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The Effect of Buried Niagaran Reefs on Overlying Strata in Southwestern Illinois

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ABSTRACT

A series of isopachous maps of rock units overlying Niagaran reefs in southwestern Illinois is analyzed to determine the effect of the reefs on these younger rocks. The isopachous data are further analyzed by low-order trend-surface fitting and residual mapping. It is a long-held belief that differential compaction between reef and non-reef rocks causes structural closure on strata many hundreds of feet above the reef. However, one possible interpretation of the maps is that some differential compaction occurred as the first of the overburden was deposited but that subsequent folding is partially responsible for the structure of the shallow rocks above the reefs.

INTRODUCTION

Many of the geologic studies involving buried Niagaran reefs in and near the Illinois Basin have attributed the structural expression of the reefs to the differential compaction of Niagaran sediments (Lowenstam, 1948; Van Horn, 1956; Ingels, 1963; Ferris, 1972); the non-reef portion of the Niagaran is assumed to have compacted more than the rigid reef core, in response to increasing weight of overlying sediments. This differential compaction is believed to have been active in post-Pennsylvanian time after several hundreds or even a few thousand feet of sediment had been laid down on the reefs (Lowenstam, 1948).

This report presents evidence to support the author's belief that tectonic activity is responsible for some of the folding in rocks above the reefs. This evidence takes the form of a series of isopachous maps of selected rock units overlying the Niagaran. A more direct approach to the analysis of structural movement would be to map the present-day structure of the beds below the reefs. Such a map would demonstrate whether or not the reef areas have been uplifted since reefs began to grow. Since adequate pre-Niagaran well control is generally lacking, the data provided by post-Niagaran strata are used to interpret structural history. In this study it is assumed that a thin area in a mapped stratum reflects either a sea-bottom high that existed prior to the deposition of that stratum or an area where active uplift occurred during the deposition of the stratum. The variations in thickness shown on the isopachous maps are further analyzed by eliminating the regional component displayed by each unit in order to examine the local anomalies. This is accomplished by fitting low-order trend surfaces to the thickness data, subtracting the trend values from observed values, and mapping the differences as residual values.

Location of the Area

An area of approximately 430 square miles in southwestern Illinois was selected for this study. Figure 1 shows the location of the area and its relation to some of the major tectonic features in and around the Illinois Basin. The area can be described, in terms of present-day structural features, as lying on the western flank of the Illinois Basin between the Fairfield Basin (the deepest part of the Illinois Basin) and the Ozark Dome. All of Townships 1, 2, 3, and 4, south, and Ranges 4, 5, and 6, west, of the Third Principal Meridian, are included. A more detailed index map is shown in figure 2. The borders of the report area enclose parts of five counties—Clinton, St. Clair, Washington, Randolph, and Perry. Figure 2 shows the location of known reefs (Meents, 1964). All of these reefs except Lively Grove are associated with oil or gas pools. (A reef named Darmstadt in 2S., 6W. of St. Clair County was discovered after the maps for this report were completed and is therefore not included.) Three other known oil pools in this area are believed to have no association with reefs; these three are shown on the other maps included in this report but will not be discussed.

STRATIGRAPHY

A typical electric log from the area is shown in figure 3. The various geologic units indicated at the left of the log are intended to orient the reader and by no means represent a complete listing of recognizable stratigraphic units. The numbered units indicated at the right of the log are the intervals selected for mapping in this study. These mapped intervals are composed of either primarily clastic or primarily non-clastic sediments with upper and lower boundaries that are defined by fairly reliable stratigraphic markers. These units will be referred to by the indicated numbers.

Previous Reef Studies and Differential Compaction

The earliest study of subsurface reefs in Illinois was made by Lowenstam and DuBois (1946) shortly after the discovery of Marine oil pool in Madison County, Illinois. Lowenstam (1948) published a later report after Marine pool had been more fully developed. He continued to study reefs in and around Illinois and published classic works on buried Niagaran reefs (Lowenstam, 1949, 1950). His discussions of the facies relationships of Silurian rocks and how the facies pertain to presence or absence of reefs appear to be quite valid today, even though many new data have been made available through continued drilling over the past twenty-five years or more.

Fig. 1 - Index map showing report area as related to major tectonic features.

In one study of Marine pool Lowenstam suggests that the structure associated with reefs is the result of differential compaction of the normal Niagaran sediments around a rigid reef complex (Lowenstam, 1948, p. 179-181). This concept has met with rather widespread acceptance and is reiterated in other reports on reefs of various ages and locales (Van Horn, 1956; Jodry, 1969; Ferris, 1972).

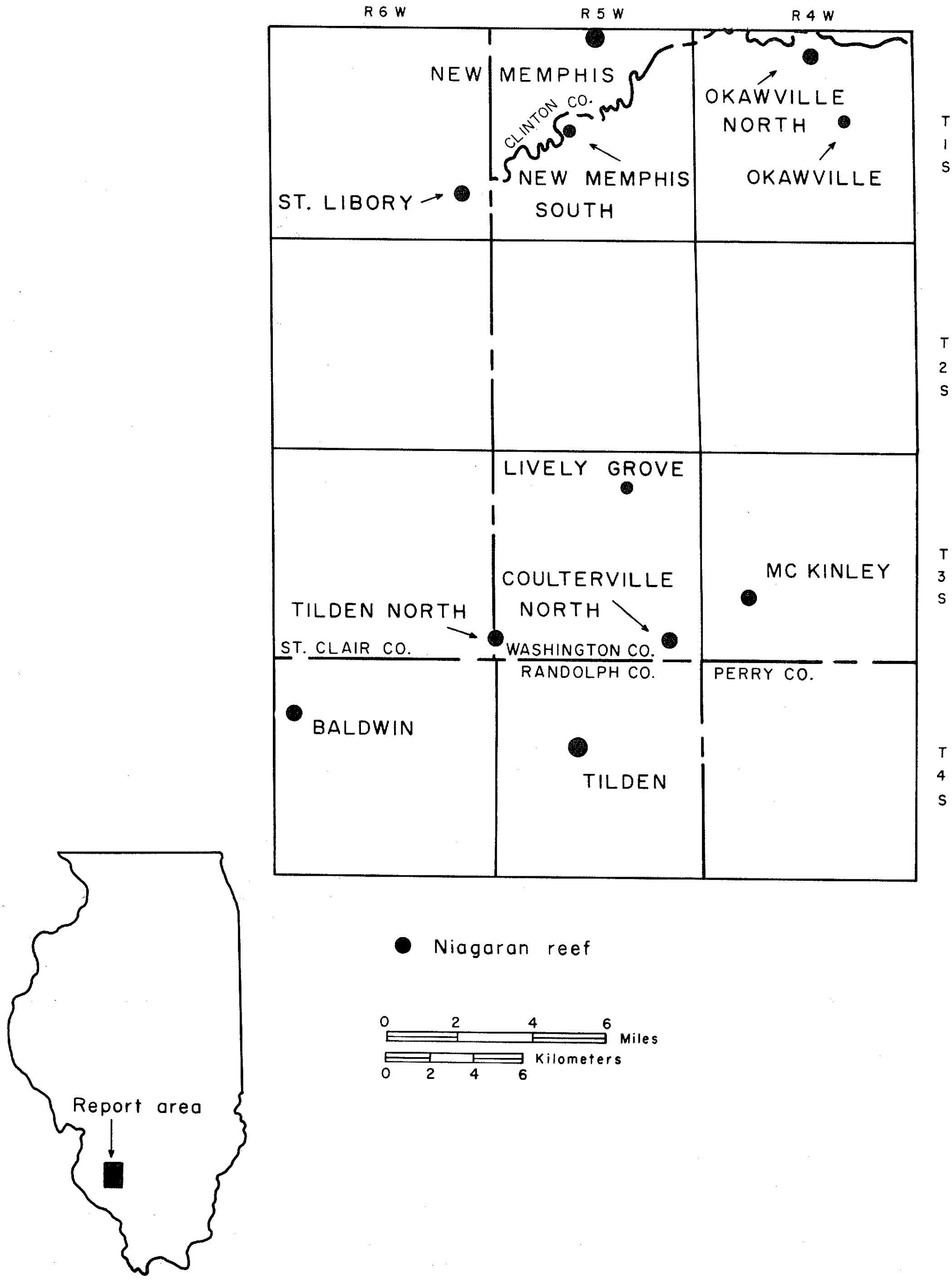

Fig. 2 - Index map showing locations of known Niagaran reefs within the report area.

