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Specific diversity of planktonic foraminifera on the continental shelves as a paleobathymetric tool

ABSTRACT

The diversity of planktonic foraminifera in sediments increases with increase in depth of water and with decrease in latitude. If the area of study is restricted, depth will be the controlling factor and can be calculated approximately from diversity. Isospecies contours based on samples from 55 wells were used to map the relative depths existing at the time of the deposition of the Upper Cretaceous sediments of an area of about 40,000 square miles in east Texas, Louisiana and Arkansas. Comparison of these contours showing depth with the planktonic/benthonic ratio contours of Stehli and Creath showing the paths of currents in the same region reveals many similarities and indicates that the principal Upper Cretaceous currents tended to occur in areas of deeper water.

INTRODUCTION

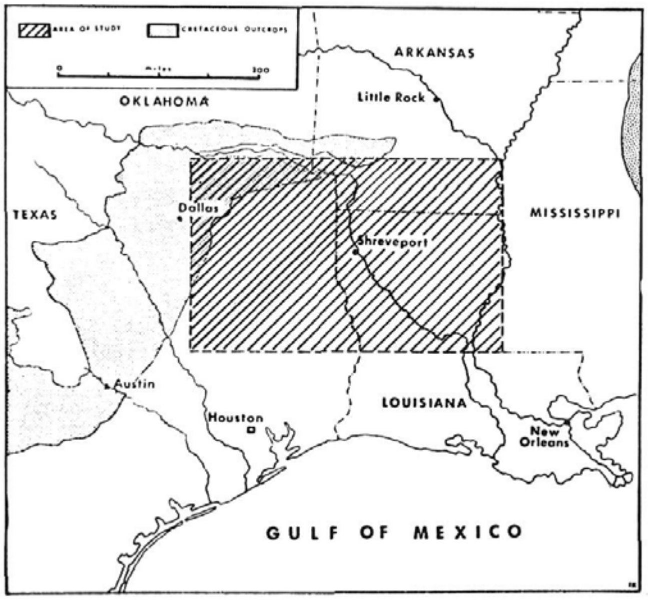
Much attention has been devoted in recent years to improving our understanding of depositional environments. From the geological point of view the most useful studies have commonly resulted from the recognition of a simple relationship between a parameter of the physical environment and the distribution of some group of organisms. Once recognized, such a relationship can serve as a model which can be tested for geological utility by application to the fossil record. It has been noted, for instance, that the ratio between planktonic and benthonic foraminifera in bottom sediments should vary as a function of differences in the volume of open ocean water moving across a continental shelf and should thus define the paths of ocean currents (Stehli and Creath, 1964). These investigators tested the model on Upper Cretaceous sediments of east Texas, Louisiana and Arkansas, and concluded that the paths of paleocurrents could indeed be defined.

Little consideration was given by Stehli and Creath to the possibility that their paleocurrents might have followed the deeper parts of the basins or that their higher planktonic concentrations were due to the existence of deep-water areas on the shelves. A model has now been suggested which should permit the recognition of deeper-water areas through the observed relationship between increasing water depth and increasing taxonomic diversity of planktonic foraminifera (Stehli, 1966). This model is here tested on Upper Cretaceous sediments from the same region studied by Stehli and Creath (1964) in order to evaluate the relative importance of paleocurrents and simple increases in water depth as causes of local high concentrations of planktonic foraminiferal tests in continental shelf sediments.

AREA OF STUDY

This study was conducted on rocks of Upper Cretaceous age in an area of approximately 40,000 square miles in the upper Gulf Coastal Plain of eastern Texas, northern Louisiana and southern Arkansas (text-figure 1). The area is essentially the same as that covered by Stehli and Creath (1964). It is well suited to the present study because of extensive control provided by several decades of oil exploration, the existence of a variety of basins and uplifts active in Upper Cretaceous time, and a stratigraphic framework available from the work of Stehli and Creath.

The limit of the study was established on the north and west by the outcrop belt of the Upper Cretaceous rocks and on the south by the limit of down-dip penetration of the sub-Austin unconformity, which formed the base of the lowest unit examined. To the east an arbitrary



TEXT-FIGURE 1
Area of study in Gulf Coastal Plain.

limit was established at the Mississippi River (text-figure 1). Within this area 55 wells were used as control points.

STRUCTURAL FEATURES

The Upper Cretaceous of the study area was characterized by a number of positive and negative tectonic elements (text-figure 2). The principal positive areas were the Sabine Uplift along the Texas-Louisiana boundary, which was shallowly submerged during the time interval studied, the Monroe Uplift in northeast Louisiana and adjacent Arkansas, which was emergent during part of the Upper Cretaceous, and the shallowly submerged Winn Axis between them.

Negative elements were the Tyler Basin in east Texas, the Interior Salt Basin of northwest Louisiana, and the Pittsburgh Syncline connecting the two north of the Sabine Uplift. The Desha Basin in southeastern Arkansas was also included in the study area, although control in this area is sparse. Along the southern margin of the study area apparently lay the deeper waters of the open Gulf.

STRATIGRAPHY

Two stratigraphic intervals within the Upper Cretaceous of the study area were selected arbitrarily as the subject of this investigation (text-figure 3). The unit designated A consists of the section between the top of the Nacatoch Sandstone and the base of the Annona Chalk, as represented in the surface sections of southwestern Arkansas and correlative strata. The unit designated B includes the strata lying between the top of the Brownstown and the sub-Austin unconformity. The rocks of Interval A are of mid-Campanian to Maestrichtian age, while those of Interval B are Coniacian to lower Campanian. The intervals are defined by easily recognized electric log markers over most of the area, so that relatively objective correlation of the units is possible.

PREVIOUS INVESTIGATIONS

Many investigators have directed their attention to various aspects of the distribution of planktonic foraminifera in the seas today in attempts to recognize significant patterns and relate them to parameters of the physical environment. Most students agree that our knowledge is still insufficient to prove conclusions that have nonetheless a high probability of being correct. Most also agree, however, that currents and water depth appear to be major factors in planktonic distribution.

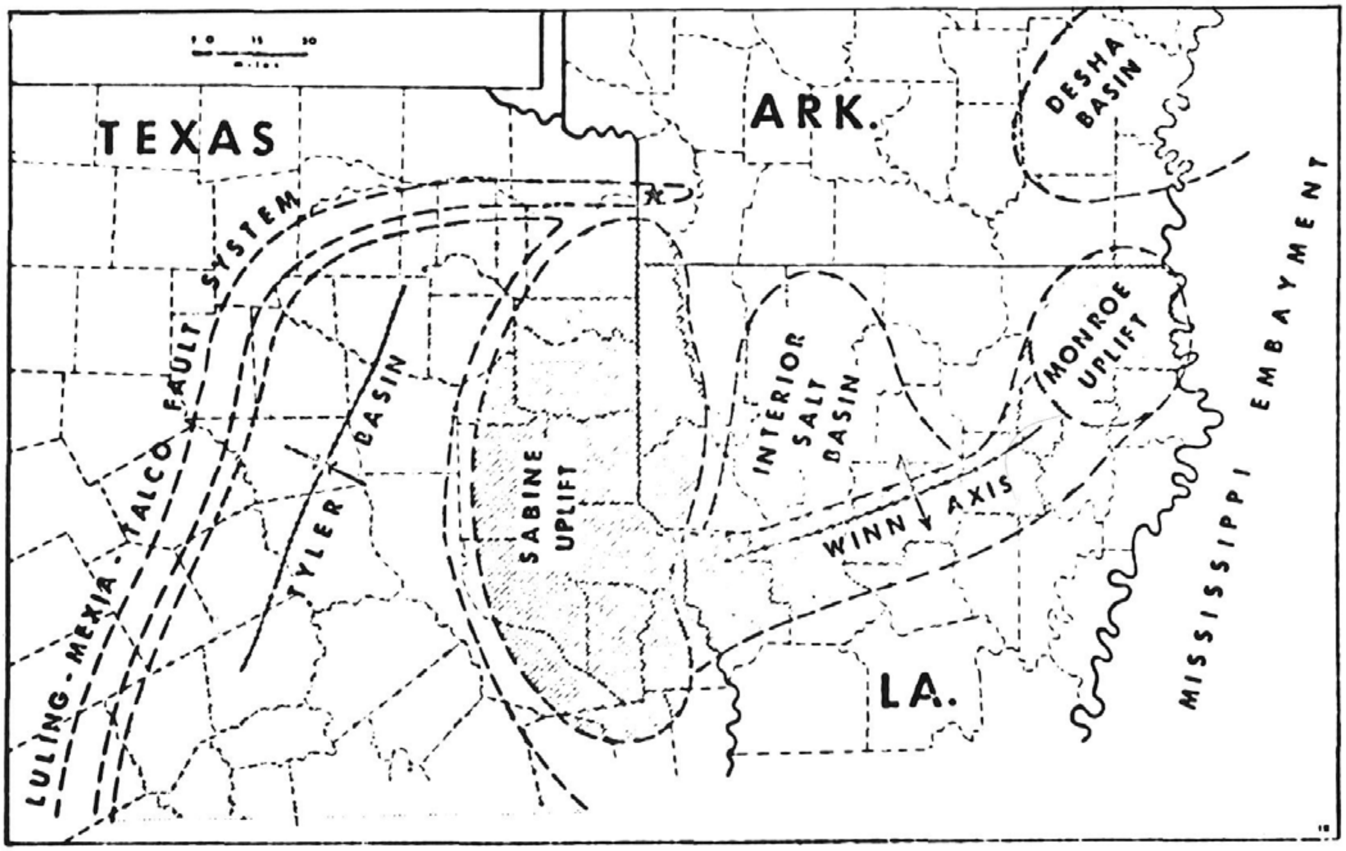
Studies of the last two decades have shown that currents influence both total abundance of planktonic foraminifera and the distribution of temperature-controlled assemblages (Arrhenius, 1950; Lubny-Gertsyk, 1955; Boltovskoy, 1959; Bé, 1959, Wilcoxon, 1964; Bandy, 1967).

