OKLAHOMA GEOLOGICAL SURVEY
OPEN-FILE REPORT 19-2003

APPLIED GEOLOGY FOR THE PETROLEUM ENGINEER

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Norman, Oklahoma

One day PTTC course on characterization of sandstone reservoirs, with emphasis on compartmentalization and its effects on reservoir performance

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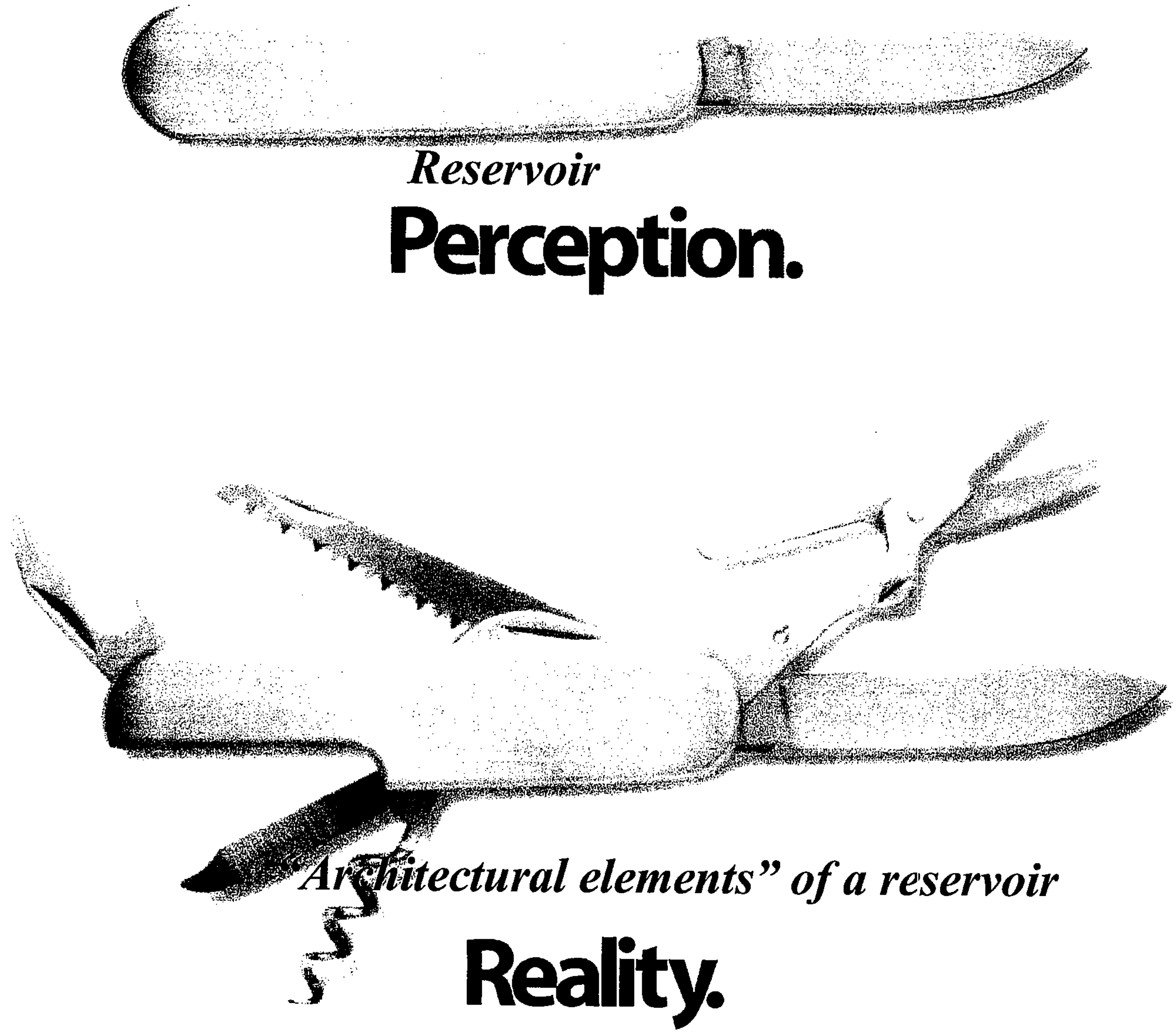
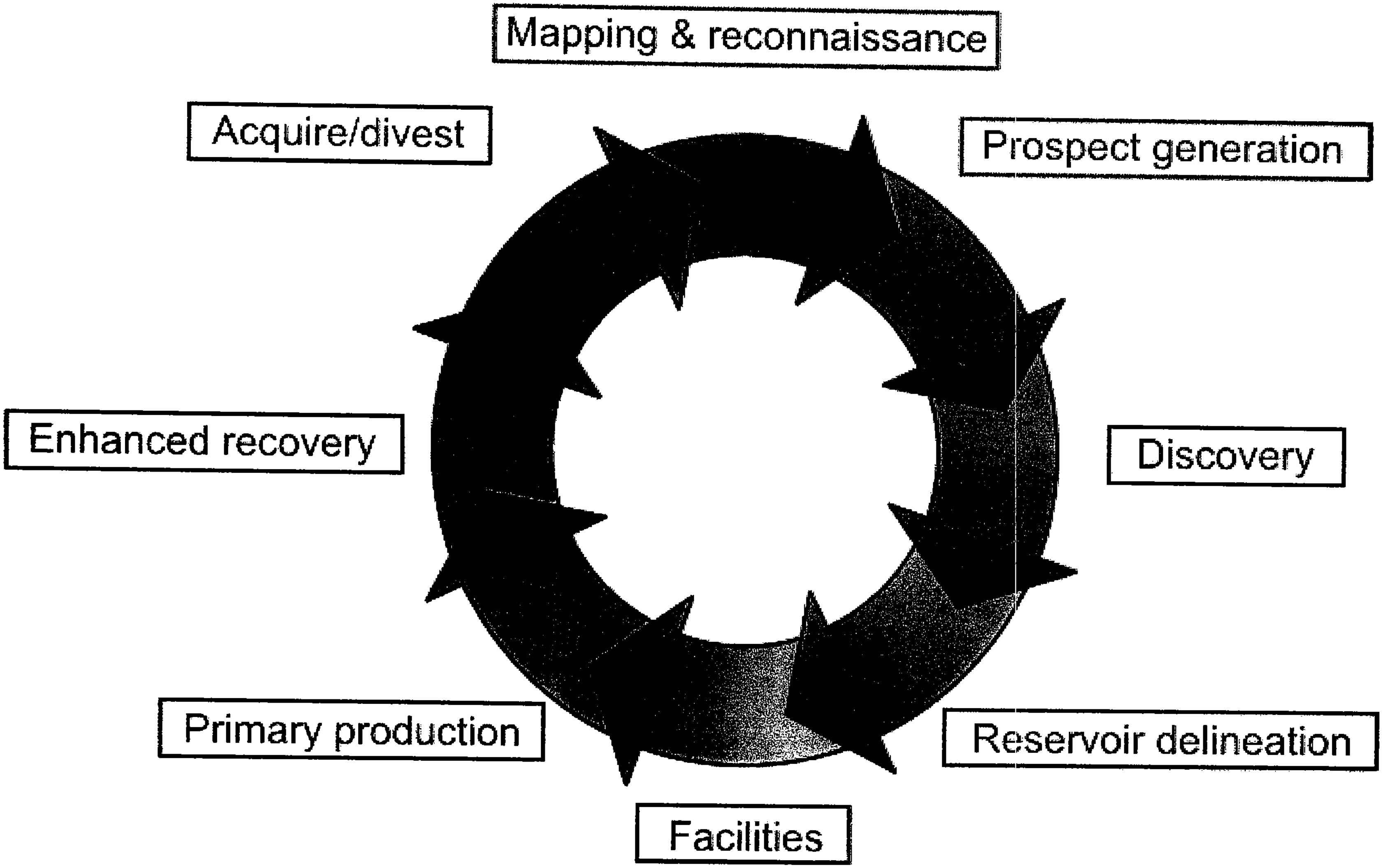
-Scales of reservoir characterization and classification
-Fluvial reservoirs
-Eolian reservoirs
-Structural compartmentalization
-Shoreface reservoirs
-Barrier Island reservoirs
-Deltaic reservoirs
-Deepwater reservoirs



(Modified from OIPA, October, 2001)

Phases of a Typical Oil Field Life Cycle



(Modified from Oil and Gas Journal)

"I thought
I knew this field . . .

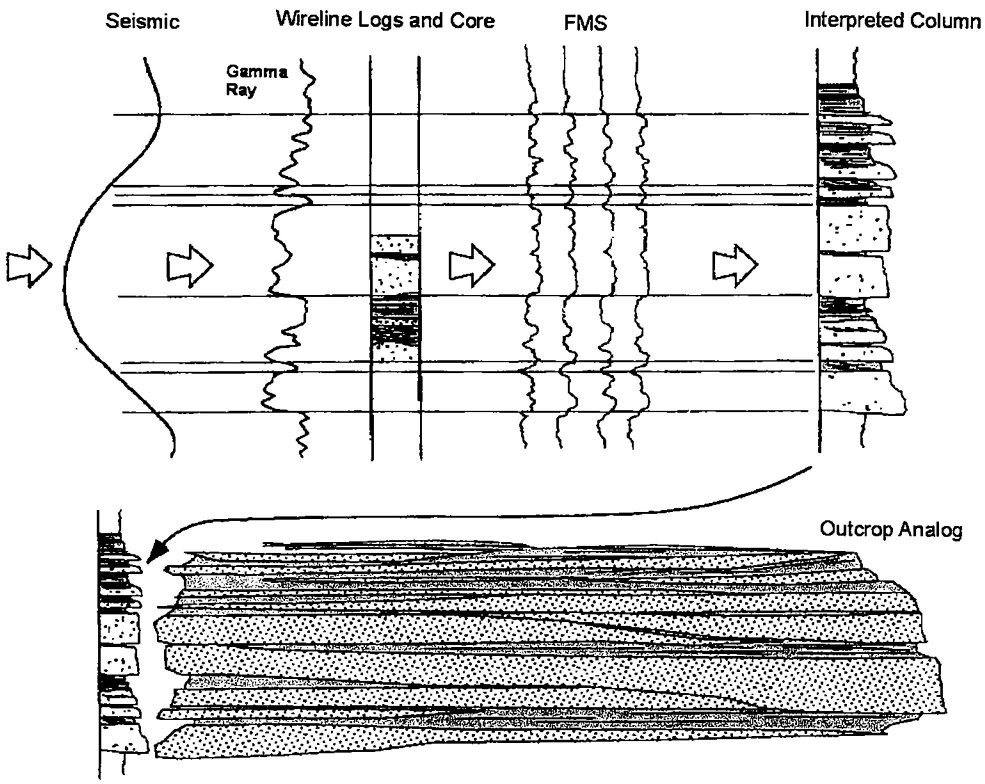
. . . but even with a 3D survey, the reservoir pressure isn't what I expected.

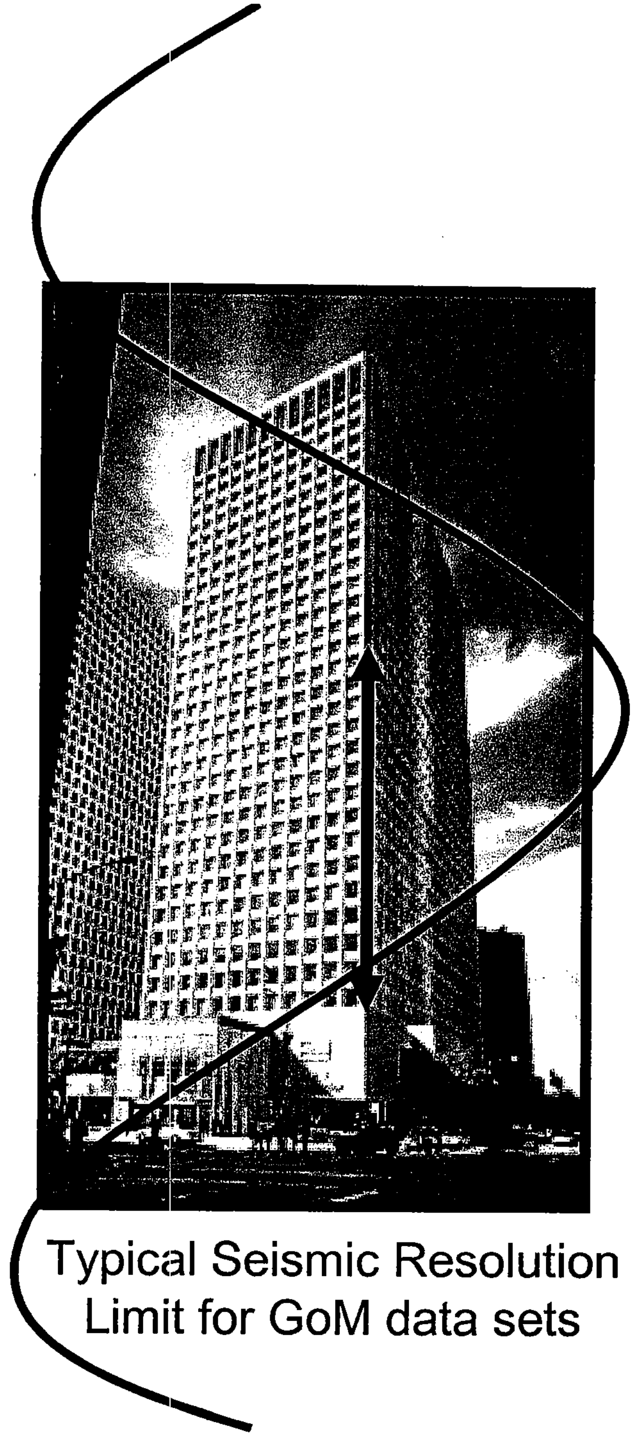
What happened to the injected gas?"

(WesternGeco ad, July, 2002, AAPG Explorer)

Reservoir performance is governed by features that are often beneath seismic resolution or detection ('sub-seismic scale")

Geology vs. Seismic Resolution

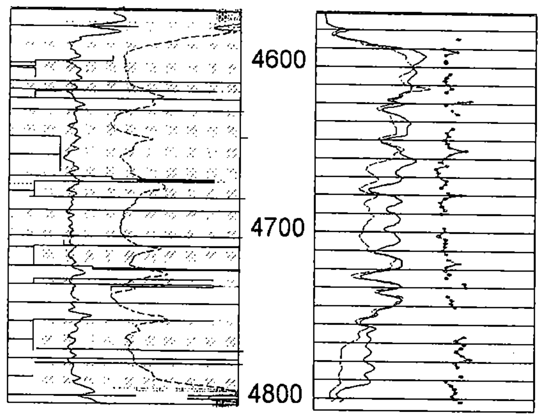




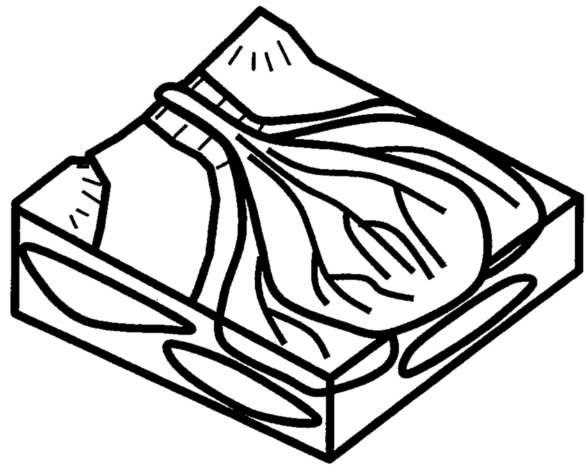
Typical Seismic Resolution Limit for GoM data sets

Buyl, M., et al., 1988

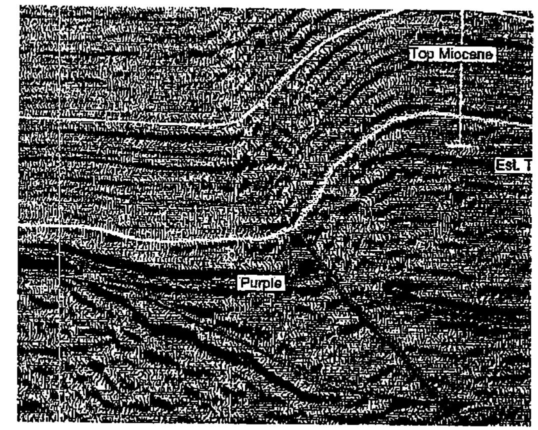
Tools for reservoir characterization



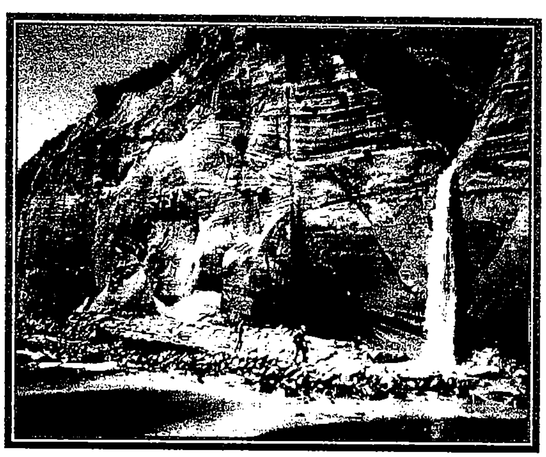
Conventional logs



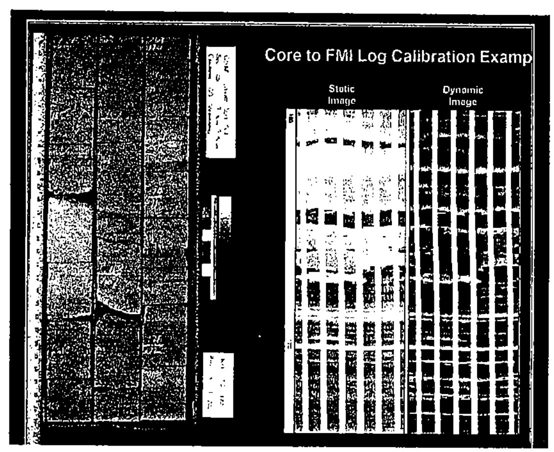
Conceptual model



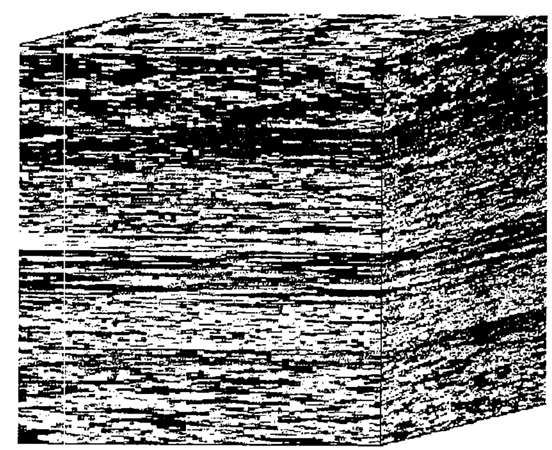
Seismic reflection



Outcrops



Cores & borehole image logs



Computer 3D geologic models

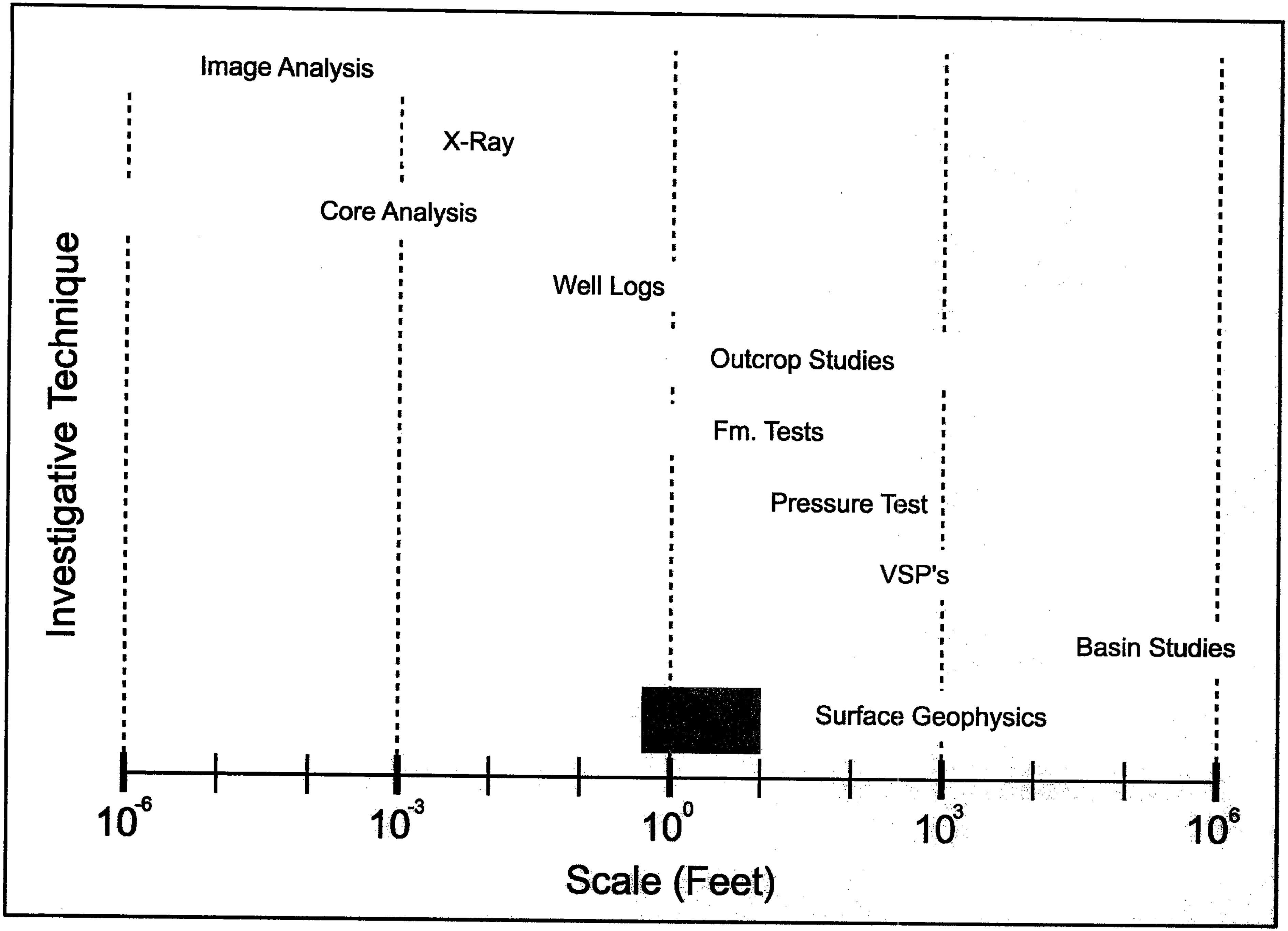
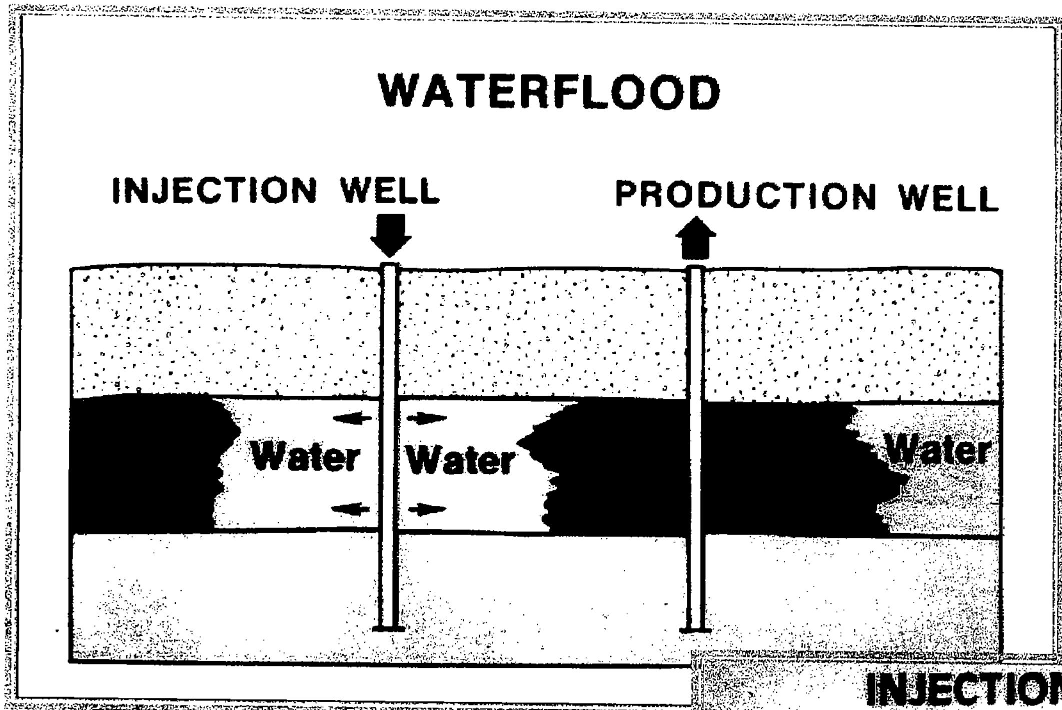
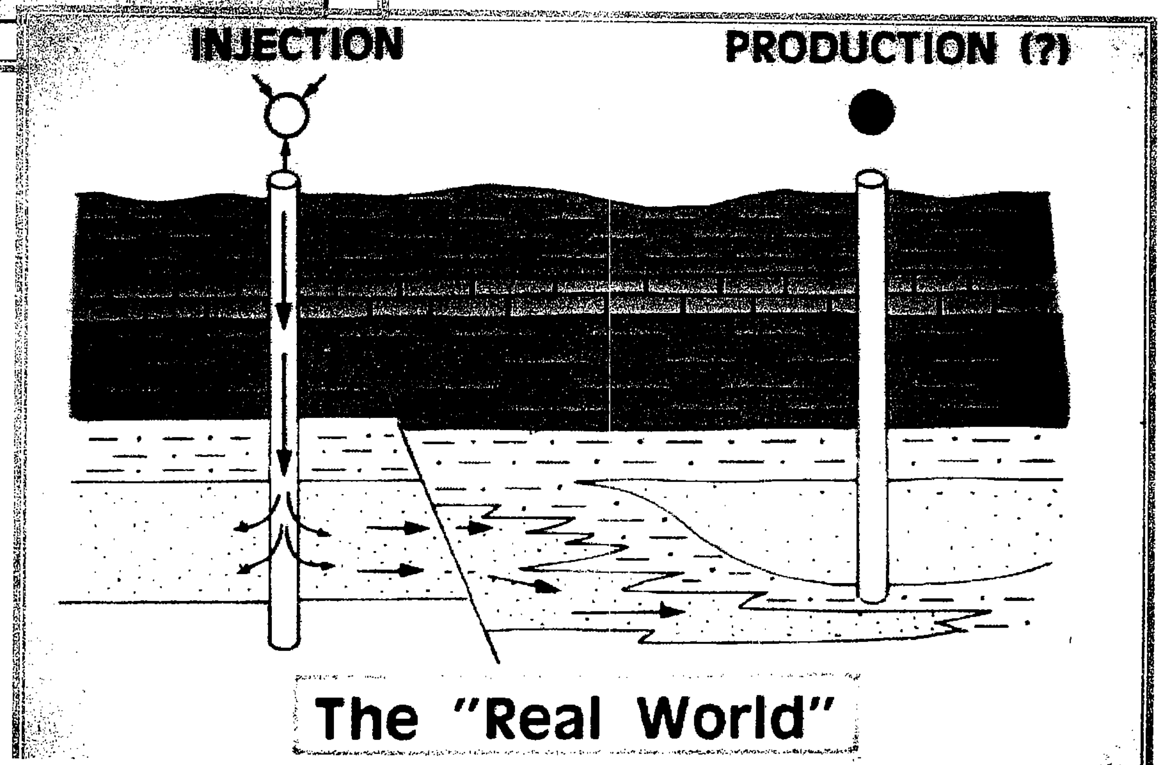
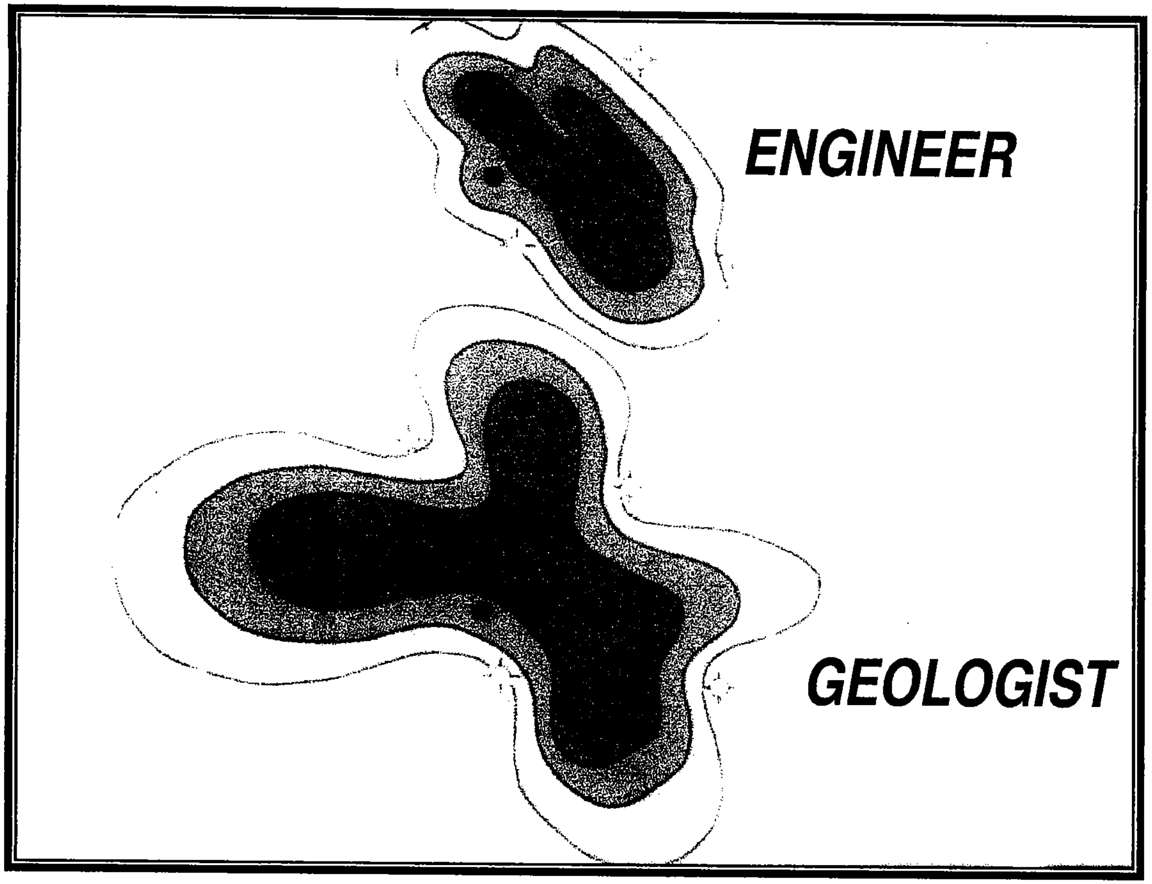


Image Analysis
X-Ray
Core Analysis
Well Logs
Outcrop Studies
Fm. Tests
Pressure Test
VSP's
Basin Studies
Surface Geophysics
Investigative Technique
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
Scale (Feet)


WATERFLOOD
INJECTION WELL
PRODUCTION WELL
Water
Water
Water


INJECTION
PRODUCTION (?)
The "Real World"



We need to work together!!!!

Two stonecutters were asked what they were doing. The first said, "I'm cutting this stone into blocks." The second replied, "I'm on a team that's building a cathedral."

-- *Author unknown*

Scales of geological heterogeneity of sandstone reservoirs:

What the geophysicicists (and reservoir engineers) need to know!!!

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Geologic features of sandstone reservoirs which control reservoir performance

-Size

-Geometry (shape)

-Architecture (internal makeup)

-Bed dimensions, continuity, & connectivity

-Structural attributes (faults, fractures, folds)

-Grain size and composition

-Porosity, permeability, and capillarity

-Burial depth and history

-Drive mechanism

"Three geophysical components:
-Source
-Medium
-Receiver"

Geologic Reservoir Characterization:

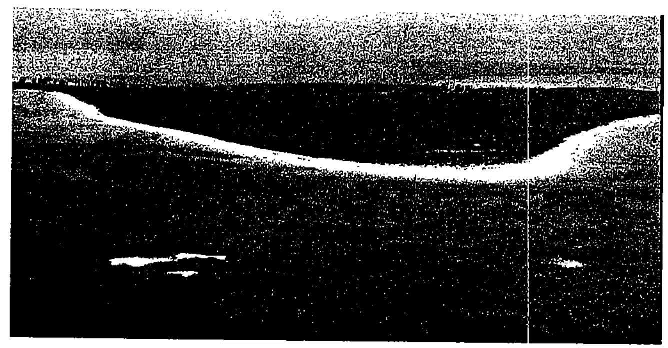
Levels of : heterogeneity	1 (big)
	2
	3
	4
	5
	6
	7 (small)

Quote from: Evgeni Chesnokov

Level 1: My reservoir is made of:

Sandstone:

Carbonate:



Shale (fractured):

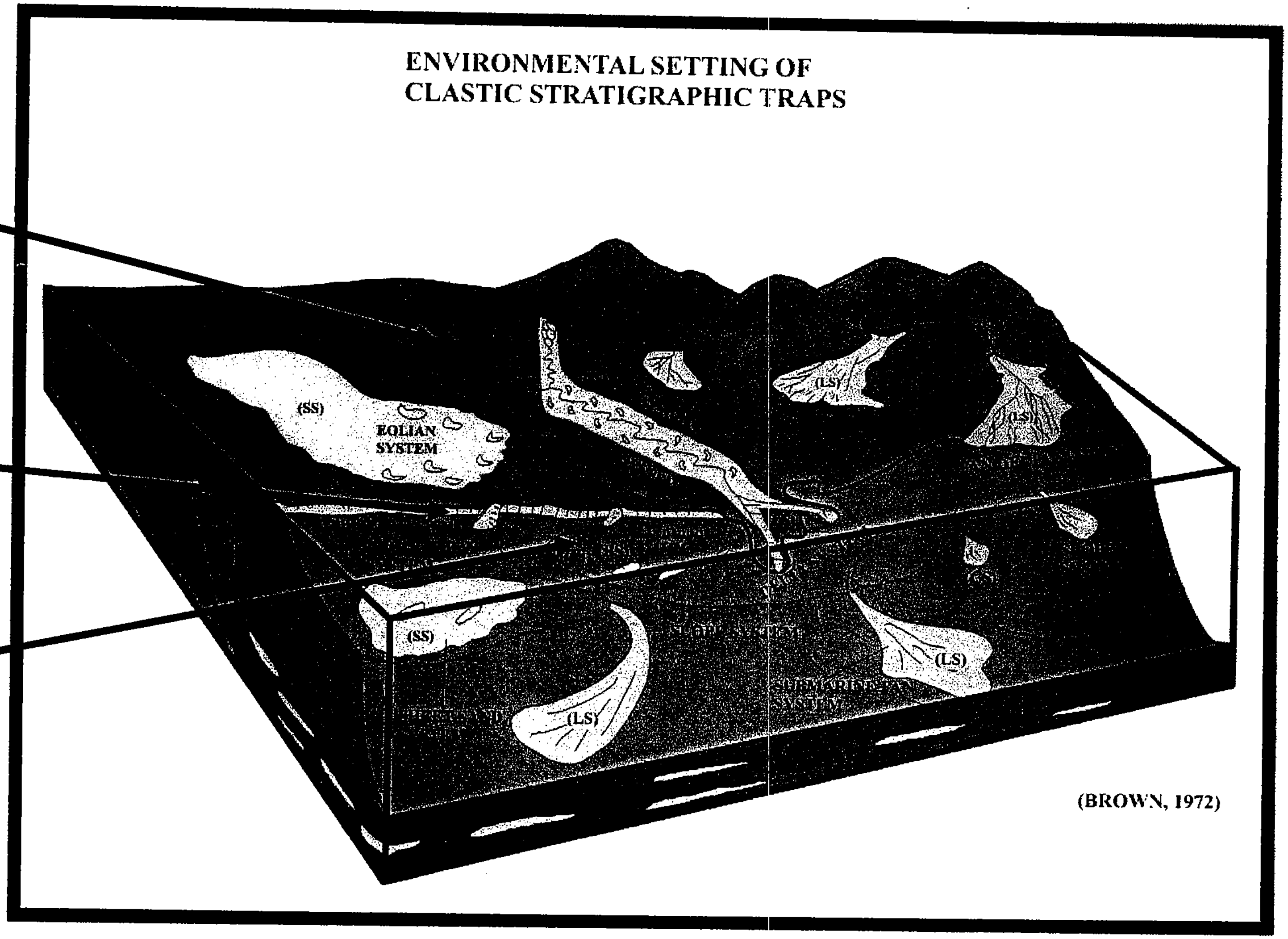
Etc:

Level 2: My sandstone reservoir is made of:

Continental deposits:

Mixed deposits:

Marine deposits:

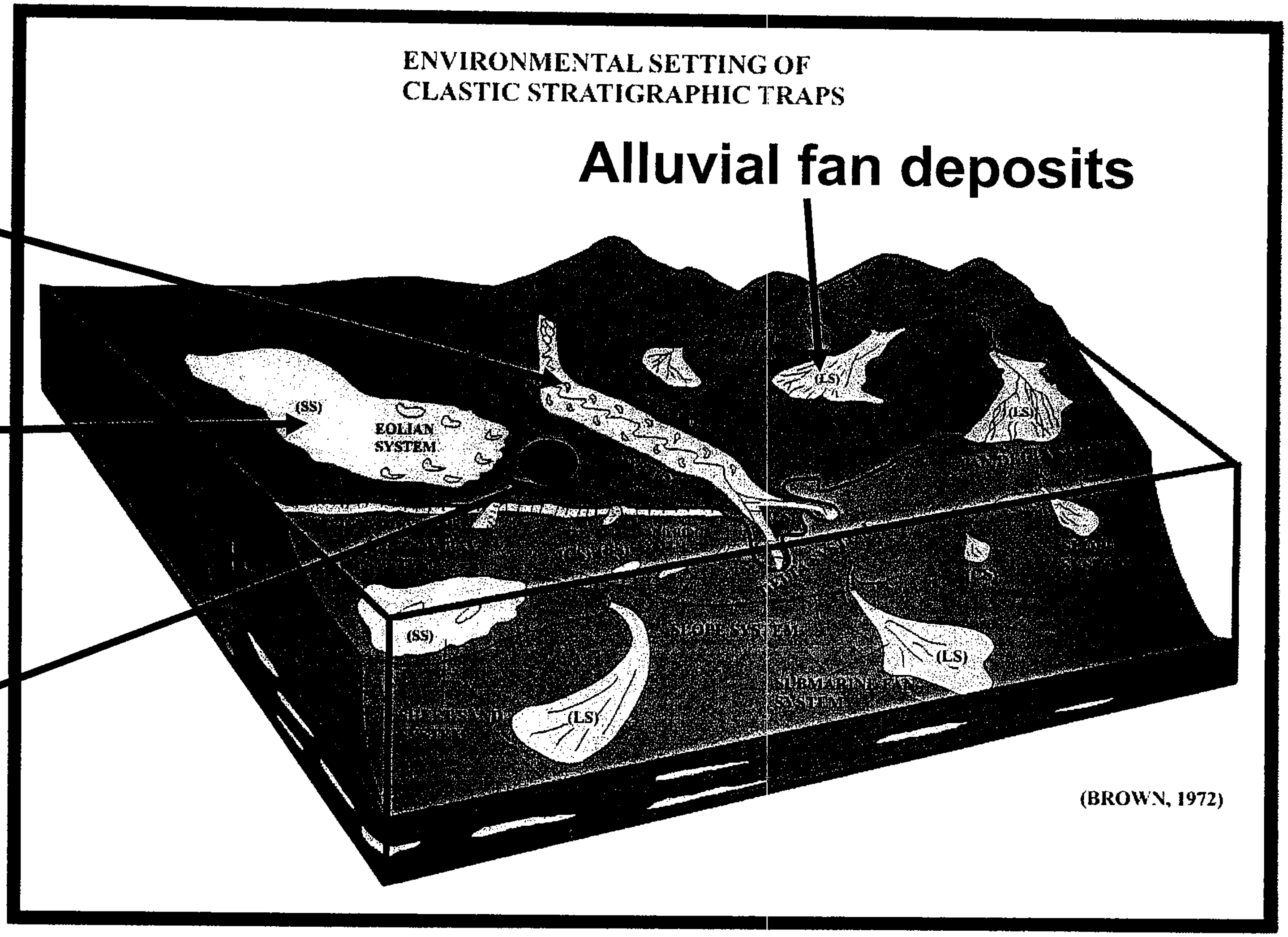


Level 3: My continental sandstone reservoir is made of:

Fluvial deposits

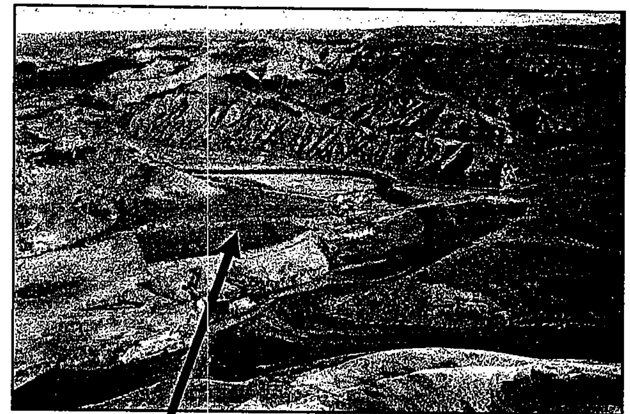
Eolian deposits

Lacustrine deposits



Level 4: My continental, fluvial sandstone reservoir is made of:

Meandering River deposits



Incised Valley Fill deposits

Braided River deposits

Level 5: My <u>continental, fluvial, meandering river sandstone</u> reservoir is made of:

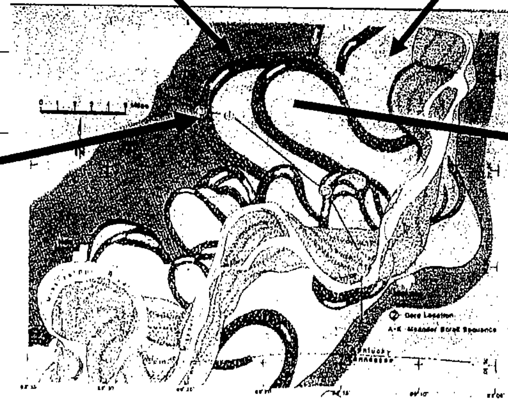
Meandering River

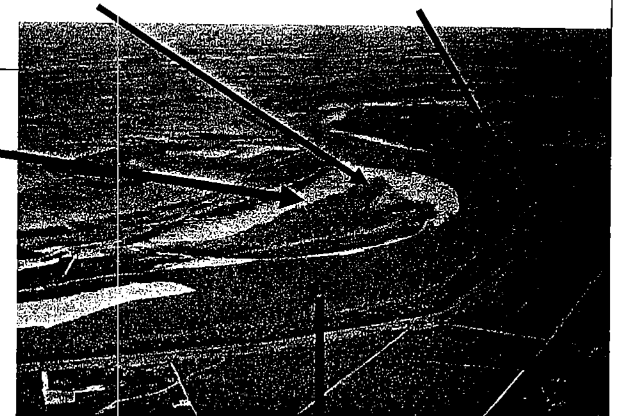
Overbank (floodplain)

Mud plug

Point bar

Cutbank

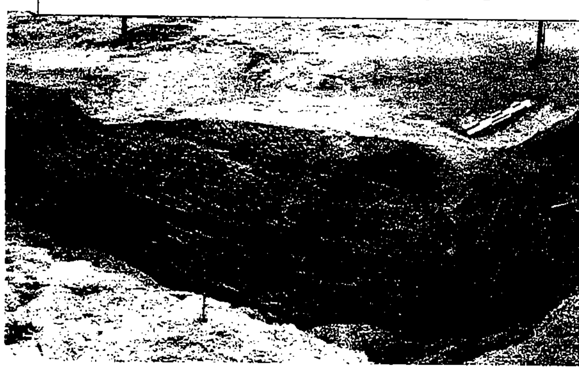


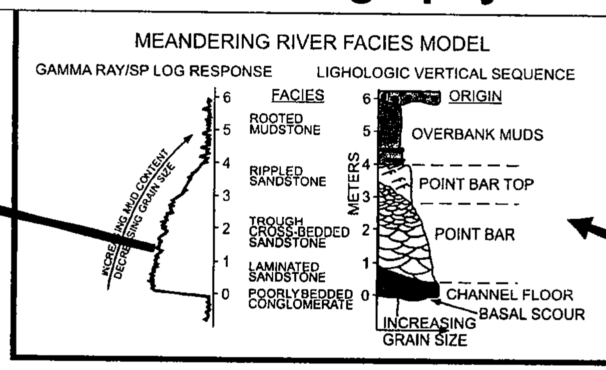


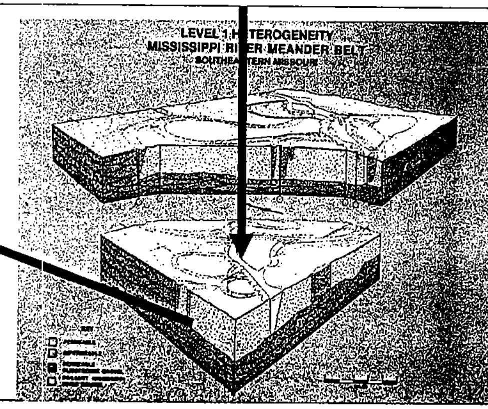
Cross bedded sand

Vertical stratigraphy

3D architecture

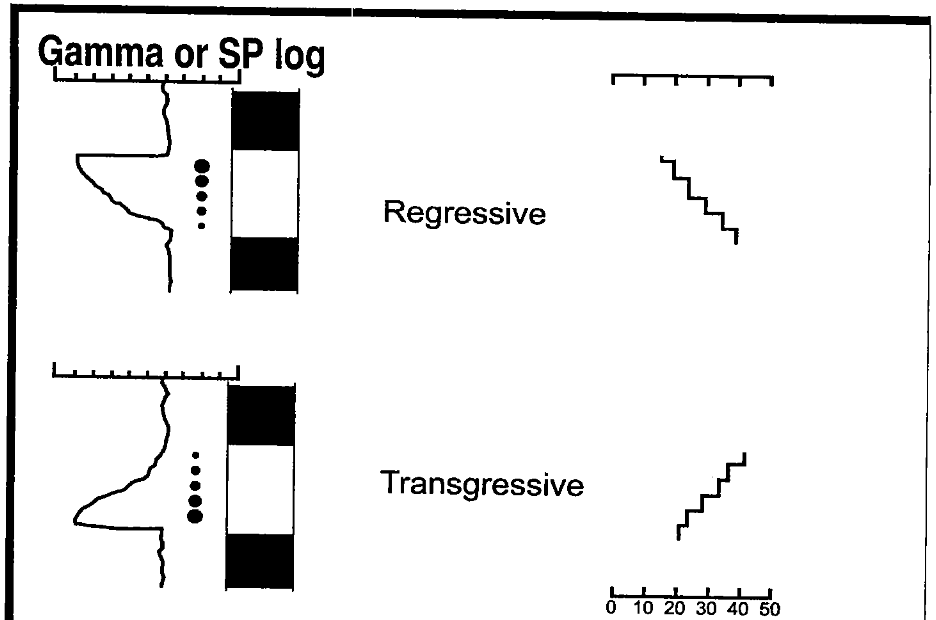




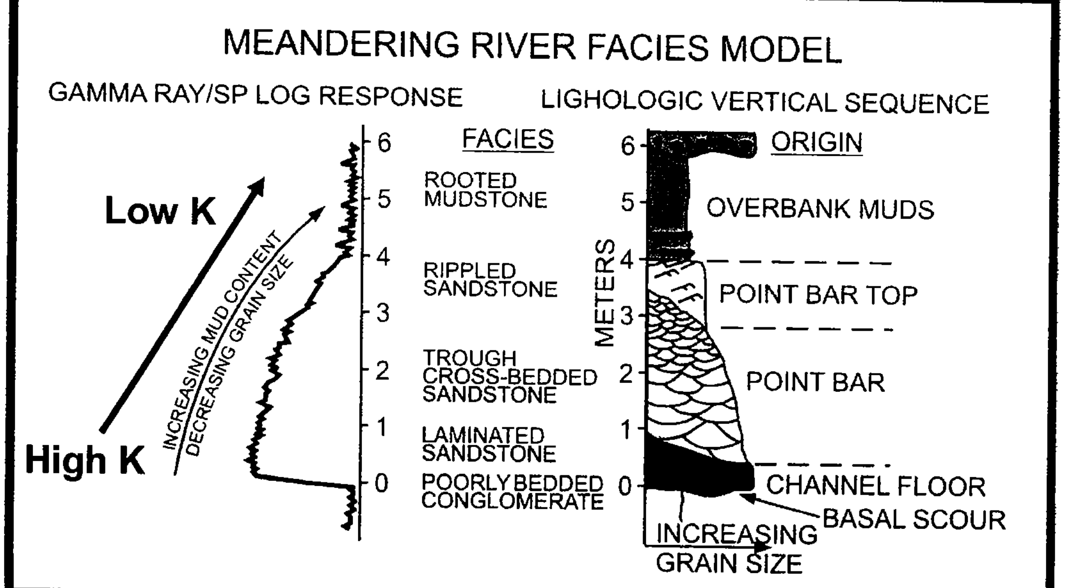


Level 6: Reservoir Quality: Porosity & Permeability

Permeability varies with sediment grain size (even after cementation)



Black dots refer to relative grain-size of sands at each stratigraphic level

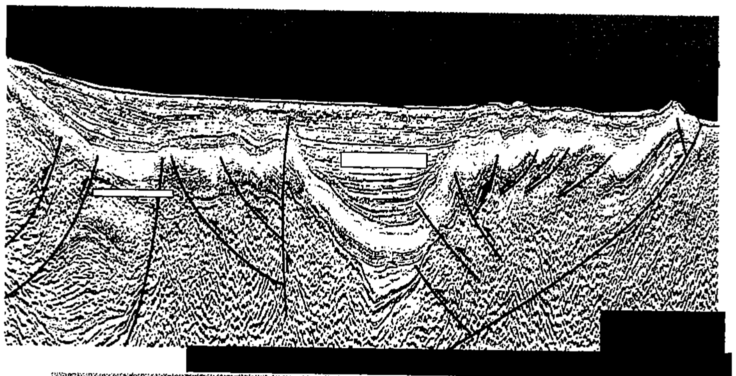


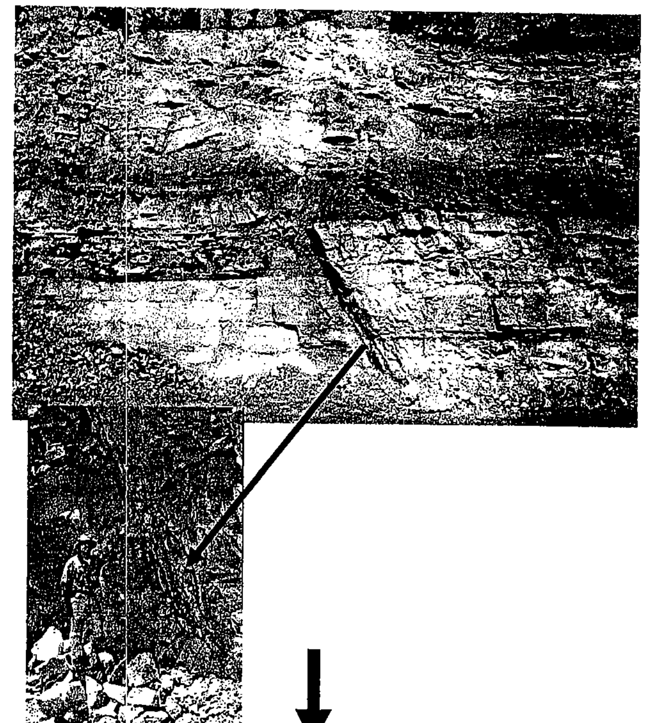
Remaining oil saturation after waterflood within a sandstone body varies with grain size, and thus, permeability.

Level 7: Structure

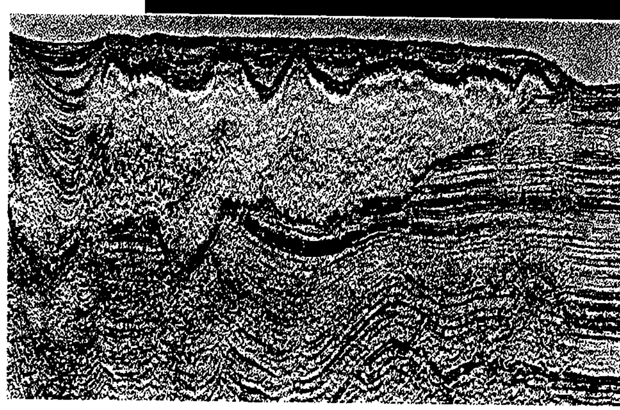
Feature | **Seismic** | **Sub-seismic**

Fault





Fold



Diapir

See next images

Fracture - - - - - -

“Three geophysical components:

-Source

-Medium

-Receiver”

Geologic Reservoir Characterization: Levels of heterogeneity:

1

2

3

4

5

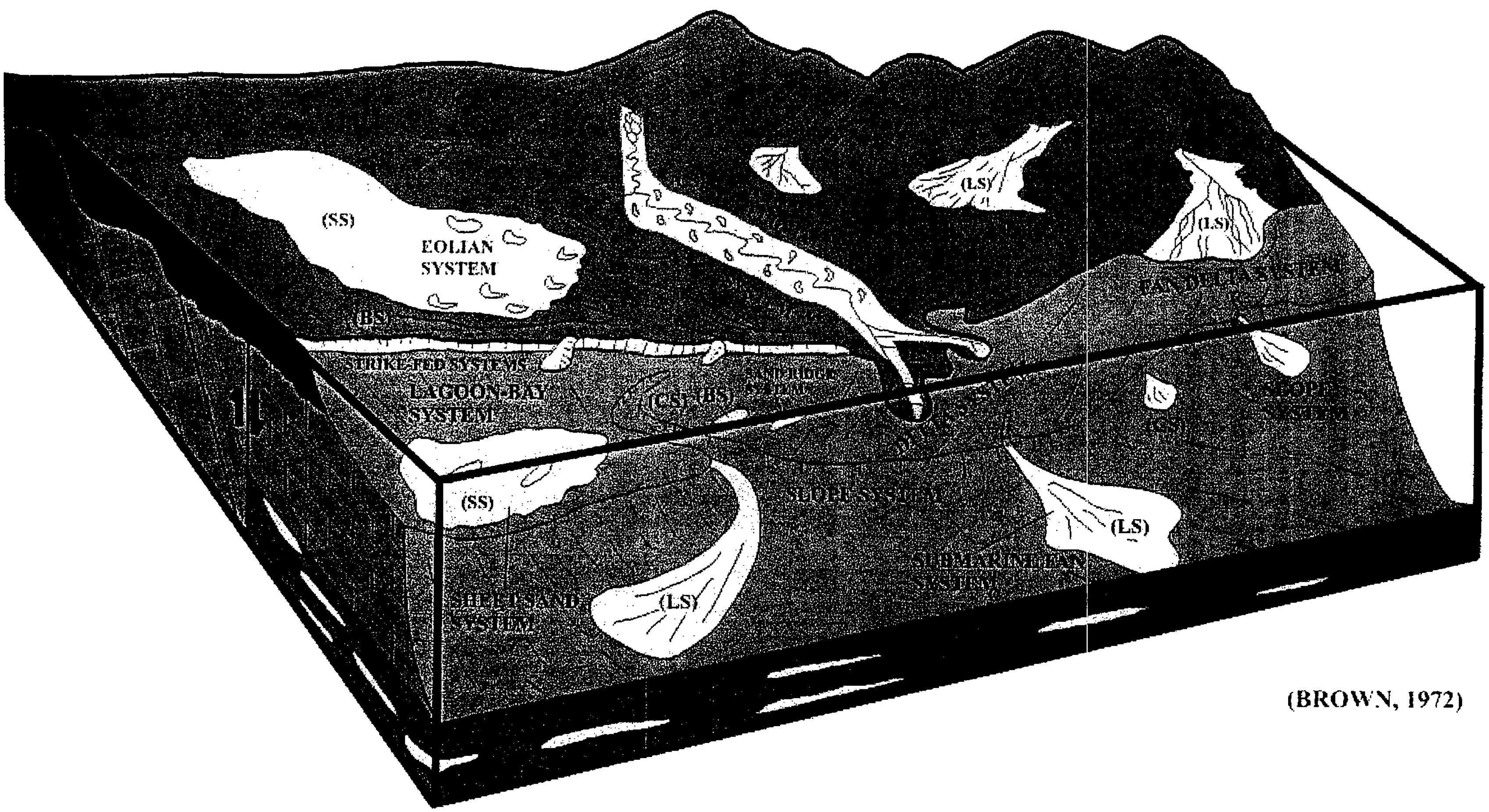
6

7

These are the important levels for reservoir development

Quote from: Evgeni Chesn

ENVIRONMENTAL SETTING OF CLASTIC STRATIGRAPHIC TRAPS



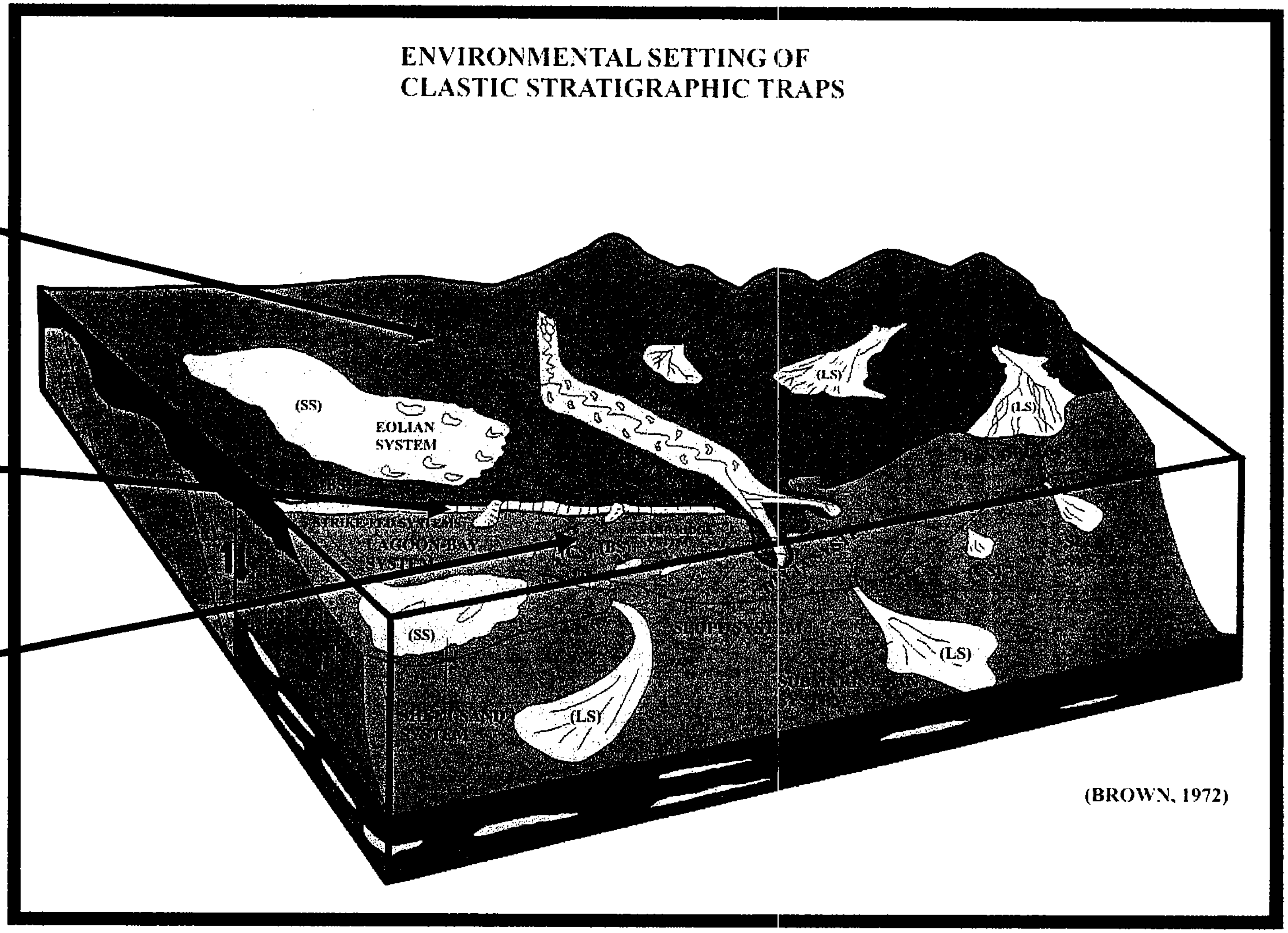
(BROWN, 1972)

Level 2: *My <u>sandstone</u> reservoir is made of:*

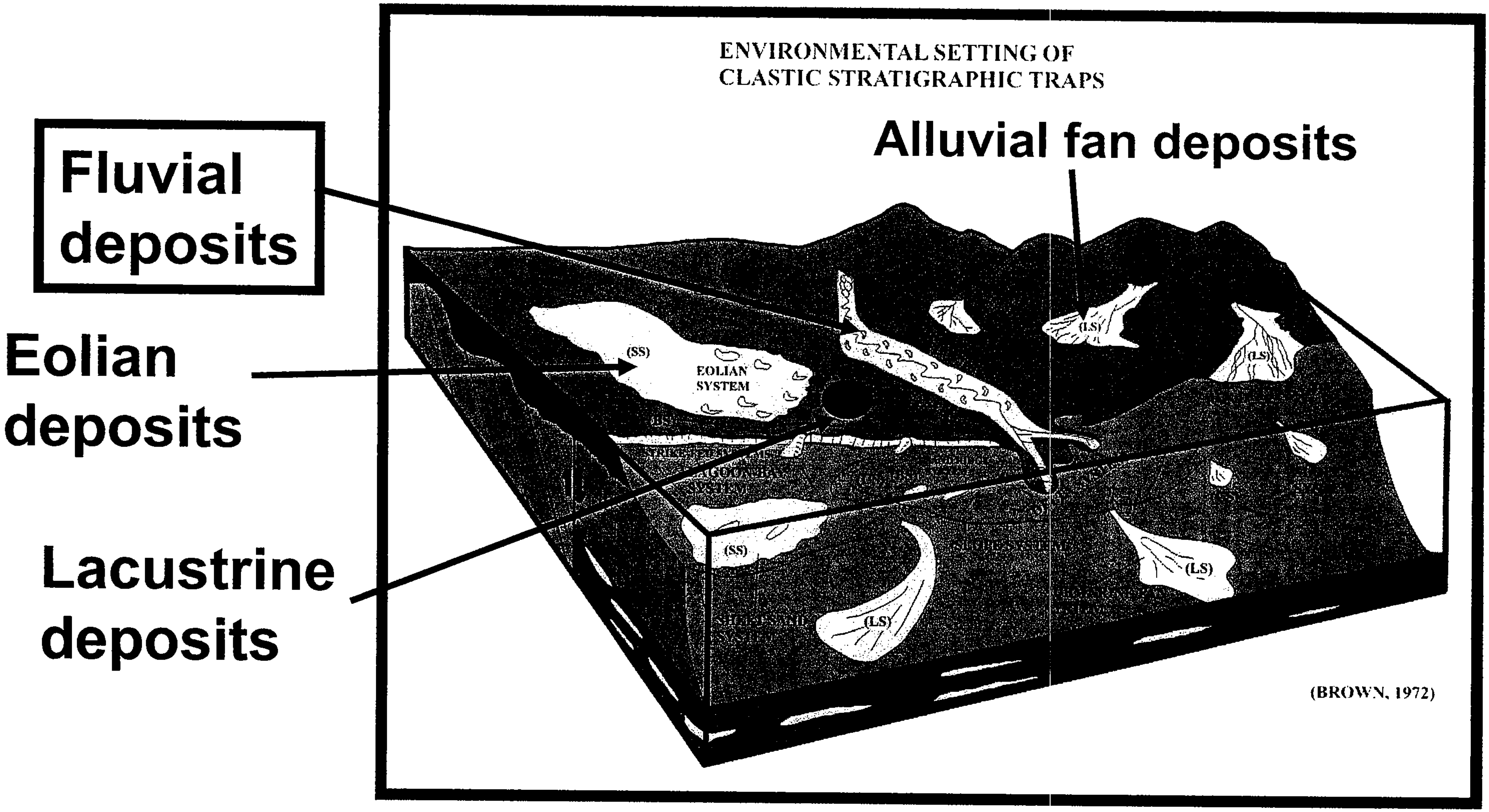
Continental deposits:

Mixed deposits:

Marine deposits:

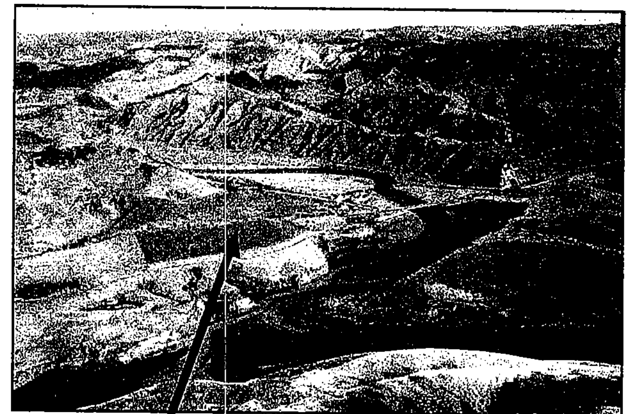


Level 3: My continental <u>sandstone</u> reservoir is made of:



Level 4: My <u>continental, fluvial sandstone</u> reservoir is made of:

Meandering River deposits



Incised Valley Fill deposits

Braided River deposits

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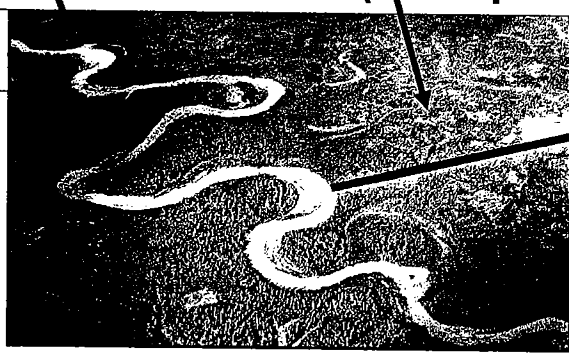
Meandering River

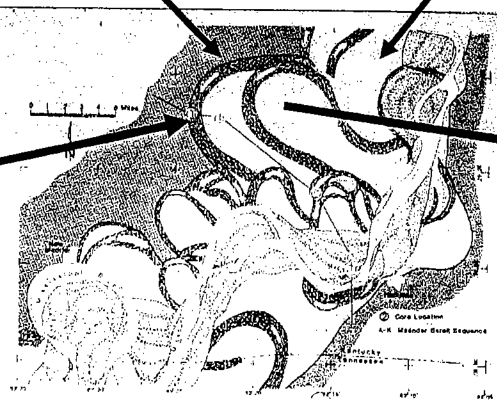
Overbank (floodplain)

Mud plug

Point bar

Cutbank

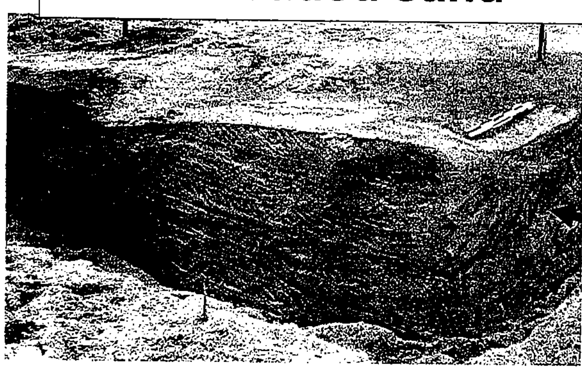


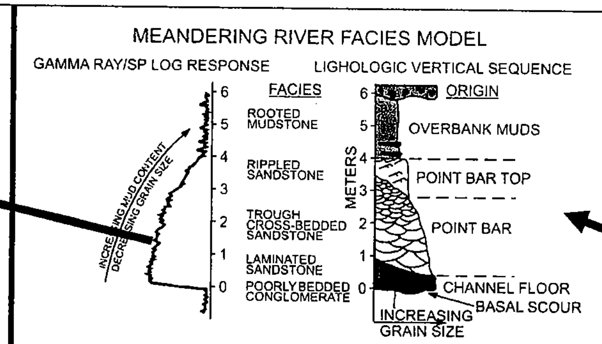


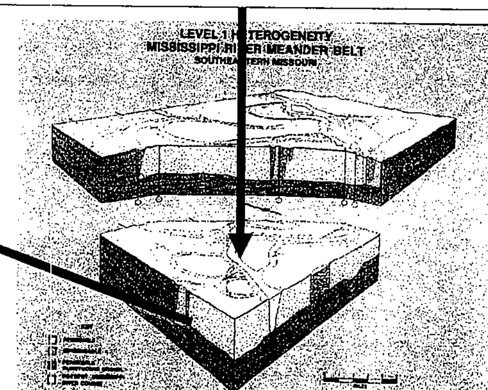
Cross bedded sand

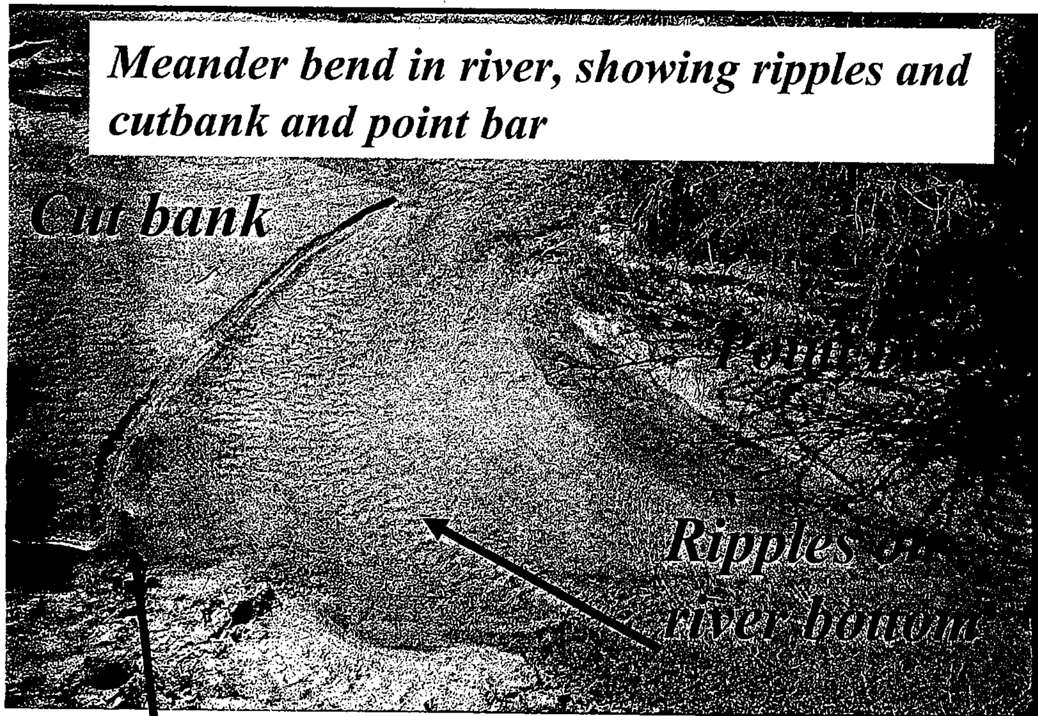
Vertical stratigraphy

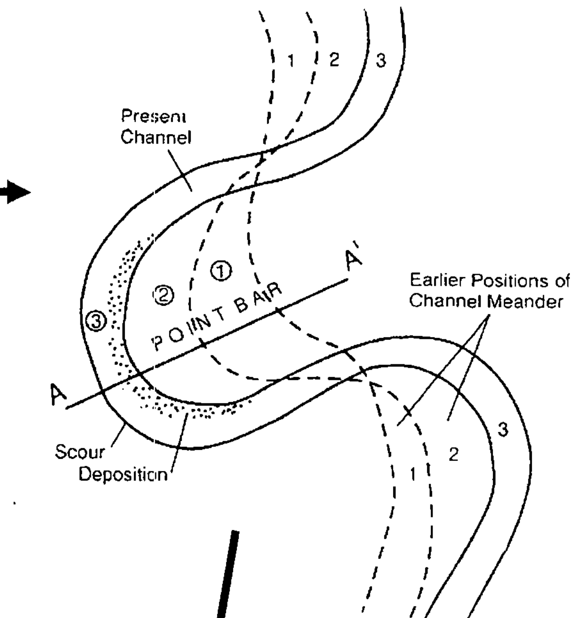
3D architecture

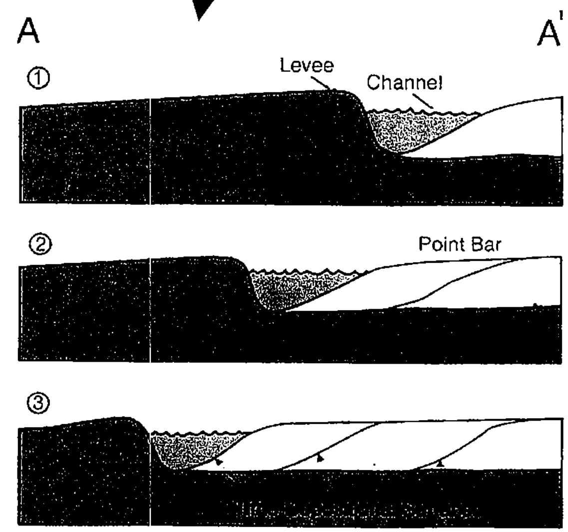




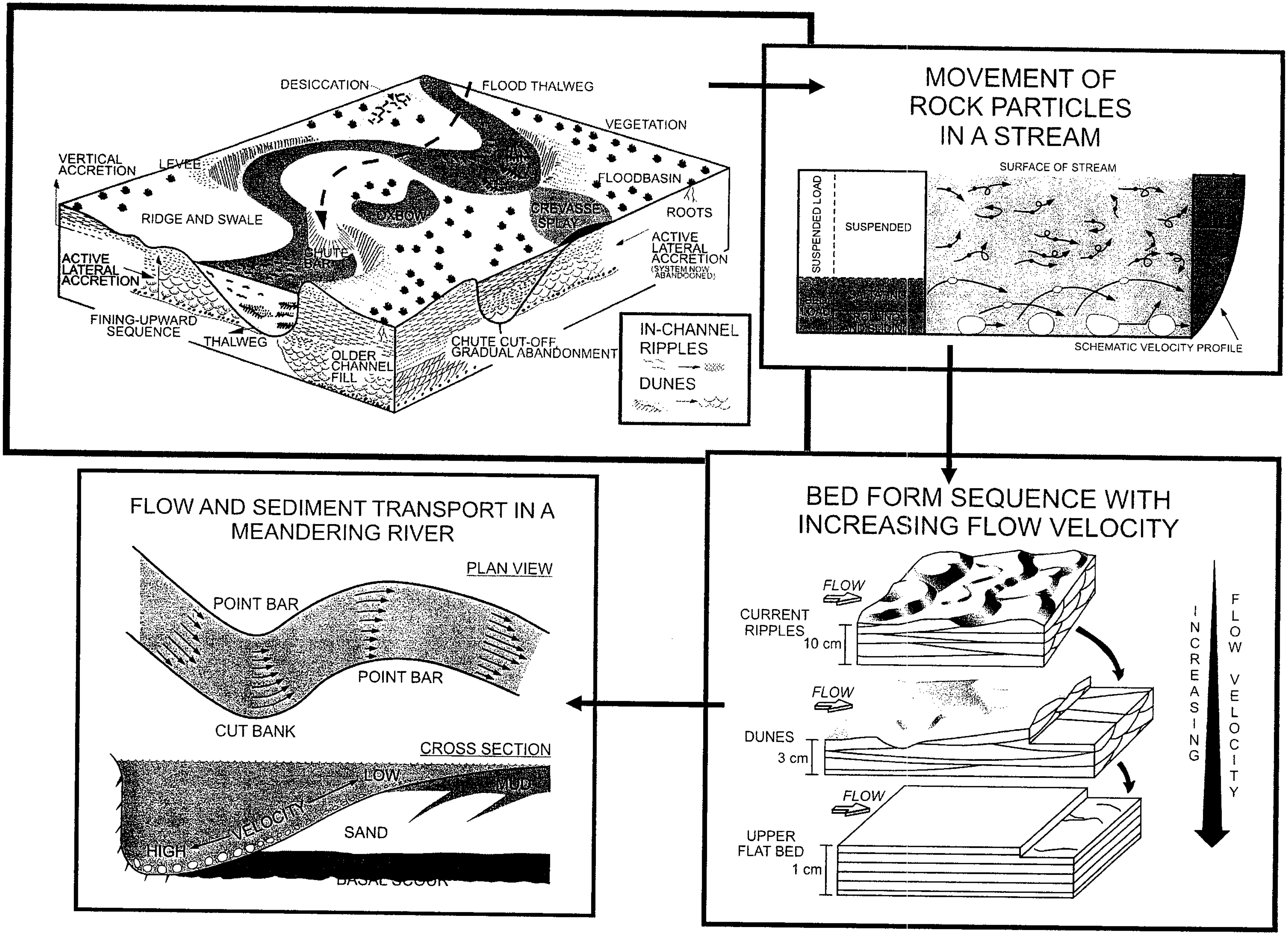


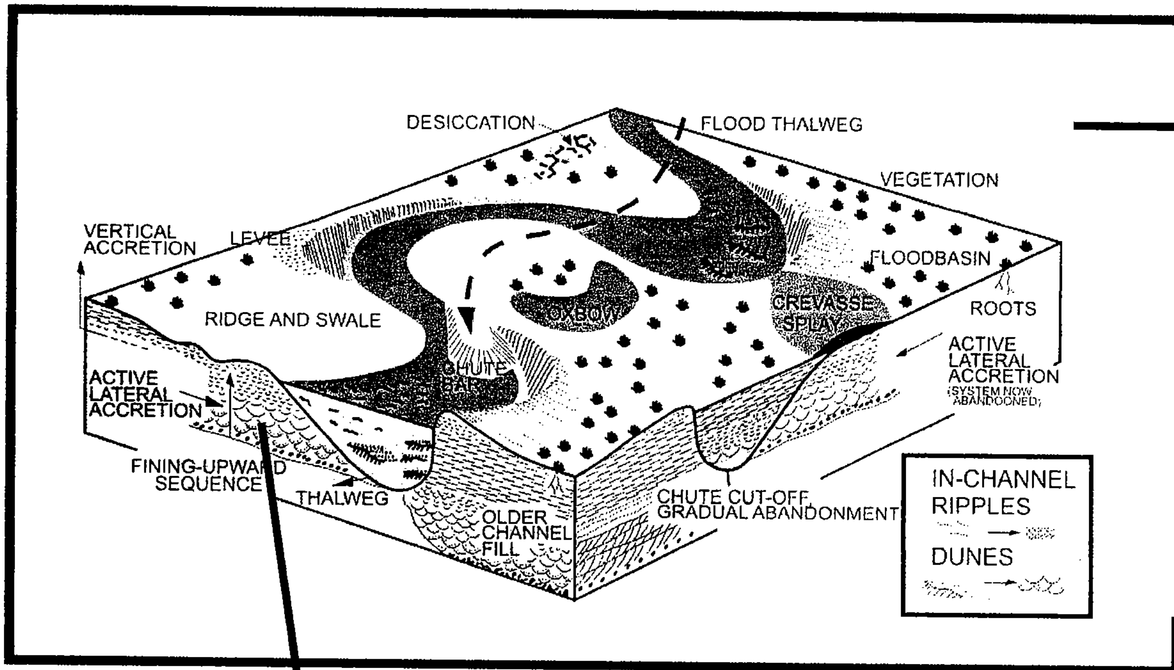


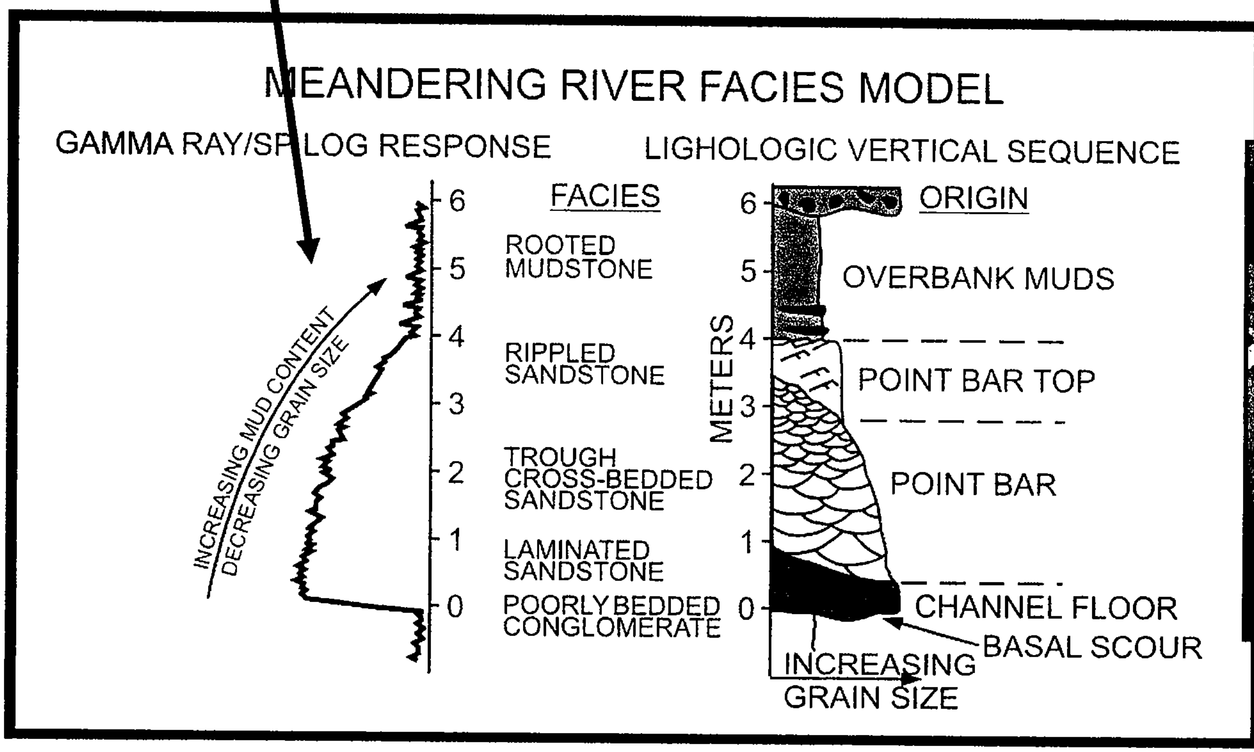


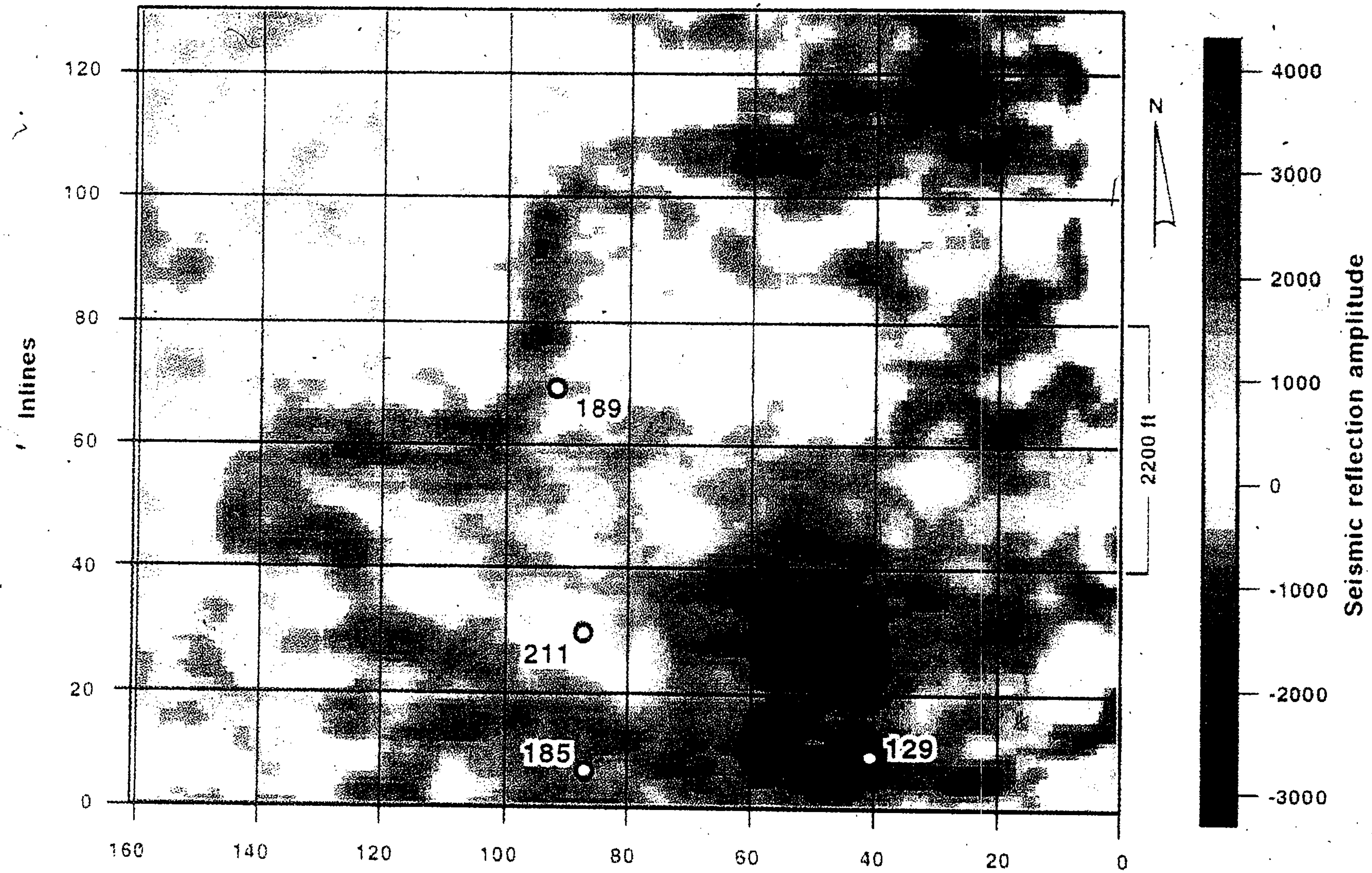


(LeBlanc, 1972)

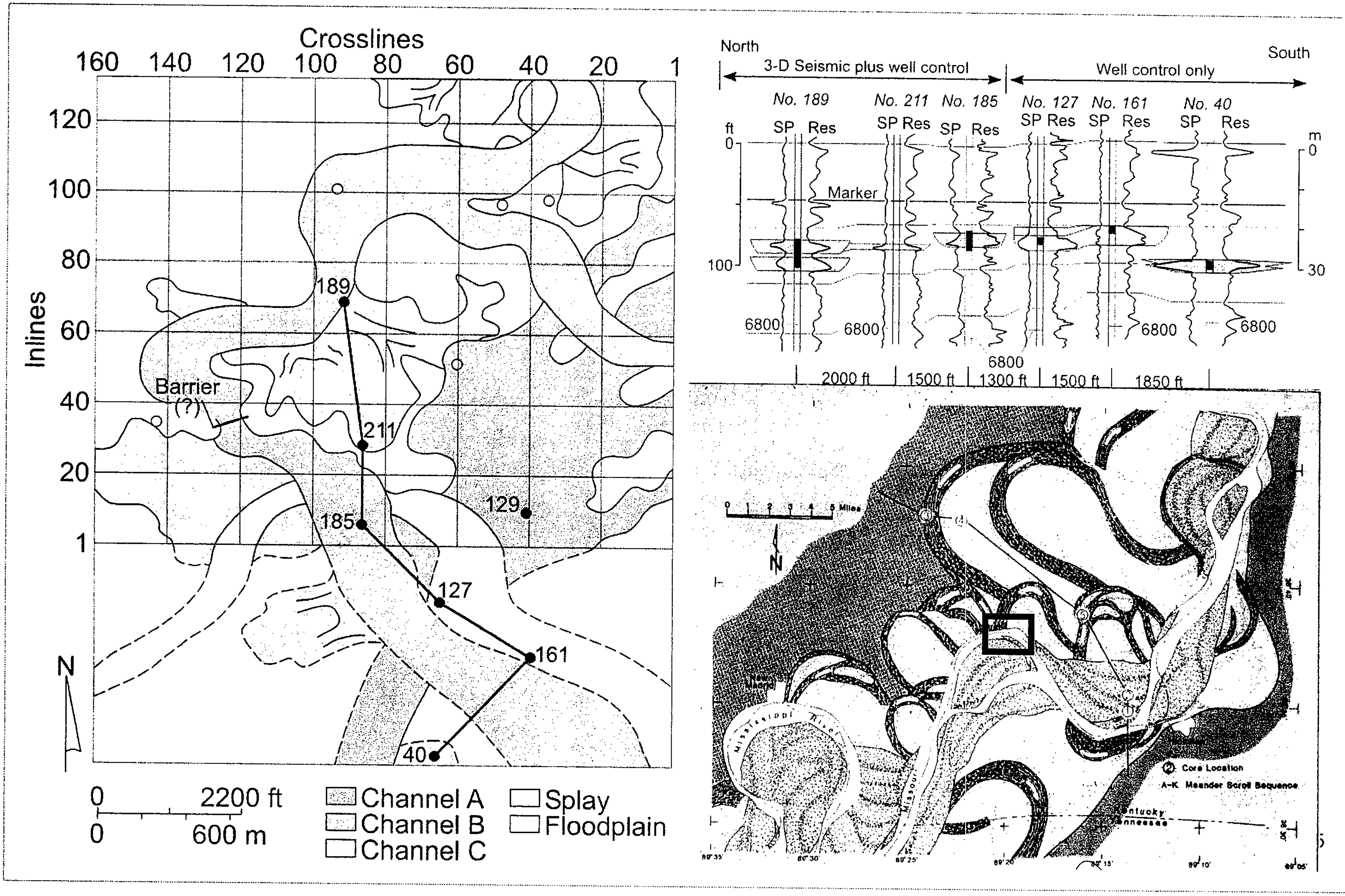

DESICCATION
FLOOD THALWEG
VEGETATION
VERTICAL ACCRETION
LEVEE
FLOODBASIN
RIDGE AND SWALE
OXBOW
CREVASSE SPLAY
ROOTS
CHUTE BAR
ACTIVE LATERAL ACCRETION
ACTIVE LATERAL ACCRETION (SYSTEM NOW ABANDONED)
FINING-UPWARD SEQUENCE
THALWEG
OLDER CHANNEL FILL
CHUTE CUT-OFF
GRADUAL ABANDONMENT
IN-CHANNEL
RIPPLES
DUNES
MOVEMENT OF ROCK PARTICLES IN A STREAM
SURFACE OF STREAM
SUSPENDED LOAD
SUSPENDED
SCHEMATIC VELOCITY PROFILE
BED FORM SEQUENCE WITH INCREASING FLOW VELOCITY
FLOW
CURRENT RIPPLES
10 cm
FLOW
DUNES
3 cm
FLOW
UPPER FLAT BED
1 cm
INCREASING
FLOW VELOCITY
FLOW AND SEDIMENT TRANSPORT IN A MEANDERING RIVER
PLAN VIEW
POINT BAR
POINT BAR
CUT BANK
CROSS SECTION
LOW
VELOCITY
HIGH
MUD
SAND


DESICCATION
FLOOD THALWEG
VEGETATION
VERTICAL ACCRETION
LEVEE
FLOODBASIN
RIDGE AND SWALE
OXBOW
CREVASSE SPLAY
ROOTS
ACTIVE LATERAL ACCRETION (SYSTEM NOW ABANDONED)
CHUTE BAR
ACTIVE LATERAL ACCRETION
FINING-UPWARD SEQUENCE
THALWEG
OLDER CHANNEL FILL
CHUTE CUT-OFF GRADUAL ABANDONMENT
IN-CHANNEL
RIPPLES
DUNES


MEANDERING RIVER FACIES MODEL
GAMMA RAY/SP LOG RESPONSE
LIGHOLOGIC VERTICAL SEQUENCE
INCREASING MUD CONTENT
DECREASING GRAIN SIZE
FACIES
ROOTED MUDSTONE
RIPPLED SANDSTONE
TROUGH CROSS-BEDDED SANDSTONE
LAMINATED SANDSTONE
POORLY BEDDED CONGLOMERATE
METERS
6
5
4
3
2
1
0
ORIGIN
OVERBANK MUDS
POINT BAR TOP
POINT BAR
CHANNEL FLOOR
BASAL SCOUR
INCREASING GRAIN SIZE



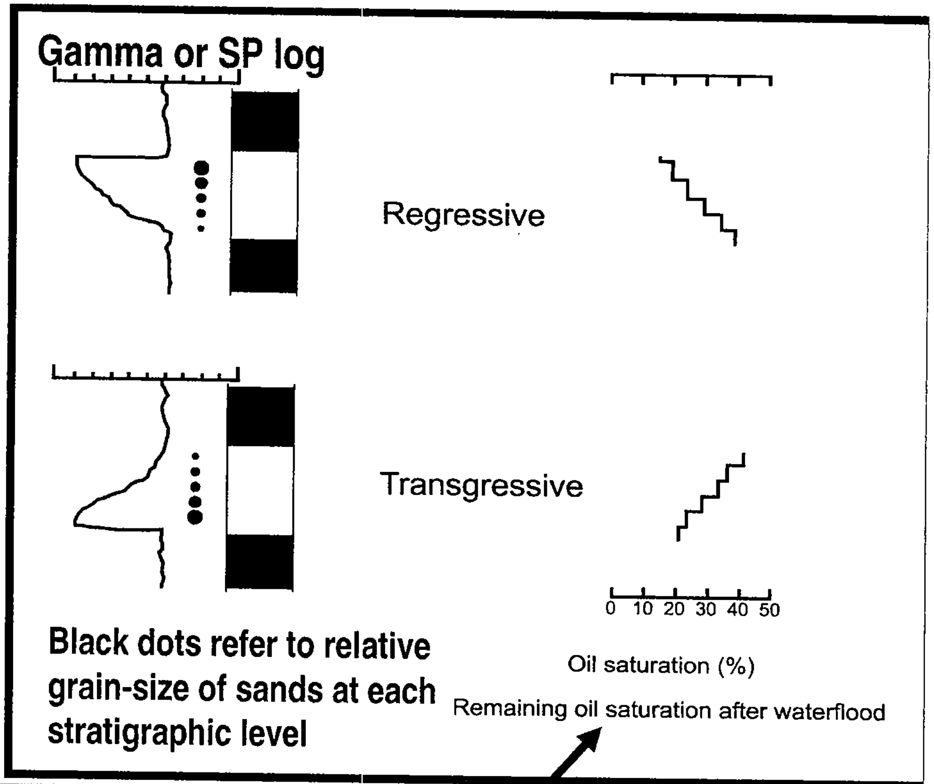
Inlines
120
100
80
60
40
20
0
160
140
120
100
80
60
40
20
0
189
211
185
129
N
2200 ft
4000
3000
2000
1000
0
-1000
-2000
-3000
Seismic reflection amplitude



Crosslines
160 140 120 100 80 60 40 20 1
Inlines
120
100
80
60
40
20
1
189
211
185
129
127
161
40
Barrier
(?)
N
0 2200 ft
0 600 m
Channel A
Channel B
Channel C
Splay
Floodplain
North
South
3-D Seismic plus well control
Well control only
No. 189
No. 211
No. 185
No. 127
No. 161
No. 40
SP Res
ft
0
100
m
0
30
Marker
6800
2000 ft
1500 ft
1300 ft
1500 ft
1850 ft
N
Miles
Core Location
A-K Meander Scroll Sequence
Mississippi River
Missouri
Kentucky
Tennessee

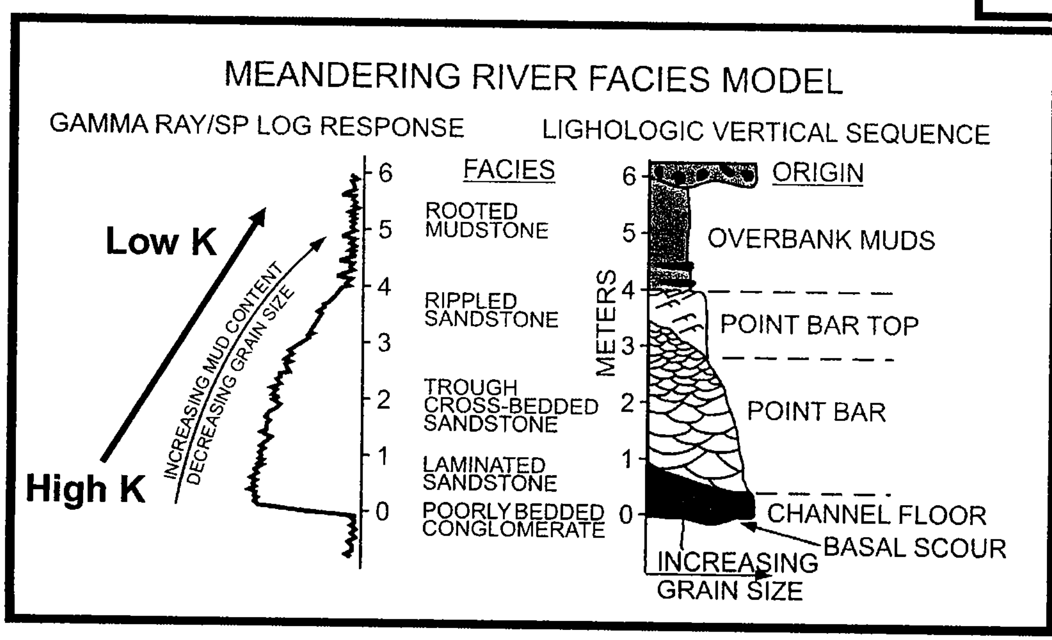
Level 6: Reservoir Quality: Porosity & Permeability

Permeability varies with sediment grain size (even after cementation)

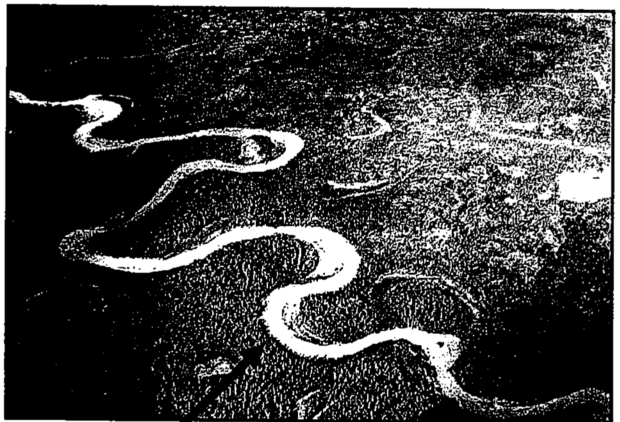


Black dots refer to relative grain-size of sands at each stratigraphic level

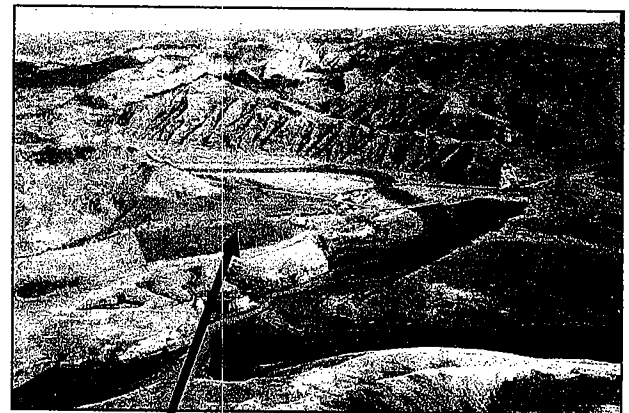
Remaining oil saturation after waterflood within a sandstone body varies with grain size, and thus, permeability.



