SEQUENCE STRATIGRAPHY OF THE PACHUTA–MARIANNA INTERVAL (UPPER EOCENE–LOWER OLIGOCENE) IN THE U.S. GULF COAST

Carlos A. Jaramillo, and Francisca E. Oboh-Ikuenobe

Abstract

The qualitative and quantitative characteristics of palynofacies and dinocyst assemblages have been used to interpret the sequence stratigraphy of upper Eocene–lower Oligocene strata in southern Mississippi and Alabama (U.S. Gulf Coast). In southern Mississippi, we identified a latest Eocene maximum flooding surface in the middle of the Shubuta Clay, but this surface was identified at the top of Shubuta Clay in southern Alabama, where the Eocene–Oligocene boundary was placed within a condensed section (of approximately 0.19 million years duration). This condensation, which was identified at the Shubuta Clay–Vicksburg Group contact, is equivalent to the accumulation of the upper Shubuta Clay and Red Bluff Clay in southern Mississippi. We also interpreted the Forest Hill–Mint Spring contact as a sequence boundary which coincides with a transgressive surface, but this interpretation differs from that of Pasley and Hazel (1995). In southern Mississippi, the Pachuta Marl and the lower Shubuta Clay comprise a late Eocene transgressive systems tract, whereas the same systems tract consists of the Pachuta and the entire Shubuta Clay in southern Alabama. The overlying early Oligocene highstand systems tract was represented by the upper Shubuta, and the Bumpnose/Red Bluff/Forest Hill Formations. Although a very thin sandstone in the Mint Spring in one southern Mississippi section was interpreted as a possible lowstand deposit, the Mint Spring, along with the Marianna Limestone, constitute the transgressive systems tract in the other four sections.

INTRODUCTION

Relative sea level fluctuations and chronostratigraphic correlations are two important points considered in any sequence stratigraphic analysis of a sedimentary basin. Frequently, in offshore environments and continental deposits, it is difficult to identify key surfaces such as sequence boundaries and their correlative conformities, transgressive surfaces, and maximum flooding surfaces. The best clue to detecting these surfaces are changes in paleobathymetry and locating time condensations or hiatuses in the stratigraphic record. Changes in paleobathymetry can be detected by lithological and paleontological studies. For time analysis, a reliable approach involves an integration of biostratigraphic datums, magnetostratigraphy and radiometric dating through the use of graphic correlation.

We have integrated dinocyst biostratigraphy, dinocyst paleoecology, and palynofacies, in order to obtain chronostratigraphic and paleobathymetric data that were used to interpret the sequence stratigraphy of upper Eocene–lower Oligocene strata in the eastern U.S. Gulf Coast. We studied five localities in southern Mississippi and Alabama: three coreholes and one outcrop in southeastern Mississippi (#1 Young, #1 Ketler, #1 Wayne, and R2089 Type Red Bluff), and one outcrop section in southwestern Alabama (St. Stephens Quarry) (Text-Figure 1). The three coreholes were drilled recently by Mobil exploration (Dockery et al., 1994) and therefore provide fresh information on this largely disputed stratigraphic interval (see discussion below).

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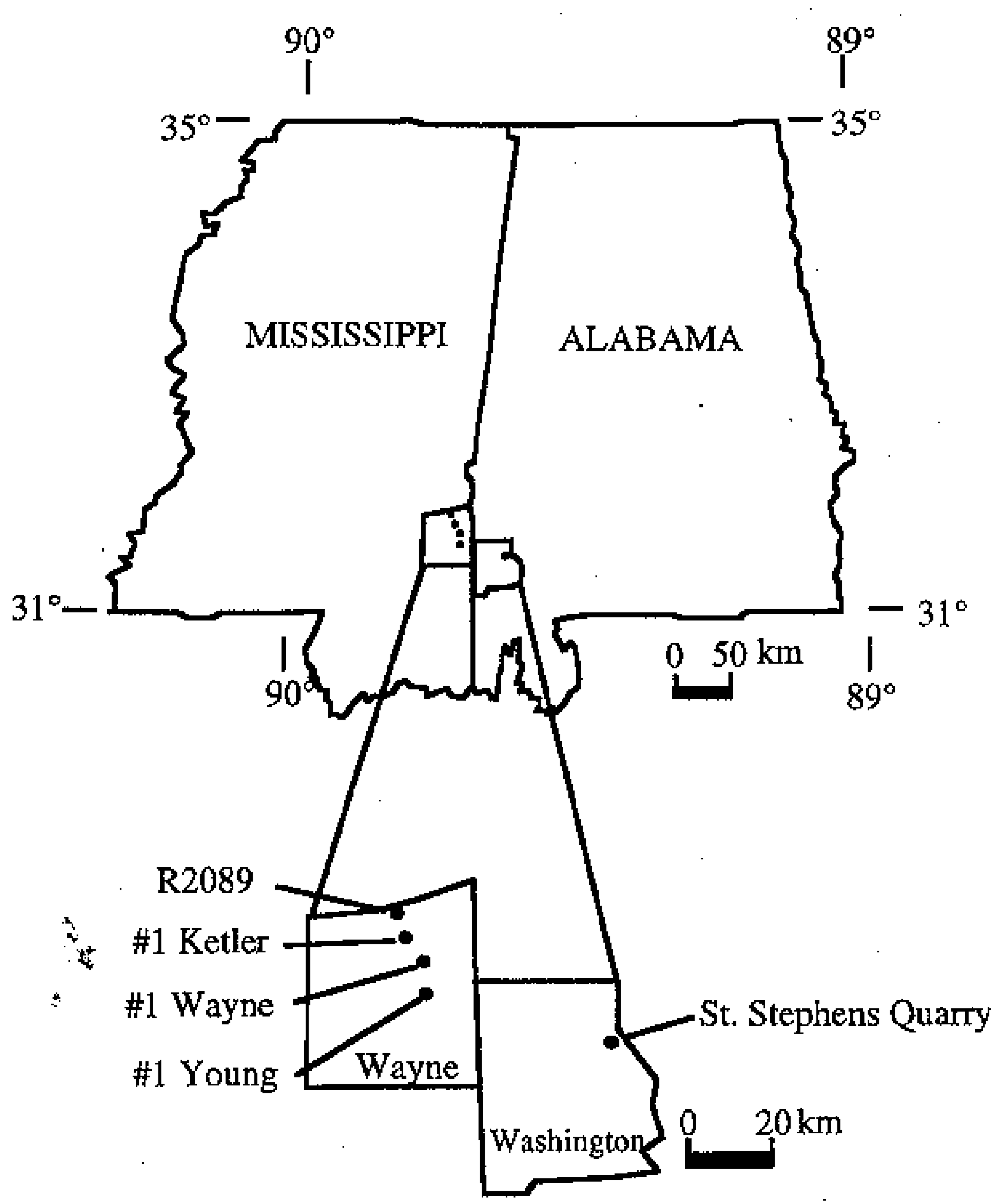
The few well exposed Eocene to Oligocene sedimentary rocks in southern Mississippi and Alabama have been extensively studied. These units are more or less continuous and have provided field data for several paleogeographic and biostratigraphic studies (e.g., Hazel et al., 1980; Siesser et al., 1985; Tew and Mancini, 1995). One section in particular, St. Stephens Quarry in southwestern Alabama,



Text-Figure 1. Map of Mississippi and Alabama showing the studied localities in the southern parts of the states.

has been the most studied, providing controversial information on the Eocene–Oligocene boundary (Mancini, 1979; Bybell, 1982; Siesser, 1983; Keller, 1985; Pasley and Hazel, 1990, 1995; and Miller et al., 1993). These biostratigraphic studies have focused mostly on microfossils other than dinoflagellates, in spite of their high abundance and diversity in these units.

Sequence stratigraphic studies for this area, mainly for the St. Stephens Quarry section, have applied biostratigraphy, magnetostratigraphy, stable isotope stratigraphy and lithostratigraphy to their interpretations (Baum and Vail, 1988; Loutit et al., 1983, 1988; Miller et al., 1993; Tew and Mancini, 1995; Pasley and Hazel, 1995). While the various sequence stratigraphic models proposed by these studies largely agree on many issues, the most notable discrepancies occur in the interpretation of the interval represented by the Shubuta Clay, Bumpnose Limestone/Red Bluff Clay/Forest Hill Sand, Mint Spring Marl and the Eocene–Oligocene boundary (Text-Figure 2A).

Our study provides new lithologic, palynofacies, and dinoflagellate cyst data from three coreholes and two outcrop sections which test the diverse hypotheses that have been formulated for the sequence stratigraphy of this area. Previous interpretations have been based mainly on the St. Stephens Quarry section.