The problem under investigation is whether or not there is a correlation with water depth in the distribution of planktonic foraminifera that is expressed with sufficient clarity and strength to be recognized and evaluated independently of the current effect. To evaluate this possibility, it is necessary to examine what is known of the relationship between the distribution of present-day planktonic foraminifera and water depth. An investigation in Recent environments has been completed by the author and is being prepared for publication. Results of these investigations support the relationship between depth and distribution of planktonic foraminifera.

DIVERSITY STUDIES

Although studies on vertical distribution of planktonic foraminifera had been started as early as 1920 by Lohmann, the first studies were not dependable because of limitations imposed by the means and methods then available. More detailed and refined investigations have been made in the last two decades, although our knowledge is still incomplete. Studies of vertical species distribution have begun to produce a significant body of reliable information only within the last decade.

Numerous studies of the areal distribution of planktonic foraminifera have shown that some species show

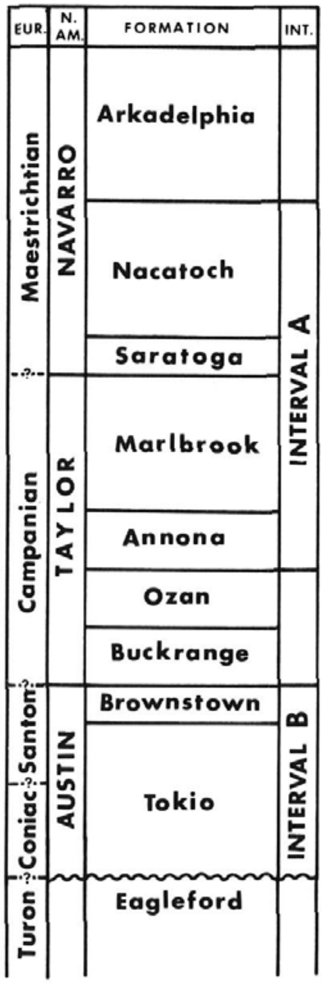


TEXT-FIGURE 2
Major tectonic features of study area in Upper Cretaceous (after Stehli and Creath, 1964). ★=location of Pittsburgh Syncline.

stratification within the water column (Emiliani, 1954; Bandy, 1956*b*; Polski, 1959; Wilcoxon, 1964; Bé and Hamlin, 1967). Hence the number of species found in the continental-shelf sediments will be in part a function of depth. As a result, relatively fewer species of planktonic foraminifera will accumulate in shallower depths than in the deeper parts of the region. Thus, diversity tends to increase concomitantly with depth in small geographical regions, providing a useful tool in the determining of existing bathymetric patterns.

The first attempt to establish a relationship between the depth and specific diversity of planktonic foraminifera was made by Emiliani (1954), who concluded from oxygen isotope paleotemperature studies that different species of planktonic foraminifera occupied different habitats with respect to depth. He was followed by Bandy (1956*a*), who observed that in the Gulf of Mexico different species of planktonic foraminifera had a minimum depth limit above which they did not occur. He concluded that the minimum depth at which species were recovered in the sediments indicated the upper level at which they floated.

Polski (1959), in his studies on the eastern Asiatic continental shelf, concluded that the specific diversity of planktonics increased with depth. In another publication, Waller and Polski (1959) have given a list of planktonic species that appeared regularly below certain depths "suggesting a zonation with depth" (table 1). Phleger (1960*a*, p. 241) interpreted the results upon which Bandy (1956*b*) established his conclusions as "reflections of species frequencies related to the size of the population". Bandy (1967), citing results taken from Bé (1960), has shown that some planktonic species, such as *Globorotalia tumida* and *Sphaeroidinella dehiscens*, are missing from the enormous populations collected in the euphotic zone. Had their distributions been reflections of species frequency related to the sizes of populations, they should have been found in this zone. The raw data from the Gulf of Mexico of Phleger (1951), despite his conclusions to the contrary, as well as those of Bandy (1956*a*), give support to the linear relation between specific diversity and depth, as shown by Stehli (1966), who concluded that "it is clear that a relationship exists and that the technique could



TEXT-FIGURE 3
Stratigraphy of Upper Cretaceous intervals studied.

probably be refined and used within a given region" (text-figure 4). Also Phleger's (1960) data from the Gulf of Mexico, which have been statistically treated by this author, clearly give support to increasing specific diversity with increasing depth. Statistical study of values from his data table down to a depth of 960 meters clearly shows that there is a relationship between depth and the number of species, as is indicated below.

One way to determine the change in one variable (Y) when another variable (X) changes is the least squares method. This method is employed to find the line of best fit, the regression line. It is the line that joins the means of the distributions corresponding to all possible values of X. It is assumed that X values are independent variables, *i.e.*, that they are selected and controlled by the investigator. It is further assumed that for each X there is a distribution of Y and that the observed Y values corresponding to a given X are a random sample for that distribution. It is also assumed that the variances of the distributions of Y are equal.

TABLE 1
Depth zonation of some species of planktonic foraminifera of the eastern Asiatic shelf (after Waller and Polski, 1959)

Species	Minimum depth (feet)
Globigerina bulloides	150
Globigerina subcretacea	160
Globorotalia trigonula	200
Globigerinoides ruber	200
Pulleniatina obliquiloculata	220
Orbulina universa	260
Globorotalia menardii	300
Globigerina quinqueloba	300
Globigerinoides conglobatus	310

When a relationship between two variables is established or assumed to be a straight line, the symbol r is used to represent the linear correlation coefficient, Pearson's product-moment correlation coefficient. r^2 is the coefficient of determination. It must be, by definition, between zero and one, inclusive. If the points determined are close to the regression line, r^2 would be close to one, but, as they scatter from the line, r^2 would be smaller. So it is a good measure of the strength of the relation.

When Pearson's product-moment correlation coefficient, r, is calculated for the values of Phleger, down to a depth of 960 meters to minimize the effect of slumping from above, one gets the following results:

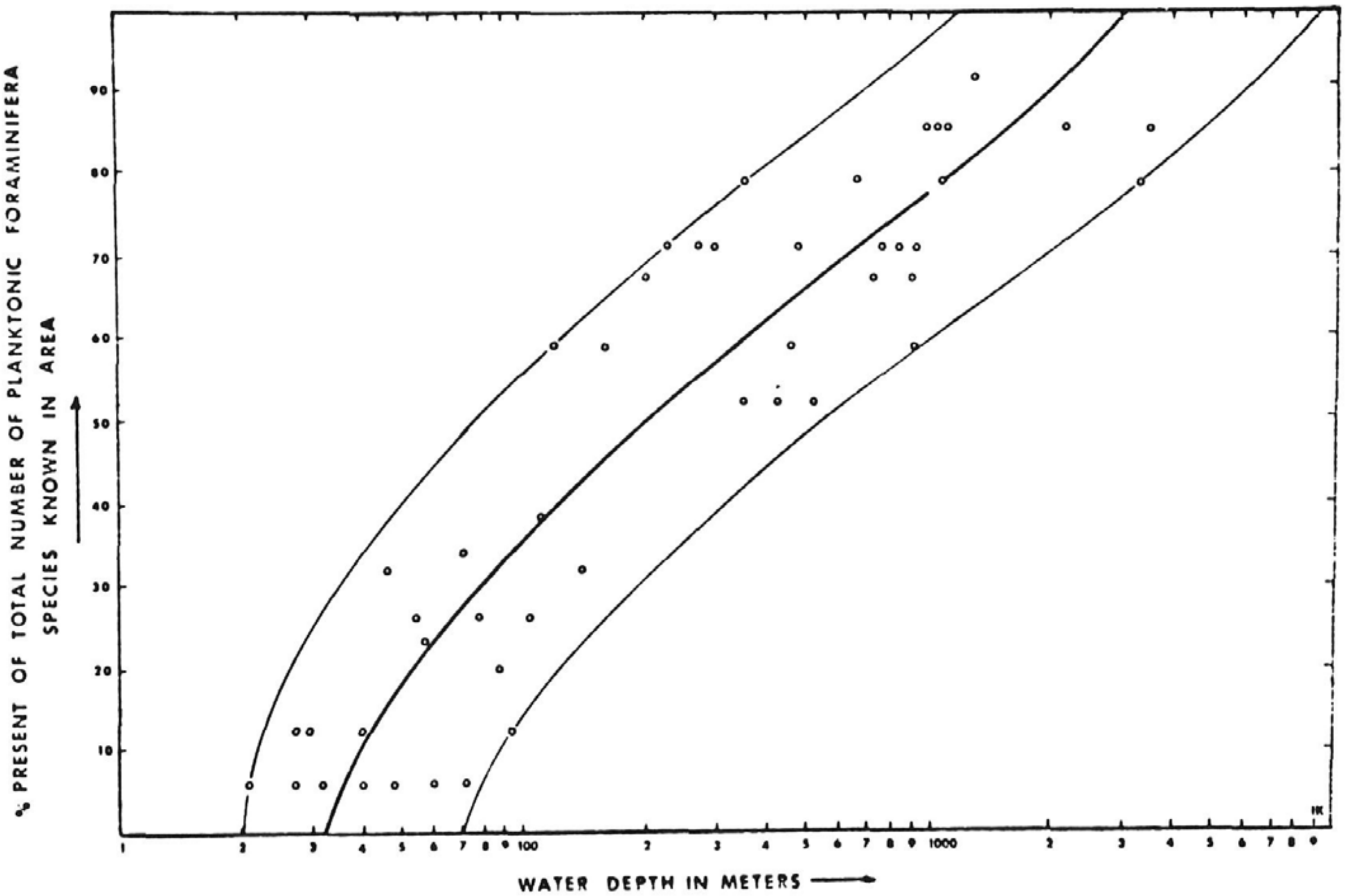
$$r = \frac{18043}{20607} = .87$$

and consequently $r^2 = .7569$.

From these results it is clear that there is a relationship between depth and number of species (75%) in this example.

Later studies have confirmed this point. In a study made on the eastern continental shelf of the United States, Wilcoxon (1964) concluded that there was a general depth stratification of the planktonic species. Bé and Hamlin (1967), in their studies on the ecology of Recent planktonic foraminifera, showed that a definite depth stratification occurs, particularly in subtropical species.

The above studies in different parts of the world reveal a depth stratification of the planktonic species as explained by the model of Stehli (1966) (text-figure 5). Although it has been shown that latitude is the most important factor in diversity on a global scale (Stehli and Helsley, 1963), the depth effect should dominate within a compact geographical region. So, in a perfect regional model, diversity should increase normal to the



TEXT-FIGURE 4
Empirically determined diversity in species of planktonic foraminifera from bottom samples in water of increasing depth (after *Stehli, 1966*; data from Phleger, 1951, and Bandy, 1956).

isobaths toward the open ocean. Conversely, approach to topographic highs, such as islands, shoals, or shore line, should be characterized by a decrease in diversity values. Thus, it is to be expected that this method can be applied to reveal paleobathymetric patterns of the regions where a diverse assemblage of fossil planktonic species is present.

METHODS OF STUDY

Electrical logs

One hundred and thirty electrical logs and much published and unpublished material formed the basis of the correlation framework used in this study. Eighty-three appropriately placed wells were selected for paleontological study. Some of these were eliminated because samples could not be obtained or because of the poor quality of the samples. The final paleontological analysis which forms the principal focus of this study was based on planktonic foraminifera from 55 wells.

Laboratory studies

During microscopic examination, intervals barren of fossils (mostly sands) were excluded from the study, as were several intervals in which so few individuals occurred that counts were considered unreliable. Intervals in which benthonics were present and planktonics absent were assigned a zero diversity value. Some samples, especially in the upper parts of Interval A, were clearly contaminated with cavings, as shown by the presence of post-Cretaceous planktonic foraminifera, and therefore these were eliminated. Additional cases of serious contamination from cavings were recognized from gross disagreement between the lithology of the cuttings and the lithology as determined from electrical and sample logs, and samples thus known to be contaminated were also eliminated.

When all of the usable samples for each of the intervals in each well had been picked, and the fossils had been identified and recorded, the results were used to calculate a diversity value (table 2).

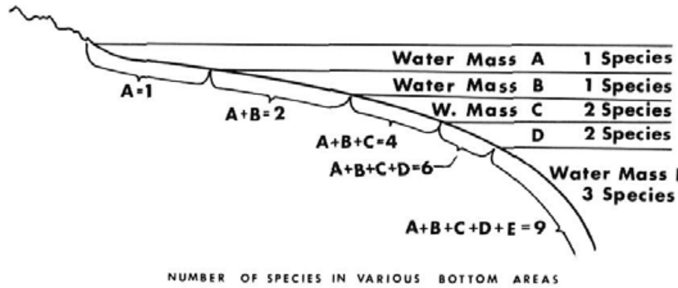
TABLE 2
Calculation of number of species for each well

1) Barren intervals were not included in the calculations.
2) Intervals with no planktonics but with benthonics were assigned 0 value.
3) Average number of species for each interval in each well was calculated as follows:

Sample interval	Net thickness	No. of planktonic species
3615–3715	100	12
3715–3895	180	10
3945–4045	100	9
4205–4265	60	14
4265–4345	60	0
	500	

$$\frac{(100\times 12)+(180\times 10)+(100\times 9)+(60\times 14)+0}{500}=\frac{4740}{500}=9.4 \text{ or } 9$$

Nine, therefore, is the normalized number of species for the interval (A or B) at a particular control station.



TEXT-FIGURE 5
Model designed to explain increasing diversity in species of planktonic foraminifera encountered in bottom samples from waters of increasing depth (after Stehli, 1966).

Trend surface analysis

Because the surface revealed by variations in the diversity of planktonic foraminifera is complex and the control sparse, a trend surface analysis of the data was made. The simplest type of trend surface is a plane in three-dimensional space. Here the map coordinates represent two independent variables, and the parameter of interest (*i.e.*, the number of species at each well in this study) represents the third and dependent variable (text-figure 6). Least square methods are available for fitting a plane, but when local irregularities are large or the parameter of interest is not planar in distribution, higher degree polynomials are required. Depending on the spacing of the data, either a) orthogonal, or b) non-orthogonal forms are employed. They are used respectively for data spaced in accordance with a grid system or for data spaced irregularly. In orthogonal form, linear, quadratic, cubic, etc. equations have the same coefficient, but, in non-orthogonal form, the coefficients have to be recalculated in each instance from linear to higher orders. In the present case the non-orthogonal form had to be employed, since the control points are irregularly spaced.

Non-orthogonal polynomial surfaces can be conveniently solved in three ways (Miller and Kahn, 1962): 1) by converting non-orthogonal form into a grid pattern and proceeding with orthogonal technique as described by Krumbein (1956, 1959), 2) by computing an approximation to the least squares regression surface with a desk calculator, or 3) by employing computers to determine the coefficients in terms of coordinates (two variables, X and Y) for each control point at which polynomial trend surface can be expressed. This method is used to fit linear, quadratic, cubic and higher order surfaces to the observed data by the least squares methods. (For examples see Krumbein, 1959; Stehli and Helsley, 1963.)

In this study the third type of solution has been employed. For each interval a 6th order surface was used to obtain a reasonable fit of the more important elements of the surface yet still allow the smoothing of minor irregularities. The calculated surfaces made possible the development of objective contour maps (text-figures 7 and 9). While these maps are objective and thus free of operator bias, they fail, of course, to allow the interpretive use of independent background information, which is the vital contribution of the geologist to such a map. For this reason, with the use of the objective surface as a general guide, interpretive maps for each interval have been prepared and are shown in text-figures 8 and 10. Because the data used in this study inevitably contained considerable "noise", the residuals from trend surface analysis were plotted as a means of evaluating "noise", and it was found to be quite random and probably to reflect only irregularities in the quality of data and not systematic variation.