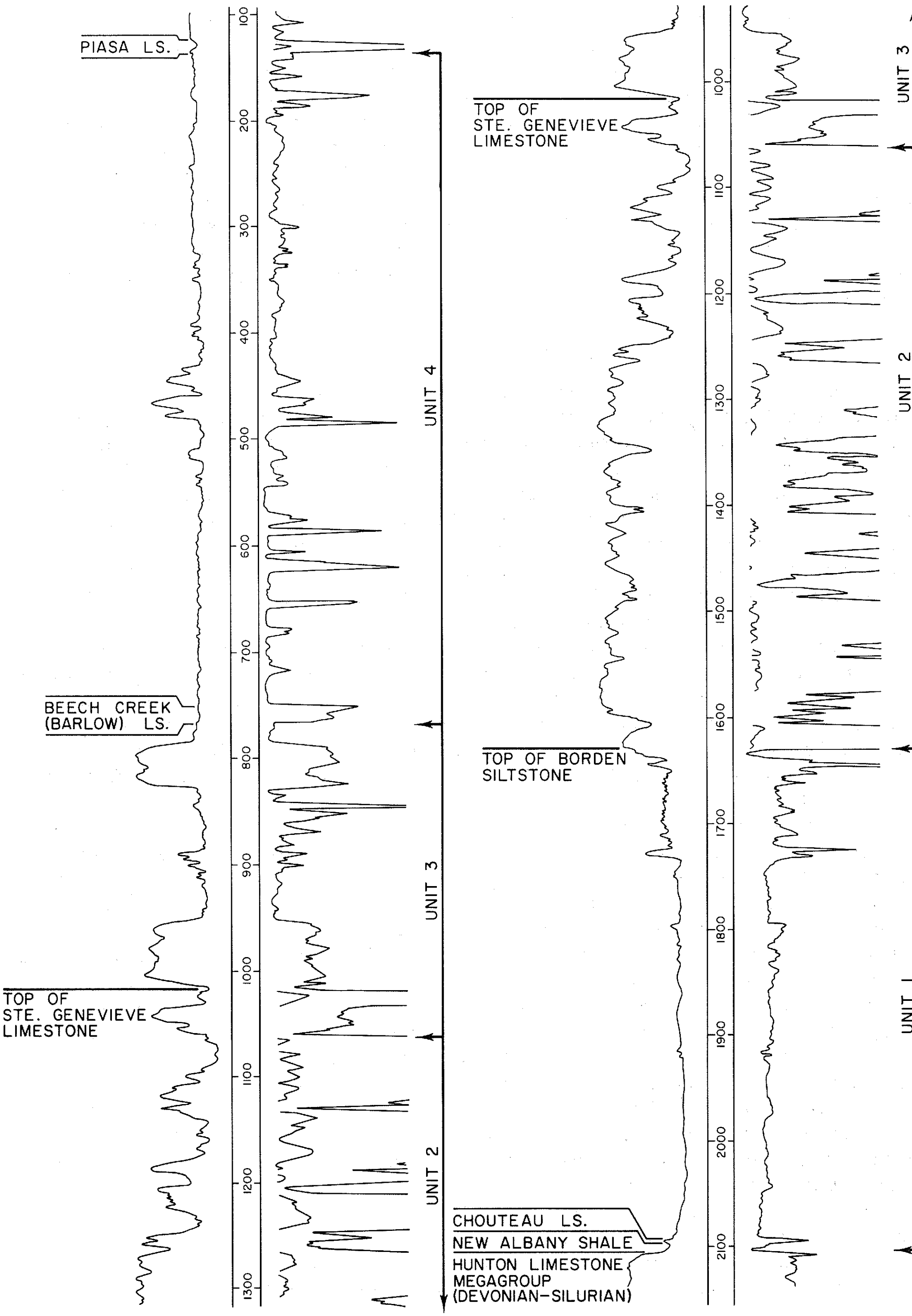

Fig. 3 - Typical electric log from the report area showing key stratigraphic marker beds and mapped units.

The series of events suggested by these writers in explaining the differential compaction between inter-reef sediments and reef core is as follows: The reef core and reef-derived material were deposited in a specific locality surrounded by an environment receiving finer grained, calcareous material. Later, after reef growth had ceased, other sediments were deposited on top of the reef and inter-reef material. As these post-reef sediments accumulated, their increased weight caused the inter-reef material to compact more than the reef-derived sediments. This process presumably continued over long periods of time while hundreds or even thousands of feet of overburden were accumulating. Some evidence indicates that 40 percent of the total compaction at Marine pool could have taken place after the close of the Pennsylvanian, according to Lowenstam (1948, p. 184).

Problems with Differential Compaction Theory

Before presenting any new theories to explain why shallow structures exist over reefs, we should point out some of the problems involved in applications of the concept of differential compaction. An early study of differential compaction made by Nevin and Sherrill (1929) employed a glass-walled tank which had one or two Plaster-of-Paris ridges on the bottom. The tank was filled with a soupy mixture of clay and water. Clay was added to the water until enough had settled on the bottom of the tank to completely cover the ridges. When the ridges were covered, colored clay was added to form a thin layer to serve as a marker bed. Additional layers of clay and sand were then deposited and, at the very top, lead shot was added for weight.

The various layers that were produced thinned over the ridges and thickened on either side of them. As the weight of the overburden increased, the thinning became more pronounced on the deeper beds and caused an increased dip with increased depth. Although this study was conducted in an attempt to analyze the conditions existing over buried limestone hills in Oklahoma, it has been used to support the differential compaction theory as applied to reefs (Ferris, 1972, p. 467).

The laboratory model used by Nevin and Sherrill is, however, quite unlike the actual situation that existed when the Niagaran reefs of Illinois were buried. A Plaster-of-Paris ridge with considerable relief buried by a clay does not duplicate the conditions of a reef surrounded by inter-reef carbonates. In Illinois the Niagaran reefs are surrounded by carbonates and, in some cases, buried by carbonates, thereby forming a surface of low relief that was subsequently buried by clay (New Albany Shale Group). Figure 4 is an isopachous map of the interval immediately above the Devonian-Silurian Hunton Limestone Megagroup. This interval combines the New Albany Shale Group and the Chouteau Limestone. The map shows a regional thickening of about 35 feet from southwest to northeast. The map reflects very little local relief at the time this interval was deposited, however. Thickness variations in the rocks overlying the reefs amount to only a few feet. The reefs apparently did not produce a surface characterized by a series of limestone hills at the time of New Albany-Chouteau deposition. Therefore we are not dealing with the compaction of a reef carbonate versus that of a shale but instead with the compaction of a reef carbonate versus that of a non-reef carbonate.