GEOLOGIC SETTING

The Cenozoic history of northwestern Gulf of Mexico is characterized by a rapid sediment input and thick prograding depositional sequences that intertongue with interdeltaic shelf-edge sediments (Galloway, 1989). These units were deposited in a shallow marine to marginal marine environments of a passive margin. Upper Eocene sediments are characterized by fine-grained sediment deposition while the lower Oligocene constitute one of the great progradational wedges in the northwestern Gulf of Mexico (Galloway, 1989).

The latest Eocene time in southern Mississippi and Alabama is recorded in two lithostratigraphic units, the Pachuta Marl and Shubuta Clay members of the Yazoo Formation, Jackson Group (Text-Figure 2A). The lowest Oligocene strata consist of five lithostratigraphic units. In ascending order, the units are the Bumpnose Limestone, Red Bluff Clay, Forest Hill Sand, Mint Spring Marl, and the Marianna Limestone. The Bumpnose Limestone, Red Bluff Clay and Forest Hill Sand are lateral equivalents of each other, with the Bumpnose and Red Bluff intertonguing in some areas in southwestern Alabama (Tew and Mancini, 1995) (Text-Figure 2A).

Four different sequence stratigraphic models have been proposed previously for the St. Stephens Quarry section (Text-Figure 2B). In general, the following facts have been recognized: (a) the Shubuta–Bumpnose contact corresponds to a maximum flooding surface, and (b) a sequence boundary is located at the base of the Mint Spring Marl. Miller et al. (1993) interpreted the Shubuta–Bumpnose contact as a sequence boundary, based on correlation to the Tejas A (TA) 4.4 cycle boundary of Haq et al. (1988) and an oxygen isotope increase at the contact. However, Loutit at al. (1988, text-fig. 21) reported a decrease in oxygen isotope at the same level. Pasley and Hazel (1995) proposed that a surface of maximum starvation was immediately overlain by a sequence boundary at the Shubuta Clay/Bumpnose contact. They also interpreted the Bumpnose Limestone and Red Bluff Clay as constituents of a lowstand systems tract, and noted the absence of a sequence boundary at the base of the Mint Spring Marl.

MATERIALS AND METHODS

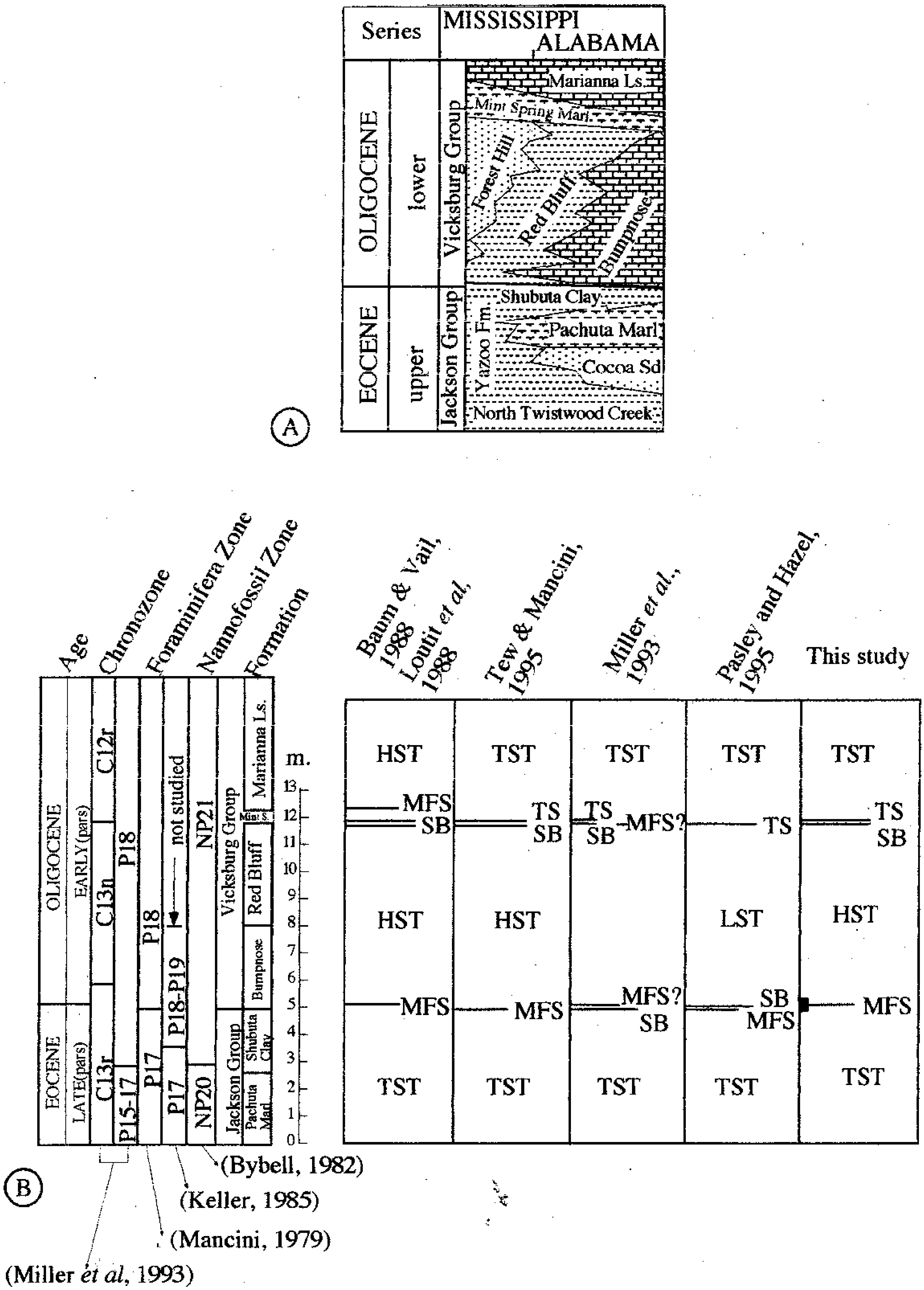
Palynological samples for this study were derived from the U.S. Geological Survey (Reston, Virginia) and Mobil Exploration and Production Services (Dallas, Texas). The oxidized samples from all the studied sites were analyzed for dinocyst richness and abundance. The resulting dinocyst ranges for the localities were then correlated using the technique of graphic correlation. The dinocyst distribution was also analyzed using multivariate techniques.

The unoxidized fractions of #1 Young samples provided the main dataset for the palynofacies aspect of this study. At least 400 organic particles per sample were identified with a Zeiss transmitted light microscope (Table 1). We used a classification system adapted from Lorente (1986), Van Vergen et al. (1990), Oboh (1992), and Jaramillo and Yepes (1995). Organic matter results were analyzed using an Euclidean-distance cluster analysis with average linkage, using Systat (1992). This method is useful because it averages all distances between pairs of objects in different clusters and decides how far apart they are (Sokal and Michener, 1958).

PALYNOFACIES ANALYSIS

Palynofacies analysis was only carried out in the #1 Young core. Euclidean-distance cluster analysis identified four groups of samples, based on their organic matter content (Text-Figure 3). In Group A, amorphous organic material dominates the palynofacies assemblage; Group B consists of yellow-brown material, pollen and plant tissue; in Group C, black-brown fragments, black debris and plant tissue dominate the assemblage; while Group D samples are dominated by dinoflagellate cysts, black debris, black-brown fragments and pollen. The differences in organic matter content between the groups are due mainly to changes in their position within the basin in relation to the paleoshoreline (Jaramillo, 1995).