Level 4: My continental, fluvial sandstone reservoir is made of:

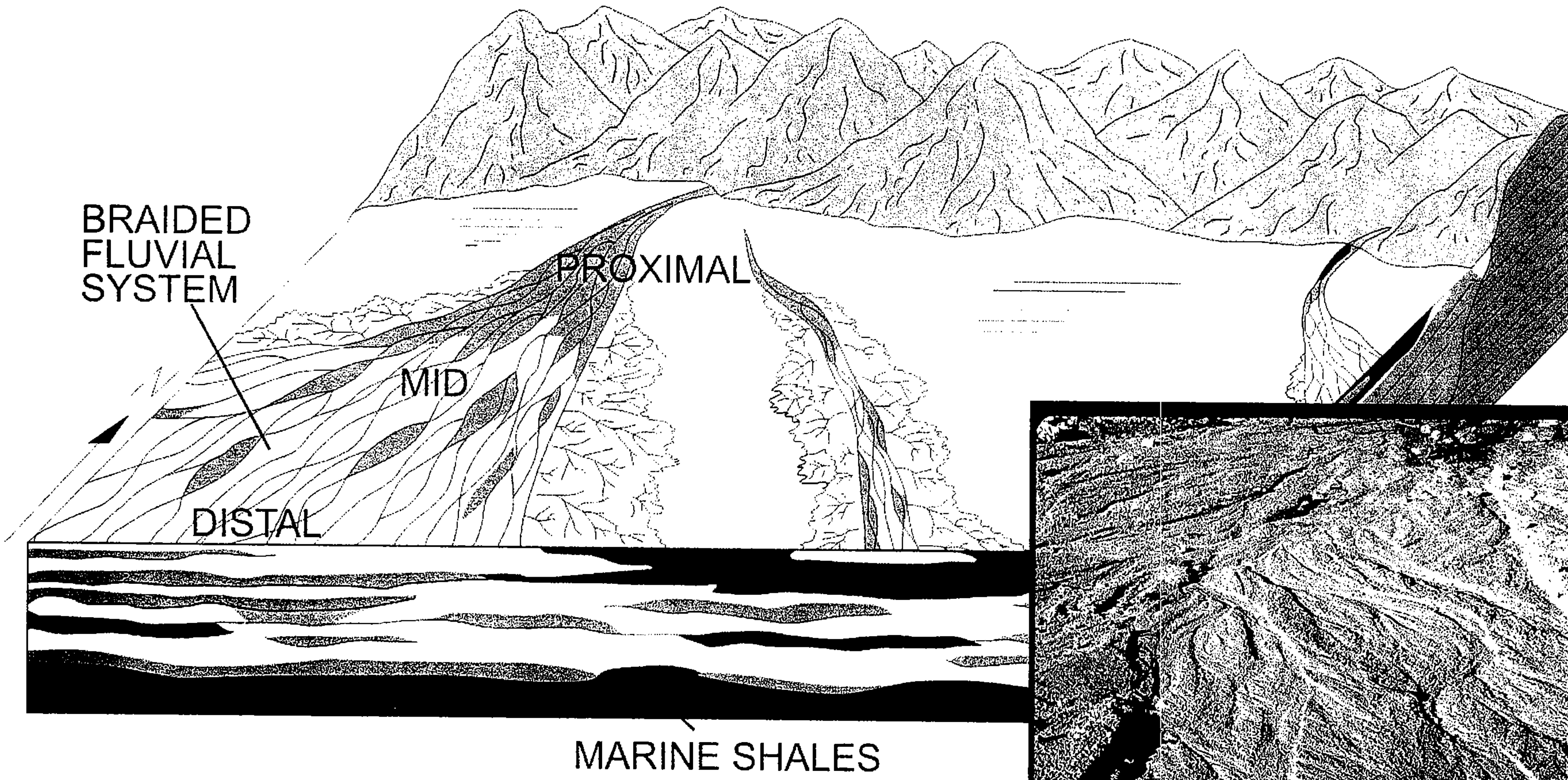


Meandering River deposits

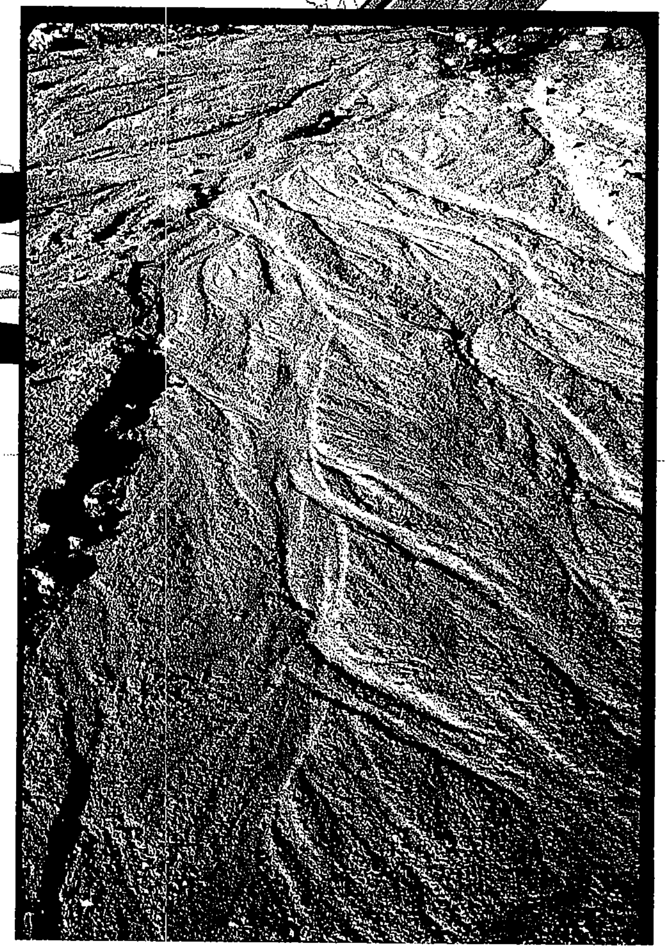


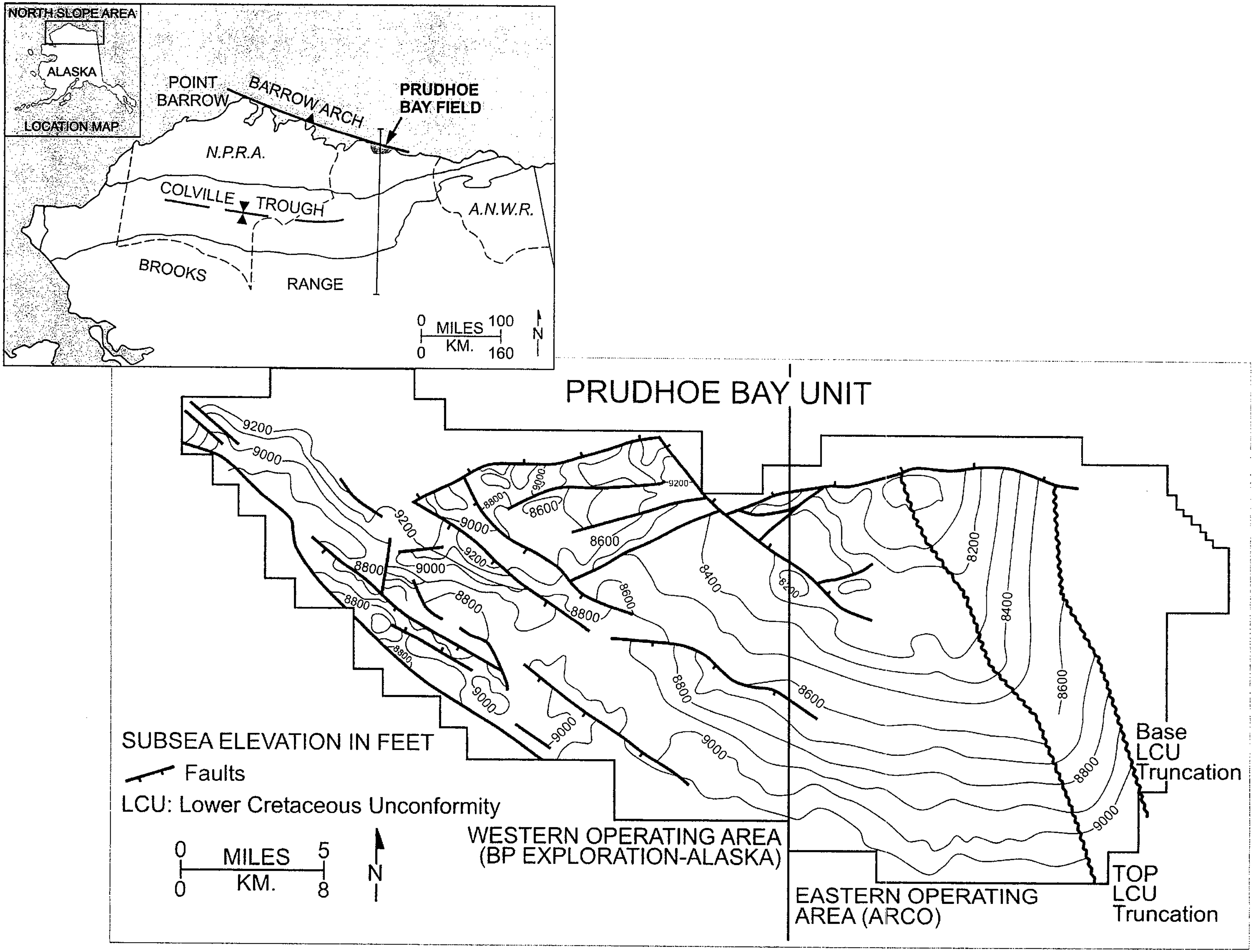
Incised Valley Fill deposits

Braided River deposits

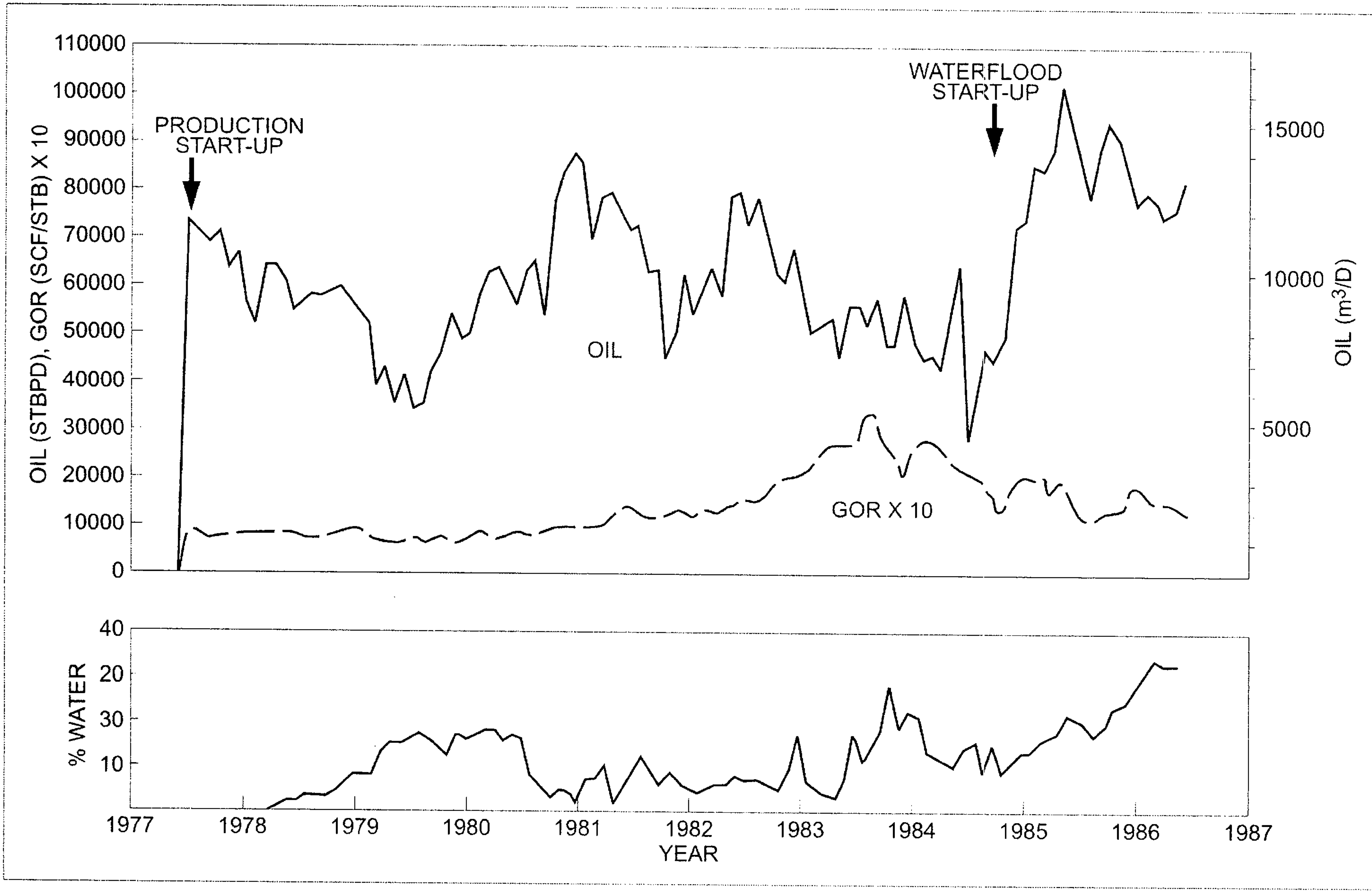


Braided river deposit

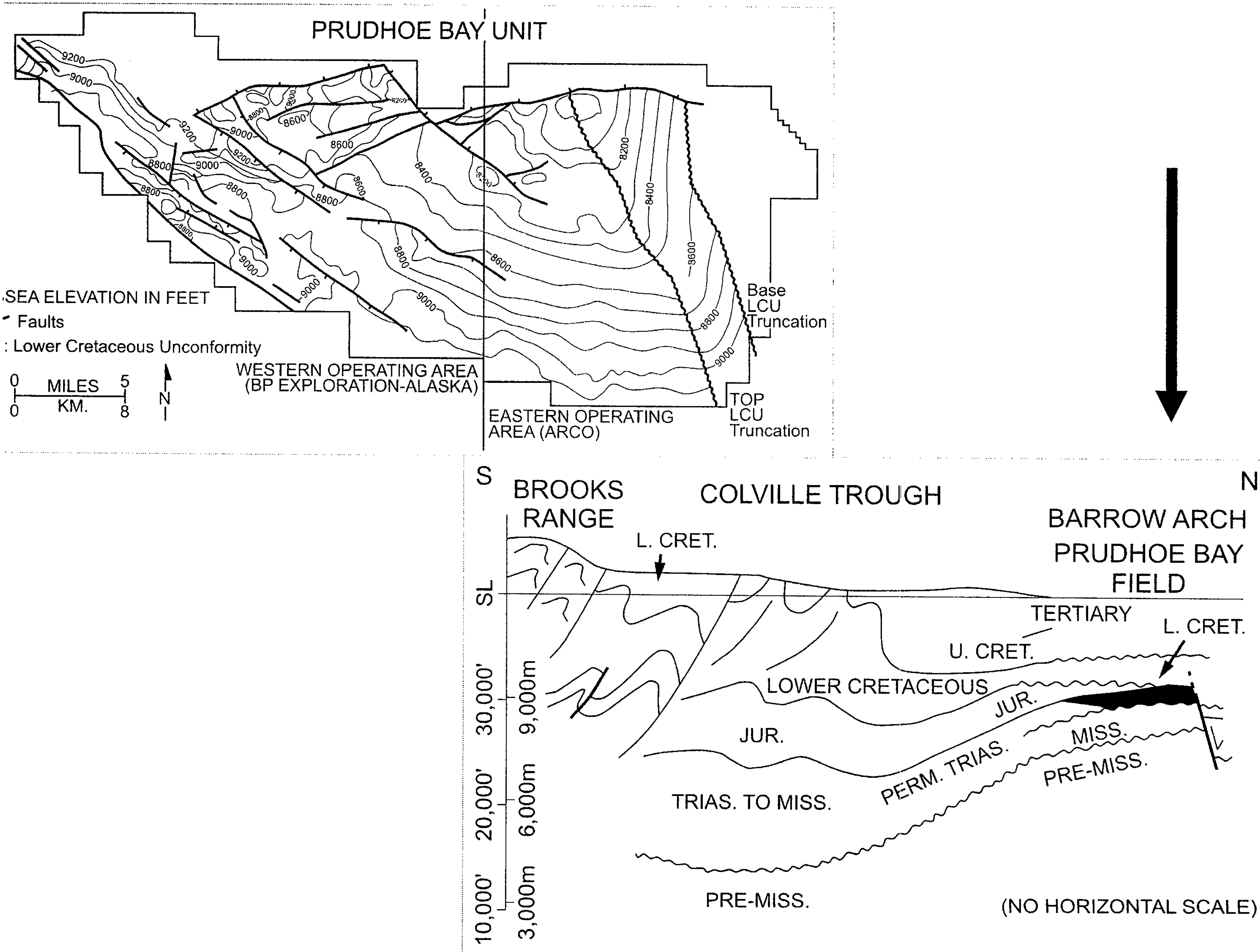




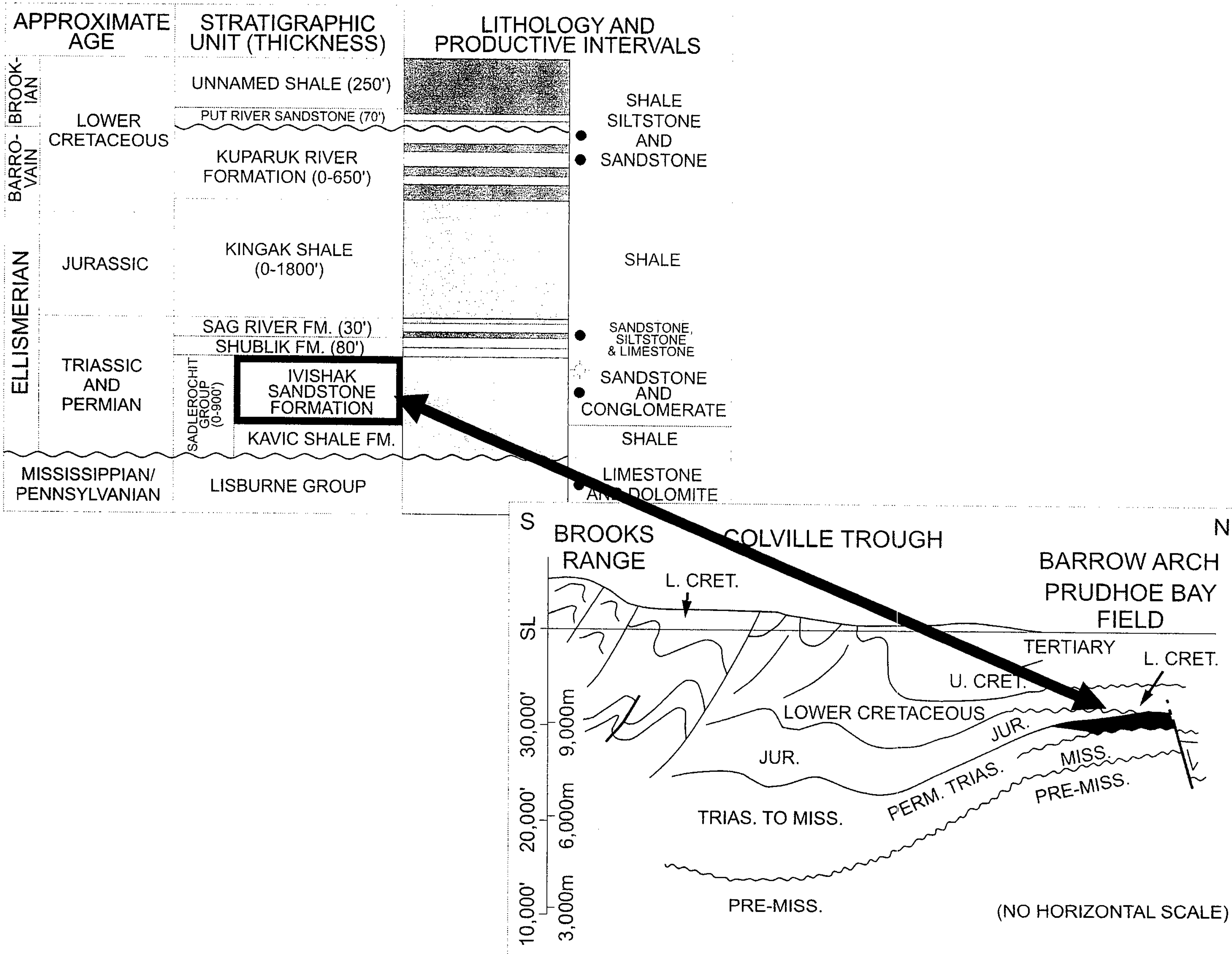
NORTH SLOPE AREA
ALASKA
LOCATION MAP
POINT BARROW
BARROW ARCH
PRUDHOE BAY FIELD
N.P.R.A.
COLVILLE TROUGH
A.N.W.R.
BROOKS RANGE
0 MILES 100
0 KM. 160
N
PRUDHOE BAY UNIT
SUBSEA ELEVATION IN FEET
Faults
LCU: Lower Cretaceous Unconformity
0 MILES 5
0 KM. 8
N
WESTERN OPERATING AREA (BP EXPLORATION-ALASKA)
EASTERN OPERATING AREA (ARCO)
Base LCU Truncation
TOP LCU Truncation
9200
9000
8800
8600
8400
8200

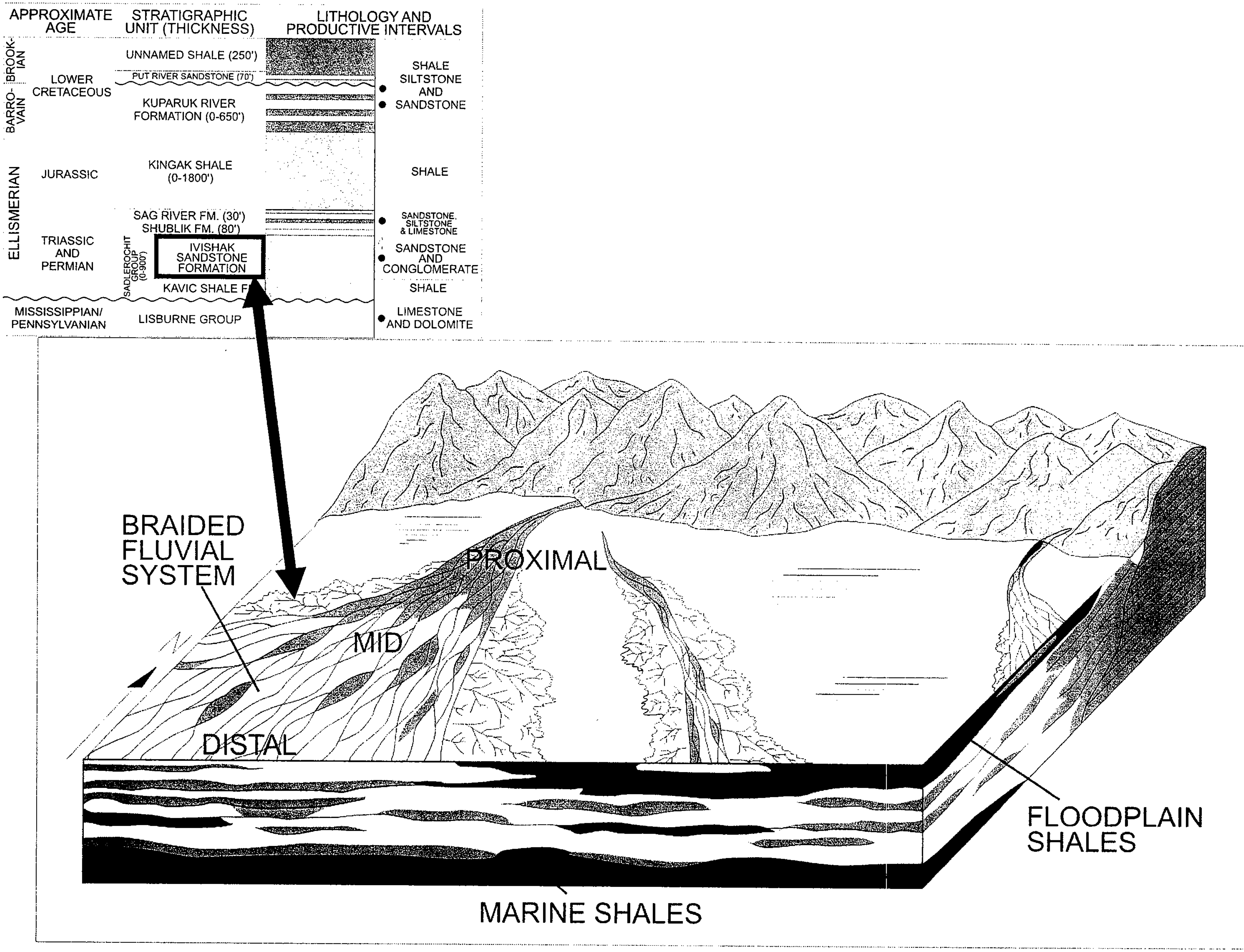


PRODUCTION START-UP
WATERFLOOD START-UP
OIL
GOR X 10
OIL (STBPD), GOR (SCF/STB) X 10
OIL (m3/D)
% WATER
YEAR
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
15000
10000
5000
40
20
30
10
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987



PRUDHOE BAY UNIT
SEA ELEVATION IN FEET
Faults
: Lower Cretaceous Unconformity
0 MILES 5
0 KM. 8
N
WESTERN OPERATING AREA
(BP EXPLORATION-ALASKA)
EASTERN OPERATING
AREA (ARCO)
Base
LCU
Truncation
TOP
LCU
Truncation
S
N
BROOKS
RANGE
COLVILLE TROUGH
BARROW ARCH
PRUDHOE BAY
FIELD
L. CRET.
SL
TERTIARY
U. CRET.
L. CRET.
LOWER CRETACEOUS
JUR.
JUR.
MISS.
PERM. TRIAS.
PRE-MISS.
TRIAS. TO MISS.
PRE-MISS.
30,000' 9,000m
20,000' 6,000m
10,000' 3,000m
(NO HORIZONTAL SCALE)


APPROXIMATE AGE
STRATIGRAPHIC UNIT (THICKNESS)
LITHOLOGY AND PRODUCTIVE INTERVALS
BROOK-IAN
BARRO-VAIN
ELLISMERIAN
LOWER CRETACEOUS
JURASSIC
TRIASSIC AND PERMIAN
MISSISSIPPIAN/ PENNSYLVANIAN
UNNAMED SHALE (250')
PUT RIVER SANDSTONE (70')
KUPARUK RIVER FORMATION (0-650')
KINGAK SHALE (0-1800')
SAG RIVER FM. (30')
SHUBLIK FM. (80')
SADLEROCHIT GROUP (0-900')
IVISHAK SANDSTONE FORMATION
KAVIC SHALE FM.
LISBURNE GROUP
SHALE SILTSTONE AND SANDSTONE
SHALE
SANDSTONE, SILTSTONE & LIMESTONE
SANDSTONE AND CONGLOMERATE
SHALE
LIMESTONE AND DOLOMITE
S
N
BROOKS RANGE
COLVILLE TROUGH
BARROW ARCH PRUDHOE BAY FIELD
L. CRET.
SL
TERTIARY
L. CRET.
U. CRET.
LOWER CRETACEOUS
JUR.
JUR.
MISS.
PERM. TRIAS.
PRE-MISS.
TRIAS. TO MISS.
PRE-MISS.
30,000' 9,000m
20,000' 6,000m
10,000' 3,000m
(NO HORIZONTAL SCALE)


APPROXIMATE AGE
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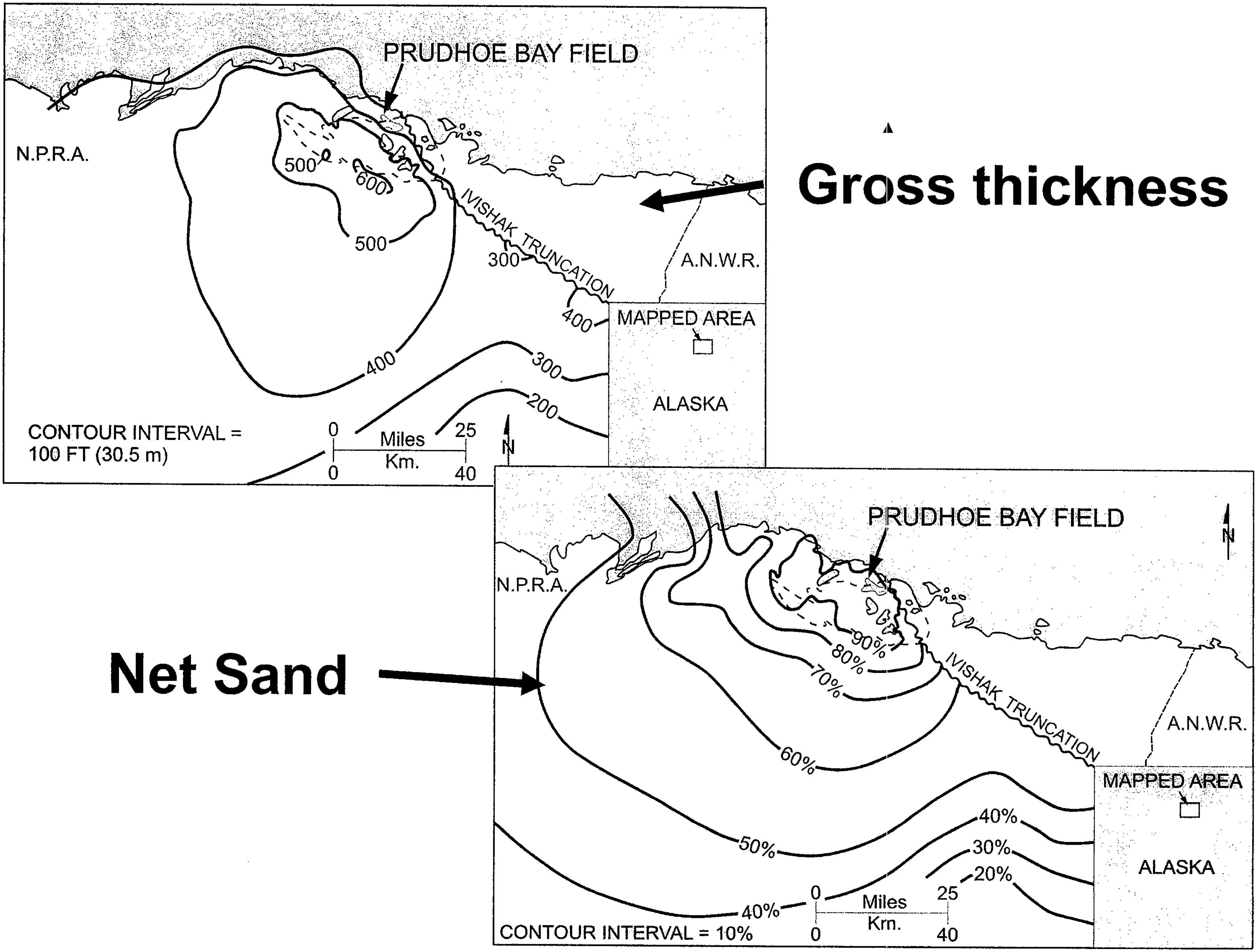
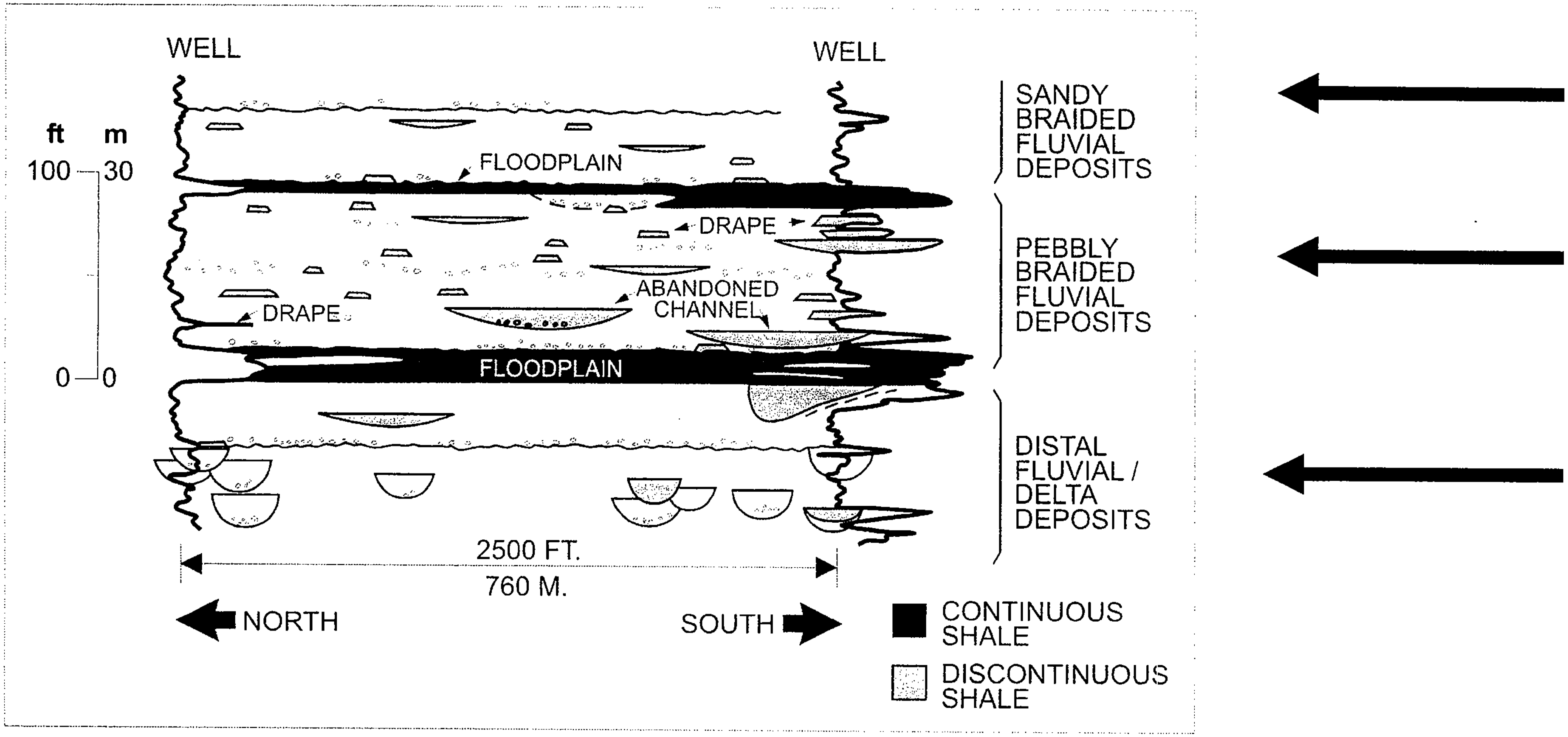
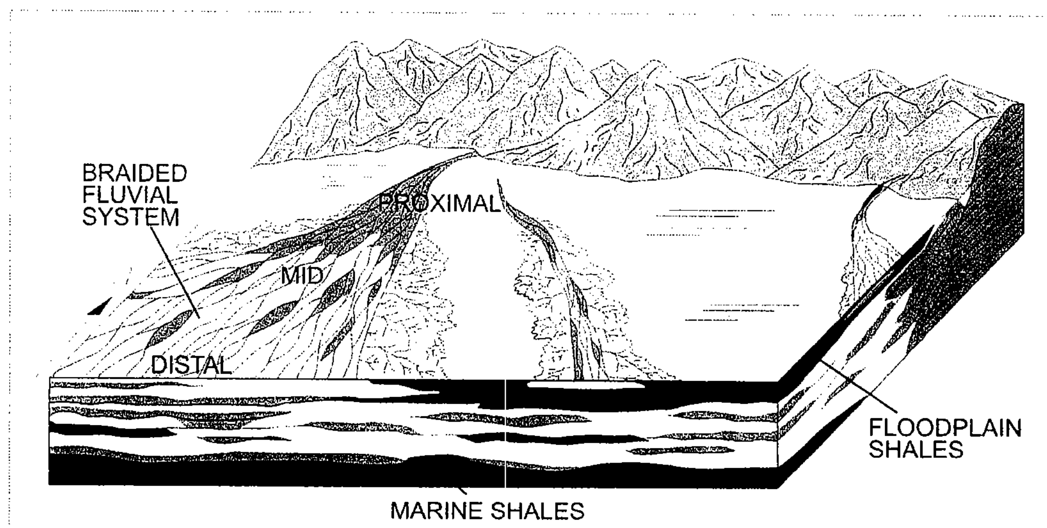
KINGAK SHALE (0-1800')
SHALE
SAG RIVER FM. (30')
SHUBLIK FM. (80')
SANDSTONE, SILTSTONE & LIMESTONE
TRIASSIC AND PERMIAN
SADLEROCHIT GROUP (0-900')
IVISHAK SANDSTONE FORMATION
SANDSTONE AND CONGLOMERATE
KAVIC SHALE F
SHALE
MISSISSIPPIAN/ PENNSYLVANIAN
LISBURNE GROUP
LIMESTONE AND DOLOMITE
BRAIDED FLUVIAL SYSTEM
PROXIMAL
MID
DISTAL
N
FLOODPLAIN SHALES
MARINE SHALES

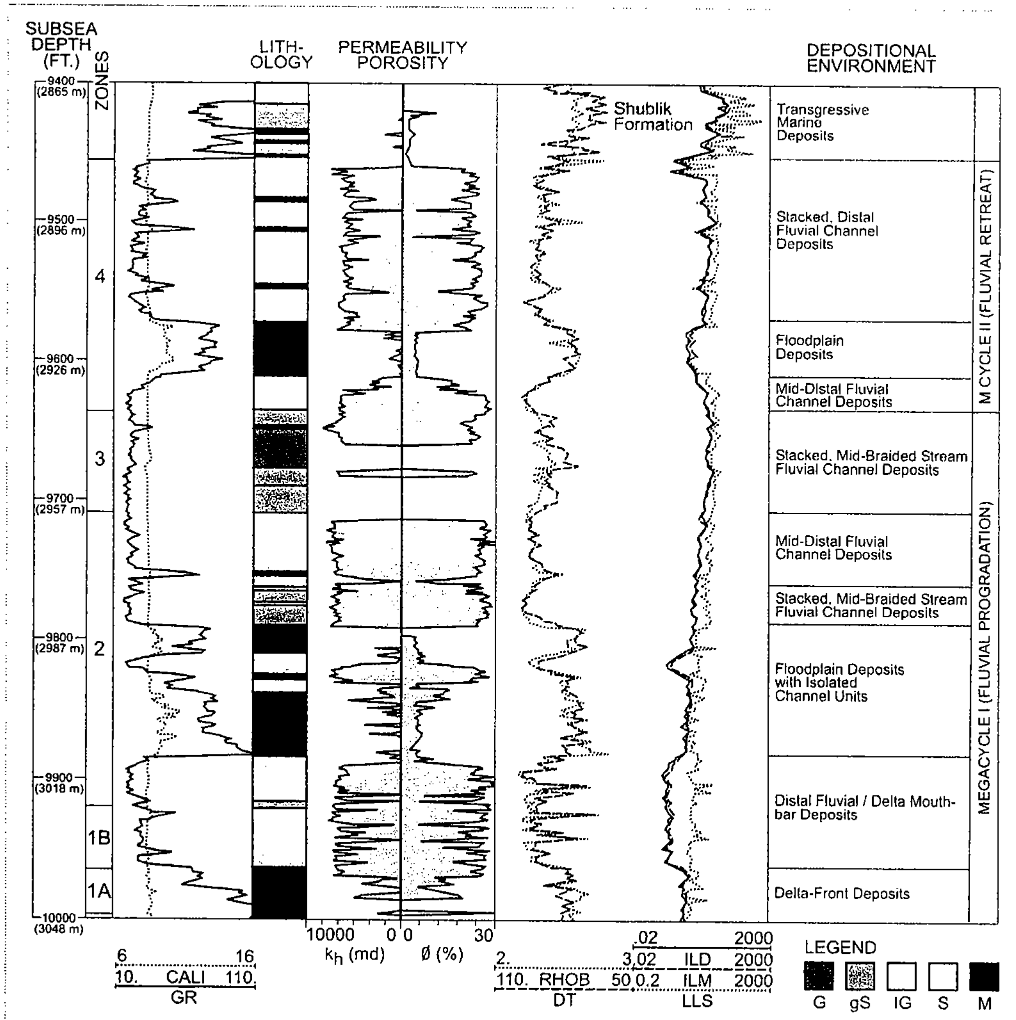
Gross thickness

Net Sand

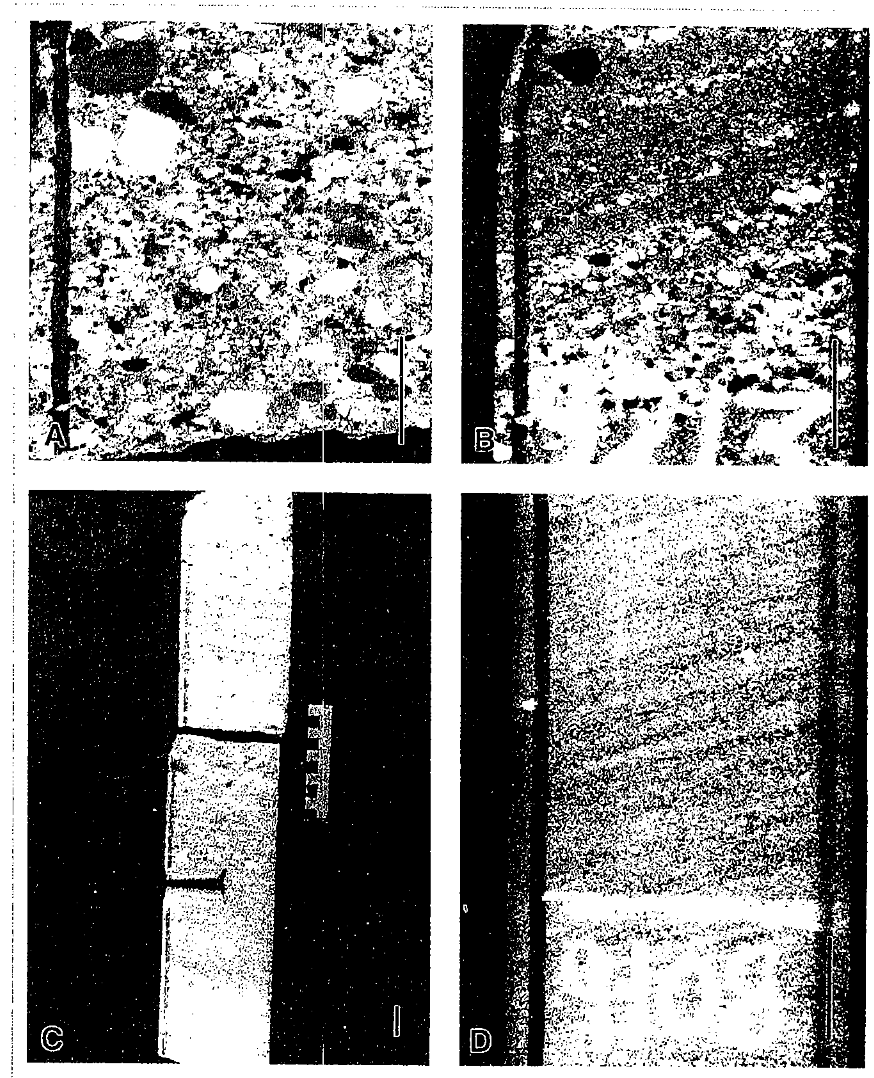



WELL
WELL
ft m
100 30
0 0
FLOODPLAIN
DRAPE
DRAPE
ABANDONED CHANNEL
FLOODPLAIN
SANDY BRAIDED FLUVIAL DEPOSITS
PEBBLY BRAIDED FLUVIAL DEPOSITS
DISTAL FLUVIAL / DELTA DEPOSITS
2500 FT.
760 M.
NORTH
SOUTH
CONTINUOUS SHALE
DISCONTINUOUS SHALE

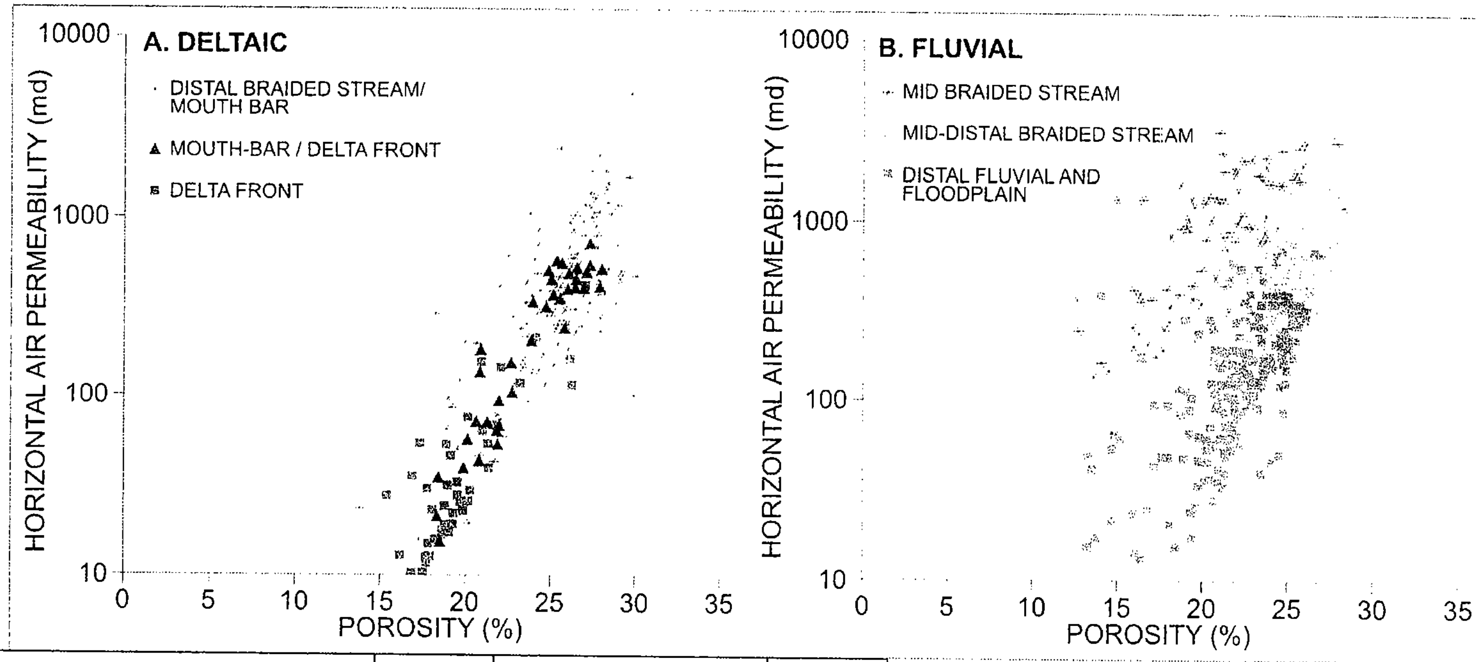

BRAIDED FLUVIAL SYSTEM
PROXIMAL
MID
DISTAL
FLOODPLAIN SHALES
MARINE SHALES

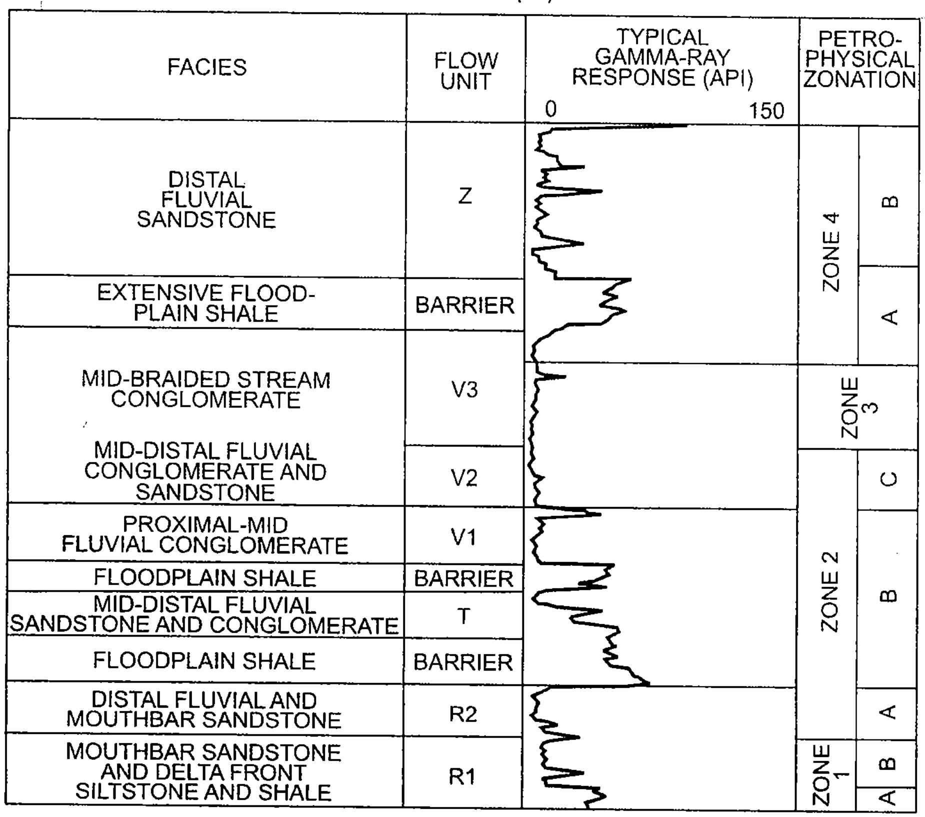


SUBSEA DEPTH (FT.)
ZONES
LITH-OLOGY
PERMEABILITY POROSITY
DEPOSITIONAL ENVIRONMENT
9400 (2865 m)
9500 (2896 m)
9600 (2926 m)
9700 (2957 m)
9800 (2987 m)
9900 (3018 m)
10000 (3048 m)
4
3
2
1B
1A
Shublik Formation
Transgressive Marine Deposits
Stacked, Distal Fluvial Channel Deposits
Floodplain Deposits
Mid-Distal Fluvial Channel Deposits
Stacked, Mid-Braided Stream Fluvial Channel Deposits
Mid-Distal Fluvial Channel Deposits
Stacked, Mid-Braided Stream Fluvial Channel Deposits
Floodplain Deposits with Isolated Channel Units
Distal Fluvial / Delta Mouth-bar Deposits
Delta-Front Deposits
M CYCLE II (FLUVIAL RETREAT)
MEGACYCLE I (FLUVIAL PROGRADATION)
6 16
10. CALI 110.
GR
10000 0 0 30
k_h (md) Ø (%)
2. 3
110. RHOB 50
DT
.02 2000
.02 ILD 2000
0.2 ILM 2000
LLS
LEGEND
G gS IG S M



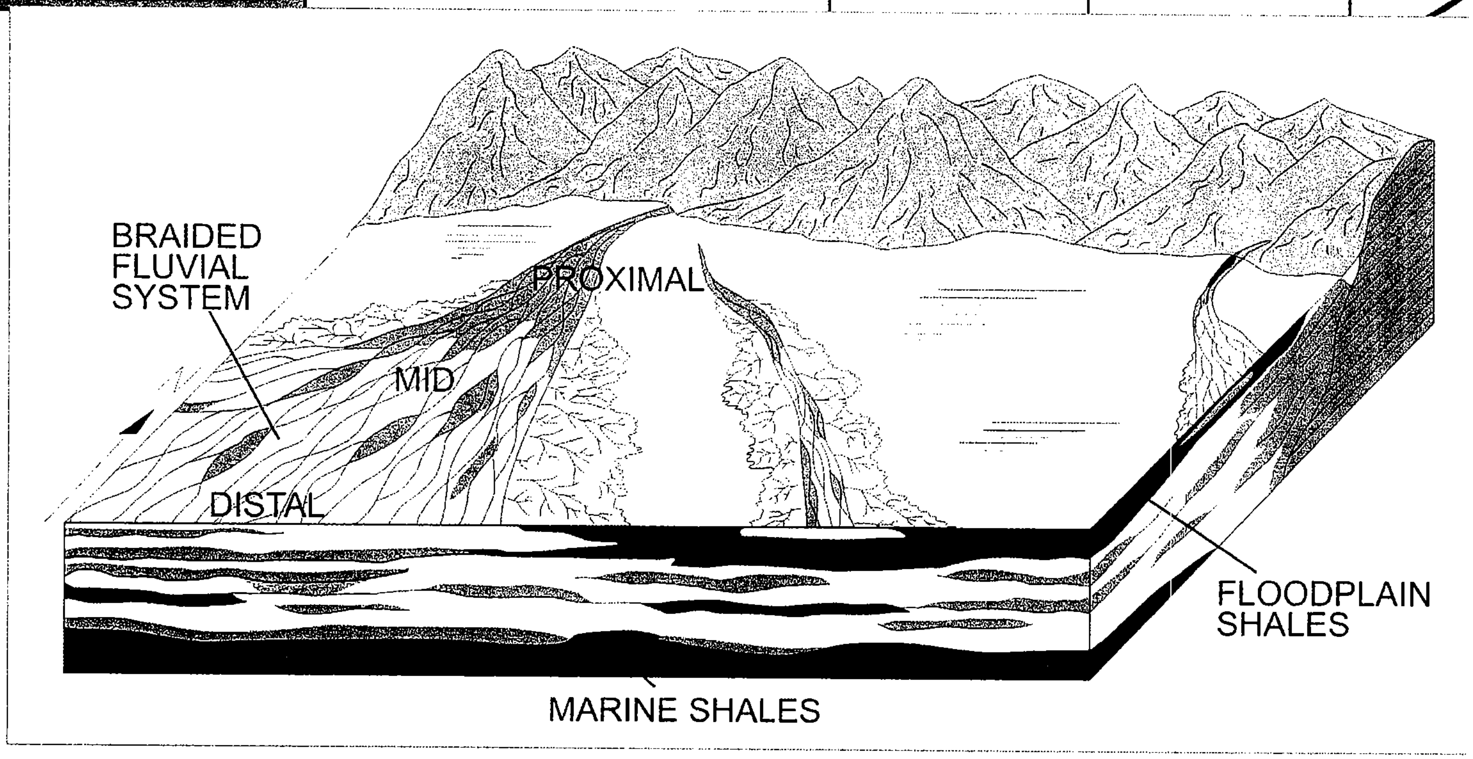
A
B
C
D

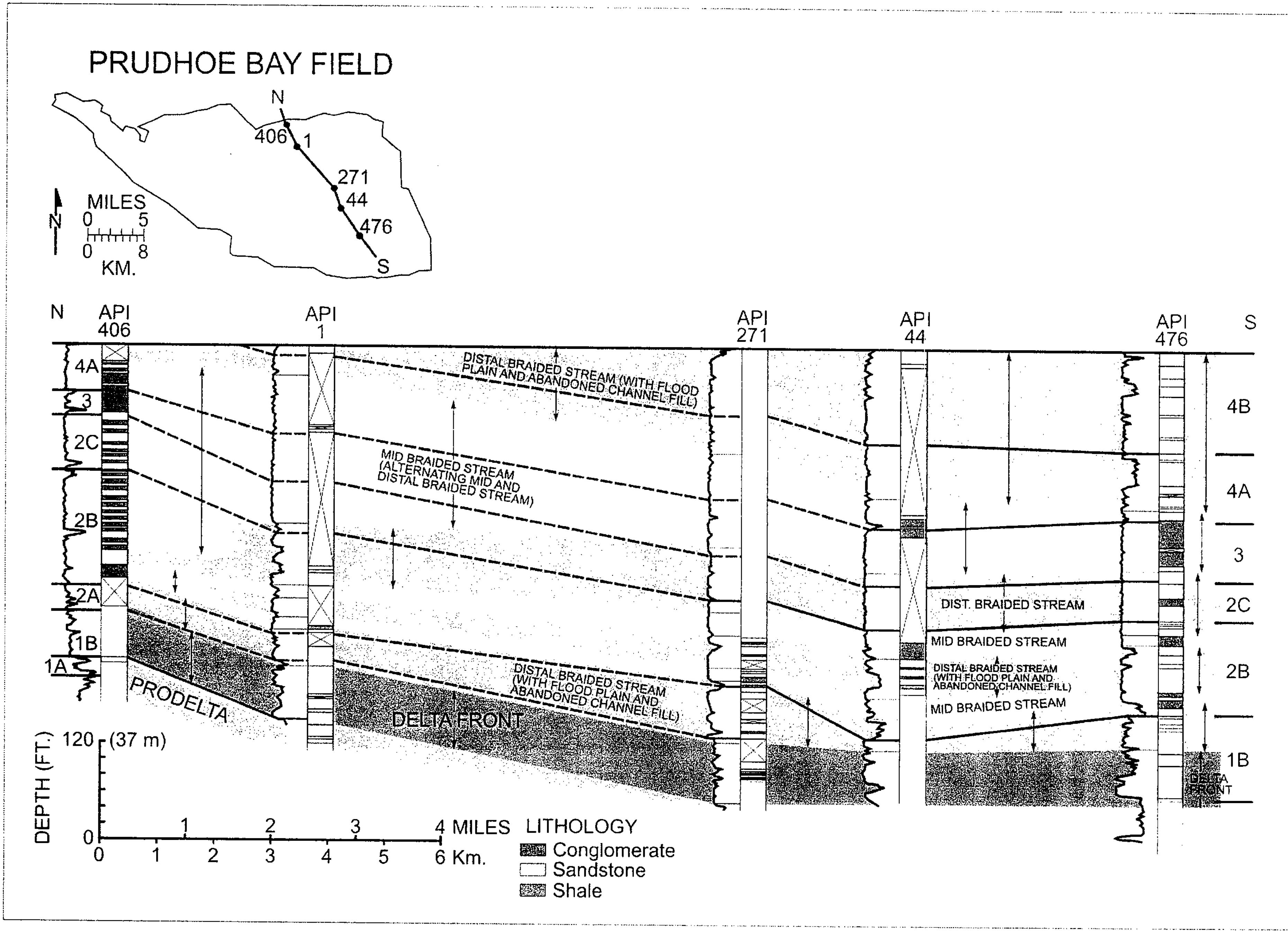


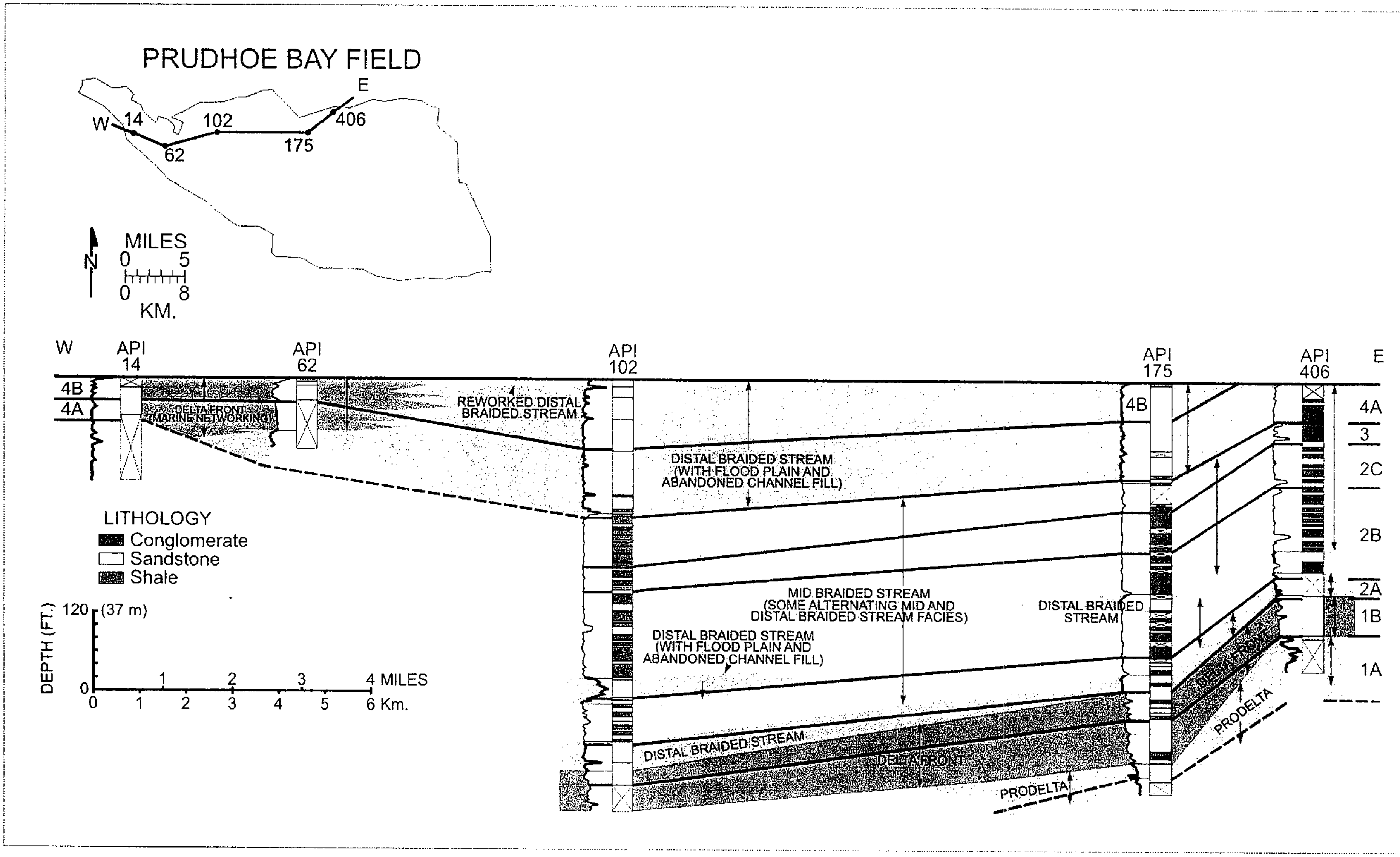


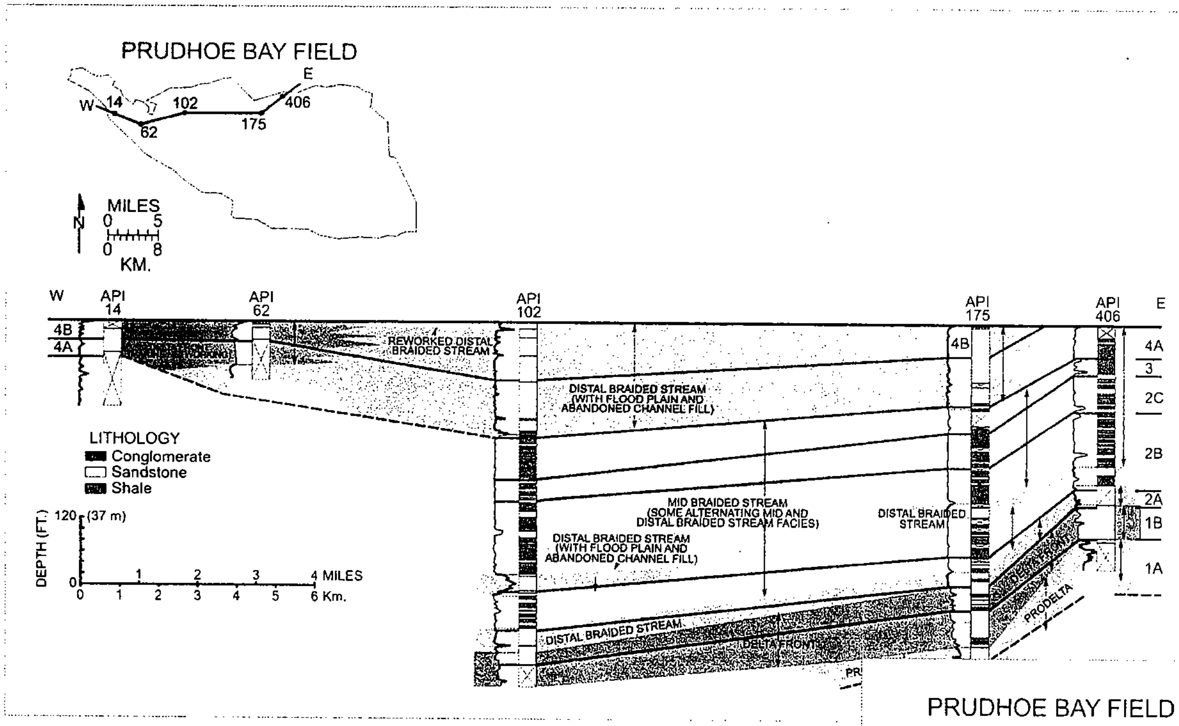
Porosity and permeability vary with grain size and depositional environment

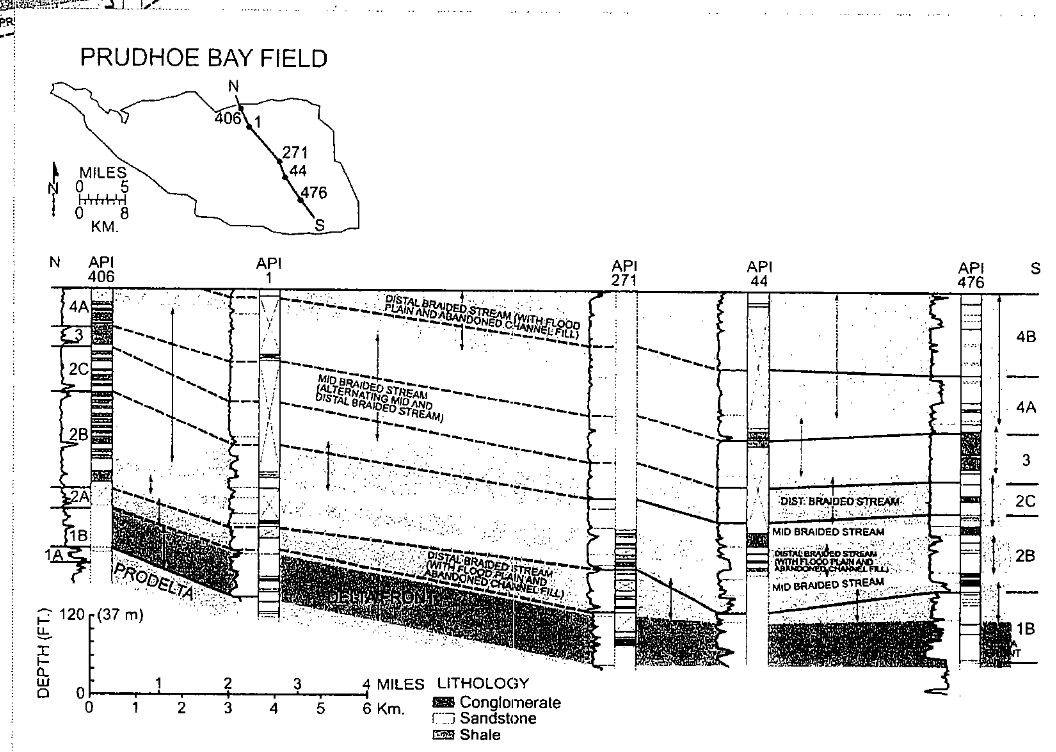
ENVIRONMENT TYPE	PREDOMINANT LITHOLOGY	GRAIN SIZE TREND	SORTING TREND	PERMEABILITY TREND LOW HIGH
MID-BRAIDED STREAM	SANDY CONGLOMERATE CONGLOMERATIC SS COARSE-GRAINED SS	DECREASE	DECREASE	
DISTAL BRAIDED STREAM	MEDIUM-GRAINED SANDSTONE			
DELTA FRONT	FINE- TO VERY FINE-GRAINED SS			

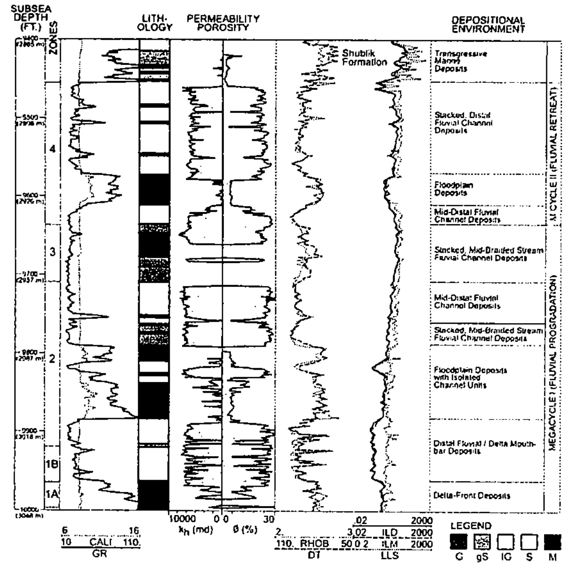



PRUDHOE BAY FIELD
N
406
1
271
44
476
S
MILES
0 5
0 8
KM.
N
API 406
API 1
API 271
API 44
API 476
S
4A
3
2C
2B
2A
1B
1A
4B
4A
3
2C
2B
1B
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
MID BRAIDED STREAM (ALTERNATING MID AND DISTAL BRAIDED STREAM)
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
DIST. BRAIDED STREAM
MID BRAIDED STREAM
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
MID BRAIDED STREAM
PRODELTA
DELTA FRONT
DELTA FRONT
DEPTH (FT.)
120 (37 m)
0
1 2 3 4 MILES
0 1 2 3 4 5 6 Km.
LITHOLOGY
Conglomerate
Sandstone
Shale

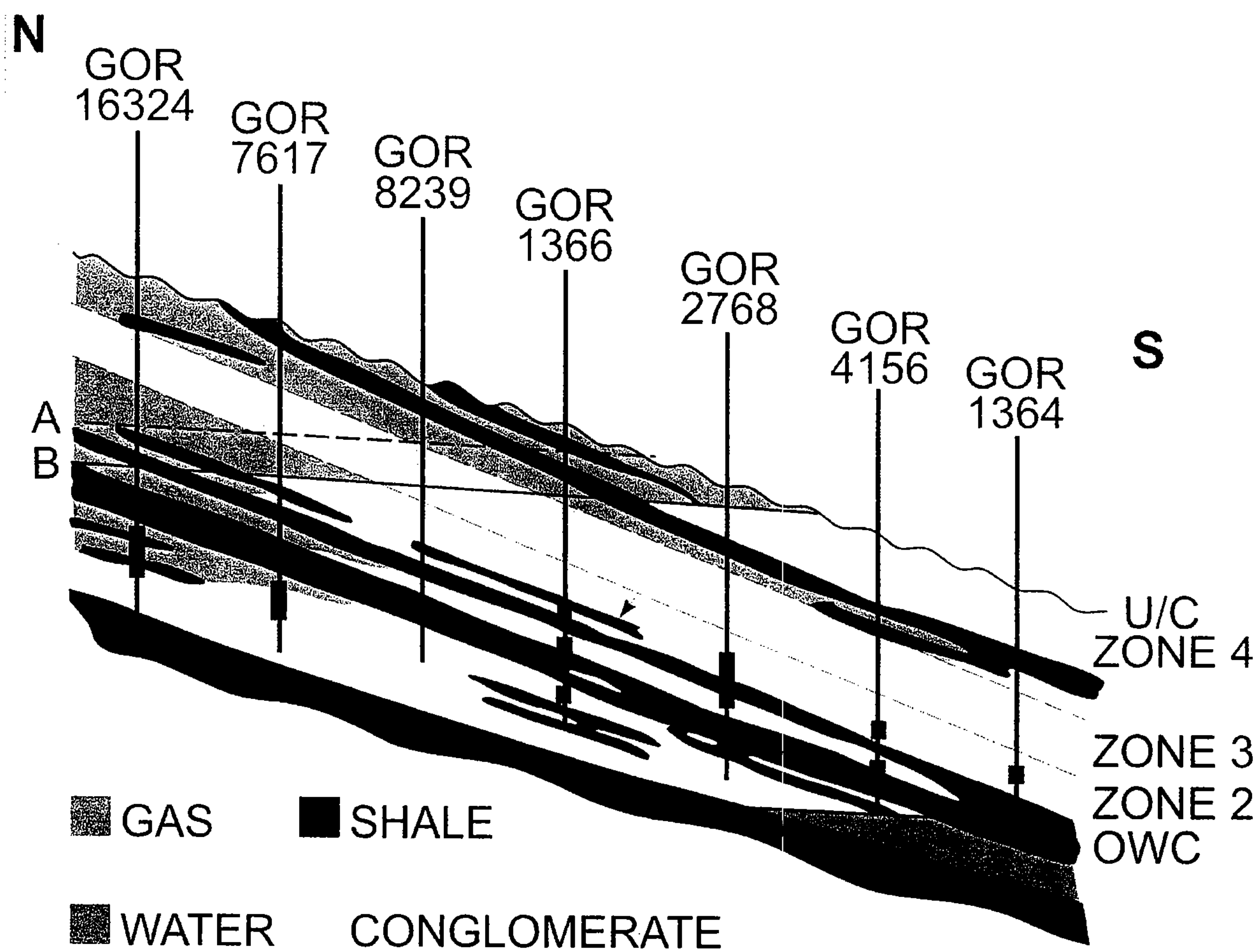

PRUDHOE BAY FIELD
W
E
14
62
102
175
406
MILES
0 5
0 8
KM.
N
API 14
API 62
API 102
API 175
API 406
4B
4A
3
2C
2B
2A
1B
1A
DELTA FRONT (MARINE NETWORKING)
REWORKED DISTAL BRAIDED STREAM
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
MID BRAIDED STREAM (SOME ALTERNATING MID AND DISTAL BRAIDED STREAM FACIES)
DISTAL BRAIDED STREAM
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
DISTAL BRAIDED STREAM
DELTA FRONT
PRODELTA
LITHOLOGY
Conglomerate
Sandstone
Shale
DEPTH (FT.)
120 (37 m)
0
1 2 3 4 MILES
0 1 2 3 4 5 6 Km.


PRUDHOE BAY FIELD
W
E
14
62
102
175
406
N
MILES
0 5
0 8
KM.
API 14
API 62
API 102
API 175
API 406
4B
4A
REWORKED DISTAL BRAIDED STREAM
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
MID BRAIDED STREAM (SOME ALTERNATING MID AND DISTAL BRAIDED STREAM FACIES)
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
DISTAL BRAIDED STREAM
DISTAL BRAIDED STREAM
DELTA FRONT
PRODELTA
4A
3
2C
2B
2A
1B
1A
LITHOLOGY
Conglomerate
Sandstone
Shale
DEPTH (FT.)
120 (37 m)
0
1 2 3 4 MILES
0 1 2 3 4 5 6 Km.

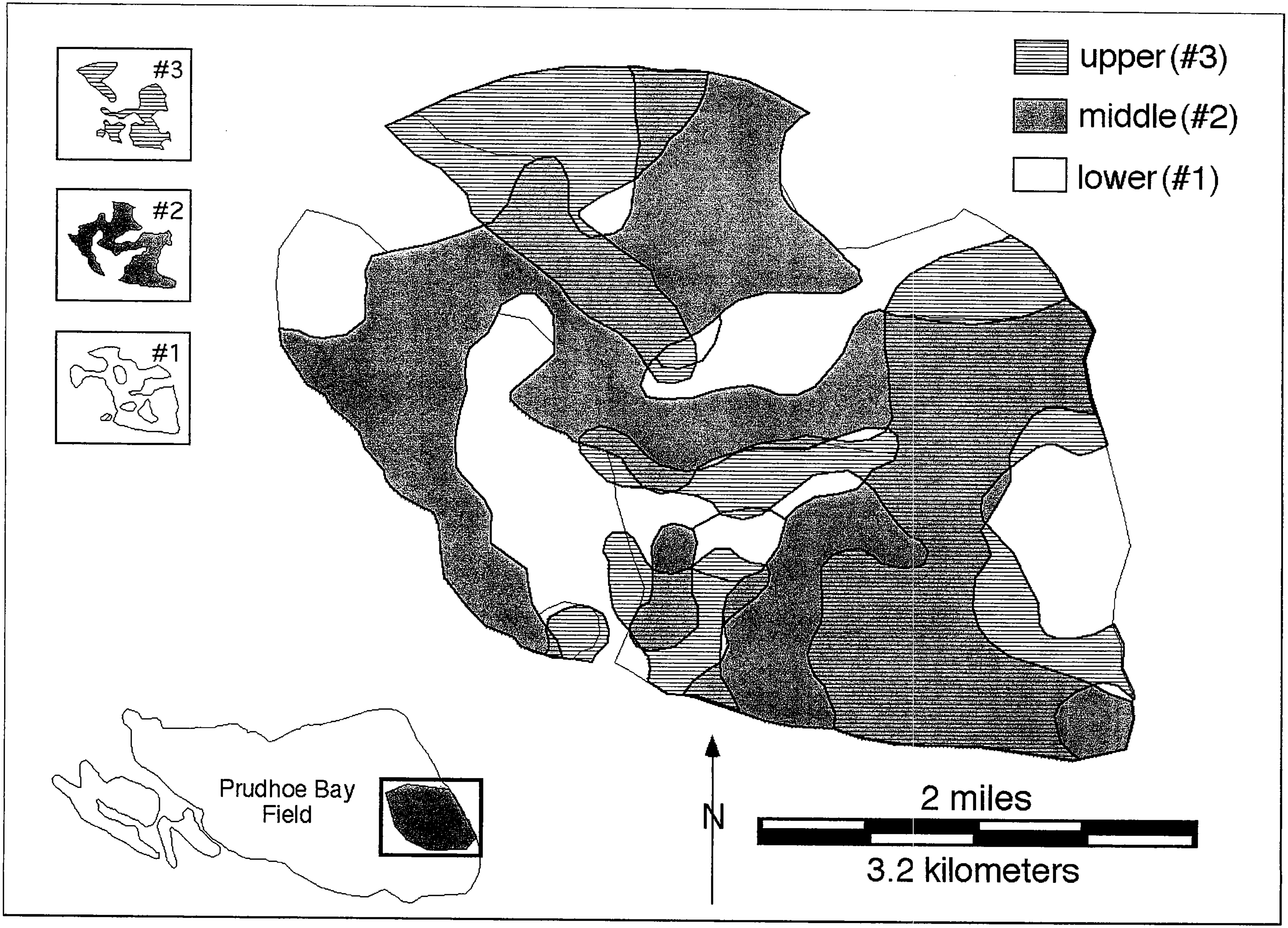

PRUDHOE BAY FIELD
N
406
1
271
44
476
S
MILES
0 5
0 8
KM.
API 406
API 1
API 271
API 44
API 476
4A
3
2C
2B
2A
1B
1A
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
MID BRAIDED STREAM (ALTERNATING MID AND DISTAL BRAIDED STREAM)
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
PRODELTA
DELTA FRONT
DIST. BRAIDED STREAM
MID BRAIDED STREAM
DISTAL BRAIDED STREAM (WITH FLOOD PLAIN AND ABANDONED CHANNEL FILL)
MID BRAIDED STREAM
4B
4A
3
2C
2B
1B
DEPTH (FT.)
120 (37 m)
0
1 2 3 4 MILES
0 1 2 3 4 5 6 Km.
LITHOLOGY
Conglomerate
Sandstone
Shale



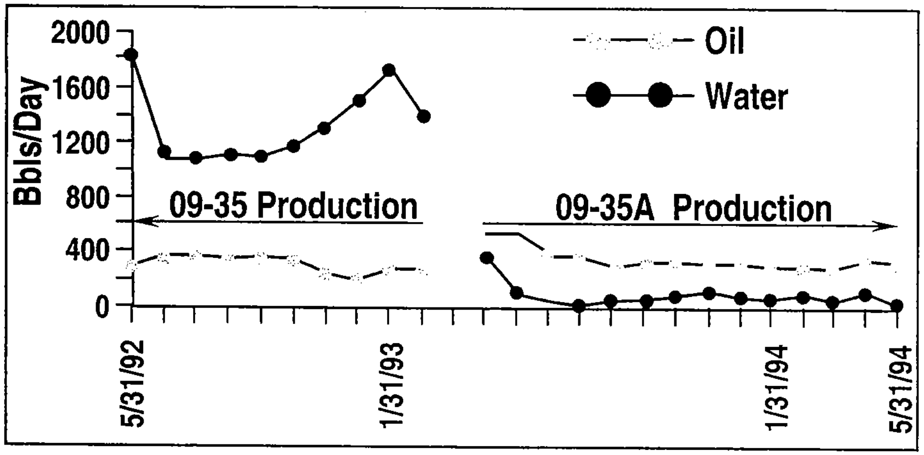
SUBSEA DEPTH (FT.)
ZONES
LITH-OLOGY
PERMEABILITY POROSITY
DEPOSITIONAL ENVIRONMENT
Shublik Formation
Transgressive Marine Deposits
Stacked, Distal Fluvial Channel Deposits
Floodplain Deposits
Mid-Distal Fluvial Channel Deposits
Stacked, Mid-Braided Stream Fluvial Channel Deposits
Mid-Distal Fluvial Channel Deposits
Stacked, Mid-Braided Stream Fluvial Channel Deposits
Floodplain Deposits with Isolated Channel Units
Distal Fluvial / Delta Mouth-bar Deposits
Delta-Front Deposits
MEGACYCLE I (FLUVIAL PROGRADATION)
4
3
2
1B
1A
GR
CALI
RHOB
DT
ILD
ILM
LLS
LEGEND
C
gS
IC
S
M

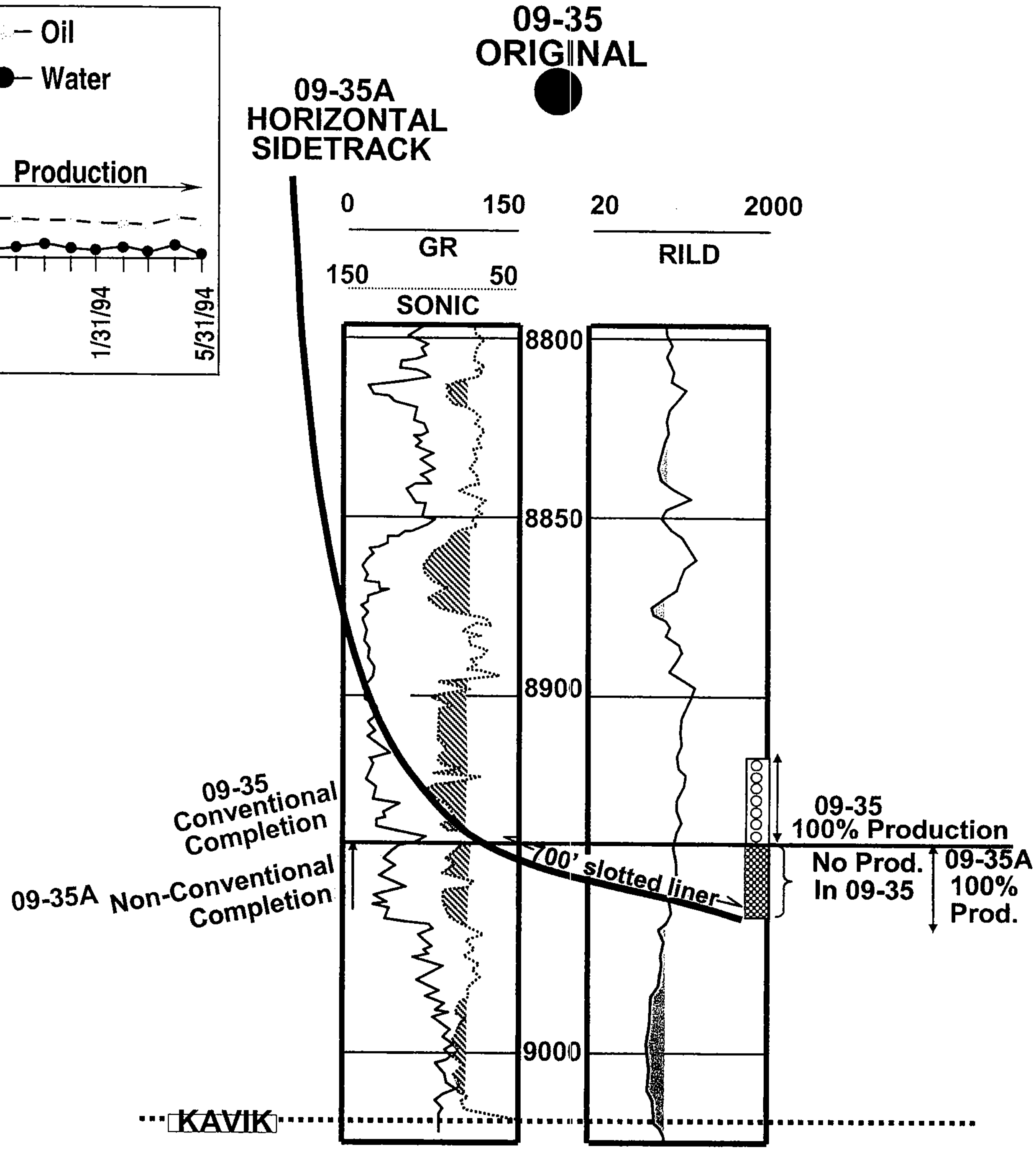


N
S
GOR 16324
GOR 7617
GOR 8239
GOR 1366
GOR 2768
GOR 4156
GOR 1364
A
B
U/C
ZONE 4
ZONE 3
ZONE 2
OWC
GAS
SHALE
WATER
CONGLOMERATE

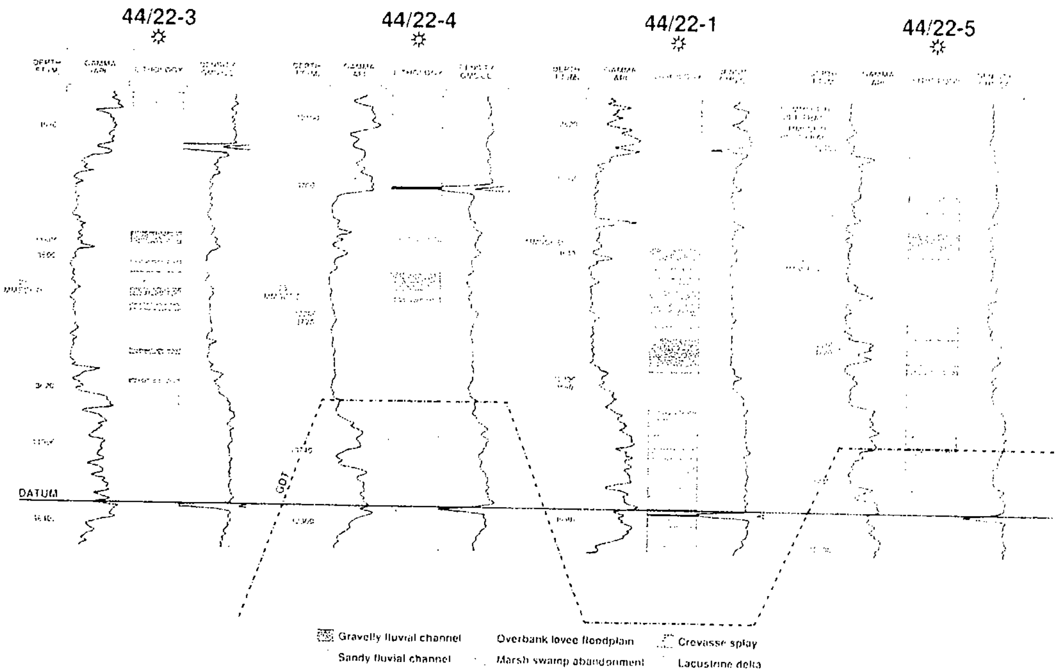


#3
#2
#1
upper (#3)
middle (#2)
lower (#1)
Prudhoe Bay Field
N
2 miles
3.2 kilometers


2000
1600
1200
800
400
0
Bbls/Day
Oil
Water
09-35 Production
09-35A Production
5/31/92
1/31/93
1/31/94
5/31/94

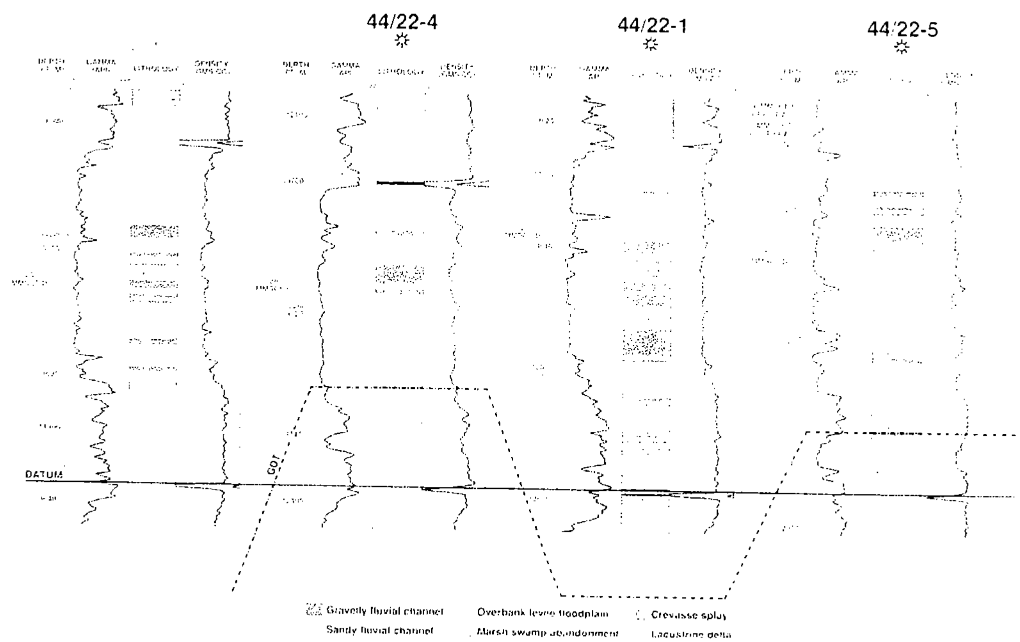

09-35
ORIGINAL
09-35A
HORIZONTAL
SIDETRACK
0
150
GR
20
2000
RILD
150
50
SONIC
8800
8850
8900
9000
09-35
Conventional
Completion
09-35A Non-Conventional
Completion
700' slotted liner
09-35
100% Production
No Prod.
In 09-35
09-35A
100%
Prod.
KAVIK

MURDOCH FIELD

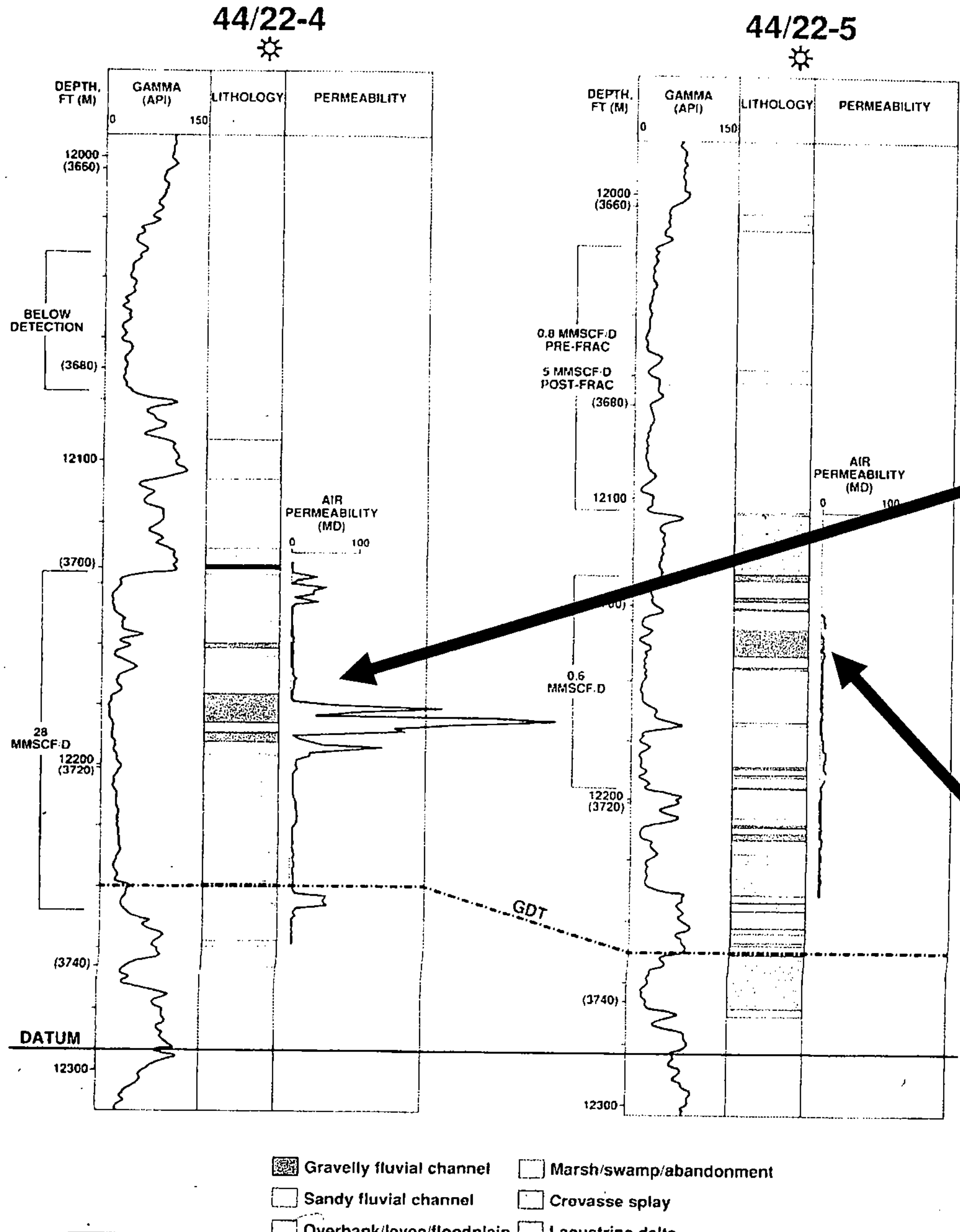


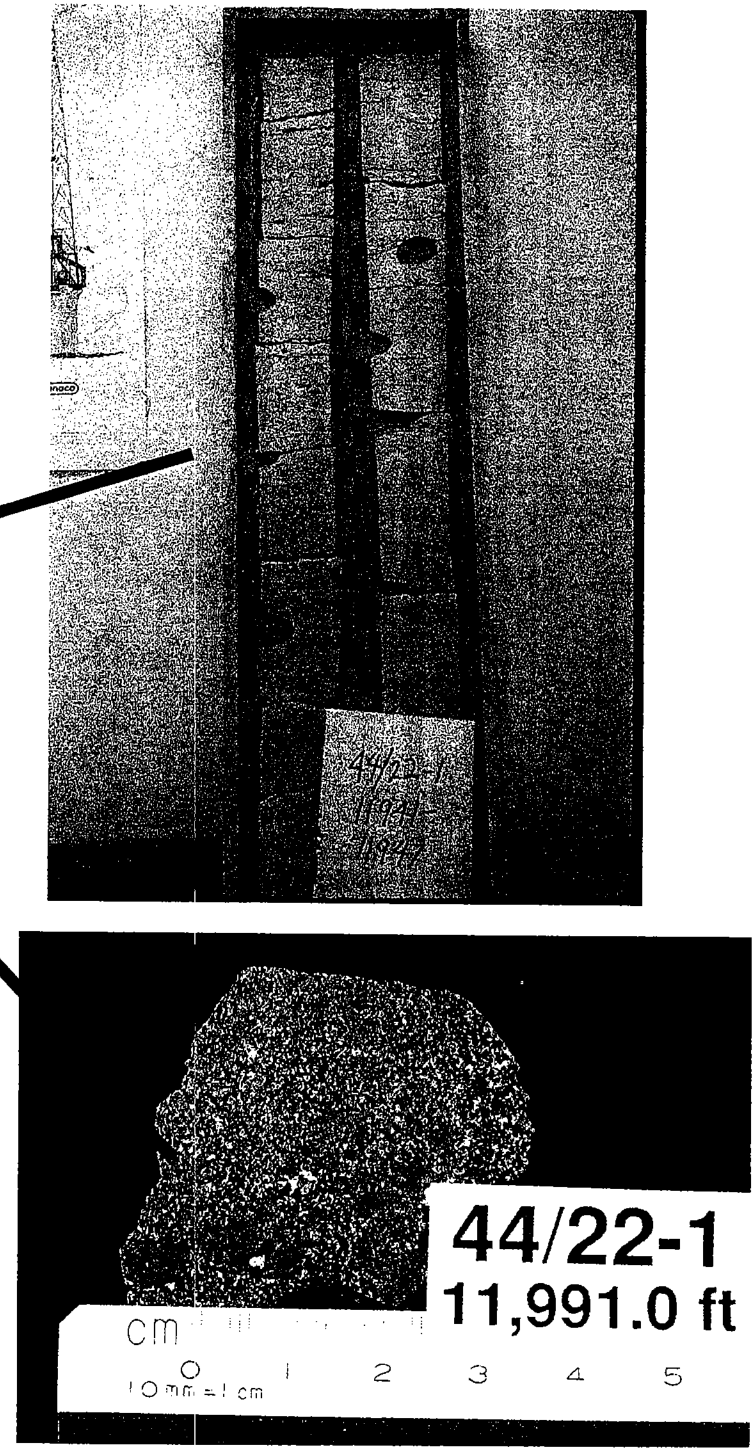
North Sea Example

MURDOCH FIELD



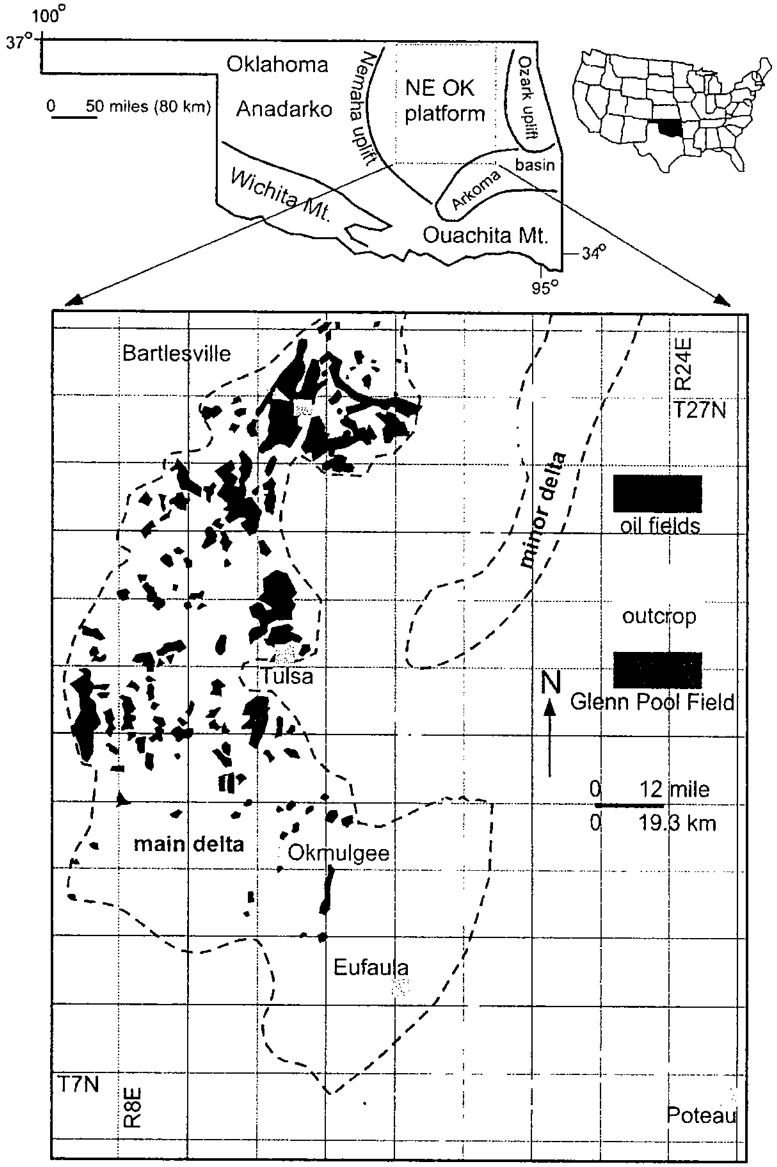
Conglomerate is reservoir. Some conglomerates are good reservoir, but others are not!!! Why???



