CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

GEOLOGY AND PALEOENVIRONMENT OF THE BUNKER GAS FIELD, SOLANO COUNTY, CALIFORNIA

A thesis submitted in partial satisfaction of the requirements for the degree of Master of Science in

Geology

by

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DEDICATION

To my loving and supportive

Kay and Shaun

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GEOLOGY AND PALEOENVIRONMENT OF THE BUNKER
GAS FIELD, SOLANO COUNTY, CALIFORNIA

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Bunker Gas Field is in Solano County, T. 6 N., R. 1 and 2 E., Mount Diablo base and meridian, in the Sacramento Valley, the northern part of the Great Valley of California.

Subsurface structure contour maps of the field indicate a northwest-trending, faulted, domal to anticlinal fold which plunges to the southeast.

Paleotopographic maps of the Bunker Gas Field demonstrate that:

1. The direction of the paleofluvial valleys and paleoslope during Late Cretaceous time was generally in a south-south-westerly direction and the sediment source was in the north-northeast.
2. The direction of the paleofluvial valleys and paleoslope during late Paleocene time was generally to the west

and the sediment source was to the east of the field. This paleotopography is inferred to have persisted during early Eocene time.

Lithologic characteristics (such as grain size, sorting, etc.) and stratigraphic sequence illustrate that subsurface deposystems in the Bunker Gas Field were predominantly of the shelf-facies type. Both progradational and retrogradational suites of strata occur within the stratigraphic sequence. The occurrence of a shallow regressive and transgressive sea was the prominent paleogeographic feature within the study area.

In Late Cretaceous the study area was covered by a shallow regressive sea and was characterized by deltaic conditions during the period that the Mokelumne sand/shale lithosome was deposited. In early late Paleocene the study area was covered by a shallow transgressive sea and a mid-neritic environment prevailed during the period that the McCormick sandstone was deposited. In late late Paleocene the area was covered by a shallow regressive sea and exhibited a littoral environment at the time when the Martinez shale was deposited. In early Eocene the study area was covered by a shallow transgressive sea and was characterized by a nearshore environment during the period that the Hamilton sandstone was deposited.

INTRODUCTION

Purpose and Geographic Setting

Bunker Gas Field is in the Sacramento Valley, which is the northern part of the Great Valley of California. The field is southwest of Sacramento and northeast of San Francisco (Fig. 1) in Solano County, about 6 mi southeast of the town of Dixon, in the vicinity of Millar and Maine Prairie gas fields (Fig. 2). The field has 850 proven acres (Hunter, 1961, p. 57) in secs. 18, 19, 20, and 29 of T. 6 N., R. 2 E. and in sec. 13 of T. 6 N., R. 1 E., Mount Diablo base and meridian (Plate II).

The main purpose of this thesis is to use geophysical logs (Spontaneous Potential log, Dual Induction Laterolog and Sonic Log) to:

1. establish the subsurface structure of the Bunker Gas Field,

2. interpret the depositional environments of the stratigraphic interval between the H and T shale of Late Cretaceous age and the Capay Shale of early Eocene age (Fig. 3), and

3. propose possible future sites for hydrocarbon exploration.

In determining these future sites, the need to reconstruct the ancient buried environments of sand deposition is emphasized.

Field History and Previous Work

The first well within the present boundaries of the Bunker Gas Field was drilled by Amerada Petroleum Corporation (APC) in 1945. The well, designated as "Comber" 1, in sec. 19, T. 6 N., R. 2 E. (Plate I), was abandoned at the total depth of 6,448 ft without en-

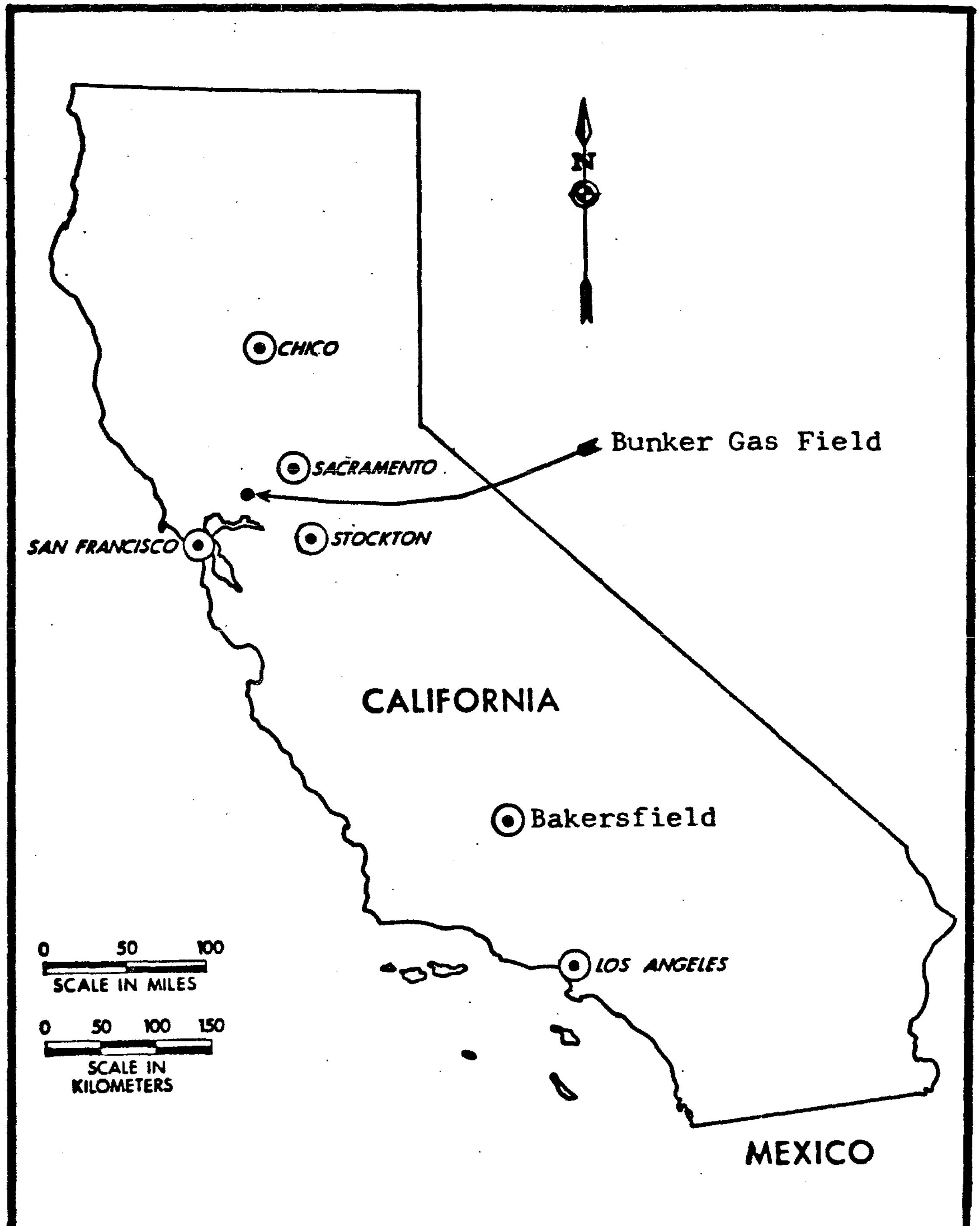


Figure 1. Location of Bunker Gas Field.

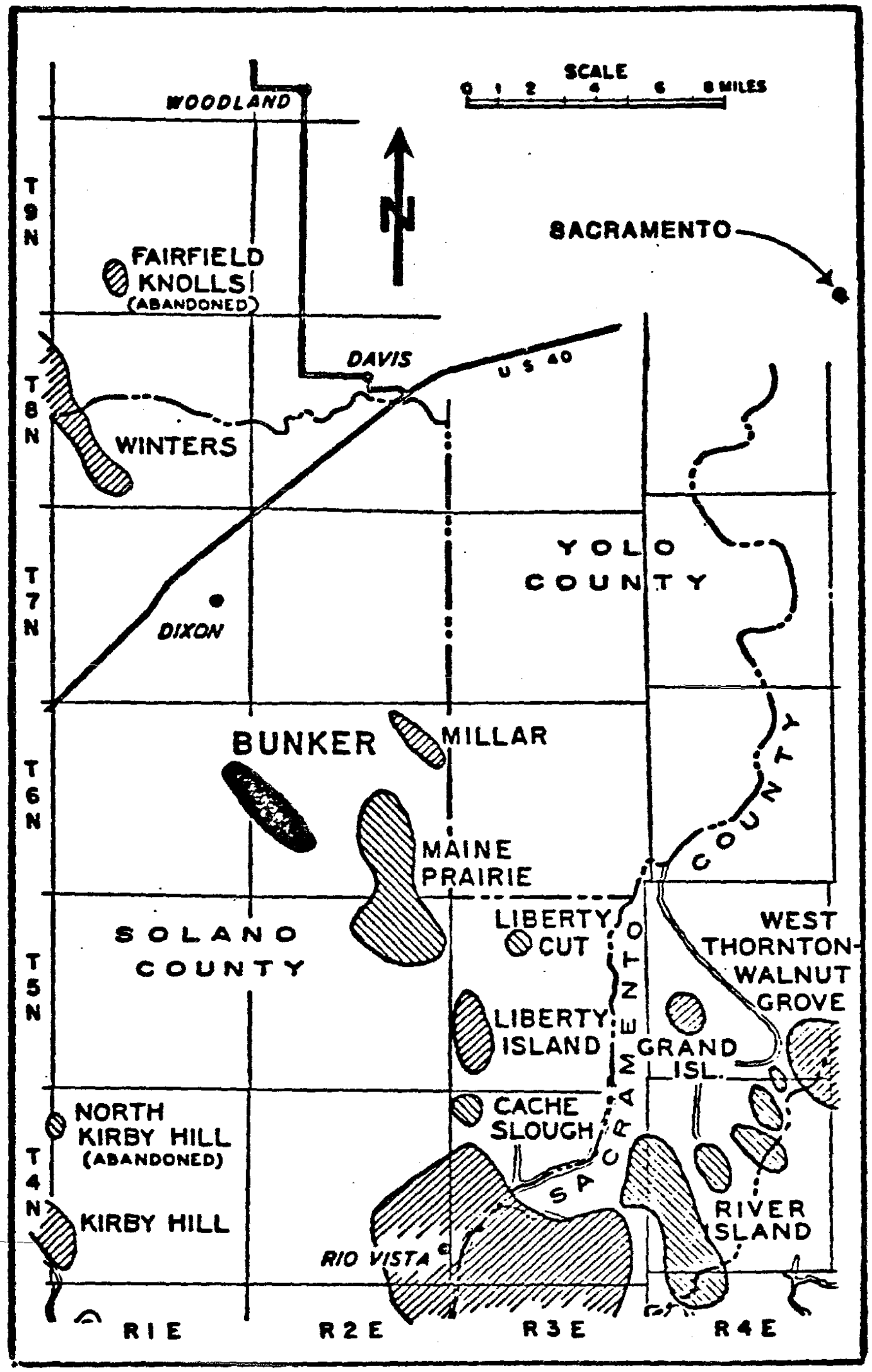


Figure 2. Location of Bunker Gas Field with respect to other gas fields (hachured areas)(from Hunter, 1961, p. 58).