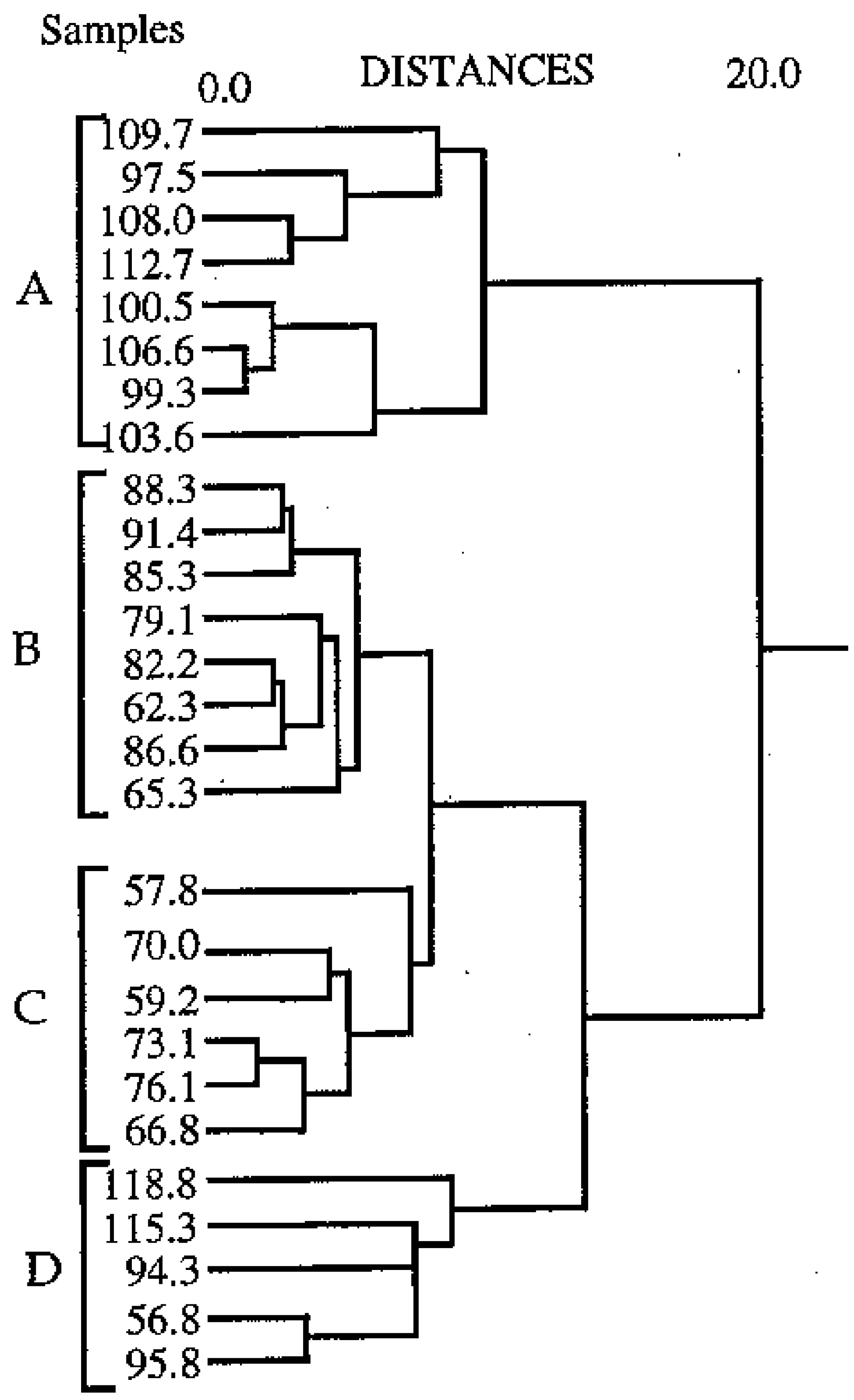
Based on the palynofacies groups identified by cluster analysis, a paleobathymetric curve has been reconstructed for the # 1 Young corehole (right-hand side of Text-Figure 4). This curve shows the relative movements of the shoreline during the latest Eocene and early Oligocene. In order to reconstruct the curve, the sample groups (A to D) were organized in a lateral palynofacies sequence from the deepest to the shallowest depositional environments as follows: Group A, Group D, Group B and Group C. Group A probably accumulated in the deepest environment because the high contents of structureless amorphous material is indicative of relatively deep offshore environments (Lorente 1986; Pasley and Hazel, 1990). Group D has a high diversity of dinoflagellate cysts, combined with terrestrial material. A diverse dinoflagellate cyst assemblage is common in shelf environments (Traverse, 1988), and in this case, we interpret a possible inner to middle shelf which is close enough to land to allow the accumulation of terrestrially derived organic material. Group B is dominated by terrestrial material but still contains dinoflagellate cysts. This assemblage probably accumulated in an inner shelf environment. Finally, Group C represents the shallowest environment because it is comprised almost exclusively of



Text-Figure 2. (A) Simplified stratigraphic correlation chart for the late Eocene–early Oligocene of the Mississippi–Alabama area (modified from Galloway et al., 1991 and Pasley and Hazel, 1995). (B) Sequence Stratigraphic, biostratigraphic and magnetostratigraphic interpretations of St. Stephens Quarry section. See discussion in the text for the position of the Eocene–Oligocene boundary. HST = highstand systems tract, TST = transgressive systems tract, LST = lowstand systems tract, TS = transgressive surface, MFS = maximum flooding surface, SB = sequence boundary.

TABLE 1. Palynodebris count data for #1 Young corehole.

		Aquatic		Terrestrial								
		Structureless	Structured	Structureless				Structured				
SAMPLE		amorphous	dinocyst/for.	resins	black debris	yellow brown	black brown	cuticles	plant tissue	woody	sporom.	fungi
meters	ft.	%	%	%	%	%	%	%	%	%	%	%
56.8	186.0–186.5	6.60	31.76	0.00	5.66	5.66	6.92	0.31	13.84	6.29	22.01	0.94
57.8	189.5–190.0	0.29	0.00	0.87	13.70	6.41	11.95	0.29	57.73	5.54	3.21	0.00
59.2	194.0–194.5	1.89	1.35	0.54	13.78	7.03	11.08	1.35	42.16	14.32	6.49	0.00
62.3	204.0–204.5	1.30	0.78	2.08	6.75	15.84	13.77	0.26	36.88	10.65	11.69	0.00
65.3	214.0–214.5	1.31	0.65	1.31	3.59	13.40	14.38	0.00	42.48	15.03	7.84	0.00
66.8	219.0–219.5	0.00	0.56	0.28	19.72	7.04	17.46	0.56	32.39	14.65	7.32	0.00
70.0	229.5–230.0	1.32	0.66	1.66	9.93	5.96	13.91	0.00	43.71	6.62	16.23	0.00
73.1	239.5–240.0	0.30	0.30	0.30	23.08	5.62	22.19	0.59	35.80	6.51	5.33	0.00
76.1	249.5–250.0	0.00	0.99	0.66	20.13	5.94	22.11	0.99	33.00	8.91	7.26	0.00
79.1	259.0–260.0	1.97	0.99	1.32	8.22	11.18	21.05	5.59	28.95	7.89	12.50	0.33
82.2	269.5–270.0	1.33	0.00	2.67	11.00	12.67	13.67	1.33	34.33	7.67	14.67	0.67
85.3	279.5–280.0	0.33	0.33	2.66	5.32	11.96	13.29	5.65	30.23	6.98	22.26	1.00
86.6	284.0–284.5	1.17	0.59	0.59	8.50	20.23	16.42	0.59	34.31	5.87	10.85	0.88
88.3	289.5–290.0	1.62	0.32	1.62	3.56	20.39	11.00	1.62	30.10	7.77	21.04	0.97
91.4	299.5–300.0	2.00	2.33	4.67	5.33	17.33	13.33	1.33	26.00	3.33	23.67	0.67
94.3	309.0–309.5	6.80	17.28	0.00	6.52	9.35	9.92	0.28	17.56	12.75	18.98	0.57
95.8	314.0–314.5	7.44	35.81	1.38	7.16	11.85	3.58	0.00	10.74	4.13	17.08	0.83
97.5	319.5–320.0	33.72	4.61	0.58	8.07	21.90	6.63	0.00	8.93	4.61	9.22	1.73
99.3	325.5–326.0	58.11	7.02	0.00	2.18	12.83	4.12	0.00	1.69	2.66	8.96	2.42
100.5	329.5–330.0	55.52	11.04	0.00	7.36	12.58	1.84	0.00	2.45	1.53	5.83	1.84
103.6	339.5–340.0	73.49	0.30	0.00	5.42	12.95	3.01	0.00	0.60	0.60	2.11	1.51
106.6	349.5–350.0	58.86	6.33	0.00	4.43	13.92	3.16	0.00	1.58	1.58	6.33	3.80
108.0	354.0–354.5	38.59	8.50	0.24	8.01	16.26	5.58	0.00	0.73	1.94	16.26	3.88
109.7	359.5–360.0	23.22	5.01	1.85	7.92	13.19	3.96	0.00	2.11	3.17	29.02	10.55
112.7	369.5–370.0	45.37	6.02	0.00	5.79	16.67	2.55	0.00	1.62	1.62	12.50	7.87
115.3	378.0–378.5	7.94	26.47	0.88	5.59	22.35	11.76	0.00	4.71	8.82	10.29	1.18
118.8	389.5–390.0	3.21	19.87	0.96	30.45	13.46	9.29	0.00	4.17	3.53	14.42	0.64



Text-Figure 3. Average linkage cluster analysis (with Euclidean distance) of the organic matter distribution of the #1 Young corehole. Each palynofacies assemblage identified by the cluster analysis represents a group of samples with similar organic matter content which accumulated in a similar position relative to the shoreline. Sample numbers are depths.

terrestrially derived organic material. This group probably accumulated in the coastal plain–innermost shelf transitional environment. Similar palynofacies studies have been successfully carried out by several authors, such as Habib and Miller (1989) and Gregory and Hart (1992).