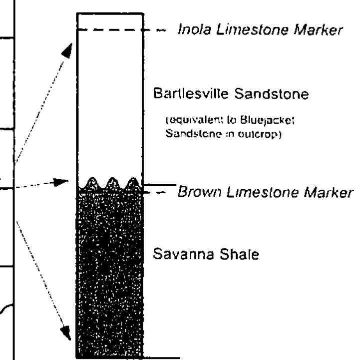


North Sea Example

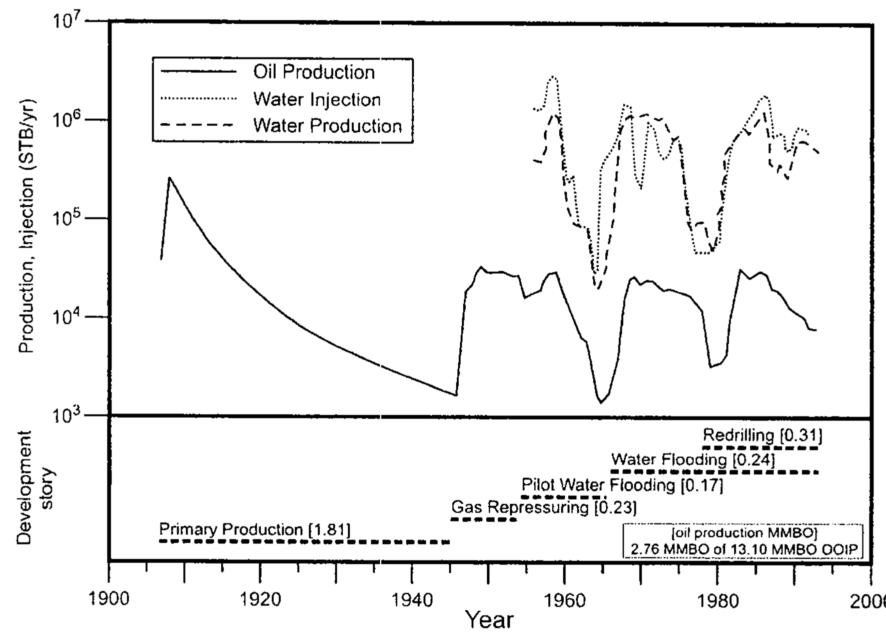
Location of Glenn Pool Field



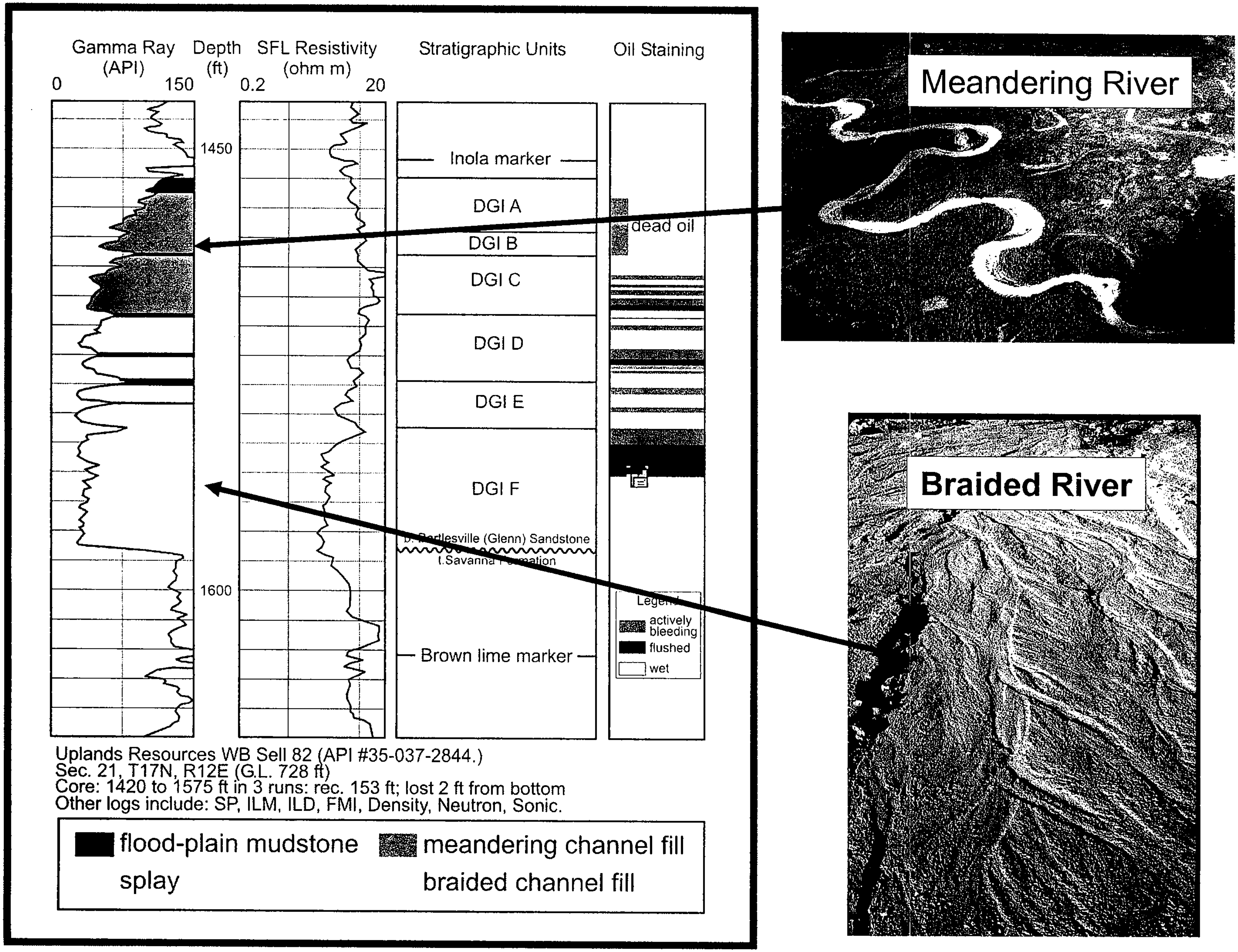
System	Series	Group		Formation and Member	
Pennsylvanian	Missourian	Skiatook		Coffeyville	
	Desmoinesian	Marmaton		Wewoka	
		Cabaniss	Cherokee	Senora	Prue Sandstone Verdigris Limestone Skinner Sandstone Pink Limestone
		Krebs		Boggy	Red Fork Sandstone Inola Limestone Bartlesville Sandstone
				Savanna Shale	Brown Limestone
				McAlester Shale	
				Hartshorne Sandstone	
		Atokan		Atoka	Dutcher
Mississippian	Chesterian	Mississippian Limestone		Mississippian Limestone	
	Meramecian				
	Osagean				
	Kinderhookian				

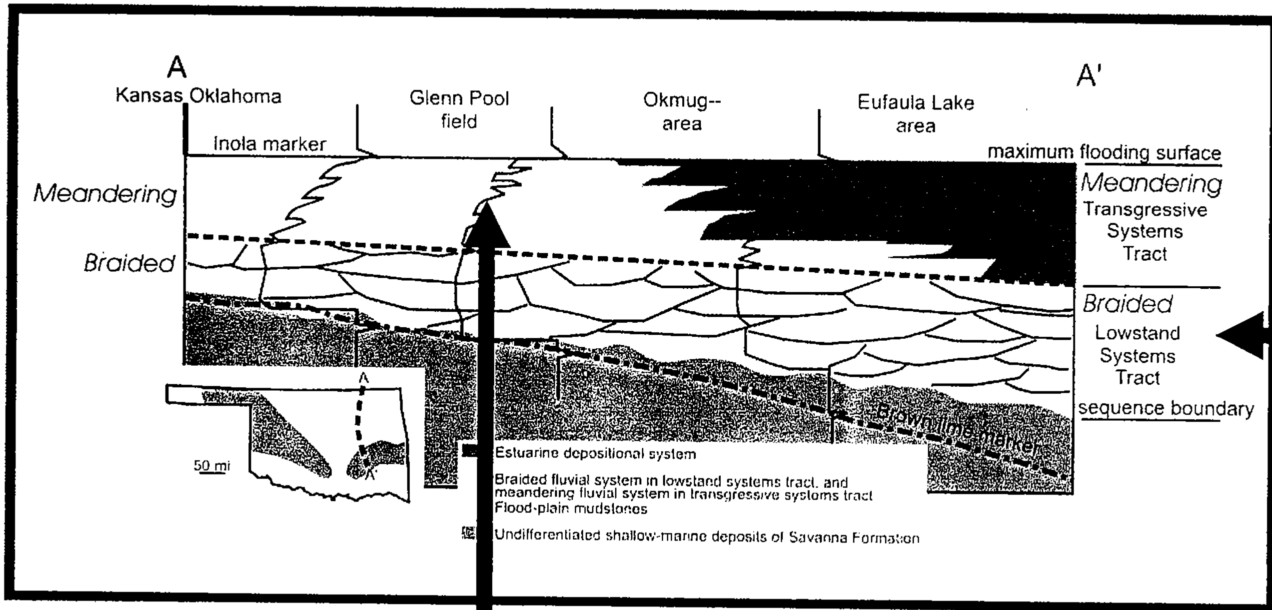


Bartlesville Sandstone
is Pennsylvanian in age



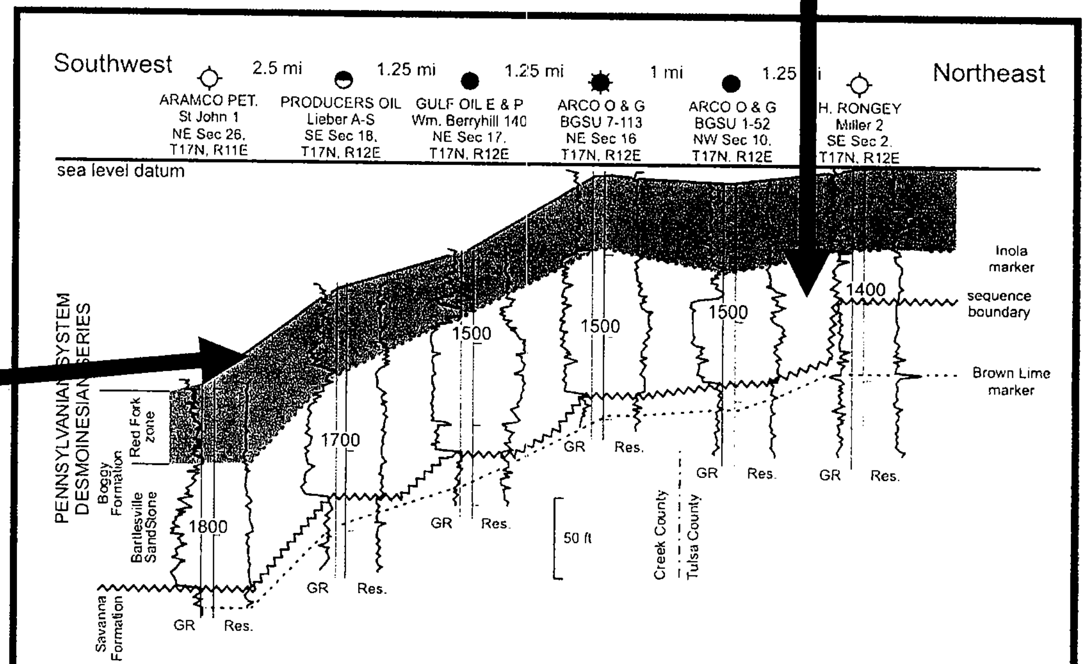
Production History of the Self Unit Glenn Pool Field, Oklahoma
Note changes in prodution as new Recovery techniques are begun in field


Gamma Ray (API)
0
150
Depth (ft)
1450
1600
SFL Resistivity (ohm m)
0.2
20
Stratigraphic Units
Inola marker
DGI A
DGI B
DGI C
DGI D
DGI E
DGI F
Bartlesville (Glenn) Sandstone
Savanna Formation
Brown lime marker
Oil Staining
dead oil
Legend
actively bleeding
flushed
wet
Uplands Resources WB Sell 82 (API #35-037-2844.)
Sec. 21, T17N, R12E (G.L. 728 ft)
Core: 1420 to 1575 ft in 3 runs: rec. 153 ft; lost 2 ft from bottom
Other logs include: SP, ILM, ILD, FMI, Density, Neutron, Sonic.
flood-plain mudstone
splay
meandering channel fill
braided channel fill
Meandering River
Braided River

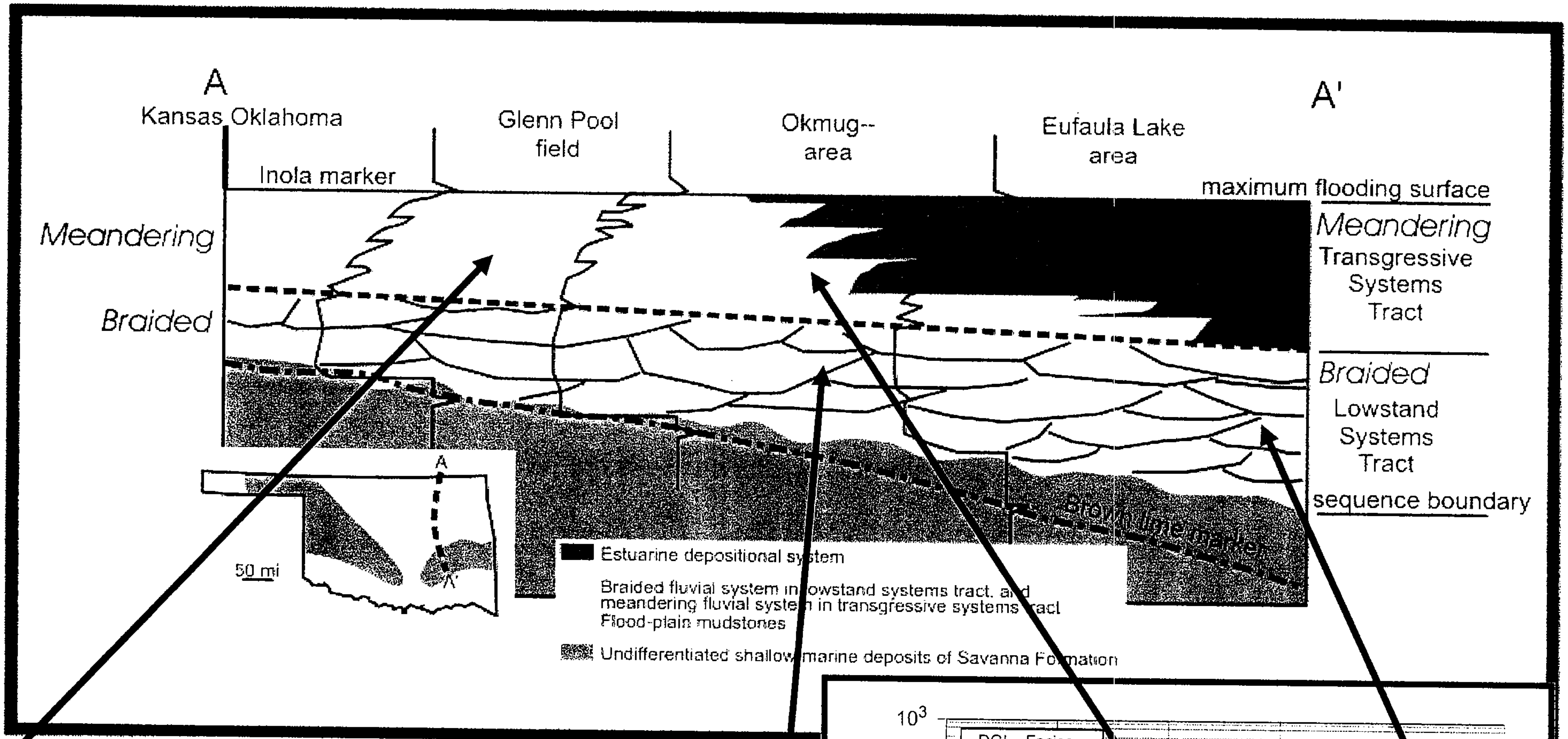


Braided River Sandstone

Meandering River Sandstone

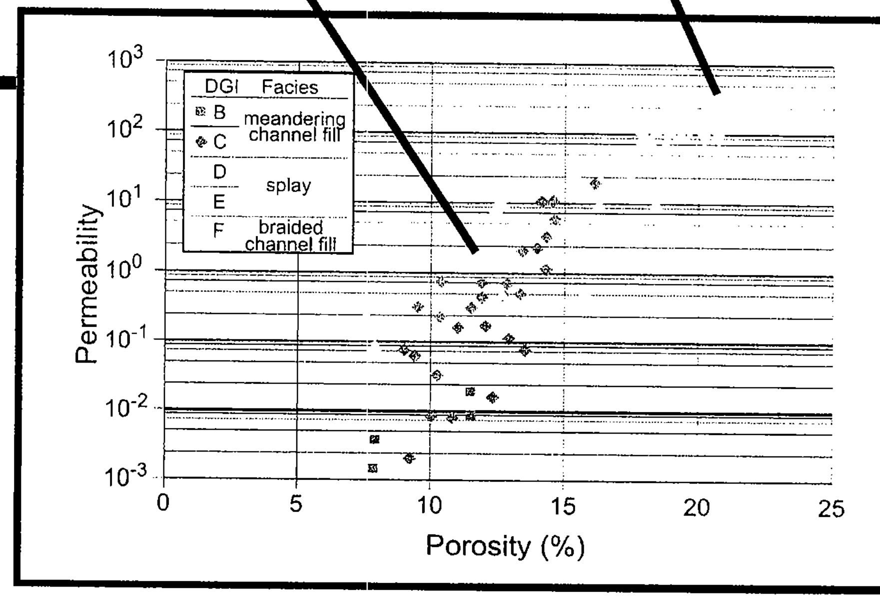


Structural cross section. Note that 'updip' is to the northeast.
Oil will migrate in the updip direction, and be more abundant there.



Meandering River sandstones are laterally discontinuous with interlayered mudstone, and highly compartmented

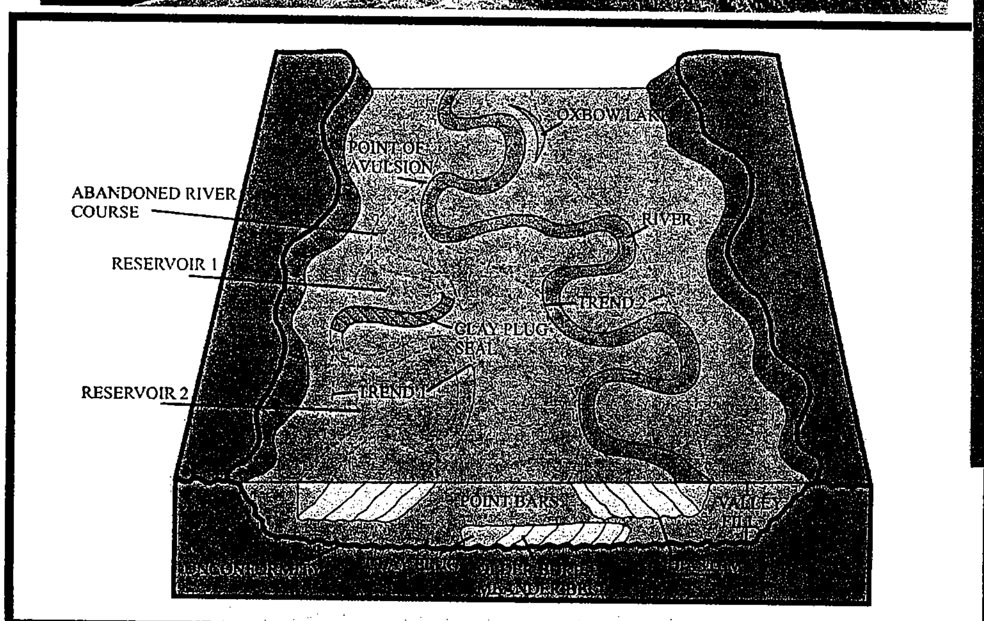
Braided River sandstones are laterally continuous without much mudstone, and are not highly compartmented

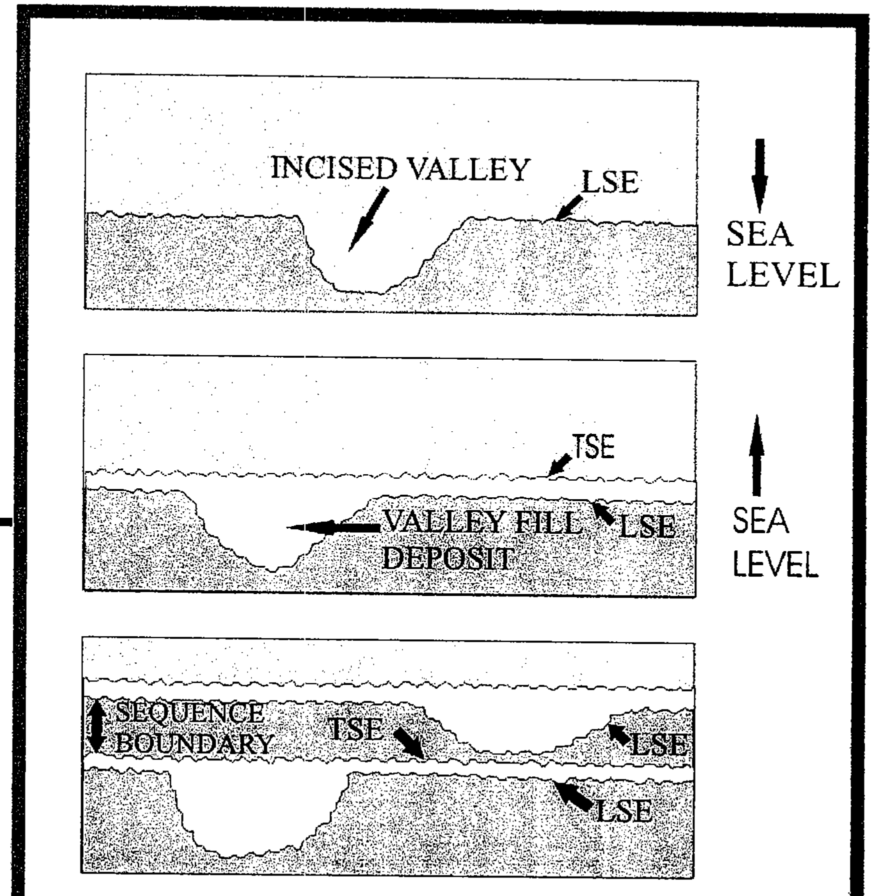


INCISED VALLEY FILL RESERVOIRS

- VALLEY IS INCISED DURING FALL IN SEA (BASE) LEVEL
- VALLEY IS FILLED DURING TURNAROUND AND RISE IN SEA (BASE) LEVEL
- IDEAL VERTICAL SEQUENCE:
  - -BASAL FLUVIAL LAG
  - -ESTUARINE STRATA
  - -OPEN MARINE STRATA
- LATERAL SEQUENCE: ESTUARINE TO FLUVIAL IN THE PALEO-LANDWARD DIRECTION
- ENCASED IN MARINE SHALE, SO GOOD STRAT. TRAP

Incised valley and its partial fill

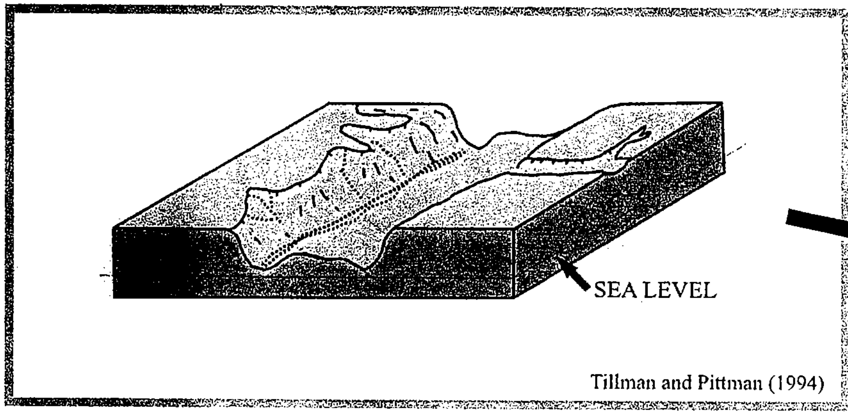


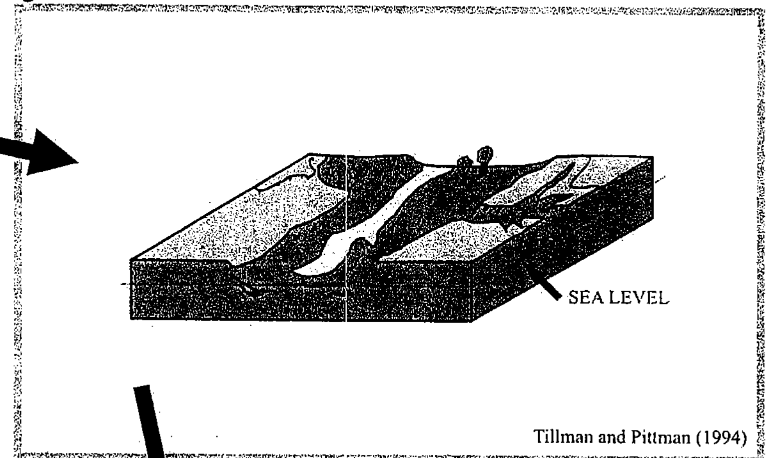


(WEIMER, 1994)

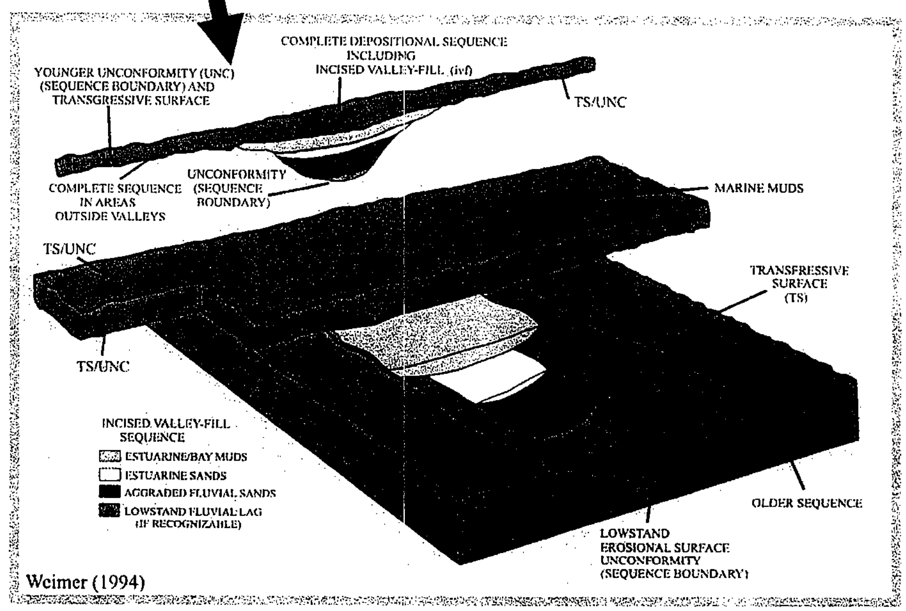
Valley carved (incised) into shelf strata (often mudstones) during drop in sea level.

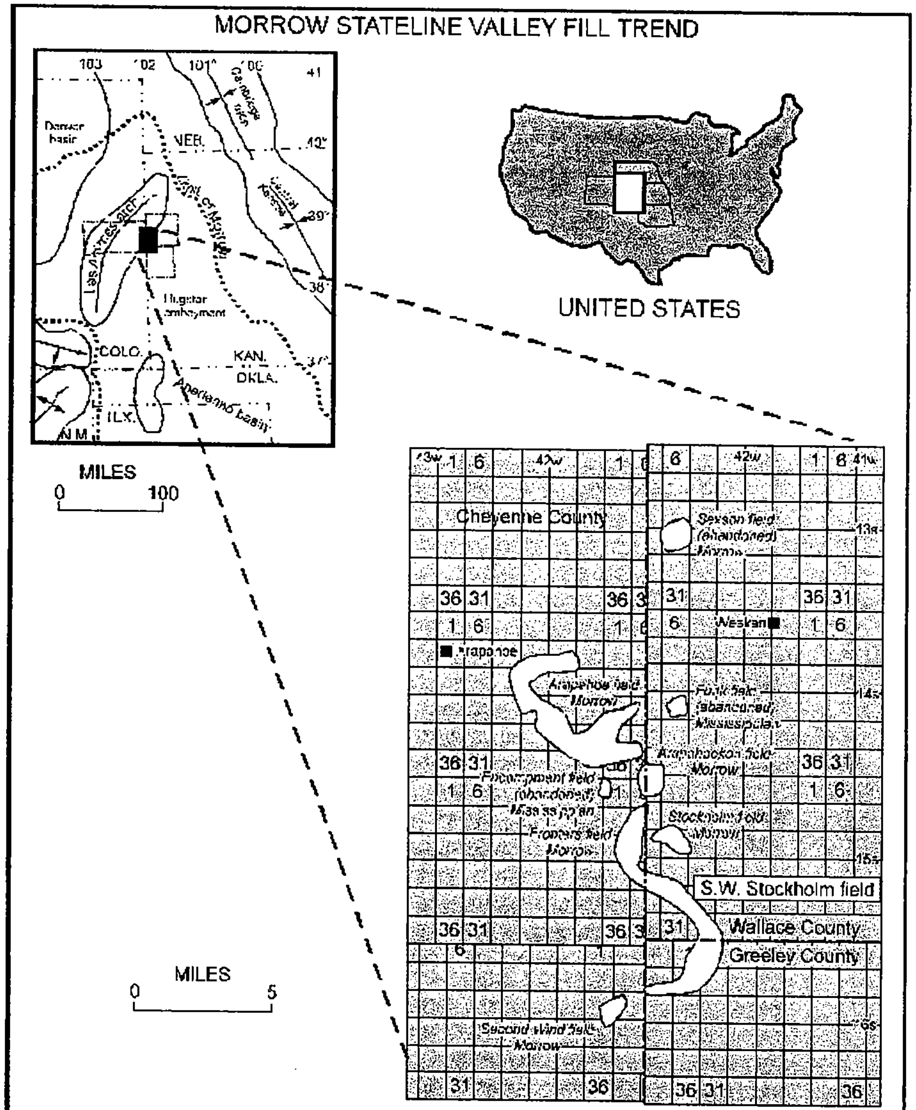
Valley begins to fill with fluvial (lag) gravels and associated deposits during turnaround and early rise in sea level. Later fill may become estuarine.





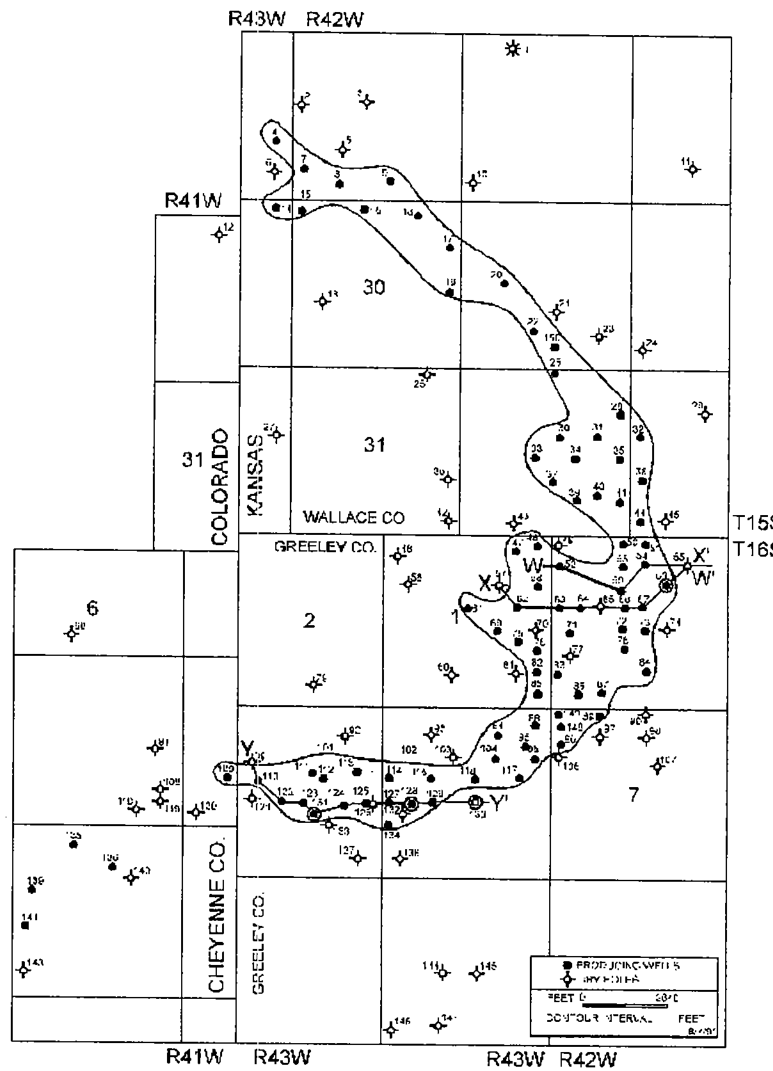
Idealized incised valley fill: incision during falling stage, fluvial during turnaround and early rise, and estuarine with later rise. Marine muds cap the sequence when the valley is filled.





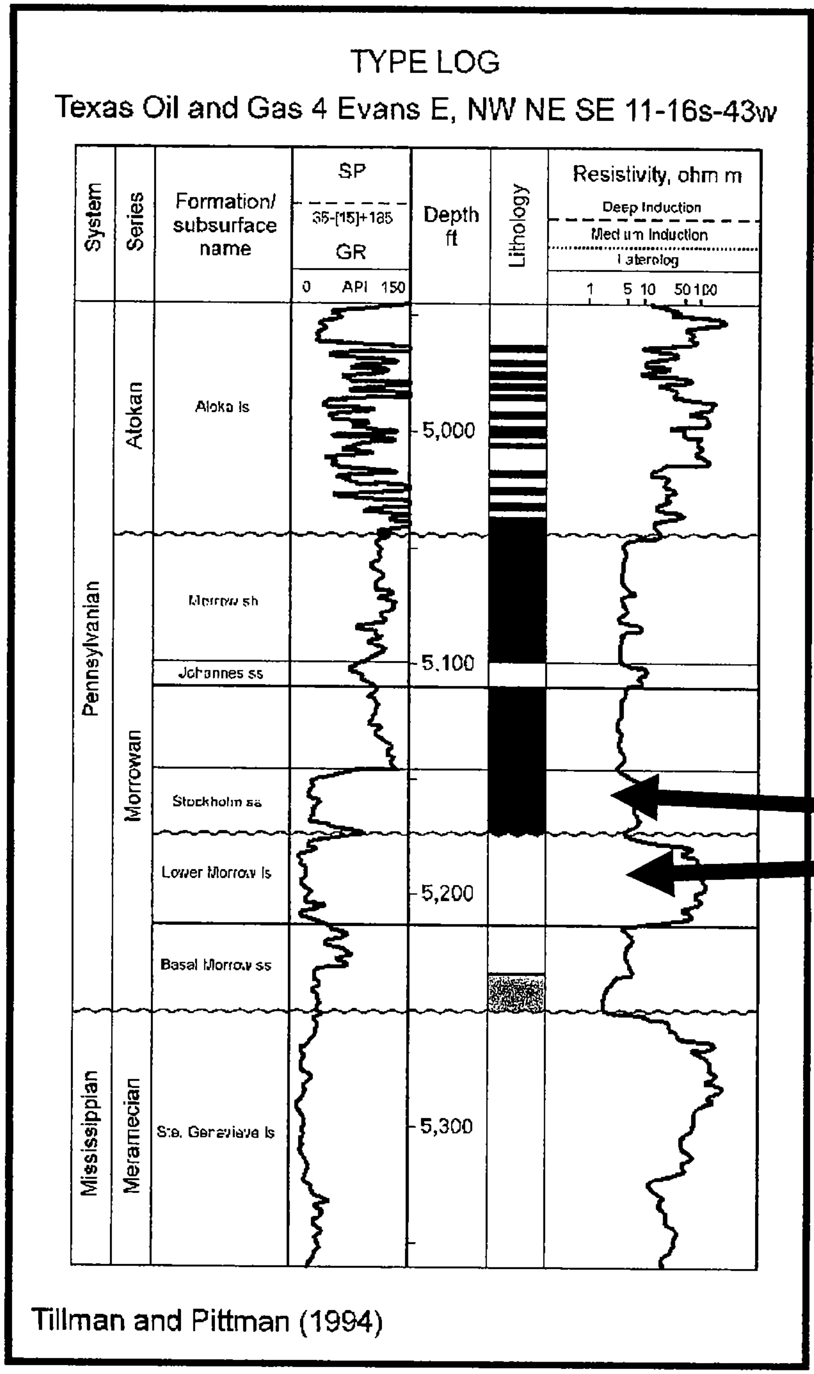
Location of 20-mile-long "Stateline Trend" Morrow Sandstone fields, which produce from valley-fill sandstone reservoirs. Southwest Stockholm field, Kansas, is located in Greeley and Wallace counties, Kansas.

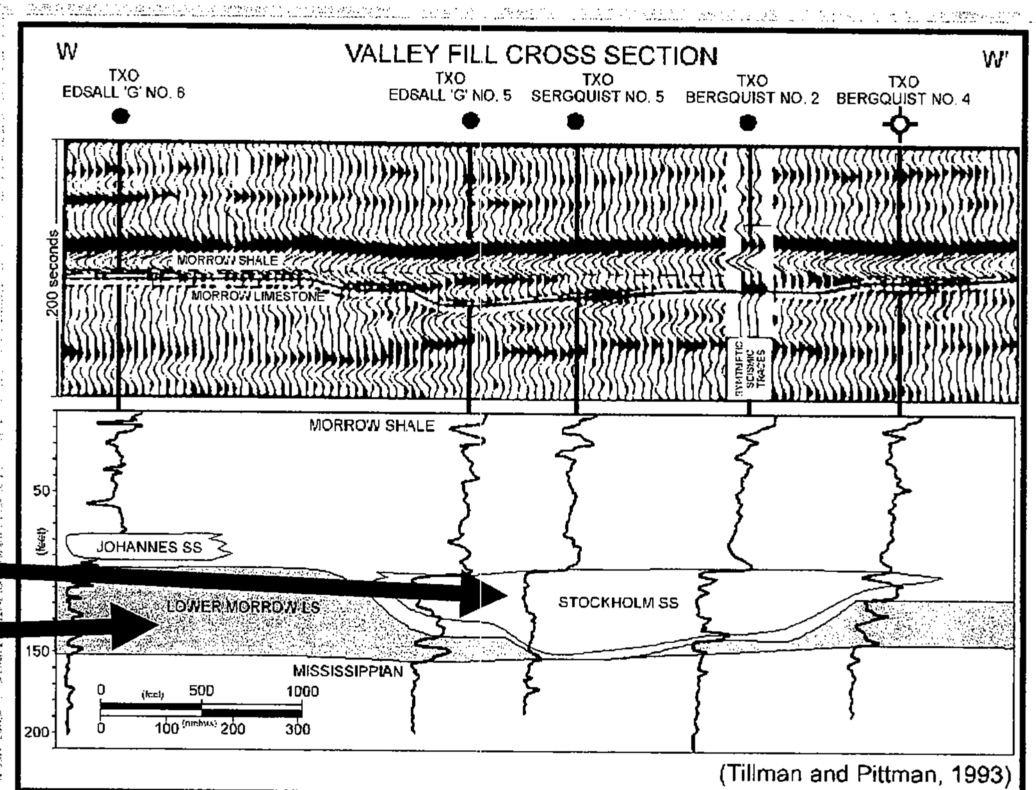
(Tillmand and Pittman, 1993)



Base map, outlining borders of Southwest Stockholm field, Kansas. Location of stratigraphic cross sections X-X', Y-Y' and W-W' is indicated. Cored wells described in this study are indicated by circles. Type log well (Fig. 5) is indicated by a triangle. A list of all numbered wells on this map is available from the senior author.

(Tillman and Pittman, 1993)


TYPE LOG
Texas Oil and Gas 4 Evans E, NW NE SE 11-16s-43w
System
Series
Formation/ subsurface name
SP
35-[15]+185
GR
0 API 150
Depth ft
Lithology
Resistivity, ohm m
Deep Induction
Medium Induction
Laterolog
1 5 10 50 100
Pennsylvanian
Atokan
Atoka ls
Morrowan
Morrow sh
Johannes ss
Stockholm ss
Lower Morrow ls
Basal Morrow ss
Mississippian
Meramecian
Ste. Genevieve ls
5,000
5,100
5,200
5,300
Tillman and Pittman (1994)


W
VALLEY FILL CROSS SECTION
W'
TXO EDSALL 'G' NO. 6
TXO EDSALL 'G' NO. 5
TXO SERGQUIST NO. 5
TXO BERGQUIST NO. 2
TXO BERGQUIST NO. 4
200 seconds
MORROW SHALE
MORROW LIMESTONE
SYNTHETIC SEISMIC TRACES
MORROW SHALE
JOHANNES SS
STOCKHOLM SS
LOWER MORROW LS
MISSISSIPPIAN
50
150
200
0 500 1000
0 100 200 300
(Tillman and Pittman, 1993)

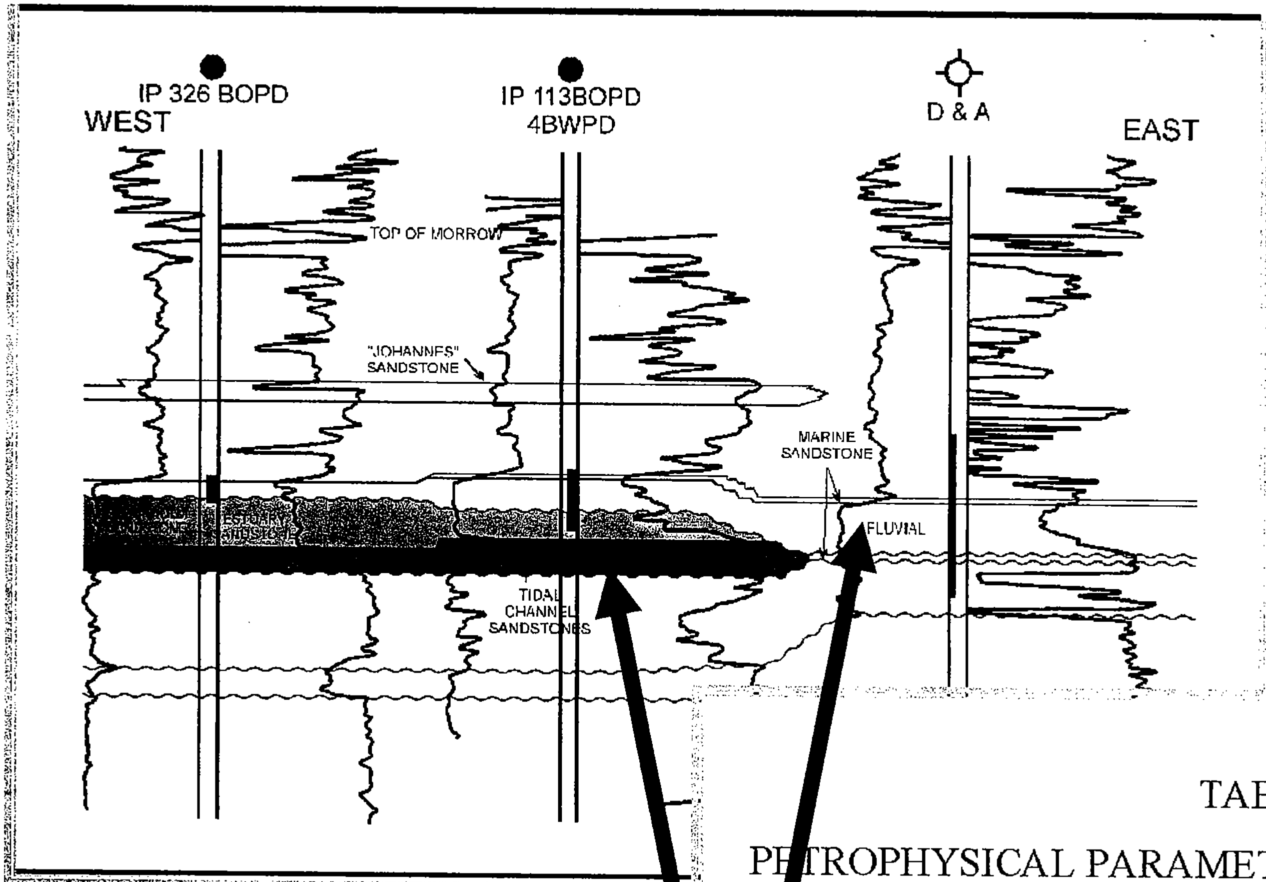
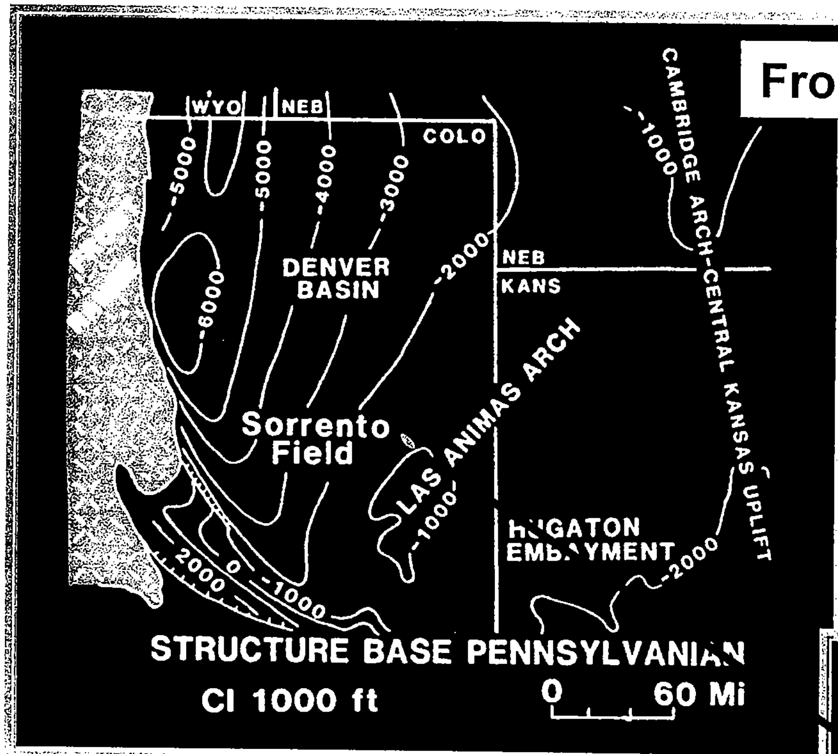


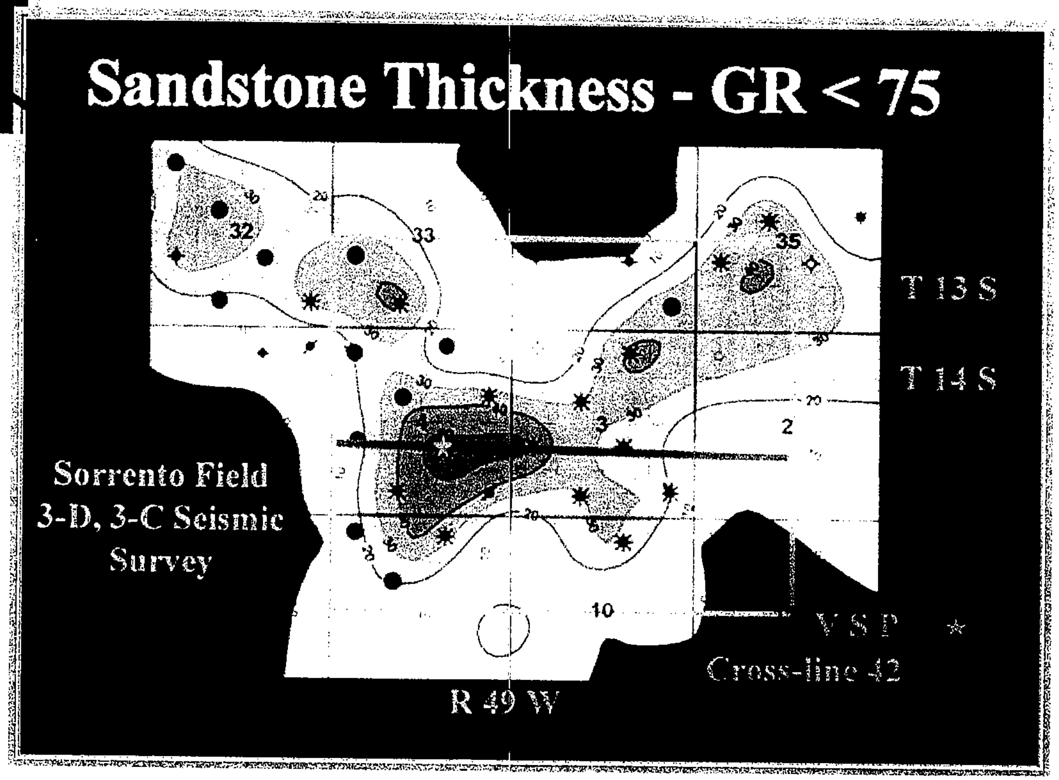
TABLE III

PETROPHYSICAL PARAMETERS FOR RESERVOIR FACIES
SOUTHWEST STOCKHOLM FIELD

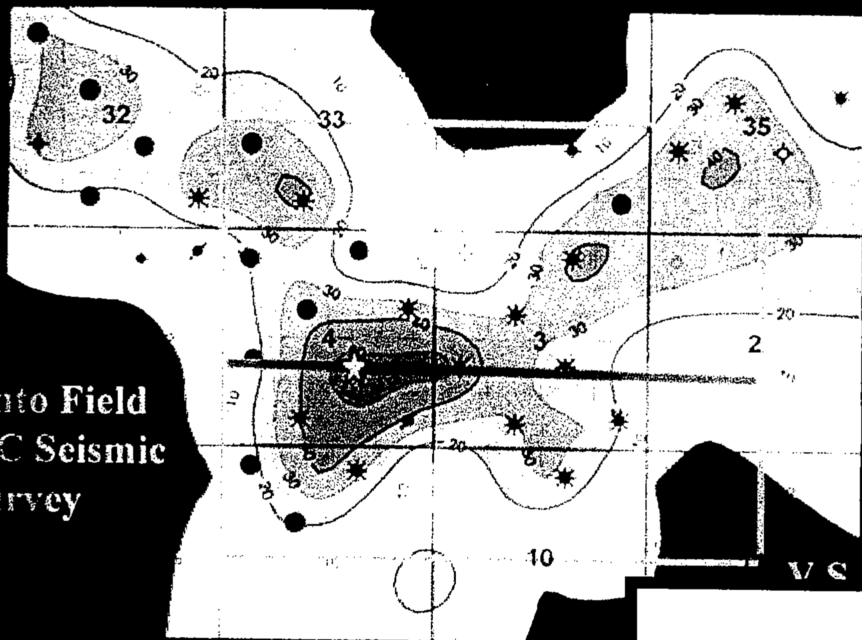
Fluvial Sandstones	K (md)	Ø (%)	K/Ø	R_{35} (microns)
Mean	703	16.3	39.8	19
Range	129-1890	11.7-20.6	11.0-92.2	11.2-33.5
Tidal Sandstones				
Mean	80.8	14.4	5.6	7.1
Range	50-111	11.5-17.8	4.1-7.2	6.0-8.4



From Mark (1998) and Ph.D. dissertation (1995)



Sandstone Thickness - GR < 75



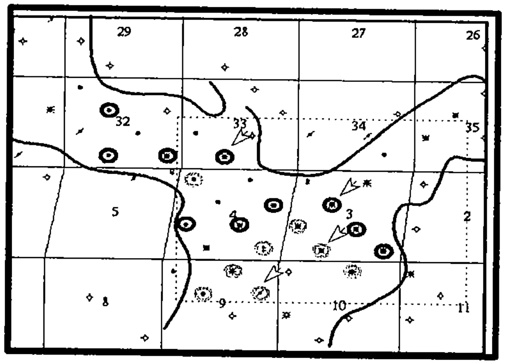
T 13 S

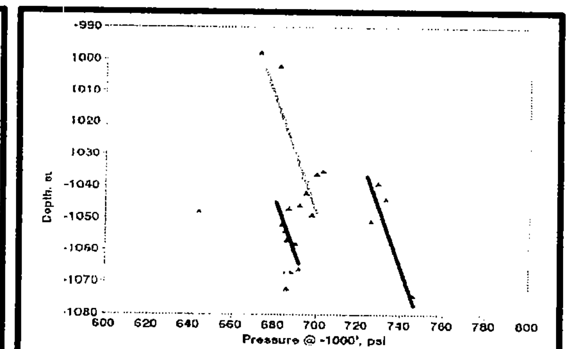
T 14 S

Sorrento Field
3-D, 3-C Seismic
Survey

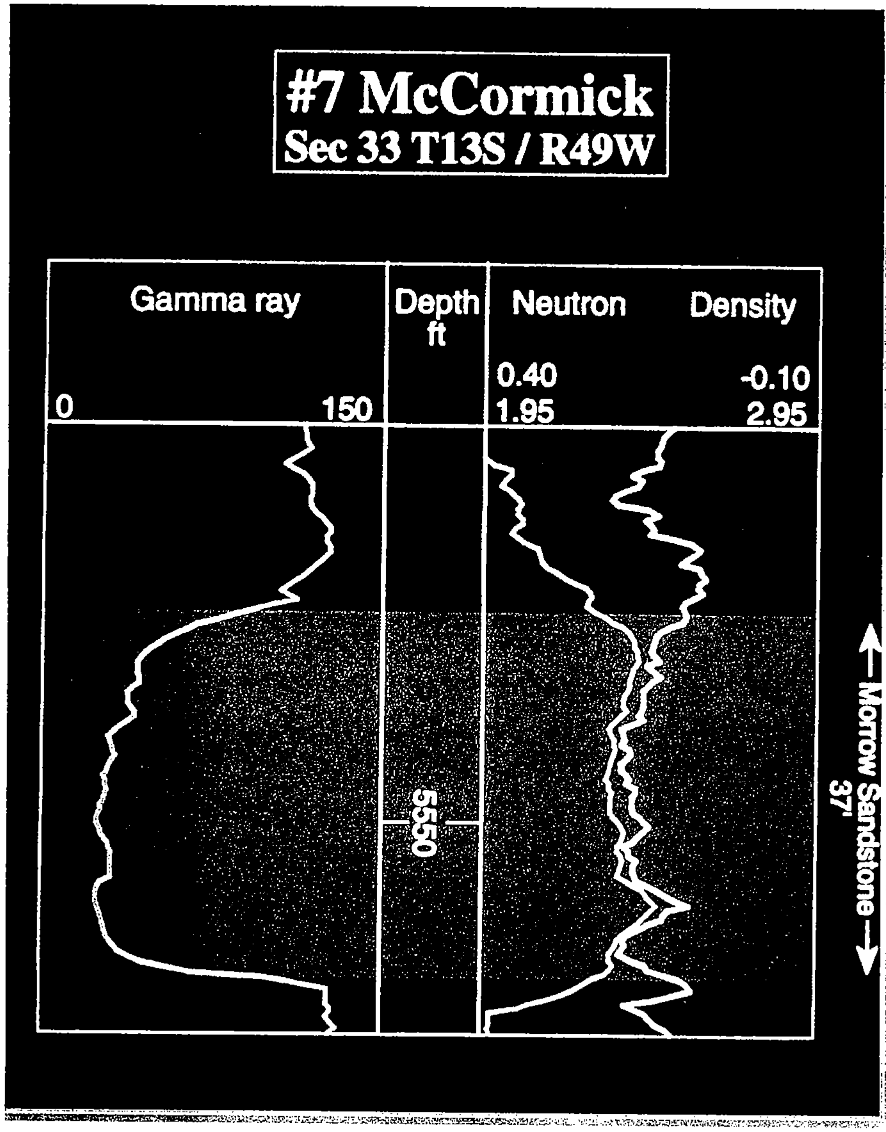
R 49 W

Static Pressure Test Results

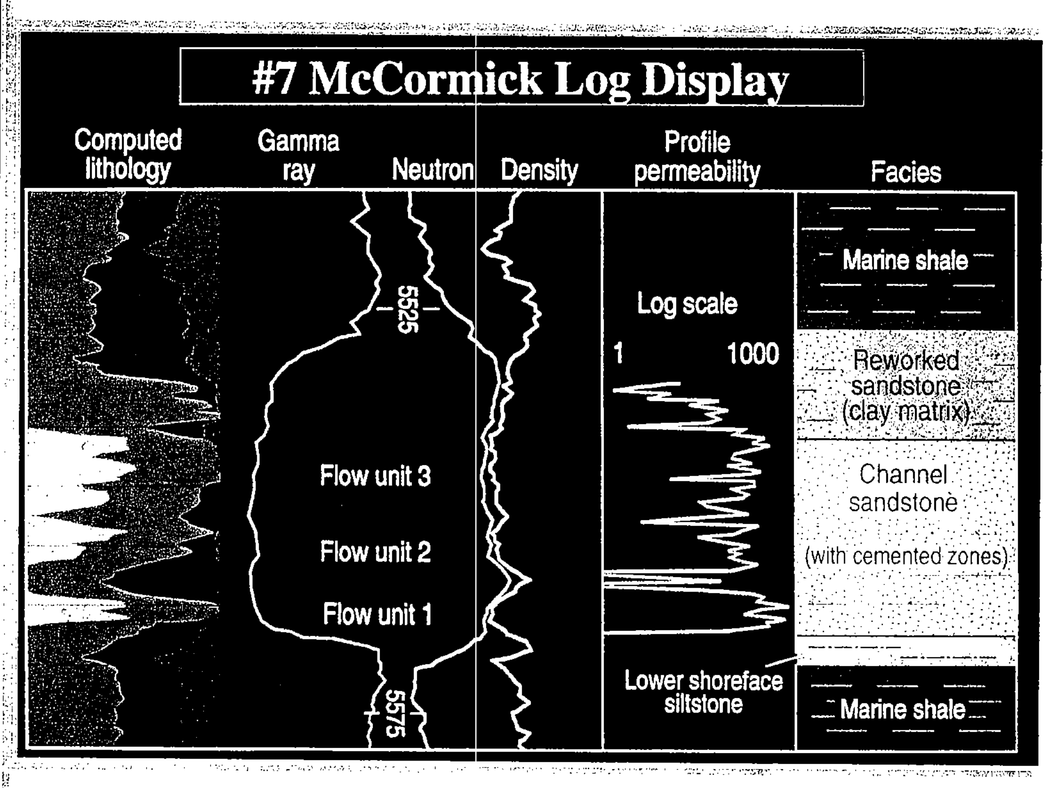




Mark, 1995

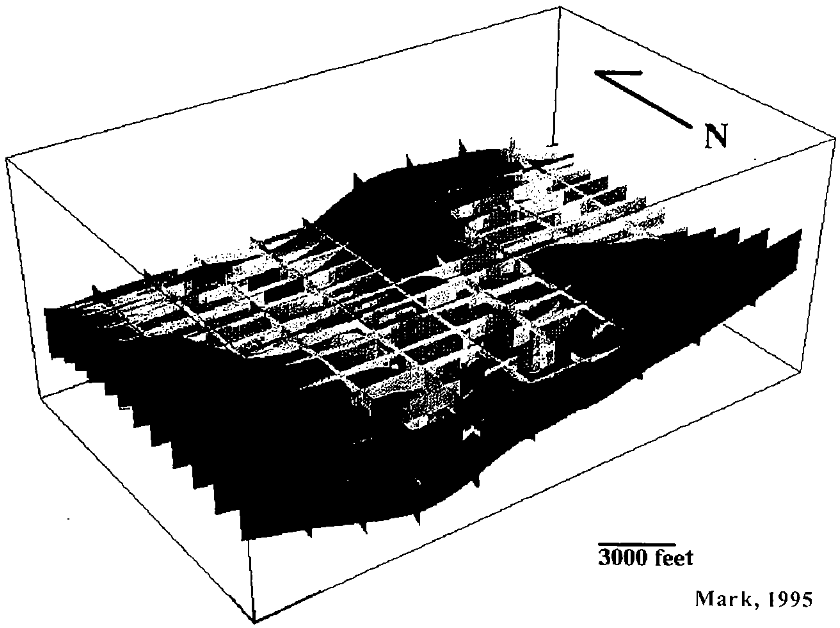


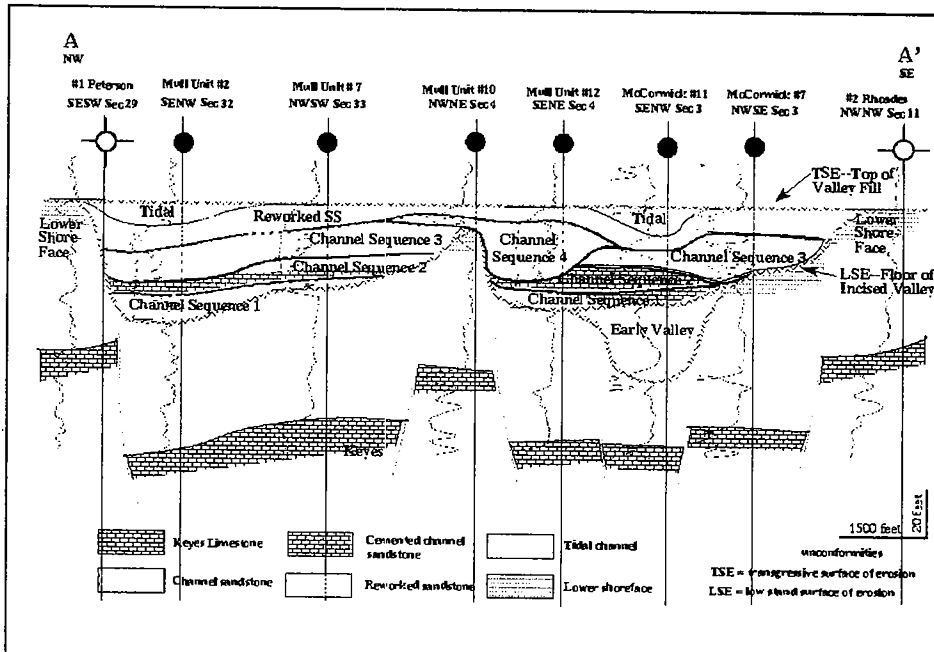
#7 McCormick
Sec 33 T13S / R49W
Gamma ray
0
150
Depth ft
Neutron
0.40
1.95
Density
-0.10
2.95
5550
Morrow Sandstone 37'

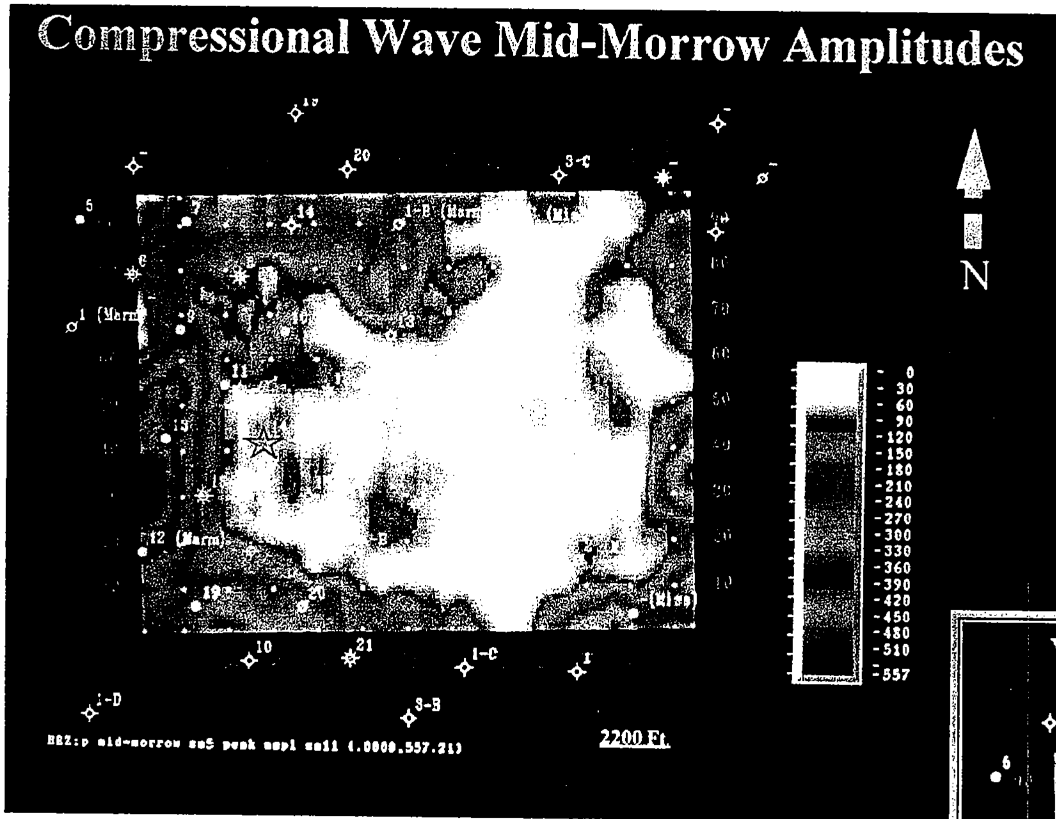


#7 McCormick Log Display
Computed lithology
Gamma ray
Neutron
Density
Profile permeability
Facies
5525
Log scale
1
1000
Marine shale
Reworked sandstone (clay matrix)
Channel sandstone
(with cemented zones)
Flow unit 3
Flow unit 2
Flow unit 1
Lower shoreface siltstone
Marine shale
5575

Incised Valley Topography and Valley Fill Facies







P Wave 3D seismic survey

Multi-component P and S Wave 3D seismic survey

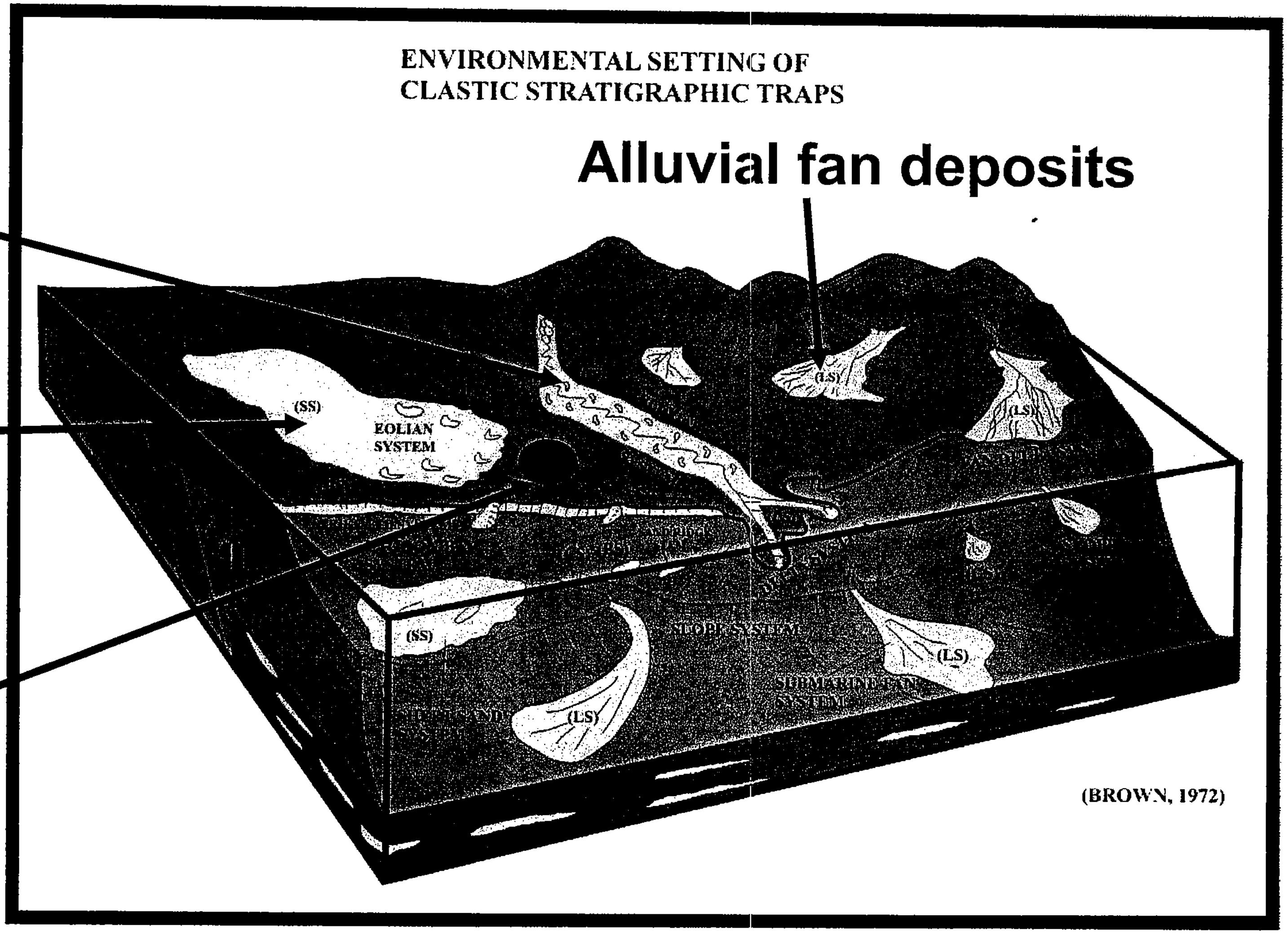
EOLIAN DEPOSITS & RESERVOIRS

Level 3: My continental <u>sandstone</u> reservoir is made of:

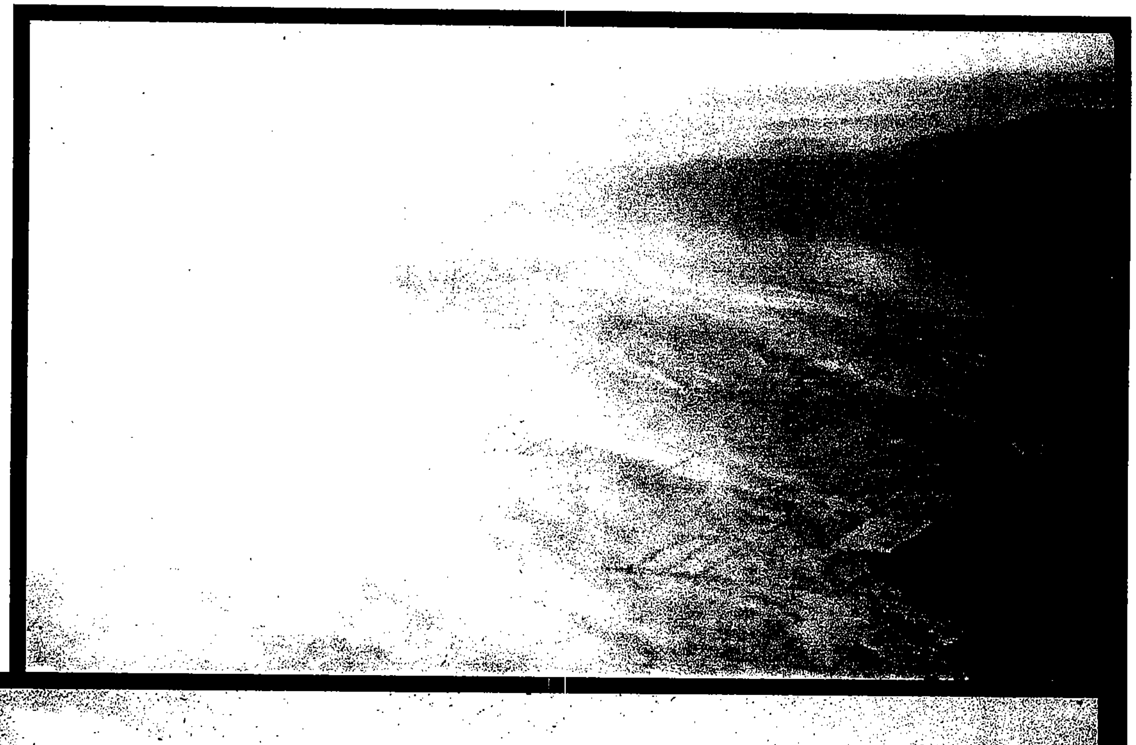
Fluvial deposits

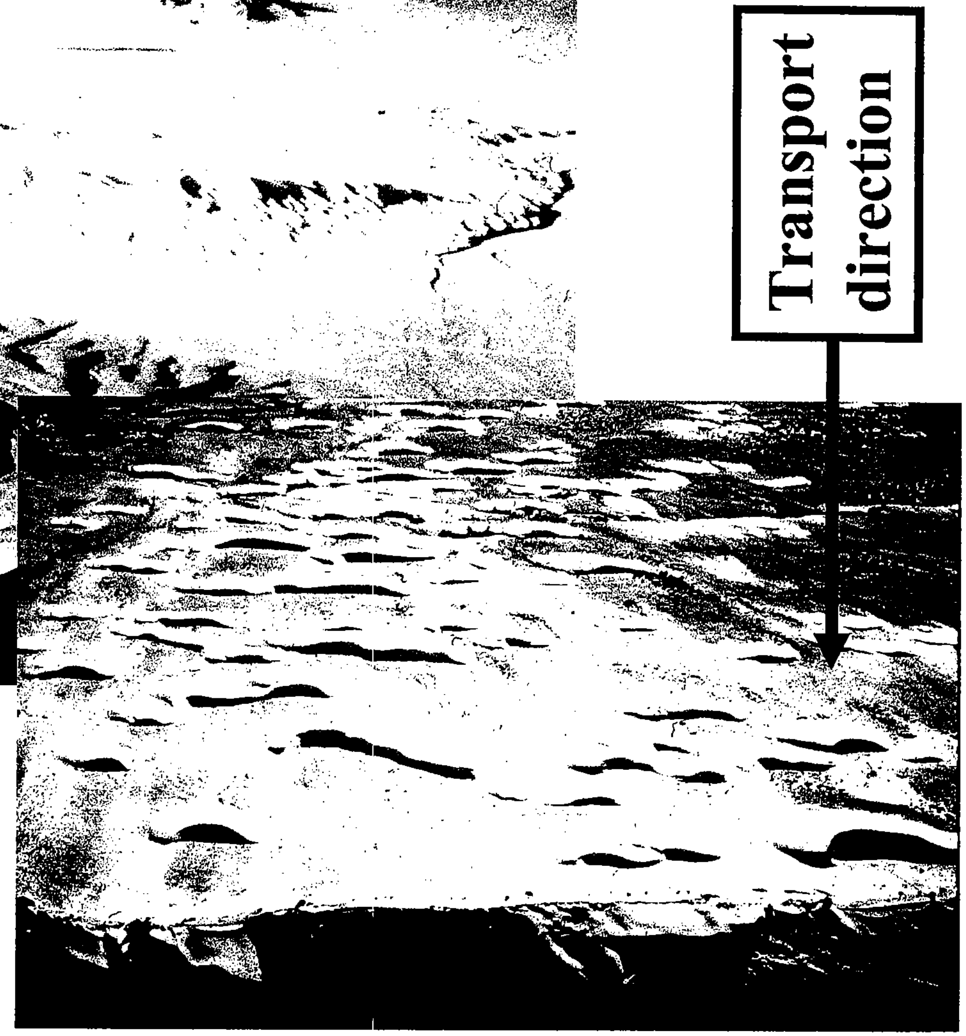
Eolian deposits

Lacustrine deposits

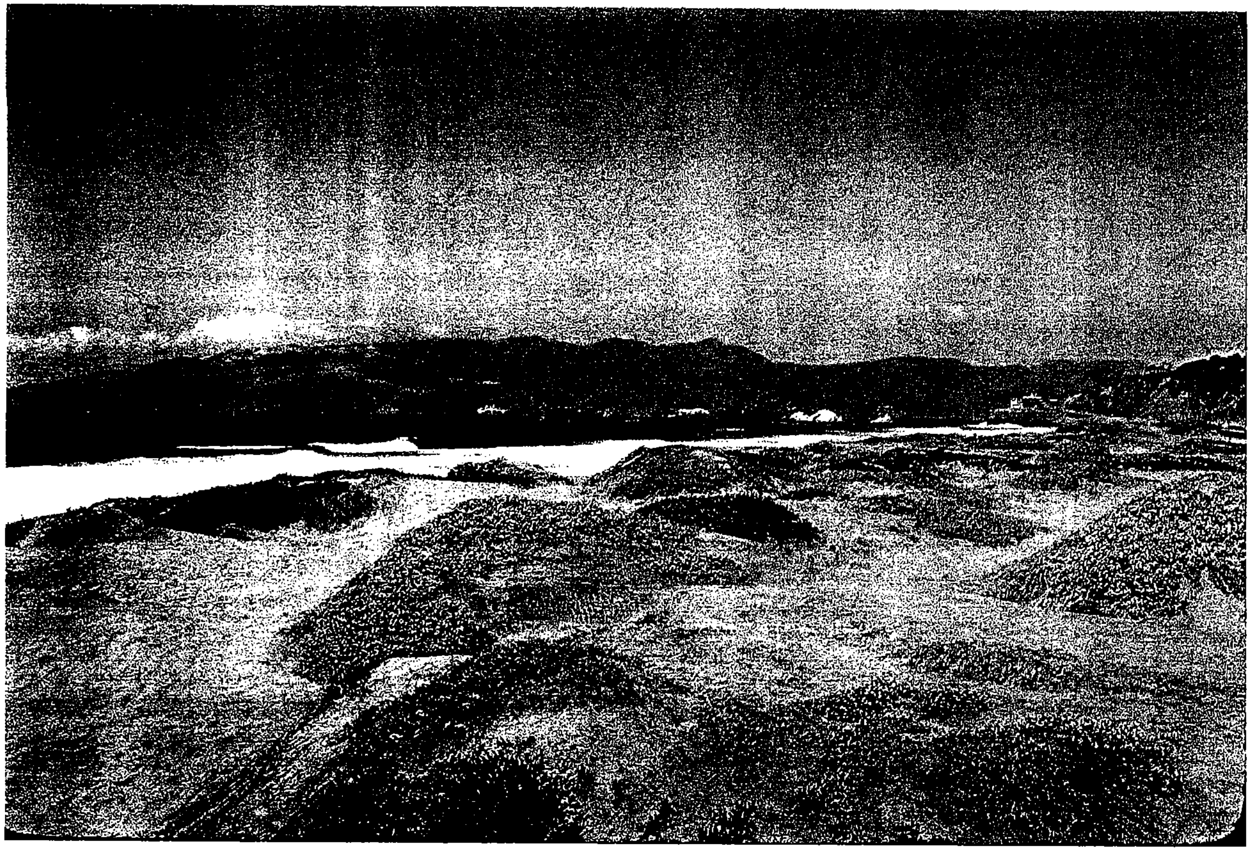


Dust storms

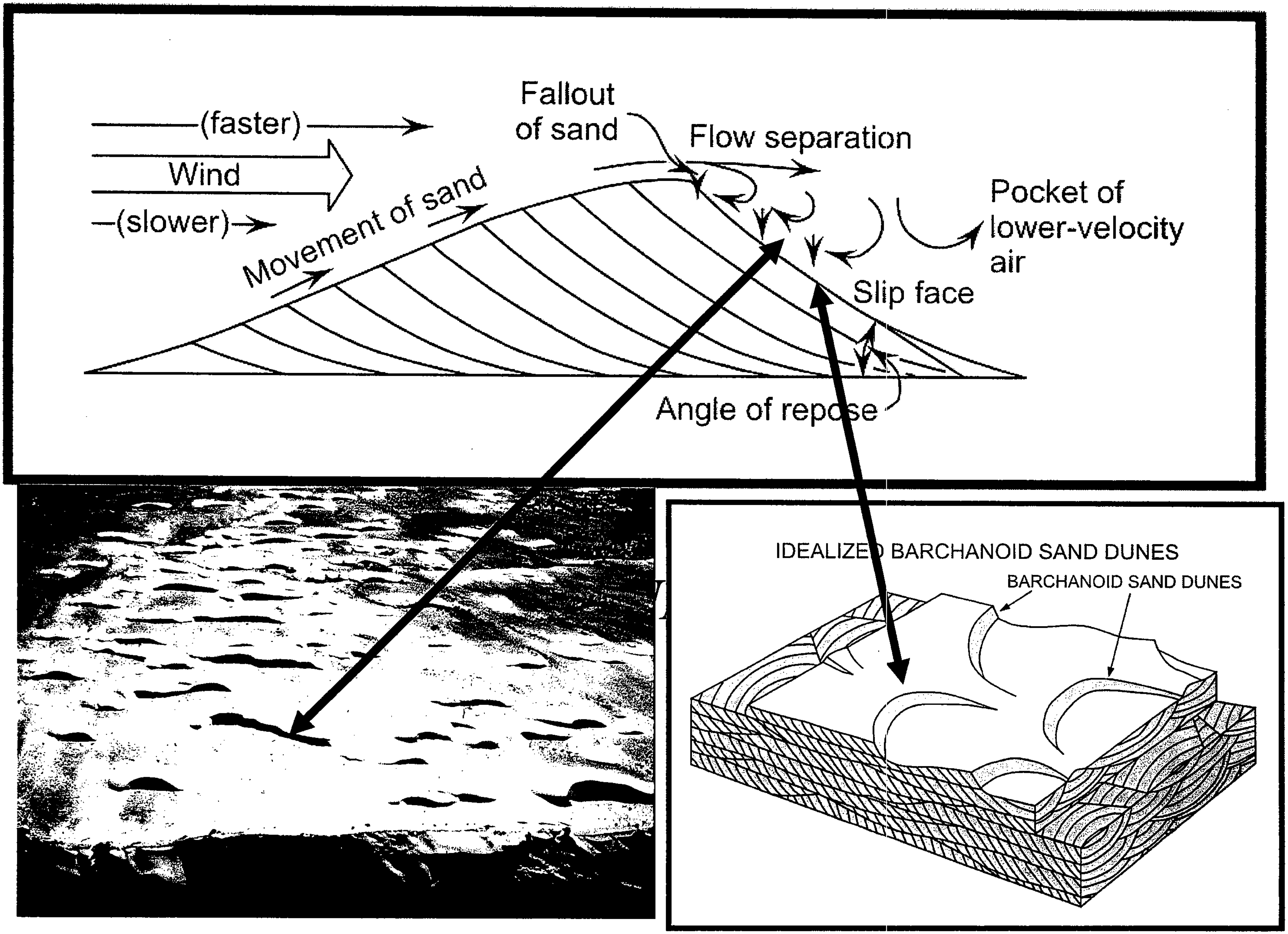


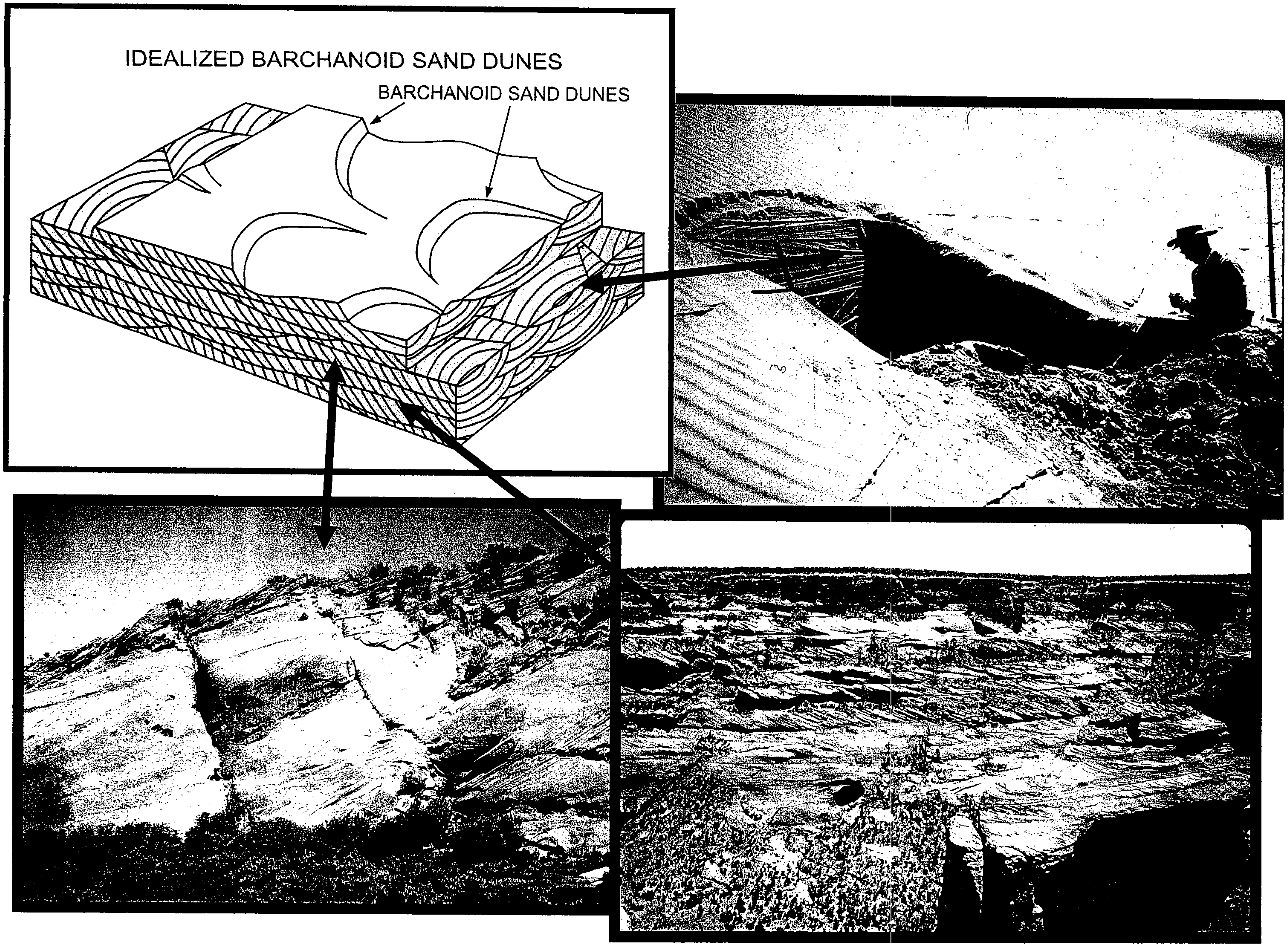


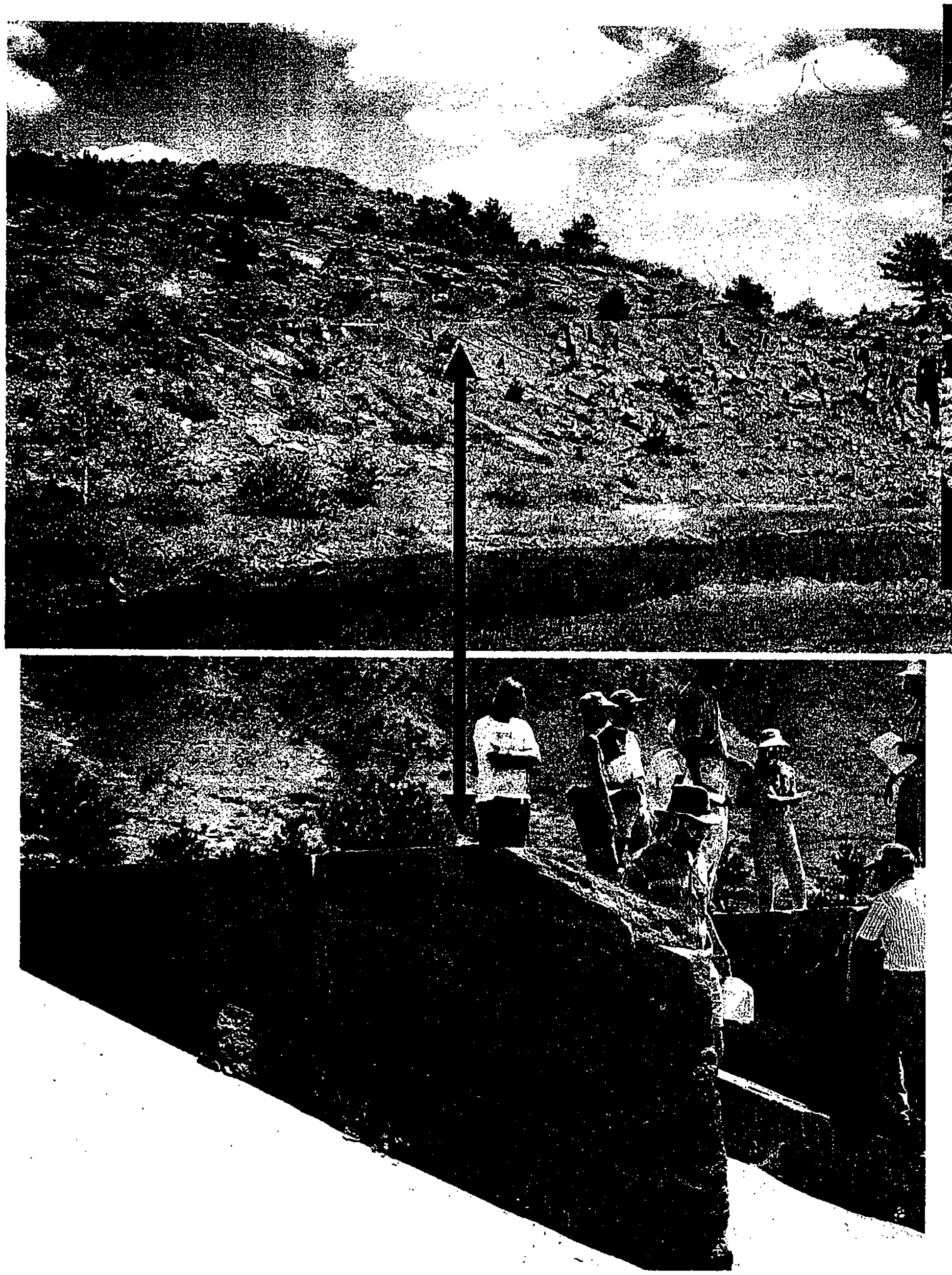
Inland sand sea

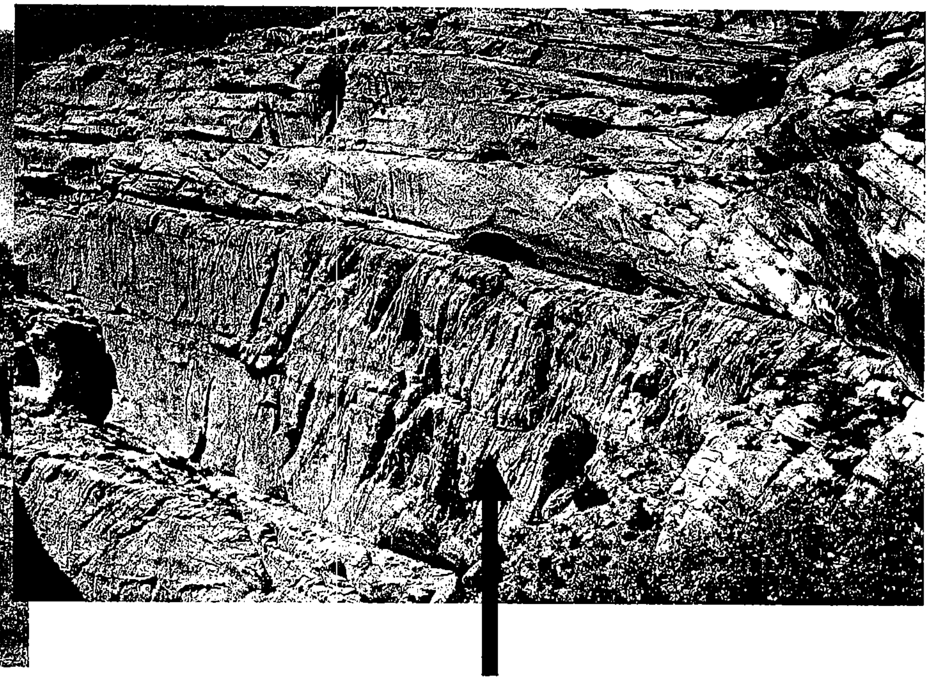


Coastal dune fields


(faster)
Wind
(slower)
Movement of sand
Fallout of sand
Flow separation
Pocket of lower-velocity air
Slip face
Angle of repose
IDEALIZED BARCHANOID SAND DUNES
BARCHANOID SAND DUNES

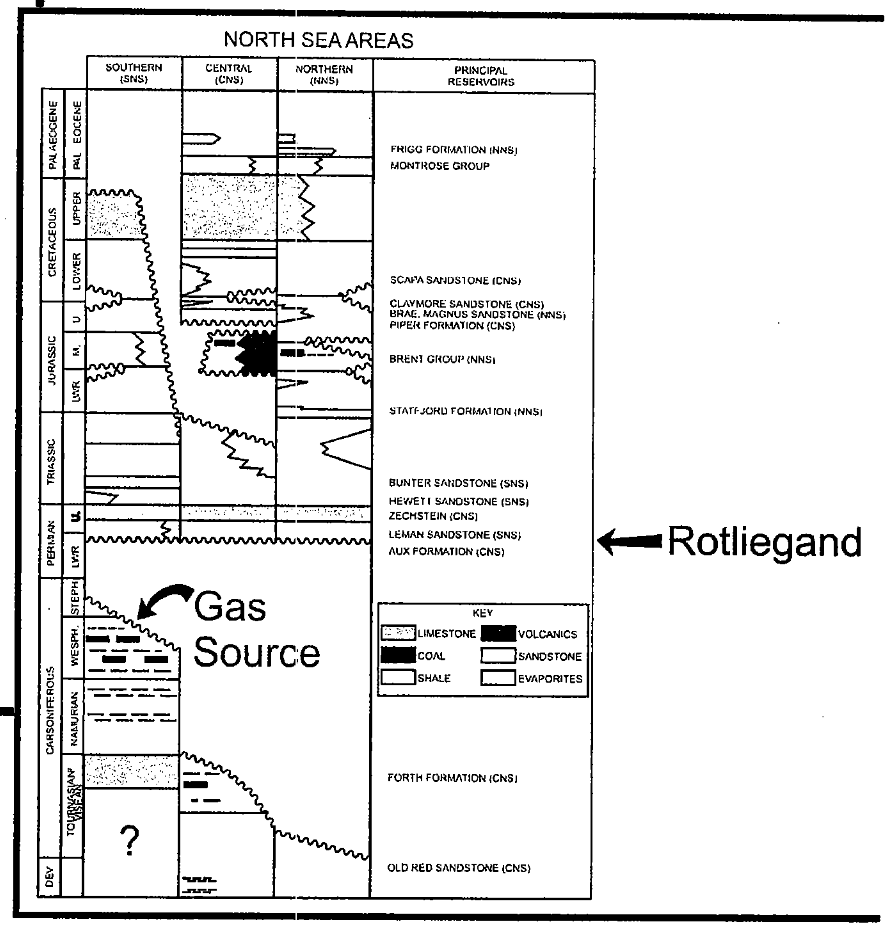

IDEALIZED BARCHANOID SAND DUNES
BARCHANOID SAND DUNES

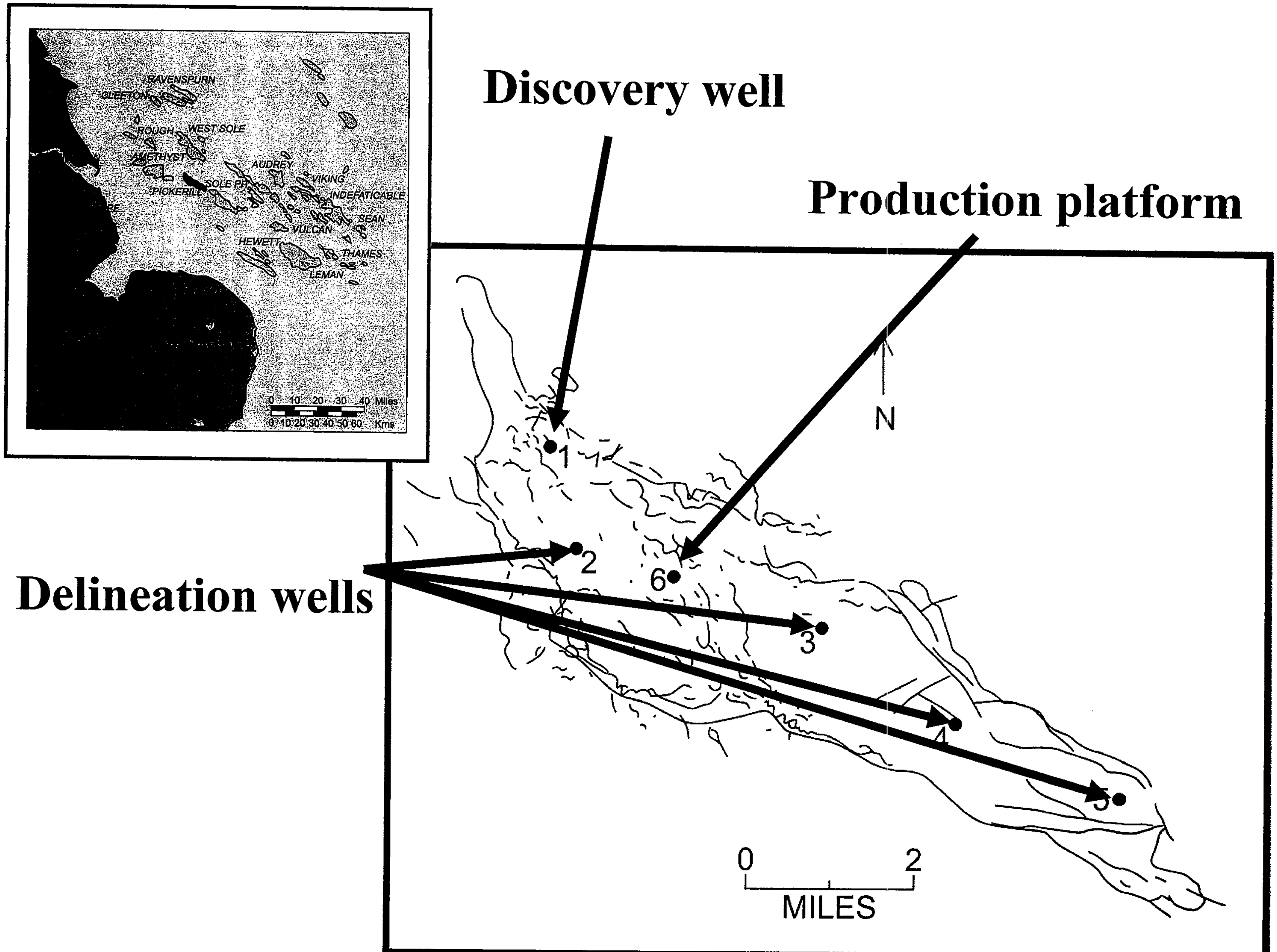




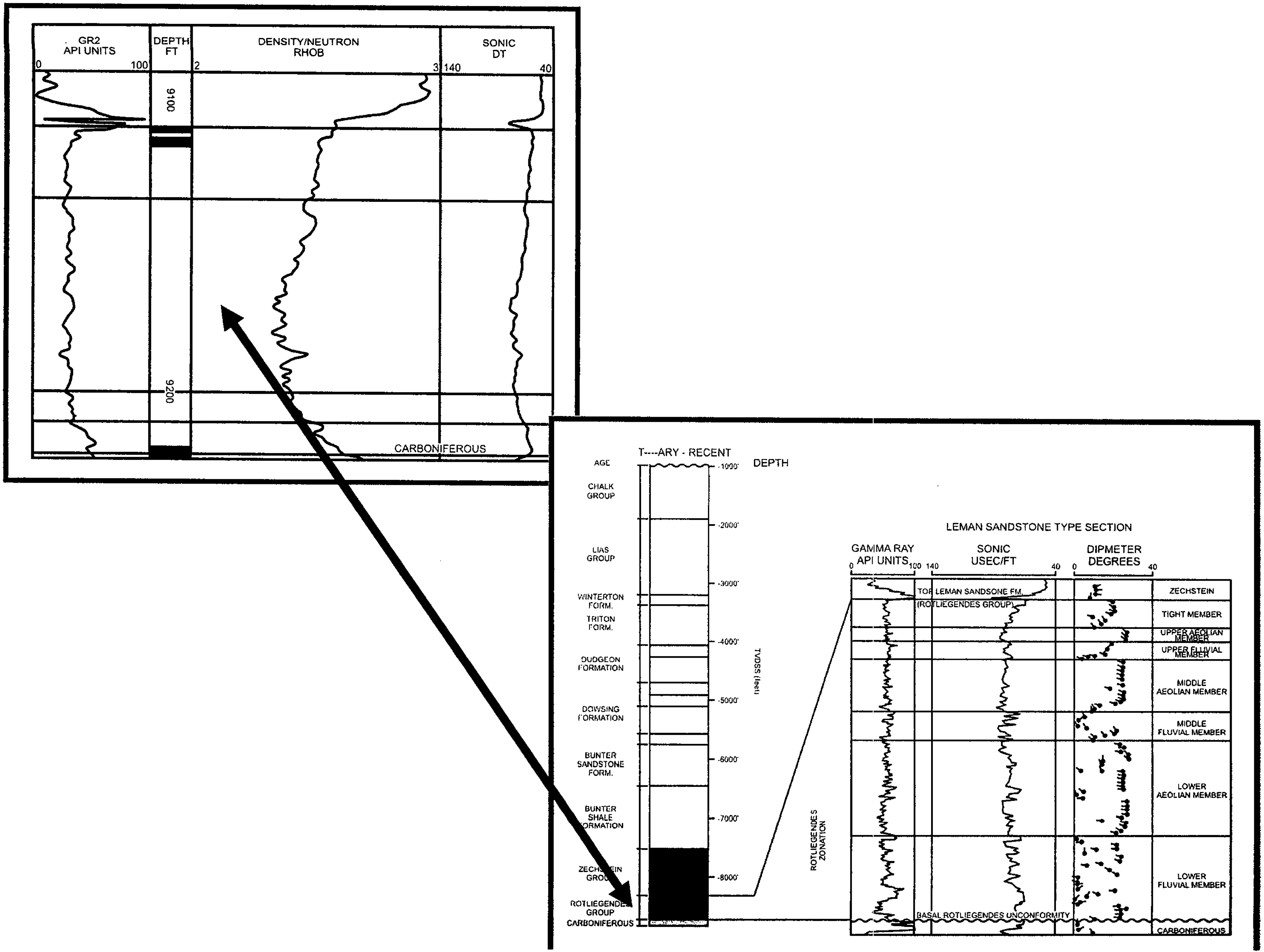
WEBER SANDSTONE, RANGELY FIELD, CO.