The compaction of carbonate sediments does not progress in the same manner as the compaction of clay. According to Athy (1930), compaction in

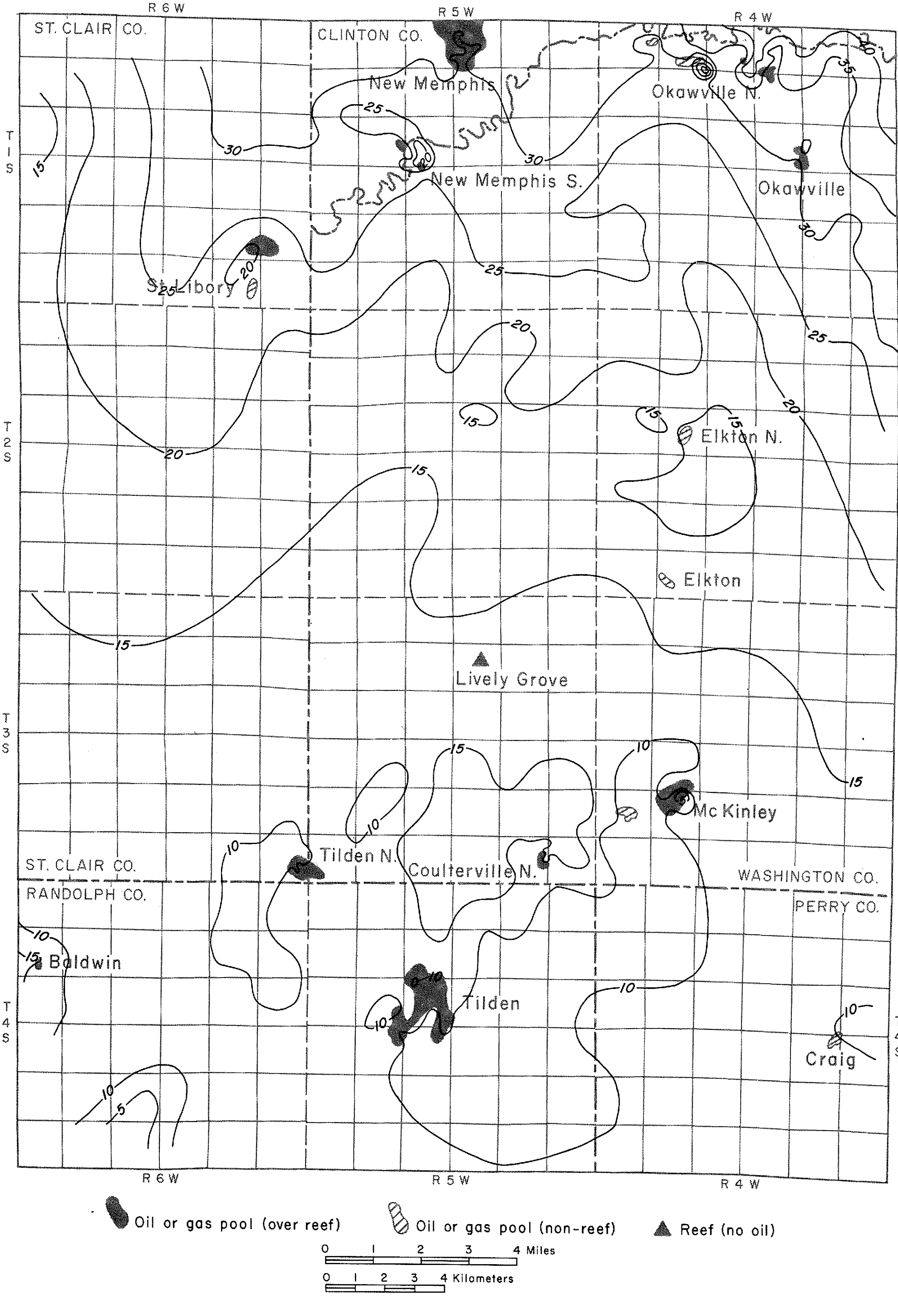

Fig. 4 - Isopachous map of the combined New Albany Shale-Chouteau Limestone unit (isopach interval 5 feet).

clays and silts continues as long as the pressure exerted on them increases. In contrast, Athy points out that compaction in carbonate sediments can take place only prior to cementation. Abundant evidence that cementation has taken place in recent lime muds indicates that the period of compaction may have been very brief. Fischer and Garrison (1967) refer to as many as 35 localities where lithification (cementation) of recent carbonate sediments in a marine environment has been observed. They also state that this lithification could have taken place in slightly compacted or even uncompacted sediments.

The rate of compaction of uncemented lime sediments appears to vary considerably. Fruth, Orme, and Donath (1966) have shown the compaction of lime mud subjected to 30 bars pressure to be about 30 percent. On the other hand, an oolite compacted by only 5 percent under the same pressure. The compaction rates of these two sediment types (and several other calcareous sediment types) became essentially equal at pressures above 350 bars. Apparently, differential compaction in carbonate sediments is significant only under relatively low pressure before, or at least early in, the lithification process, when cementation has not advanced far.

To summarize the data on compaction of carbonate sediments:

(1) The amount of compaction of carbonate sediments varies considerably in response to pressures up to 30 bars.

(2) Compaction rates of different carbonates may vary considerably soon after deposition, but later, under increasing pressure, these rates become similar. Under high pressure the compaction rates of many carbonate sediments are essentially the same.

(3) Most of the compaction takes place before cementation progresses very far.

(4) Cementation of carbonate sediments in a marine environment can take place soon after deposition, while the carbonates are in an uncompacted state.

These data appear to indicate that any differential compaction occurring between any two carbonate rock types must take place in uncemented sediments subjected to relatively low pressures.

Laboratory conditions involved with the high pressure work on lime sediments (Fruth, Orme, and Donath, 1966) cannot demonstrate what effect many millions of years would have on compaction rates. Over a long time, lower pressures probably would be required to achieve similar compaction rates in different types of carbonate sediments. Cementation would have time to progress further, and each addition to the overburden would have more time to compact the underlying sediments. Nevin and Sherrill (1929) showed that overburden could be increased quickly without compacting the underlying sediments appreciably. After a certain time interval, however, compaction did take place.

Many of the above data do not support Lowenstam's suggestion that 40 percent of the differential compaction at Marine took place in post-Pennsylvanian time (Lowenstam, 1948). The many millions of years between Niagaran time and the close of the Pennsylvanian period would quite probably be adequate for the Silurian sediments to become well cemented. Also, the weight of several hundred or a few thousand feet of overlying sediment deposited during that time would have compacted the Niagaran rocks to a point at which their compaction rates were essentially uniform.

POSSIBILITY OF TECTONIC MOVEMENT

The theory that will be examined in the remainder of this paper is this: The distribution of Niagaran reefs in the Illinois Basin was determined by the location of sea-bottom highs produced by slight upward folding of pre-Niagaran strata. After the end of the Silurian, Devonian carbonate deposition and subsequent erosion prior to New Albany deposition produced a fairly featureless surface. During the long period of time following the burial of the reefs, a thick blanket of sediments was laid down on top of the Silurian. Intermittent, minor uplifts recurred at the reef sites throughout this period of deposition, producing structural highs over the reefs; these highs are seen on structure maps of any stratum above the reefs, including the shallowest Pennsylvanian rocks.

A reliable way to evaluate this theory would be to map the structure below the Niagaran to see whether the older strata are uplifted in the areas where reefs are known to exist. Generally, we do not have sufficient subsurface data to allow such a map to be drawn with adequate detail to suit our purpose. At least two reefs exist where the data suggest no underlying structural highs. The Ordovician tests in and around the Marine reef give no indication of a structural high under the reef. Similarly, at Sandoval reef in Marion County three Ordovician tests (two through the reef and one to the west of the reef) show no evidence of a structural high under the reef. The structural data on pre-reef strata in these two examples are not sufficient to rule out the possibility of an Ordovician high under at least a portion of the reef, but the fact that no highs are indicated shows that there are problems involved in relating reef structures to tectonic uplift. Perhaps the formation of the structures over reefs is the result of more processes than the combination of differential compaction and tectonism suggested in this report.

Another way to evaluate the theory is to reconstruct the structural history of an area by mapping the thickness of the rock units, assuming that thin anomalies were produced in areas where active uplift occurred during the deposition of an interval and thick anomalies were created in areas where relative downwarping took place.

UNITS SELECTED FOR MAPPING

The units chosen for the isopach maps are indicated on the right-hand side of the electric log in figure 3. They are gross lithologic units that can be picked reliably on most of the electric logs run in this area. They are:

Unit 1

The first unit overlying the Hunton Limestone Megagroup is composed almost entirely of fine clastic sediments of Mississippian and Devonian age. The lowermost part includes the New Albany Shale Group and the overlying Chouteau Limestone of Upper Devonian age. These formations are very thin where they are present in the area. The remainder of Unit 1 is Mississippian in age and is composed, for the most part, of the Borden Siltstone.