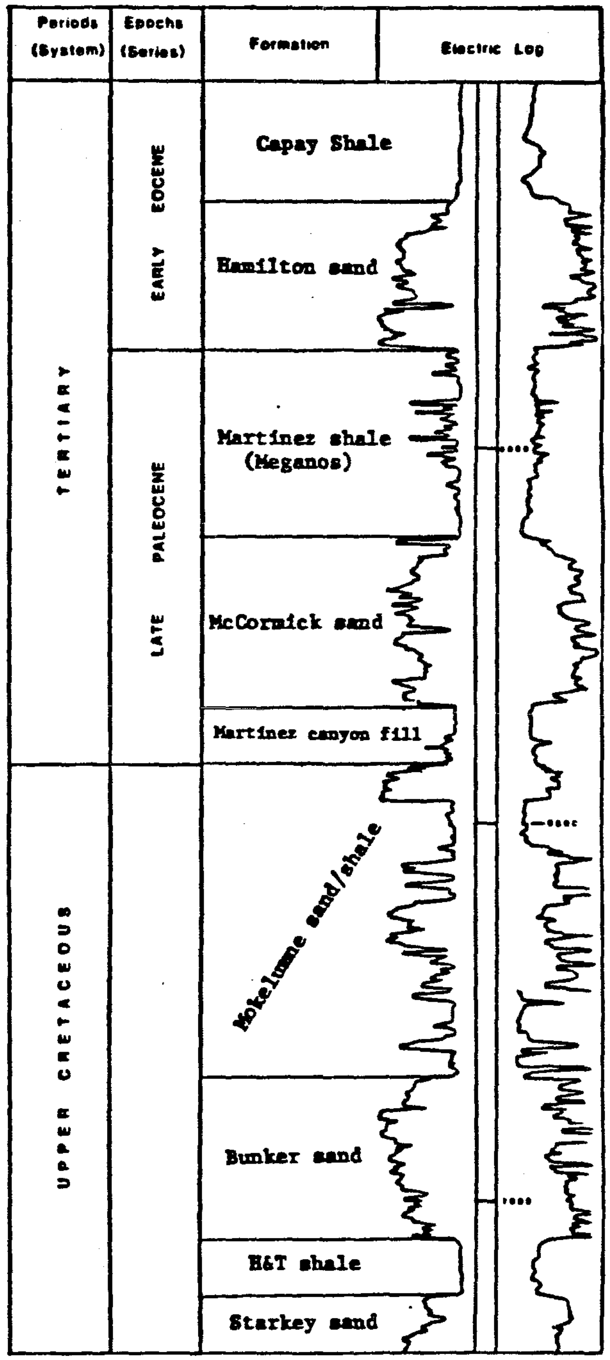


Figure 3. Composite electric log and stratigraphic column.

countering any commercial showings of oil or gas. The second well, "Wm. Comber" 1, was drilled by the same operator (APC) in 1955 in sec. 24, T. 6 N., R. 1 E. to a depth of 7,200 ft and was also abandoned. Union Oil Company of California drilled the third well in 1959, "Union-Amerada-Pedrick" 1, in sec. 12, T. 6 N., R. 1 E., to a depth of 7,690 ft and abandoned it due to no commercial shows (Hunter, 1961, p. 57).

Bunker Gas Field was finally discovered in June, 1960, when well Maine Prairie Gas Unit A No. 1, sec. 20, T. 6 N., R. 2 E., was drilled by G. E. Kadane and Sons and commercial gas was encountered in the interval of 6,831 to 6,845 ft in the Bunker sand of Late Cretaceous age (Plate VII). Shortly thereafter, Amerada Petroleum Corporation became the operator and several other wells were completed in the Bunker sand. The area was officially designated Bunker Gas Field in January, 1961, by the State Oil and Gas Supervisor. In August of 1961, Amerada Petroleum Corporation drilled well Zimmerman No. 1, sec. 29, T. 6 N., R. 2 E., and encountered commercial gas in the interval 6,772 to 6,790 ft in a sand immediately above the Bunker sand. Thus, the two zones of commercial gas were designated as the Zimmerman gas zone and the Bunker sand gas zone (Plate VII).

The only published previous works on the Bunker Gas Field are the two summary reports by Hunter (1961, p. 57) and Musser (1962, p. 244). 244). The two reports do not contain any information on the subsurface structure or paleoenvironment of the Bunker Gas Field.

Method of Investigation

Information used was derived from geophysical logs such as Dual-Induction Electric Logs and Sonic Logs, complemented by micropaleontological correlations, sidewall sample descriptions, core descriptions, and mud logs in each well. Published surface lithologic descriptions of the stratigraphic units, when correlatable, were also reviewed in establishing the stratigraphy of the field. A total of 57 wells was correlated and analyzed for preparation of structure contour maps, isopach maps, and structural and stratigraphic cross sections. Union Oil Company of California (Ventura District Office) provided all the data that were used in this project.

Plate I shows the base map that is issued by the California Division of Oil and Gas and that is used commonly by the oil industry in preparing subsurface maps. Plate II provides the modified version of the base map which is more appropriate for this project. In Plate II, beneath each well location, is a number designated as "Well Reference No.". This number, when referenced in Table 1, provides the detailed particulars about each well.

Acknowledgments

I would like to thank and extend my appreciation to Union Oil Company of California, Ventura Office, for providing much of the data and information used in writing the thesis.

My thanks to Akbar Sheriff, geologist with Union Oil Company (Ventura Office), for his critical review and discussion of subsurface geology and related maps.

TABLE 1. INDEX OF WELLS IN STUDY AREA

Reference Number	Well Name	Location
1	S and I, Moss No. 1	Sec. 3, T. 6 N., R. 1 E.
2	Reserve, Halbouty-Reserve Culver No. 1	Sec. 2, T. 6 N., R. 1 E.
3	Signal, Pedrick No. 1	Sec. 1, T. 6 N., R. 1 E.
3A	Texaco, T-U-A Unit No. 1	Sec. 1, T. 6 N., R. 1 E.
4	Hunnicutt and Camp, Anderson-Rohwer Unit No. 1-1	Sec. 5, T. 6 N., R. 2 E.
5	Amerada, Harris No. 1	Sec. 16, T. 6 N., R. 2 E.
6	Hunnicutt and Camp, H & C-S-MC-SRD Unit No. 1	Sec. 16, T. 6 N., R. 2 E.
7	Tri-Valley, Amerada-O'Keefe No. 1	Sec. 16, T. 6 N., R. 2 E.
8	Tri-Valley, Donovan No. 1	Sec. 21, T. 6 N., R. 2 E.
8A	Amerada Hess, M.E. Wineman No. 2	Sec. 21, T. 6 N., R. 2 E.
9	G.E. Kadane, Elmira 1-21	Sec. 21, T. 6 N., R. 2 E.
10	S.M. Reynolds, Amerada Brooks No. 1	Sec. 28, T. 6 N., R. 2 E.
11	Amerada, Triplet No. 1	Sec. 32, T. 6 N., R. 2 E.
12	Signal, Amerada-Kadane-Brown No. 1	Sec. 31, T. 6 N., R. 2 E.
13	Gulf, Greenwood No. 1	Sec. 22, T. 6 N., R. 2 E.
14	Union Oil, Anderson No. 1	Sec. 12, T. 6 N., R. 1 E.
15	Union Oil, Union-Amerada-Pedric No. 1	Sec. 12, T. 6 N., R. 1 E.
16	G.E. Kadane, Union Anderson No. 2	Sec. 13, T. 6 N., R. 1 E.
17	Amerada Hess, Horigan No. 1	Sec. 13, T. 6 N., R. 1 E.
18	Amerada Hess, Cyrus Rayon No. 1	Sec. 13, T. 6 N., R. 1 E.
19	Amerada, Kunder Community No. 1	Sec. 18, T. 6 N., R. 2 E.
20	Amerada, C.E. Rayon No. 1	Sec. 18, T. 6 N., R. 2 E.
21	Amerada, C.E. Rayon No. 2	Sec. 18, T. 6 N., R. 2 E.
22	Amerada, WE Rayon Gas Unit No. 1	Sec. 18, T. 6 N., R. 2 E.
23	Amerada, Comber No. 1	Sec. 19, T. 6 N., R. 2 E.
24	U.S. Signal, A-K-U-Comber No. 1	Sec. 24, T. 6 N., R. 1 E.
25	Amerada, Wm. Comber No. 1	Sec. 24, T. 6 N., R. 1 E.
26	Amerada, Amerada-Texaco-Kadane-Peter Unit No. 1	Sec. 24, T. 6 N., R. 1 E.
27	Amerada, David Comber No. 2	Sec. 19, T. 6 N., R. 1 E.
28	G.E. Kadane, Maine Praire Gas Unit "A" No. 2	Sec. 19, T. 6 N., R. 2 E.
29	Amerada, Maine Praire Gas Unit "A" No. 2	Sec. 20, T. 6 N., R. 2 E.
30	G.E. Kadane, Maine Praire Gas Unit "A" No. 1	Sec. 20, T. 6 N., R. 2 E.
31	Capitol, Ciccarelli No. 1	Sec. 20, T. 6 N., R. 1 E.
32	Union, Ciccarelli No. 1	Sec. 20, T. 6 N., R. 1 E.
33	Amerada Norton No. 1	Sec. 29, T. 6 N., R. 2 E.
34	Amerada Zimmerman No. 1	Sec. 29, T. 6 N., R. 1 E.
35	Amerada Zimmerman Gas Unit No. 1	Sec. 29, T. 6 N., R. 1 E.
36	Signal, Signal-Amerada-Kadane-Peterson No. 1	Sec. 30, T. 6 N., R. 2 E.
37	Signal, Signal-Amerada-Kadane-Norris No. 1	Sec. 25, T. 6 N., R. 1 E.
38	Prudential, Alpine-Ulatis Unit No. 1	Sec. 25, T. 6 N., R. 1 E.
39	Proffessional, Getty Evani-Koff No. 81-30	Sec. 30, T. 6 N., R. 1 E.
40	Hilliard, AHC-Norton Unit No. 1	Sec. 32, T. 6 N., R. 2 E.
41	Texaco-Amerada Vassar et al, Unit No. 1	Sec. 5, T. 6 N., R. 2 E.
42	Parker No. 1	Sec. 4, T. 5 N., R. 2 E.
43	Miller Unit No. 2	Sec. 4, T. 5 N., R. 2 E.
45	Miller Unit No. 1	Sec. 3, T. 5 N., R. 2 E.
48	Wineman et al No. 2	Sec. 3, T. 5 N., R. 2 E.
51	H & T (23-2) No. 1	Sec. 2, T. 5 N., R. 2 E.
52	Ernest Wineman No. 2	Sec. 2, T. 5 N., R. 2 E.
60	Wineman et al No. 1	Sec. 35, T. 6 N., R. 2 E.
61	I & L Wineman No. 3	Sec. 27, T. 6 N., R. 2 E.
62	Edward Wineman No. 2	Sec. 27, T. 6 N., R. 2 E.
75	TIMM Unit-1, No. 2	Sec. 4, T. 6 N., R. 2 E.
76	U.S.S. TIMM Unit-1, No. 1	Sec. 5, T. 6 N., R. 2 E.
77	TIMM Unit 1-3	Sec. 5, T. 6 N., R. 2 E.
78	Anderson Brothers Unit 1-2	Sec. 5, T. 6 N., R. 2 E.
79	Anderson-Raycraft Unit-1, No. 1	Sec. 5, T. 6 N., R. 2 E.

I am grateful to Dr. A. E. Fritsche at California State University, Northridge, for his diligent and exhaustive review of the whole thesis project from beginning to completion.

REGIONAL GEOLOGIC SETTING

The Bunker Gas Field is within the Sacramento Basin, which is the northern part of the Great Valley Basin, a very large, elongate, northwest-trending, inclined syncline or structural trough (Dickinson, 1971, p. 15) that has been filled with a very thick sequence of sediments ranging in age from Jurassic to Holocene. The Great Valley Basin is between the Sierra Nevada on the east and the Coast Ranges on the west (Hackel, 1966, p. 217). The regional southerly and westerly tilt of the Great Valley Basin is interrupted by two significant cross-valley faults, one in the southernmost part of the basin known as the White Wolf fault and another in the north, the Stockton arch fault. The Stockton arch fault is a reverse-separation fault, upthrown to the south. This fault is used by most geologists to separate the Great Valley Basin into two sub-basins, the Sacramento and San Joaquin Basins (Hackel, 1966, p. 217).

The Sacramento Basin is inclined and has a gently dipping east flank, a regional syncline close to the west side of valley, and a rather steeply dipping west flank. This basin has a pronounced southerly plunge, with a much thicker and generally younger series of sediments south of Sacramento in the Delta area. The Delta area, the northwest portion of which would include the Bunker Gas Field, is by far the most prolific producer of gas in the Sacramento Basin (Musser, 1962, p. 244).

The stratigraphic section present at the north end of the Sacramento Basin consists entirely of Upper Cretaceous marine strata overlain unconformably by nonmarine Miocene-Pliocene beds. Further to the south, marine Paleocene and Eocene strata overlie the Upper Cretaceous strata and underlie the nonmarine beds of Miocene-Pliocene age. Production is restricted to strata of Late Cretaceous age (Safonov, 1962, p. 85).

The Delta area of the Sacramento Basin is crossed by one somewhat minor and two major Tertiary canyons (gorges). These are ancient river (or submarine) canyons which were carved out of the pre-existing strata and later filled with marine mud and sand. They include the fairly restricted Martinez Canyon (Plates VII and XI) of Paleocene age (Edmondson, 1967b), the larger Meganos Canyon of probable Paleocene age (Edmondson, 1965, p. 36) and the Markley Canyon of Oligocene (?) age (Almgren and Schlax 1957, p. 326).

The Midland fault, with its various branches, is one of the most important features of the Delta area. This fault and its major extensions are normal faults, upthrown to the east. The displacement on this fault, up to several thousand feet in the lower beds, diminishes in the upper beds of the section. In Plates III, IV, V, and VI, some of the major faults in the southeast corner are interpreted as possible extensions of the main Midland fault (which is present in the region southeast of the Bunker Gas Field).

