SEQUENCE STRATIGRAPHY WORKSHOP

MAY 20 - MAY 30, 1993
Crimea, Ukraine

P.R. Vail

in collaboration with:
J.E. van Hinte, J. Smit
A.M. Nikishin, A.S. Alekseev, L.F. Kopaevich, B.T. Yanin,
E.J. Baraboschkin and V.V. Yutsis

Book 2.

Course notes
Sequence Stratigraphy Applications

Pete R. Vail

Onderzoekschool Sedimentaire Geologie
CMA Centrum voor Mariene Aardwetenschappen,
Vrije Universiteit Amsterdam.

Department of Historical Geology and
Centre for Marine Geology & Geophysics,
Moscow State University.

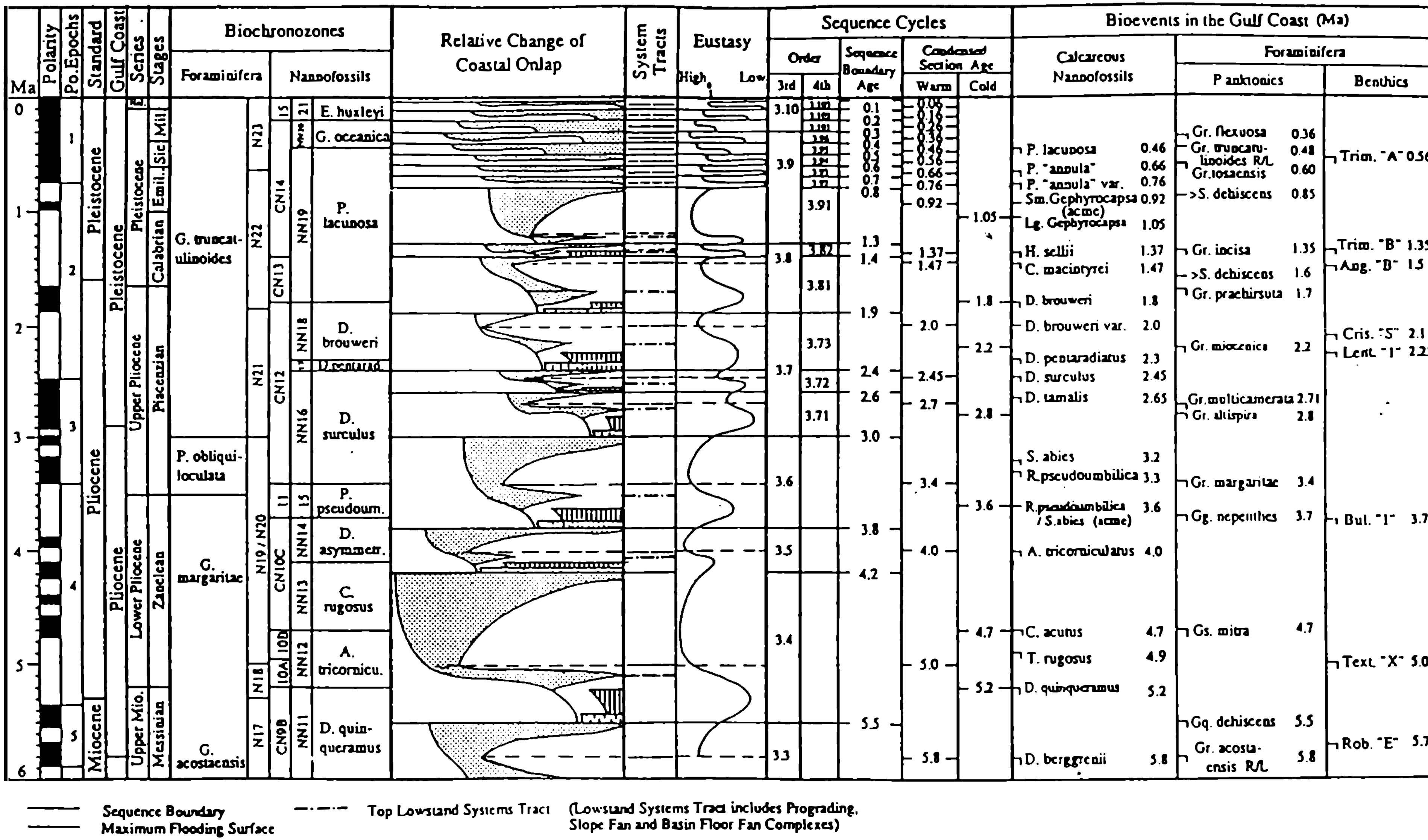
THE TECHNIQUES OF SEQUENCE STRATIGRAPHY

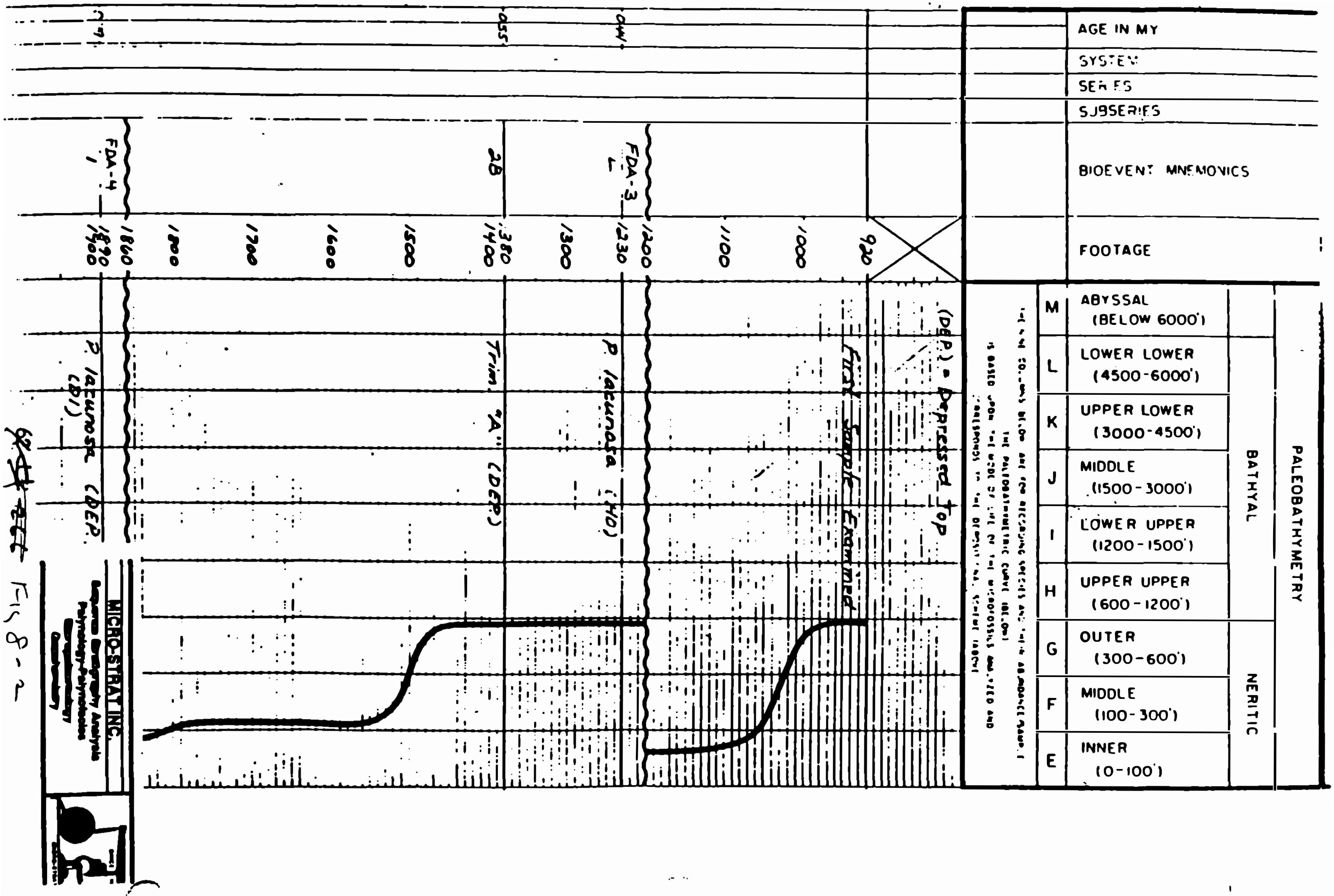
PART 8
USE OF BIOSTRATIGRAPHY IN SEQUENCE STRATIGRAPHY

Order 3rd	Order 4th	Sequency Boundary Age	Condensed Section Age Warm	Condensed Section Age Cold	Calcareous Nannofossils		Foraminifera Planktonics		Foraminifera Benthics	
3.10	3.10.3	0.1	0.06							
	3.10.2	0.2	0.16							
	3.10.1		0.26							
3.9	3.9.6	0.3	0.36				Gr. flexuosa	0.36		
	3.9.5	0.4	0.46		P. lacunosa	0.46	Gr. truncatulinoides R/L	0.48	Trim. "A"	0.56
	3.9.4	0.5	0.56							
	3.9.3	0.6	0.66		P. "annula"	0.66	Gr. tosaensis	0.60		
	3.9.2	0.7	0.76		P. "annula" var.	0.76				
		0.8								
	3.9.1		0.92		Sm. Gephyrocapsa (acme)	0.92	>S. dehiscens	0.85		
		1.1		1.05	Lg. Gephyrocapsa	1.05				
3.8	3.8.2		1.3		H. sellii	1.3	Gr. incisa	1.35	Trim. "B"	1.35
		1.4	1.47		C. macintyrei	1.47			Ang. "B"	1.5
	3.8.1						>S. dehiscens	1.6		
							Gr. praehirsuta	1.7		
				1.8	D. brouweri	1.8				
		1.9								
3.7	3.7.3		2.0		D. brouweri var.	2.0			Cris. "S"	2.1
				2.2	D. pentaradiatus	2.3	Gr. miocenica	2.2	Lent. "1"	2.25
	3.7.2	2.4	2.45		D. surculus	2.45				
	3.7.1	2.6	2.7		D. tamalis	2.65	Gr. multicamerata	2.71		
				2.8			Gr. altispira	2.8		
		3.0								
3.6					S. abies	3.2				
			3.4		R. pseudoumbilica	3.3	Gr. margaritae	3.4		
				3.6	R. pseudoumbilica / S. abies (acme)	3.6	Gg. nepenthes	3.7	Bul. "1"	3...
		3.8								
3.5			4.0		A. tricorniculatus	4.0				
		4.2								
3.4					C. acutus	4.7	Gs. mitra	4.7		
			5.0						Text. "X"	5.0
				5.2	D. quinqueramus	5.2				
		5.5								
3.3			5.8		D. berggrenii	5.8			Rob. "E"	5.9

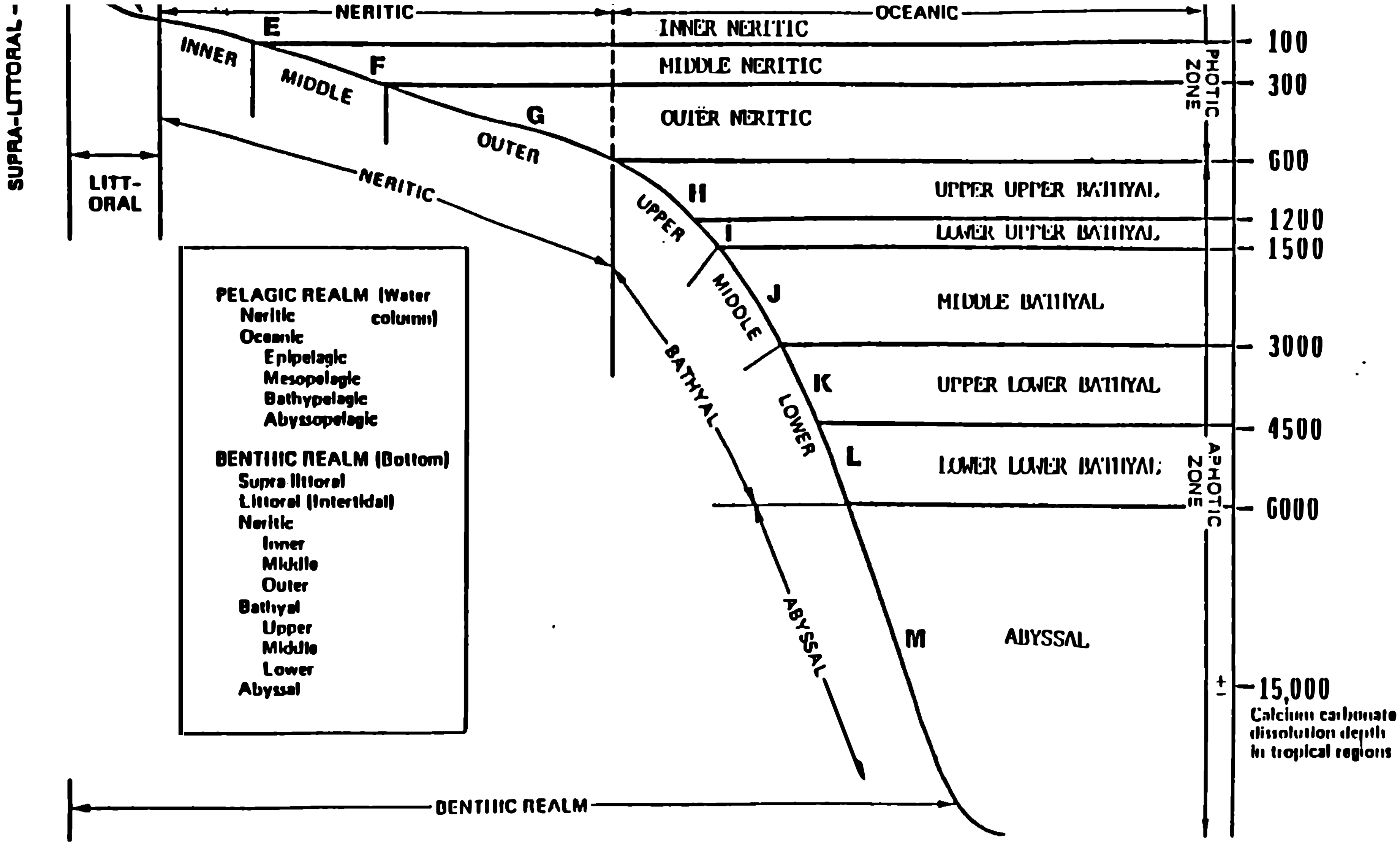
MICRO-STRAT INC.
Sequence Stratigraphy Analysis
Palynology-Palynofacies
Micropaleontology
Geochemistry

PLIO-PLEISTOCENE SEQUENCE CHRONOSTRATIGRAPHY





AGE IN MY
SYSTEM
SERIES
SUBSERIES
BIOEVENT MNEMONICS
FOOTAGE
ABYSSAL (BELOW 6000')
LOWER LOWER (4500-6000')
UPPER LOWER (3000-4500')
MIDDLE (1500-3000')
LOWER UPPER (1200-1500')
UPPER UPPER (600-1200')
OUTER (300-600')
MIDDLE (100-300')
INNER (0-100')
BATHYAL
NERITIC
PALEOBATHYMETRY
M
L
K
J
I
H
G
F
E
FDA-4
FDA-3
28
1900
1890
1860
1800
1700
1600
1500
1400
1380
1300
1230
1200
1100
1000
920
P. lacunosa (DEP.)
Trim. "A" (DEP.)
P. lacunosa (HO)
First Sample Examined
(DEP.) = Depressed Top
MICRO-STRAT INC.
Fig 8-2



Classification of marine depth-related environments
(modified after Hedgpeth, 1957; Lamb, 1981)

Fig 8-1

MICRO-STRAT INC.
Sequence Stratigraphy Analysis
Palynology-Palynofacies
Micropaleontology
Geochemistry

6

The third order maximum flooding surface and its depositional facies, the condensed section, are very valuable biostratigraphic and chronostratigraphic elements in Sequence and Seismic Stratigraphy. The condensed section depositional facies consists of thin, marine, hemipelagic to pelagic sediments, deposited at very slow rates during sediment starvation, rapid rise of relative sea level and maximum transgression of the shoreline. The thickness of the stratigraphic section is therefore "condensed". They are associated with authigenic minerals and maximum abundance peaks of planktonic microfossils such as foraminifers and calcareous nannofossils. The condensed section, therefore, is the time-stratigraphic correlation tool that links together the deep and shallow water sediment packages.

Important chronostratigraphic species within the condensed sections permit an absolute age (in millions of years) to be assigned to each third order condensed section. These condensed sections along with third order sequence boundaries are very important elements in sequence stratigraphy analysis. An E-log is annotated with condensed sections and paleobathymetry. The E-log is calibrated with the seismic record section by noting the placement of the condensed sections on a two-way time log which is overlain on a seismic record section. There it is found to coincide with regionally continuous, parallel, high amplitude seismic reflectors that are usually downlap surfaces. The contained chronologically significant species permit these seismic reflectors to be accurately dated in millions of years. Thus the geologists and their E-logs are directly linked to the geophysicists and their seismic record sections through the time-stratigraphic condensed section.

Through the use of condensed sections, you can:

- Calibrate E-logs and the seismic record sections through two-way time logs
- Recognize the downlap surfaces on seismic sections
- Enhance reservoir prediction
- Correlate from well to well
- Provide absolute ages, based on the association of condensed sections with age-datable microfossil assemblages
- Tie other events to a common standard of reference (e.g., the Haq, et al. chart)

Detailed zonation based on benthic foraminifers for the shallow water offshore environments on the Continental Shelf has been used for fifty years in the Gulf of Mexico. As companies' exploration efforts moved toward the edge of the Continental Shelf and into deeper water sediments, correlations using "standard industry tops" of benthic foraminifers became difficult and undependable. When the companies moved their exploration program into even deeper water (600 to 4500 feet) on the Continental Slope in the early 1980's, they found that their correlation tool, the benthic foraminifers "climbed time" down dip, were washed down slope, were associated with deepwater sands and had no time significance.

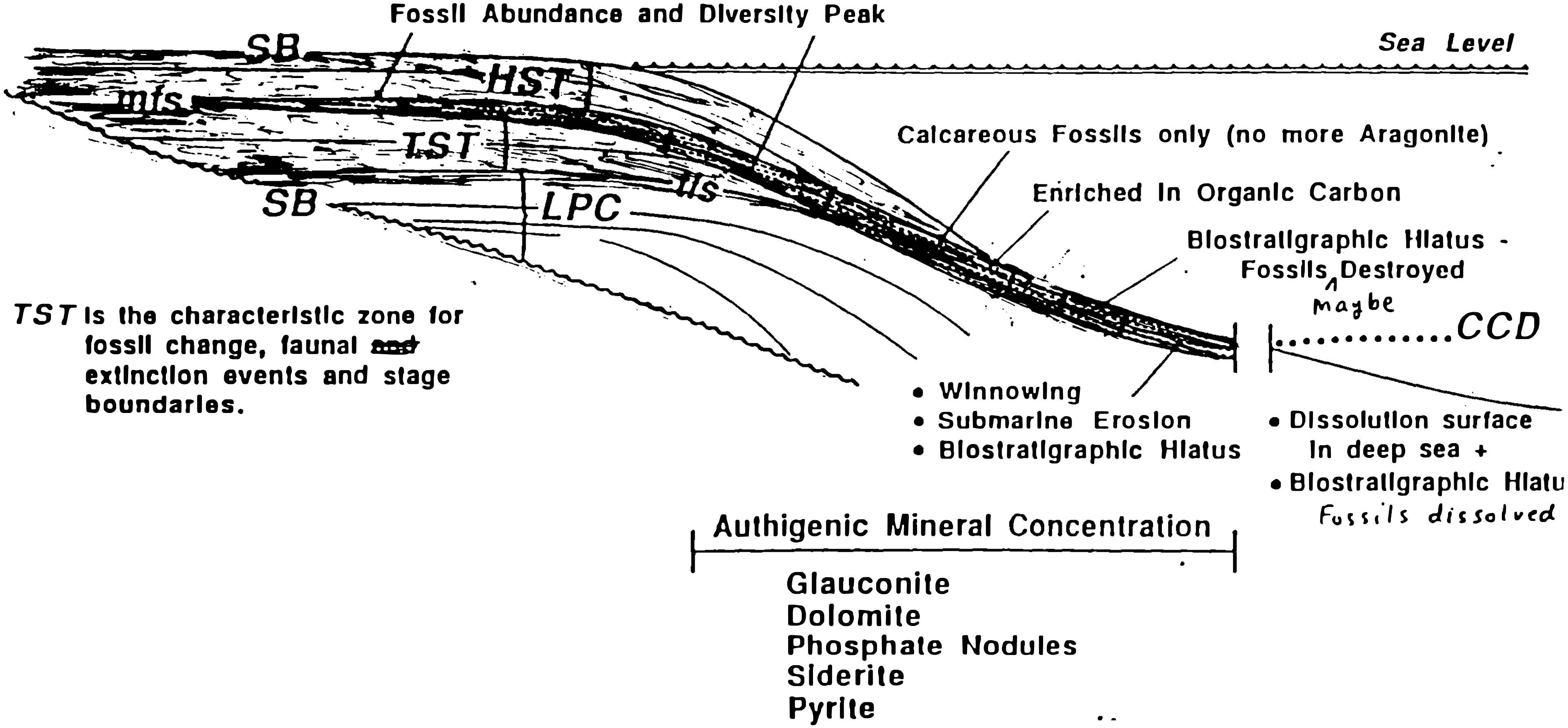
Because the Gulf of Mexico is dominated by gradual, regressively deposited sediments, the neritic sediments of the Continental Shelf thicken rapidly gulfward into massive shales, mudstones and sandstones, largely on the downthrown side of normal faults. As the environment shifts, the sediments and their corresponding benthic foraminiferal assemblages peculiar to the environment shift with it and are diachronous in nature. In the Gulf Coast, these sediments become almost impossible to correlate for any distance on the basis of electric logs.

In 1983, the first commercially available chronological zonation for the Pliocene-Pleistocene sediments throughout the Gulf of Mexico was established, based on planktonic foraminifers and calcareous nannofossils. This zonation is highly dependable and is facilitated by a unique, computer-generated checklisting program. This program lists the species and their abundances in each sample and provides a paleowater depth curve for the entire well. The foraminiferal and calcareous nannofossil bioevents ("tops") are assigned an absolute age. An E-log is annotated with these absolute ages and with a paleowater depth curve for the entire well. Subsequently, computer-generated histograms of microfossil abundance are made from the checklist and are used to recognize various condensed sections in the well. The same E-log is annotated with these condensed sections. This is the key to linking together deep and shallow water sediment packages.

Accurate regional time-stratigraphic correlation of Pleistocene through Miocene sequences on the Gulf of Mexico Continental Shelf and deepwater Slope is absolutely necessary to understanding the problems of locating favorable structures, lithofacies (reservoir), and time of structural growth -- all factors mandatory to the development of a hydrocarbon trap.

The Maximum Flooding Surfaces (condensed sections) are the "bentonites" of the marine environment and are time lines that can be recognized and mapped from shallow updip to deep downdip wells from offshore Louisiana to offshore Texas. The Maximum Flooding Surfaces are the major downlap surfaces on seismic record sections.

MAXIMUM FLOODING SURFACE
CONDENSED SECTION
(SEDIMENT STARVATION)



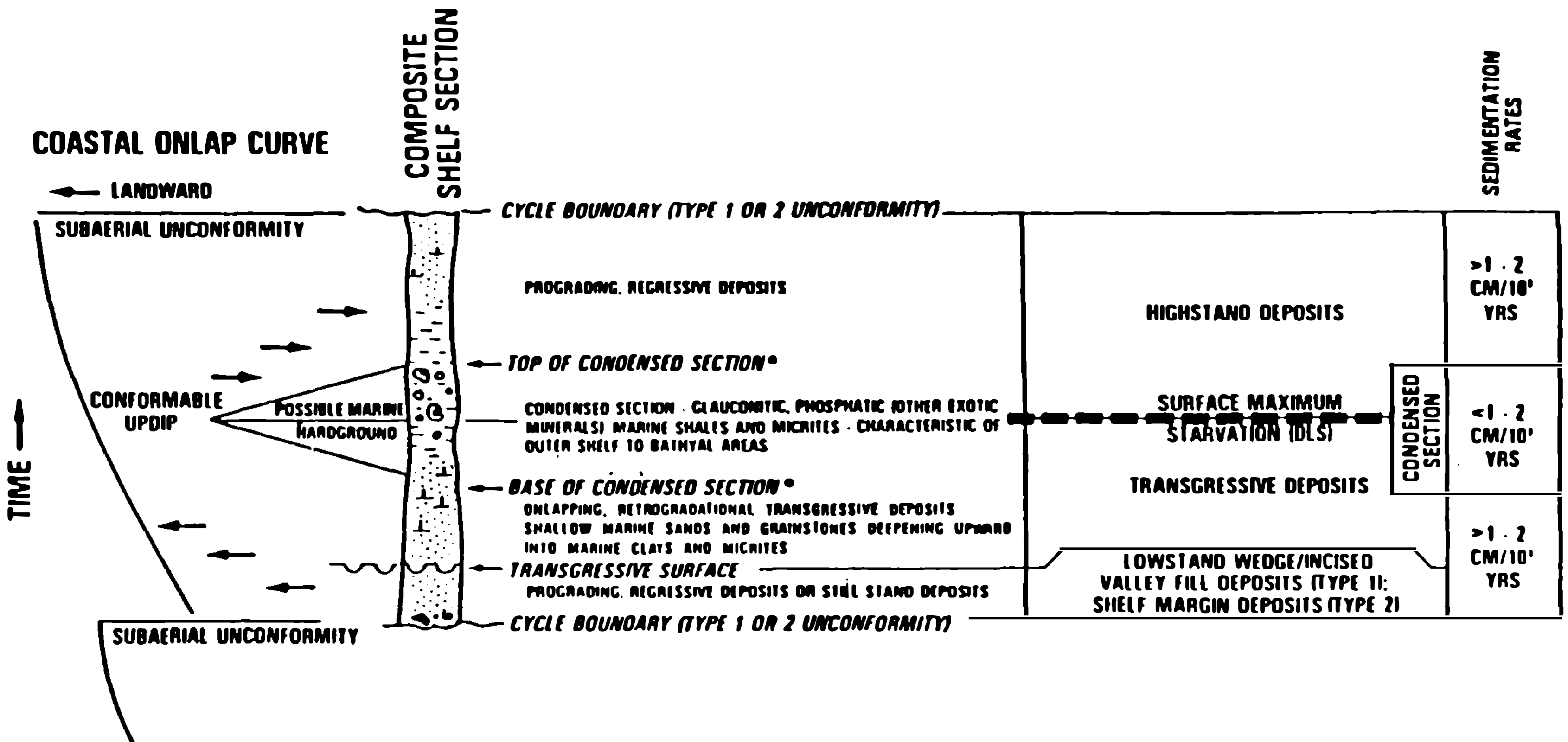
CONDENSED SECTION characteristics

Low Sedimentation rates with low TOC
- fossil abundancy peaks
- fossil diversity peaks
- thin clay intervals
- firm grounds with open burrows
- diagenetic minerals
  - glauconite
  - siderite
  - phosphorite
  - authogenic dolomite
  - algal-rich source material

Total organic matter (TOC) peaks when condensed section is anoxic

very low sedimentation rates
- biostratigraphic gaps
- hard grounds with bored surfaces
- winnowing
- deep water current erosion
- diagenetic minerals as above

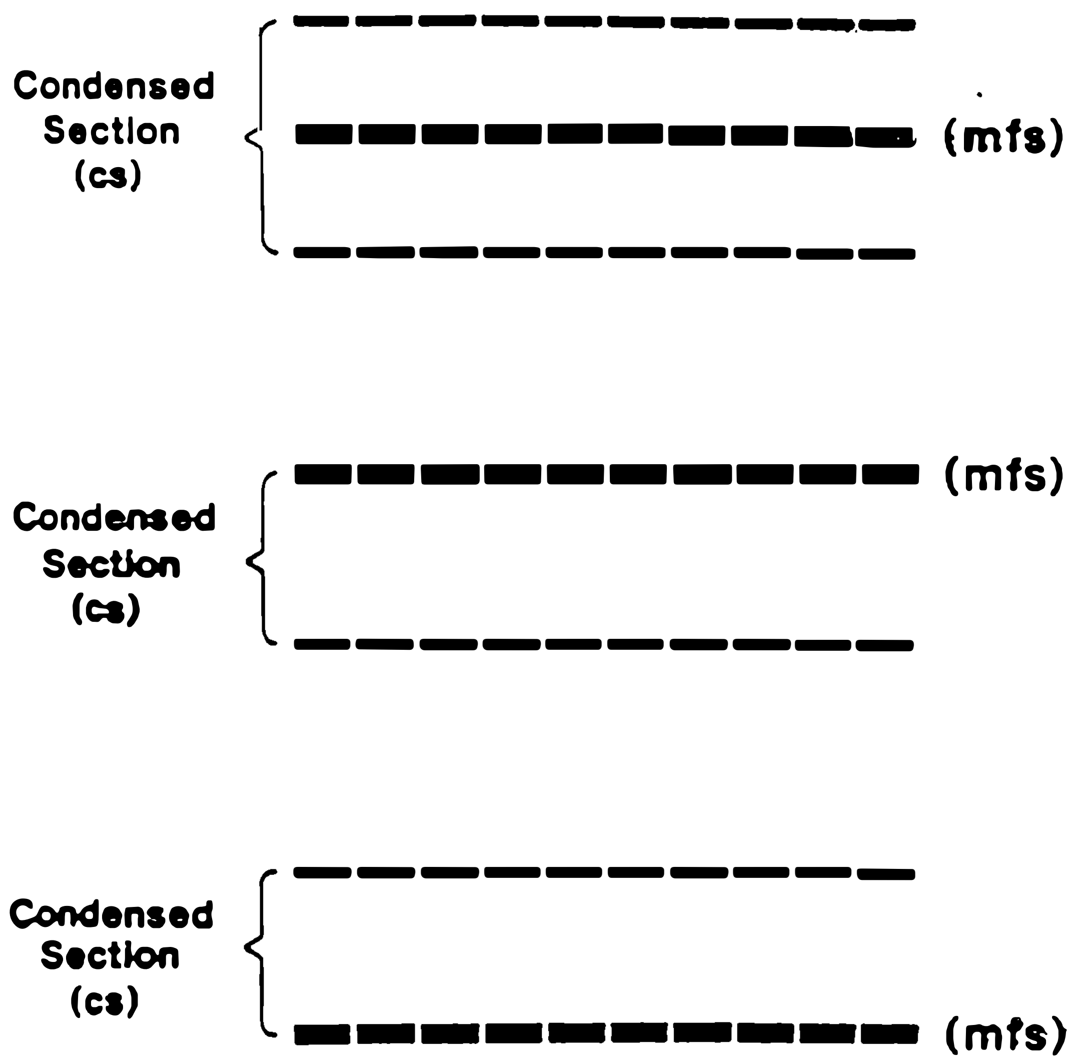
Fig 8-4



• BASE OF CONDENSED SECTION AND TOP OF CONDENSED SECTION DEPENDENT ON SHELF POSITION; SEDIMENT INFLUX; AND RATE OF EUSTATIC SEA LEVEL CHANGE

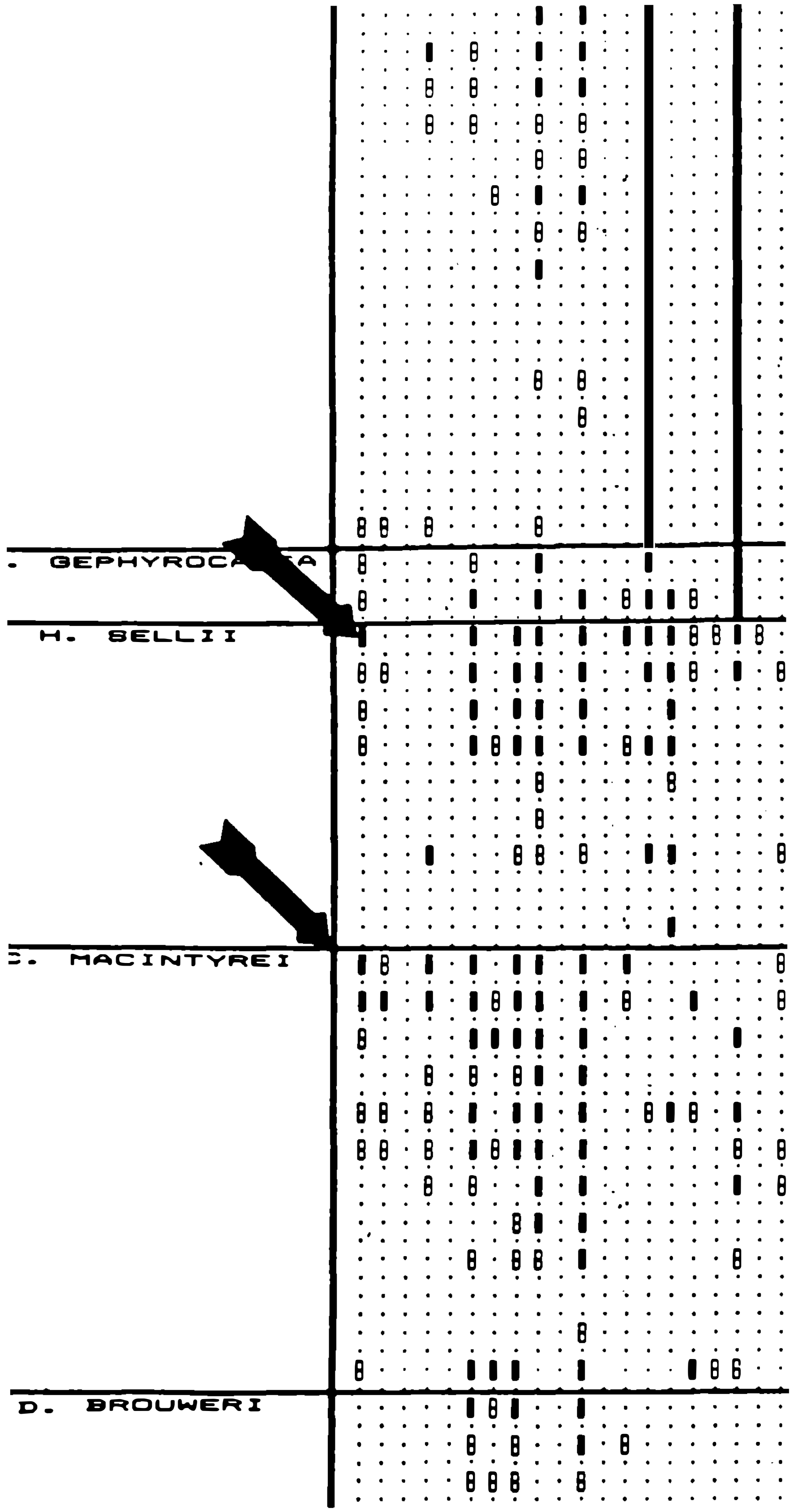
Modified after Baum and Vail, SEPM Research Conference, 1987

Fig 8-5



Location of Maximum Flooding Surface (mfs) within the Condensed Section (cs)

Fig 8-6



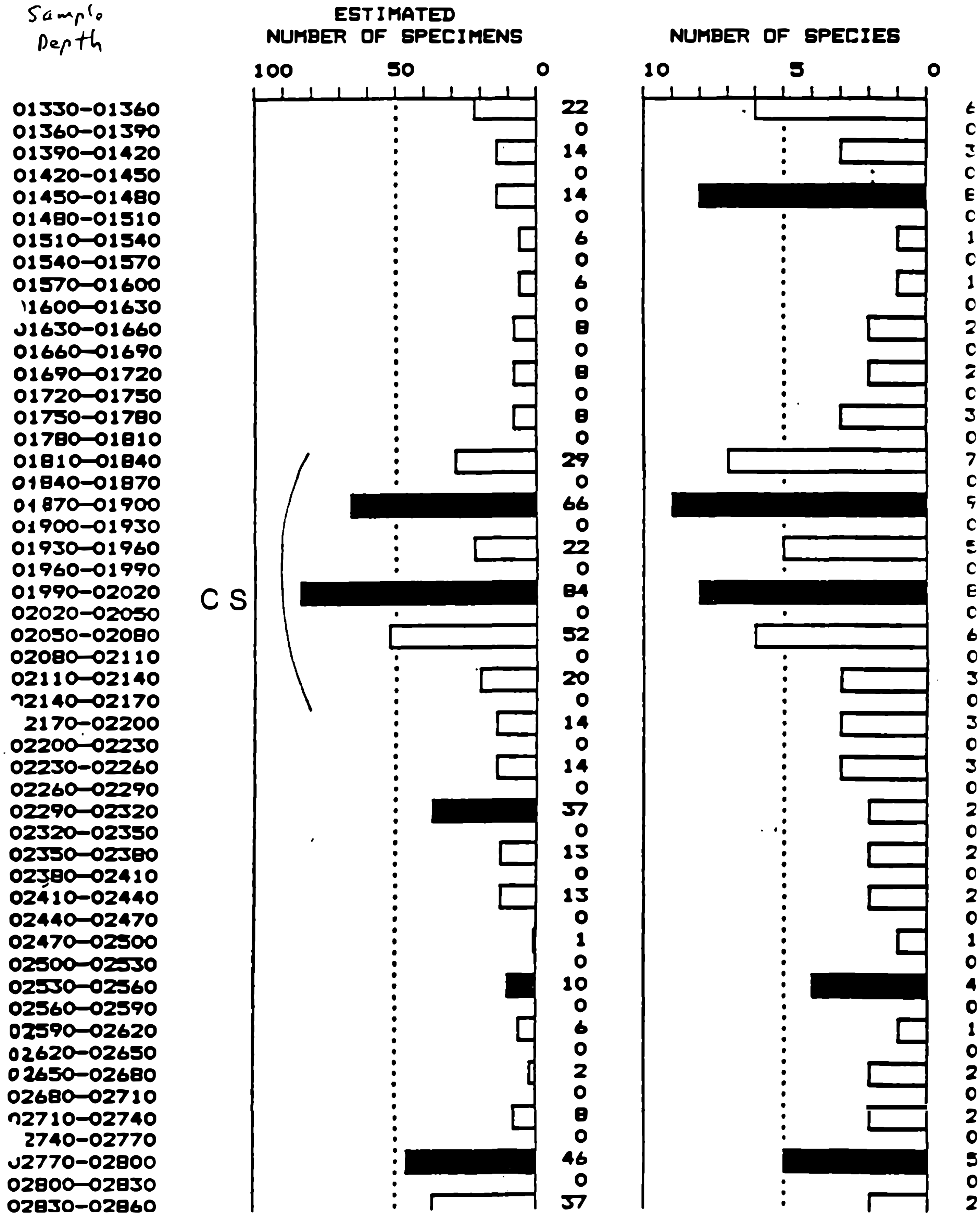
SMALL GEPHYROCAPSA, H.

02740-02770	0		0	
02770-02800	46		5	
02800-02830	0		0	
02830-02860	37		2	
02860-02890	0		[illegible]	
02890-02920	10		4	
02920-02950	0		0	
02950-02980	3		3	
02980-03010	0		0	
03010-03040	1		1	
03040-03070	0		0	
03070-03100	2		2	
03100-03130	0		0	
03130-03160	78	mcs	8	
03160-03190	0		0	
03190-03220	46		6	
03220-03250	0		0	
03250-03280	16		5	
03280-03310	0		0	
03310-03340	8		3	
03340-03370	0		0	
03370-03400	32		3	
03400-03430	0		0	
03430-03460	32		3	
3460-03490	0		0	
03490-03520	8		3	
03520-03550	0		0	
03550-03580	0		0	
03580-03610	0		0	
03610-03640	1		[illegible]	
03640-03670	0		[illegible]	
03670-03700	63	mcs	4	
03700-03730	0		0	
03730-03760	13		2	
03760-03790	0		0	
03790-03820	20		4	
03820-03850	0		0	
03850-03880	15		4	
03880-03910	0		0	
03910-03940	4		4	
03940-03970	0		0	
03970-04000	2		2	
1000-04030	0		0	
04030-04060	14		3	
04060-04090	0		0	
04090-04120	2		2	
04120-04150	0		0	
04150-04180	6		1	
04180-04210	0		0	
04210-04240	0		0	
04240-04270	0		0	
04270-04300	0		0	
04300-04330	0		0	
04330-04360	2		2	mcs
04360-04390	0		[illegible]	
04390-04420	1		[illegible]	
04420-04450	0		0	
04450-04480	0		0	
04480-04510	0		0	
04510-04540	0		0	
04540-04570	0		0	
04570-04600	4		4	

138

File: A218#1CN

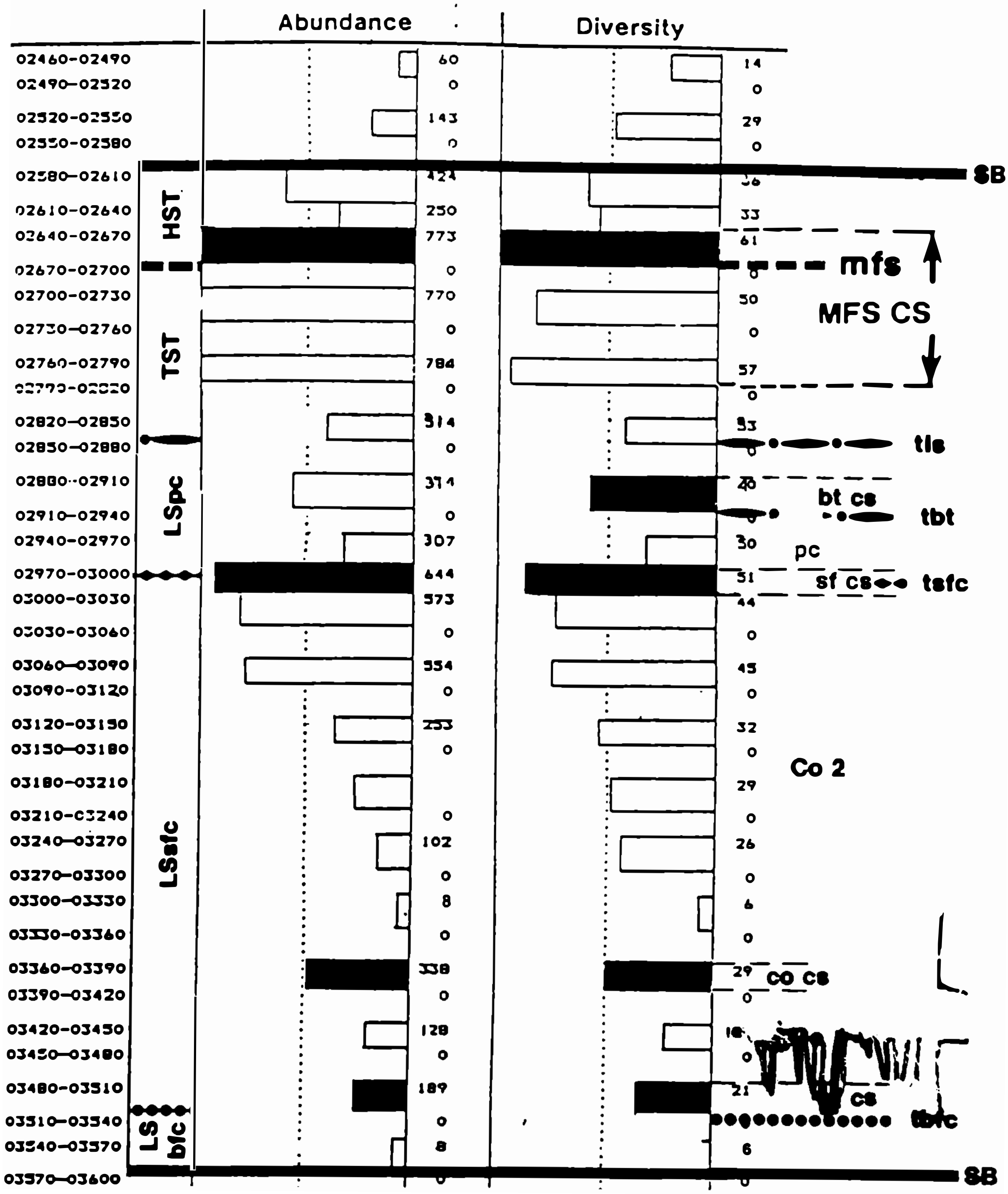
Title: AMOCO #1 SO. GALVESTON AREA BLK. A-218 CALC. NANNOS



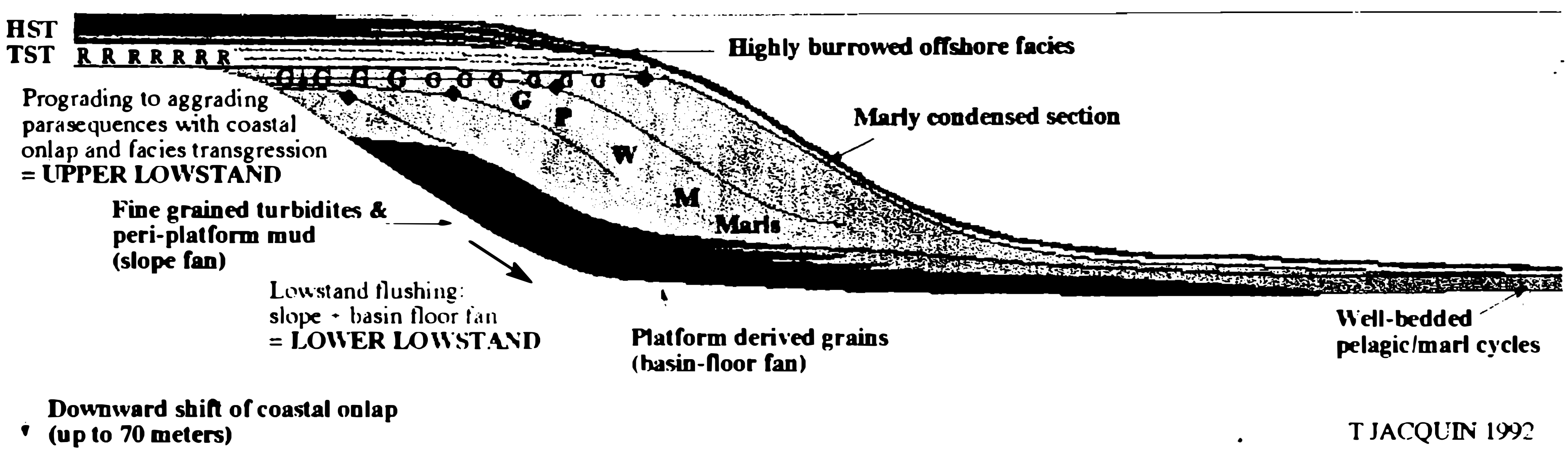
231 Fig 8-8

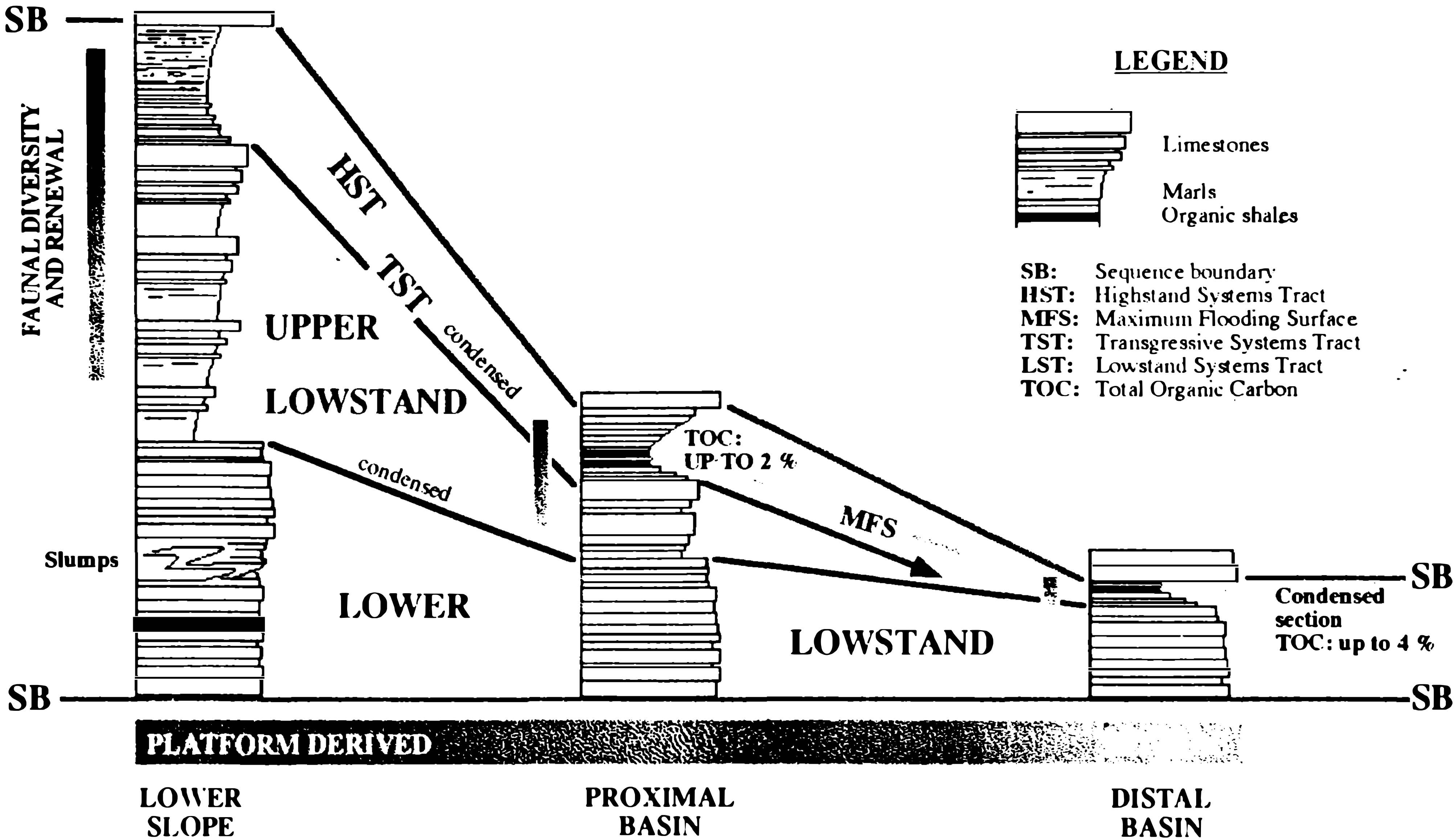
Pattern Recognition of Condensed Sections and Systems Tracts Based on Detailed Analysis of Microfossils

HISTOGRAMS



GENERALIZED RELATIONSHIP OF FACIES TO THIRD-ORDER SYSTEMS TRACTS WITHIN THE 2ND ORDER REGRESSIVE PHASE - VERCORS PLATEAU
(H4 to B4 depositional sequences)





SB
FAUNAL DIVERSITY AND RENEWAL
Slumps
HST
TST
condensed
UPPER
LOWSTAND
condensed
LOWER
TOC:
UP TO 2 %
MFS
LOWSTAND
SB
Condensed section
TOC: up to 4 %
SB
SB
PLATFORM DERIVED
LOWER SLOPE
PROXIMAL BASIN
DISTAL BASIN
LEGEND
Limestones
Marls
Organic shales
SB: Sequence boundary
HST: Highstand Systems Tract
MFS: Maximum Flooding Surface
TST: Transgressive Systems Tract
LST: Lowstand Systems Tract
TOC: Total Organic Carbon

THE TECHNIQUES OF SEQUENCE STRATIGRAPHY

PART 9
CHRONOSTRATIGRAPHY AND GLOBAL CYCLES

Time in Stratigraphy

Time-Synchronous Surface
- stratal surfaces
- para sequence boundaries

) Time boundaries
- unconformities
- Sequence and system tract boundaries

3) Diachronous surfaces
(surfaces that cross stratal surfaces)
· gas/hydrate
· bottom simulating reflectors
gas hydrates
opaline/ct conversion

4) Diachronous boundaries
(no continuous surface at boundary – boundary steps across stratal surfaces)
· Time-Transgressive Formation boundary

Fig 9-1

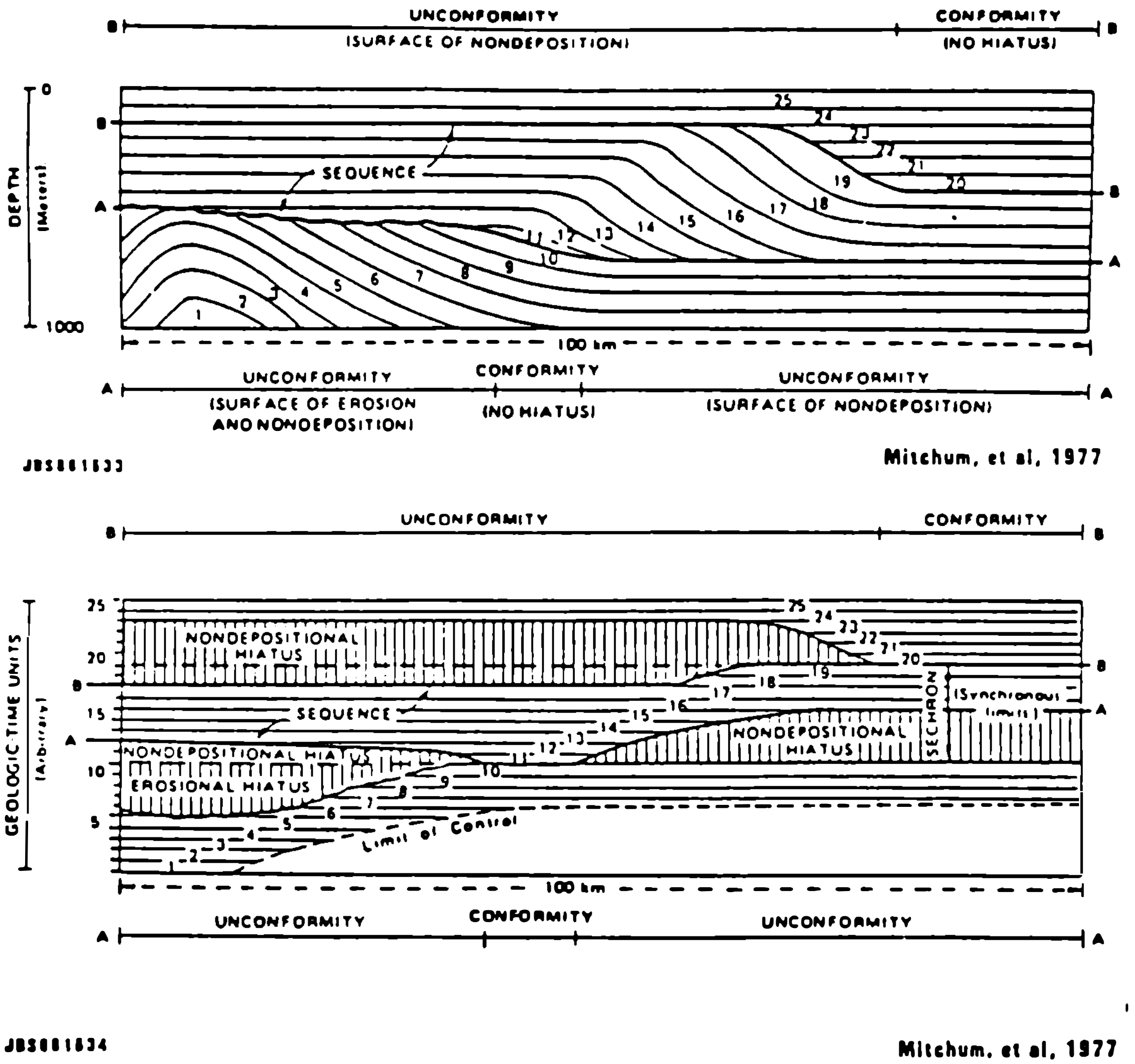


Fig. 11

The upper figure shows patterns of chronostratigraphic surfaces for a strongly prograding sequence, the vertical scale is in depth and the horizontal scale in distance. The lower figure shows the same depositional unite, but now shown as a chronostratigraphic chart, displaying both depositional units and hiatuses created by erosion and non-deposition.

Fig 9-2

DIACHRONOUS SURFACE EXAMPLES

CONTINUOUS PHYSICAL BOUNDARY CROSSING STRATA

FLUID CONTACTS

PERMAFROST

GAS HYDRATE LAYER

LOW ANGLE FAULT TRACE

LOW ANGLE IGNEOUS DIKE

DEEP DESERT WEATHERING SURFACE

KARSTIC SOLUTION BASE LEVEL

JBS882436

Fig. ~~12~~ 9-3

STRATIGRAPHIC TERMINOLOGY

LITHOSTRATIGRAPHY	CHRONOSTRATIGRAPHY	GEOCHRONOLOGY
(rock)	(time-rock)	(time)
Group	Erathem	Era
Formation	System	Period
Member	Series	Epoch
	Stage	Age
BIOSTRATIGRAPHY	**BIOCHRONOSTRATIGRAPHY**	**BIOCHRONOLOGY**
Superzone (Superbiozone)		
Zone (Biozone)	Biochronozone	Biochron
Subzone (Subbiozone)		
Biohorizon	Biochronohorizon	
MAGNETOSTRATIGRAPHY	**MAGNETOCHRONOSTRATIGRAPHY**	**MAGNETOCHRONOLOGY**
Polarity Superzone	Polarity Superchronozone	Polarity Superchron
Polarity Zone	Polarity Chronozone	Polarity Chron
Polarity Subzone	Polarity Subchronozone	Polarity Subchron
SEQUENCE STRATIGRAPHY	**SEQUENCE CHRONOSTRATIGRAPHY**	**SEQUENCE CHRONOLOGY**
	First Order Sequence Chronozone	Megasechron
Sequence Set	Second Order Sequence Chronozone	Supersechron
Sequence Systems Tract	Third Order Sequence Chronozone	Sechron
Parasequence	Fourth Order Sequence Chronozone	Parasechron

Haq, Hardenbol & Vail (1987 in press)

* Chart showing types os stratigraphy, FIG. 4-1

Fi, 9-4

PLIO-PLEISTOCENE SEQUENCE CHRONOSTRATIGRAPHY

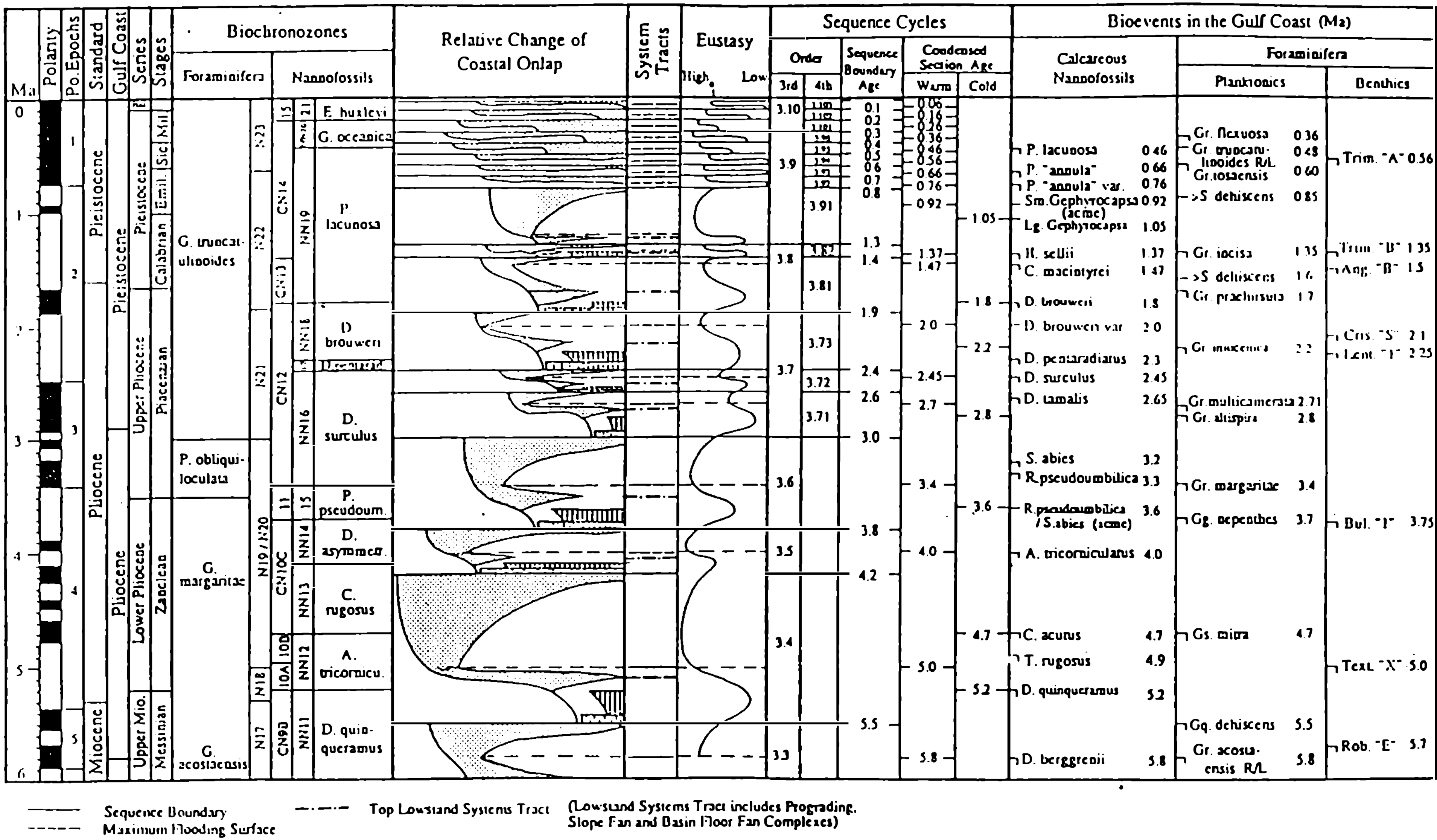
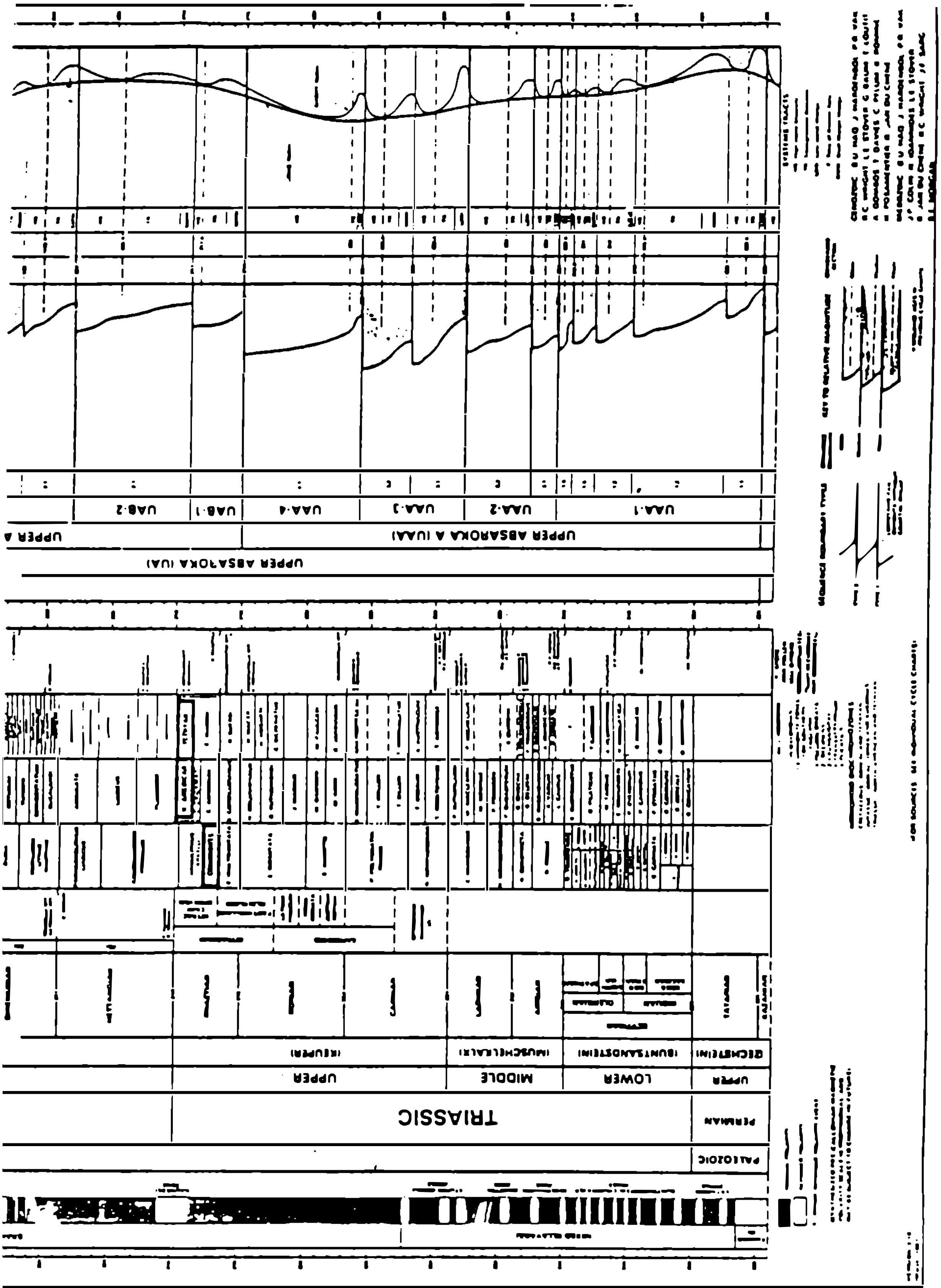


Fig 9-5



:G. 4-3d : Triassic chronostratigraphy and cycles of sea level change. Linear ime scale is in millions of years before present. Collaborators for the 'iassic cycle chart are B.U. Haq, P.R. Vail, J. Harenbol, J.F. Sarg and E. Morgan. For sources see text and references in Haq and others (1987b). ie Triassic magnetic polarity reversal model is synthesized from available ta and may be subject to change in future as new data become available.