CHRONOSTRATIGRAPHY

A time-framework based on the stratigraphic distribution of dinoflagellate cysts was developed, using graphic correlation (Shaw, 1964; Edwards, 1989). The dinoflagellate range charts for each section, and illustrations of the most important dinoflagellates and acritarchs used in this study can be found in Jaramillo and Oboh-Ikuenobe (1999). The #1 Young core was chosen as the reference section. Several rounds of correlation were performed on all five stratigraphic sections in order to produce a composite section. The important fossil events in the composite section are listed in Table 2. The composite section was then tied to a worldwide chronostratigraphic framework.

The Eocene–Oligocene boundary is currently defined by the last occurrence of the foraminifera *Hantkenina* spp. in the Massignano section of the Apennine Mountains (Italy), which is located in the youngest part of the magnetostratigraphic Chron C13r (C13r.14) and has an age estimated at 33.7 Ma (Berggren et al., 1995). These markers, last occurrence of *Hantkenina* and Chron C13n, were used to tie our composite section to the world-wide chronostratigraphy of Berggren et al. (1995).

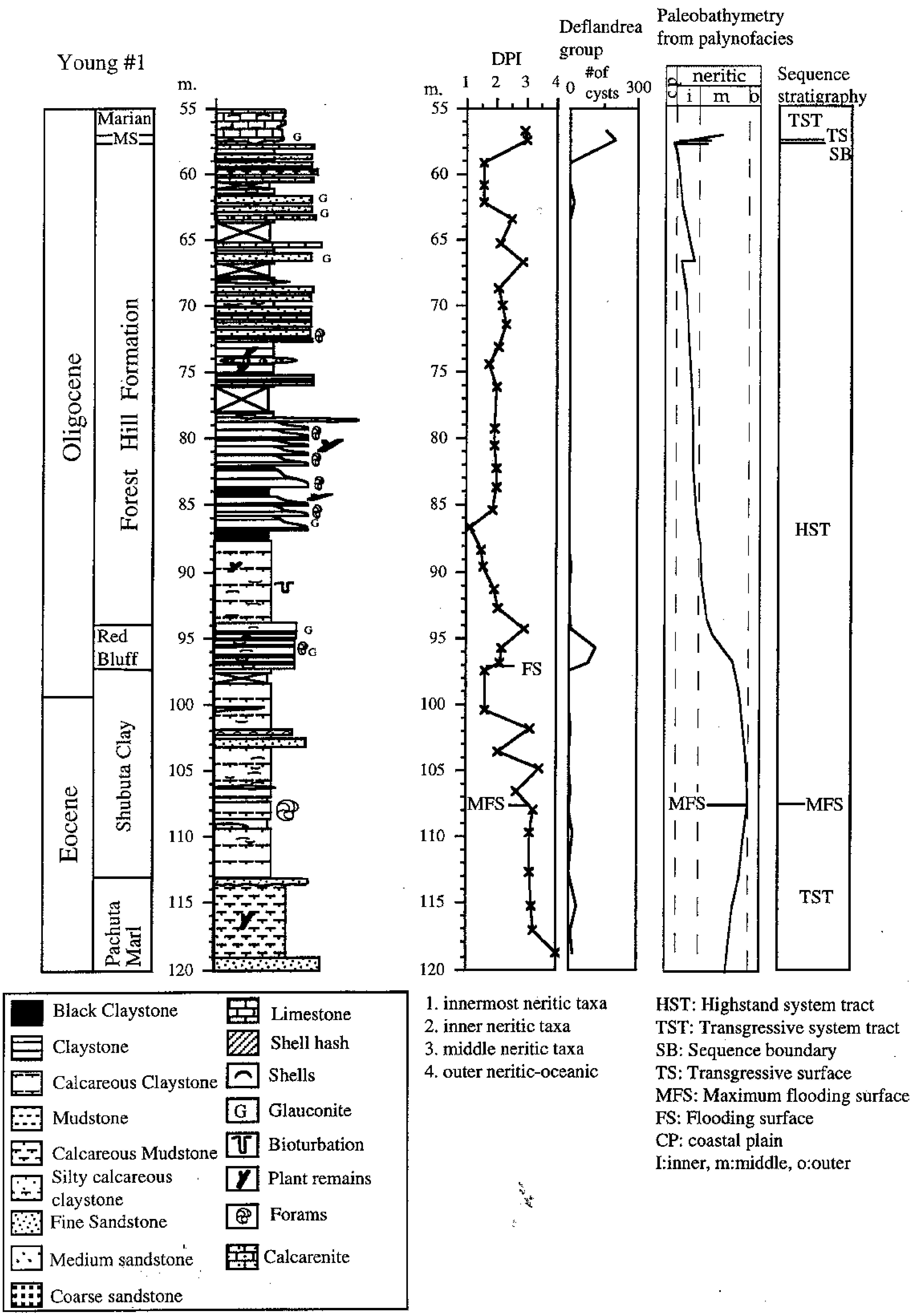
At the St. Stephens Quarry section, Pasley and Hazel (1990, 1995) noted that the last occurrence of *Hantkenina alabamensis* occurred 24 cm above the Shubuta–Bumpnose contact. The location of this boundary is reinforced by the position of the C13n–C13r magnetoboundary in St. Stephens Quarry, located approximately 1.5 m above the Shubuta–Bumpnose contact in a core that was drilled 1.6 km from the St. Stephens Quarry section (Miller et al., 1993). The age of this magnetoboundary is 200ky younger than the Eocene–Oligocene boundary (Berggren et al., 1995). This would indicate that the Eocene–Oligocene boundary is approximately coincident or slightly above the Shubuta–Bumpnose boundary.

The second datum used to tie the composite section to chronostratigraphy was the Chron C13n–C12r magnetoboundary of Miller et al. (1993) at the Red Bluff–Mint Spring contact in the St. Stephens Quarry section. This magnetoboundary is dated as 33.05 Ma (Berggren et al., 1995).

The two datums were projected onto the correlation line drawn by the comparison of the composite section with the St. Stephens Quarry (Text-Figure 5). The line of correlation for St. Stephens Quarry suggests an interval of 80 cm of extreme condensation lasting approximately 13.7 composite units (c.u.). This condensed interval starts 20 cm below the Shubuta–Bumpnose boundary and ends 60 cm above it. Several fossil events that are not coeval appear together in the same sample, thereby indicating condensation. For example, in sample 4.7m (refer to Text-Figures 5 and 7 for position), the following biostratigraphic events occur together even though they occur at different levels in the standard composite section: first occurrence of *Hemiplacophora semilunifera*, peak of *Hemiplacophora semilunifera*, first occurrence of *Wetzeliella lobisca*, last occurrence of *Elytrocysta* sp. A, last occurrence of *Hemiplacophora semilunifera* and first occurrence of taxon *Operculodinium placitum*. A similar case can be made for sample 5.0m. Sample 5.3m has an assemblage which is similar to that in sample 5.0m but it does not show up in the correlation because all of the f.o. datums were already in sample 5.0m. Loutit et al (1988) also interpreted the first 60 cm of the Bumpnose (or unnamed blue clay) as a condensed section, based on the gamma ray and foraminifera fauna. The last occurrence of *H. alabamensis* at 24 cm above the base of the Bumpnose lies in the middle of the condensed section. In order to project this datum on the composite section, we marked the stratigraphic interval containing the condensed section as indicated by the correlation line. Then, we established an average rate of accumulation for this condensed section, and projected the *H. alabamensis* datum into the composite section (Text-Figure 5). A level at 99.5 c.u. in the composite section was found. The second datum, the Bumpnose–Mint Spring boundary, when projected onto the composite section gave a location of 53 c.u. for the C13n–C12r boundary (33.05 Ma) (Text-Figure 5). A duration of 0.014 Ma per composite unit is calculated from the age-data points used.

DINOCYST PALEOBATHYMETRY

Several studies (e.g., Wall et al., 1977; Dale, 1996) have indicated that dinoflagellate cysts are sensitive environmental indicators today, and are therefore of potential use



Text-Figure 4. Sequence stratigraphic interpretation for the #1 Young corehole. Refer to Table 3 for taxa used in calculating the dinocyst paleobathymetric index (DPI), and Text-Figure 3 for derivation of paleobathymetric curve from palynofacies. The Eocene–Oligocene boundary is 8 composite units (c.u.) younger (0.112 Ma) than the inferred maximum flooding surface in the middle of the Shubuta Clay.