Pickerill Field, North Sea produces from Rotliegendes Sandstone (Permian)



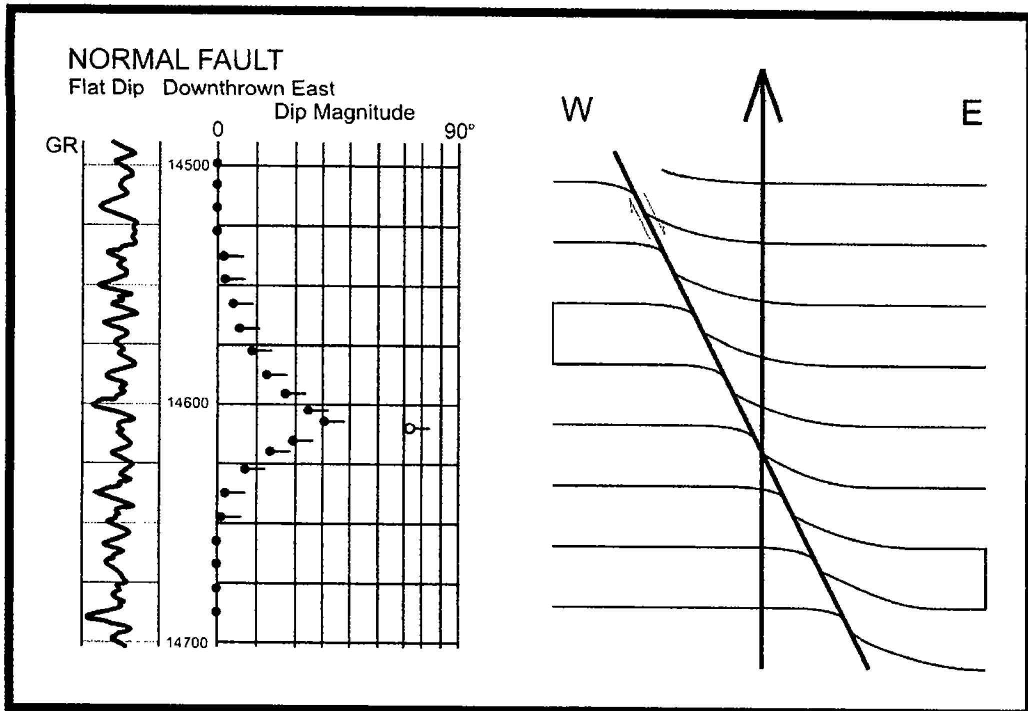


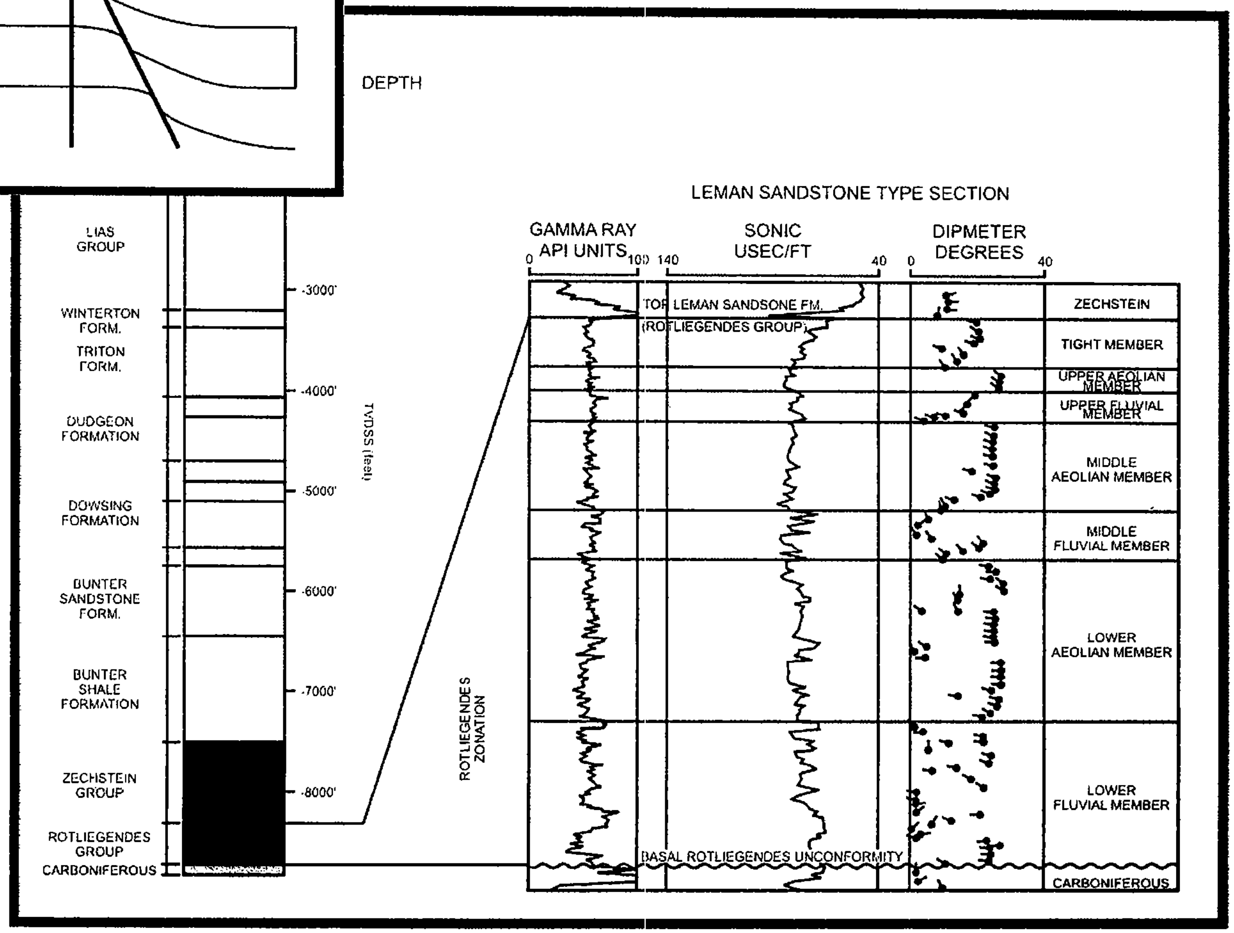
Discovery well
Production platform
Delineation wells
RAVENSPURN
CLEETON
ROUGH
WEST SOLE
AMETHYST
AUDREY
VIKING
PICKERILL
SOLE PIT
INDEFATIGABLE
SEAN
VULCAN
HEWETT
THAMES
LEMAN
0 10 20 30 40 Miles
0 10 20 30 40 50 60 Kms
N
1
2
6
3
4
5
0
2
MILES

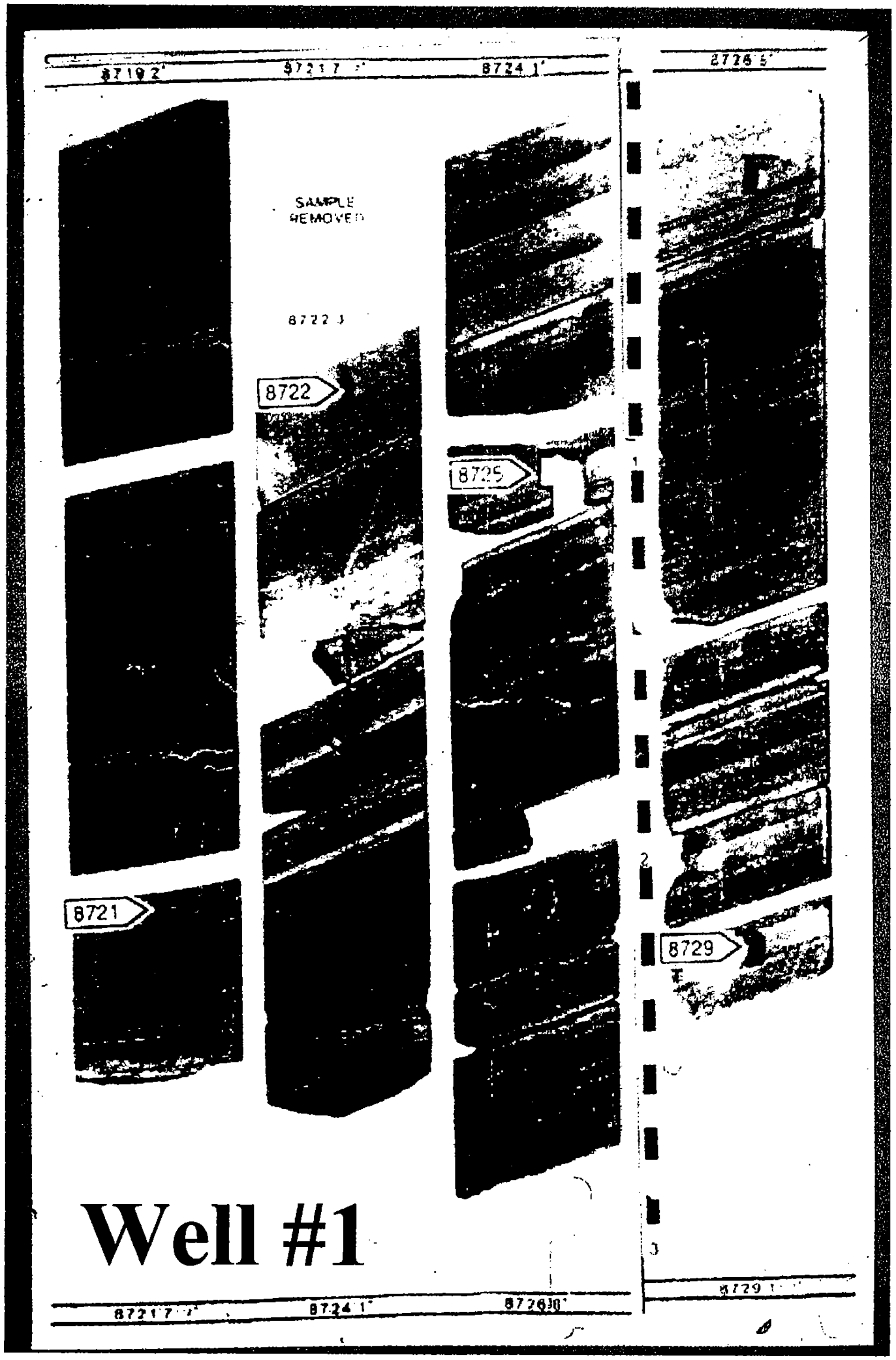


GR2
API UNITS
0
100
DEPTH
FT
9100
9200
DENSITY/NEUTRON
RHOB
2
3
SONIC
DT
140
40
CARBONIFEROUS
AGE
T----ARY - RECENT
DEPTH
CHALK GROUP
LIAS GROUP
WINTERTON FORM.
TRITON FORM.
DUDGEON FORMATION
DOWSING FORMATION
BUNTER SANDSTONE FORM.
BUNTER SHALE FORMATION
ZECHSTEIN GROUP
ROTLIEGENDES GROUP
CARBONIFEROUS
-1000'
-2000'
-3000'
-4000'
-5000'
-6000'
-7000'
-8000'
TVDSS (feet)
ROTLIEGENDES ZONATION
LEMAN SANDSTONE TYPE SECTION
GAMMA RAY
API UNITS
0
100
SONIC
USEC/FT
140
40
DIPMETER
DEGREES
0
40
TOP LEMAN SANDSONE FM.
(ROTLIEGENDES GROUP)
BASAL ROTLIEGENDES UNCONFORMITY
ZECHSTEIN
TIGHT MEMBER
UPPER AEOLIAN MEMBER
UPPER FLUVIAL MEMBER
MIDDLE AEOLIAN MEMBER
MIDDLE FLUVIAL MEMBER
LOWER AEOLIAN MEMBER
LOWER FLUVIAL MEMBER
CARBONIFEROUS

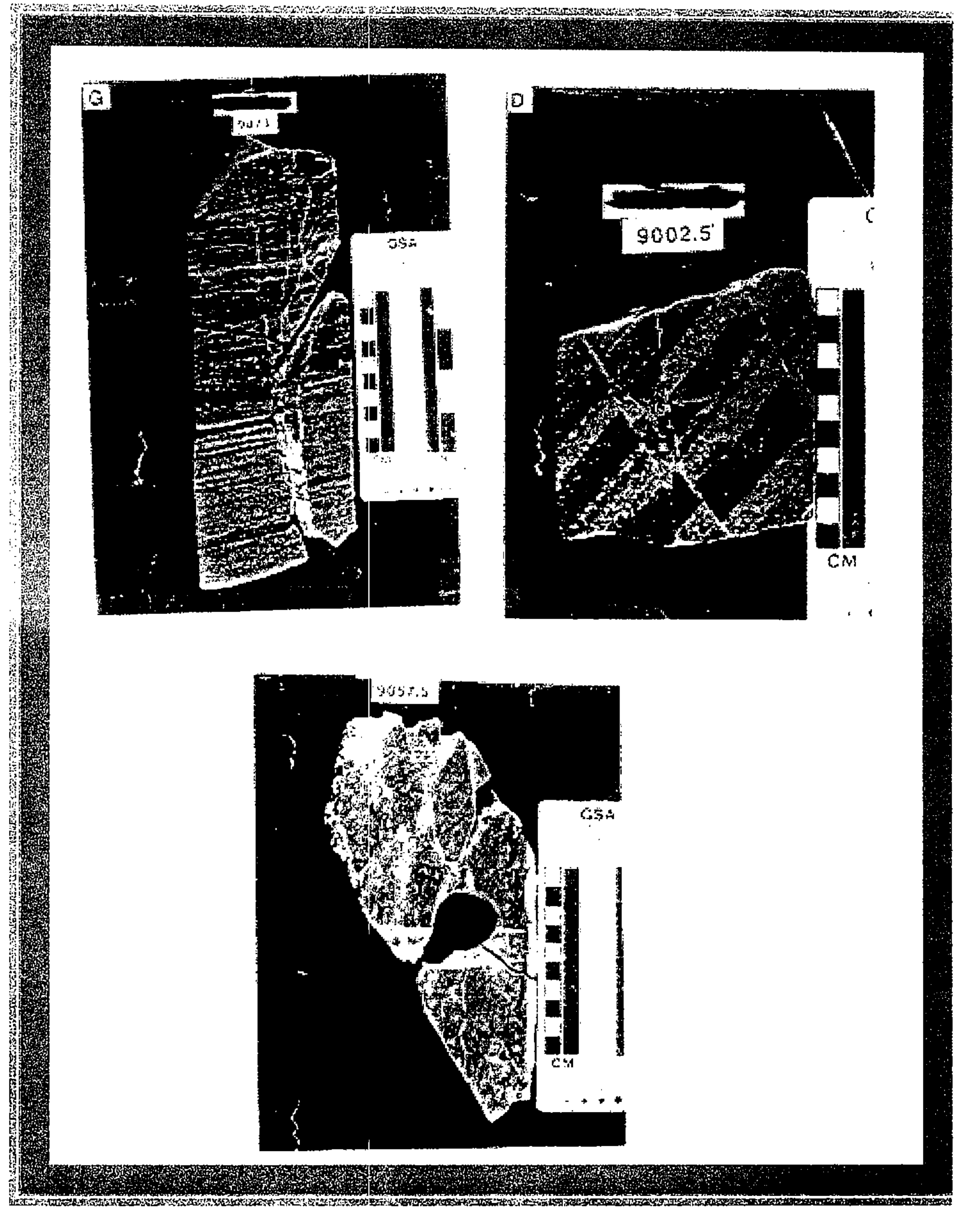
Dipmeter logs applied to eolian reservoirs



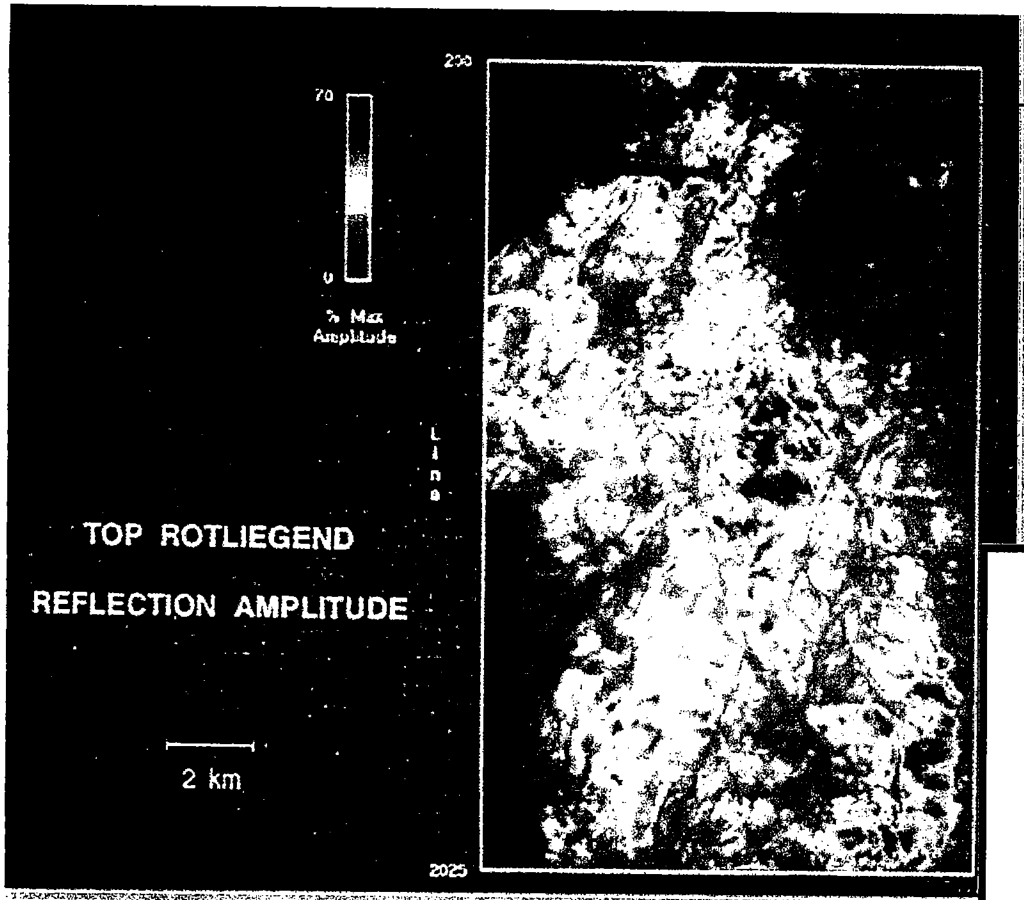


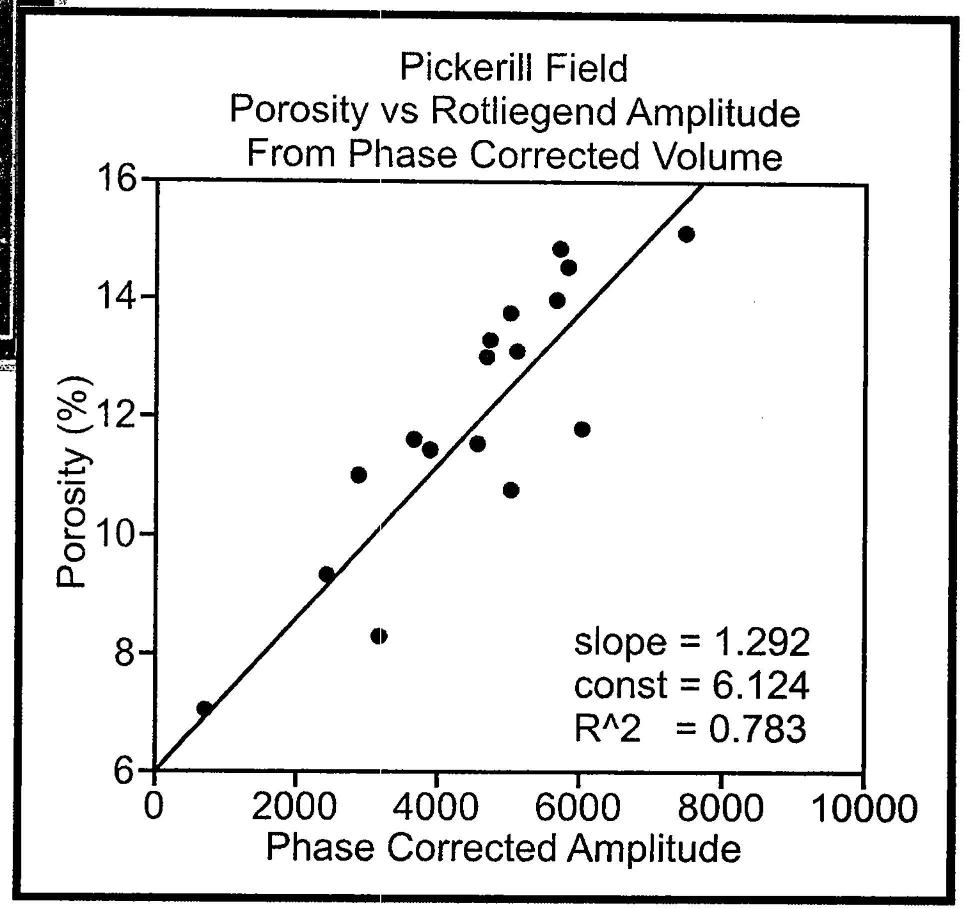

SAMPLE REMOVED
8722.3
8722
8725
8721
8729

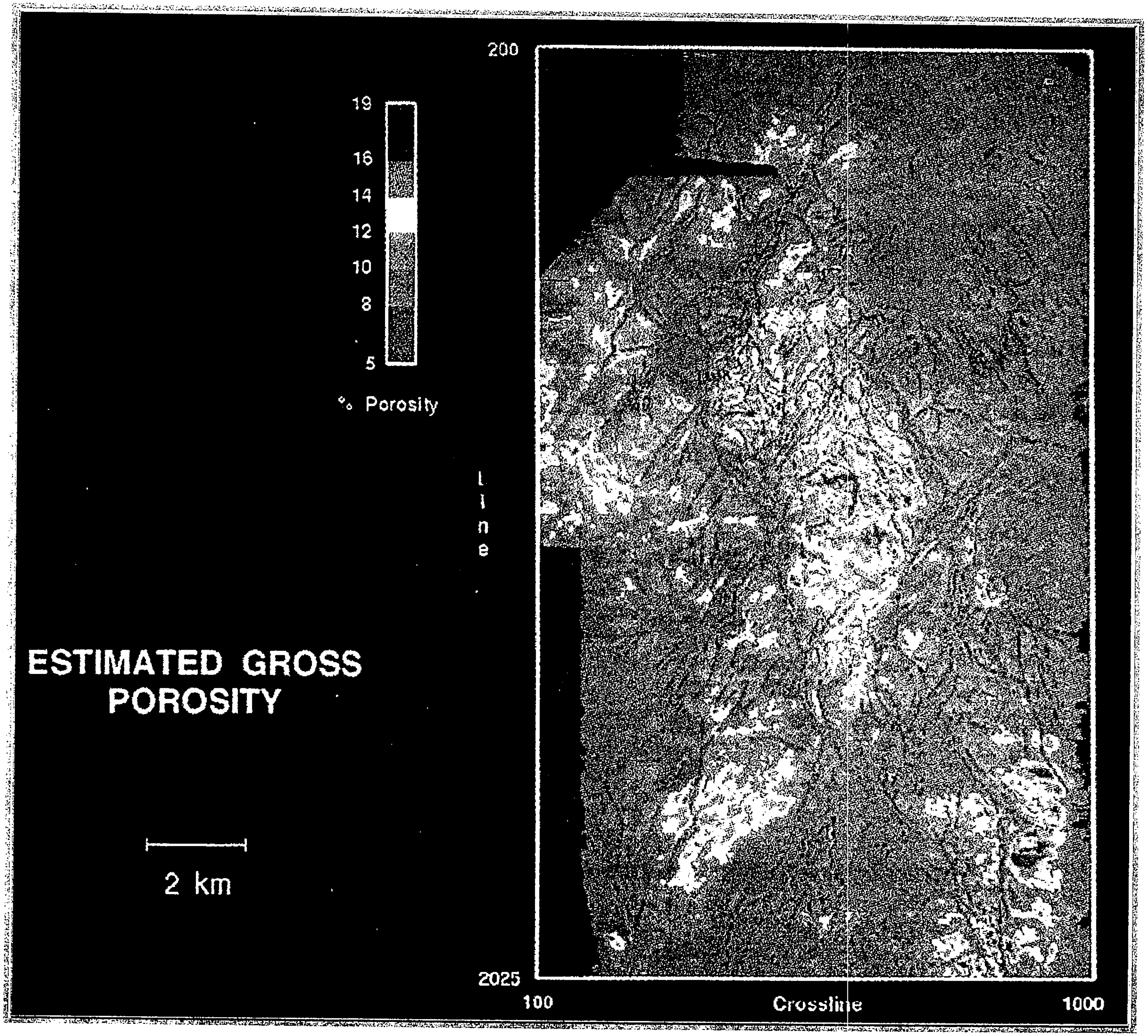
Well #1


G
D
9002.5'
GSA
CM
GSA
CM

Well #6

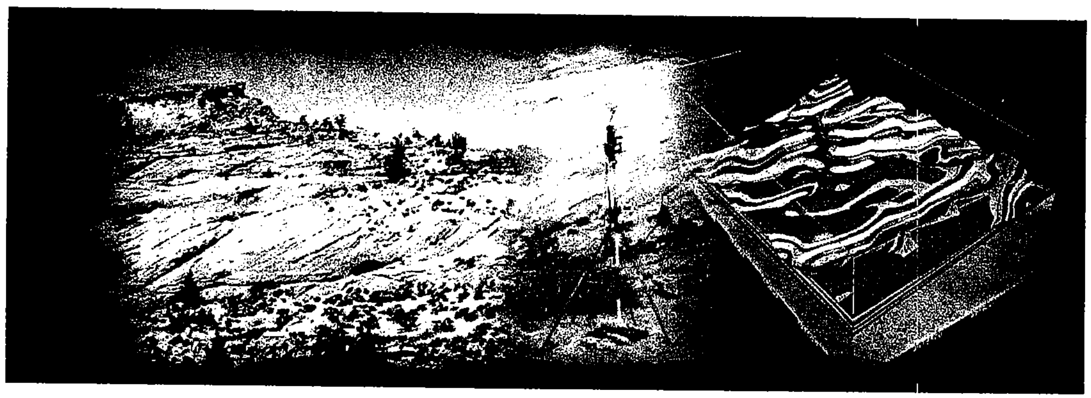

70
0
% Max Amplitude
200
Line
TOP ROTLIEGEND
REFLECTION AMPLITUDE
2 km
2025


Pickerill Field
Porosity vs Rotliegend Amplitude
From Phase Corrected Volume
Porosity (%)
Phase Corrected Amplitude
slope = 1.292
const = 6.124
R^2 = 0.783
16
14
12
10
8
6
0
2000
4000
6000
8000
10000



ESTIMATED GROSS POROSITY
19
16
14
12
10
8
5
% Porosity
2 km
200
2025
Line
100
Crossline
1000

Recent Advances in Outcrop-Based 3-D Modeling

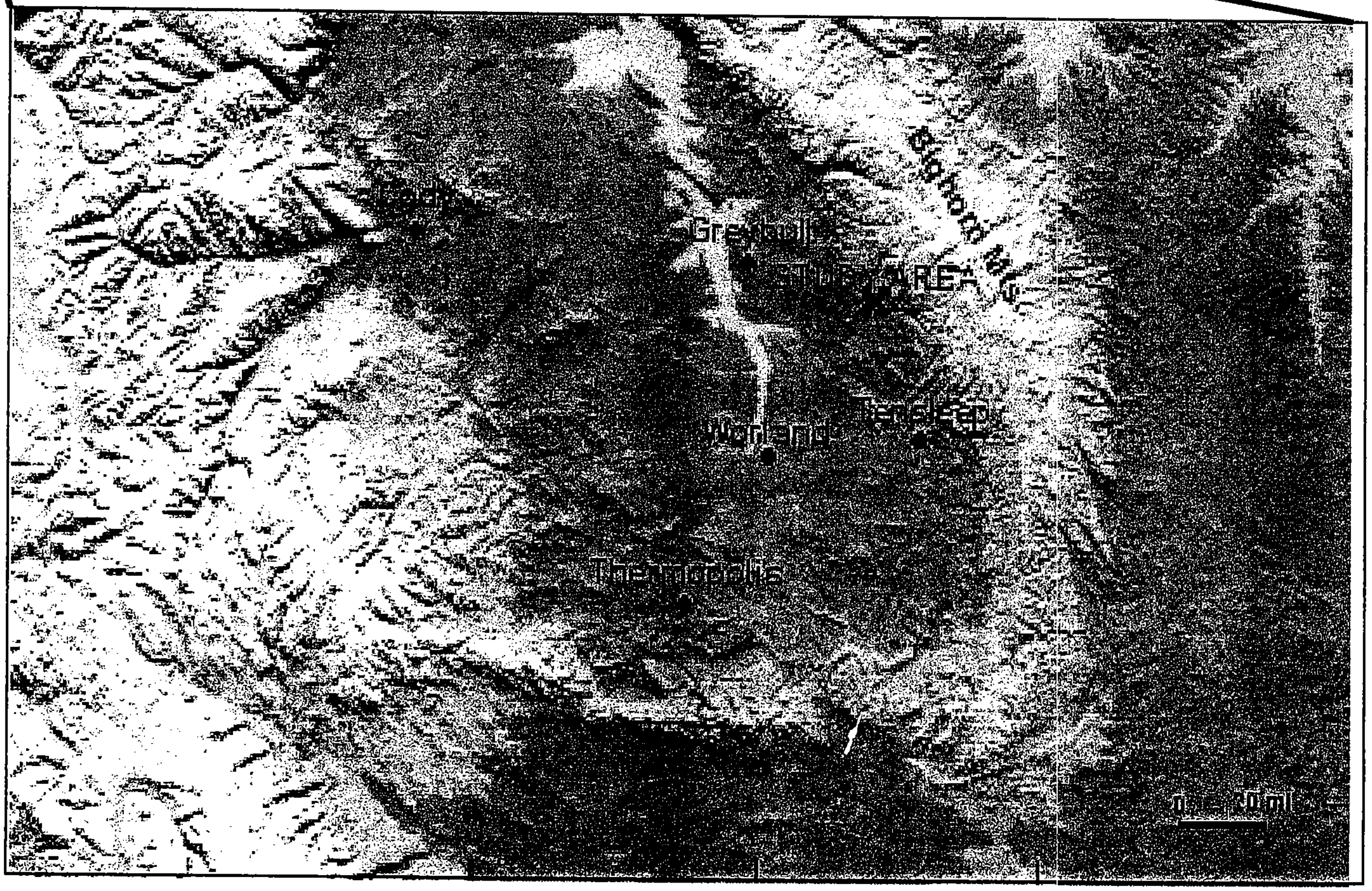


Neil Hurley
Bozkurt Ciftci
Ali Raba'a
Chris Zahm
Colorado School of Mines

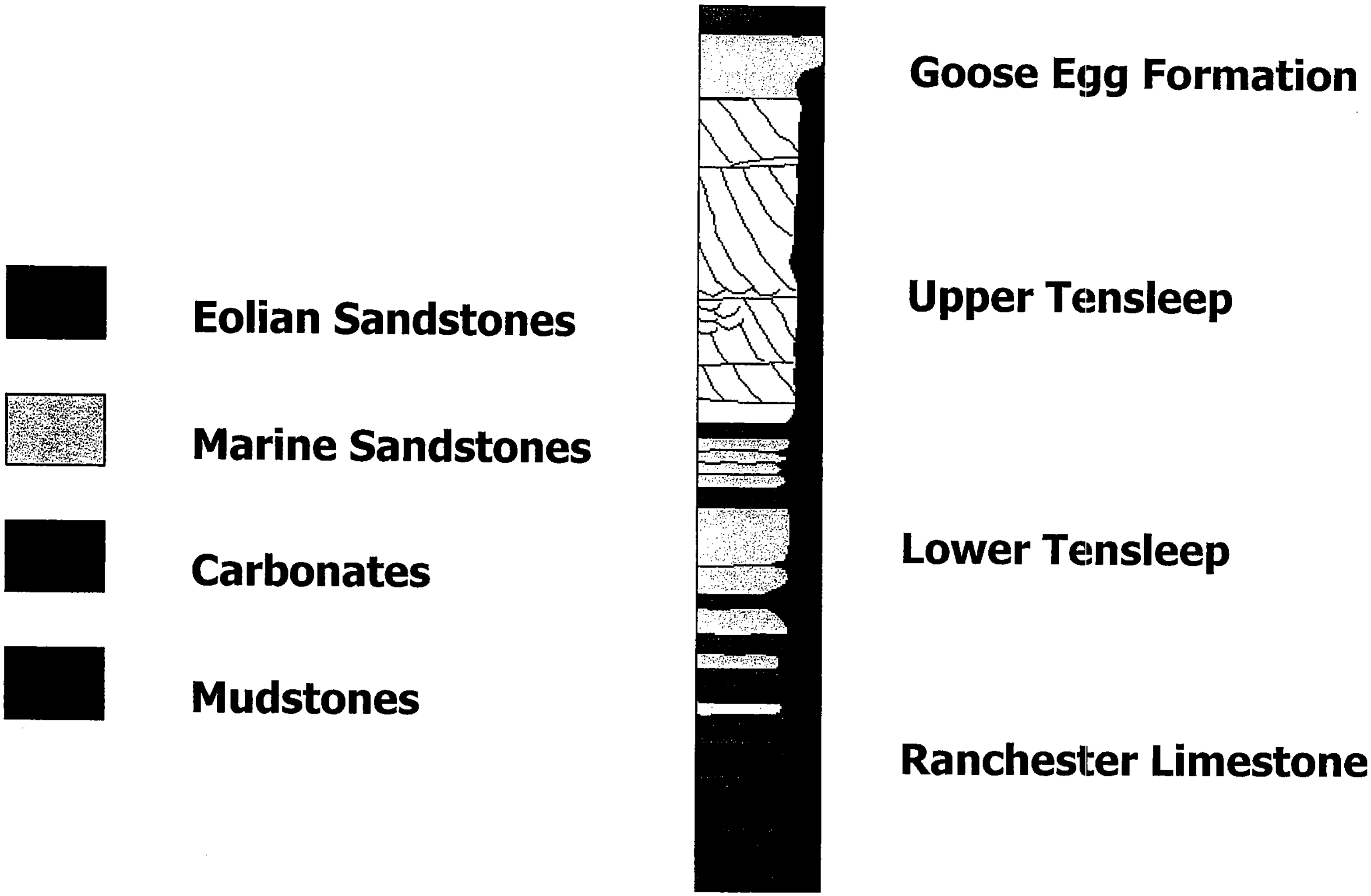
Research Objectives: Tensleep Sandstone

Use superb outcrop exposures in parallel canyon walls to identify the geometry and volumetric sizes of dune-related reservoir compartments.

Bighorn Basin

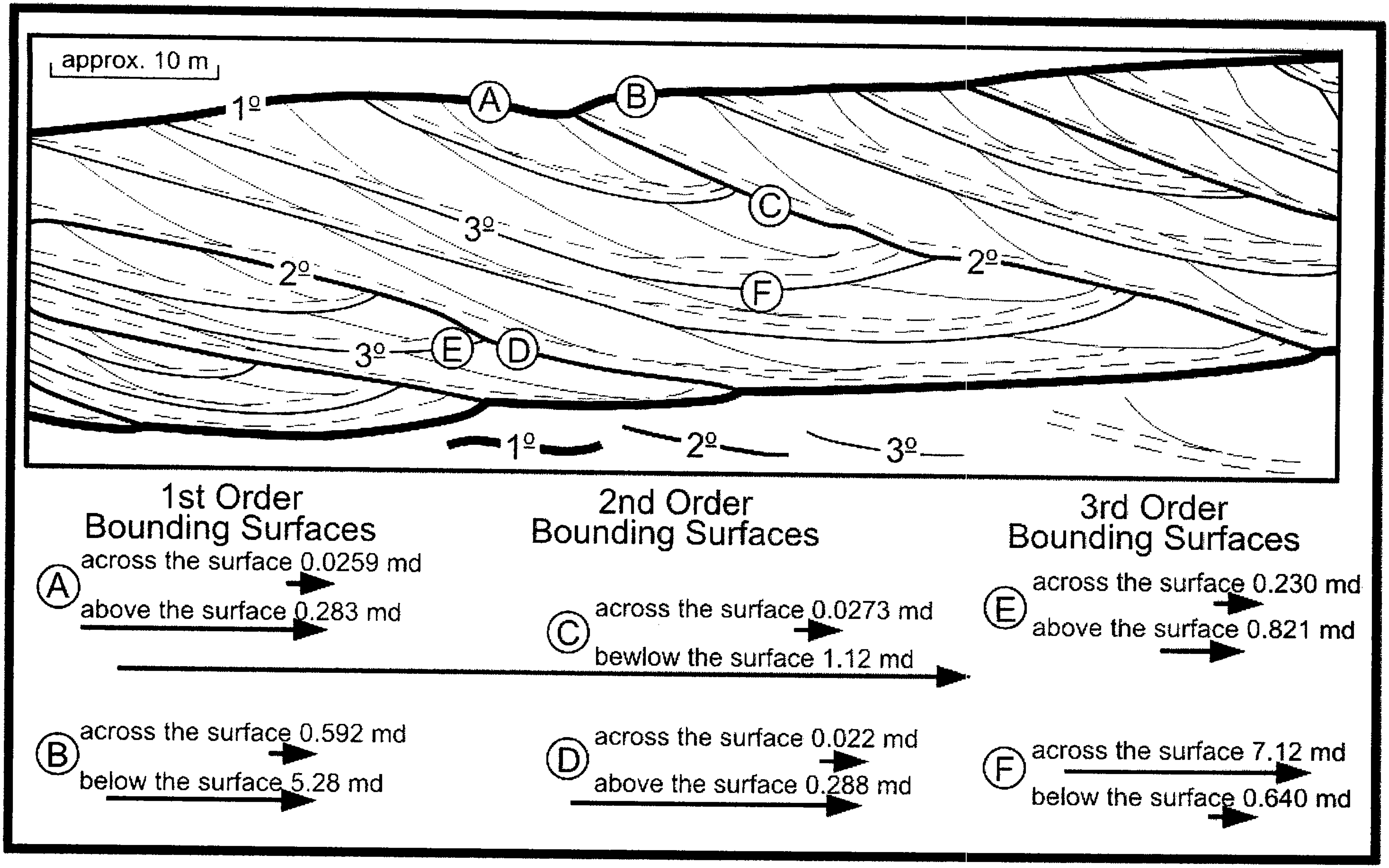


Tensleep Sandstone



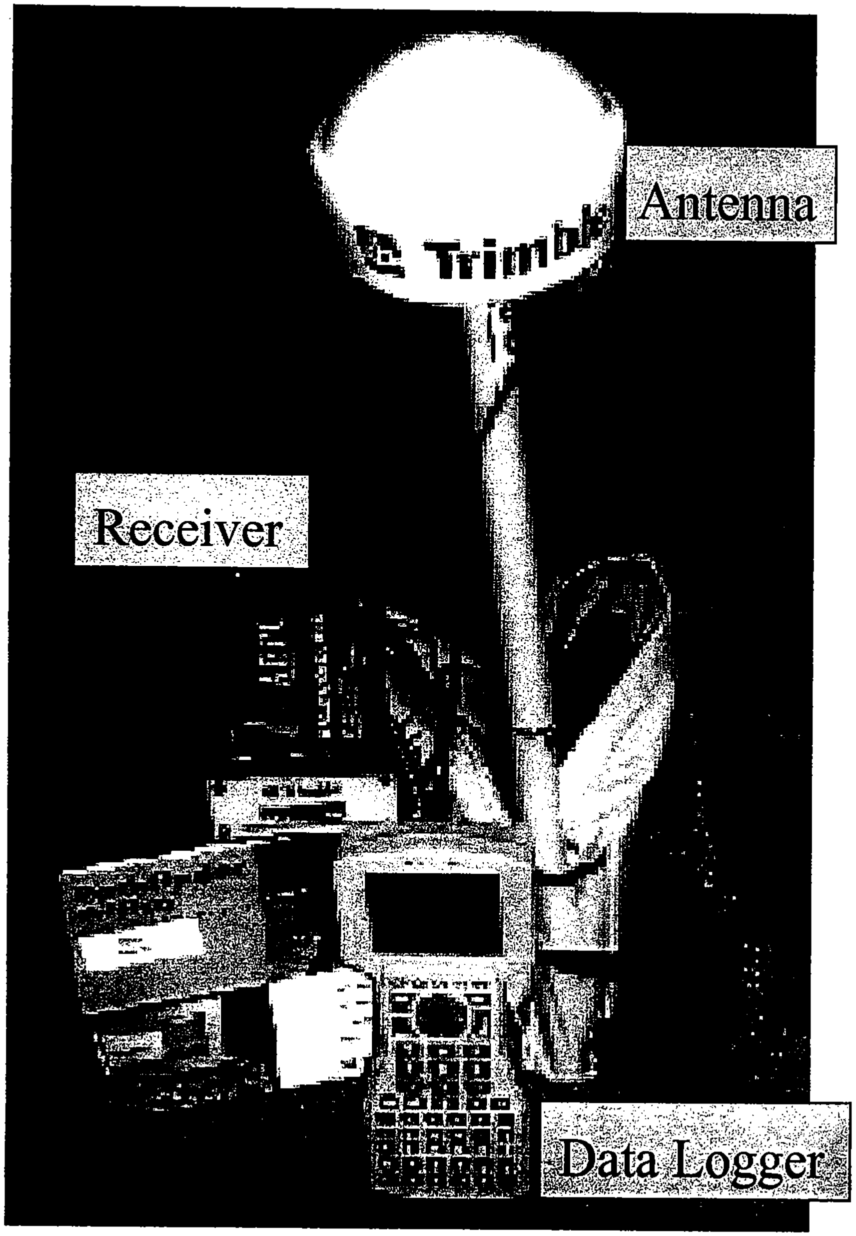
Wheeler, 1986

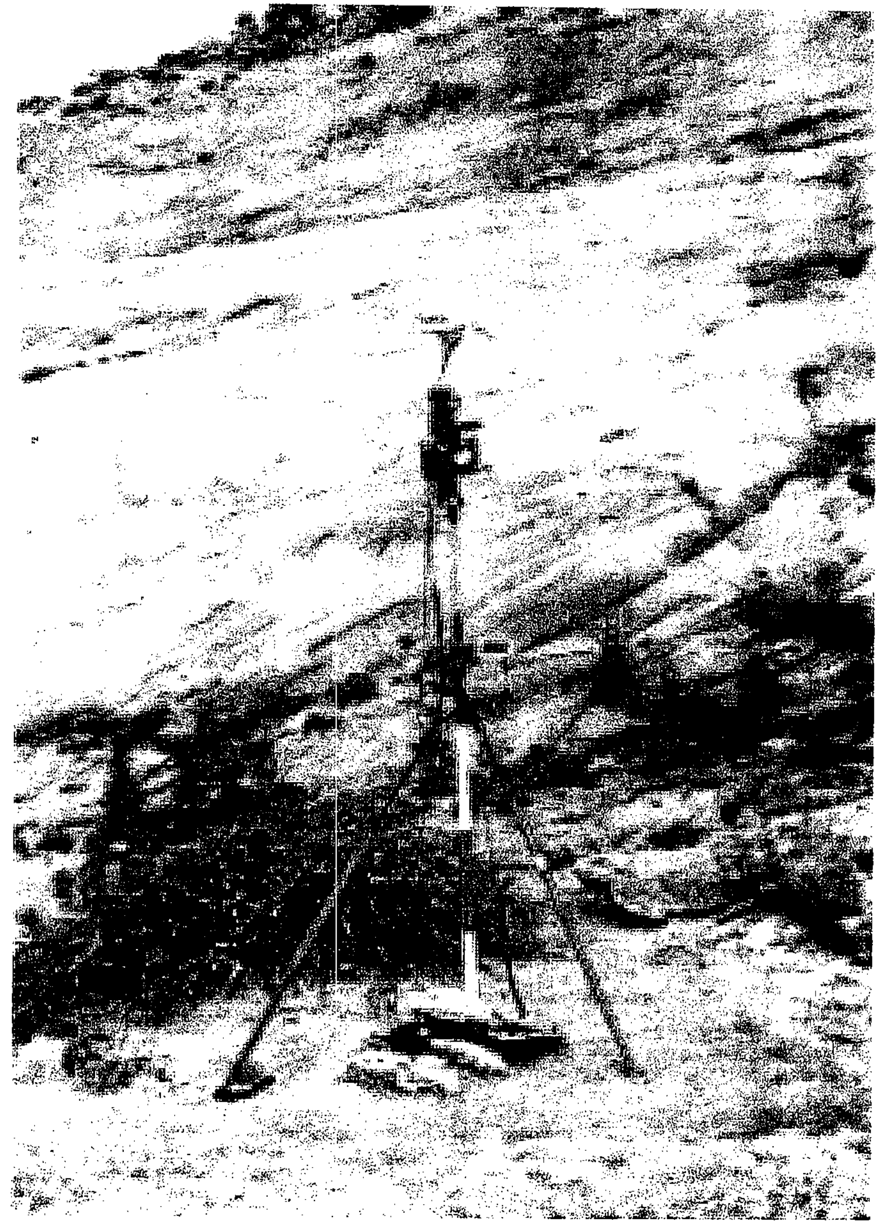
Bounding Surfaces in the Tensleep



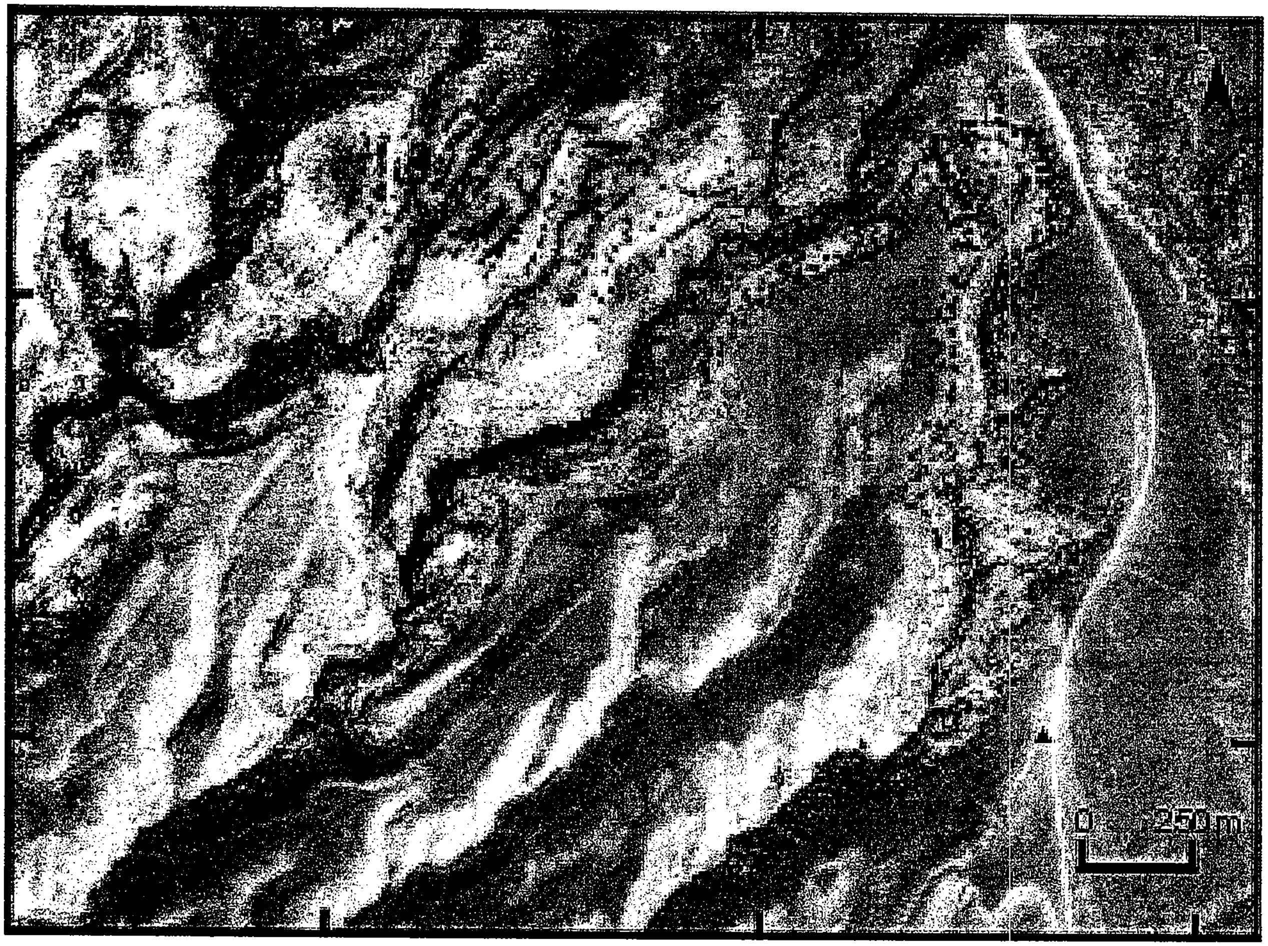
approx. 10 m
1º
2º
3º
A
B
C
D
E
F
1st Order Bounding Surfaces
A across the surface 0.0259 md
above the surface 0.283 md
B across the surface 0.592 md
below the surface 5.28 md
2nd Order Bounding Surfaces
C across the surface 0.0273 md
bewlow the surface 1.12 md
D across the surface 0.022 md
above the surface 0.288 md
3rd Order Bounding Surfaces
E across the surface 0.230 md
above the surface 0.821 md
F across the surface 7.12 md
below the surface 0.640 md

GPS (Global Positioning System)

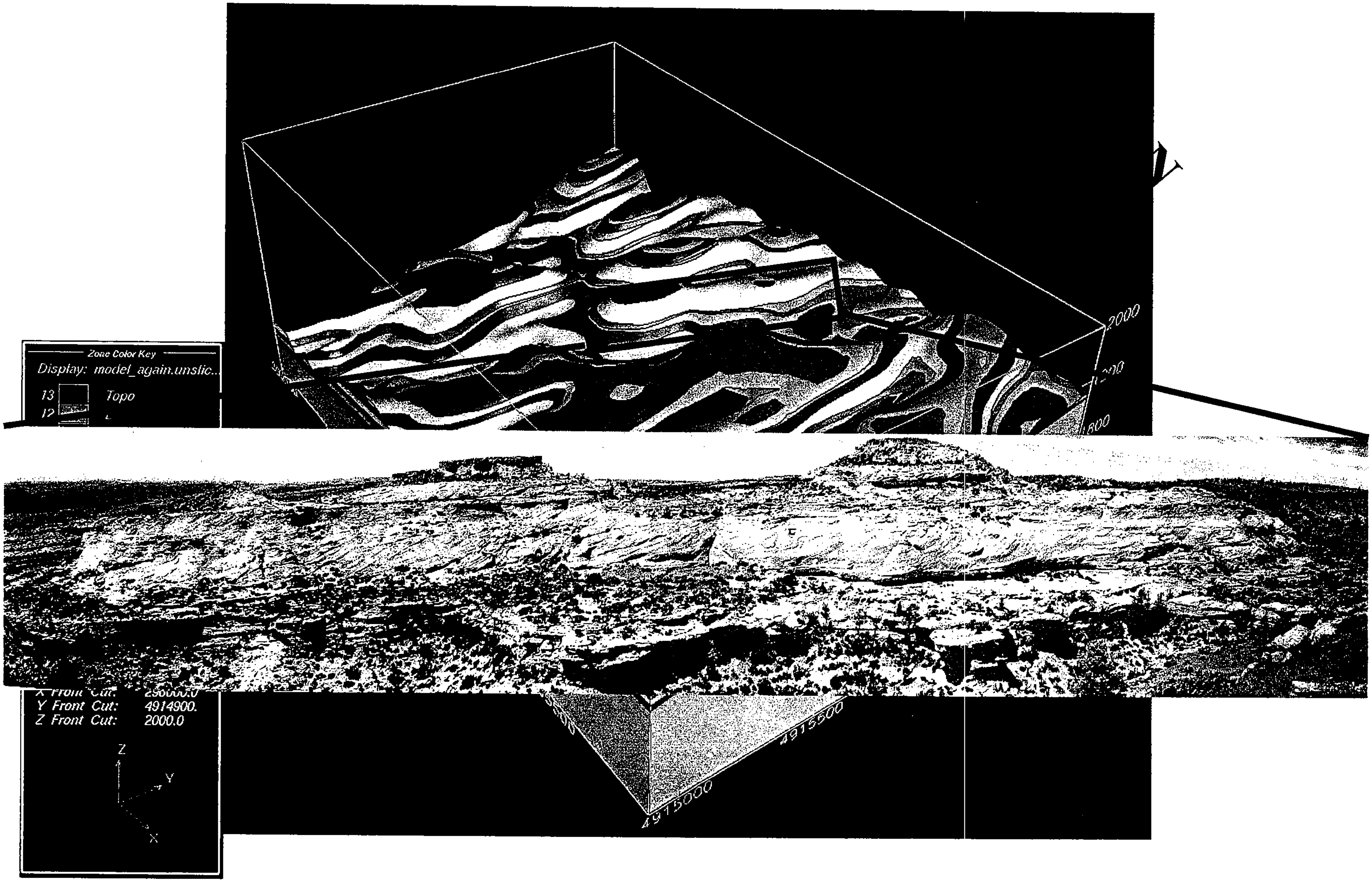




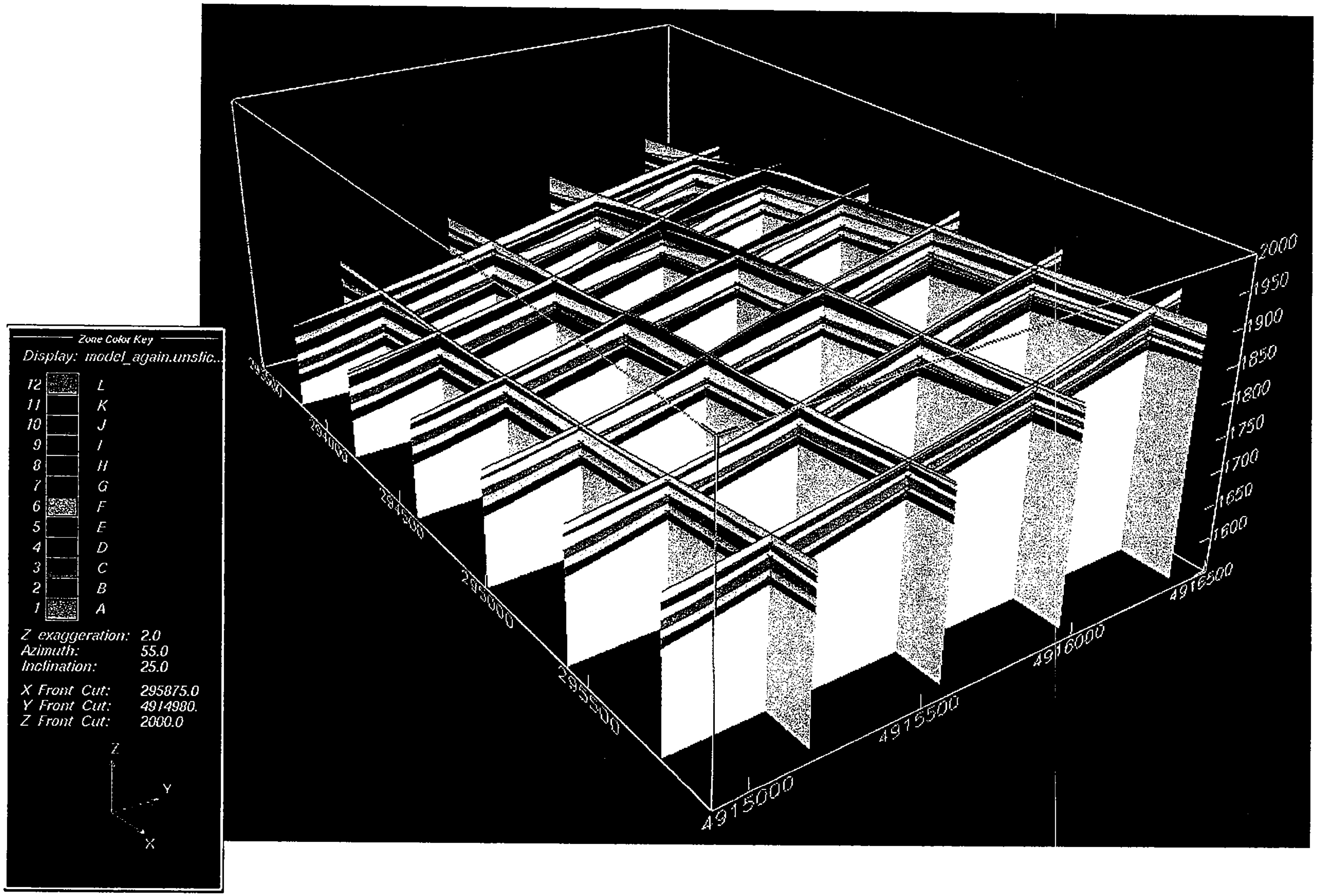
Field Work



Accuracy Control



3-D Model



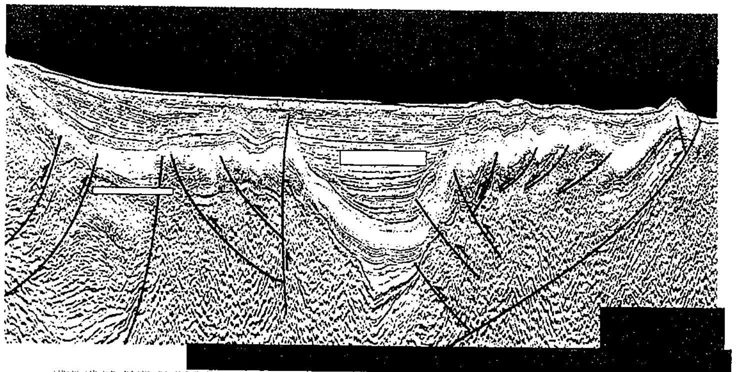
Zone Color Key
Display: model_again.unslic...
12 L
11 K
10 J
9 I
8 H
7 G
6 F
5 E
4 D
3 C
2 B
1 A
Z exaggeration: 2.0
Azimuth: 55.0
Inclination: 25.0
X Front Cut: 295875.0
Y Front Cut: 4914980.
Z Front Cut: 2000.0
Z
Y
X
2000
1950
1900
1850
1800
1750
1700
1650
1600
293500
294000
294500
295000
295500
4915000
4915500
4916000
4916500

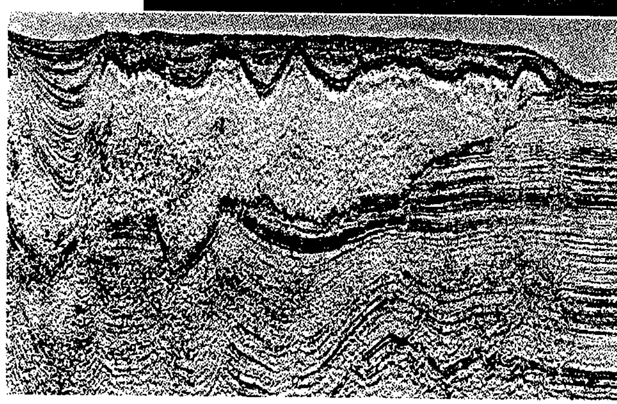
<u>Feature</u>   Structure <u>Seismic</u>   <u>Sub-seismic</u>

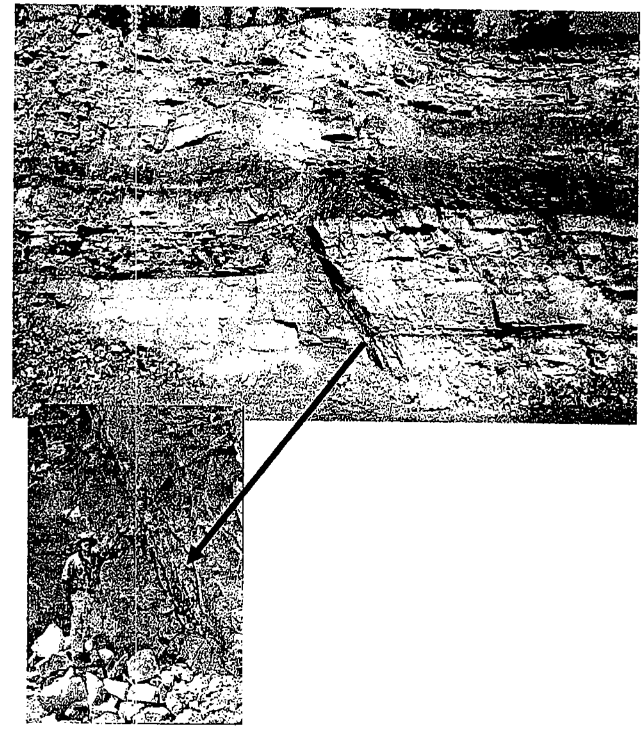
Fault

Fold

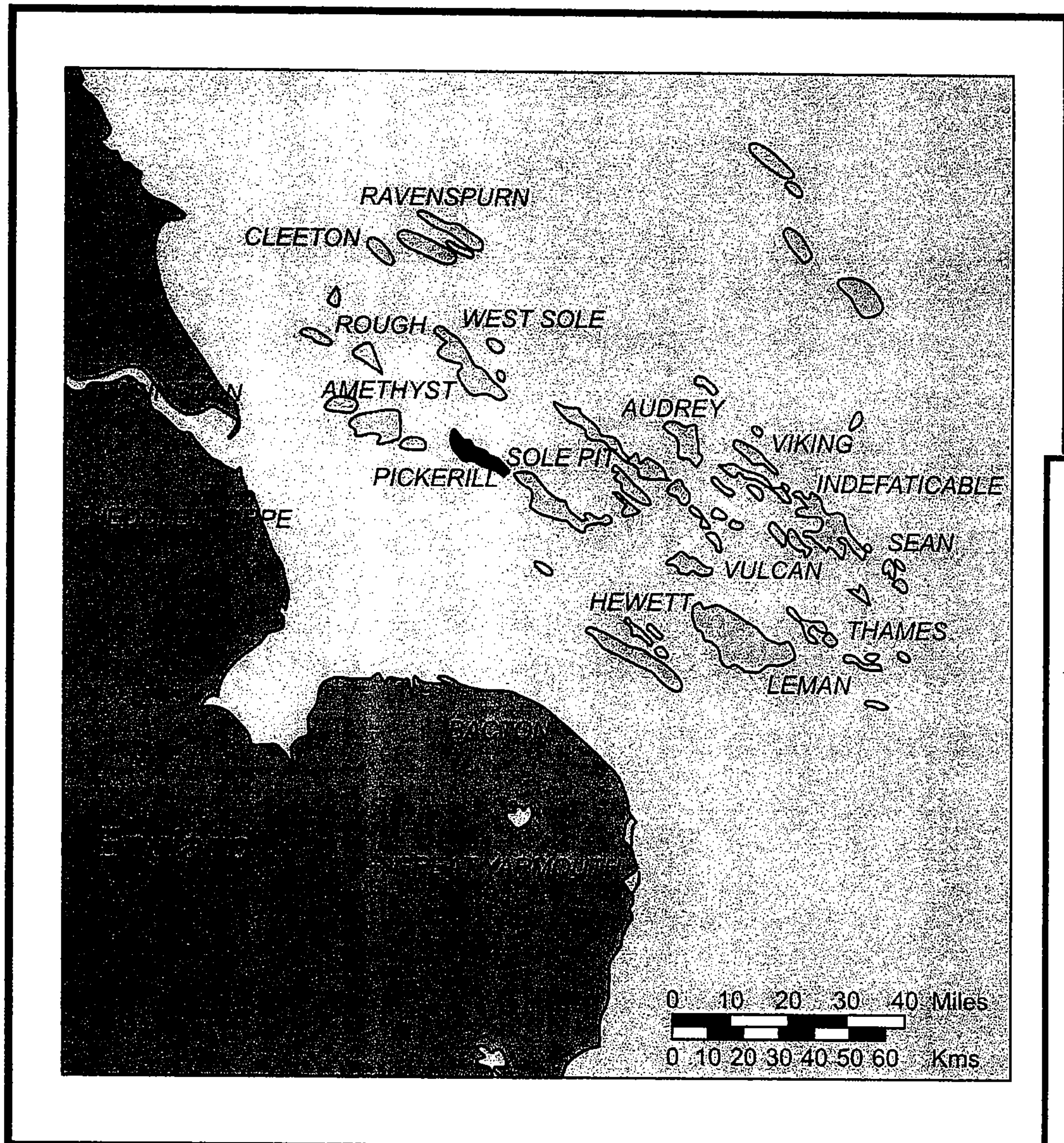
Diapir



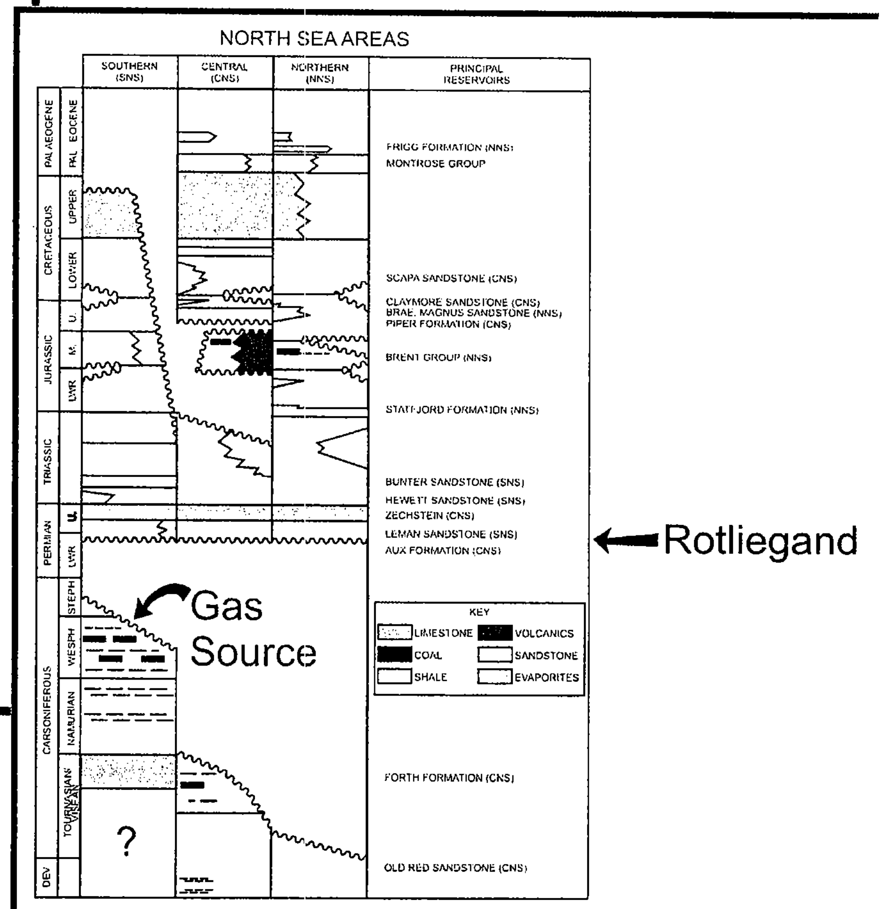


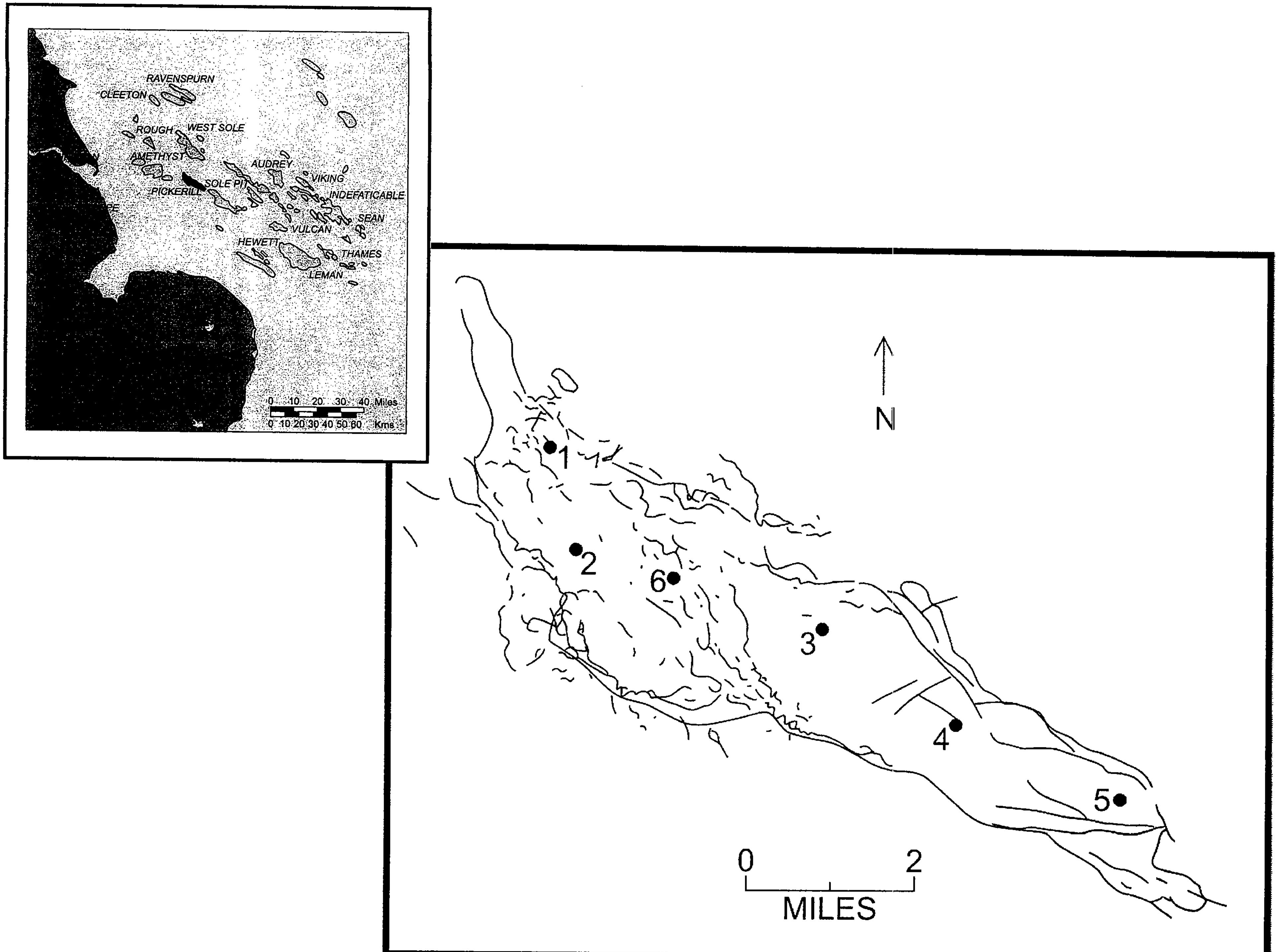


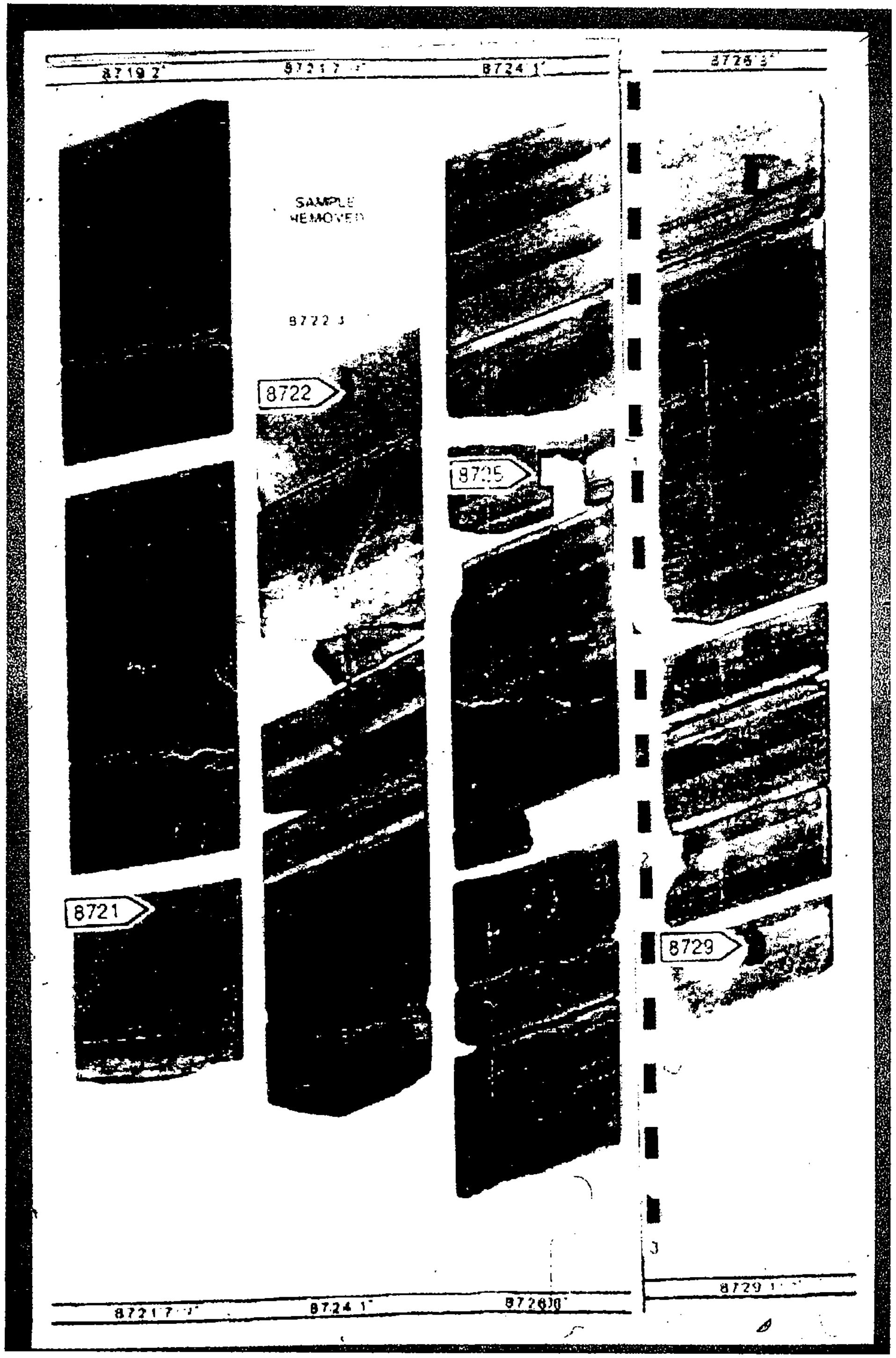
Fracture - - - - - -

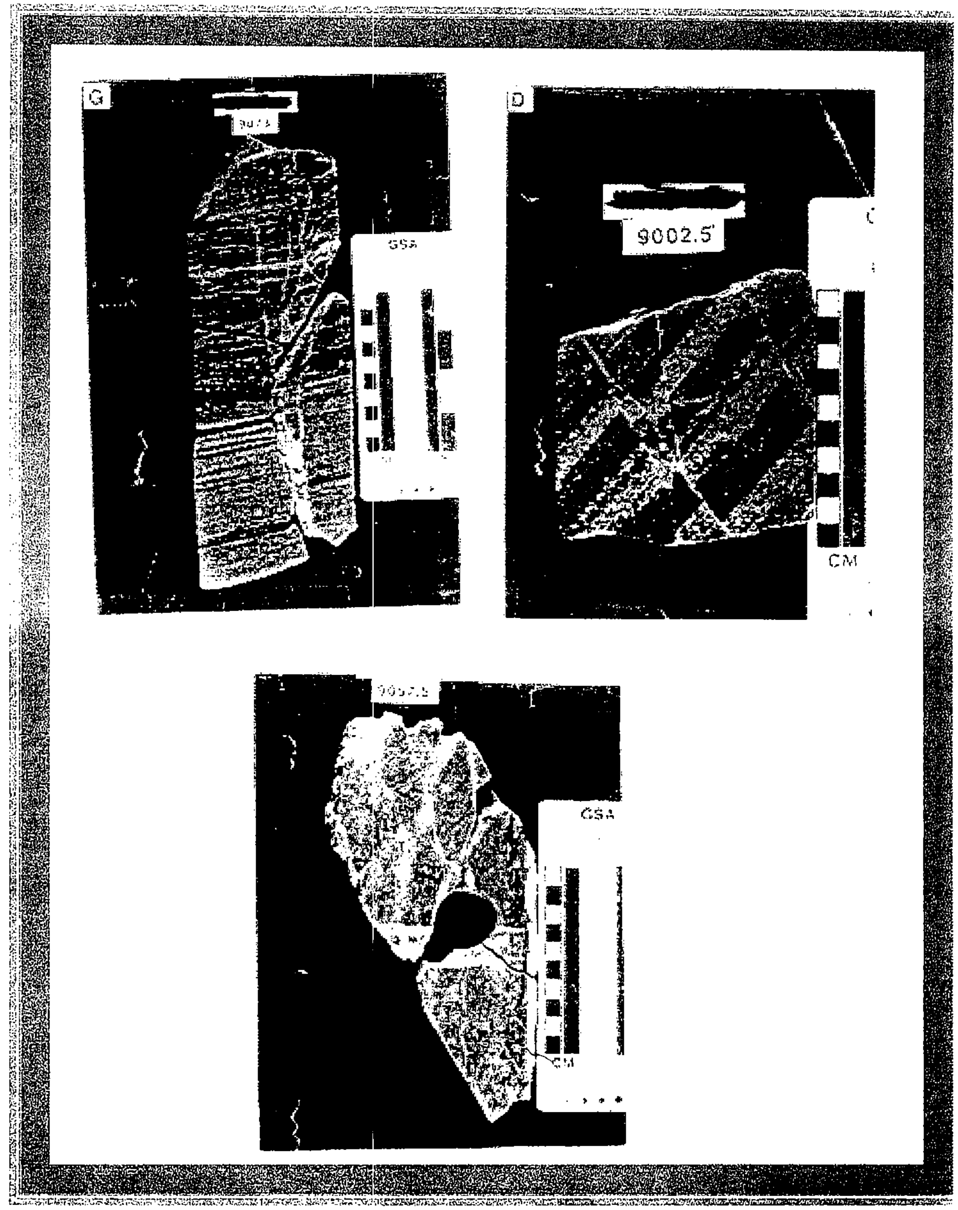


Pickerill Field, North Sea produces from Rotliegendes Sandstone (Permian)




RAVENSPURN
CLEETON
ROUGH
WEST SOLE
AMETHYST
AUDREY
VIKING
SOLE PIT
PICKERILL
INDEFATICABLE
SEAN
VULCAN
HEWETT
THAMES
LEMAN
0 10 20 30 40 Miles
0 10 20 30 40 50 60 Kms
N
1
2
3
4
5
6
0 2
MILES


SAMPLE REMOVED
8722
8725
8721
8729


G
GSA
D
9002.5'
CM
GSA
CM

Well #1 RFT RESULTS

MDRKB (FT)	TVDSS (FT)	HYDROSTATIC PRESSURE (PSIA)	FORMATION PRESSURE (PSIA)	REMARKS
9136	--	5306.6	--	Supercharged
9162	9026	5323.9	4081.4	Good Test
9172	9036	5328.9	4082.4	Good Test
9181	9045	5334.9	4082.6	Good Test
9193	9057	5341.1	4082.6	Good Test
9193	9057	5339.1	4082.4	Good Test
9172	--	5317.2	--	Tight
9212	9076	5354.2	4083.8	Good Test
9262	--	5379.2	--	Seal Failure
9270	--	5384.3	--	Tight
9324	--	5416.6	--	Tight

Well #2 RTF RESULTS

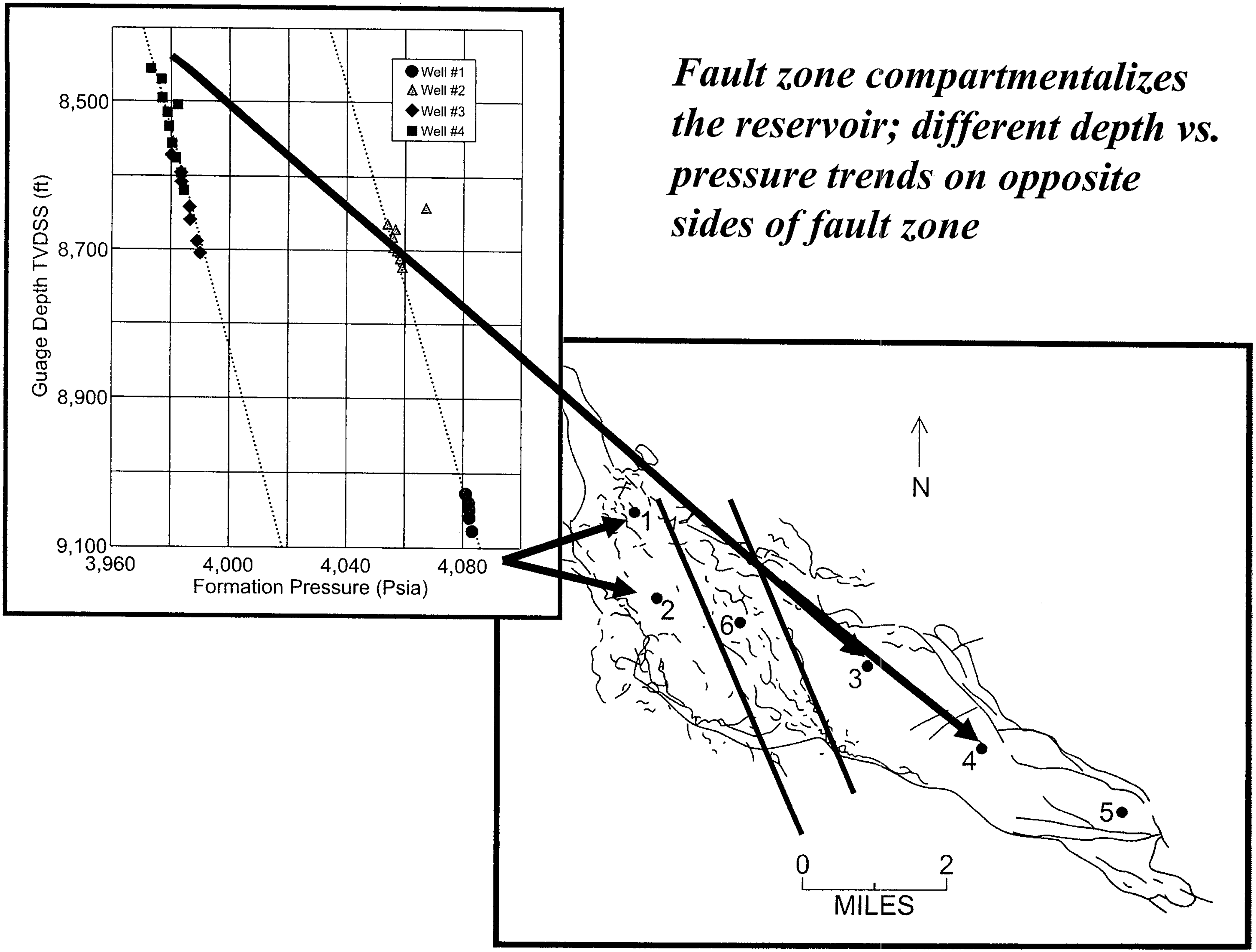
MDRKB (FT)	TVDSS (FT)	HYDROSTATIC PRESSURE (PSIA)	FORMATION PRESSURE (PSIA)	REMARKS
8787	8640	4628	4067.5	Tight
8811	8664	4643	4053.8	Good Permeability
8818	8671	4649	4056.7	Sample Taken
8829	8682	4655	4055.7	Good Permeability
8843	8696	4657	4056.4	Good Permeability
8849	8702	4659	4057.6	Good Permeability
8857	8710	4663	4058.1	Good Permeability
8869	8722	4671	4059.2	Tight

Well #3 RFT RESULTS

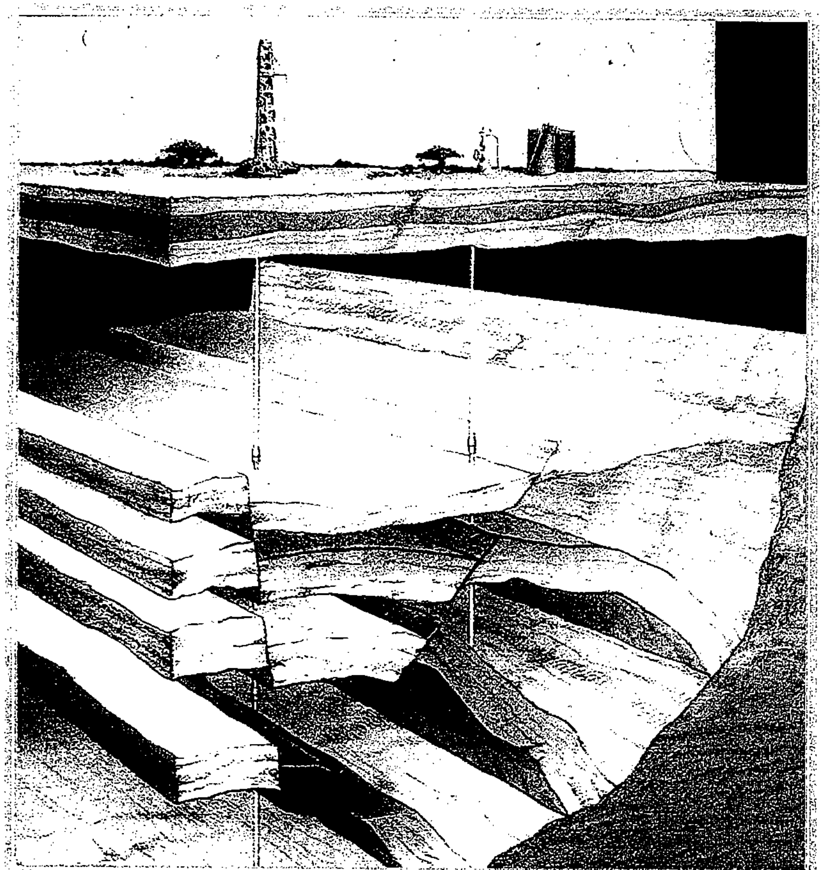
MDRKB (FT)	TVDSS (FT)	HYDROSTATIC PRESSURE (PSIA)	FORMATION PRESSURE (PSIA)	REMARKS
8698	8572	4431	3980.0	Good Permeability
8720	8596	4440	3983.2	Good Permeability
8732	8608	4445	3983.4	Good Permeability
8740	--	4448	--	Tight
8766	8642	4445	3986.3	Good Permeability
8784	8660	4447	3986.5	Good Permeability
8814	8690	4490	3989.1	Good Permeability
8828	8704	4488	3990.0	Good Permeability
8830	--	497	--	Tight
8843	--	4497	--	Tight
8845	--	4501	--	Tight
8847	--	4499	--	Tight