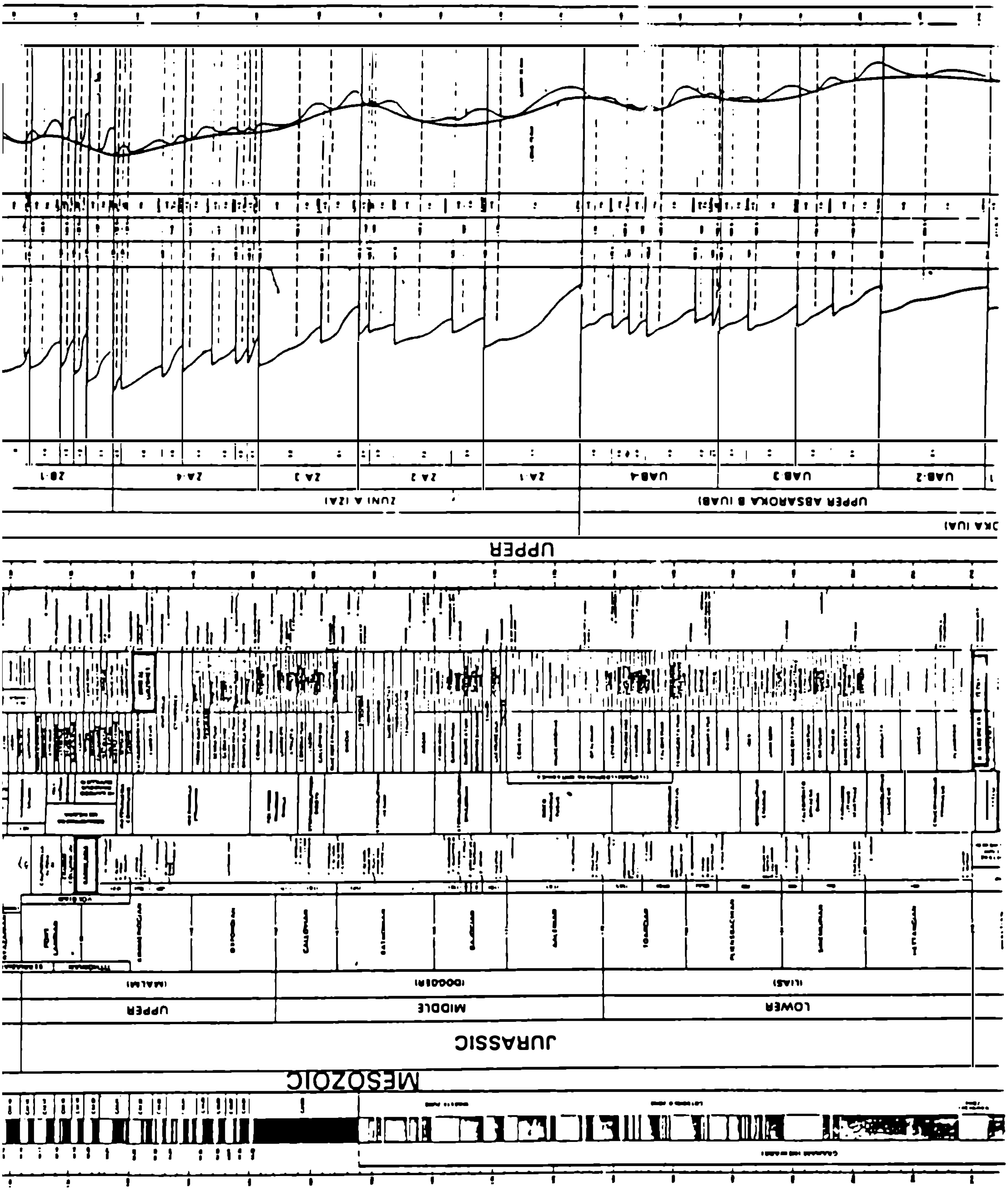
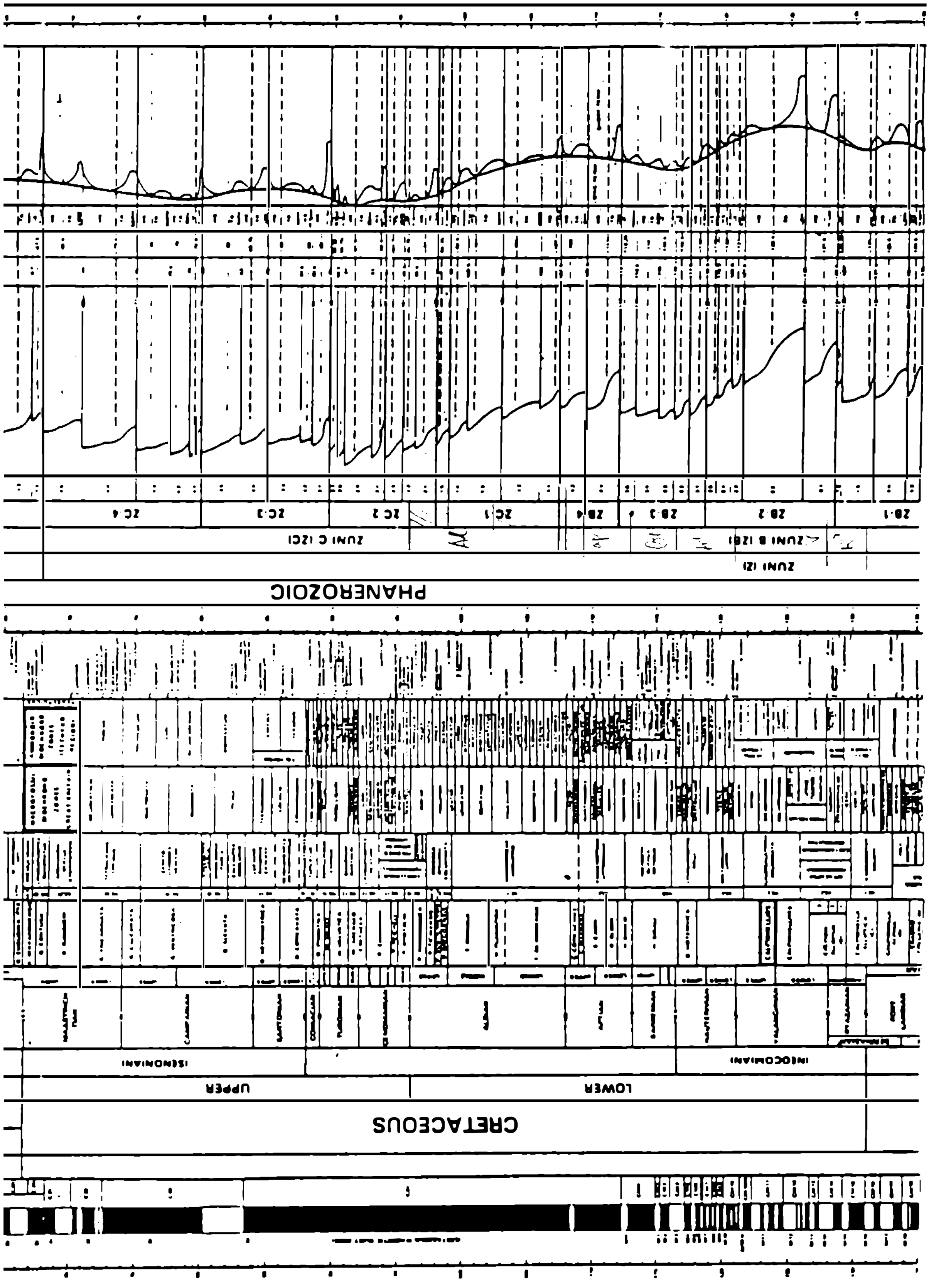


Fig. 4-3c : Jurassic chronostratigraphy and cycles of sea level change. Linear time scale is in millions of years before present. Collaborators for the Jurassic cycle chart are B.U. Haq, P.R. Vail, J. Harenbol, J.P. Colin, L.E. Stover and N. Ioannides For sources see text and references in Haq and others (1987b). The pre-Callovian magnetic polarity reversal model is tentative and may be subject to change.



g. 4-3b : Cretaceous chronostratigraphy and cycles of sea level change. Linear me scale is in millions of years beforepresent. Collaborators for the etaceous cycle chart are B.U. Haq, J. Harenbol, P.R. Vail, L.E. Stover, C. Wright and R. Jan du Chene. For Sources and references in Haq and others 987b). Slightly modified after Haq and others (1987a).

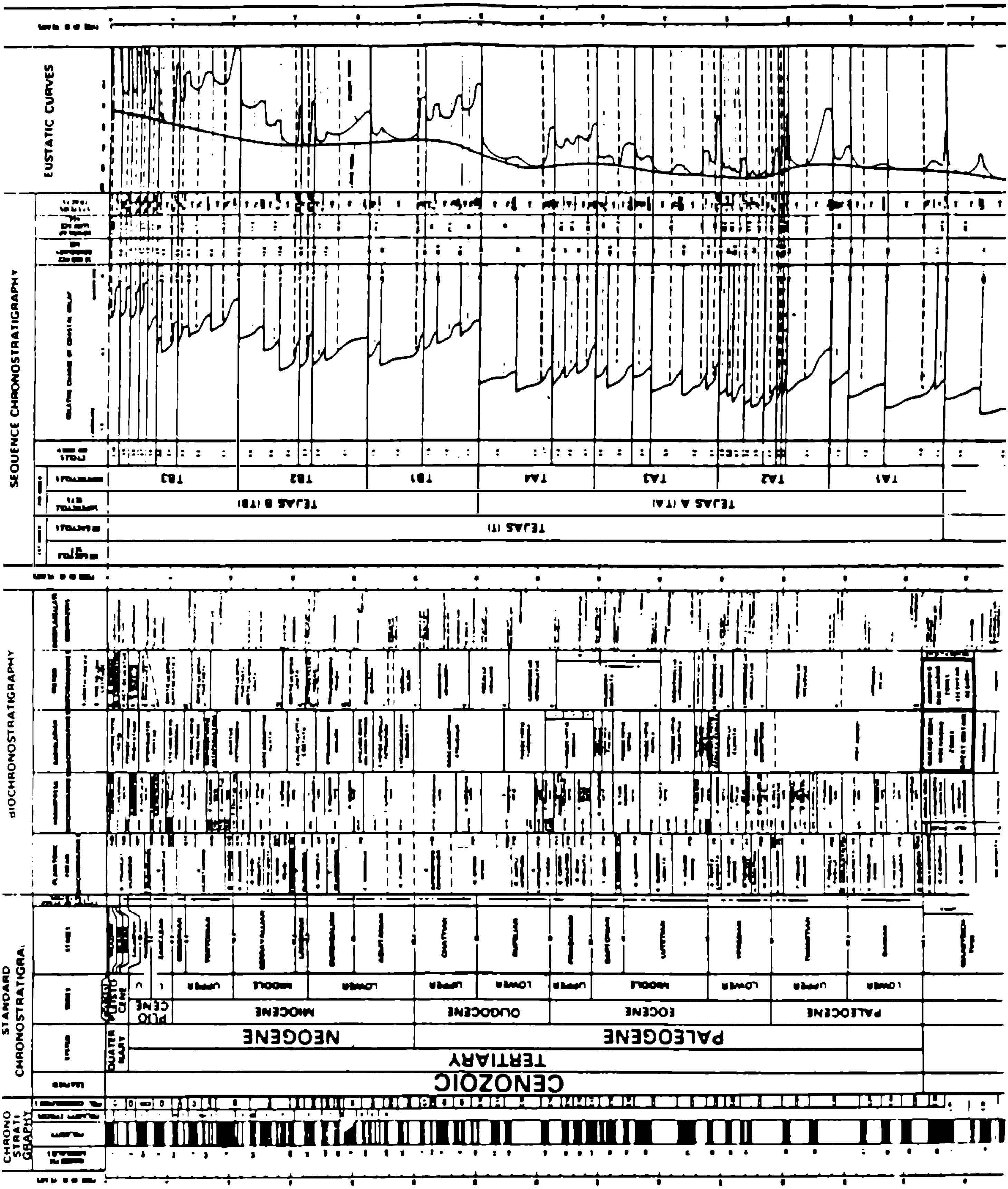


Fig. 4-3a : Cenozoic chronostratigraphy and cycles of sea level change. Linear time scale is in millions of years before present. Collaborators for the Cenozoic cycle chart art listed in the upper right corner of the figure 4-3d. For sources see text and references in Haq and others (1987b).

PART 4 - SECTION 7: SEQUENCES, SYSTEMS TRACTS AND SILICICLASTIC DEPOSITIONAL SYSTEMS AND LITHOFACIES

OBJECTIVE:

To illustrate the relation between the depositional systems and lithofacies and determine their position within the systems tracts.

GIVEN:

* Work sheet for location of the coarse-grained material within the systems tracts, Figure 4/5-1

* Summary diagrams of depositional systems, processes and lithofacies within each systems tract, Figures 4/5-2 to 4/5-17

* Answer sheet of distribution of the coarse-grained sediments, Figure 4/5-18

TERMS TO KNOW:

Depositional systems
Depositional environments
Lithofacies

EXERCISE: DETERMINE THE DISTRIBUTION OF THE COARSE-GRAINED MATERIAL WITHIN EACH SYSTEMS TRACT

As the instructor goes through the explanation of the distribution of the depositional systems and lithofacies within each systems tract, color on the work sheet the corresponding location of the coarse-grained sediments.

DISCUSSION:

Sediments are deposited episodically by depositional systems and are packaged in cyclic stratigraphic units. The principal depositional systems and lithofacies units are listed below:

DEPOSITIONAL SYSTEMS	LITHOFACIES
Submarine fans:	
basin floor fan	sheet lobe sands
	channelized sands
slope fan	overbank turbidites
	meandering channel sands
	debris flows
	slumps
	canyon fill deposits
Deltas:	
highstand deltas	distributary mouth bars
	prodelta turbidites
	coastal beach and storms
	prodelta muds
lowstand deltas	same as highstand, but tend to be coarser grain size
	slumps
	toe-of-slope turbidites
Coastal belt sands:	barrier islands and beaches
	storm deposits
Offshore shelf deposits:	burrowed muds
	laminated muds
	organic
	rapid deposition
	authigenic minerals
	glauconite
	dolomite
	phosphorite
	siderite
Estuarine/lagoonal deposits:	tidal flats
	tidal inlet and deltas
	burrowed muds and sands
	oyster banks
Marsh (paludal) deposits:	peat bogs
Lake (lacustrine) deposits:	
Incised valley fills:	braided stream deposits

Fluvial plain deposits: meandering stream deposits

alluvial fan deposits

Wind (eolian) deposits: sand dunes

Soils:

SUMMARY OF SILICICLASTIC DEPOSITIONAL SYSTEMS, PROCESSES AND LITHOFACIES BY SYSTEMS TRACT:

LOWSTAND SYSTEMS TRACT

Setting: Deep water basin with well developed shelf/slope break

- Basin Floor Fan: see Figures 4/5-4 and 4/5-5

Setting: Relative sea level falls below the depositional coastal break and the sea surface and stream profile continuously move downward with respect to the land surface.

Major economic potential:

Excellent quality hydrocarbon reservoirs.

Hydrocarbon migration pathways.

Question: Why do basin floor fans have a high percentage of sand?

- Slope Fan: see Figures 4/5-6 and 4/5-7.

Setting: Relative sea level is low but rising slowly.

Major economic potential:

Excellent quality hydrocarbon reservoir sands within leveed channel fills

Poor quality but often large volume hydrocarbon reservoir sands in very thin (below E-log resolution) turbidites of leveed channel / overbank deposits

Occasional discontinuous displaced shallow water sand reservoirs within slumps

Generally poor hydrocarbon source rock except in a few silled basins

- Lowstand Prograding Wedge see Figures 4/5-8, 4/5-9 and 4/5-10.

Setting: Relative sea level is rising above the shelf/slope break quickly enough to allow progradation

Major economic potential:

Possible hydrocarbon reservoirs in the coastal belt sands in the incised valley fill sands if the valley are already filled

A summary of the possible lowstand reservoir sands is presented in Figure 4/5-12.

TRANSGRESSIVE SYSTEMS TRACT

Setting: Relative sea level is rising rapidly and drowning the platform

* See Figures 4/5-13 and 4/5-14

HIGHSTAND SYSTEMS TRACT

Setting: Relative sea level is high and during a gradual slowing of rise

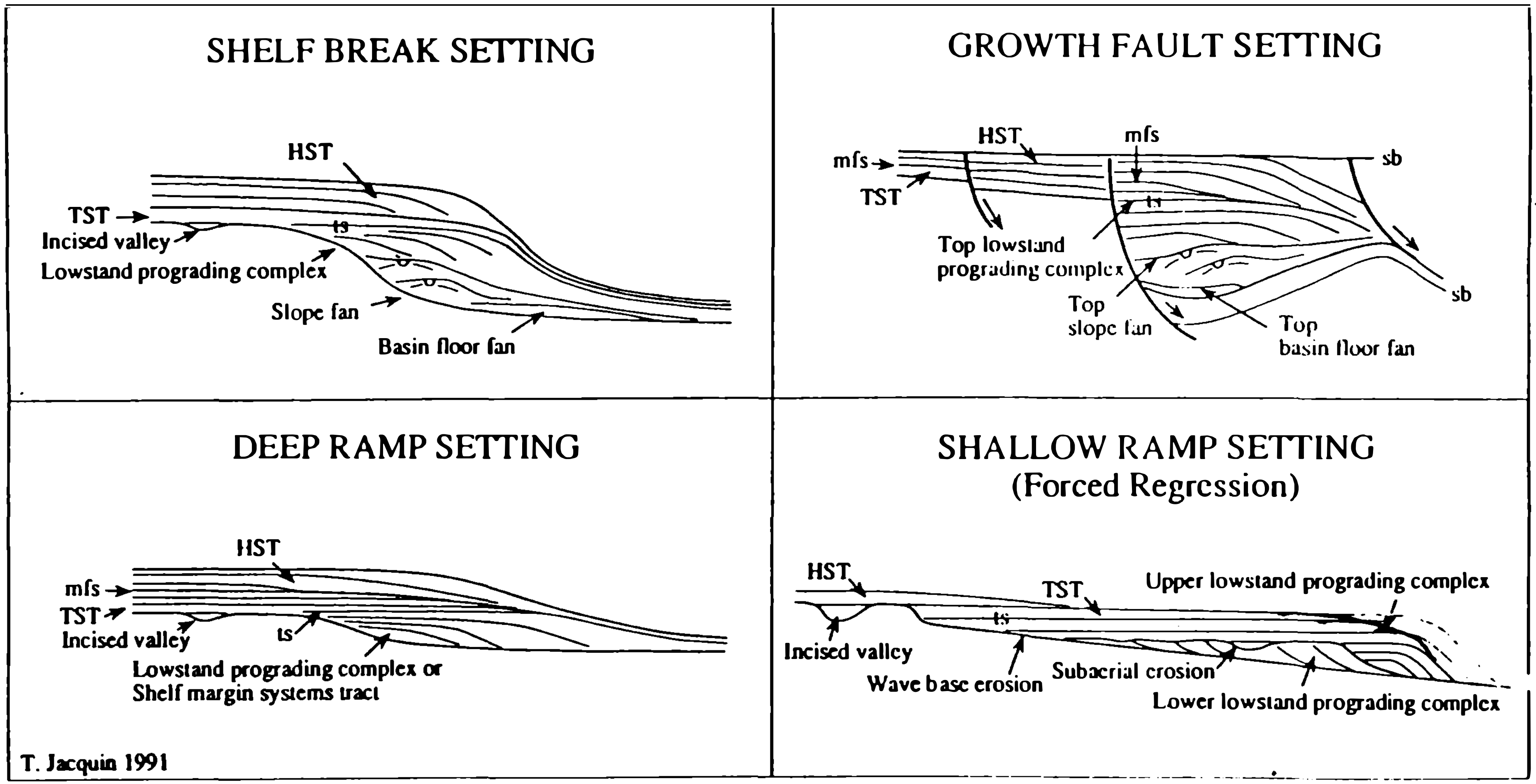
* See Figures 4/5-15 and 4/5-16

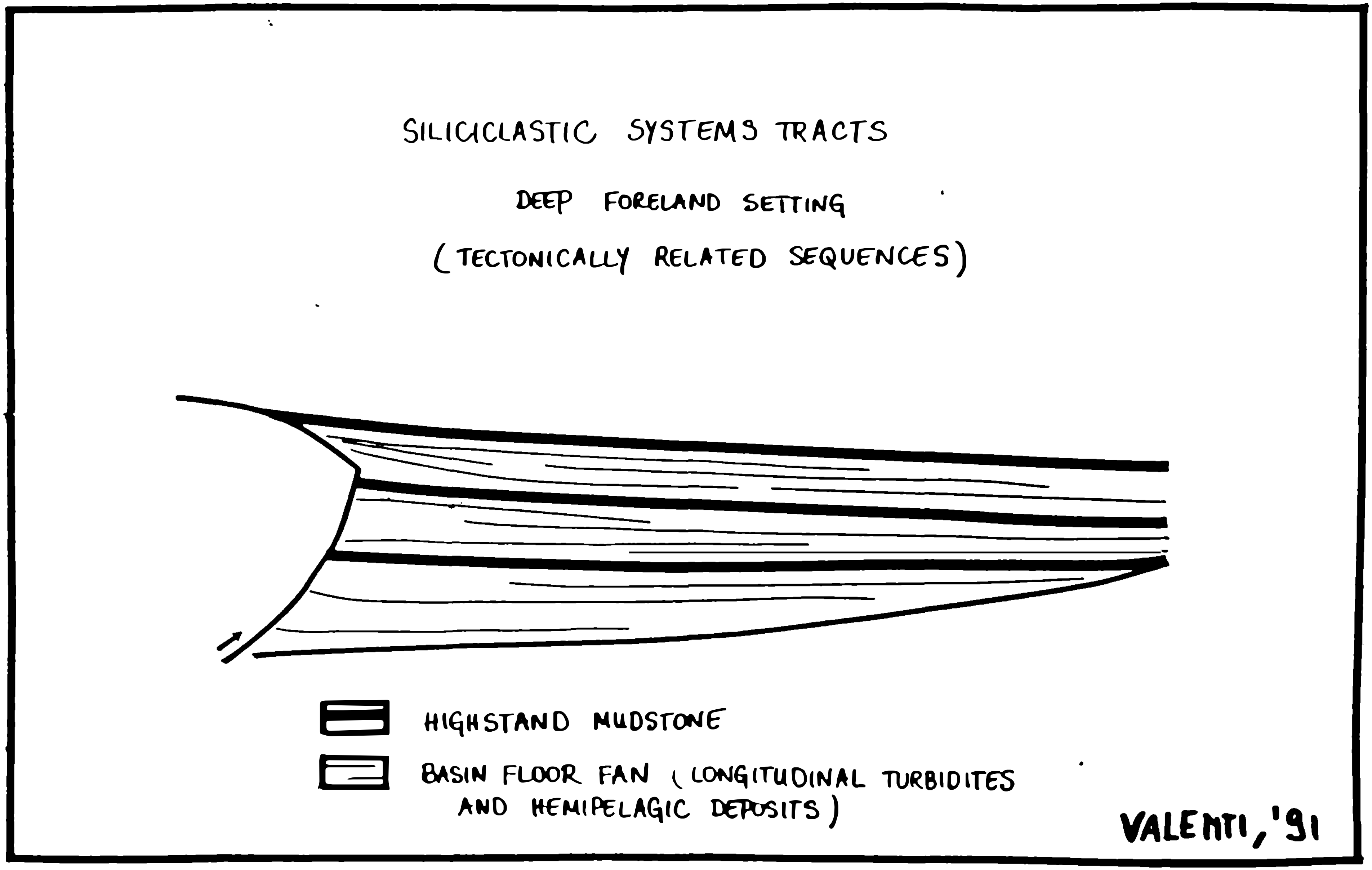
SHELF MARGIN SYSTEMS TRACT

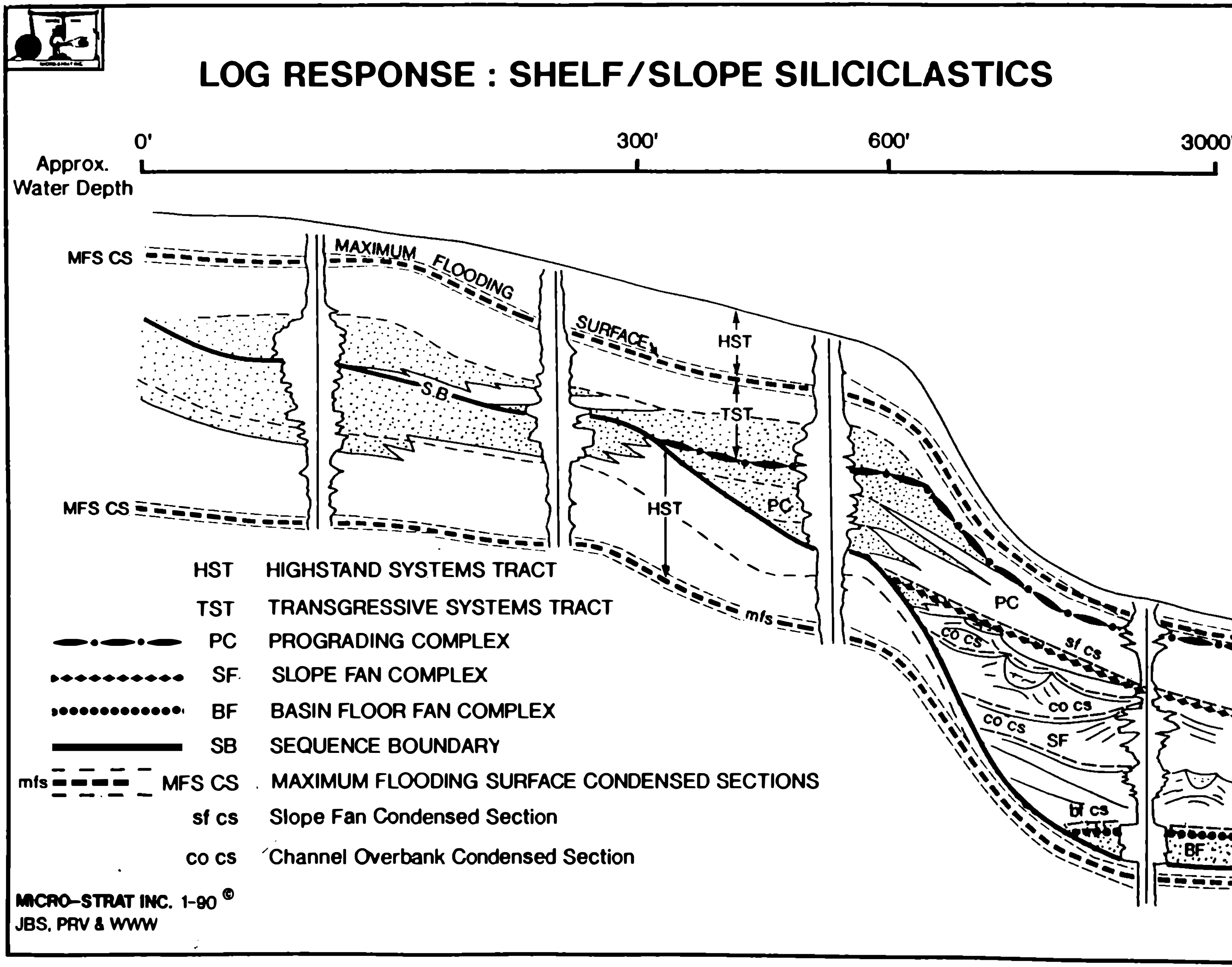
Setting: The unit is deposited following a gentle eustatic fall and during a progressive increase in the rate of relative sea level

* See Figure 4/5-17

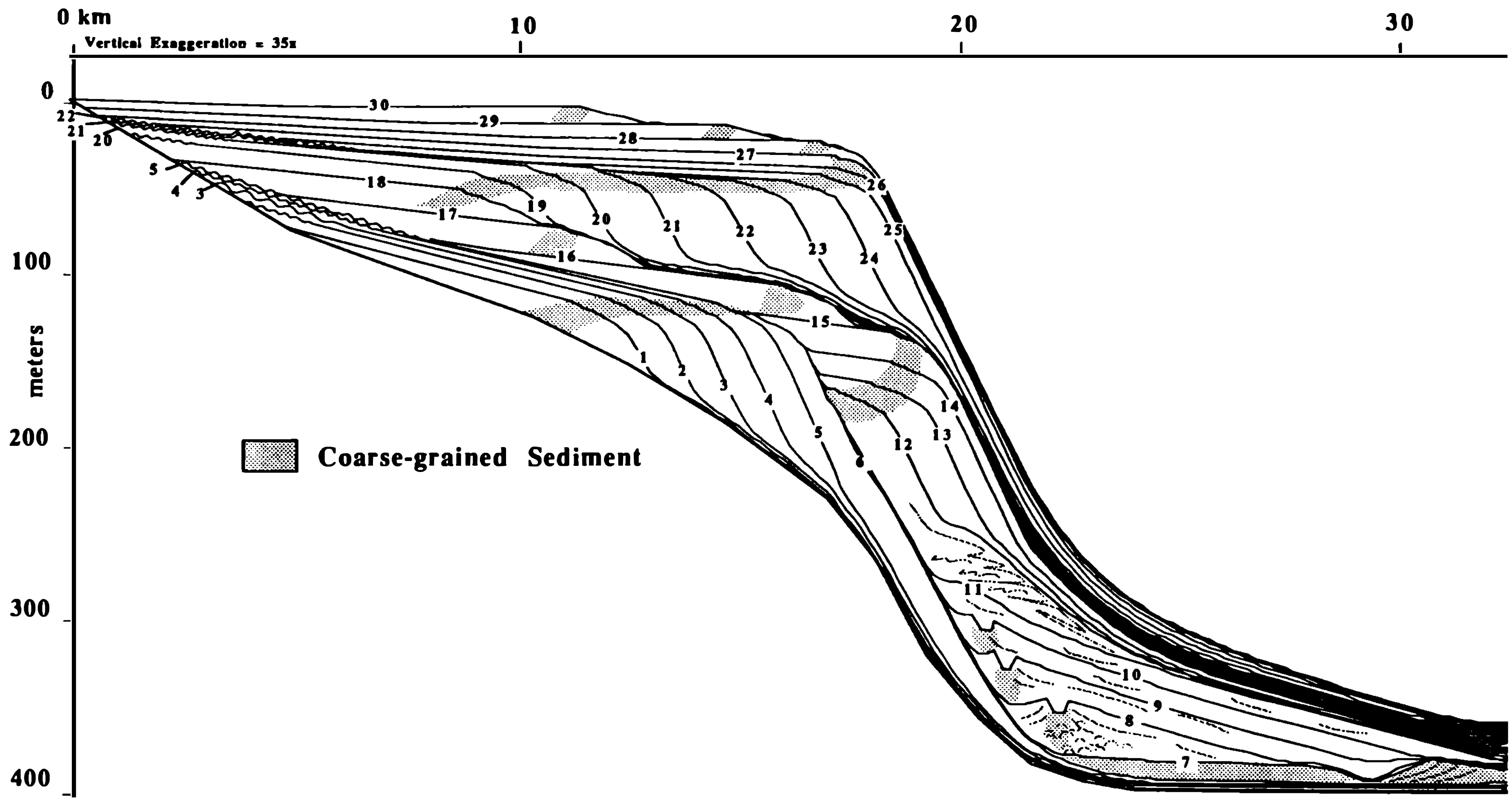
VARIATIONS IN SILICICLASTIC SYSTEMS TRACTS




SILICICLASTIC SYSTEMS TRACTS
DEEP FORELAND SETTING
(TECTONICALLY RELATED SEQUENCES)
HIGHSTAND MUDSTONE
BASIN FLOOR FAN (LONGITUDINAL TURBIDITES AND HEMIPELAGIC DEPOSITS)
VALENTI, '91

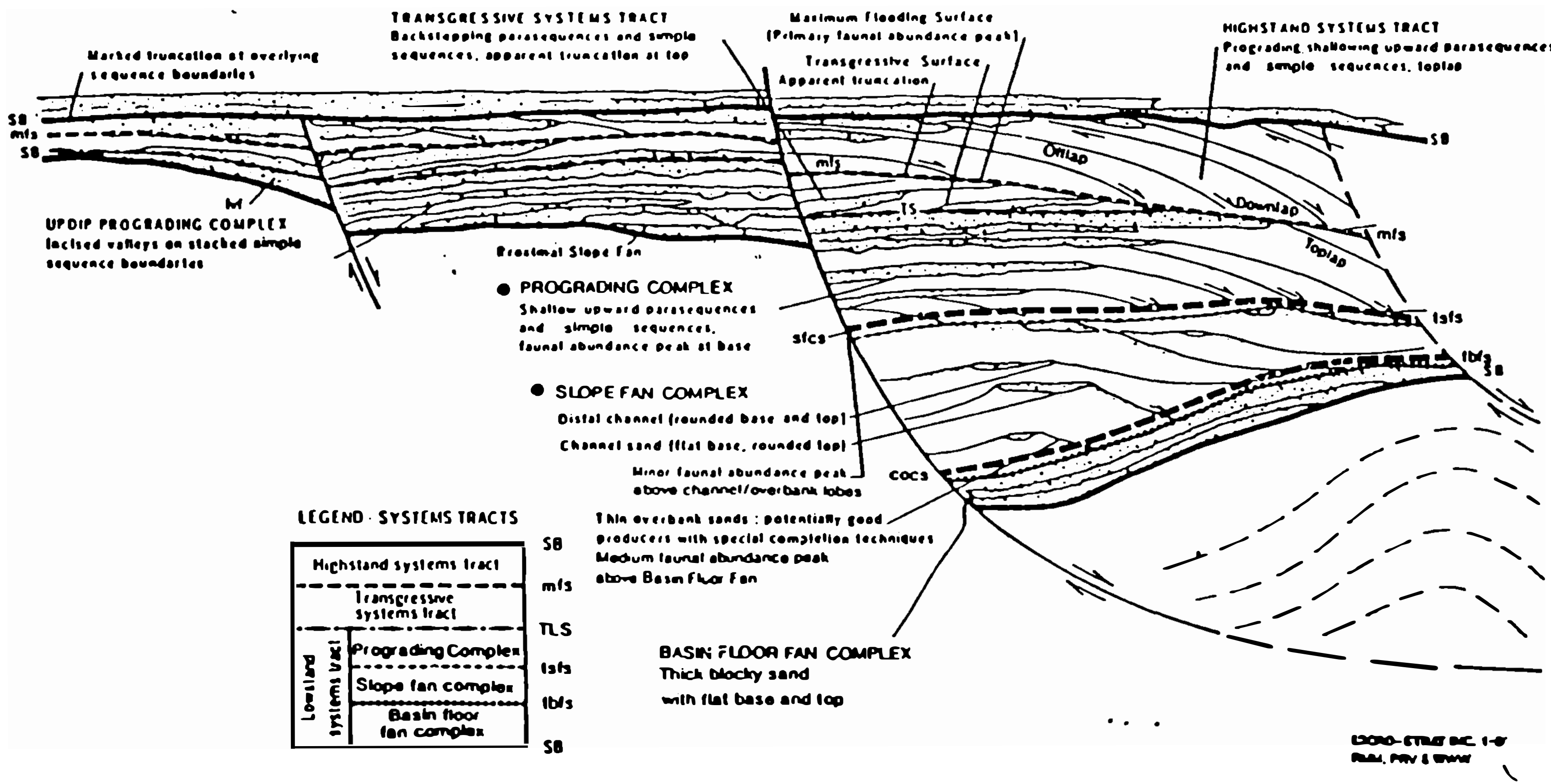

LOG RESPONSE : SHELF / SLOPE SILICICLASTICS
Approx. Water Depth
0'
300'
600'
3000'
MFS CS
MAXIMUM FLOODING SURFACE
S.B.
HST
TST
HST
PC
PC
MFS CS
mfs
co cs
sf cs
co cs
co cs
SF
bf cs
BF
HST HIGHSTAND SYSTEMS TRACT
TST TRANSGRESSIVE SYSTEMS TRACT
PC PROGRADING COMPLEX
SF SLOPE FAN COMPLEX
BF BASIN FLOOR FAN COMPLEX
SB SEQUENCE BOUNDARY
mfs MFS CS MAXIMUM FLOODING SURFACE CONDENSED SECTIONS
sf cs Slope Fan Condensed Section
co cs Channel Overbank Condensed Section
MICRO-STRAT INC. 1-90 ©
JBS, PRV & WWW

istribution of Coarse-Grained ediment

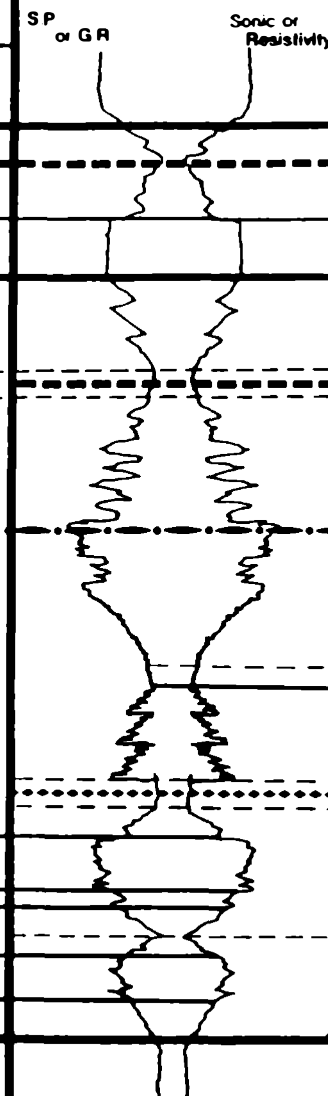


SYSTEMS TRACTS IN EXPANSION FAULTS

GULF OF MEXICO CENOZOIC COMPOSITE SEQUENCE

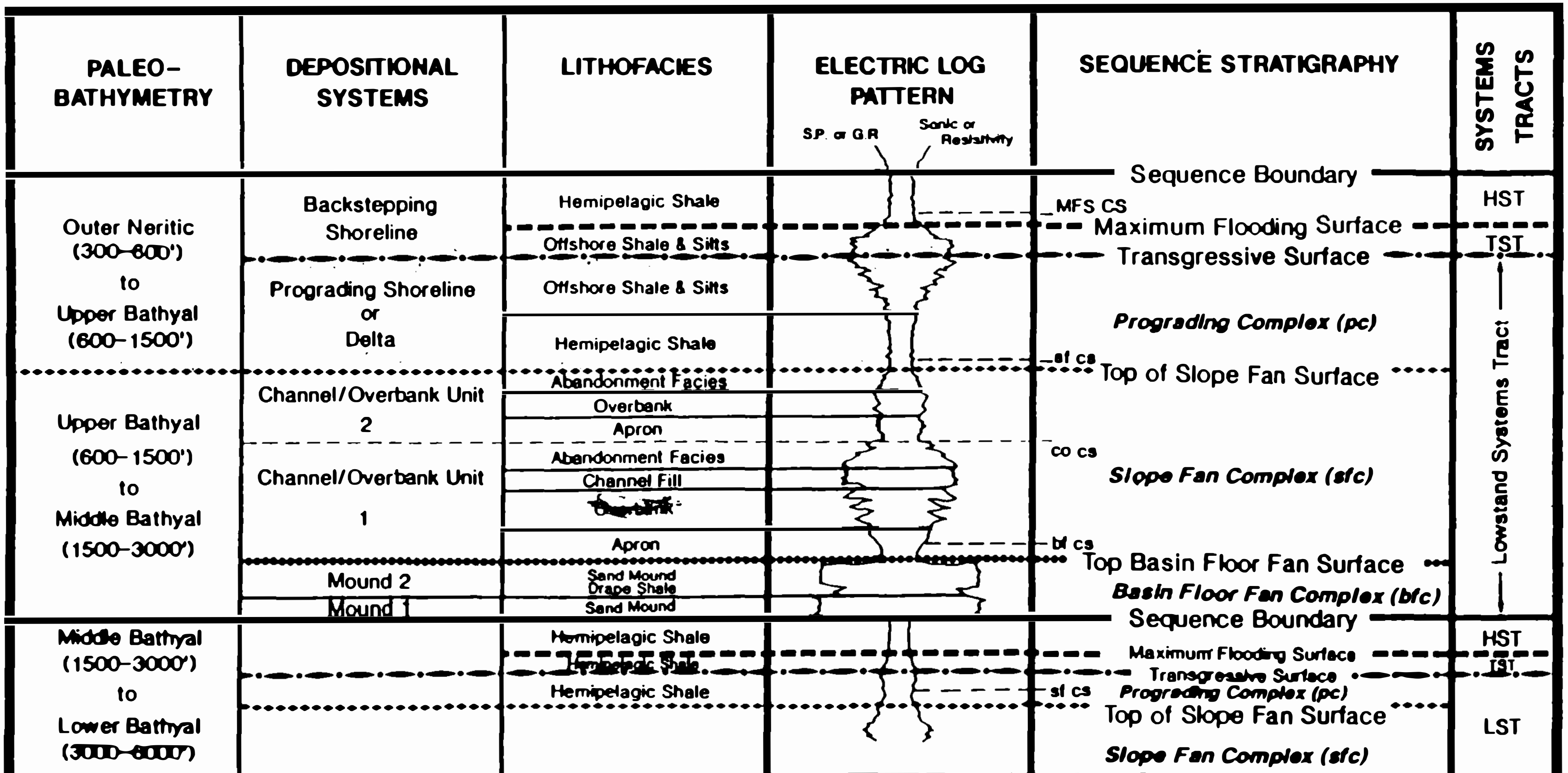


TYPICAL LOG PATTERNS ASSOCIATED WITH GULF OF MEXICO DEPOSITIONAL SEQUENCES AND SYSTEMS TRACTS



PALEO-BATHYMETRY	DEPOSITIONAL SYSTEMS	LITHOFACIES	ELECTRIC LOG PATTERN (SP or GR / Sonic or Resistivity)	SEQUENCE STRATIGRAPHY	SYSTEMS TRACTS
Inner Neritic (0-100') to Fluvial	Fluvial, Estuarine or Shoreface Sands	Sand		*Incised Valley Fill (ivf)*	LST
				Sequence Boundary	
Inner Neritic (0-100') to Mid. Neritic (100-300')	Prograding Deltas or Shorelines	Shoreface Sands and offshore Silts & Sands			HST
				Maximum Flooding Surface	
	Backstepping Shoreline	Hemipelagic Shales, Shoreface Sands, Offshore Silts & Sands		MFS	TST
Inner Neritic (0-100') to Fluvial	Fluvial Estuarine or Shoreface Sands	Sand		*Incised Valley Fill (ivf)*	LST
				Sequence Boundary	
Middle Neritic (100-300')	Prograding Shoreline or Delta	Shoreface Sands and Offshore Silts & Shales			HST
		Hemipelagic Shales		Maximum Flooding Surface; MFS CS	
	Backstepping Shorelines	Shoreface Sands and Offshore Silts & Shales			TST
Inner Neritic (0-100')				*Top Lowstand Surface*	
Middle Neritic (100-300')	Prograding Shoreline or Delta	Shoreface Sands and Offshore Silts & Shales		*Prograding Complex (pc)*; bt cs; Bottom-set (shingled) turbidites	Lowstand Systems Tract
Outer Neritic (300-600') to Upper Bathyal (600-1500')				sf cs; Top of Slope Fan Surface	
	Channel/Overbank Unit 2	Abandonment Facies; Channel Fill; Overbank; Apron		*Slope Fan Complex (sfc)*	
	Channel/Overbank Unit 1	Abandonment Facies; Overbank; Apron		co cs	
				Sequence Boundary	
					HST

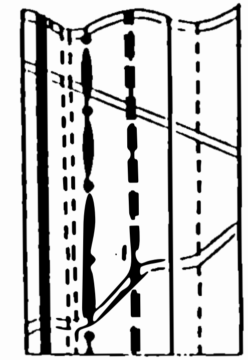
TYPICAL LOG PATTERNS ASSOCIATED WITH GULF OF MEXICO DEPOSITIONAL SEQUENCES AND SYSTEMS TRACTS

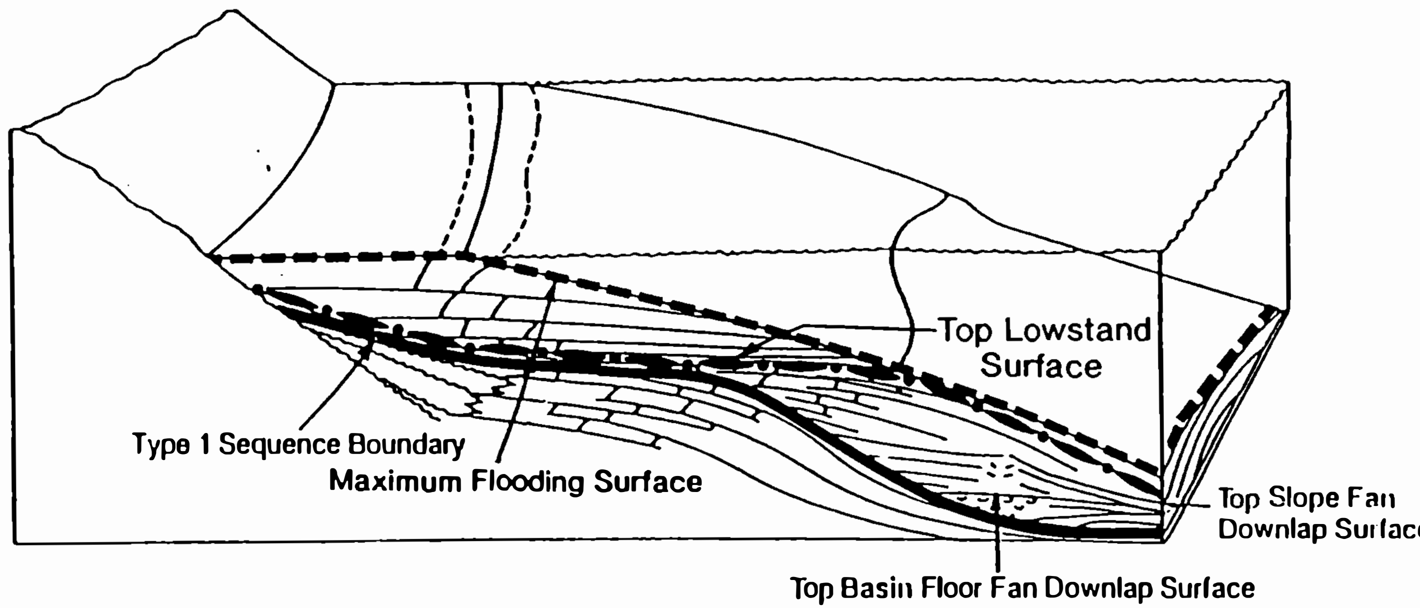


MICRO-STRAT INC. 1-90 ©

JBS, PRV & WWW

TRANSGRESSIVE SYSTEMS TRACT

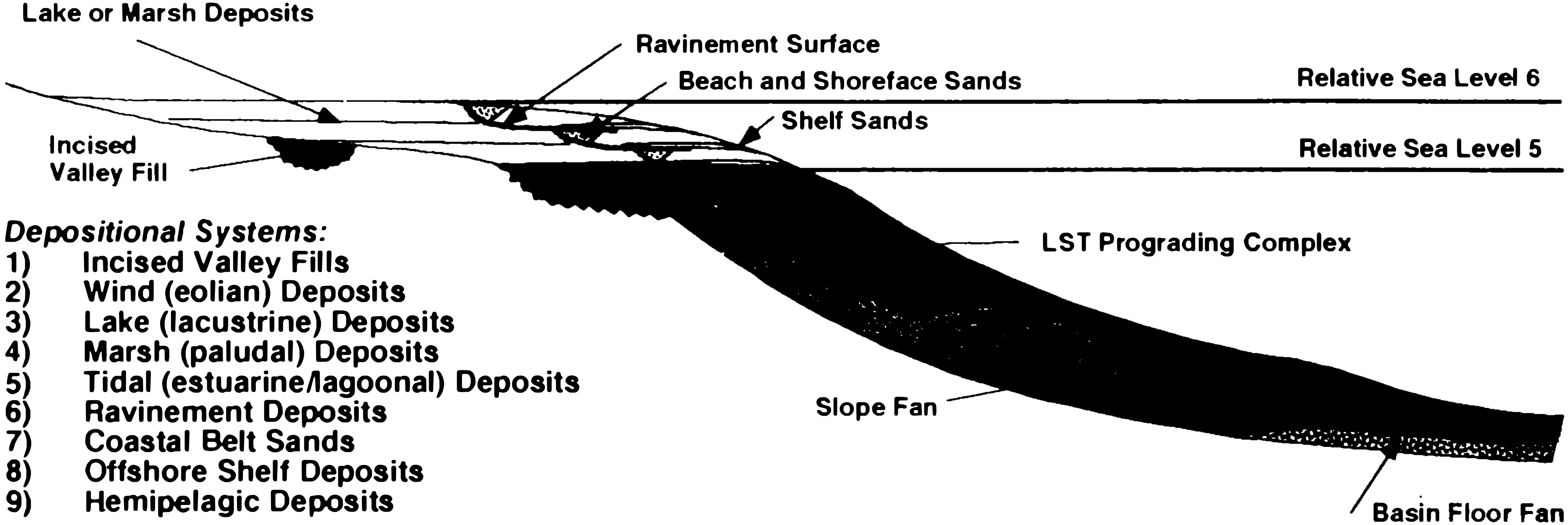




MICRO-STRAT INC. 1-90 ©

JBS, PRV & WWW

TRANSGRESSIVE SYSTEMS TRACT
Siliciclastics



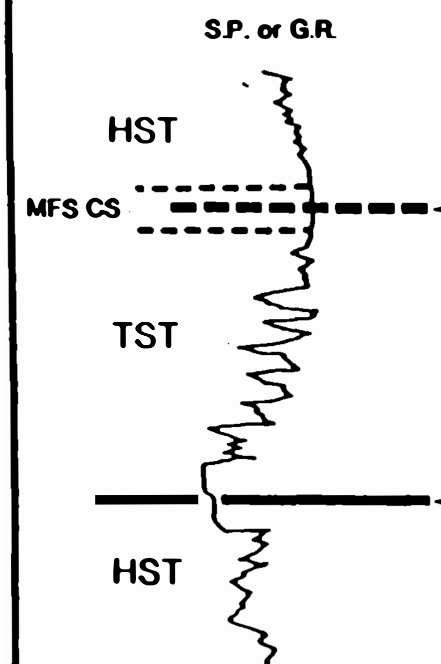
Depositional Systems:
1) Incised Valley Fills
2) Wind (eolian) Deposits
3) Lake (lacustrine) Deposits
4) Marsh (paludal) Deposits
5) Tidal (estuarine/lagoonal) Deposits
6) Ravinement Deposits
7) Coastal Belt Sands
8) Offshore Shelf Deposits
9) Hemipelagic Deposits

Dominant Depositional and Erosional Processes:
1) Estuarine
2) Wind
3) Lake
4) Marsh
5) Tidal (estuarine/lagoonal)
6) Ravinement
7) Storm
8) Beach
9) Reworked Authigenic Minerals
10) Authigenic Minerals
11) Suspension

Major Lithofacies:
1) Estuarine Sands in Incised Valley Fills
2) Dune Sands
3) Lake Sands, Muds and Carbonates
4) Widespread Peat, Lignite and Coal
5) Oyster Banks
6) Tidal (estuarine/lagoonal) Deposits
7) Pebble Lags
8) Beach and Storm Sands
9) Authigenic Minerals
10) Laminqted (organic rich) Shales
11) Offshore Burrowed Mudstone

TRANSGRESSIVE SYSTEMS TRACT

Characteristic Well Response



MAXIMUM FLOODING SURFACE

- Commonly lowest resistivity–highest gamma
- Most clay rich shale (most starved)
- Faunal abundance peak (MFS Condensed Sections)
- Apparent truncation common below boundary
- Downlap common above boundary

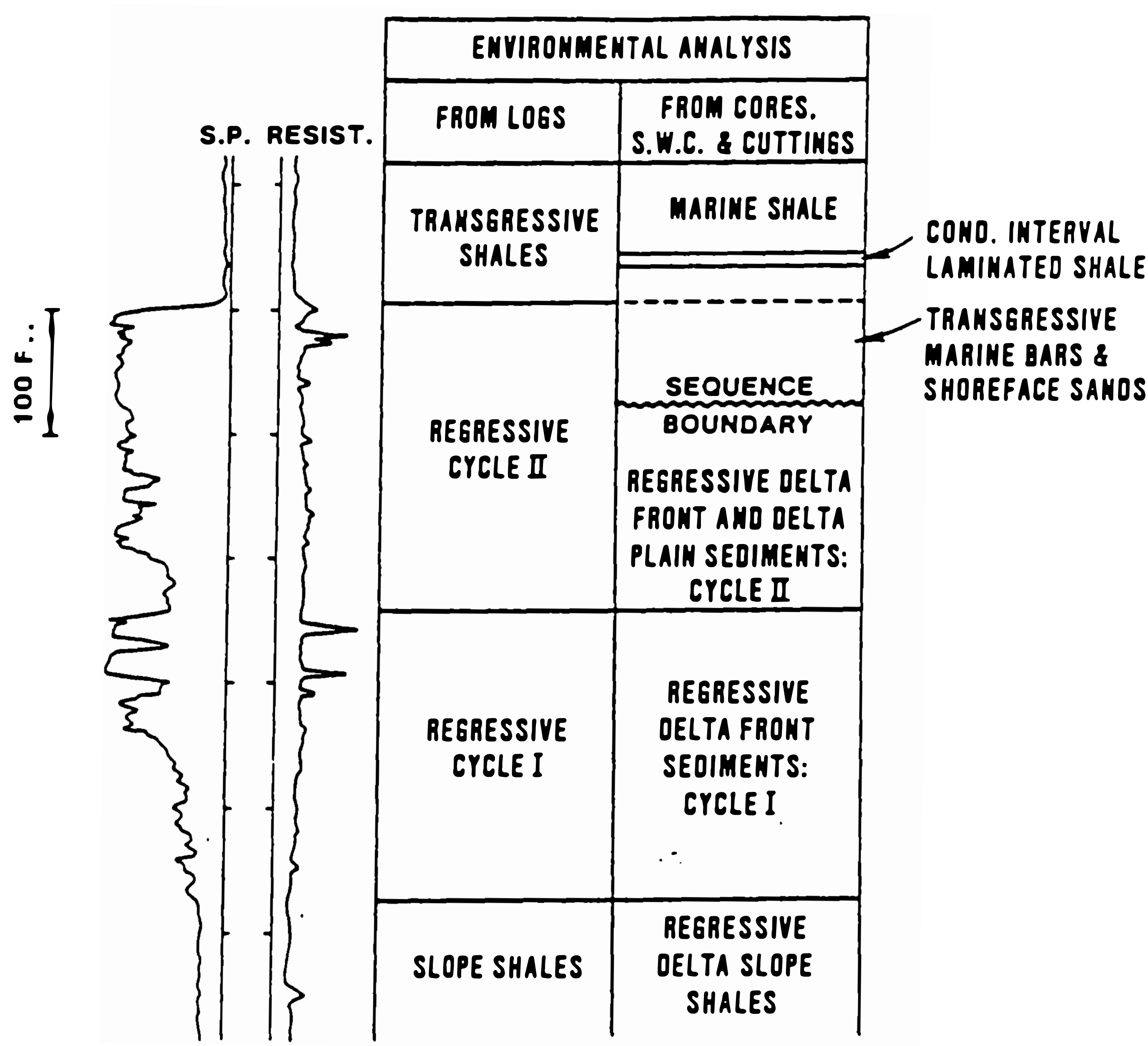
INTERVAL

- Individual parasequences prograde, fine and thin upward (backstep)
- Beach and shoreface sands common near base
- Basinal equivalent is thin hemipelagic shale
- Correlation is good, but backstepping transgressive surface of erosion are time–transgressive
- Sands often better sorted than HST
- Authigenic minerals common

SEQUENCE BOUNDARY

- Onlaps sequence boundary
- Commonly transgressive surface of erosion (ravinement surface) over LST, IVF or older shelf sediments near shelf edge
- Nonmarine sediments (coastal plain, coal or lake sediments) onlap sequence boundary in more landward areas
- Top Lowstand surface at base of TST

TYPICAL LOG EXPRESSION OF TRANQRESSIVE SYSTEM TRACT AND SEQUENCE BOUNDARY



JBS861713

Vail, Pers. Comm., 1986

Fig. 4

TRANSGRESSIVE SYSTEMS TRACTS (TST)
EXPLORATION APPLICATIONS

RESERVOIR
BEACH-SHOREFACE EXCELLENT k & ϕ.
LAGOONAL VARIABLE.
PREDICTABLE LINEAR TRENDS.

SOURCE
GOOD TOP AND LATERAL TST.

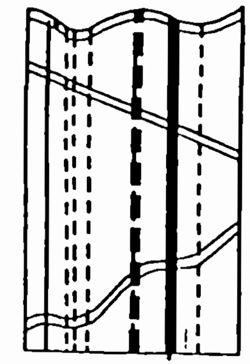
SEAL
GOOD TOP TST.
VARIABLE LATERAL AND BASE.

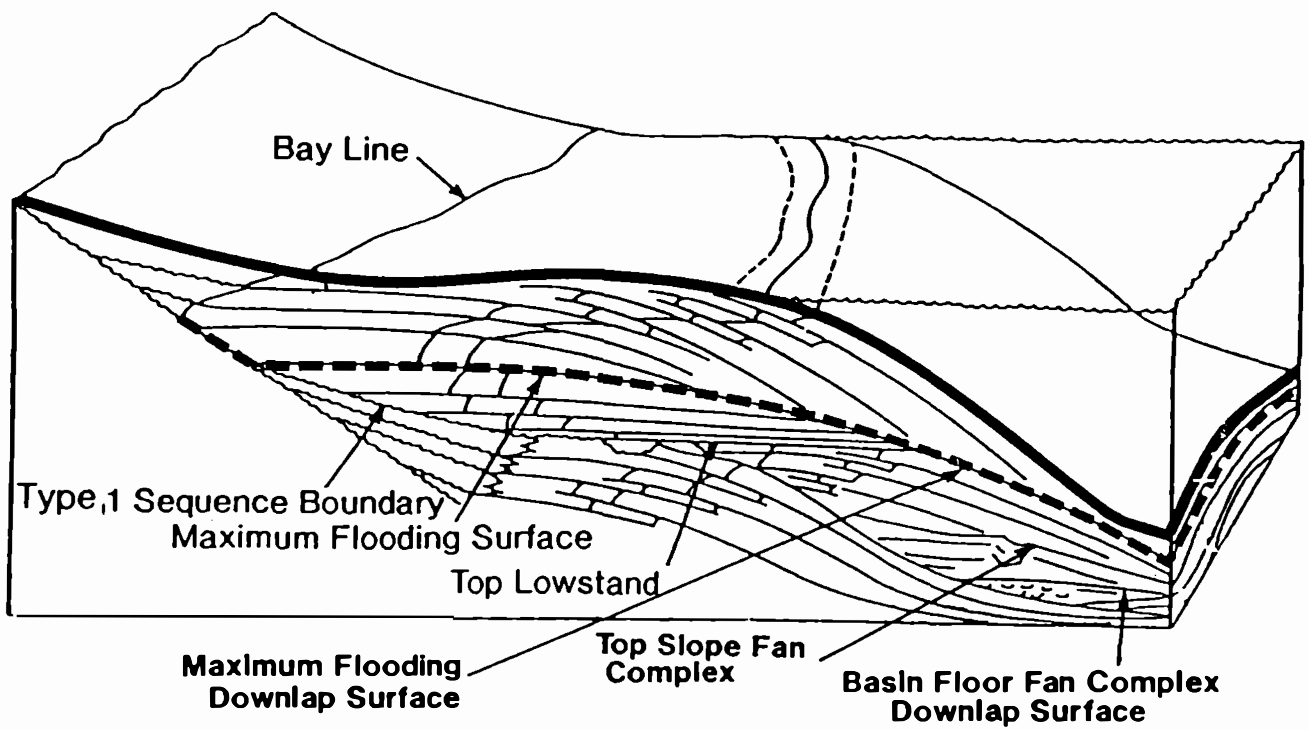
MIGRATION
TYPICALLY DOWNWARD AND LATERAL WITHIN TST.