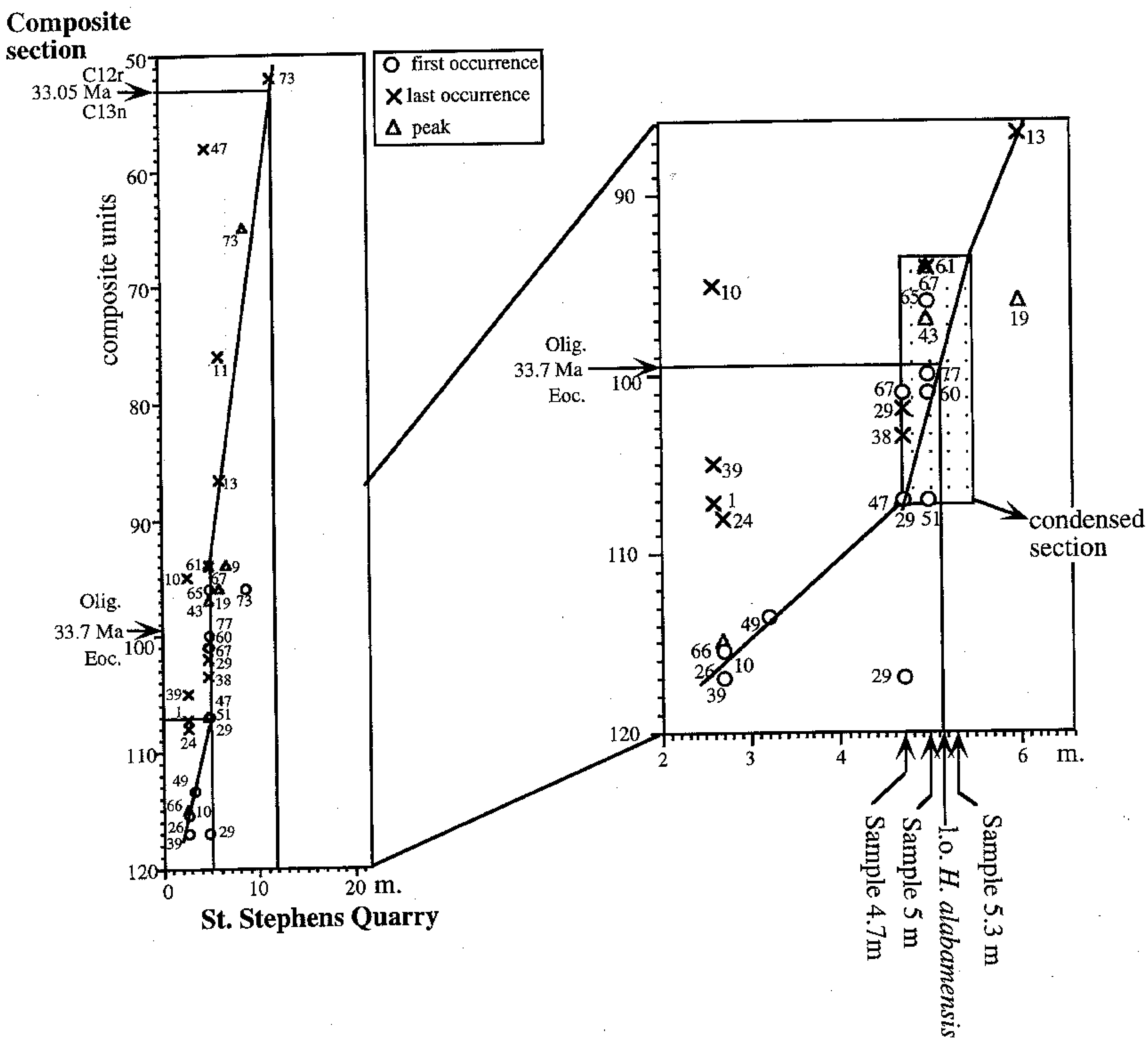
TABLE 2. Fossil events used in the composite section. C.u. refers to composite unit, f.o. first occurrence, l.o. last occurrence, peak refers to high abundance levels of individual taxa with locally important chronostratigraphic significance. The Eocene–Oligocene boundary (33.7 Ma) occurs at 99.5 c.u., while Chron C13n–C12r magnetoboundary (33.05 Ma) occurs at 53 c.u. Each composite unit has an equivalence of 0.014 Ma.

No.	Species	c.u.	event
73	*Pentadinium* sp. A	52	l.o.
47	*Wetzeliella lobisca*	58	l.o.
82	*Polysphaeridium zoharyi*	59	f.o.
71	*Wetzeliella articulata*	62	l.o.
80	*Systematophora* sp. A	62	l.o.
73	*Pentadinium* sp. A	65	peak
58	*Wetzeliella symmetrica*	65	l.o.
26	*Cribroperidinium tenuitabulatum*	67	l.o.
55	*Heteraulacacysta campanula*	74	l.o.
11	*Cordosphaeridium cantharellum*	73	l.o.
75	*Impagidinium* sp. B	82	f.o.
62	*Cordosphaeridium gracile*	84	l.o.
31	*Dinopterygium cladoides sensu* Morgenroth	85	l.o.
13	*Diphyes colligerum*	86.5	l.o.
71	*Wetzeliella articulata*	93	f.o.
9	*Operculodinium* aff. *centrocarpum*	94	peak
67	*Operculodinium placitum*	94	peak
61	*Tectatodinium pellitum*	94	l.o.
10	*Trigonopyxidia fiscellata*	95	l.o.
65	*Cyclopsiella vieta*	96	f.o.
73	*Pentadinium* sp. A	96	f.o.
80	*Systematophora* sp. A	96	f.o.
19	*Deflandrea phosphoritica*	96	peak
43	*Deflandrea heterophlycta*	97	peak
62	*Cordosphaeridium gracile*	98	f.o.
46	*Areosphaeridium multicornutum*	98	l.o.
68	*Apteodinium australiense*	100	f.o.
77	*Membranophoridium aspinatum*	100	f.o.
60	*Operculodinium divergens*	101	f.o.
67	*Operculodinium placitum*	101	f.o.
56	*Distatodinium* aff. *ellipticum*	102	f.o.
58	*Wetzeliella symmetrica*	102	f.o.
59	*Glaphyrocysta* sp.	102	f.o.
98	*Heteraulacacysta leptalea*	102	f.o.
15	*Muratodinium fimbriatum*	102	l.o.

No.	Species	c.u.	event
29	*Hemiplacophora semilunifera*	102	l.o.
36	*Cannosphaeropsis* sp. A	102	l.o.
38	*Elytrocysta* sp. A of Head and Norris (1989)	103.5	l.o.
55	*Heteraulacacysta campanula*	105	f.o.
14	*Charlesdowniea coleothrypta*	105	peak
26	*Cribroperidinium tenuitabulatum*	105	peak
44	*Systematophora placacantha*	105	peak
39	*Rhombodinium draco*	105	l.o.
42	*Batiacasphaera* aff. *baculata*	104.5	l.o.
46	*Enneadocysta multicornuta*	107	f.o.
47	*Wetzeliella lobisca*	107	f.o.
50	*Cordosphaeridium inodes*	107	f.o.
51	*Ascostomocystis potane*	107	f.o.
52	*Homotryblium vallum*	107	f.o.
29	*Hemiplacophora semilunifera*	107	peak
61	*Tectatodinium pellitum*	106.5	f.o.
1	*Batiacasphaera compta*	107.2	l.o.
24	*Batiacasphaera baculata*	108	l.o.
44	*Systematophora placacantha*	110	f.o.
45	*Homotryblium plectilum*	111	f.o.
43	*Deflandrea heterophlycta*	113	f.o.
49	*Enneadocysta arcuata*	113.5	f.o.
36	*Cannosphaeropsis* sp. A	115	f.o.
37	*Histiocysta* sp. A	115	f.o.
10	*Trigonopyxidia fiscellata*	115	peak
16	*Lingulodinium pugiatum*	115	l.o.
34	*Hystrichokolpoma globulum?*	115	l.o.
41	*Hystrichokolpoma cinctum*	115	l.o.
66	*Nematosphaeropsis pusulosa*	116	f.o.
24	*Batiacasphaera baculata*	117	f.o.
26	*Cribroperidinium tenuitabulatum*	117	f.o.
29	*Hemiplacophora semilunifera*	117	f.o.
31	*Dinopterygium cladoides sensu* Morgenroth	117	f.o.
32	*Rottnestia borussica*	117	f.o.
39	*Rhombodinium draco*	117	f.o.