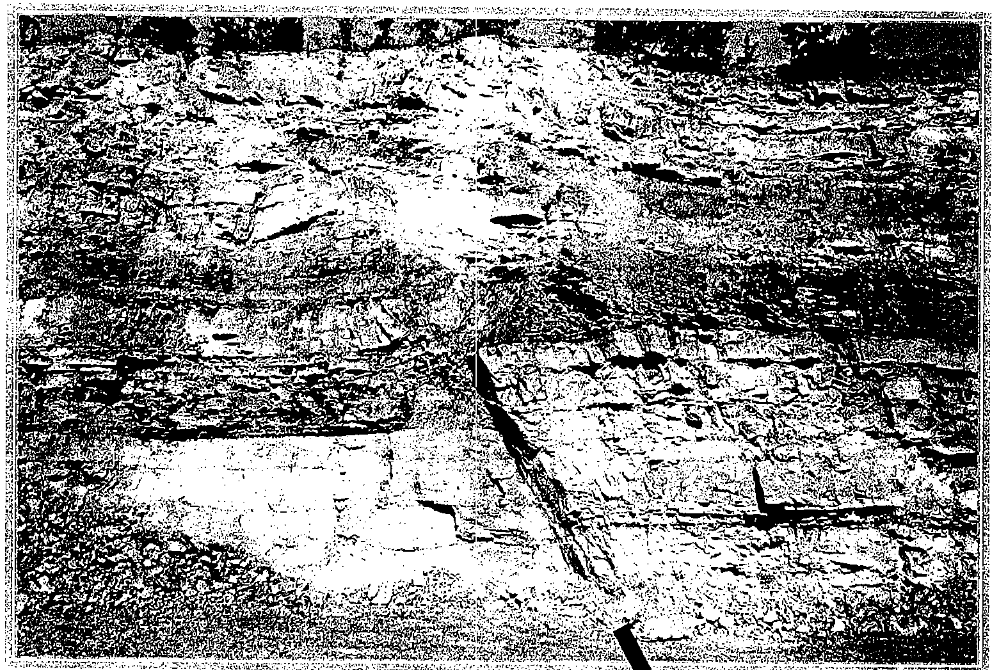
Well #4 RFT RESULTS

MDRKB (FT)	TVDSS (FT)	HYDROSTATIC PRESSURE (PSIA)	FORMATION PRESSURE (PSIA)	REMARKS
8578	--	4485	--	Tight
8582	8457	4447.9	3972.9	Good Test
8596	8471	4494.1	3976.4	Good Test
8620	8495	4468.5	3976.7	Good Test
8630	8505	4504.5	3982.2	Supercharged?
8640	8515	4478.3	3978.6	Good Test
8660	8535	4522.5	3978.9	Good Test
8680	8555	4533.6	3980.3	Good Test
8697	--	4542.3	--	Tight
8700	8575	4541.8	3981.2	Good Test
8721	8596	4518.0	3983.2	Good Test
8745	8620	4565.8	3984.2	Good Test
8760	--	4572.2	--	Tight
8764	--	4550.2	--	Tight
8770	--	4575.8	--	Tight

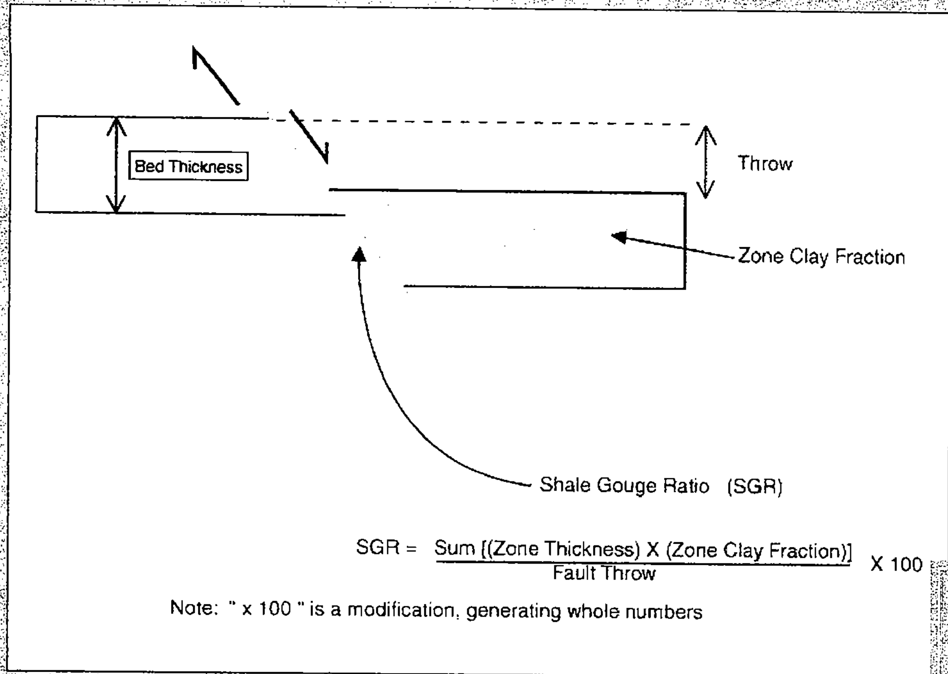


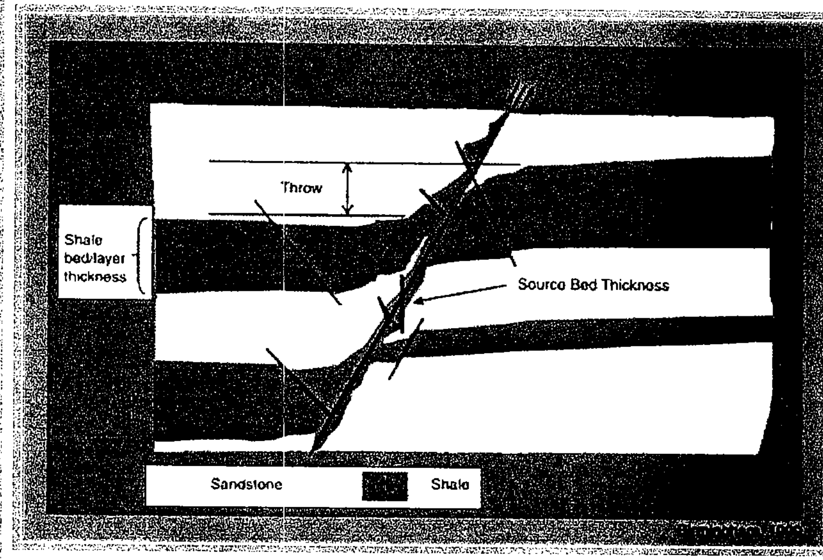
Fault zone compartmentalizes the reservoir; different depth vs. pressure trends on opposite sides of fault zone

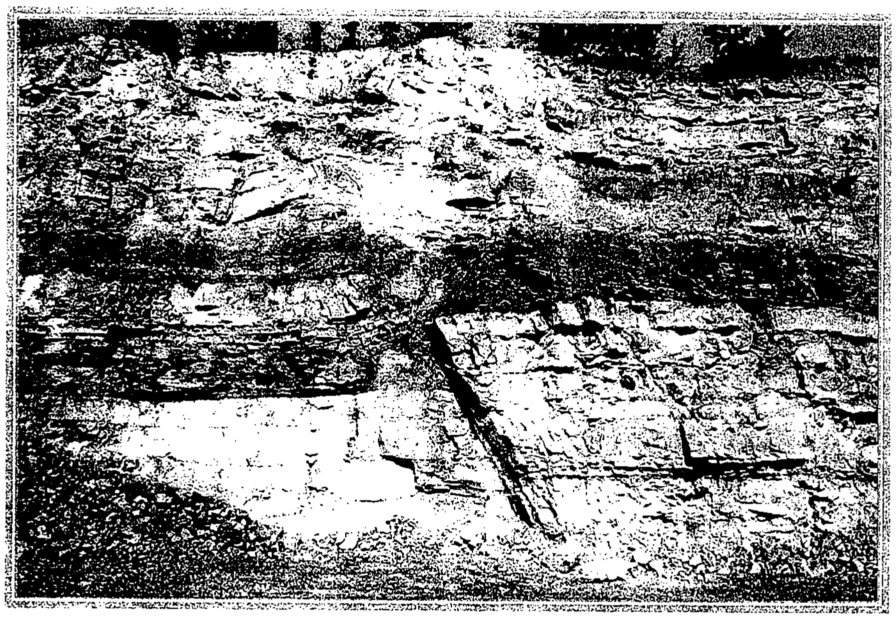


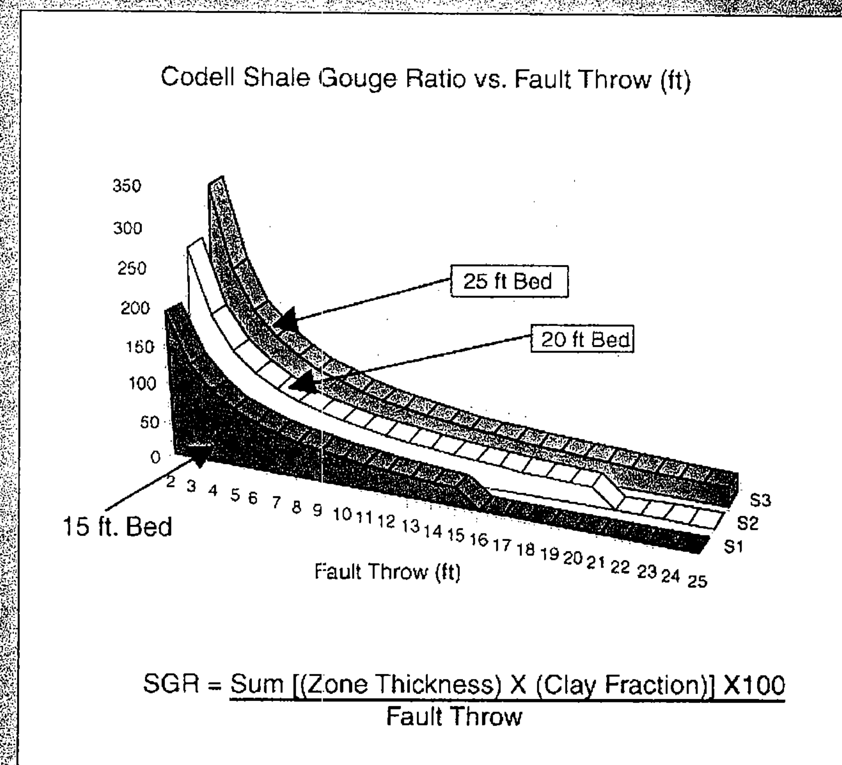


Small faults can compartmentalize a reservoir

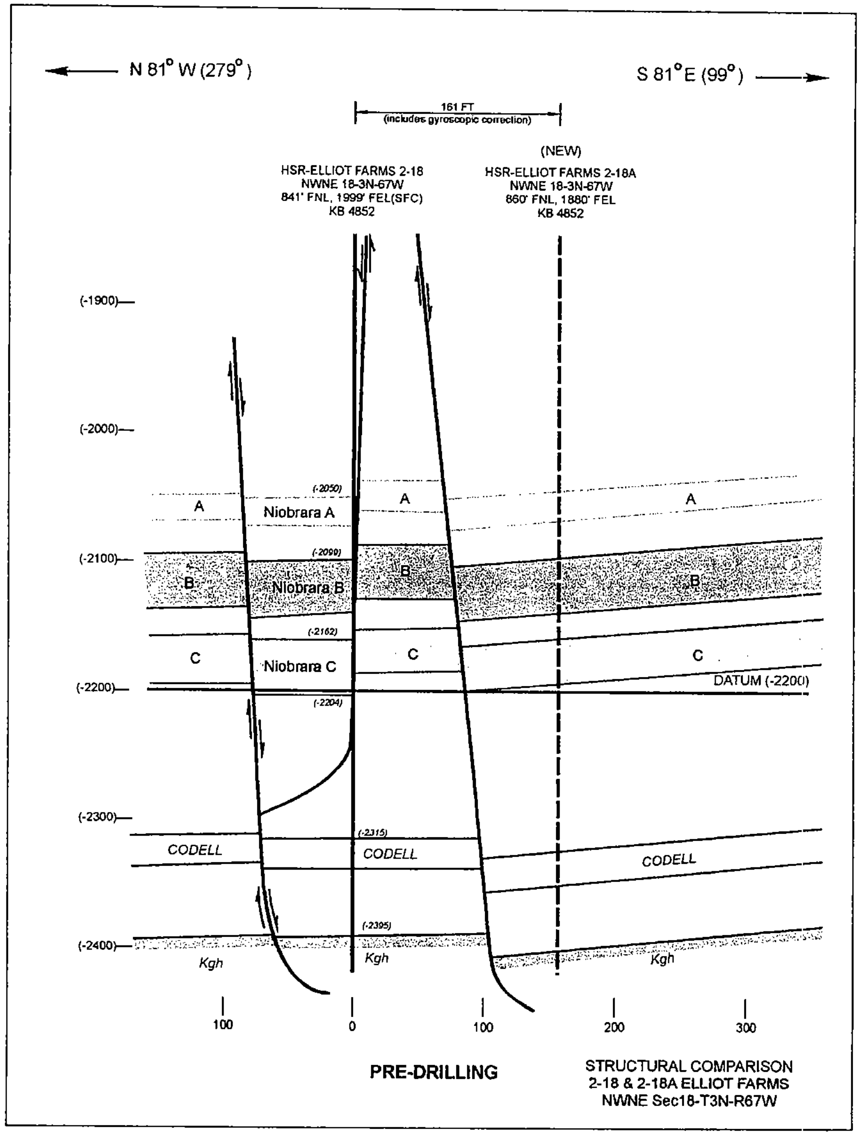

Bed Thickness
Throw
Zone Clay Fraction
Shale Gouge Ratio (SGR)
SGR = Sum [(Zone Thickness) X (Zone Clay Fraction)] / Fault Throw X 100
Note: " x 100 " is a modification, generating whole numbers


Throw
Shale bed/layer thickness
Source Bed Thickness
Sandstone
Shale

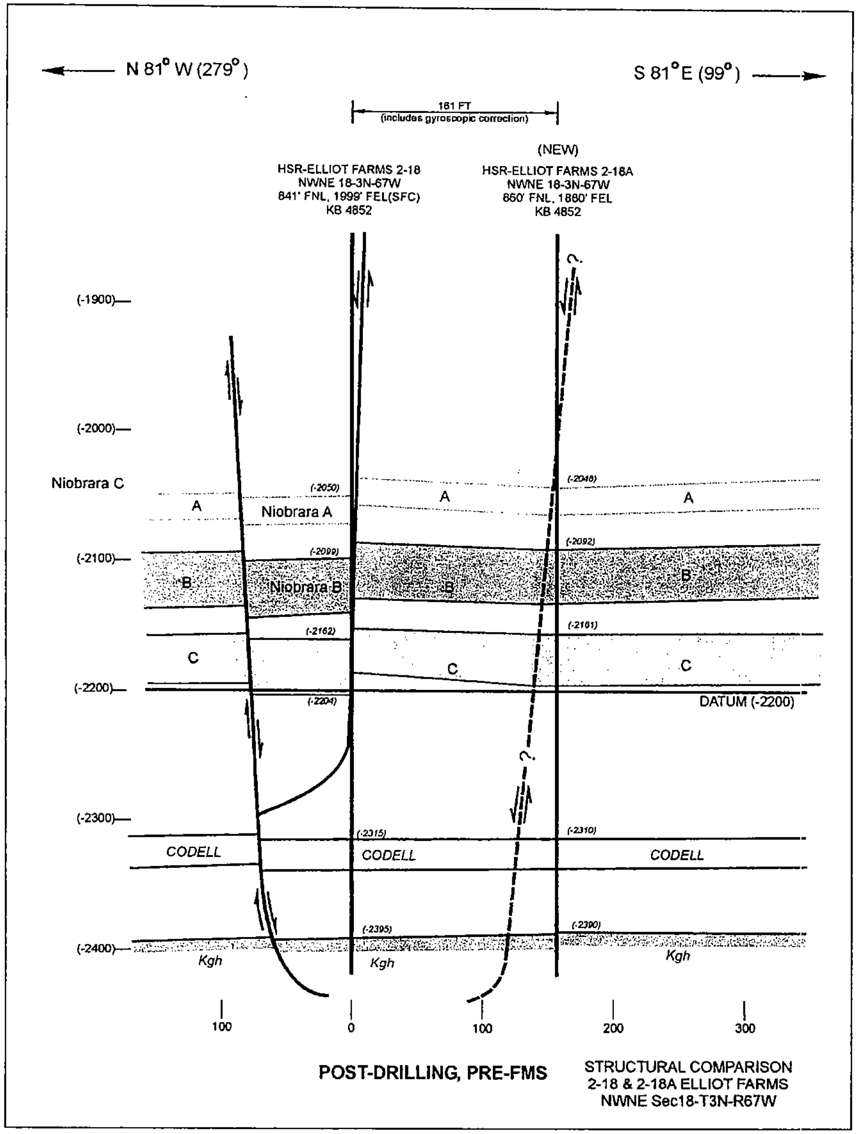



Codell Shale Gouge Ratio vs. Fault Throw (ft)
350
300
250
200
150
100
50
0
25 ft Bed
20 ft Bed
15 ft. Bed
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Fault Throw (ft)
S3
S2
S1
SGR = Sum [(Zone Thickness) X (Clay Fraction)] X100 / Fault Throw
Birmingham, 1999

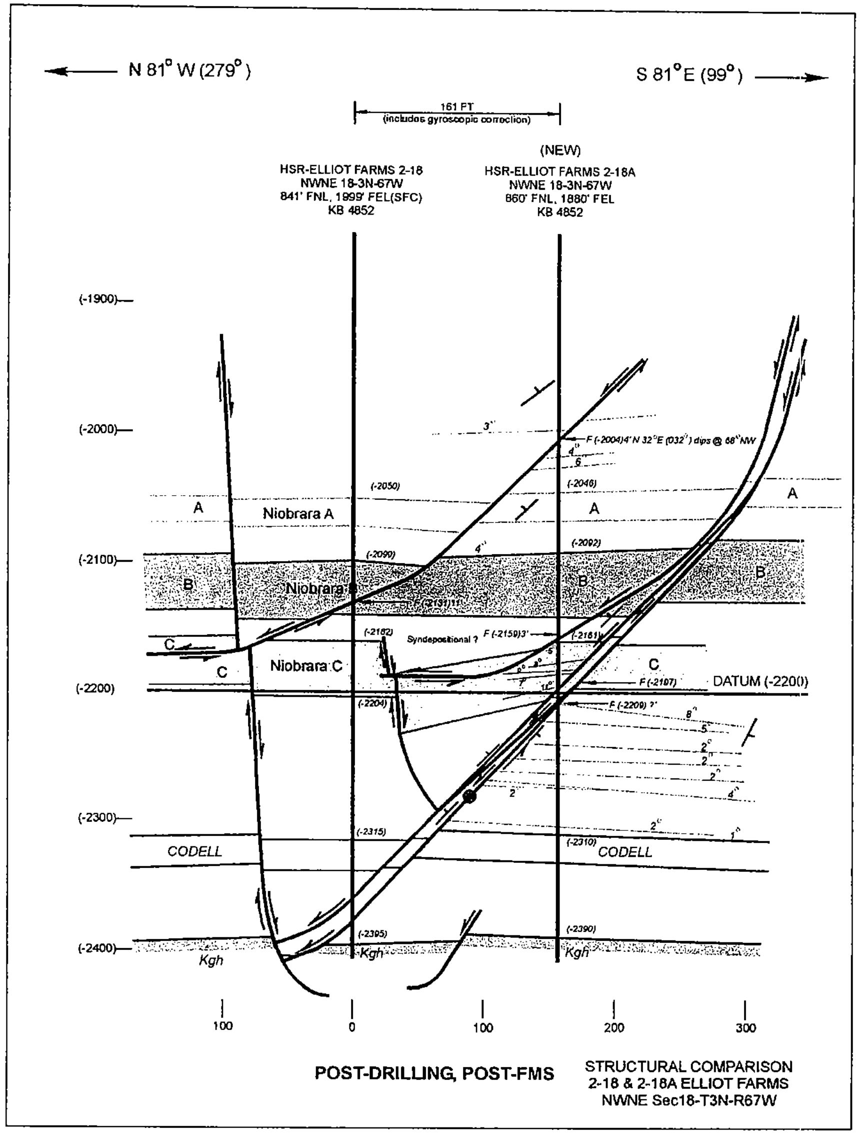
Pre Drill

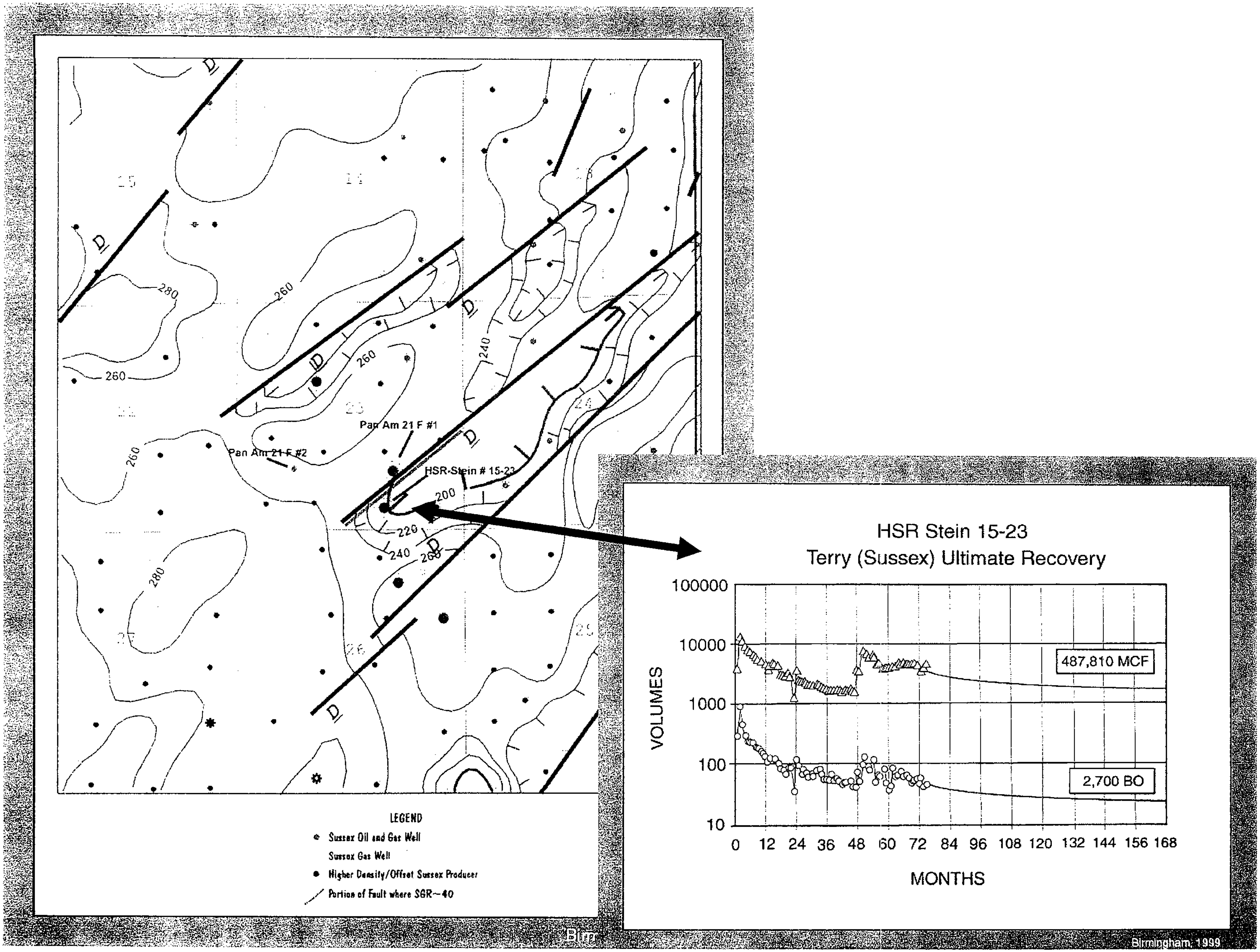

N 81° W (279°)
S 81° E (99°)
161 FT
(includes gyroscopic correction)
HSR-ELLIOT FARMS 2-18
NWNE 18-3N-67W
841' FNL, 1999' FEL(SFC)
KB 4852
(NEW)
HSR-ELLIOT FARMS 2-18A
NWNE 18-3N-67W
860' FNL, 1880' FEL
KB 4852
(-1900)
(-2000)
(-2100)
(-2200)
(-2300)
(-2400)
(-2050)
(-2090)
(-2162)
(-2204)
(-2315)
(-2395)
A
Niobrara A
B
Niobrara B
C
Niobrara C
DATUM (-2200)
CODELL
Kgh
100
0
100
200
300
PRE-DRILLING
STRUCTURAL COMPARISON
2-18 & 2-18A ELLIOT FARMS
NWNE Sec18-T3N-R67W

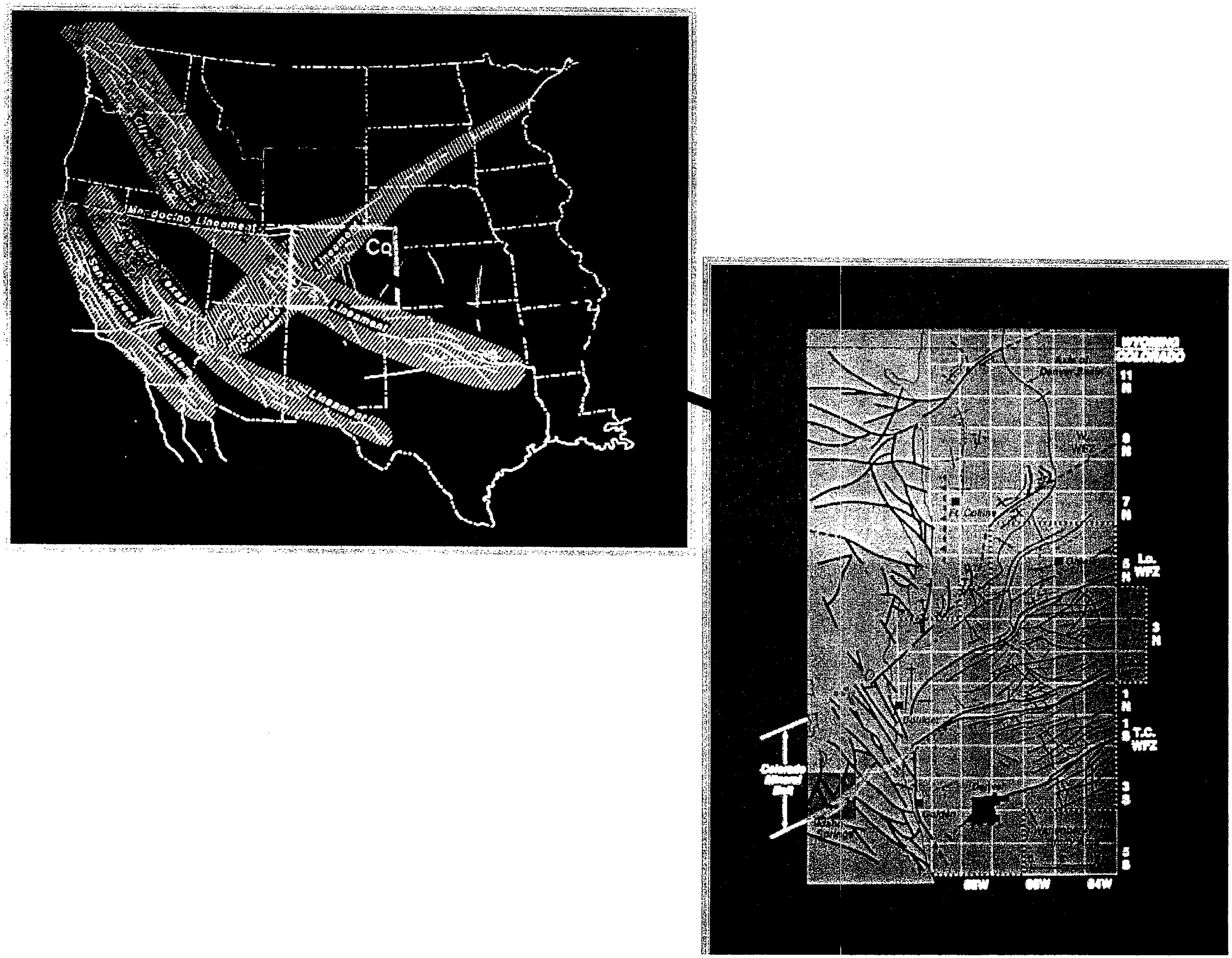
Post Drill, Pre FMS log



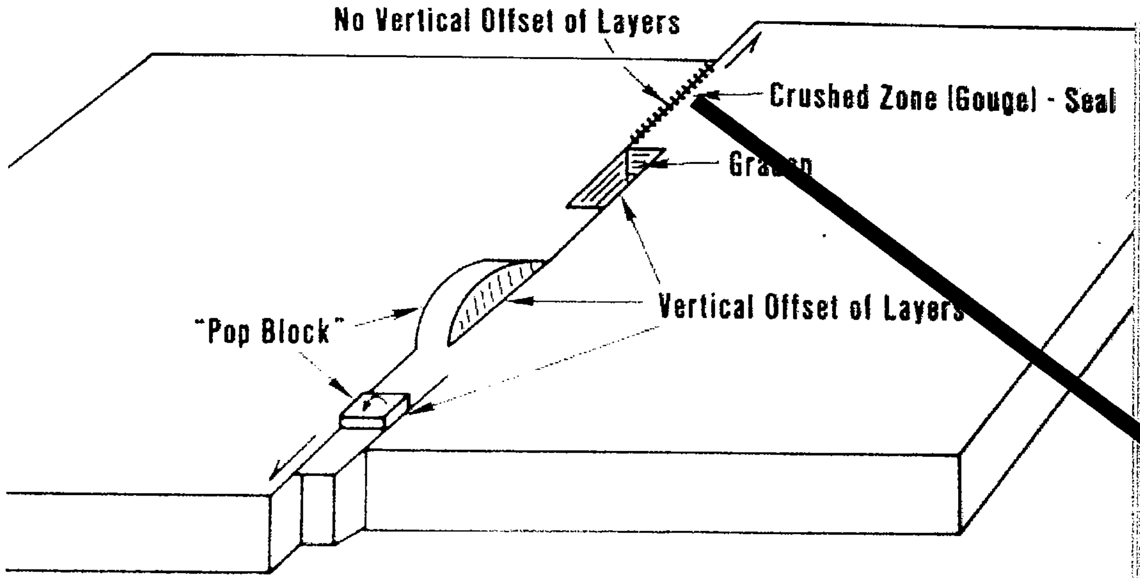
Post Drill, post FMS log



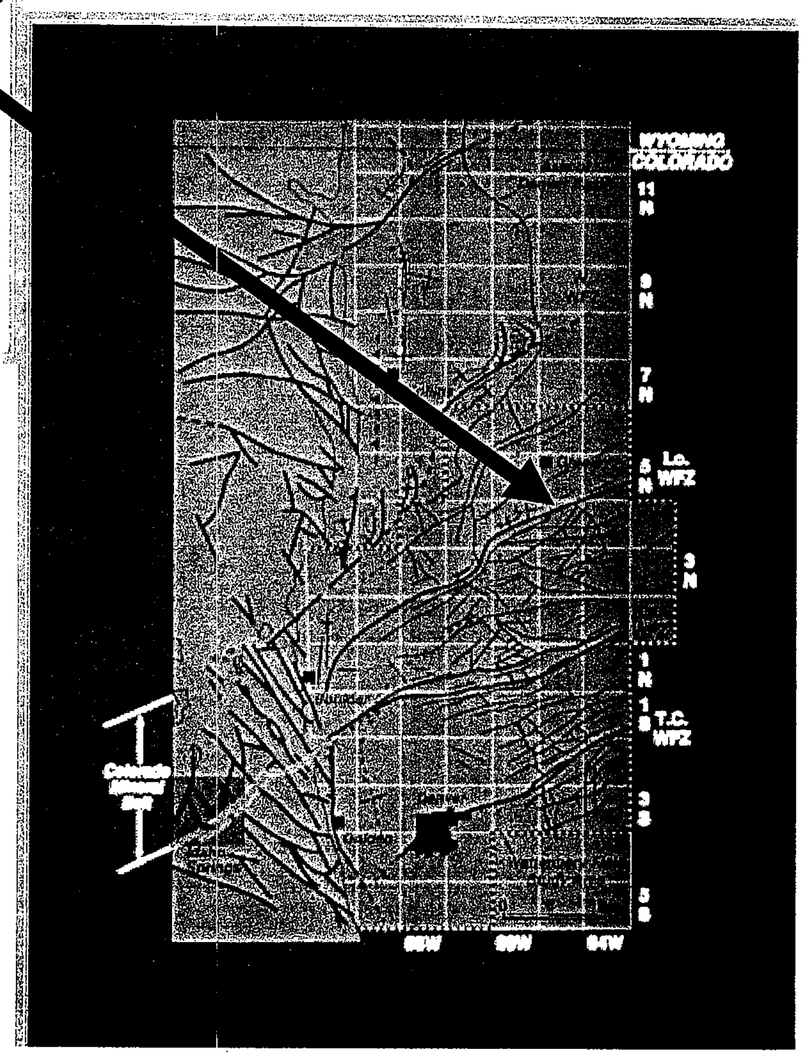

Pan Am 21 F #1
Pan Am 21 F #2
HSR-Stein # 15-23
LEGEND
Sussex Oil and Gas Well
Sussex Gas Well
Higher Density/Offset Sussex Producer
Portion of Fault where SGR~40
HSR Stein 15-23
Terry (Sussex) Ultimate Recovery
100000
10000
1000
100
10
VOLUMES
0 12 24 36 48 60 72 84 96 108 120 132 144 156 168
MONTHS
487,810 MCF
2,700 BO
Birmingham, 1999

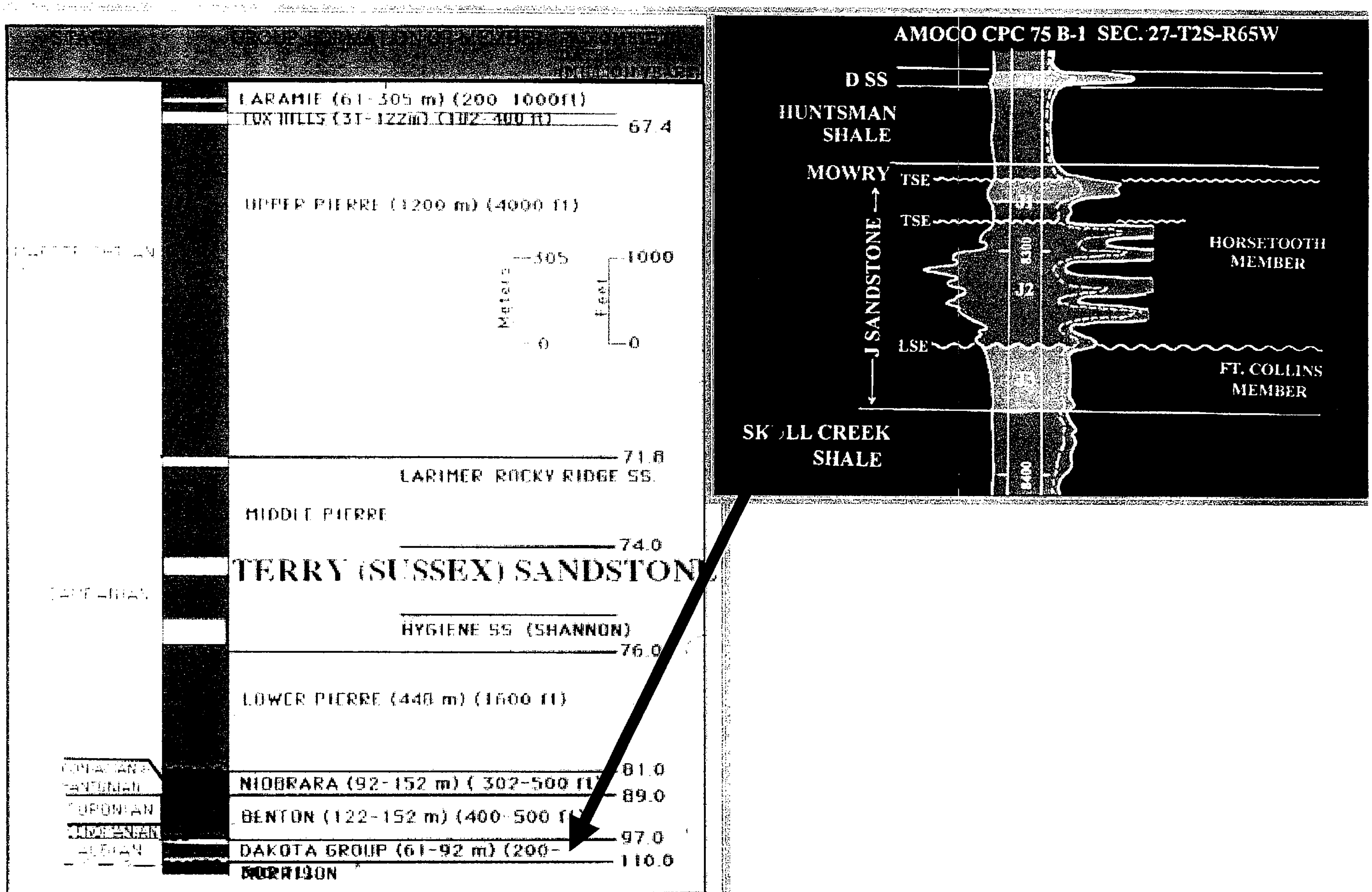


Mendocino Lineament
San Andreas
System
Lineament
Lineament
Lineament
Colorado
Cq
WYOMING
COLORADO
Denver Basin
11 N
9 N
7 N
Ft. Collins
5 N
Lo. WFZ
3 N
1 N
1 S
T.C. WFZ
3 S
5 S
68W
66W
64W



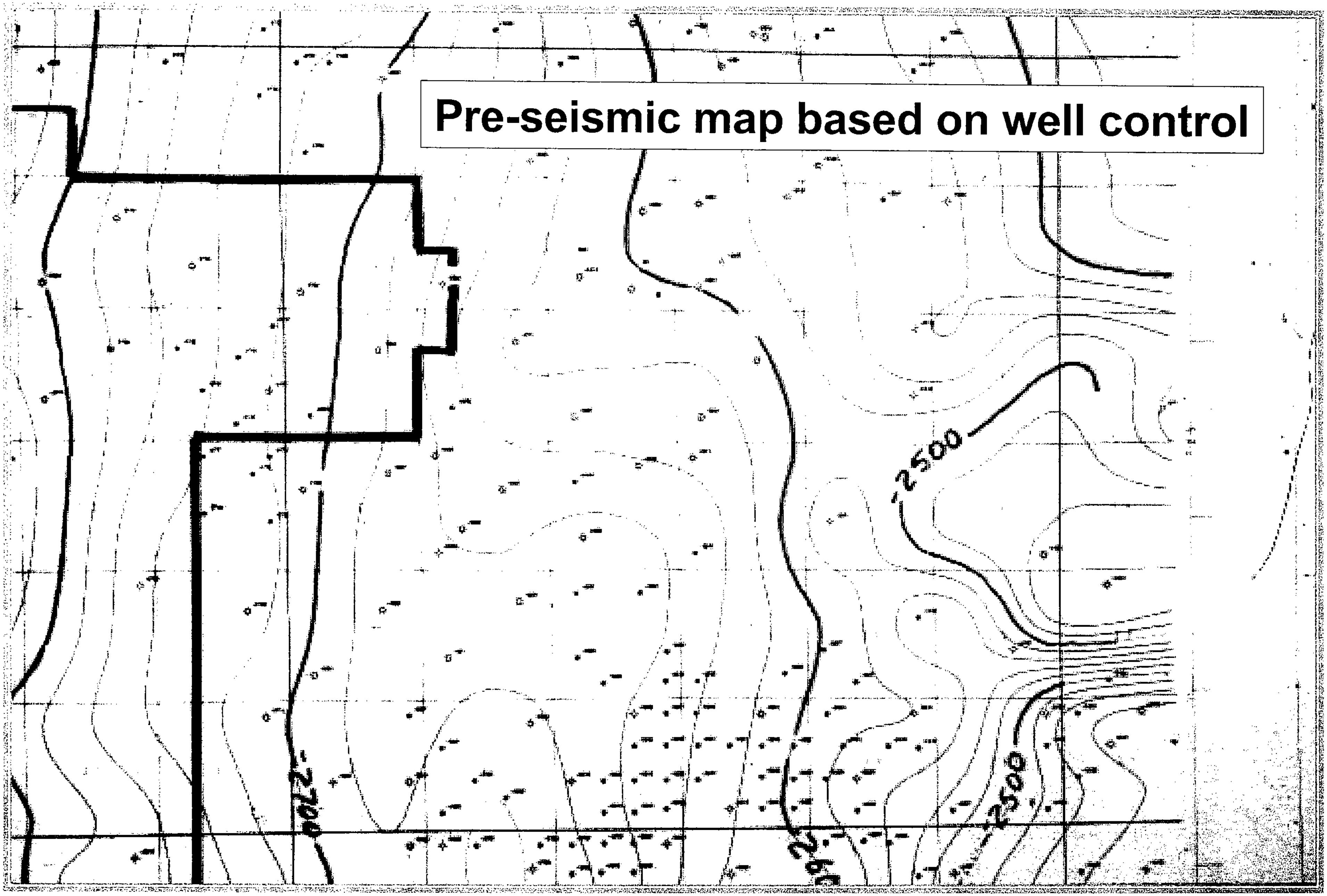
Wrench - Fault System

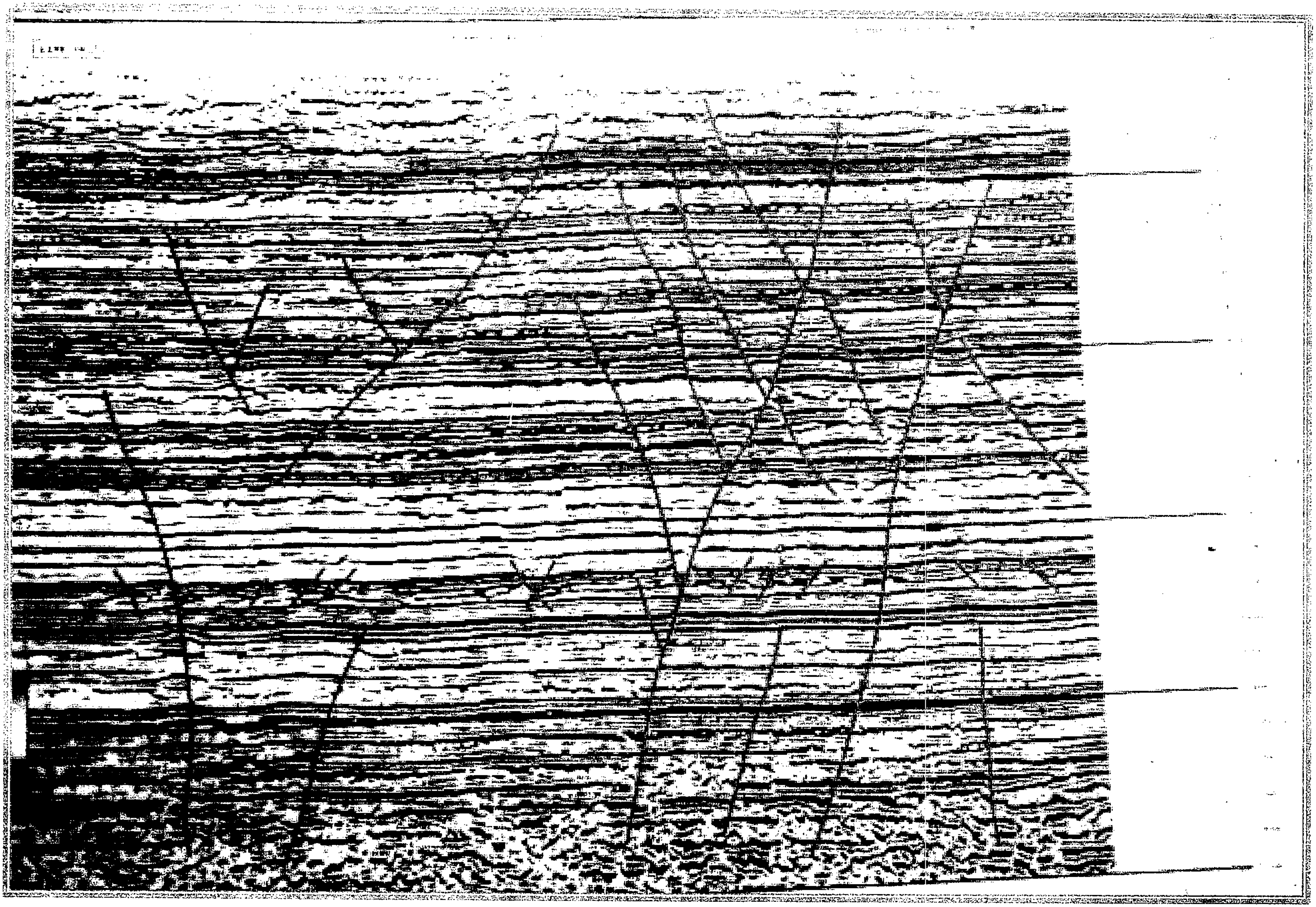


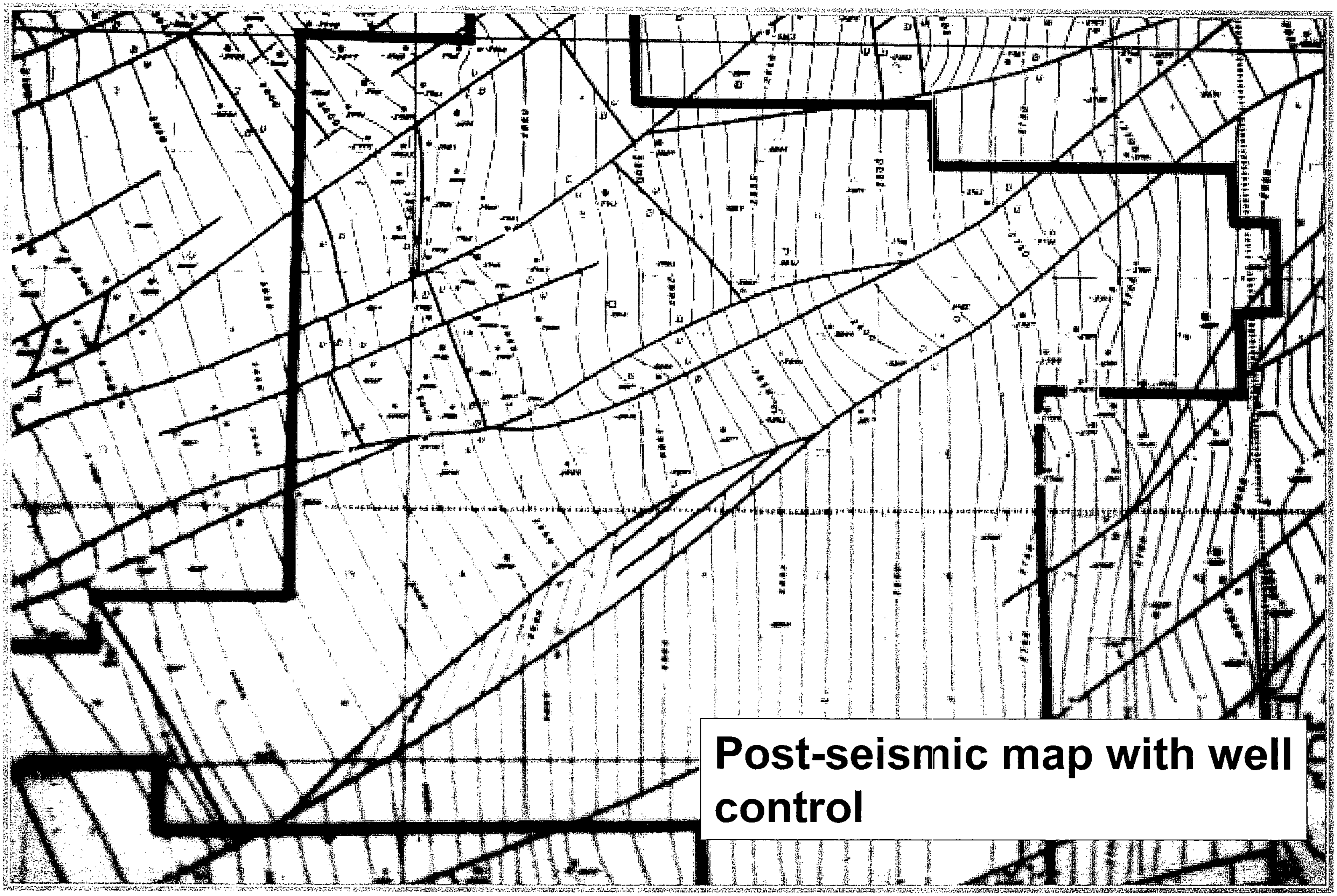


CRETACEOUS FORMATIONS, DENVER BASIN, COLORADO (after Porter and Weimer, 1982).

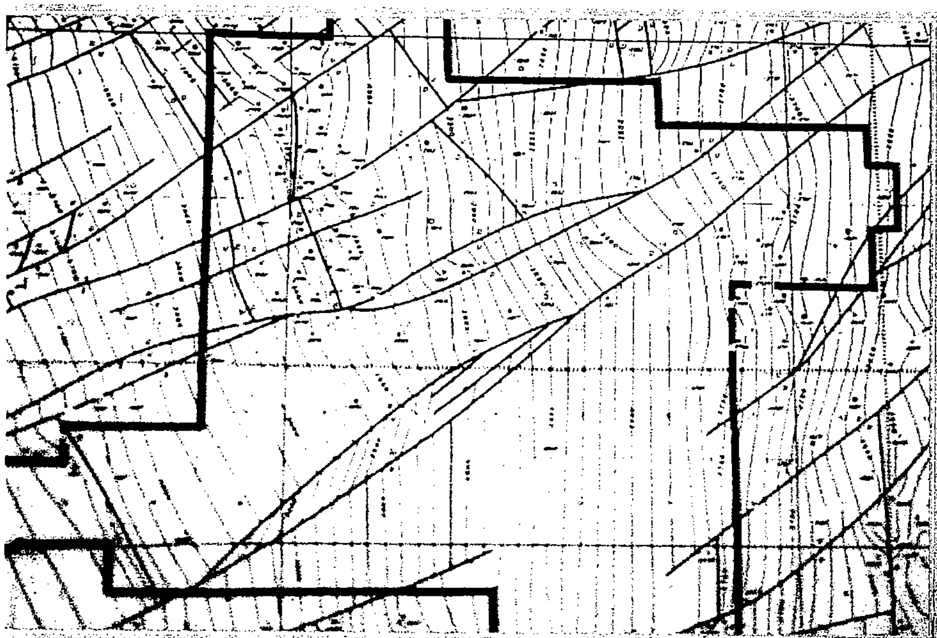
Pre-seismic map based on well control







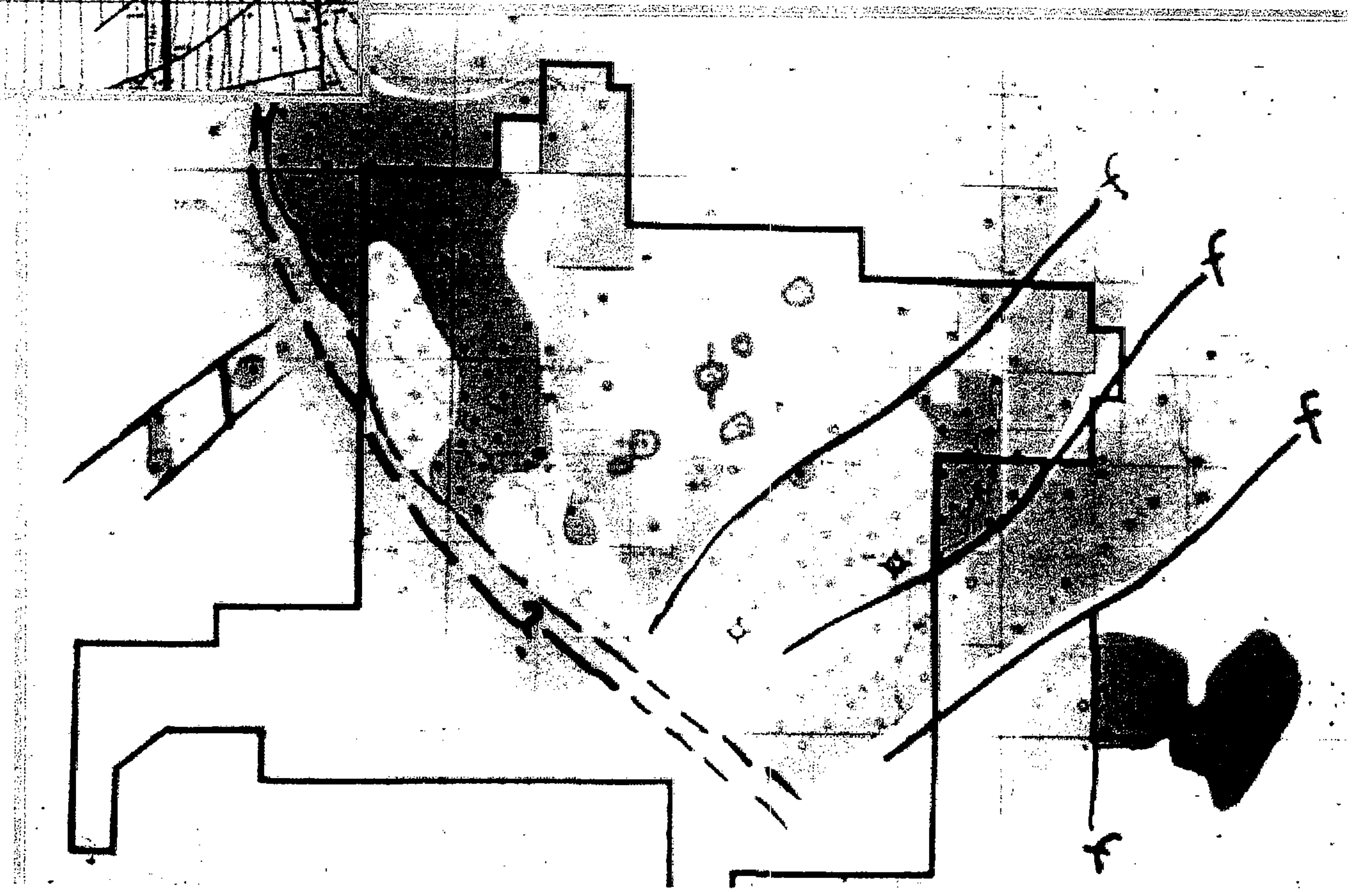
Post-seismic map with well control



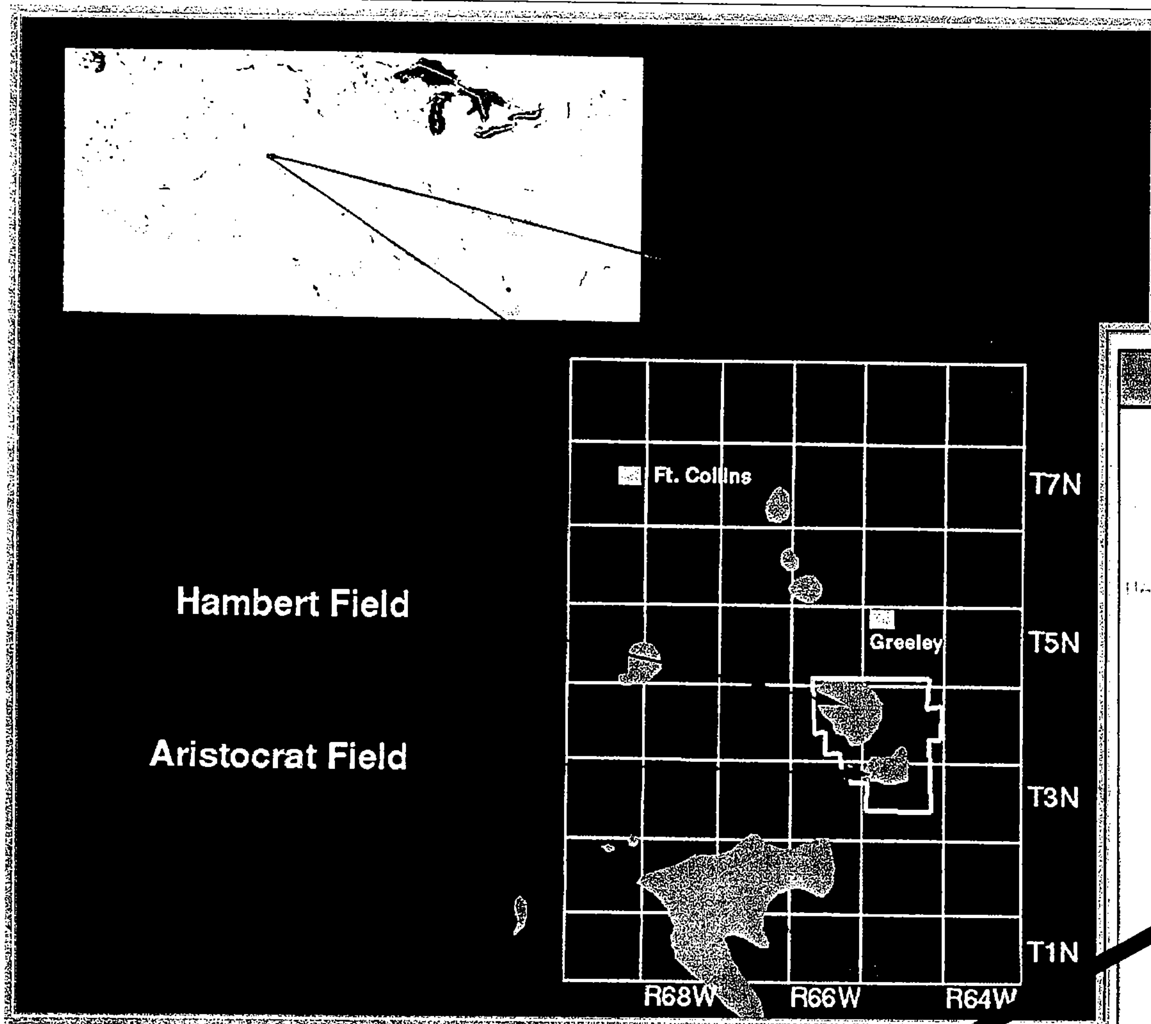
Gas or oil at same structural elevations in different wells

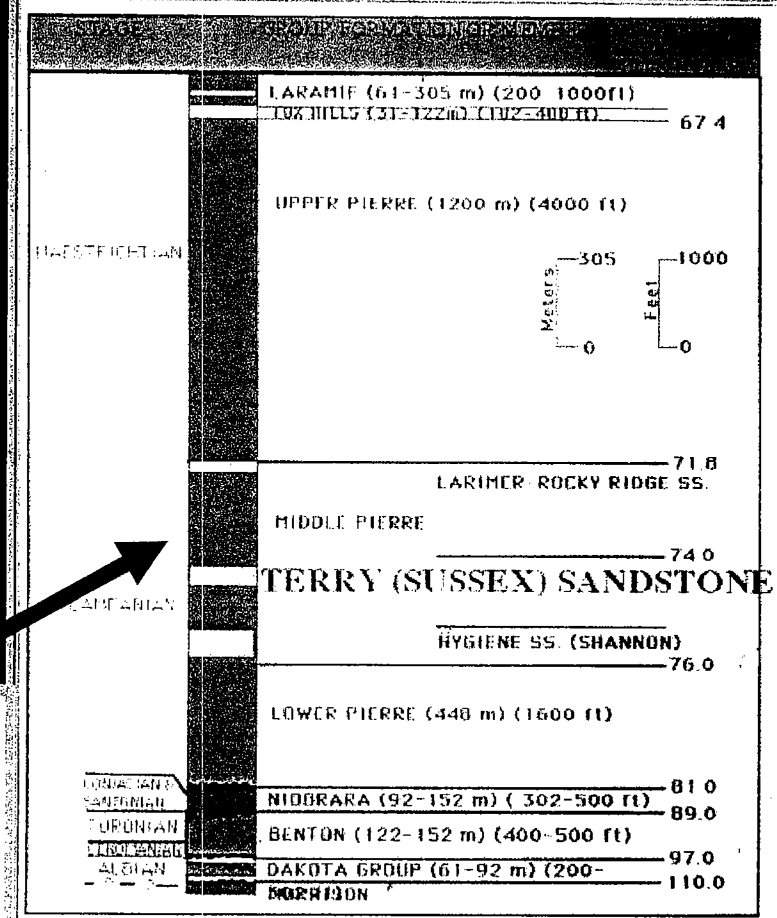
Green = oil

Pink = gas

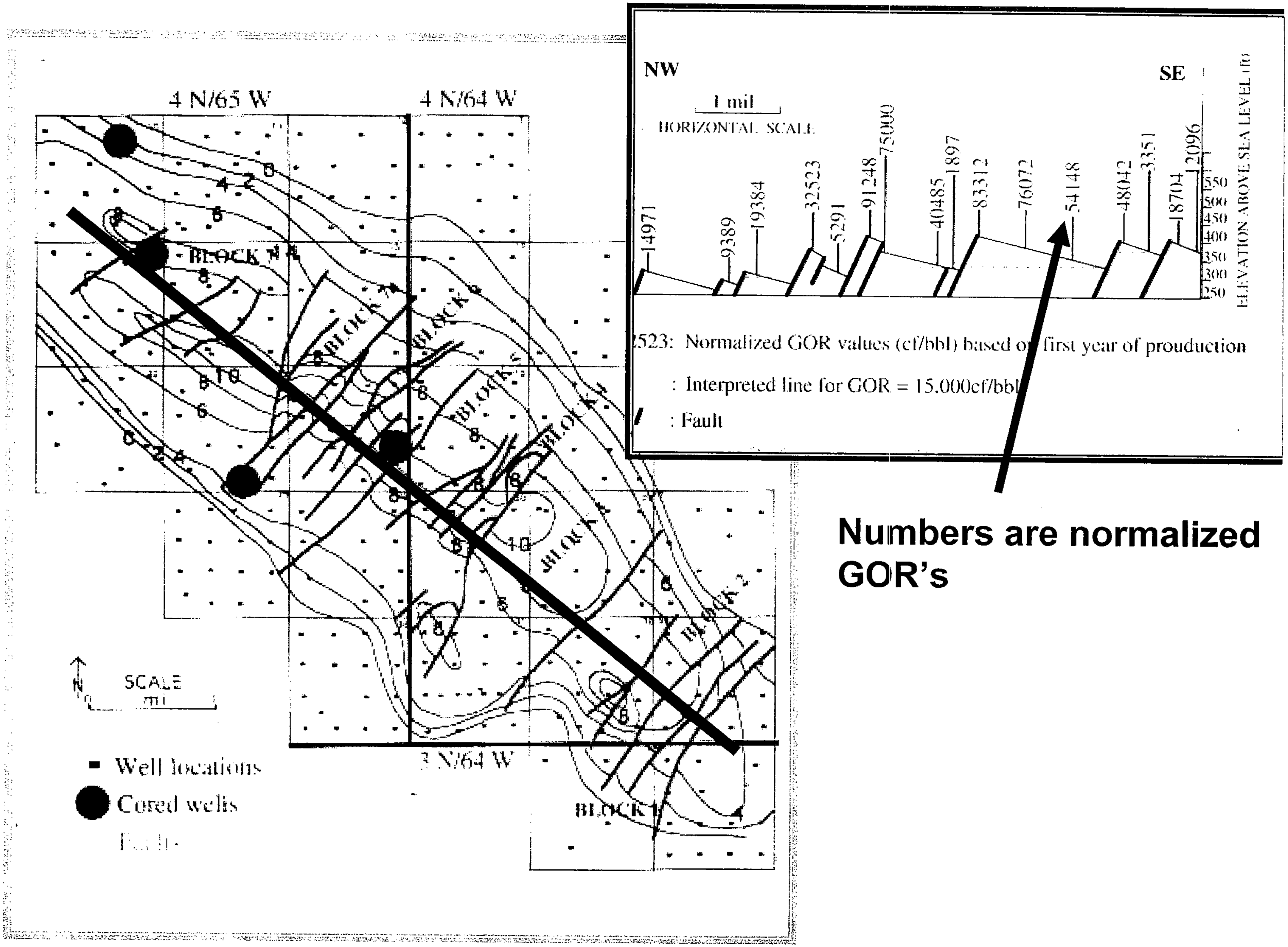


Hambert-Aristocrat Field,Colorado

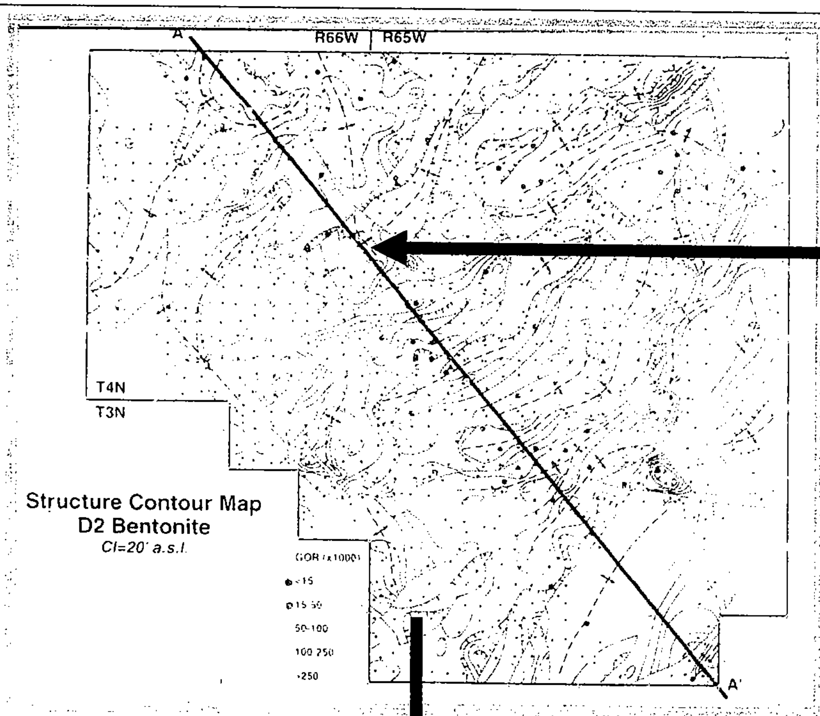




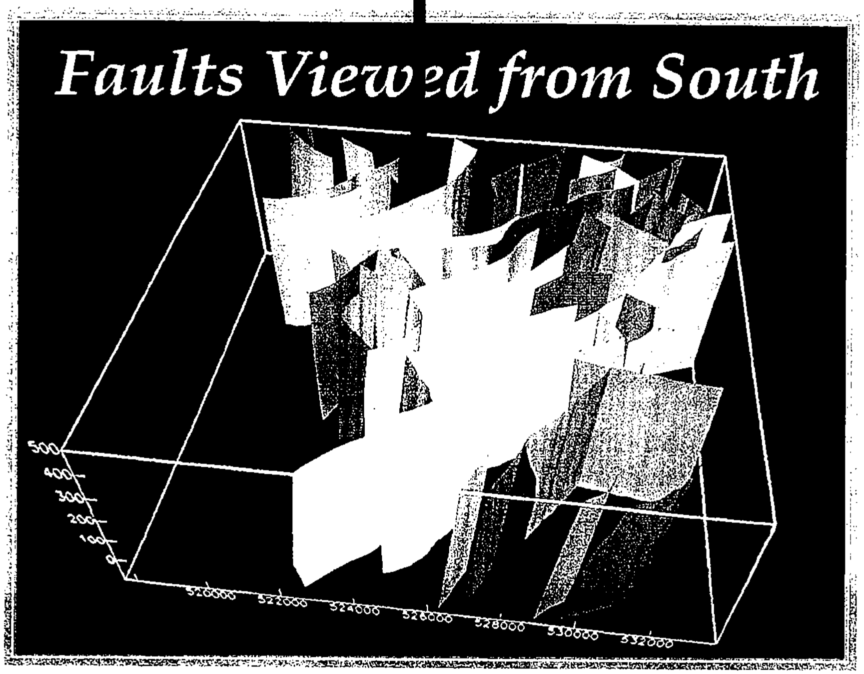
CRETACEOUS FORMATIONS. DENVER BASIN. COLORADO (after Porter and Weimer, 1982).

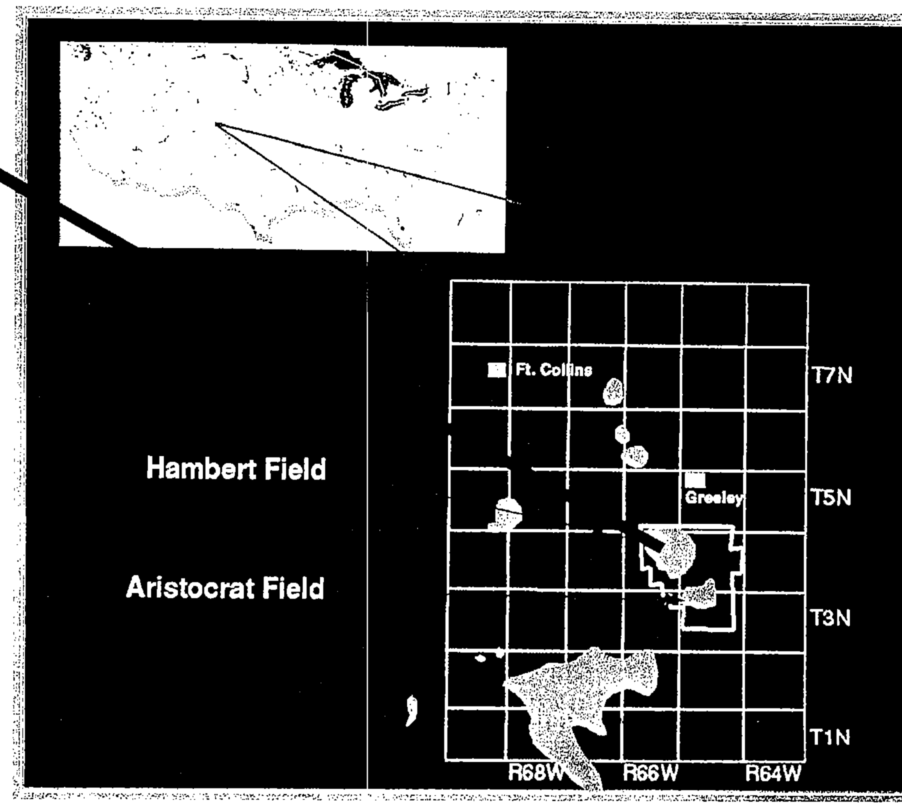


Numbers are normalized GOR's

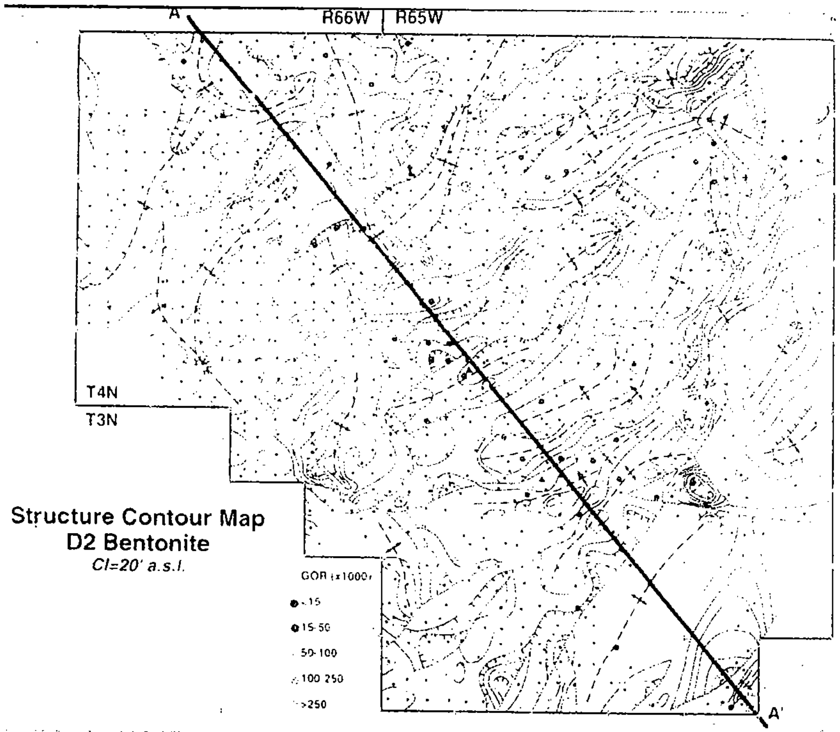


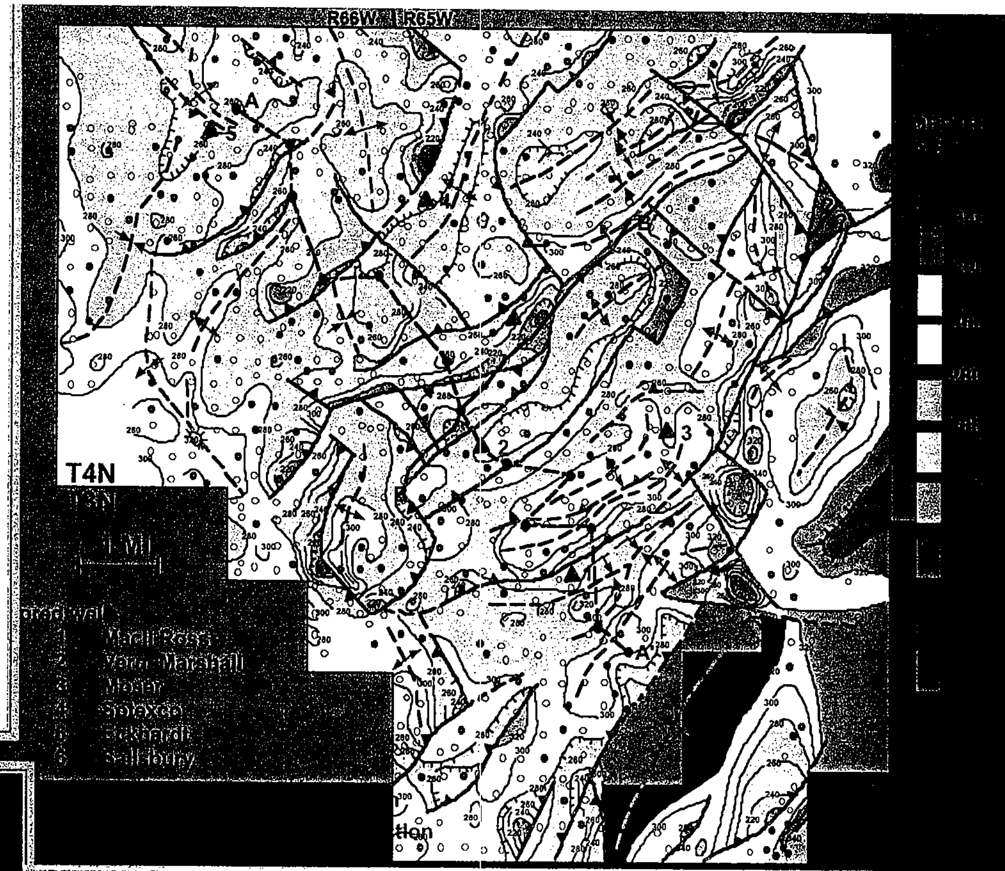
Structure cross section

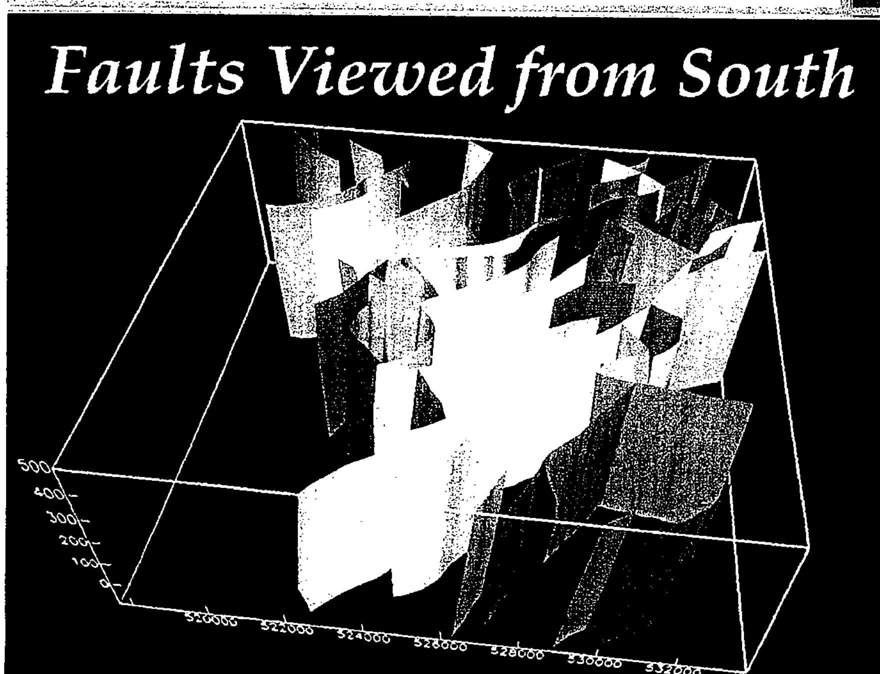


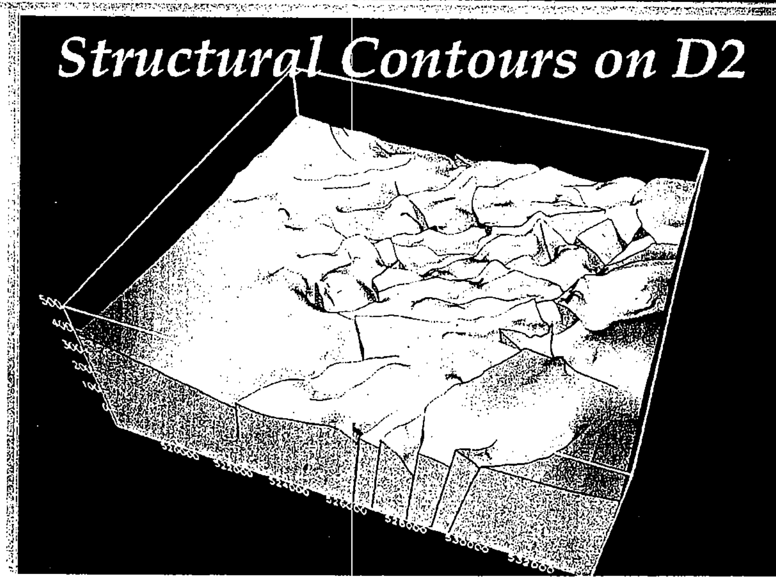


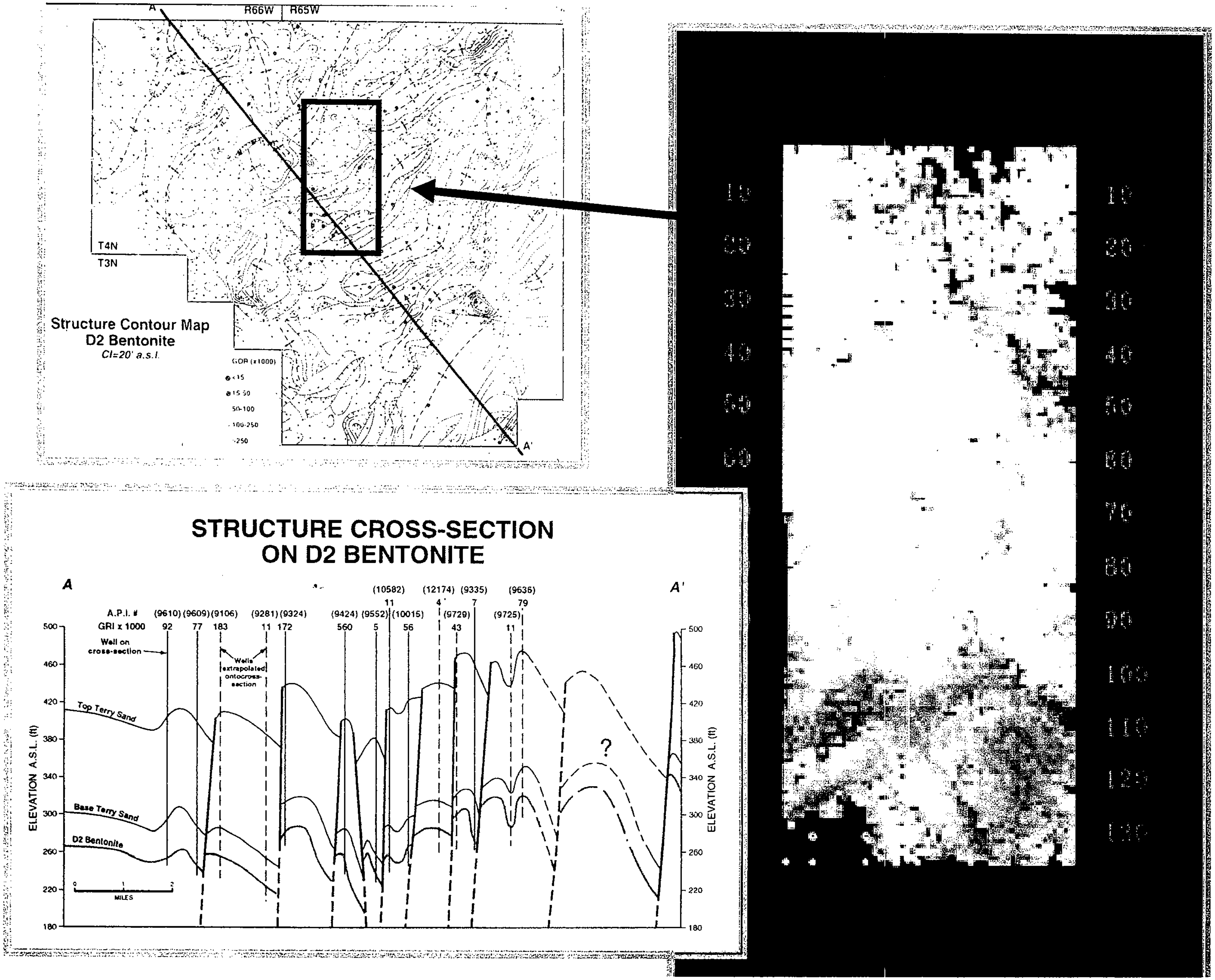
Hambert-Aristocrat Field, Colorado


A
R66W
R65W
T4N
T3N
Structure Contour Map
D2 Bentonite
CI=20' a.s.l.
GOR (x1000)
<15
15-50
50-100
100-250
>250
A'

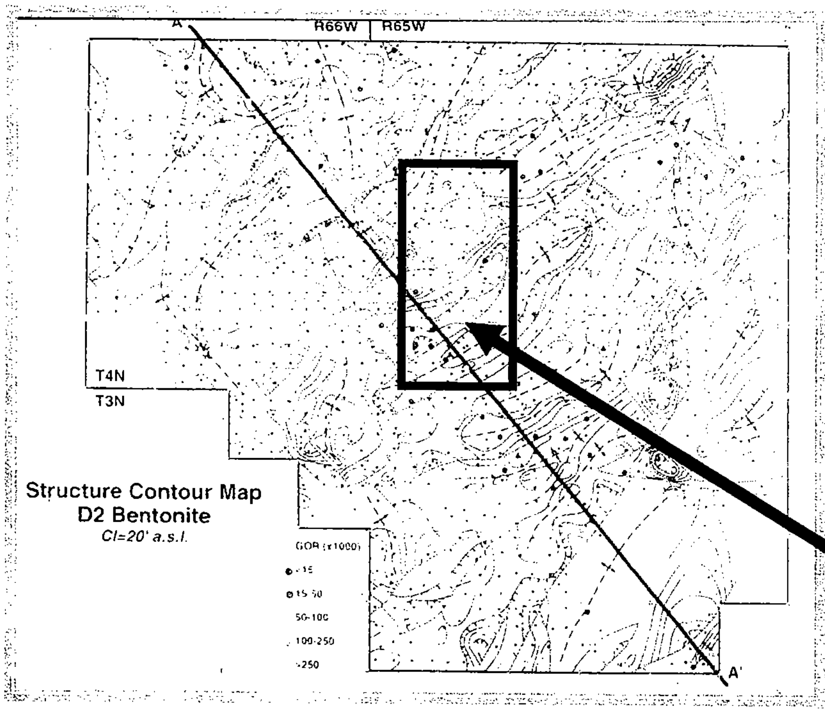

R66W
R65W
A
T4N

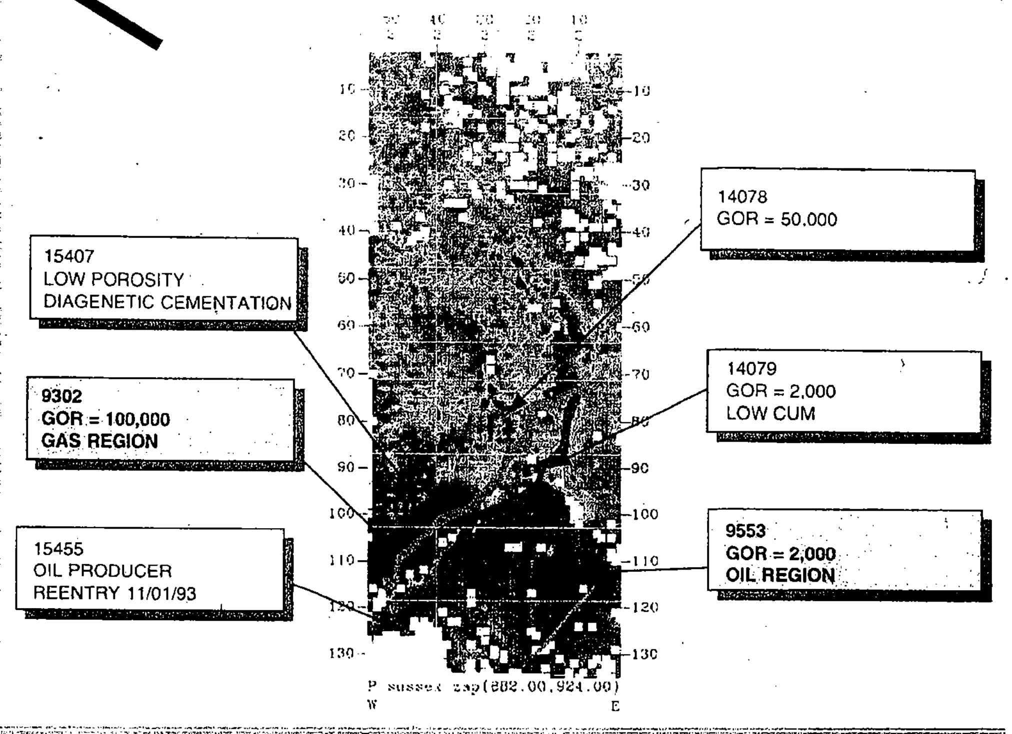

Faults Viewed from South
500
400
300
200
100
0
520000
522000
524000
530000
532000

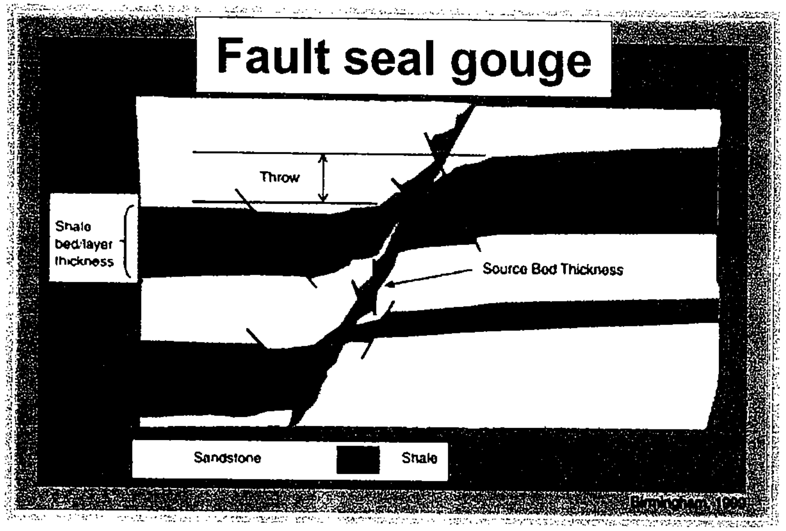

Structural Contours on D2



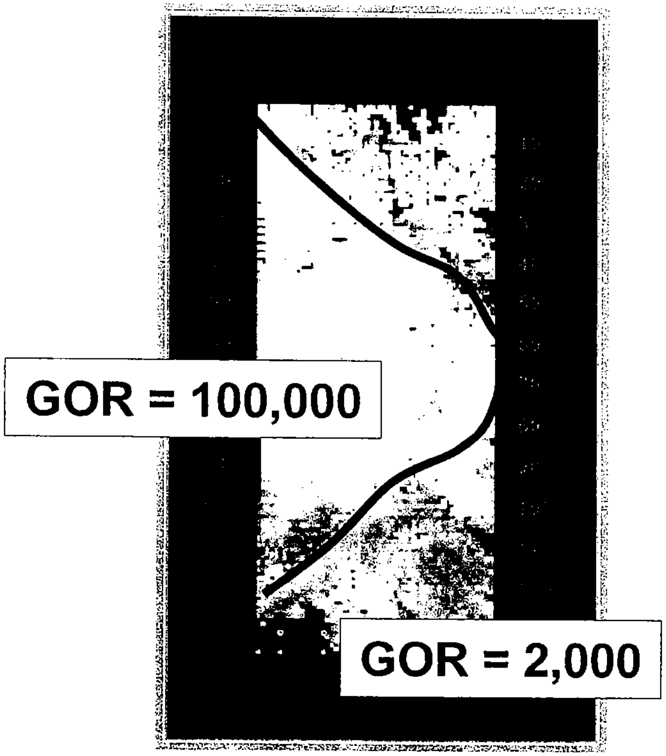
A
R66W
R65W
T4N
T3N
Structure Contour Map
D2 Bentonite
CI=20' a.s.l.
A'
STRUCTURE CROSS-SECTION
ON D2 BENTONITE
A
A'
A.P.I. #
GRI x 1000
(9610) 92
(9609) 77
(9106) 183
(9281) 11
(9324) 172
(9424) 560
(9552) 5
(10582) 11
(10015) 56
(12174) 4
(9729) 43
(9335) 7
(9725) 11
(9636) 79
Well on cross-section
Wells extrapolated ontocross-section
Top Terry Sand
Base Terry Sand
D2 Bentonite
ELEVATION A.S.L. (ft)
MILES
?


A
R66W
R65W
T4N
T3N
Structure Contour Map
D2 Bentonite
CI=20' a.s.l.
GOR (x1000)
15-50
50-100
100-250
>250
A'

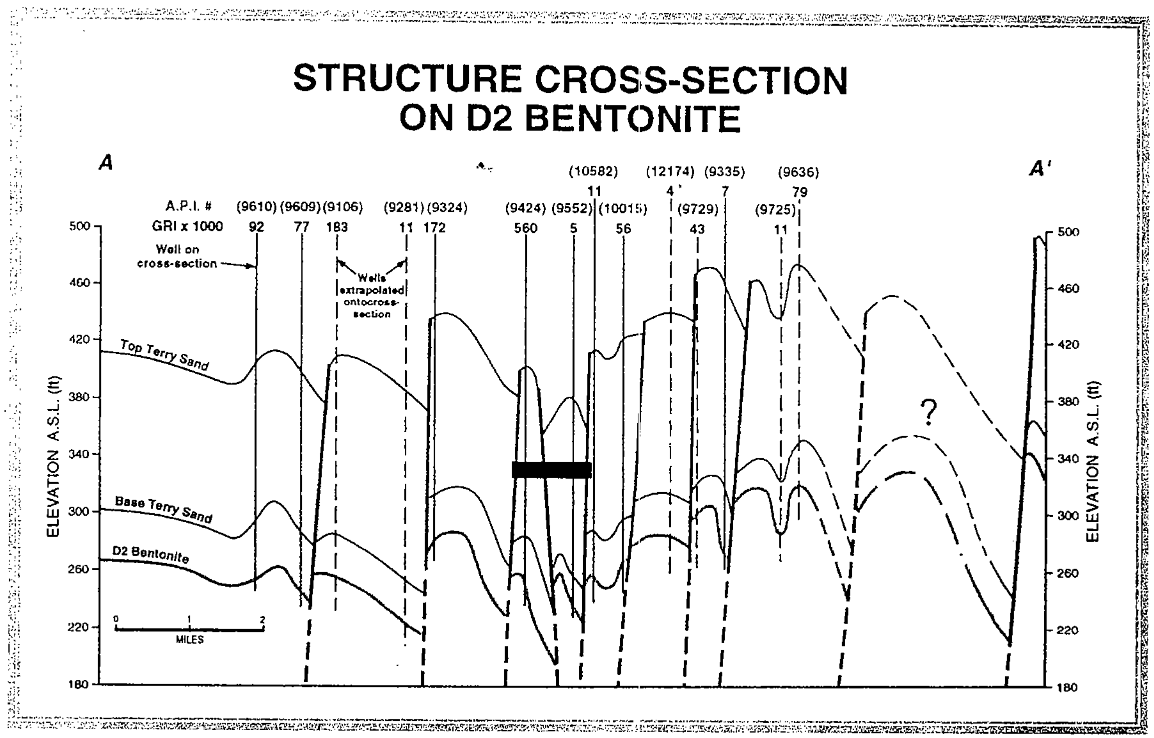

15407
LOW POROSITY
DIAGENETIC CEMENTATION
9302
GOR = 100,000
GAS REGION
15455
OIL PRODUCER
REENTRY 11/01/93
14078
GOR = 50,000
14079
GOR = 2,000
LOW CUM
9553
GOR = 2,000
OIL REGION
10
20
30
40
50
60
70
80
90
100
110
120
130
W
E



Each fault is a seal, so that each fault block is a reservoir compartment!