TRAPS
STRAT TRAPS IN ISOLATED SANDS. CONTINUOUS BASAL TST REQUIRES A STRUCTURAL TRAP.

JBS07235I

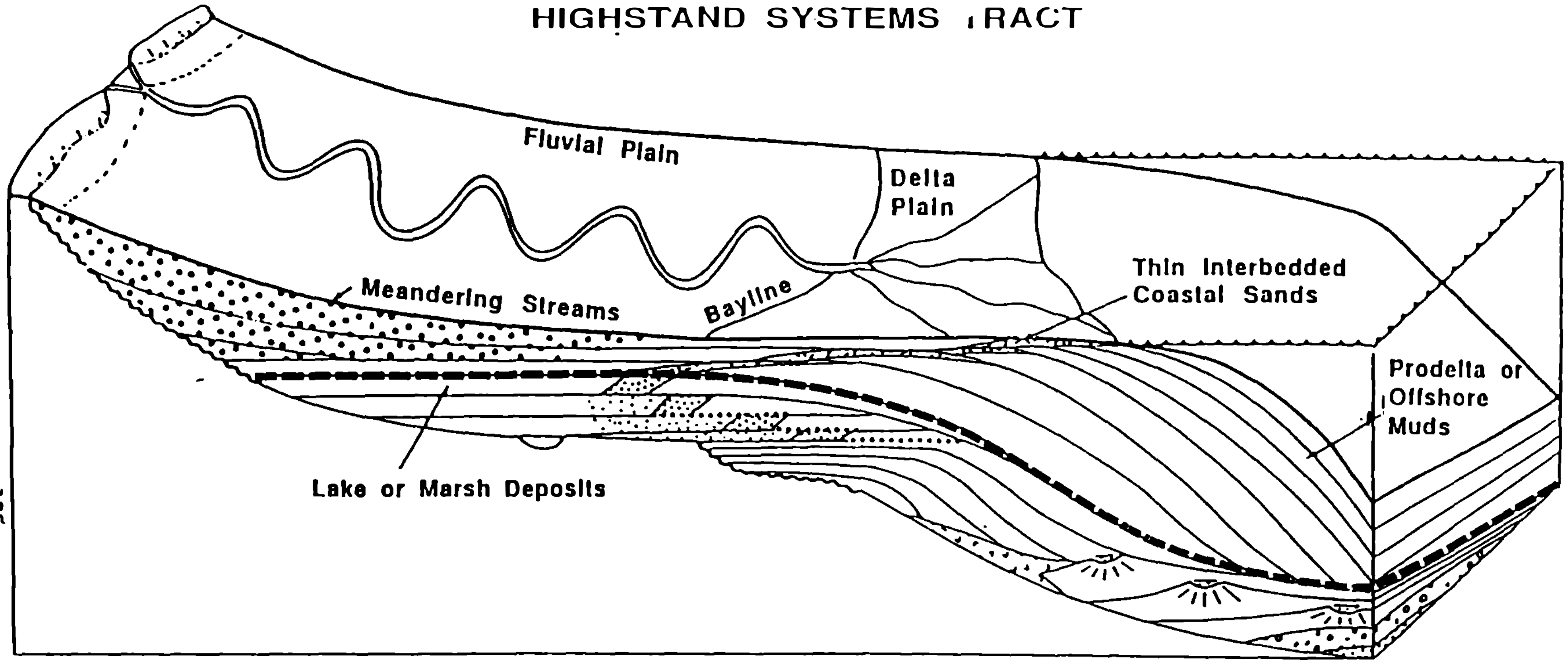
HIGHSTAND SYSTEMS TRACT





MICRO-STRAT INC. 1-90 •
JBS, PRV & WWW

HIGHSTAND SYSTEMS TRACT



DEPOSITIONAL SYSTEMS

1) Fluvial Plain Delta
2) Delta Deposits
3) Coastal Plain Deposits
4) Coastal Delt Sands
5) Offshore Silts and Muds

DOMINANT DEPOSITIONAL AND EROSIONAL PROCESSES

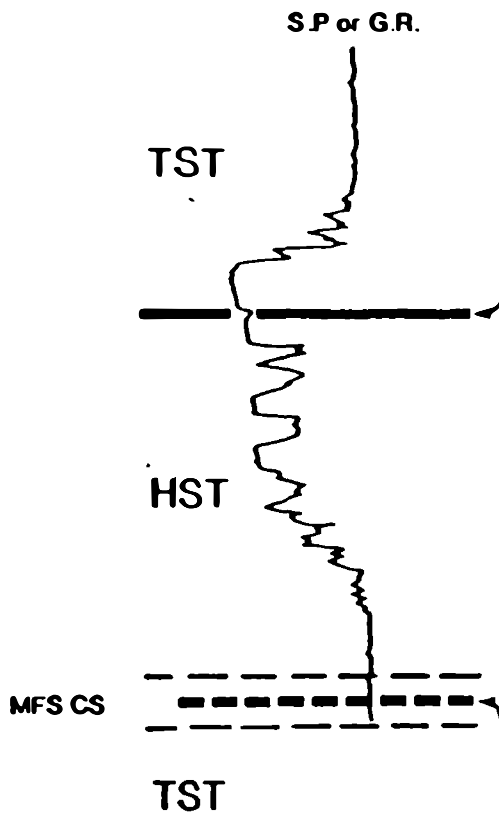
1) Fluvial
2) Fluvial
3) Bay and Marsh
4) Beach and Storm
5) Suspension

MAJOR LITHOFACIES

1) Meandering Streams Aluvial Fans
2) Deltaic
3) Bay and Marsh
4) Sand
5) Silt and Mud

HIGH STAND SYSTEMS TRACT

Characteristic Well Response



SEQUENCE BOUNDARY

- Onlap above boundary
- Lowstand erosion on shelf
- Incised valleys on shelf
- Canyon cuts and slump scars on upper slope
- Truncation or toplap below boundary
- Fluvial (meandering streams, alluvial fans) below boundary in more landward areas

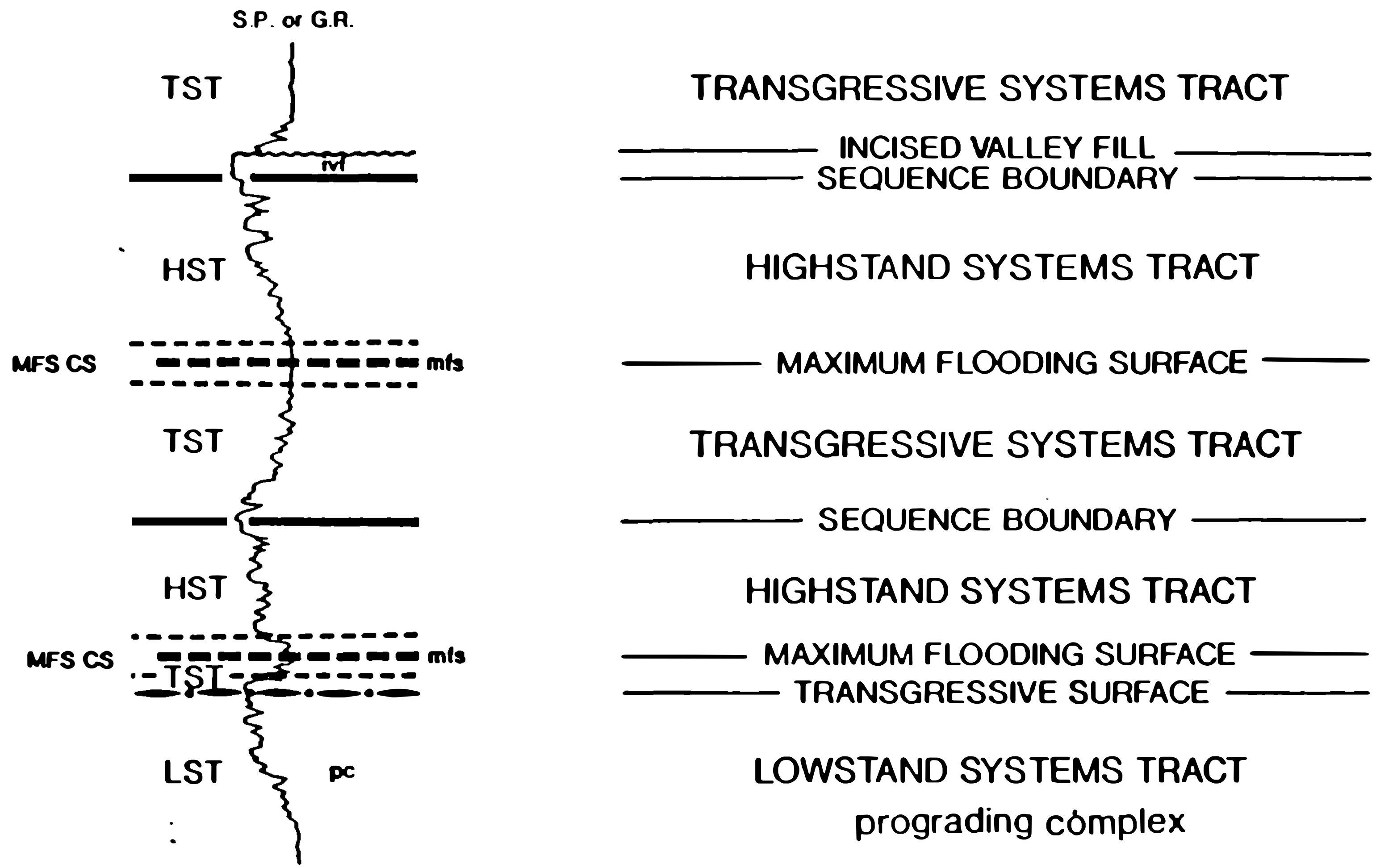
INTERVAL

- Coarsening and shallowing upward sand and silt interbedded
- Shoreface & deltaic sands near top
- Progrades laterally into offshore shales
- Basinal equivalent is hemipelagic shales
- Log correlation is difficult in upper part
- Reservoir continuity is fair to poor

MAXIMUM FLOODING SURFACE

- Commonly lowest resistivity-highest gamma
- Most clay rich shale (most starved) .
- Faunal abundance peak (MFS CS)
- Downlap common above boundary
- Apparent truncation common below boundary

NERITIC FACIES SYSTEMS TRACTS



MICRO-STRAT INC. 1-90 ©
JBS, PRV & WWW

HIGHSTAND SYSTEMS TRACTS (HST)
EXPLORATION APPLICATIONS

RESERVOIR
DISCONTINUOUS FLUVIAL, DELTAIC FACIES PREDOMINATE. MINOR SHOREFACE FACIES.

SOURCE
OFTEN A PROBLEM. DEEP SOURCE TYPICAL. HST SHALES OFTEN LEAN AND GAS-PRONE.

SEAL
LEAKS UPDIP INTO TST. LEAKS LATERALLY. FLOODING SURFACE USUALLY TOP SEAL.

MIGRATION
GAS AND LEAN OIL TYPICAL FROM CONTEMPORANEOUS SOURCE. GOOD OIL SOURCE OFTEN REQUIRES VERTICAL FAULT CONDUIT.

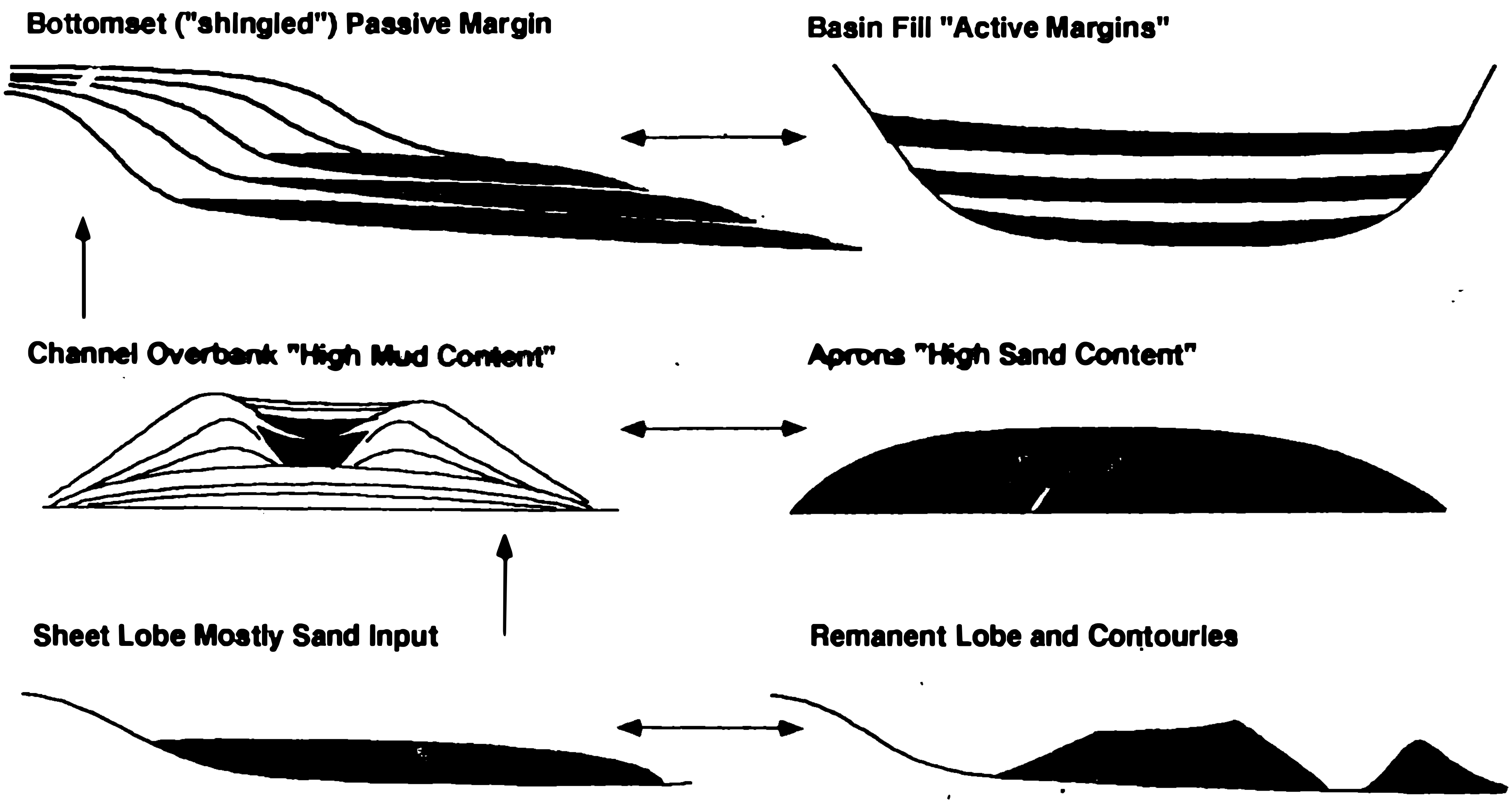
TRAPS
PREDOMINANTLY STRUCTURAL. EARLY TIMING CRITICAL.

JOS872350

318

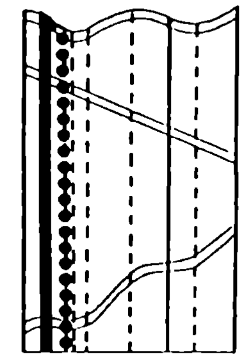
2202

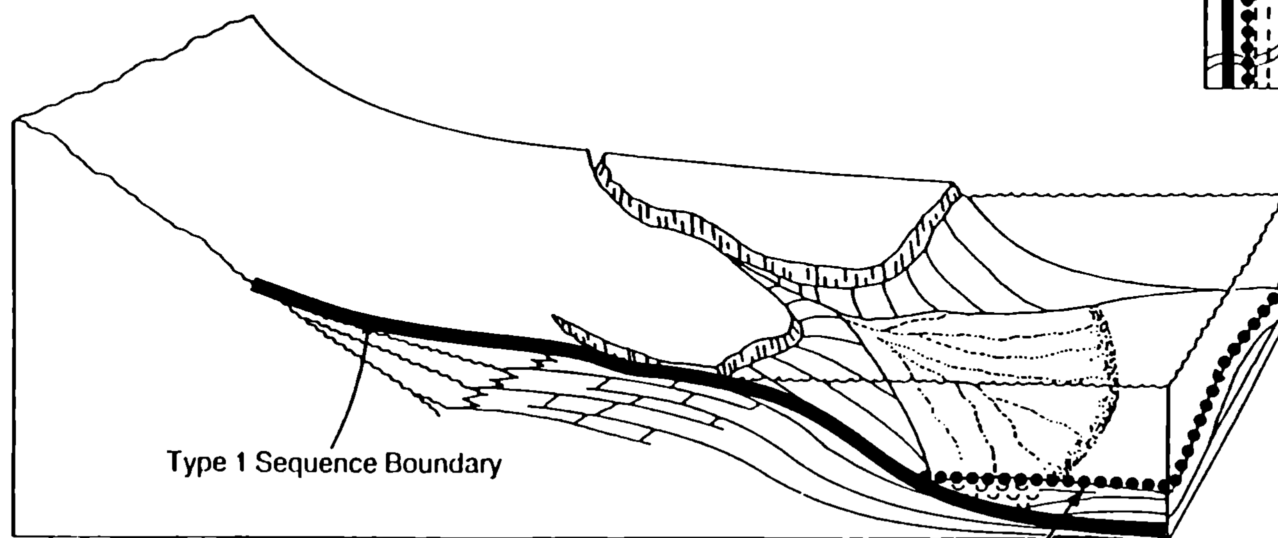
LOWSTAND SYSTEMS TRACT
MORPHOLOGIES OF TURBIDITES



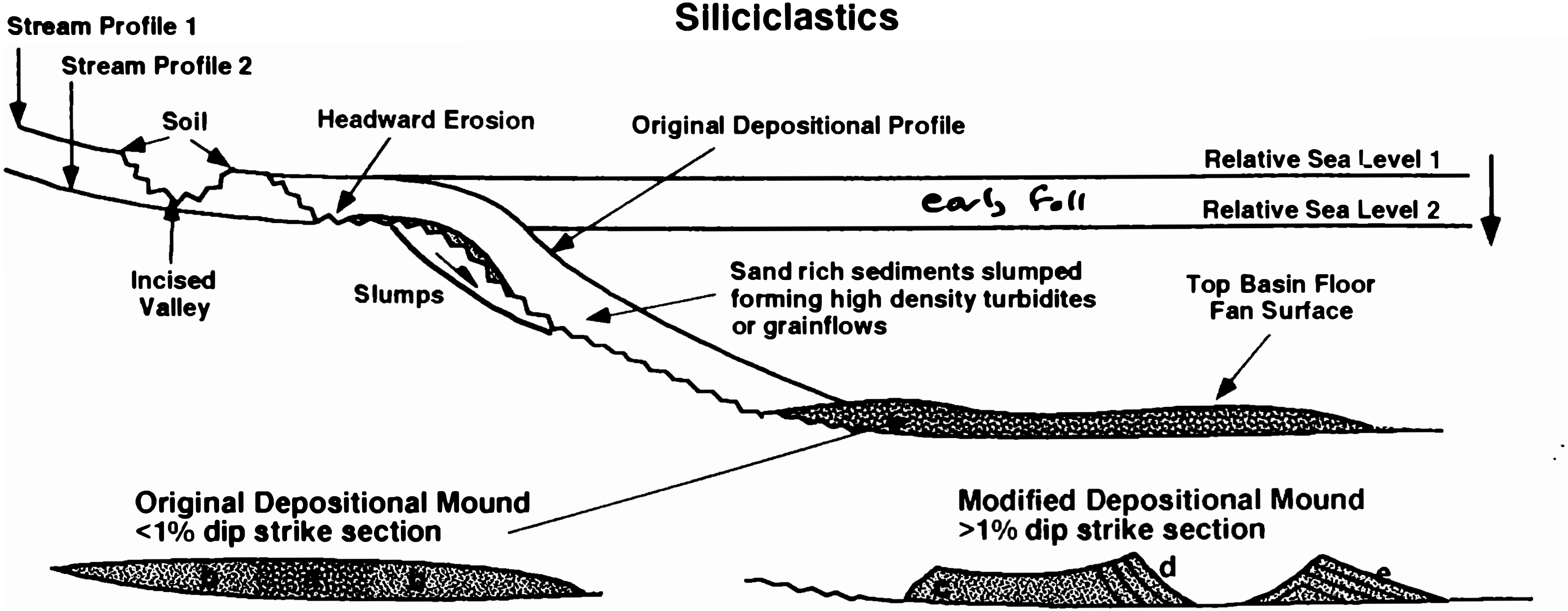
AV 12/

LOWSTAND SYSTEMS TRACT
BASIN FLOOR FAN COMPLEX





LOWSTAND SYSTEMS TRACT - BASIN FLOOR FAN COMPLEX
Siliciclastics



Depositional Systems:

1) Soils
2) Basin Floor Fan
3) ~~High Density Turbidites or Grainflows~~
4) Basin Floor Contourites

Dominant Depositional and Erosional Processes:

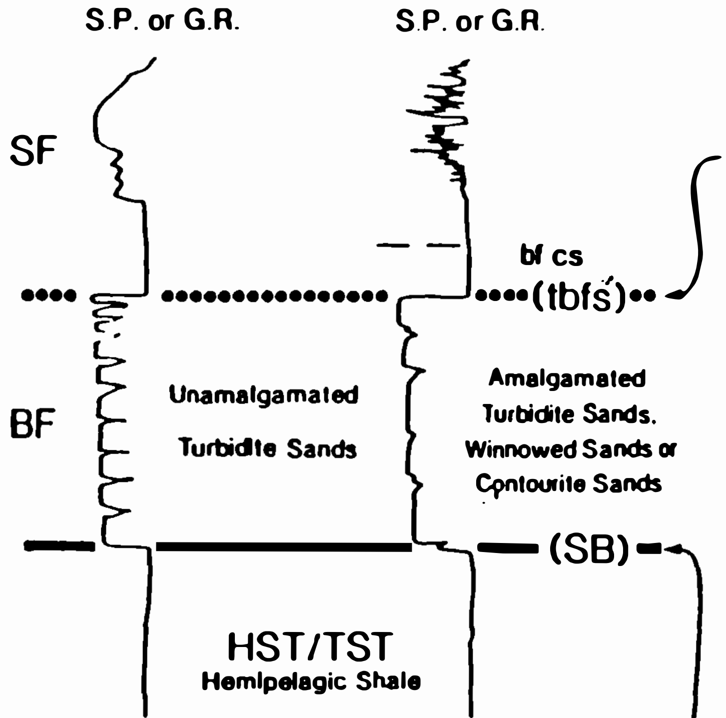
1) Soils
2) Headward Erosion
   - Incised Valleys
   - Flushing of River Valley Sand into Basin
3) Slumping
   - Submarine Canyons and Slope Scars
4) High Density Turbidity Currents
5) Grainflows
6) Basin Floor "Contour" Currents

Major Lithofacies:

1) Soils
2) Massive Basin Floor Sheet Mounds
   - Winnowed amalgamated sands (a)
   - Unamalgamated sands (b)
   - Remenant mounds (c)
   - Attached contourites (d)
   - Basin Floor Contourites (e)
3) Minor Interbedded Lithofacies
   - Hemipelagic silts and shales
   - Thin bedded turbidites
   - Debris flows at proximale edge

AV 12/92

Characteristic Log Response



UPPER BOUNDARY

- Hemipelagic shale or channel/overbank apron facies above boundary
- Sharp boundary with minimal transition

INTERVAL

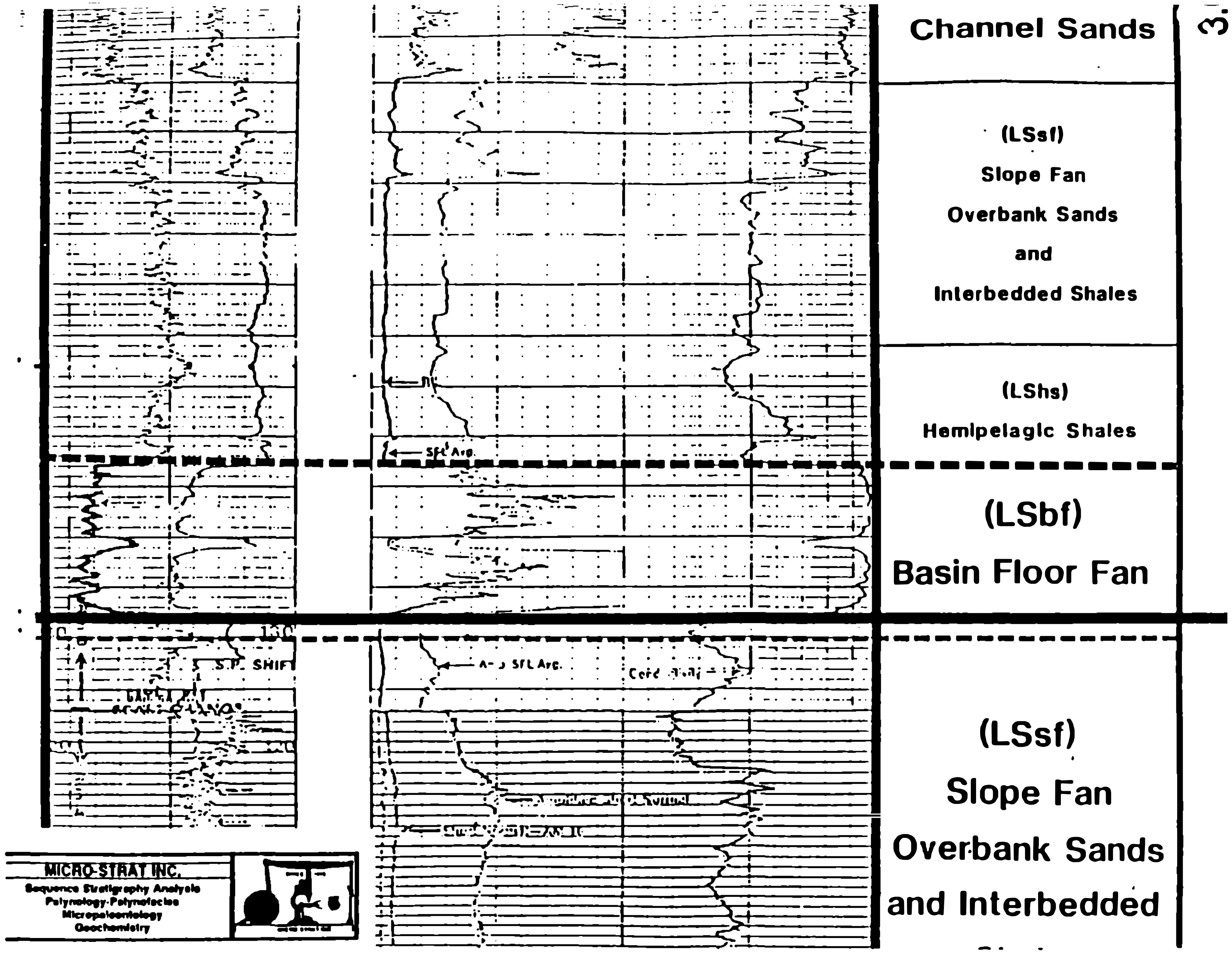
- Turbidite sands
  - Amalgamated massive turbidite sands
  - Unamalgamated massive turbidite sands, with shale breaks
  - Minor erosional surfaces within sand
  - Commonly a major erosional surface at top of fan
  - May be remnant fan mounds
- Redeposited massive shingled sands bordering fan mounds
- Contourite sands
  - Redeposited massive sands in separate mounds

SEQUENCE BOUNDARY

- Massive sand above hemipelagic shale (railroad track shale)
- Sharp boundary
- No erosion at base except sometimes at proximal portion of fan

1930

3.



Channel Sands
(LSsf)
Slope Fan
Overbank Sands
and
Interbedded Shales
(LShs)
Hemipelagic Shales
(LSbf)
Basin Floor Fan
(LSsf)
Slope Fan
Overbank Sands
and Interbedded
SFL Avg.
SFL Avg.
S.P. SHIFT
MICRO-STRAT INC.
Sequence Stratigraphy Analysis
Palynology-Palynofacies
Micropaleontology
Geochemistry

5/57

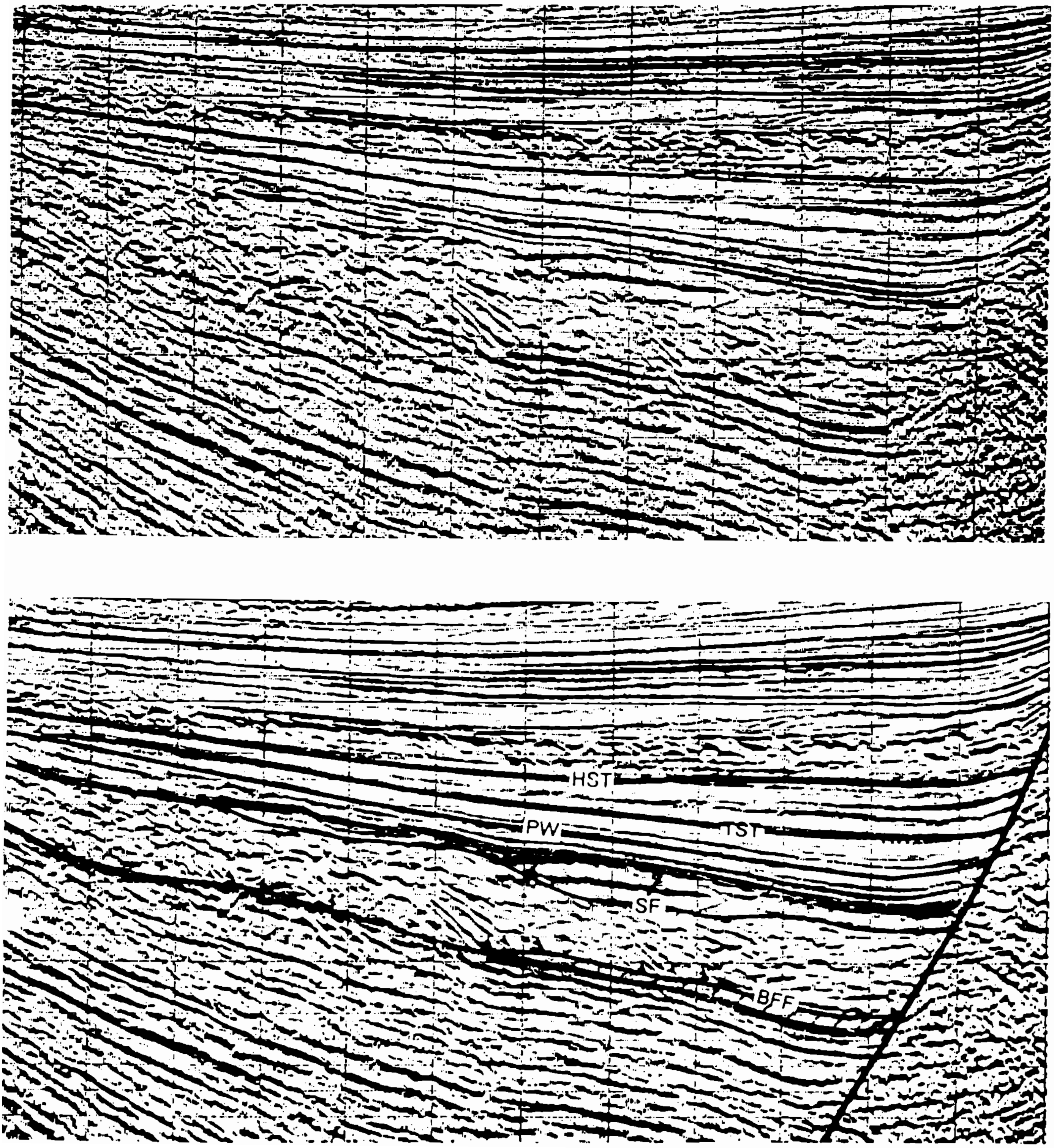


Figure 6. Seismic section which shows systems tracts within an individual depositional sequence in the offshore Louisiana South Additions. Above, uninterpreted; below, interpretation.

After Pacht et al., 1990

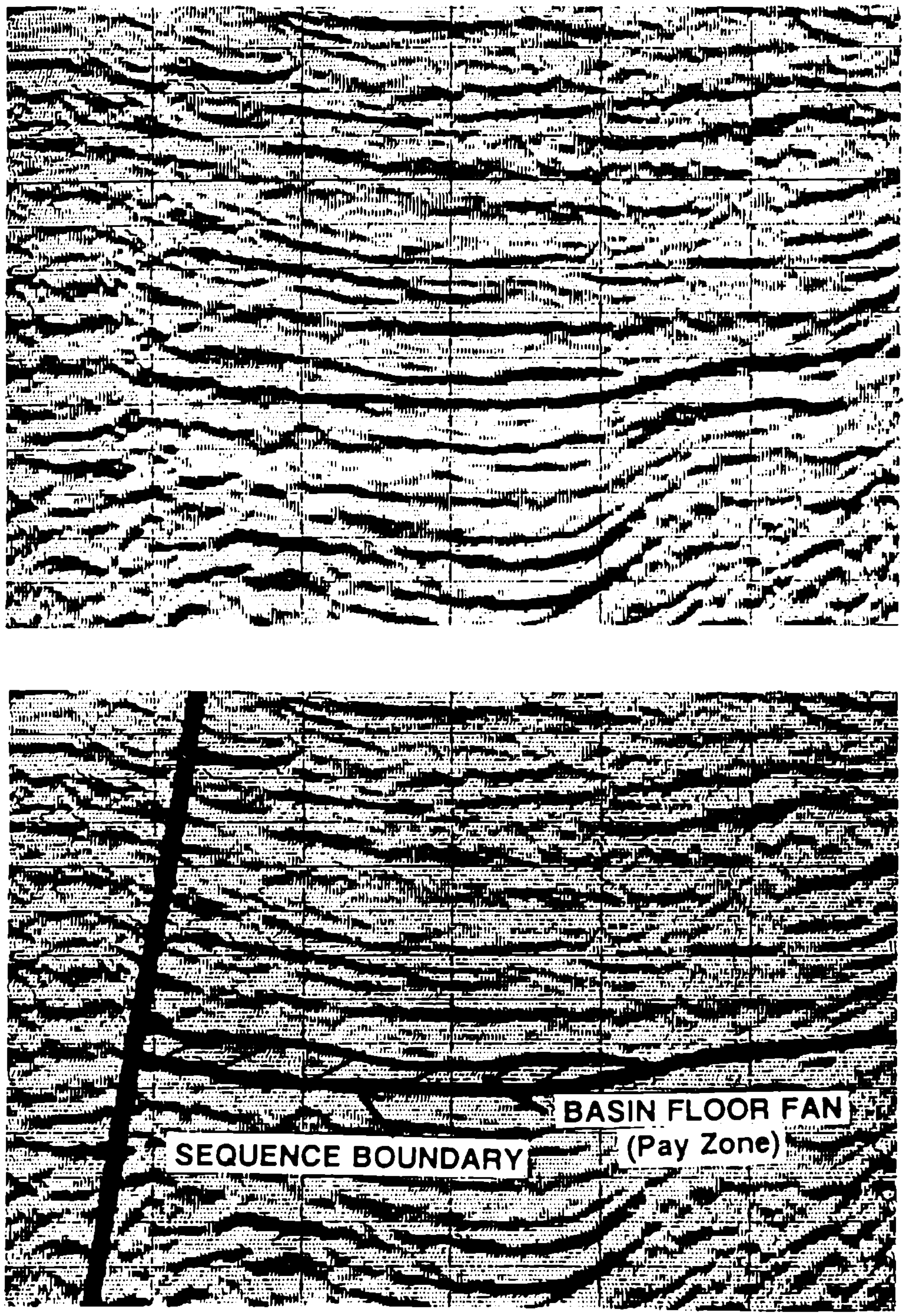
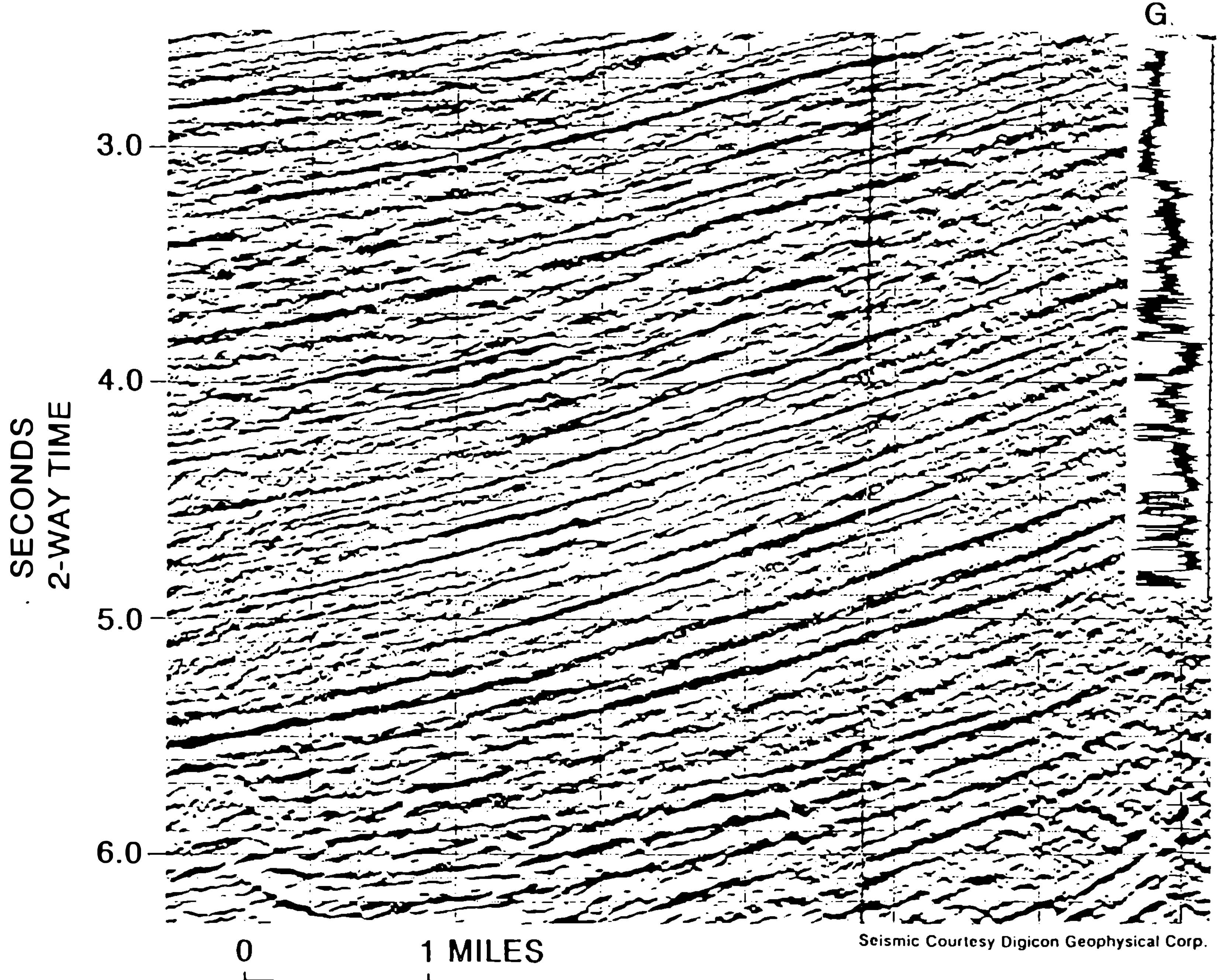


Figure 9. Seismic section which shows a gas field developed within a basin-floor fan.

After Pacht et al. 1990



After Mitchum et al. 1990

BASIN FLOOR LOWSTAND FAN SYSTEMS TRACTS (LSF)
EXPLORATION APPLICATIONS

RESERVOIR

TYPICALLY EXCEL-LENT k & ϕ. CONTINUITY VARIABLE, OFTEN A PROBLEM IN UPPER CHANNELIZED LOBES.

SOURCE

LEAKAGE FROM DEEPER BEDS. POSSIBLE TOP & LATERAL CONDENSED SECTION (C.S.) SHALES.

SEAL

EXCELLENT, PELAGIC SHALES OF C.S. RISK NO SEAL IF OVERLAIN BY SLOPE FAN.

MIGRATION

VERTICAL FROM DEEPER SOURCE. POSSIBLE DOWNWARD AND LATERAL FROM C.S. SHALES.

TRAPS

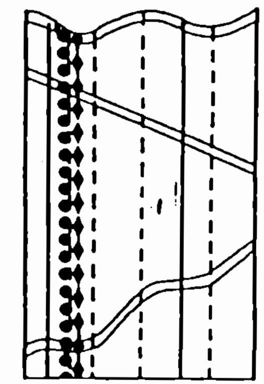
TYPICALLY STRATIGRAPHIC.

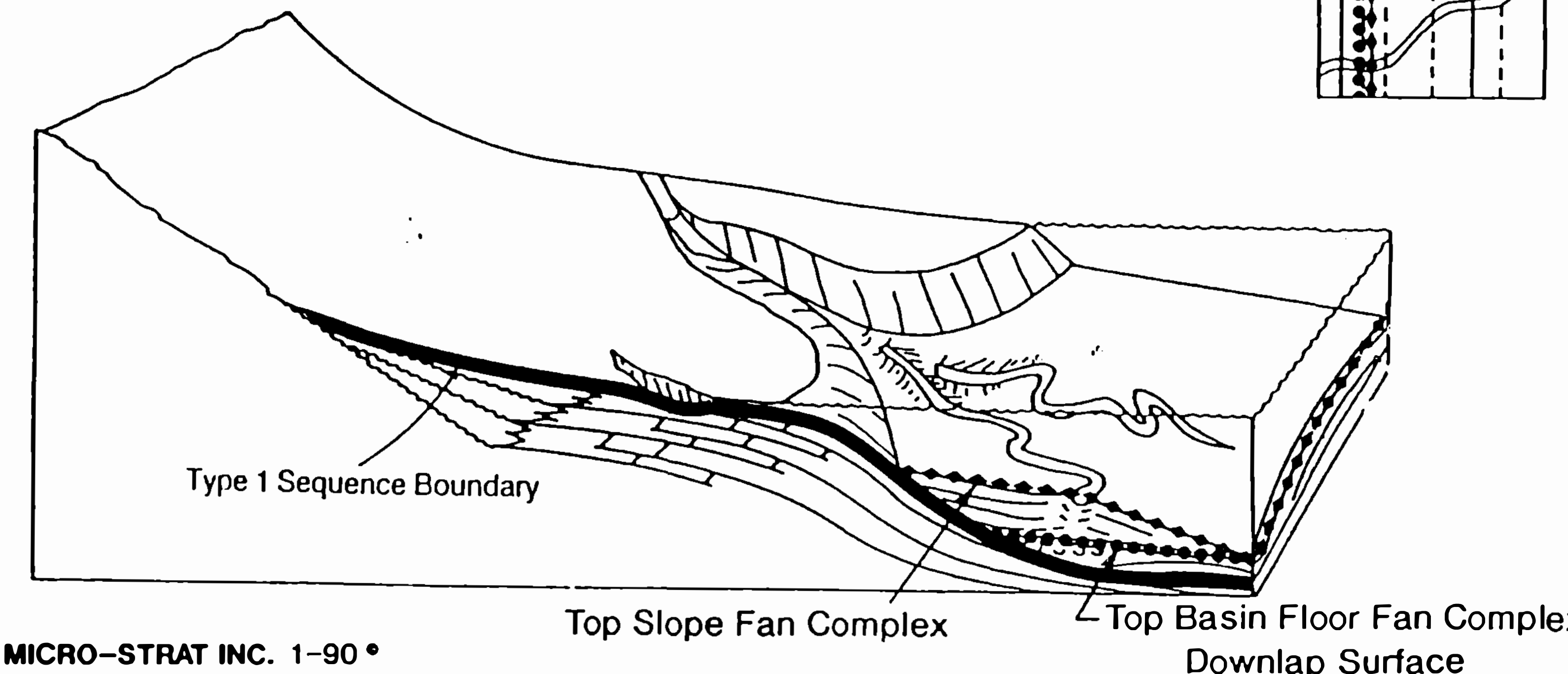
JOS072347

FIG. 4

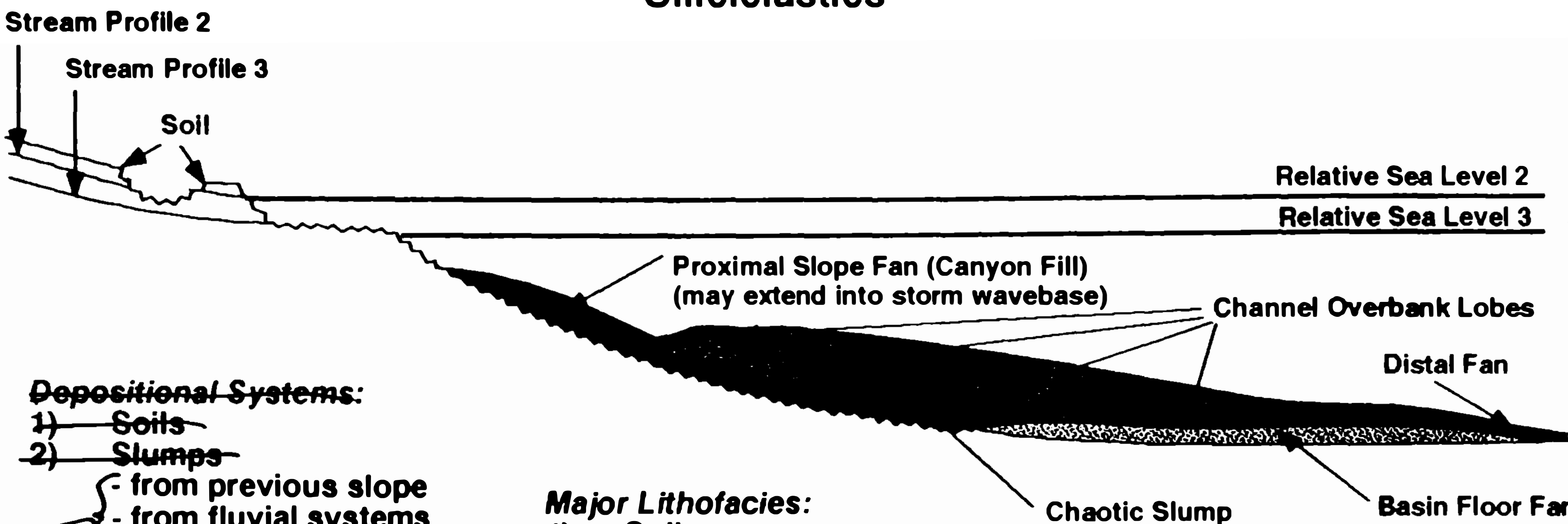
LOWSTAND SYSTEMS TRACT

SLOPE FAN COMPLEX





LOWSTAND SYSTEMS TRACT - SLOPE FAN COMPLEX
Siliciclastics

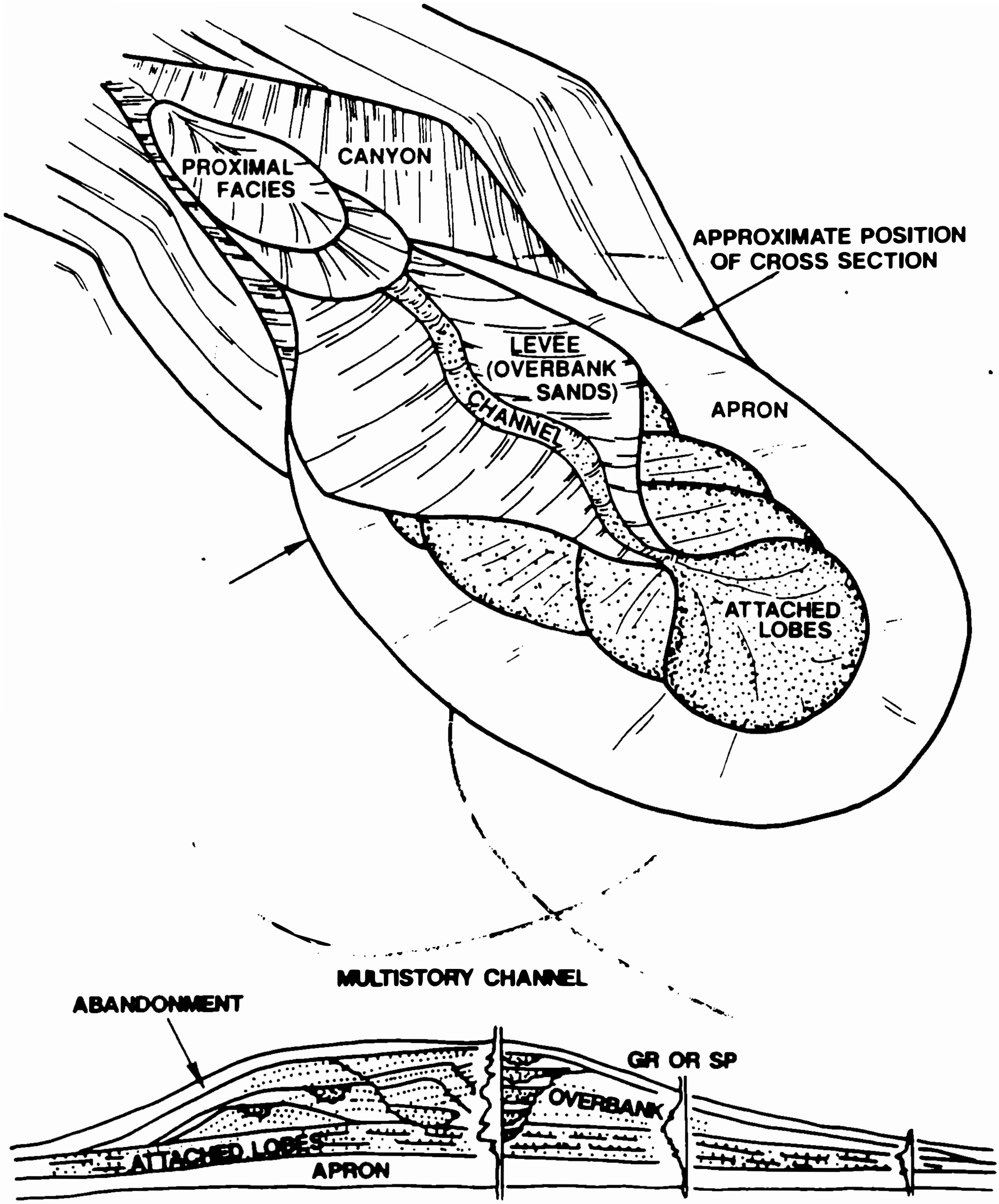


~~*Depositional Systems:*~~
~~1) Soils~~
~~2) Slumps~~
- from previous slope
- from fluvial systems
- from headward erosion of canyons

~~3) Turbidites~~ Channel/overbank lobe
~~4) Hemipelagic~~ shales

Dominant Depositional and Erosional Processes:
1) Soil formation
2) Slumping
3) Mass Flow
4) Turbidity Currents
5) Suspension

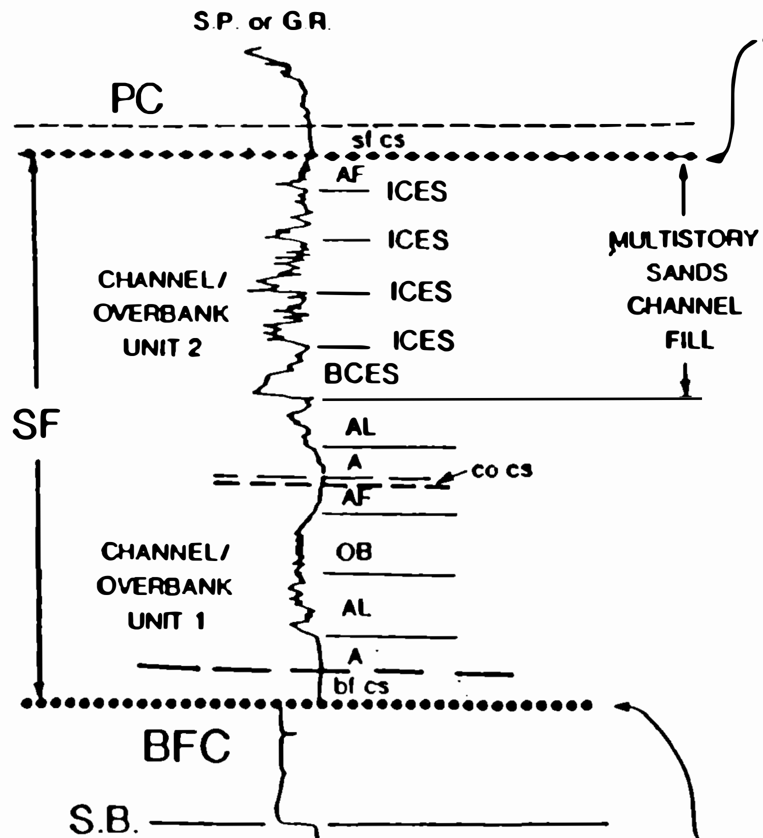
Major Lithofacies:
1) Soils
2) Proximal Slope Fan:
   - Slumps
   - Conglomerates
   - Massive sands
   - Debris flows
3) Channel Overbank Lobes:
   - Abandonment facies
   - Channel fill (turbidite sands or silts)
   - Overbank thin-bedded turbidites
   - Thickening upward channel attached lobes
   - Distal mudstone apron
4) Chaotic slumps
5) Hemipelagic shales between lobes



R. M. Mitchum
P. R. Vail

LOW STAND SYSTEMS TRACT – SLOPE FAN COMPLEX

Characteristic Well Response



LEGEND

AF - Abandonment facies
CF - Channel fill
OB - Overbank
AL - Attached lobes
A - Apron
ICES - Internal channel erosional surface
BCES - Basal channel erosional surface
MCS - Minor condensed section

UPPER BOUNDARY

- Downward shift from hemipelagic shale to laminated fine grained turbidites
- Fining upward digitated log character below boundary
- Faunal abundance peak (sf cs)

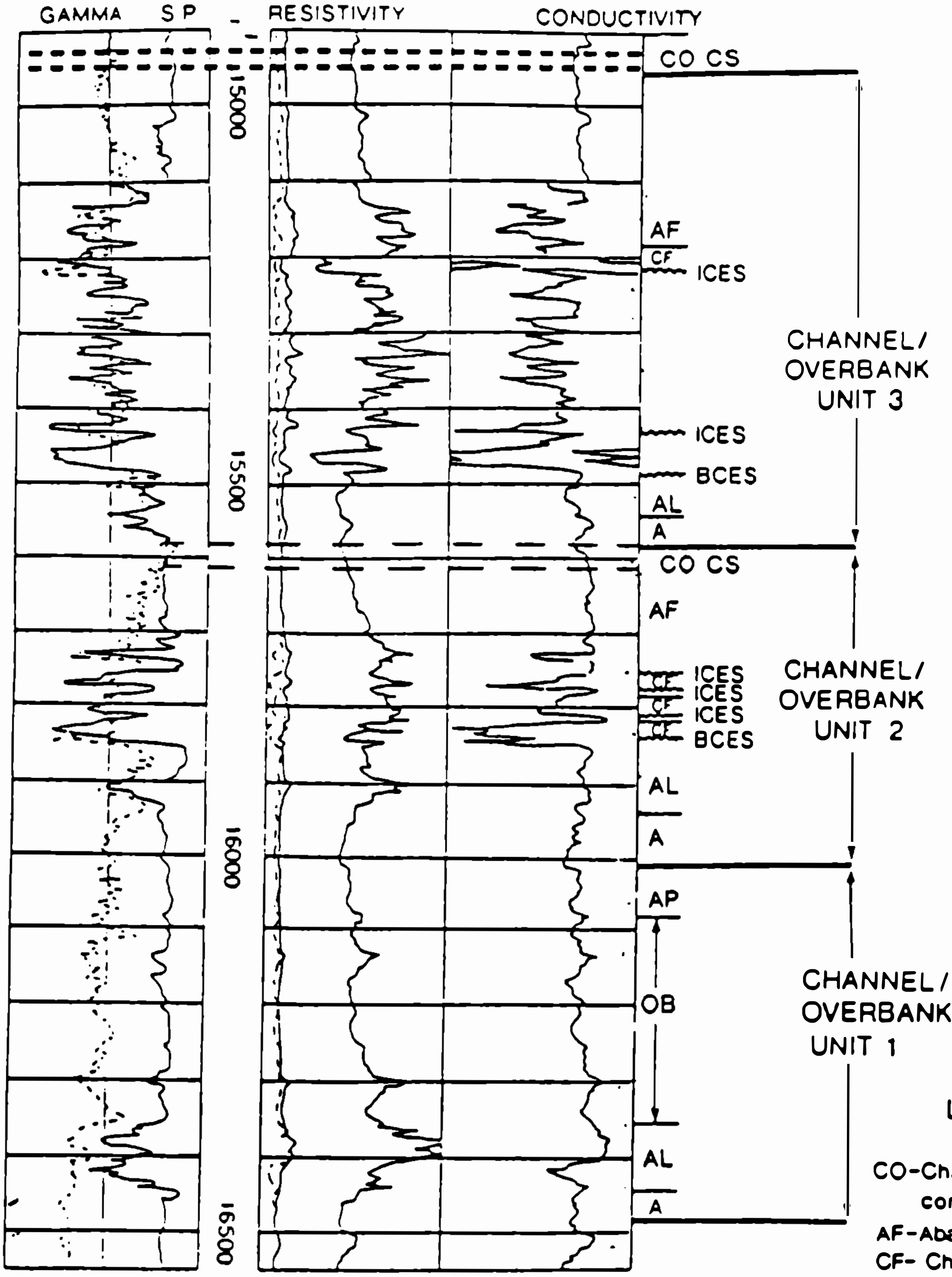
INTERVAL

- Crescent shape to individual channel/overbank units
- Within channel/overbank units, sands thicken, then thin upward
- 1-10 channel/overbank units within each slope fan
- Proximal facies may be highly sand-prone near source
- Channel fill facies may be:
  - Massive turbidite sands
  - Massive turbidite sands fining upward with sharp bases
  - Mudstone-fine grained turbidites

LOWER BOUNDARY

- Hemipelagic shale with faunal abundance peak commonly at base of slope fan complex (bf cs)
- Lies on Sequence Boundary or on Low Stand Systems Tract Basin Floor Fan Complex
- Boundary commonly conformable in basin and erosional on slope

EXAMPLE 1: LOWSTAND SYSTEMS TRACT–SLOPE FAN



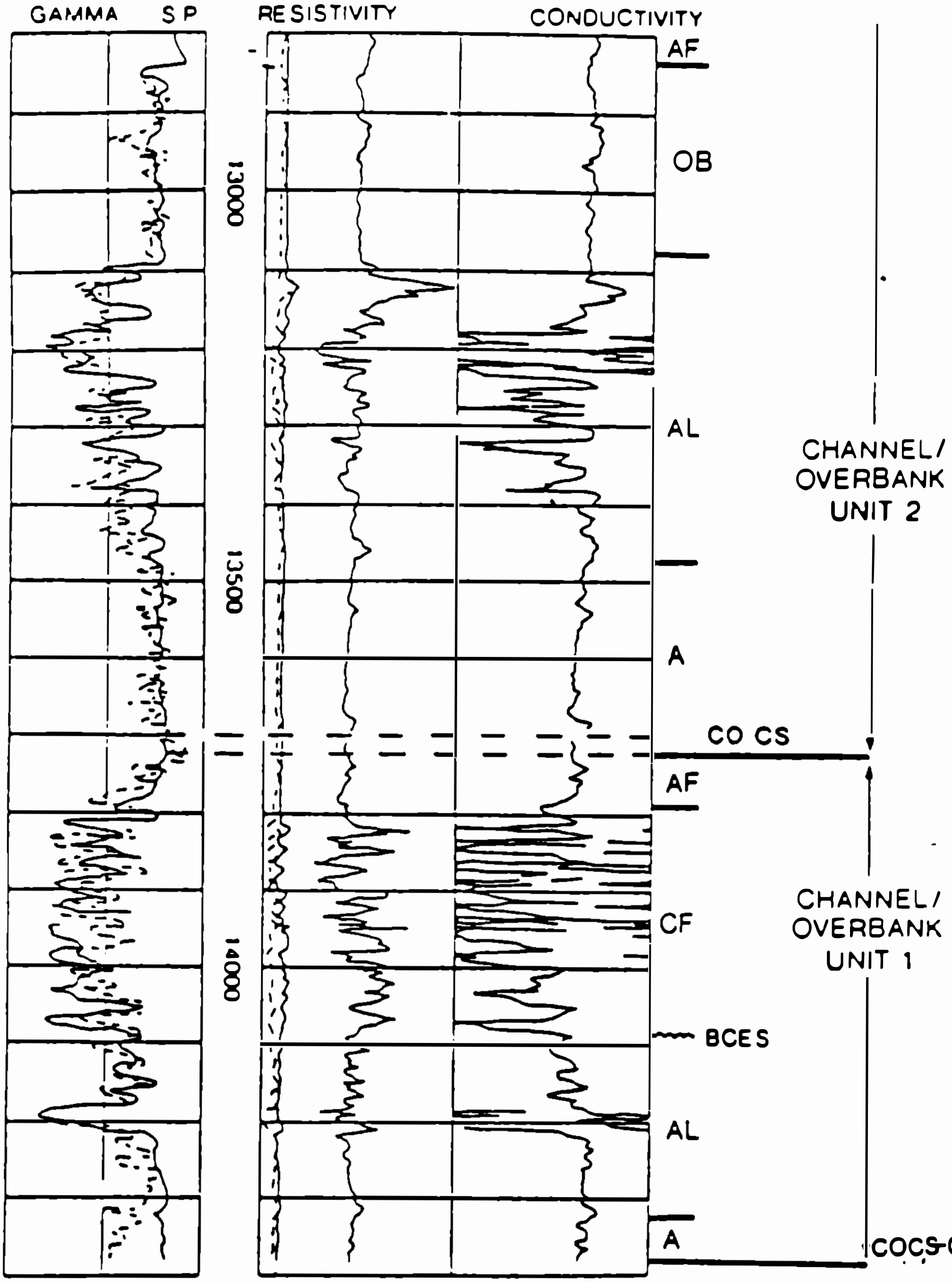
OFFSHORE LA. PLEISTOCENE

LEGEND

CO–Channel overbank condensed section
AF–Abandonment facies
CF– Channel fill
OB– Overbank
AL– Attached lobes
A– Apron
ICES– Internal channel erosional surface
BCES– Basal channel erosional surface

1952

EXAMPLE 2: LOWSTAND SYSTEMS TRACT-SLOPE FAN



OFFSHORE LA. PLEISTOCENE

LEGEND

COCS-Channel overbank condensed section
AF- Abandonment facies
CF- Channel fill
OB- Overbank
AL-attached lobes
A- Apron
ICES- Internal channel erosional surface
BCES- Basal channel erosional surface

195c

LOW RESISTIVITY PLIOCENE SANDS

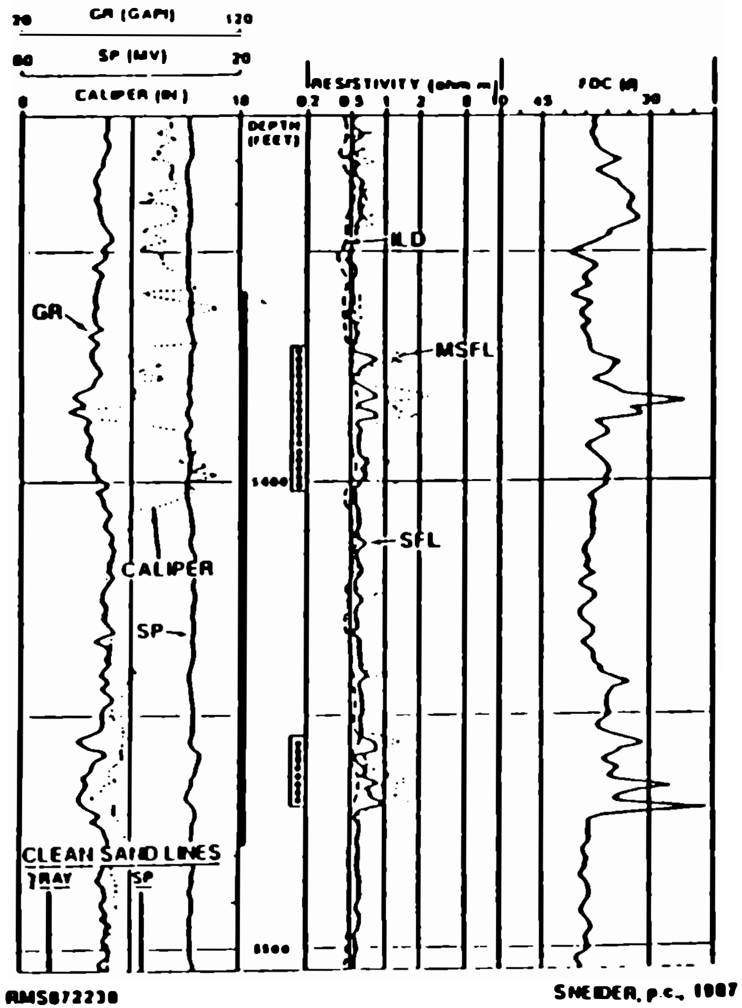
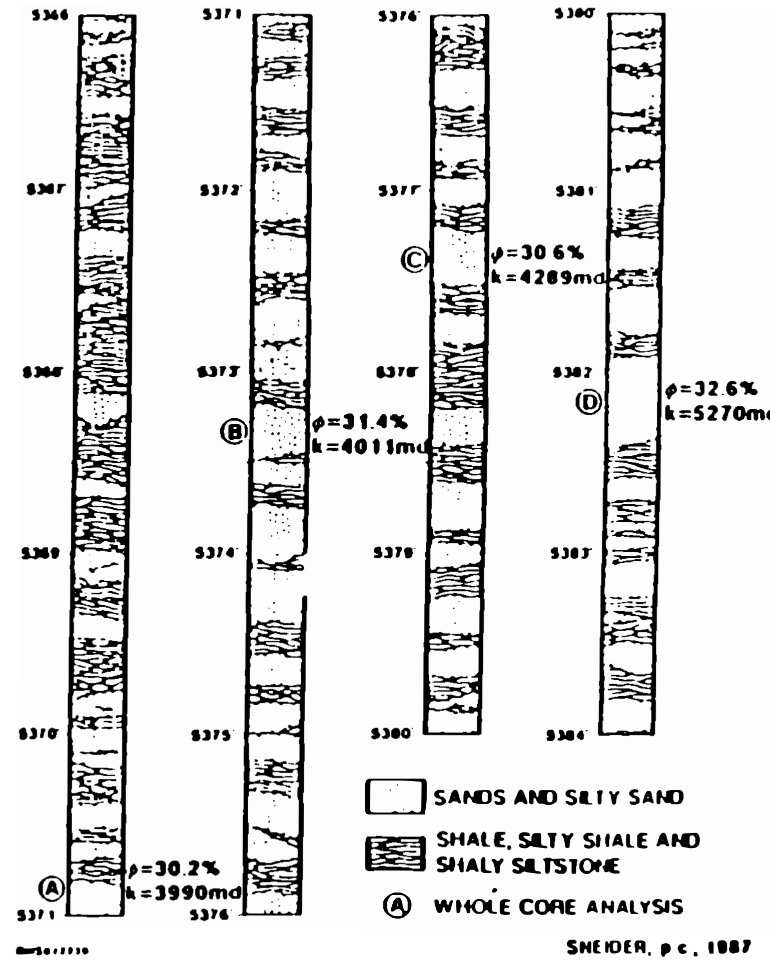


Figure Log of slope fan overbank sands.