GEOLOGIC STRUCTURE

Correlation and analysis of the 57 wells within the study area and its perimeter indicate: a) the presence of many faults, the attitudes of which could not be easily determined and b) the presence of unconformities within the stratigraphic sequence.

Due to the presence of regional unconformities within the stratigraphic sequence, as well as other correlation problems, structure contour maps were prepared on key horizons in order to help interpret the attitudes of the faults and to establish the structure of the field. Information from a seismic line, crossing the region from east to west in the southern part of the field, was also used in interpreting the structure of the field. Thus, structure contour maps were drawn: on the base of the H and T shale (Plate III), on the top of the Bunker sand (Plate IV), on the top of the McCormick sand (Plate V), and on the base of the Capay Shale (Plate VI). Comparison of these four structure contour maps indicates a northwest-trending, faulted, domal to anticlinal fold which plunges to the southeast and whose major limb dips southwest.

There are numerous faults in the area (Plates III to VI). A seismic profile from the above mentioned seismic line substantiated the presence and attitude of most of the faults in the field. The faults are normal-separation faults with relative dip separations of 50 to 200 ft, except for the two to three major faults in the extreme southeastern corner which have separations of 300 to 400 ft (Plates III and IV). As indicated in the structural cross section (Plate VII), the type of trap in the Bunker Gas Field is a structural trap with faults playing an important role in providing closure.

ISOPACH MAPS AND PALEOTOPOGRAPHY

A number of isopach maps were prepared to aid the interpretation of the paleotopography of the area (Plates VIII-X). Thicknesses were taken from geophysical logs of more than 40 wells. Isopach maps were constructed using the total thickness of the sand units of interest in each individual well.

Isopach maps, as demonstrated in Siever (1951), Pepper and others (1954), Hopkins (1958), Busch (1959), and Andresen (1961), are used to interpret paleotopography, which in turn is used to make inferences about the paleodrainage and paleotectonic activity.

Isopach maps serve this purpose because of the assumption that the sediment filled the pre-existing lows (valleys) in the area; thus the isopach map thicknesses reflect paleotopography. Lines drawn along the areas of thickest accumulation indicate where the valleys were deepest. These isopach maps exhibit the paleodrainage pattern that existed just prior to deposition of the unit.

GEOPHYSICAL LOGS AND LITHOFACIES

Lithofacies analysis was based, in part, on the interpretation of electric log pattern and, in part, on the interpretation of stratigrapic and micropaleontologic studies.

Some log patterns, especially SP curve shapes, exhibit a definite trend in grain size and sorting that can be interpreted to represent regressive or transgressive lithofacies (Selley, 1978, p. 22-25; Pirson, 1977, p. 44-54; Holt, 1976, p. 43-45). SP and resistivity log profiles (curve shapes) and their inferred lithofacies are summarized below and illustrated in Figure 4. It should be pointed

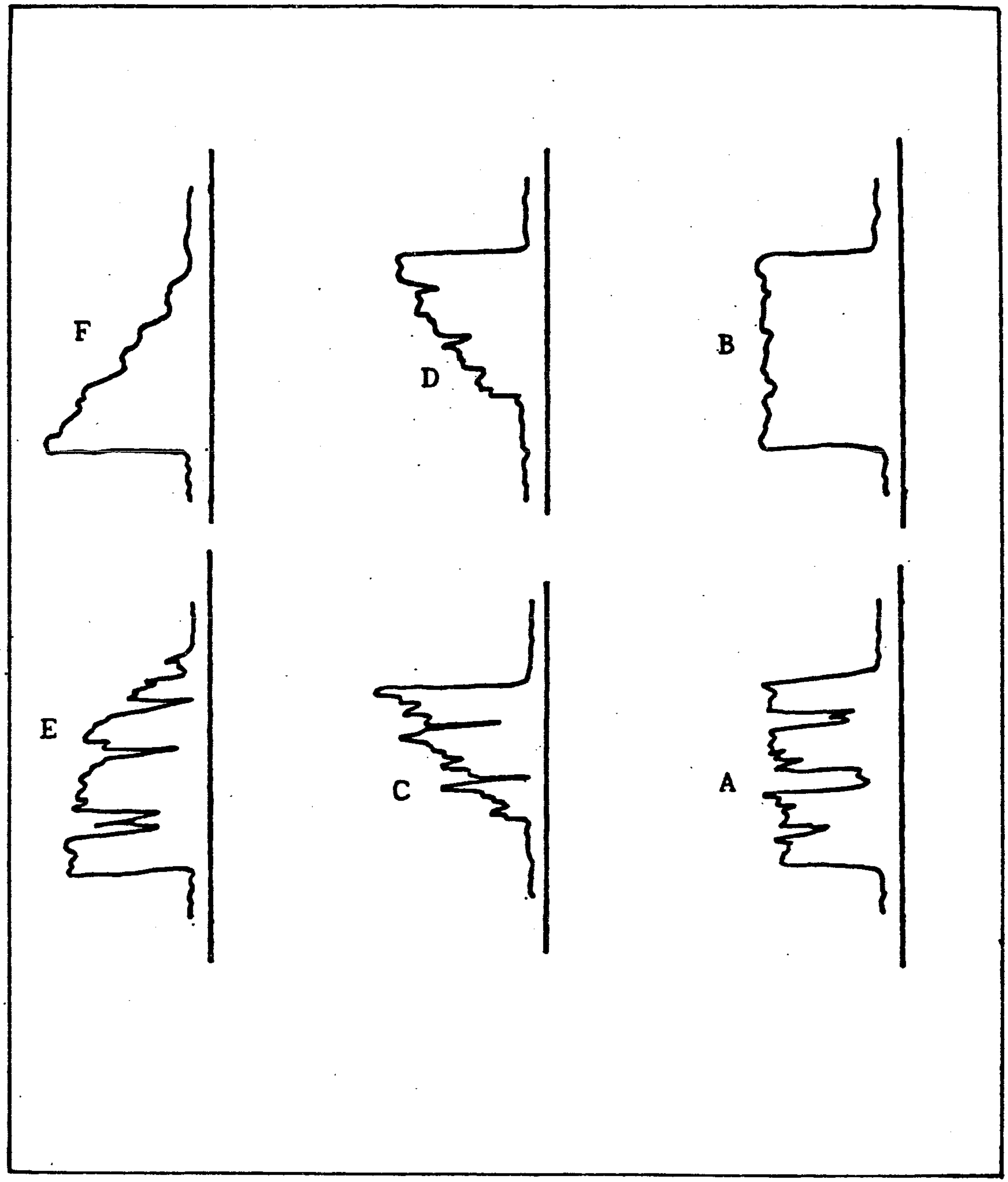


Figure 4. Classification of SP log curve shapes (modified from Holt, 1976, p. 45).

out that these patterns are not unique to specific lithofacies. Therefore, the stratigraphy together with associated microfossils play a very important role in interpreting the depositional environment.

SP log curve shapes have been categorized (Holt, 1976, p. 45) according to their appearance as follows:

a - cylindrical, abrupt lower and upper contacts (Fig. 4 A and B).

b - funnel shaped, abrupt upper contact and gradational lower contact (Fig. 4, C and D).

c - bell shaped, abrupt lower contact and gradational upper contact (Fig. 4, F and E).

Further descriptive terms such as smooth (Fig. 4, B, D, and F) and serrated (Fig. 4, A, C, and E) are added to define the depositional conditions.

An abrupt contact between the sandstone and shale, as indicated on the SP curve, implies that there is a rapid change in the energy distribution. Such rapid transitions are likely produced in areas where small differences in water depth or energy distribution cause considerable variation in a depositional environment. On the other hand, if one observes a gradual transition on the SP curve, it would imply that this sequence of lithofacies was deposited under more stable conditions and that there were small variations in the sedimentary processes (Pirson, 1977, p. 44-54; Holt, 1976, p. 43-45).

Figure 5 shows some typical SP curve shapes from several wells in the Bunker Gas Field. A highly serrated SP curve shape is observ-

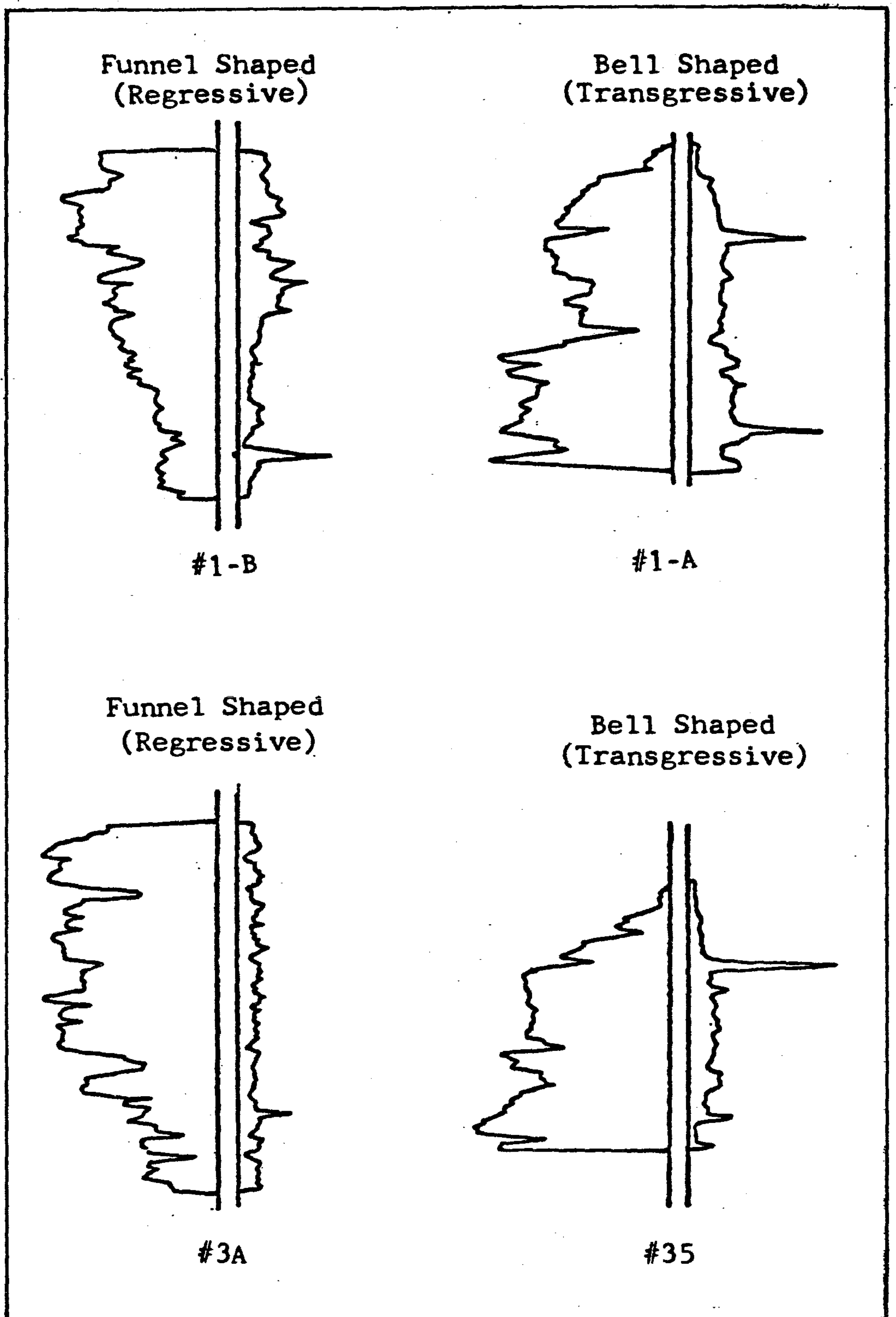


Figure 5. Representative SP log motifs from wells #1, #3A, and #35 in Bunker Gas Field.

ed, suggesting rapid transition and nonequilibrium conditions. When SP response decreases upward (moves toward the shale line, Fig. 5, well Nos. 35 and 1-A), it suggests fining of the grains upward and an overall decrease in energy. Such a condition is the result of deposition in a basin with landward migration of shoreline, generating onlapping lithofacies representative of a transgressive environment (Fig. 6A). On the other hand, if the SP response increases upward (moves away from the shale line), it suggests coarsening of the grains upward and an overall increase in energy (Fig. 5, Nos. 3A and 1-B). Such a condition is the result of deposition in a basin with seaward migration of strandline, generating offlapping lithofacies representative of a regressive environment (Fig. 6B).