Unit 2

Unit 2, immediately overlying Unit 1, is composed entirely of Valmeyeran (middle Mississippian) carbonate rocks. The base of Unit 2 is the top of the uppermost clastic bed in Unit 1. Similarly, the top of Unit 2 is formed by the base of the lowest clastic bed in the overlying Unit 3. The rocks in Unit 2 make up part or all of the Ste. Genevieve, St. Louis, Salem, and Ullin Limestones. The boundaries of this unit are more difficult to pick than those of the other three because the limestones interfinger with the clastic units both at the top and the bottom of Unit 2.

Unit 3

The third unit in this sequence is predominantly clastic and is composed of rocks with mixed lithologies of Valmeyeran and Chesterian age. It is primarily a shale-sandstone unit but contains minor amounts of limestone. The lower boundary of the unit is defined by the top of Unit 2, and the upper boundary is the base of the Beech Creek (Barlow) Limestone.

Unit 4

The youngest unit in the sequence consists of rocks of Mississippian and Pennsylvanian age. It is unique because it contains a major unconformity, which represents a long period of erosion. Limestone is a minor rock type in this unit; sandstone and shale predominate. The top and bottom of the unit are formed by the base of two thin limestones—the Beech Creek Limestone at the bottom and the Piasa Limestone Member of the Modesto Formation at the top.

Analysis of Isopach Maps

Figures 5-8 are the isopach maps of the four units defined above. In most cases some thinning occurs above each reef on each map. Unit 1 (fig. 5) is an interval that should reflect reefs quite well if differential compaction were the only factor in forming reef structures. Compaction of the Niagaran should have progressed quite far during the deposition of this interval. Thin anomalies (thins) are quite noticeable over McKinley, Tilden, Okawville, Okawville North, New Memphis, and New Memphis South. However, St. Libory shows up as a thick anomaly (thick). Lively Grove is offset from a nearby thin. Baldwin, Tilden North, and Coulterville North all show very minor thinning. Craig, a nonreef feature, shows some thinning that might well indicate the minor amount of localized uplift that this report suggests as an important cause of the reef structures.

The remaining isopachous maps, those of Units 2, 3, and 4 (figs. 6, 7, and 8), can be examined to determine what association can be seen between thins and underlying reefs. On each map it appears that some reefs lie under thins, that some lie to the side of a thin, and that some do not appear to be associated with any anomalous feature at all.

The McKinley reef in the southeast quadrant of the area is the only reef in this report that is closely associated with thinning in each of the four units mapped.

If differential compaction were fully responsible for the structures over reefs, the type of thinning seen over McKinley should be seen over all of the reefs in the area. However, McKinley is the exception. The thinning shown by these maps is not of a uniform, consistent pattern that would result from the increasing weight of ever-thickening overburden over a long period of time. Neither

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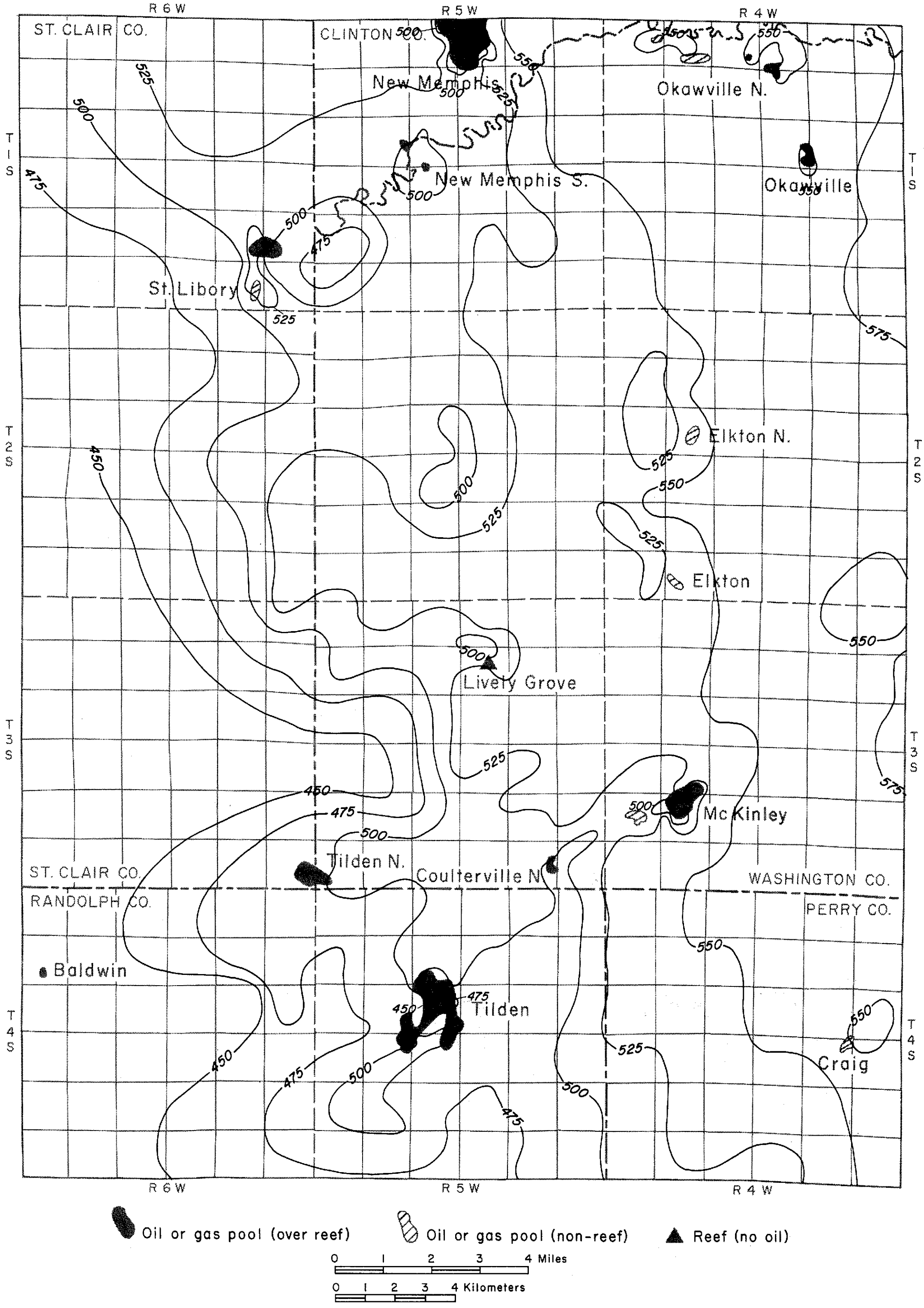

Fig. 5 - Isopachous map of Unit 1 (isopach interval 25 feet).