Eocene–Oligocene boundary 99.5 cu (33.7 Ma)
Chron C13n–C12r boundary 53 cu (33.05 Ma)
Duration of one composite 0.014 Ma

in paleopalynology. Four types of environmental signals can be deduced from recent dinocyst distributions: (1) surface water temperature, (2) a coastal/oceanic trend, (3) salinity, and (4) productivity. The coastal/oceanic trend is a variable which correlates strongly with variations in dinocyst assemblages (Wall et al., 1977, Dale, 1996). The distribution of dinocysts in our study was analyzed using multivariate techniques to identify changes in the composition and abundance of dinocyst assemblages. These changes were interpreted in terms of coastal/oceanic trends which ultimately could be related to changes in paleobathymetry. We used the Spearman rank-order coefficient to perform a non-metric multidimensional scaling (MDS) analysis on the dinocyst and acritarch abundance data. This analysis



Text-Figure 5. Line of correlation for St. Stephens Quarry section versus the composite section. The position of the Eocene–Oligocene boundary (33.7 Ma) in the composite section is found by projecting the last occurrence of *Hantkenina alabamensis* onto the composite section (i.e., 0.24 m above the Shubuta–Bumpnose contact at the St. Stephens Quarry section, Pasley and Hazel, 1990, 1995). C13n–C12r magnetoboundary (33.05 Ma) occurs at 11.8 m (Miller et al., 1993) and is also projected onto the composite section. Note that the line of correlation shows an 80 cm interval of extreme condensation lasting for 13.7 c.u. Meter 4.9 in this section corresponds to the Shubuta Clay/Red Bluff Clay–Bumpnose boundary (meter 3.95 in the column of Pasley and Hazel, 1990, fig. 4).

identifies major environmental gradients along the first and second axes (Kovach 1989). Based on an extensive literature review of dinocyst paleoecology, some of the groups produced by the cluster analysis could be referred to a relative position of the dinocyst community with respect to the paleoshoreline (Jaramillo and Oboh, 1999 to see literature consulted).

Six dinocyst paleoecological groups were identified in our study, and five of them are interpreted as representing an inshore–offshore trend (Table 3). The environmental interpretations (e.g., inner, middle, outer neritic) are used in a relative sense rather than an absolute one. A dinocyst paleobathymetric index (DPI) was calculated using a weighted mean (Σn_i (i)/n) of the innermost, inner, middle, and outer neritic to oceanic groups, where n represents the total number of specimens in a particular sample, and n_i represents the abundance of each ecological group. The scale of the index goes from 1 to 5,

TABLE 3. Dinocyst ecological groups used in the determination of the paleobathymetric index (Jaramillo, 1995; Jaramillo and Oboh-Ikuenobe, unpubl. results).

Innermost Neritic
Homotryblium plectilum
Pediastrum

Inner Neritic
Ascostomocystis potane
***Glaphyrocysta* group**

Middle Neritic
Charlesdowniea coleothrypta
Hystrichokolpoma rigaudiae

Outer Neritic
***Cannosphaeropsis* sp. A**
Cribroperidinium tenuitabulatum
Hemiplacophora semilunifera
Batiacasphaera compta
***Impagidinium* spp.**
Tectatodinium pellitum

Neritic (inner to outer)
***Cleistosphaeridium* spp.**
***Enneadocysta* group**
Spiniferites pseudofurcatua
Systematophora placantha
***Cordosphaeridium* spp.**
Operculodinium* aff. *centrocarpum
Spiniferites ramosus
***Lingulodinium* spp.**
Pentadinium laticinctum

Deflandrea group
***Deflandrea* spp.**
Samlamdia clamydophora
Corrudinium incomposita

with 1 representing innermost neritic taxa and 5 outer neritic to oceanic neritic taxa. The index value for each sample was plotted for each entire section to obtain a dinocyst paleobathymetric curve for that section. In the reconstruction of the curves, samples with less than 10 dinocyst specimens were excluded from the analysis. A second plotted curve used the abundance of the *Deflandrea* dinocyst group which can be related to, among other factors, run-off changes and the introduction of nutrients in the photic zone associated with flooding events (Brinkhuis, 1994).

SEQUENCE STRATIGRAPHIC INTERPRETATION

#1 Young Corehole

The Eocene–Oligocene boundary was identified at 99.5 m, 2.3 m below the Shubuta Clay–Red Bluff boundary (Eocene/Oligocene boundary is at composite unit 99.5, and #1 Young is the reference section). Two important flooding surfaces were identified in the corehole (see Text-Figure 4). The strongest one occurs at 107.5 m (353 ft), 10.3 meters below the Shubuta Clay–Red Bluff boundary, and other at 57.72 m (189.4 ft) at the Forest Hill–Mint Spring contact. The level at 107.5 m is interpreted as a maximum flooding surface (MFS) because: (a) it is a green calcareous claystone with abundant uvigerinids, which are deep water benthic foraminifera (Dockery et al., 1994), and (b) it occurs between two of the samples with the highest concentration of total marine derived organic matter (amorphous and dinocysts, Table 1). This level also corresponds to a high value (3.2) in the dinocyst paleobathymetric index (Text-Figure 4), and is 0.9 m above a gamma ray peak (on gamma ray log in Dockery et al., 1994). A minor flooding surface is identified at the Shubuta–Red Bluff contact at 97.2 m (319 ft), based on the lithological change (olive gray clay to gray fossiliferous, glauconitic mudstone) and an increase in the *Deflandrea* group.

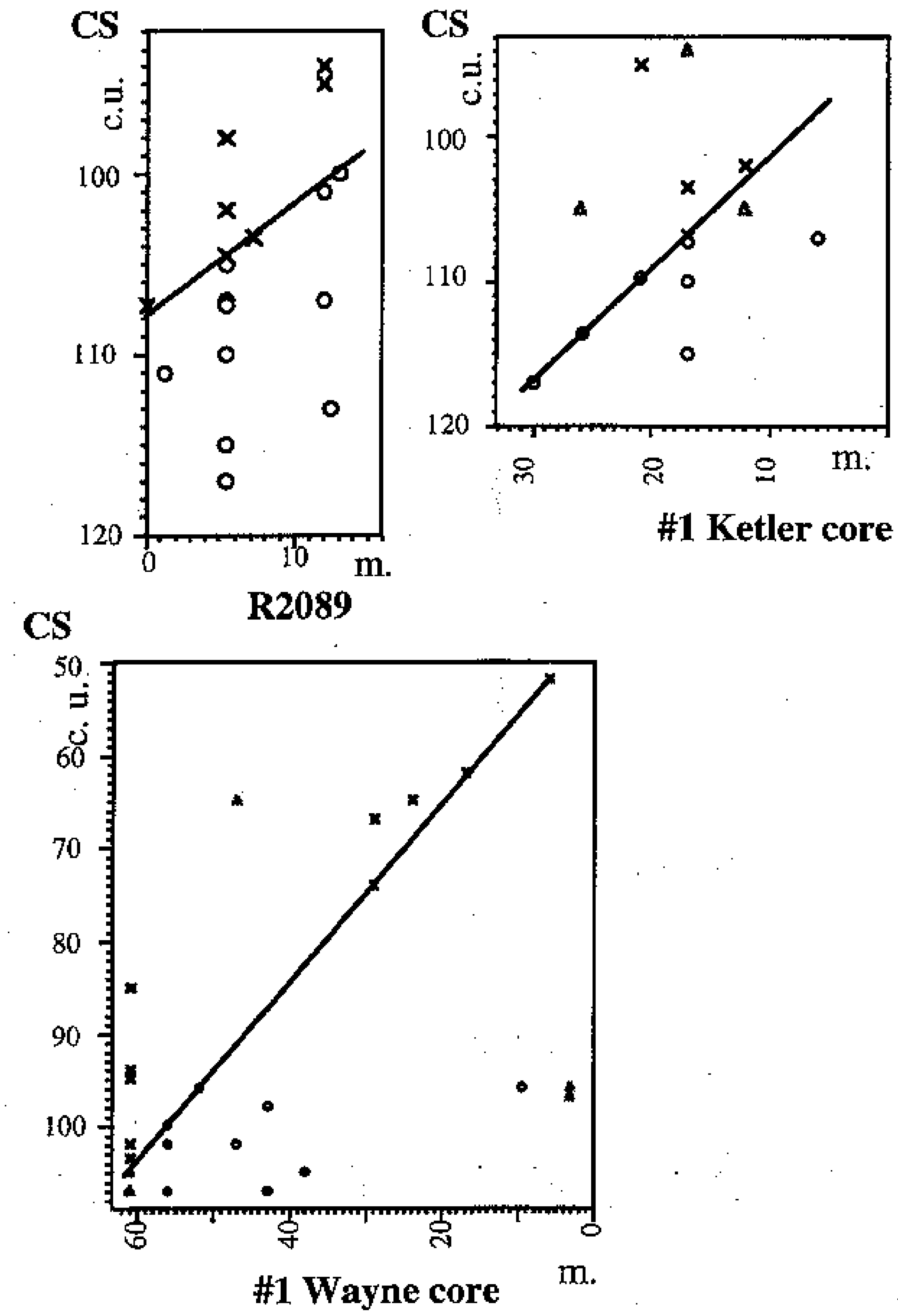
The paleobathymetry interpreted from palynofacies and dinocyst paleoecology indicates a flooding event at the Forest Hill–Mint Spring contact at 57.72 m (33.1 Ma). We believe that a sequence boundary is merged here with a transgressive surface (Text-Figure 4). The contact is sharp, irregular, burrowed and marked by an abraded shell lag and rounded intraclasts. This hypothesis can be confirmed in up-dip and down-dip sections if forced regressions or incised valleys are found (Posamentier et al., 1992). The proposed lowstand deposit in the #1 Wayne corehole, if proved true, (see below) would confirm this sequence boundary.