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

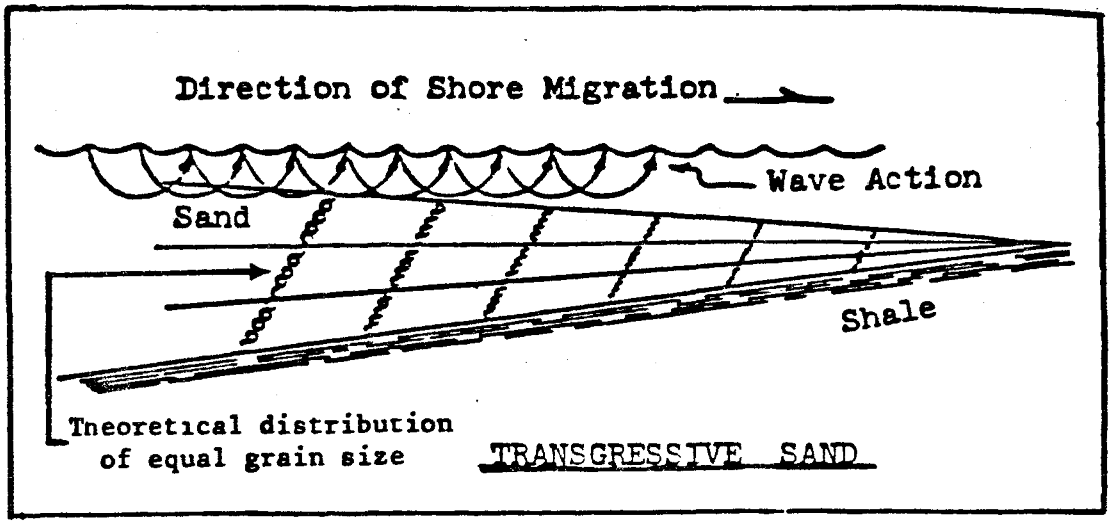
The stratigraphic section of the Bunker Gas Field (Fig. 3) is characterized almost exclusively by alternate sandstone and shale units. The rhythmical interbedding of the shale and sandstone, together with other environmental parameters such as lignite and carbonaceous clay in various parts of the section, suggest rapid deposition in a marine environment of moderately shallow depth.

Of the stratigraphic names presented here, only the Capay Shale is a formally defined formational unit. The rest are all informal names accepted by the petroleum industry as mappable subsurface units (Edmondson, 1967a and 1967b).

Starkey sand

The sandstone is very fine to fine grained, moderately to well sorted, has subangular grains, a clay matrix, and is interbedded with

A



B

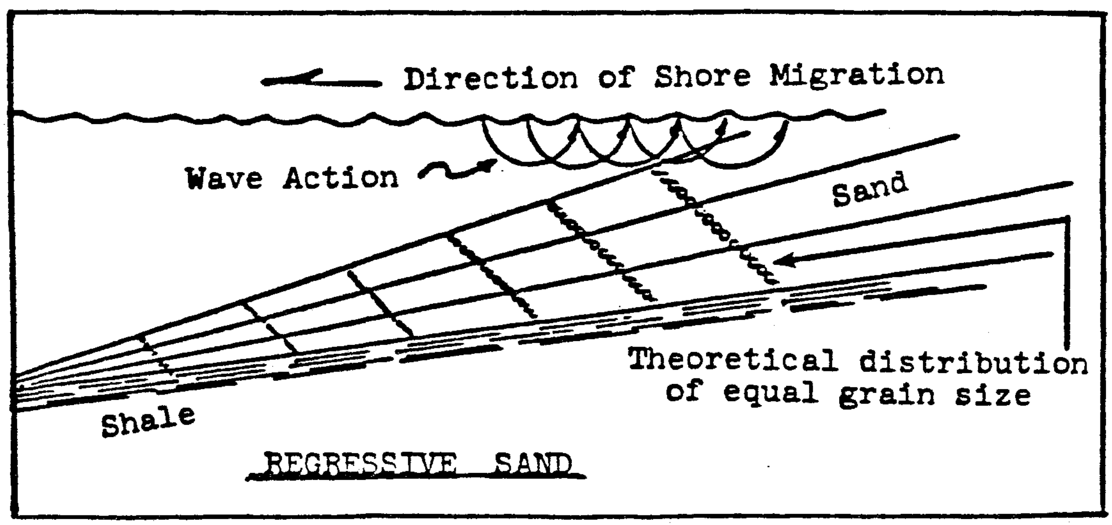


Figure 6. Schematic representation of trangressive and regressive sand development with respect to grain size distribution (interpreted from Pirson, 1977, p. 12-17 and Spearing, 1974, chart 4 of 7).

claystone (or siltstone). The sandstone is light gray to gray in color and grades into a predominantly medium-grained and poorly sorted sandstone in the northwestern part of the field where it also contains a thin-bedded layer of lignite, disseminated glauconite and some pyrite in the upper parts of the formation. The formation is approximately 900 ft thick in the Bunker Gas Field (Edmondson, 1967a and 1967b). Paleontological studies have indicated the Starkey sand to be marine,to be of Late Cretaceous age, and to represent Goudkoff's (1945) D-2 faunal zone (Tables 2 and 3).

H and T shale

Medium to dark gray, well indurated, and highly micromicaceous claystone constitutes the major part of the H and T shale. The claystone is interbedded with gray, fine-grained siltstone throughout the field. H and T shale has an average thickness of 150 ft and contains some well rounded glauconite grains, carbonaceous material, and lignite. The glauconite content increases in a westerly direction. Figure 7 shows the representative log motifs of H and T shale. Foraminiferal analysis of the H and T shale shows the age to be Late Cretaceous (Tables 2 and 3). H and T shale is marine and is in Goudkoff's (1945) D-1 zone.

Bunker sand

The formation is composed of very fine- to medium-grained sandstone which is poorly to well sorted, has subangular to subrounded grains, and has a claystone matrix. The sandstone is 180 ft thick, commonly light gray in color, and contains some pyrite and carbonaceous material. It is interbedded with claystone and siltstone. Some

TABLE 2. MICROFAUNA FROM FORMATIONS ENCOUNTERED IN A FEW SELECTED WELLS

Well Reference Number	Formation	Foraminiferal Species
15	Upper part of Martinez Shale	Ammodiscus incertus Silicosigmoilina californica
15	Lower part of Martinez Shale	Bathysiphon sp. Nodosaria latejugata Cribrostomoides sp. Haplophragmoides sp.
15	Hamilton Sand	Amphistegina californica
15	Capay Shale	Angulogerina willcoxensis Pseudouvigerina sp.
26	Lower part of Martinez Shale	Bathysiphon sp. Cibicides sp.
26	McCormick Sand	Cibicides alazanensis Globorotalia membranacea Bulimina arkadelphiana
26	Upper part of Martinez Shale	Amphistegina sp. Asterigerina sp.
39	Capay Shale	Robulus sp. Marginulina mexicana Eponides prims Cibicides whitei Globigerina sp.
39	McCormick Sand	Bathysiphon striata Cibicides sp. Bulimina arkadelphina Bulimina taylorensis
39	Upper part of Martinez Shale	Ammodiscus turbinatus
39	Mokelumne Sand/Shale	Siphogenerinoides whitei Planulina nacatockensis
39	Bunker Sand and H & T Shale	Lycopods sp. Gyroidina nitida
39	Starkey Sand	Gaudryina crassaformis Anomelina rubiginosa Bulimina triangularis

TABLE 3. UPPER CRETACEOUS BIOSTRATIGRAPHY OF BUNKER GAS FIELD

Formation	Goudkoff Foram. Zone	Foraminiferal Species
Mokelumne Sand/Shale	C	*Siphogenerinoides whitei* *Planulina nacatockemsis*
Bunker Sand and H & T Shale	D_1	*Lycopods* sp. *Gyroidina nitida*
Starkey Sand	D_2	*Gaudryina crassaformis* *Anomelina rubiginosa* *Bulimina triangularis*

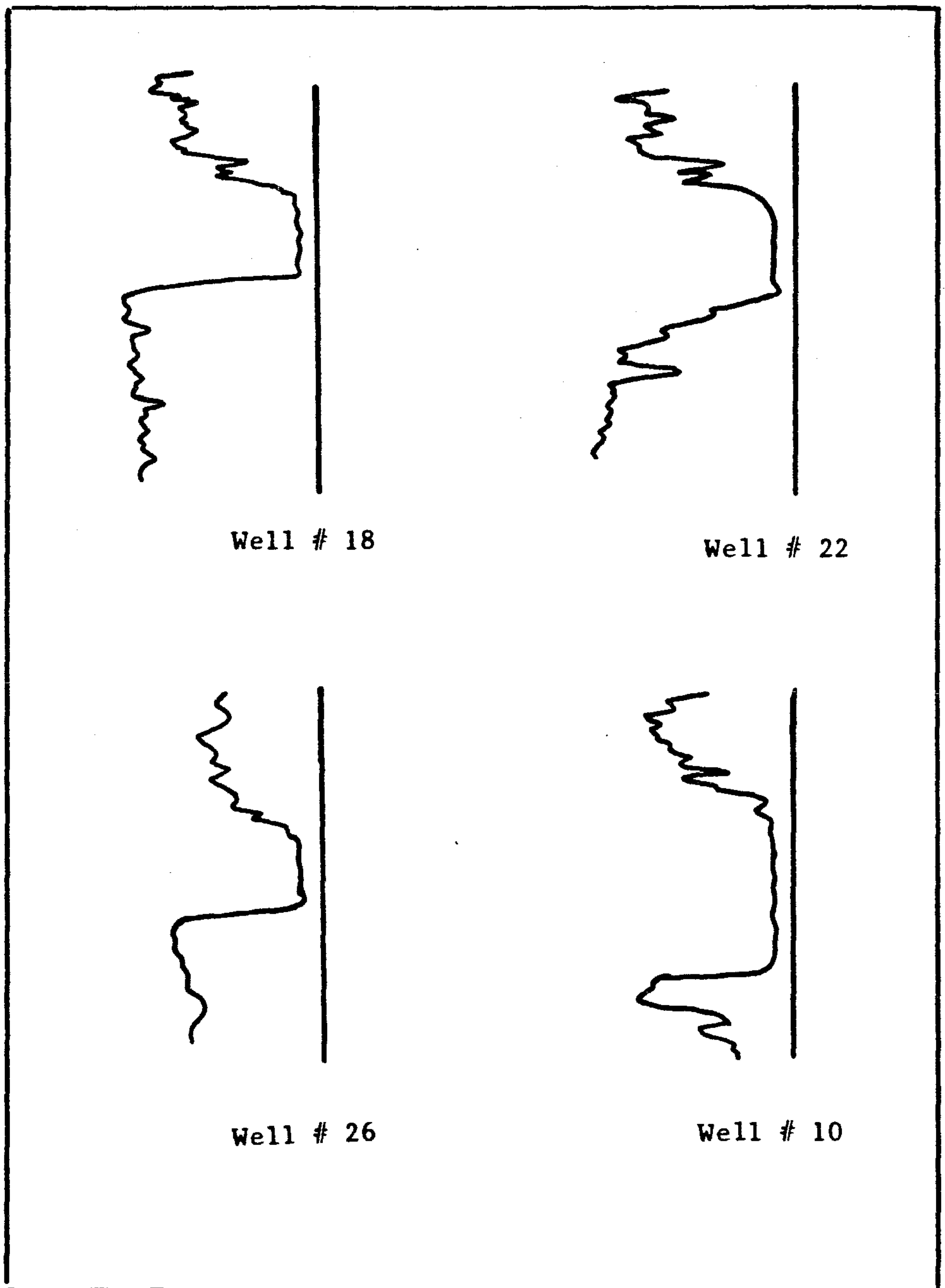


Figure 7. Representative log motifs of H & T shale in Bunker Gas Field.

thin layers of glauconite are present in the lower part of the formation. Figure 8 illustrates the representative log motifs of Bunker sand in wells numbered 7, 15, 38, and 40. For areal distribution of these wells, reference should be made to Plate II. The Bunker sand grades to coarse-grained sandstone in an upward direction and contains a few thin beds of lignite at the top (Plate XII). The thickness and abundance of this lignite increases in an easterly to northeasterly direction. Foraminifera collected from this formation identify the Bunker sand as marine of Late Cretaceous age and correlate it to Goudkoff's (1945) D-1 zone (Tables 2 and 3). Almost all of the gas production in the Bunker Gas Field is from the top 20 to 50 ft of this formation. The Bunker sand unit is inferred to have been deposited at a relatively slow rate in a shoal and slowly regressive marine environment. Microfossils (Tables 2 and 3) and the occurrence of glauconite indicate a shallow marine environment. Comparison of the log motifs in Figure 8 with log curve shapes discussed in Figures 4 (C and D) and 5 (1B and 3A) shows that the log motifs of Figure 8 are funnel shaped and have the characteristics of regressive sand bodies. The physical-sedimentary aspects of the Bunker sand, such as increasing grain size, also support the regressive nature of this sand unit (Visher, 1965, p. 44-46; Selly, 1978, p. 26-29; Spearing, 1974, Figs. 5, 6, 7, 8, and 9). The presence of glauconite (Compton 1962, p. 233; Pettijohn and others, 1973, p. 230; Krumbein and Sloss, 1963, p. 186) and the convex cusp shape (Pirson, 1977, p. 49, Figs. 2-4) of the Bunker sand log curves illustrated in Figure 8 (well Nos. 14 and 40) suggest a slow rate of deposition