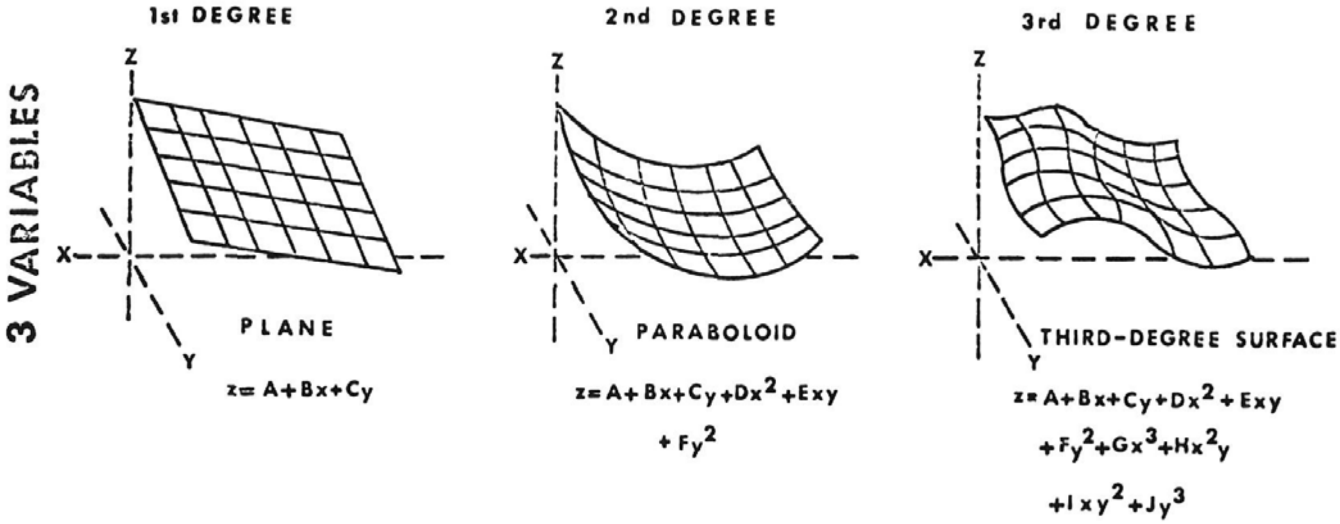
Difference between ratio and diversity methods

The technique used in this study differs from the ratio method used by Stehli and Creath (1964) in the following ways:

a) In this method only the planktonics need be picked *versus* both planktonics and benthonics in the ratio method. A relatively larger amount of material is needed in this method to obtain an approximately equal number of individuals to be examined.

b) In the ratio method only two groups have to be separated, planktonics and benthonics. Since in this method one has to study each planktonic individual at a specific level, it is more time-consuming.

c) Having to work at specific levels may confront one with many difficult decisions regarding the identification of juvenile or poorly preserved individuals, and the technique can thus become quite subjective, especially if poor material must be handled. To minimize such a



TEXT-FIGURE 6
Relationship between number of variables and degree of generalized equations and their geometric equivalents (after Harbaugh, 1964).

problem from any given bore hole, each interval was examined for state of preservation. When badly preserved specimens were found to form the bulk of the fauna, the complete interval was rejected. This was done to ensure that all records were strictly comparable; the elimination of just one sample interval would not affect the weighting procedure. Also, it is believed that, following standard procedures, sieving samples through a 250-mesh sieve removed almost all juveniles. This treatment appears to have been reasonably successful.

d) The use of the diversity technique requires an operator of considerably more experience than is necessary for the ratio method because of the need for specific determinations.

e) To check the reproducibility of the method, some samples have been re-examined by another worker. His results were uniformly lower in value than my own. This discrepancy resulted from differences in the species concept of the two operators. Division into species would be constant for each worker and thus leave relative values unaffected, though absolute values would vary. From this test it was concluded that operator error was small but that uniform taxonomic standards are required, if it is desirable to have the absolute number of species agree between operators.

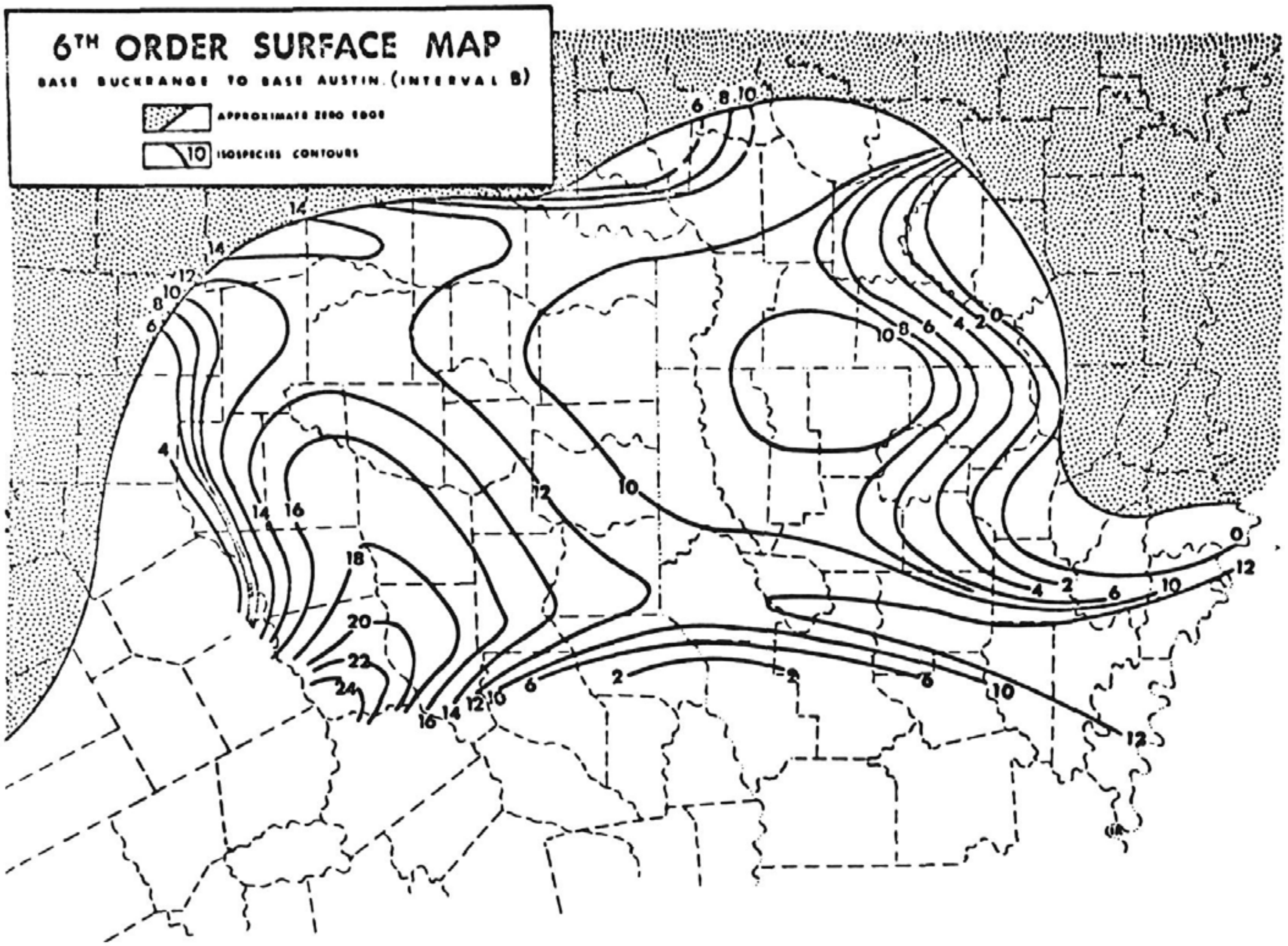
In summary, it is believed that the precision of the technique in reflecting depositional water depth may more than compensate for the extra time involved in its use.

RESULTS

The isospecies contour maps prepared for the average specific values of each study interval in each well are presented in text-figures 8 and 10. For comparison of the results of the two methods, the figures of Stehli and Creath (1964) are given in text-figures 11 and 12 for the same intervals. Interval A is, as has been shown in text-figure 3, the stratigraphic continuation of Interval B, with the exception of a small intervening interval (Ozan-Buckrange). The two sets of maps differ from each other in many respects. To allow consideration of the differences as they relate to the evolution of different structural elements of the region, both units will be examined successively for each of the principal elements of the study area.