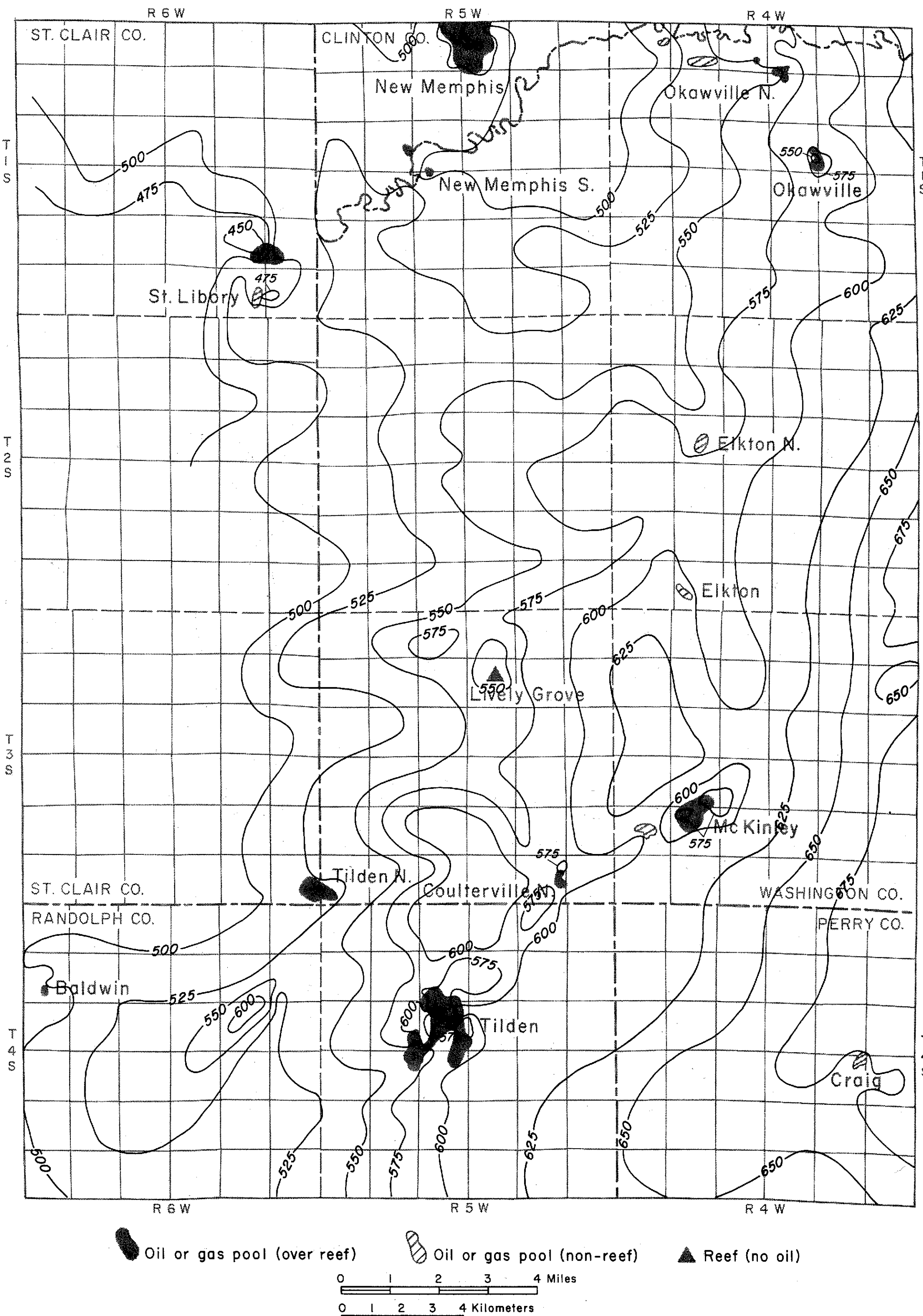

Fig. 6 - Isopachous map of Unit 2 (isopach interval 25 feet).

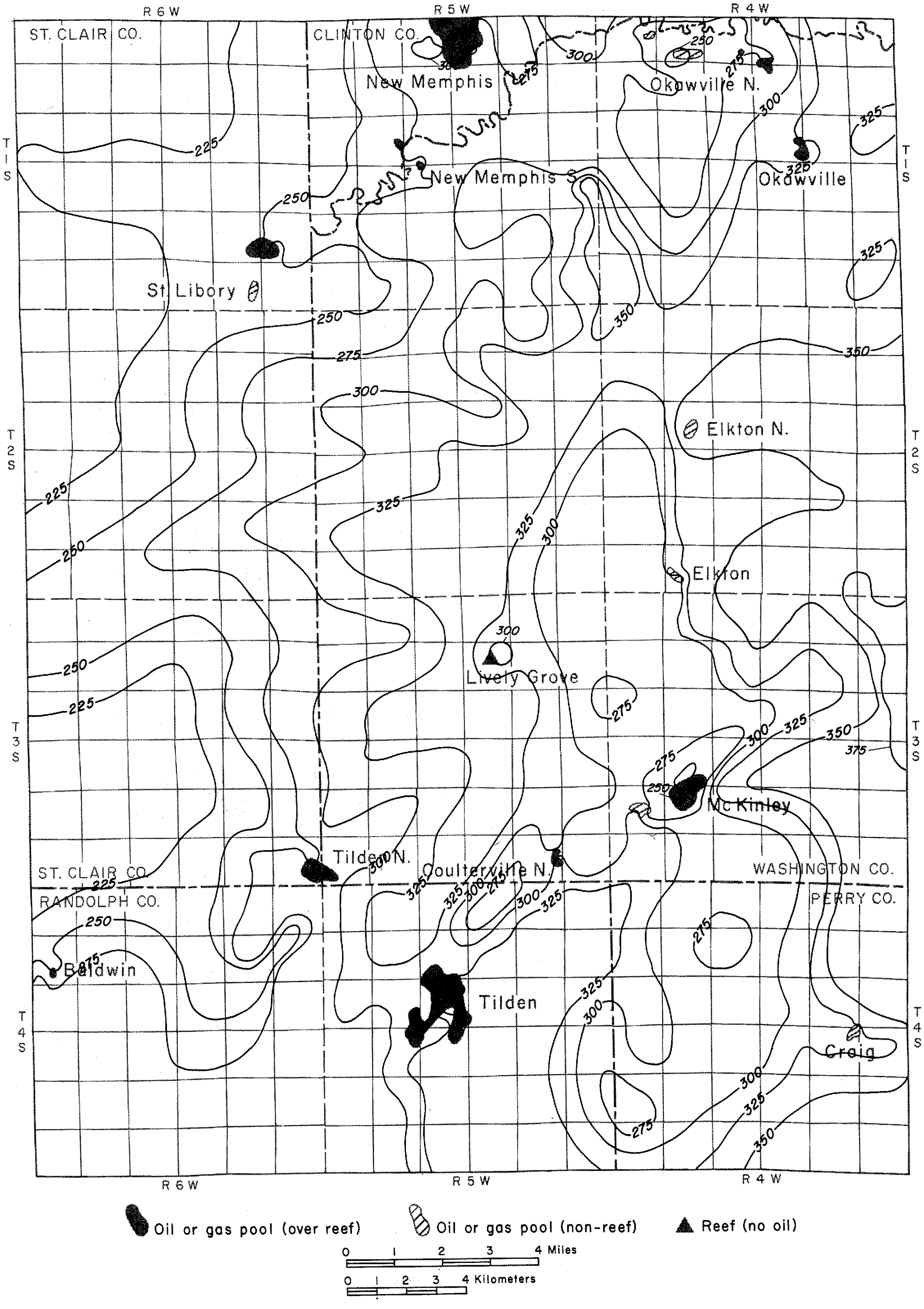

Fig. 7 - Isopachous map of Unit 3 (isopach interval 25 feet).