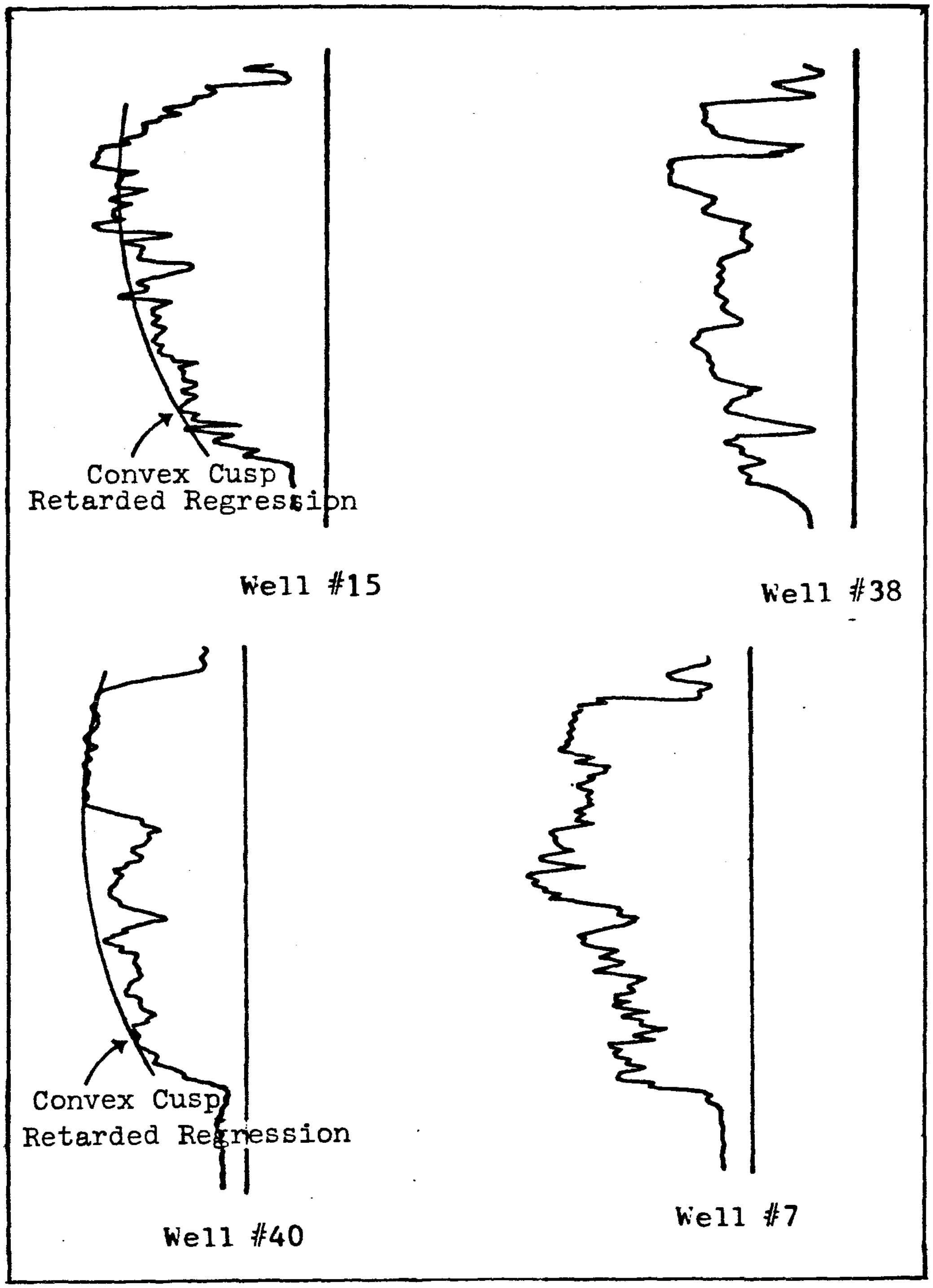


Figure 8. Representative log motifs of Bunker sand in Bunker Gas Field.

and regression. Bedding nature of the sand unit defined in terms of its relatively uniform thickness and lateral persistence (Plate VIII) indicates the consistency of the depositional process.

The isopach map of the Bunker sand unit (Plate VIII) illustrates the paleotopography of the study area at a time prior to deposition of this unit during Late Cretaceous time. The paleotopography depicted by the isopach map shows a relatively broad local high in secs. 17, 18, 19, and 20, T. 6 N., R. 2 E. and two minor ones in sec. 21, T. 6 N., R. 2 E. and secs. 25 and 30, T. 6 N., R. 1 E. One major valley (canyon) trending in a south-southeasterly direction and four other smaller valleys (each trending in a different direction) in the northern, western, eastern, and southwestern part of the area are observed.

Although no particular drainage pattern could be detected from the above valleys, a reasonable interpretation can be made concerning paleoslope of the region and the sediment source for the Bunker lithosome. Deposition of the Bunker sand unit was most probably controlled and/or affected by the preexisting regional topography. In that respect the major valley (canyon), trending in a southeasterly direction and deepening at the same time, could be inferred to indicate the direction of the paleoslope and presence of a basin in the extreme southeastern region outside the study area. Although there is some sediment contribution from sources to the east of the Bunker Gas Field, the major and general source for the Bunker sand unit is interpreted to have been somewhere to the north and/or northwestern regions of the field.

Mokelumne sand/shale

The average total thickness of the Mokelumne formation is approximately 450 ft. This formation is dominantly a sandstone sequence with interbedded siltstone and claystone.

The sandstone is composed of predominantly fine- to medium-grained, moderately to poorly sorted, subangular to subrounded sand grains in a claystone matrix. It has a light to medium gray color and contains a fair amount of quartz, biotite, and lignite grains.

The claystone is dark gray, soft to friable, and very carbonaceous. It is interbedded with gray siltstone and dark-brown lignite beds (Plate XII). These lignite beds are common throughout the formation, but their abundance and thickness increases downward and also in an easterly to northeasterly direction in the study area. The presence of carbonaceous clay, lignite, and wood-like material throughout the formation may be inferred to indicate proximity to a land mass and the presence of deltaic conditions in the north and northeastern areas of the field during deposition of the Mokelumne sand/shale unit. Figure 9 shows representative log motifs of the Mokelumne units.

Foraminifera collected from this formation indicate a shallow-marine environment that corresponds to Goudkoff's C to D-1 (?) zone (Tables 2 and 3).

The Mokelume formation is equivalent (?) to Colburn's (1961, p. 32-34) unnamed Upper Cretaceous formation of Deer Valley Road. Older publications refer to the Mokelumne formation as Meganos-Martinez Undifferentiated.

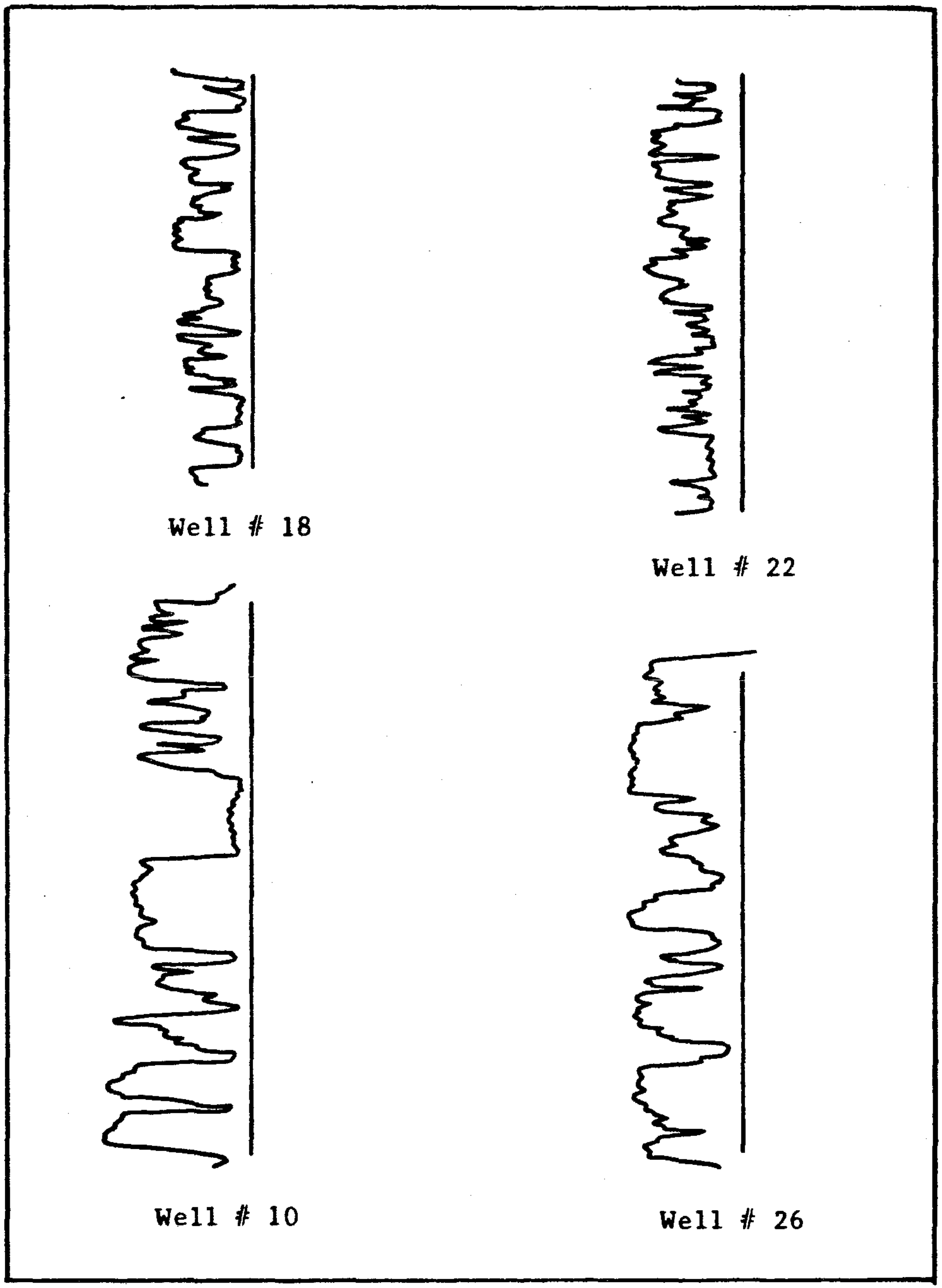


Figure 9. Representative log motifs of Mokelumne sand/shale in Bunker Gas Field.

Late Cretaceous-Paleocene unconformity

The regional unconformity that occurs between the Mokelumne sand/shale (Upper Cretaceous) and the Martinez canyon fill unit (late Paleocene), discussed below, is an important feature, both structurally and stratigraphically (Plates VII, XI, and XII).

Some of the evidence for the presence of this important regional unconformity includes:

1. Thinning of the Mokelumne sand/shale in the north, east, and west of the study area (Plates VII and XI).

2. Presence of basal conglomeratic sandstone in the Martinez canyon fill, which is predominantly claystone interbedded with shale and siltstone (Plates VII, XI, and XIII).

3. Onlapping of younger late Paleocene McCormick sand on much older Upper Cretaceous Mokelumne sand/shale in the east, west, and north of the field (Plate VII).

4. Martinez canyon fill unit is missing in the east, west, and north of the field, but it rests discordantly on Mokelumne sand/shale in the central part of the field (Plates VII, XI, and XII).

5. Paleontological studies also indicate that there is a hiatus between the Late Cretaceous (Mokelumne sand/shale) and the late Paleocene (Martinez canyon fill and McCormick sand). Apparently the early and middle Paleocene records are missing regionally as well as in the study area.

This regional unconformity is the same one as Colburn (1961, p. 37-43) discovered between Oil Canyon and Kellogg Creek of the Mount Diablo region.