Tyler Basin

High numbers of planktonic species occur throughout the central and the northwestern parts of the Tyler Basin. The highest values are found toward the south where the basin presumably is connected with the open gulf. In general, high values (between 15 and 20 species per well (SPW)) follow a roughly north-south trend. Slightly lower values tend to occur around the margins of the basin. A low value was observed in the north central part of the basin, in Rains County, Texas. Facies data (700 feet of marine calcareous shale) do not suggest that this area lay near the shore, and structural data (text-figure 13) indicate that it is located in the deeper part of the basin. Correlation data indicate that Interval B is complete here, so the low value can not be due to partial loss of the section. Possible explanations of this situation seem to be selective destruction of some of the contained fossils or the local existence of shallower water in this area. The latter condition is thought to be the more probable, because Rains County is near the Luling-Mexia-Talco

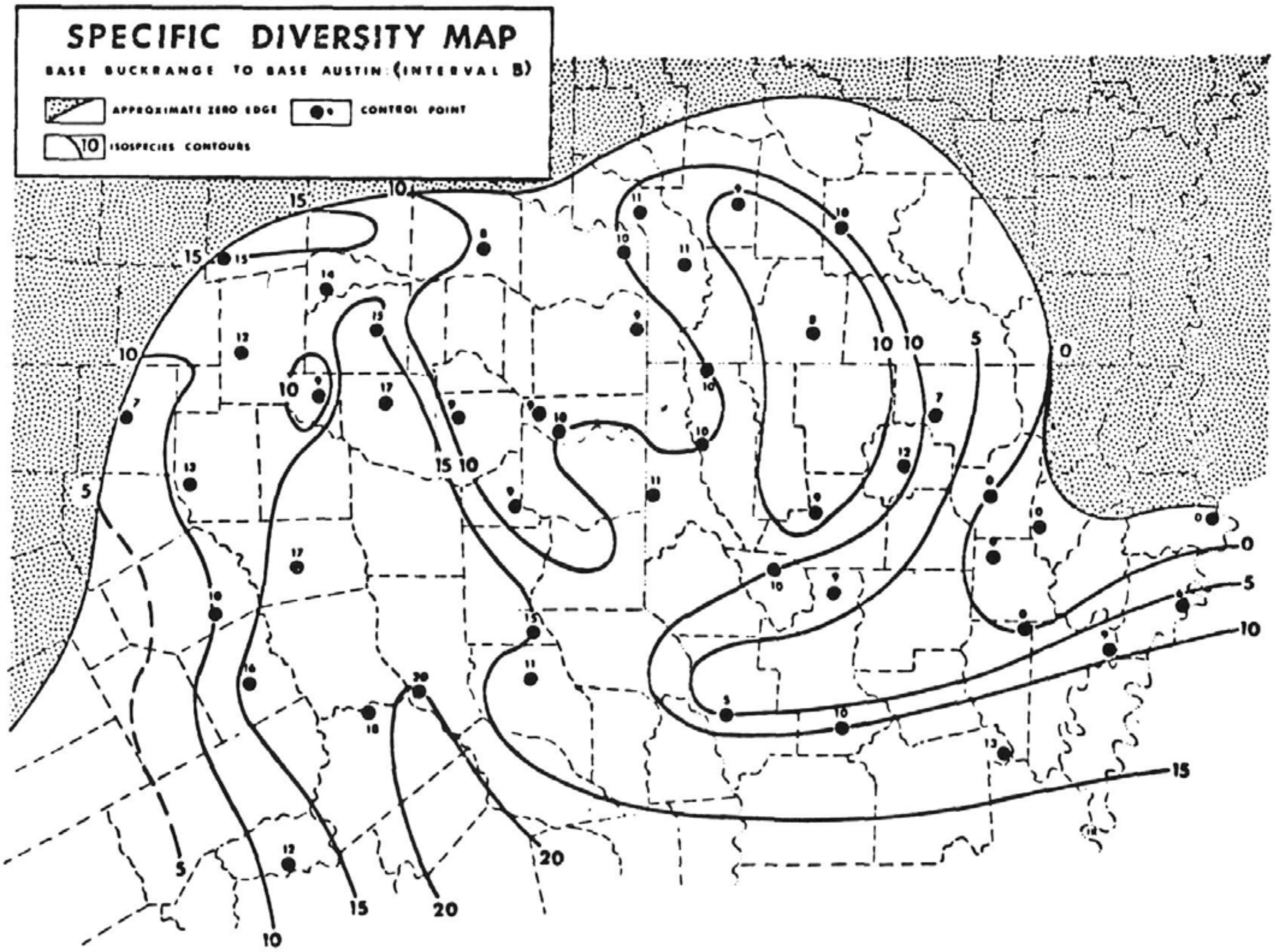


TEXT-FIGURE 7
Sixth order surface contour map of Interval B (base of Buckrange to base of Austin) objectively made by computer.

Fault Zone. Tectonic disturbances known to have taken place on this fault system during Upper Cretaceous time could have caused either local shallowing or disturbance of the sediments in the region and possible loss or destruction of a portion of the planktonic foraminiferal population.

Values which are somewhat higher than the normal for the margin of the basin occur at its northern end in Fannin, Delta and Hopkins Counties, Texas. The calcareous shales characterizing Interval B in this area are similar to but thicker than those in Rains County and are likewise believed to have been deposited at some distance from shore. From an examination of ratio data Stehli and Creath (1964) concluded that a current system might have flowed across this area and suggested that the Cretaceous seas once extended far beyond the zero edge of the preservation of sediments in this direction. Taken together with the ratio data, the species diversity data suggest the existence of both a current system and comparatively deep waters in this area.

The northeast end of the Tyler Basin is connected with the Interior Salt Basin of Louisiana by a structural trough, the Pittsburgh Syncline. Structural data suggest that the Pittsburgh Syncline was generally more subsident than the regions to the south and north. But isopachous data for Interval B do not indicate by unusual thickness that it subsided strongly at this time. It appears possible that the influx of sediments formed a shallow-water barrier or sill across the syncline between the northern end of the Sabine Uplift and the positive area in Arkansas, which made access of open-ocean water into the Interior Salt Basin by this route difficult. The species diversity map suggests that such a barrier might have existed. The slightly low value in Red River County, Texas, seems consistent with this interpretation. Such an explanation is also compatible



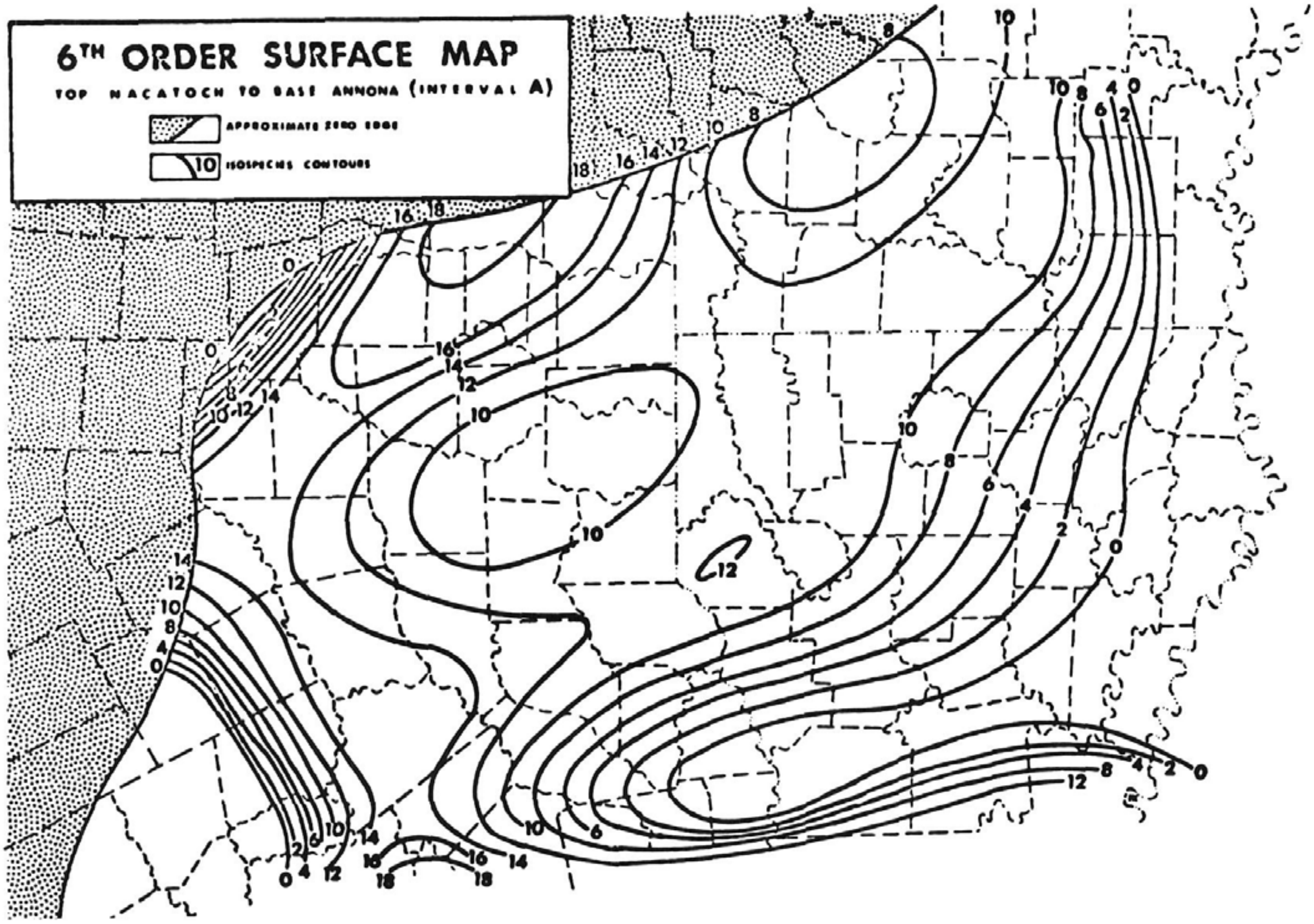
TEXT-FIGURE 8
Specific diversity map of Interval B (base of Buckrange to base of Austin).

with the ratio data of Stehli and Creath (1964), who show little indication of a current through the syncline at this time. High values in Little River and Bowie Counties of Texas may indicate the influence of the Interior Salt Basin, which had a connection with the open sea over the Sabine Uplift.

