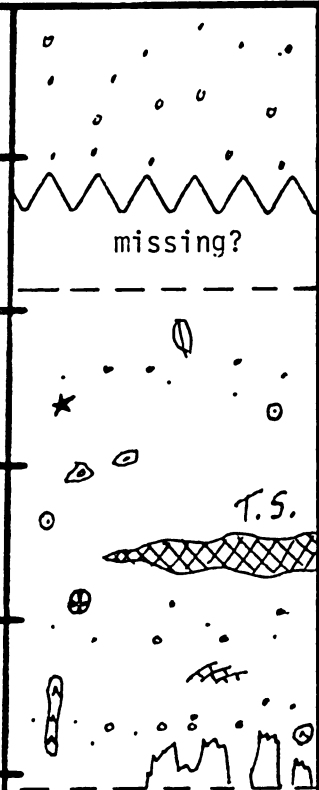
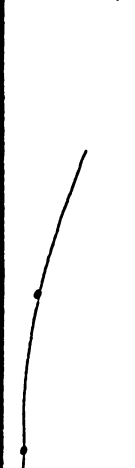


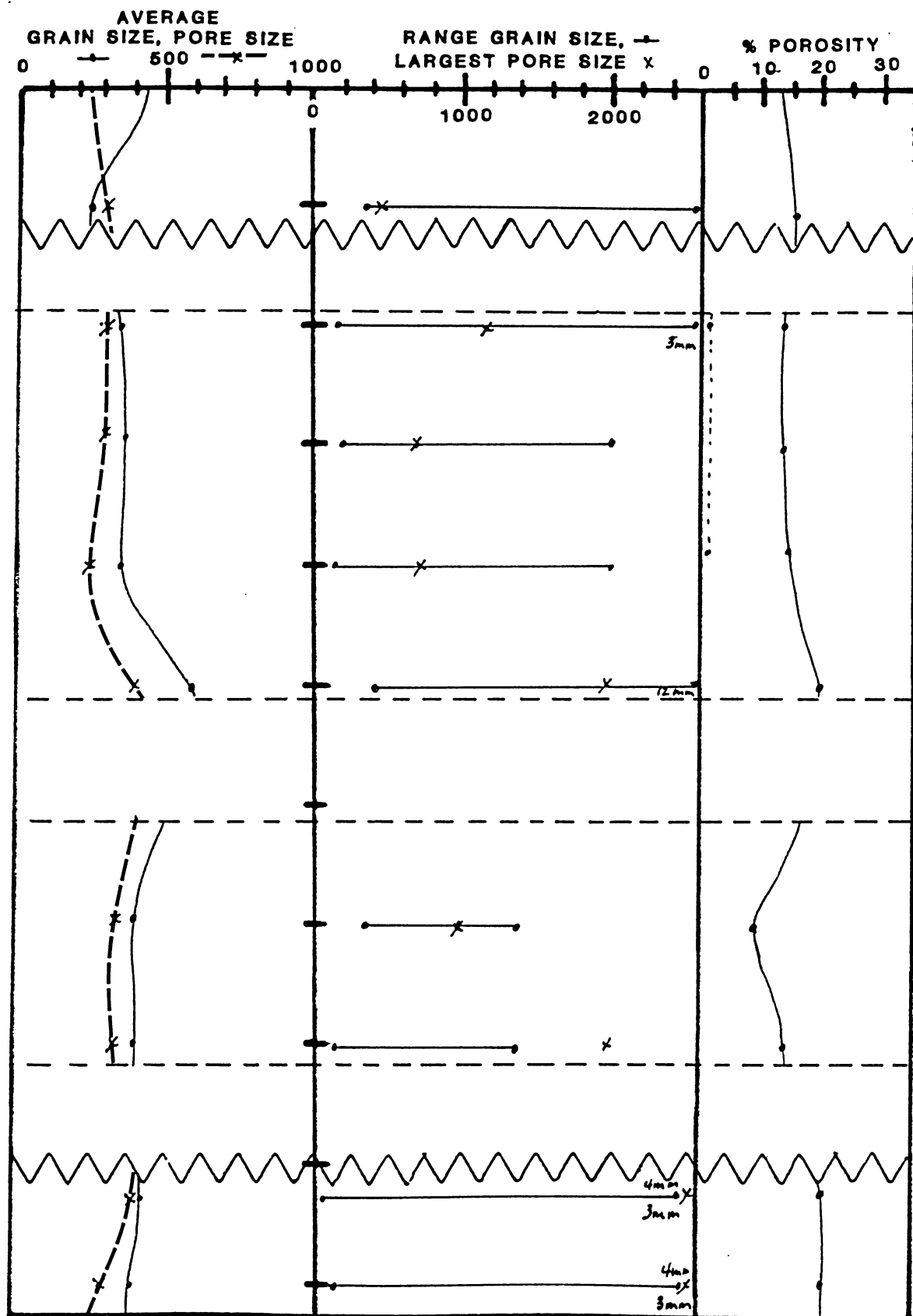
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 30%; bioclasts 10%. Moderately well sorted. Porosity randomly scattered; some pores filled with baroque dolomite.		
Grainstone Ooids 25%; bioclasts 15%. Relatively well sorted. Some bioclasts aligned horizontally. Stylolite at top.		

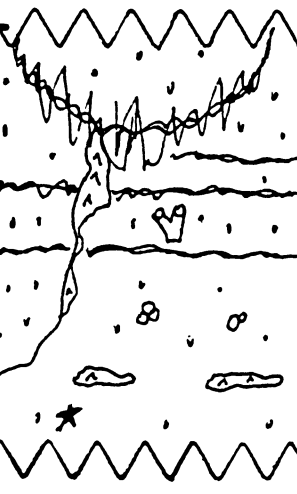


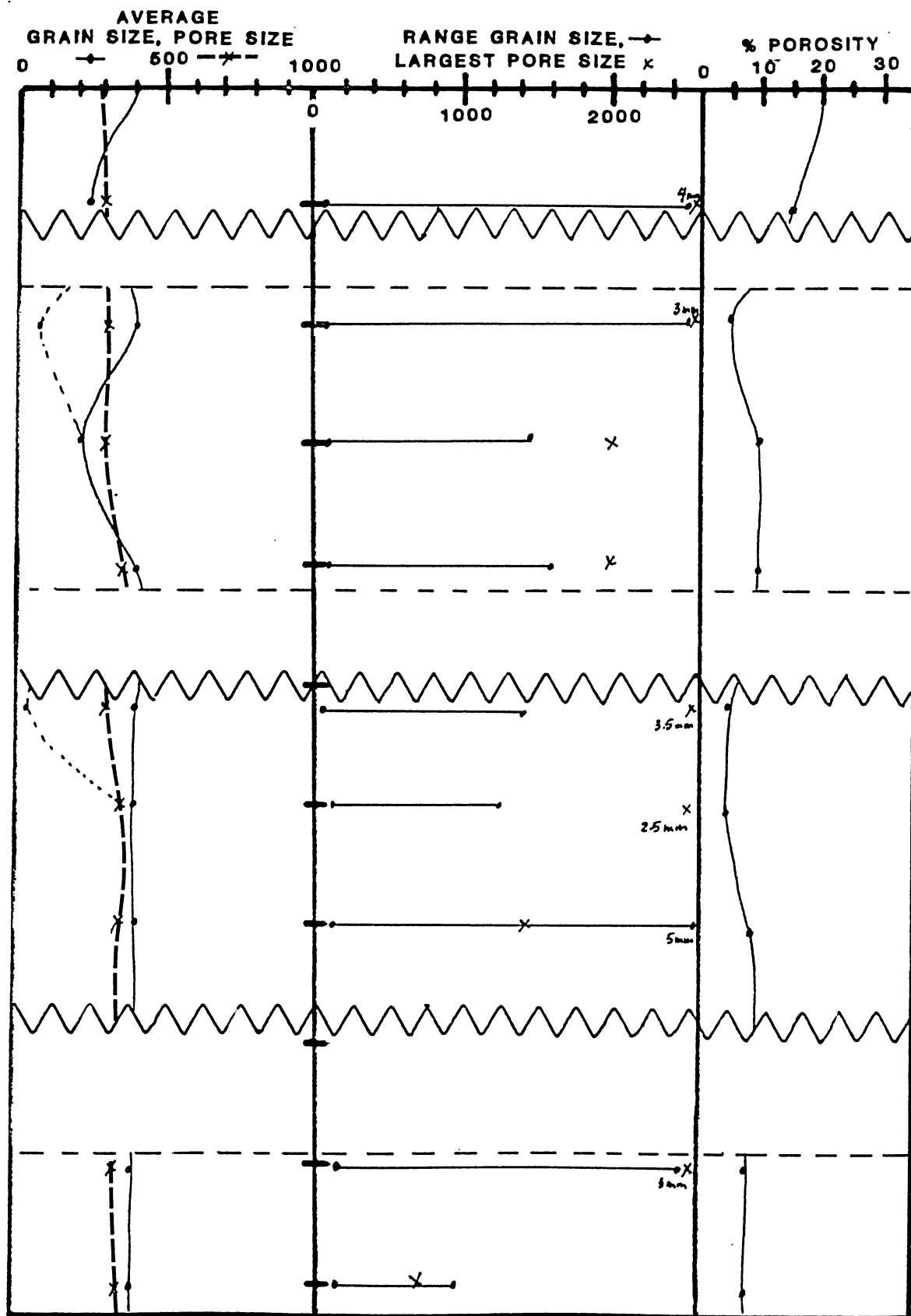
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 15%; bioclasts 40%. Well sorted. Some aligned echinoderm spines at bottom. Porosity scattered randomly; reduced by sparry calcite.	missing  3611	
Grainstone Ooids 25%; bioclasts 25%. Well sorted ooids. Some grains have white coatings, and/or are recrystallized(?) Porosity randomly scattered, except top, which is cemented tightly. Pores have scalenohe- dral calcite crystals lining them	missing? 	

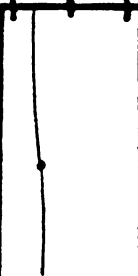
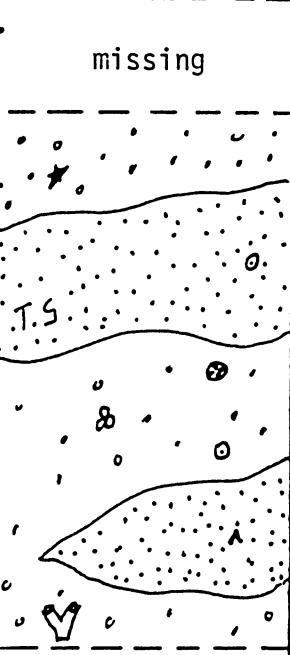
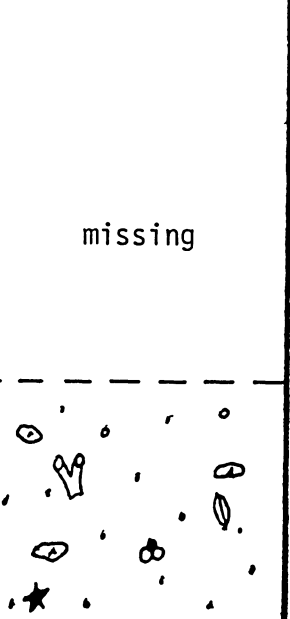


DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 50%; bioclasts 10%. Sorting variable. Zone in center which is tightly cemented with creamy gray calcite. A mottled texture. Some vugs filled with anhydrite and baroque dolomite.	 missing? 3612 T.S. missing	
Packstone-Grainstone Ooids 30%; bioclasts 10%. Patches of well sorted, highly cemented ooids; and patches with very little cement. Unusual texture, with some ooids completely dissolved directly adjacent to undissolved ooids. Some pores filled with baroque dolomite.	 3613 missing?	
Packstone-Grainstone Ooids 20%; bioclasts 10% Sorting variable. Mottled texture, with patches	 missing?	

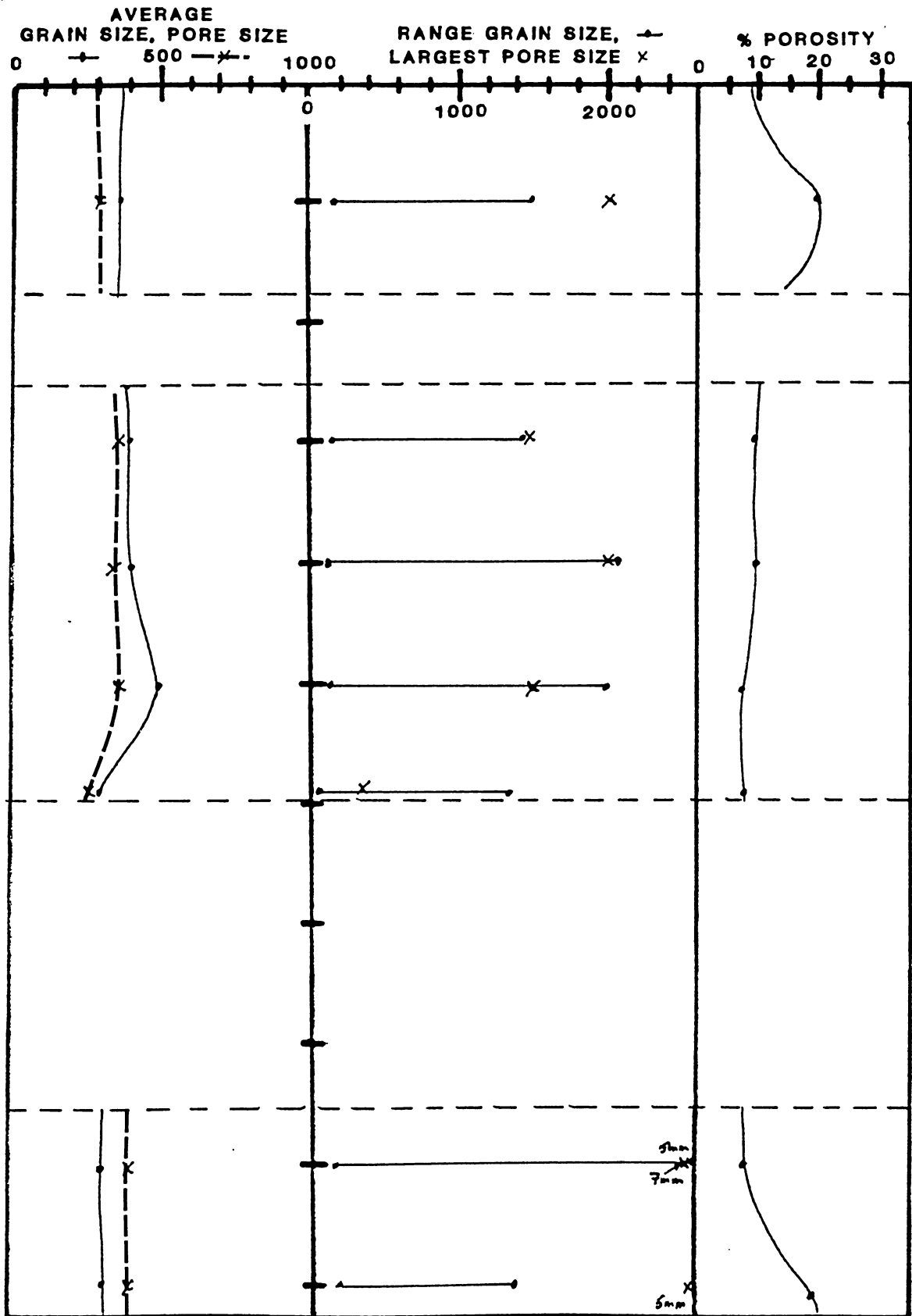


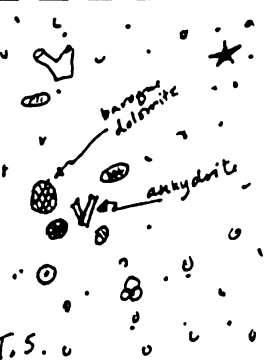
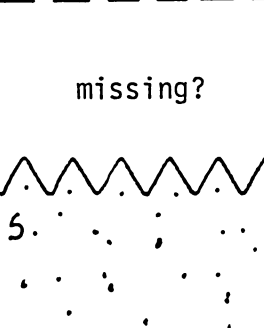
DESCRIPTION	CORE	PACKING to med hl
of mud and ooids. Poor sorting. Some large vugs aligned horizontally, and filled with anhydrite. Vertical stylolite		
Packstone-Grainstone Ooids 15%; bioclasts 10%. Sorting poor. Vugs filled with anhydrite, some of which is replacive into the surrounding rock with a radial pattern. Baroque dolomite also fills vugs. Vertical stylolites.	missing?  3614	
Packstone-Grainstone Ooids 20%; bioclasts 10%. Sorting poor. Mottled texture, with ooids in patches with mud in between. Vugs tend to occur around ooid patches, and can be filled with baroque dolomite or anhydrite. Many stylolites.	missing? 	
Packstone-Grainstone Ooids 25%; bioclasts 15%. Sorting variable. Ooids occur in bands, which are quite well sorted. In between are grainy muddy layers. A mottled texture. 3615	missing? 	

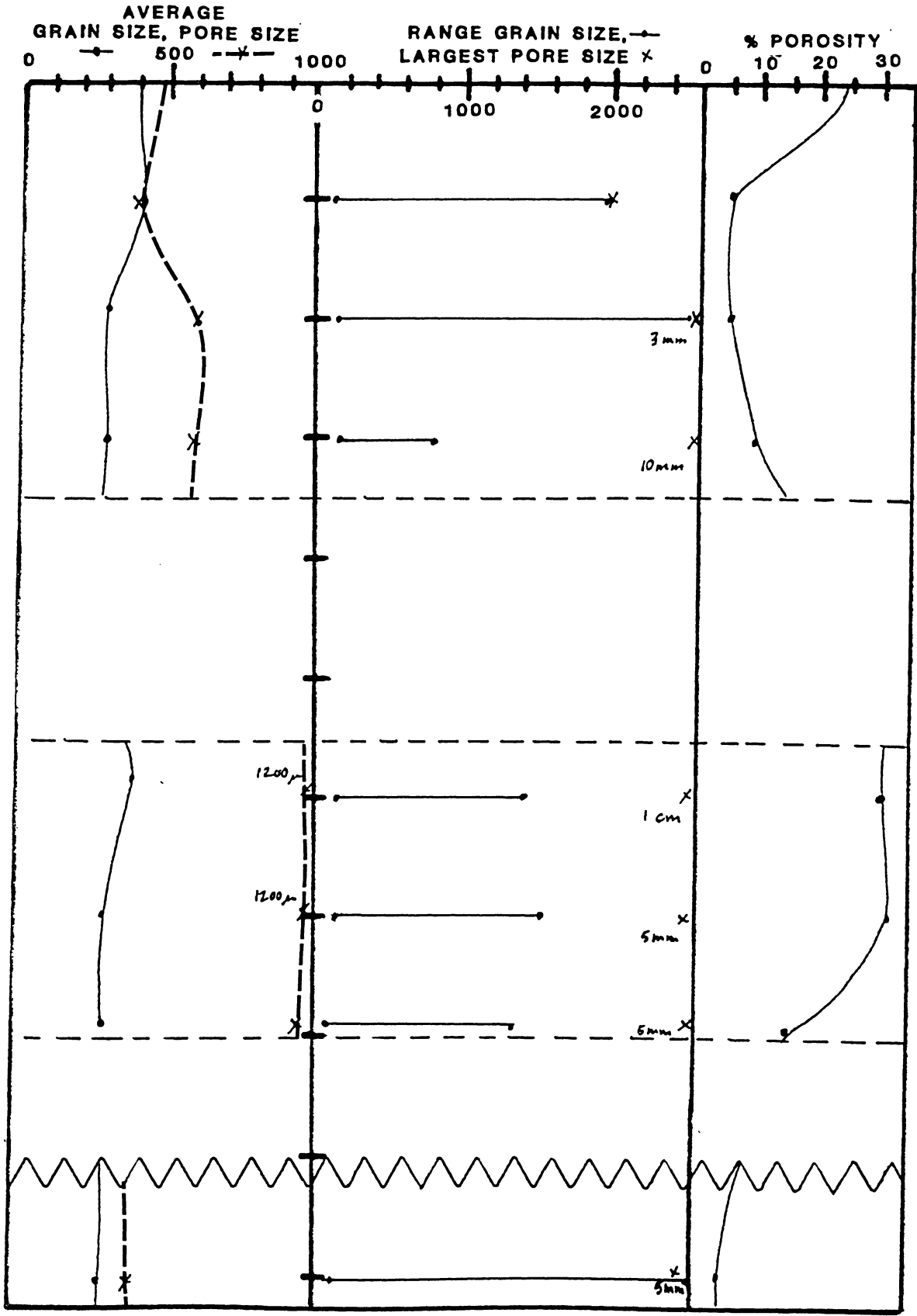


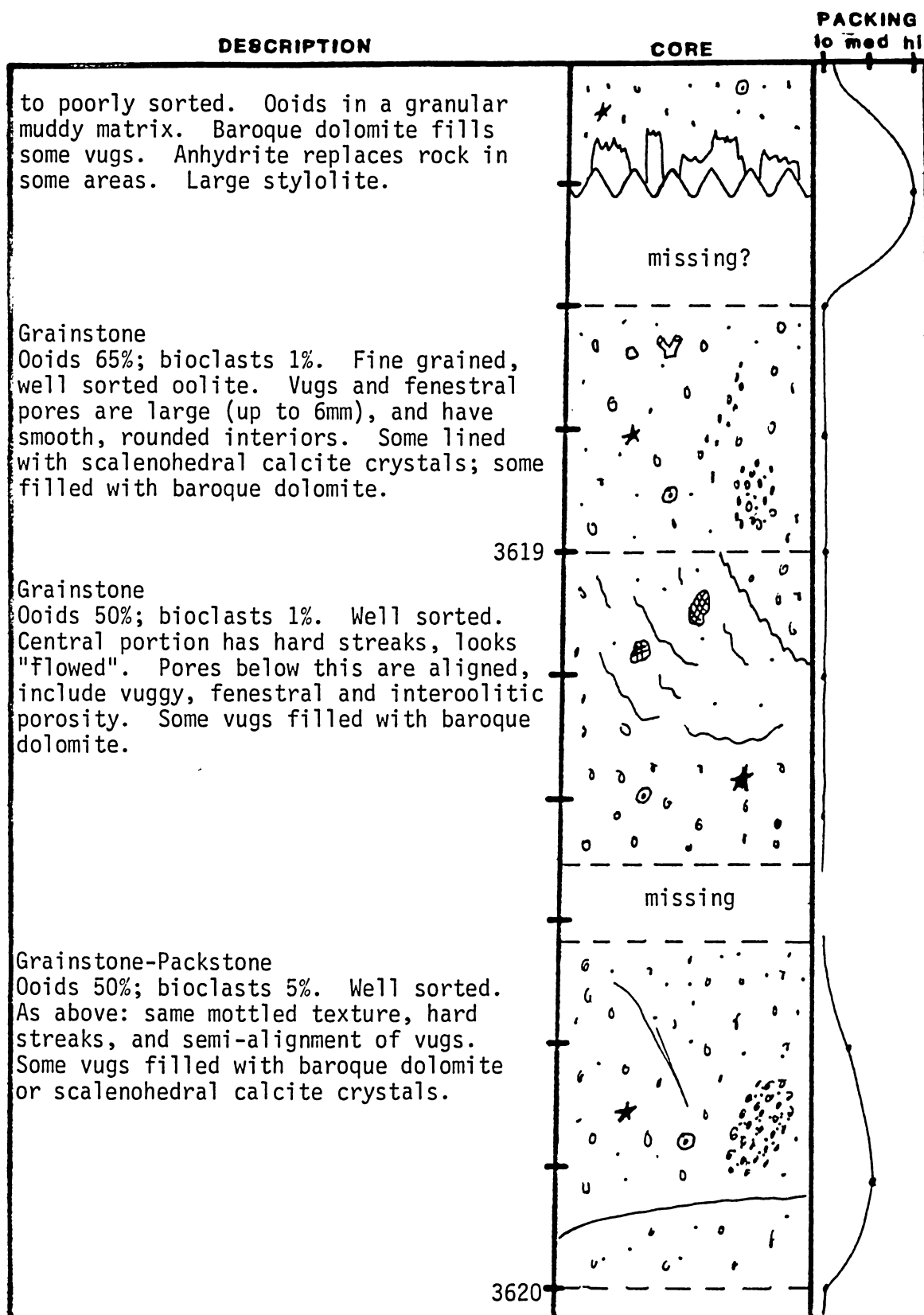
DESCRIPTION	CORE	PACKING lo med hi
Fenestral birdseye vugs can be filled with baroque dolomite or anhydrite, which is also replacive into surrounding rock.		
Packstone-Grainstone Ooids 25%; bioclasts 15%. Sorting and texture variable--cementation of ooids varies in a mottled "layering". Porosity varies with cementation; some vugs filled with anhydrite, calcite, or baroque dolomite.	missing 	
Packstone-Grainstone Ooids 40%; bioclasts 20%. Poor sorting; mottled texture. Pores and vugs large, up to 7mm. Some vugs filled with clear or milky anhydrite, some with scalenohedral calcite crystals. Patches of dolomite cement. Microstylolites.	missing 	