#1 Wayne Corehole

The Eocene–Oligocene boundary is projected to be at 55.7 m, 1.9 m above the Shubuta–Red Bluff contact (Text-Figures 6 and 8). A sequence boundary is interpreted at the Forest Hill–Mint Spring contact. This contact is sharp, irregular, and burrowed with a pavement of intraclasts. The facies below the contact is a brown carbonaceous mudstone while above it is a 60 cm-thick, white medium-grained quartz sandstone with calcareous cement. Although samples from this sandstone interval were not analyzed, the unit is interpreted as a forced regression of a possible lowstand system tract based on lithological analysis. This sandstone is overlain by a gray porous limestone that corresponds to the lower Marianna Limestone, and the Mint Spring–Marianna contact is interpreted as a transgressive surface. The paleobathymetric data indicates a deepening across the Mint Spring–Marianna interval.

#1 Ketler Corehole

The Eocene–Oligocene boundary is projected to be at 7.5 m, 3.7 m above the Shubuta–Red Bluff contact (Text-Figures 6 and 8). A maximum flooding surface is identified at 17 m. This maximum flooding surface is characterized by a high index of dinocyst paleobathymetry, a high concentration of marine derived organic matter (amorphous material and dinocysts; Oboh and Yepes, 1995), and a green calcareous claystone with abundant uvigerinids. It is also 0.9 m above a pronounced peak of gamma ray (Dockery et al., 1994). The Pachuta and lower Shubuta constitute a transgressive system tract while the upper Shubuta and Red Bluff represent a highstand system tract.



Text-Figure 6. Line of correlation for #1 Wayne corehole, #1 Ketler corehole and R2089 Type Red Bluff section versus the composite section (CS). The Eocene–Oligocene boundary in the #1 Wayne corehole is at 55.7 m, 1.9 m above the Shubuta–Red Bluff contact, while the C13n–C12r magnetoboundary occurs at 7.1 m, 2 m above the Mint Spring–Marianna contact. In the #1 Ketler corehole, the Eocene–Oligocene boundary is located at 7.5 m, 3.7 m. above the Shubuta–Red Bluff contact. At the R2089 section, the Eocene–Oligocene boundary is located at 13.3 m, 0.1 m above the Shubuta–Red Bluff contact. Meter 13.2 in this section corresponds to the Shubuta Clay/Red Bluff Clay contact of Pasley and Hazel (1995, fig. 6).

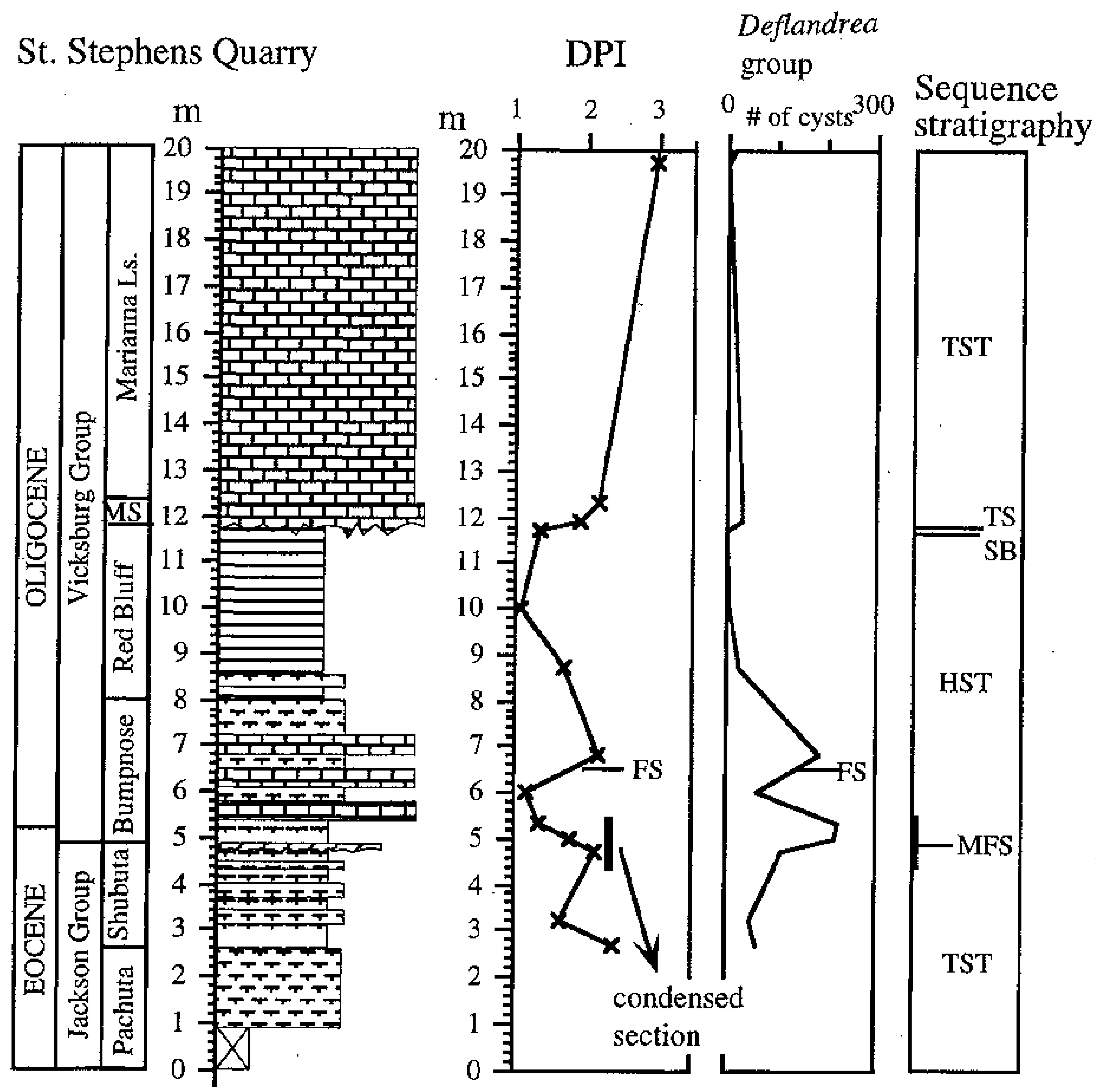
R2089 Section

The Eocene–Oligocene boundary is identified at 13.3 m measured from the base of the section, which is 0.1 m above the Shubuta–Red Bluff contact (Text-Figures 6 and 8). A tentative marine flooding surface is identified at 0 m, 8.3 c.u. (0.116 Ma) older than the Eocene–Oligocene boundary. Unfortunately, this flooding could not be confirmed because samples below 0m were not observed. A minor flooding surface is identified at the Shubuta–Red Bluff contact based on the *Deflandrea* group.

St. Stephens Quarry Section

A maximum flooding surface, marked by a thin phosphatic shell layer, is identified at the Shubuta–Bumpnose contact (Text-Figure 7). It occurs in an 80 cm-thick condensed section, which begins 20 cm below the Shubuta–Bumpnose contact and ends 60 cm above it. This condensation lasted for 13.7 c.u. (0.19 Ma), and also included the Eocene–Oligocene boundary (see discussion in chronostratigraphy and Text-Figure 5). This interpretation basically agrees with Loutit et al (1988) and Pasley and Hazel (1990). Pasley and Hazel (1995) identified a hiatus lasting 0.288 Ma at the Shubuta–Bumpnose contact. They concluded that this hiatus was the product of starvation during the accumulation of the highstand deposits following the maximum flooding surface. They interpreted this contact as a sequence boundary merged with the surface of maximum starvation. However, the reconstructed paleobathymetric curves (from DPI and *Deflandrea* group) are very similar immediately below and above the contact. Using foraminifera paleoecology, Loutit et al. (1988) also showed that the maximum water depth occurred 60 cm above the contact. If deposits of lowermost Red Bluff/Bumpnose (including unnamed "blue clay") were deposited during the lowstand systems tract, a drastic change in paleobathymetry should be evident. Furthermore, if a significant hiatus were present at the contact, the fossil assemblages immediately above it would show a gap in the fossil record. The dinocyst fossil record, however, does not show a gap. Instead, it registers a condensation of datums in a short stratigraphic interval. Pasley and Hazel's (1995) graphic correlation shows a possible hiatus because of the relative time-coarseness of each composite unit of their composite section in relation with ours. Whereas one composite unit in their scheme corresponds to 0.2 Ma, one unit in our study represents 0.014 Ma. Therefore, even though they observed a similar number of samples than us around the boundary in St. Stephens Quarry, the coarseness of their composite units would create an artificial compression of the correlation line that would suggest a hiatus.