In Interval A higher SPW values have a more widespread pattern, indicating probable deepening of the Tyler Basin. The trend of the highest values is still in a roughly north-south direction, becoming southwest-northeast in the northern part of the basin. During this interval low SPW values appear at the northern end of the Sabine Uplift in Marion County, Texas, suggesting shallower-water conditions there.

In the northwestern part of the area, near the erosional edge of the Upper Cretaceous rocks, a thick shale sequence occurs in Rains, Wood, Hopkins and Morris Counties, Texas, that shows high SPW values. The high SPW values here might indicate either that the basin was larger at this time or that it had a connection to the west. The former possibility seems more probable, since the general pattern of isospecies contours also increased toward the east, showing an expansion to the east as well as to the north. Such an expansion could, of course, provide a connection with the west through the northwestern part of the basin, so a unique interpretation seems impossible.

A rather low SPW value of 8 has been observed in Interval A in Madison County, Texas. The facies data of Stehli *et al.* (MS. in press) suggest that the region lay far from the shore, and no evidence of local shallowing has been found. A selective preservation process of some kind seems to provide the most reasonable explanation of this low value. Examination of surface material from farther west in Travis County,



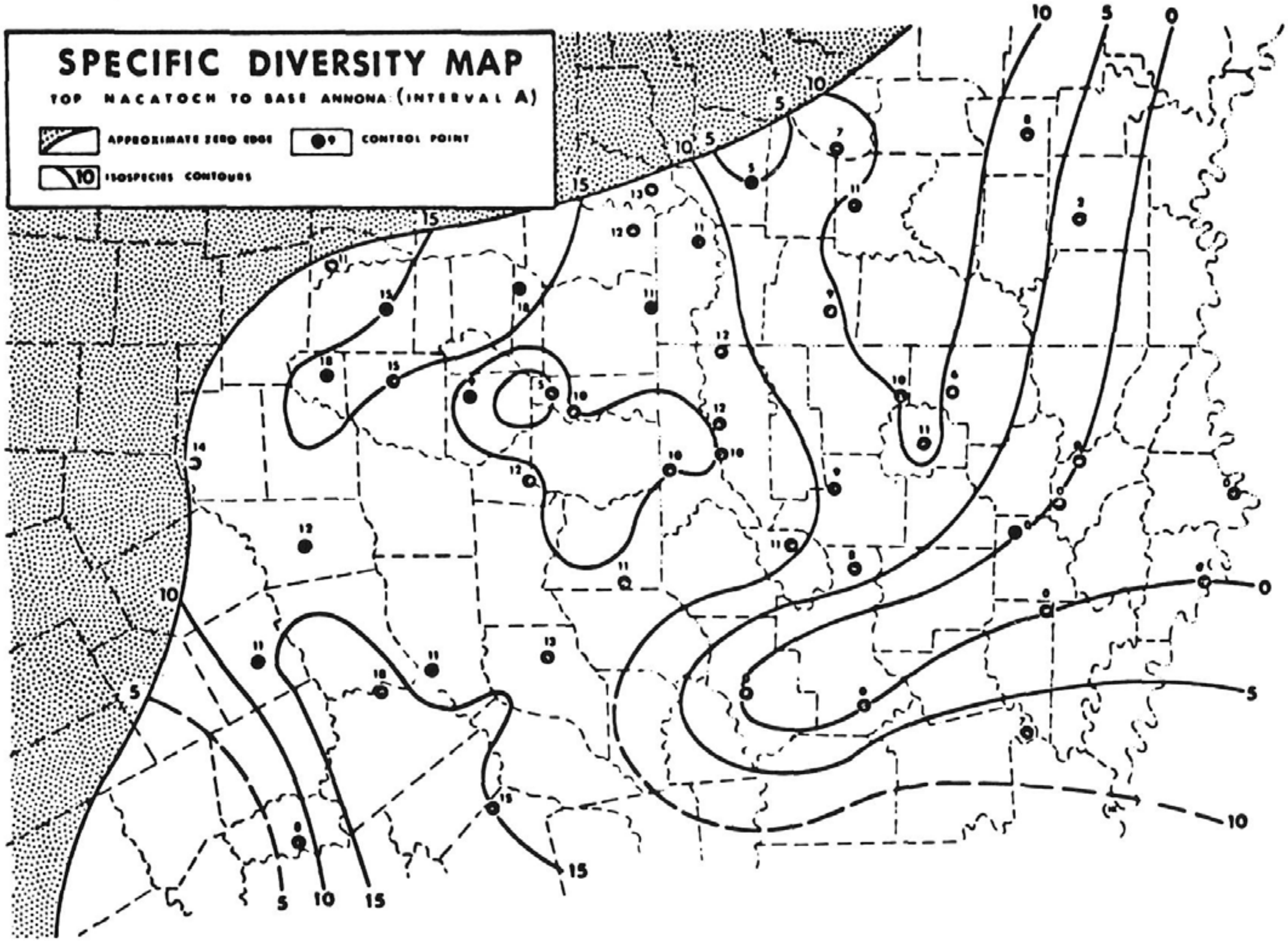
TEXT-FIGURE 9
Sixth order contour map of Interval A (top of Nacatoch to base of Annona) objectively made by computer.

Texas, supports this conclusion by showing a higher diversity.

In general, the central region of the Tyler Basin is characterised by high species diversity, while somewhat lower values tend to occur toward the margins, except in the presumed direction of the open ocean to the south. These data, interpreted in the light of modern planktonic foraminiferal distribution, suggest deeper water in the structural basin during the deposition of both Interval A and Interval B, and shallower conditions in the surrounding areas. There is a suggestion that deeper water occurred at the south end of the basin, where it probably was united to the open sea, and in the north central part of the basin. In general, the species diversity data are compatible with interpretations made from the other lines of evidence that have been investigated.

Sabine Uplift

On the Sabine Uplift, during the deposition of Interval B, the lowest SPW values seem to have occurred in the northwestern and north central areas. This suggests that the northern portion of the uplift stood close to the ancient sea level and was covered only by relatively shallow water. In contrast, rather high SPW values occur on the southern end of the uplift, suggesting the existence of deeper water. This interpretation is compatible with the facies data at the actual sampling wells. Both of the wells are at the extreme western margin of the uplift and allow the possibility that near its crest the southern end stood close to sea level, as did its northern counterpart. It was not possible to obtain SPW values for this region due to difficulty in getting appropriate samples. Values intermediate between those of the southwestern and northern parts of the uplift were found in its central area, where their occurrence coincides with a structural sag in the crest of the uplift (text-figure 13). In southeastern Rusk County, Texas, near Panola County, the highest SPW value on the uplift was observed. Panola County,



TEXT-FIGURE 10
Specific diversity map of Interval A (top of Nacatoch to base of Annona).