CORE OF LOW RESISTIVITY PLIOCENE SAND



Core of slope fan overbank sands (from Fig. 6)

SLOPE FAN (LEVEED CHANNEL FACIES - LCF)
EXPLORATION APPLICATIONS

RESERVOIR

5-40 m SANDS IN CHANNELS. THIN (1-30 cm) SANDS IN OVERBANK FACIES. CHANNEL SANDS DISCONTINUOUS. OVERBANK SANDS MAY BE QUITE WIDESPREAD. OVERBANK SANDS DIFFICULT TO RECOGNIZE AND EVALUATE.

SOURCE

UNCERTAIN, PROBABLY DEEP.

SEAL

INTERNAL SHALE SEALS. TOP SEAL C.S. OVERBANK SANDS LIMITED BY LEVEES AND APRON-EDGE PINCH OUTS.

MIGRATION

UNCERTAIN, PROBABLY VERTICAL, VIA FAULT CONDUITS OR FROM LSF.

TRAPS

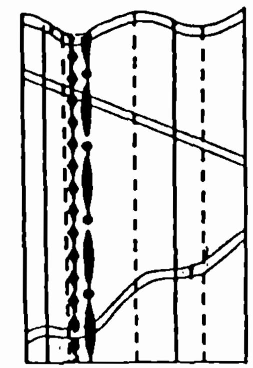
TYPICALLY STRATIGRAPHIC. SOME STRUCTURAL ENHANCEMENT.

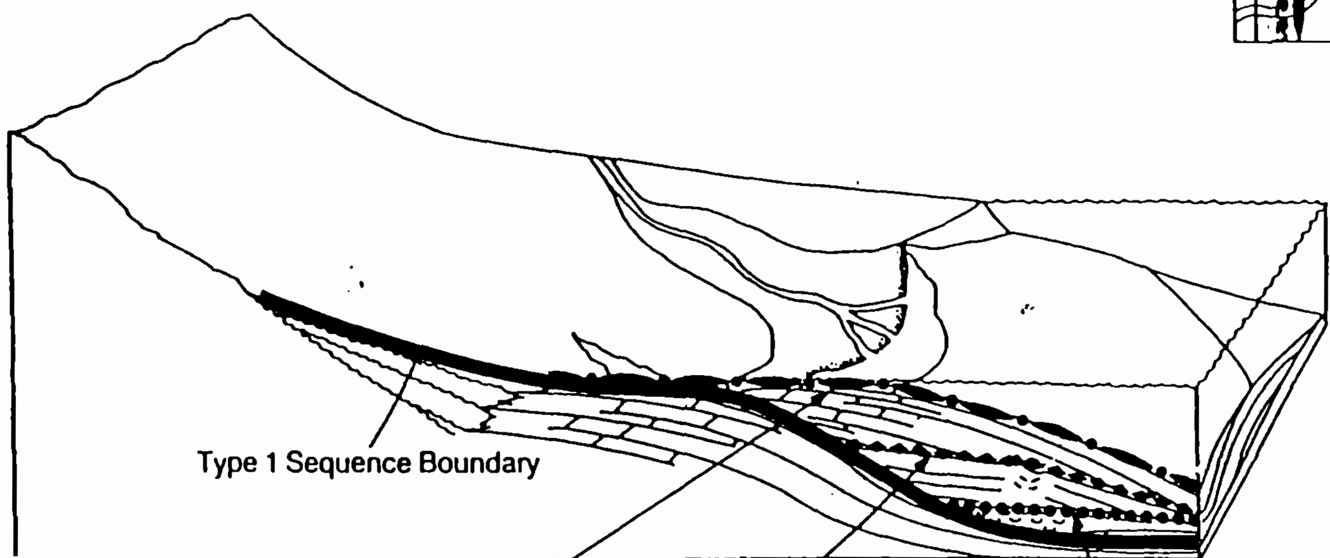
JOS872346

Fig. 5

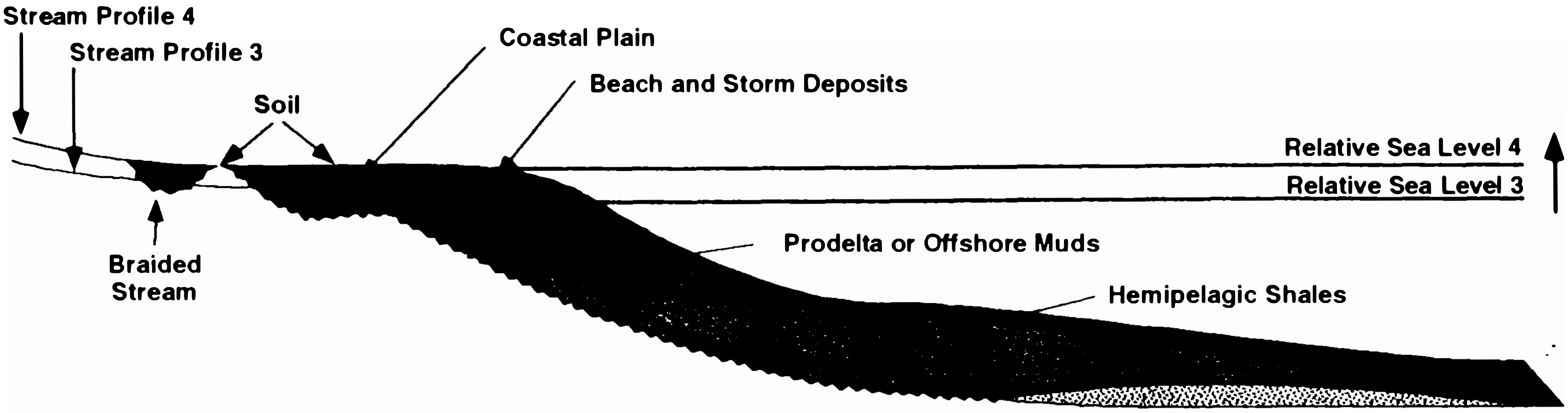
MICRO-STRAT INC. 1-90 ©
JBS, PRV & WWW

LOWSTAND SYSTEMS TRACT
PROGRADING COMPLEX





LOWSTAND SYSTEMS TRACT - PROGRADING COMPLEX
LOW TO MODERATE SEDIMENTATION RATES
Siliciclastics



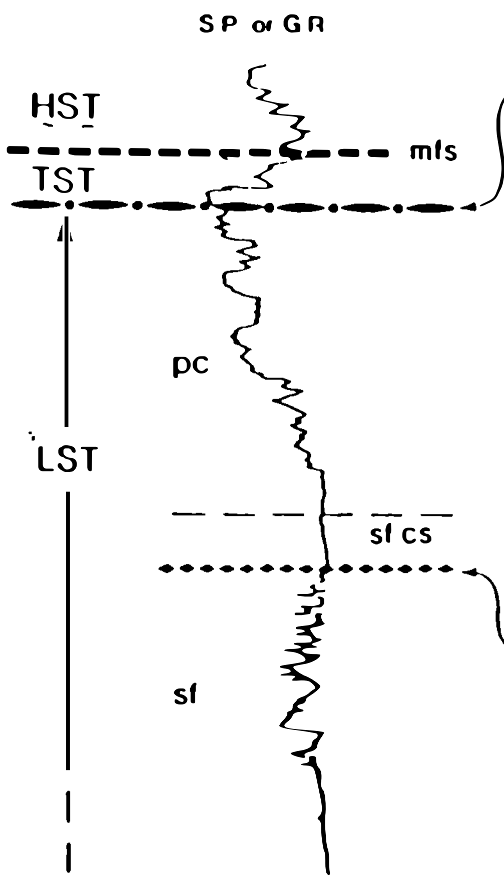
Depositional Systems:
1) Soils
2) Incised Valley Fills
3) Wave Dominated Deltas
4) Beach and Storm Deposits
5) Tidal Dominated Deltas
6) Slide Blocks

Dominant Depositional and Erosional Processes:
1) Soil Formation
2) Fluvial
3) Deltaic
4) Beach
5) Storm
6) Tidal
7) Shallow Marine
8) Hemipelagic

Major Lithofacies:
1) Soils
2) Braided Streams
3) Tidal Deposits
4) Coastal Plain
   - usually sand rich
   - sometimes shale rich
5) Beach and Storm Sands
   - Foreshore
   - Upper Shoreface
   - Lower Shoreface
   - Transitional
6) Prodelta
7) Offshore
8) Hemipelagic

LOWSTAND SYSTEMS TRACT–PROGRADING COMPLEX

Characteristic Well Response



TOP LOWSTAND SURFACE

- Transition from upward shallowing to upward deepening
- Toplap common below boundary
- Transgressive surface of erosion (ravinement surface) on the shelf

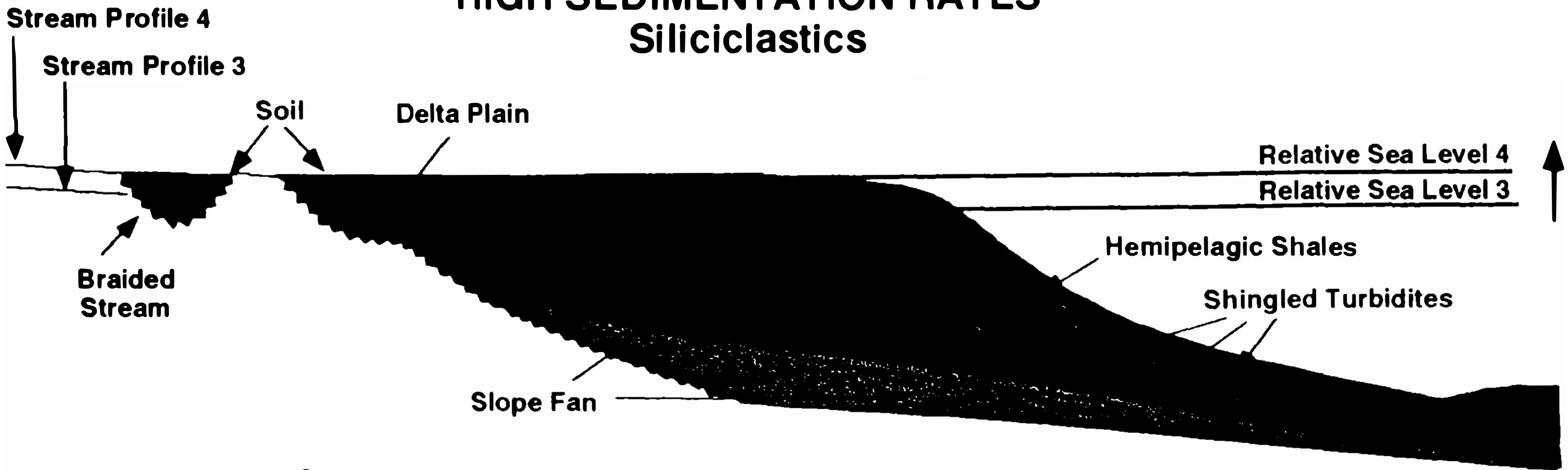
INTERVAL

- Thick intervals of coarsening upward sands common near top
- Shoreface and deltaic sands typical
- Progrades laterally into bathyal hemipelagic shale
- Pinches out near offlap break of underlying highstand
- May contain shingled turbidite mounds at base

LOWER BOUNDARY

- Slope fan Condensed Sections
- Maximum clay–shale point
- Faunal abundance peak
- Downlap common above boundary

LOWSTAND SYSTEMS TRACT - PROGRADING COMPLEX
HIGH SEDIMENTATION RATES
Siliciclastics

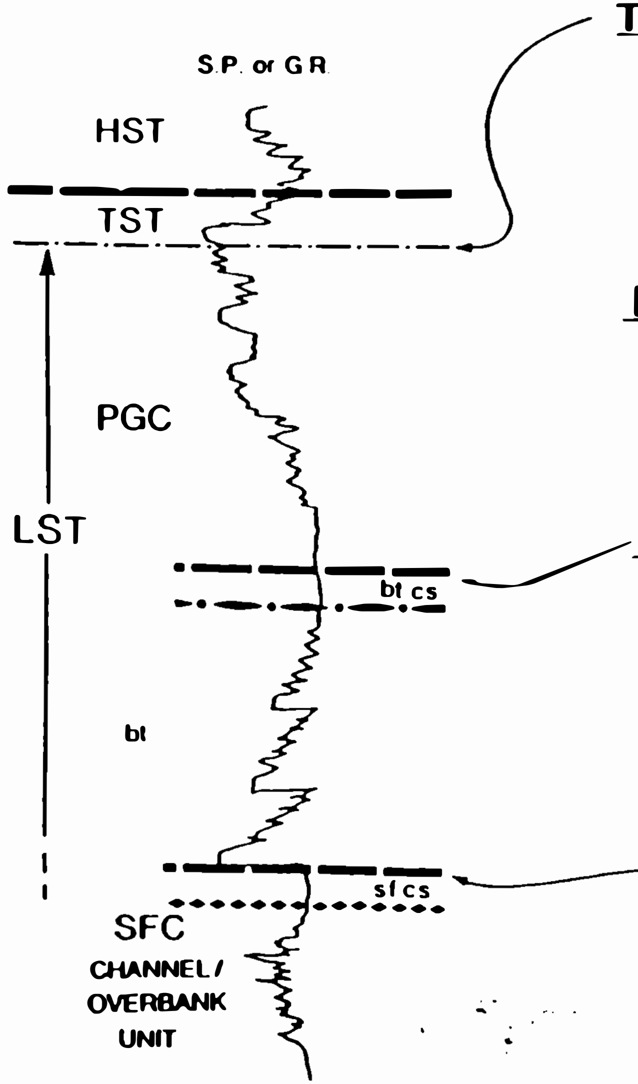


Depositional Systems:
1) Soils
2) Incised Valley Fills
3) Deltas
4) Slumps
5) Bottom Set (Shingled) Turbidites
6) Hemipelagic Deposits

Dominant Depositional and Erosional Processes:
1) Soil Formation
2) Fluvial
3) Deltaic
4) Slumping of Delta Front
5) Turbidites
6) Suspension

Major Lithofacies:
1) Soil
2) Braided Streams
3) Deltaic (usually wave or fluvial dominated)
   - Delta Plain
   - Delta Front
4) Tidal Sands in absense of deltas
5) Slump blocks and Olistostroms at end of LPC in tectonically active areas
6) Bottom Set (Shingled) Turbidite Sands
7) Hemipelagic Shales

PROGRADING COMPLEX
BOTTOM-SET (SHINGLED) TURBIDITES
CHARACTERISTIC WELL RESPONSE



TOP LOWSTAND SURFACE

Transition from upward shallowing to upward deepening
Toplap below boundary
Transgressive surface of erosion on the shelf

INTERVAL

Thick intervals of blocky sands common near top
Fluvial and deltaic sands typical
Progrades laterally into bathyal shales
PGC pinches out against break-in-slope at shelf edge

UPPER BOUNDARY

Maximum clay-shale point
Minor faunal abundance peak (bt cs)

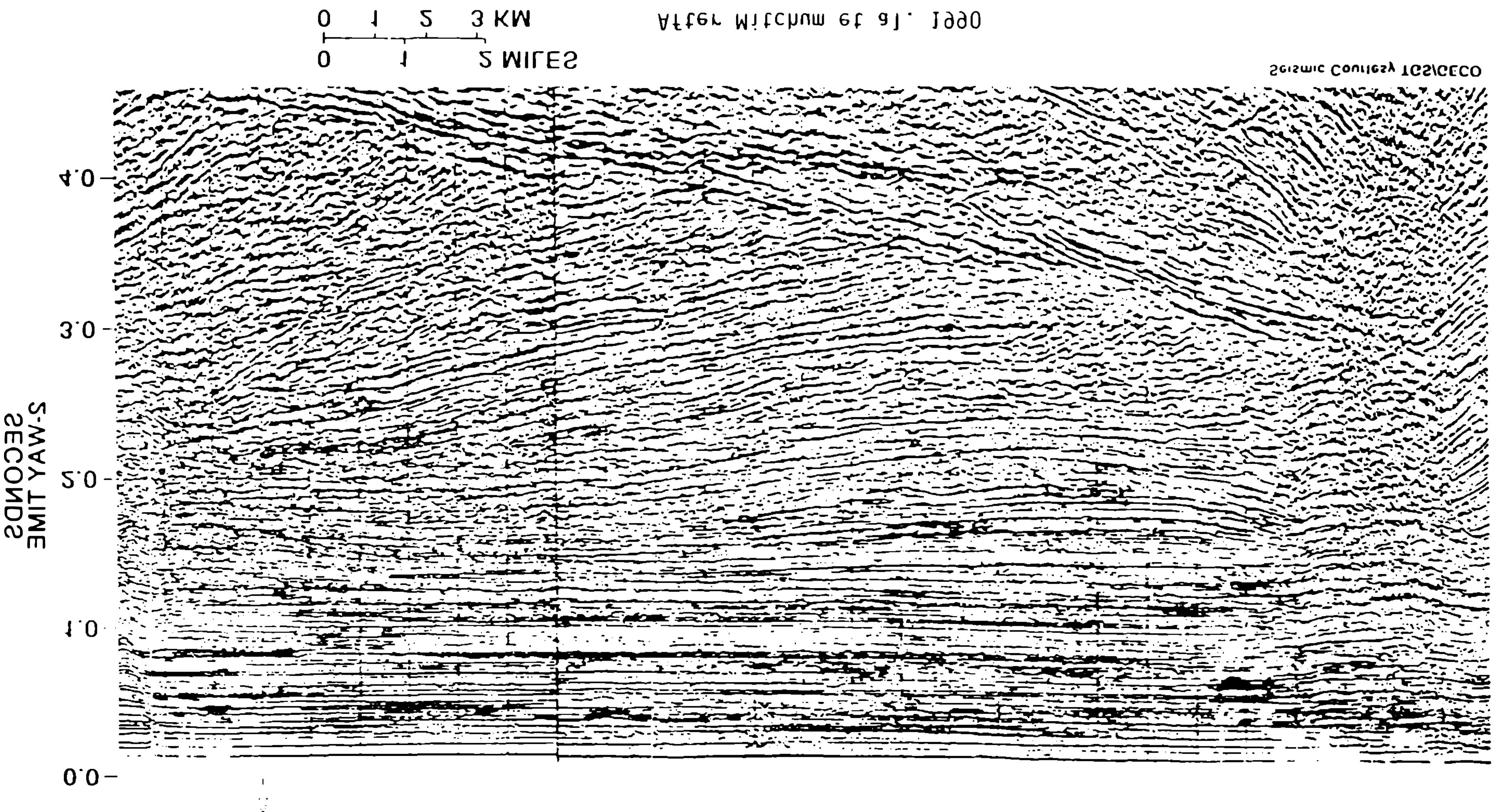
INTERVAL

Series of thin units with blocky sand at base and each unit fines upward ("Christmas tree" pattern)
Sand units are separated by thin hemipelagic shales
Overall pattern is commonly fining upward

LOWER BOUNDARY

Hemipelagic shale
Well developed abundance peak (sf cs)

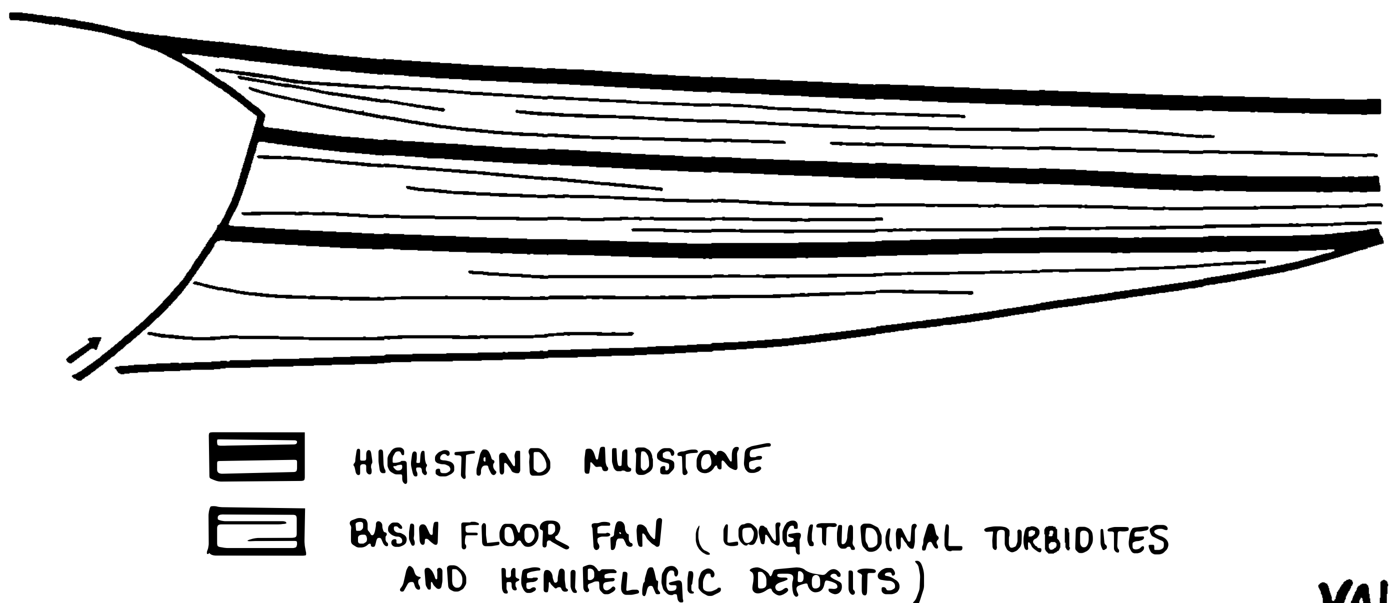
Figure 2A. Uninterpreted seismic section, Gulf of Mexico, in a typical Late Cenozoic expanded section on the downthrown side of a large expansion fault. An associated calibration well is not shown. Section courtesy of TGS Offshore Geophysical Corporation.



SILICICLASTIC SYSTEMS TRACTS

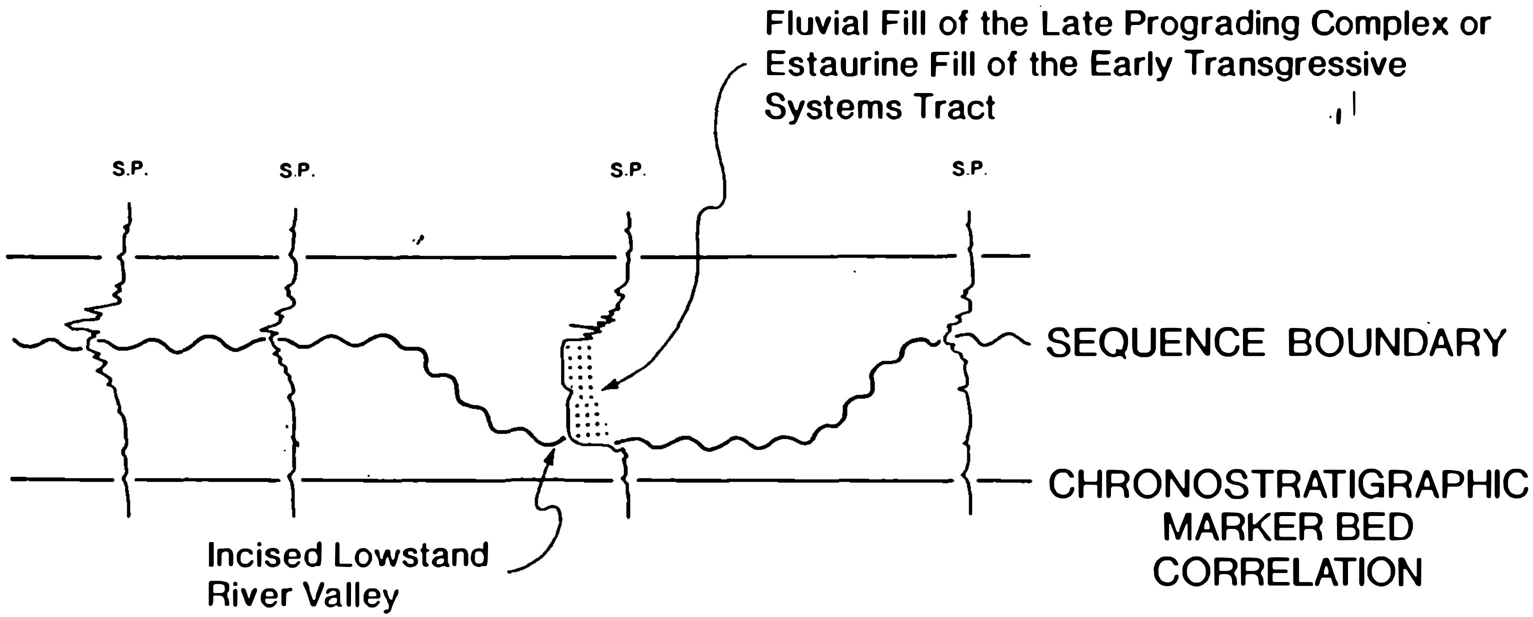
DEEP FORELAND SETTING

(TECTONICALLY RELATED SEQUENCES)



VALENTI, '91

CHANNELIZED SEQUENCE BOUNDARY



PROGRADING COMPLEX

EXPLORATION APPLICATIONS

RESERVOIR

VARIABLE: STACKED FLUVIAL, DELTAIC AND SHOREFACE. VARIABLE CONTINUITY.

SOURCE

DEEPER BEDS, OR TST SOURCE AT TOP.

SEAL

GOOD TST TOP SEAL. LATERAL SEAL MAY BE POOR.

MIGRATION

PROBABLY DEPENDS ON FAULT CONDUITS FROM DEEPER SOURCE. POSSIBLE DOWNWARD MIGRATION FROM TST.

TRAPS

TYPICALLY STRUCTURAL. POSSIBLE COMPACTION CLOSURE.

J8S872345

INCISED VALLEY FILL (IVF)
EXPLORATION APPLICATIONS

RESERVOIR

BRAIDED STREAM SANDS TYPICAL. GOOD TO FAIR CONTINUITY.

SOURCE

TOP SOURCE FROM TST. POSSIBLE DEEP SOURCES.

SEAL

TST SHALES. POOR LATERAL SEAL.

MIGRATION

DOWNWARD FROM TST. POSSIBLE VERTICAL MIGRATION VIA FAULTS.

TRAPS

TYPICALLY REQUIRES STRUCTURAL CLOSURE OR NOSE.

J8S872348

SUBMARINE CANYON FILL (SCF)

EXPLORATION APPLICATIONS

RESERVOIR

VERY VARIABLE. SUBMARINE CHANNEL SANDS, TURBIDITES. POOR CONTINUITY.

SOURCE

UNCERTAIN. CONTEMPORANEOUS SOURCE IS PROBABLY GAS PRONE.

SEAL

LOCAL SHALE SEALS.

MIGRATION

UNCERTAIN. VERTICAL MIGRATION VIA FAULTS MAY BE BEST.

TRAPS

STRATIGRAPHIC PINCH-OUTS.

J0S872344

Fig. 10

SURFACES

(SB) SEQUENCE BOUNDARIES
- (SB 1) = TYPE 1
- (SB 2) = TYPE 2

(DLS) DOWNLAP SURFACES
- (mfs) = maximum flooding surface
- (tbfs) = top basin floor fan surface
- (tsfs) = top slope fan surface

(TS) TRANSGRESSIVE SURFACE
- (First flooding surface above maximum progradation)

SYSTEMS TRACTS

HST = HIGHSTAND SYSTEMS TRACT

TST = TRANSGRESSIVE SYSTEMS TRACT
- ivf = incised valley fill

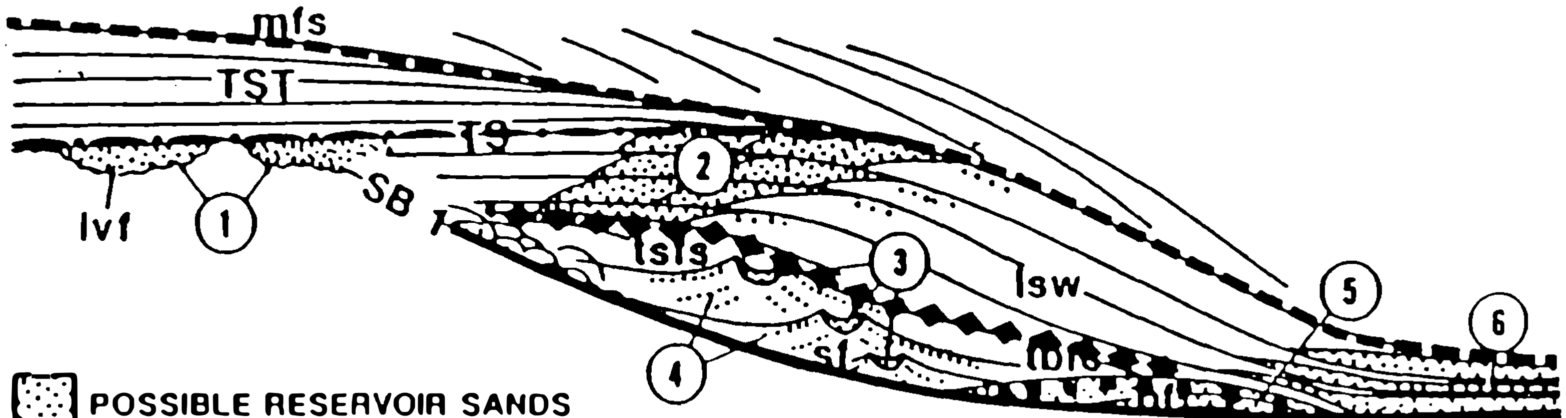
LST = LOWSTAND SYSTEMS TRACT
- ivf = incised valley fill
- lsw = lowstand wedge-prograding complex
- sf = lowstand slope fan
- bf = lowstand basin floor fan

SMST = SHELF MARGIN SYSTEMS TRACT

JBS882398

VAIL, 1987

Figure



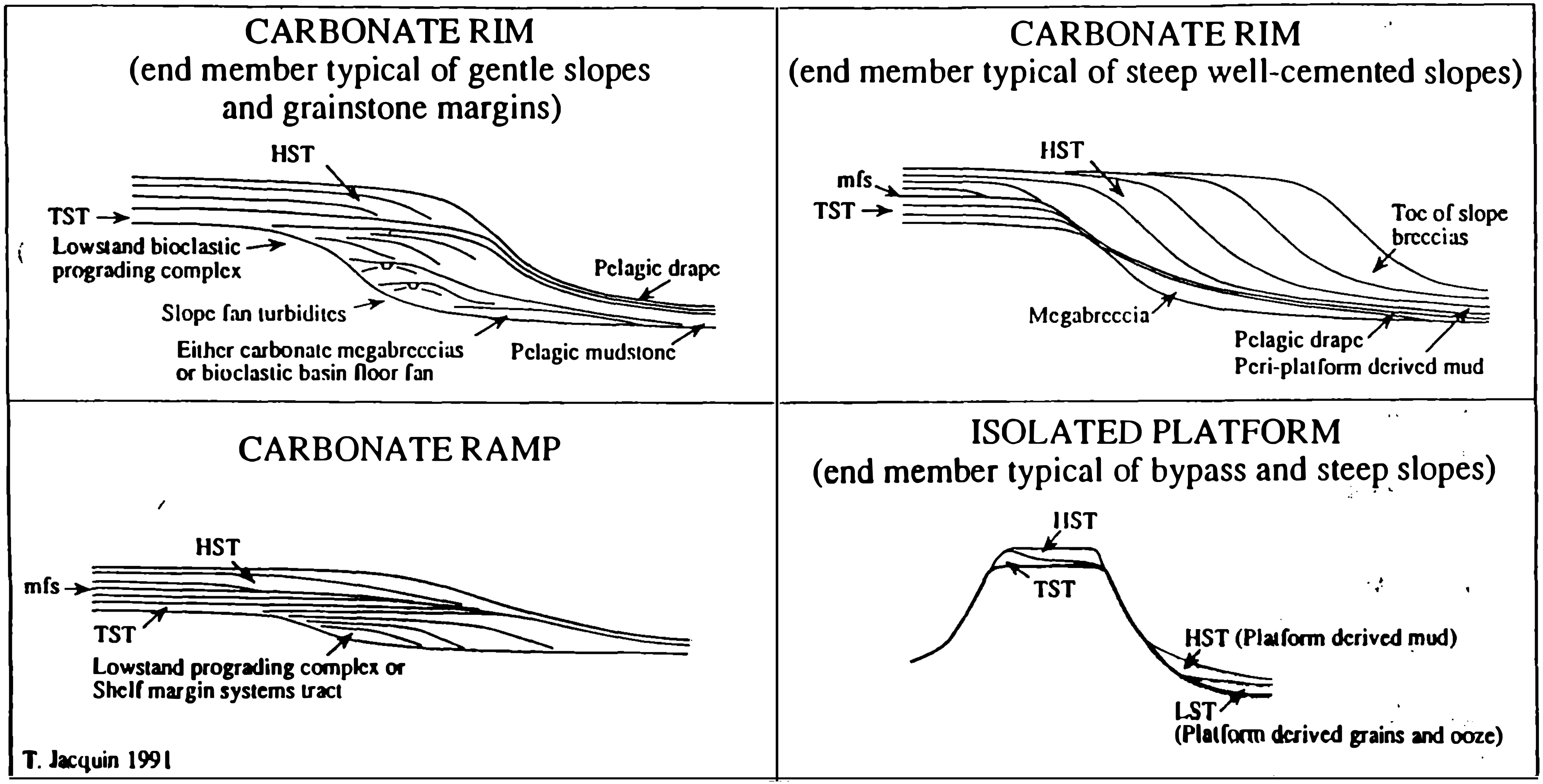
POSSIBLE RESERVOIR SANDS

1. INCISED VALLEY FILL SANDS
2. COASTAL BELT SANDS
3. CHANNEL/OVERBANK CHANNEL SANDS
4. OVERBANK SANDS
5. BASIN FLOOR FAN
6. SHINGLED TOE OF LOWSTAND PROGRADING WEDGE SANDS

JBS882399

VAIL 1987

VARIATIONS IN CARBONATE SYSTEMS TRACTS



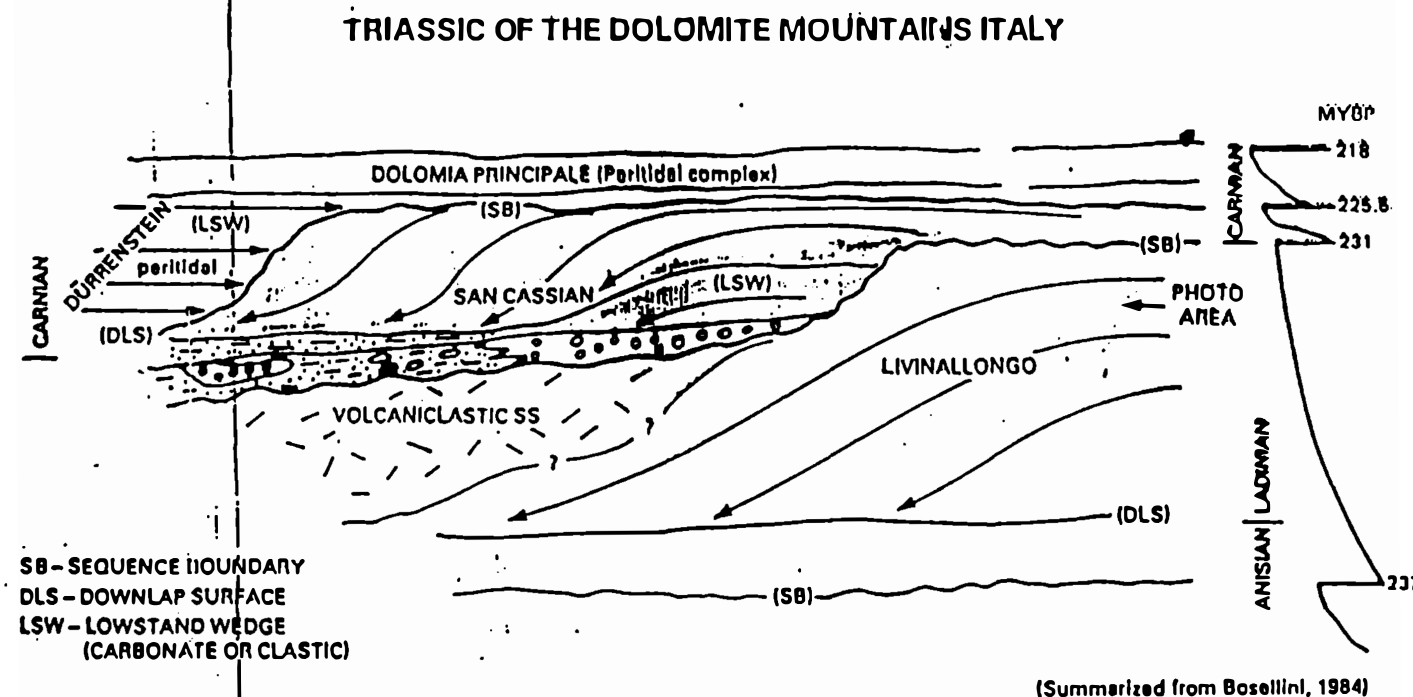
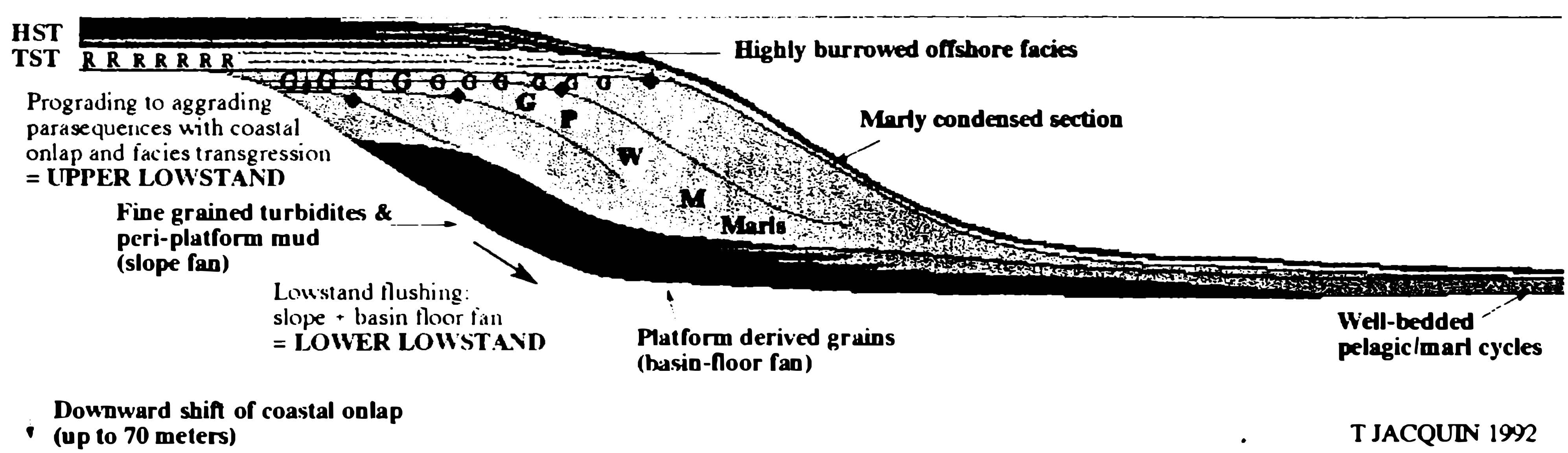
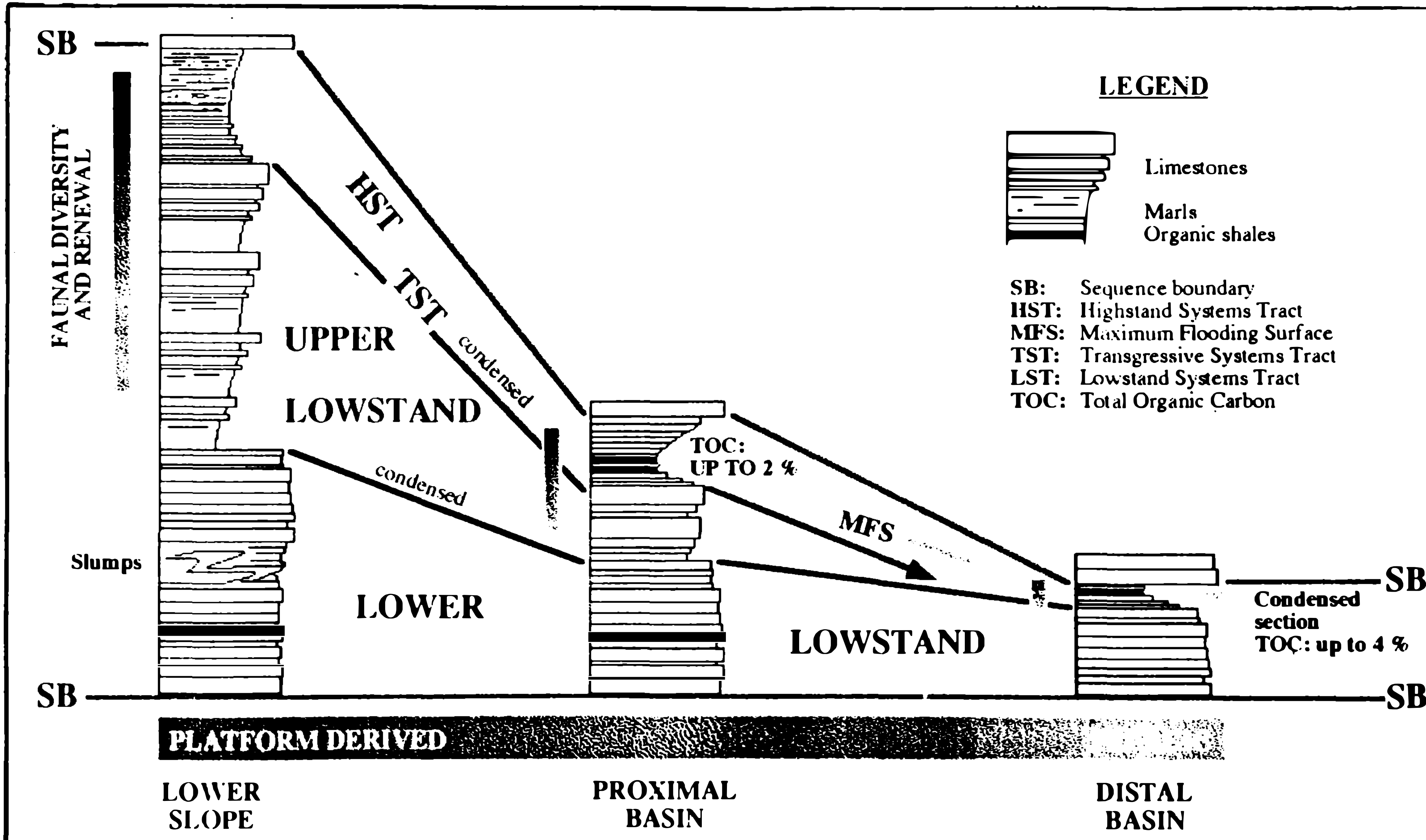


FIG. 23.—Schematic summary of Triassic carbonate sequences, Dolomite Mountains, northern Italy (Interpreted from Bosellini, 1984).

Sarg, 1988

GENERALIZED RELATIONSHIP OF FACIES TO THIRD-ORDER SYSTEMS TRACTS WITHIN THE 2ND ORDER REGRESSIVE PHASE - VERCORS PLATEAU
(H4 to B4 depositional sequences)




SB
FAUNAL DIVERSITY AND RENEWAL
Slumps
HST
TST
condensed
UPPER
LOWSTAND
condensed
LOWER
TOC: UP TO 2 %
MFS
LOWSTAND
SB
Condensed section TOC: up to 4 %
SB
SB
PLATFORM DERIVED
LOWER SLOPE
PROXIMAL BASIN
DISTAL BASIN
LEGEND
Limestones
Marls
Organic shales
SB: Sequence boundary
HST: Highstand Systems Tract
MFS: Maximum Flooding Surface
TST: Transgressive Systems Tract
LST: Lowstand Systems Tract
TOC: Total Organic Carbon

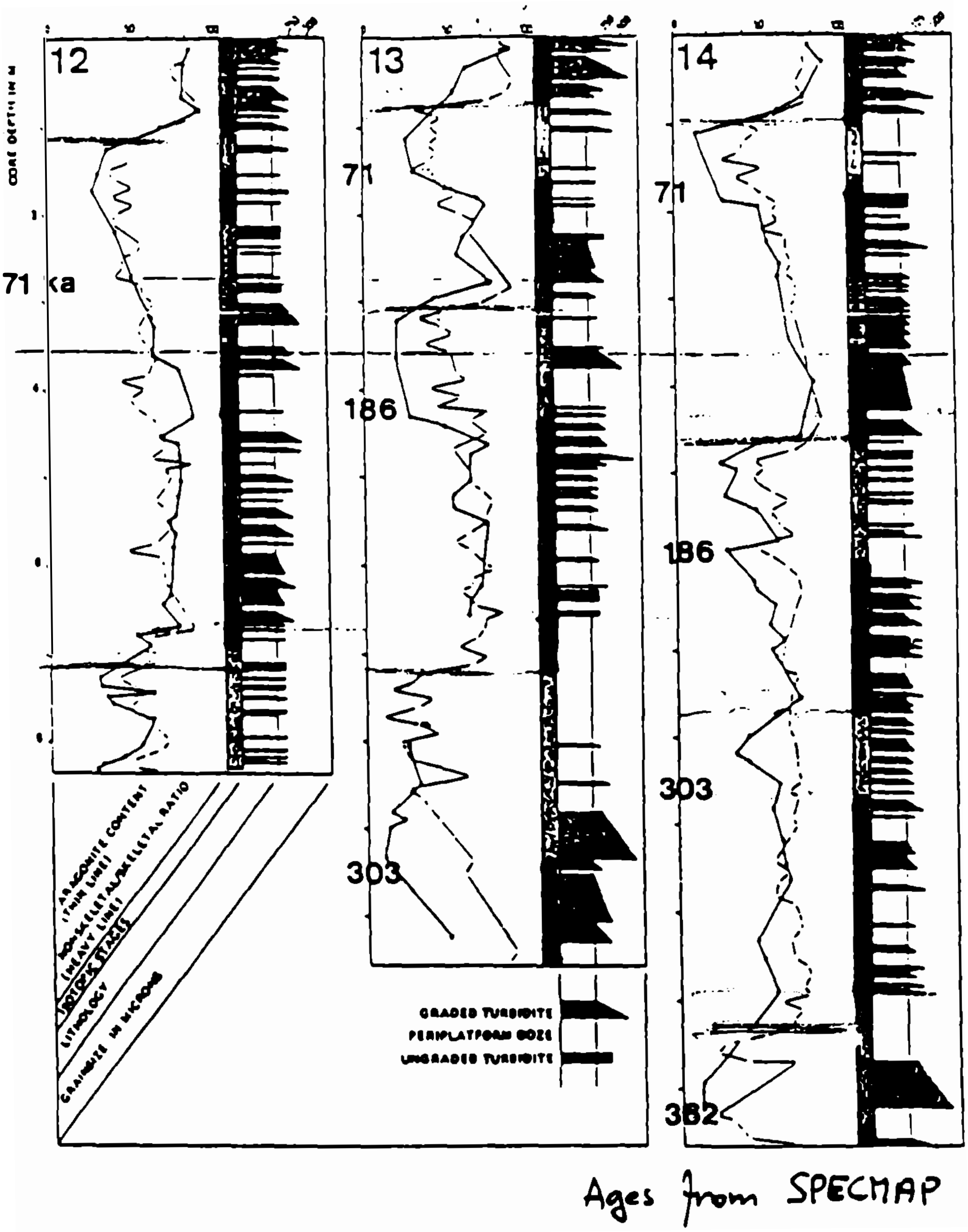


Fig.4 Highstand bundles and compositional signals in calciturbidites from Quaternary cores of Tongue of the Ocean, a basin surrounded by the Great Bahama Bank. Turbidites are most abundant during interglacial highstands of the sea, when platform tops are flooded and produce sediment. Turbidites also vary in composition: Highstand layers are rich in pellets and ooids - i.e. grains that form on the shallow banks by the interaction of tidal currents and waves. Lowstand turbidites consist mainly of skeletal material, including reef detritus, because fringing reefs and skeletal sand can migrate downslope with falling sea level. Glacial-interglacial stratigraphy is provided by variation in aragonite/calcite ratio, a property that is closely correlated with the oxygen isotope curve (glacial isotope stages are shaded). After Haak & Schlager (1989).

adapted from Haak and Schlager, 1989

reinterpreted by Vail, 1991

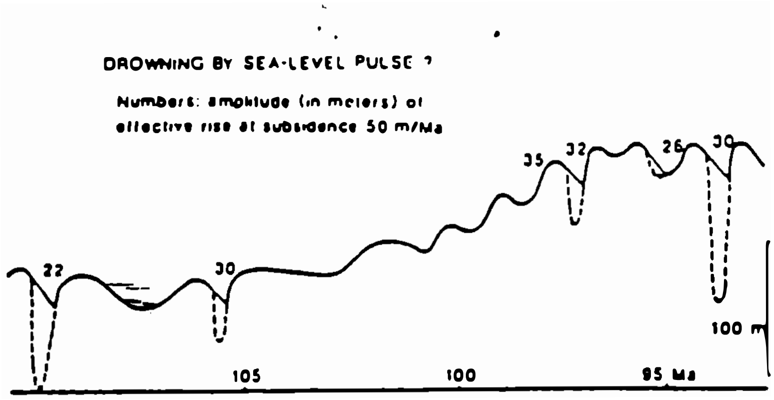


Fig.15 Postulated eustatic sea level curve (Haq et al., 1987) for the mid-Cretaceous, a time of global platform drowning. A platform that kept up with rising sea level and subsided at 50 m/Ma must have been exposed during the dotted intervals of the curve and experienced only the fluctuations drawn in full. The amplitudes of these effective sea-level rises are shown in meters on the graph. They are too small to move a platform out of the photic zone and often too small to even remove it from the zone of light saturation.

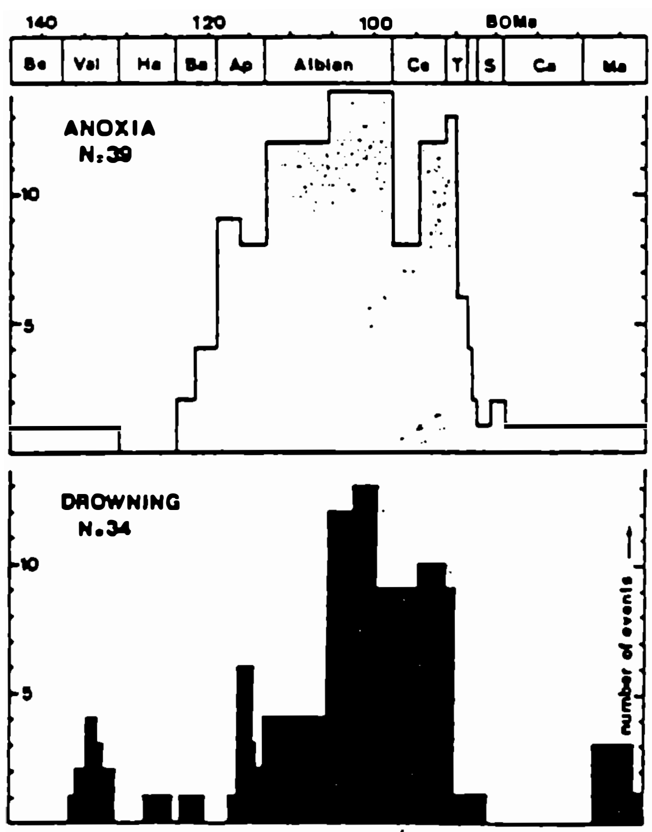


Fig.16 Frequency distribution through time of oceanic anoxic events (top) and platform drownings (bottom). The coincidence in time supports the idea of a causal link. This may be one example of environmental control on depositional sequences and sequence boundaries. After Schlager & Philip (1990).

HST-ALLUVIAL FAN FACIES (AF)
EXPLORATION APPLICATIONS

RESERVOIR
ALLUVIAL GRAVELS AND SANDS. POOR TO FAIR CONTINUITY. PERMEABILITY POOR TO FAIR. BEST RESERVOIR SANDS ARE AT TOP IN TST LAG GRAVELS.

SOURCE
DIFFICULT. BEST CHANCE IS A DEEP OLDER SOURCE.

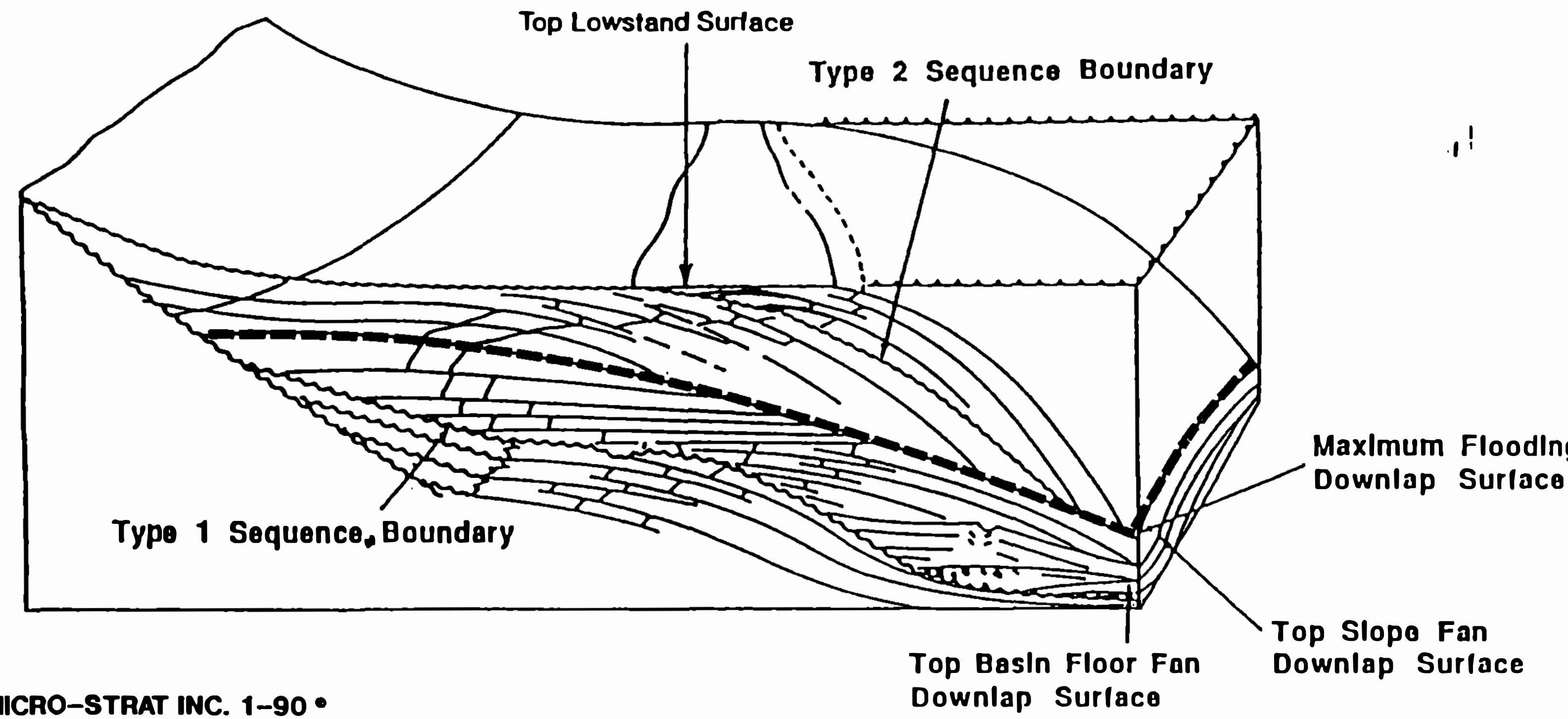
SEAL
HIGH RISK OF NO SEAL. SHALES ASSOCIATED WITH TST ARE BEST, BUT CUT BY CHANNELS.

MIGRATION
VERTICAL MIGRATION VIA FAULTS, OR MIGRATION THROUGH LATERAL HST FACIES.

TRAPS
STRUCTURAL TRAPS BEST. DEEP BASIN STRATIGRAPHIC TRAPS.

JBS872349

SHELF MARGIN SYSTEMS TRACT
SHELF MARGIN WEDGE



MICRO-STRAT INC. 1-90 ©

JBS, PRV & WWW

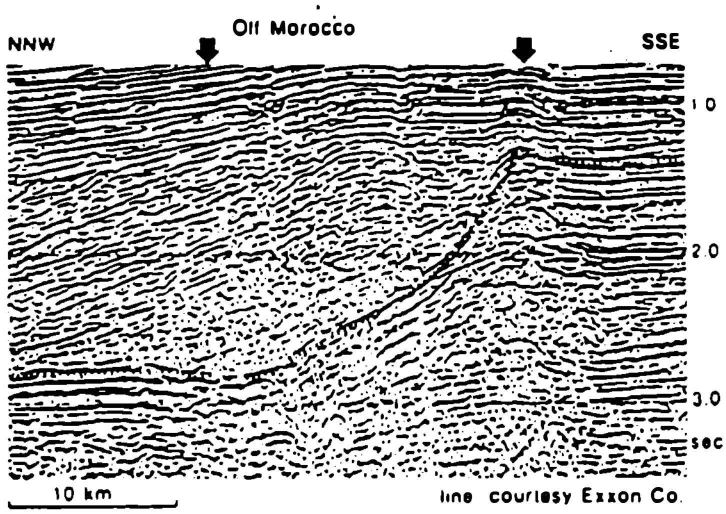
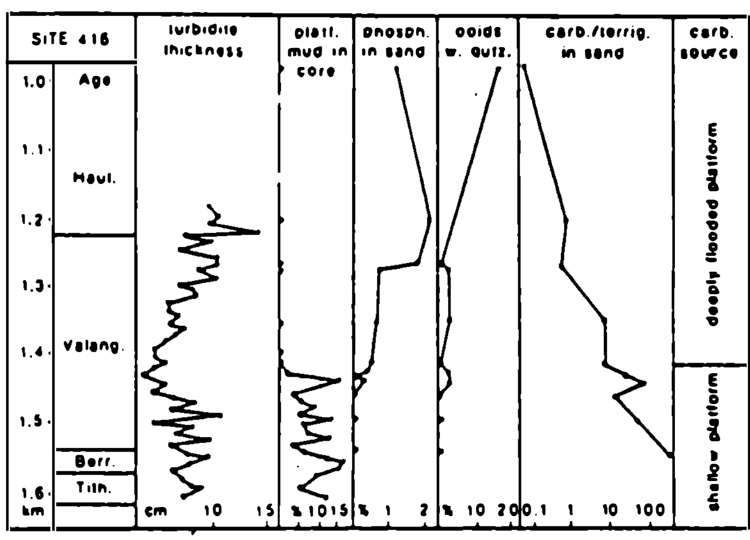


Fig.8a Unconformity on a Cretaceous-Jurassic platform off Morocco (dotted). This sequence boundary was attributed to a Valanginian lowstand by Vail et al. (1977). Schlager (1989) interpreted it as drowning unconformity. Note similarity with the coeval Wilmington platform in the nearly conjugate American margin. Note furthermore the raised rim at the platform margin and differential compaction, causing folds in overlying siliciclastics. Arrows mark positions of boreholes.



b) Turbidites in DSDP Hole 416 monitor the drowning of this platform belt: The disappearance of platform mud indicates reduction of growth; phosphate grains and ooids with quartz nuclei are new grain types, not present deeper in the section; their formation indicates continued flooding of the platform and increase of water depth rather than exposure. After Schlager (1980), modified.