Seismic horizon slice



Structure cross section

SHALE GOUGE RATIO CALCULATION FOR TERRY SANDSTONE

Two wells in Sec. 20

12519	Structural Elev. = 433 ft.	GOR= 104,500
14079	Structural Elev. = 380 ft.	GOR= 200

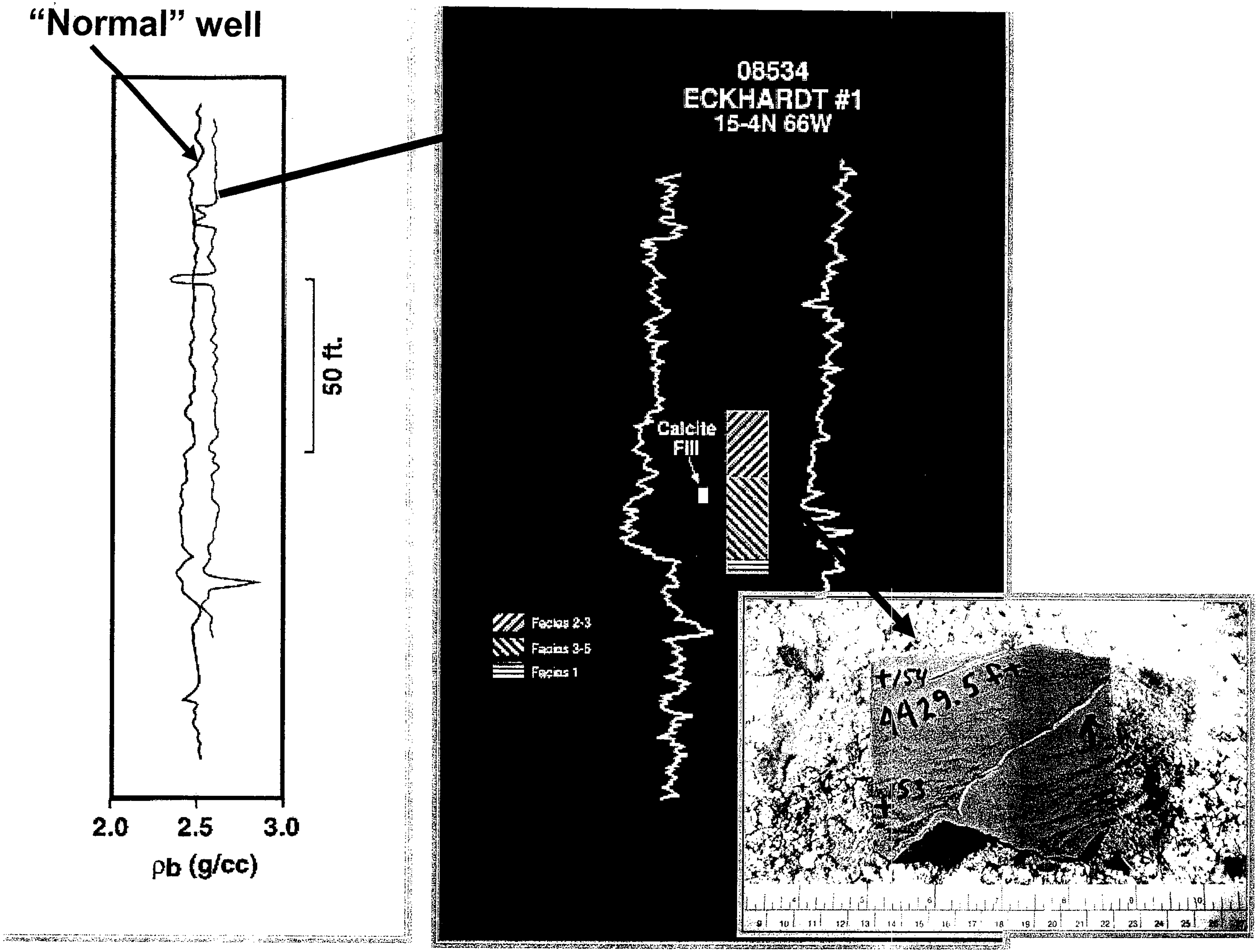
Well	GOR	Spud Date	Distance Apart
12519	104,500	11/88	app. 1300ft. (420m)
14079	200	12/88	

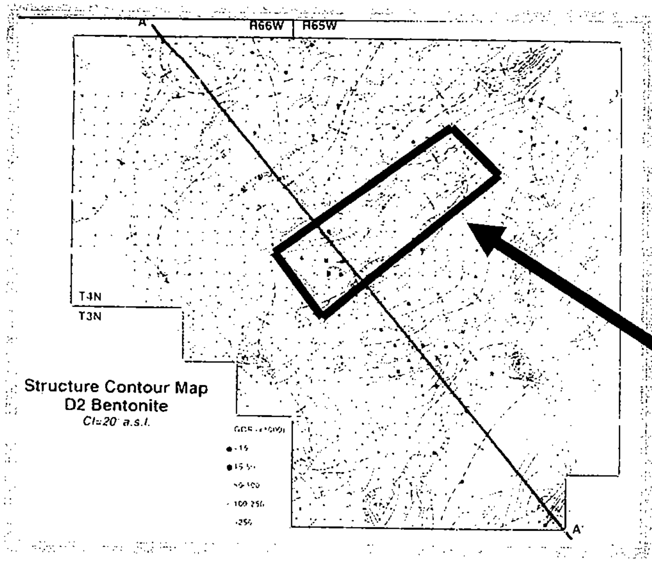
Assume 15% clay in the Terry Sandstone

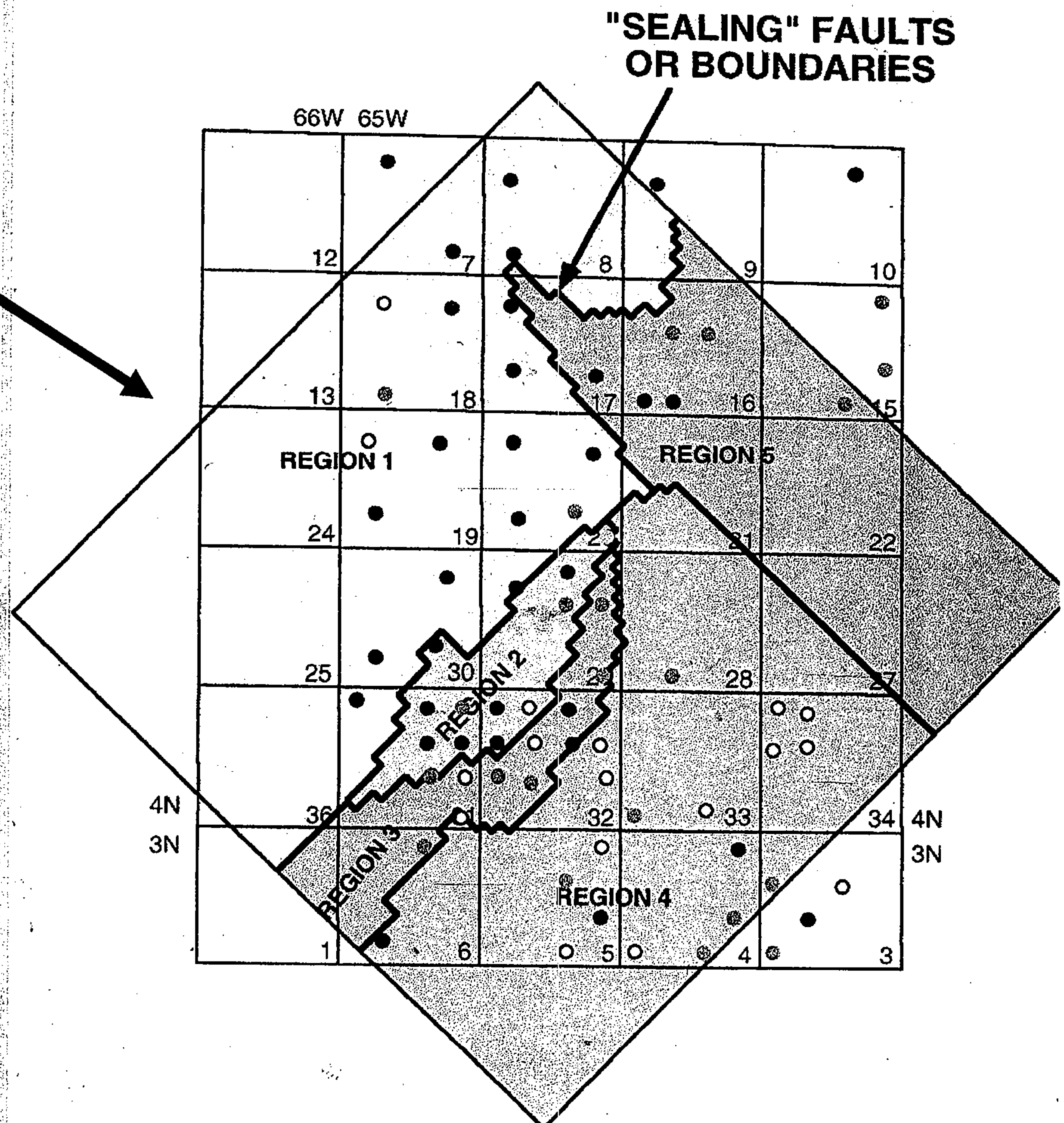
Assume 150ft. thickness of Terry Sandstone

Shale Gouge Ratio = (150ft.)(15)/(433 – 380) = **42**

Assume SGR = 25 for fault gouge to occur, therefore <u>there is gouge present.</u>

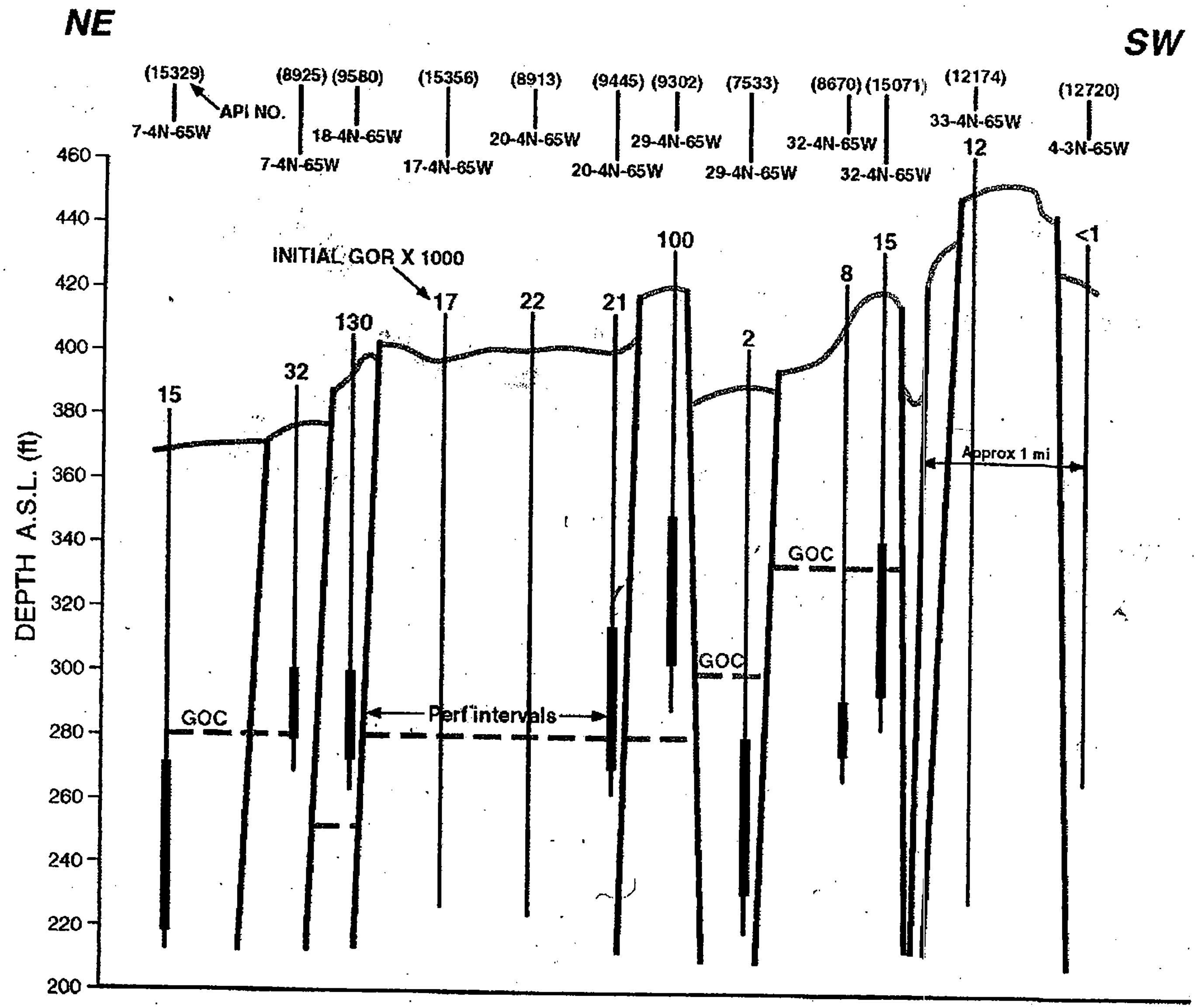

"Normal" well
50 ft.
2.0
2.5
3.0
ρb (g/cc)
08534
ECKHARDT #1
15-4N 66W
Calcite
Fill
Facies 2-3
Facies 3-5
Facies 1





Simulation matched production for a numberof wells, Indicating the faults are sealing.

STRUCTURE CROSS-SECTION
TOP TERRY SANDSTONE

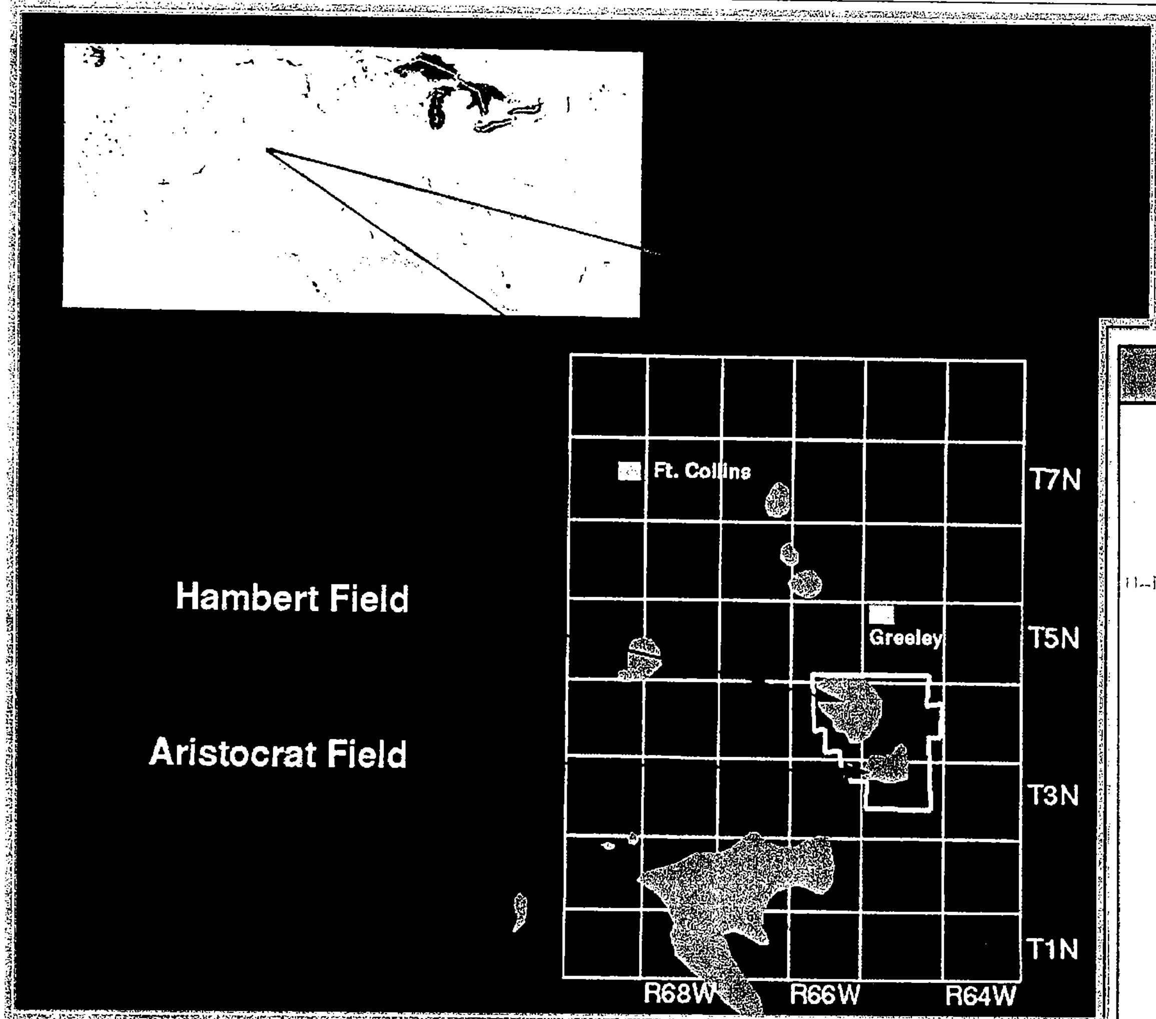


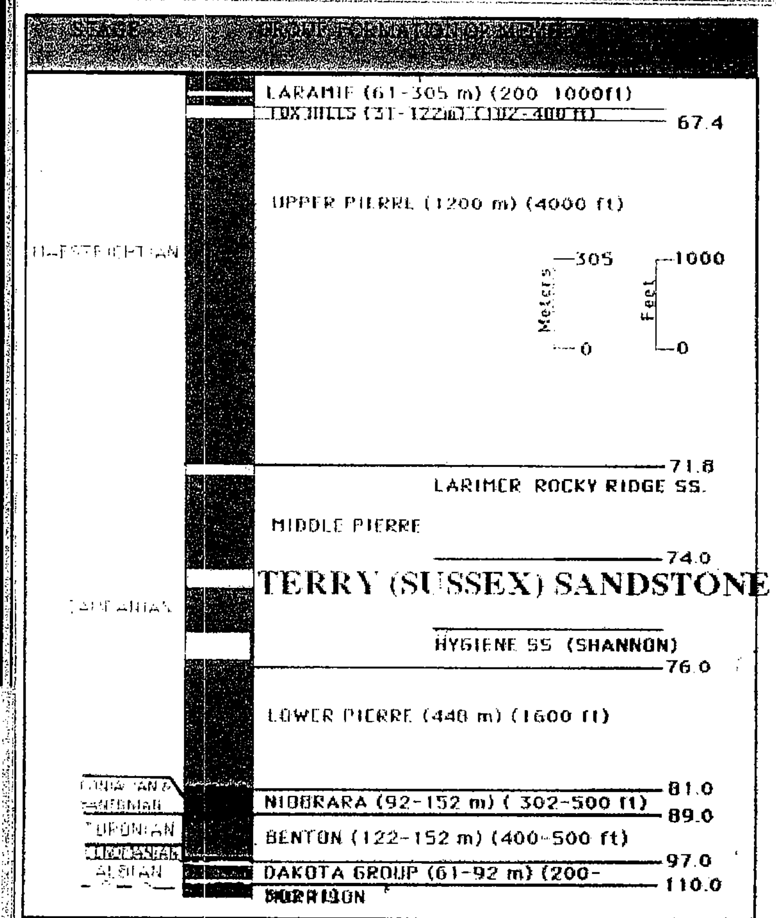
CONCLUSIONS

- FAULTS MAY BE SEALING IF FILLED WITH CEMENT AND/OR GOUGE
- GOR'S MAY BE USEFUL FOR DETECTING SEALING FAULTS IN THE ABSENCE OF PRESSURE DATA
- FAULTS MAY BE BENEATH SEISMIC RESOLUTION
- TO DETECT SUB-SEISMIC SCALE FAULTS REQUIRES DETAILED MAPPING
- SMALL COMPARTMENTS MAY BE UNTAPPED; CLOSELY SPACED WELLS MAY BE PRODUCTIVE

SHOREFACE DEPOSITS & RESERVOIRS

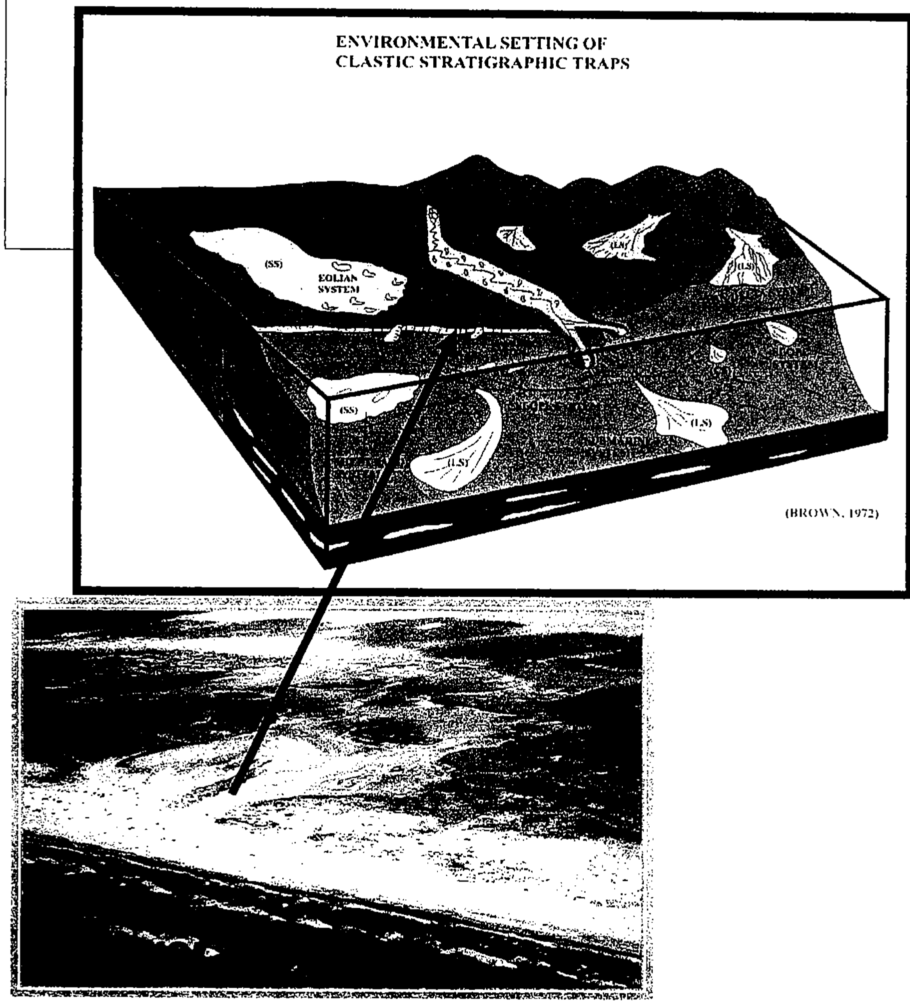
Hambert-Aristocrat Field,Colorado

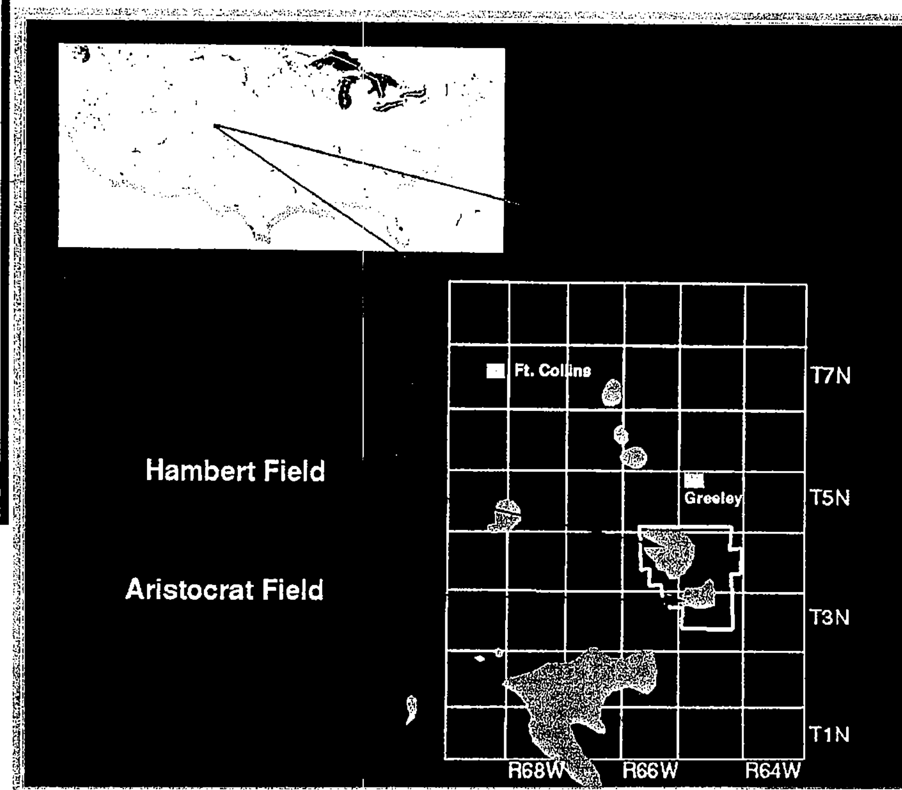




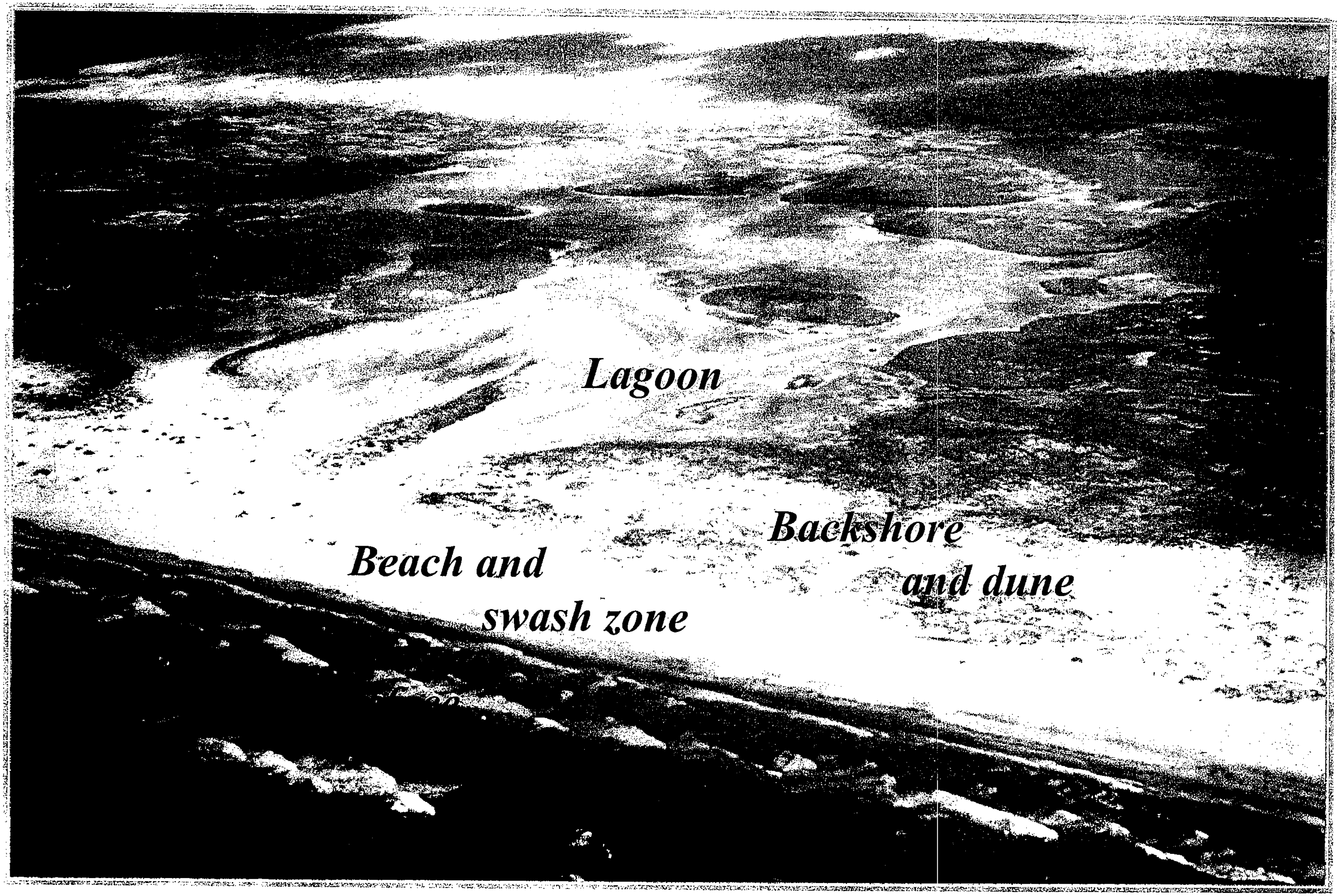
CRETACEOUS FORMATIONS, DENVER BASIN, COLORADO (after Porter and Weimer, 1982).

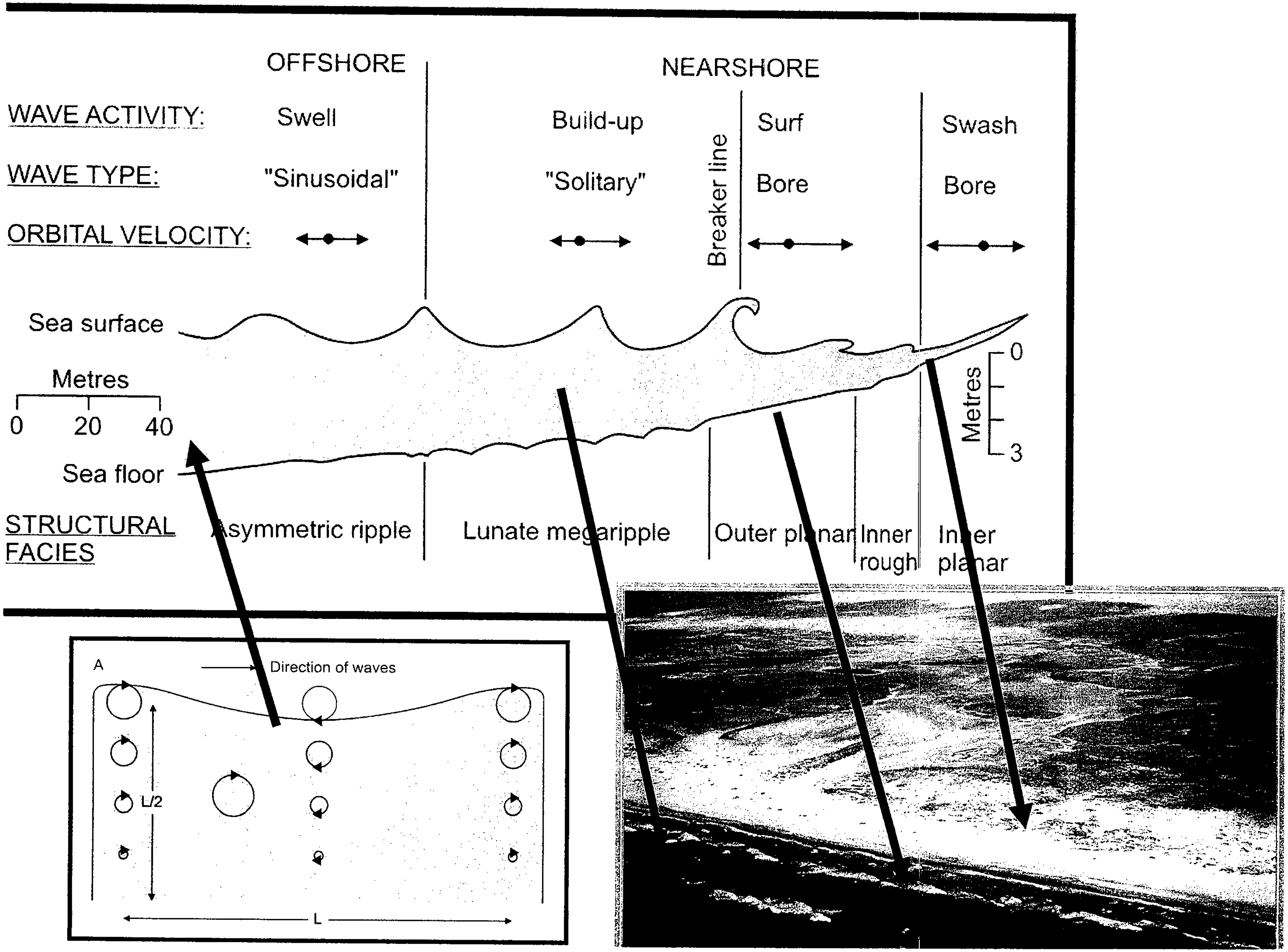
Level 5, 6, & 7: My <u>mixed</u>, <u>shoreface sandstone</u> reservoir is highly <u>faulted</u> :



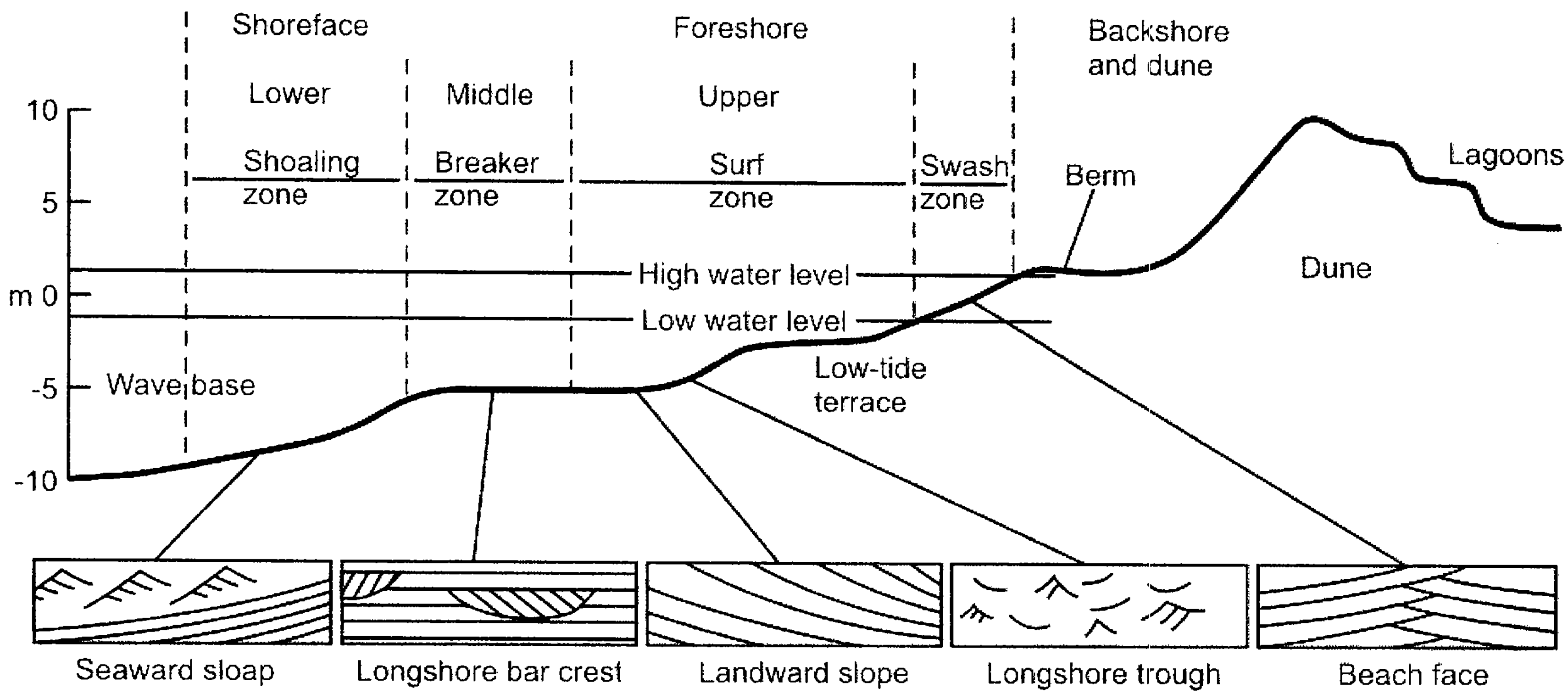


Hambert-Aristocrat Field, Colorado


Lagoon
Backshore
and dune
Beach and
swash zone



OFFSHORE
NEARSHORE
WAVE ACTIVITY:
Swell
Build-up
Surf
Swash
Breaker line
WAVE TYPE:
"Sinusoidal"
"Solitary"
Bore
Bore
ORBITAL VELOCITY:
Sea surface
Metres
0
20
40
Sea floor
Metres
0
3
STRUCTURAL FACIES
Asymmetric ripple
Lunate megaripple
Outer planar
Inner rough
Inner planar
A
Direction of waves
L/2
L



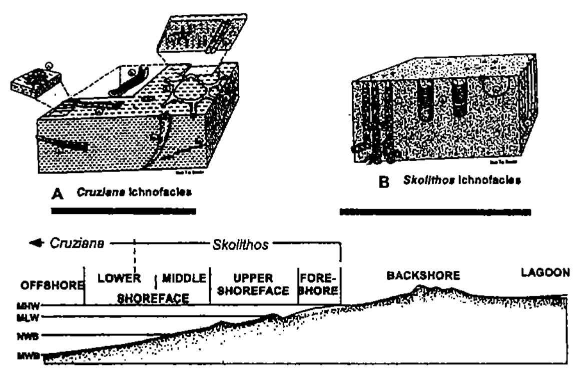
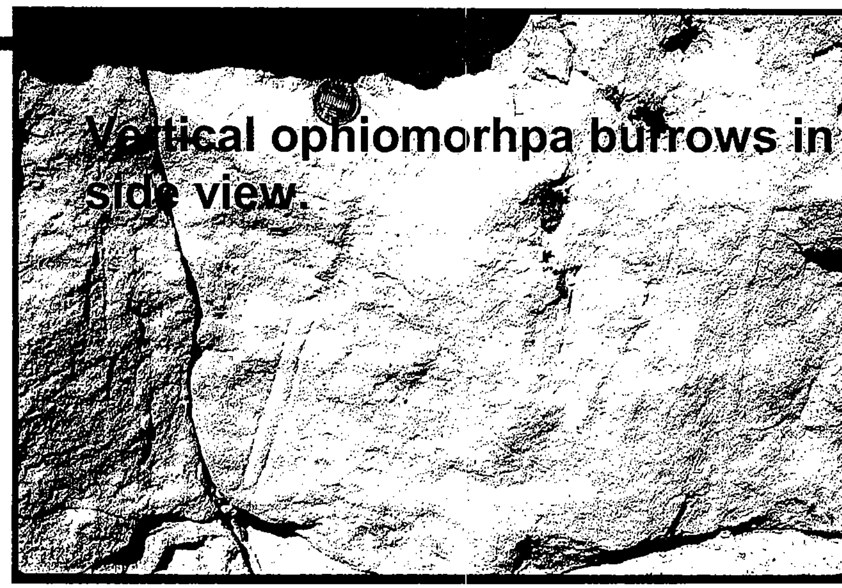


Figure 3.20 The offshore to coastal plain cross section, and distribution of the facies relative to normal wave base. Note the distibution of the Cruzians and Skolithos ichnofacies to the Cretaceous of the Western Interior Sea way of North America. A)The Cruziana ichnofacies comprises 1) Asteriacites*, 2) Cruziana*, 3) Rhizocorallium, 4) Aulichnites*, 5) Thalassinoides, 6)Chondrites, 7) Teichichnus, 8) Asterosoma, 9) Rosselia and 9) Planolites. . The trace fossils marked with asterisk are not represented in the Cruziana ichnofacies described in the reference study. B) The skolithos ichnofacies comprises 1) Ophiomorpha 2) Diplocraterion, 3) Skolithos and 4) Arenicolites.(MHW - Mean High Water, MLW - Mean Low Water, NWB - Normal Wave Base, MWB - Maximum Wave base. (Modified from Pemberton, el al. 1997)



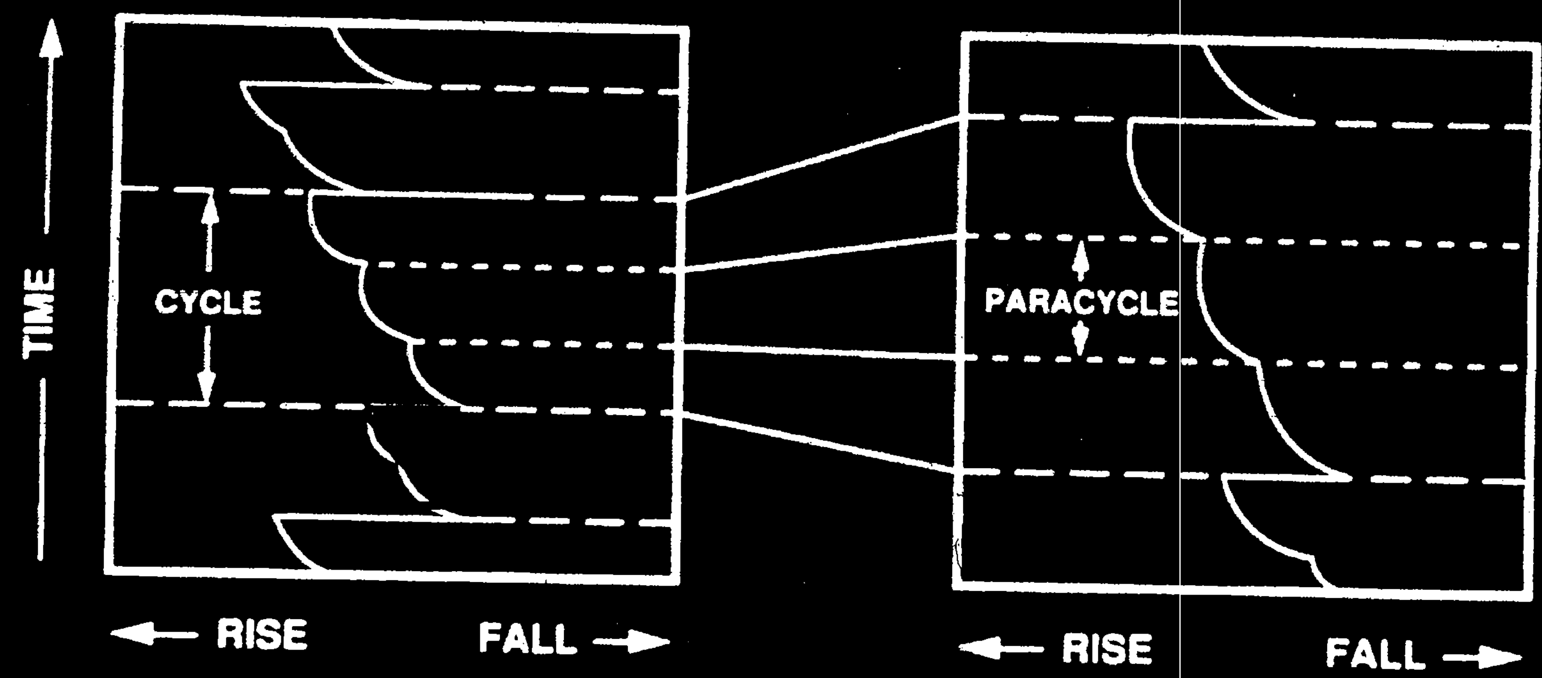
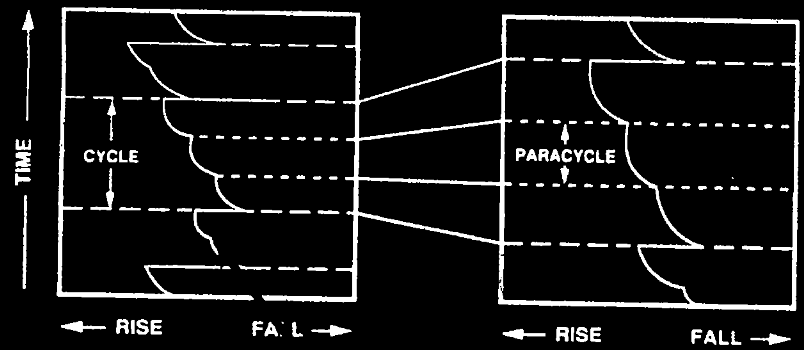


Figure 1. This figure (based on figure 1, p. 64, in Vail et al., 1977) illustrates the original relationship between cycle and paracycle, as defined by Vail, Mitchum, and Thompson. According to the original figure, "cycles consist of relative rises and falls of sea level, commonly containing several paracycles, which are smaller scale pulses of relative rises to stillstands" (Vail et al., 1977, p. 64). Cycles deposit sequences (Vail et al., 1977), paracycles deposit parasequences (Van Wagoner, 1985). *(Kamola, P. Van Wagoner, 1995)*



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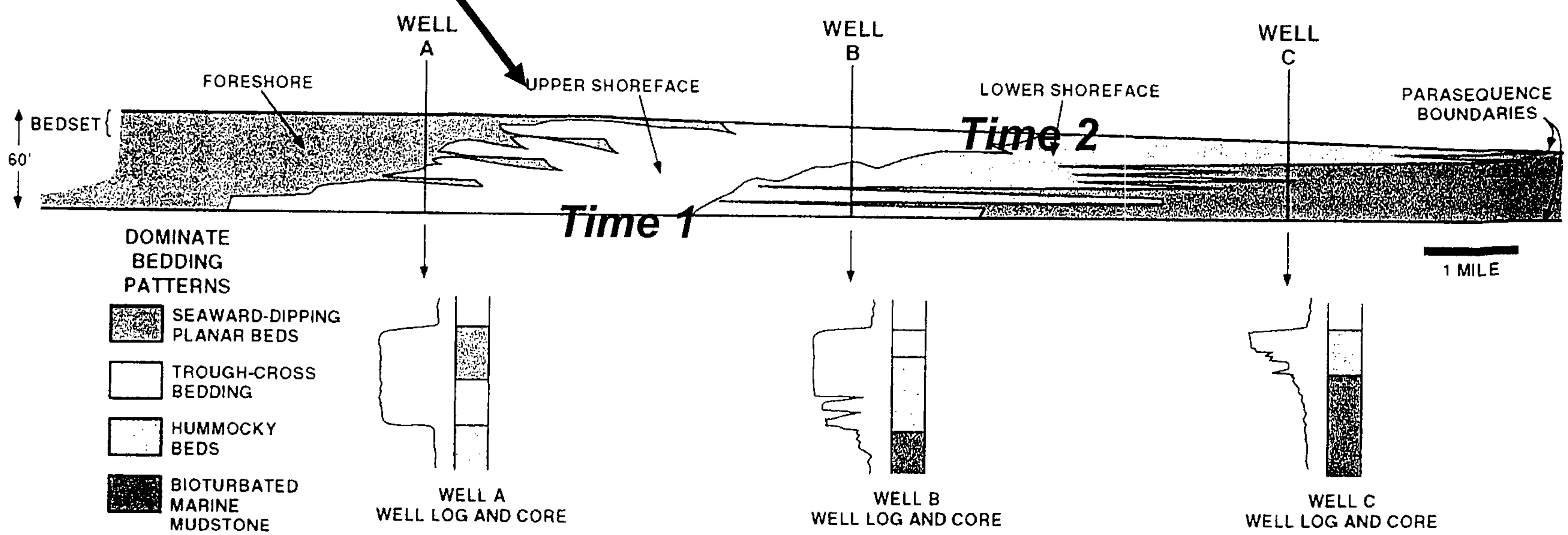
Seaward to right



Seaward progradation during relative stillstand of sea level *(Van Wagoner, et al., 1990)*

Vertical sequence indicates progradation followed by rapid deepening (transgression) of water

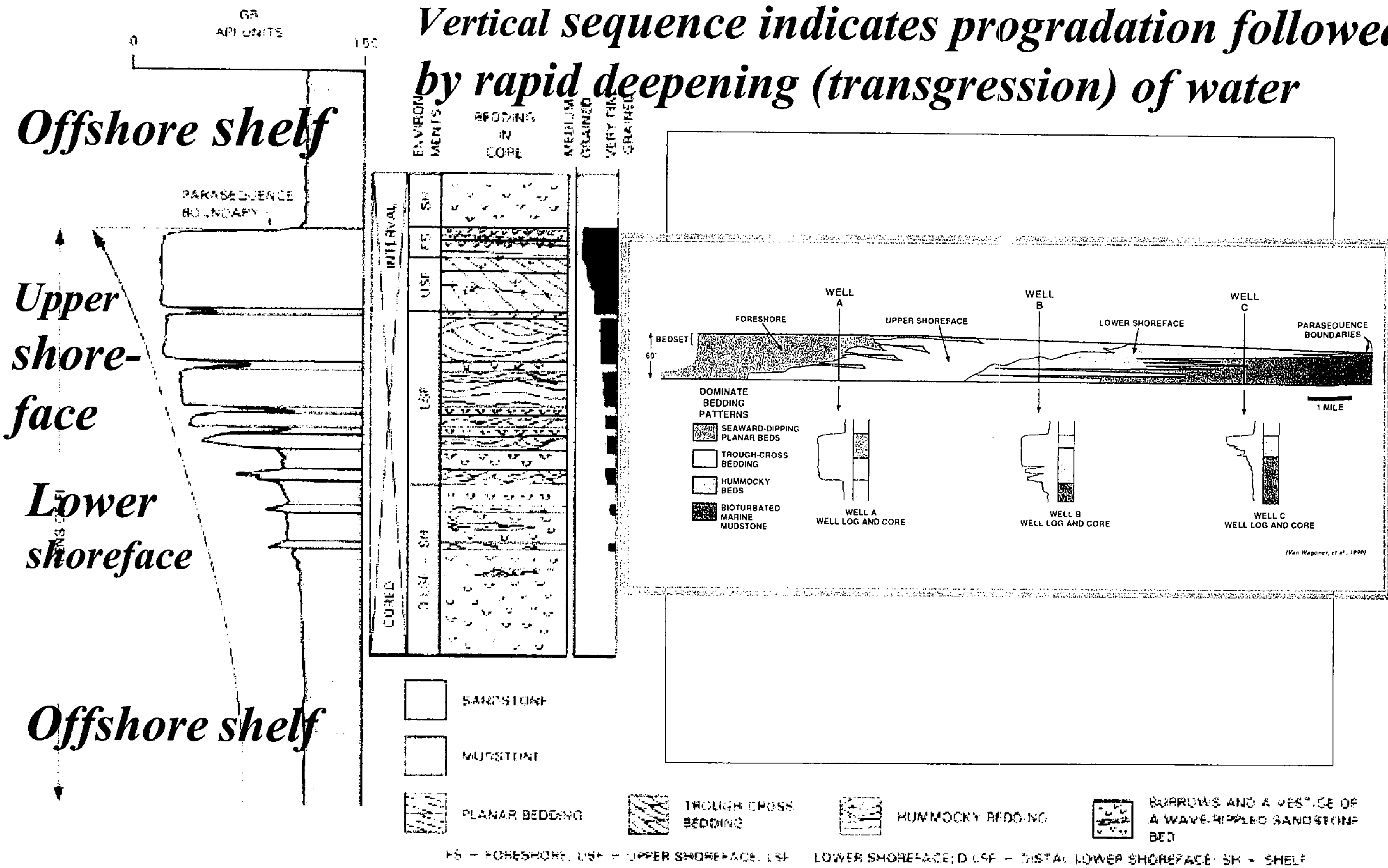


Figure 3A—Stratal characteristics of an upward-coarsening parasequence. This type of parasequence is interpreted to form in a beach environment on a sandy, wave- or fluvial-dominated shoreline.

Upward-coarsening/thickening shoreface parasequence

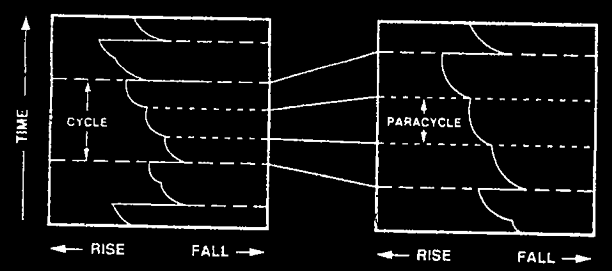


Figure 1. This figure (based on figure 1, p. 64, in Vail et al., 1977) illustrates the original relationship between cycle and paracycle, as defined by Vail, Mitchum, and Thompson. According to the original figure, "cycles consist of relative rises and falls of sea level, commonly containing several paracycles, which are smaller scale pulses of relative rises to stillstands" (Vail et al., 1977, p. 64). Cycles deposit sequences (Vail et al., 1977), paracycles deposit parasequences (Van Wagoner, 1985). *(Kamola, P. Van Wagoner, 1995)*

Two cycles of progradation and transgression to give two parasequences

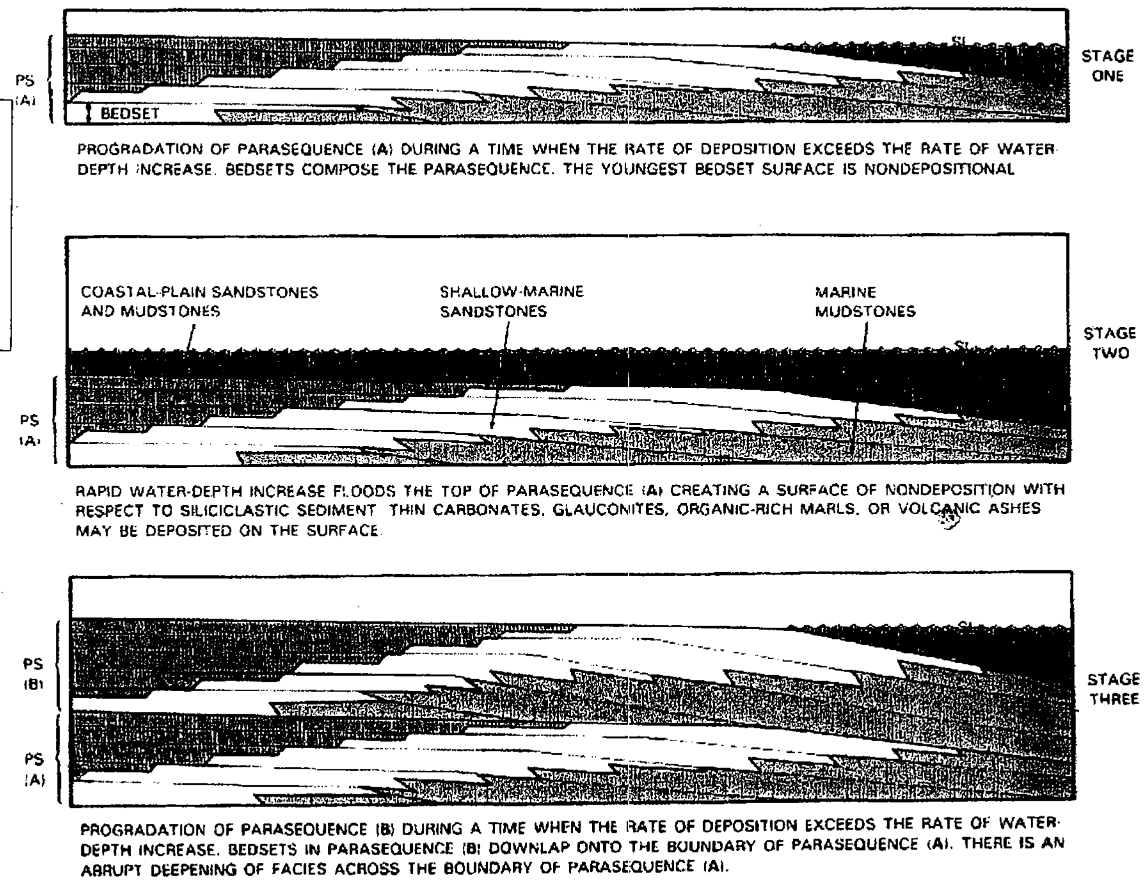


Figure 4—Progressive development of a parasequence boundary.

Four cycles to give four parasequences

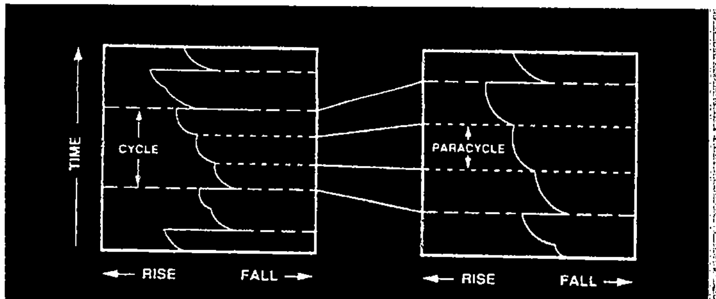


Figure 1. This figure (based on figure 1, p. 64, in Vail et al., 1977) illustrates the original relationship between cycle and paracycle, as defined by Vail, Mitchum, and Thompson. According to the original figure, "cycles consist of relative rises and falls of sea level, commonly containing several paracycles, which are smaller scale pulses of relative rises to stillstands" (Vail et al., 1977, p. 64). Cycles deposit sequences (Vail et al., 1977), paracycles deposit parasequences (Van Wagoner, 1985). *(Kamola, P. Van Wagoner, 1995)*

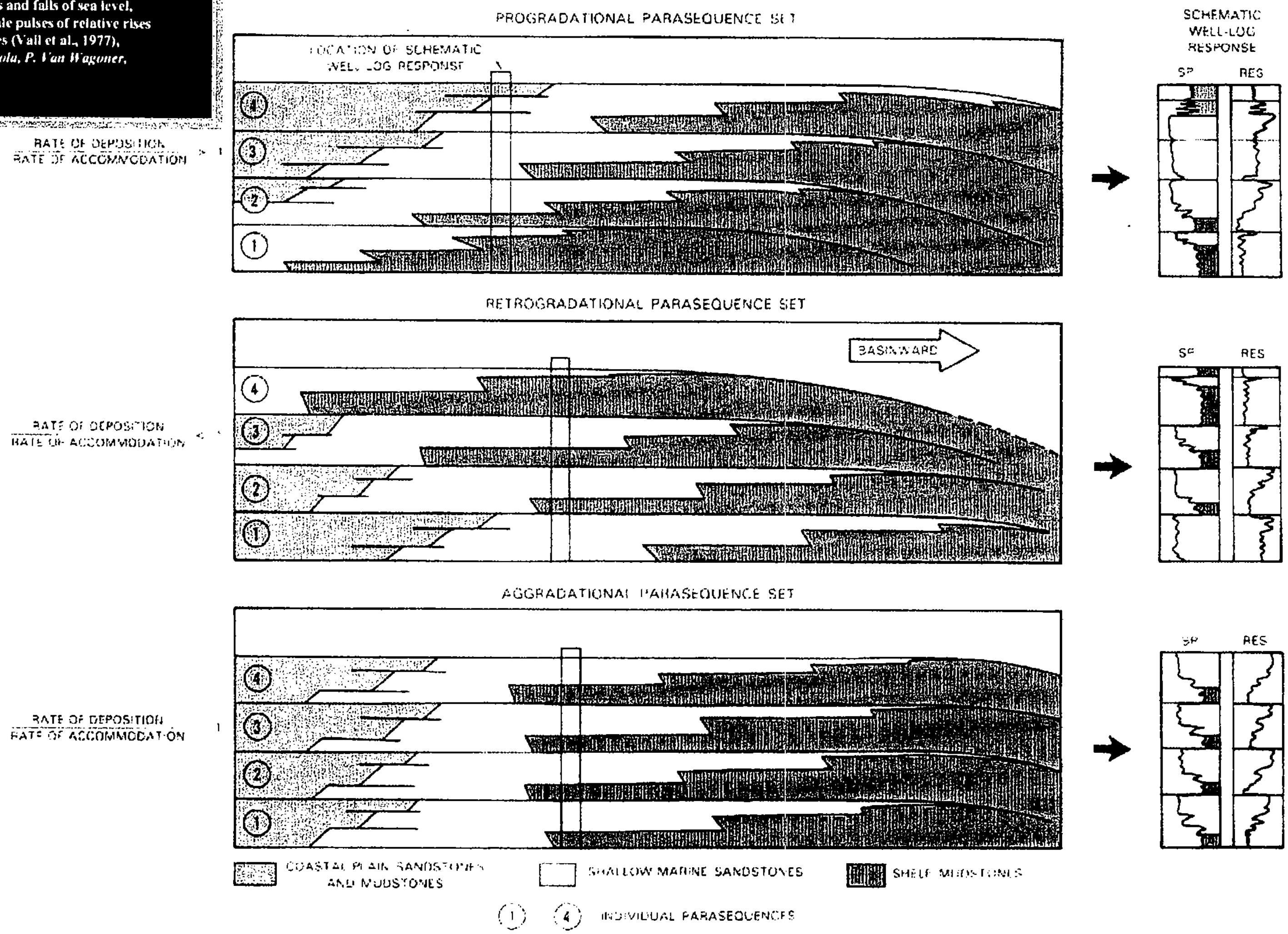
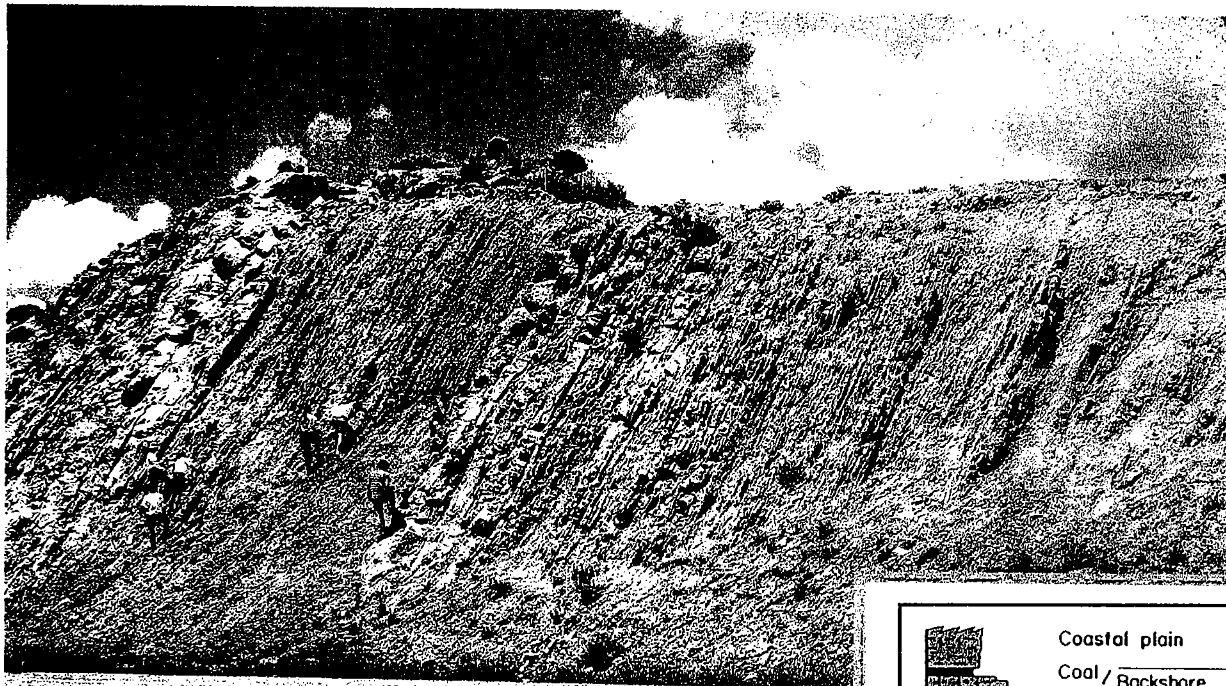
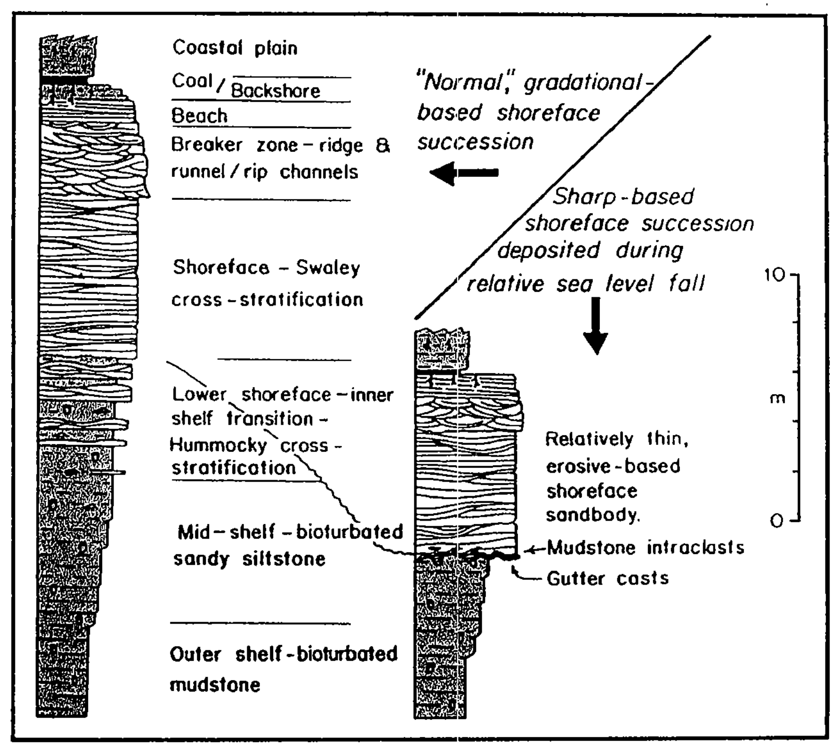


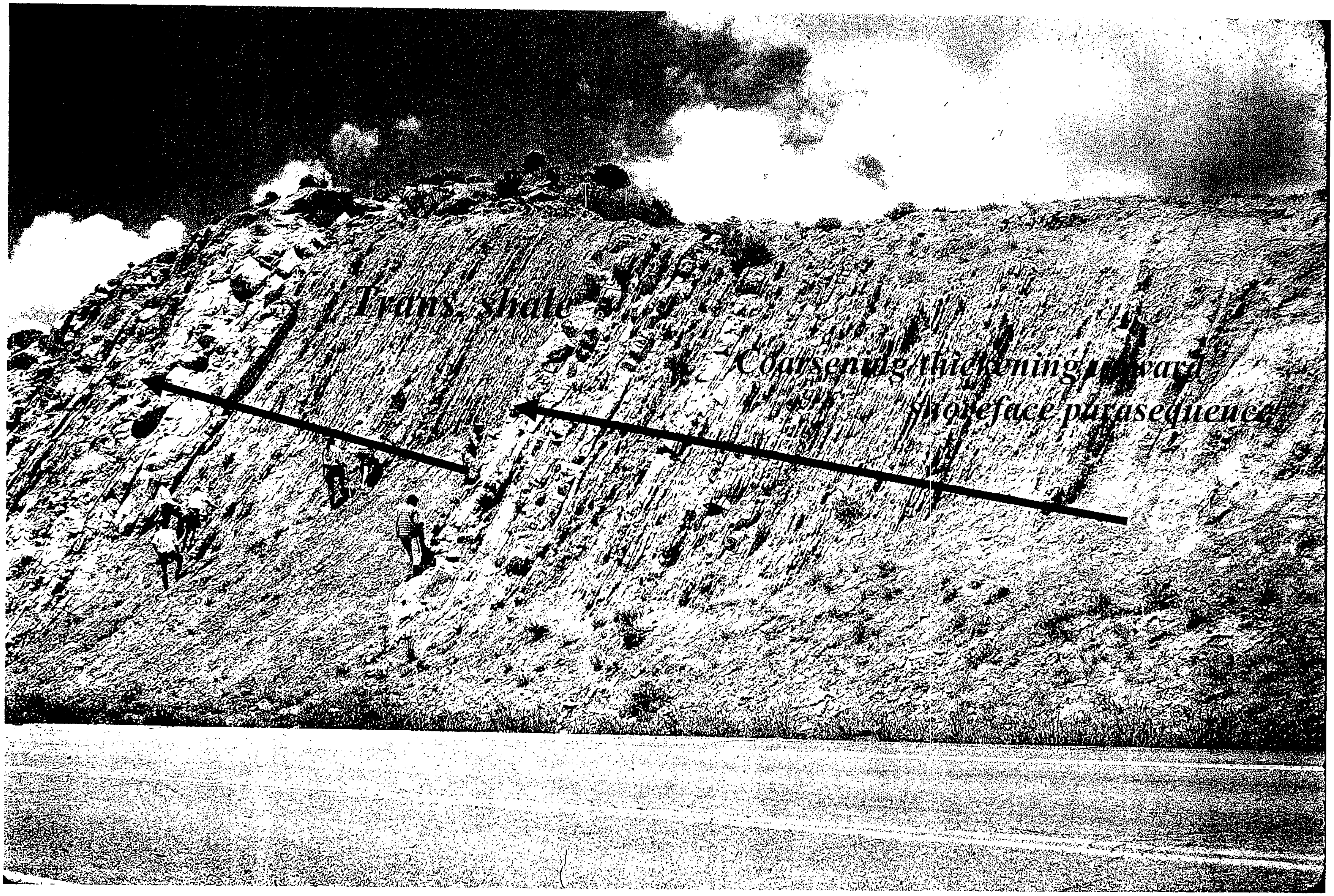
Figure 10—Parasequence-stacking patterns in parasequence sets; cross-section and well-log expression.

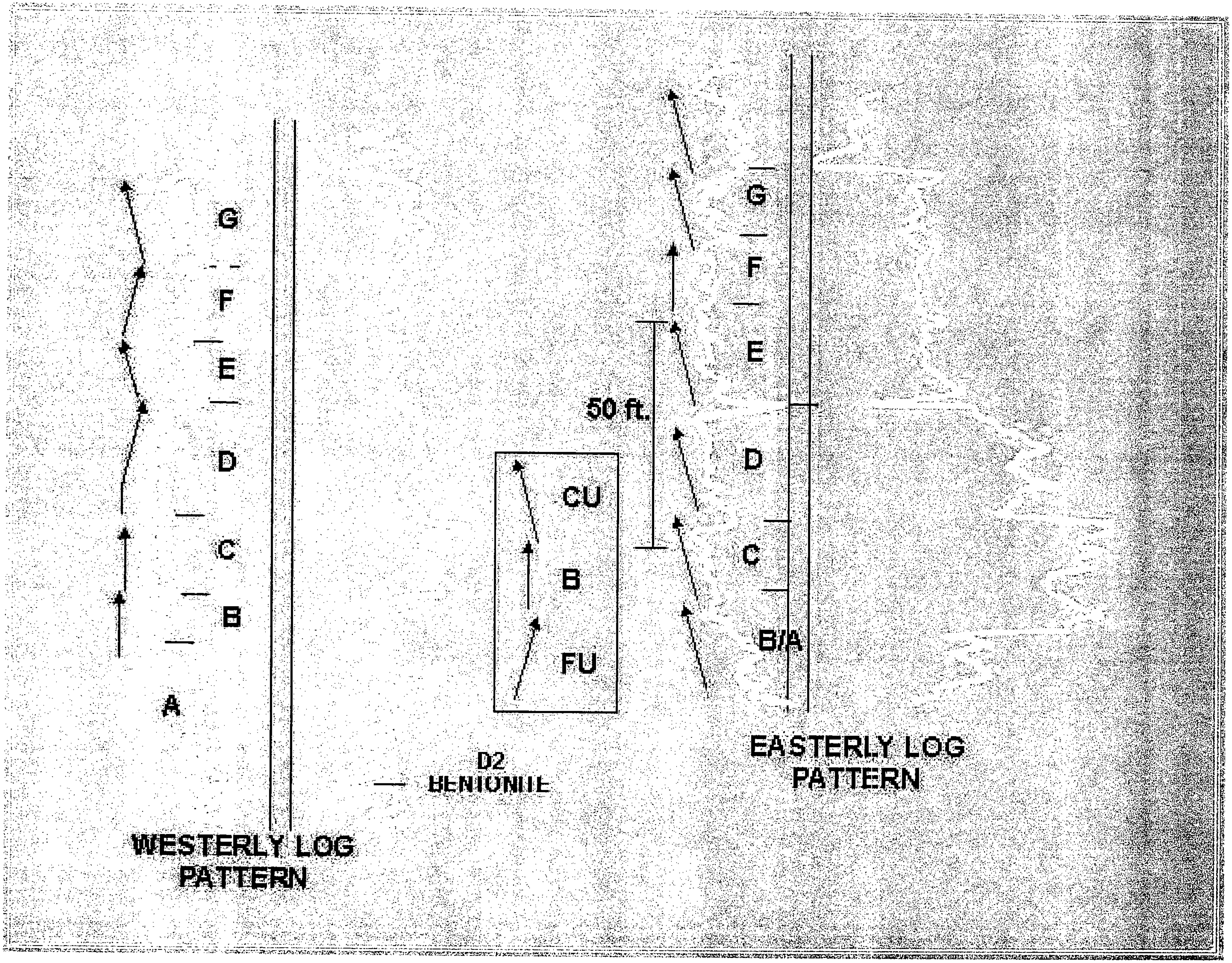




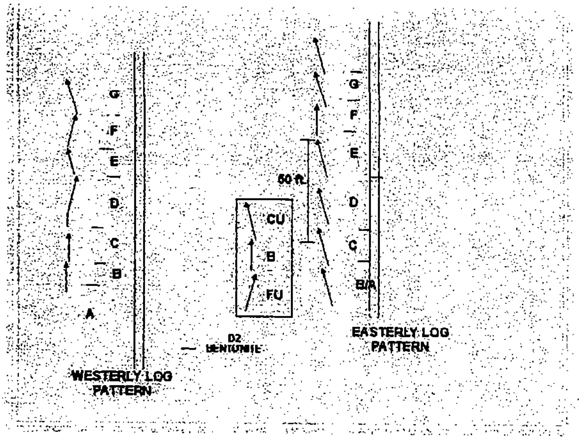
Coastal plain
Coal / Backshore
Beach
Breaker zone - ridge & runnel / rip channels
Shoreface - Swaley cross-stratification
Lower shoreface - inner shelf transition - Hummocky cross-stratification
Mid-shelf - bioturbated sandy siltstone
Outer shelf - bioturbated mudstone
"Normal," gradational-based shoreface succession
Sharp-based shoreface succession deposited during relative sea level fall
10
m
0
Relatively thin, erosive-based shoreface sandbody.
Mudstone intraclasts
Gutter casts

(Walker, 1992)

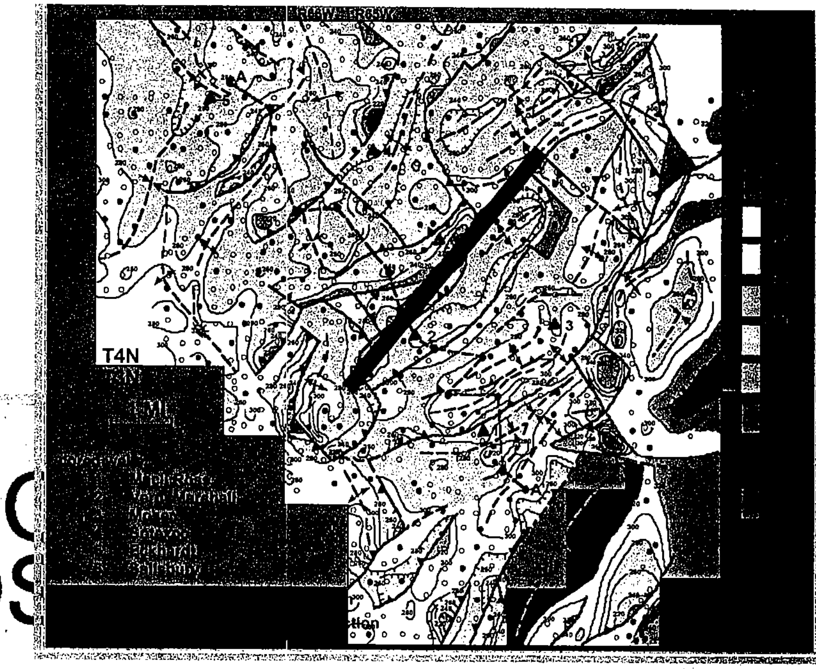

Trans. shale
Coarsening/thickening upward
shoreface parasequence

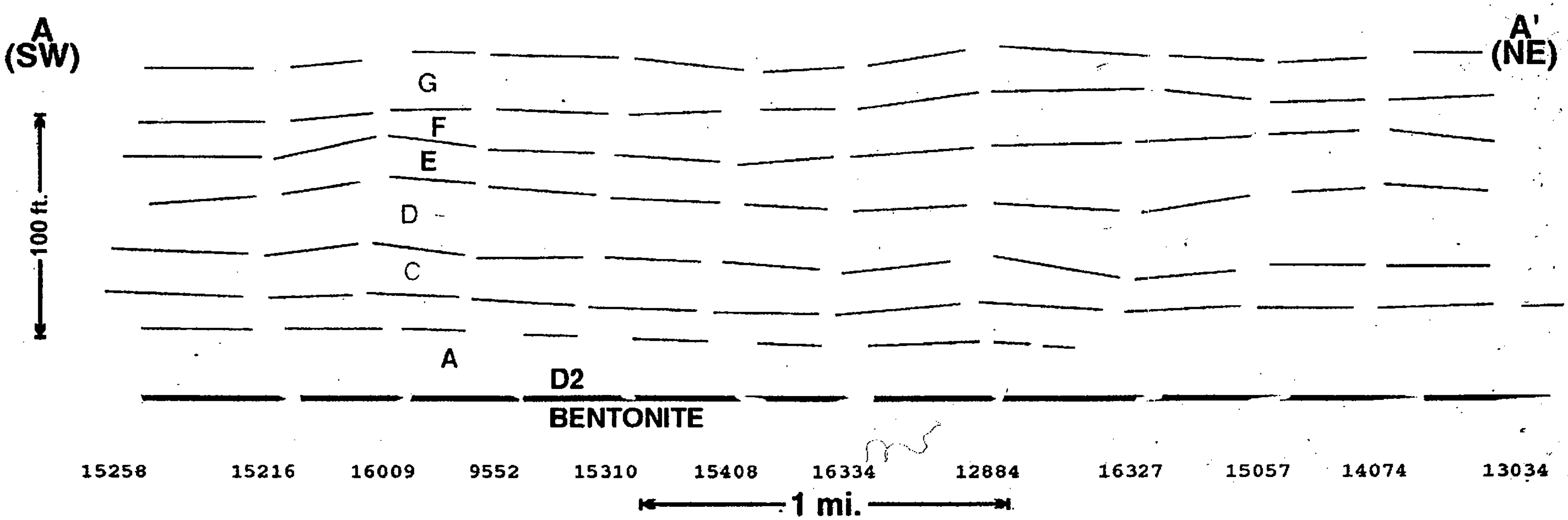


G
F
E
D
C
B
A
WESTERLY LOG PATTERN
CU
B
FU
D2 BENTONITE
50 ft.
G
F
E
D
C
B/A
EASTERLY LOG PATTERN

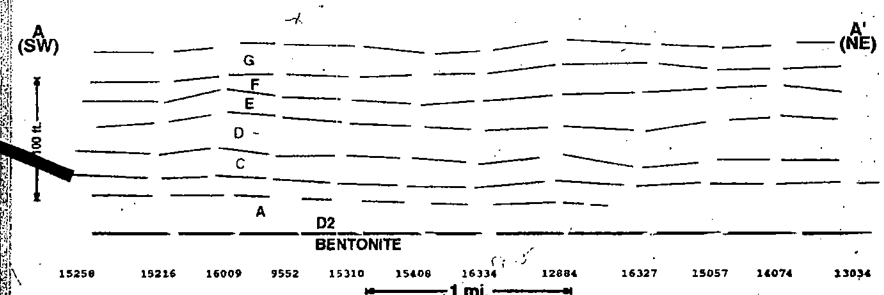


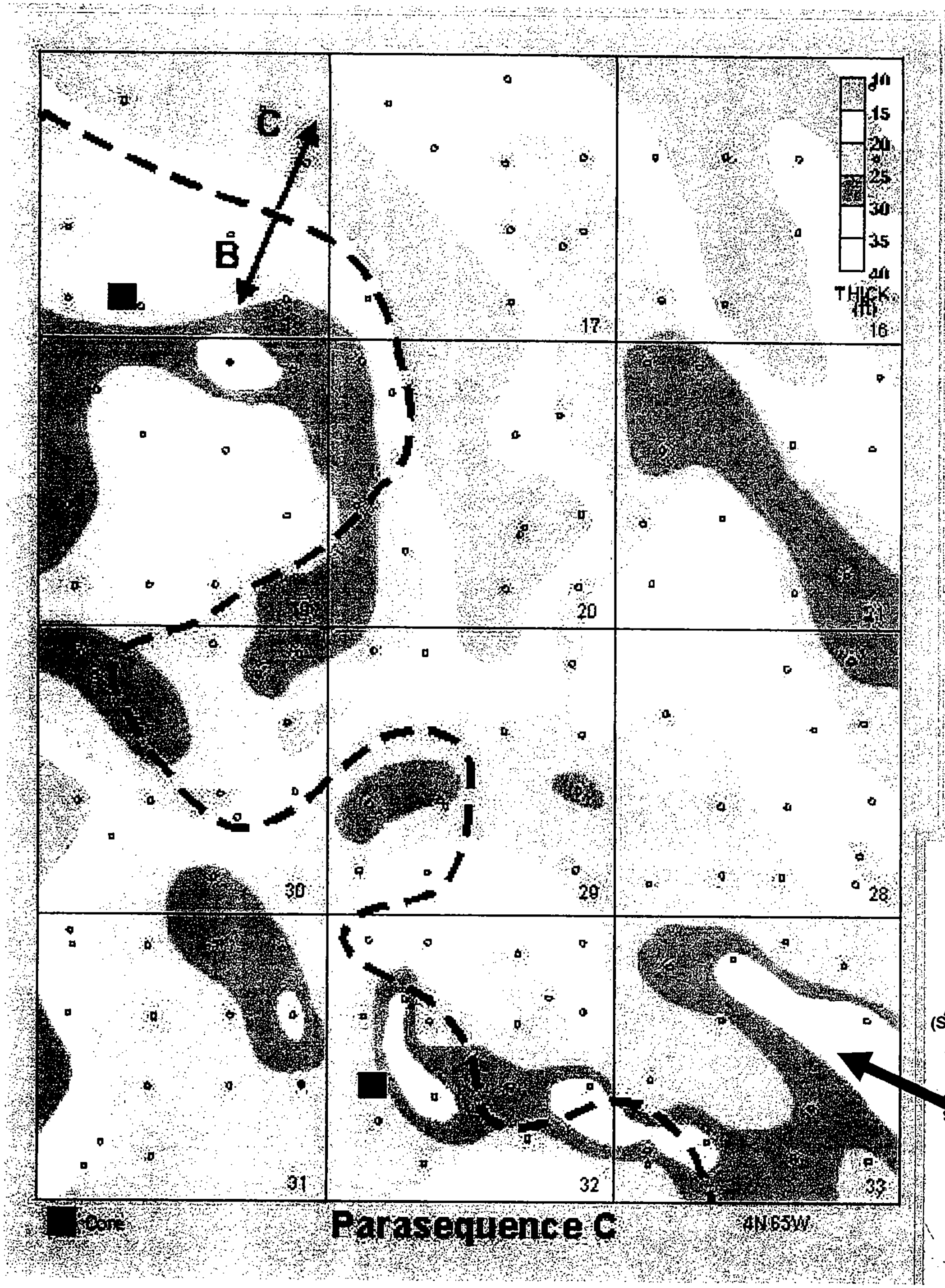
STRATIGRAPHIC CRO
TERRY SANDS



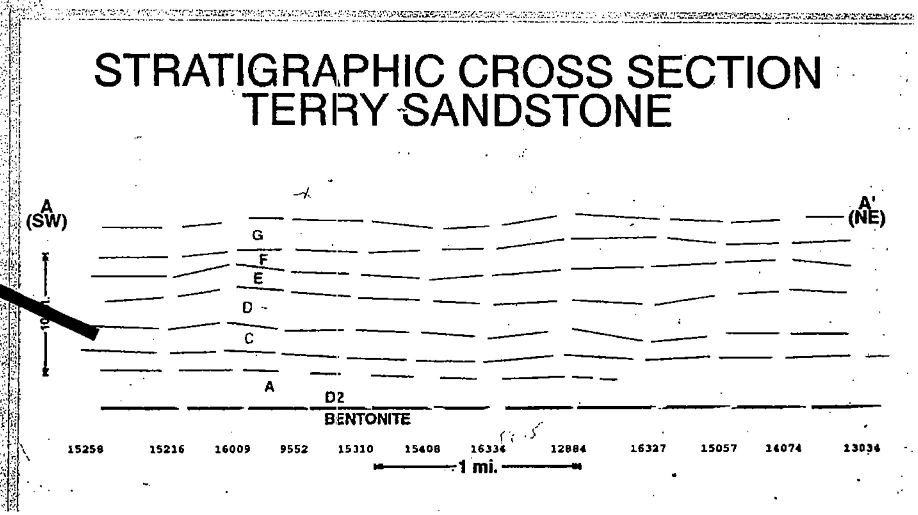


STRATIGRAPHIC CROSS SECTION
TERRY SANDSTONE

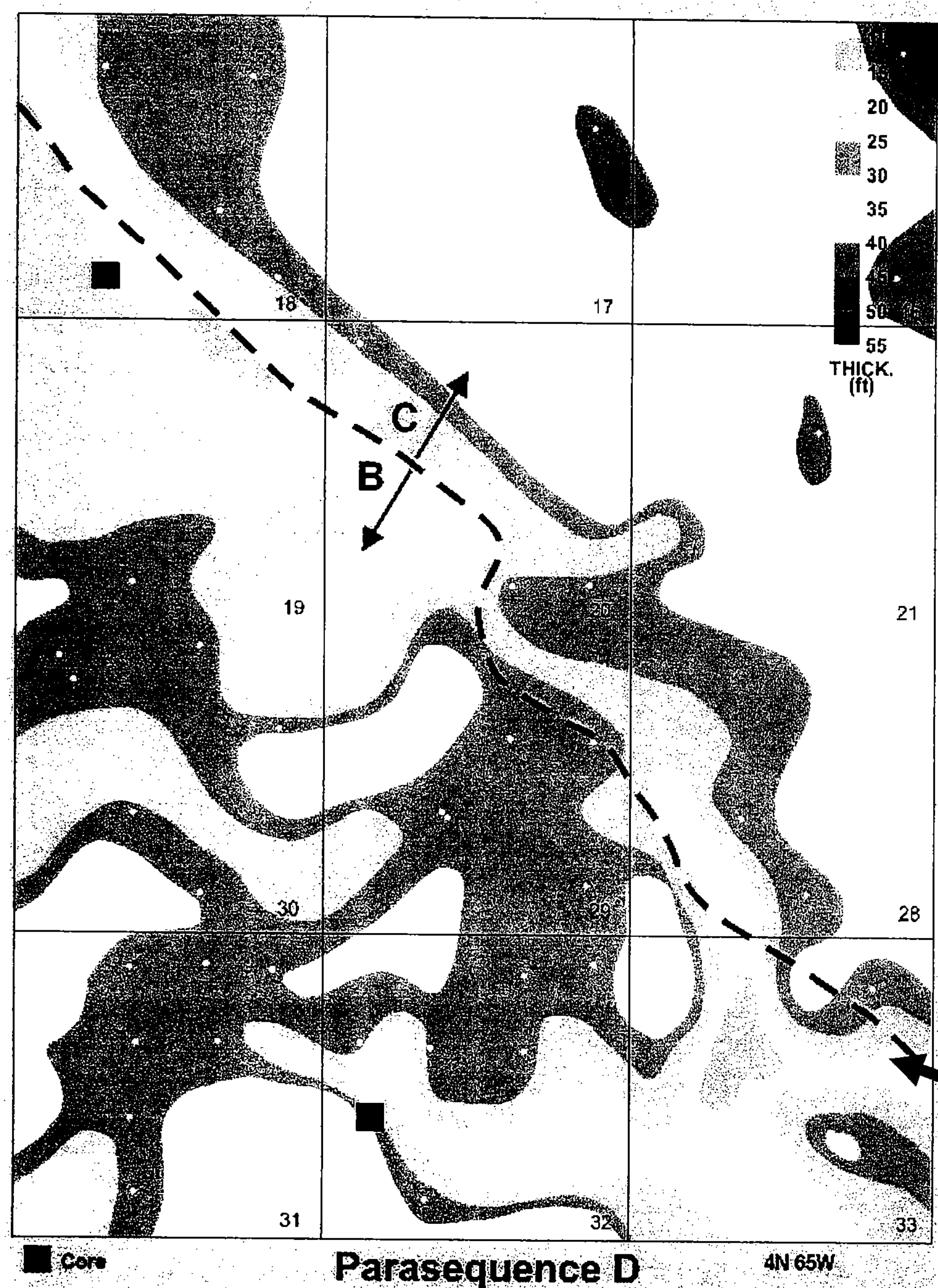




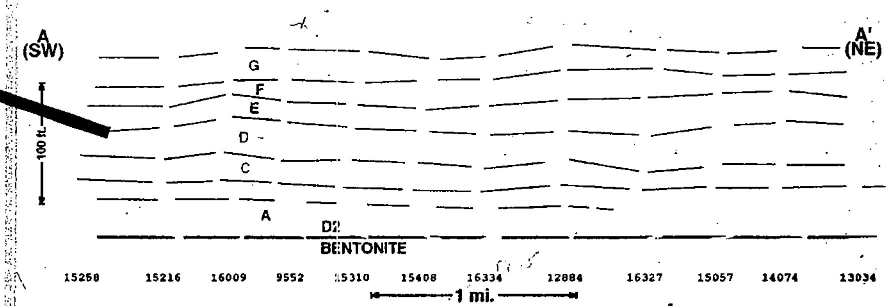
C
B
10
15
20
25
30
35
40
THICK (ft)
17
16
19
20
21
30
29
28
31
32
33
Core
Parasequence C
4N 65W

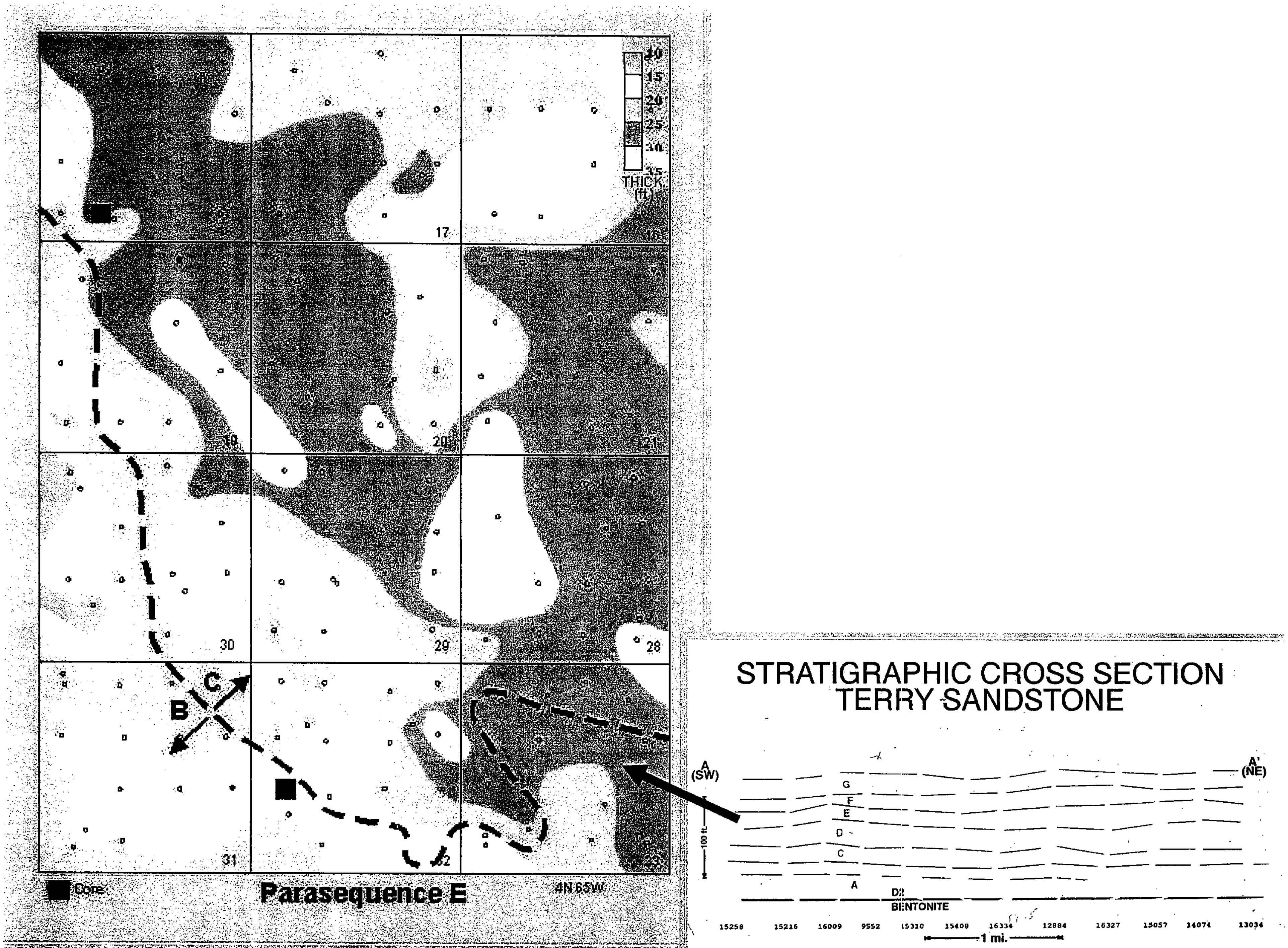


STRATIGRAPHIC CROSS SECTION
TERRY SANDSTONE
A (SW)
A' (NE)
G
F
E
D
C
A
D2
BENTONITE
15258
15216
16009
9552
15310
15408
16336
12884
16327
15057
14074
13036
1 mi.

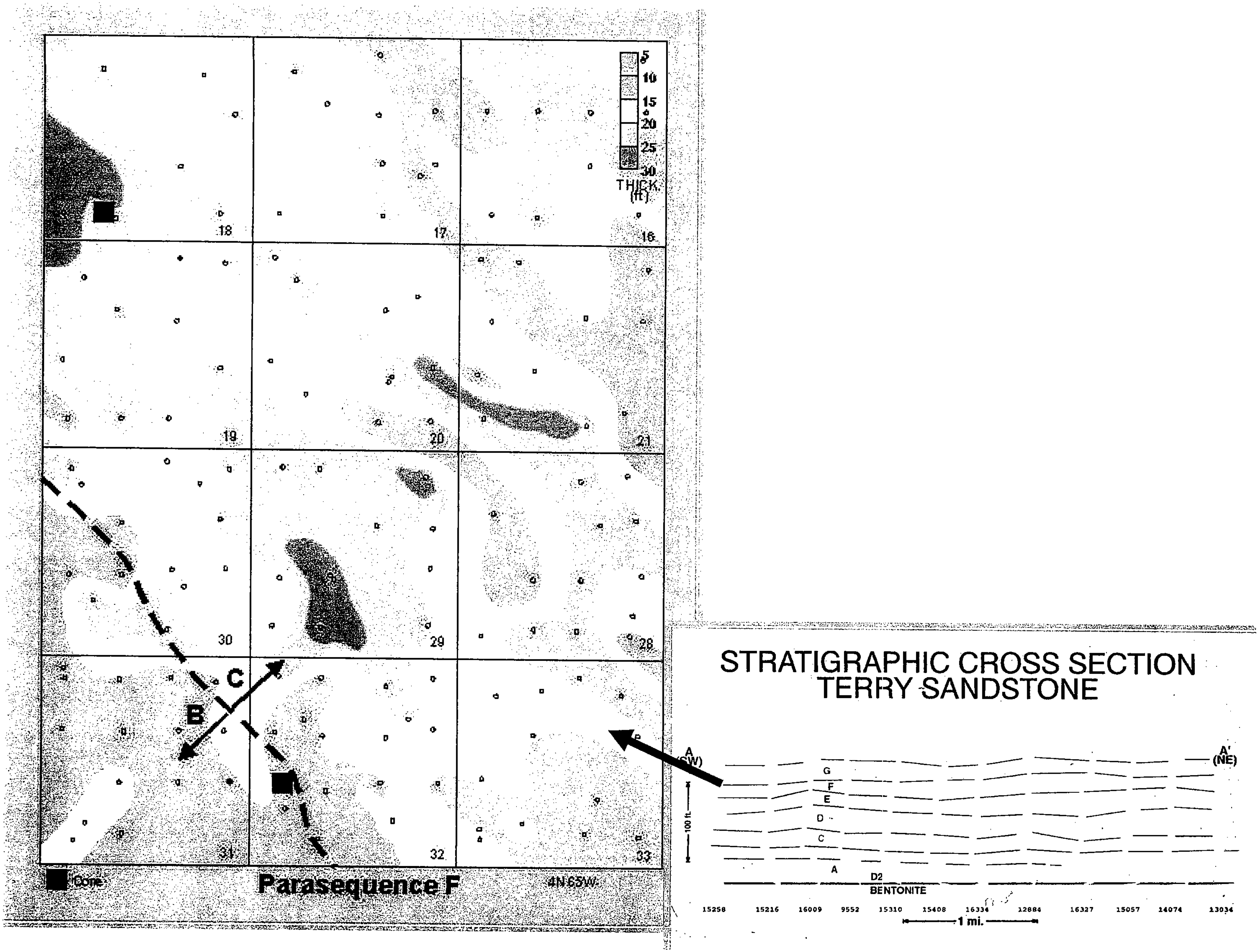


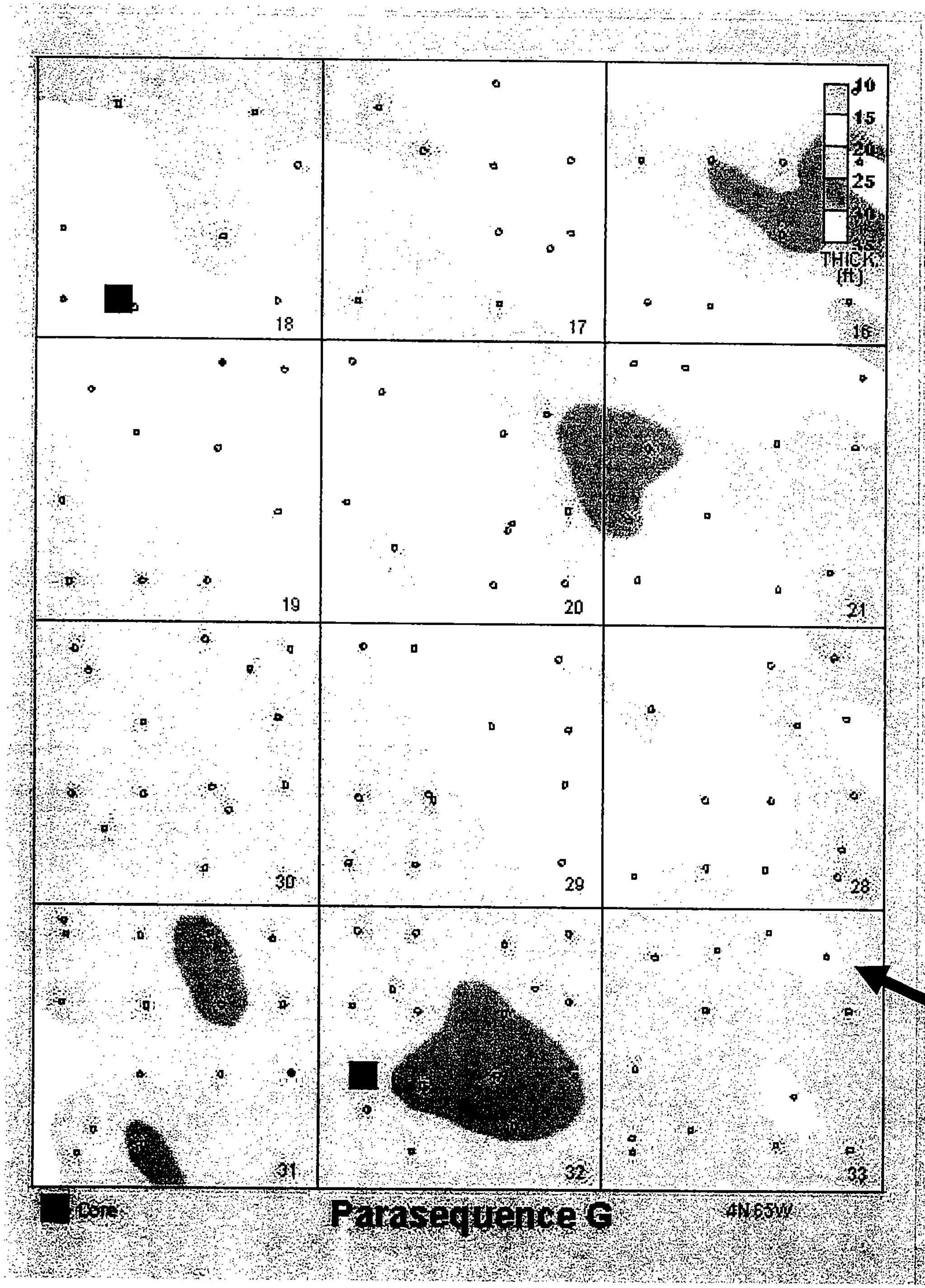
STRATIGRAPHIC CROSS SECTION
TERRY SANDSTONE



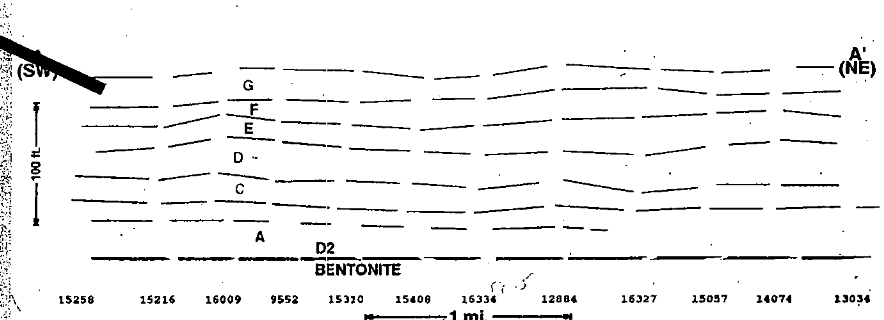


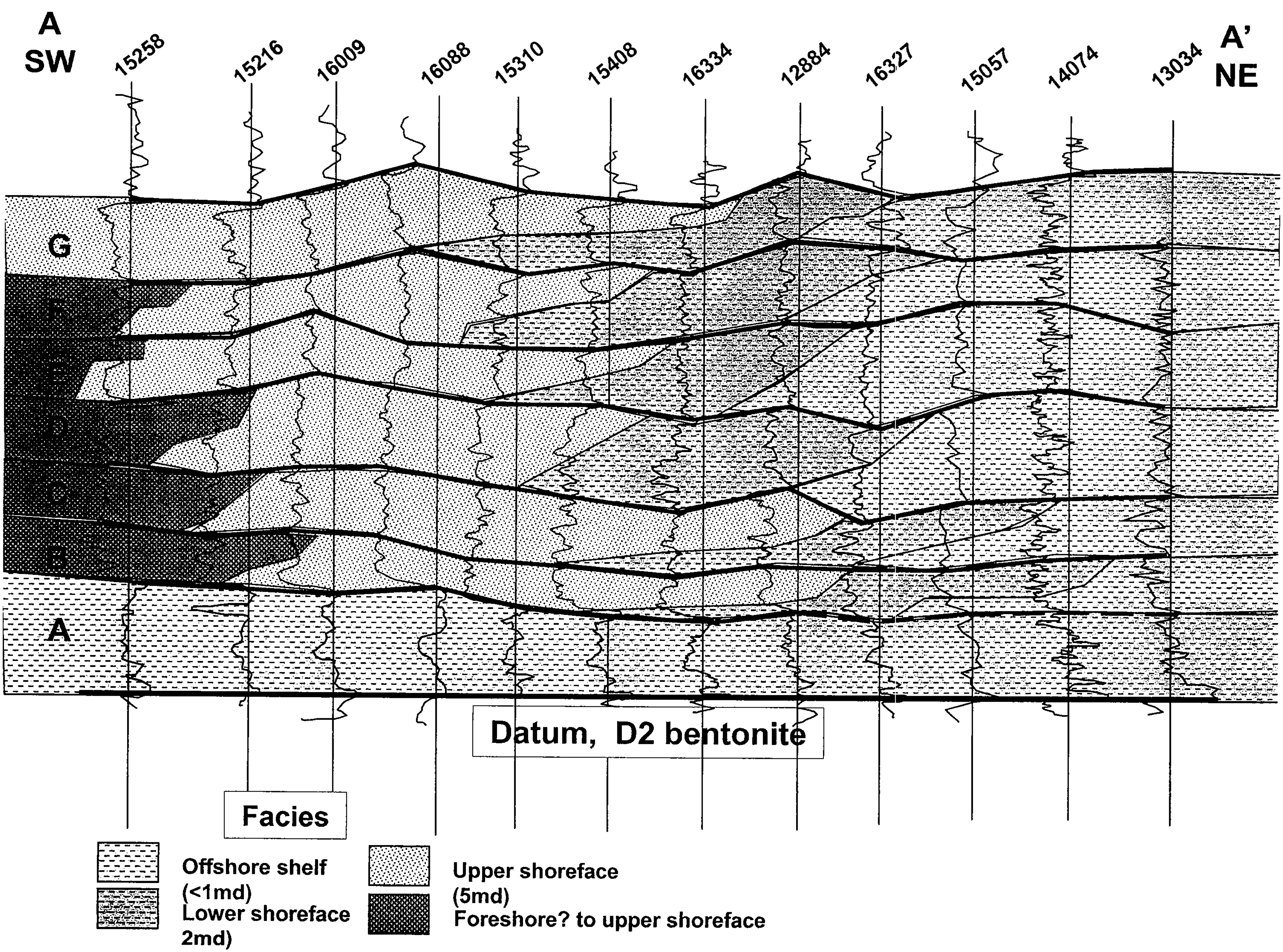
10
15
20
25
30
35
THICK (ft.)
17
18
19
20
21
30
29
28
31
32
33
C
B
Core
Parasequence E
4N 65W
STRATIGRAPHIC CROSS SECTION
TERRY SANDSTONE
A (SW)
A' (NE)
G
F
E
D
C
A
D2
BENTONITE
100 ft.
15258
15216
16009
9552
15310
15408
16334
12884
16327
15057
14074
13034
1 mi.