Martinez canyon fill

Basal Sandstone: This conglomeratic sandstone is present in most of the wells and its thickness varies between 50 and 75 ft. Figure 10 shows representative log motifs of the Martinez canyon fill. In some wells, the basal conglomeratic sandstone is difficult to distinguish from lower Mokelumne sandstone (Plate XII). In well no. 33 (Plate XI) and surrounding wells (Plate XII), the sand is well developed. In these wells, the basal sandstone is fine to predominantly medium grained, moderately to well sorted, and has angular to subangular grains. The sandstone is friable, light to medium gray, and has a clay matrix. The unit has abundant quartz grains, and is highly to moderately conglomeratic.

Claystone: This claystone (mudstone) constitutes almost 90% of the Martinez canyon fill (Plate XI). Its thickness varies from 10 ft in the northwest to 800 ft in the southeast. The formation is medium to dark gray, thick bedded, well indurated, interbedded with siltstone, and is highly micromicaceous. It is commonly interbedded with thin layers of lignite in the upper parts of the fill (Plate XII). Foraminifera collected from the claystone represent late Paleocene age and correspond to Laiming's (1940, p. 1923) E zone (Tables 3 and 4).

McCormick sand

The sandstone is fine to medium grained, moderately sorted, has subangular to subrounded grains, is greenish gray, and contains a good amount of pyrite and biotite. Figure 11 is a representative log motif of the McCormick sand. A large amount of lignite and shell fragments

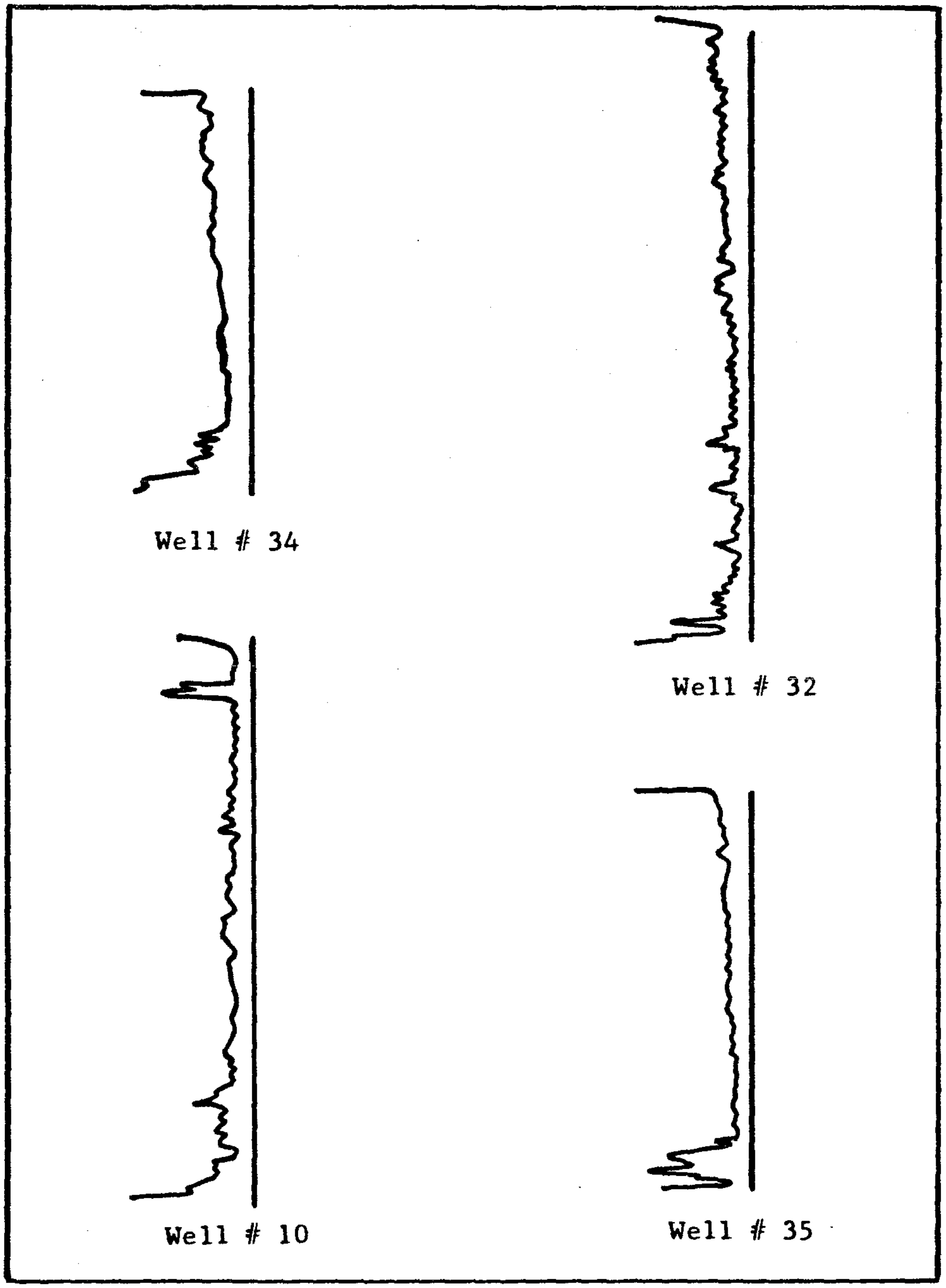


Figure 10. Representative log motifs of Martinez canyon fill in Bunker Gas Field.

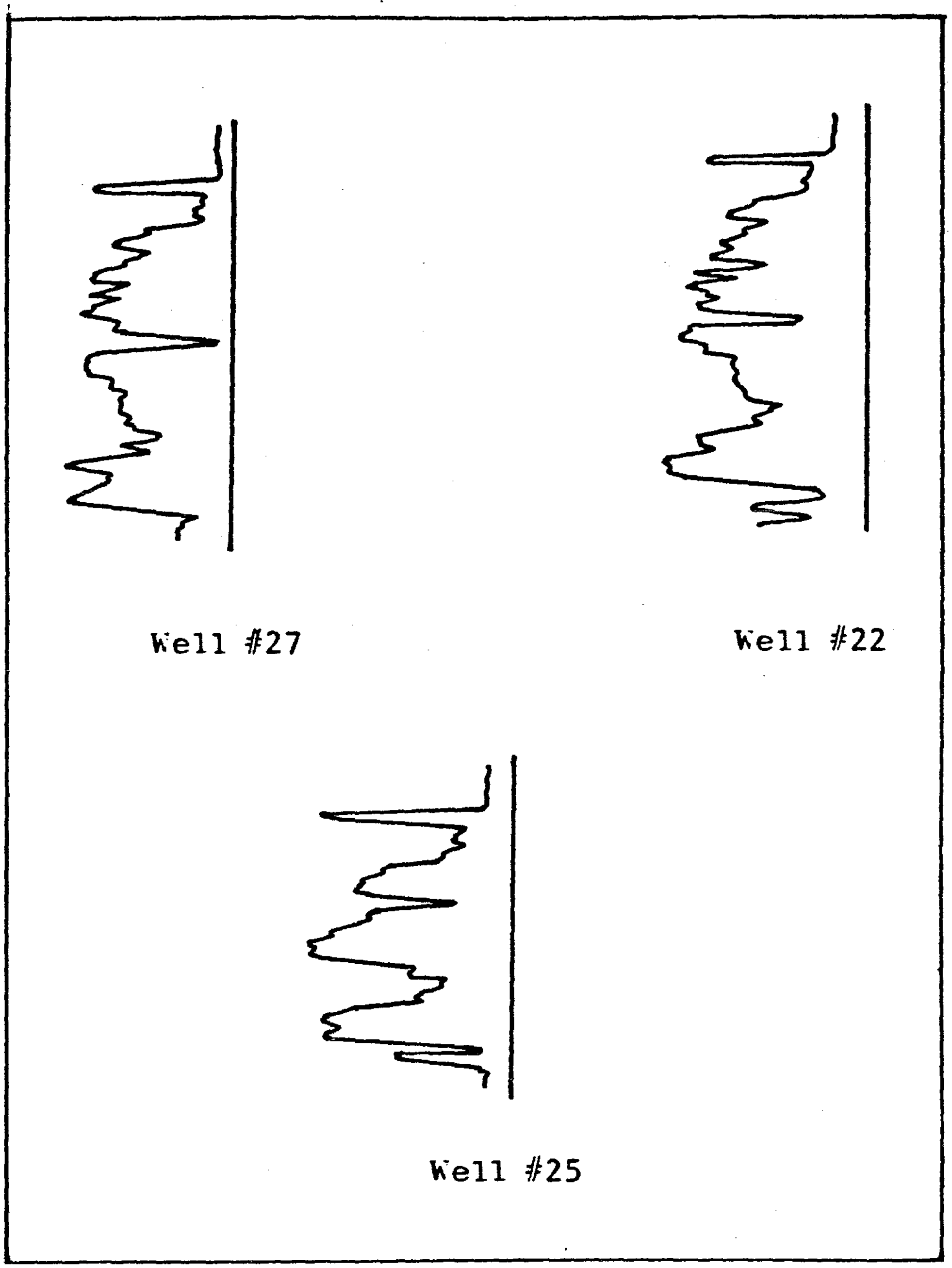


Figure 11. Representative log motifs of the McCormick sand in Bunker Gas Field.

are present in the lower part of the formation (Plate XII) and their abundance increases laterally in the north, northeast, and northwest parts of the field. Abundant glauconite is present in the upper part of the formation (Plate XII) in wells in the south, southeast, and southwest parts of the field. Sandstone becomes better sorted and finer grained upward in the section. Foraminifera collected from a number of selected wells (Table 2) indicate McCormick sand to be of late Paleocene age and equivalent to Laiming's (1943, p. 193) E zone (Table 4). Comparison of Figure 11 with Figures 4(F and E) and 5(1A and 35) illustrates the resemblance of log motifs in Figure 11 to the bell-shaped log curves, which are indicative of transgressive sand units.

The basic process of transgressive sedimentation is the erosion and redeposition of clastic detritus by wave action. According to Curray (1960, p. 221-223), most of the basal Holocene transgressive sediments are less than 20 ft thick (Visher, 1965, p. 55). Comparatively, the average thickness of the McCormick sand (Plate IX) is 150 ft, much greater than the average thickness of most transgressive sand bodies. The bedding characteristics of the McCormick, its moderately uniform and thick-bedded nature, as well as its geographic distribution and persistence, suggest consistency of the depositional environment. The depositional process capable of producing thick-bedded transgressive sand units, such as the McCormick, requires a subaqueous plain of low gradient where the rate of sedimentation supply and sea transgression are in close balance (Visher, 1965, p. 55).

TABLE 4. PALEOCENE BIOSTRATIGRAPHY OF BUNKER GAS FIELD

Formation	Age (Series)	Laiming Foram. Zones	Mallory Foram. Stages	Foraminiferal Species
Capay Shale	Early Eocene	B	Ulatisian	*Angulogerina willcoxensis* *Pseudouvigerina* sp. *Robulus* sp. *Marginulina mexicana* *Eponoides prims* *Cibicides whitei* *Globigerina* sp.
Hamilton Sand	"	C	Penutian	*Amphistegina californica* *Amphistegina* sp. *Discocyclina* sp.
Martinez Shale	Late Paleocene			
Upper Part	"	D	Bulitian	*Ammodiscus incertus* *Ammodiscus turbinatus* *Amphistegina* sp. *Asterigerina* sp.
Lower Part	"	E	Ynezian	*Silicosigmoilina californica* *Bathysiphon* sp. *Nodosaria latejugata* *Cribrostomoides* sp. *Haplophragmoides* sp.
McCormick	"	E	Ynezian	*Cibicides alazanensis* *Globorotalia membrancea* *Bulimina arkadelphiana* *Bathysiphon striata* *Bulimina taylorensis*
Martinez Canyon Fill	"	E	Ynezian	*Globorotalia pseudomenardii*

The isopach map of the McCormick sand unit (Plate IX) portrays the paleotopography of the study area at a time prior to deposition of this unit during early Paleocene time. The paleotopography depicted by the isopach map shows a major valley (canyon) trending in a southeasterly direction. A number of smaller tributary valleys, from the western part of the field, join this major valley.

The drainage pattern of the McCormick isopach, although not a classical example, does seem to be dendritic. The drainage pattern indicates that the underlying rocks are probably homogenous, and that the stream patterns were not influenced by geologic controls such as faults or folds. The gradual deepening of the major valley in a southeasterly direction can be attributed to a gradual subsidence of the area in that direction and presence of a basin in the far southeastern region outside the study area.

The drainage pattern clearly illustrates that the paleoslope is in a southeasterly direction, and that the source for the McCormick sand unit is in the north and/or northwest.

Information from microfossils (Tables 2 and 4) together with the lithology of the McCormick sand suggest a shallow and transgressive marine environment.