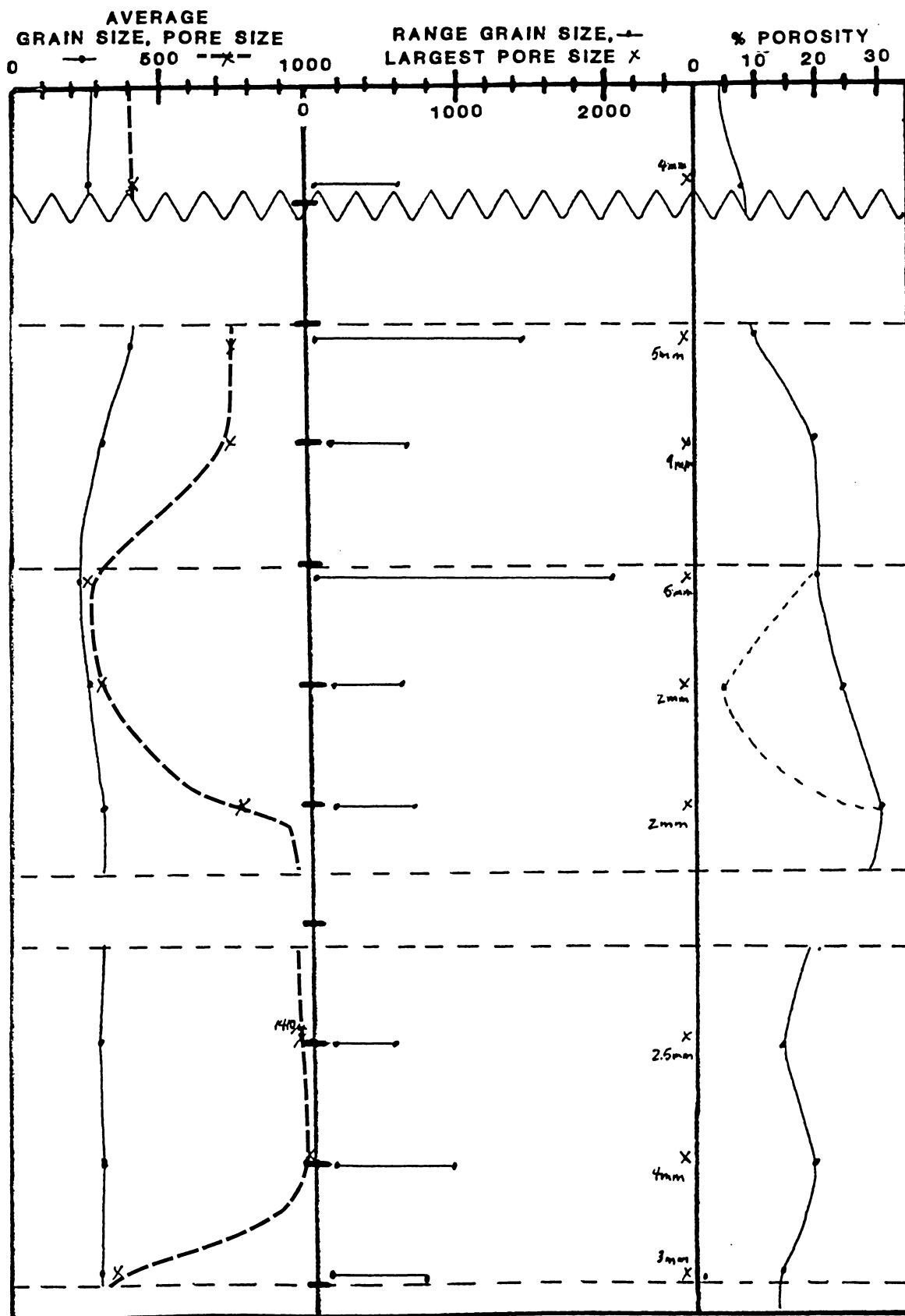
3616

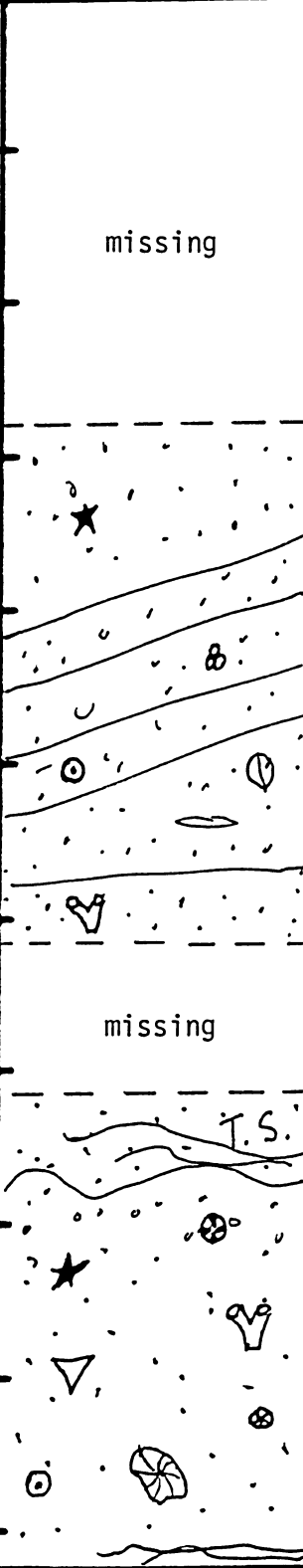


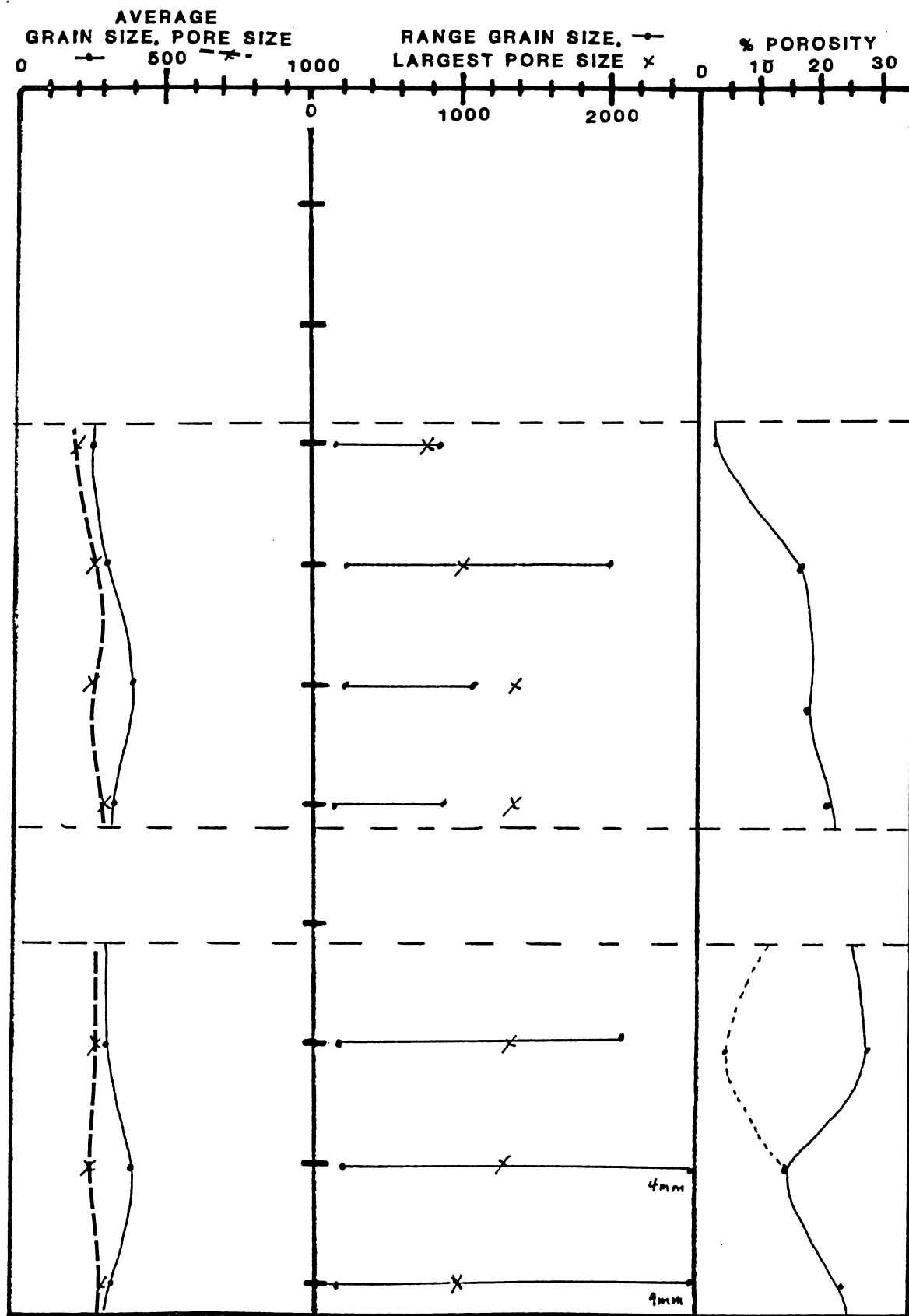
DESCRIPTION	CORE	PACKING lo med hi
		
Packstone-Grainstone Ooids 30%; bioclasts 10%. Well sorted. Abundant pores are about the same size, (2mm), and are round--pores look as though they were formed by 2mm ooids. Abundant baroque dolomite filling voids and anhydrite replacing calcite matrix.	3617 missing 	
Packstone Ooids 25%; bioclasts 10%. Moderately	3618 missing? 	

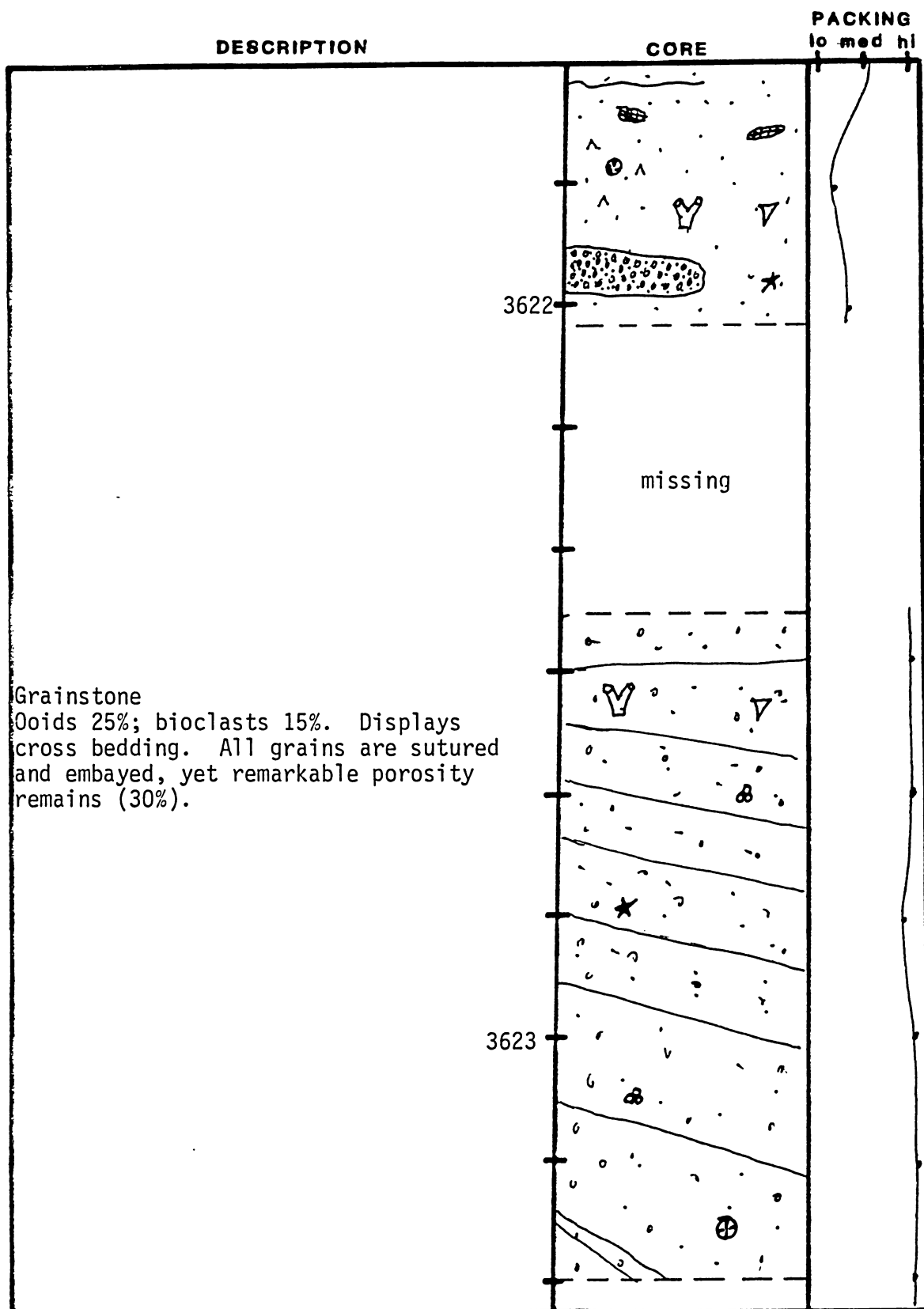


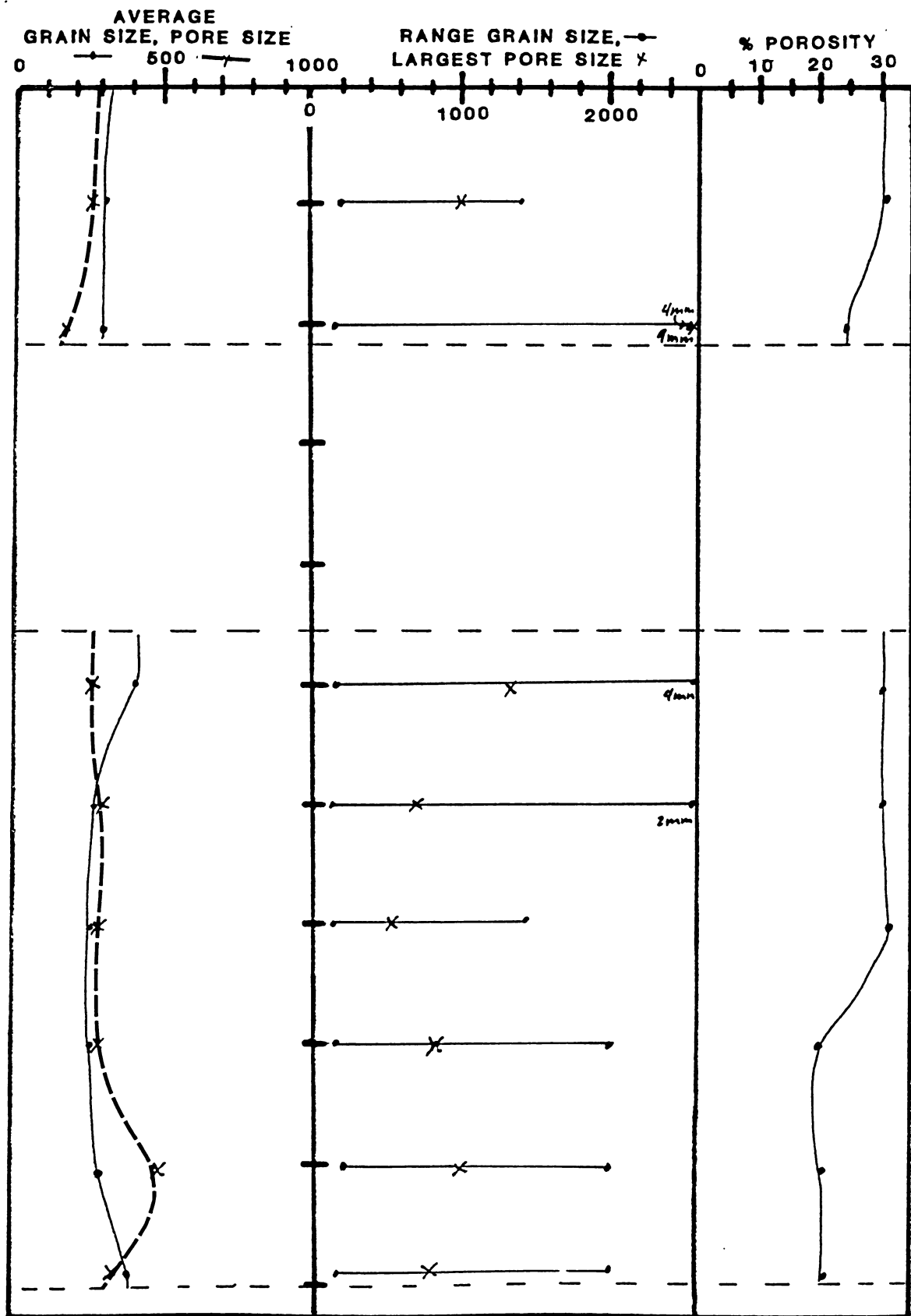


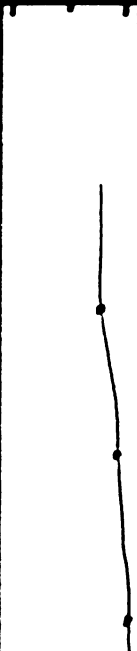
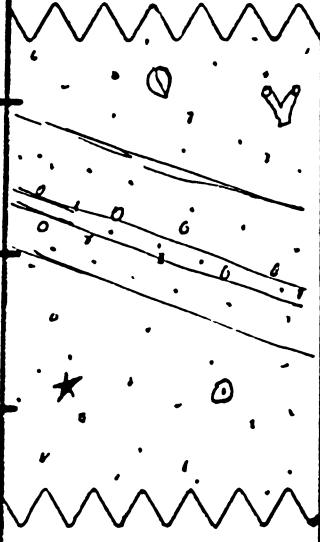


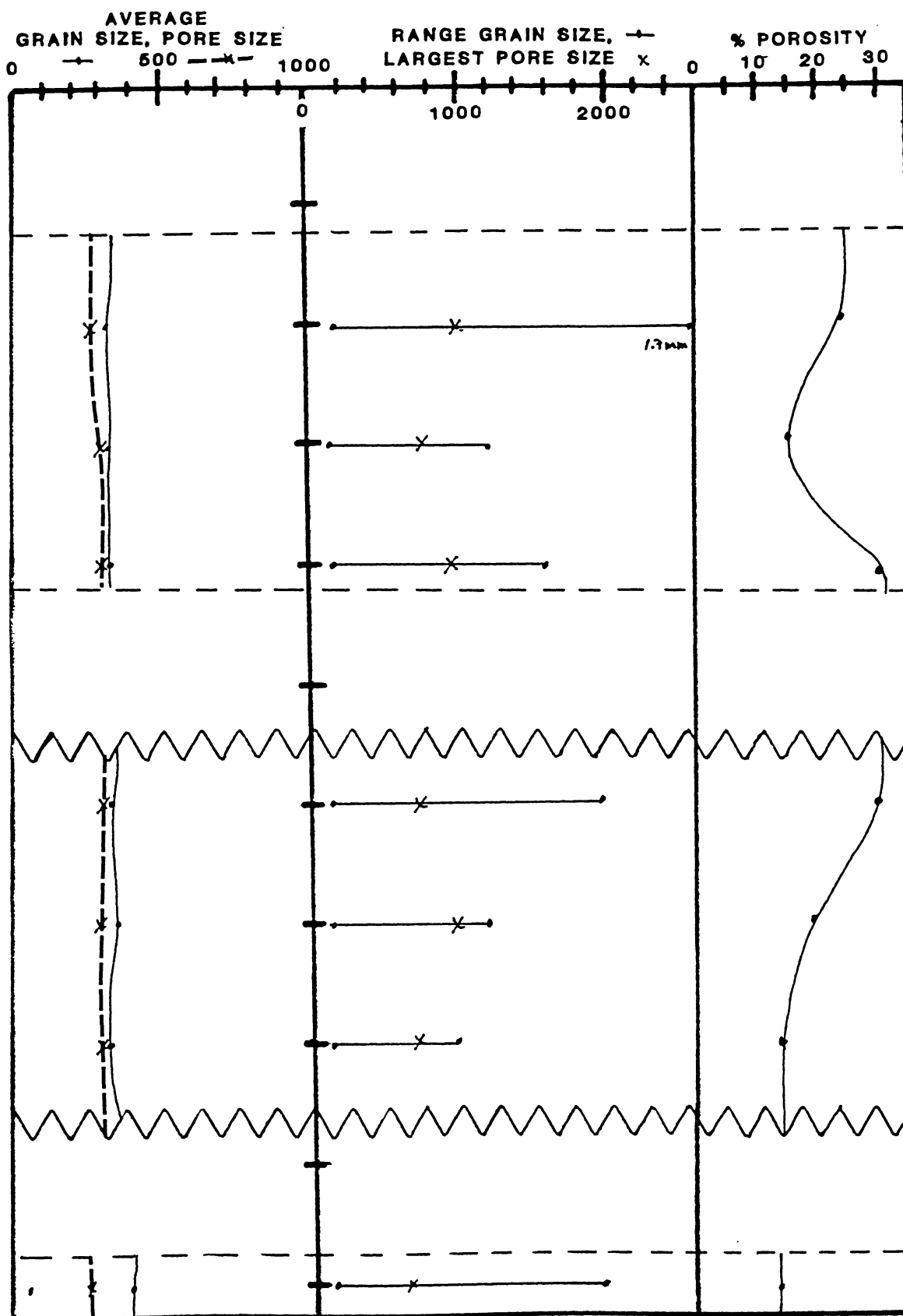
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 60%; bioclasts 10%. Well sorted oolite displaying cross bedding. Porosity includes fenestral, vuggy and intraoolitic	missing  3621	
Grainstone Ooids 40%; bioclasts 15%. Sorting variable, fair to poor. Mottled texture, with cemented zones surrounding non-cemented zones. Some clasts of small, well sorted ooids which are cemented tightly. Both anhydrite and baroque dolomite cements present. A 2cm zone where all grain boundaries are sutured.	missing  T.S.	