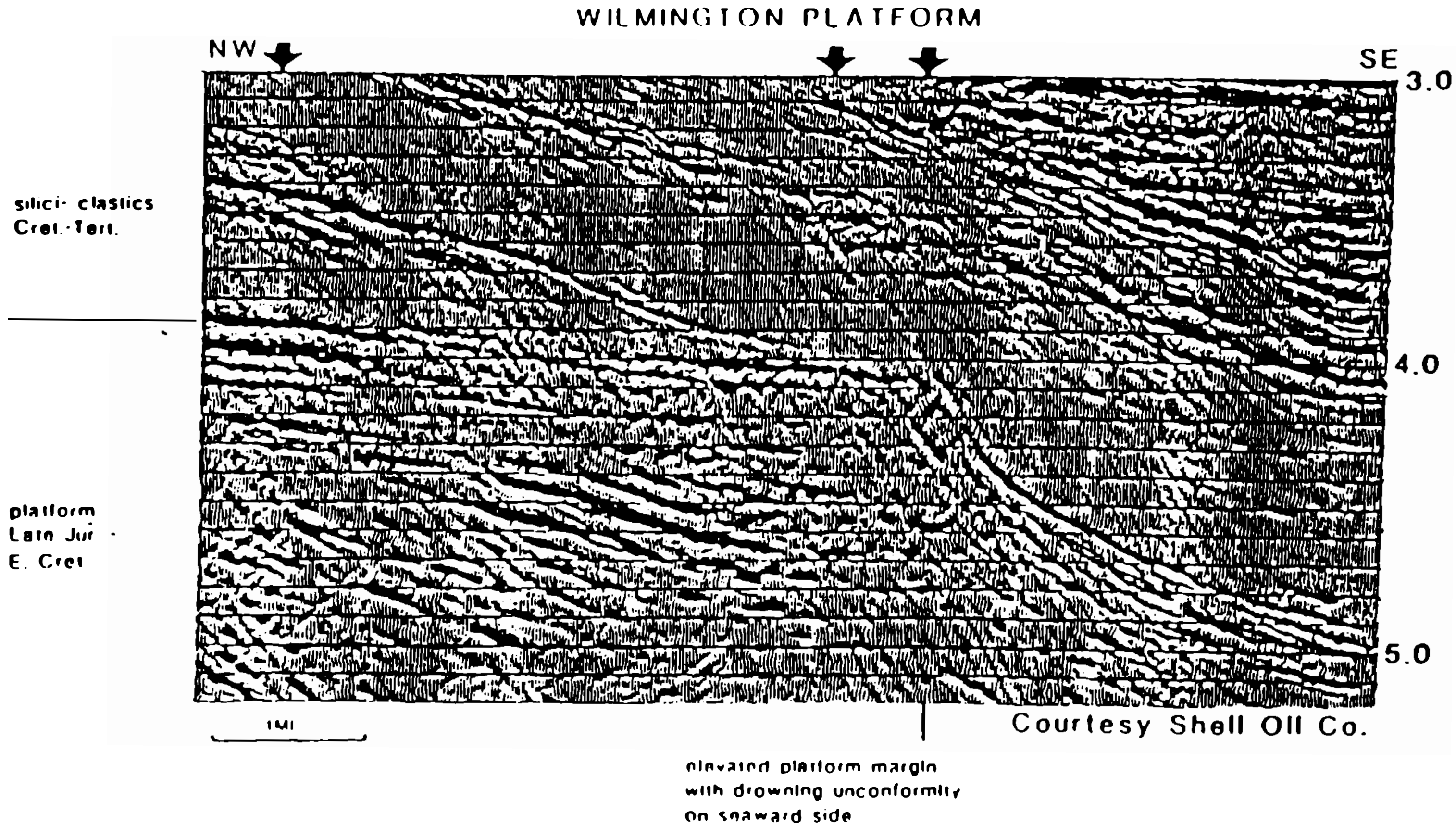


Fig.7 Drowning unconformity on Wilmington Platform. The seaward flank is over 2500 m high and is onlapped by more gently dipping, almost transparent siliciclastics. Clastics prograde over and downlap on the platform top; they also onlap the seaward flank, mimicking the geometry of a lowstand wedge. See Erlich et al. (1988), Meyer (1989) and Schlager (1989) for detailed interpretations

PART 2C:
Results of Changes in Shelfal Accommodation: Introduction to Basin Fill Model

Description Of Fig. 2-21

Initial depositional surface is shown as a heavy black line. It depicts, from left to right, the equilibrium stream gradient, shelf, slope, and basin floor.

Subsidence is shown in meters per 100,000 years by vertical arrows located below the initial surface of deposition (heavy line). The subsidence rate is 0.0 m/100 ky at the left hand edge of the figure, and increases with distance to 2.0 m/100 ky at the basin margin. The basin subsides at a constant rate of 3.0 m/100 ky.

Eustatic changes of sea level are shown in meters versus geologic time on the graph located in the upper right hand portion of the figure. Each time interval is 100,000 years in duration. Thus the total interval of time represented by geologic time lines 1 through 30 is 3 million years. Two eustatic falls are shown. The magnitude of the first eustatic fall is 80 meters and the second is 15 meters. The first fall (stratal surfaces 5-12) has a rate of eustatic fall greater than the rate of tectonic subsidence. The second fall (stratal surfaces 20-27) has a rate of eustatic fall less than the rate of subsidence.

Volume of sediments per unit time (100,000 years) corresponds to the area of the rectangular box in the left hand portion of the figure (0.01 sq. km./ 100,000 years).

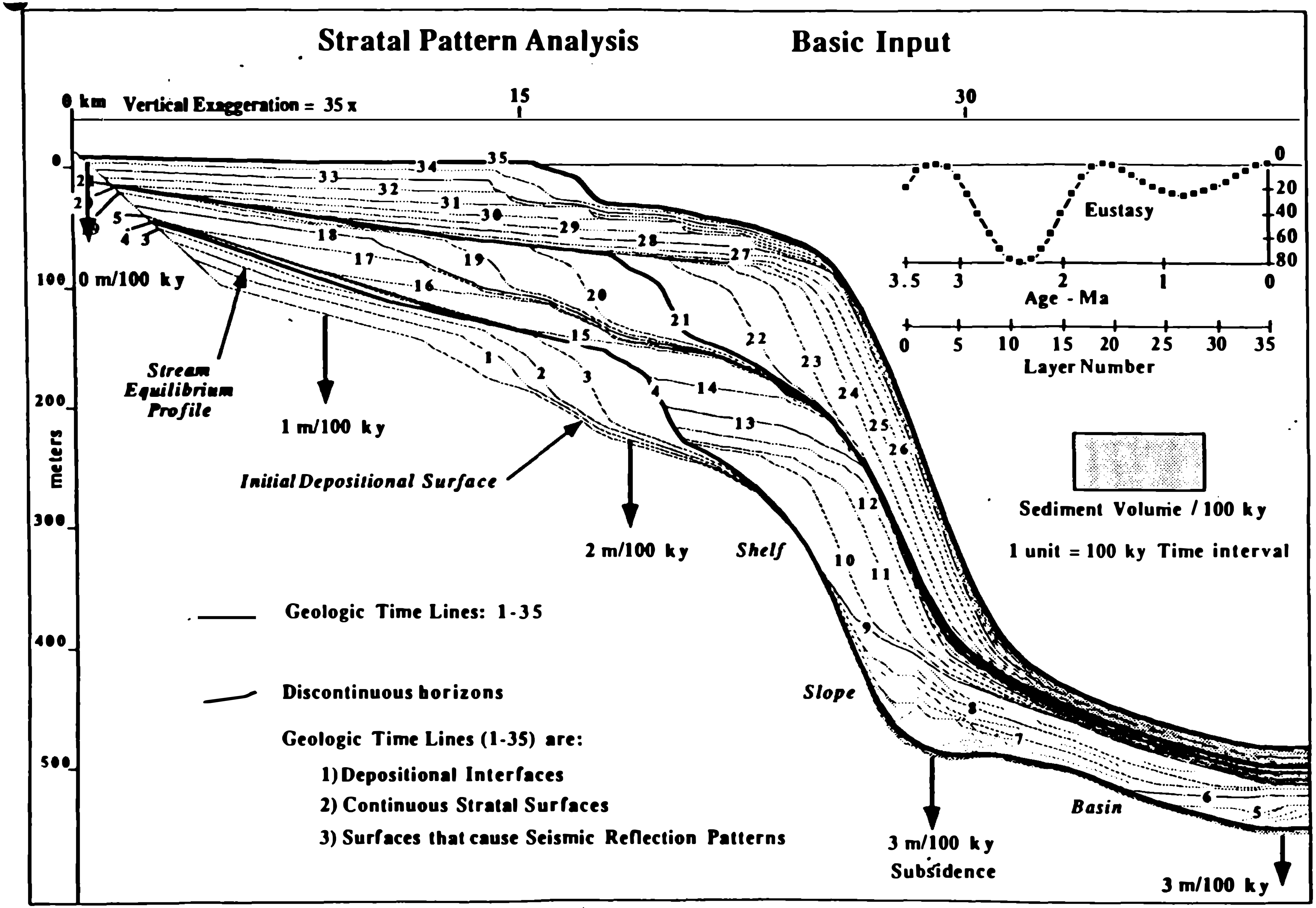
Lines mark the depositional interface after the sediment supply is exhausted at the end of each 100,000 year time increment. Therefore, the lines mark the position of each 100,000 year geologic time line at the end of the model run. They form continuous stratal surfaces that correspond to reflection events in a seismic depth section. They are depositional interfaces that separate older from younger rocks. The diagram simulates the primary reflection patterns as recorded on seismic profiles.

Basic Assumptions of diagram:

The sediment supply rate is constant through time.

Erosion is not present.

All depositional processes occur within the two-dimensional cross-section.



Bowman 9.26.91.1

Fig. 2-21

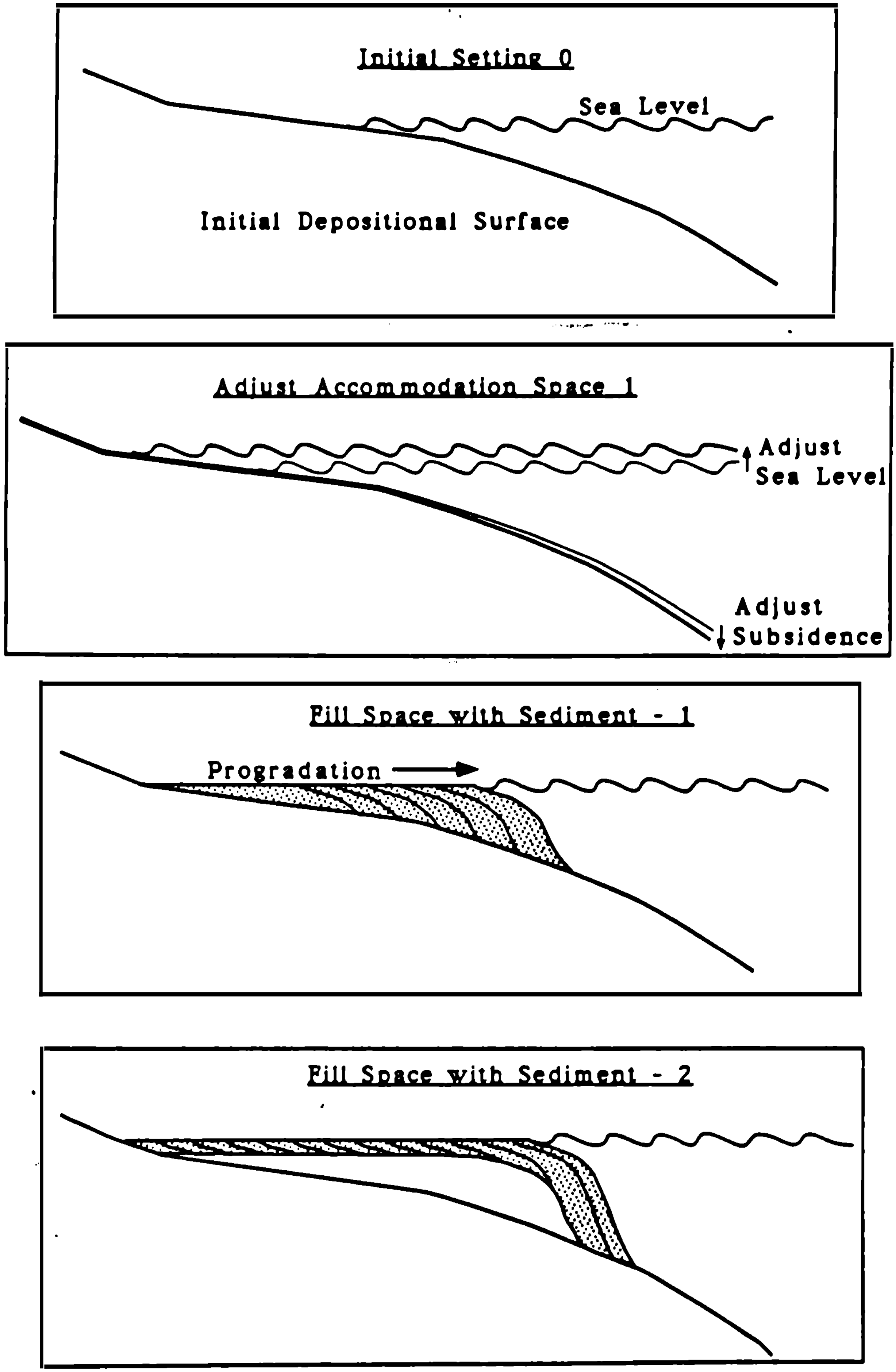

Initial Setting 0
Sea Level
Initial Depositional Surface
Adjust Accommodation Space 1
Adjust Sea Level
Adjust Subsidence
Fill Space with Sediment - 1
Progradation
Fill Space with Sediment - 2

Fig. 2-22

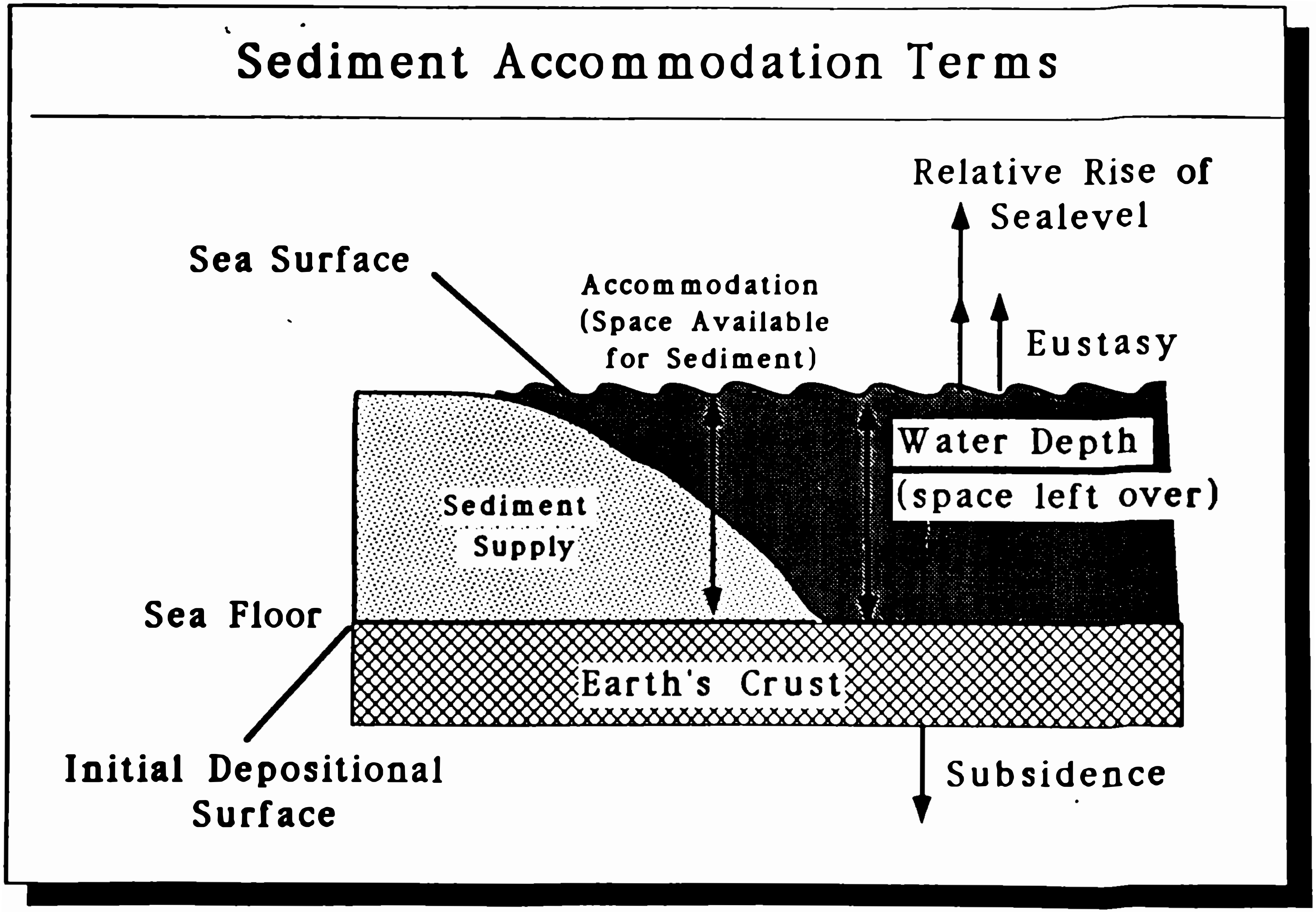
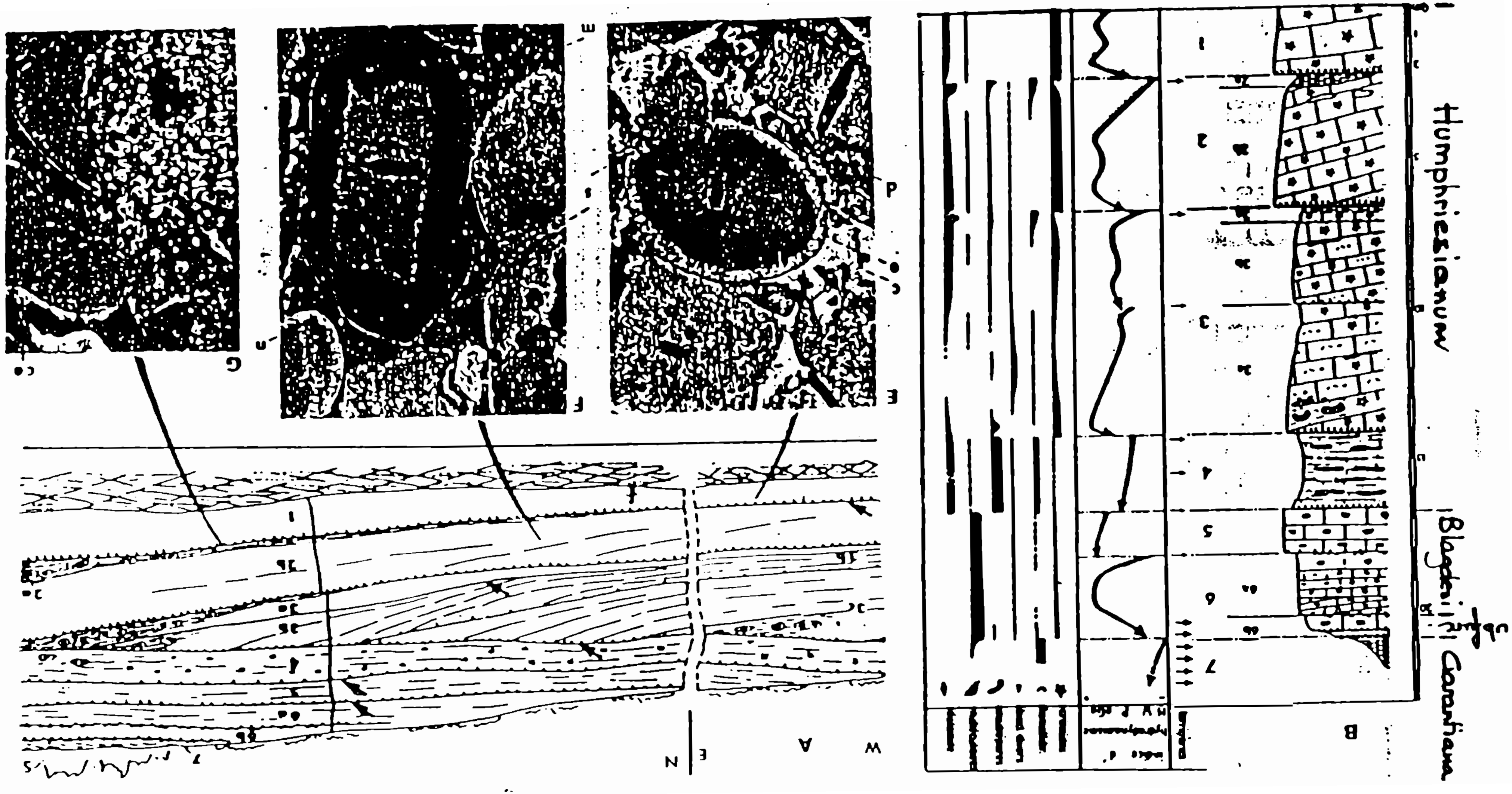
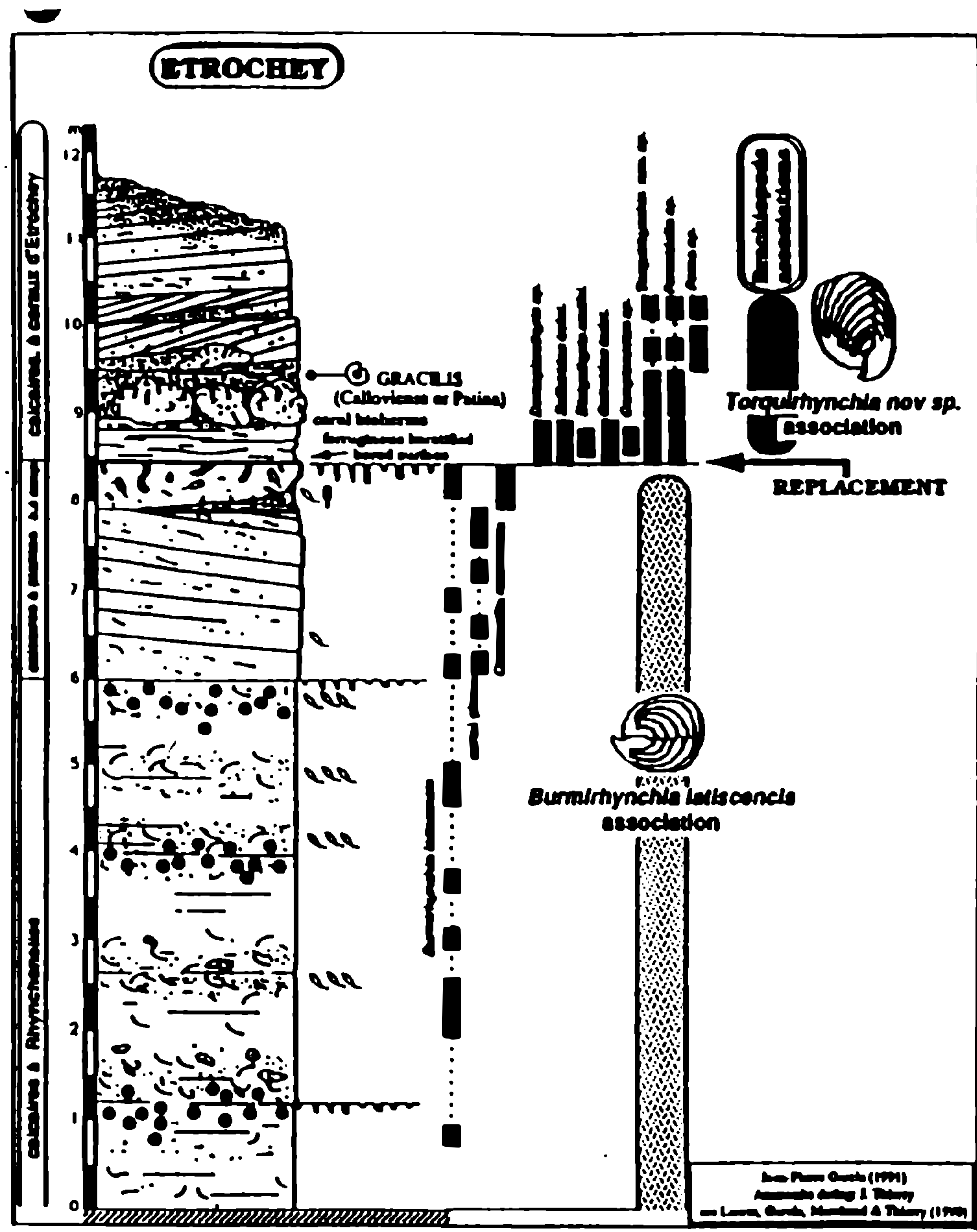

Sediment Accommodation Terms
Relative Rise of Sealevel
Sea Surface
Accommodation (Space Available for Sediment)
Eustasy
Water Depth
(space left over)
Sediment Supply
Sea Floor
Earth's Crust
Initial Depositional Surface
Subsidence

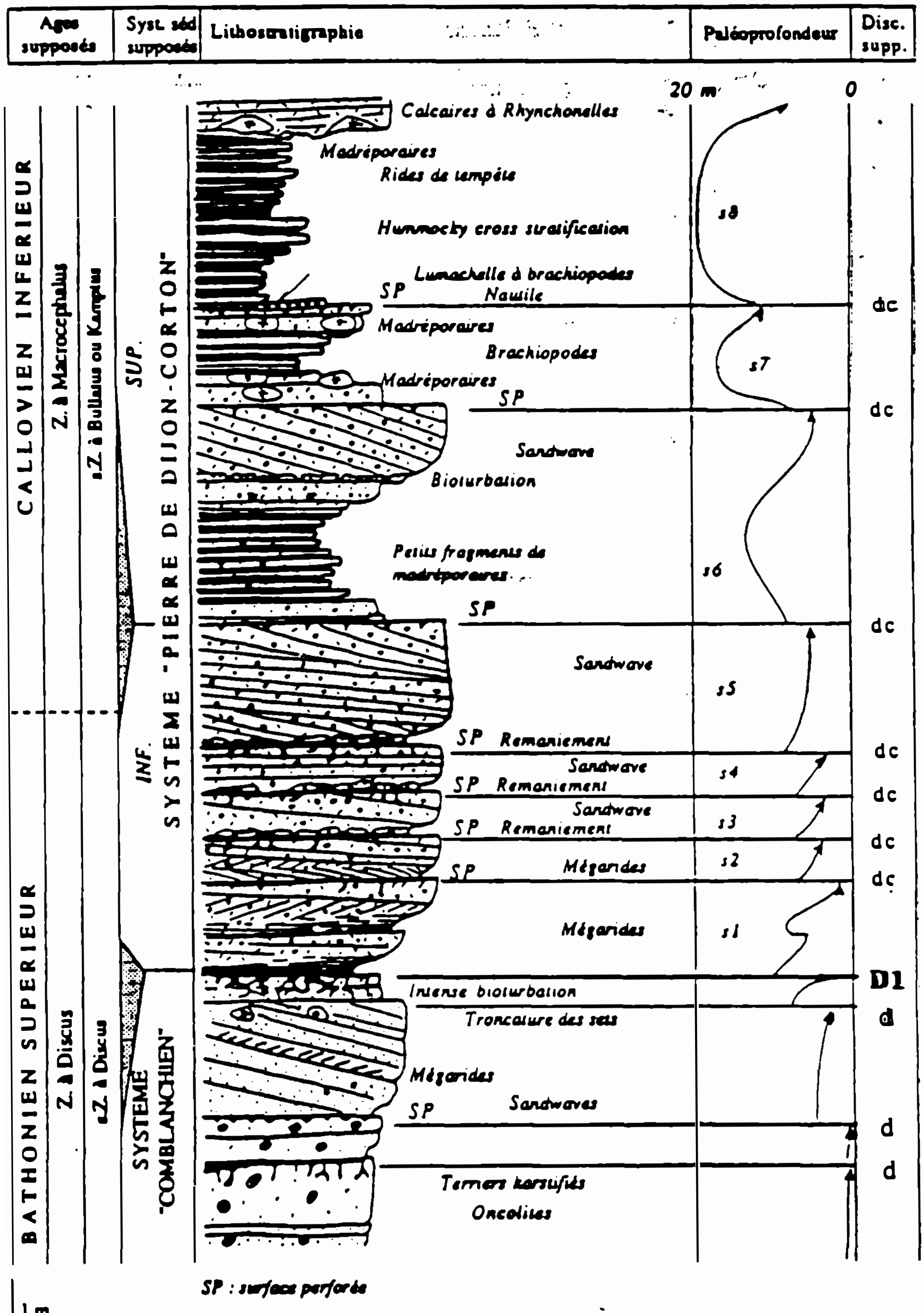
Fig. 2-23


Humphriesianum
Blagdeni
Garantiana
upper
A
B
W
E
N
G
F



Stratigraphical section of Rochs Quarry at Etrochey.

**PIERRE DE LADOIX SYSTEM
(BURGUNDY COSTA)**



BUFFON : En Charibeau

THE TECHNIQUES OF

SEQUENCE STRATIGRAPHY

PART 13:

SEQUENCE STRATIGRAPHY INTERPRETATION PROCEDURE

WELL LOG/SEISMIC/BIOSTRATIGRAPHY SEQUENCE STRATIGRAPHY INTERPRETATION PROCEDURE APPLIED TO THE NEOGENE OF THE GULF OF MEXICO

STEP 1 - UNDERSTAND DEPOSITIONAL SETTING

* Seismic Overview In Vicinity Of Well Log To Be Interpreted
* Interpret Rock Type From Well Logs
* Interpret Depositional Environments From Biostratigraphy And Well Logs
* Interpret Major Regressive/Transgressive Facies Cycle Wedges On Well Logs
* Identify Discontinuities From Dipmeter Logs

STEP 2 - IDENTIFY CONDENSED SECTIONS FROM BIOSTRATIGRAPHY

* Identify Condensed Sections And Locate On Well Logs
* Age Date Condensed Sections With Biostratigraphy

STEP 3 - INTERPRET SEQUENCES AND SYSTEMS TRACTS

* Interpret Sequences, Systems Tracts, And Faults On Well Logs
* Interpret Sequences, Systems Tracts, And Faults On Seismic Data
* Interpret Sequences and Systems Tracts on Adjacent Outcrops
* Tie To Global Cycle Chart

STEP 4 - CORRELATE WELL LOGS BY UTILIZING PARASEQUENCES AND MARKER BEDS WITHIN SYSTEMS TRACTS

* Correlate Well Logs By Parasequence/Marker Bed Correlation

STEP 5 - CONSTRUCT SUMMARY DIAGRAMS

* Cross Sections Showing Sequences, Systems Tracts, Parasequence Boundaries and Lithofacies
* Interpreted Key Seismic Sections That Coincide With Geologic Cross Section Where Possible
* Summary Chronostratigraphic Charts Showing Sequences, Systems Tracts, and Lithofacies
* Map Sequences And Systems Tracts For Interpreting Paleogeography And Geologic History

STEP 6 - MAKE SEQUENCE BOUNDARY BASED TECTONIC SUBSIDENCE CURVES AND CORRELATE TO CHRONOSTRATIGRAPHIC CHART

STEP 7 - IDENTIFY RESOURCE PLAYS AND PROSPECTS

WELL LOG/SEISMIC/BIOSTRATIGRAPHY SEQUENCE STRATIGRAPHY INTERPRETATION PROCEDURE APPLIED TO THE NEOGENE OF THE GULF OF MEXICO

DATA AND MATERIALS

- Well logs (approximately 1 inch equals 100 feet)
- High resolution biostratigraphy check lists, for reference wells
- Well log sequence stratigraphy interpretation charts, where possible (Paleowater depth, Faunal abundance, Faunal diversities, and well logs)
- Seismic sections
- Synthetic seismograms and/or time depth conversion charts
- Well log cross sections (uninterpreted and approximately 1 inch equals 400 to 500 feet)
- Graph paper for chronostratigraphic chart
- Color pencils (red, orange, green, rose, brown, tuscan red, yellow, and blue) and straight edge

STEP 1 - UNDERSTAND DEPOSITIONAL SETTING

* Seismic Overview In Vicinity Of Well Log To Be Interpreted
    - Identify faults
    - Identify truncation unconformities
    - Identify incised valleys and canyons
    - Interpret approximate paleowater depths
* Interpret Rock Type From Well Logs
    - Gamma and/or spontaneous potential curves
    - Sonic and/or resistivity curves
    - Porosity logs
* Interpret Depositional Environments From Biostratigraphy And Well Logs
    - Paleontology
    - Cores and cuttings
    - Well log patterns.
    - Compare to seismic interpretation from Step 1
* Interpret Major Regressive/Transgressive Facies Cycle Wedges On Well Logs
    - Second order cycles (3-50 My)
* Identify Discontinuities From Dipmeter Logs

STEP 2 - IDENTIFY CONDENSED SECTIONS FROM BIOSTRATIGRAPHY

* Identify Condensed Sections And Locate On Well Logs
  - Faunal and floral abundancy peaks from high resolution biostratigraphy
  - Faunal and floral diversity peaks from high resolution biostratigraphy
  - Total organic matter peaks
  - Authigenic mineral peaks
  - Hardgrounds
* Age Date Condensed Sections With Biostratigraphy
  - Determine age of condensed section from high resolution biostratigraphy
  - Check for missing or stacked condensed sections, i. e. for indications of faults, slump scars, canyons, or multiple sequence starvation.

STEP 3 - INTERPRET SEQUENCES AND SYSTEMS TRACTS

* Interpret Sequences, Systems Tracts, And Faults On Well Logs
  - Use scale that is approximately 1 inch equals 100 feet
* Interpret Sequences, Systems Tracts, And Faults On Seismic Data
  - Identify and correlate discontinuities from reflection termination patterns
  - Identify sequences and systems tracts
  - Tie sequence and systems tract boundaries to wells with synthetic seismograms or time-depth conversion charts
  - Check consistency of seismic correlations by closing loops on the seismic grid
  - Color systems tracts on key seismic sections, highlighting sand and porous carbonate beds
* Interpret Sequences and Systems Tracts on Adjacent Outcrops
* Tie To Global Cycle Chart
  - Determine correspondance of number and age of sequences with number and age of sequences predicted by the chart
  - if different, evaulate the reason for the difference

STEP 4 - CORRELATE WELL LOGS BY UTILIZING PARASEQUENCES AND MARKER BEDS WITHIN SYSTEMS TRACTS

* Correlate Well Logs By Parasequence/Marker Bed Correlation
  - On individual wells identify parasequences and marker beds within the systems tracts
  - Correlate sequences and systems tracts between well logs, following seismic correlations and biostratigraphic ages
  - Correlate parasequences and marker beds between wells, starting in the vicinity of maximum flooding surfaces
  - Evaluate systems tract boundaries using parasequence stacking patterns

STEP 5 - CONSTRUCT SUMMARY DIAGRAMS

* Cross Sections Showing Sequences, Systems Tracts, Parasequence Boundaries and Lithofacies
* Interpreted Key Seismic Sections That Coincide With Geologic Cross Section Where Possible
* Summary Chronostratigraphic Charts Showing Sequences, Systems Tracts, and Lithofacies
* Map Sequences And Systems Tracts For Interpreting Paleogeography And Geologic History
  - Well log isopachs and facies
  - Seismic isochrons and facies

STEP 6 - MAKE SEQUENCE BOUNDARY BASED TECTONIC SUBSIDENCE CURVES AND CORRELATE TO CHRONOSTRATIGRAPHIC CHART

- Relate changes in rate of tectonic subsidence to major transgressive/regressive facies wedges
- Calculate eustatic variations
- Plot summary tectonic subsidence curve on chronostratigraphic chart

STEP 7 - IDENTIFY RESOURCE PLAYS AND PROSPECTS

AN INTEGRATED APPROACH TO EXPLORATION AND DEVELOPMENT IN THE 90s: WELL LOG-SEISMIC SEQUENCE STRATIGRAPHY ANALYSIS

Peter R. Vail,[1] and Walter Wornardt Jr.[2]

ABSTRACT

Well Log-Seismic Sequence Stratigraphy Analysis is a new technology that integrates high resolution biostratigraphic and paleobathymetric data and the characteristics of the well log signatures with seismic reflection profiles. This methodology permits the biostratigrapher, geologist and geophysicist to work together to subdivide a stratigraphic section into packages of sediments bounded by chronostratigraphically significant condensed sections and their associated maximum flooding surfaces and sequence boundaries using well logs and seismic profiles. Each sequence is subdivided into smaller lithogenetic (facies linked) units called systems tracts on the basis of characteristic well-log patterns. The systems tract boundaries, are identified on well logs, marked on two-way time logs or synthetic seismograms and correlated with corresponding systems tracts that have been independently identified on the seismic profiles using seismic-stratigraphic interpretation procedures (Vail and Wornardt, 1990).

Faunal and floral abundance and diversity histograms provide critical information to make reproducible chronostratigraphic correlations (Huang and Wornardt, 1986; Shaffer, 1987; Wornardt, 1989; and Shaffer, 1990). The paleobathymetric interpretations permit the identification of rock types in relation to the depositional environment and systems tracts. The high resolution biostratigraphy is critical in integrated well log-seismic sequence stratigraphic analysis because it provides information for identifying fossil abundance and diversity peaks that are important for recognizing and correlating condensed sections and maximum flooding surfaces on well logs and seismic profiles. High resolution biostratigraphy and paleobathymetry data provides the additional data package that has heretofore been missing in seismic sequence stratigraphy. Added to the well log and seismic data set, they provide an integrated data package that permits the inexperienced person to use the concepts of seismic well log-sequence stratigraphy to develop expertise and confidence in its practice. In order to obtain consistently reliable results in well log-seismic sequence stratigraphy, a particular procedure must be followed and specific data sets must be used.

INTRODUCTION

During the past few years we have developed a totally integrated technology called *Well-Log Seismic Sequence Stratigraphy Analysis*. This technique helps unravel the complex stratigraphy in various parts of the world, and dramatically increases the ability of explorationists to interpret the rock types associated with AVO anomalies or to predict hydrocarbons where AVO anomalies do not exist.

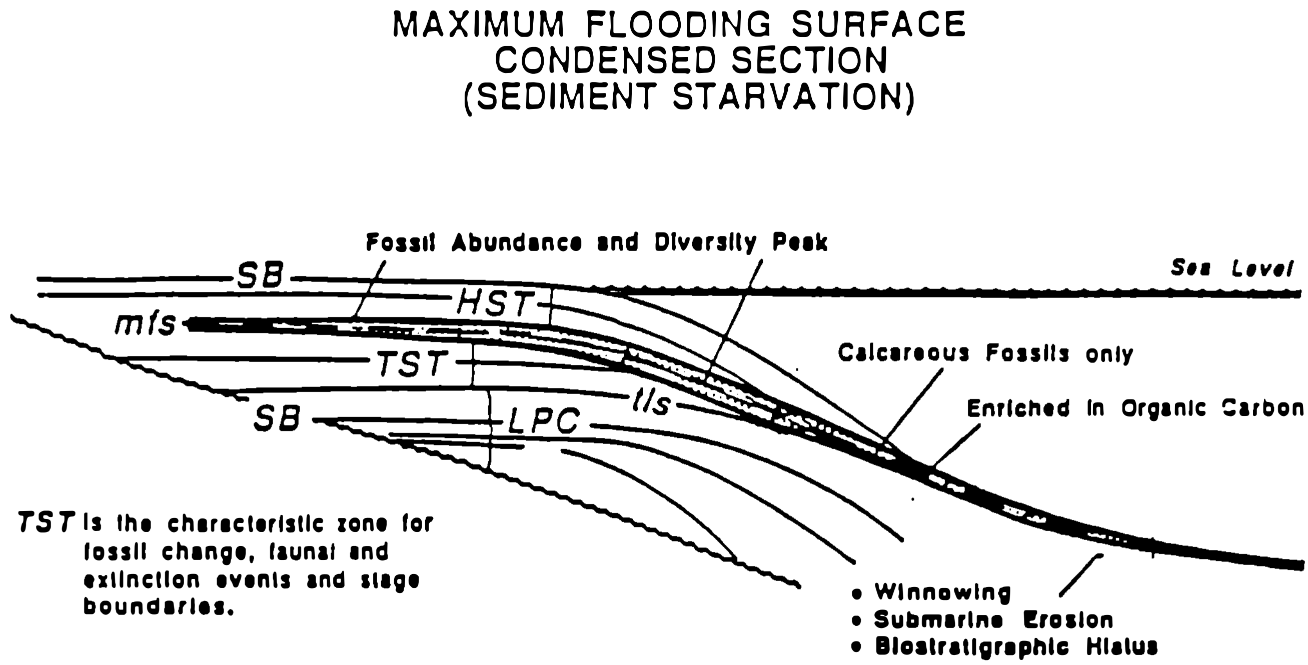
Well-Log Seismic Sequence Stratigraphy is a new technique that integrates high resolution biostratigraphic and paleobathymetric data, and the characteristics of the well-log signatures with seismic-reflection profiles. This methodology permits the geologist and geophysicist to divide a rock section into a series of genetic units bounded by condensed sections and their chronostratigraphic maximum flooding surface and sequence boundaries using well logs and seismic profiles. When the maximum flooding surfaces and sequence boundaries are dated at their minimum hiatus or their conformities, they are chronostratigraphic boundaries. All the rocks deposited between these surfaces are therefore chronostratigraphic intervals. Condensed sections and sequence boundaries are dated on the basis of high resolution biostratigraphy. Subsequently, each sequence is subdivided into smaller packages called systems tracts on the basis of characteristic well-log patterns.

The boundaries of systems tracts identified on well logs are marked on two-way time logs or synthetic seismograms and then correlated with corresponding systems tracts that have been independently identified on the seismic profiles using seismic-stratigraphic principles. Faunal and floral abundance and diversity data plus paleobathymetric interpretations provide extremely valuable additional data to make reproducible chronostratigraphic correlations and to identify the rock types in relation to the depositional environments and systems tracts. High resolution biostratigraphy provides the biological and geological data set that has heretofore been missing in seismic sequence stratigraphy. It provides a data package that allows the inexperienced person to use the concepts of seismic sequence stratigraphy and to develop expertise and confidence using this methodology.

Identification of the maximum flooding surface and its associated depositional facies, the condensed section (Figure 1), through the analysis of faunal and floral abundance/diversity data obtained from the detailed checklists (stratigraphic distri-

[1] Professor, Department of Geology & Geophysics, Rice University, P.O. Box 1892, Houston, Texas 77251

[2] MICRO-STRAT, INC., and Adjunct Professor, Department of Geology & Geophysics, Rice University, P.O. Box 1892, Houston, Texas 77251



ture 1. The position of maximum flooding surface and condensed section, and their relationship to different systems tracts within a positional sequence.

ion charts), are critical in well log-seismic sequence strati- phic analysis and permit subdivision of E-logs and seismic ord sections into a series of packages of sediments that are inded by chronostratigraphic surfaces (Womardt, 1989). alysis of faunal and floral abundance/diversity data pro- es a method of reliably and consistently recognizing differ- types of condensed sections on well logs. Condensed sec- is develop not only in association with the maximum oding surface, but also at the base of the lowstand prograd- complex/top of slope fan complex. Minor condensed sec- is are also present between the channel overbank lobes hin the slope fan complex/top of the basin floor fans. The imum flooding surfaces are associated with warm water and floras. Whereas the condensed sections in the low- id systems tracts are associated with cold water fauna and as.

order to obtain consistently reliable results, specific data t be used and a particular procedure (Table 1) must be owed.

DATA REQUIREMENTS

iree types of data are necessary: well logs, high resolution tratigraphic and paleobathymetric data, and seismic-re- ion profiles. A full suite of petrophysically corrected wire- logs (if possible), including a dipmeter log, is optimum; ever, an E-log with S.P., resistivity and Gamma Ray and/or curves is adequate for sequence stratigraphic interpreta- A log scale of 100' = 1" is most useful for the first steps of nalysis.

Biostratigraphic data have been commonly presented in four general formats: (1) "Paleo tops" information is based on the first downhole occurrence of a particular species in a well which may or may not be its true extinction point in time. In the Gulf of Mexico "Paleo tops" have been commonly based on benthic foraminifers that usually climb in section downdip and become very rare in bathyal environments. (2) "Paleo tops" with minimum faunal and floral abundance data (Rare, Few, Common, Abundant). The abundancy peaks from these data are often very misleading. (3) "Paleo tops" using benthic foraminifers and the "bioevents" of the planktonic foraminif- ers and calcareous nannofossils are recorded (Womardt and Lamb, 1985). Diversity is usually not accurate because of the limited number of species identified per sample and the abun- dances can be misleading because only the samples with many fossils are deemed important.

Therefore, these three types of "paleo top" and abundance reports alone are inadequate for well log-seismic sequence stratigraphy analysis. (4) Very detailed biostratigraphic and paleobathymetric analyses of the total fauna and flora in each sample at 30-or 60-foot intervals are annotated on a checklist or stratigraphic distribution chart, using benthic foraminifers for paleobathymetry; and the "bioevents" of the planktonic foraminifers and calcareous nannofossils for age dates in mil- lions of years (Womardt and Lamb, 1985). We have also found the diversity and frequency histograms to be very accurate when a fair amount of original sample was processed.

This high resolution biostratigraphy is the integration of a very detailed biostratigraphic checklists, bioevents, recogni- tion of the warm and cold condensed sections and it is the only

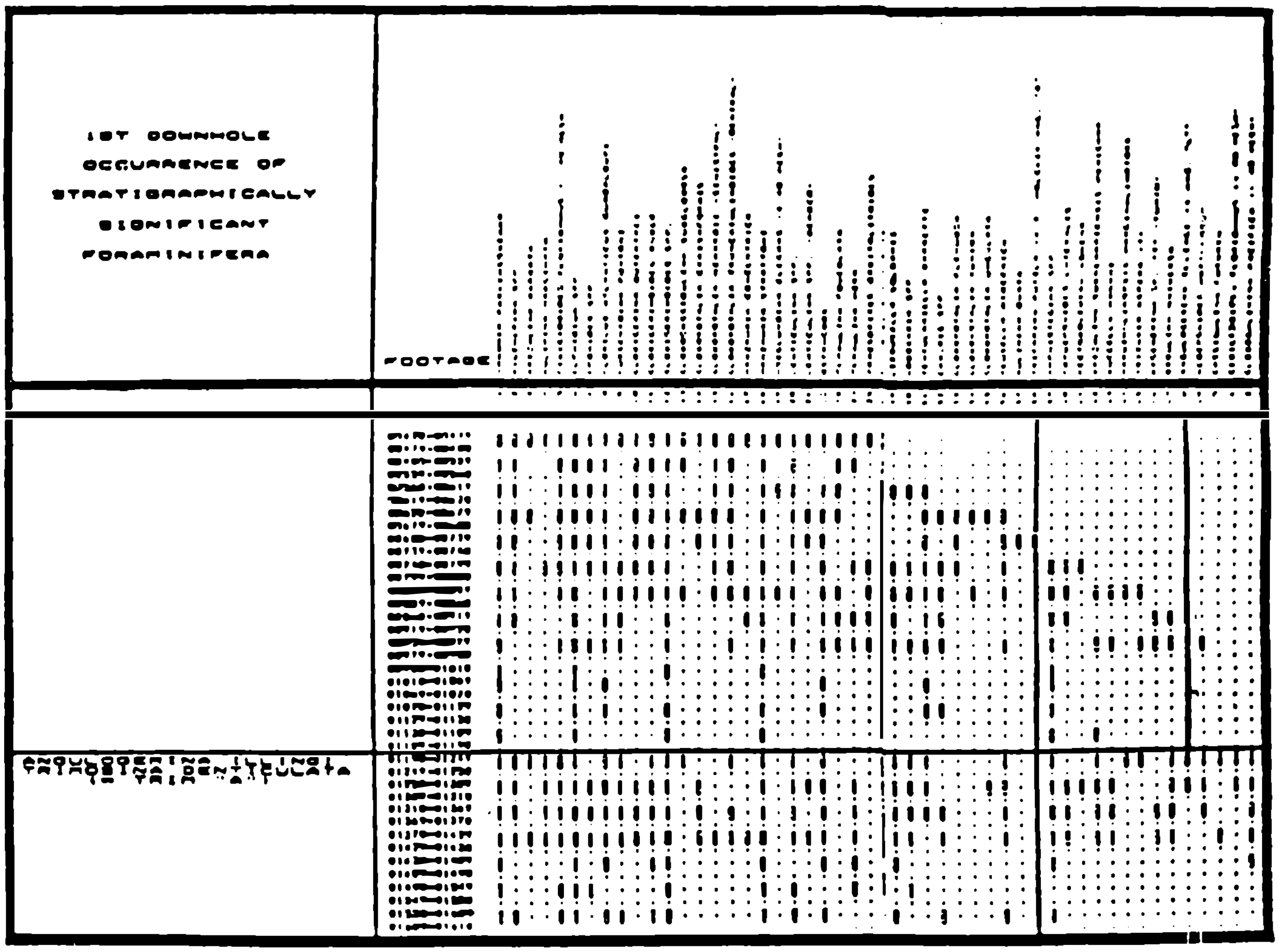
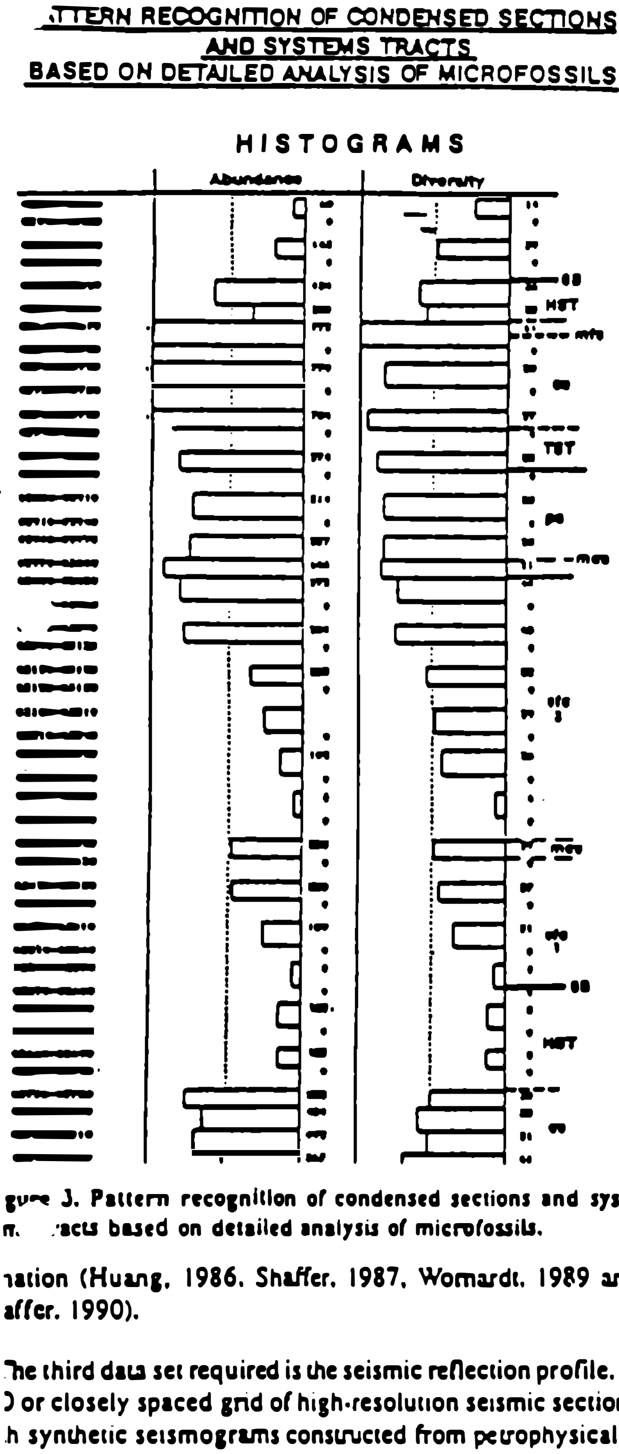


Figure 2. Part of microfossil checklist, which provides the detailed stratigraphic and paleobathymetric information for sequence stratigraphic analysis.

methodology that provides the adequately detailed data necessary to properly perform seismic sequence stratigraphy analysis in a cost-effective manner.

The basis of the high resolution biostratigraphy is the checklist (Figure 2). It is constructed by recording the detailed occurrence and abundance of planktonic and benthic foraminifers and calcareous nannofossils in cuttings samples at 30- to 60-foot intervals (Womardt and Lamb, 1985). These checklists provide the detailed stratigraphic and paleobathymetric information necessary to evaluate all of the important foraminiferal and calcareous nannofossil bioevents as they relate to the recognition of the major condensed sections and their maximum flooding surfaces. They are also very valuable because they provide an opportunity to evaluate the placement of a species' first downhole occurrence (its "top"), and identify shallow-water species that have been transported down slope into a deepwater environment. High resolution biostratigraphy integrates the occurrences and abundances of species on a sample by sample basis (Lamb, *et al.*, 1987). It provides the basic descriptive detailed information necessary to calculate small variations in paleowater depth especially the deepenings associated with the condensed sections associated with warm water species, and the means to construct histograms showing microfossil abundance and diversity variation (not just abundance peaks) throughout the stratigraphic section in a well (Figure 3). These histograms, in turn, provide detailed information that permits the recognition and verification of warm condensed sections associated with the maximum flooding surface, and cold condensed sections on the top of basin floor fans, top of slope fans, and minor condensed sections on the top of individual lobes within the slope fan and sequence boundaries by the lack of fossils.

Age dating and correlation in well log-seismic sequence stratigraphy analysis is based on the condensed section, its assemblage of fossils and its association with significant microfossil bioevents and their age in millions of years and correlation with the global cycle chart. Using this methodology the condensed sections gives much more reliable results for chronostratigraphic correlation than the usual biostratigraphic



gure 3. Pattern recognition of condensed sections and sys- n. acts based on detailed analysis of microfossils.

iation (Huang, 1986, Shaffer, 1987, Wornardt, 1989 and affer, 1990).

The third data set required is the seismic reflection profile. A) or closely spaced grid of high-resolution seismic sections h synthetic seismograms constructed from petrophysically rected well logs with check shots is optimum. However, a key seismic lines tied to the available well control with stratigraphy commonly provides adequate information for ll log-seismic sequence stratigraphic analysis.

'o facilitate our interpretations in well log-seismic sequence tigraphy, we prepare a well-log sequence-stratigraphic lysis chart which shows from left to right, at the same scale, following data:

Paleowater depth

2) Nannofossil abundance and diversity with important bioevents ("tops")

3) Planktonic and benthonic foraminiferal abundance and diversity with important bioevents ("tops")

4) Well logs (SP/Gamma & Resistivity/Sonic)

5) Interpretation of depositional systems and lithofacies

6) Interpretation of sequences and systems tracts

7) Absolute age

INTERPRETATION PROCEDURE

Table 1. Procedure for well log-seismic sequence stratigraphic analysis

1) Seismic overview
2) Interpret lithology from log character (confirm with cores and cuttings when possible)
3) Interpret depositional environments and paleobathymetry from micropaleontology/paleoecology and then from well log character
4) Identify major 2nd-order, transgressive and regressive wedges
5) Interpret condensed sections from faunal and floral abundance and diversity to recognize:
   - Warm-water condensed sections associated with maximum flooding surfaces
   - Cold-water condensed sections associated with
     - Base of lowstand prograding wedges-top slope fan complex
     - Minor condensed sections between channel overbank lobes in slope fan complexes and top of basin floor fan complexes
6) Age date condensed section with high resolution biostratigraphy
7) Locate discontinuities on dipmeter log
8) Interpret sequence and systems tract boundaries from log character
9) Interpret sequence boundaries, maximum flooding surfaces and systems tracts on seismic data and tie the seismic interpretation to the well logs
10) Tie to global cycle chart
11) Identify and correlate parasequences and marker beds
12) Construct well log-seismic sequence stratigraphic cross-sections
13) Prepare a chronostratigraphic chart from key cross-sections to summarize stratigraphic framework

The specific procedure we recommend for well log-seismic sequence stratigraphic analysis has 13 steps (Table 1). Sequence stratigraphic terminology used in this procedure is illustrated in Figure 4.

1) The first step is a seismic overview in the area of the well. A seismic overview provides information on location of ma-

jor faults, truncation, unconformities, general paleobathymetry.

2) The second step is to interpret lithology from log character. Any error in this step can lead to misinterpretations in the later stages of the procedure, thus confirmation with cores and cuttings, where possible, is very important.

3) The third step involves the detailed interpretation of the paleoenvironments and paleobathymetry from the benthic foraminifers within the cuttings or core samples. The data available for these interpretations are obtained from the high resolution biostratigraphic checklist. The benthic foraminifers are plotted on a separate checklist with the shallow water species on the right and the species that are characteristic of successively deeper environments plotted to the left in each sample. This checklist is made from the original checklist that is plotted with first occurrence downhole. After the occurrence and abundance of each species has been plotted from shallow to deep water for every 60-foot sample downhole, a paleobathymetric curve is drawn based on the interpretation of the benthic foraminifers in each sample. Detailed analysis of each sample and the assignment of that sample to a certain paleowater depth permits the recognition of the deepenings that are associated with the warm condensed sections. These levels are checks against changes in abundance/diversity curves, where maximum values generally reflect transgressive conditions and minimum values regressive conditions (Clement, et al., 1989). This paleobathymetric curve is plotted directly on the checklist, and provides valuable information with regard to the "actual" depositional environment of the reservoir sand.

Once the paleowater depths are determined from the *in situ* benthic foraminifers, rather than from the species that have been washed downslope, a number of paleoenvironments associated with the different water depths can be interpreted directly from the well logs. A classification of paleoenvironments is shown in Table 2 (Wornardt and Lamb, 1985). It is important to determine the paleowater depth from paleobathymetric interpretations before interpreting the log patterns because similar log patterns may be observed in deep and shallow water environments.

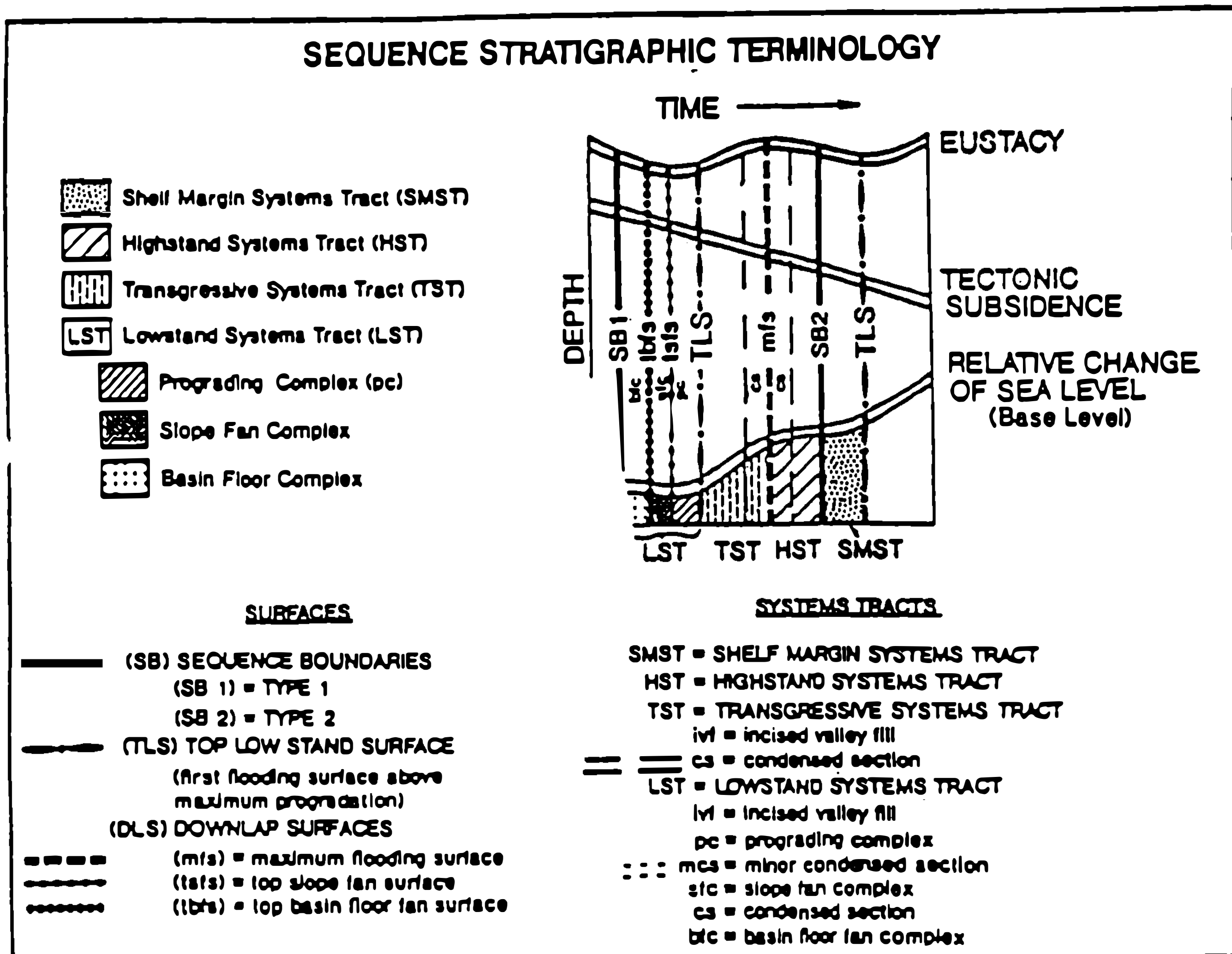


Figure 4. Sequence stratigraphic terminology.