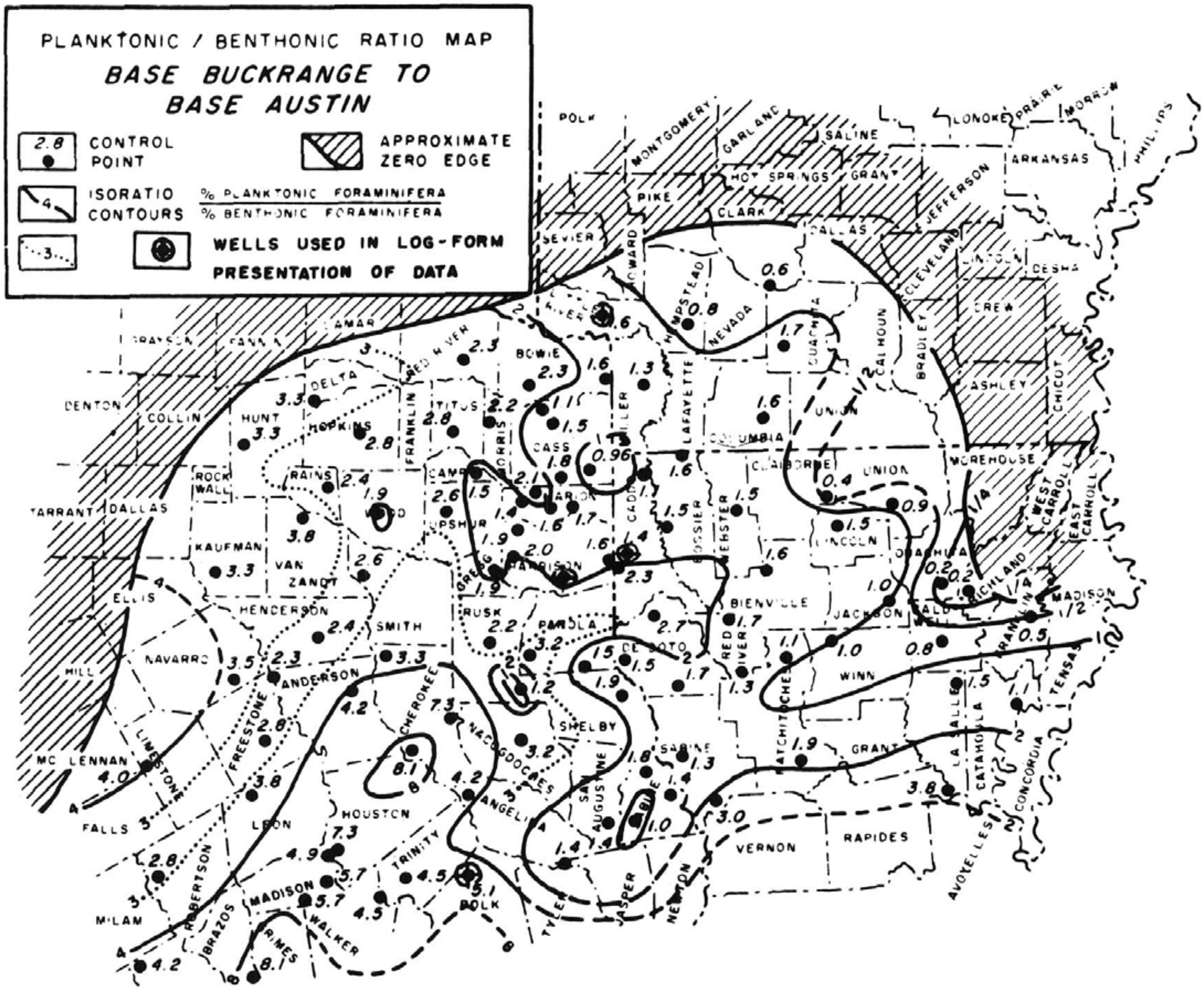
Texas, and DeSoto Parish, Louisiana, coincide with the structural sag. This sag probably provided a connection between the Tyler Basin and the Interior Salt Basin, as suggested by Stehli and Creath (1964). However, it was impossible to obtain a detailed picture of this region because of poor preservation in the samples studied.

During the deposition of Interval A at the northern end of the Sabine Uplift, high SPW values appear and suggest relatively deeper water. No data were obtained for conditions at the south end of the uplift for this interval. In the central area the connection through the sag probably continued on a larger scale. The increasing values in Panola County, Texas, and Red River Parish, Louisiana, indicate this.

Winn Axis

Available control points on the Winn Axis are in Caldwell, La Salle, Richland and Sabine Parishes, Louisiana. The benthonic population found in these samples was sparse, and in most the planktonics were rare as well. It seems clear that during the deposition of Interval B the Winn Axis was characterized by rather shallow water. Specific diversity data suggest a strongly positive element in the east, which became less positive toward the southern end of the Sabine Uplift in the west. The Winn Axis thus seems to have been a very real barrier to circulation at its eastern end, while toward the west, where it lay deeper under water, it may have permitted some limited interchange between the open ocean and the Interior Salt Basin.

During the deposition of Interval A, the Winn Axis appears to have been considerably more positive than during that of Interval B. The eastern end remained very shallow, and the area of shallow water seems to have extended much farther to the west. Perhaps at this time the water was so shallow as to virtually isolate



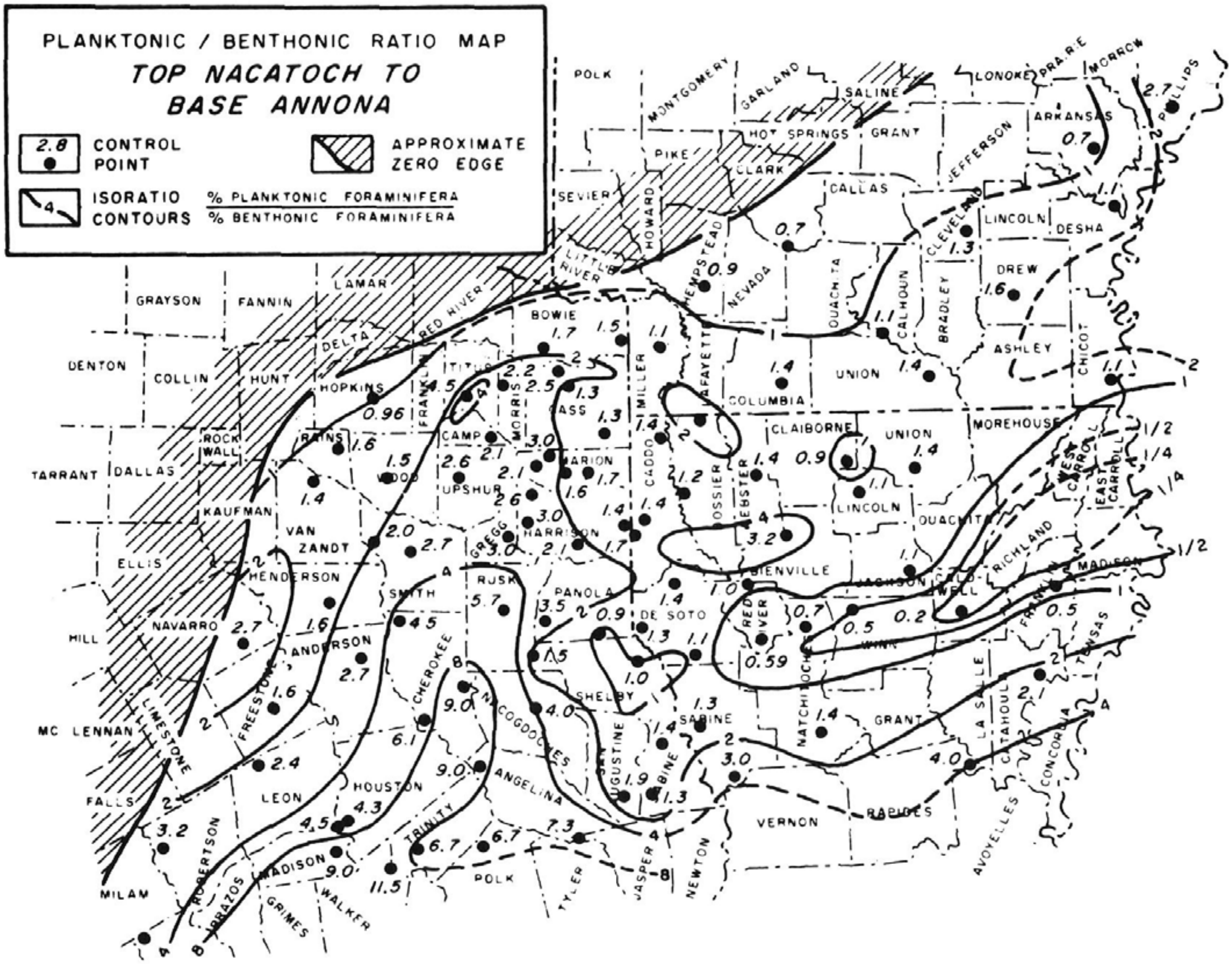
TEXT-FIGURE 11
Planktonic/benthonic foraminiferal ratio map for Interval B (base of Buckrange to base of Austin). After Stehli and Creath (1964).

the Interior Salt Basin from the open ocean, except from the west across the Sabine Uplift and also possibly through the Desha Basin in the northeast.