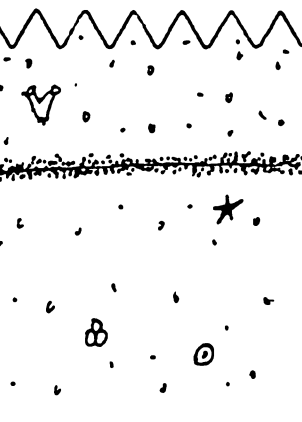


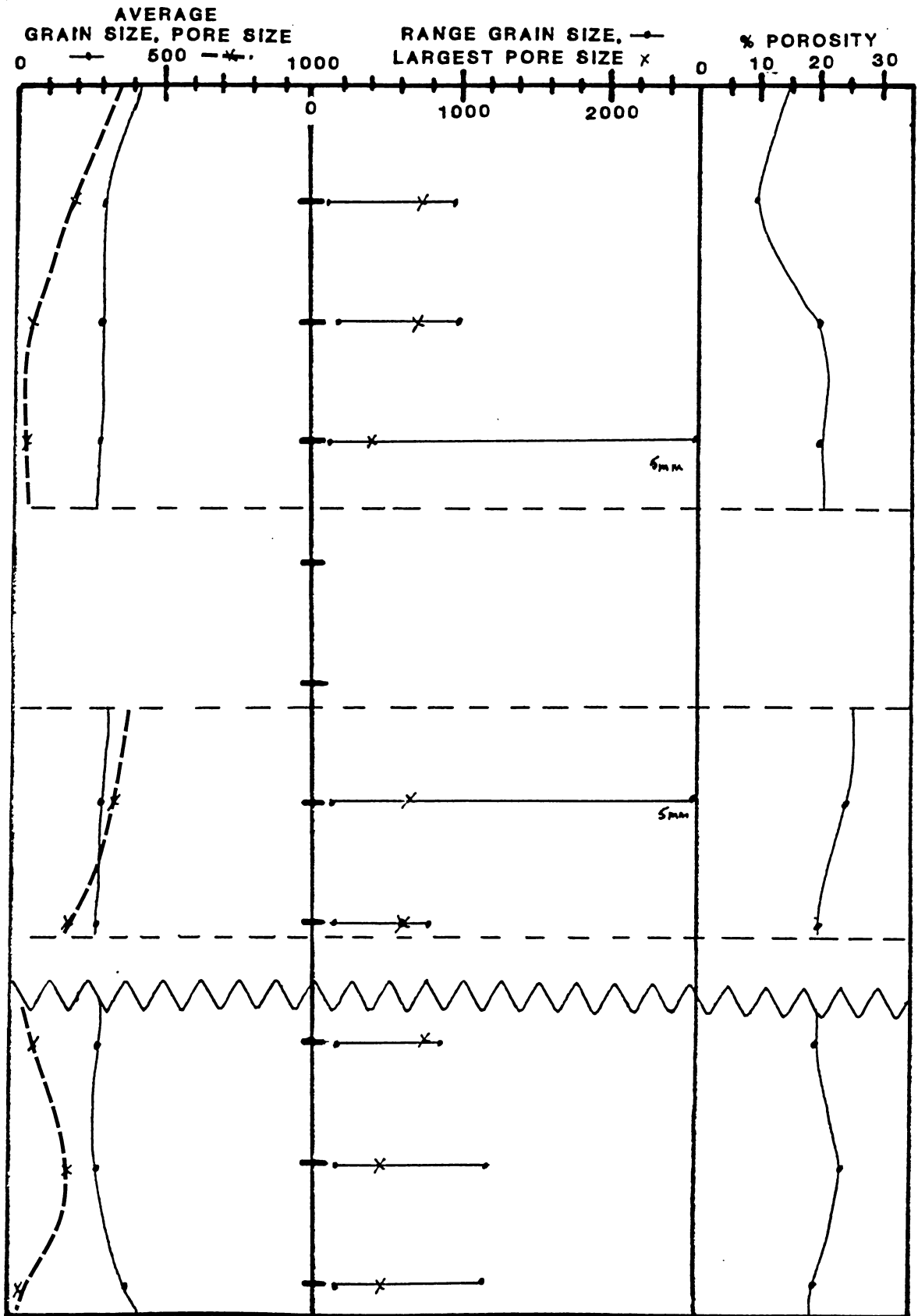


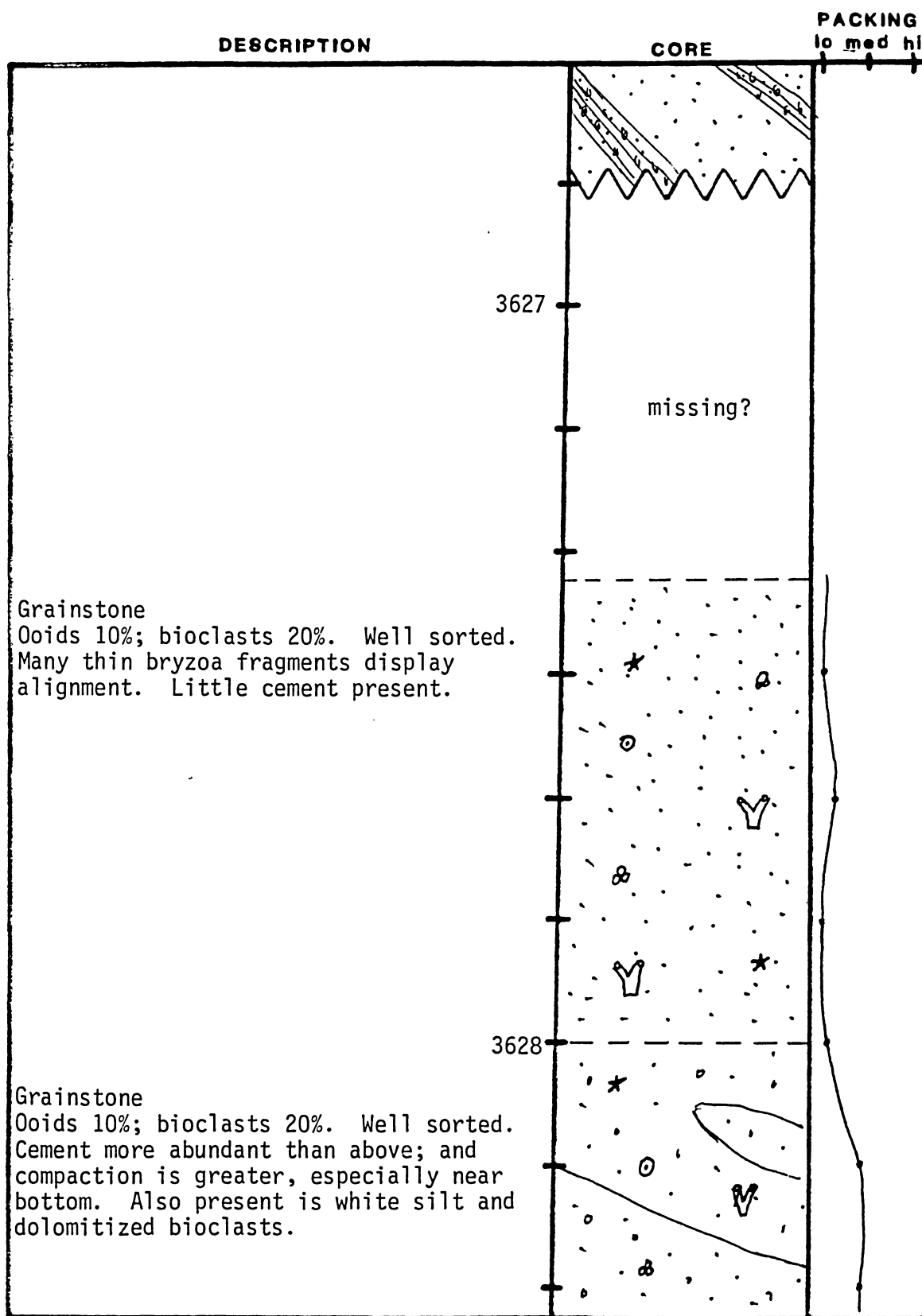


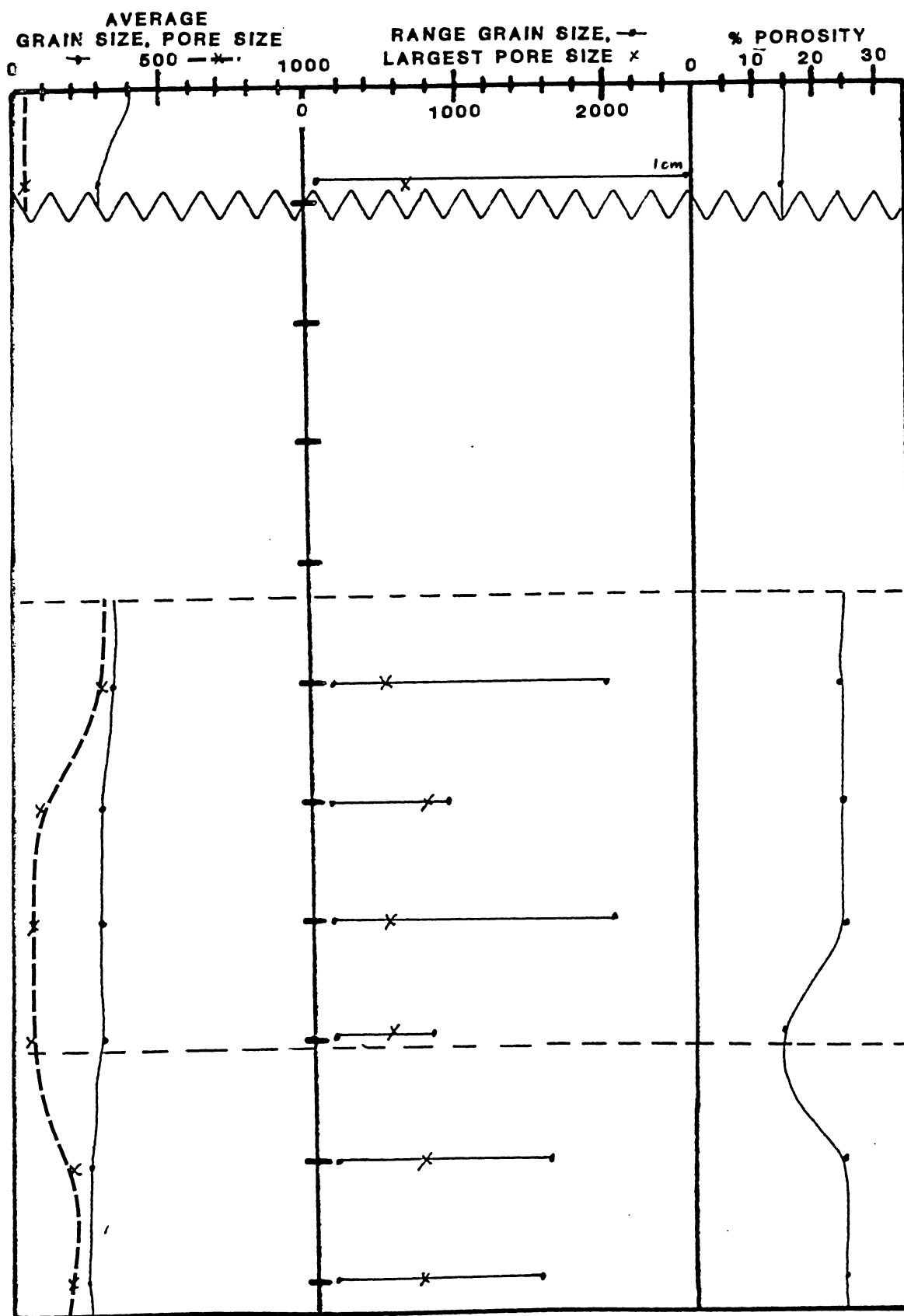
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 25%; bioclasts 25%. Well sorted into bands of large and small grain sizes. Faint cross beds, with aligned bioclasts. Inter and intraparticle porosity; very little cement present.	missing  3624	
Grainstone Ooids 25%; bioclasts 25%. Well sorted into bands of large and small grain sizes. Faint cross beds. Intraparticle porosity occluded by cloudy calcite cements and white silt.	missing?  missing? 3625	

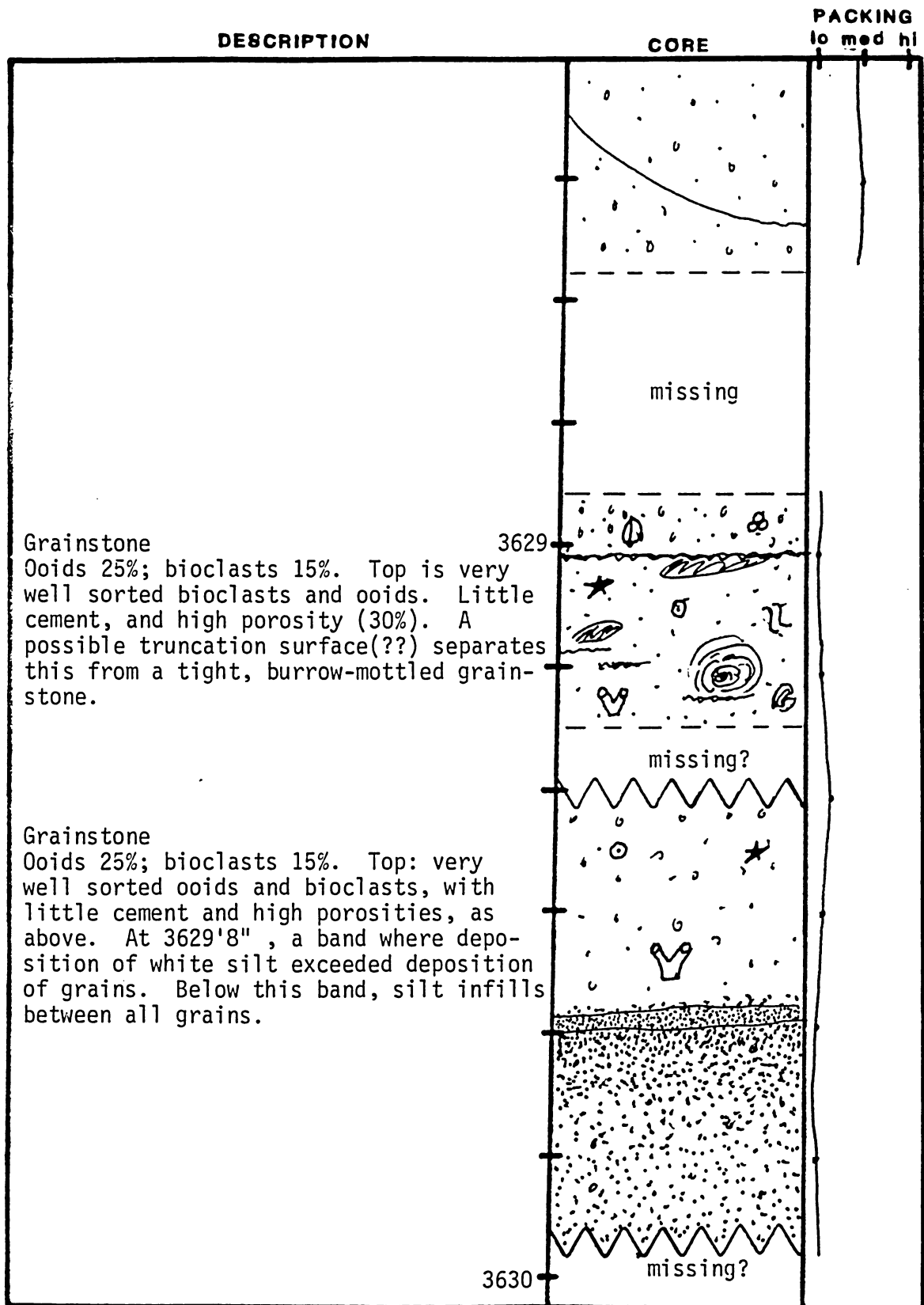


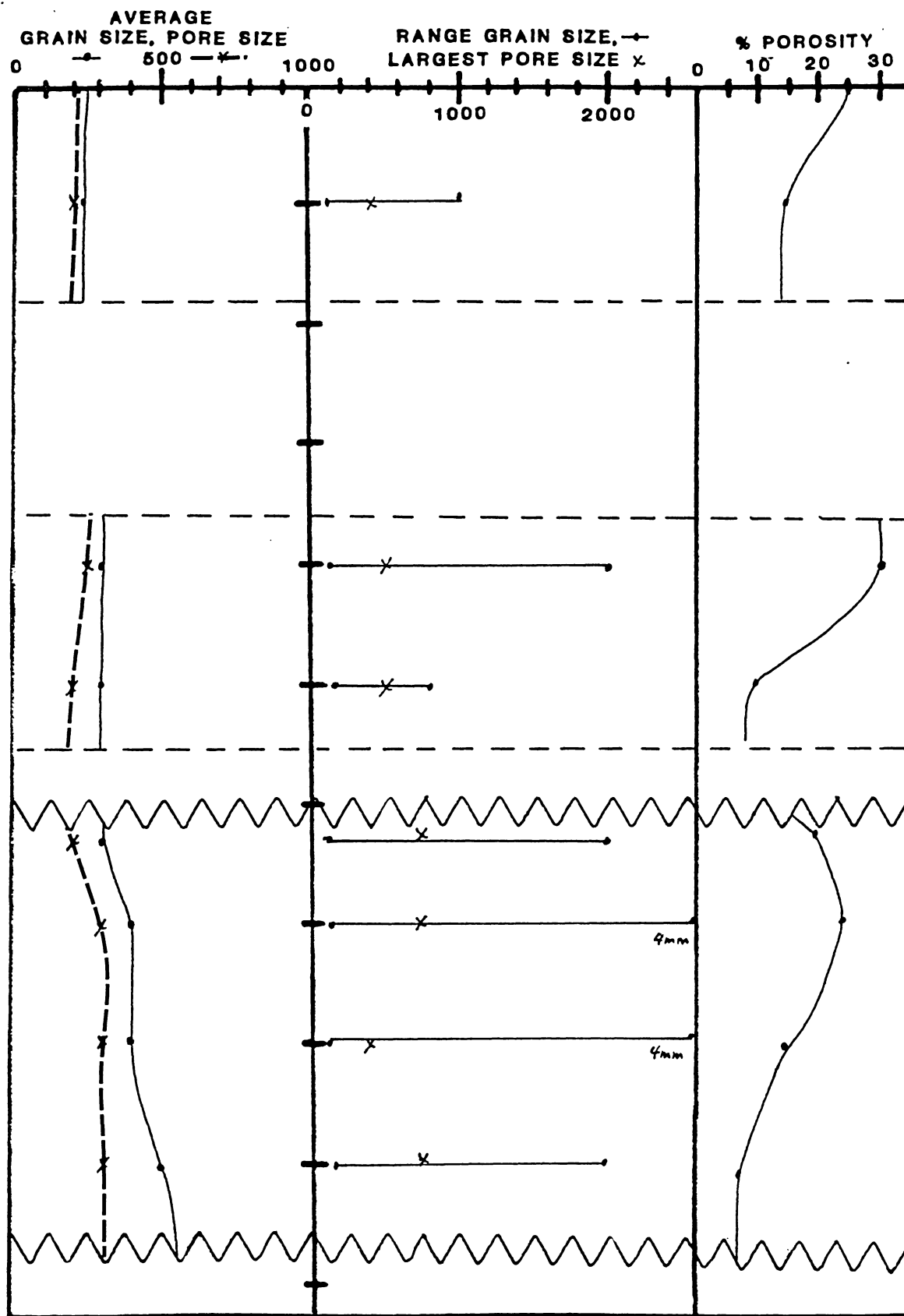
DESCRIPTION	CORE	PACKING lo med hi
Grainstone. Ooids 60%; bioclasts 20%. Extremely well sorted oolite. Porosity is abundant and absent in a blotchy pattern; porosity is interparticle and moldic. Anhydrite cement present. Large stylolite		
Grainstone Ooids 30%; bioclasts 30%. Well sorted. Little cement occluding interparticle porosity. White silt at bottom.	missing 	
Grainstone Ooids 30%; bioclasts 30%. Well sorted. Little cement occluding intergranular and moldic porosity. Some white silt-cement in a layer at 3626'5". Above this layer, silt-cement. Below, little cement and abundant porosity, both moldic and intergranular.	missing? 	