Thus similar log patterns can represent very different depositional environments.

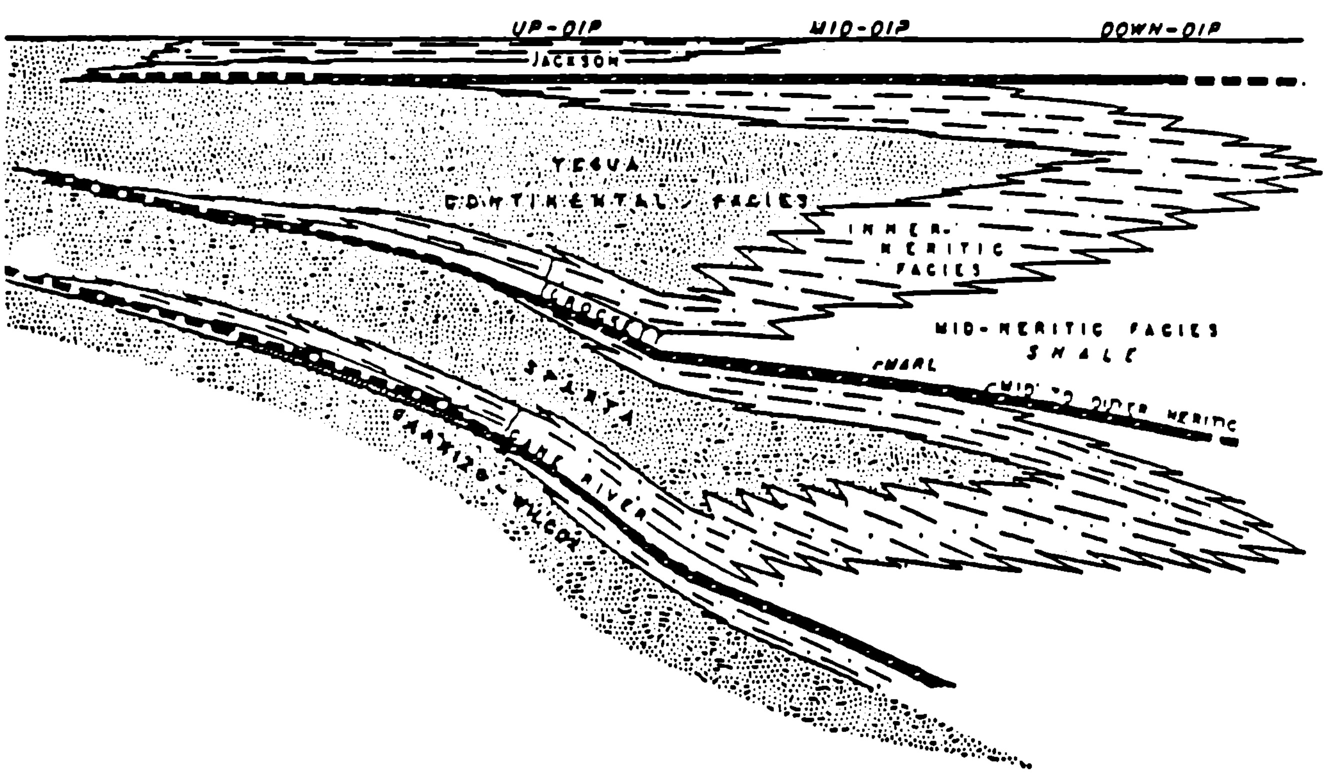
Table 2. Paleobathymetric Zonation

Paleobathymetry (In feet)	Paleoenvironment	
0-100	Inner Neritic	Neritic
100-300	Middle Neritic	
300-600	Outer Neritic	
600-1200	Upper Upper Bathyal	Upper Bathyal
1200-1500	Lower Upper Bathyal	
1500-3000	Middle Bathyal	Middle
3000-4500	Upper Lower Bathyal	Lower Bathyal
4500-6000	Lower Lower Bathyal	
Below 6000	Abyssal	

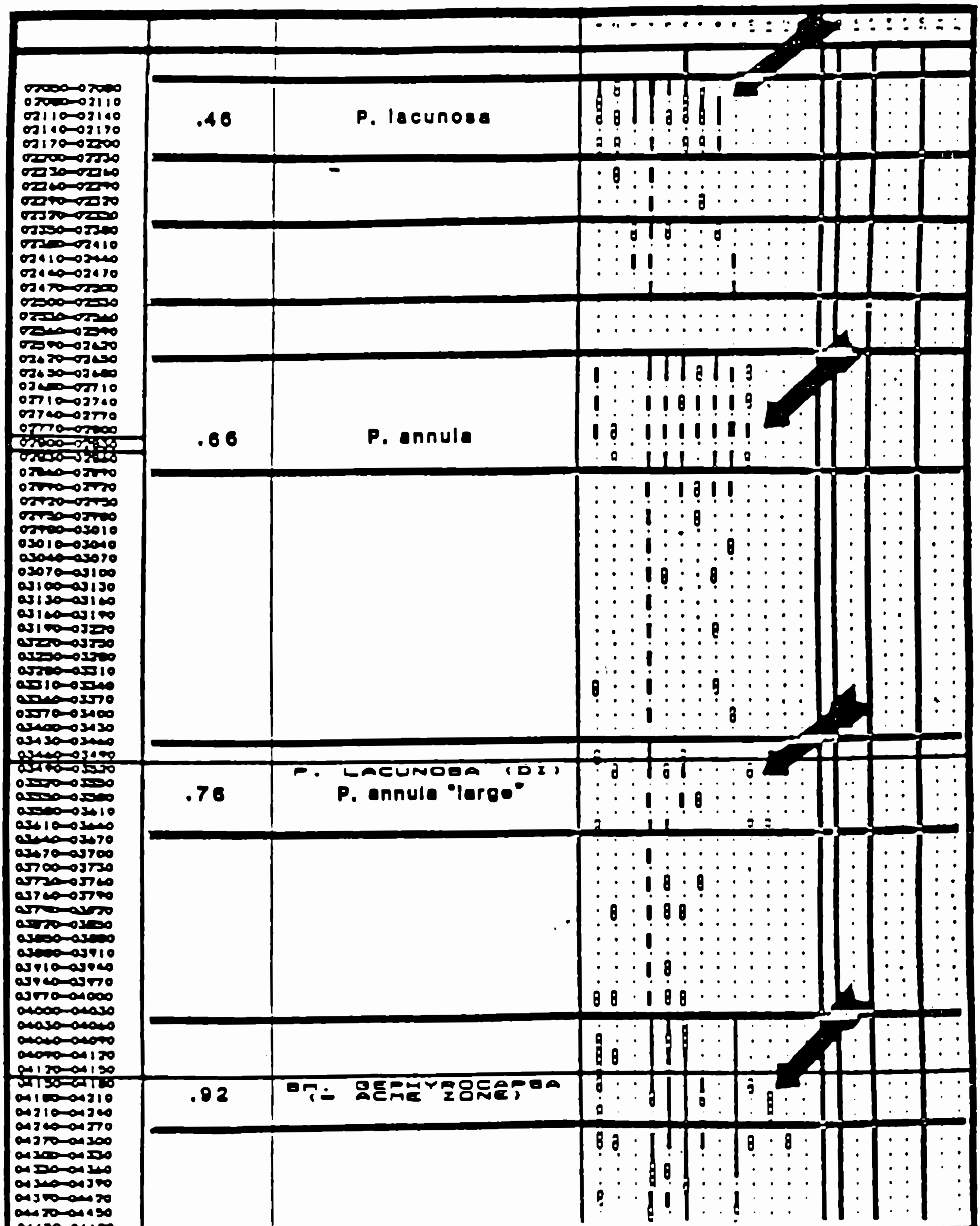
The fourth step is to identify the major transgressive and regressive facies wedges (Smith, 1965). These wedges are related to the rate and type of sediment supply (Figure 5). They also control how well the lithofacies are developed within the systems tracts.

5) The fifth step is to identify the 3rd and 4th order condensed sections using faunal and floral abundance and diversity peaks (Figure 3). These are correlated with 2nd-order cycles that are tectonically or tectono-eustatically controlled. The condensed section depositional facies consists of thin, marine, hemipelagic to pelagic sediments deposited at a relatively slow rate (sediment starvation) in comparison to the over- and underlying sediments. Condensed sections may occur at four different positions within a depositional sequence. The major condensed section is associated with warm water faunas and floras, the maximum flooding surface, and flooding onto the shelf (Figures 6, 7, 8 and 9). It separates the back stepping transgressive systems tract from the fore stepping highstand systems tract. Additional condensed sections associated with cold water faunas and floras are present at the toes of the lowstand prograding complex/top of slope fan (Figure 10). Minor condensed sections also occur between channel overbank lobes within the lowstand slope fan and the top of the basin floor fan complex below the slope fan complex.

The major condensed section which contains the maximum flooding surface and which separates the transgressive systems tract from the highstand systems tract is commonly associated with authigenic minerals, warm water fossils, fossil abundance peaks and hemipelagic laminated shales (Figure 1). In the Cenozoic section of the Gulf of Mexico, where the sedimentation rates are extremely high, these major condensed sections are characterized by



...ure 5. Stratigraphic diagram of Claiborne group (Eocene), showing cyclical sedimentary units in Cane River-Sparta and ...ckett-Yegua, Central Louisiana partly after H. N. Fisk (1940) (Modified after Lohman 1949, AAPG).

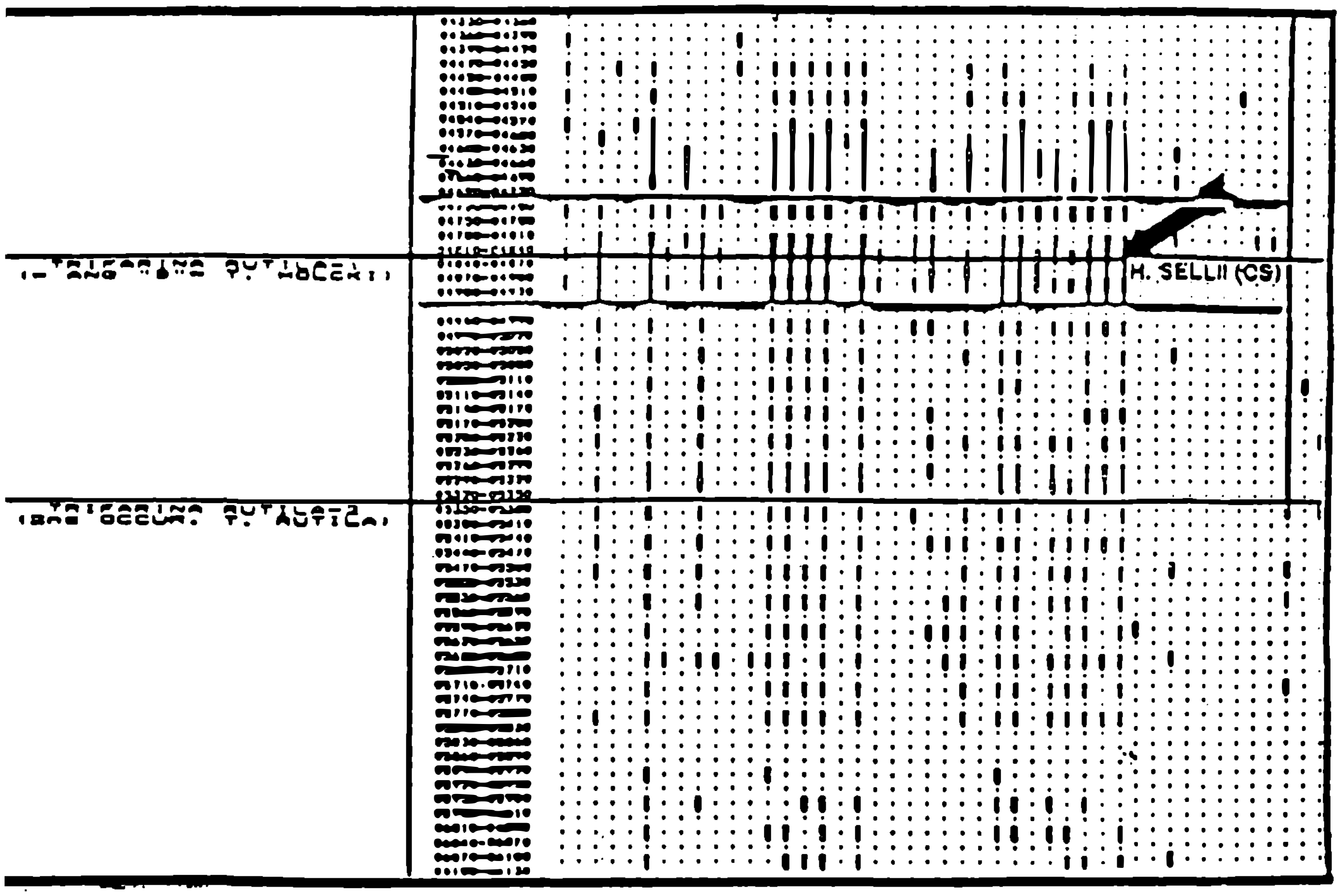


P. LACUNOSA, P. ANNULA, P. ANNULA (LARGE) AND SMALL GEPHYROCAPSA

CONDENSED SECIONS

Figure 6. Checklist showing *P. lacunosa*, *P. annula*, *P. annula* (large) and small *gephyrocapsa* condensed sections.

H. SELLII & ANG "B" CONDENSED SECTION



gure 7. Checklist showing *H sellii* & Ang "B" condensed section.

hemipelagic shales which may be hundreds of feet thick. The major condensed section contains a maximum flooding surface which is recognizable on an E-log. This maximum flooding surface is a correlatable physical surface that commonly represents the maximum shale point between the fining upward transgressive systems tract and coarsening upward highstand systems tract. In some cases the maximum flooding surface may be represented by a thin shale spike, or limestone bed.

The sixth step is to evaluate chronostratigraphically important bioevents so that an absolute age can be assigned to each condensed section (Figure 11). The first downhole occurrence of important microfossils species are evaluated against each other using the high resolution checklist to determine whether they are true last occurrences up hole, depressed tops, or have climbed section down dip (diachronous). If the bioevent of an important species is interpreted as its extinction point an age in millions of years (ma) is assigned to the species.

The seventh step is to evaluate the dipmeter log, if available, for discontinuities. Dipmeter logs will not show discontinuities at all systems tract boundaries, but are very helpful.

8) In the eighth step we interpret sequence and systems tract boundaries from log character. First, the maximum flooding surfaces are identified within the major condensed sections on the E-logs. Maximum flooding surfaces are identified as the high gamma, low SP, low resistivity, low sonic log pick characteristic of the shaliest part of the section. In the neritic environment this pick should mark a point where a fining upward pattern changes to a coarsening upward pattern. In some cases a high resistivity spike may occur at the maximum flooding surface because of a concentration of calcareous fossils. Maximum flooding surfaces are associated with major faunal and floral abundance and diversity peaks and a characteristic assemblage of fossils in the Cenozoic of the Gulf of Mexico. In the deep water environment, maximum flooding surfaces represent the intervals of lowest sedimentation rate within the hemipelagic shales of the condensed section.

Sequence boundaries are identified within the coarsening upward pattern between the maximum flooding surfaces. In the neritic environment, sequence boundaries mark an abrupt shallowing or an abrupt increase in depositional rates. The typical log pattern is an aggradational (massive) log pattern that overlies an interbedded log pattern. In the deep-water environment sequence boundaries commonly

C. MACINTYREI CONDENSED SECTION

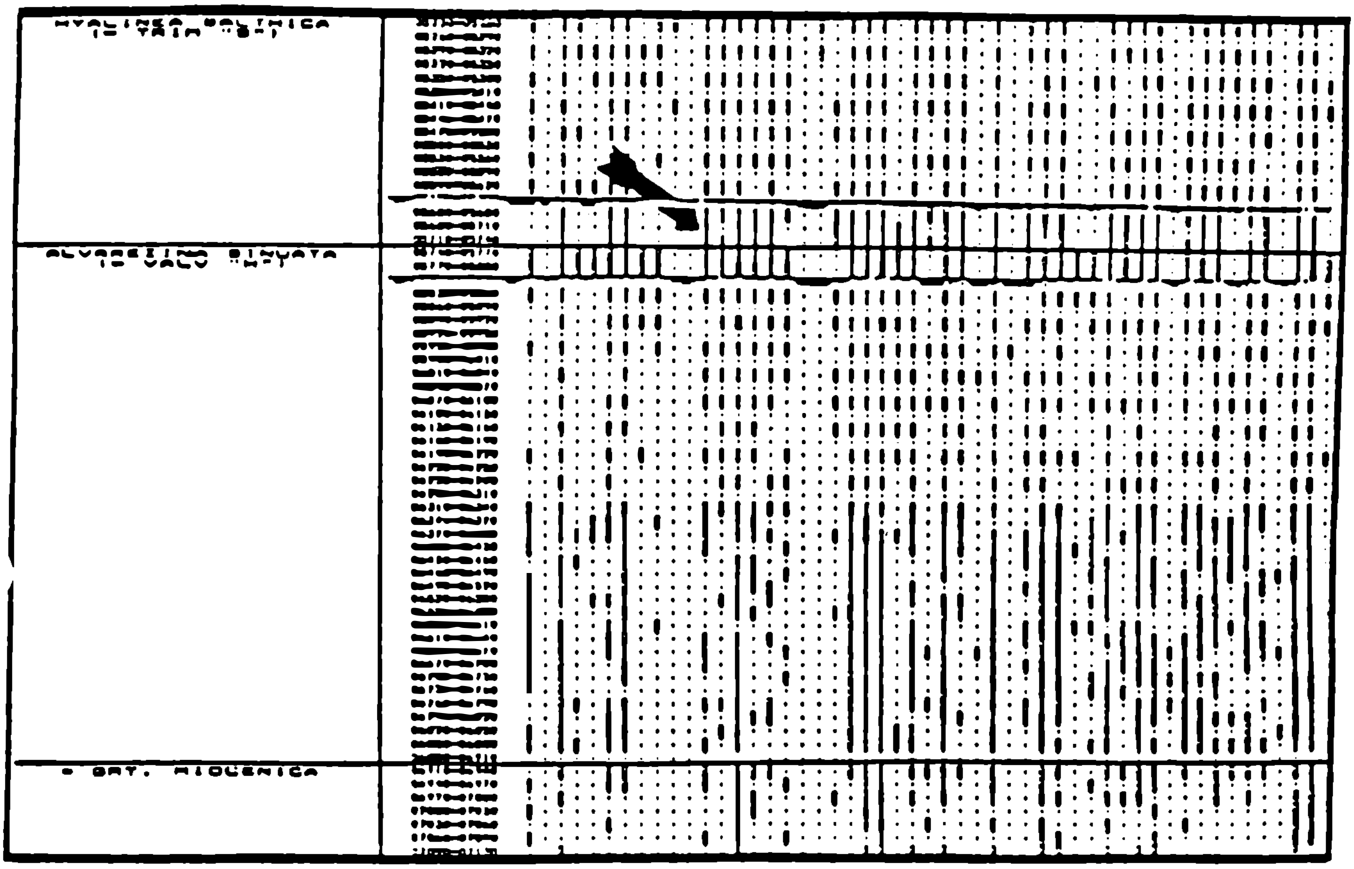


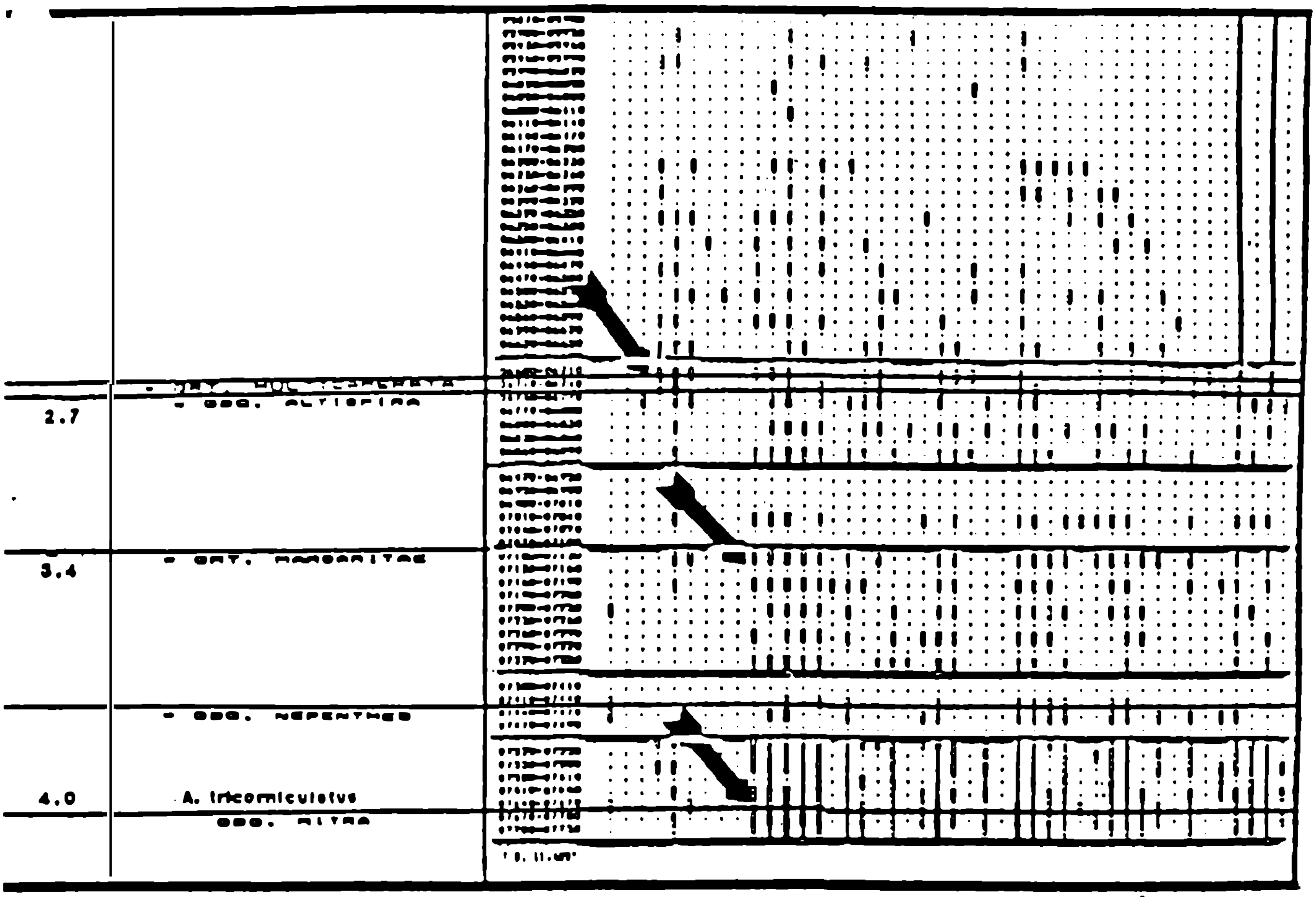
Figure 8. Checklist showing *C. macintyrei* condensed section.

occur at the base of log patterns indicating an abrupt increase in silt or sand which overlie hemipelagic shales. Sequence boundaries located at submarine erosion surfaces and penecontemporaneous slump surfaces may be the most difficult to recognize on logs because they interrupt the repetitious trend and systems tracts. However, the log patterns and biostratigraphy commonly change significantly at such surfaces. In general, the section overlying the submarine erosional or slump surface is shalier. Seismic data is especially important in locating these surfaces.

Within the deep water (bathyal) environment the log pattern typical of a sequence boundary shows an abrupt increase in silt or sand deposition over the hemipelagic shales. For example, sequence boundaries at the base of basin-floor fans are the easiest to recognize (Figure 12). They are characterized by a blocky (box car) sand log pattern over railroad track log patterns typical of hemipelagic shales (Figure 13). The sequence boundary is located at the base of the blocky sand. A variation of this pattern occurs at the margin of a basin floor fan, where the sands are unamalgamated. In this case, the blocky log pattern will show thin shale spikes within.

In cases where the slope fan rests directly on older sequences and no basinfloor fan exists, the sequence boundary is more difficult to identify (Figure 14). In general the boundary is placed at the first significant increase in siltiness above a hemipelagic shale. The sequence boundary separates the railroad track shale pattern of the underlying hemipelagic shale section from the crescent-shaped log pattern of the coarsening/fining upward lobes of the slope fan (Figure 15). Several crescent-shaped lobes may be present within one slope fan (Figure 16). Individual lobe boundaries are characterized by minor faunal and floral abundances and diversity peaks in minor condensed intervals. The individual sands and silts within the crescent-shaped lobes are highly digitated and show a characteristic fining upward pattern. Variations of this pattern occur where slumps within a slope fan overlie the sequence boundary or in the distal portions of slope fans. Distal slope fans tend to be siltier than the underlying hemipelagic shales, but lack sands and well developed crescent-shaped log patterns. The sequence boundary is located at the shale/silt boundary.

The boundary between the slope fan and basin-floor fan is located at the maximum shale point immediately above the



GRT. MARGARITAE, A. TRICORNICULATUS AND GBG. MITRA CONDENSED SECTIONS

gure 9. Checklist showing *Grt margaritae, A. tricorniculatus* and *Gbg. mitra* condensed sections.

basin floor fan. A faunal and floral abundance and diversity peak often marks a well developed condensed interval at this boundary.

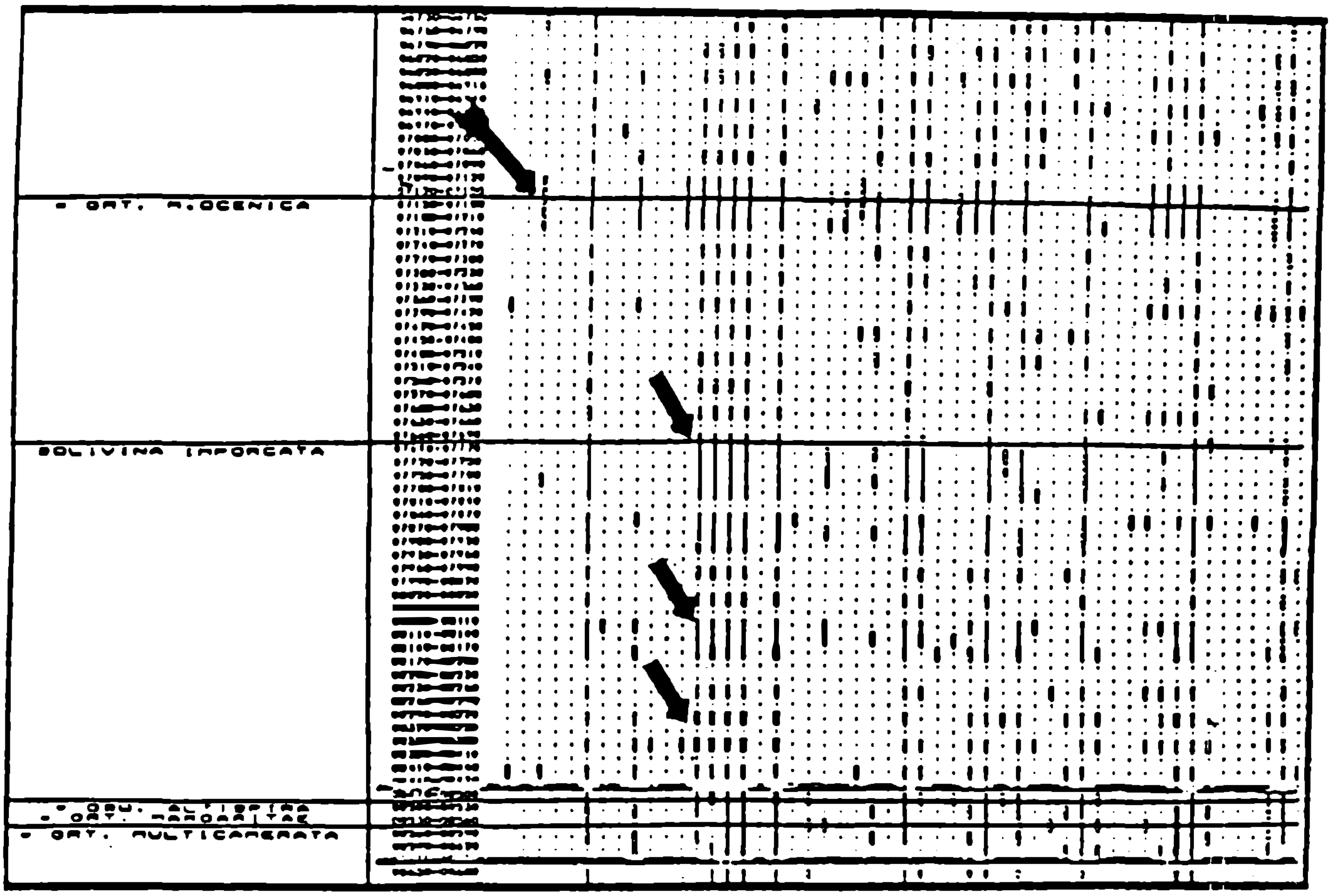
The surface at the top of the lowstand systems tract was viously referred to as the transgressive surface. We felt that this change was necessary because transgressive surfaces of erosion or ravinement surfaces within the transgressive systems tract were sometimes confused with the transgressive surface (Fig. 18).

Where the lowstand prograding complex rests directly on the underlying sequence, several log patterns may mark the sequence boundary. In inner or inner-middle neritic environments this boundary may be t the base of a blocky (massive) sand log pattern (Figure 19). In outer-middle or outer neritic and uppermost bathyal environments the sequence boundary may be at the base of a coarsening upward pattern representing the downlapping toes of the lowstand prograding complex. This is the region where lowstand prograding complexes attain their maximum thickness (Fig. 17). In bathyal and deeper water environments the lowstand prograding complex typically has the railroad-track pattern of a hemipelagic shale. Sometimes a slight coarsening upward pattern may be identifiable.

Where the lowstand prograding complex rests directly on the underlying slope fan complex of previous sequence, bottom set turbidite sands and shales at the toes of the lowstand prograding complex may develop. These turbidites commonly have a set of Christmas-tree shaped log patterns. We call these shingled turbidites. These turbidites can be well developed and are characteristically found to be deposited parallel to strike.

The boundary between the lowstand prograding complex and slope fan is generally marked by a maximum shale point and a well developed condensed section associated with a cold water fauna and flora. The abundance and diversity peaks associated with this boundary are often confused with the warm condensed section and its maximum flooding surface. If this cold-water condensed section is mistaken for the warm-water condensed section, then the shingled turbidites may be misinterpreted as sand packages in the highstand systems tract.

The transgressive systems tract (Figure 20) is characterized by an over all fine and thin upward (backstep) even



GRT. MIOCENICA TOP OF SLOPE FAN CONDENSED SECTION AND MINOR CONDENSED SECTIONS WITHIN SLOPE FAN

Figure 10. Checklist showing *Grt. miocenica* top of slope fan condensed section and minor condensed sections within slope fan.

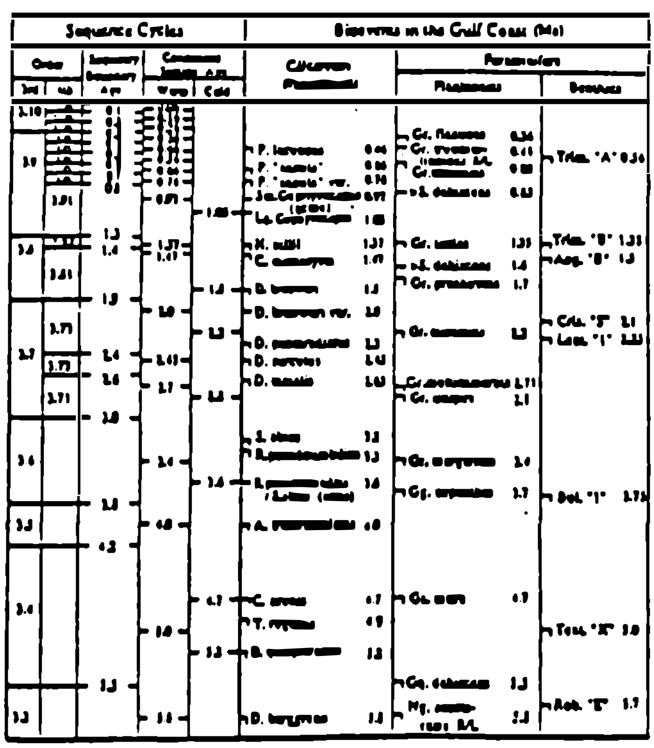


Figure 11. Plio-Pleistocene sequence chronostratigraphy for the Gulf of Mexico.

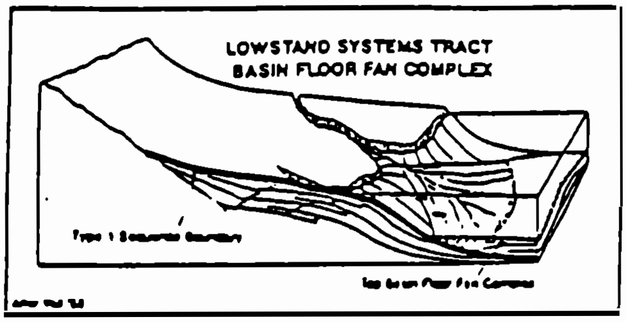


Figure 12. Lowstand systems tract basin floor fan complex.

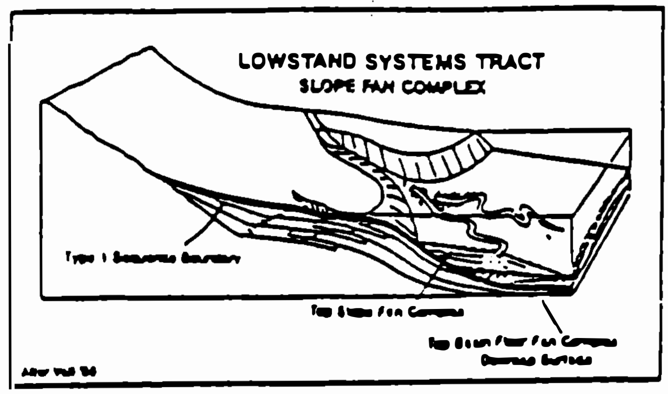


Figure 13. Lowstand systems tract slope fan complex.

though the individual parasequences tend to prograde (Figure 21). The sequence boundary between the transgressive systems tract and the underlying sequence is commonly recognized by one of two log patterns (Figure 22): 1) the point of change between coarsening upward (fore stepping) and fining upward (back stepping) prograding packages (parasequences), or (2) the base of a blocky (massive) sand pattern that is located between the coarsening upward and fining upward pattern. This massive sand is commonly an incised valley fill. In the deep marine environment the transgressive systems tract is commonly represented by a very thin hemipelagic shale which has a railroad track log pattern showing a slight fining upward

The high stand systems tract (Figure 23) is characterize by a set of prograding, coarsening upward and shallowing upward parasequences that terminate at a sequence boundary (Figure 24). Where the shallowing upward pattern includes the coastal or delta plain depositional facies, the

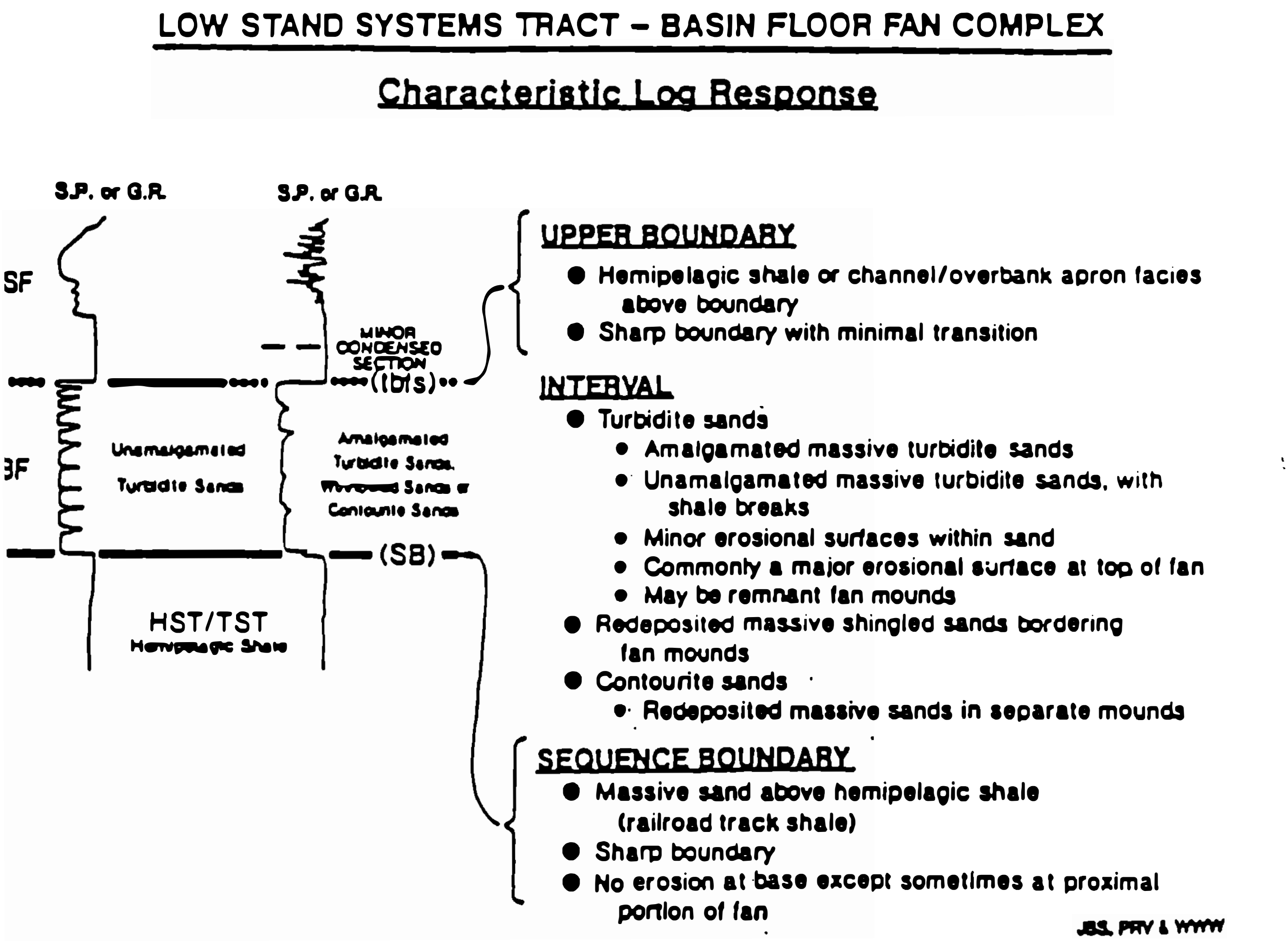


Figure 14. Log characteristics of a basin floor fan complex.

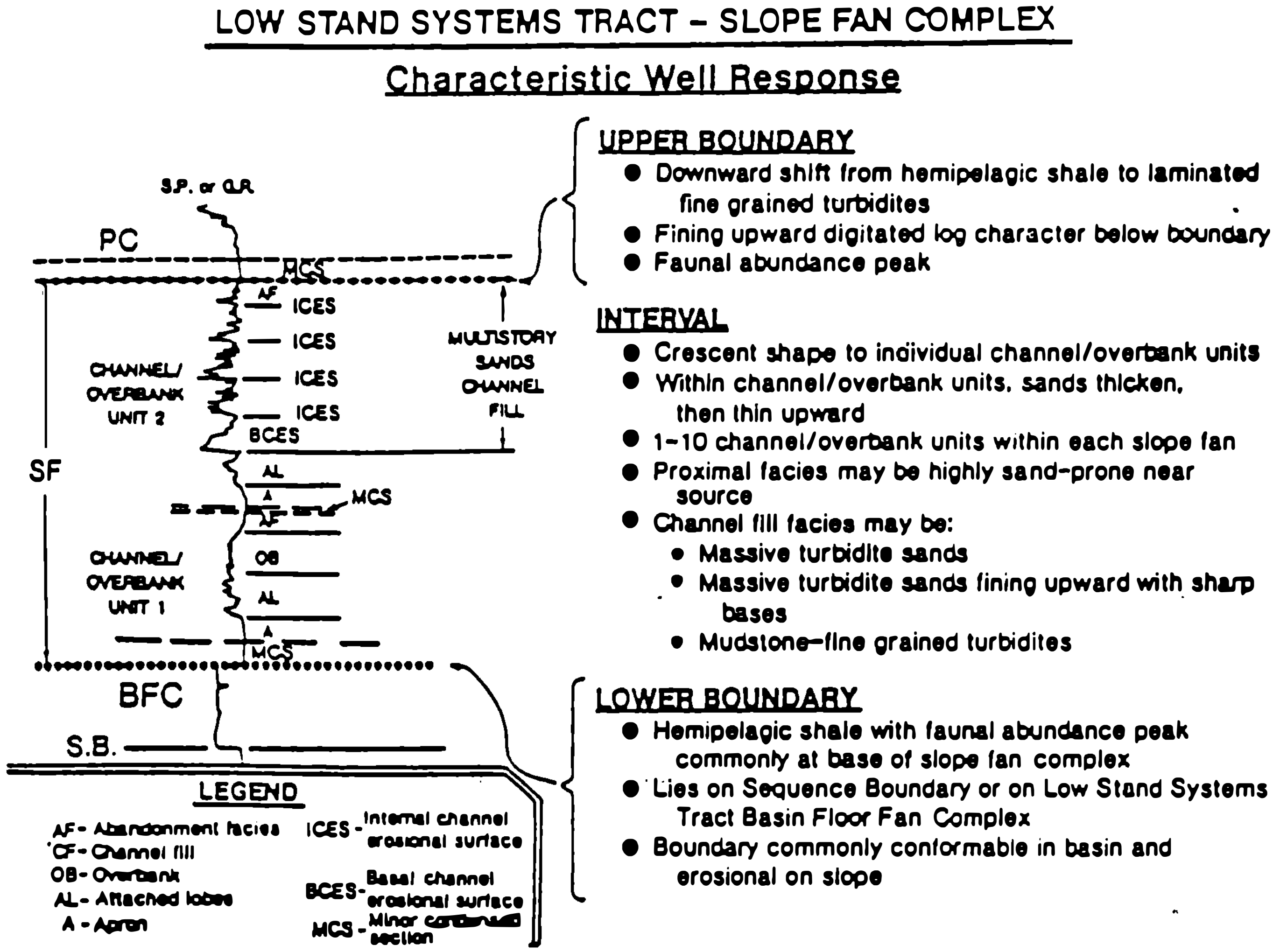


Figure 15. Log characteristics of a slope fan complex.

log pattern commonly indicates an interbedded sand and shale lithologic facies The sequence boundary commonly occurs at the boundary between the interbedded coastal or delta plain sediments and overlying massive sandstone pattern at the base of the transgressive systems tract or incised valley fill (Figure 19).

9) The ninth step is to compare the ages of the depositional sequences defined on the well logs to the global cycle chart. This comparison can help you evaluate whether all sequences have been identified. Haq, et al. (1987) have the latest published versions (3.2B) of the global cycle chart (Figure 25). Our recently revised Plio-Pleistocene chart for the Gulf Coast is illustrated in Figure 26.

10) The tenth step is to identify the sequence boundaries, maximum flooding surfaces and systems tracts on seismic profiles. Once the sequences and systems tracts have been identified independently on the well logs and seismic data, they can be tied, by use of 2-way time logs, synthetics based on check shots, or synthetics based on petrophysical relationships. In general, most of the sequence and systems tract boundaries will tie, but occasionally some will not. Where ties are not possible, re-evaluation of the well log and seismic interpretation must be made to resolve the problem.

In general seismic profiles from Gulf of Mexico Cenozoic slope basins, offshore Texas and Louisiana, can be divided into four intervals: (1) a lower zone of apparently continuous reflections interrupted by faults and diapirs, (2) a thick overlying zone of complex mounds with thin zones of continuous reflectors, (3) a zone of continuous reflectors, and, (4) near the upper portion of the section, a zone of continuous reflectors with erosional surfaces.

The facies of the four zones typically have the following interpretation: Zone 1 consists of distal slope fans with thin hemipelagic shales of the highstand, transgressive and lowstand prograding complex. Zone 2 is mostly slope fan, with basin floor fans near the base and thin hemipelagic shales of the highstand, transgressive, and lowstand prograding complex. Paleowater depths are commonly bathy-

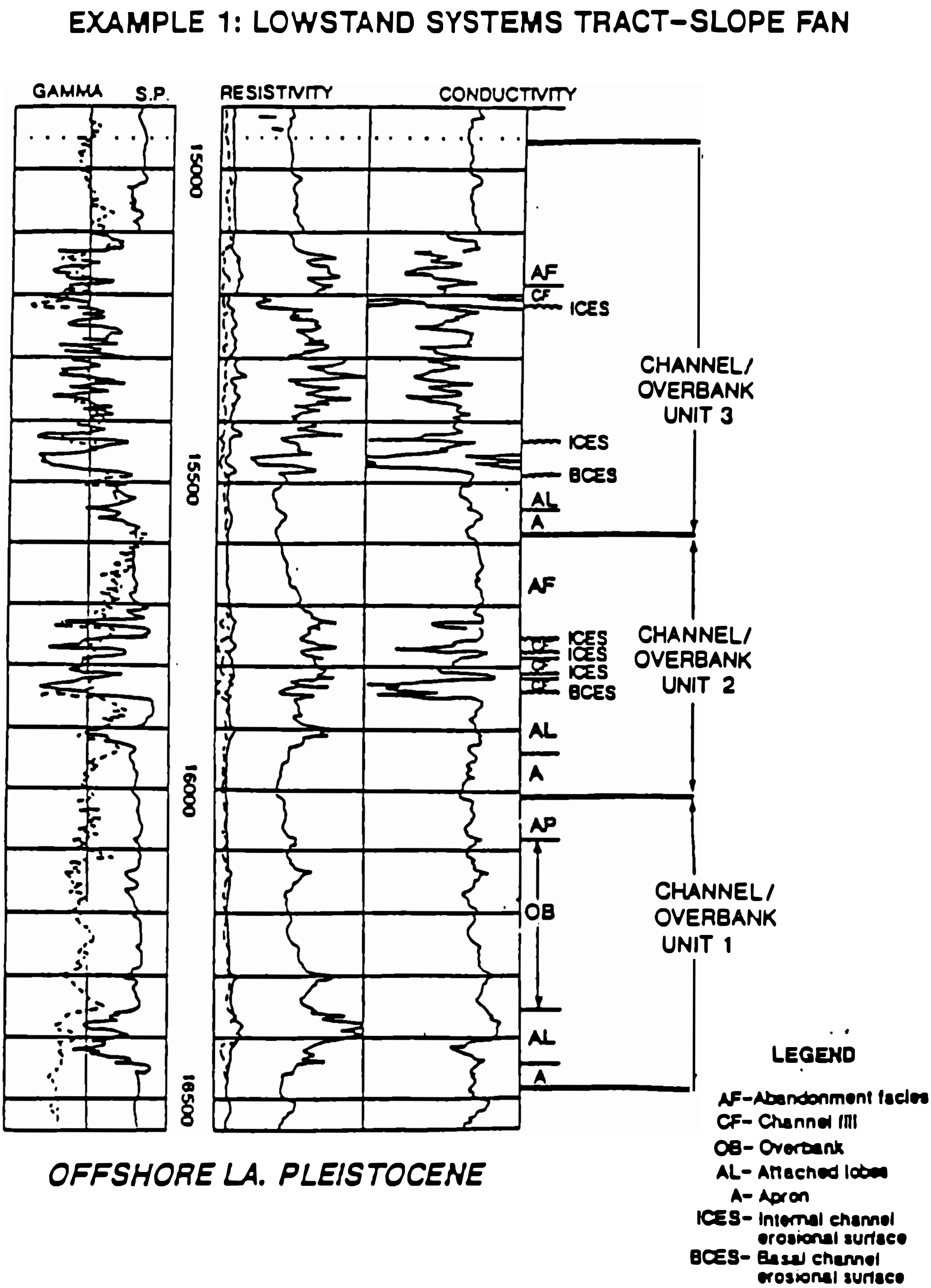


Figure 16. Example showing crescent-shaped log response of a slope fan complex.

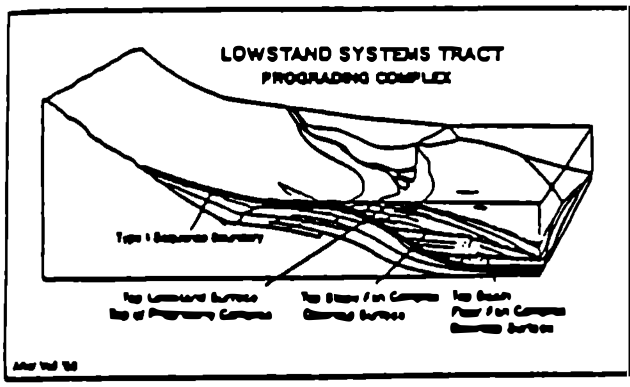


Figure 17. Lowstand systems tract prograding complex.

al. but will sometimes include outer neritic environments. Zone 3 is mostly lowstand prograding complex and transgressive and highstand systems tracts. Reservoir quality shingled turbidites may be developed in the lower portion of this zone. Zone 4 is transgressive and highstand systems tracts that are deposited in a neritic environment with

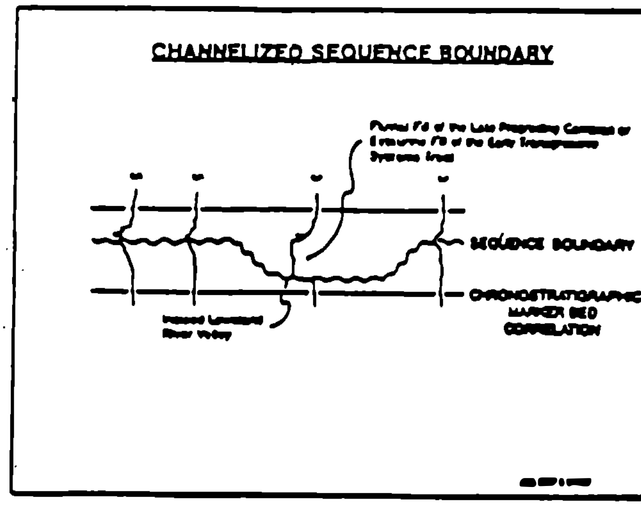


Figure 19. Log characteristics of a incised valley fill.

incised valley fill deposits in a fluvial or estuarine environment.

Sequences and systems tracts are difficult to recognize in Zone 1, but are readily identifiable in Zone 2. In general

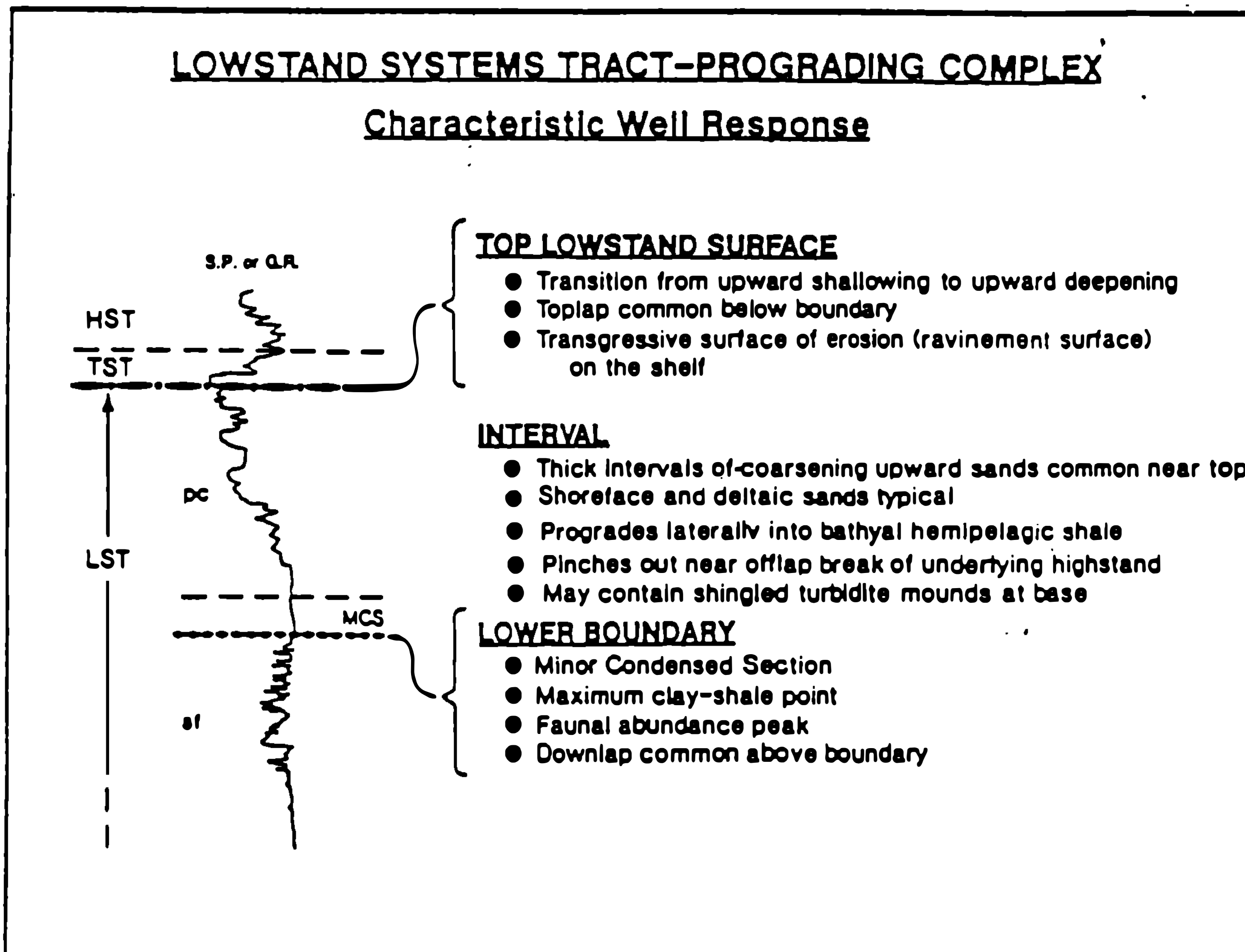
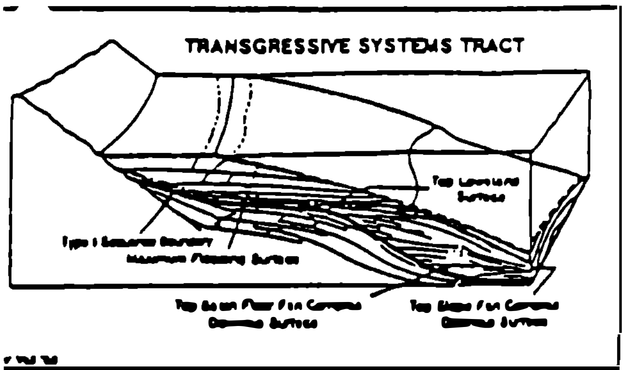


Figure 18. Log characteristrics of a prograding complex.



ure 20. Transgressive systems tract.

the sequence boundary is at the top of the continuous reflectors, marking the hemipelagic shales and the base of the complex mounds in the slope fans. When a basin floor fan is present it is usually difficult to recognize. The basin floor fans are characterized by one or two continuous r· ·ctors that onlap the edge of the penecontemporaneous slope basin and show evidence of mounding. The sequence boundary is placed below these onlapping reflectors. The

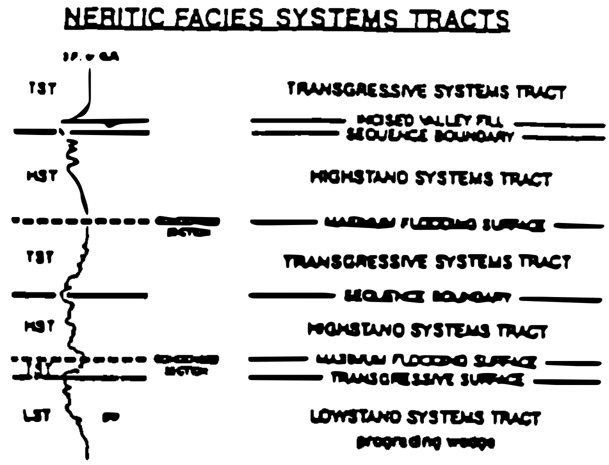
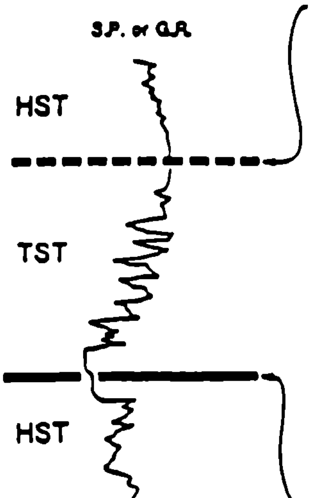


Figure 22. Log characteristics of neritic facies systems tracts.

top and base of the transgressive systems tracts characteristically produces the most correlatable reflectors. These

TRANSGRESSIVE SYSTEMS TRACT

Characteristic Well Response



MAXIMUM FLOODING SURFACE
- Commonly lowest resistivity–highest gamma
- Most clay rich shale (most starved)
- Faunal abundance peak
- Apparent truncation common below boundary
- Downlap common above boundary

INTERVAL
- Individual parasequences prograde, fine and thin upward (backstep)
- Beach and shoreface sands common near base
- Basinal equivalent is thin hemipelagic shale
- Correlation is good, but backstepping transgressive surface of erosion are time–transgressive
- Sands often better sorted than HST
- Authigenic minerals common

SEQUENCE BOUNDARY
- Onlaps sequence boundary
- Commonly transgressive surface of erosion (ravinement surface) over LST, IVF or older shelf sediments near shelf edge
- Nonmarine sediments (coastal plain, coal or lake sediments) onlap sequence boundary in more landward areas
- Top Lowstand surface at base of TST

JBS, PRV & WWW

ire 21. Log characteristics of a transgressive systems tract.

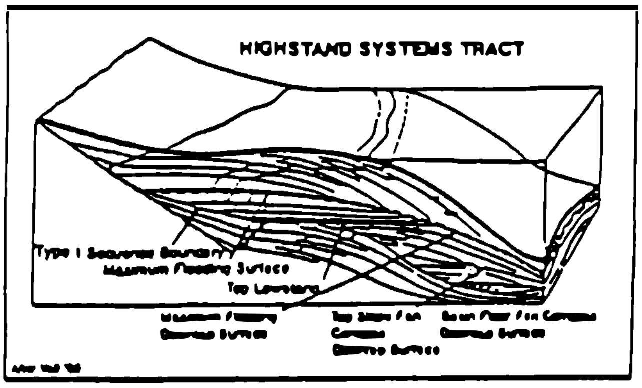


Figure 23. Highstand systems tract.

are the regionally continuous, parallel, high amplitude reflectors.

In Zone 2 systems tract boundaries are often difficult to identify within the continuous reflections of Zone 2, and well log ties are especially important in this zone. In general, Zone 2 is mostly lowstand prograding complex that may include shingled turbidites. The top and base of the transgressive systems tracts commonly produce the most continuous reflectors. Highstand systems tracts are variable in thickness, but may be well developed. Zone 4 is typically very sandy because it is composed of the massive sands in incised valley fills: stacked, backstepping sands of the transgressive systems tract and stacked sands of the highstand systems tract. The incised valley erosional surfaces are commonly readily identifiable on seismic data.