Martinez shale

This formation has a thickness of 50 ft in the north to northeast part of the Bunker field and it thickens rather rapidly toward the south to southwest, where it attains a thickness of 500 ft. Figure 12 is representative E-log motifs of the Martinez shale.

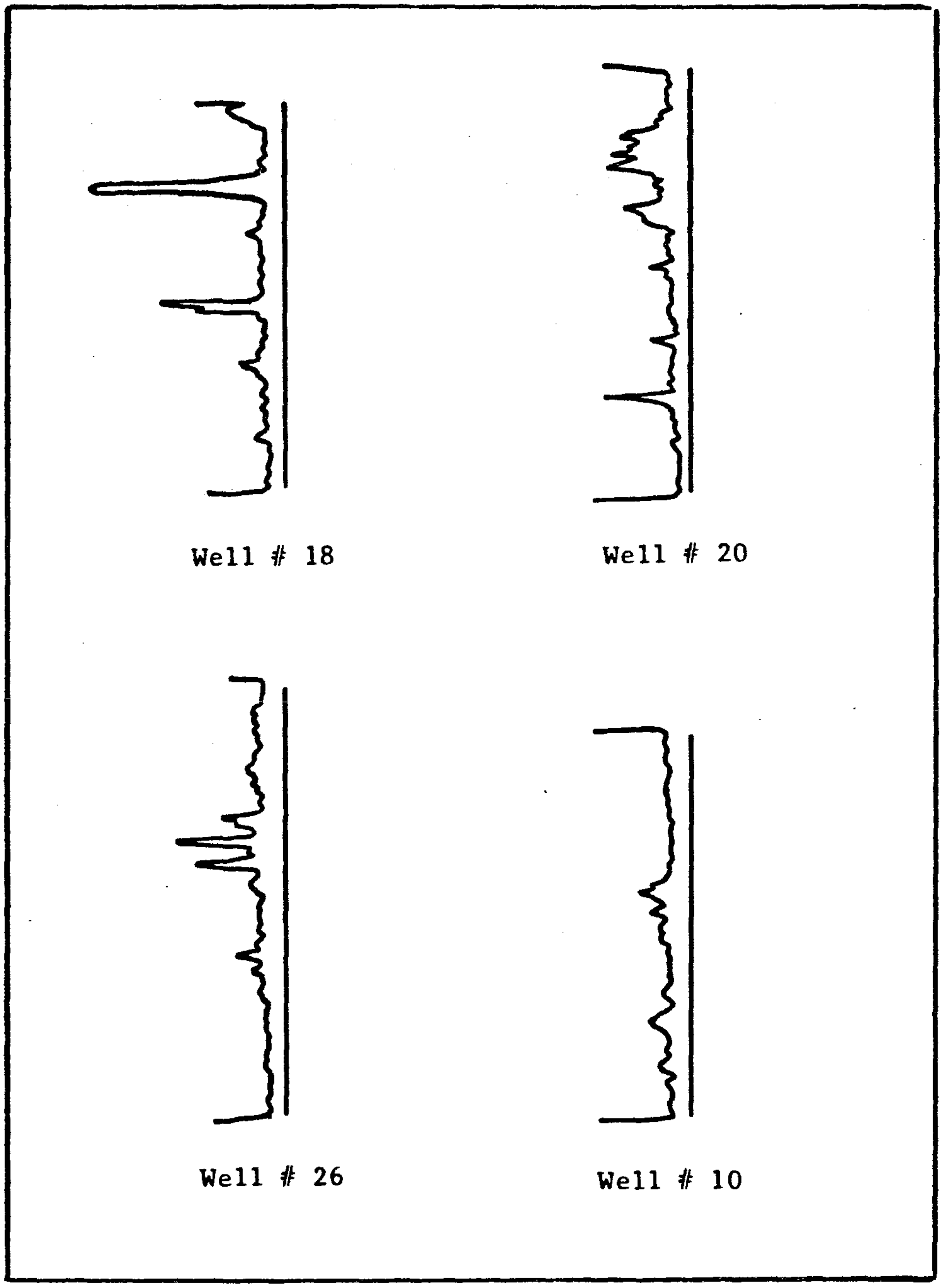


Figure 12. Representative log motifs of Martinez shale in Bunker Gas Field.

The lower two thirds of the formation is totally claystone and the rest is interbedded with conglomeratic sandstone lenses. The sandstone is fine to predominantly coarse grained, poorly sorted, contains subangular grains, and has a fair amount of glauconite. A conglomeratic sand, 10 to 30 ft thick, in the upper part of the Martinez shale has been referred to by some as the Anderson sand (Edmondson, 1967a and 1967b). Comparison of the log motifs in Figure 13 with Figures 4(C and D) and 5(3A and 1-B) shows the regressive nature of this conglomeratic sand unit in the Martinez shale. The claystone associated and interbedded with the above sand lens is referred to as the Meganos shale.

The claystone is dark gray, well indurated, thick bedded, micromicaceous, and contains some glauconite.

The mudstone bed above the sandstone lens, at the top of the Martinez shale (Fig. 13), contains thin layers of lignite (Plate XII).

Foraminifera collected from the Martinez shale indicate a late Paleocene age and represent Laiming's (1943, p. 193) E and D zones (Tables 2 and 4).

<u>Paleocene-Eocene unconformity</u>

The unconformity that separates the Hamilton sand from the Martinez shale is a regional one (Plates VII and XII). Even though the presence of this unconformity within the boundaries of the Bunker Gas Field may not be easily established, its presence is very well documented outside the field (Edmondson, 1967a and 1967b).

Meganos Canyon, to the east outside the Bunker Gas Field, was cut during the hiatus represented by this unconformity (Edmondson,

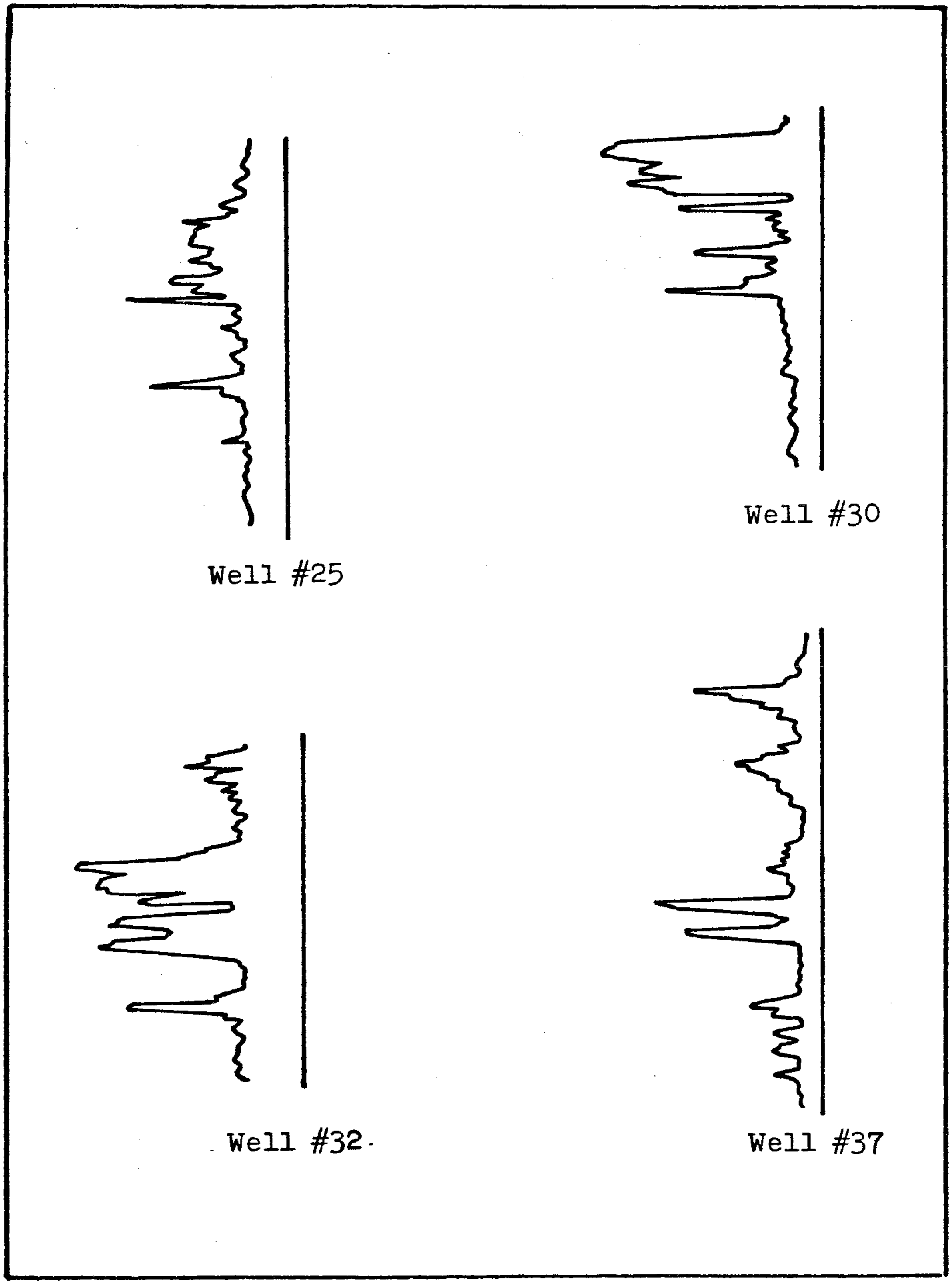


Figure 13. Log motifs of conglomeratic sandstone in the upper part of the Martinez shale in Bunker Gas Field.

1965, p. 36.)

Some of the evidence which points to the presence of the unconformity within Bunker field includes:

1. The Martinez shale thins rapidly to the north, west, and east of the field, especially in the east where it is almost totally missing.

2. The presence of conglomeratic sand on top of the Martinez shale and the regressive nature of the Martinez unit (Plate XII).

3. Onlapping of Hamilton sand on the older Martinez shale beds outside Bunker field.

4. Rather uniform thickness of the Hamilton sand and its transgressive nature (Plate XII).

This unconformity may be (?) the one which Colburn (1961, p. 58) refers to as "post-lower Eocene, pre-middle Eocene unconformity." The correlative evidence in this case, however, is very sketchy and weak.

Hamilton sand

The sandstone has an average thickness of 180 ft (Plate X), is fine to coarse grained, moderately sorted, and contains subangular to subrounded grains. It is light gray and, in some wells, conglomeratic. Figure 14 is representative log motifs of the Hamilton sand. The formation contains abundant glauconite, lignite, and carbonaceous materials throughout the field. The sandstone becomes finer grained and better sorted upward and contains abundant shell fragments in the upper part of the unit (Plate XII).