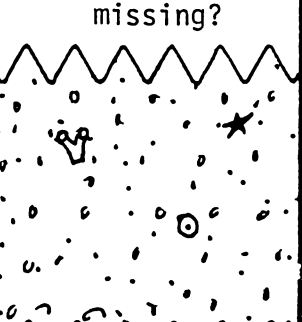


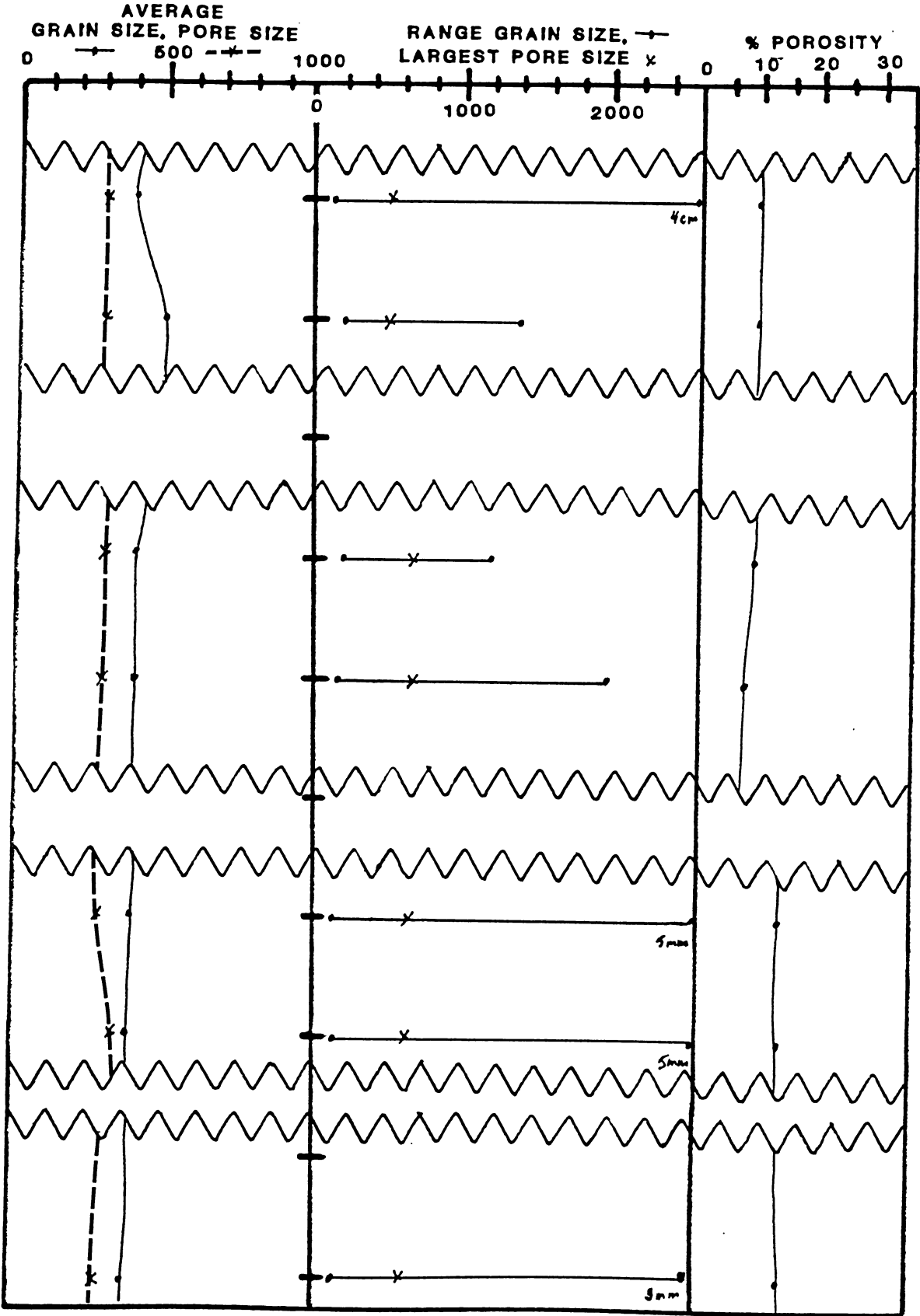


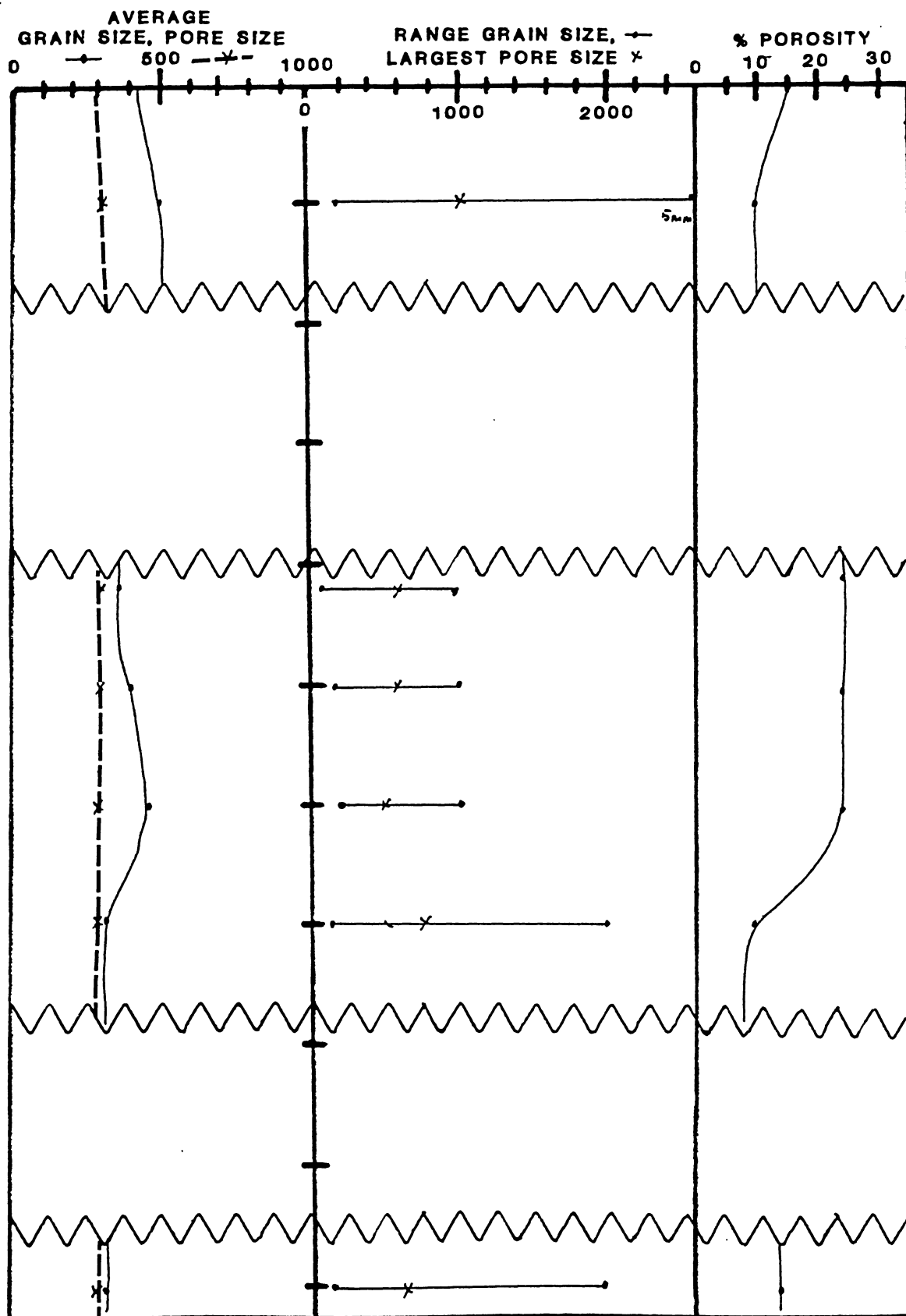


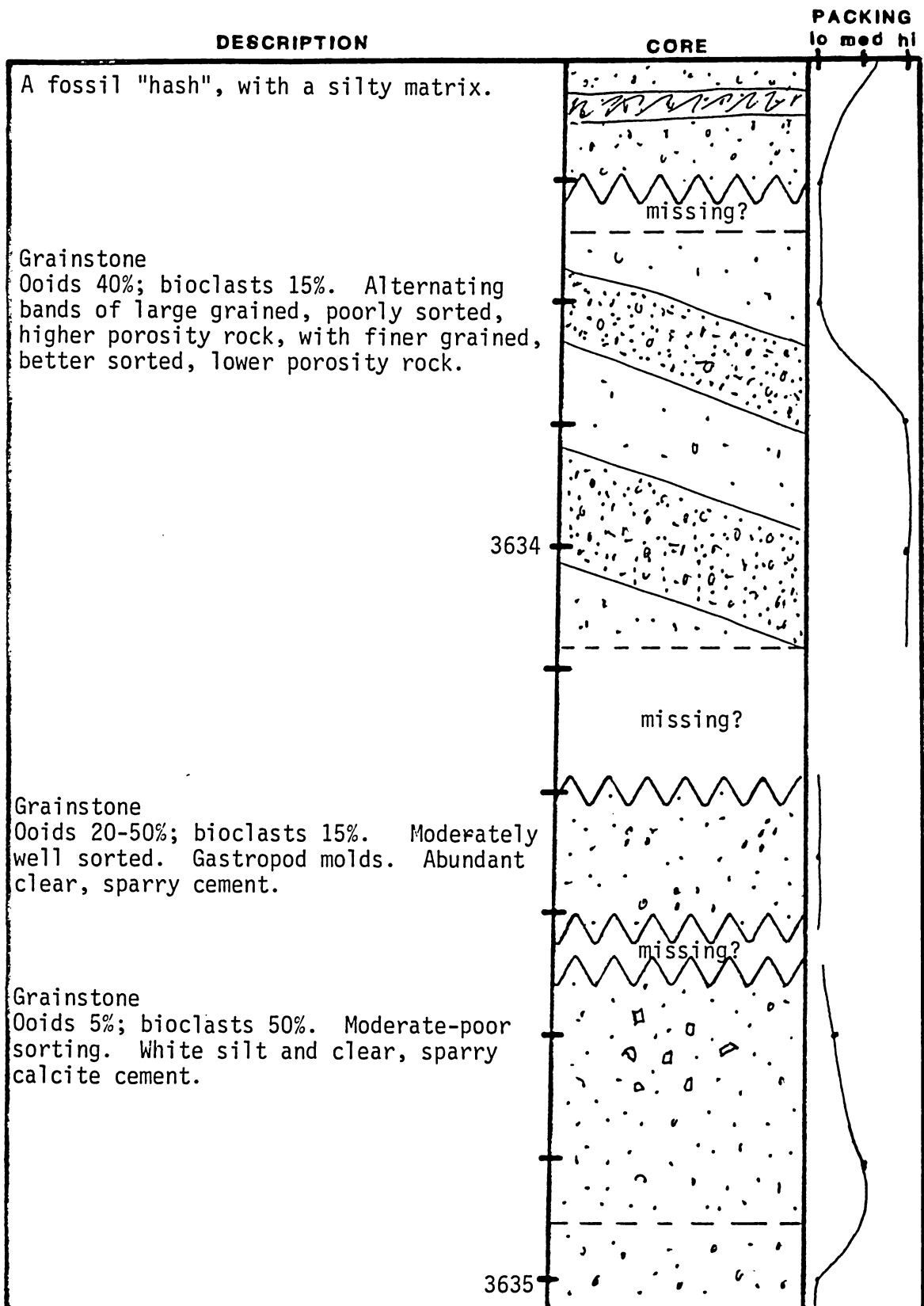


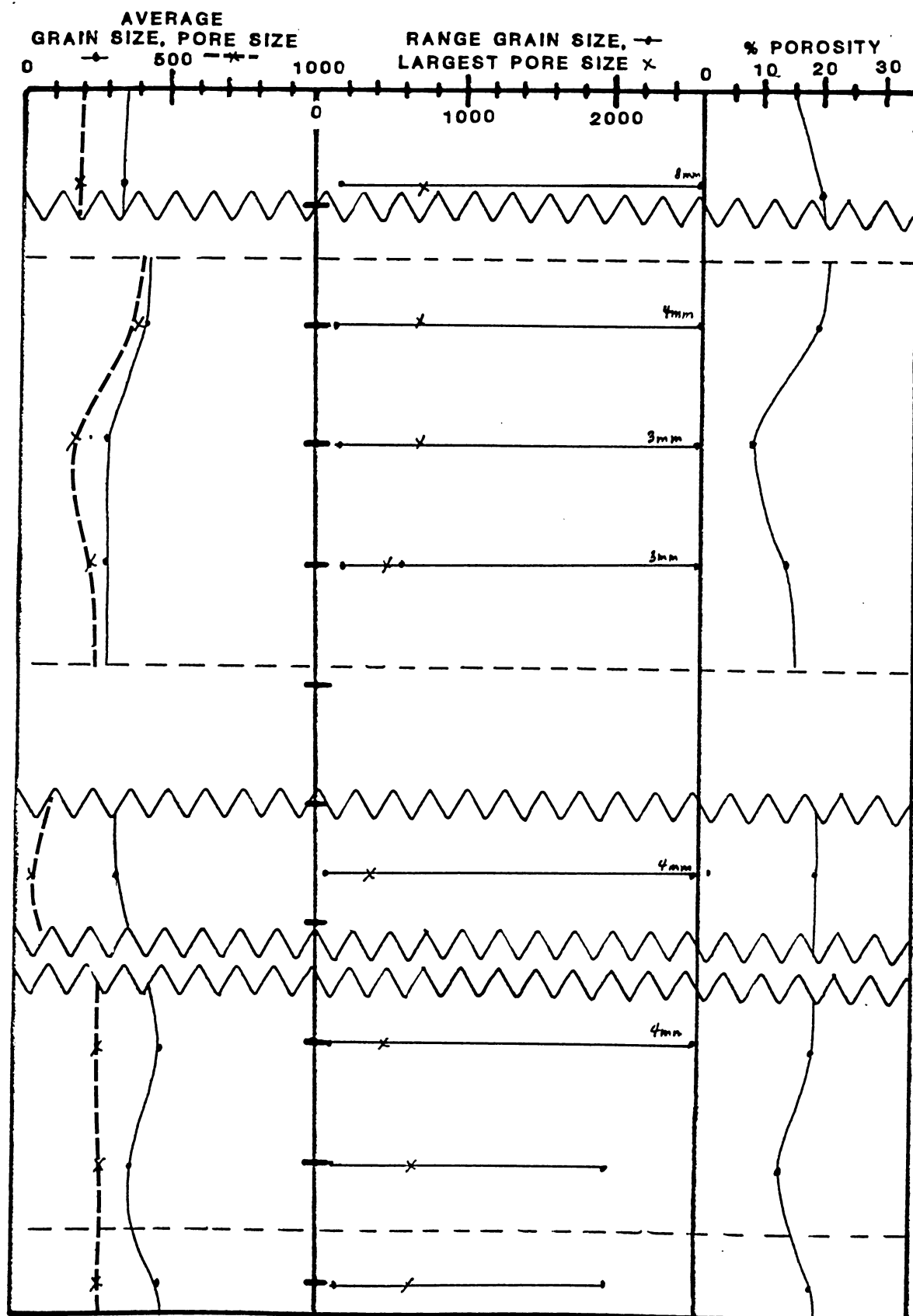


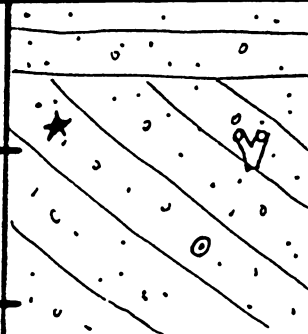
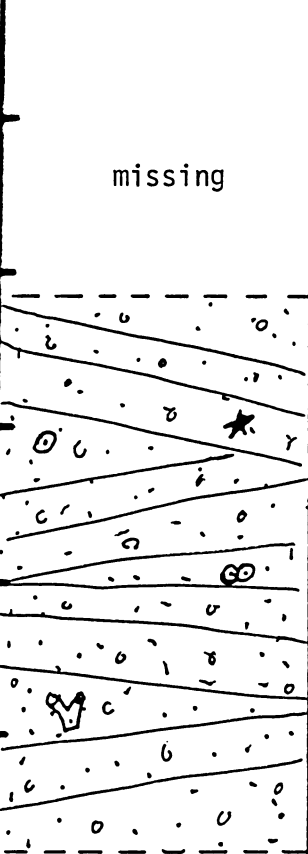
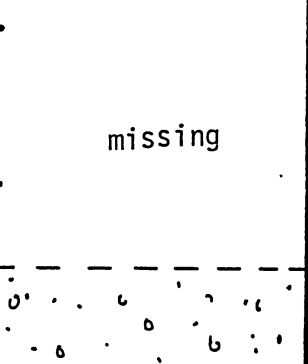
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 5%; bioclasts 45%. Moderately well sorted. Porosity is reduced by abundant cement and silt.	missing? 	
Grainstone Ooids 5%, bioclasts 45%. Moderately well sorted. Top, higher porosity because not much silt present. Below, cross beds are truncated, and porosity is lower because white silt fills intergranular spaces.	missing? 	
Grainstone Ooids 10%; bioclasts 40%. Moderately well sorted. Porosities are higher because of relative absence of white silt.	missing? 	
Grainstone Ooids 8%; bioclasts 40%. Well sorted. Ooids may be dolomitized(?). Large stylolite, with associated abundant	missing? 	

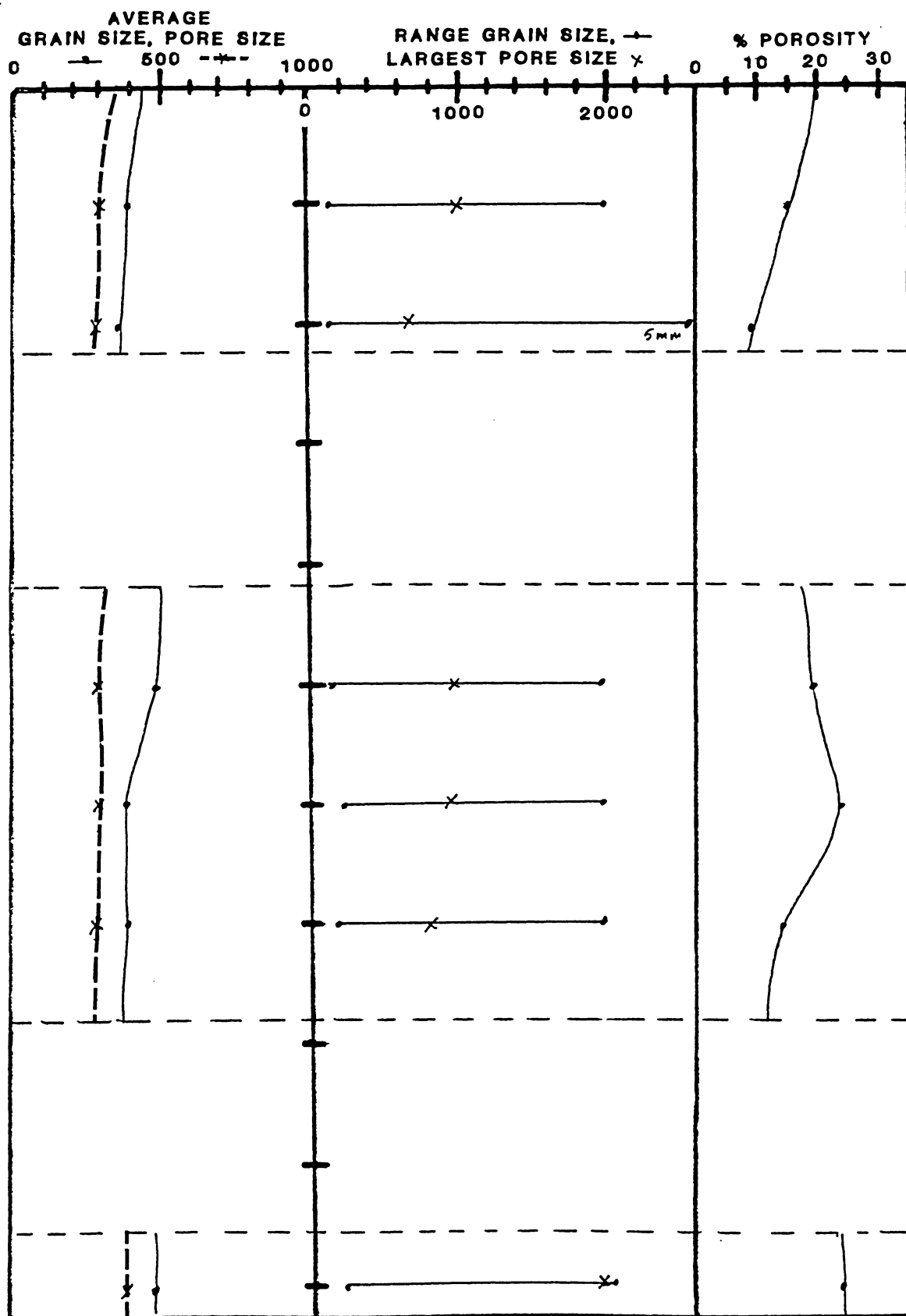


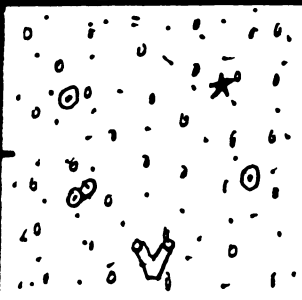
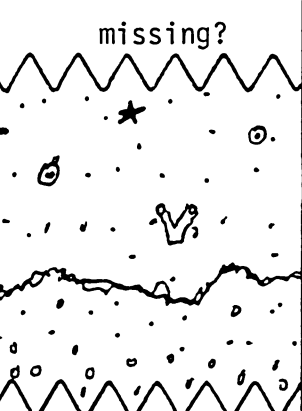


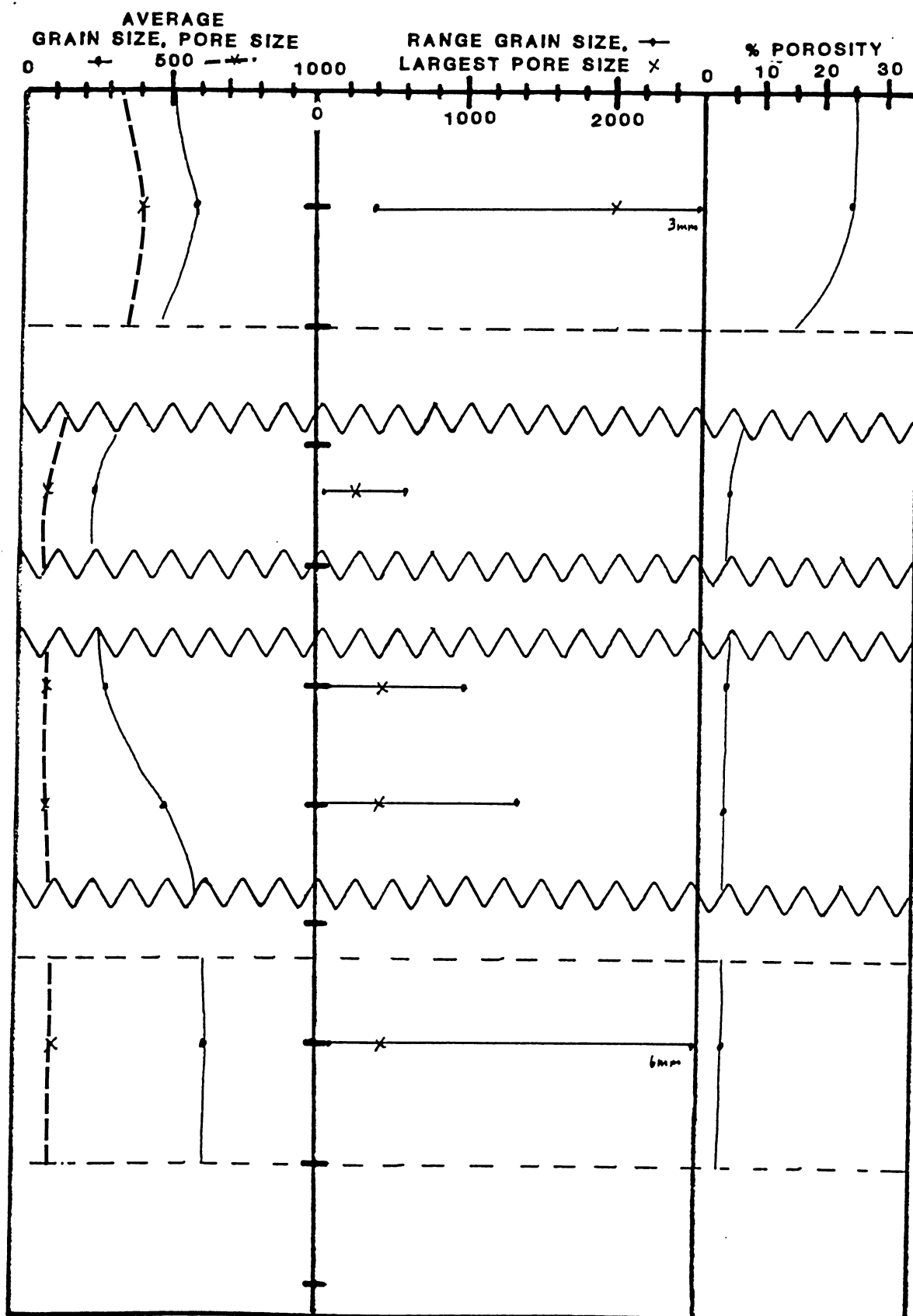


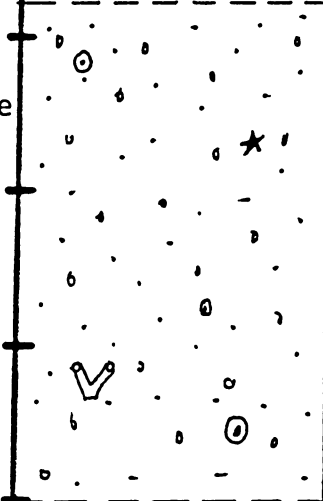
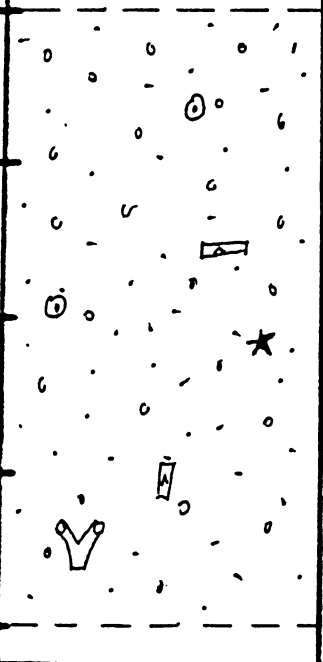


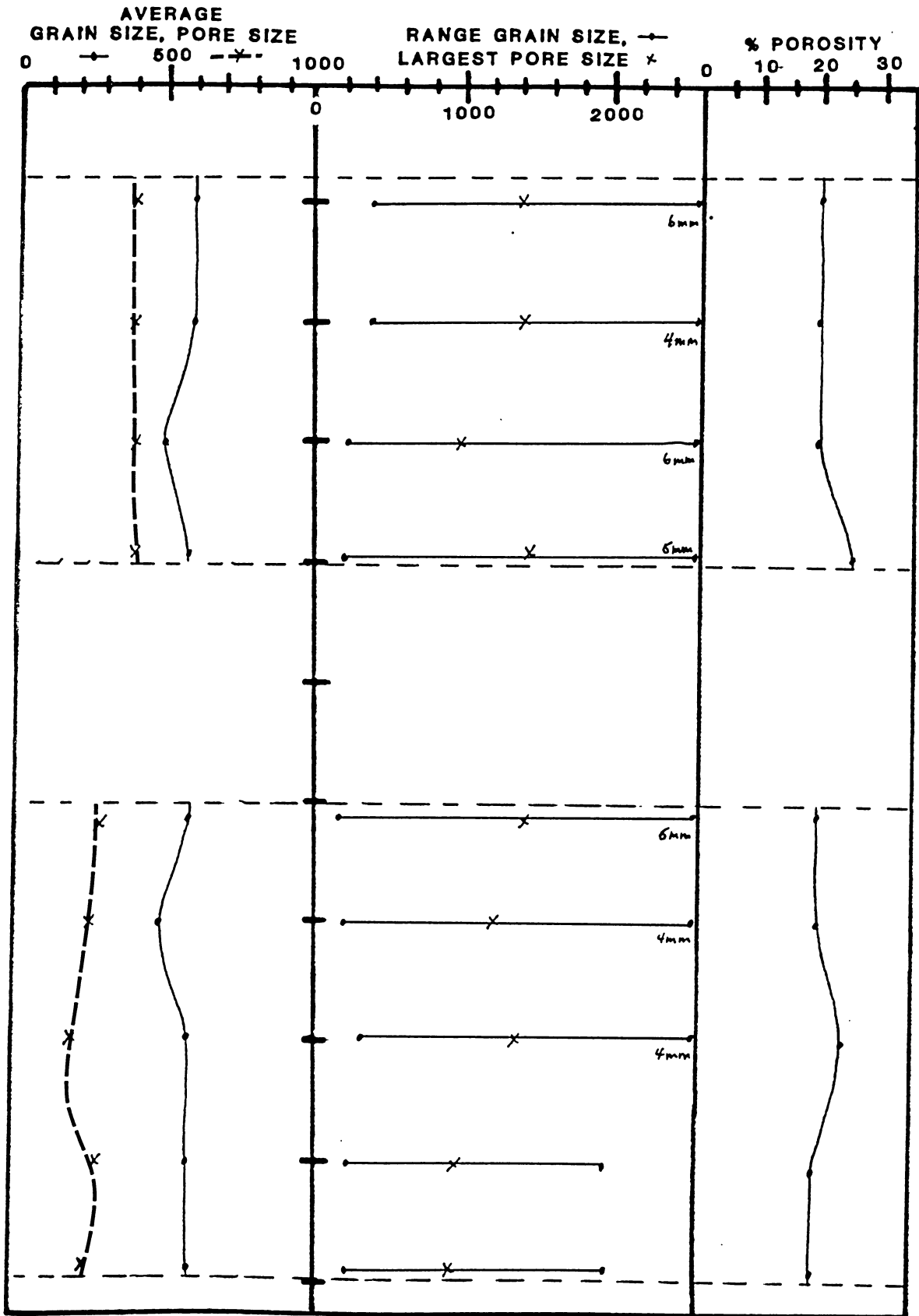
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 25%; bioclasts 25%. Moderate - poor sorting. Ooids dolomitized? Large fossil fragments; grains are sutured and embayed.		
Grainstone Ooids 25%; bioclasts 25%. Moderately well sorted. Faint cross beds. Some grapestone, and white silt.		
3636		
		

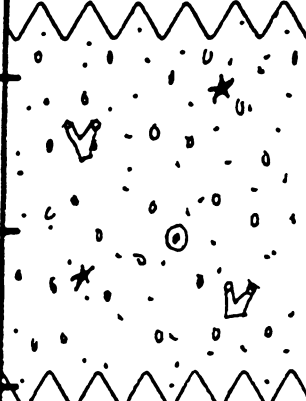
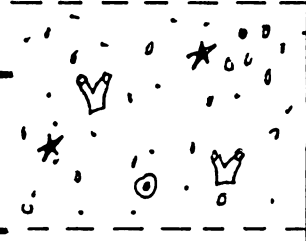


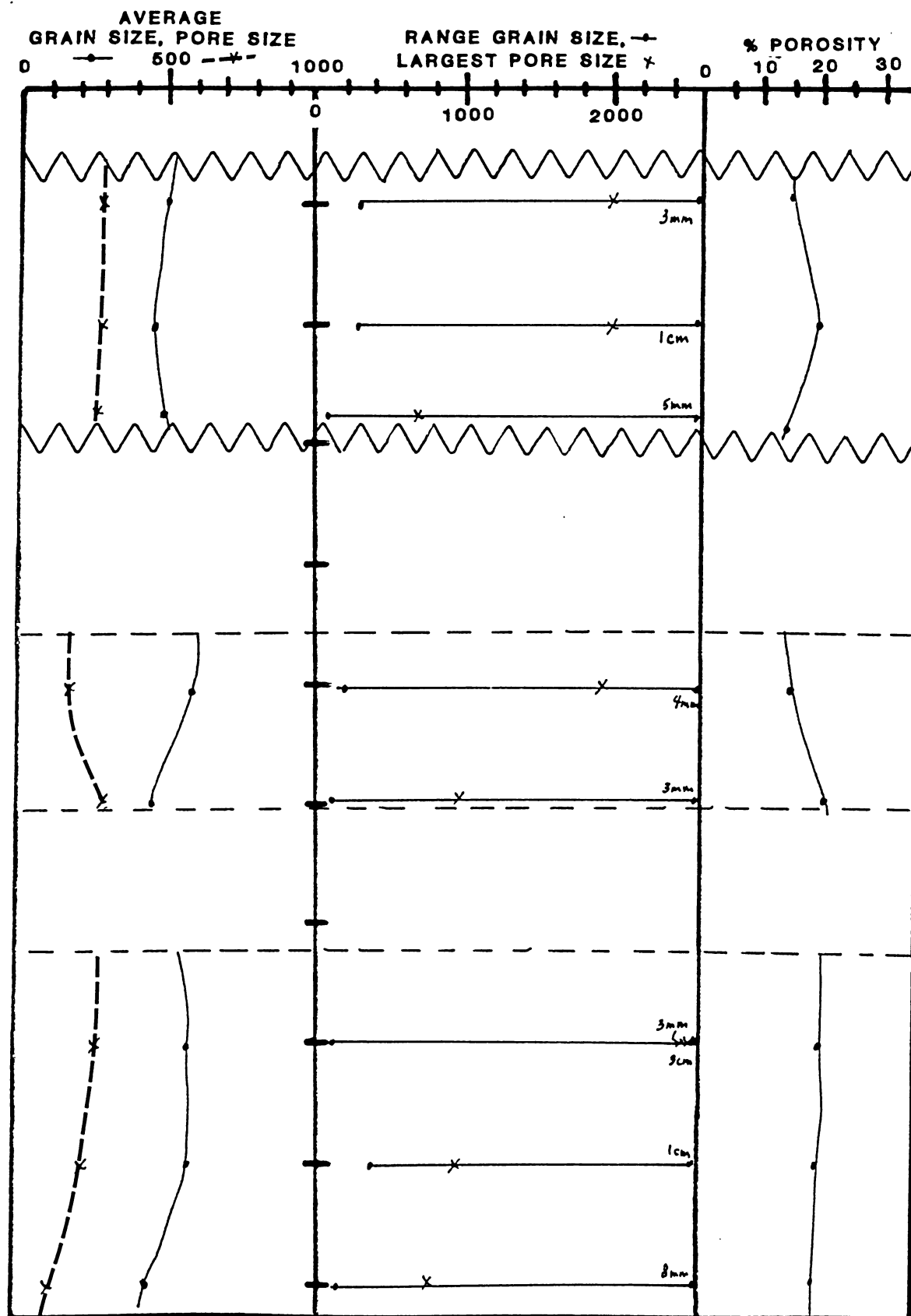
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 5%; bioclasts 50%. Moderate-poor sorting. Fossil fragments are large; pore space reduced by white silt and clear sparry calcite cement.		
Grainstone Ooids 20%; bioclasts 20%. Well sorted, generally fine grained. Porosity substantially reduced by abundant clear sparry calcite and white silt. Vertical microstylolites.	3637 missing? 	
Grainstone Ooids 30%; bioclasts 20%. Well sorted. Above stylolite, white silt matrix. Below stylolite, very well sorted oolite without white silt matrix. Abundant clear sparry calcite cement throughout causes low porosities.	missing? 	
Grainstone Ooids 30%; bioclasts 30%. Sorting variable. Some areas of large, well formed ooids with good sorting; some layers of bioclastic sand with moderate sorting. Some grapestone. Abundant cement, both calcite and baroque dolomite.	3638 missing 	