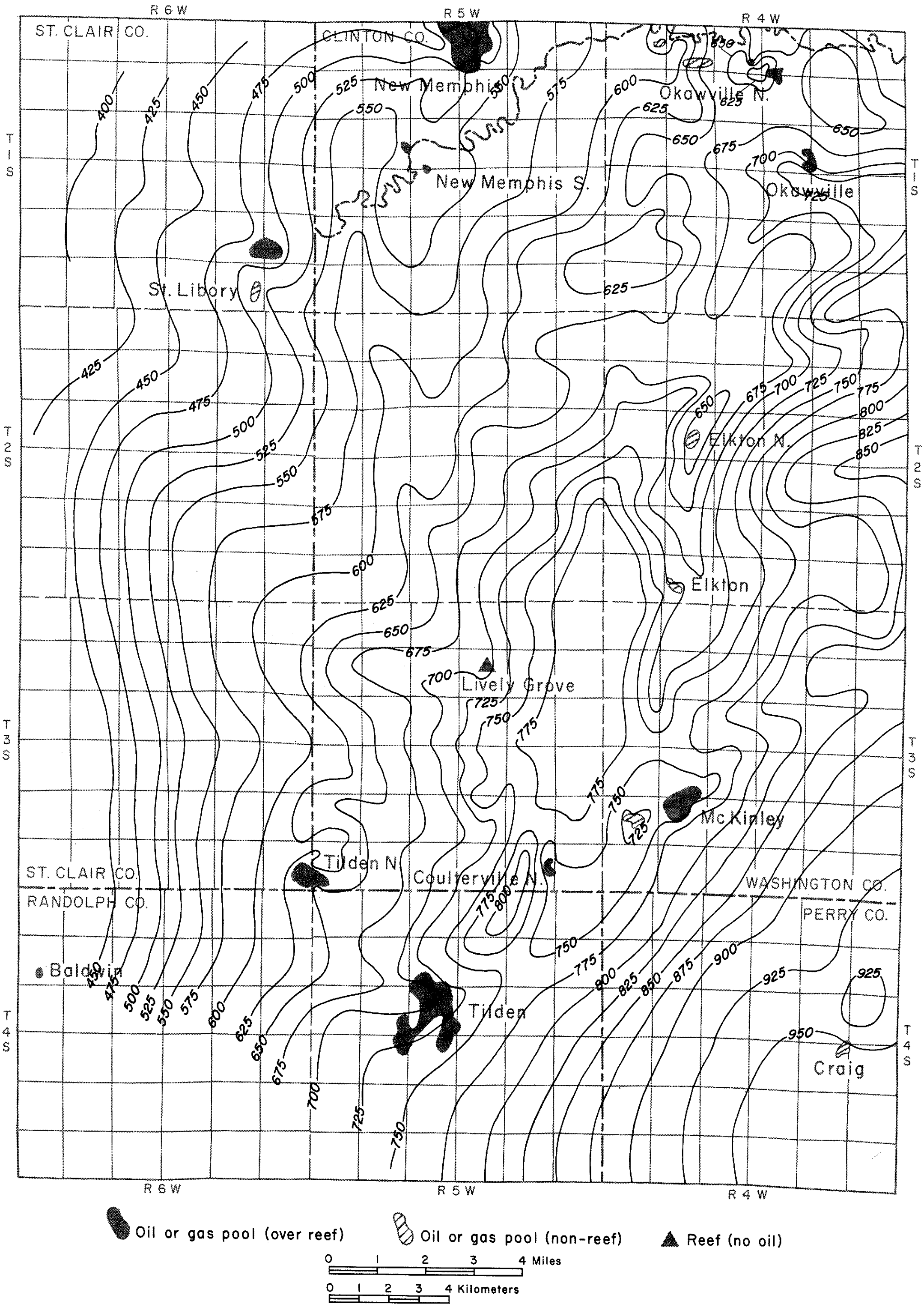

Fig. 8 - Isopachous map of Unit 4 (isopach interval 25 feet).

is there a pattern that is common to all, or even most, reefs in the area. If each structure had a characteristic history of folding, however, it would produce its own distinct pattern of thinning in overlying beds. The result could be a variety of thinning patterns much like that shown by the isopachous maps (figs. 5-8).

Because of the ever-present risk of small local anomalies being obscured by large regional variations in thickness, a method of removing the regional variations is desirable. Such a method is available through the use of modern electronic computers. The method is referred to as trend-surface fitting and residual mapping.

Trend-Surface Analysis

The following trend-surface analysis employs essentially the same methods as those used in previous studies in Illinois (Stevenson, 1969, 1970). In those earlier studies, structural data (elevations) were analyzed, but in this one isopach data (thicknesses) are analyzed. The process of analysis, however, is the same. The purpose of the trend-surface analysis of the thickness data is to evaluate the local effect of a reef on the thickness of the overlying beds. The thickness of any unit is a combination of a regional component and a local component (Krumbein, 1956, p. 2165). In fitting a low-order trend surface to the thickness values, an attempt is made to approximate the regional variations in thickness. The local variations in thickness are examined separately by constructing a residual map of the differences between trend-surface values and actual observed values. The observed thickness can be greater or less than the calculated regional component, resulting in residual values that will be either positive or negative.

The choice of the degree of the polynomial to be used in a trend-surface analysis depends upon the purpose of a particular study. In this study, the intent was to remove the large regional thickness variations; therefore, a low-order polynomial was desired. A first-order surface takes the form of a plane and can show no thicks or thins; therefore, it was rejected. The second-order surface was also rejected because it can show only a thick or a thin, but not both. The lowest order surface that can show both a thick and a thin in the regional trend is the third order, which was selected for this study. In some of the units mapped in this report, the third-order surface differs very little from the second-order surface but the third-order was used in each case for the sake of uniformity.

Figures 9 through 12 show the third-order residual maps of Units 1 through 4. These maps show essentially the same features as the isopachous maps, but greater emphasis is placed on local variations. The McKinley reef underlies a strong thinning in every map except for figure 10 (Unit 2 residual), where the reef lies to the northwest of the nearest thin. The Lively Grove reef is associated with a much smaller thin than the one at McKinley. New Memphis is located on a thin in figures 9 and 10 but on a thick in figure 11. Figure 12 again shows New Memphis as a thin. St. Libory shows a very different pattern: first it is on a thick (fig. 9), then on a thin (fig. 10), then on the edge of a thin (fig. 11), and finally between a thick and a thin (fig. 12). Tilden reef is not associated with an anomaly having either a large positive or a large negative value except in figure 12, where it is on a strong thin (-40 feet). It is unlikely

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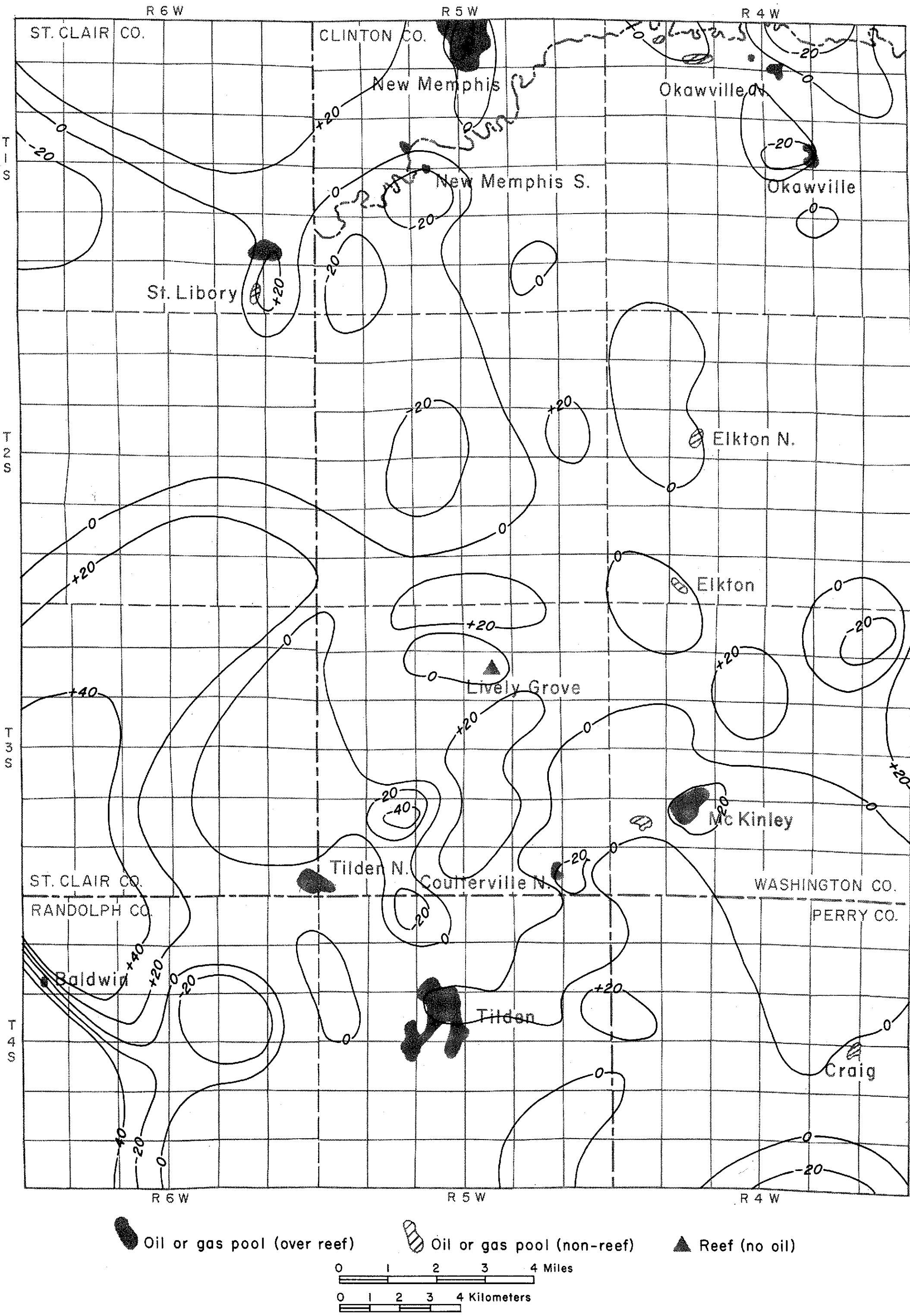

Fig. 9 - Third-order residual map of thickness of Unit 1 (interval 20 feet).