5
10
15
20
25
30
THICK (ft)
18
17
16
19
20
21
30
29
28
C
B
31
32
33
Core
Parasequence F
4N 65W
STRATIGRAPHIC CROSS SECTION
TERRY SANDSTONE
A (SW)
A' (NE)
G
F
E
D
C
A
D2
BENTONITE
100 ft.
15258
15216
16009
9552
15310
15408
16334
12884
16327
15057
14074
13034
1 mi.

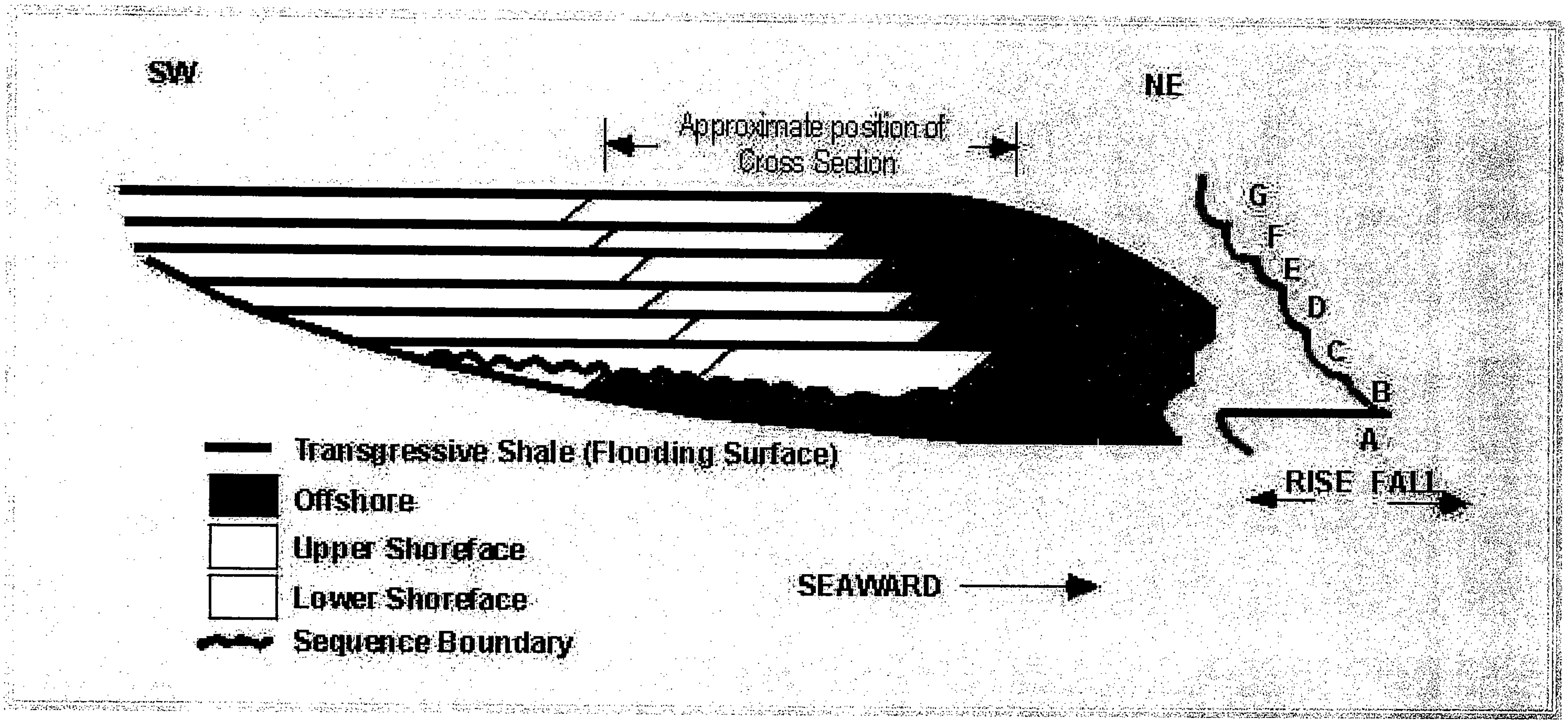


STRATIGRAPHIC CROSS SECTION TERRY SANDSTONE



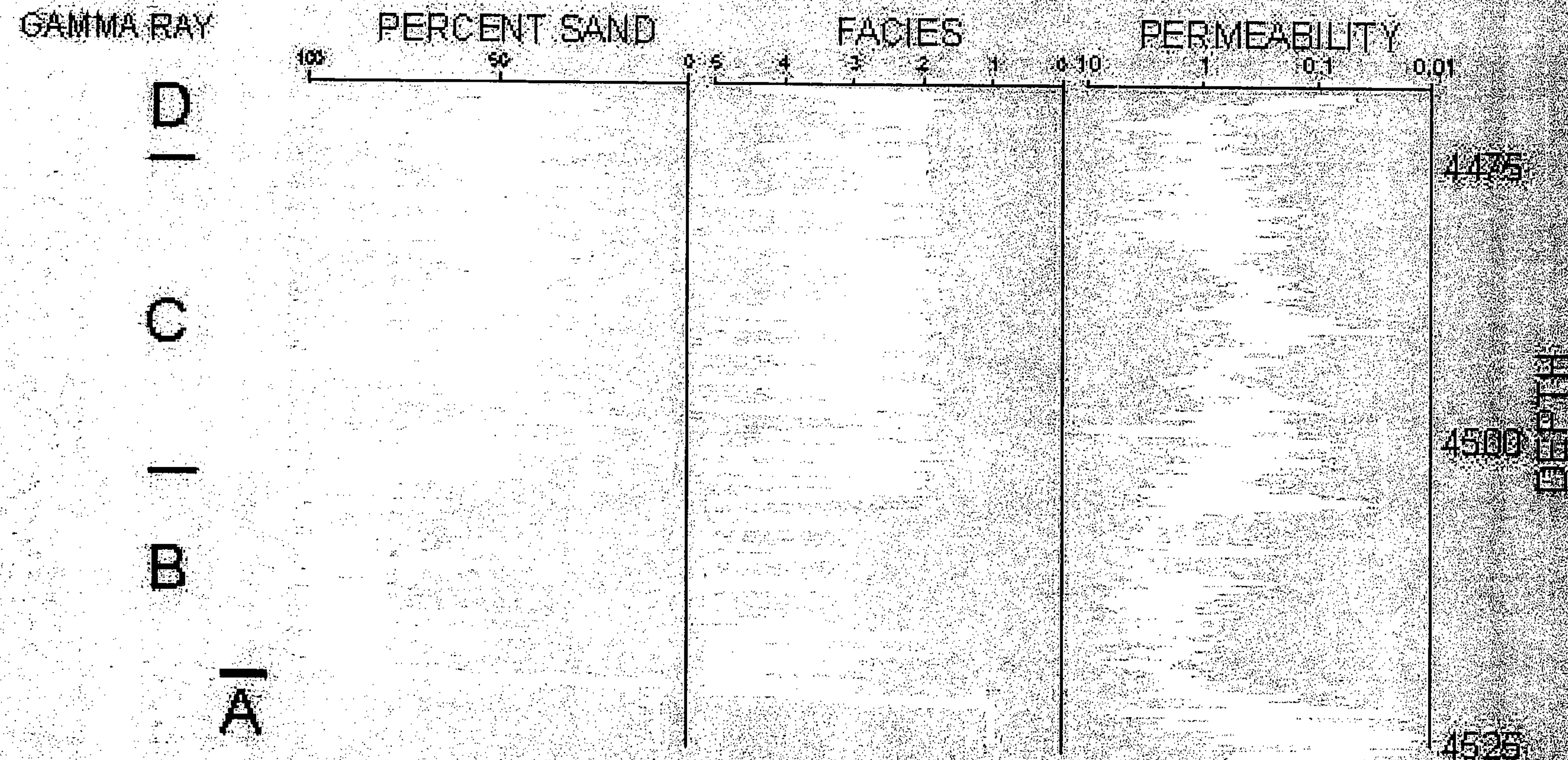


A
SW
A'
NE
15258
15216
16009
16088
15310
15408
16334
12884
16327
15057
14074
13034
G
F
E
D
C
B
A
Datum, D2 bentonite
Facies
Offshore shelf (<1md)
Lower shoreface 2md)
Upper shoreface (5md)
Foreshore? to upper shoreface



SW
NE
Approximate position of Cross Section
G
F
E
D
C
B
A
RISE
FALL
Transgressive Shale (Flooding Surface)
Offshore
Upper Shoreface
Lower Shoreface
Sequence Boundary
SEAWARD

MACHII-ROSS ARISTOCRAT ANGUS 14-4
4-T3N-R65W

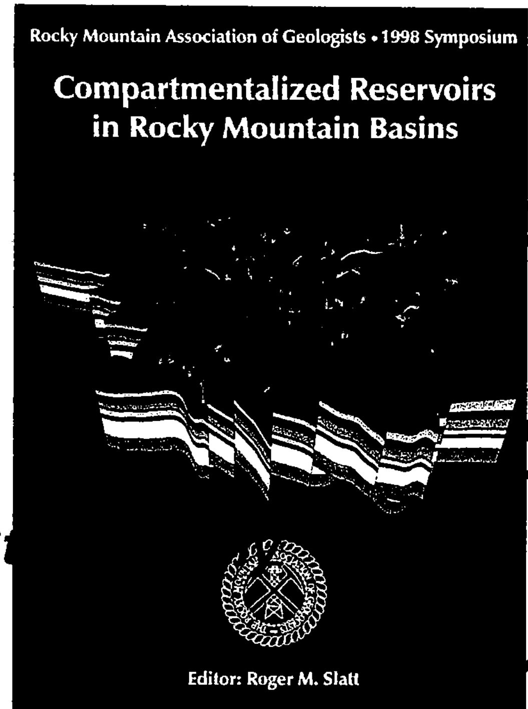


Faults

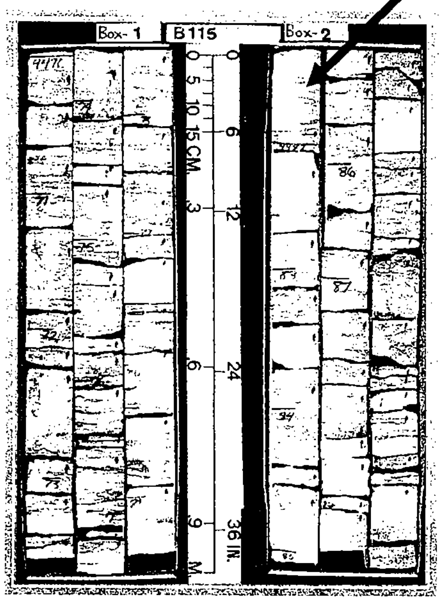
2md permeability

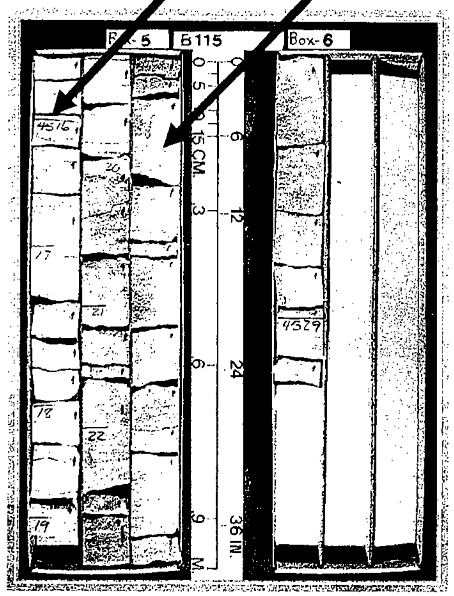
5 md permeability

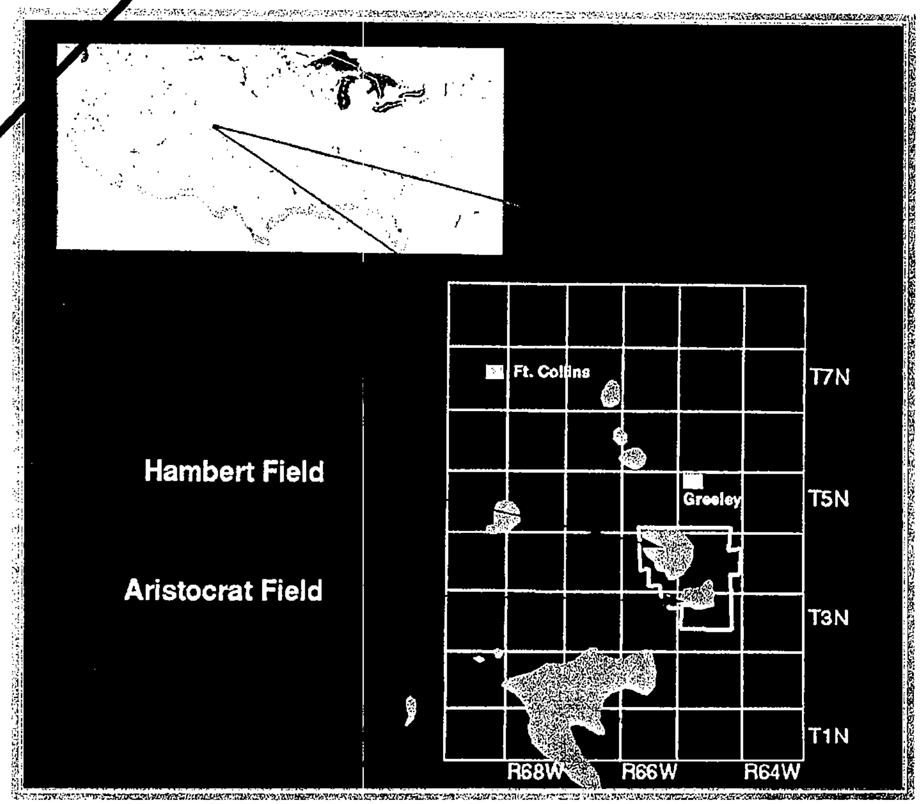
<1md permeability



St







Hambert-Aristocrat Field, Colorado

SHOREFACE RESERVOIRS

- HAMBERT FIELD EXAMPLE FORMED DURING OVERALL PERIOD OF MARINE TRANSGRESSION

- INDIVIDUAL SANDSTONES DEVELOPED DURING PERIODS OF RELATIVE STILLSTAND OF SEA (BASE) LEVELWHEN SEDIMENT SUPPLY EXCEEDED SEA (BASE)LEVEL RISE. RESULTED IN PROGRADATION.

- END RESULT IS A SERIES OF SHOREFACE SANDSTONES SEPARATED BY LATERALLY CONTINUOUS SHALES; i.e. COMPLEXELY COMPARTMENTALIZED RESERVOIR

CONCLUSIONS

- SHOREFACE SEQUENCES ARE INTERNALLY COMPLEX
- INDIVIDUAL SANDSTONES ARE SEPARATED BY LATERALLY CONTINUOUS TRANSGRESSIVE MARINE SHALES WHICH CAN VERTICALLY ISOLATE INDIVIDUAL SANDSTONES
- PORO./PERM. VALUES WILL VARY WITH FACIES (UPPER, MIDDLE, LOWER SHOREFACE)
- HIGH RESOLUTION SEQUENCE STRATIGRAPHY SHOULD BE APPLIED TO SHOREFACE SEQUENCES

BARRIER
ISLAND DEPOSITS & RESERVOIRS

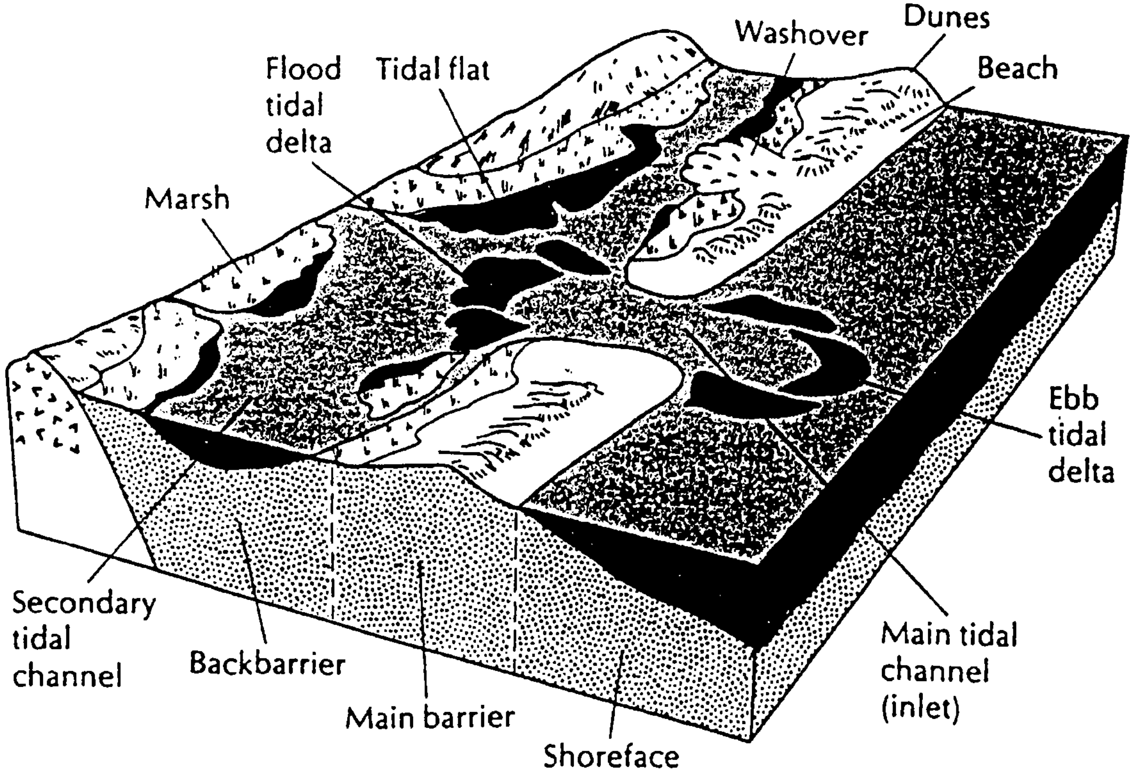
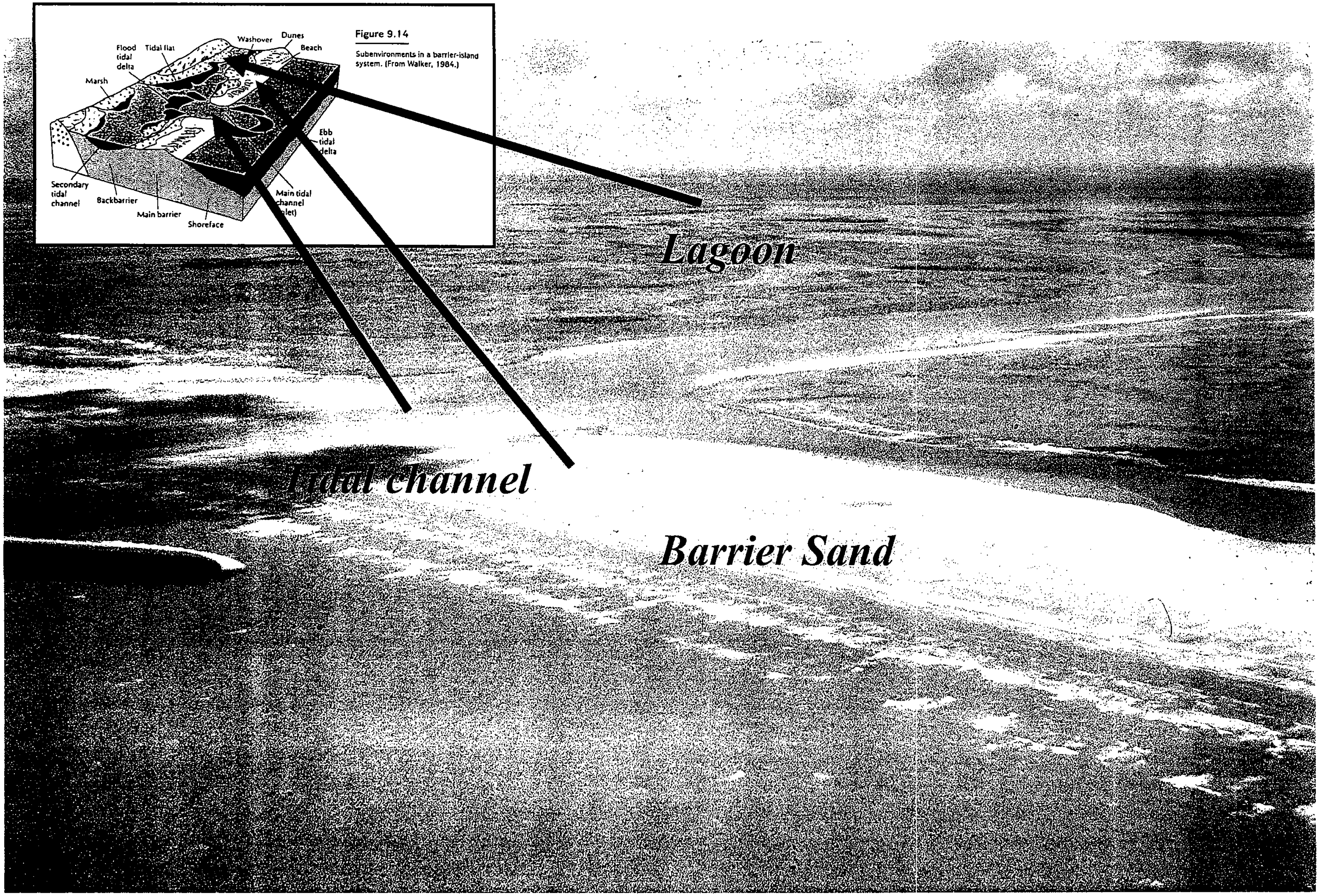


Figure 9.14

Subenvironments in a barrier-island system. (From Walker, 1984.)


Flood tidal delta
Tidal flat
Washover
Dunes
Beach
Marsh
Ebb tidal delta
Secondary tidal channel
Backbarrier
Main barrier
Shoreface
Main tidal channel
Figure 9.14
Subenvironments in a barrier-island system. (From Walker, 1984.)
Lagoon
Tidal channel
Barrier Sand

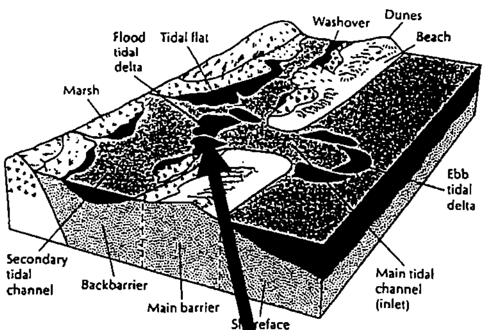


Figure 9.14

Subenvironments in a barrier-island system. (From Walker, 1984.)

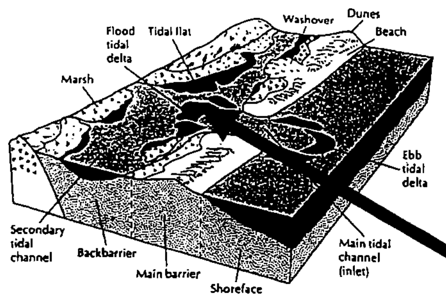


Figure 9.14

Subenvironments in a barrier-island system. (From Walker, 1984.)

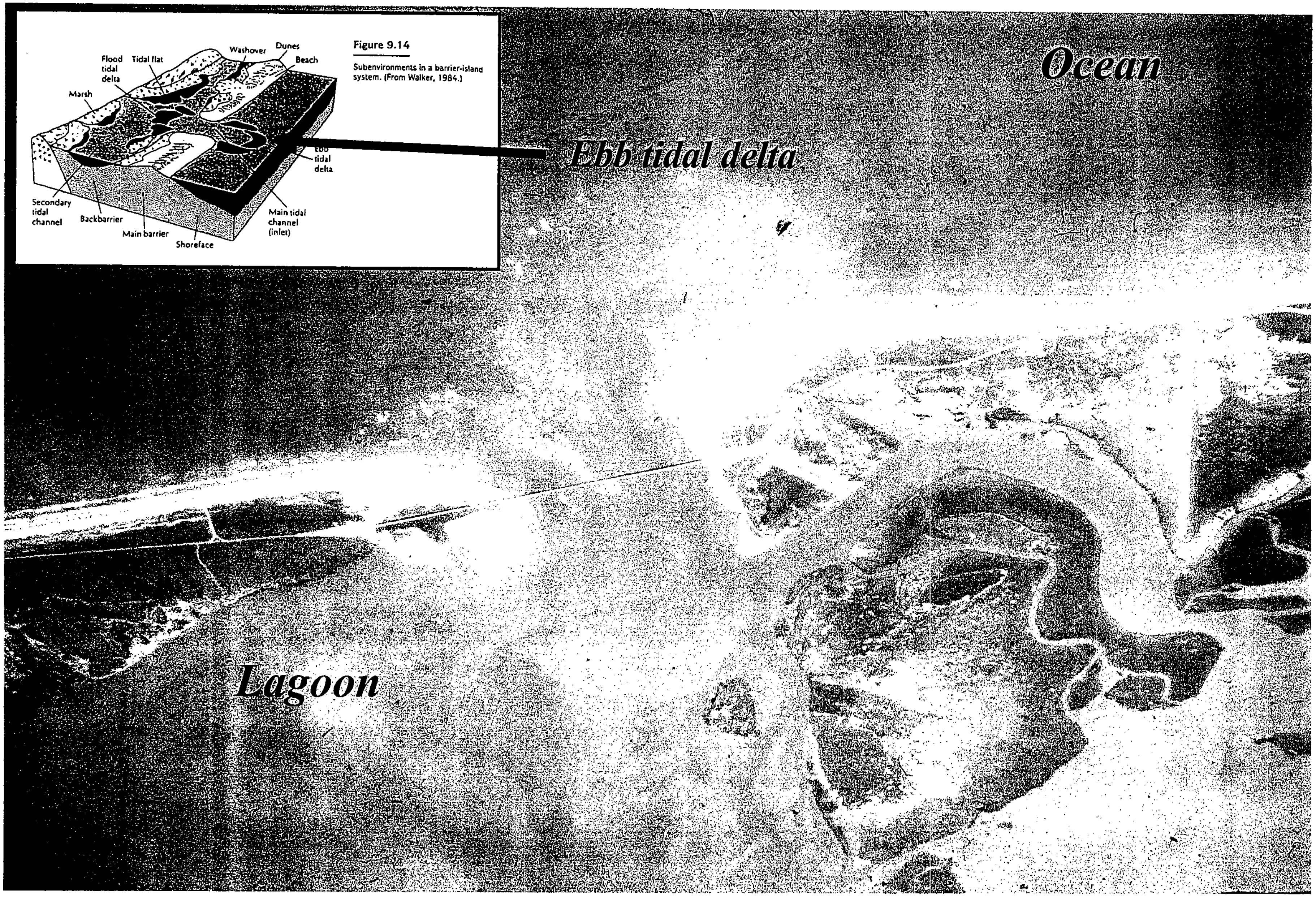


Figure 9.14
Subenvironments in a barrier-island system. (From Walker, 1984.)
Washover
Dunes
Beach
Flood tidal delta
Tidal flat
Marsh
Ebb tidal delta
Secondary tidal channel
Backbarrier
Main barrier
Shoreface
Main tidal channel (inlet)
Ocean
Ebb tidal delta
Lagoon

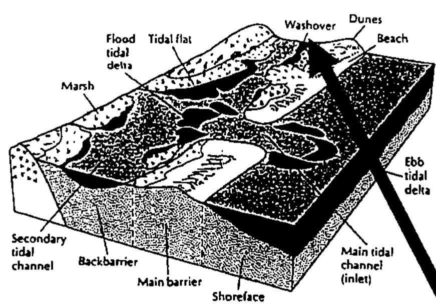
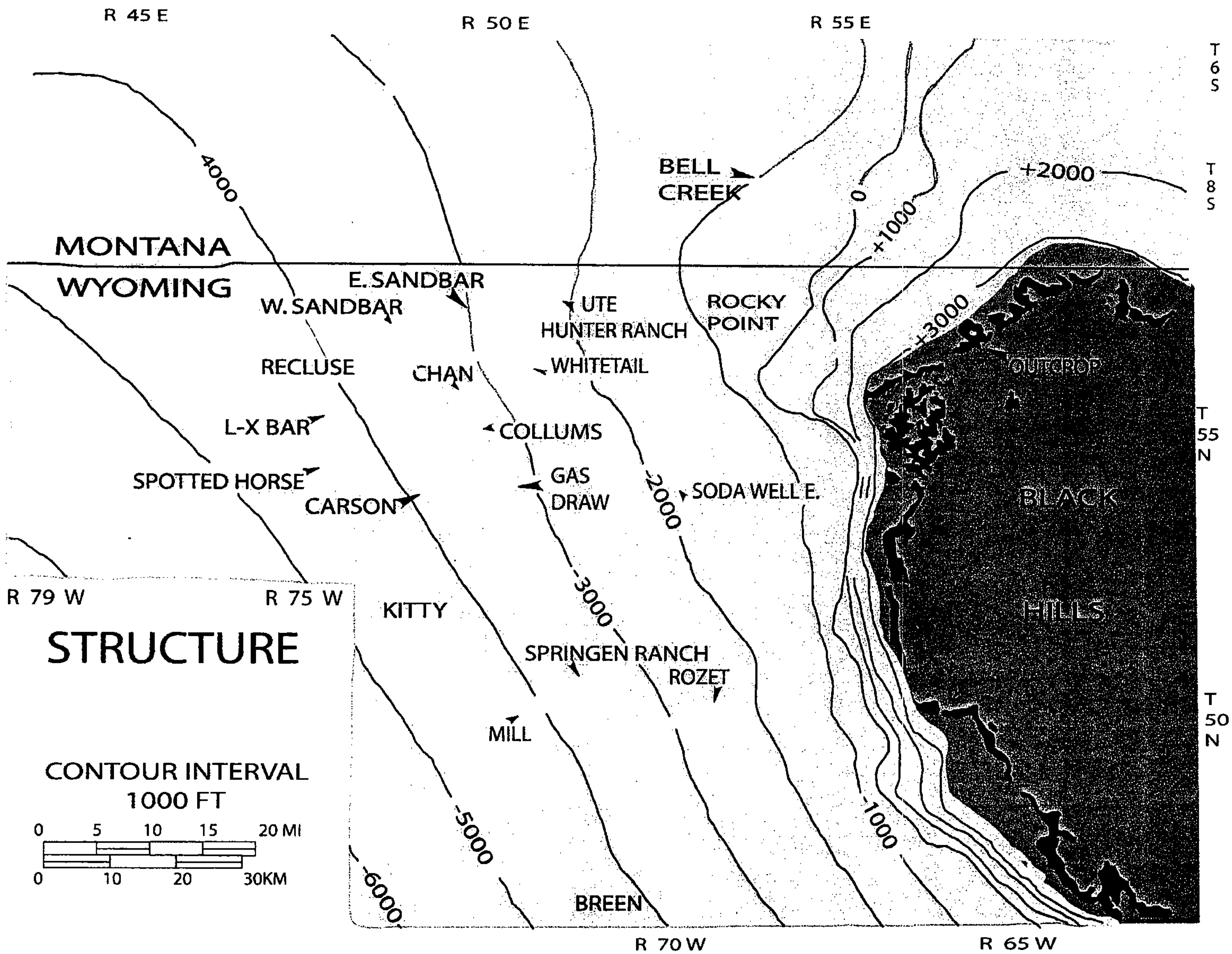


Figure 9.14

Subenvironments in a barrier-island system. (From Walker, 1984.)



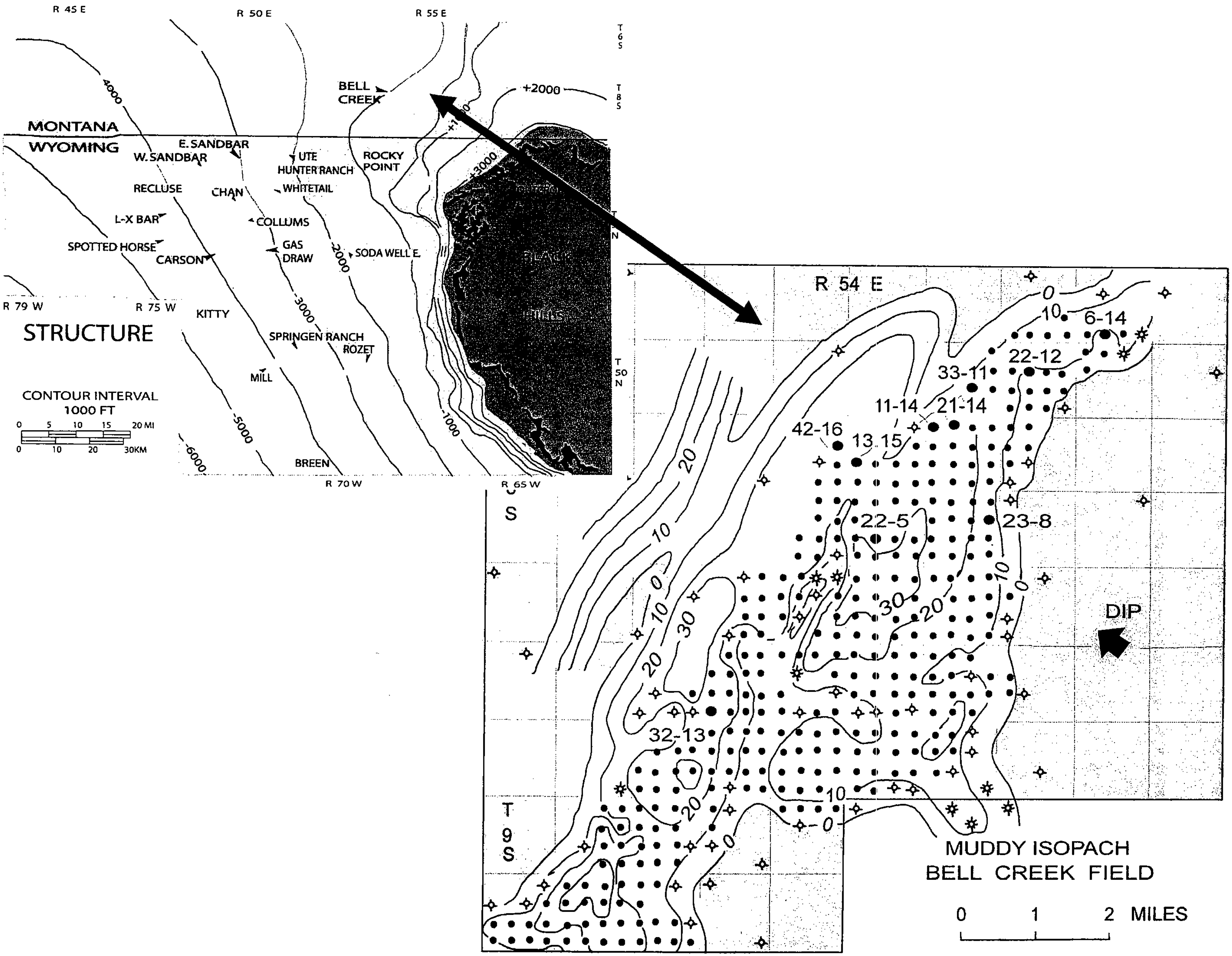
Bell Creek and Recluse Fields

TABLE 7-1. OIL PRODUCTION FROM SELECTED MUDDY FIELDS, NORTHEASTERN POWDER RIVER BASIN, MONTANA AND WYOMING

Name	Discovery date (mo/yr)	Producing wells (Total Jan. 1, 1977)		Production[a] (Annual 1976)	Production[a] (Cumulative Jan. 1, 1977)
Bell Creek B	6/67	196	180	8.75	86.3
Hilight	2/69	195	176	3.82	57.6
Recluse R	8/67	58	46	8.38	20.8
Gas Draw	8/68	83	47	1.8	19.7
Rozet	4/59	28	28	0.70	15.7
Kitty	8/65	175	161	0.50	15.1
Springen Ranch	11/68	43	28	0.70	8.9
Collums	2/69	42	23	0.20	5.4
Sandbar, East	1/68	24	12	0.10	4.2
Sandbar, West	2/68	16	11	0.06	3.3
Rozet East	6/61	8	8	0.16	1.7
Mill	3/69	22	22	0.01	1.5
Gillette	10/62	11	0	0	1.3
Recluse SE	12/68	5	4	0.02	0.4
L-X Bar	2/73	7	7	0.10	0.6

SOURCE: Data from International Oil Scouts Association, *Yearbook 1977.*

[a] Production in million barrels of crude oil.

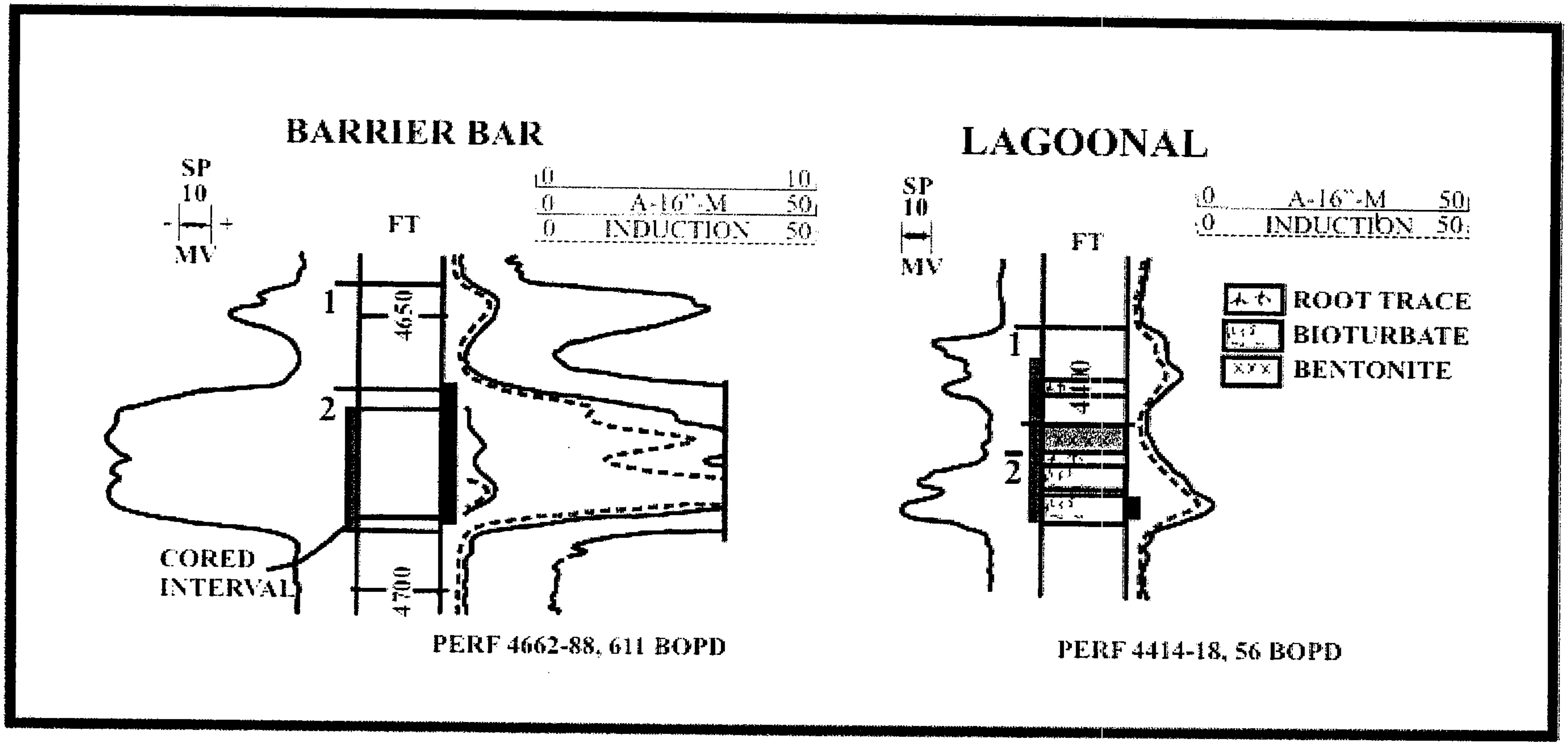


R 45 E
R 50 E
R 55 E
BELL CREEK
+2000
MONTANA
WYOMING
E. SANDBAR
W. SANDBAR
UTE
HUNTER RANCH
ROCKY POINT
RECLUSE
CHAN
WHITETAIL
L-X BAR
COLLUMS
SPOTTED HORSE
CARSON
GAS DRAW
SODA WELL E.
R 79 W
R 75 W
KITTY
STRUCTURE
SPRINGEN RANCH
ROZET
MILL
CONTOUR INTERVAL
1000 FT
BREEN
R 70 W
R 65 W
R 54 E
DIP
T 9 S
MUDDY ISOPACH
BELL CREEK FIELD
0 1 2 MILES

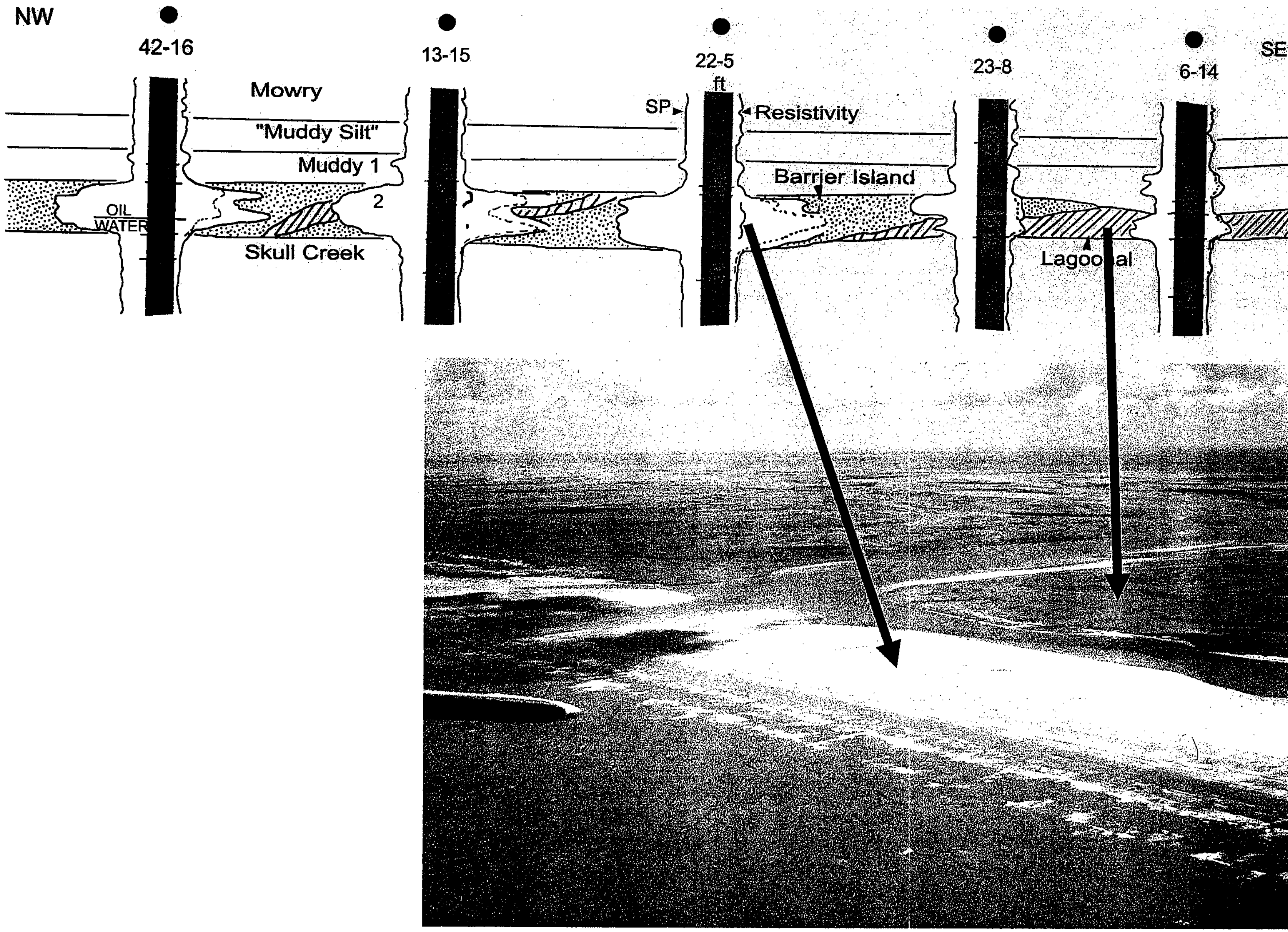
Sedimentary structures. The Muddy sandstone shows a sequence similar to that of the barrier island, and a typical section is shown in a core from the well Boekel 21–14, as follows:

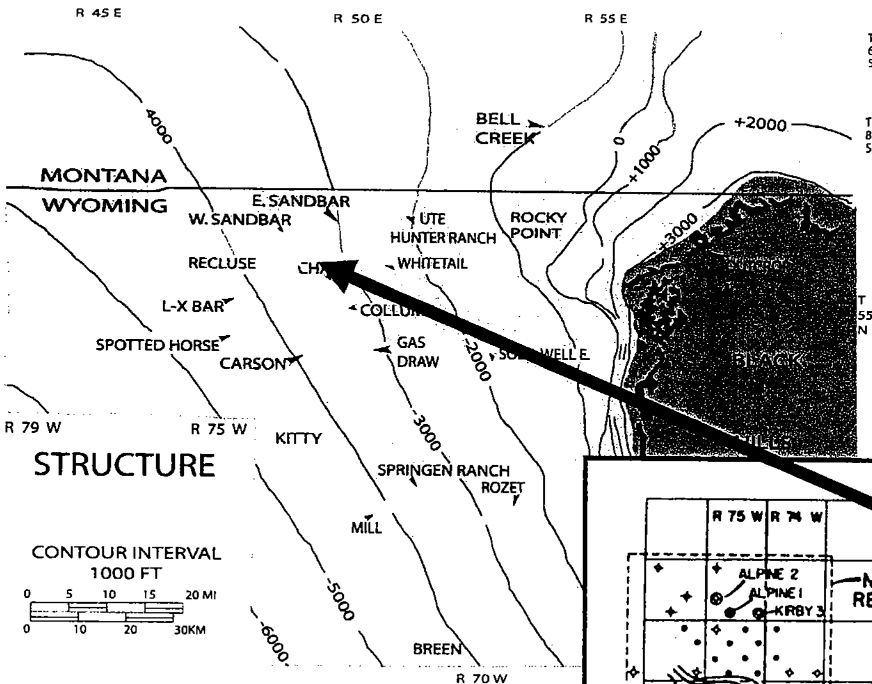
Unit	*Thickness ft (m)*
1. Eolian sandstone, very fine grained, massive.	5 (1.5)
2. Beach and upper-shoreface sandstone, fine grained, laminated.	5 (1.5)
3. Middle-shoreface sandstone, fine grained, massive or with discontinuous laminae.	10 (3)
4. Lower-shoreface mudstone, shaly, highly bioturbated.	3 (0.9)
Total	23 (7)

This sequence is identical to that of the modern barrier island at Galveston Island (Figure 7–4).



Typical logs for different facies; Bell Creek Field


NW
42-16
13-15
22-5
ft
23-8
6-14
SE
Mowry
"Muddy Silt"
Muddy 1
2
OIL
WATER
Skull Creek
SP
Resistivity
Barrier Island
Lagoo al



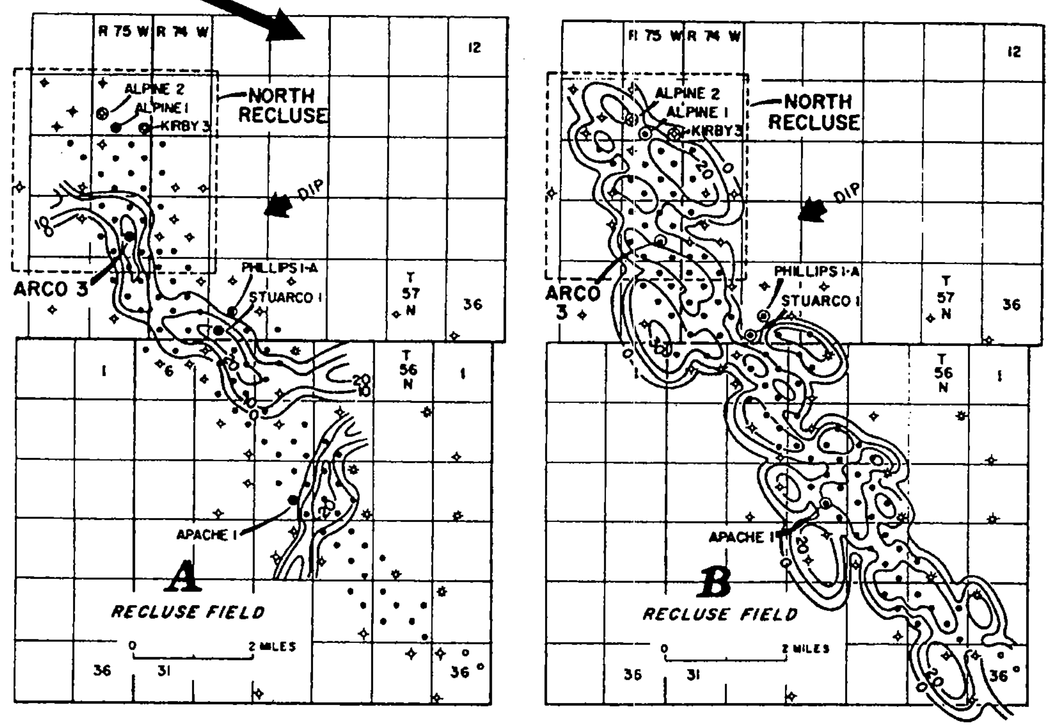
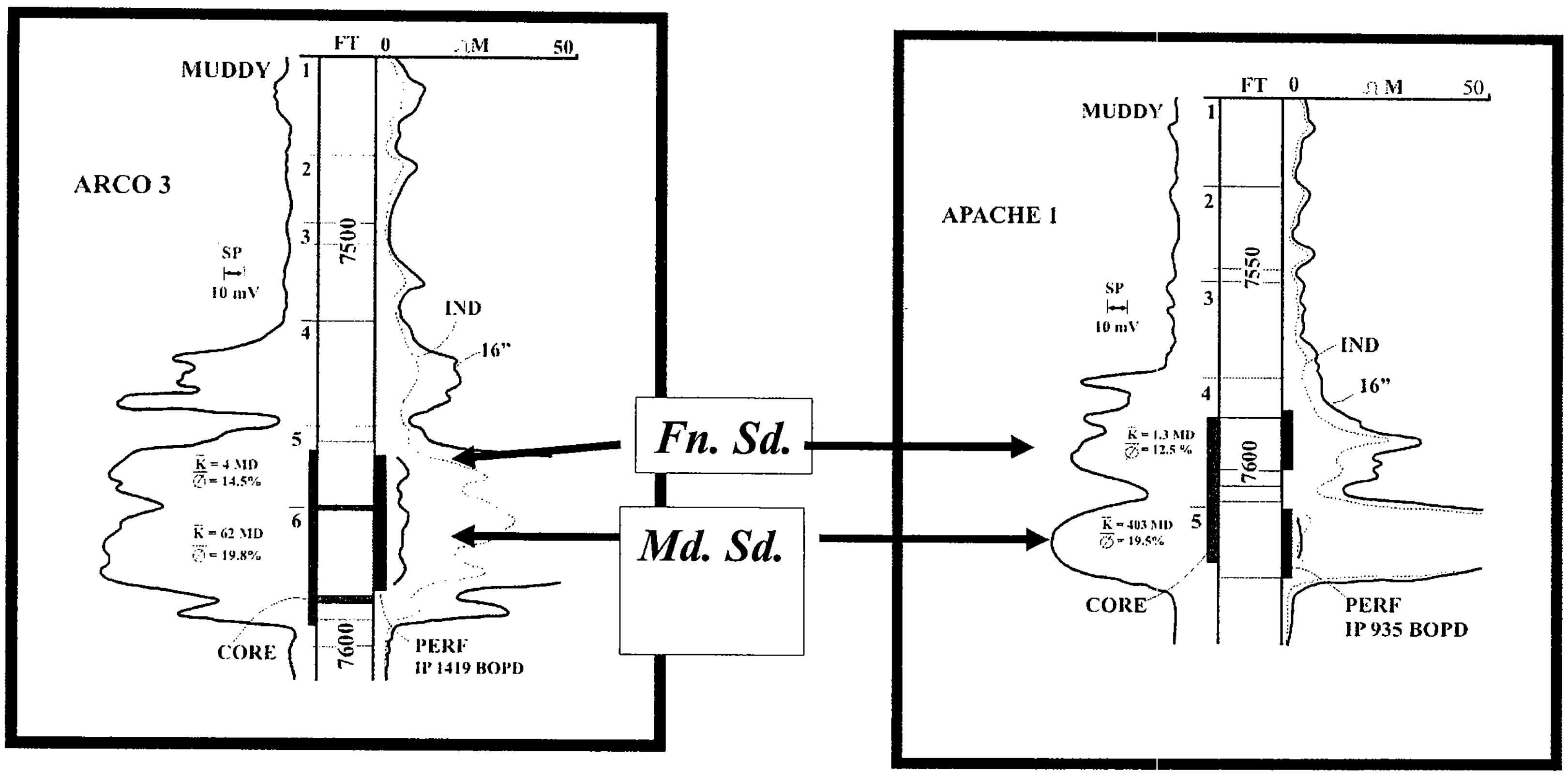
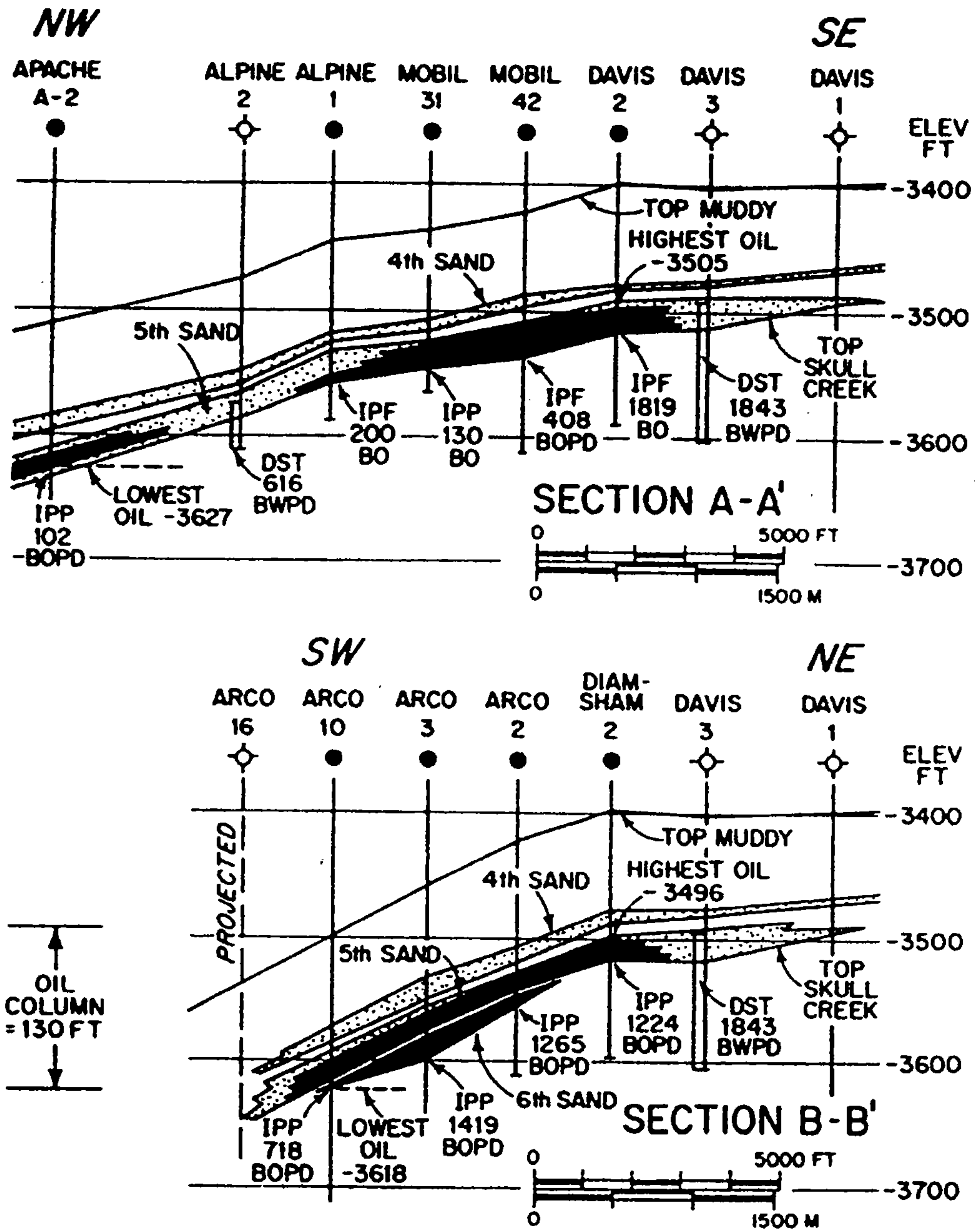


Figure 7-24 Gross thickness of sixth Muddy sandstones (A) and Fifth Muddy sandstones (B) at Recluse field. Contour interval 10 ft (3 m). Cores or samples were examined from circled and named wells. The north Recluse area is shown in Figure 7-25. [Maps from Berg 1976*a* and published with the permission of the Wyoming Geological Association.]

Recluse Field





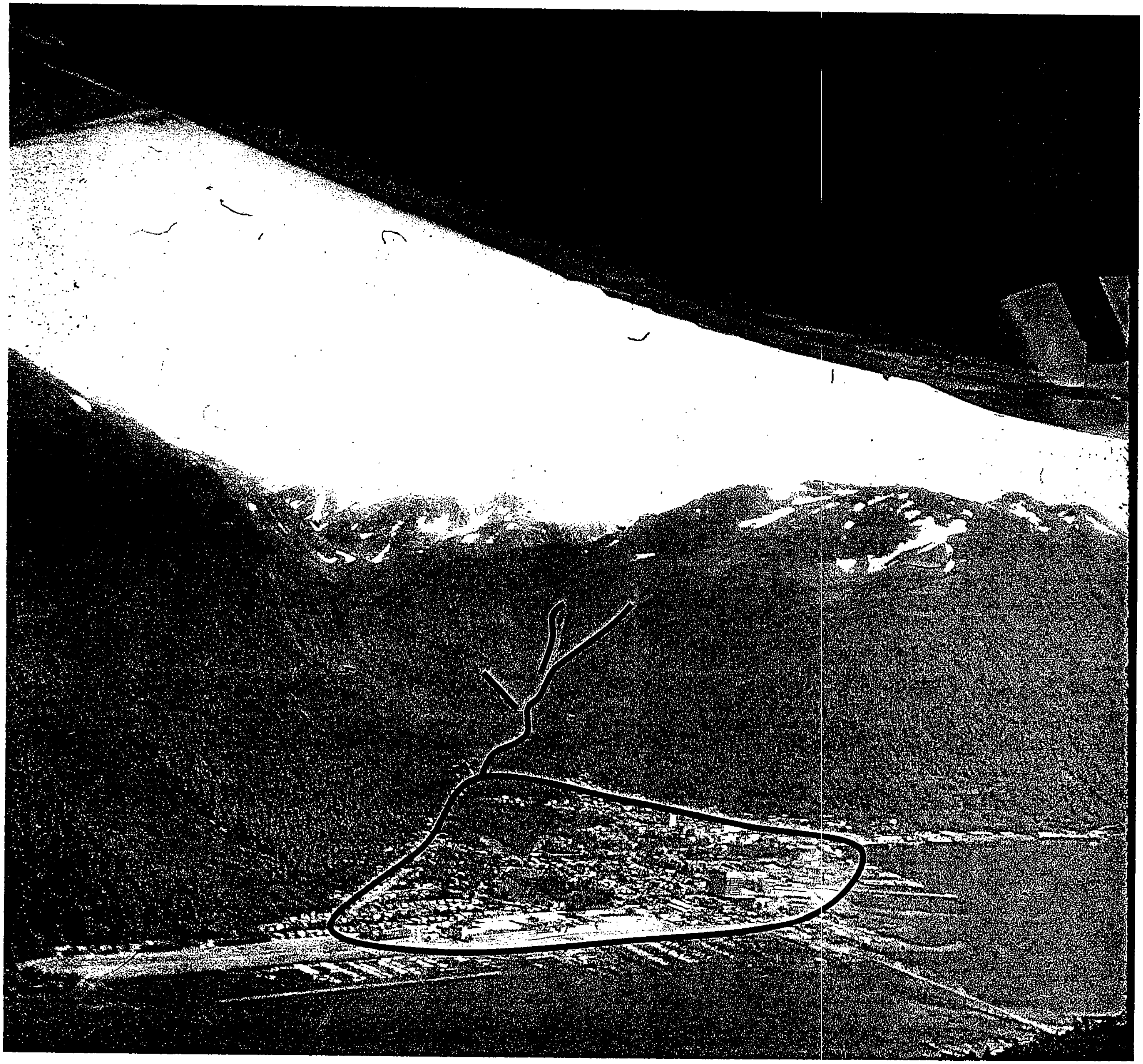
Note upward (structurally) increase in IPF oil, then water.

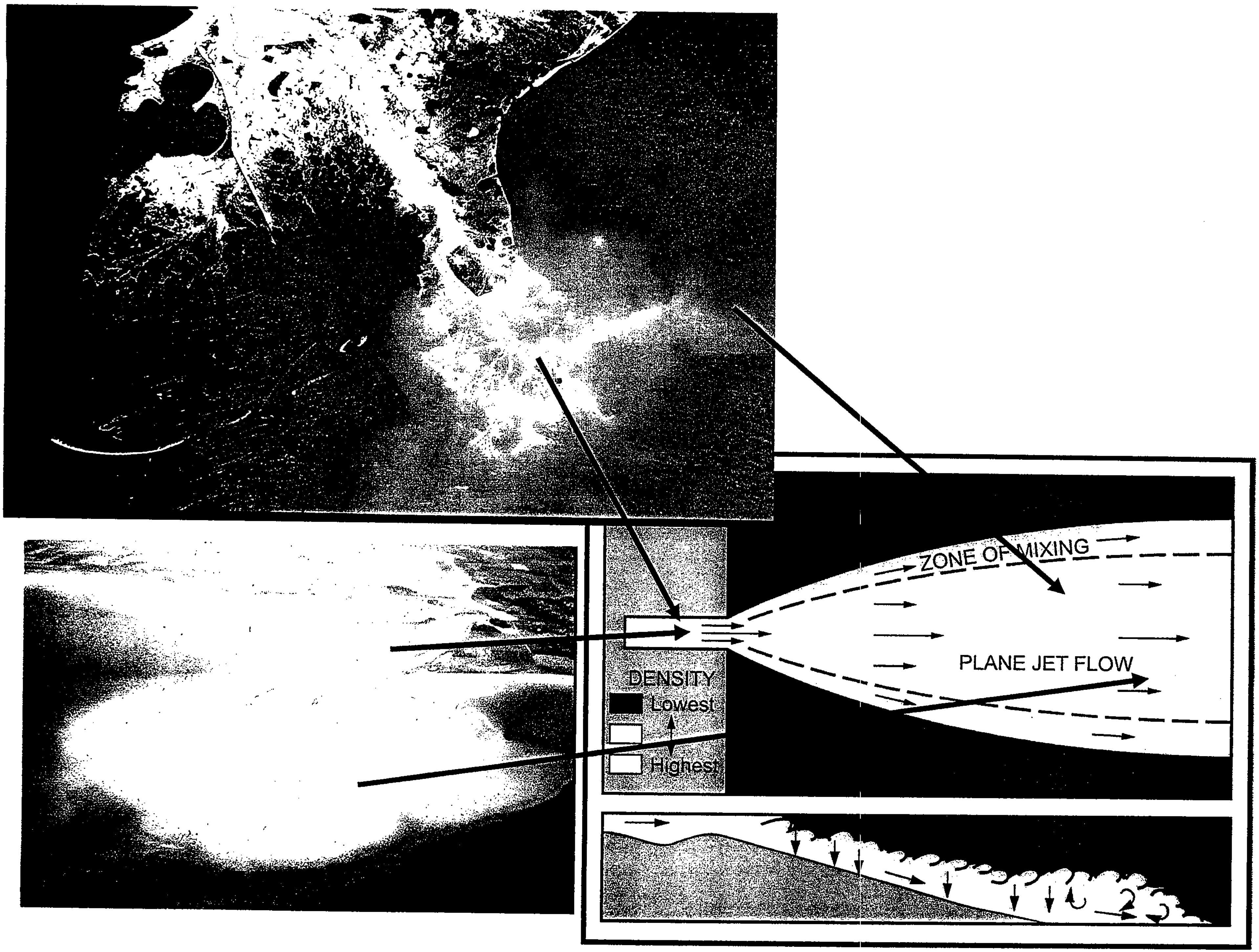
Figure 7-26 Cross sections AA′ and BB′ in the north part of Recluse field showing water recovery adjacent to oil production and an oil column greater than 100 ft (30 m). Location of cross sections shown in Figure 7-25. BOPD = bbls oil/day; BWPD = bbls water/day. [From Berg 1976*a* and published with the permission of the Wyoming Geological Association.]

CONCLUSIONS

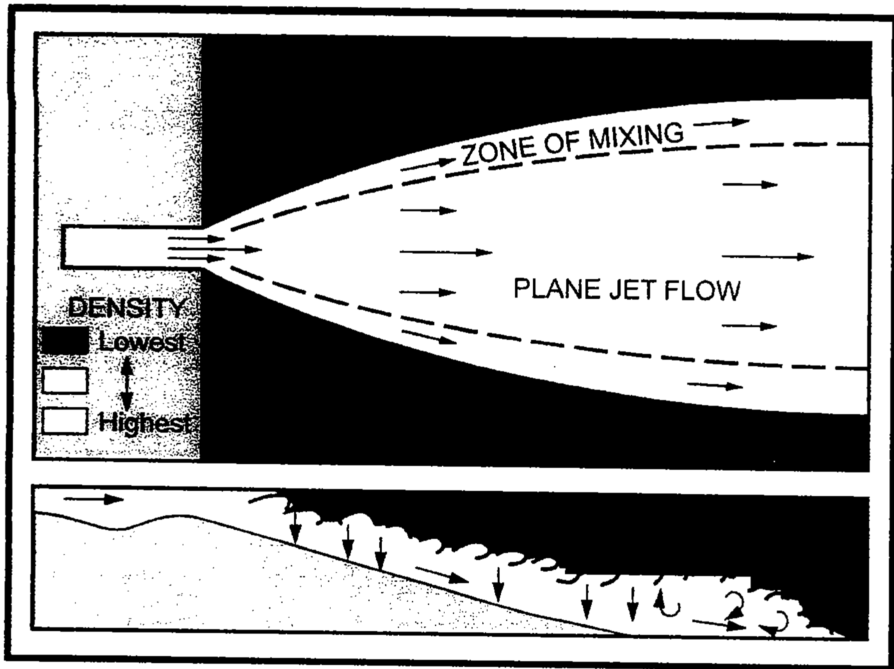
- BARRIER ISLAND DEPOSITS ARE INTERNALLY COMPLEX
- INDIVIDUAL SANDSTONES MAY BE SEPARATED BY LAGOONAL SHALES WHICH CAN ISOLATE INDIVIDUAL SANDSTONES
- PORO./PERM. VALUES WILL VARY WITH FACIES AND GRAIN SIZE

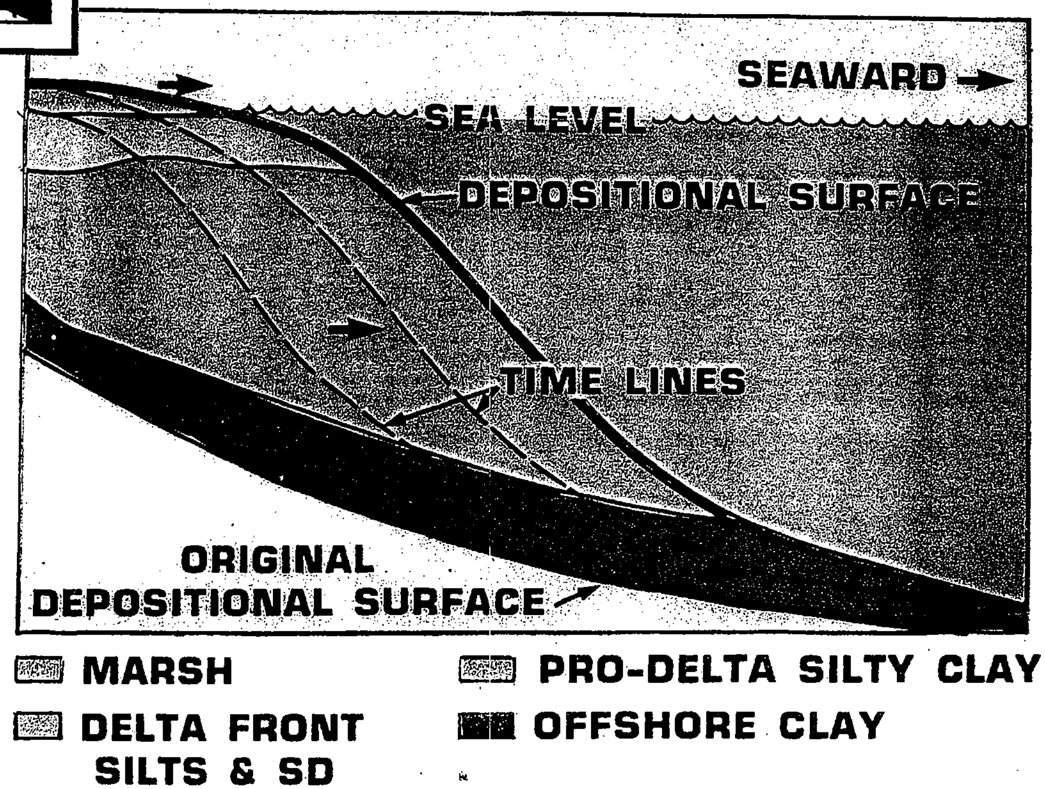
DELTAIC DEPOSITS & RESERVOIRS

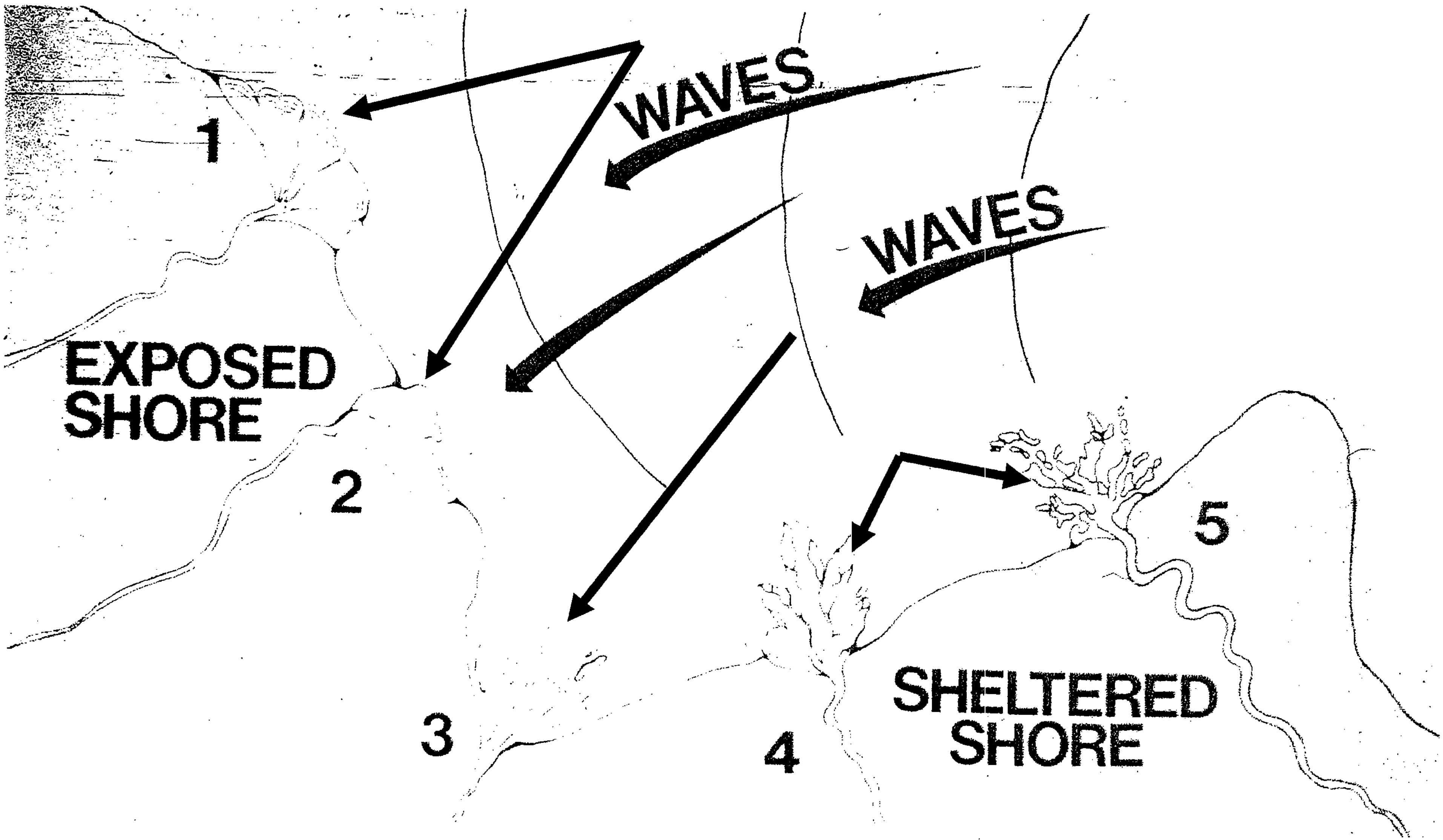



ZONE OF MIXING
PLANE JET FLOW
DENSITY
Lowest
Highest

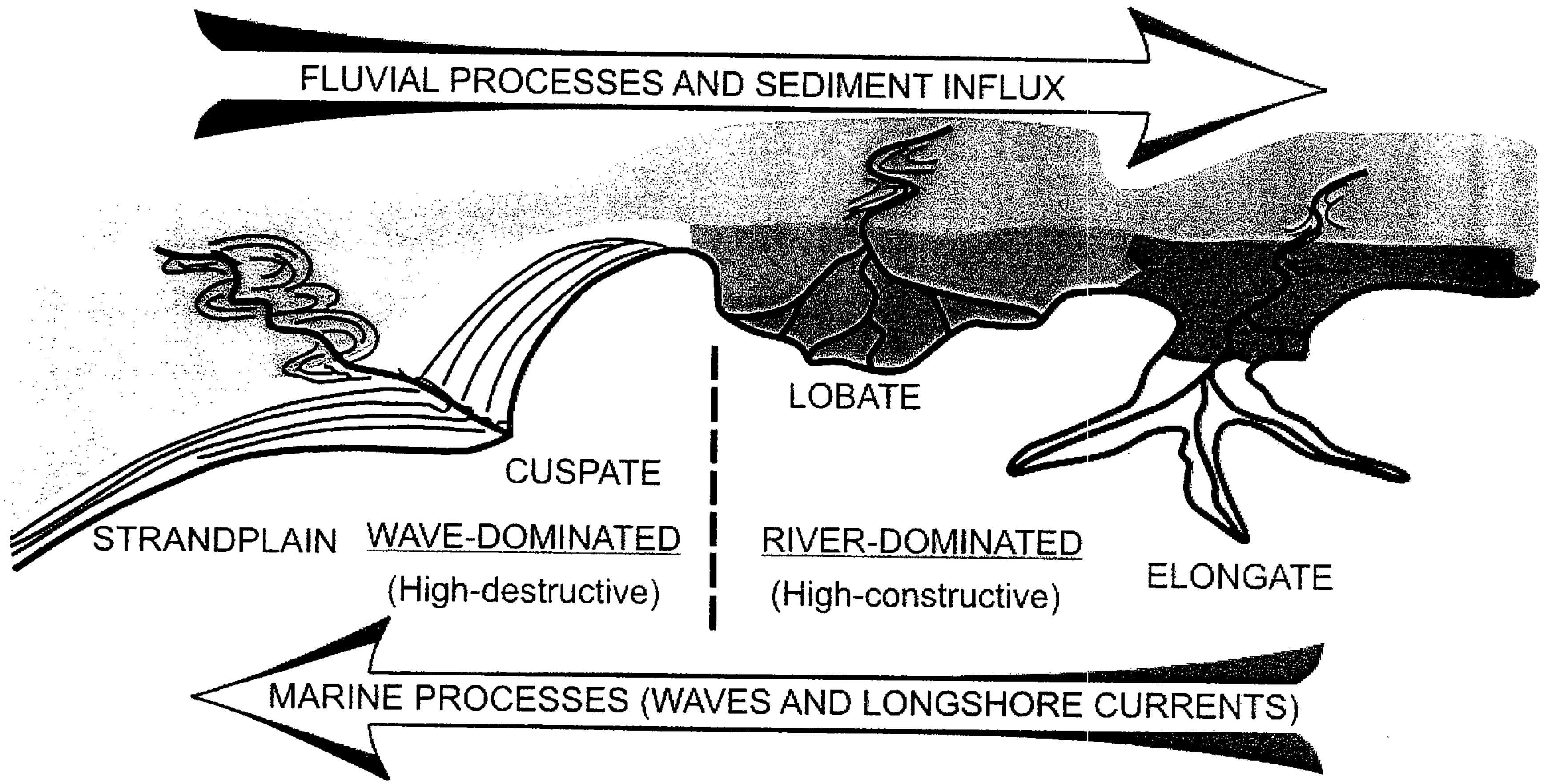
PROGRADATION





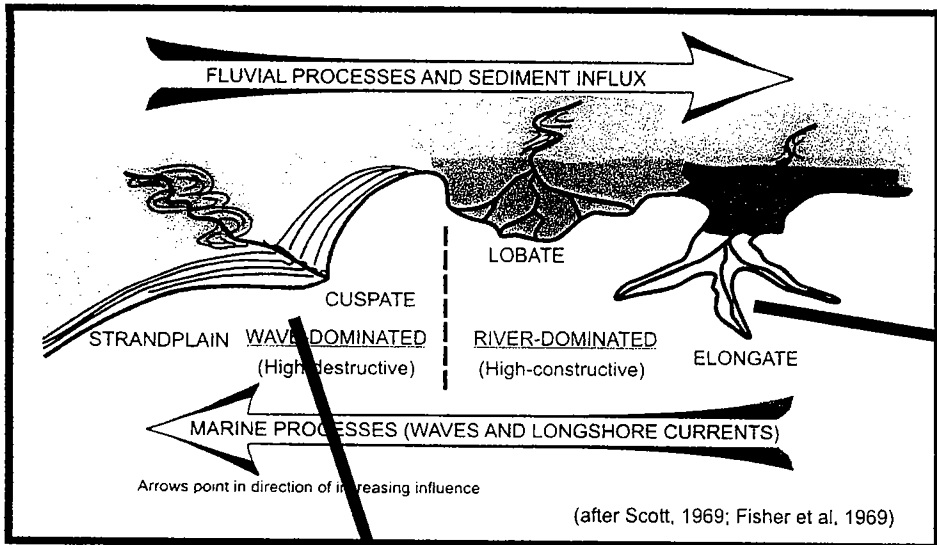


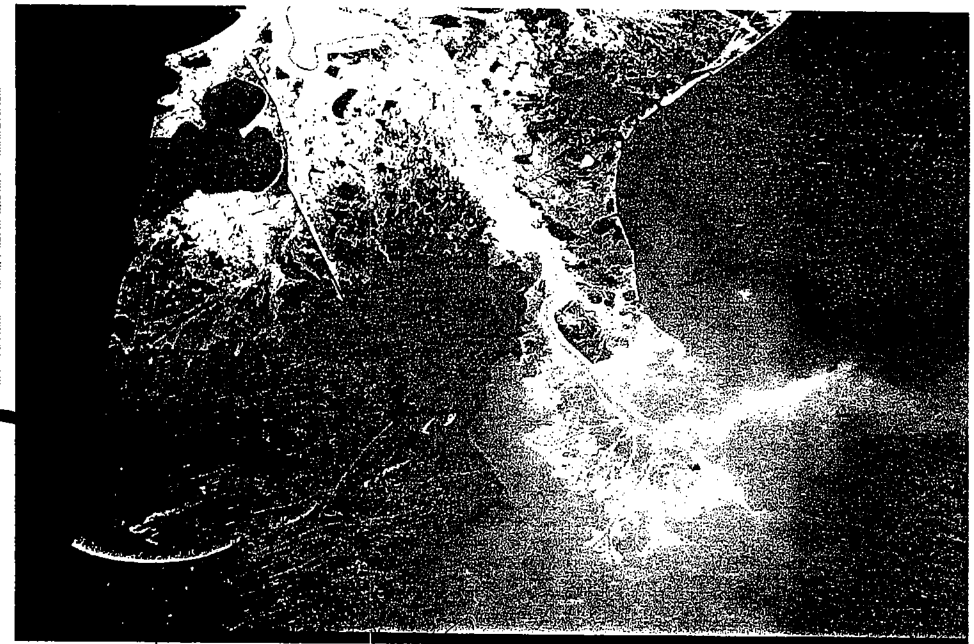
Delta Types - Shoreline Embayment



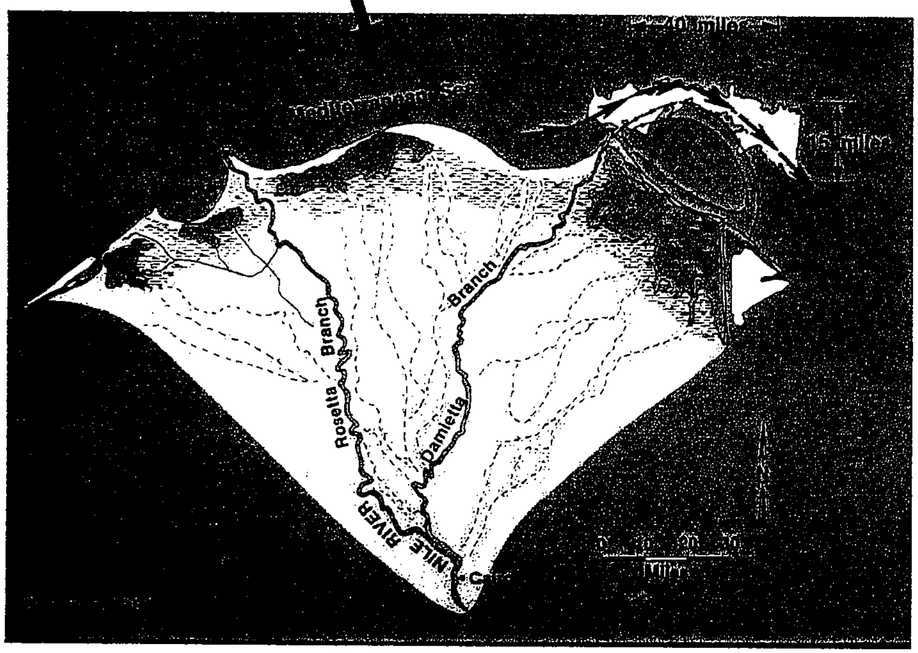
Arrows point in direction of increasing influence

(after Scott, 1969; Fisher et al, 1969)

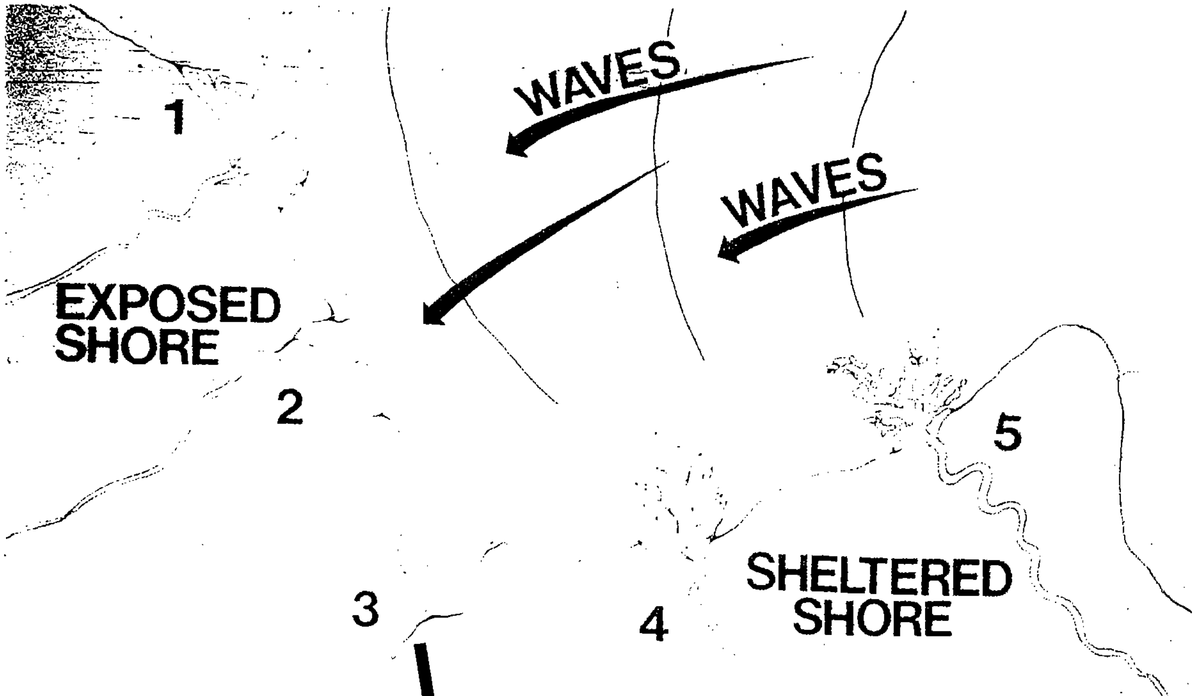




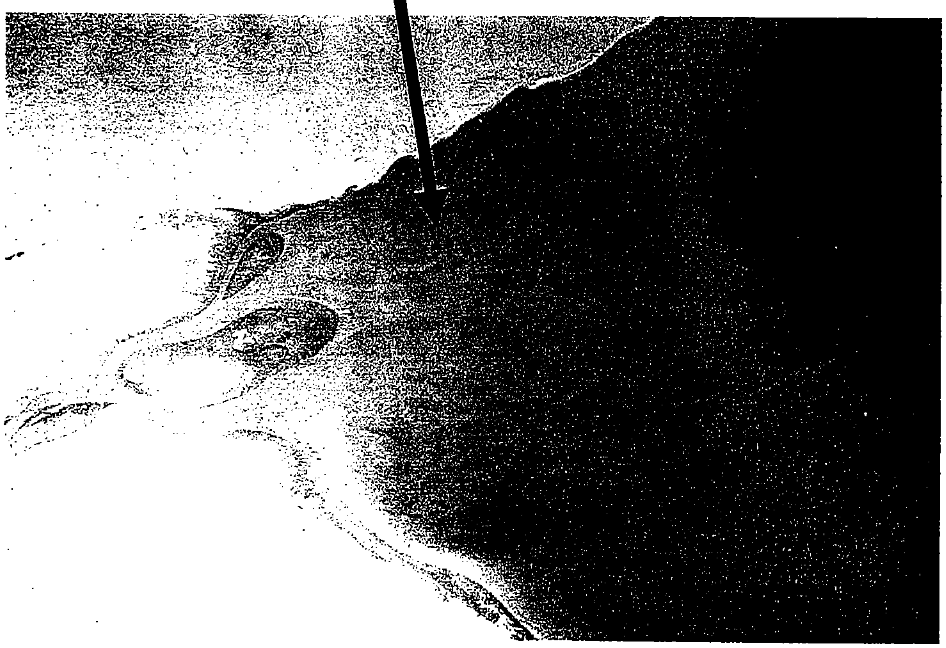
Mississippi River delta

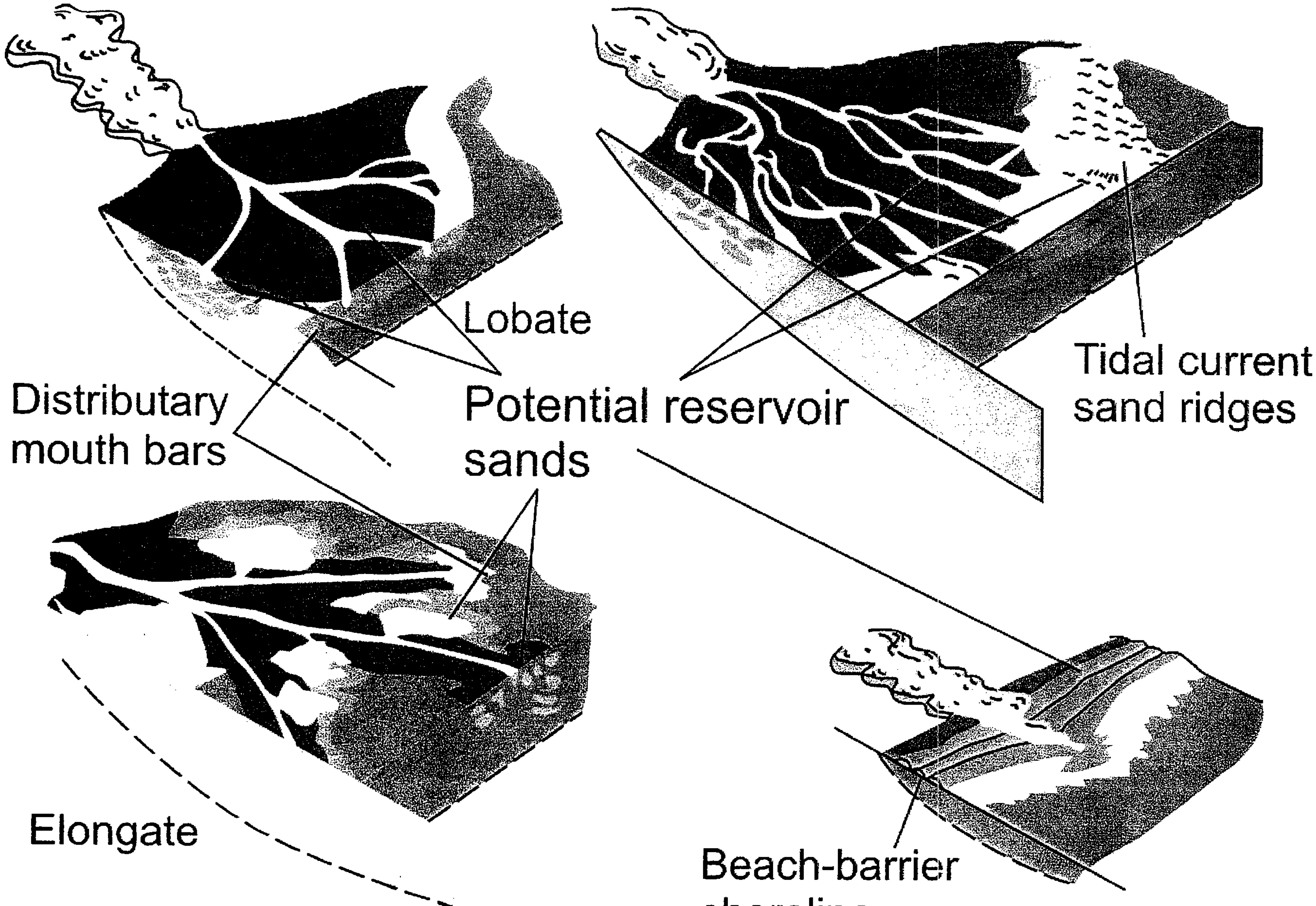


Nile River delta

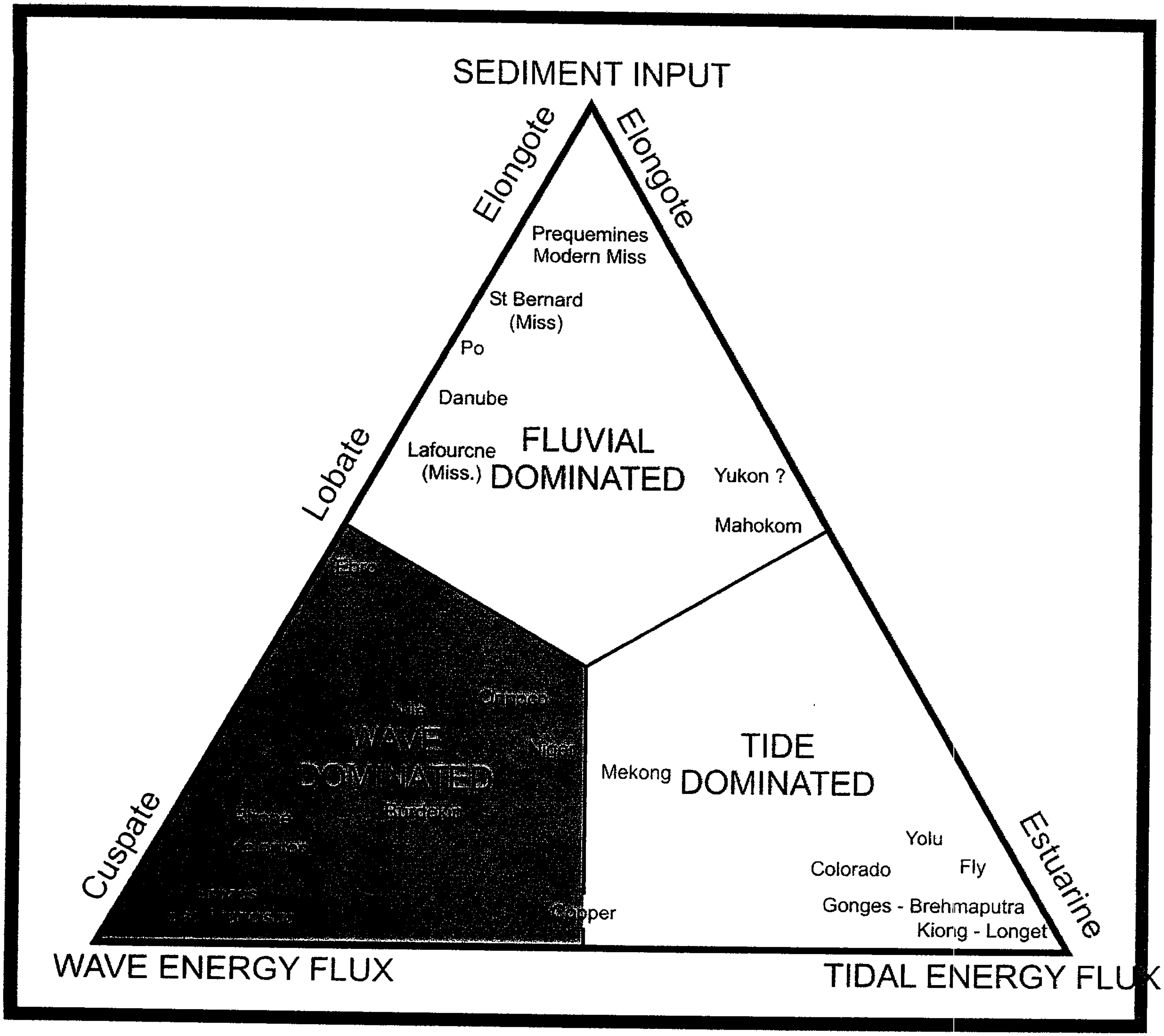


Delta Types - Shoreline Embayment



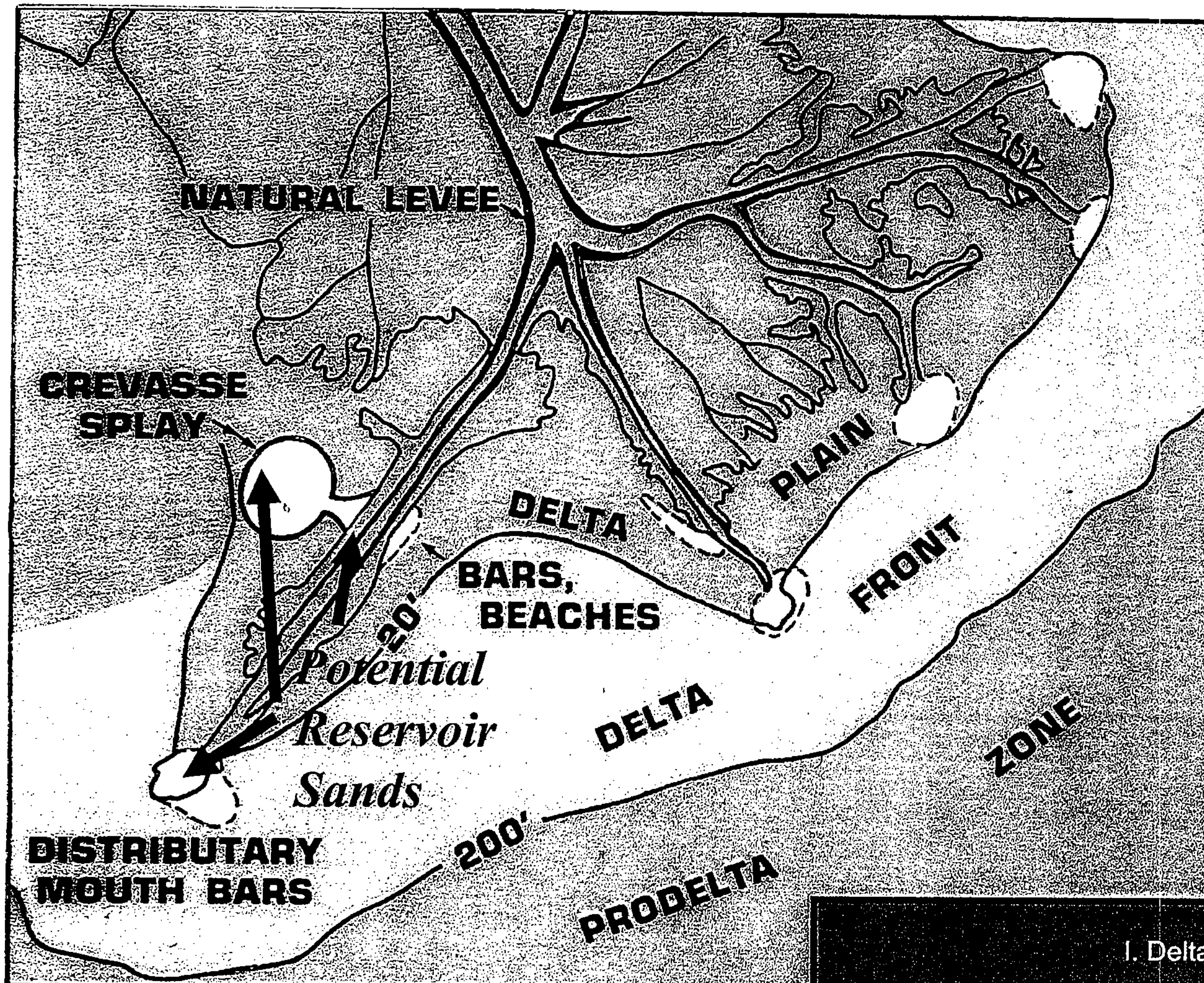


(Modified from Reading, 1986, Sedimentary Environments and Facies p. 117)



SEDIMENT INPUT
Elongote
Elongote
Prequemines
Modern Miss
St Bernard
(Miss)
Po
Danube
Lafourcne
(Miss.)
FLUVIAL
DOMINATED
Yukon ?
Mahokom
Lobate
WAVE
DOMINATED
Copper
Cuspate
Mekong
TIDE
DOMINATED
Yolu
Colorado
Fly
Gonges - Brehmaputra
Kiong - Longet
Estuarine
WAVE ENERGY FLUX
TIDAL ENERGY FLUX

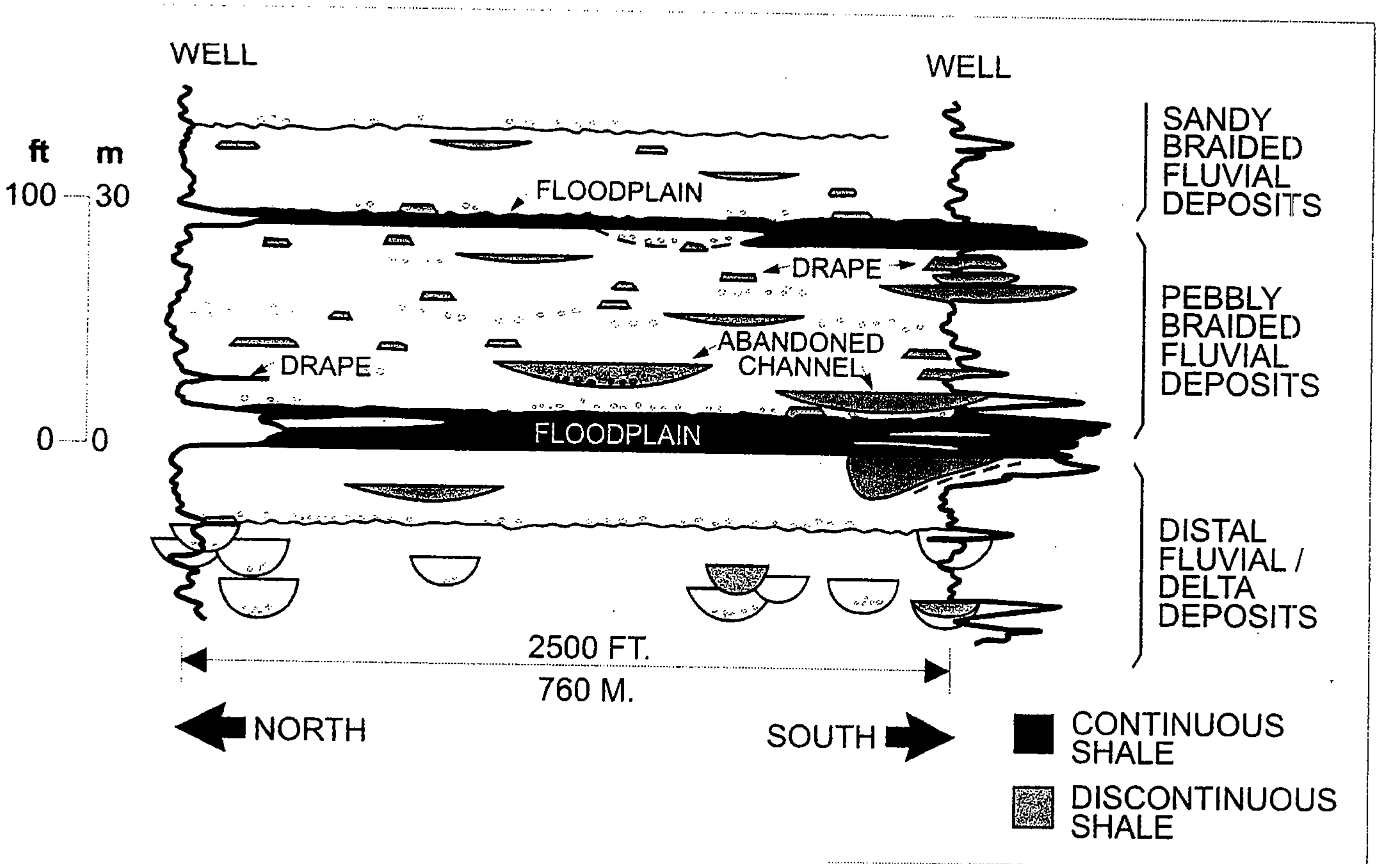
PRINCIPAL DELTA ENVIRONMENTS



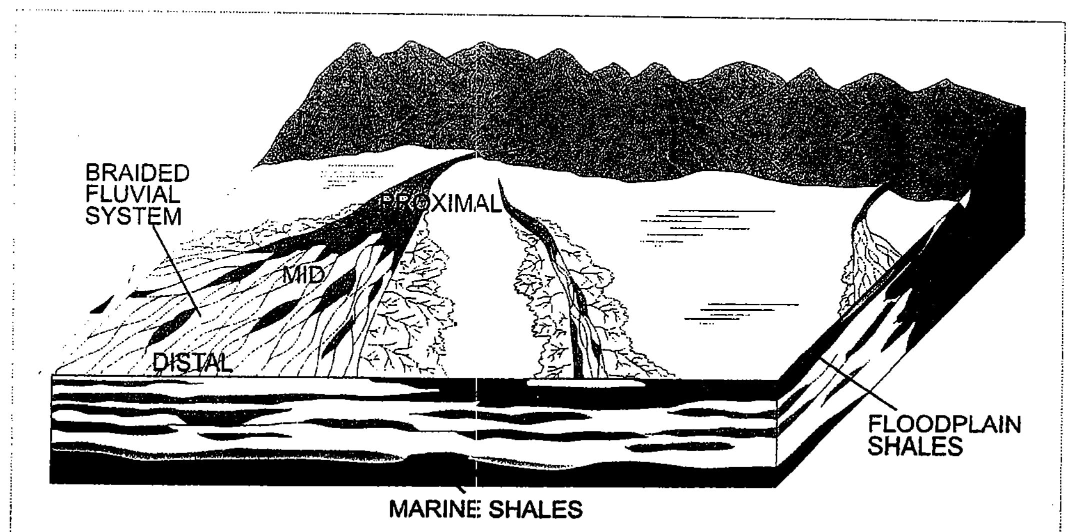
River dominated deltas

I. Deltaic Environments*

Deltaic coasts have three principal gradational bathymetric zones and related facies. 1) the delta plain, comprised largely of fresh and brackish water muds, sands and peats; 2) the delta front, comprised of sands reflecting decreasing energy to the depth of effective wave base (EWB = 10-15m); and 3) the prodelta, comprised largely of mud with minor sand. Farther offshore, prodelta muds grade into shelf muds.