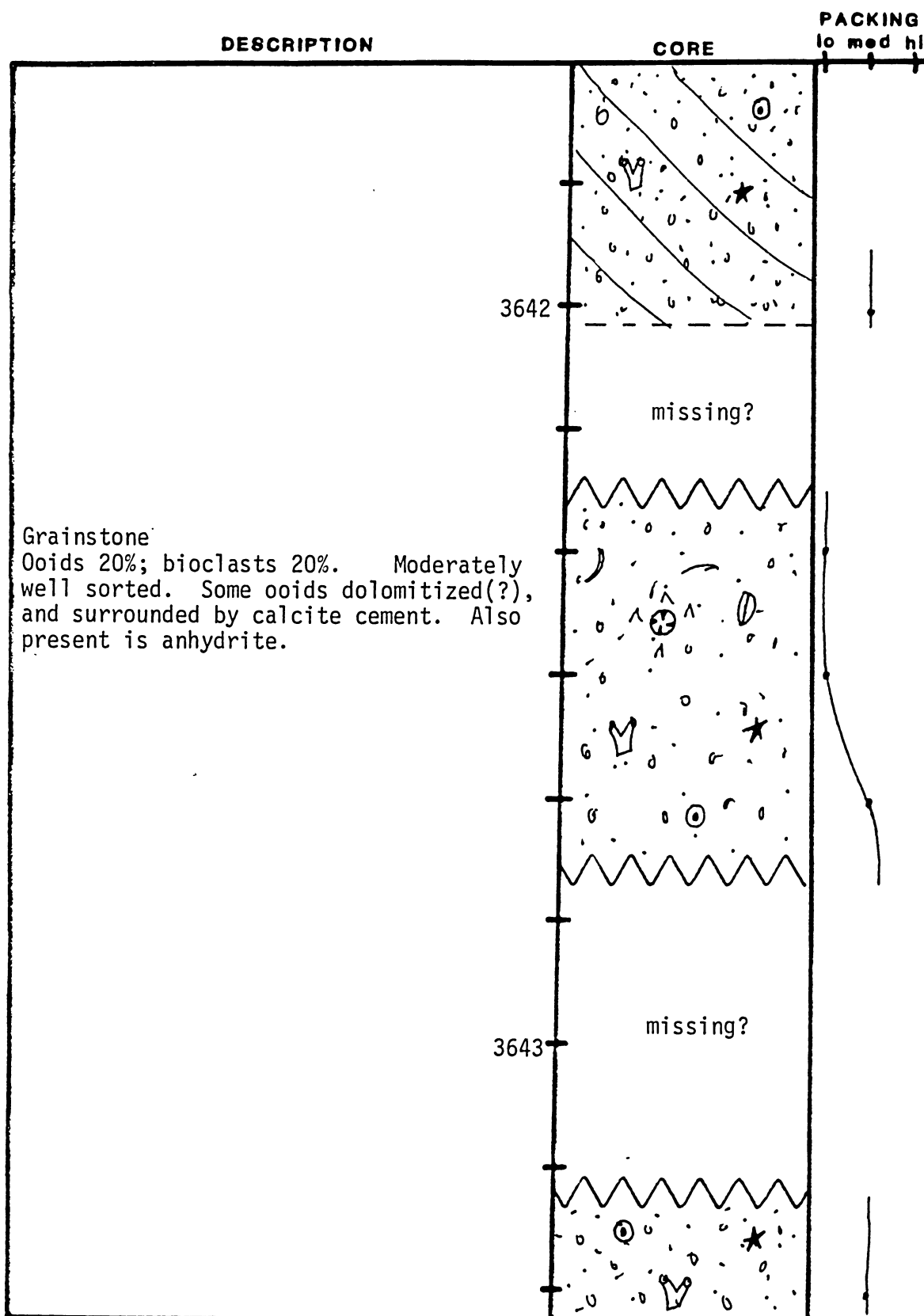


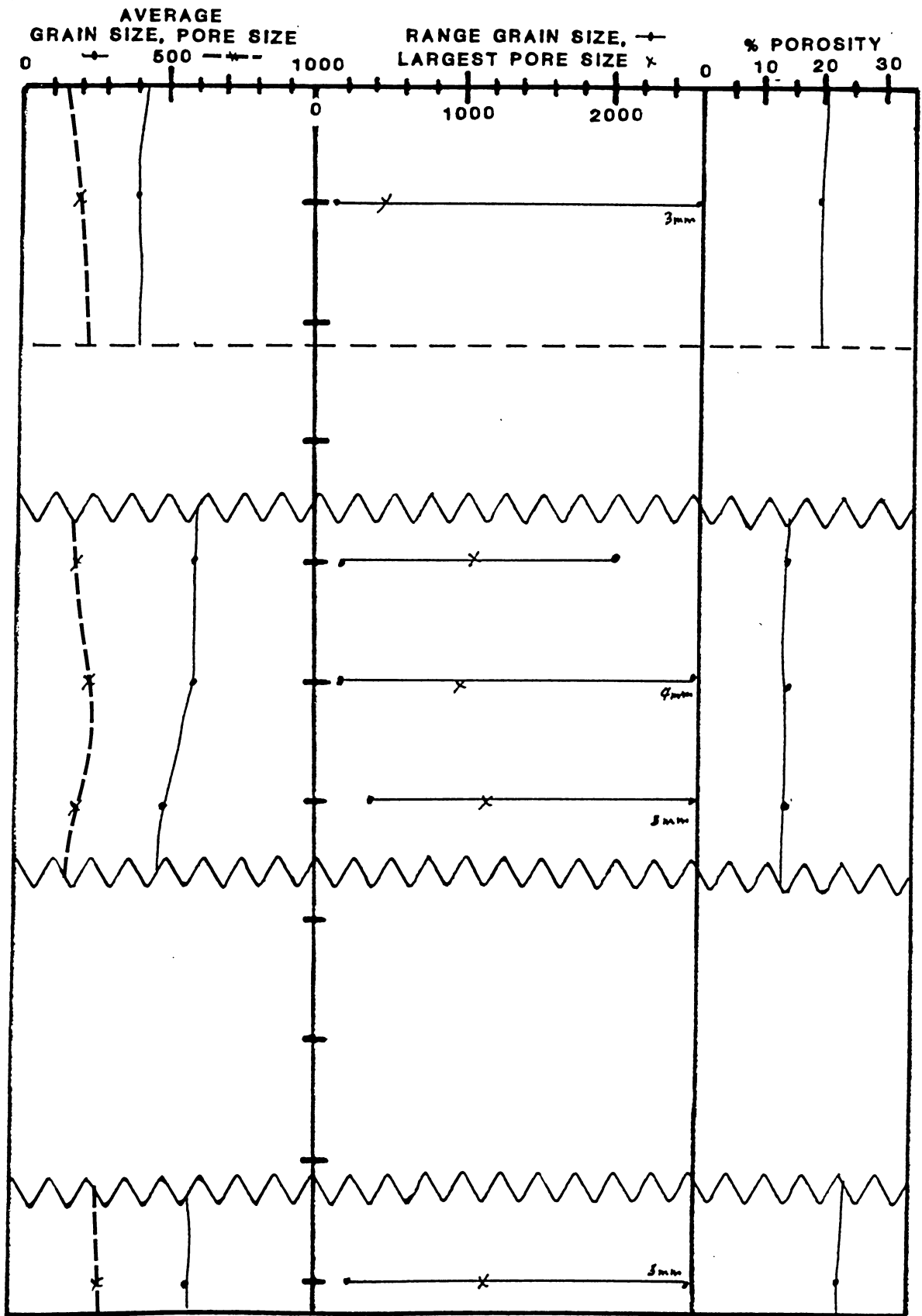
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 25%; bioclasts 25%. Moderately well sorted. Large fossil fragments; large void-filling, clear calcite cement.	missing?	
		
3639	missing	
Grainstone Ooids 25%; bioclasts 20%. Sorting variable. Some areas have a larger grain size, with much vuggy porosity and little dolomitization. Other areas are finer grained, more compacted, and have more dolomitization. Also present is clear, brown anhydrite replacing rock.		
3639		

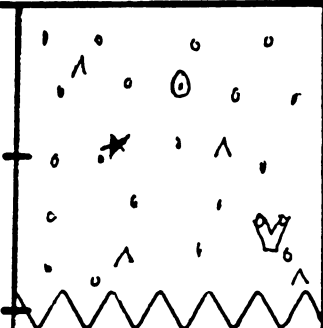
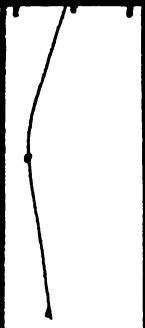
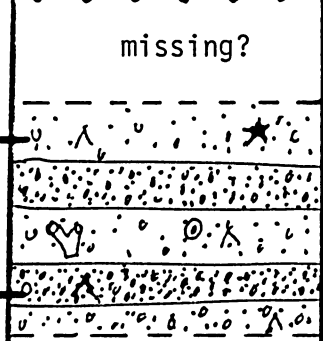
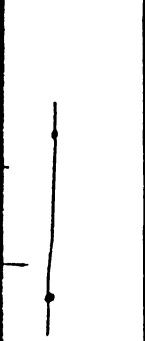
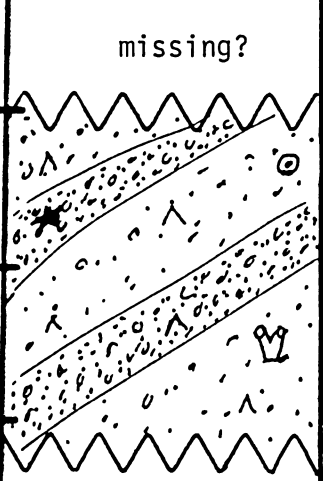
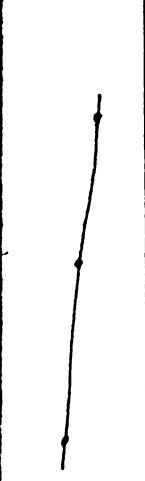
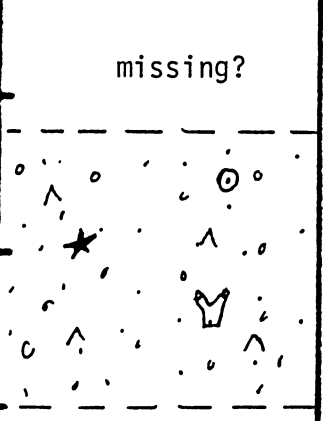
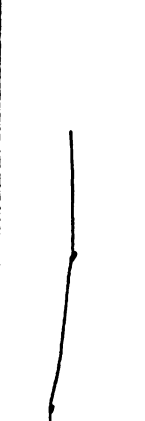


DESCRIPTION	CORE	PACKING lo mod hi
Grainstone Ooids 10%; bioclasts 30%. Moderately well sorted. Grapestone and white silt.	missing? 	
Grainstone Ooids 30-40%; bioclasts 10-15%. Moderate sorting. Very clear calcite cement	missing?  3641	
Grainstone Ooids 30%; bioclasts 25%. Moderate sorting. Some faint cross beds. Very clear calcite and anhydrite cement.	missing 	



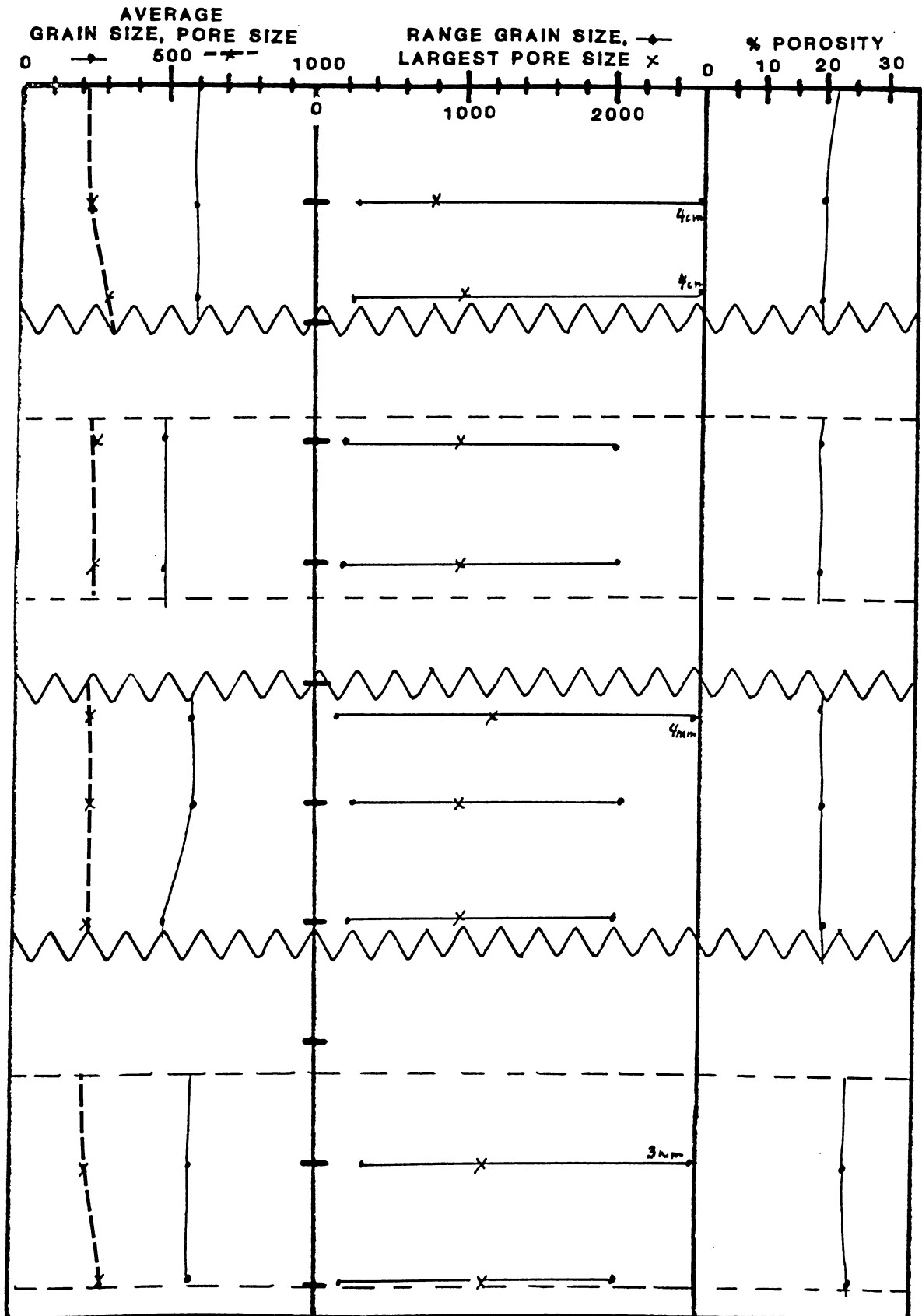


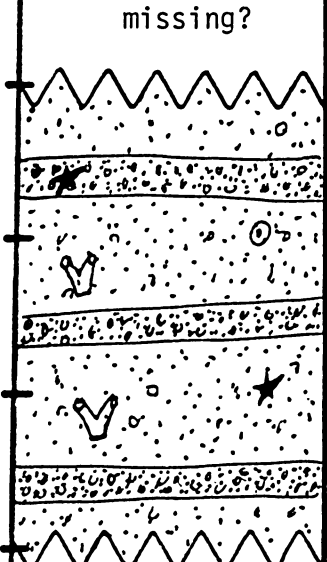
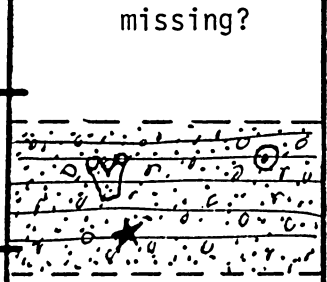


DESCRIPTION	CORE	PACKING lo mod hi
Grainstone Ooids 15%; bioclasts 20%. Well sorted. Anhydrite and calcite cement.		
Grainstone Ooids 20%; bioclasts 20%. Moderately well sorted. White silt and anhydrite.	missing? 	
Grainstone Ooids 10%; bioclasts 30%. Moderately well sorted. Cross bedded? Porosity reduced by both calcite and dolomite cement.	missing? 	
Grainstone Ooids 8%; bioclasts 40%. Moderately well sorted. Porosity reduced by anhydrite, calcite and baroque dolomite cements.	missing? 	

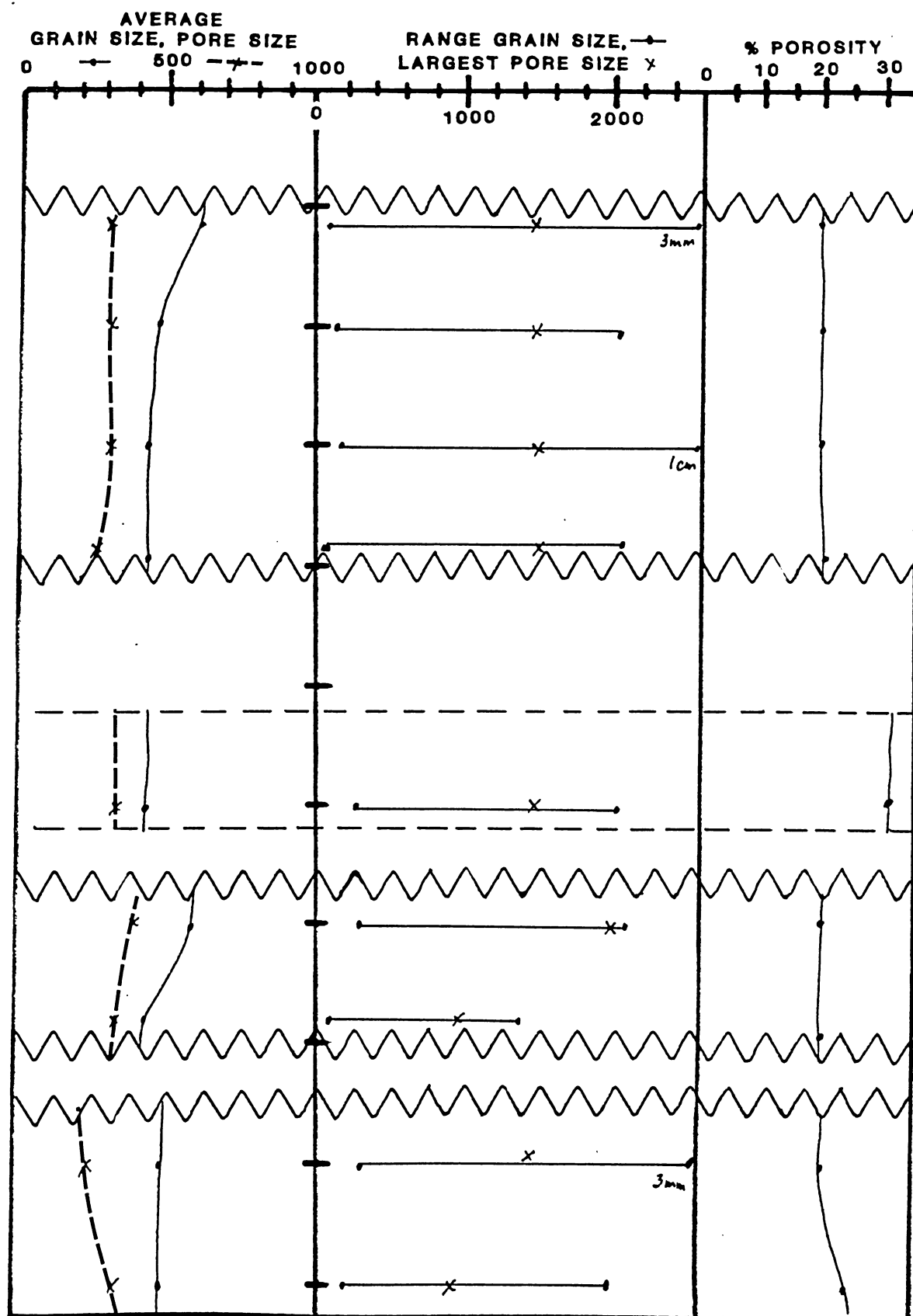
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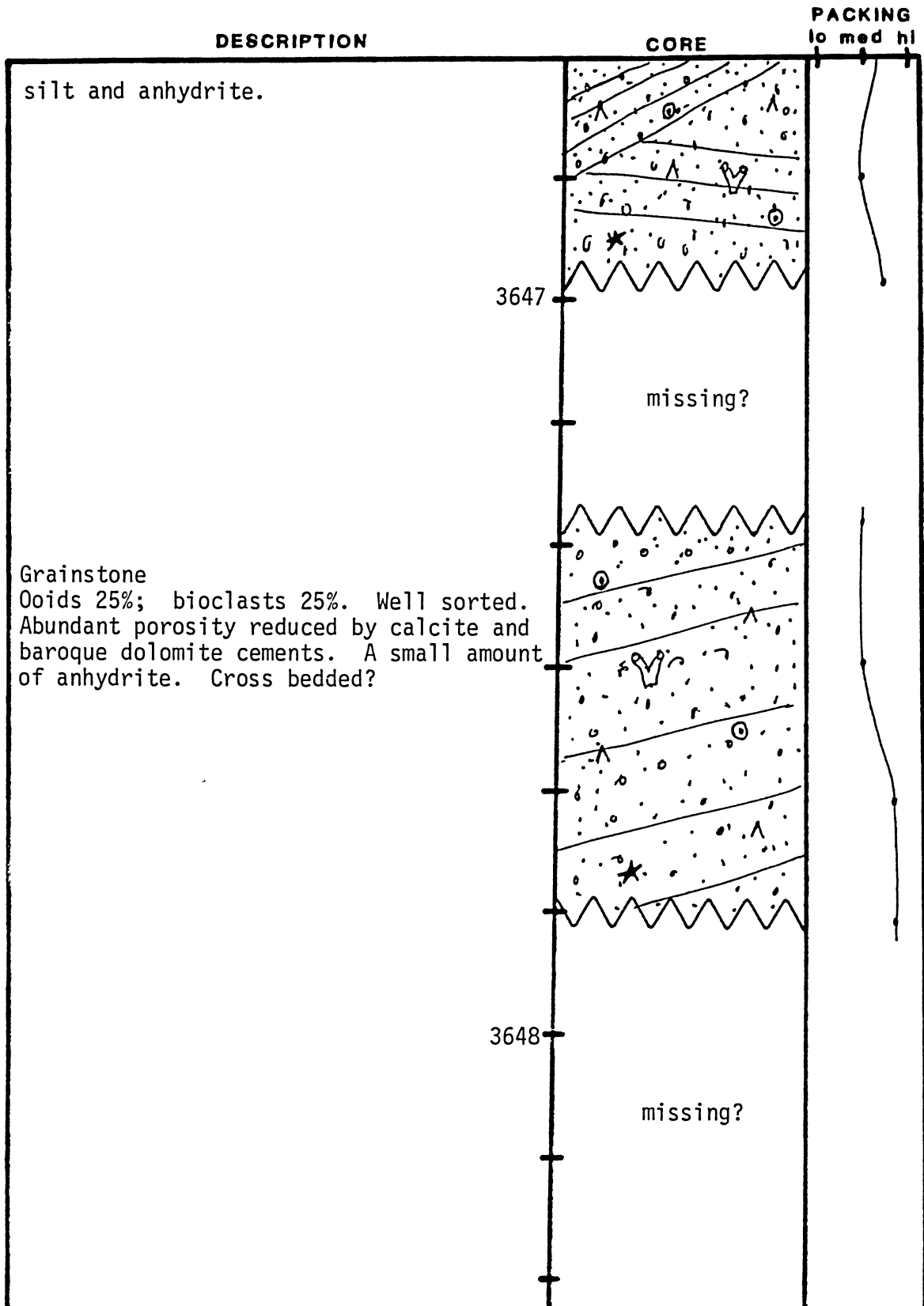
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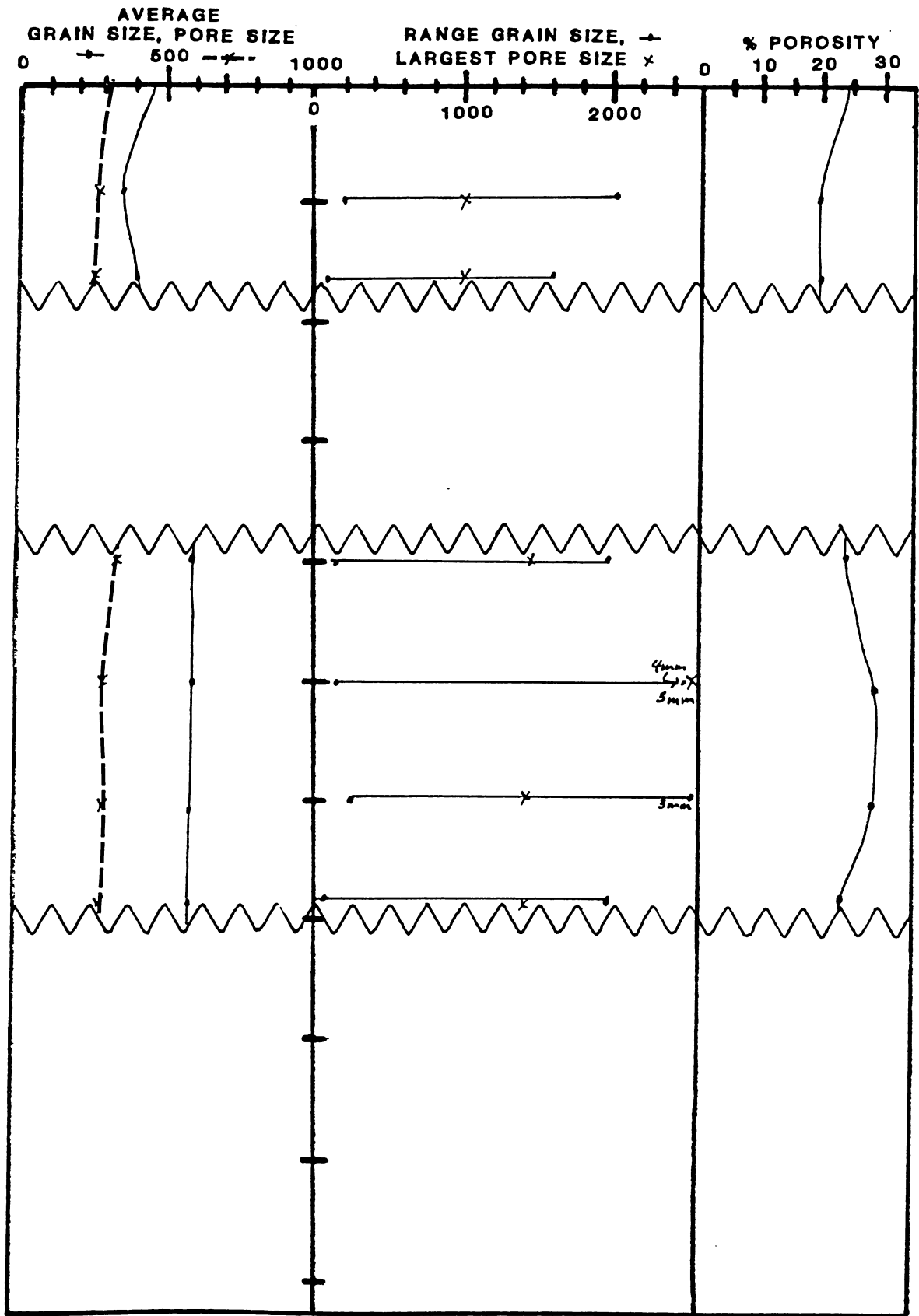


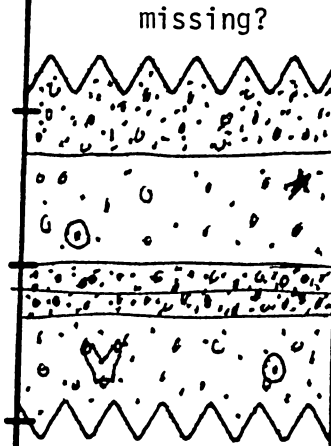
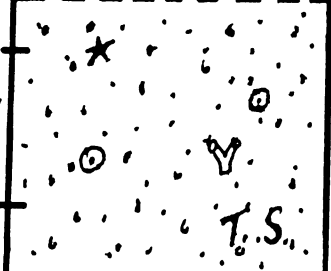
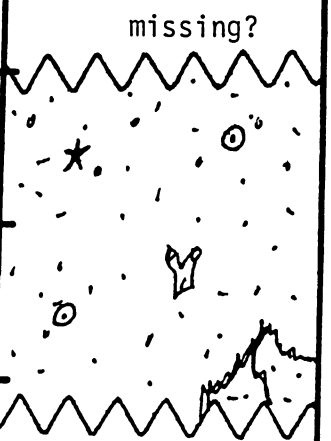
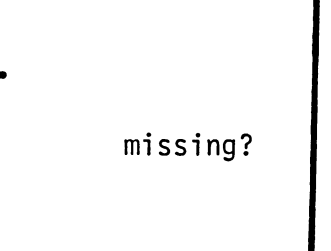
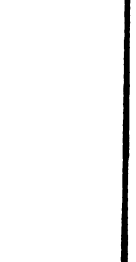
DESCRIPTION	CORE	PACKING lo mod hi
Grainstone Ooids 15%; bioclasts 25%. Moderately well sorted. Grapestone present. Porosity reduced by calcite and baroque dolomite cement.	missing? 	
Grainstone Ooids 40%; bioclasts 15%. Moderately well sorted. Both calcite and baroque dolomite cement.	missing? 	
Grainstone Ooids 10%; bioclasts 30%. Moderately well sorted. Cross bedded. Calcite and anhydrite cements, with a small amount of pyrite.	missing? 	
Grainstone Ooids 30%; bioclasts 25%. Well sorted. Banding in cross beds indicates: light colored bands=well sorted, dolomitized, fine grained ooids; dark bands=large fossil fragments, less well sorted, and mostly micritized. Abundant white	missing? 	