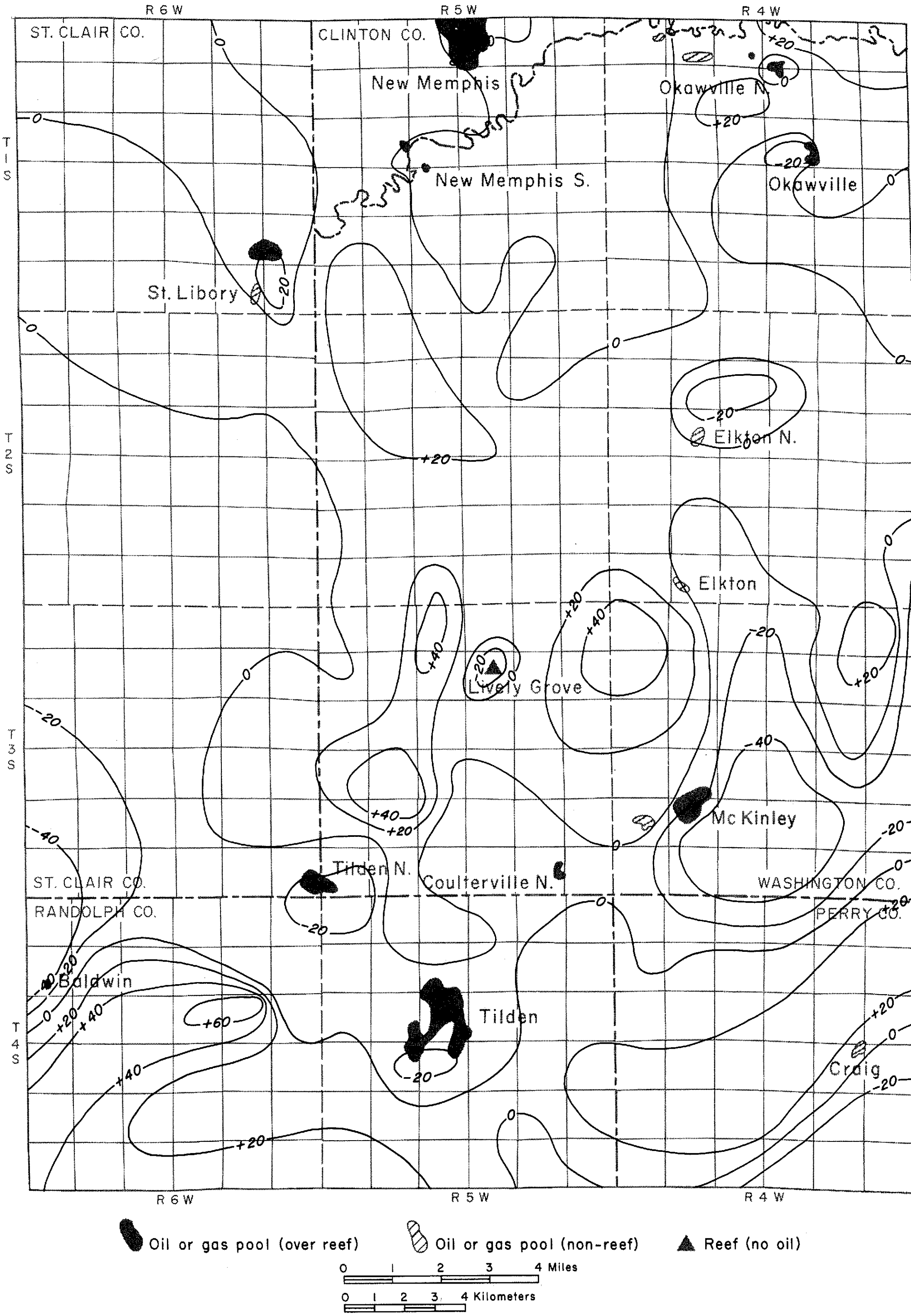

Fig. 10 - Third-order residual map of thickness of Unit 2 (interval 20 feet).

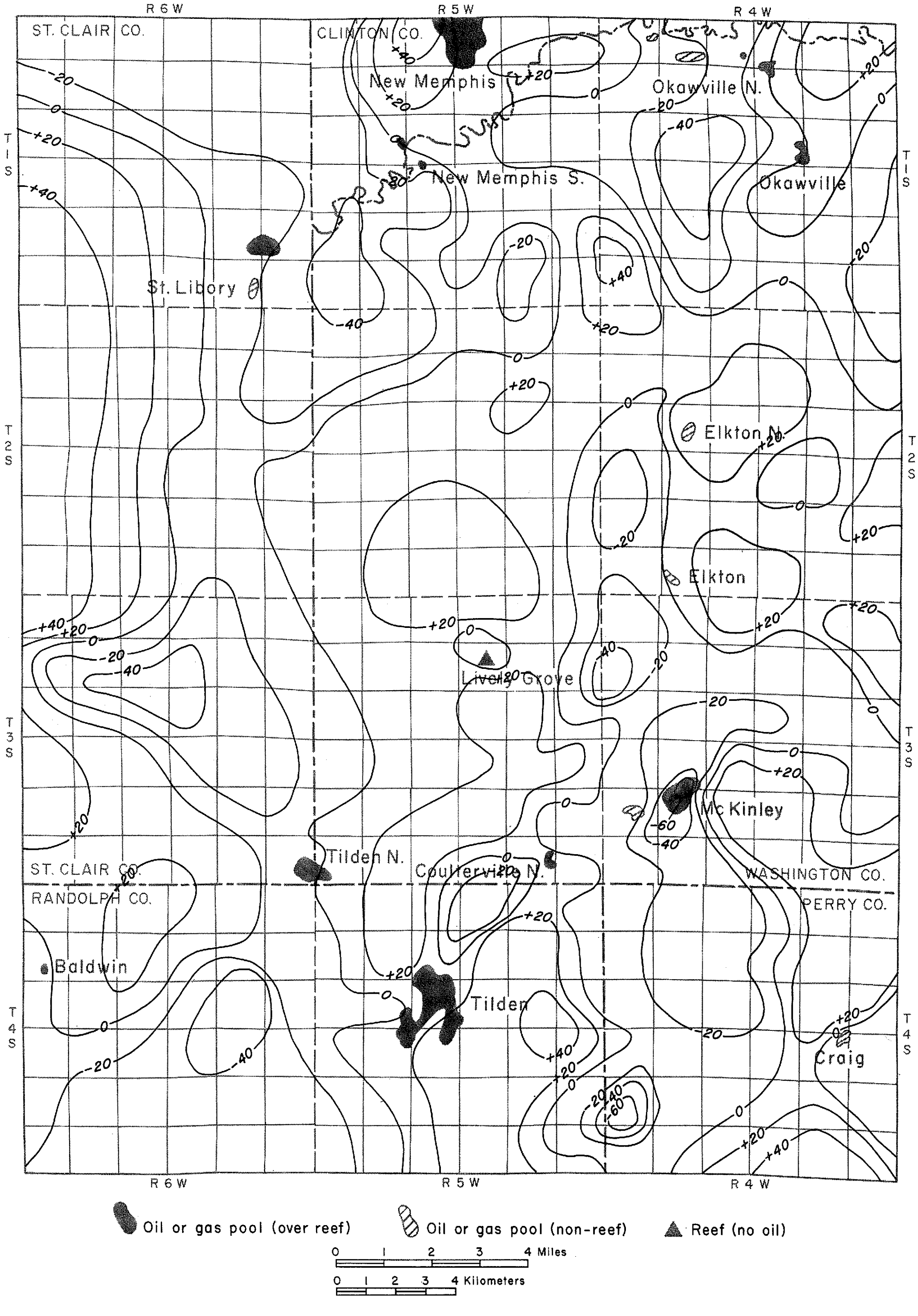

Fig. 11 - Third-order residual map of thickness of Unit 3 (interval 20 feet).