The Red Bluff–Mint Spring contact is suggested here as a sequence boundary that coincides with a transgressive surface. A sequence boundary is inferred based on similar reasons discussed above for the #1 Young corehole. Pasley and Hazel (1990, 1995) indicated that there was no evidence of a sequence boundary at this contact because the contact climbed stratigraphically landward (from SSQ in Alabama toward Jason County in Mississippi, Pasley and Hazel, 1995 their figure 8). Our data shows the opposite: this surface is older in Mississippi and is younger in Alabama (Text-Figure 8). Also, Tew and Mancini (1995) showed several localities in Mississippi and Alabama where this contact was sharp and disconformable with broken and abraded shell material. Furthermore, sandstones in the Mint Spring Marl in the Wayne core could be part of a forced regression that is "the most unequivocal indication of a relative sea level fall in sea level" (Posamentier et al., 1992, p. 1704). The nature of the Red Bluff–Mint Spring remains, however, a problem. The sequence boundary hypothesis could be tested in up-dip and down-dip sections if more forced regressions or incised valleys are found.



Text-Figure 7. Sequence stratigraphic interpretation for the St. Stephens Quarry section. Refer to Table 3 for the taxa used in calculating the dinocyst paleobathymetric index (DPI), and Text-Figure 4 for the key to lithologic symbols. An 80 cm-condensed section containing the maximum flooding surface and the Eocene–Oligocene boundary begins 20 cm below the Shubuta–Bumpnose contact and ends 60 cm above the contact. Meter 4.9 in this section corresponds to the Shubuta Clay/Red Bluff Clay–Bumpnose boundary (meter 3.95 in the column of Pasley and Hazel, 1990, fig. 4).

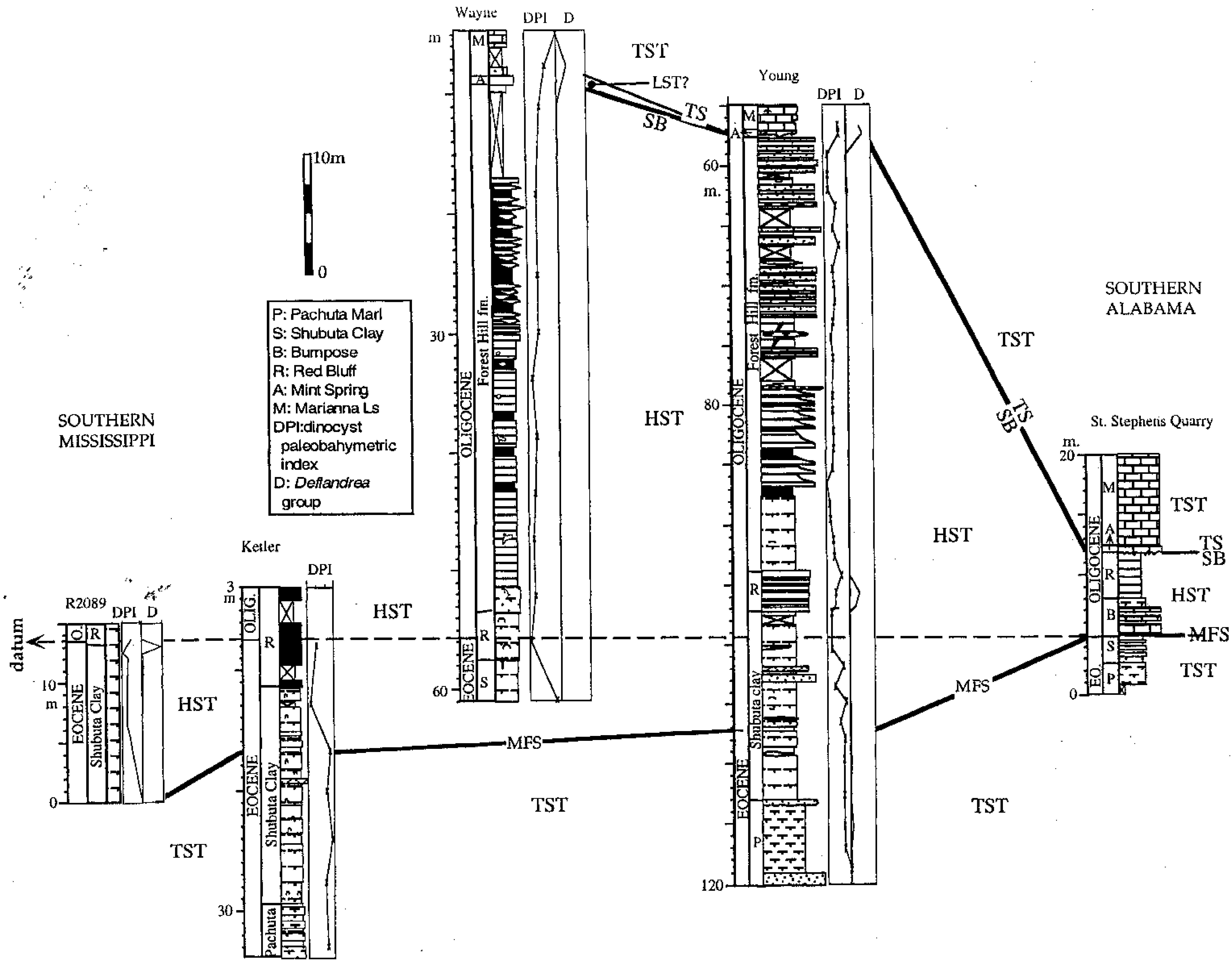
GENERAL CORRELATION

A correlation of all the studied sections (Text-Figure 8) shows the maximum flooding surface in all the sections except the St. Stephens Quarry to be coeval and approximately 7.5 c.u. (0.105 Ma) older than the Eocene–Oligocene boundary. At the St. Stephens Quarry section, this surface is 3 c.u. (0.042 Ma) younger than the other sections. This maximum flooding surface occurs in the middle part of the Shubuta Clay in the four southern Mississippi sections and at the Shubuta–Bumpnose contact in the St. Stephens Quarry section. This contact represents a minor flooding surface in southern Mississippi. The Pachuta Marl and the lower Shubuta Clay (the entire Shubuta in Alabama) constitute a transgressive system tract, with the upper Shubuta Clay and Bumpnose/Red Bluff/Forest Hill Formations representing the overlying highstand systems tract (see Text-Figure 2B). The stratigraphic condensation at the St. Stephens Quarry section corresponds to the accumulation of the early Oligocene highstand in southern Mississippi. The continuation of normal sedimentation in the St. Stephens Quarry area appears to correspond to the accumulation of the Forest Hill in southern Mississippi.

Up in the section, the Forest Hill–Mint Spring contact is interpreted as a sequence boundary which coincides with a transgressive surface. This contact is slightly older in the southeastern Mississippi sections relative to southeastern Alabama. The Mint Spring Marl and Marianna Limestone represent a transgressive system tract. However, a possible lowstand deposit (forced regression) is interpreted in the #1 Wayne section where a sandy deposit occur in Mint Spring.

Rates of accumulation increase from southern Alabama (St. Stephens Quarry) to the farthest section (R2089) in southern Mississippi. Areas in southeastern Mississippi experienced more rapid and prograding clastic sedimentation, whereas shelf-edge sediments were deposited much more slowly by longshore transport at St. Stephens Quarry area.

Our sequence stratigraphy interpretation is in general agreement with previous studies (in particular, Tew and Mancini, 1995; see Text-Figure 2B), although there are some distinct differences. First, the maximum flooding surface of the Shubuta–Forest Hill sequence occurs in the middle of the Shubuta Clay in southern Mississippi but at the Shubuta–



Text-Figure 8. Stratigraphic correlation of all studied sections. The DPI curve represents dinoflagellate paleobathymetric index (scale 1–4), while the D curve shows *Deflandrea* group abundance (scale 0–300 dinocysts). Text-Figures 4 and 7 also show the DPI and D curves for the #1 Young corehole and St. Stephens Quarry section, respectively. The Eocene–Oligocene boundary is chosen as a datum, and is 0.11 Ma younger than a maximum flooding surface identified in the sections. Note the increase in the thicknesses of the stratigraphic sections toward southern Mississippi.

Bumpnose contact in the St. Stephens Quarry section. Second, the age of this maximum flooding surface is latest Eocene. Third, the lower 60 cm of the Bumpnose Limestone in the St. Stephens Quarry section is recognized as a condensed section which accumulated while the upper Shubuta and Red Bluff were being deposited in southern Mississippi.

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Authors' addresses

CARLOS A. JARAMILLO
Paleobotany Laboratory
Florida Museum of Natural History
University of Florida
Gainesville, Florida 32611
U.S.A.

FRANCISCA E. OBOH-IKUENOBE
Department of Geology and Geophysics
University of Missouri-Rolla
Rolla, Missouri 65409-0410
U.S.A.