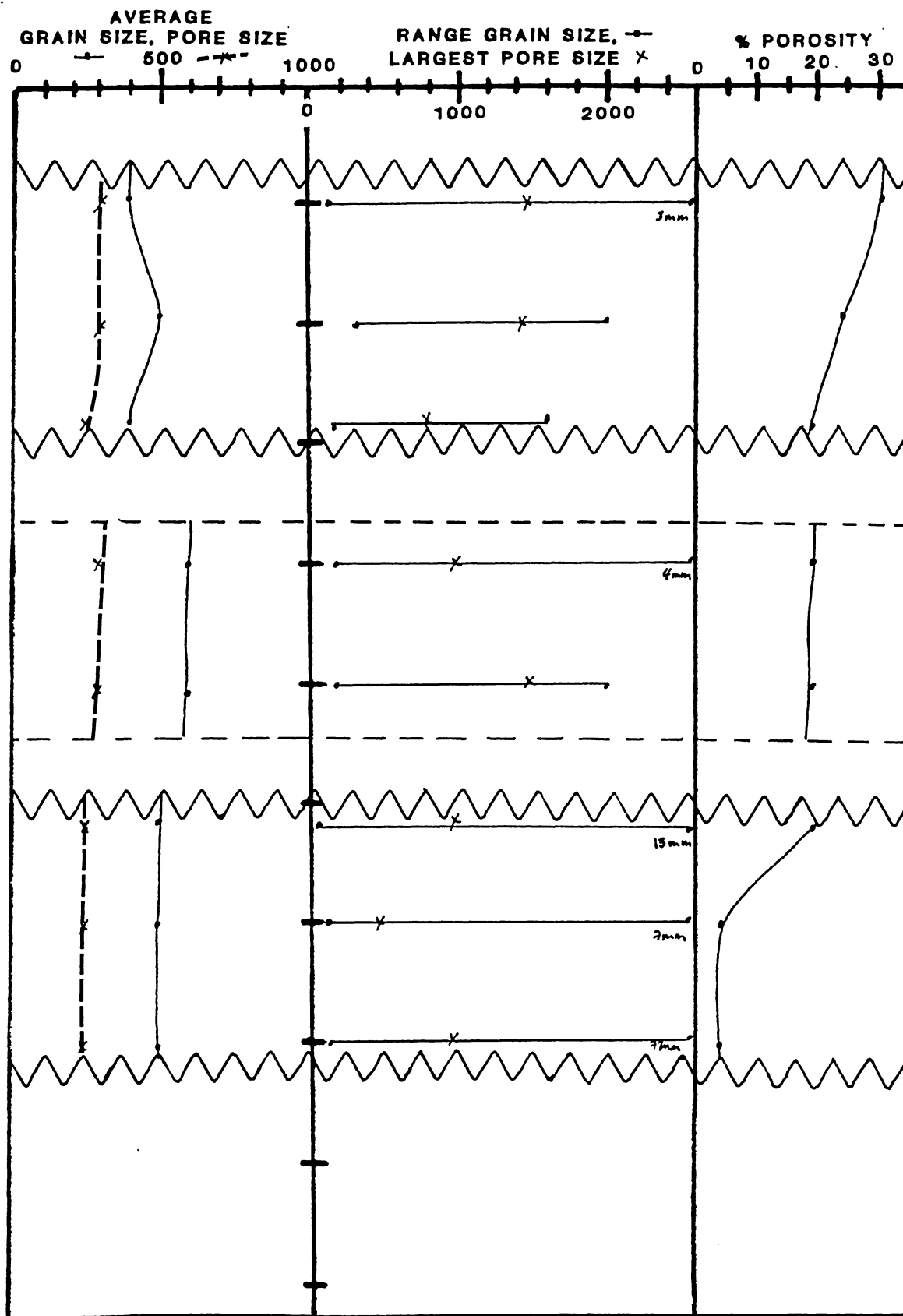
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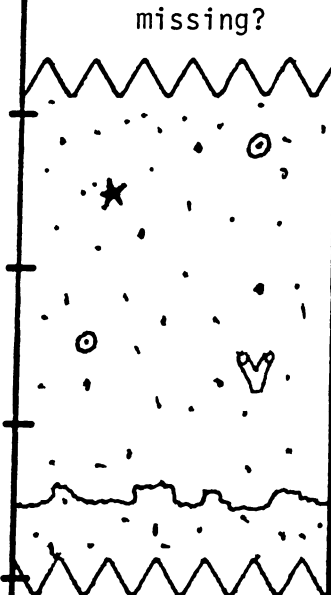
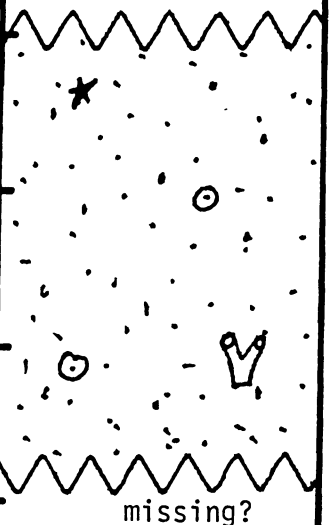


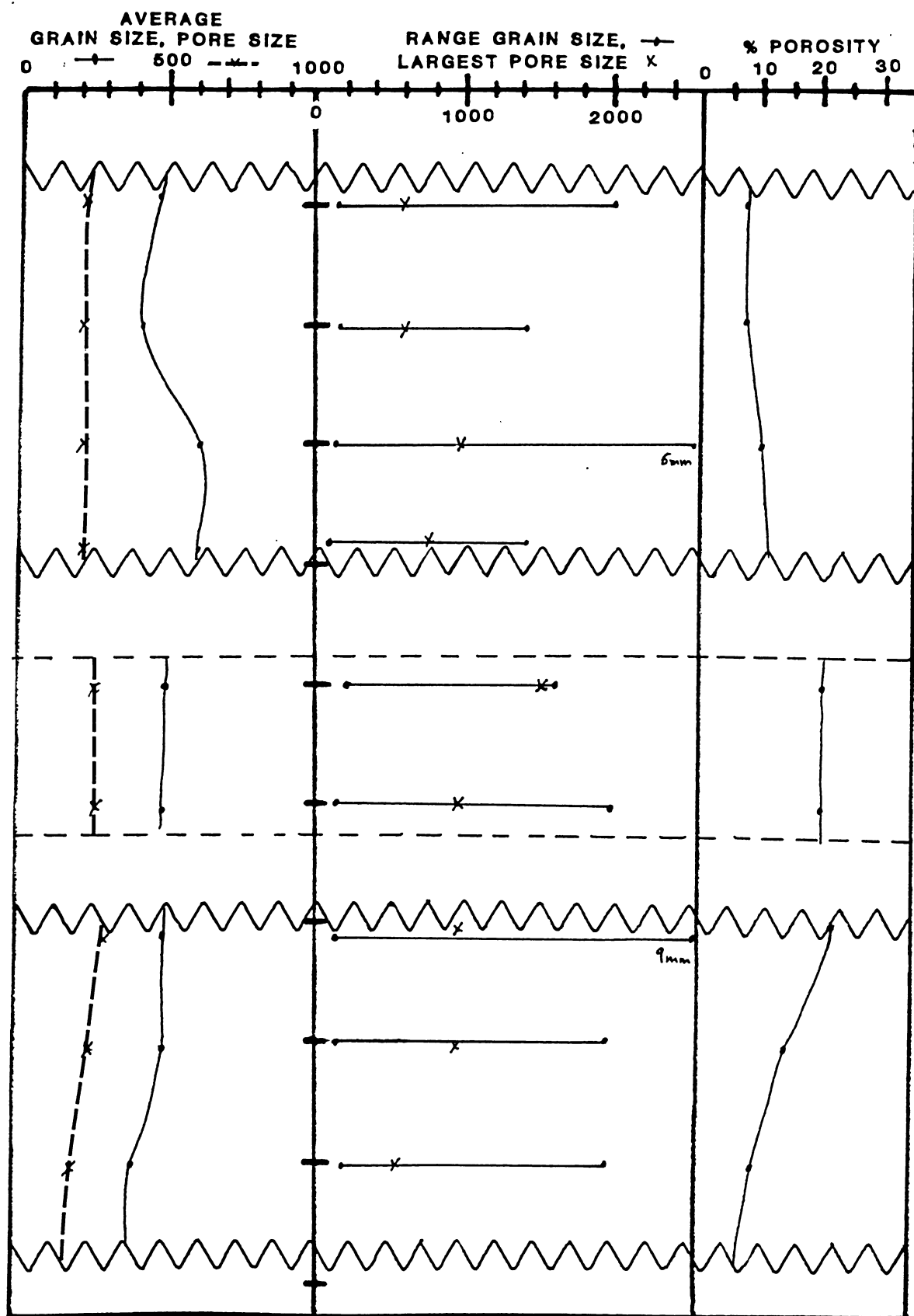


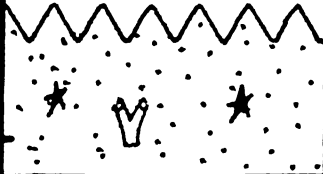


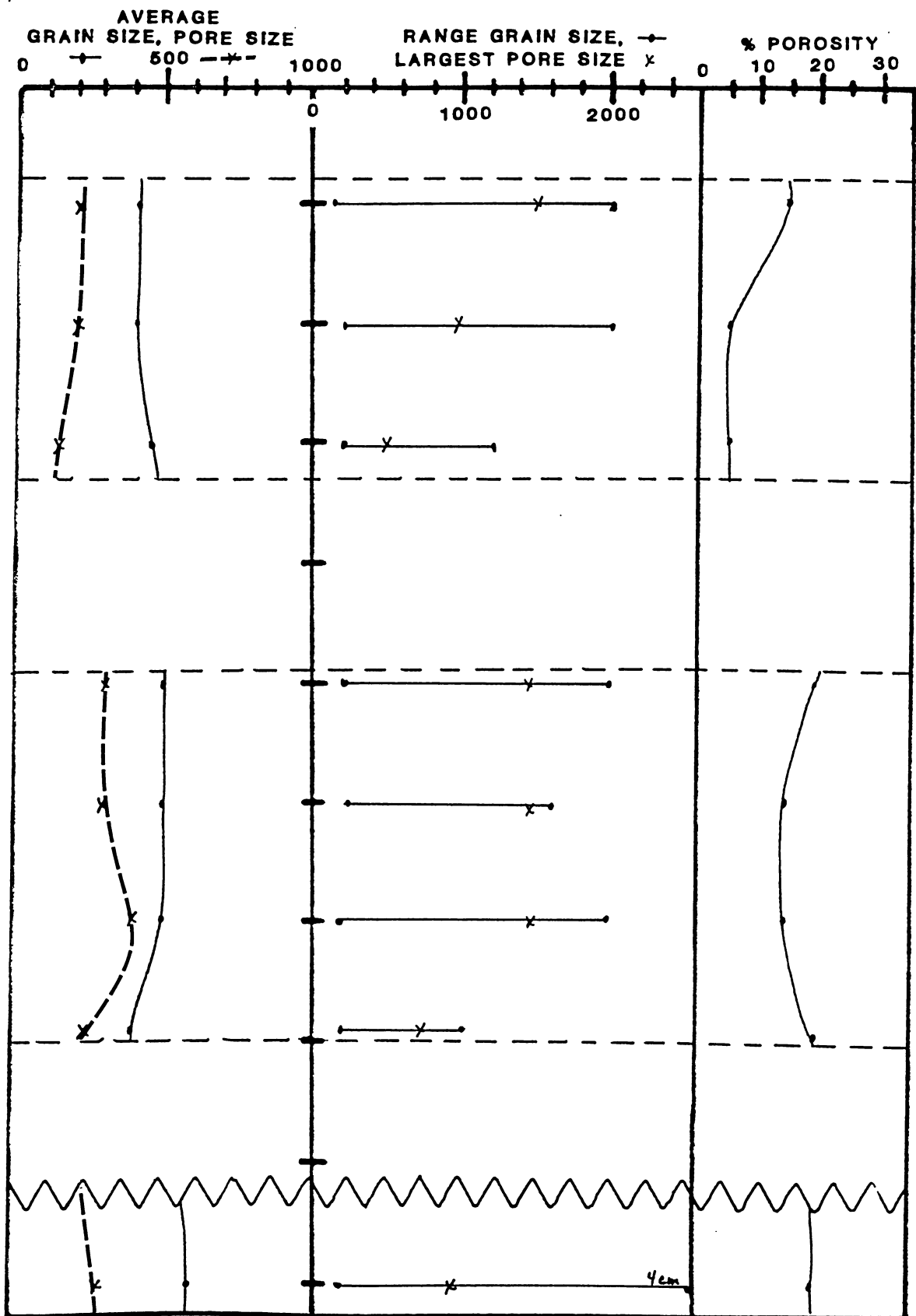
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 20%, bioclasts 20%. Well sorted. Ooids dolomitized? Porosity reduced by calcite and dolomite cement.	missing? 	
Grainstone Ooids 35%; bioclasts 20%. Extremely ³⁶⁴⁹ well sorted ooids. Abundant clear sparry calcite and baroque dolomite.	missing? 	
Grainstone Ooids 30%; bioclasts 10%. Very well sorted; relatively fine grained. Stylolite associated with abundant clear sparry calcite and baroque dolomite cement. Grapestone present.	missing? 	
3649	missing? 	

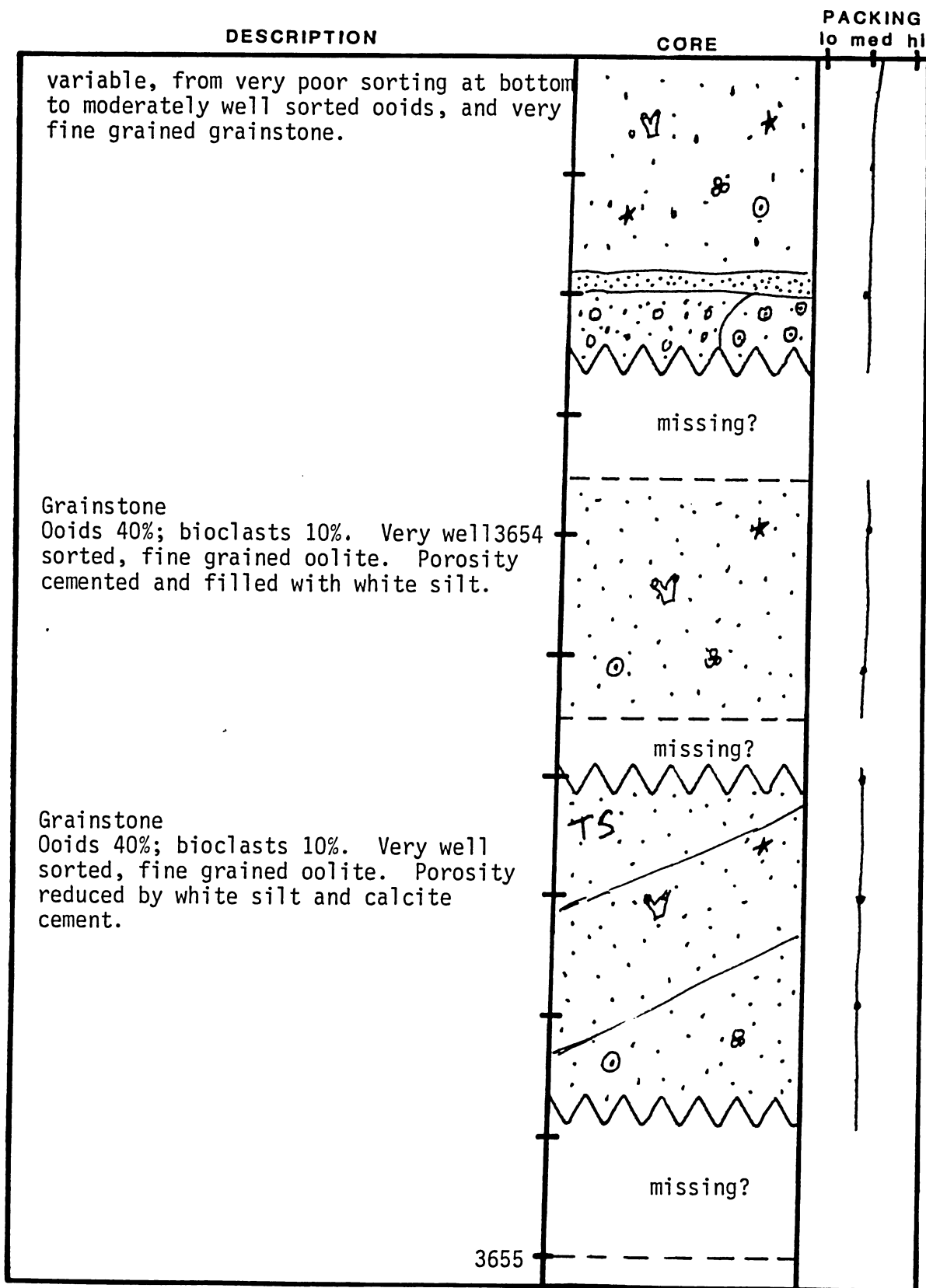


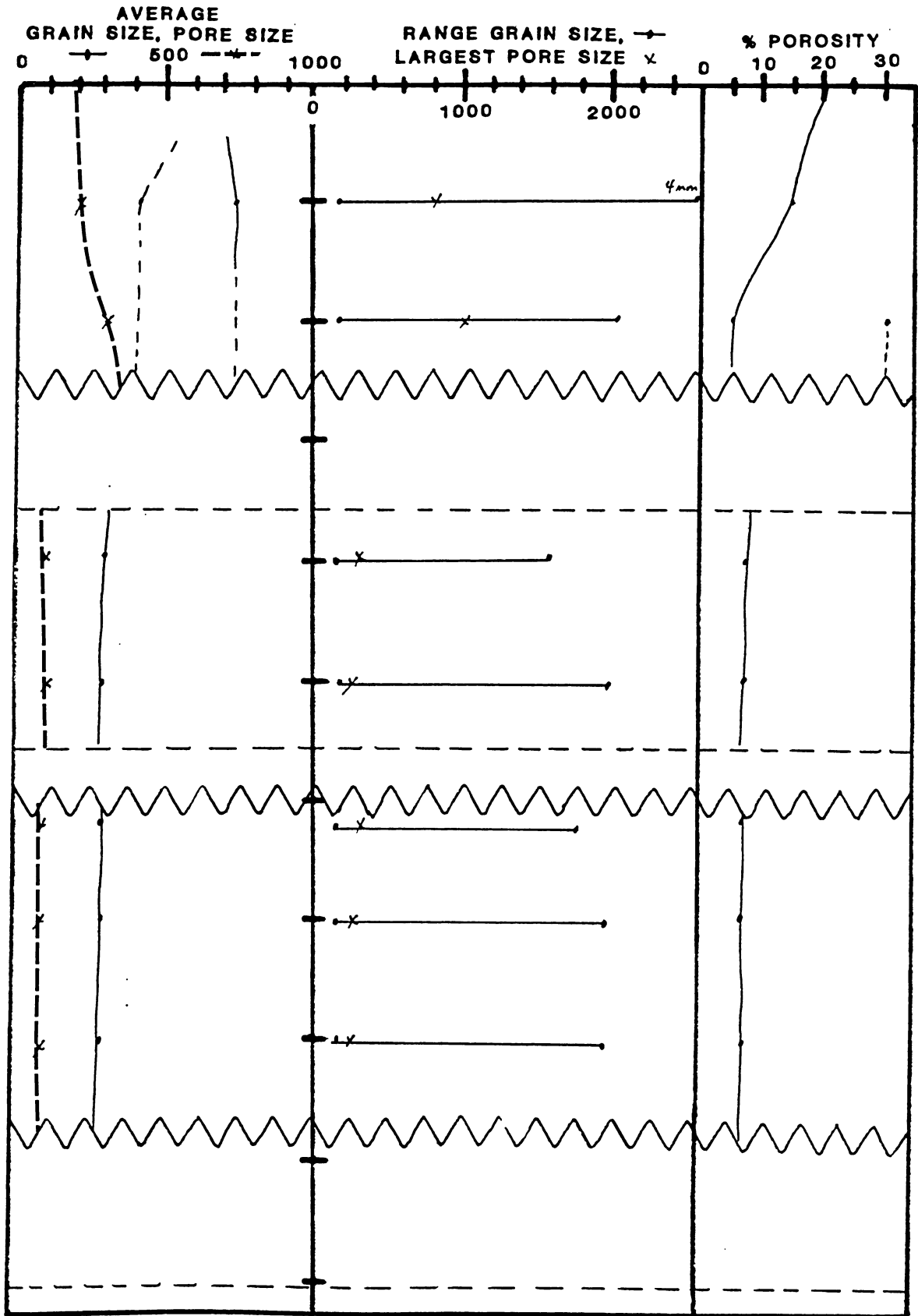
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 30%; bioclasts 30%. Well sorted ooids. Stylolite and sutured grains. Below stylolite, abundant white silt, which prevents compaction and suturing.	missing? 	
Grainstone Ooids 25%; bioclasts 25%. Moderate-poor sorting. White silt, anhydrite, and calcite cement reduce porosity. Sutured grains.	missing? 	
Grainstone Ooids 5%; bioclasts 40%. Moderately well sorted. Abundant calcite cement and white silt. Sutured grains.	missing? 	



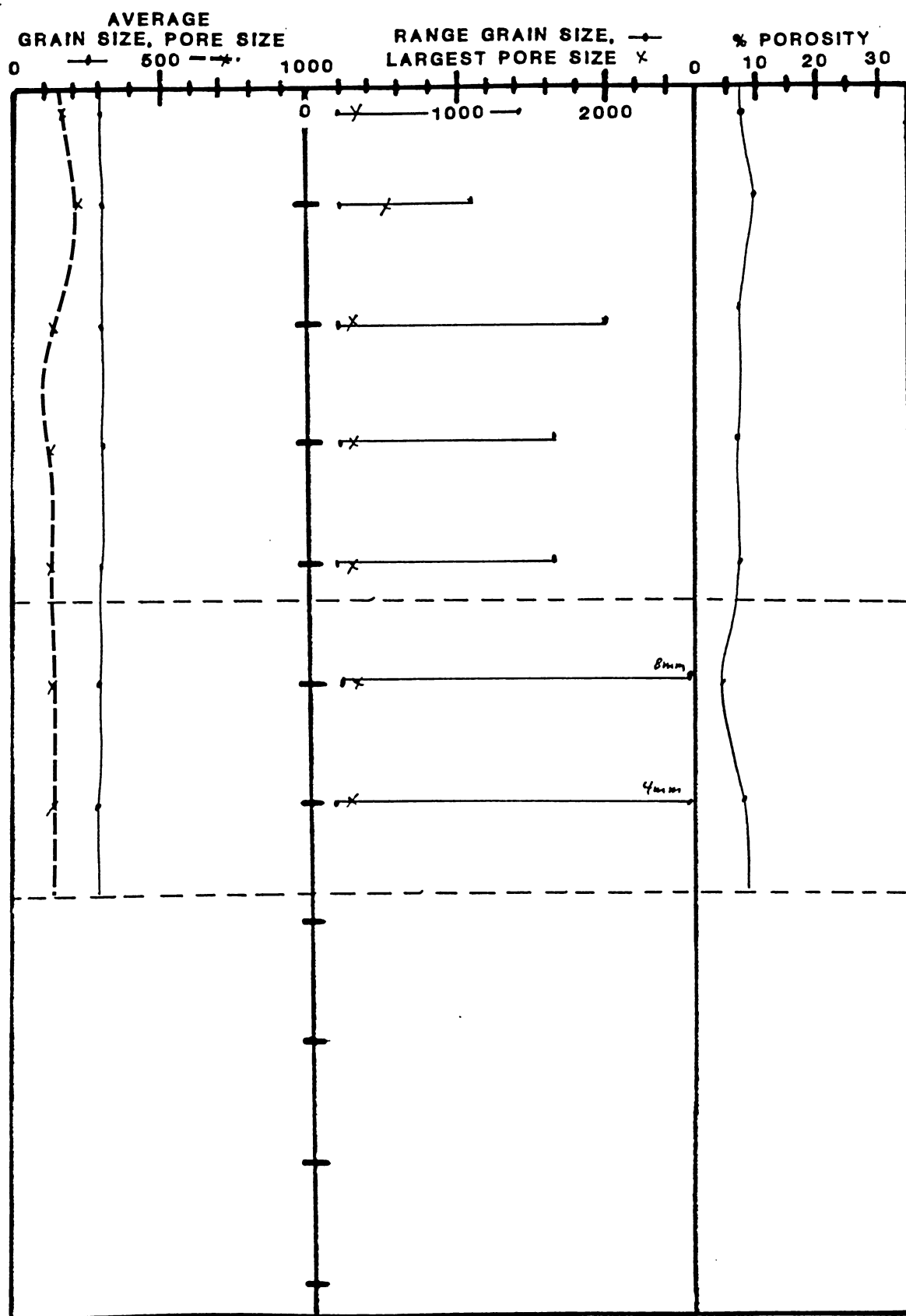
DESCRIPTION	CORE	PACKING lo med hi
Grainstone Ooids 5%; bioclasts 40%. Well sorted. Grains appear equally spaced, separated by white silt. Abundant calcite cement.	missing 3652 TS	
Grainstone Ooids 8%; bioclasts 40%. Moderate-poor sorting. Abundant white silt and calcite cement.	missing 3653	
Grainstone Ooids 10%; bioclasts 30%. Sorting	missing? 	