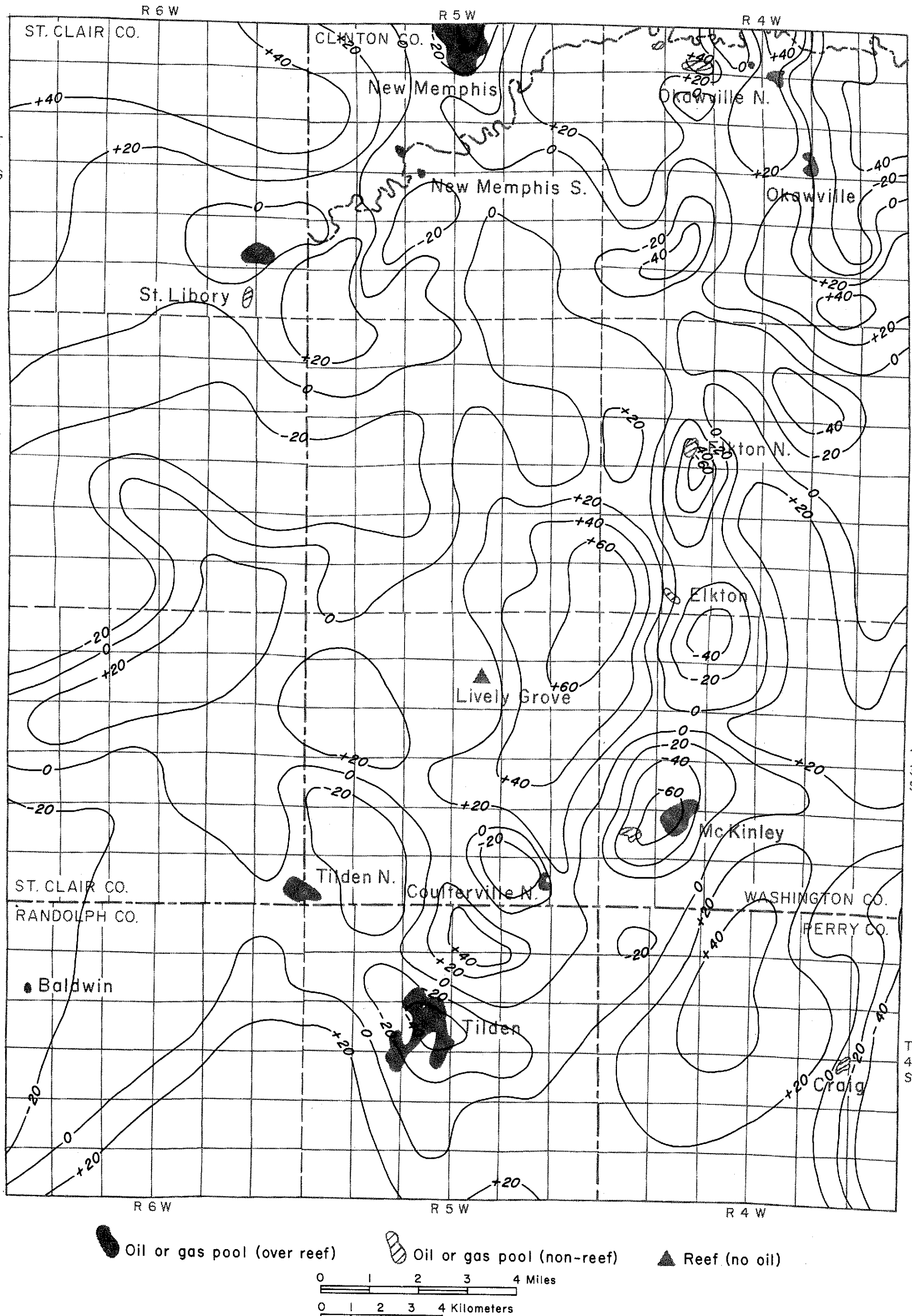

Fig. 12 - Third-order residual map of thickness of Unit 4 (interval 20 feet).

that differential compaction would have been a significant factor in forming the Tilden structure just during the time represented by Unit 4. On the other hand, it is conceivable that tectonic uplift occurred during the time represented by this unit.

Like the isopachous maps (figs. 5-8), the residual maps (figs. 9-12) can be interpreted as showing a pattern of thinning over reefs that suggests recurring tectonic movement more strongly than it suggests differential compaction.

If tectonic movement is responsible for the formation of the structures that overlie reefs, it is necessary to explain why the tectonic movement occurred at the reef sites. This task becomes simple if it can be demonstrated that the tectonic uplift predated the reefs and was, therefore, instrumental in determining the sites of reef development. Examples of reefs growing on pre-existing structural highs are not rare. Brigham (1971) believes that the localization of Niagaran reefs in Michigan and Ontario may have been affected by pre-existing structural highs. Scholle and Kling (1972) think that underlying structures may control the distribution of reefs in lagoons of southern British Honduras.

Several examples of Ordovician Galena highs under Silurian reefs are present in Illinois. Smoot (1958) dealt with one in the Patoka oil pool area. He presented evidence that the reef structures are on the northeast noses of pre-existing Ordovician structures that controlled reef development. Howard (1963, 1964) recognized the importance of tectonism in highs containing reef material along the north rim of the Illinois Basin. The Niagaran rocks have been deeply eroded in that area, however, so it is impossible to determine whether reefs of the type dealt with in this report actually existed there. Whiting and Stevenson (1965) showed a high on the top of the Galena under reef-type rock in Logan County. Here again, post-Silurian erosion precludes direct comparison with southwestern Illinois reefs. These examples do suggest, however, that many Silurian reefs in Illinois may be related to Ordovician highs. Unfortunately, adequate control is not available to map the Ordovician in enough detail to be certain. The examples cited show that it is not uncommon to find reefs on older, deeper structures. Once the stage has been set for a reef to form on a tectonically active area, it is reasonable to expect later activity in the same locality. Non-reef structures with histories of recurring uplift are common. The result is the formation of structures characterized by increasing closure with increasing depth (supratenuous folds).

CONCLUSIONS

The evidence supplied by the isopachous and residual maps suggests a more complex mechanism for the origin of structural highs over the reefs selected for this study than simply the differential compaction of Niagaran strata. The following sequence of events is inferred from the thickness data used to create the maps:

1. Small, low-relief sea-bottom highs were present in the Niagaran ocean. Many of these highs could have been the result of minor tectonic uplift.

2. Reef-building organisms flourished on these highs if they presented a surface at the proper depth to provide the sunlight and water circulation required for the growth of such organisms.

3. Changing water depth brought the period of reef growth to a close, and Lower Devonian sediments filled in the low places on the Silurian surface. A subsequent period of erosion was followed by deposition of Middle Devonian carbonates, producing an area of fairly low relief that received Upper Devonian and Mississippian clastics.

4. The weight of these clastic sediments caused some differential compaction of the Niagaran sediments, which imposed a certain amount of reef-top topography on the previously nearly flat contact of the Hunton Megagroup with the New Albany Shale Group.

5. While later sediments were accumulating over the reefs, gentle uplifts recurred from time to time. These uplifts involved some reefs and left others relatively unaffected. The various reefs involved are indicated by thinning in the rock units deposited during the time of uplift. The end result is a structural high over each reef on any horizon that can be reliably mapped, including the shallowest of the bedrock units.

If the theory relating reefs to pre-Silurian structures is valid, pre-Silurian structures should be considered in exploring for reef oil pools. It would mean that the reefs could be oriented along some Ordovician structural trends and not just randomly scattered about a generally favorable area. Modern geophysical techniques and additional Ordovician tests could supply geological data, including more information, such as the thickness of the Maquoketa Shale Group, that could provide clues to the location of Ordovician structures worthy of more detailed examination in the search for Silurian reefs.

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