11) The eleventh step is to identify and correlate parasequences and marker beds within the systems tracts on well logs. The best interval to identify correlative parasequence marker beds is associated with the marine flooding surface. Parasequence boundaries are flooding surfaces at the base of coarsening upward patterns. They are useful for developing a consistent log correlation pattern. Marker beds are commonly associated with the parasequences. Parasequence correlations are important for basin reservoir evaluation because they can be used:
(1) to evaluate correlation consistency
(2) to define chronostratigraphic horizons
(3) to correlate with seismic patterns

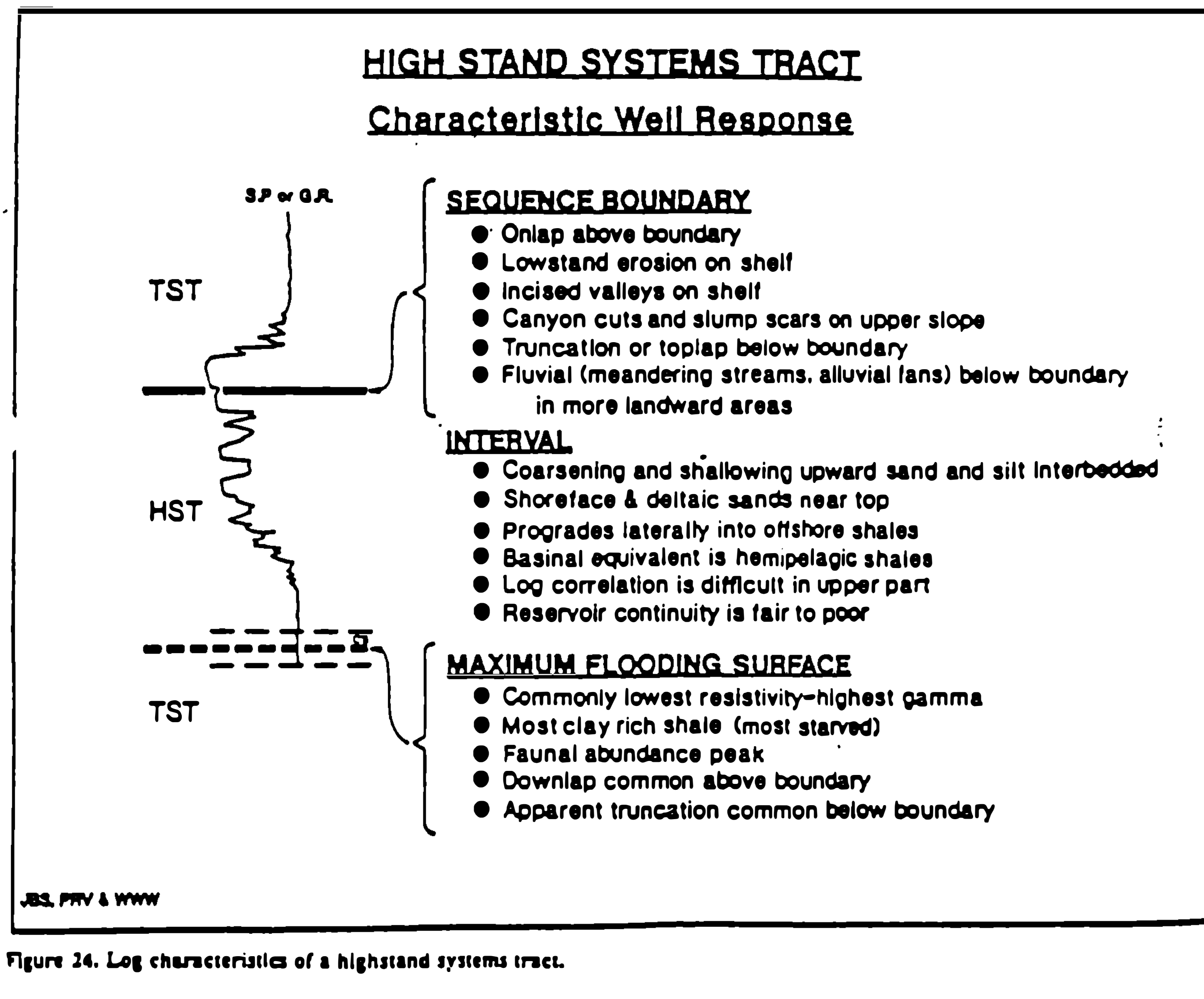
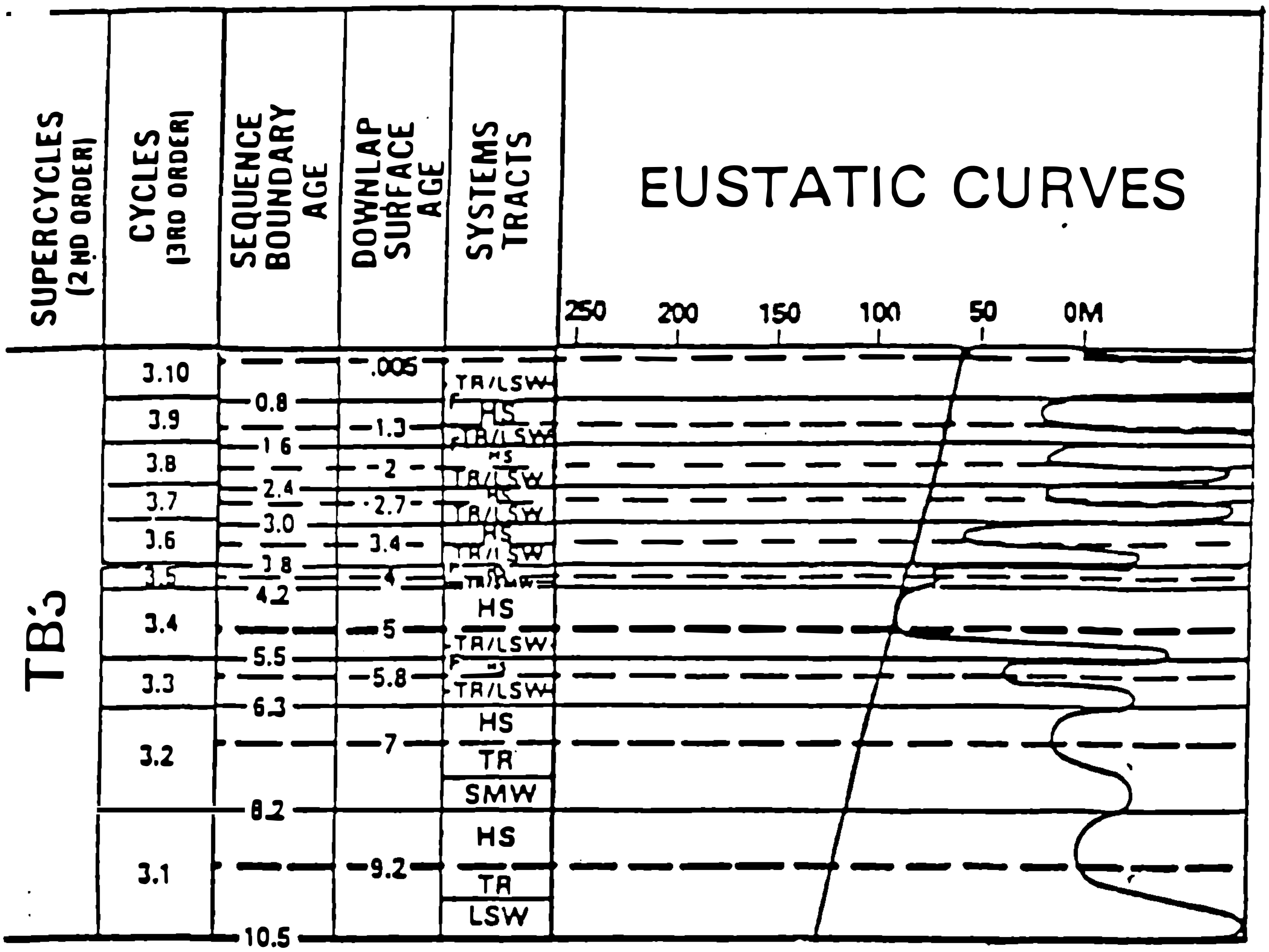


Figure 24. Log characteristics of a highstand systems tract.



ure 25. Global Mesozoic-Cenozoic cycle chart (In part, after Haq et al., 1987).

(4) to serve as units for reservoir description, since they define the primary porosity distributions.

Step twelve is one of the most important and involves construction of a well log-seismic sequence stratigraphic cross section in which the maximum flooding surfaces, sequence boundaries and systems tracts are correlated from well to well (Figure 27). In a dip section that has been tied to a seismic section the lowstand basin floor fans and slope fans are well developed in the lower (downdip) portion of the section. In the updip direction the basin floor fans are generally absent, the slope fans are less well developed and the prograding wedges become well developed. The basin floor fans, the slope fans and prograding wedges of the lowstand systems tracts progressively pinch out in a landward (updip) direction. The updip portion of the section shows well developed backstepping transgressive and forestepping and highstand systems tracts and occasional incised valleys.

The final step, number 13, involves the preparation of a chronostratigraphic chart from key cross-sections to summarize the stratigraphic framework interpreted from the paleontologic data, well logs and seismic profiles.

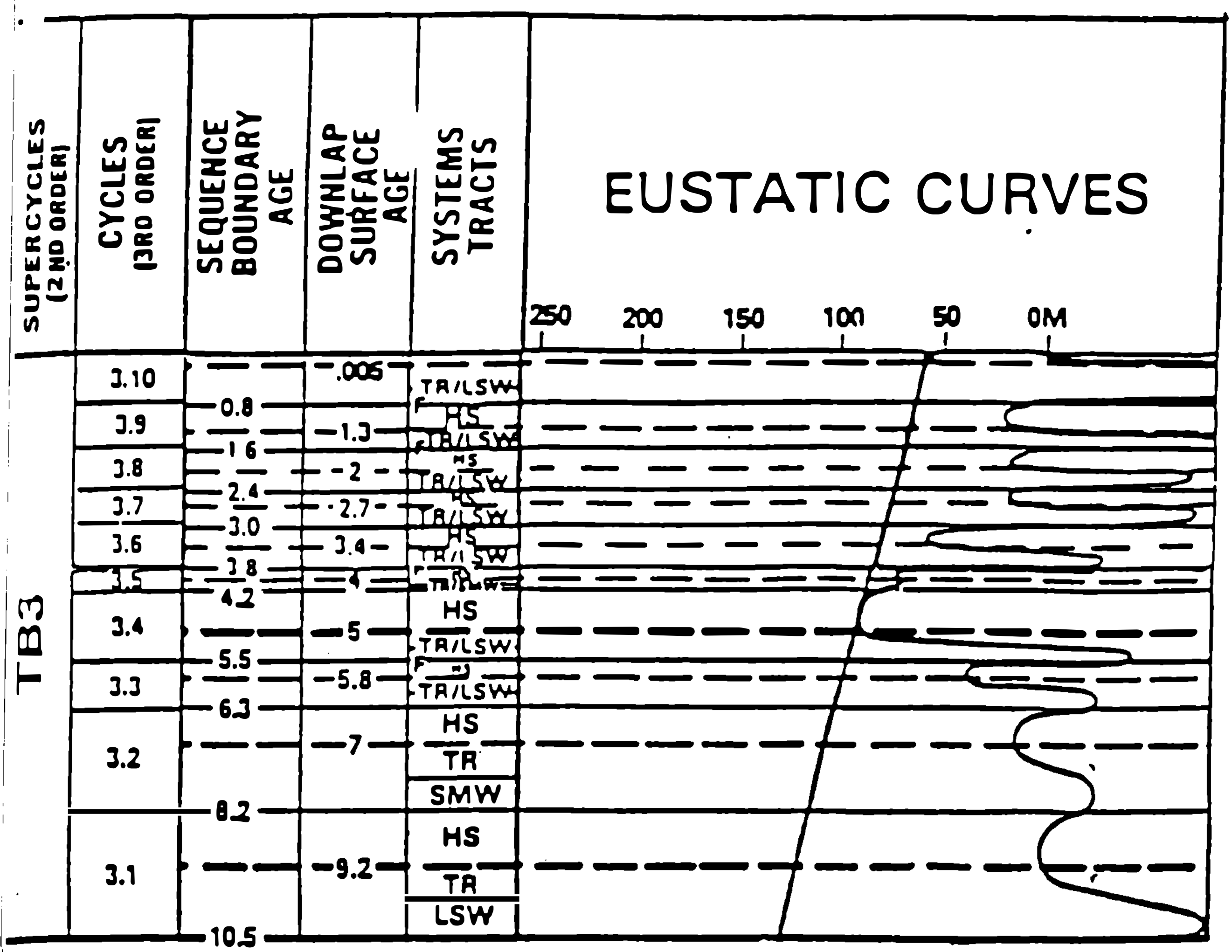
CONCLUSIONS

We believe that the use of well-log seismic sequence stratigraphy will give companies a competitive advantage and substantially reduce their risk in bidding on offshore blocks by allowing them to properly evaluate new and previously leased blocks. This methodology can be used to:

- More accurately age date, correlate and calibrate condensed sections, sequence boundaries and systems tracts with the seismic reflections on seismic profiles between wells.

- Identify the type of systems tract that is associated with potential hydrocarbon reservoirs, source rocks and seals and determine the play concept for the reservoir sands (shelf or slope) because each system tract requires a different exploration philosophy.

- Understand the geometry of the reservoir (e.g., basin floor fan, channel or overbank sands, shingled turbidites, delta lobes, longshore bar or incised valley fill).



re 15. Global Mesozoic-Cenozoic cycle chart (In part, after Haq et al., 1987).

4) to serve as units for reservoir description, since they define the primary porosity distributions.

Step twelve is one of the most important and involves construction of a well log-seismic sequence stratigraphic cross section in which the maximum flooding surfaces, sequence boundaries and systems tracts are correlated from well to well (Figure 27). In a dip section that has been tied to a seismic section the lowstand basin floor fans and slope fans are well developed in the lower (downdip) portion of the section. In the updip direction the basin floor fans are generally absent, the slope fans are less well developed and the prograding wedges become well developed. The basin floor fans, the slope fans and prograding wedges of the lowstand systems tracts progressively pinch out in a landward (updip) direction. The updip portion of the section shows well developed backstepping transgressive and forestepping and highstand systems tracts and occasional incised valleys.

The final step, number 13, involves the preparation of a chronostratigraphic chart from key cross-sections to summarize the stratigraphic framework interpreted from the paleontologic data, well logs and seismic profiles.

CONCLUSIONS

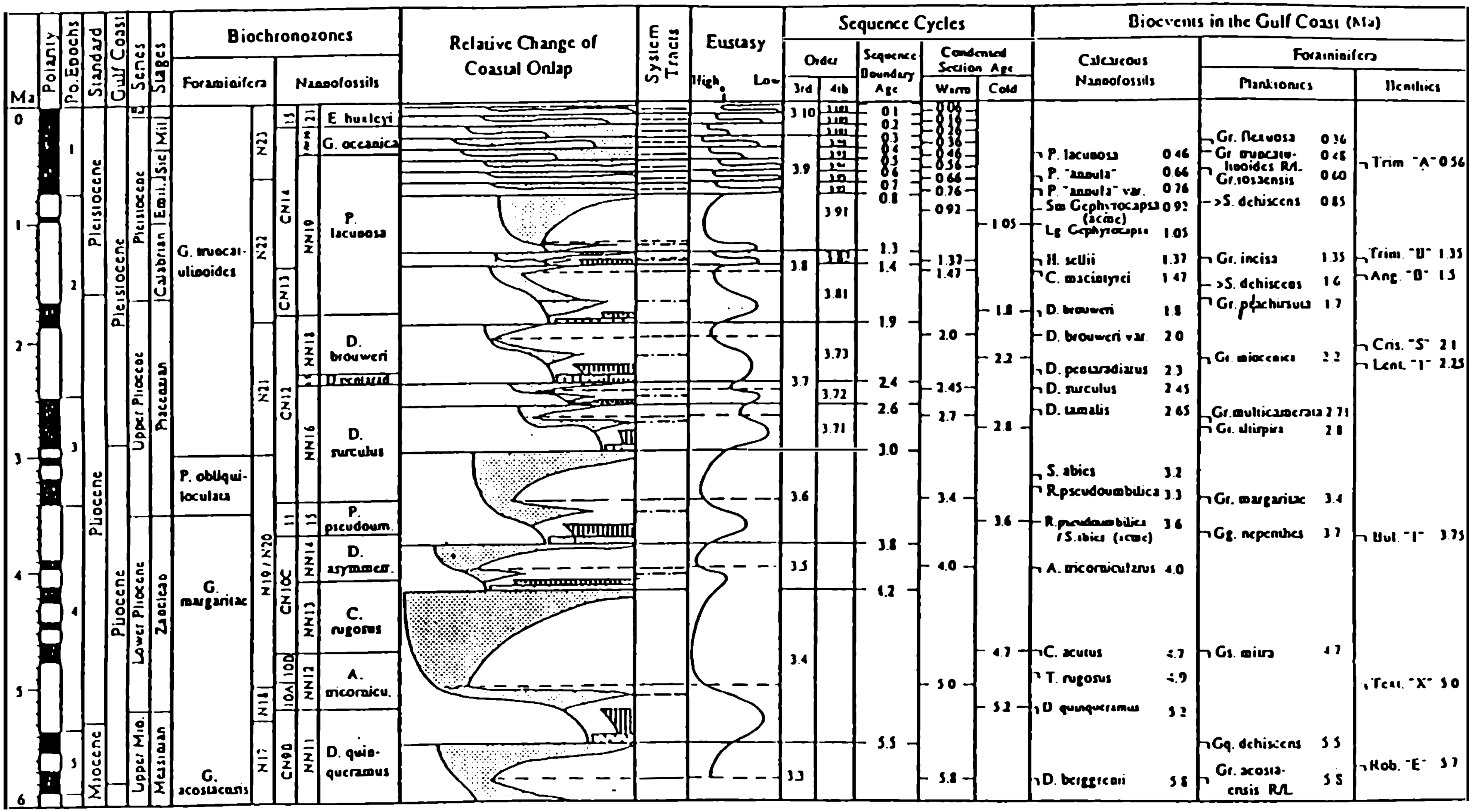
We believe that the use of well-log seismic sequence stratigraphy will give companies a competitive advantage and substantially reduce their risk in bidding on offshore blocks by allowing them to properly evaluate new and previously leased blocks. This methodology can be used to:

- More accurately age date, correlate and calibrate condensed sections, sequence boundaries and systems tracts with the seismic reflections on seismic profiles between wells.

- Identify the type of systems tract that is associated with potential hydrocarbon reservoirs, source rocks and seals and determine the play concept for the reservoir sands (shelf or slope) because each system tract requires a different exploration philosophy.

- Understand the geometry of the reservoir (e.g., basin floor fan, channel or overbank sands, shingled turbidites, delta lobes, longshore bar or incised valley fill).

PLIO-PLEISTOCENE SEQUENCE CHRONOSTRATIGRAPHY



Sequence Boundary
Maximum Flooding Surface
Top Lowstand Systems Tract (Lowstand Systems Tract includes Prograding Slope Fan and Basin Floor Fan Complexes)

Wornardt and Vail 1991

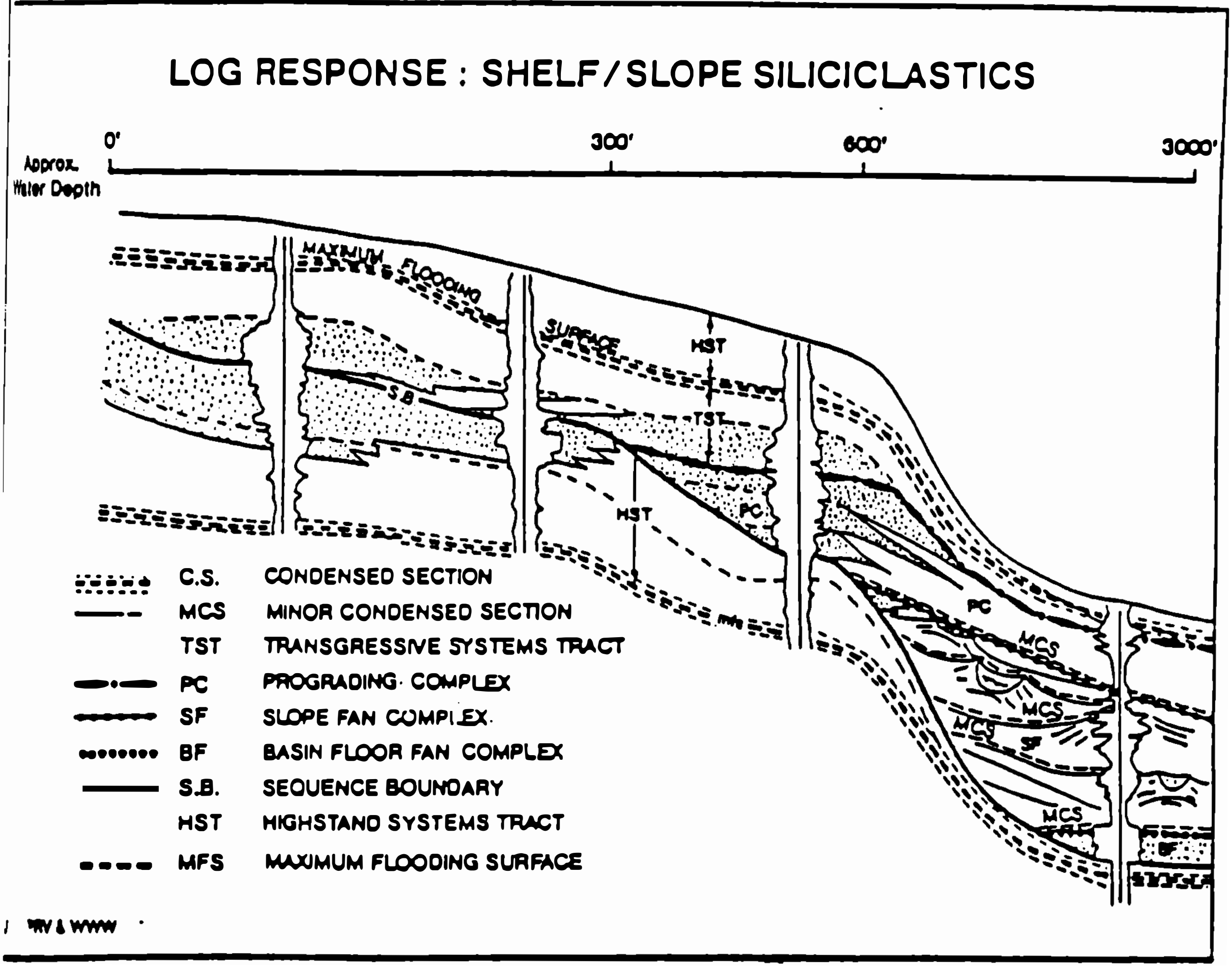


Figure 27. Distribution and log response of different systems tracts on the shelf and slope.

- Correlate sand packages from upthrown to downthrown fault blocks, around salt domes, up-dip, down-dip and along strike with a very high confidence level.

- Date condensed sections on the seismic record section (the downlap surfaces) to determine time of faulting and salt movement.

- Construct maps based on systems tracts.

- Develop a seismic-sequence stratigraphy grid for the Gulf of Mexico. The creative application of this well log-seismic sequence stratigraphy technology provides an opportunity for companies to take a quantum leap into the 90's by providing a methodology that may present the greatest potential to discover new and extend old oil and gas fields.

ACKNOWLEDGMENTS

The interpretation procedure described in this report was developed in cooperation with J.B. Sangree and R.M. Mitchum, Jr., especially the methodology for interpreting sequences and systems tracts from well logs and seismic data.

REFERENCES CITED

Haq, B. U., J. Hardenbol, and P. R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1166.

Huang, T. C. and W. W. Wornardt, 1986, Plio-Pleistocene sequence stratigraphy, abundance peak correlation of seven wells in Green Canyon, offshore Louisiana. MICRO-STRAT INC. company reports.

Lamb, J. L., W. W. Wornardt, T. C. Huang, and T. E. Dube, 1987, Practical application of Pleistocene eustacy in offshore Gulf of Mexico, Cushman Foundation for Foraminiferal Research, Special Publication 24, pp. 33–39.

Pacht, J. A., B. E. Bowen, J. H. Beard, and B. L. Shaffer, 1990, Sequence-stratigraphy of Plio-Pleistocene depositional facies in the offshore Louisiana south additions: Gulf Coast Assoc. Geol. Socs., Trans., v. XL, p. 643–659.

Shaffer, B. L., 1987, The potential of calcareous nannofossils for recognizing Plio-Pleistocene climatic cycles and sequence boundaries on the shelf: Eighth Annual Research Conference, Gulf Coast Section, SEPM, Selected Papers and Illustrated Abstracts, p. 142–145.

Shaffer, B. L., 1990, The nature and significance of condensed sections in Gulf Coast late Neogene sequence stratigraphy: Gulf Coast Assoc. Geol. Socs., Trans., v. XL, p. 767–776.

Smith, L. A., 1965, Paleoenvironmental variation curves and paleoeustatics, Gulf Coast Assoc. Geol. Socs., Trans., v. XV, p. 47–60.

Vail, P. R. and W. W. Wornardt, 1990, Well log seismic sequence stratigraphy: an integrated tool for the 90's. Eleventh Annual Research Conference, Gulf Coast Section, SEPM, Program and Extended and Illustrated Abstracts, p.379–397.

Vail, P. R., 1988, Sequence stratigraphy workbook, fundamentals of sequence stratigraphy: 1988 Am. Assoc. Petrol. GEol., Annual Convention Short Course: Sequence stratigraphy interpretation of seismic well and outcrop data, presented by P. R. Vail and J. B. Sangree, March 19, 1988, Houston, Texas.

Wornardt, W. W. and J. L. Lamb, 1985, Pliocene-Pleistocene eustacy in offshore Gulf of Mexico and its correlation with planktonic and benthonic foraminiferal and calcareous nannofossils datums, eustatic cycles, species abundance, paleotemperature and oxygen isotopes, SEPM, Program and Abstracts, SEPM Res. Conf., "Sea-Level Changes-An Integrated Approach", October 1985.

Wornardt, W. W. and P. R. Vail, 1990, Revision of the Plio-Pleistocene based on seismic sequence stratigraphy. Eleventh Annual Research Conference, Gulf Coast Section, SEPM, Program and Extended and Illustrated Abstracts, p.391–397.

Wornardt, W. W., 1989, Calcareous nannofossils and condensed sections in sequence stratigraphy. International Nannoplankton Association Conference, Florence, Italy, Book of Abstracts p. 3.

PART 10

EXERCISES

SECTION 1

WELL LOG / SEISMIC LITHOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY IN THE TRANSGRESSIVE AND HIGHSTAND SYSTEMS TRACTS

PART 10 - SECTION 1: WELL LOG / SEISMIC LITHOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY TRANSGRESSIVE AND HIGHSTAND SYSTEMS TRACTS

GIVEN:

* Well log sequence stratigraphy procedure

* Big sheet with the five well logs to correlate

* Characteristic Log responses for each systems tract, Figures 4/7b-1 to 4/7b-6

* Some informations on the different logs, Figures 4/7b-7 to 4/7b-12

* Answer sheet, Figure 4/7b-13

EXERCISE
LITHOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY FROM WELL LOGS

Peter R. Vail And John B. Sangree

Contributions From T.R. Nardin And J. Van Wagoner, Exxon Production Research Company and R.M. Sneider, Richardson, Sangree and Sneider

OBJECTIVE

To understand the relationship between lithostratigraphy (rock) and chronostratigraphy (time-rock) units and to explore the usefulness of sequence and parasequence concepts in log correlation and interpretation.

DEFINITIONS

STRATIGRAPHY is the science of rock strata.

CHRONOSTRATIGRAPHY (TIME-ROCK STRATIGRAPHY) is a type of stratigraphy that subdivides a sedimentary section into units composed of all the sediments deposited during a specific interval of geologic time.

LITHOSTRATIGRAPHY (ROCK STRATIGRAPHY) is a type of stratigraphy that subdivides a sedimentary section into units composed of the same general rock type. The basic unit is a FORMATION defined as a mappable rock unit. A formation may have time-transgressive boundaries. (Hedberg and Salvador 198-)

PARASEQUENCE is a relatively conformable succession of genetically related beds bounded by marine flooding surfaces or their correlative conformities (Van Wagoner, 1985).

WORK MATERIALS

Five well logs (spontaneous Potential - SP, short normal resistivity, amplified short normal resistivity and lithology)

Index map showing subsea structure of unconformity surface

Plate I: Log cross-section,

Plate III: Chronostratigraphic chart.

ANSWER MATERIALS:

Plate II: Lithostratigraphic and chronostratigraphic correlation

Plate IV: Chronostratigraphic chart.

LOG CHARACTERISTICS

LITHOLOGIC LOG: The lithologic log is located in the center of each well and shows the rock type. In this case the rock type shown is the interpreted distribution of sandstone and shale. The sandstone and shale beds are interpreted from the SP and resistivity curves.

SPONTANEOUS POTENTIAL - SP: The curve at the left of each lithologic log is the SP log. Excursions to the left indicate permeable sediments, in this case sandstone. The more nearly straight portion along the right side of the SP track indicates impervious sediments, in this case shale. The SP is a measure of the difference between the potential of a movable electrode in the borehole and a fixed reference electrode at the surface. It provides a measure of formation permeability.

SHORT NORMAL RESISTIVITY: The curve at the right of each lithologic log is a resistivity log. It measures the inverse of the electrical conductivity. The short normal curve is a resistivity curve with a short source to receiver distance. Excursions of the resistivity log can be caused by changes in porosity, tortuosity, minerologic composition, and type and degree of fluid saturation. The AMPLIFIED SHORT NORMAL is the same curve with an expanded lateral scale. It is especially useful for making well log correlations in shaly sections.

PART I

INSTRUCTIONS (use separate logs and index map).

Arrange the logs in the order shown on the index map and make a quick preliminary correlation. Our purpose at this point is to decide what is an appropriate chronostratigraphic datum for a cross-section. Can we use the top of the sand that overlies the unconformity surface? Do you see a better correlation surface in the more continuous shale section?

PART II

INSTRUCTIONS: (use Plate I).

1. Identify lithologic formations using the S.P. curve.
   * Color the sands yellow
   * Identify the top of the "basal sand" that lies above the unconformity.
   * Identify the top of the marine shale, and consequently the base of the sand overlying the shale wedge.
   * Mark the top and base of the sand,complexes with a

yellow marker on each log.

2. Identify and correlate the parasequences.
   * Each parasequence boundary occurs of the top of a unit that both coarsens and thickens upward. Our interpretation of the parasequence boundaries is indicated by arrowheads on well 5.
   * Identify and correlate as many of the parasequences as you can. Note that the easiest parasequence correlation occurs in the marine shale wedge. The correlation can be extended into the sands once the shale correlation pattern is established.

3. Identify the sequence boundary overlying the shale wedge. This is best seen in wells 2,3, and 4 where a massive well sorted marine sand overlies thinner bedded deltaic sands and shales.

4. Identify the surface corresponding to the maximum marine invasion, the condensed section. This lies at the center of the marine shale wedge in the lowest resistivity shales.

5. Connect the formation boundaries using a yellow line. Begin at the left of the section and carry the yellow line along the top of the sand at the parasequence boundary until the sand grades laterally into shale, then drop vertically to the next sand-shale boundary and repeat the process. The same procedure is used to identify the top of the shale wedge, except that the boundary steps up instead of down.

6. Now take out Plate II and compare your solution with our interpretation. We have defined the individual sand beds with sloping ("Shazam") lines and the formation boundary with a dashed line.

PART III

INSTRUCTIONS (Use Plates II and III)

1. Using biostratigraphic data and the eustatic cycle chart we have identified the age of the sequence boundaries and we have esta.lished proportional ages for each parasequence. Identify these in Plate II.

2. Using the formation boundaries and ages of Plate II, construct a chronostratigraphic diagram of the age relationships of the two sand formations and the intervening shale wedge. Plot these boundaries on Plate

III. Use wide-spaced vertical lines to indicate an erosional or depositional hiatus. Color the sand formations yellow.

3. Compare your solution with our own shown on Plate IV.

DISCUSSION:

There are two types of physical stratigraphic surfaces in the sediments at the time of deposition - bedding or stratal surfaces and stratal discontinuities.

Bedding surfaces are the physical depositional surfaces that separate the principal sedimentary rock layers. They represent periods of nondeposition or a change in the depositional regime. Within a given interval, bedding surfaces may extend from a region where they separate recognizable different layers to a region where the bordering layers are the same type rock. Thus, at any particular point, bedding surfaces may or may not be readily recognizable. Stratal surfaces are major through-going bedding surfaces that separate the principal sedimentary strata and form practical geologic time-lines through a stratigraphic section.

Stratal discontinuities are physical surfaces caused by erosion or nondeposition. Discontinuities are commonly unconformities or nondepositional hiatuses. An unconformity is a surface representing a significant time gap with erosional truncation (subaerial or subaqueous) and/or subaerial exposure. These surfaces separate older strata below from younger strata above and often (but not always) are marked by the discordant patterns of truncation, onlap or toplap. (Vail, Hardenbol and Todd, 1985). Nondepositional hiatuses are time gaps in the stratigraphic record caused by nondeposition or very slow depositional rates. In the latter case the nondepositional hiatus is commonly associated with a condensed interval. Subaqueous nondepositional hiatuses are commonly characterized by the pinchout of the toes of prograding clinoforms. This pattern is called downlap. (Vail, Hardenbol and Todd, 1981).

Both bedding or stratal surfaces and stratal discontinuities are geologic time surfaces. Bedding and stratal surfaces are synchronous geologic time surfaces because they represent former depositional surfaces that existed at a specific time in geologic history. We can observe bedding surfaces forming today in beaches, turbidites, varves, ash falls and fluvial deposits.

Comparison of these recent sediments with ancient rocks shows identical bedding features. Therefore, if these surfaces form in hours, days, or even years, they are practical synchronous surfaces representing an instant of geological time. Stratal discontinuities are not time synchronous, but they are geologic time boundaries that separate older from younger rocks. Their exact geologic age is determined by dating the stratal surface where they become conformable.

STRUCTURE ON UNCONFORMITY SURFACE

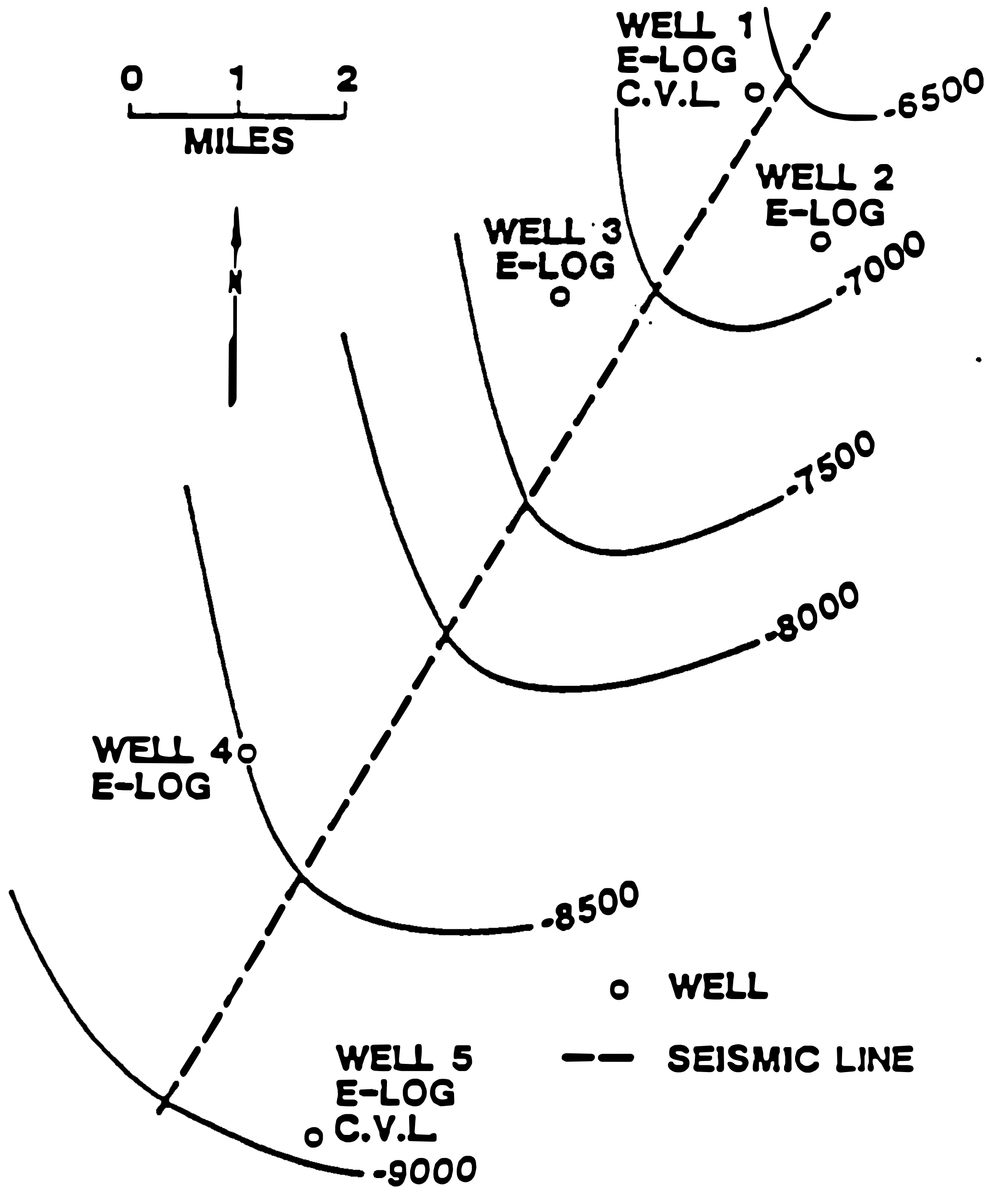
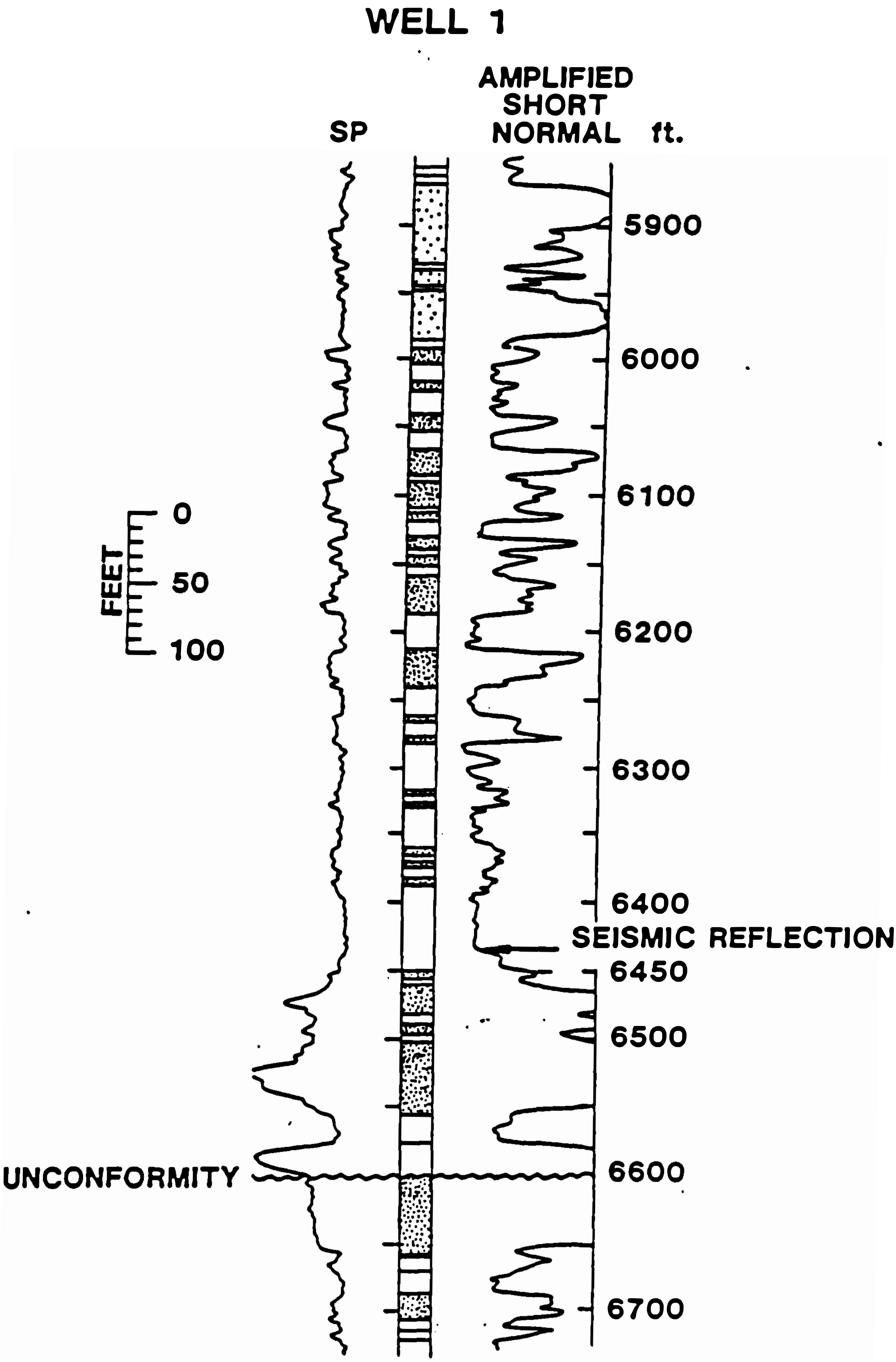
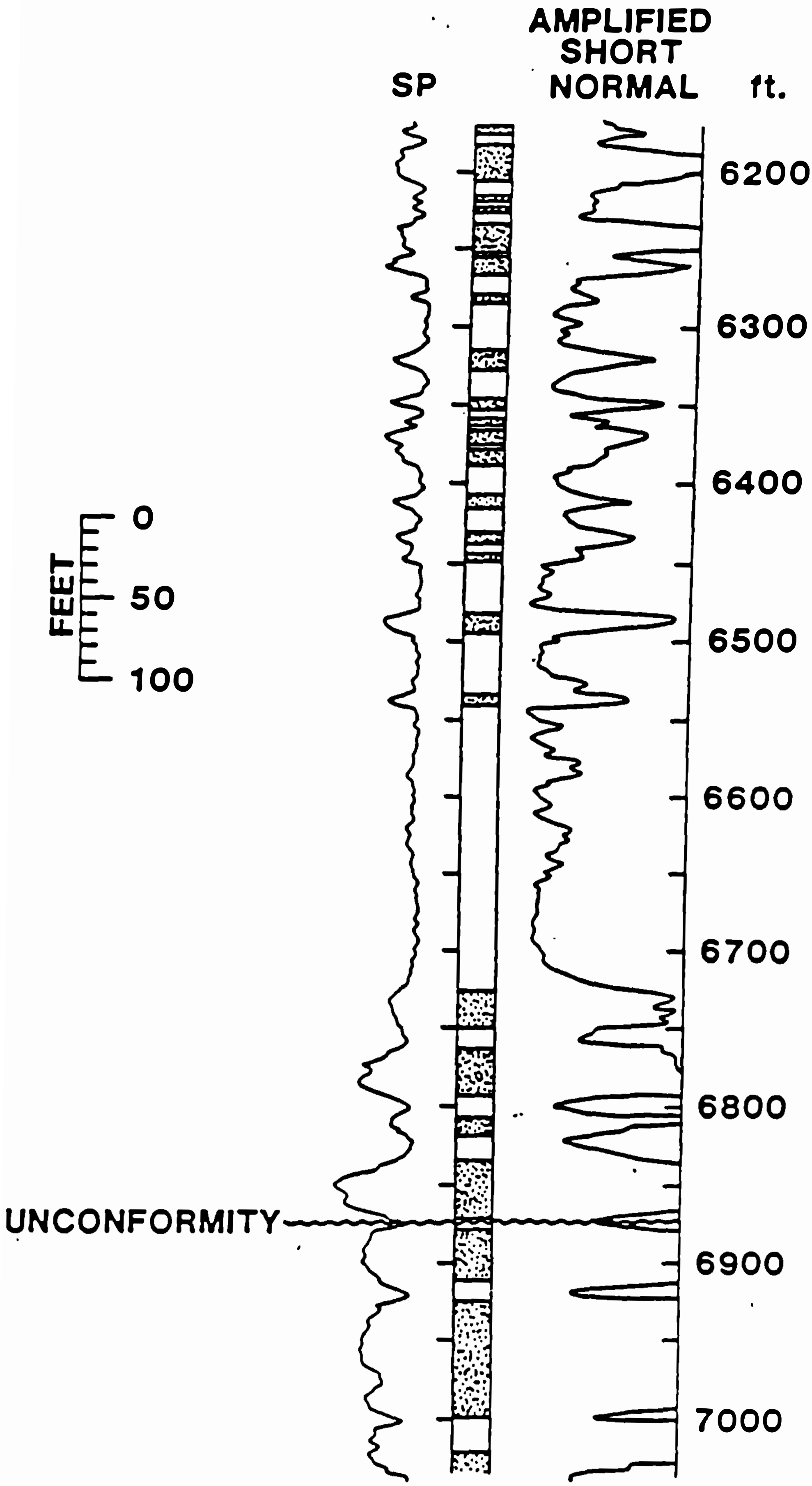


FIG. 1
AFTER VAIL, et. al.

FIG. 3-2

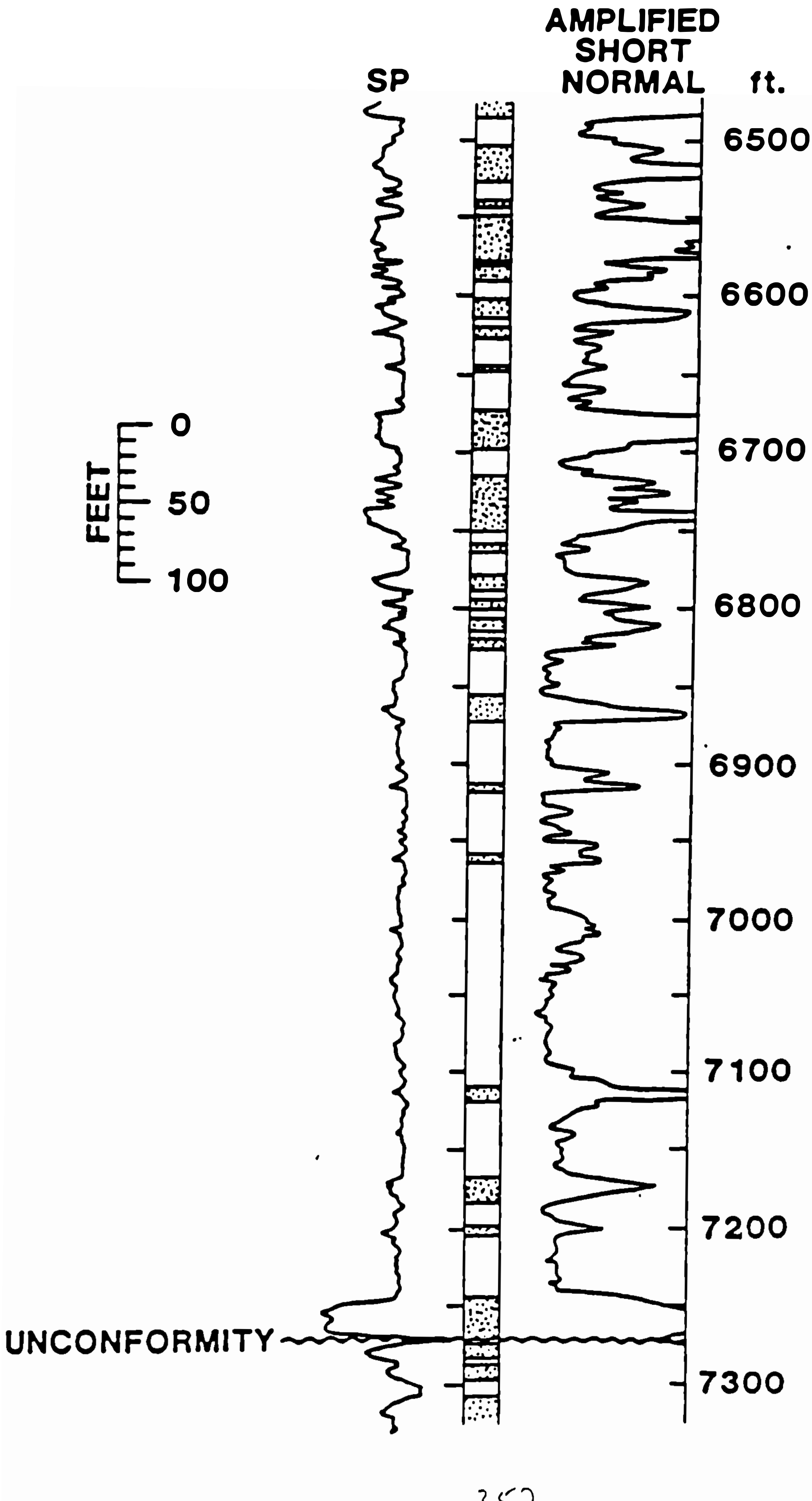


RMS-SEIS STRAT-



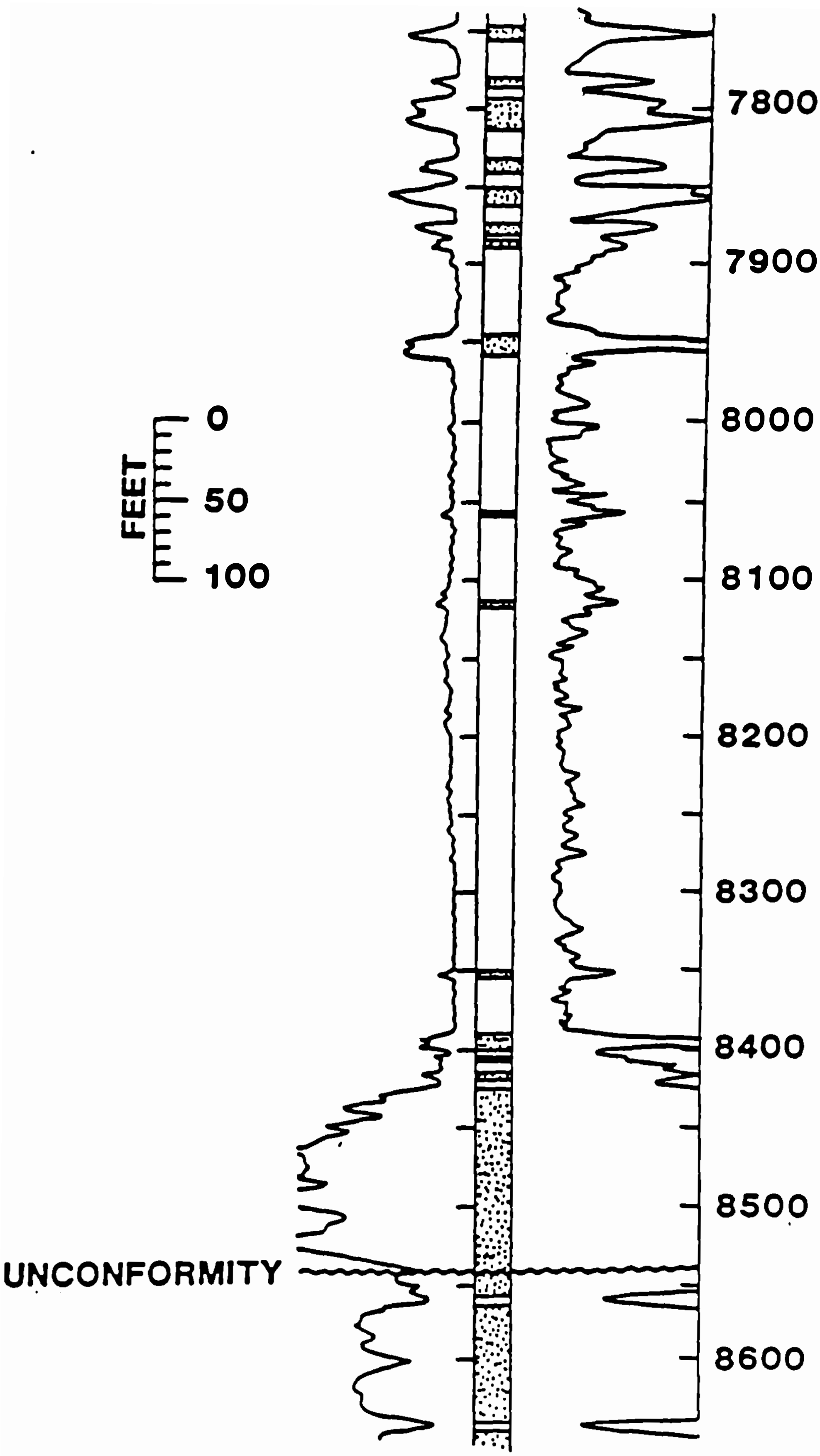
RMS-SEIS STRA

WELL 3

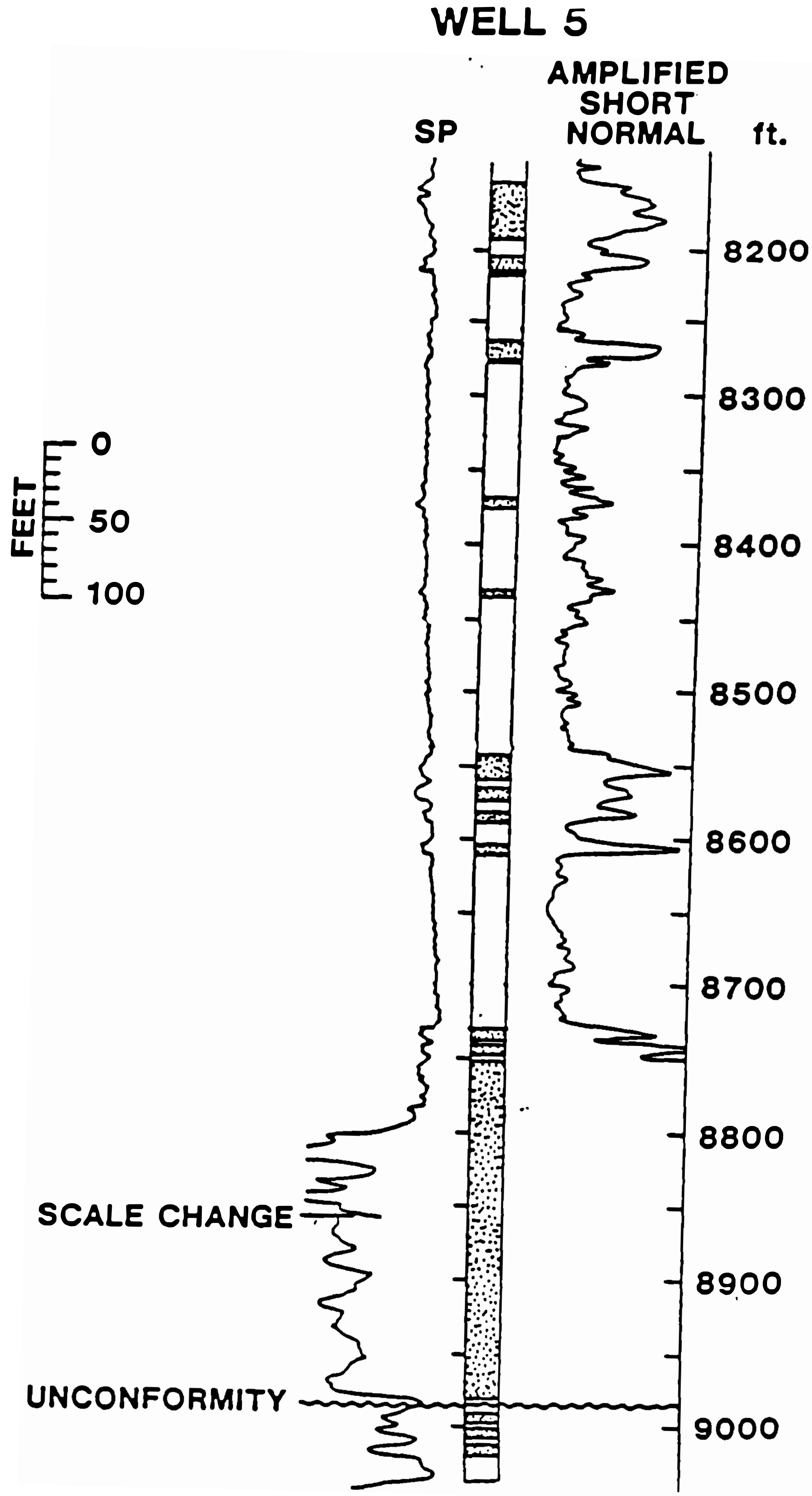


RMS-SEIS STRAT-4

WELL 4



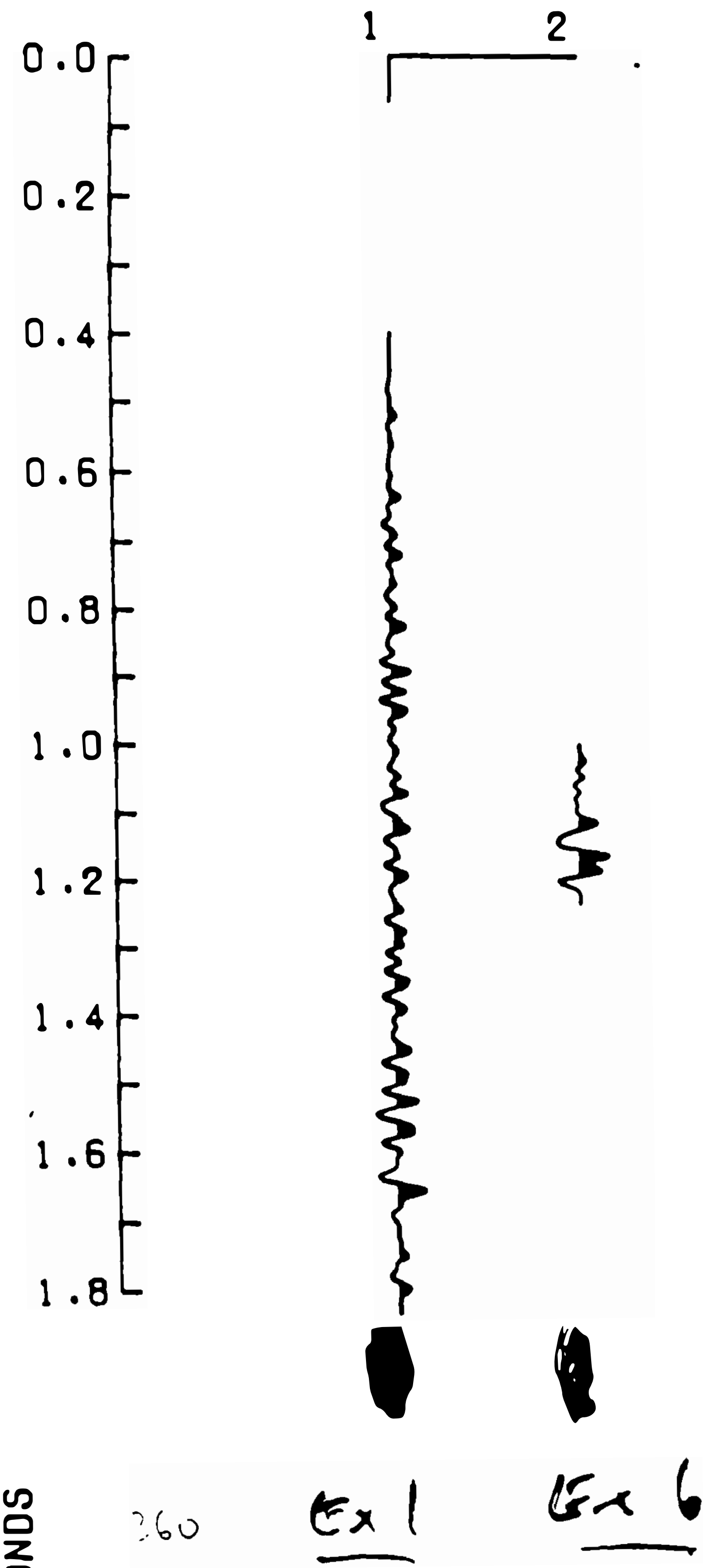
RMS-SEIS STRAT-4



RMS-SEIS STRAT-

PULSE NO 1   TYPE=1

TIME OVERLAY



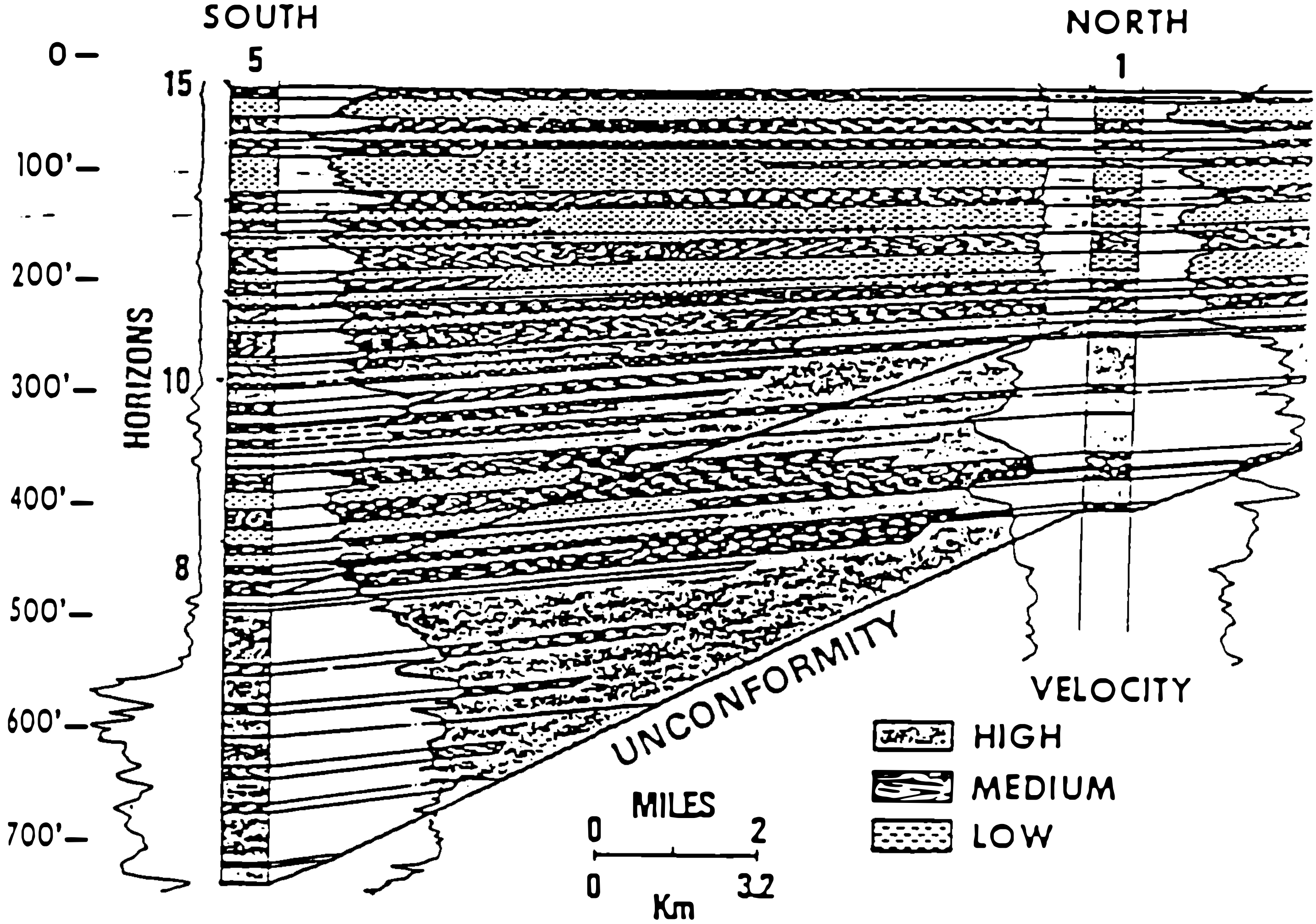


Fig. 4-1. Distribution of velocity based on continuous velocity logs (CVL). Correlations established using stratal surfaces. (After Vail et al, 1979).

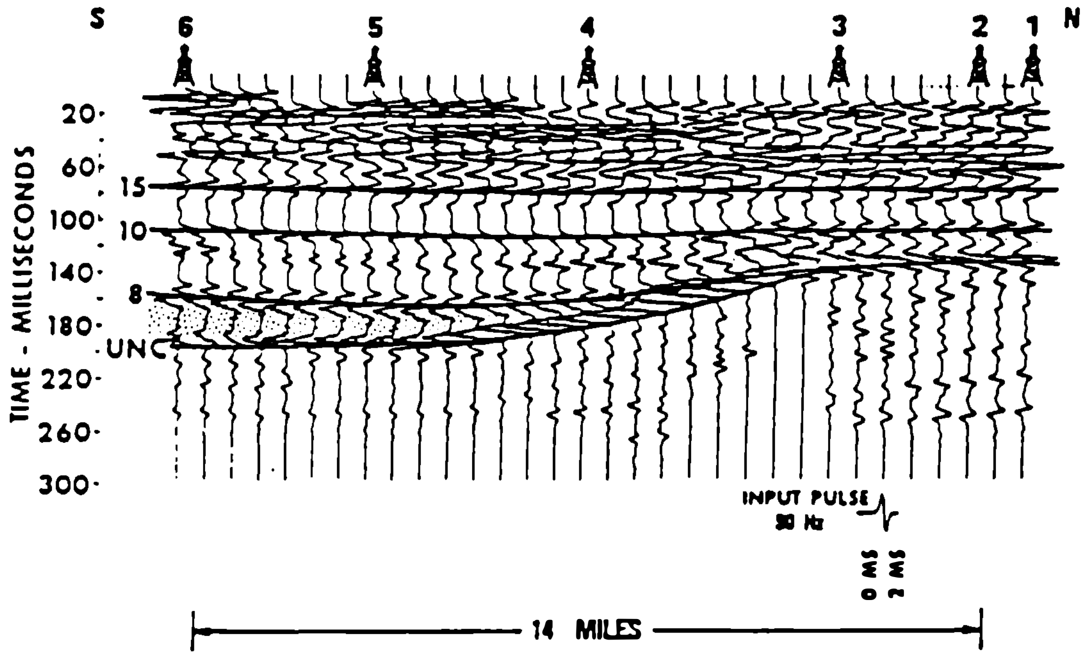


Fig. 4-2. High frequency synthetic seismic section using a 90-Hz sine wave (After Vail et al, 1977).