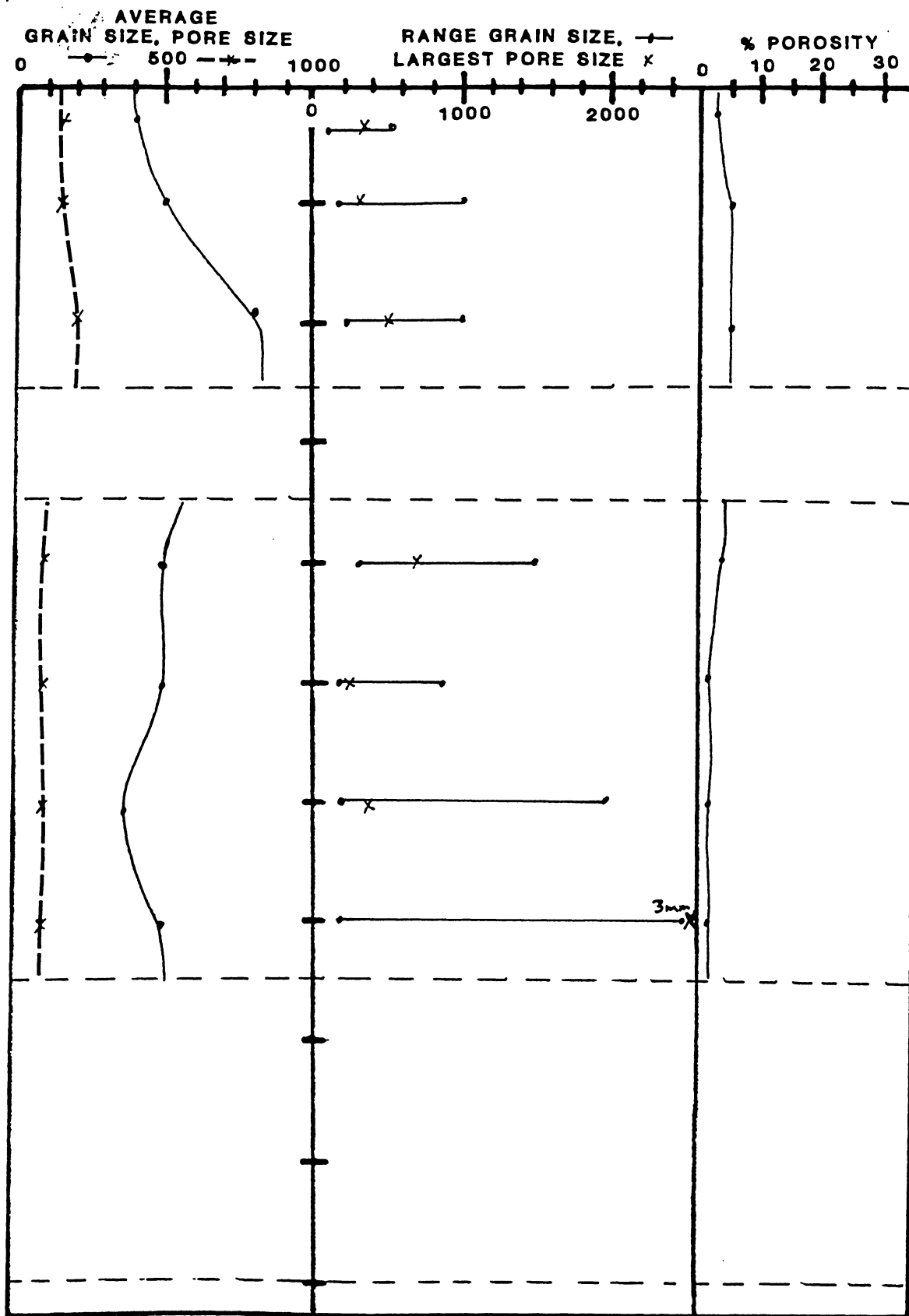


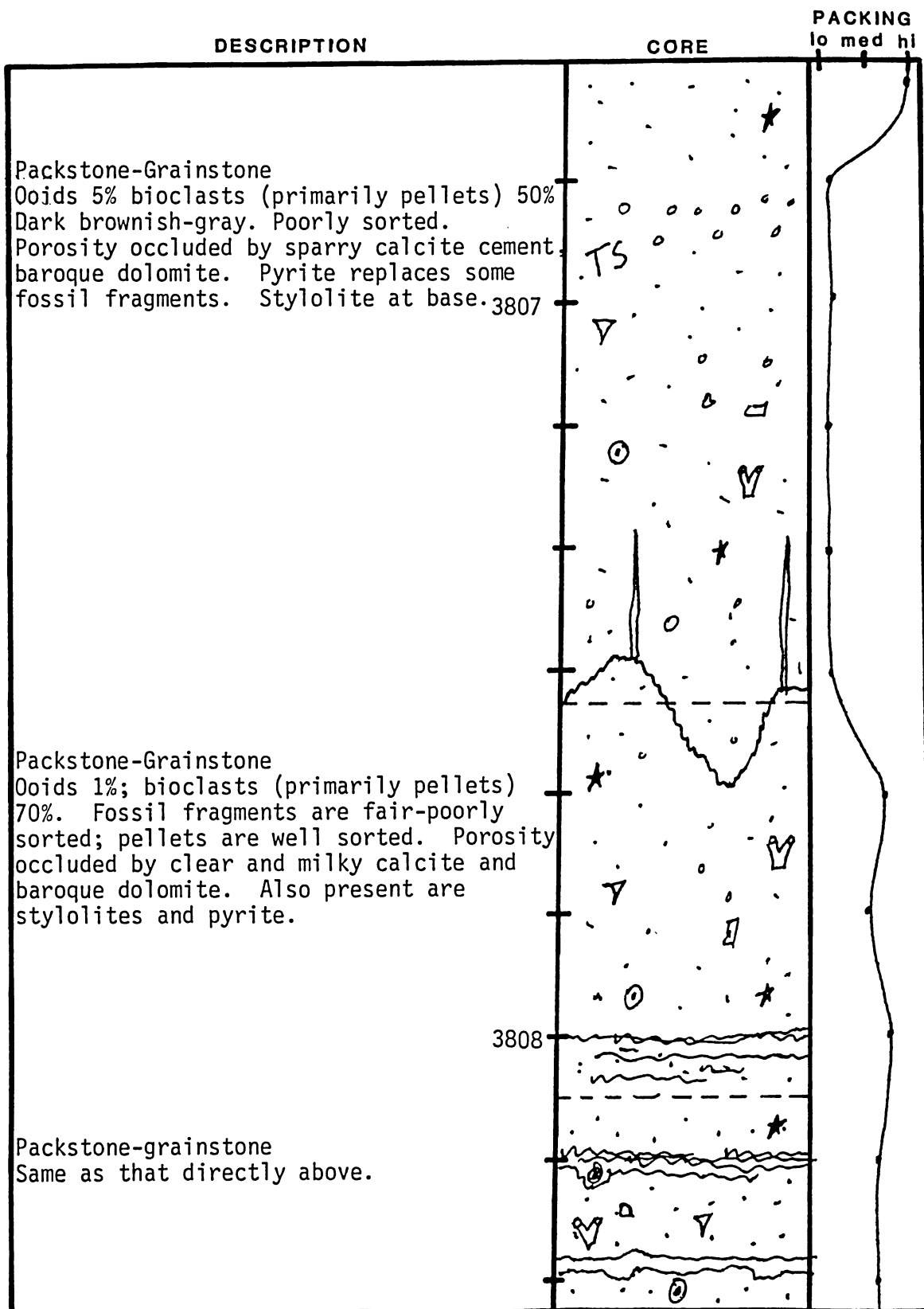


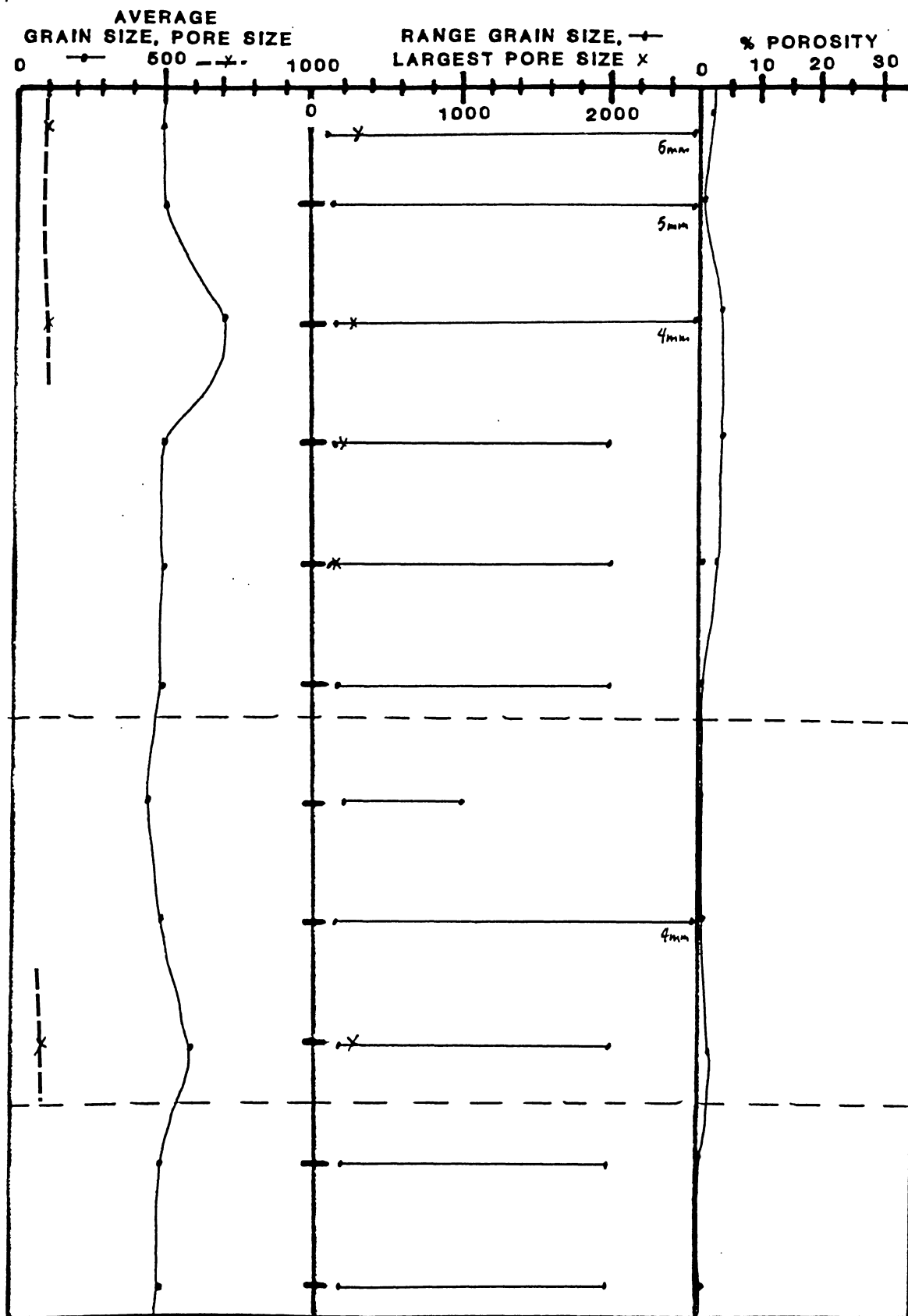
DESCRIPTION	CORE	PACKING lo med hi
3655 Grainstone Ooids 25-35%; bioclasts 25%. Well sorted. Porosity occluded by white silt, a small amount of baroque dolomite, and abundant calcite cement. At bottom, where small stylolites occur, the white silt is absent		
Grainstone Ooids 20%; bioclasts 30%. Sorting variable. In general, very fine grained, with porosity occluded by abundant white silt and calcite cement. A small amount of baroque dolomite. Large stylolite.	3656	

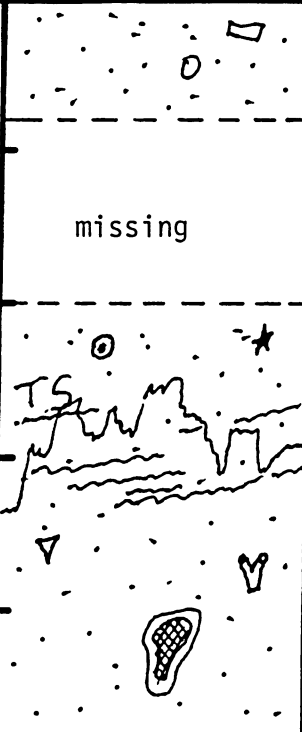
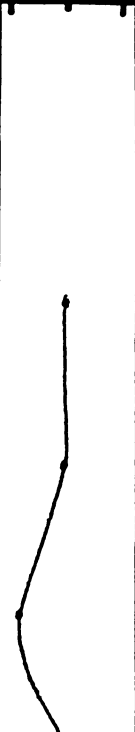
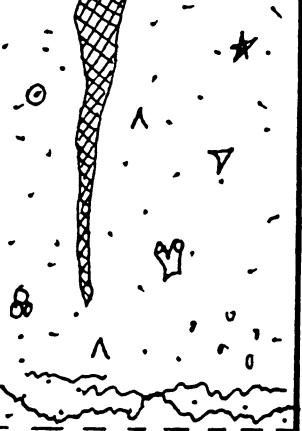


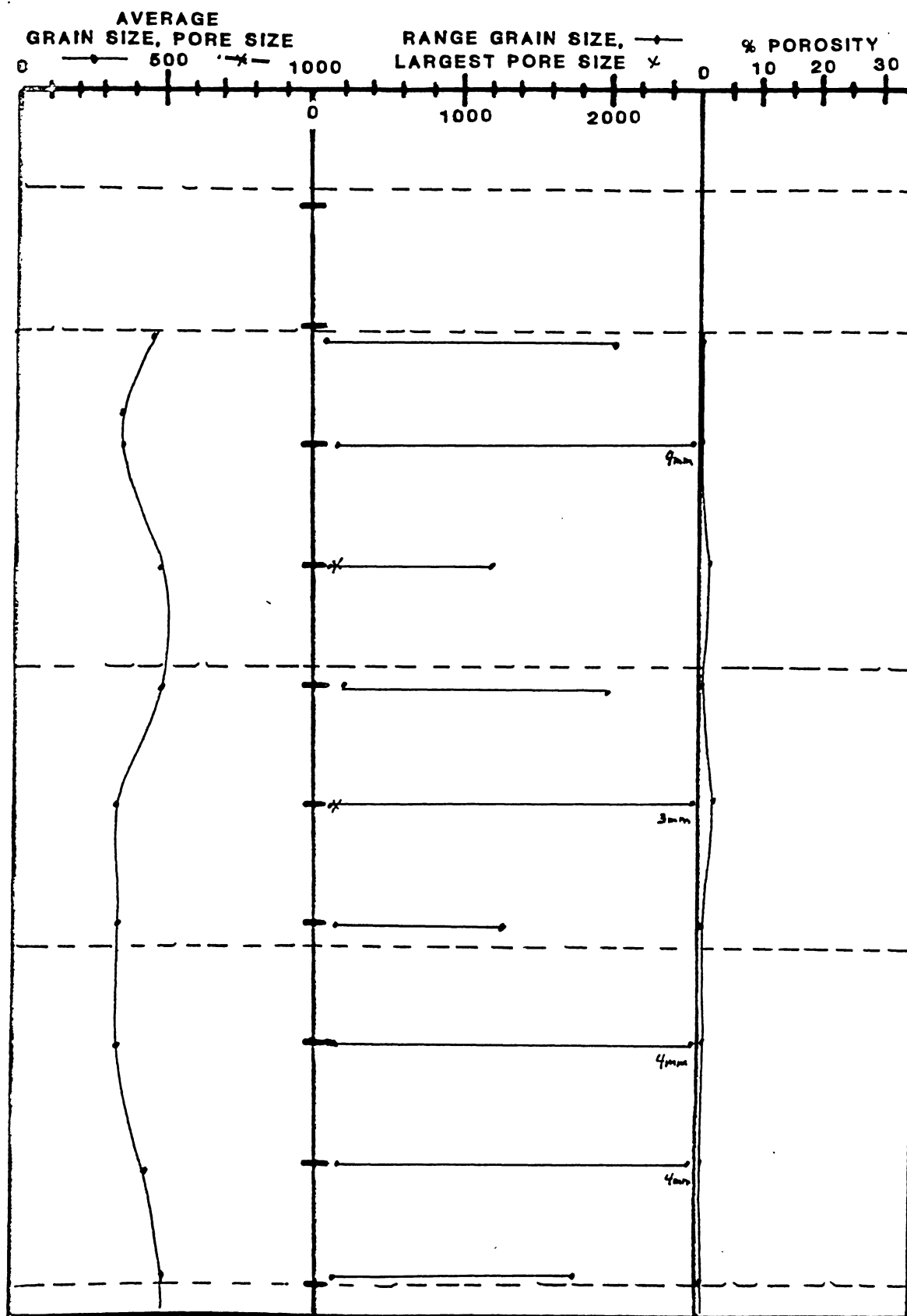
MEPCO DESCRIPTION	CORE	PACKING lo med hi
3805 Packstone Ooids 50%; bioclasts 30%. Dark gray. Well sorted. Porosity reduced by sparry calcite. Pyrite grains around fossil fragments. Pellets also present.		
Packstone-Grainstone Ooids 40-50%; bioclasts 10-15%. Dark brownish gray. Moderately well sorted. Pellets present. Porosity reduced by sparry dolomite and calcite, some of which is brown. Stylolites at base.	missing 	
3806 missing	missing	

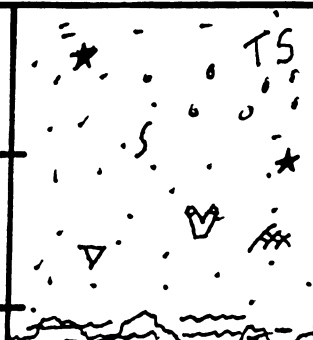
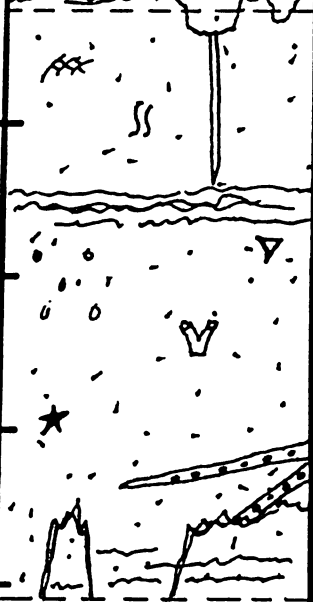
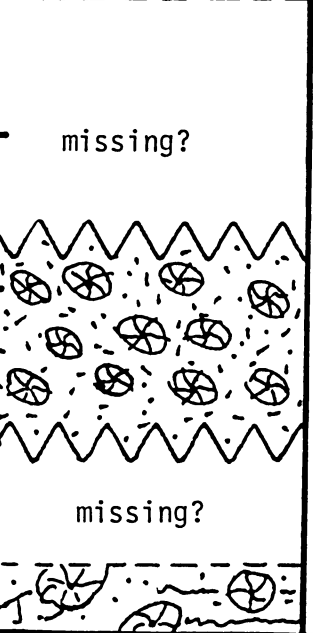


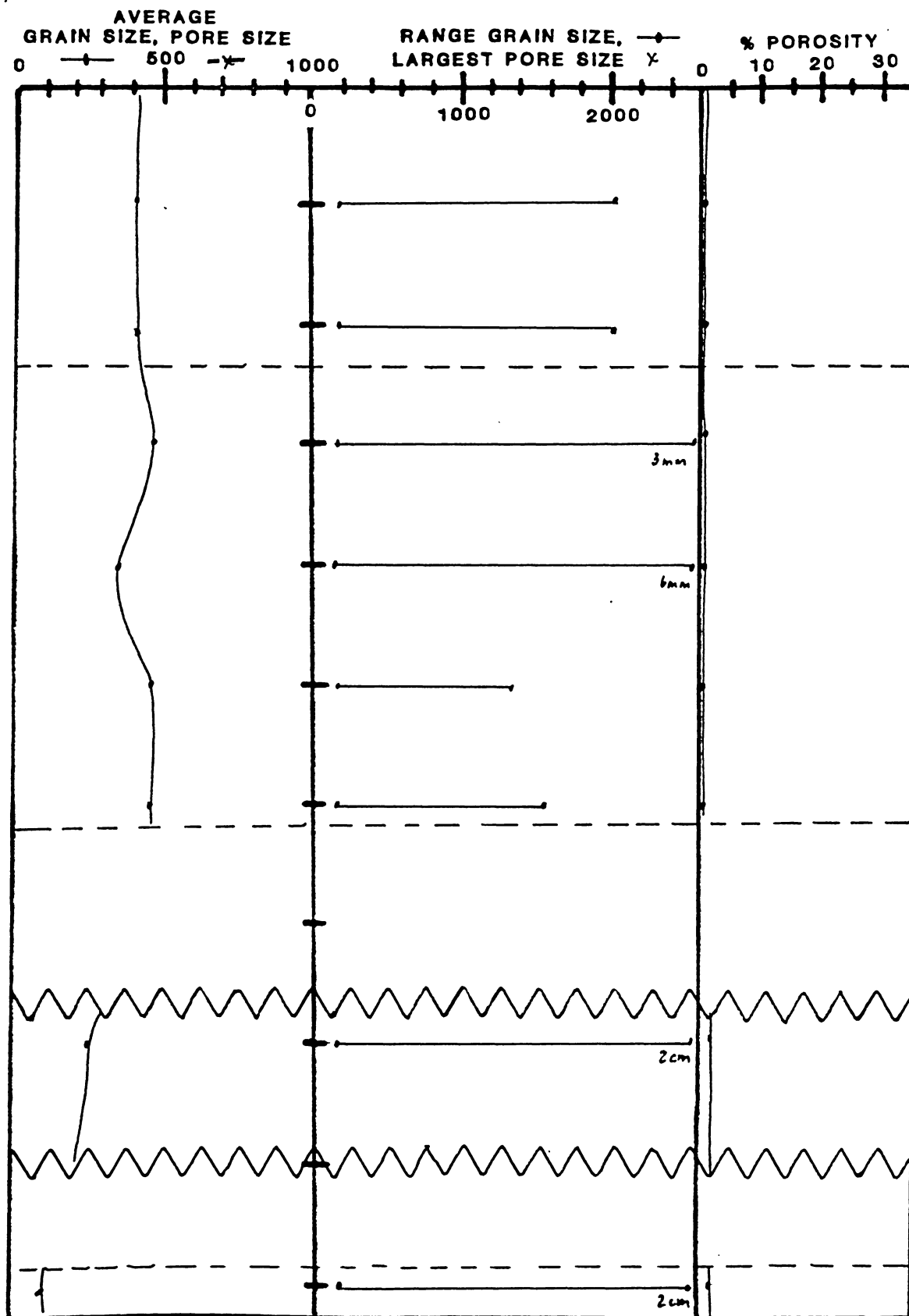


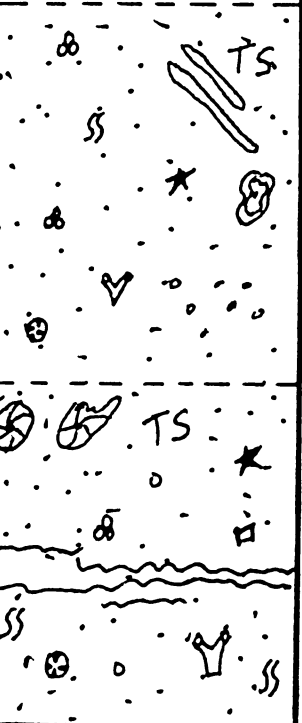


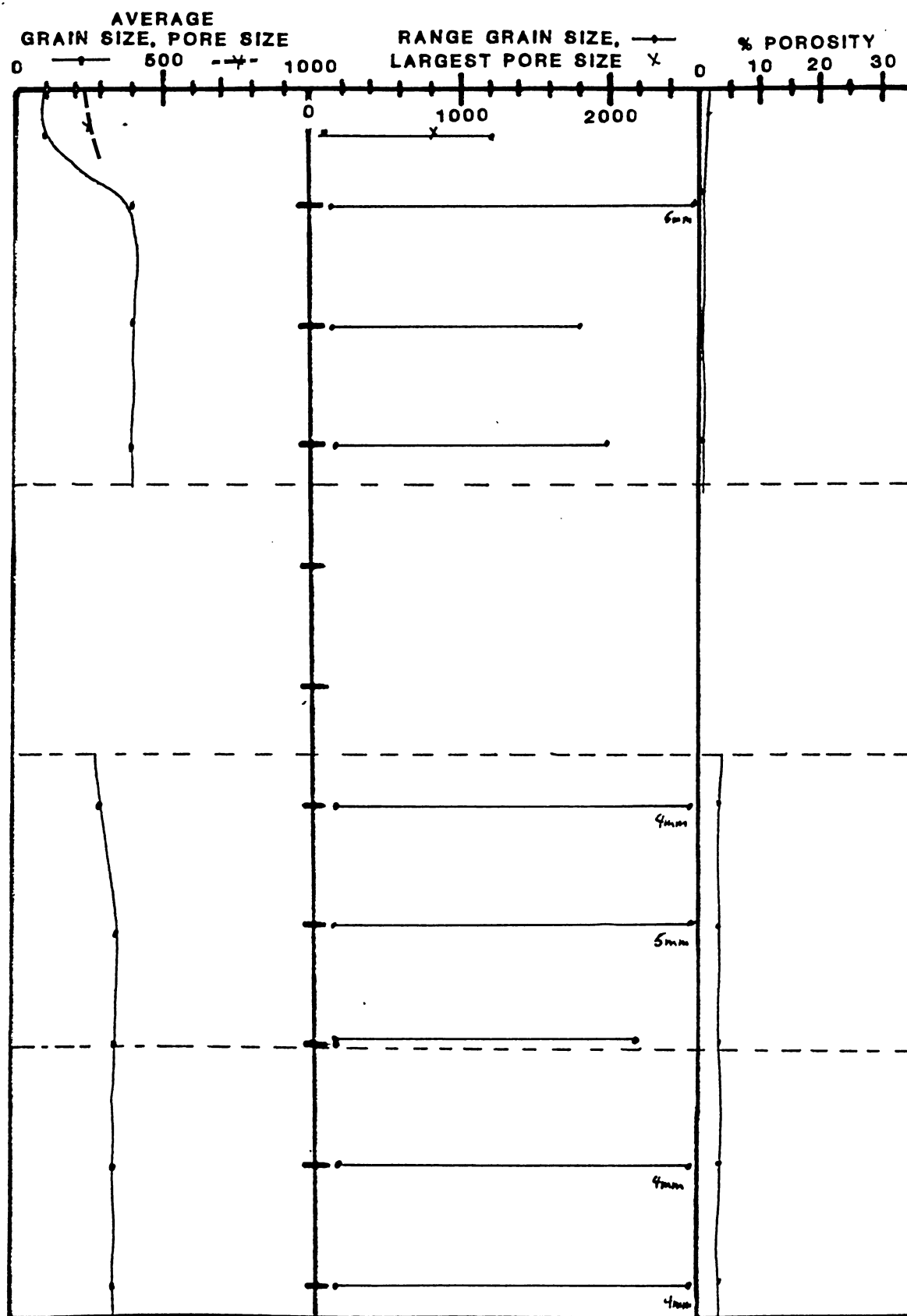
DESCRIPTION	CORE	PACKING lo med hi
Grainstone. Oolitically-coated grains 20%; bioclasts (primarily pellets) 70%. Well sorted. Geopetal silt in whole fossil fragments. Porosity occluded by milky calcite and baroque dolomite. Stylolites.	 missing 3809	
Grainstone. Bioclasts 15-20%; pellets 60%. Medium gray-brown. Well sorted. Porosity occluded by calcite cement, baroque dolomite, and anhydrite.		
Grainstone Bioclasts 25%; pellets 40%. Well sorted. Fracture filled with sparry calcite. Porosity occluded by calcite, baroque dolomite, and a small amount of anhydrite.	 3810	