Lignite and shell fragments are much less common in the wells

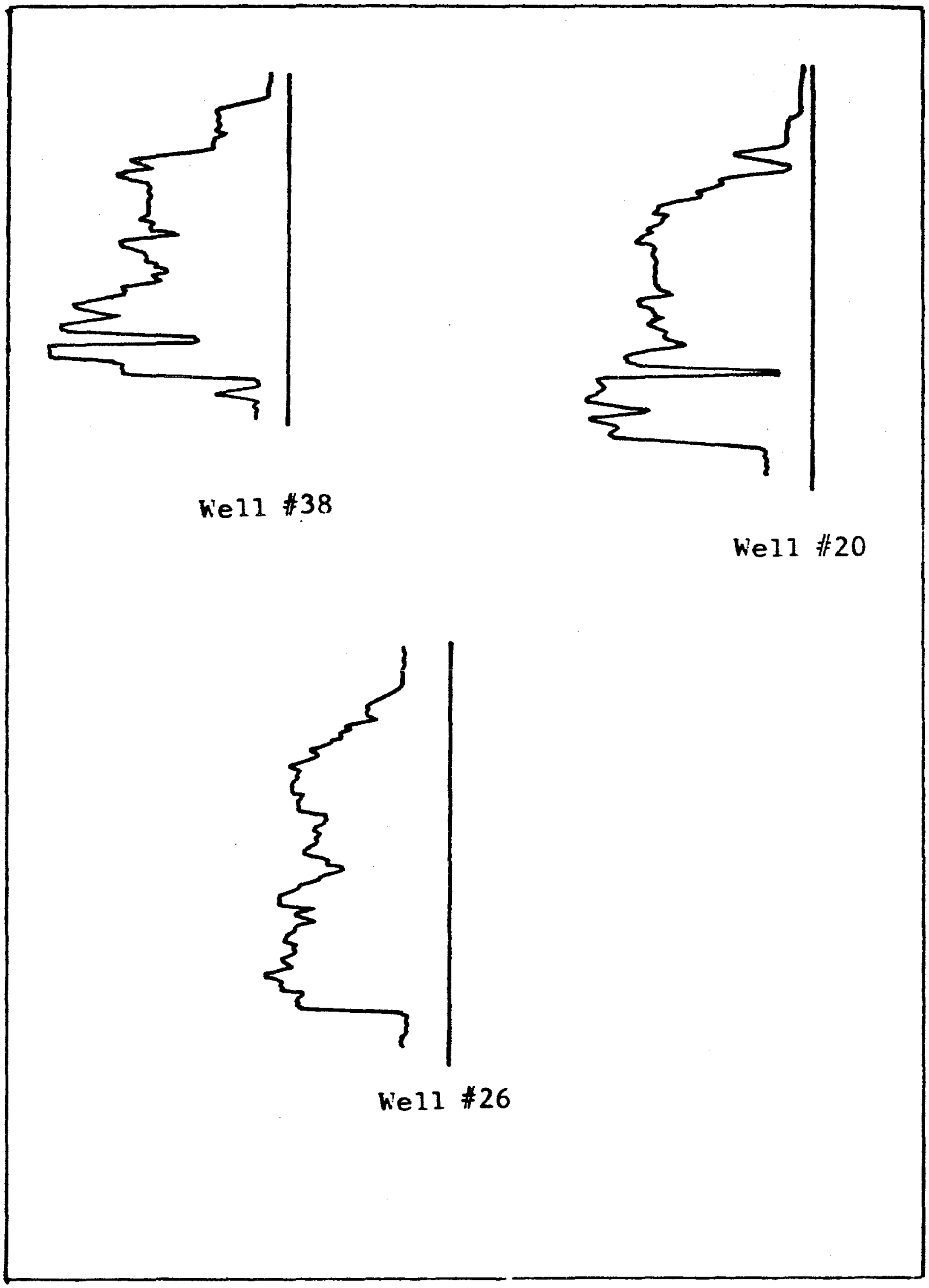


Figure 14. Representative log motifs of the Hamilton sand in Bunker Gas Field.

located in the southwest part of the field.

Foraminifera recovered from the Hamilton sand are representative of a nearshore environment. The foraminifera indicate an early Eocene age and relate to Laiming's (1943, p. 193) D and, probably, B-1 and B-4 zones (Tables 2 and 4).

The sedimentation process of the Hamilton sand is similar to that of the McCormick which establishes the Hamilton to be a transgressive sedimentary unit.

The isopach map of the Hamilton sand unit (Plate X) portrays the paleotopography of the study area at the end of regional subaerial erosion, which is substantiated by the presence of a regional unconformity at the base of the Hamilton sand (Plate XII). The paleotopography is characterized by a broad local high (in secs. 19 and 29, T. 6 N., R. 2 E. and sec. 24, T. 6 N., R. 1 E.) and two major valleys to the north and south of the above mentioned topographic high.

The deposition of the Hamilton lithosome seems to have been controlled by the erosional topography that prevailed during late Paleocene and early Eocene time. The drainage pattern depicted by the isopach map does not conform to any known patterns, but a number of interpretations can be made as follows:

a) The two major streams trend and deepen in a westerly course, which suggests a western paleoslope direction and an eastern source for the Hamilton sand.

b) Comparison of the Hamilton and the McCormick sand isopachs shows a shift of paleoslope direction from the south (preceeding McCormick deposition) to the west (preceeding Hamilton deposition). A plausible explanation for this change in paleoslope direction is translocation of regional tectonic activity.

Similar conclusions have been reached by other researchers (Safonov, 1968, p. 611-623; Ojakangas, 1968, p. 973-1005) who have done regional surface studies in the part of the Sacramento Basin that embodies the Bunker Gas Field.

Information from microfossils (Tables 3 and 4) together with the lithology of the Hamilton sand suggest a shallow and transgressive marine environment.

Capay Shale

The formation was named by Crook and Kirby (1934, p. 334). Its type locality is exposed on the west side of Capay Valley, west of Rumsy Hills, west of the town of Winters, Yolo County, California. Subsurface correlation of Capay Shale and the use of the name was established by Edmondson (1967a and 1967b). Capay Shale is composed predominantly of claystone interbedded with shale and siltstone. The claystone is dark gray, well indurated, micromicaceous, bentonitic, well hydrated, and over 700 ft thick (Plate XII). It contains abundant glauconite, foraminifera, and minor amounts of olivine, quartz, and gypsum.

Foraminiferal assemblages in the Capay are representative of a deep-marine environment and indicate an early Eocene age. The Capay includes Laiming's (1940, p. 1923) B-2, B-3, B-4, and C zone (Tables 3 and 4).

SEDIMENTARY CYCLES AND PALEOENVIRONMENTS

Introduction

Plate XII portrays the vertical lithologic relationships and provides some of the criteria which were applied in the interpretation of the paleoenvironment of the Bunker Gas Field.

As stated by Visher (1965, p. 46), "The boundaries of the sedimentary sequence are defined by unconformities. The upper limit is a product of non-deposition and possibly erosion, and represents a transgression across the top of the regressive marine sequence."

As such, the unconformities are the natural starting points for reconstruction of the sedimentary sequence and interpretation of the paleoenvironments.

The Upper Cretaceous and Paleogene sequence of strata in Bunker Gas Field are represented by three cycles of deposition as follows (Plate XII):

Cycle I - Late Cretaceous regressive shallow-marine sedimentation.

Cycle II - Late Paleocene transgressive and regressive shallow-marine sedimentation.

Cycle III - Early Eocene transgressive shallow-marine sedimentation.

The cycles are separated by two major and regional unconformities, one at the base of the Martinez canyon fill and the other at the base of the Hamilton sand.

Sedimentary Cycle I

The overall sedimentary sequence (from bottom to top) of Cycle I portrayed in Plate XII consists of dark gray, poorly sorted siltstone and fine-grained sandstone of the Bunker sand which becomes better sorted and coarser grained in an upward direction. This Lithosome overlain by alternating beds of shale and sandstone of the Mokelumne with its topmost bed being composed mainly of well sorted, coarse-grained sandstone. This lithologic profile is representative of a regressive marine environment (Visher, 1965, p. 44-46; Selley, 1978, p. 26-29; Spearing, 1974, Figs. 5, 6, 7, 8, and 9).

The presence of a thin glauconite bed in both the H and T shale and the Bunker sand suggests a slow rate of deposition (Compton, 1962, p. 233; Pettijohn and others, 1973, p. 230; Krumbein and Sloss, 1963, p. 186; Reineck and Singh, 1973, p. 132). This slow rate of deposition, when coupled with the log pattern of the Bunker sand (Fig. 9 and Pirson, 1977, p. 45, Fig. 2-1, p. 49, Fig. 2-4), indicates a retarded or slow rate of shoreline regression. The occurrence of lignite beds in the Mokelumne (Plate XII) and the topmost part of the Bunker, the presence of carbonaceous clay (thick clay interval) in the upper section of the Mokelumne, together with the log motif could be inferred, on the other hand, to indicate that the regression of the sea, while fluctuating, was accelerated and culminated with the introduction of the regional unconformity (sedimentary break) present at the base of the Martinez canyon fill. The thick marine H and T shale and numerous thin and thick marine shale layers in the Mokelumne are clear indications of fluctuations of the strandline during the Cycle I regressive process (Visher, 1965, p. 45-46) which started prior to Late Cretaceous and continued until late Paleocene time.

Lithologic characteristics, geophysical log motifs, and microfossils (Tables 2 and 4) of the entire sedimentary sequence of Cycle I exemplify a shallow-marine regressive sequence fluctuating between neritic and littoral environments (Visher, 1965, p. 44-45).

The abundance of carbonaceous clay, lignite, and wood-like material in the Mokelumne in the eastern and northeastern parts of the Bunker Gas Field may also be inferred to suggest proximity to a land mass and the presence of deltaic conditions in the northern and northeastern areas of the field. Correlation of the foraminifera from the Cycle I sedimentary sequence (Tables 2 and 3) with Goudkoff's foraminifera zones (Goudkoff, 1945, p. 959-987) indicates that Bunker Gas Field was covered by a Cretaceous sea during Late Cretaceous time (Goudkoff, 1945, p. 998-1007). The shallow sea covering the study area during Late Cretaceous time regressed in a south to southeasterly direction prior to deposition of the Bunker sandstone (Plate VIII). The regressive direction of the shallow sea seems to have shifted to a south to southwesterly course during the deposition of the Bunker sandstone (?) and Mokelumne sand/shale as indicated by the paleoenvironment characteristics of the Mokelumne unit mentioned above.

Cycle I sedimentation ended with strong uplift in the western and northern regions and the introduction of a regional unconformity (Mallory, 1959, p. 99) that exposed the entire region to subaerial erosion during late early to middle (?) Paleocene time. It was during this early to middle (?) Paleocene erosion that Martinez canyon was cut (Plate XI).

Sedimentary Cycle II

The second cycle (II) of sedimentation was initiated by the rapid infilling of Martinez canyon prior to deposition of the transgressive shallow-marine McCormick sand in early late Paleocene time (Plate XII). Rapid infilling of Martinez canyon, in a shallow environment, is indicated by the presence of lignite (Krumbein and Sloss, 1963, p. 187-188; Bateman, 1965, p. 640-641) and a very sparse foraminiferal assemblage.

Lithologic characteristics, the geophysical log motif, and the foram assemblage of the McCormick sand represent a shallow-marine transgressive environment.

Transgression of the sea and deepening of the basin continued as indicated by the thick shale bed at the base of the Martinez shale (Plate XII). The presence of glauconite (Compton, 1962, p. 233; Pettijohn and others, 1973, p. 230; Krumbein and Sloss, 1963, p. 186) in the lower part of the McCormick sand and the upper part of the thick shale bed in the Martinez shale (Plate XII) could imply a slow rate of deposition.

The microfaunal assemblage (Table 4) and the presence of shell fragments in the upper part of the McCormick sand (Plate XII) are both indicative of a mid-neritic to neritic environment for this lithosome (Mallory, 1959, p. 22-27).

The gradual replacement of the transgressive trend of the sea, prevalent in the basal shale bed of the Martinez shale, by a regressive trend (Plate XII) is indicated by the distinct changes observed in lithology, log motif, and foraminiferal assemblage of the conglomeratic sand of the upper part of the Martinez shale. Lithologically the gradual change upward in grain size (fine grained to coarse grained), sorting (poorly sorted to well sorted), and energy level (low energy to high energy) are characteristic of regressive processes (Visher, 1965, p. 44-46; Selley, 1978, p. 26-29; Spearing, 1974, Figs. 5, 6, 7, 8, and 9).

The foraminifera from the Bulitian Stage of the Martinez shale (Table 4) are considered to represent a regressive mid-neritic to littoral environment (Mallory, 1959, p. 29-32 and p. 99). The presence of lignite (Bateman, 1965, p. 640-641; Krumbein and Sloss, 1963, p. 187-188) in conglomeratic sand of the upper part of Martinez shale could be inferred to imply a fast rate of regression.

To summarize, Cycle II sedimentary sequence is distinguished by a transgressive phase, exemplified by McCormick sand (mid-neritic environment), which was gradually superseded by a regressive phase exemplified by the conglomeratic sand (littoral environment) of the upper part of the Martinez shale.

The regressive sedimentary phase of Cycle II ended with the introduction of another regional unconformity (Mallory, 1959, p. 99) at the base of the Hamilton sand (Plate XII).

<u>Sedimentary Cycle III</u>

Following probable subaerial erosion, sedimentation was resumed with deposition of the early Eocene, shallow-marine, transgressive Hamilton sand. In the Mt. Diablo area, the Hamilton sand is correlated with Meganos D sand (Clark and Woodford, 1927, p. 63) which represents the start of a transgressive cycle with shallow-water deposits at the base (Johnson, 1964, p. 23).

Transgression of the sea continued with deepening of the basin as exemplified by deposition of the low energy and fossiliferous Capay Shale (Plate XII).

PALEOENVIRONMENT SETTING

The preceeding structural, paleotopographic, and paleontological information, as well as lithofacies and geophysical log analysis of the data from the gas wells in the Bunker field, reflect the following paleoenvironment setting:

> In Late Cretaceous, and during sedimentary Cycle I time interval, the study area was covered by shallow regressive sea. The environment of the study area fluctuated between neritic and littoral during this period.
>
> In late Paleocene, and during the period that McCormick sand was deposited, the study area was covered by a transgressive shallow sea and was characterized by a mid-neritic environment. In late Paleocene, and during the time when upper part of the Martinez shale (Plate XII) was deposited, the study area was covered by a regressive shallow sea and a littoral environment prevailed.
>
> During early Eocene, and at the time Hamilton sand was deposited, the study area was covered by a transgressive sea and was characterized by a nearshore environment.

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