Southeastern region

In this area the control points are very difficult to obtain because of down-dip conditions. A few available points, however, gave satisfactory results. Earlier works, such as that of Stehli and Creath (1964), have suggested that the open ocean lay to the south of the Winn Axis. If this is true, one would expect evidence of deeper waters in this direction. It was possible to obtain control points for Interval B in Tensas, Catahoula, Rapides, and southern Natchitoches Parishes, Louisiana, south of the Winn Axis. These samples all show SPW values increasing to the south and thus strongly support the thesis of deeper water in that direction during this time. Values also rise to a modest degree as one enters the Interior Salt Basin to the north, suggesting somewhat deeper waters in this direction as well.

For Interval A the control is less extensive. It indicates, however, that the influence of the axis extended farther south than in the preceding interval, for only the southernmost station shows the expected increase in SPW. From the data one could conclude either that



TEXT-FIGURE 12
Planktonic/benthonic foraminiferal ratio map for Interval A (top of Nacatoch to base of Annona). After *Stehli and Creath (1964).*

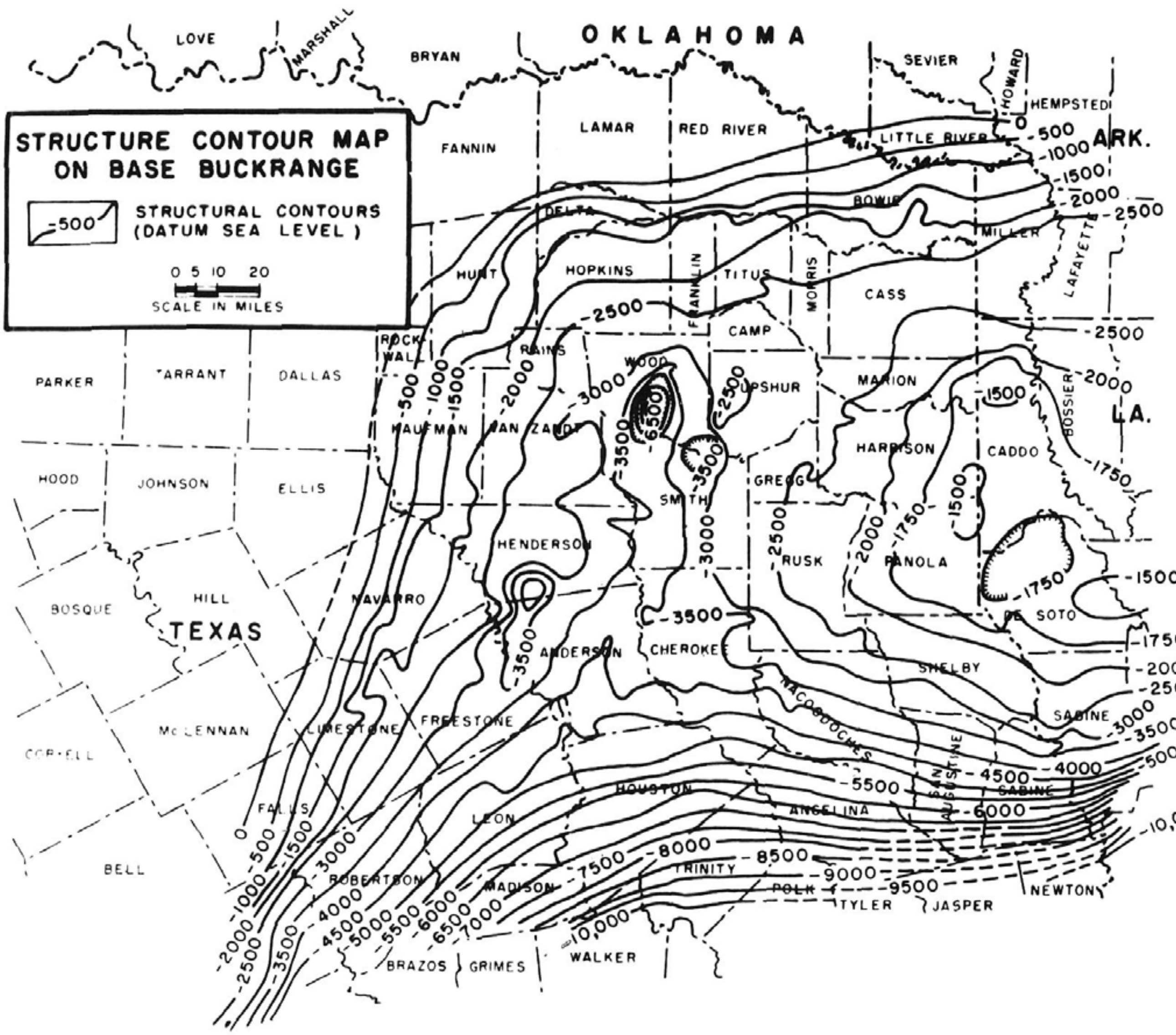
the sea level had dropped in Interval A relative to Interval B or that the axis had undergone some structural growth. The latter explanation is preferred because no supporting evidence of a drop in the sea level is known in the region.

Monroe Uplift

Few control points were obtained on the Monroe Uplift. However, none of those studied for either Interval B or Interval A yielded any planktonic foraminifera. A few benthonic foraminifera show that the samples are at least in part from marine strata, and one is forced to conclude that only extremely shallow water covered this uplift and then perhaps intermittently. The presence of many unconformities in this part of the section, the development of the partially reefal Monroe Gas Rock, and many other features provide independent support for this conclusion.

Interior Salt Basin

During the deposition of Interval B the central region of the Interior Salt Basin is characterized by SPW values of about 9, suggesting the existence of moderately deep water. It is quite clear from text-figure 8 that a connection between the Interior Salt Basin and the Tyler Basin existed across the Sabine Uplift and that communication with the open sea was provided by this route, for, as we have already seen, the Winn Axis existed as at least a partial barrier to the south. No clear evidence of a connection between the Interior Salt Basin and the Tyler Basin around the north end of the Sabine Uplift exists in the available data, although



TEXT-FIGURE 13
Structure contour map on base of Buckrange in east Texas. After Stehli and Creath (1964).

control is not so dense in the region as to preclude this possibility. Available information regarding the northeastern part of the basin is not sufficient to decide whether a connection existed through the Desha Basin. The SPW values suggest, then, a relatively open basin restricted most severely to the east by the Monroe Uplift and to a lesser degree to the south by the Winn Axis and to the west by the northern part of the Sabine Uplift.

During the deposition of Interval A, a picture exists which differs from that of Interval B. The central part of the basin seems to be covered by deeper water. This may be because of better connections with the northeast in addition to an improved connection over the Sabine Uplift to the west. In the northwest part of the basin there is more secure evidence of shallow water for this interval, and it is probable that the shore lay not far toward the north, since SPW values drop significantly toward the edge of the sediments preserved. Once more there is a possibility of some connection between the Interior Salt Basin and the Desha Basin across the northeastern corner of the study area. The tendency of SPW contours surrounding the central part of the basin to open toward the north and a relatively high SPW value of 8 for the area of the Desha Basin support this suggestion. The Winn Axis and the Monroe Uplift, as previously noted, were more severely *restricting* at this time. Communication of the Interior Salt Basin with the open ocean was by means of the connection between the south end of the Sabine Uplift and the west end of the Winn Axis and also to some extent by means of the Pittsburgh Syncline north of the Sabine Uplift.

In general, the water in the Interior Salt Basin may have been shallower toward the margins and deeper in the central part. Southeastern shallowing may have been caused by the expansion of the Winn Axis.

No information was available concerning the Desha Basin for Interval B. It was most probably shallow during both intervals but had a probable connection with the Mississippi Embayment during Interval A.

CONCLUSIONS

Although only 55 wells were studied in a rather large area, it appears that the species diversity of planktonic foraminifera yields information which is compatible with what is known or can be deduced regarding probable depositional water depths. A rigorous evaluation of the technique is of course not possible, since no independent means of determining water depth exists. Comparison of the species diversity data with the planktonic/benthonic ratio data of Stehli and Creath (1964) shows that many similarities exist in the patterns revealed by the two methods. If the models upon which the two methods depend are correct, then it appears that the principal Upper Cretaceous currents of this part of the Gulf Coast region tended to occur in areas of deeper water.

It is believed that the method shows considerable promise and, with detailed coverage, could be made to yield a detailed picture of relative depositional water depth. Exploration for stratigraphic traps around former submarine topographic highs is an outstanding example of an exploration situation in which precise information relative to depositional water depth would be important. As far as I am aware, this method is being applied to ancient rocks for the first time in this study.

A later study (Kafescioglu, in preparation) in a Recent environment has clearly shown that this method gives the general bathymetric pattern quite clearly. The fact that the technique appears to work successfully on Upper Cretaceous rocks suggests that it might be extended backwards in time as well to the first abundant appearance of planktonic foraminifera in the early Cretaceous.

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