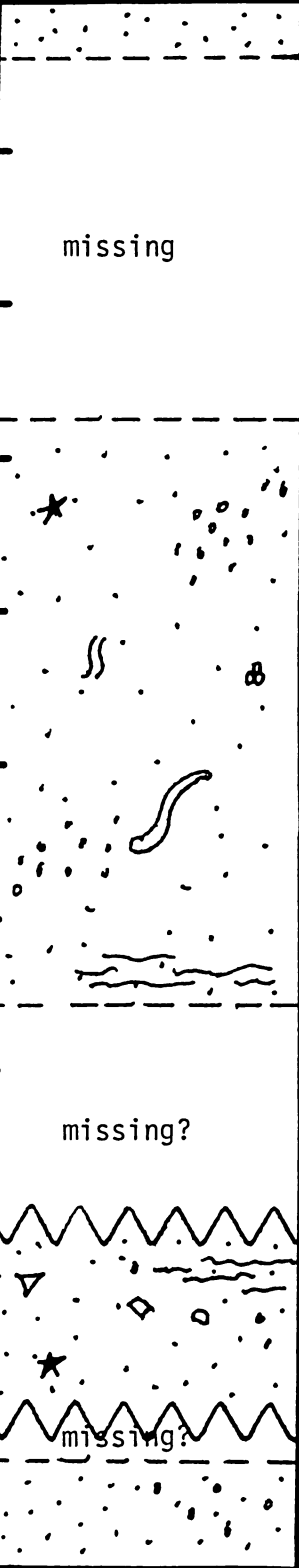


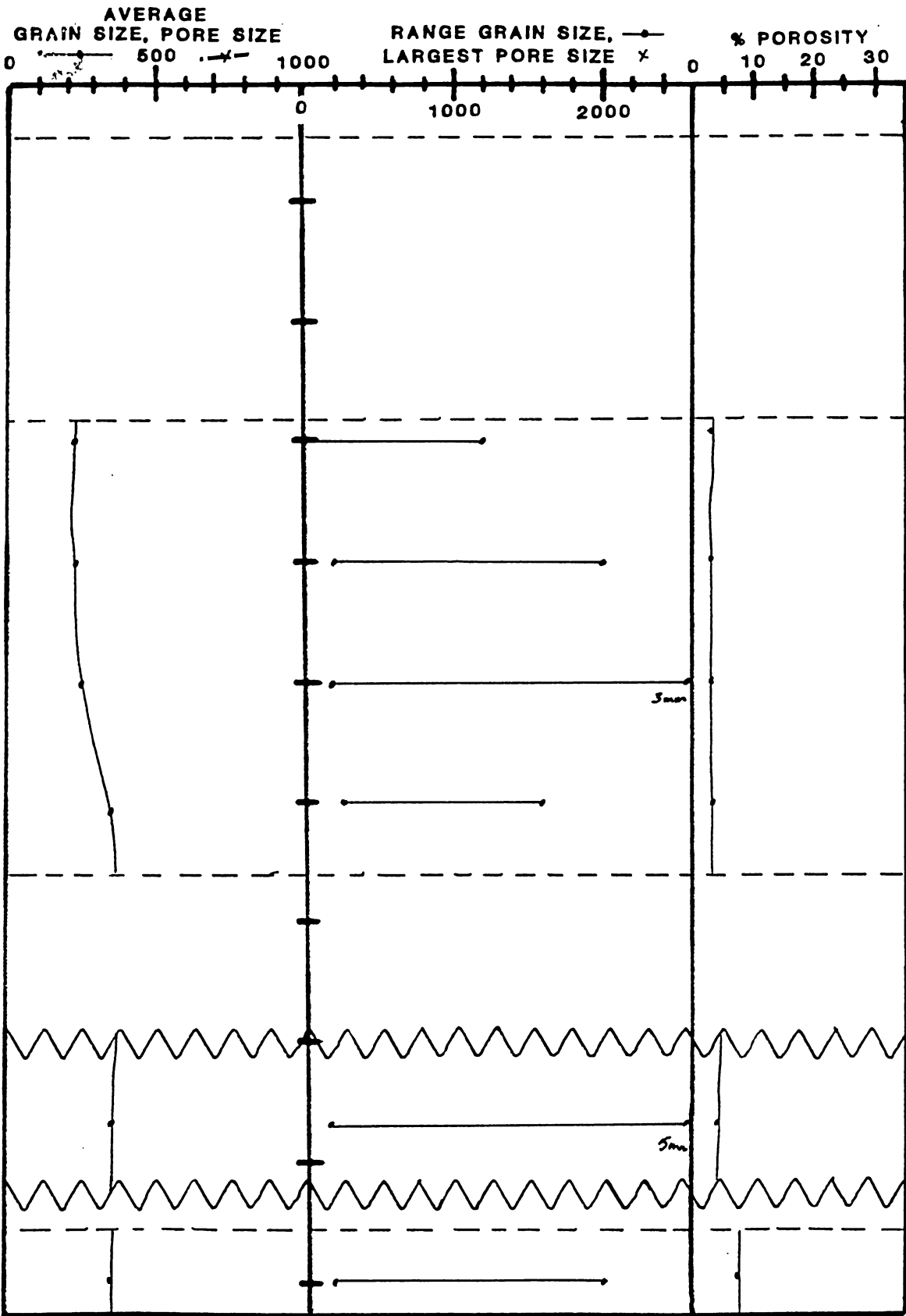
DESCRIPTION	CORE	PACKING lo med hi
Packstone-Grainstone Fossil fragments 15-20%; pelloids 60%. Moderately well sorted. Geopetal fillings and pyrite replacement in some fossil fragments. Porosity reduced by calcite cement and baroque dolomite. Many microstylolites.		
Packstone-Grainstone Fossil fragments 20%; pelloids 60%. Dark gray-brown. Moderate-poor sorting. Porosity occluded by several generations of calcite cement; baroque dolomite. Some pyrite in fossil fragments. Many stylolites.		
Dolostone Rugose coral colony in fine-grained dolomite matrix. Some of this matrix has filtered into corallites, others are matrix-free. All corallites are filled with clear, sparry anhydrite	missing?  missing?	



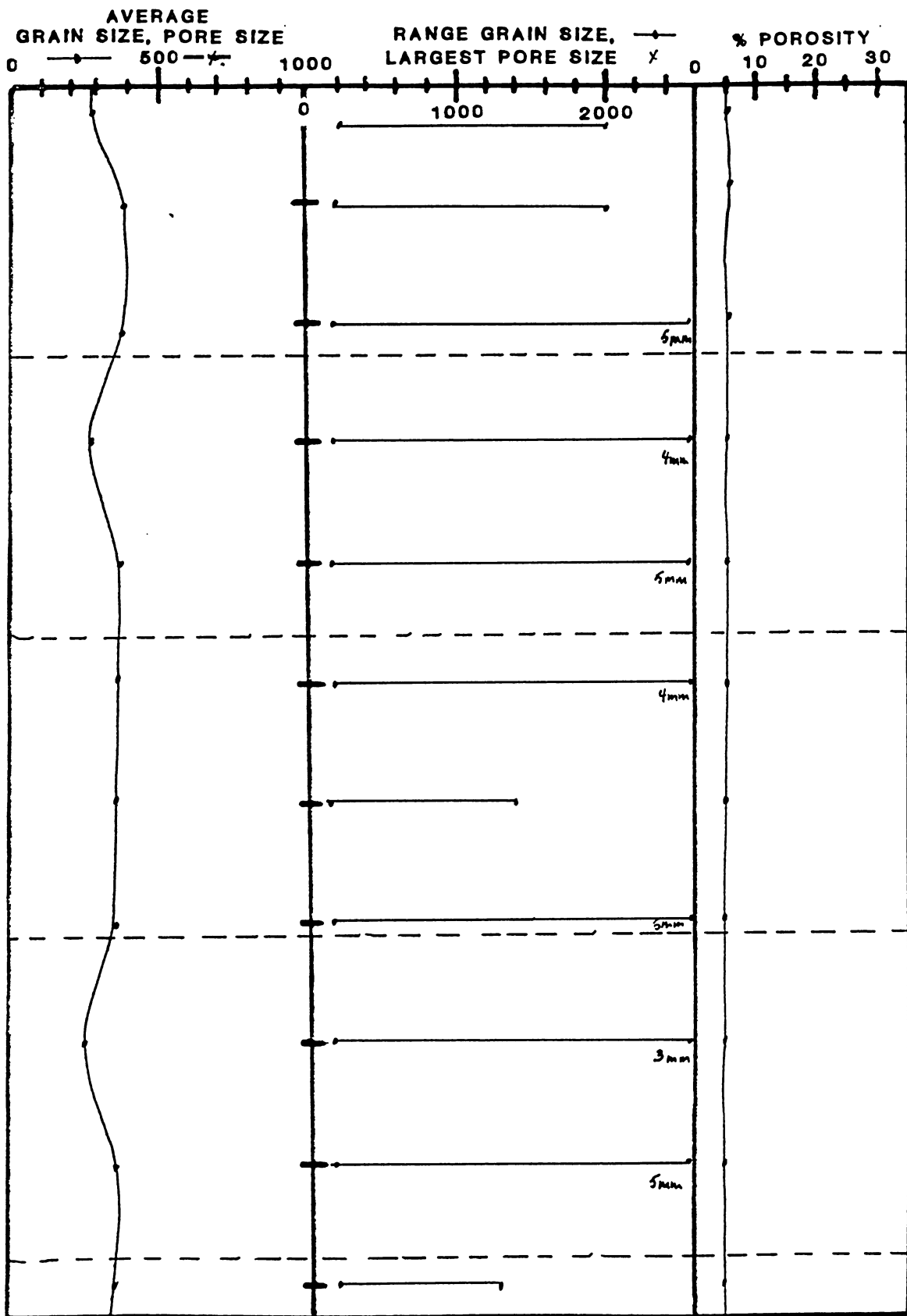
DESCRIPTION	CORE	PACKING lo med hi		
Dolostone Fossil fragments 20%. Brownish-gray. Moderately well sorted. Fossil fragments in a fine grained dolomite matrix. Rugose corals replaced with anhydrite. Many small stylolites.	 3812			
	missing			
Dolostone Fossil fragments 10-15%. Brownish-gray. Moderately well sorted. Fossil fragments in dolomite matrix; corallites replaced by anhydrite. Some small stylolites.	 3813			

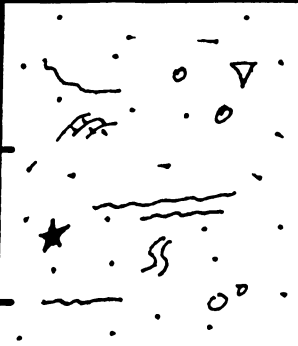
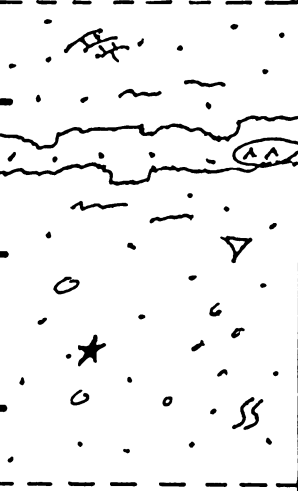


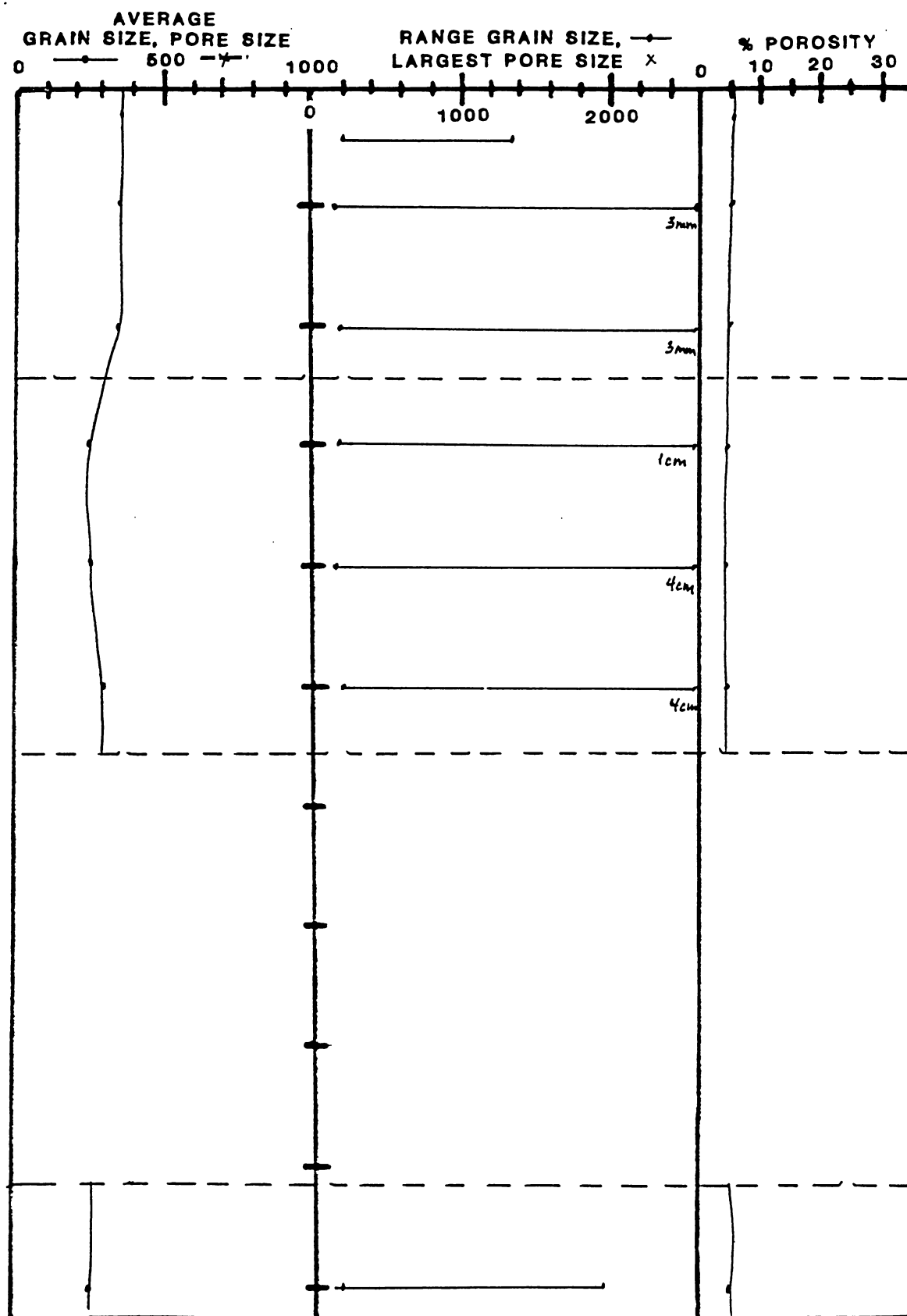
DESCRIPTION	CORE	PACKING lo med hi
Dolostone Fossil fragments 20%. Brownish-gray. Well sorted, fine grained. Some micro- stylolites at bottom.	 missing 3814 missing? 3815	

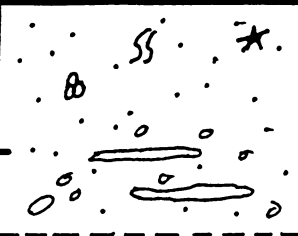
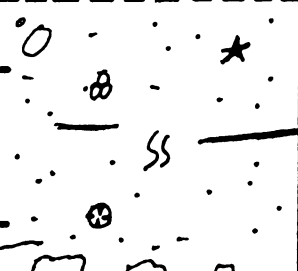
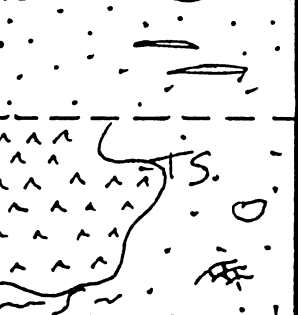
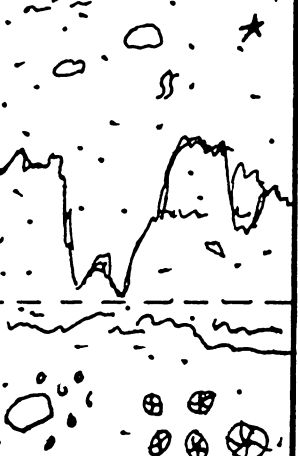
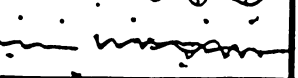


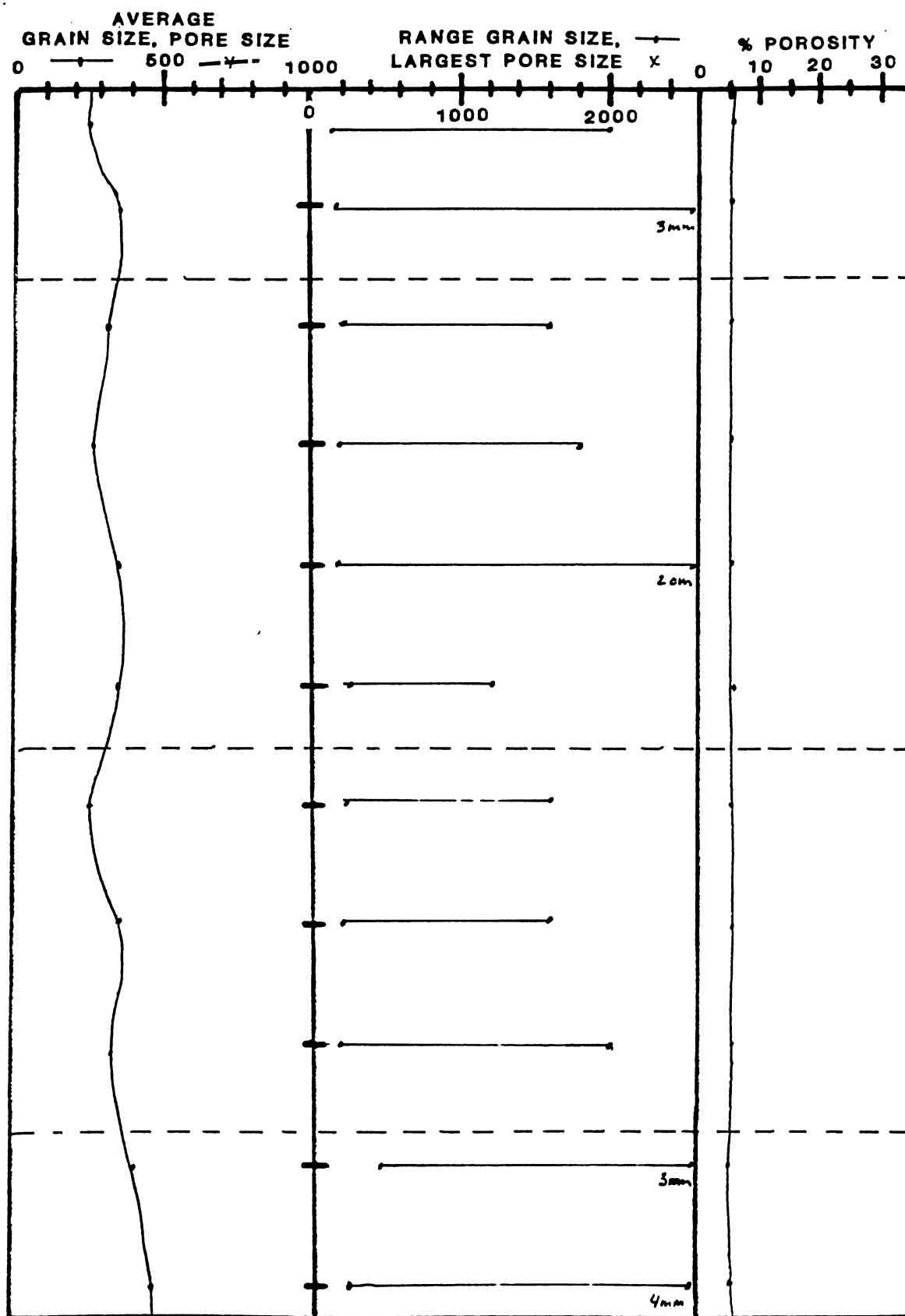
DESCRIPTION	CORE	PACKING lo med hi
3815 Dolostone Fossil fragments 15%. Brownish-gray. Fossil fragments in fine grained dolomite matrix. Some anhydrite and microstylolites		
Dolostone Fossil fragments 20%. Brownish-gray. Fossil fragments, well bioturbated, in a fine grained dolomite matrix. Abundant microstylolites		
Dolostone Same as that directly above.		
3816 Dolostone Fossil fragments 20%. Brownish-gray. Very well sorted and fine grained. Fossil fragments in a dolomite matrix. Many burrows, some eye-shaped. Many microstylolites. Some anhydrite.		

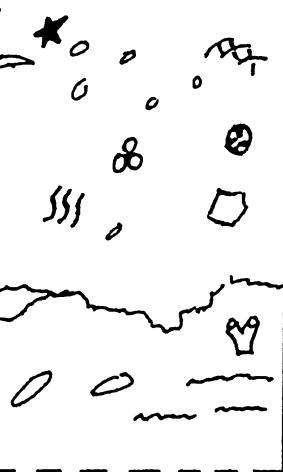


DESCRIPTION	CORE	PACKING lo med hi
Dolostone Fossil fragments 20%. Brownish-gray. Very well sorted and fine grained. Fossil fragments in a dolomite matrix. Many burrows, some eye-shaped. Many microstylolites. Some anhydrite.	 3817	
Dolostone Same as that directly above.	 3818	
Dolostone Fossil fragments 20%. Brownish-gray. Well sorted and fine grained. Abundant	missing 	



DESCRIPTION	CORE	PACKING lo med hi
horizontal burrows and microstylolites.		
Dolostone Fossil fragments 10%. Brownish-gray. Well sorted, fine grained. Rugose corals filled with sparry calcite and anhydrite, and surrounded by stylolites. Abundant burrows, many filled with lighter colored dolomite. Some birdseye anhydrite nodules		
3819		
Dolostone Fossil fragments 20%. Brownish-gray. A large anhydrite nodule at top. Burrows with micrite rims. Large stylolite at base.		
Dolostone Fossil fragments 25-30%. Brownish-gray. Moderately well sorted. Burrows with micrite rims and microstylolites.		
3820		



DESCRIPTION	CORE	PACKING lo med hi
	3820 	
Dolostone Fossil fragments 20%. Brownish-gray. Moderately well sorted; highly bio- turbated. Stylolites.		
Dolostone Fossil fragments 15%. Brownish-gray. Moderately well sorted. Highly bio- turbated. Trilobite fragments. Abundant microstylolites.	3821 	
Dolostone Fossil fragments 15%. Brownish-gray. Moderately well sorted. Abundant <u>Endothyra</u> sp.; highly bioturbated. Some whole bivalves filled with sparry dolomite	