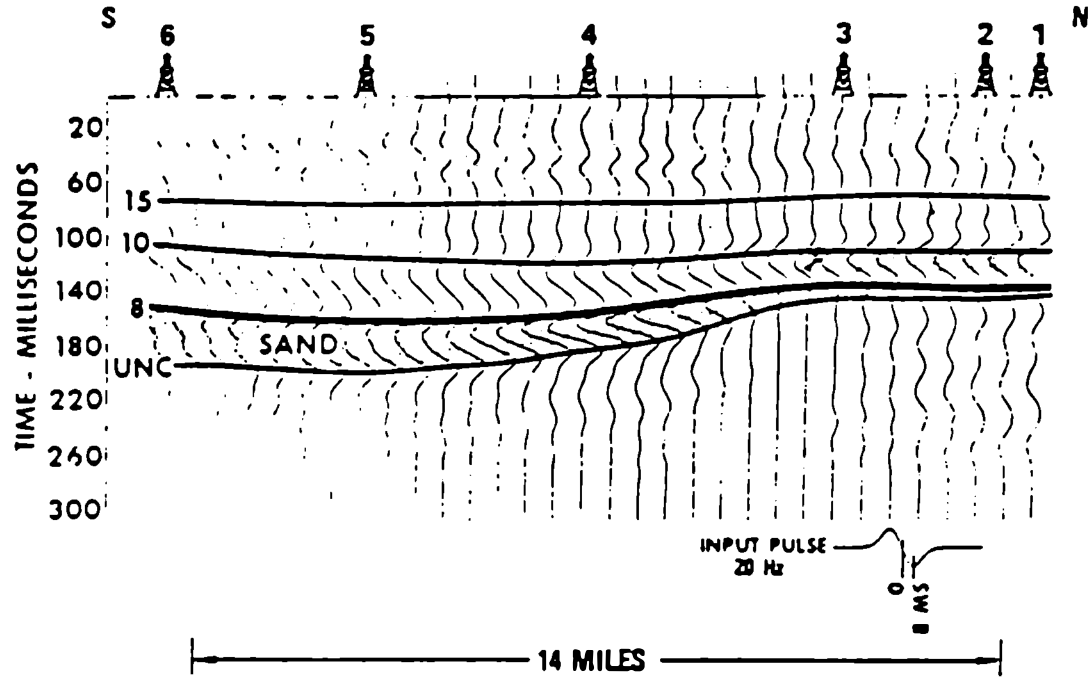


Fig. 4-3. Low frequency synthetic seismic section using a 20-Hz sine wave. Stipple pattern represents sandstone. After Vail, Todd and Sangree, 1977.

363-364

PART 10

EXERCISES

SECTION 2

WELL LOG / SEISMIC - GULF COAST PLIO-PLEISTOCENE

Well Log / Seismic Sequence Stratigraphy
and
High Resolution Biostratigraphy Exercise

<u>Materials</u>

A) SEPM Transect A: Plio-Pliestocene Offshore Galveston, Texas
- Index Map
- Well locations
- Seismic line
- Well log cross section
- Seismic section (display copy only)

B) Wells A70, 158, 188, 218, 248, 160, 247
- Sequence stratigraphy interpretation chart
- Seismic panel
- Time - depth overlay

<u>Instructor exhibits</u>

A) Overhead projector clear films
- Interpreted well logs
- Interpreted histograms
- Overview seismic panels
- Interpreted seismic panels

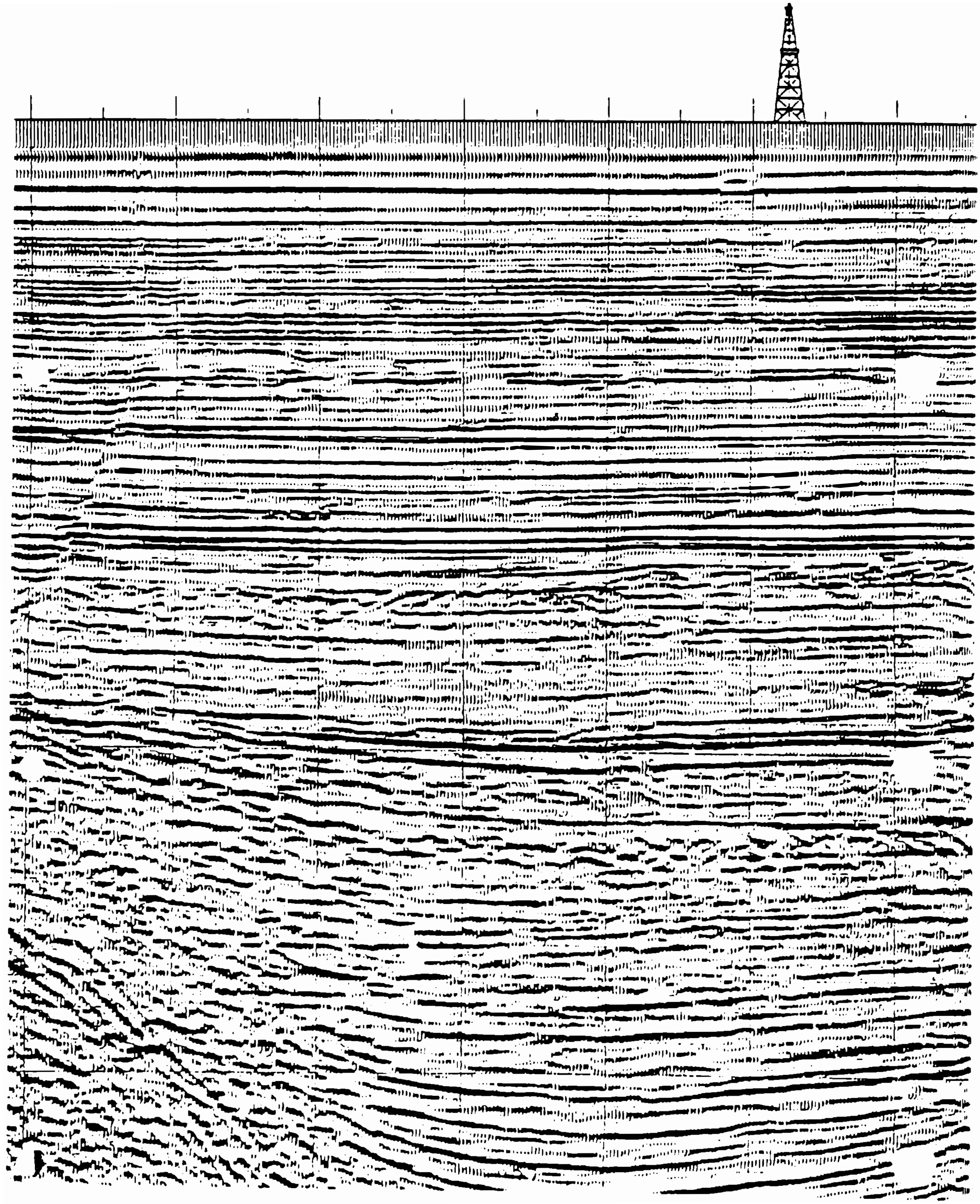
B) Posters
- Well log interpretations
- Well log cross section
- Seismic section interpretation
- Chronostratigraphic chart

<u>Problem</u>

1) Interpret depositional systems and lithofacies on well logs and seismic panels.
2) Interpret sequences and system tracts on well logs and seismic section.
3) Construct stratigraphic cross section and chronostratigraphic chart.

GALVESTON SOUTH ADDITION
BLOCK A158
T.D. 8624

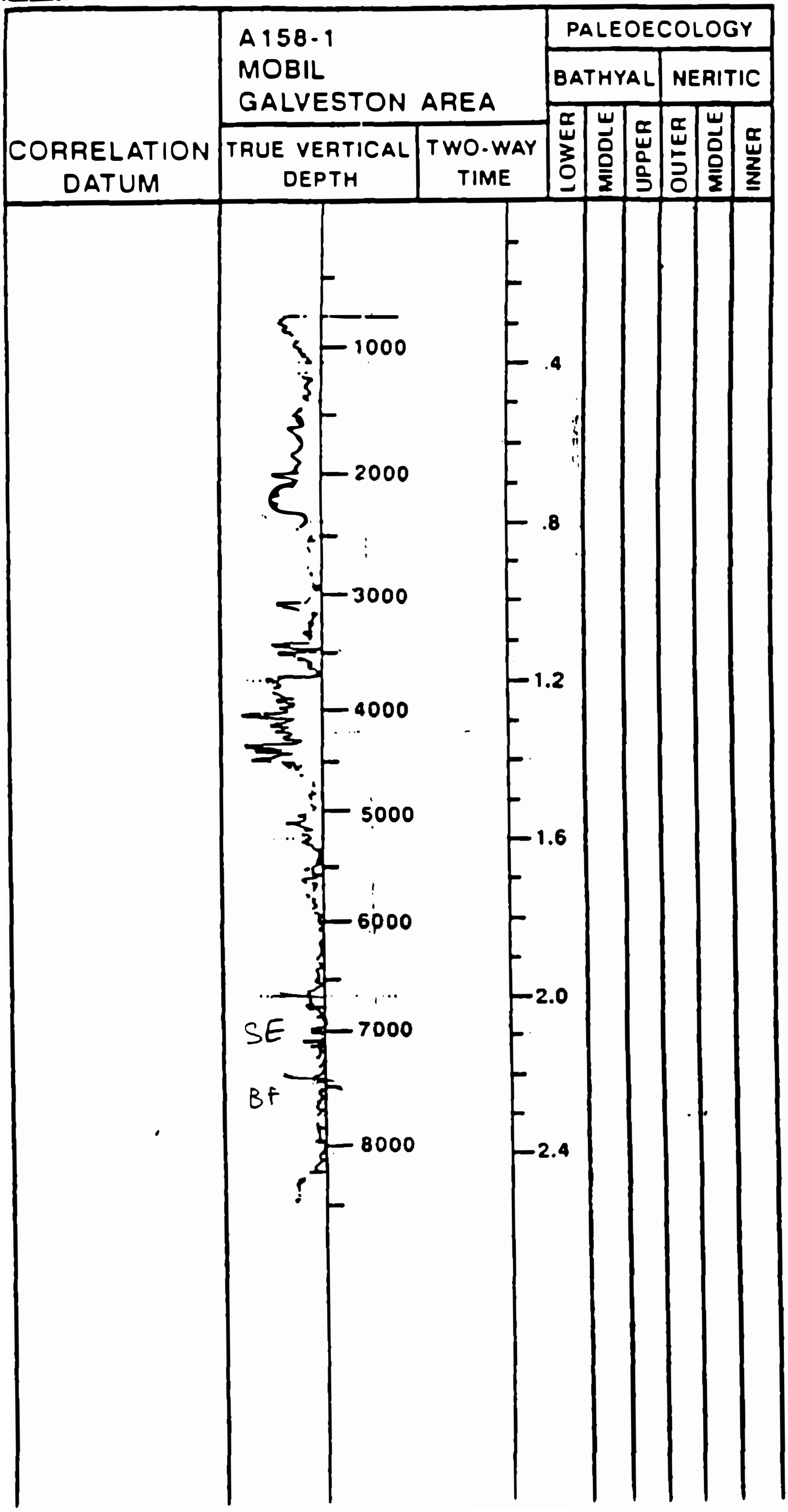
PROJECTION 3200'e



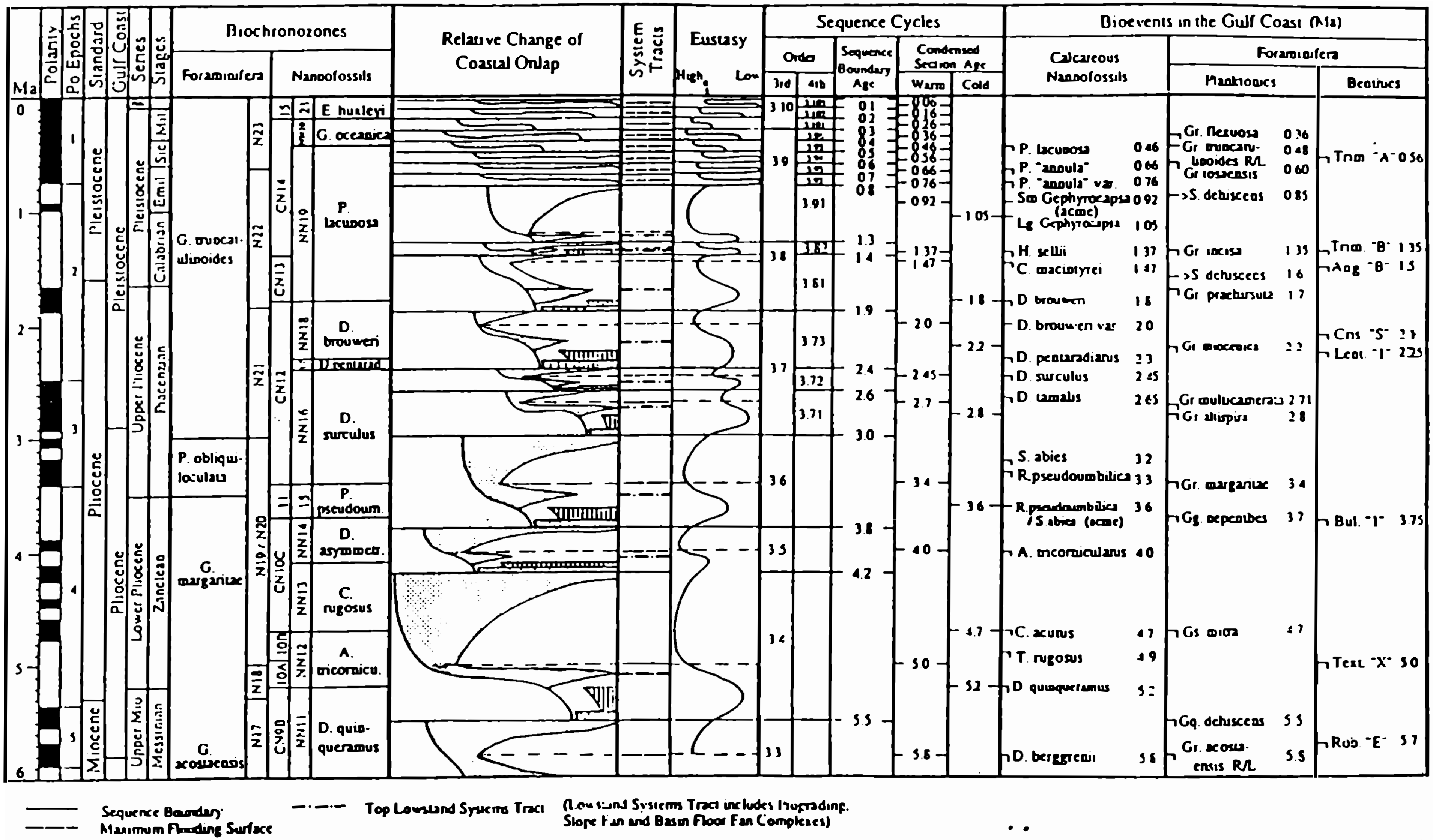
TRANSECT "A"

BLOCK A158

VELOCITY SURVEY FROM MOBIL A158-1
PROJECTED 0.6 MILES TO EAST



PLIO-PLEISTOCENE SEQUENCE CHRONOSTRATIGRAPHY



PART ~~10~~ 14

EXERCISES

High Resolution Biostratigraphy Exercise

Materials

A) East / West Cameron region, Offshore Louisiana Plio-Pleistocene Well log
- Sequence stratigraphy interpretation chart

B) Seismic section

C) Time depth table

D) Time - depth overlay
- Linear time scale that overlays sesimic section
- Non-linear depth scale
- Paleowater depths
- Fossil abundance curve
- Key fossil tops

E) Well log seismic tie overlay

Instructor exhibits

A) Overhead projector clear films
- Interpreted well log
- Interpreted histogram
- Overview seismic panel
- Interpreted seismic panel

B) Posters
- Well log interpretation
- Seismic section interpretation

Problem

1) Interpret depositional systems and lithofacies on well log and seismic panel.

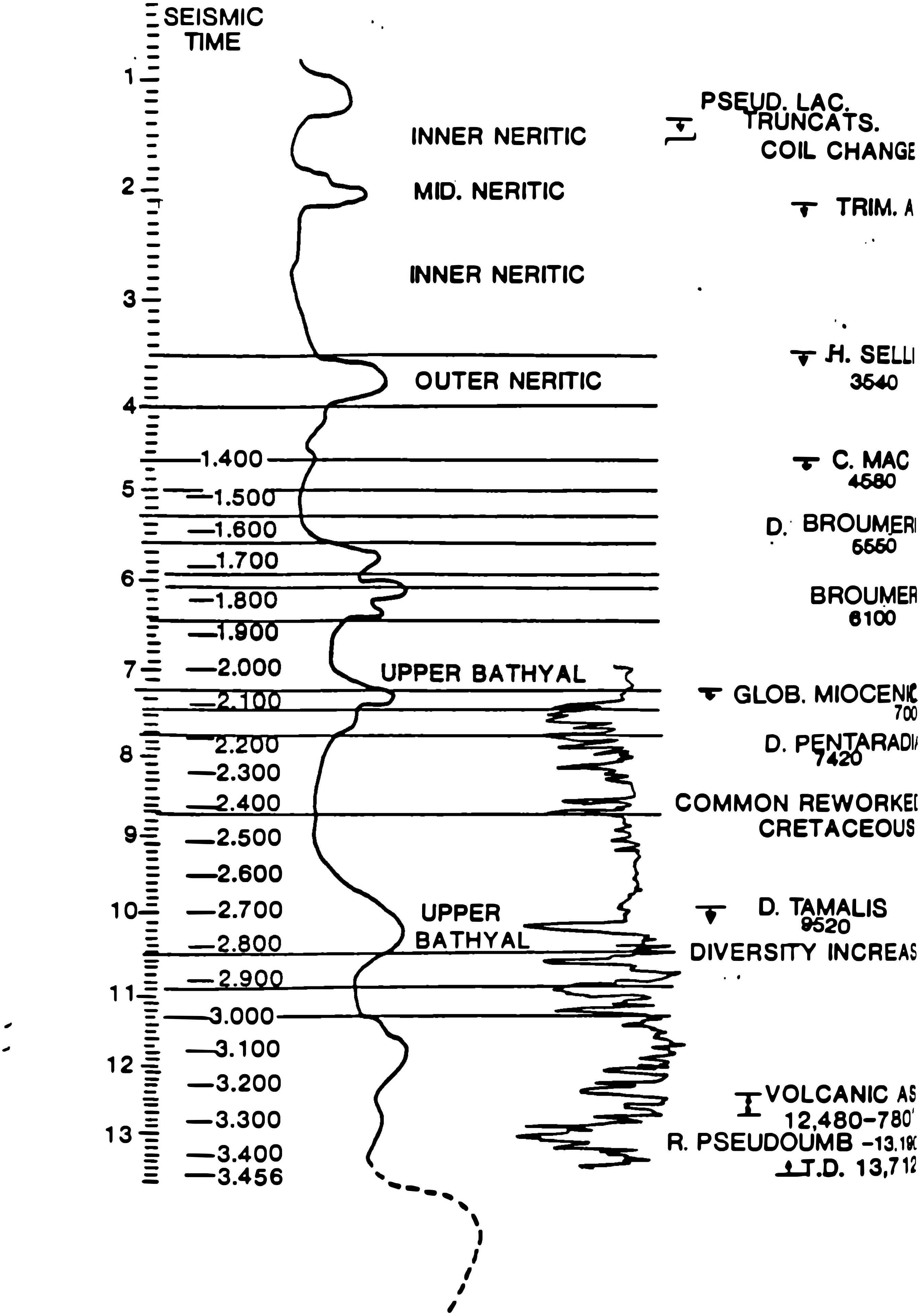
2) Interpret sequences and system tracts on well log and seismic section.

Procedure - Follow Sequence Stratigraphy Interpretation Procedure in workbook

1) On well log color
- Sand: yellow
- Shale: green
- turbidite mudstone : brown

- inner neritic: yellow
- middle neritic: light green
- outer neritic: dark green
- upper bathyal: light blue
- middle bathyal: dark blue
- lower bathyal: purple

3) On abundance/diversity overlay, mark abunadancy peaks in green.
4) On abundance/diversity overlay, mark fossil top numerical ages.
5) On well log mark depositional systems.
   - forestepping parasequences
   - backstepping parasequences
   - incised valley fills
   - shingled turbidites
   - hemipelagic shales
   - channel overbank lobes
     - channel
     - overbank
     - attached lobes
     - distal apron
   - sheet lobe sands
   - See step 3 in workbook interpretation procedure for complete list
6) On well log mark sequence and systems tract boundaries using standard colors (in conjunction with step 7).
7) On seismic section interpret sequences and system tracts in vincinity of well log (with step 6).
   - Color system tracts using standard colors
   - Highlight sand occurence in yellow
8) On well log, age date sequence boundaries and maximum flooding surfaces using Plio-Pleistoc sequence stratigraphy cycles.



REVISED DEC. 12, '88 LAS

Time = 11:43 AM Date = September 5, 1990

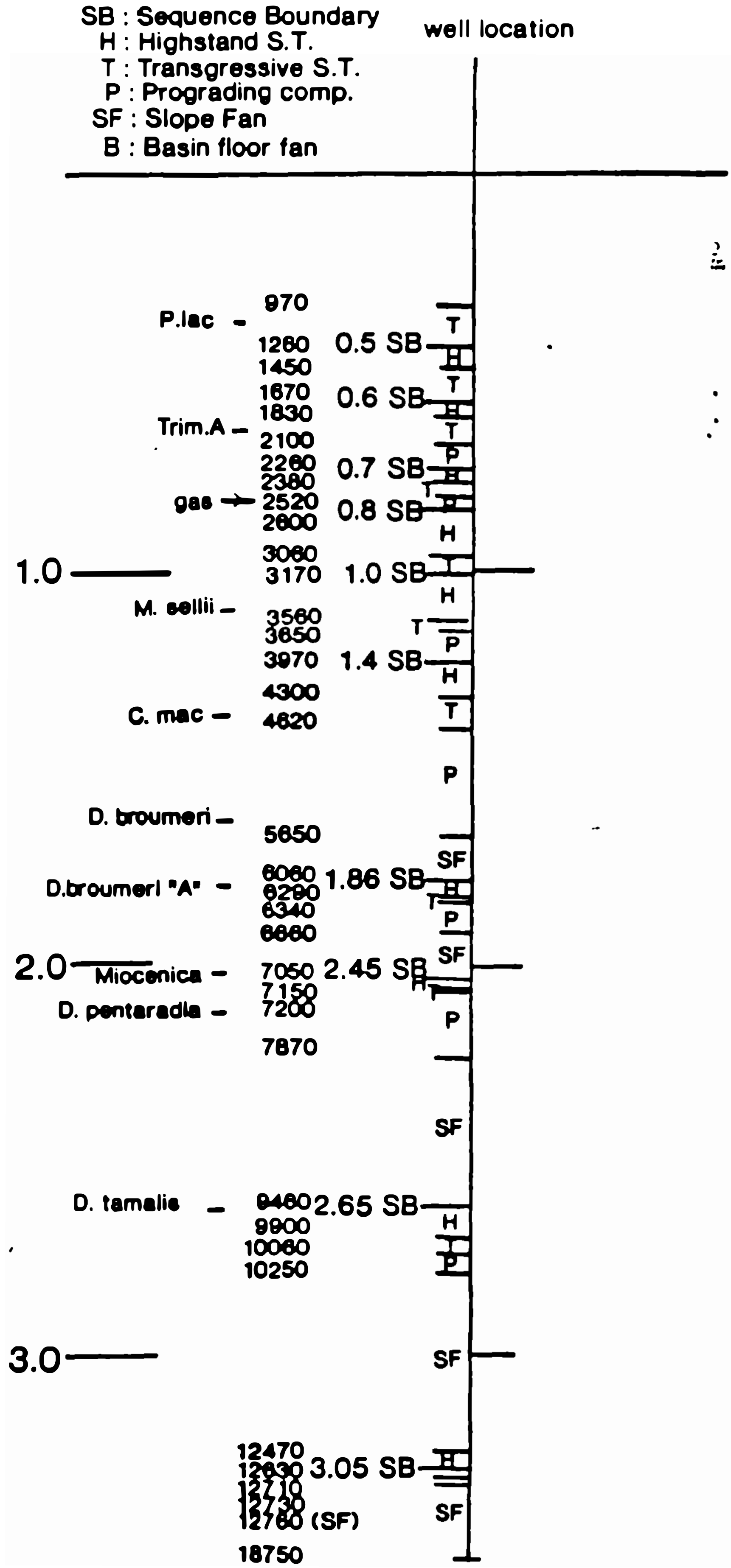
KI 38 (subetract from depth)

= 1464912 Y = -181444

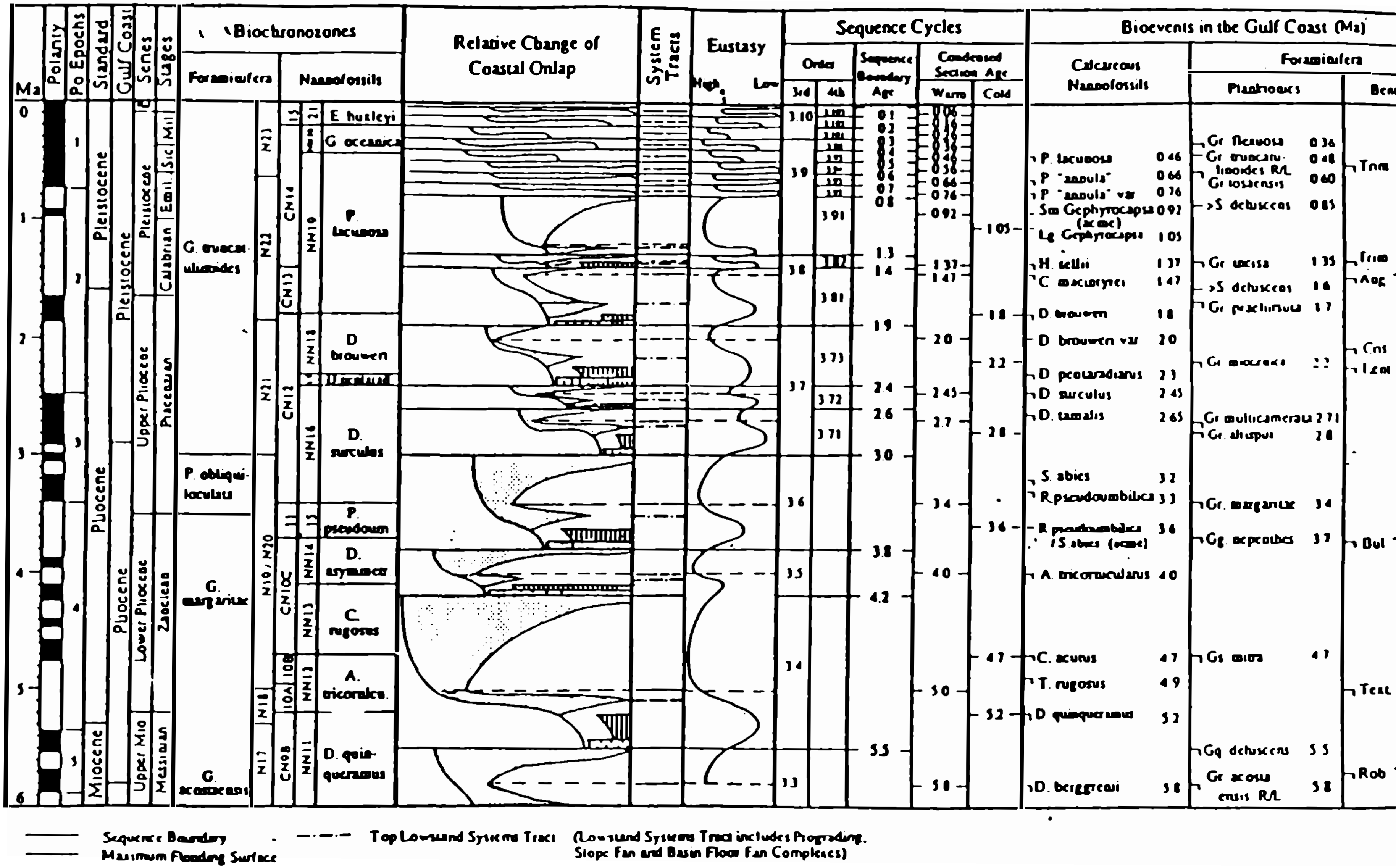
Depths at 10 ms increments measured in feet.

TIME	0	10	20	30	40	50	60	70	80	90
200	505	533	561	590	618	646	675	703	731	760
300	788	816	845	873	901	930	958	986	1015	1043
400	1071	1103	1134	1165	1197	1228	1259	1291	1322	1353
500	1384	1416	1447	1478	1510	1541	1572	1604	1635	166
600	1697	1731	1764	1797	1830	1863	1896	1929	1962	1991
700	2028	2062	2095	2128	2161	2194	2227	2260	2293	232
800	2359	2394	2428	2462	2496	2531	2565	2599	2634	266
900	2702	2736	2771	2805	2839	2873	2908	2942	2976	301
1000	3045	3079	3114	3149	3183	3218	3253	3287	3322	335
1100	3391	3426	3461	3495	3530	3565	3599	3634	3669	370
1200	3738	3775	3811	3848	3884	3921	3957	3994	4030	406
1300	4103	4140	4176	4213	4249	4286	4322	4359	4395	4
1400	4468	4507	4546	4585	4623	4662	4701	4740	4779	4[illegible]
1500	4856	4895	4934	4973	5012	5050	5089	5128	5167	520
1600	5244	5284	5323	5362	5401	5440	5479	5518	5557	559
1700	5635	5674	5713	5753	5792	5831	5870	5909	5948	598
1800	6026	6064	6103	6141	6180	6218	6256	6295	6333	637
1900	6410	6448	6486	6525	6563	6601	6640	6678	6716	675
2000	6793	6833	6872	6912	6952	6991	7031	7071	7110	715
2100	7190	7229	7269	7309	7348	7388	7428	7467	7507	754
2200	7586	7628	7670	7712	7755	7797	7839	7881	7923	796
2300	8007	8049	8091	8133	8175	8217	8260	8302	8344	838
2400	8428	8472	8516	8560	8604	8648	8692	8736	8781	882
2500	8869	8913	8957	9001	9045	9089	9133	9177	9221	926
2600	9310	9355	9401	9446	9492	9538	9583	9629	9675	972
2700	9766	9811	9857	9903	9948	9994	10040	10085	10131	1017
2800	10222	10269	10316	10362	10409	10456	10503	10549	10596	1064
2900	10689	10736	10783	10830	10876	10923	10970	11017	11063	1111
3000	11157	11205	11253	11301	11348	11396	11444	11492	11540	1158
3100	11636	11684	11732	11780	11827	11875	11923	11971	12019	1206
3200	12115	12163	12211	12259	12308	12356	12404	12452	12501	17
3300	12597	12645	12693	12742	12790	12838	12886	12934	12983	1[illegible]
3400	13079	13127	13175	13224	13272	13320	13368	13417	13465	1351
3500	13561	13609	13658	13706	13754	13802	13851	13899	13947	1399
3600	14043	14091	14139	14187	14235	14283	14331	14379	14427	1447
3700	14523	14571	14619	14667	14715	14763	14811	14859	14907	1495
3800	15003	15051	15098	15146	15193	15241	15288	15336	15383	1543
3900	15478	15526	15573	15620	15668	15715	15763	15810	15858	1590
4000	15953	16000	16046	16093	16140	16187	16234	16281	16327	1637
4100	16421	16468	16515	16562	16608	16655	16702	16749	16796	1684
4200	16889	16936	16982	17028	17074	17120	17166	17212	17258	1730
4300	17350	17396	17442	17488	17535	17581	17627	17673	17719	1776
4400	17811	17857	17903	17948	17994	18040	18086	18132	18177	1822
4500	18269	18315	18361	18406	18452	18498	18544	18589	18635	1868
4600	18727	18773	18818	18864	18910	18956	19002	19047	19093	1913
4700	19185	19231	19276	19322	19368	19414	19460	19505	19551	1959
4800	19643	19688	19734	19779	19825	19870	19915	19961	20006	2005
4900	20097	20143	20188	20233	20279	20324	20370	20415	20461	2050

TIME	0	10	20	30	40	50	60	70	80	90
5000	20552	20597	20642	20688	20733	20779	20824	20870	20915	20960
5100	21006	21051	21097	21142	21188	21233	21279	21324	21369	21415
5200	21460	21506	21551	21597	21643	21688	21734	21779	21825	21870
5300	21916	21962	22007	22053	22098	22144	22189	22235	22281	22326
5400	22372	22417	22463	22508	22554	22600	22645	22691	22736	22782
5500	22827	22873	22919	22964	23010	23055	23101	23146	23192	23238
5600	23283	23329	23375	23421	23466	23512	23558	23604	23650	23695
5700	23741	23787	23833	23879	23924	23970	24016	24062	24108	24153
5800	24199	24245	24291	24337	24384	24430	24476	24522	24568	24614
5900	24660	24706	24752	24798	24844	24890	24936	24983	25029	25075
6000	25121	25168	25214	25261	25308	25355	25401	25448	25495	25543
6100	25589	25635	25682	25729	25776	25822	25869	25916	25963	26009
6200	26056	26103	26151	26198	26245	26292	26339	26386	26433	26480
6300	26528	26575	26622	26669	26716	26763	26810	26857	26905	2695
6400	26999	27046	27094	27141	27188	27236	27283	27330	27378	2742
500	27472	27520	27567	27614	27662	27709	27756	27804	27851	2789
6600	27946	27994	28042	28090	28138	28186	28234	28283	28331	2837
6700	28427	28475	28523	28571	28619	28668	28716	28764	28812	2886
6800	28908	28956	29004	29051	29099	29147	29194	29242	29290	2933
6900	29385	29433	29480	29528	29576	29623	29671	29719	29766	2981
7000	29862									


SB : Sequence Boundary
H : Highstand S.T.
T : Transgressive S.T.
P : Prograding comp.
SF : Slope Fan
B : Basin floor fan
well location
P.lac
Trim.A
gas
1.0
M. sellii
C. mac
D. broumeri
D.broumeri "A"
2.0
Miocenica
D. pentaradia
D. tamalis
3.0
970
1260
1450
1670
1830
2100
2260
2380
2520
2600
3060
3170
3560
3650
3970
4300
4620
5650
6060
6290
6340
6660
7050
7150
7200
7870
9460
9900
10060
10250
12470
12630
12710
12730
12760 (SF)
18750
0.5 SB
0.6 SB
0.7 SB
0.8 SB
1.0 SB
1.4 SB
1.86 SB
2.45 SB
2.65 SB
3.05 SB
T
H
T
H
T
P
H
T
H
H
T
P
H
T
P
SF
H
T
P
SF
H
P
SF
H
P
SF
H
SF

PLIO–PLEISTOCENE SEQUENCE CHRONOSTRATIGRAPHY



PART 10

EXERCISES

SECTION 3

WELL LOG / SEISMIC - MIDLAND BASIN TEXAS

EXERCISE SEQUENCE STRATIGTRAPHY

Midland Basin

(Seismic data courtesy J. F. Sarg)

Situation:

Interbedded Permian sands and carbonates in the Midland Basin present an ideal opportunity for rapid changes in depositional facies resulting from rapid eustatic sea level changes. The combination of a rich source of hydrocarbons and low permeability sands and carbonates presents excellent opportunities for stratigraphic traps and fractured reservoirs.

Given:	**Figure**
Location map and Permian eustatic cycle chart	1
North-West seismic section	2

Problem: Stage 1

Correlate the sequence boundaries, using onlap and downlap criteria. Can you identify lowstand fan mounds?

Problem: Stage 2

Supplied: Three well logs
Synthetic seismograms and lithologs — Figure 4

1) Identify sequence boundaries and systems tracts on logs.
2) Tie synthetics to seismic section and identify carbonate banks and lowstand sands in wells and on seismic sections.
3) Complete your seismic correlation and seismic facies analysis.

Discussion:

1) What plays can you see in the area, both carbonates and sands?
2) What criteria could be used to predict sand occurrence and sand porosity?
3) If you had to select a single play to pursue as an exploration venture, where would you put your time and money?

Stage 3		**Figure**
Supplied:	Interpreted seismic section	3
	Well log correlation section	5
	Synthetic model from log correlation	6

Discussion:

1) Are you convinced of the congruence of time-stratigraphic log correlation and seismic reflections?
2) Do you see the utility of combining log and seismic data in a sequence framework to develop a complete time-stratigraphic interpretation?

MIDLAND BASIN TENNCRUM

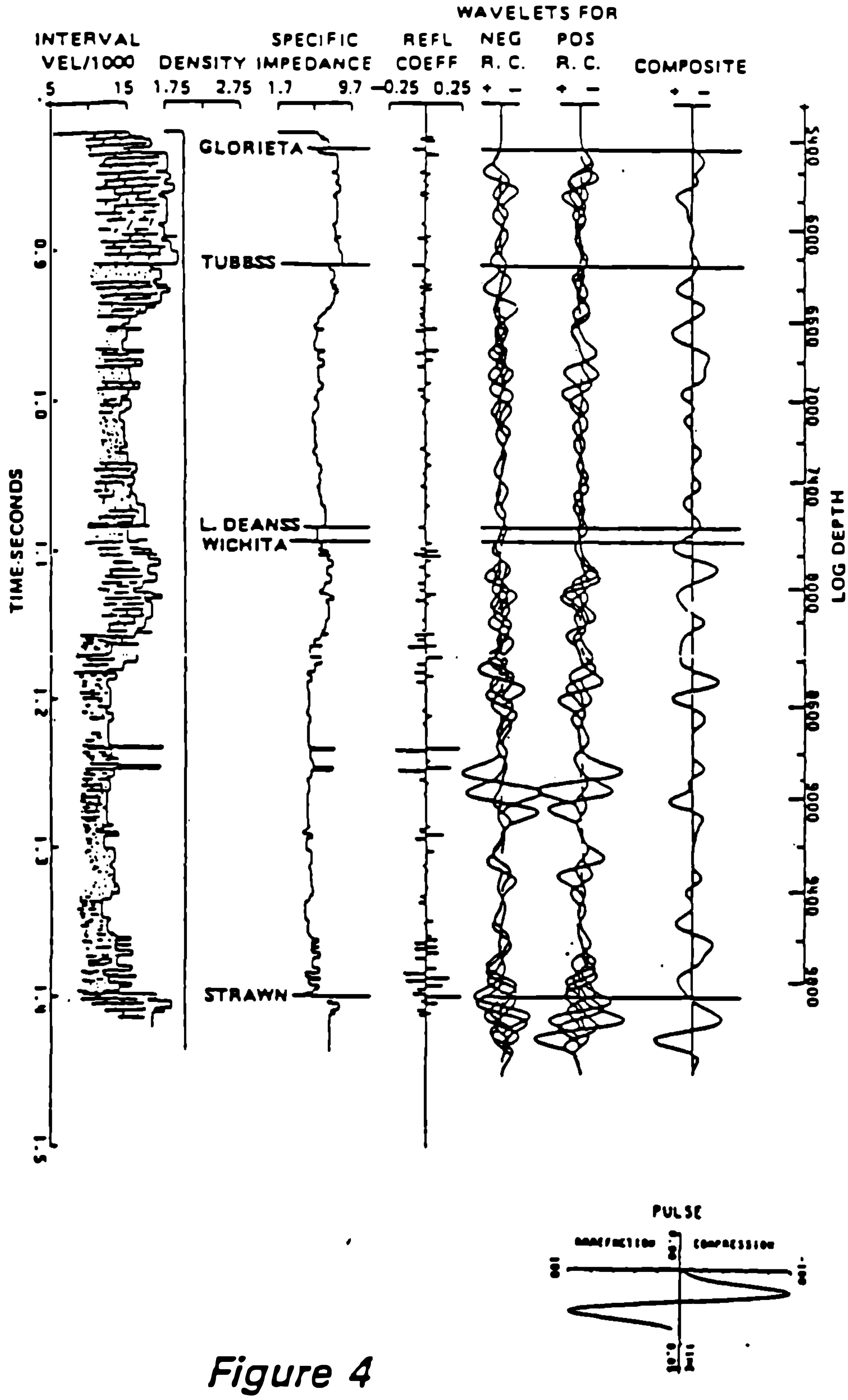
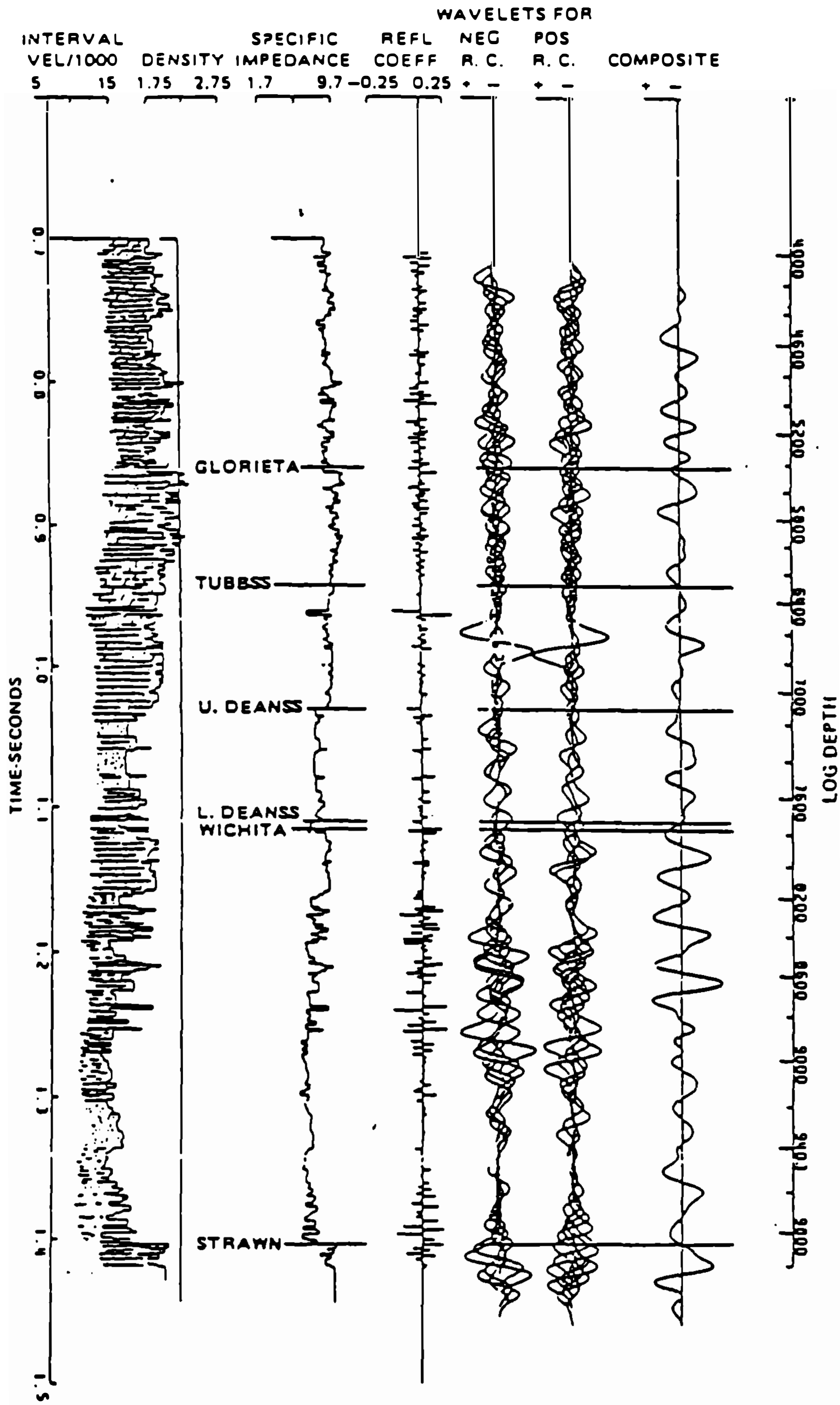


Figure 4

After J. F. Sarg, 1986

MIDLAND BASIN PAFOWLER



MIDLAND BASIN HSWINSON

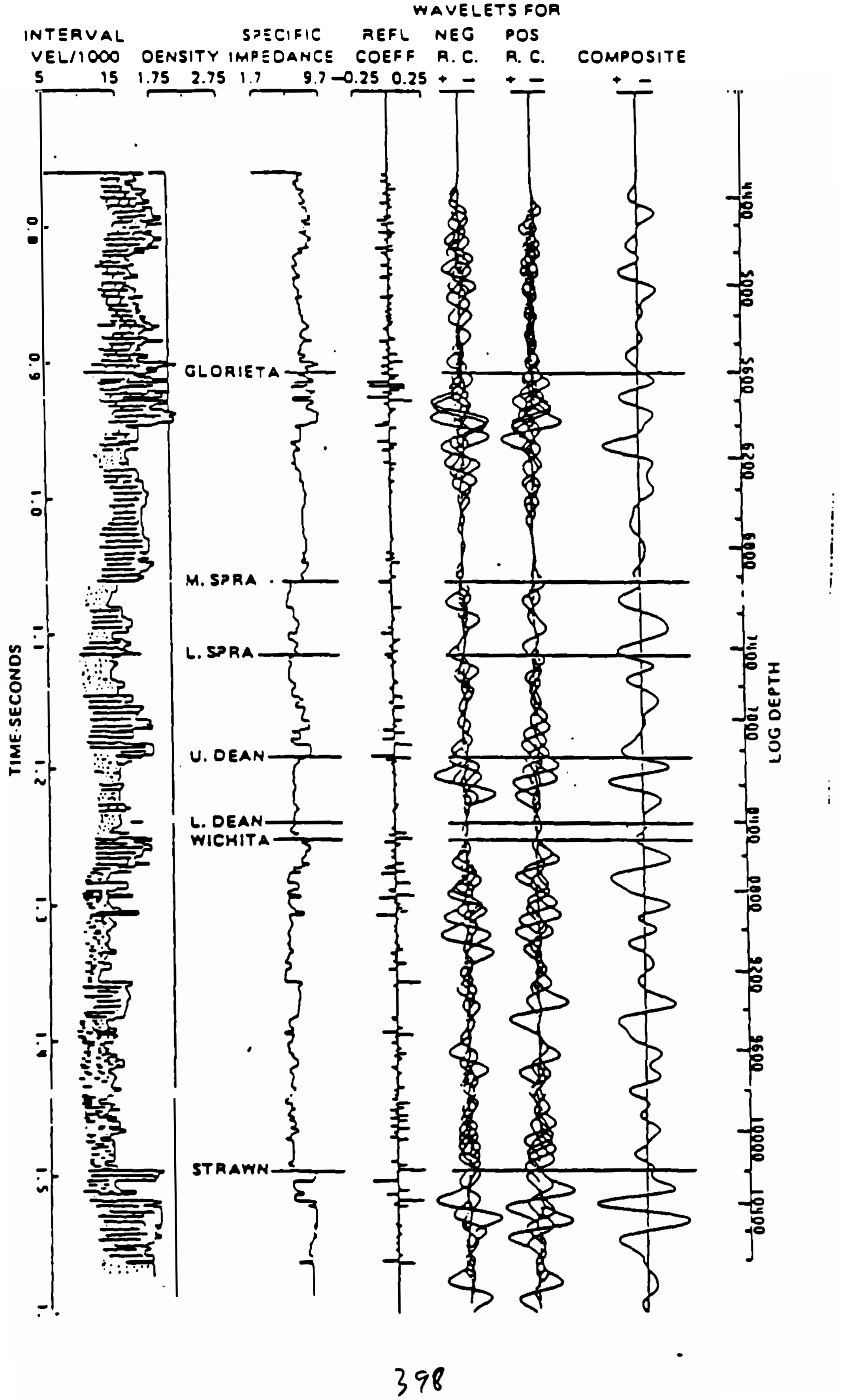


Figure 4A

MIDLAND BASIN EXERCISE

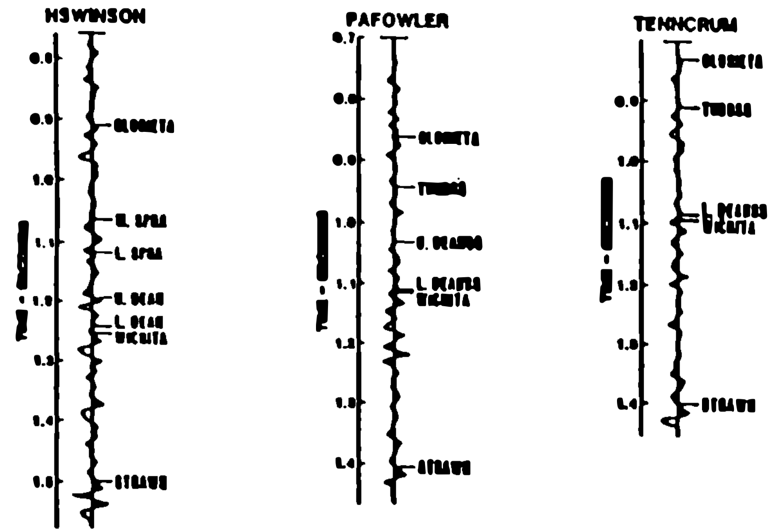
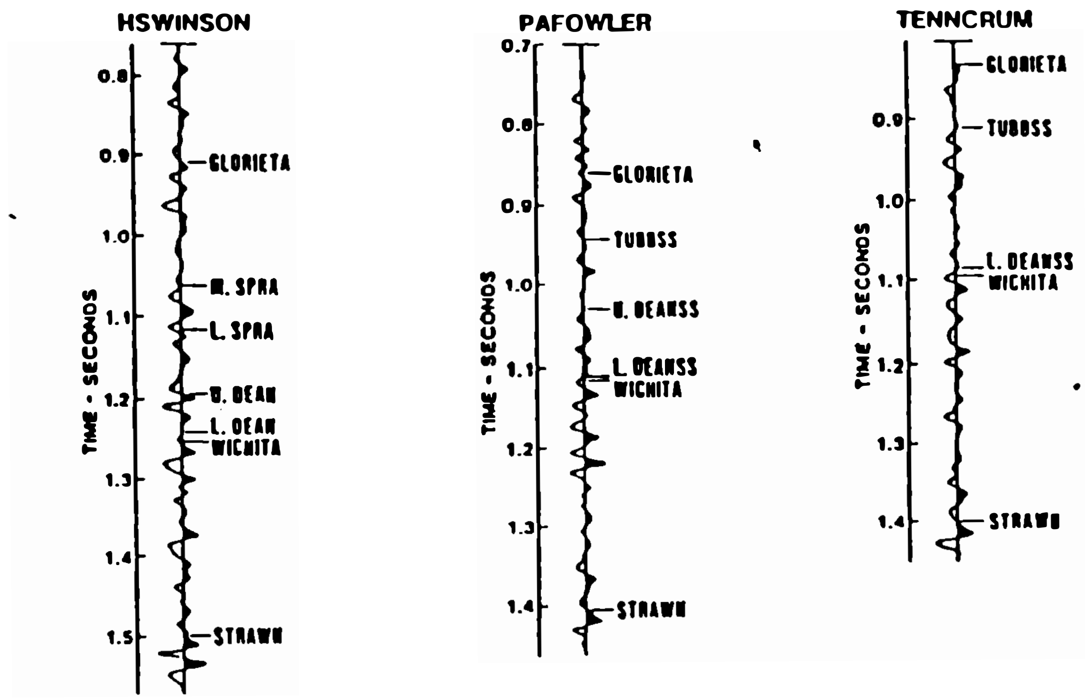


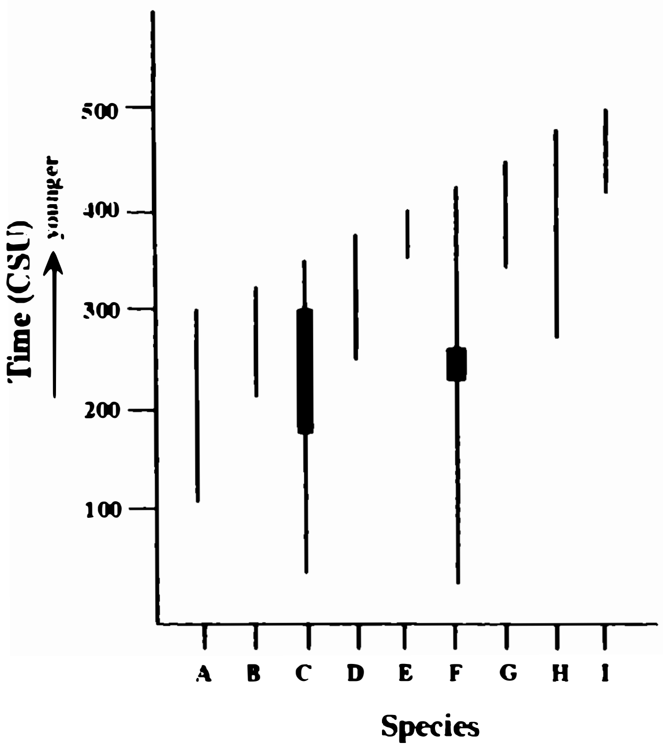
Figure 4A

MIDLAND BASIN EXERCISE

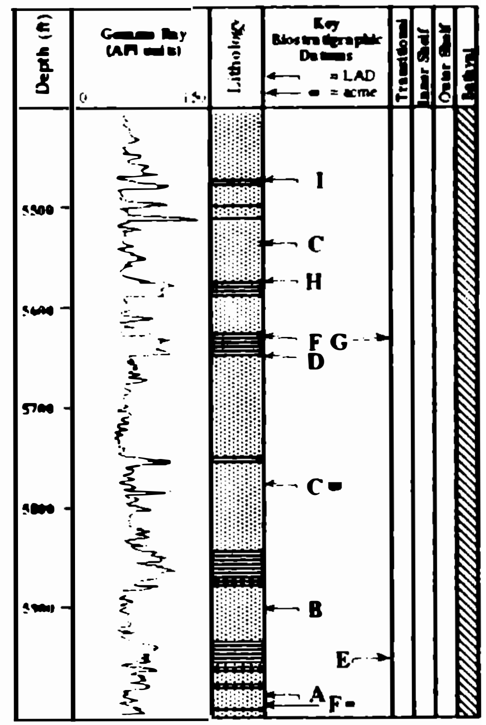


Graphic Correlation Exercise

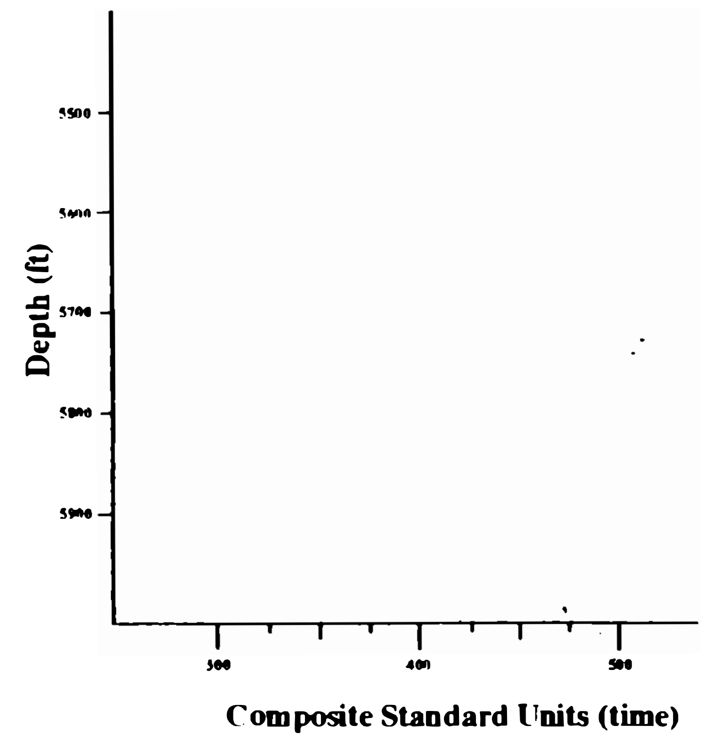
Biostratigraphic Range Chart



Well Data with Biostratigraphy



Graphic Correlation Interpretation

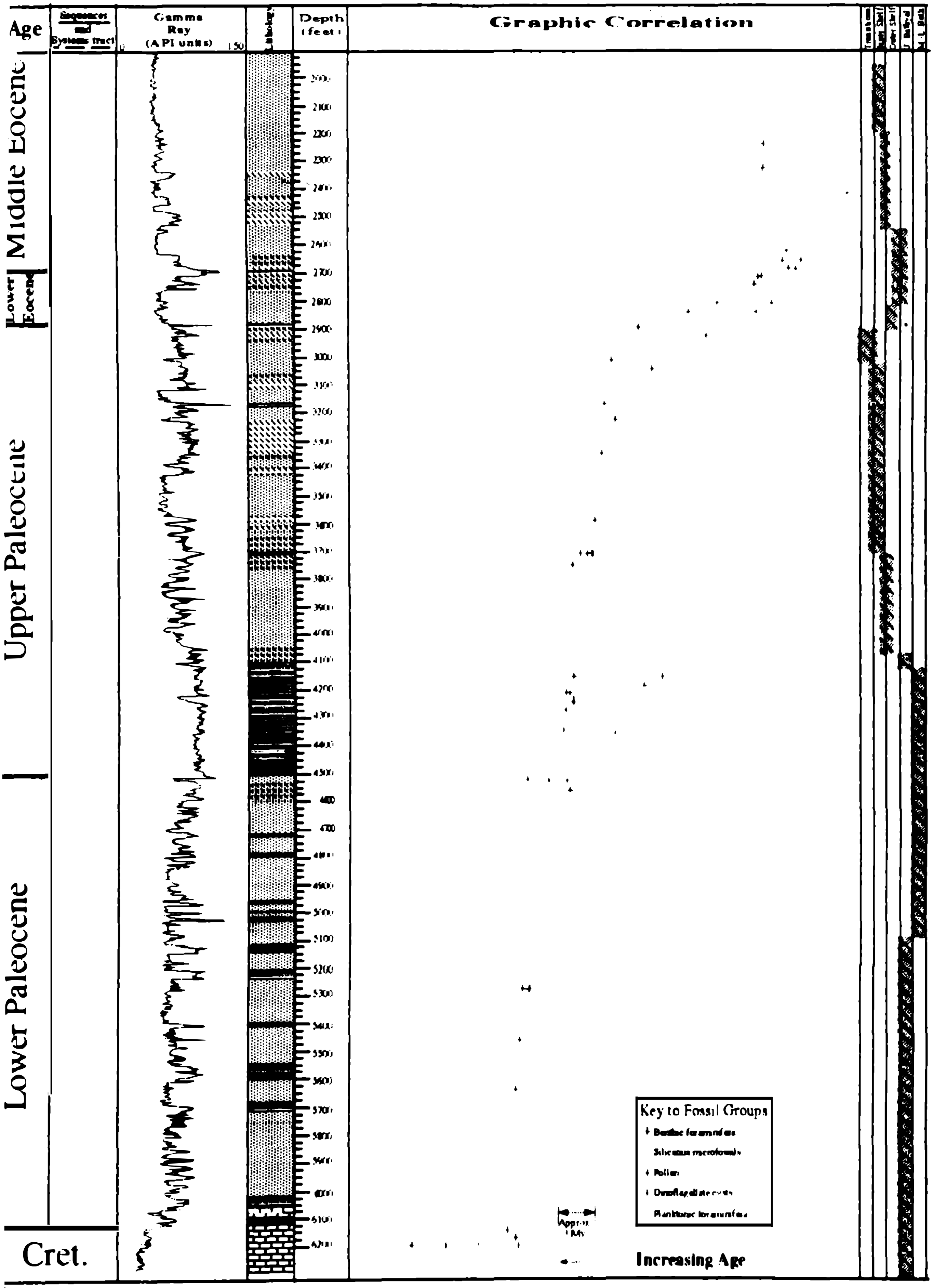


Procedure

1. Identify Time value (in CSU) from the Biostratigraphic Range Chart of the various significant tops and acme occurances in the Well with Biostratigraphic Data
2. Plot the data from the well in Time and Depth on the Graphic Correlation Interpretation diagram
3. Draw a Line of Correlation connecting the maximum number of data points
4. Interpret the Sequence Stratigraphy based on observations from the well and biostratigraphic data

J.E. Neal

UK North Sea Paleogene Shelfal Well Exercise



J.E. Neal 11/92

Well Data courtesy of Robertson Group | Graphic Correlation courtesy of **ETS Paleo-Amoco Production**

PART 10

EXERCISES

SECTION 4

SEQUENCE STRATIGRAPHY
From Literature Diagrams

SECTION 4 - SEQUENCE STRATIGRAPHY FROM LITERATURE DIAGRAMS

INTRODUCTION

Consider Figure 1 to be a geologic Cross Section published in a geologic magazine what would be your working hypotheses on how this Cross Section could be interpreted in terms of sequence stratigraphy? The following questions are to guide your answers.

QUESTIONS

1) On figure 1 draw the following:
   * Parasequence boundaries in blue.
   * Parasequence boundary terminations with red arrows.
   * Sequence boundaries in orange.
   * Maximum flooding surfaces in green.
   * Top lowstand systems tracts in rose.
   * Top slope fans in brown.
   * Top basin floor fans in Tuscan (dark) red.

2) On Figure 1 number the parasequence boundaries from 1 to ....n.... and name the following:
   * Stratal termination patterns.
   * Stratal patterns.

3) On Figure 1 label:
   * Highstand Systems Tracts (HST)
   * Transgressive Systems Tracts (TST)
   * Lowstand Systems Tracts (LST)
     * prograding complex (1pc)
     * slope fan (sf)
     * basin floor fan (bf)

4) On Figure 1 label:

* Meandering streams .... ms
* Braided streams .... bs
* Coals and lignites ....
* Lakes and marshes ....
* Coastal belt sands ....
  * beach to shoreface
  * tidal
  * distributary mouth bars
* Major ravinement surfaces .... RS (color red)
* Authogenic Minerals .... G
* Organic matter deposited .... TOC m
* Organic matter deposited in a non-marine environment ..... TOC nm
* Hemipelagic shales
* Offshore facies
* Turbidite mudstones

5) Consider the basal unconformity to have on age of 30 M.A. Estimate the age of the over lying sequence boundaries and maximum flooding surfaces.

6) On a separate piece of graph paper draw a chronostratigraphic chart and include:
   * Systems tracts.
   * Lithofacies.

7) Sketch shape of Tectonic Subsidence curve at location A. Draw at same time scale as chronostratigraphic chart.

8) Indicate major transgressive and regressive cycles on tectonic subsidence curve and include:
   * Peak transgressions
   * Maximum regressions

9) Sketch shape of eustatic curve at same scale as chronostratigraphic chart.

10) Indicate type 1 and possible type 2 sequence boundaries.

GEOLOGIC CROSS SECTION