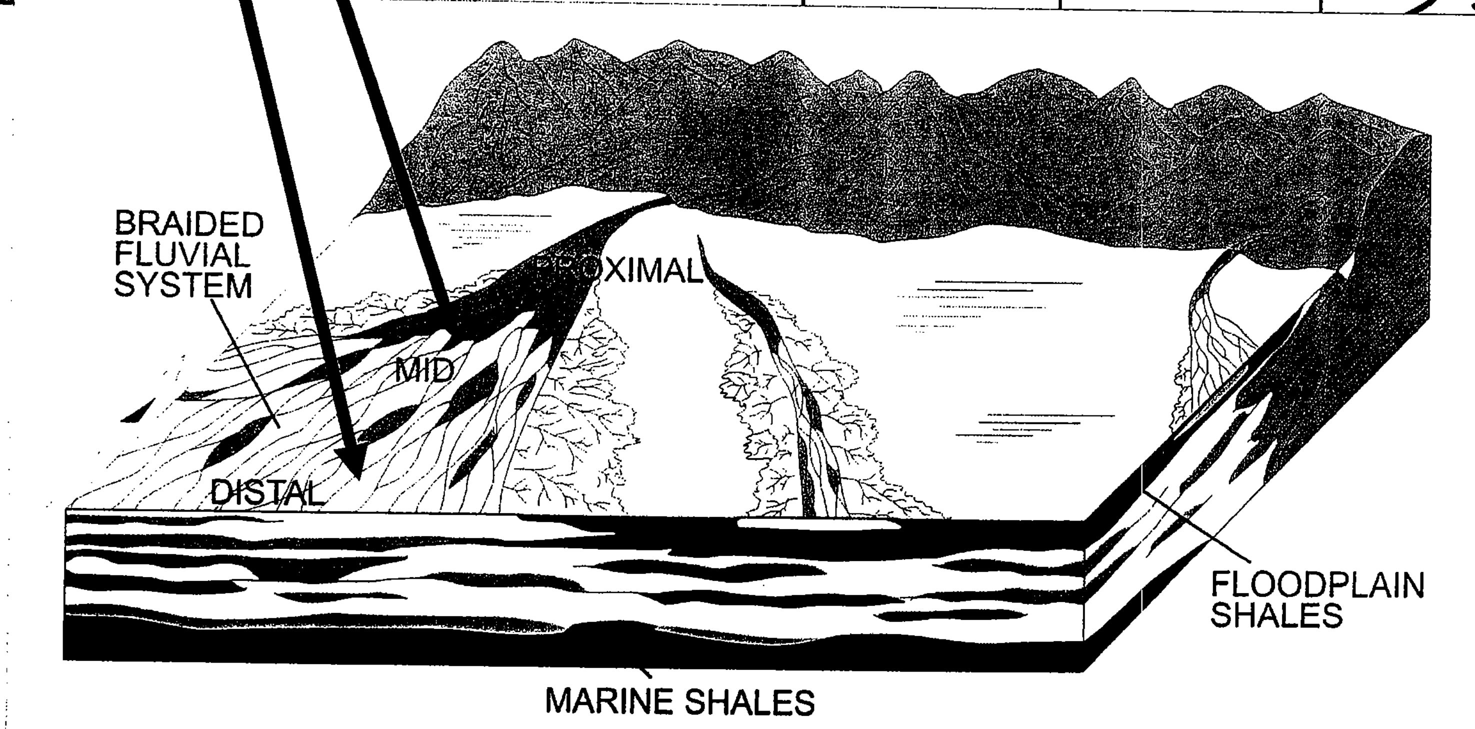


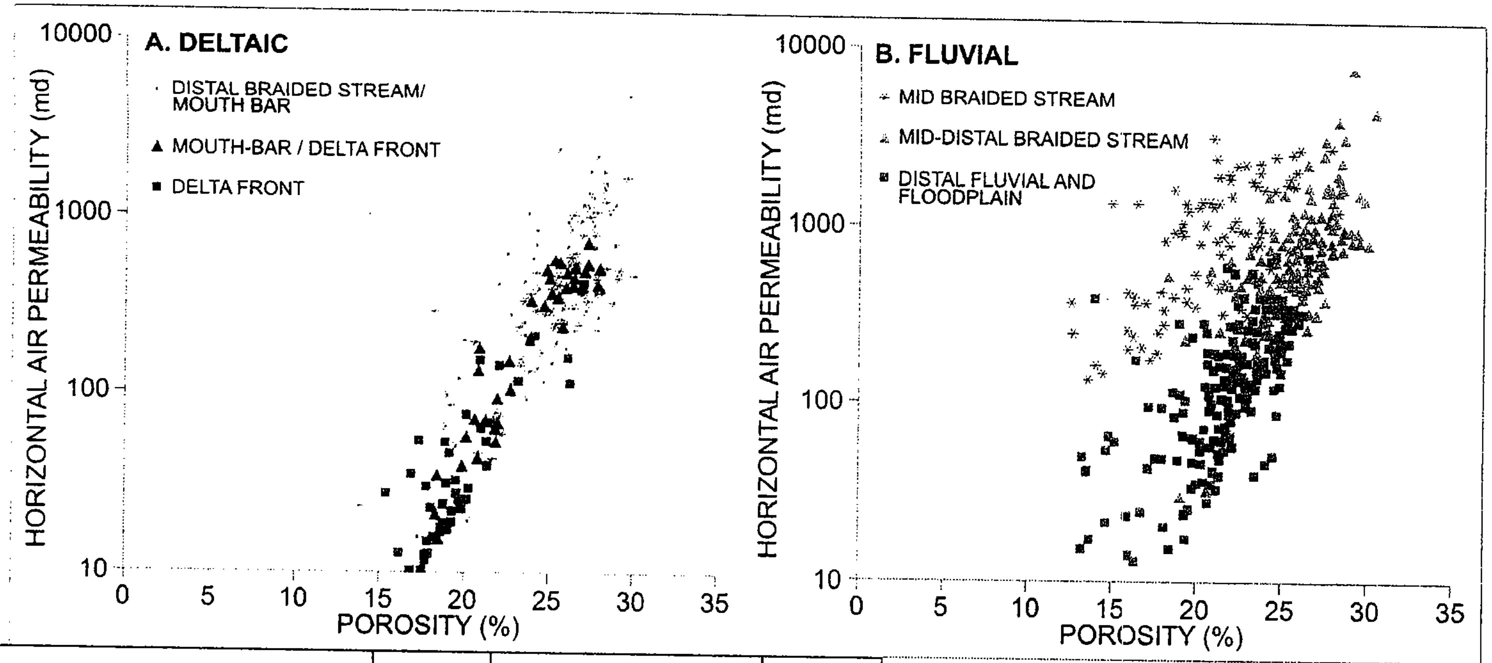
WELL
WELL
ft
m
100
30
0
0
FLOODPLAIN
DRAPE
DRAPE
ABANDONED CHANNEL
FLOODPLAIN
SANDY BRAIDED FLUVIAL DEPOSITS
PEBBLY BRAIDED FLUVIAL DEPOSITS
DISTAL FLUVIAL / DELTA DEPOSITS
2500 FT.
760 M.
NORTH
SOUTH
CONTINUOUS SHALE
DISCONTINUOUS SHALE



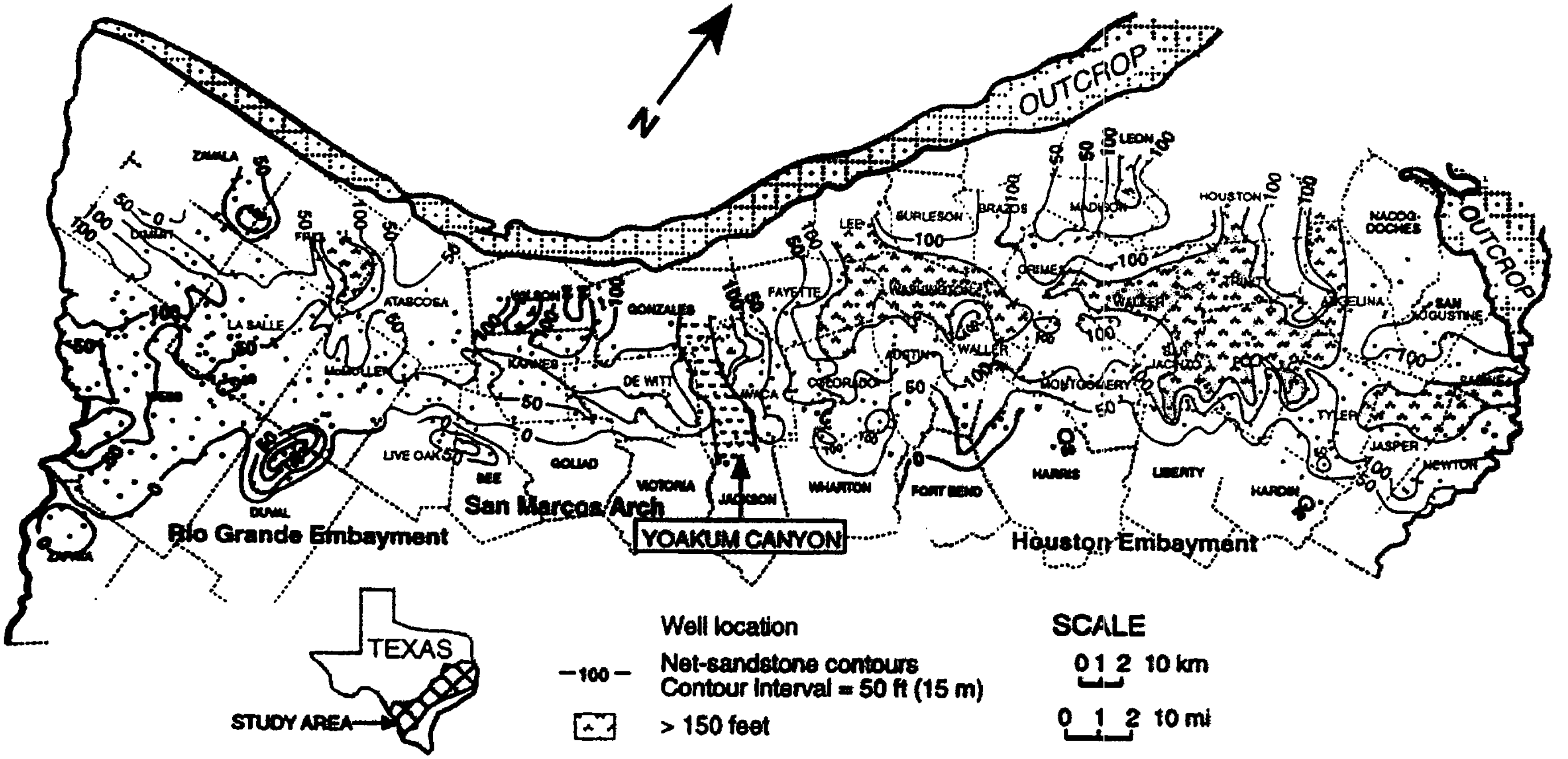
BRAIDED FLUVIAL SYSTEM
PROXIMAL
MID
DISTAL
FLOODPLAIN SHALES
MARINE SHALES

ENVIRONMENT TYPE	PREDOMINANT LITHOLOGY	GRAIN SIZE TREND	SORTING TREND	PERMEABILITY TREND LOW HIGH
MID-BRAIDED STREAM	SANDY CONGLOMERATE CONGLOMERATIC SS COARSE-GRAINED SS			
DISTAL BRAIDED STREAM	MEDIUM-GRAINED SANDSTONE	DECREASE	DECREASE	
DELTA FRONT	FINE- TO VERY FINE-GRAINED SS			



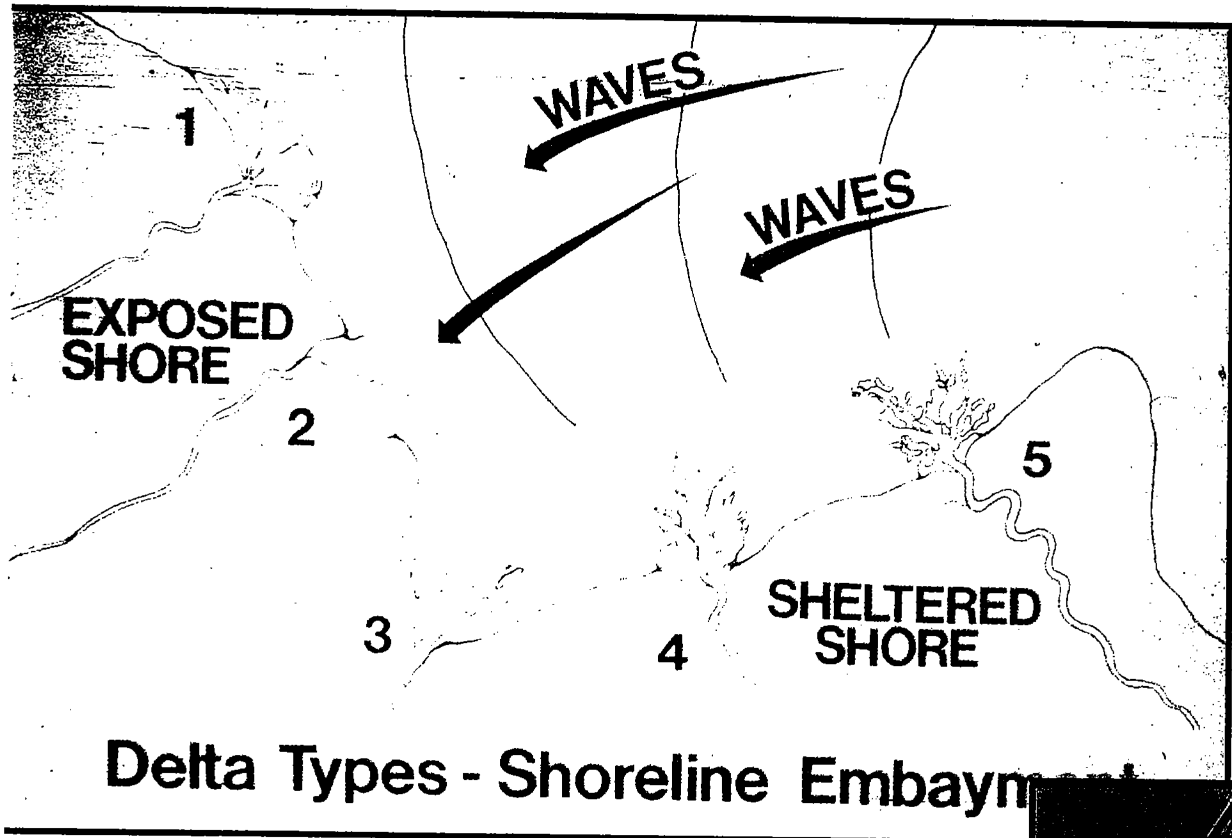


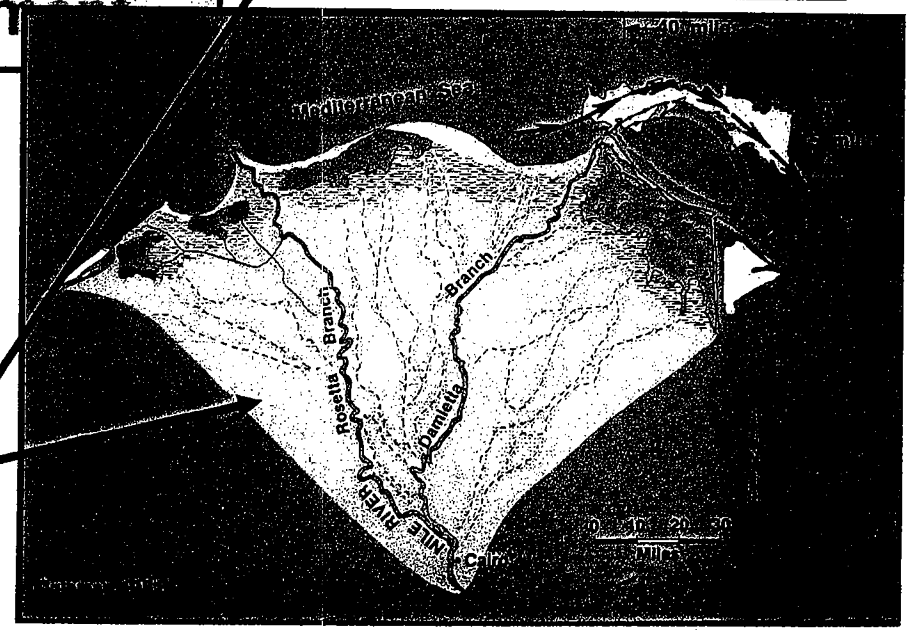
FACIES	FLOW UNIT	TYPICAL GAMMA-RAY RESPONSE (API) 0–150	PETRO-PHYSICAL ZONATION	
DISTAL FLUVIAL SANDSTONE	Z		ZONE 4	B
EXTENSIVE FLOOD-PLAIN SHALE	BARRIER		ZONE 4	A
MID-BRAIDED STREAM CONGLOMERATE	V3		ZONE 3	
MID-DISTAL FLUVIAL CONGLOMERATE AND SANDSTONE	V2		ZONE 2	C
PROXIMAL-MID FLUVIAL CONGLOMERATE	V1		ZONE 2	B
FLOODPLAIN SHALE	BARRIER		ZONE 2	B
MID-DISTAL FLUVIAL SANDSTONE AND CONGLOMERATE	T		ZONE 2	B
FLOODPLAIN SHALE	BARRIER		ZONE 2	B
DISTAL FLUVIAL AND MOUTHBAR SANDSTONE	R2		ZONE 2	A
MOUTHBAR SANDSTONE AND DELTA FRONT SILTSTONE AND SHALE	R1		ZONE 1	B, A



Tertiary subsurface deltaic reservoirs, south Texas (yellow)

Figure 20—Sequence B net-sandstone distribution resembling that of sequence A: dip-dominated trends in the Houston and Rio Grande embayments and strike-oriented pattern in the San Marcos arch. Highest values in the updip area reflect the main fluvial or distributary-channel axes; however, sequence B depocenters have prograded further seaward.



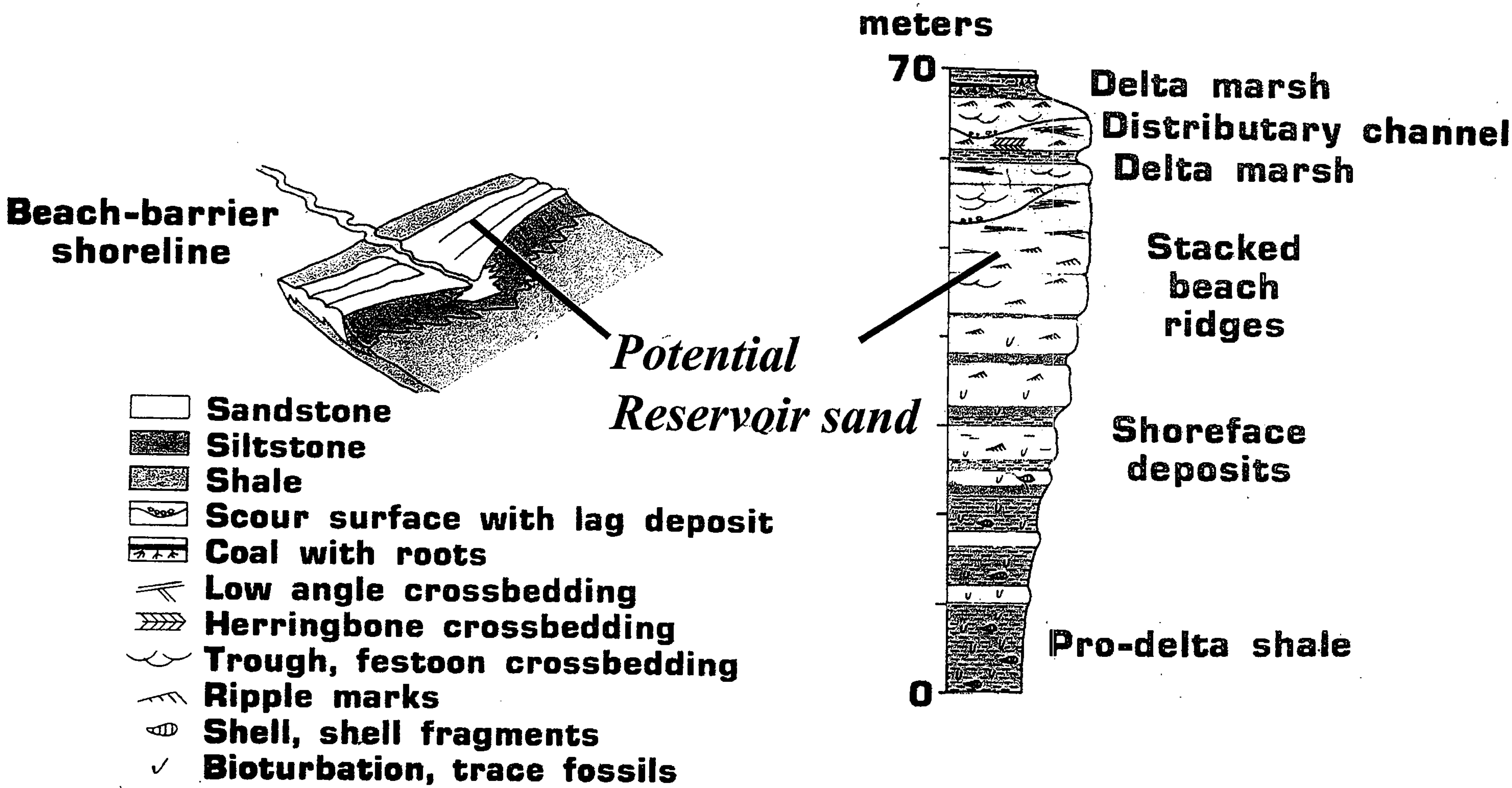


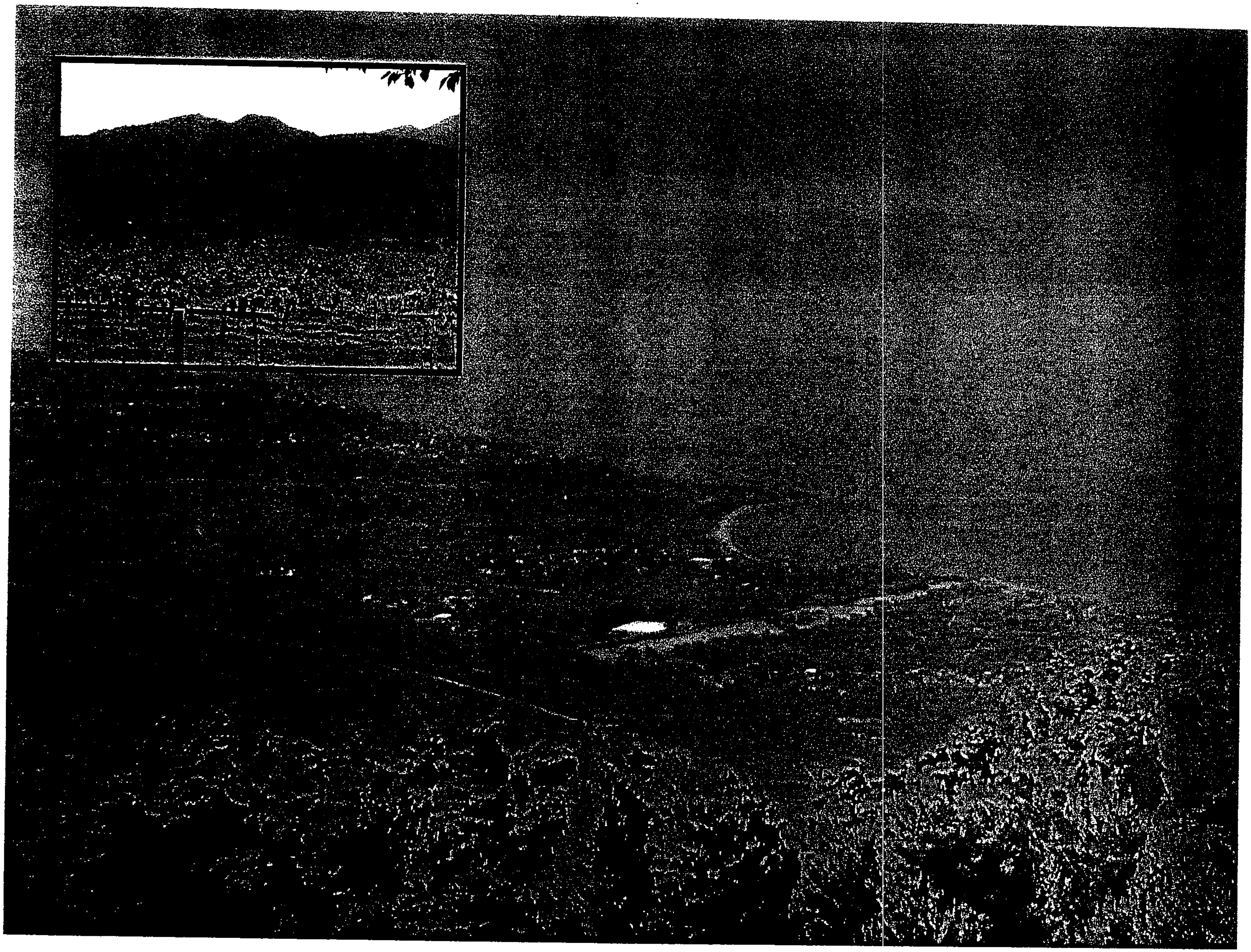
WAVE DOMINATED DELTAS

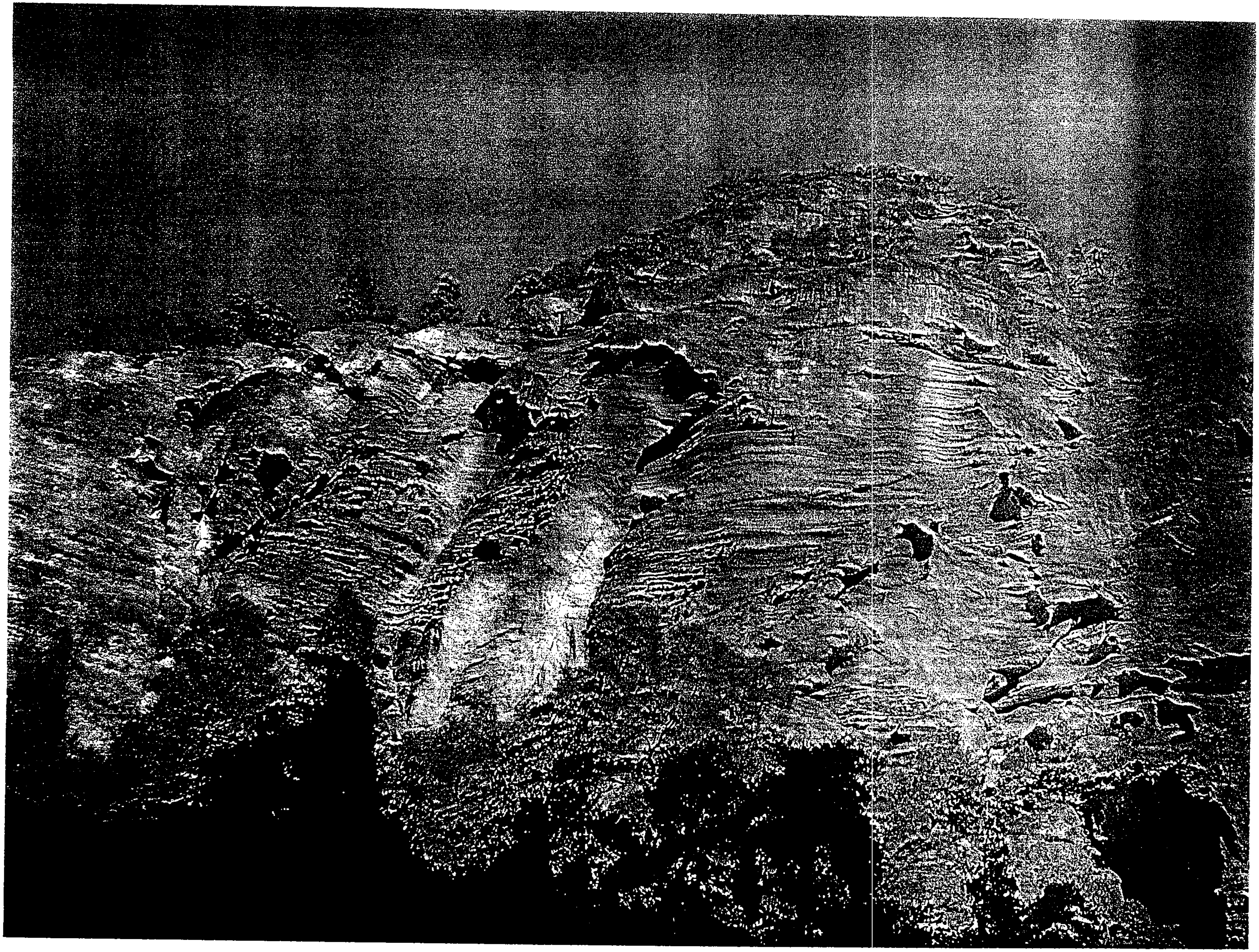
Modern Nile Delta

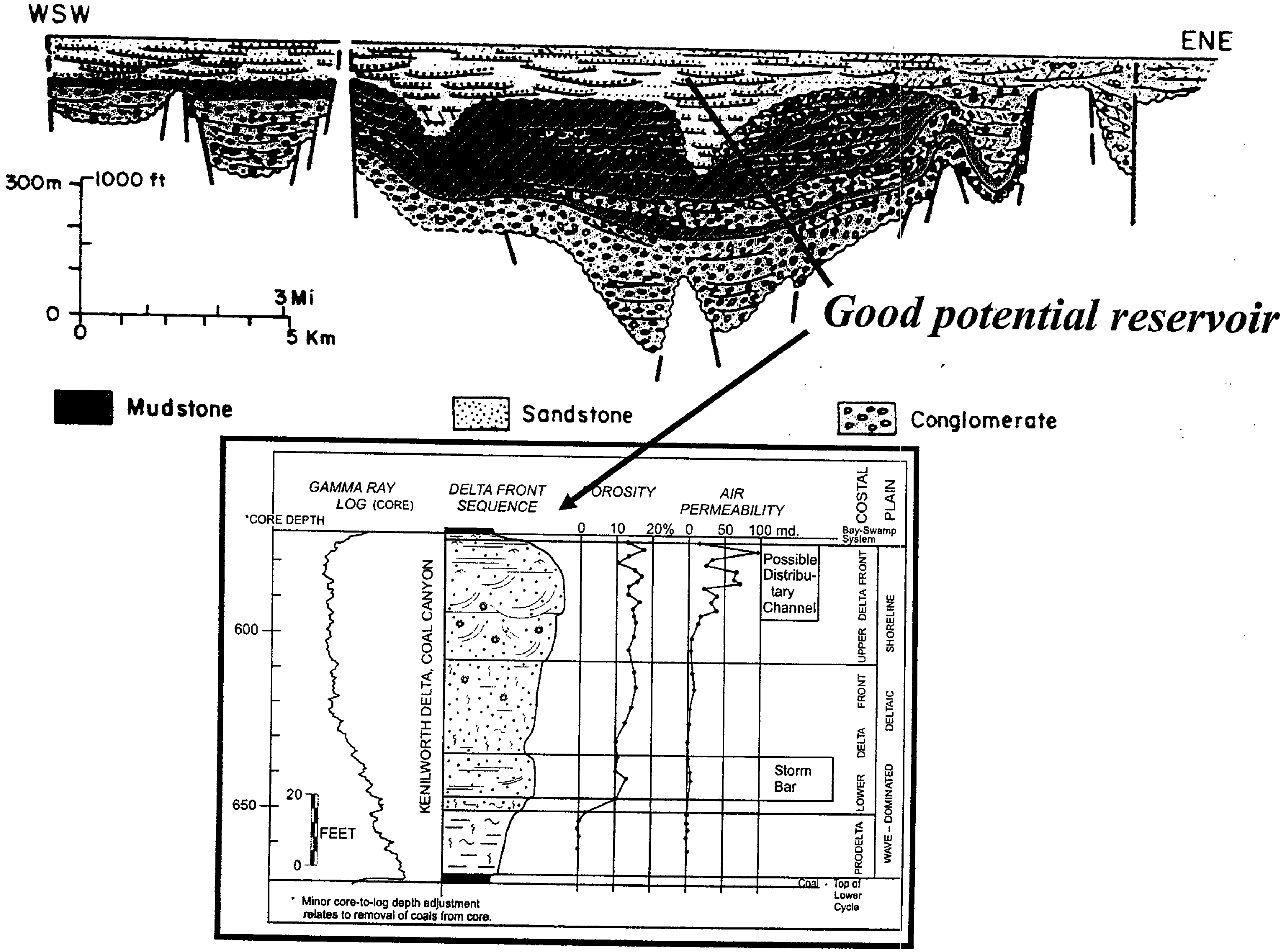


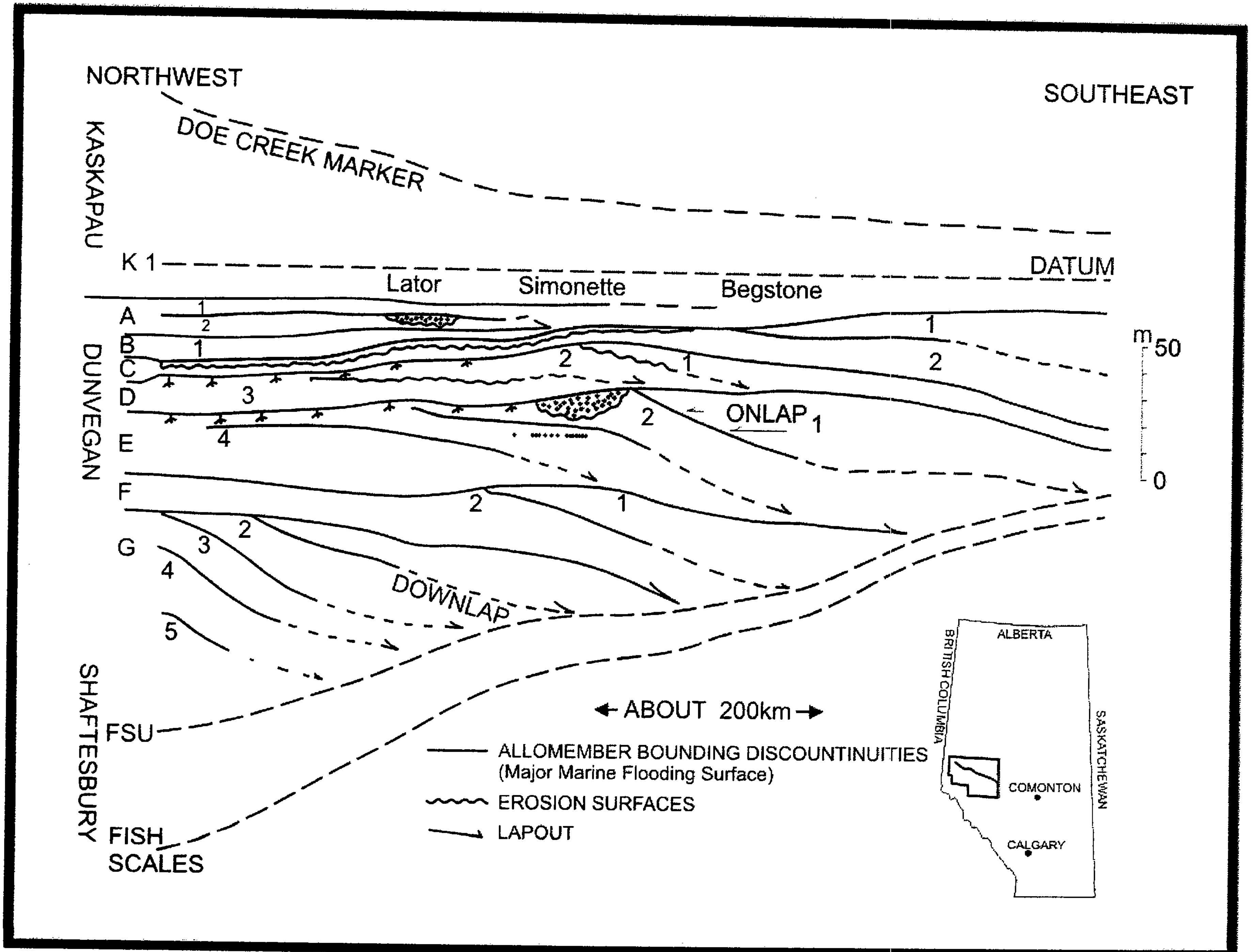
WAVE DOMINATED DELTA



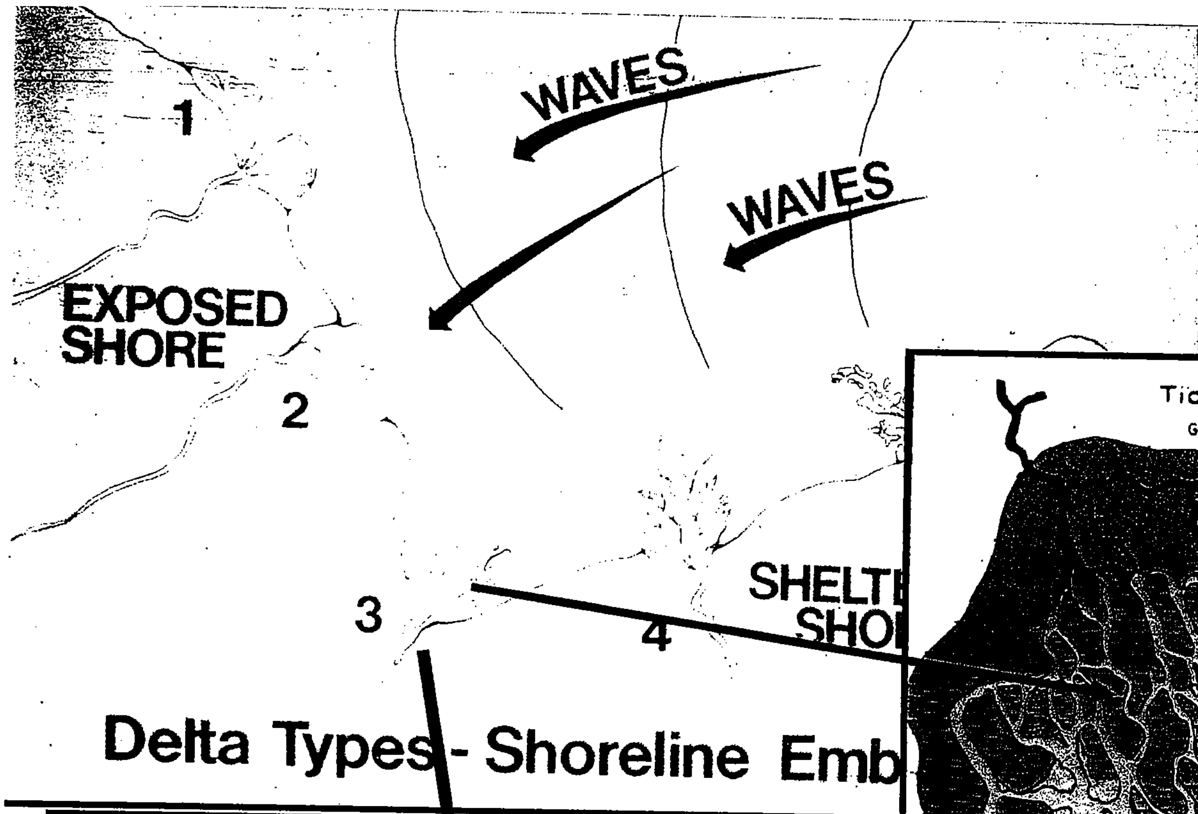


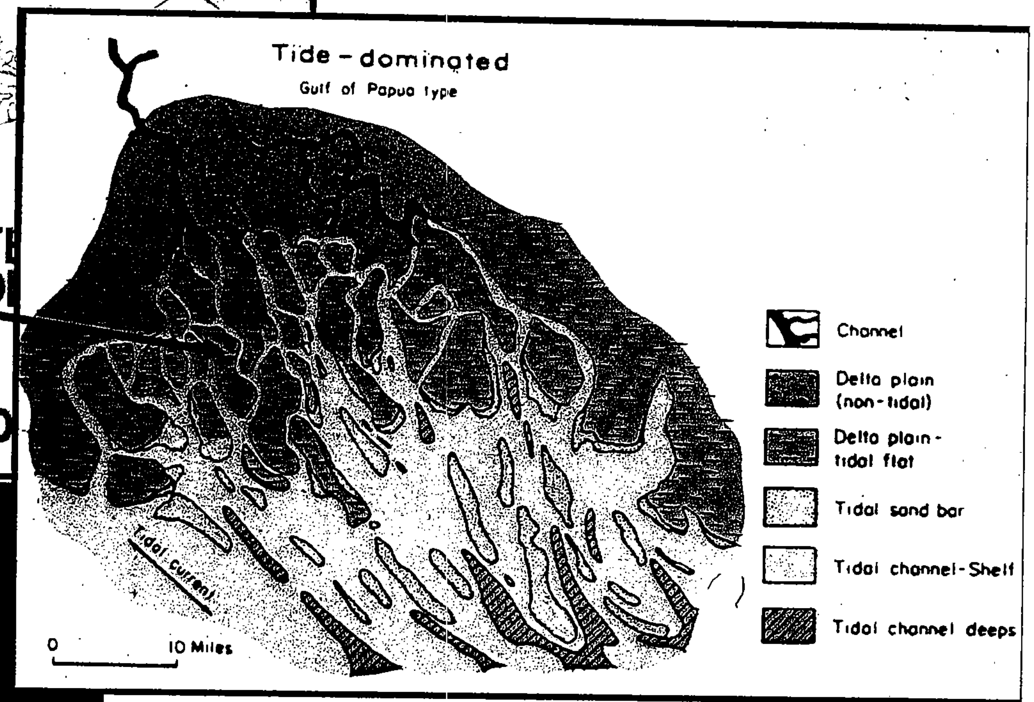



WSW
ENE
300m
1000 ft
0
0
3 Mi
5 Km
Good potential reservoir
Mudstone
Sandstone
Conglomerate
GAMMA RAY LOG (CORE)
DELTA FRONT SEQUENCE
POROSITY
AIR PERMEABILITY
*CORE DEPTH
0 10 20%
0 50 100 md.
COSTAL PLAIN
Bay-Swamp System
KENILWORTH DELTA, COAL CANYON
600
650
20
0
FEET
Possible Distribu-tary Channel
Storm Bar
UPPER DELTA FRONT
LOWER DELTA FRONT
PRODELTA
SHORELINE
WAVE - DOMINATED DELTAIC
Coal
Top of Lower Cycle
* Minor core-to-log depth adjustment relates to removal of coals from core.

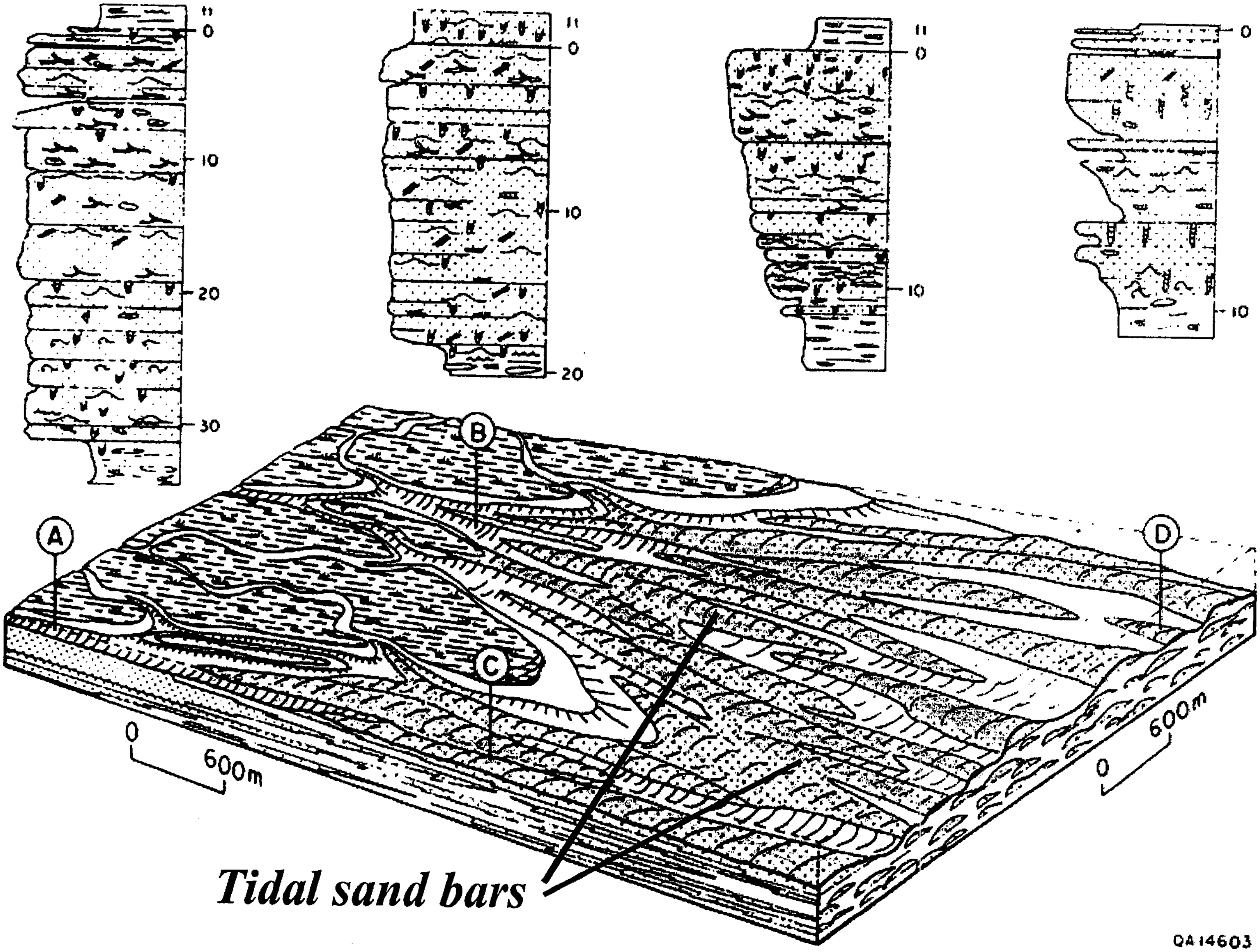


NORTHWEST
SOUTHEAST
DOE CREEK MARKER
KASKAPAU
K 1
DATUM
Lator
Simonette
Begstone
A
B
C
D
E
F
G
DUNVEGAN
ONLAP
DOWNLAP
m
50
0
SHAFTESBURY
FSU
FISH SCALES
← ABOUT 200km →
ALLOMEMBER BOUNDING DISCOUNTINUITIES
(Major Marine Flooding Surface)
EROSION SURFACES
LAPOUT
ALBERTA
BRITISH COLUMBIA
SASKATCHEWAN
COMONTON
CALGARY





Tide dominated delta



ft
0
10
20
30
ft
0
10
20
ft
0
10
0
10
A
B
C
D
0
600m
0
600m
Tidal sand bars
QA14603

Characteristics of tidal sand-ridge sandstones

Thickness: Range 3-12 ft. average 6 ft.

Basal contact: Transitional with marine shales.

Texture and Composition

Grain size: Upward-coursening from siltstone/very fine-grained sandstone at the base to upper fine-grained sandstone at the top.

Sorting: Well to very well.

Clay interbeds: Very common and gradually decreasing toward the top. Their relative content defines the upward-coursening, thickening trendl.

Clay clasts and wood fragments: Common in the upper half.

Shell clasis: Mainly in the sandier levels of the upper part. Frequently in high concentrations at the top.

Sedimentary Structures

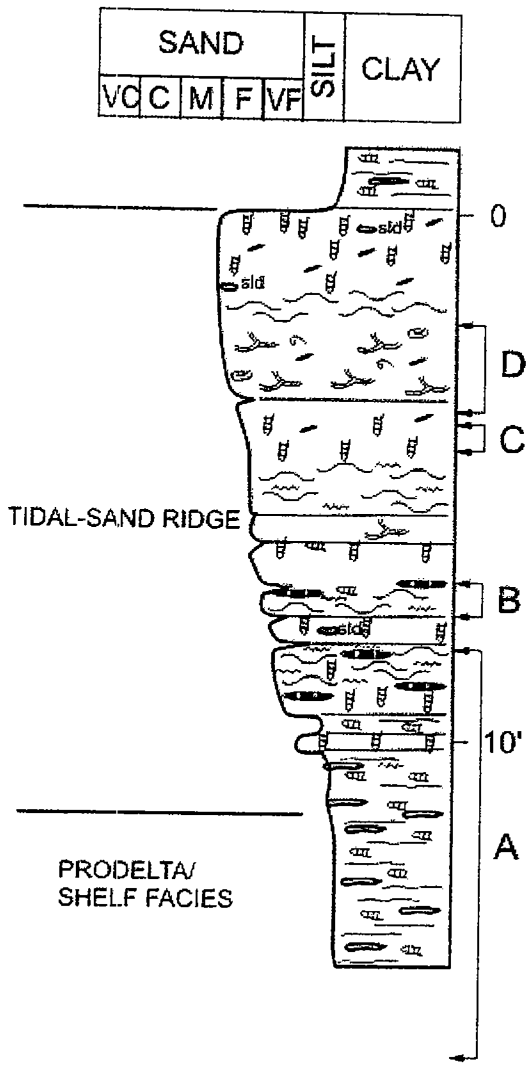
Wavy lamination and ripples are dominant in the lower two thirds of the facies.

Small-scale trough cross-stratification is usually present in the upper one-third facies.

Burrows

Most common within the lower half or at the very top of the facies. Frequently muddy sandstones are homogenized by bioturbation. Ophiomorpha traces are common in sand-rich levels.

TIDAL SAND-RIDGE AND PRODELTA/SHELF FACIES



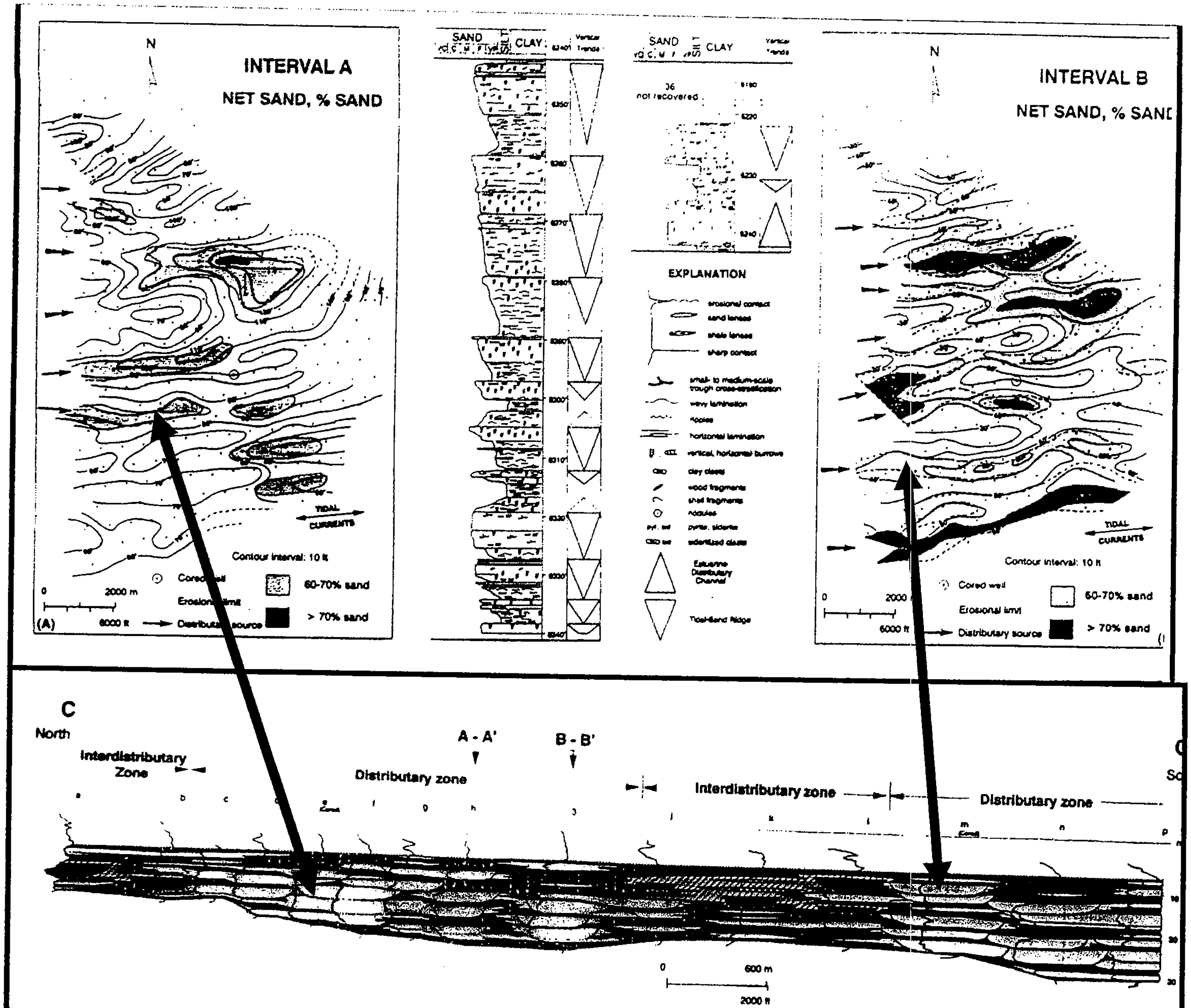
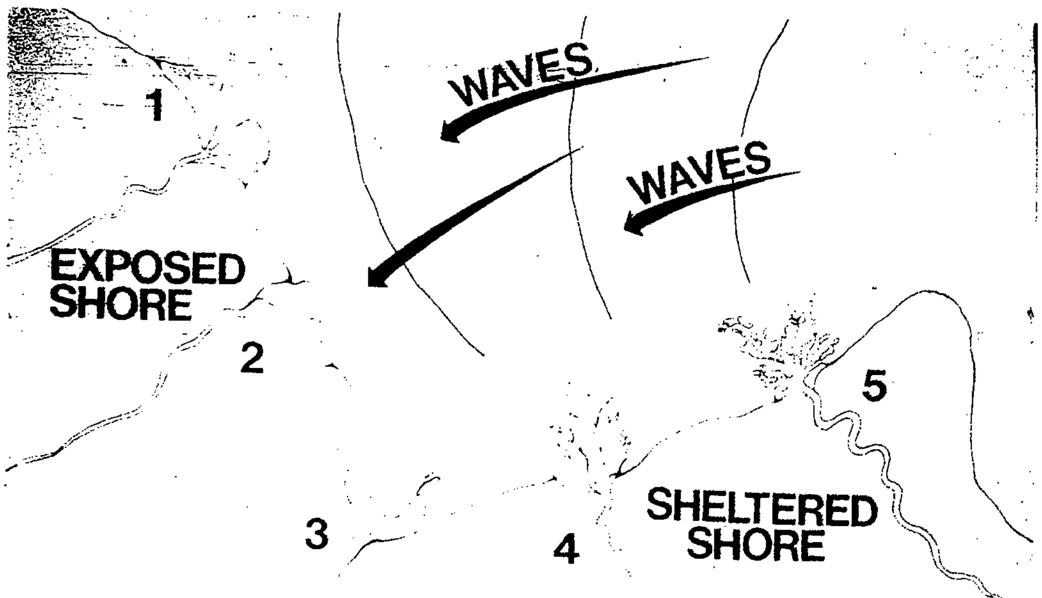
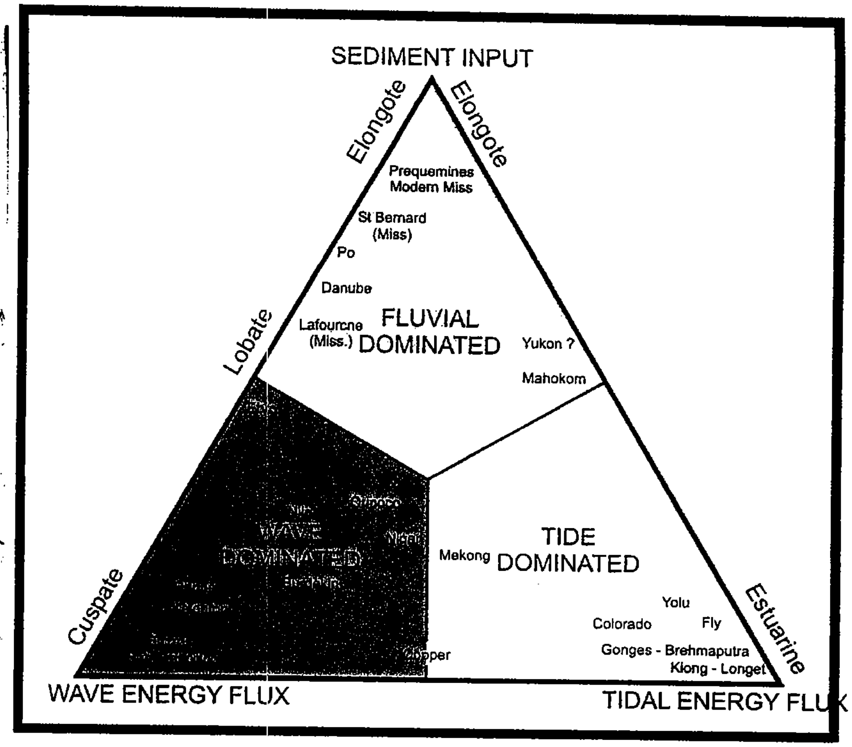
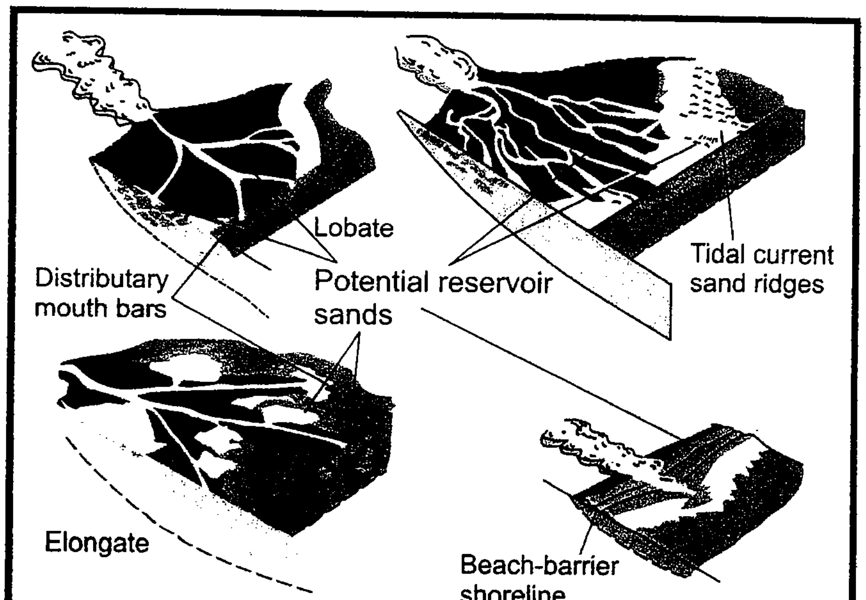


Fig. 14—Strike-oriented log facies cross section C-C' of interval G, uppermost interval of deltaic cycle 3. Contrary to dip-oriented cross sections, lithofacies in this strike-oriented cross section exhibit poor lateral sandbody continuity. Interpreted tidal channel sandstone facies show the poorest lateral continuity. Tidal sand-ridge areas are shown as being laterally more continuous; however, individual tidal sand-ridge sandstone bodies are expected to have very low lateral continuity in the north-south direction. Two main sandstone depocenters, deposited as a result of two estuarine distributary systems, are separated by interdistributary zones having low-sand content. (Section located on Fig. 11; see Fig. 13 for explanation of symbols.)



Delta Types - Shoreline Embayment





(Modified from Reading, 1986, Sedimentary Environments and Facies p. 117)

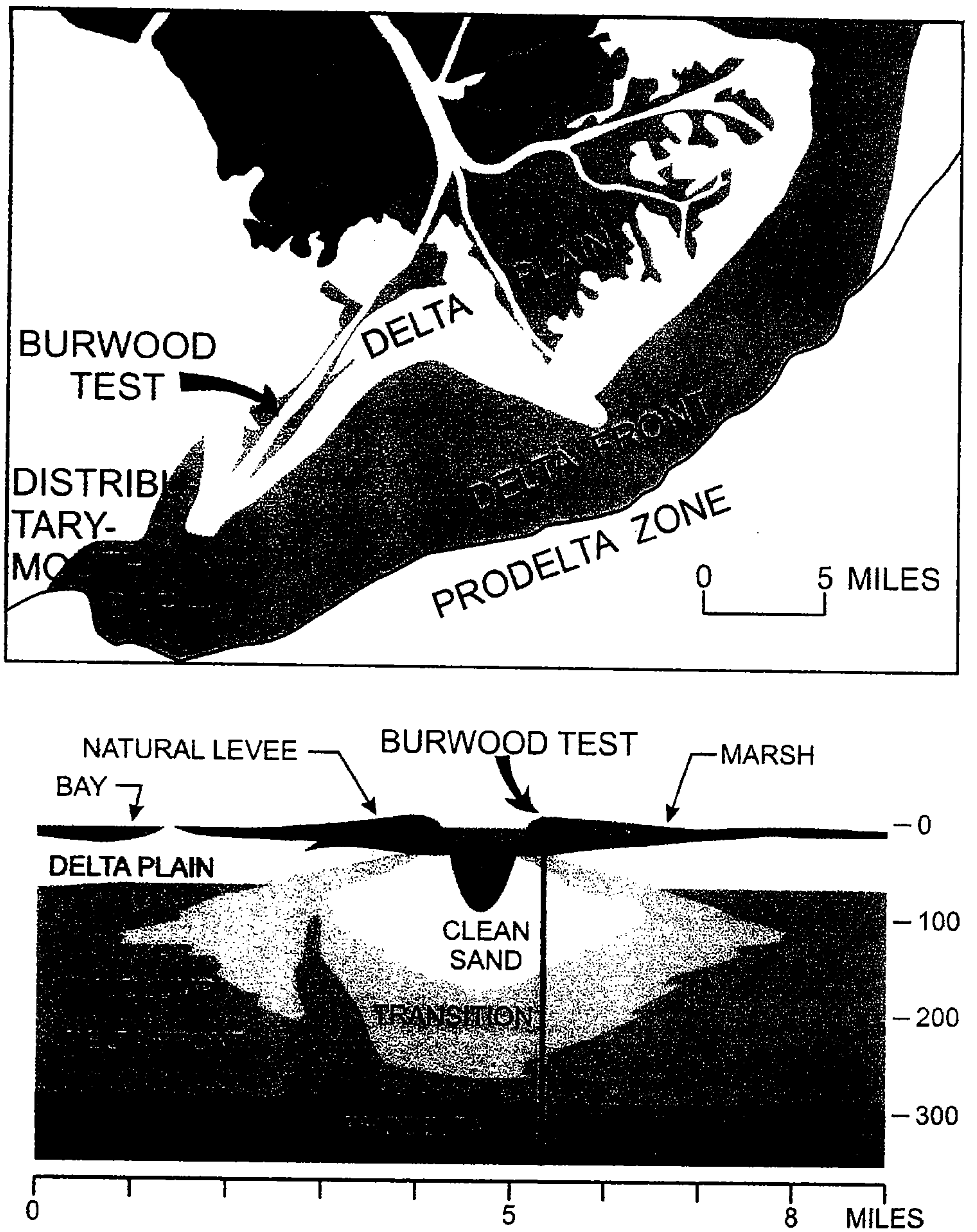
Different delta types due to different processes and environments of deposition. Each of the three types exhibits different orientations and types of reservoir sands.

CONCLUSIONS

- ***DELTAS ARE COMPLEX SEDIMENT BODIES***

- ***DIFFERENT DELTA TYPES HAVE DIFFERENT TYPES OF SAND BODIES WITH DIFFERENT TRENDS***

- ***IT IS IMPORTANT TO UNDERSTAND WHICH DELTA TYPE YOUR RESERVOIR IS IN IF YOU WANT TO MAXIMIZE OR IMPROVE PRODUCTION AND RESERVOIR MANAGEMENT***



(Modified from Fisk, 1961)

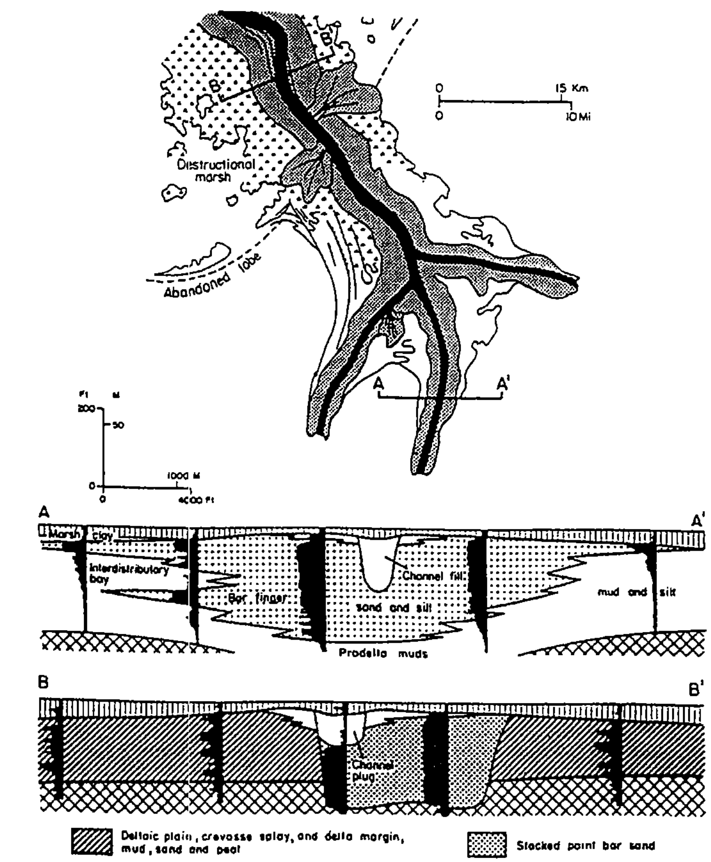


Figure 5-10. Interpretative facies cross-sections of (A) progradational channel mouth bar and (B) distributary channel-fill sand bodies of an elongate, fluvial-dominated delta lobe. Geophysical log profiles are based on bore hole data from the Wilcox (Eocene) Holly Springs delta system of the northern Gulf Coast basin. (Modified from Galloway, 1968.)

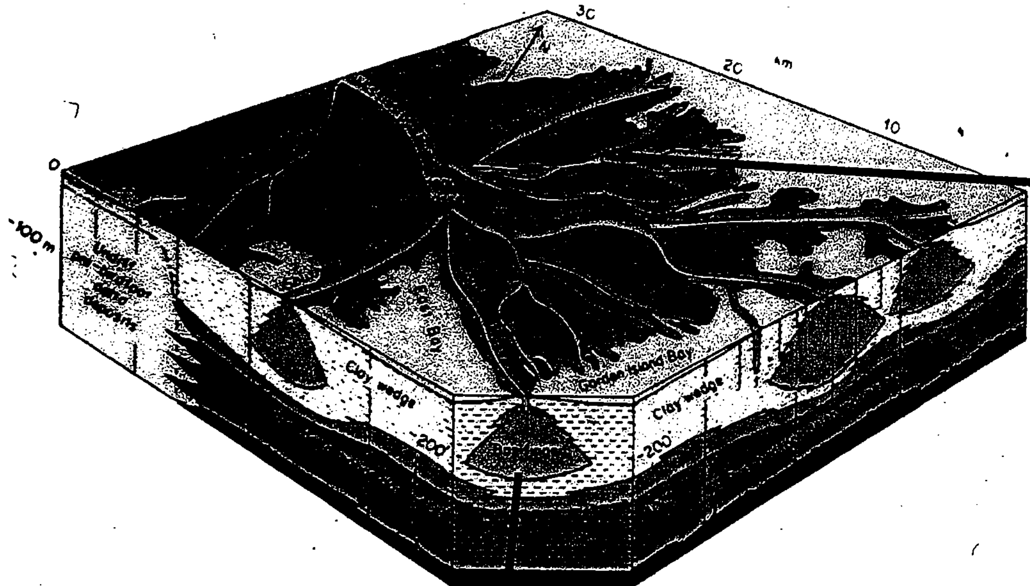
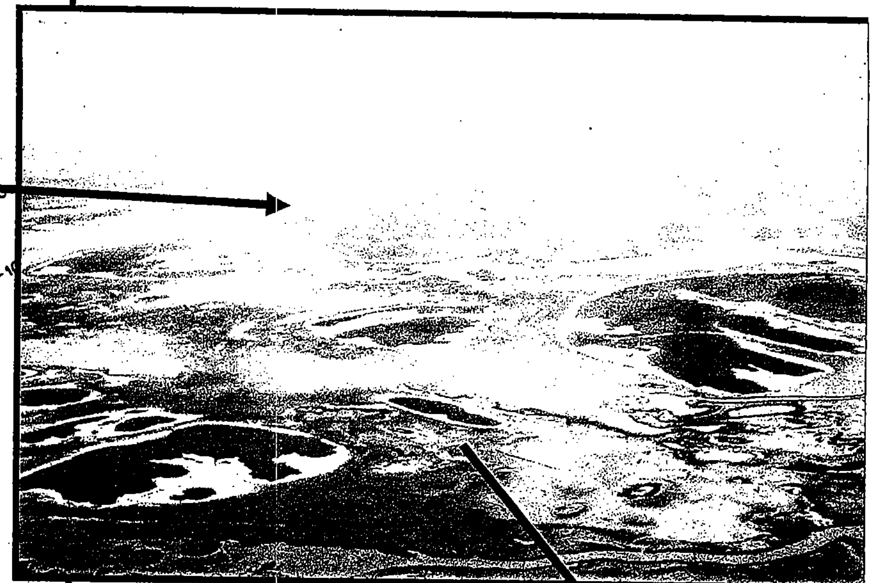


Fig. 7-11 Block diagram indicating geometric arrangement of bar-finger sand, fine-grained sediments, and topset marsh deposits of the modern Birdfoot delta of the Mississippi River. (After Fisk *et al.*, 1954.)



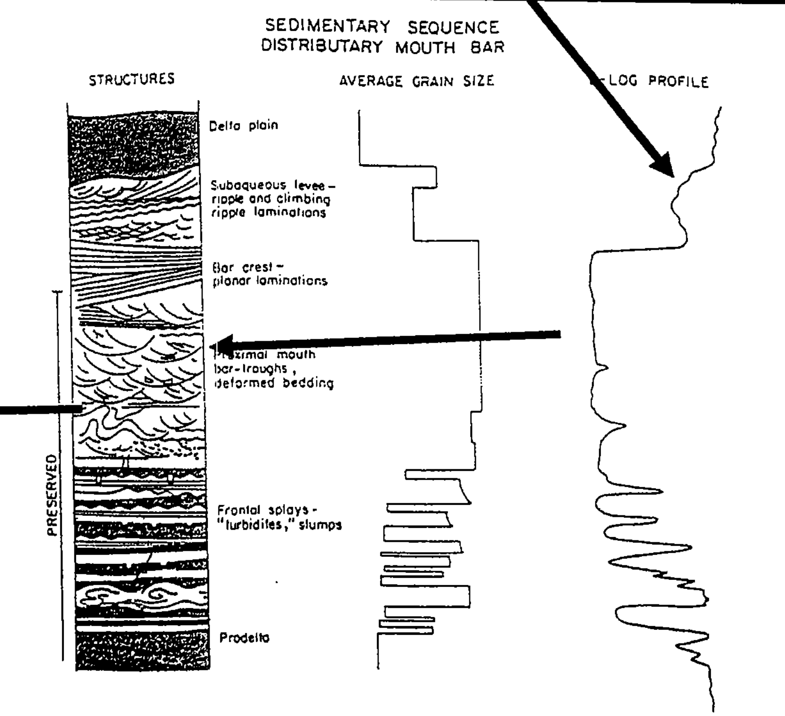
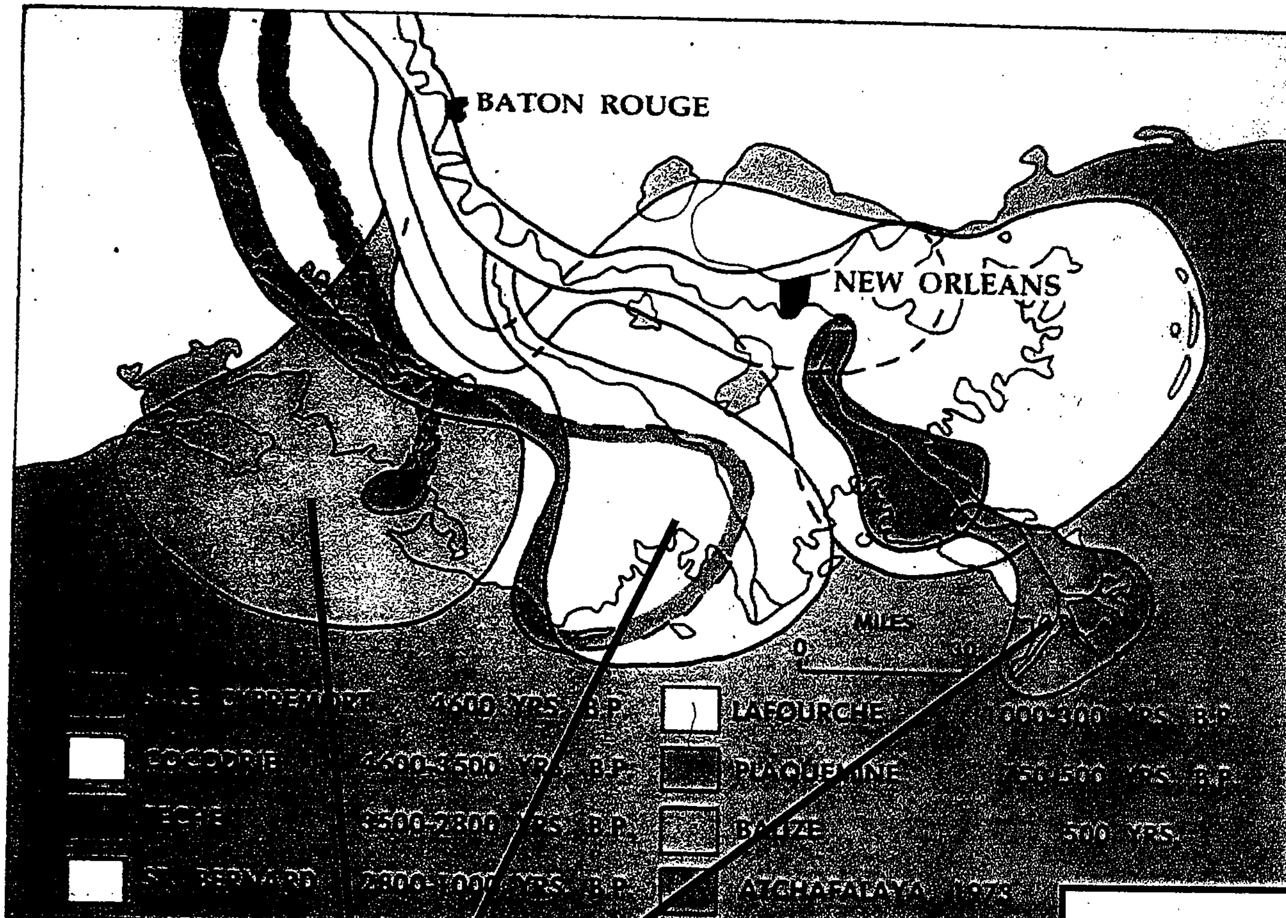


Figure 5-11. Generalized vertical profile through a channel mouth bar sand body. As in fluvial system profiles, sedimentary structures are illustrated schematically, grain size increases to the right on the average grain size plot, and the log profile is drawn to resemble either an S.P. or gamma-ray curve.



MODIFIED FROM: FISK, KOLB, VAN LOP

Delta Lobes

One delta lobe

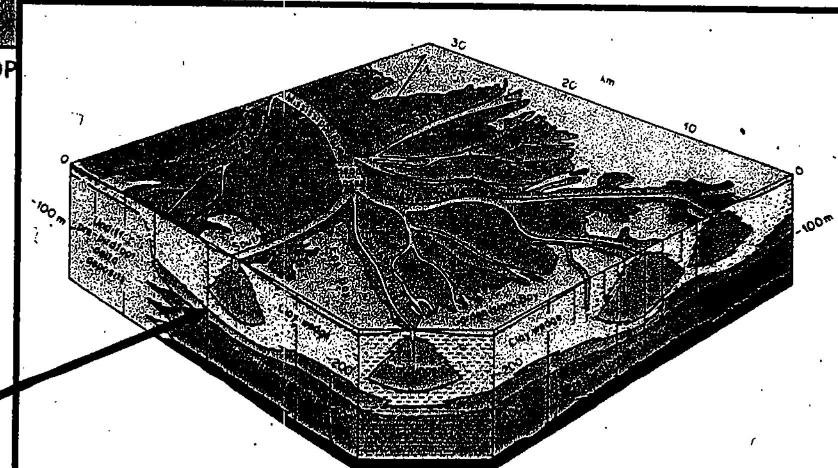
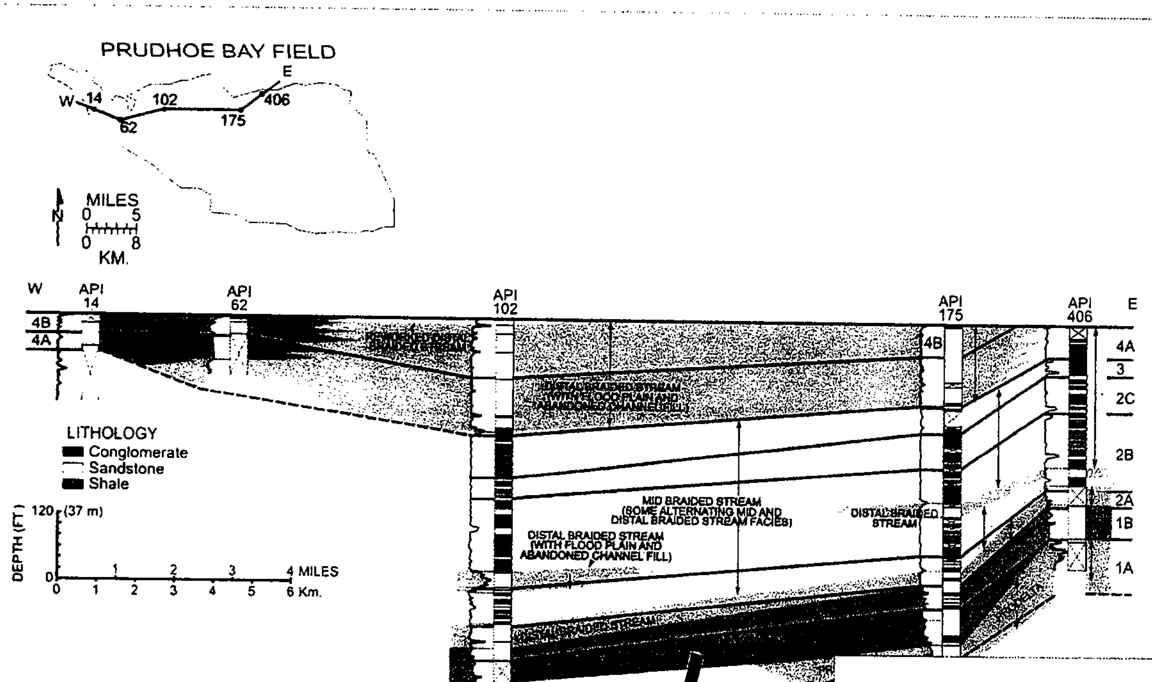
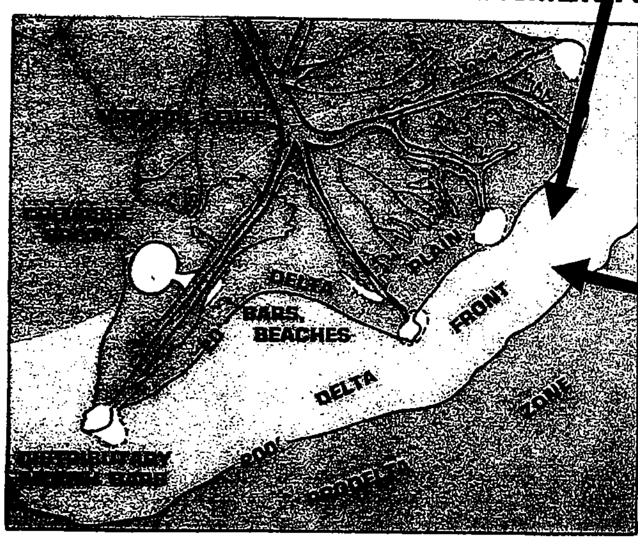
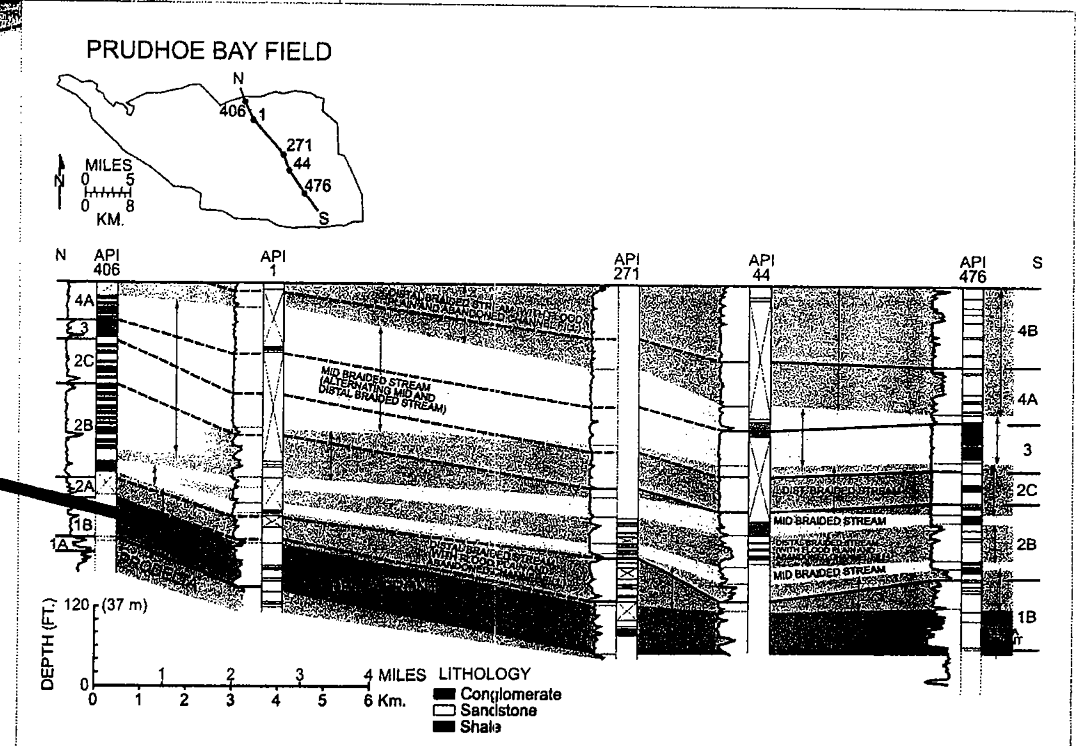


Fig. 7-11 Block diagram indicating geometric arrangement of bar-finger sand, fine-grained sediments, and topset marsh deposits of the modern Birdfoot delta of the Mississippi River. (After Fisk *et al.*, 1954.)



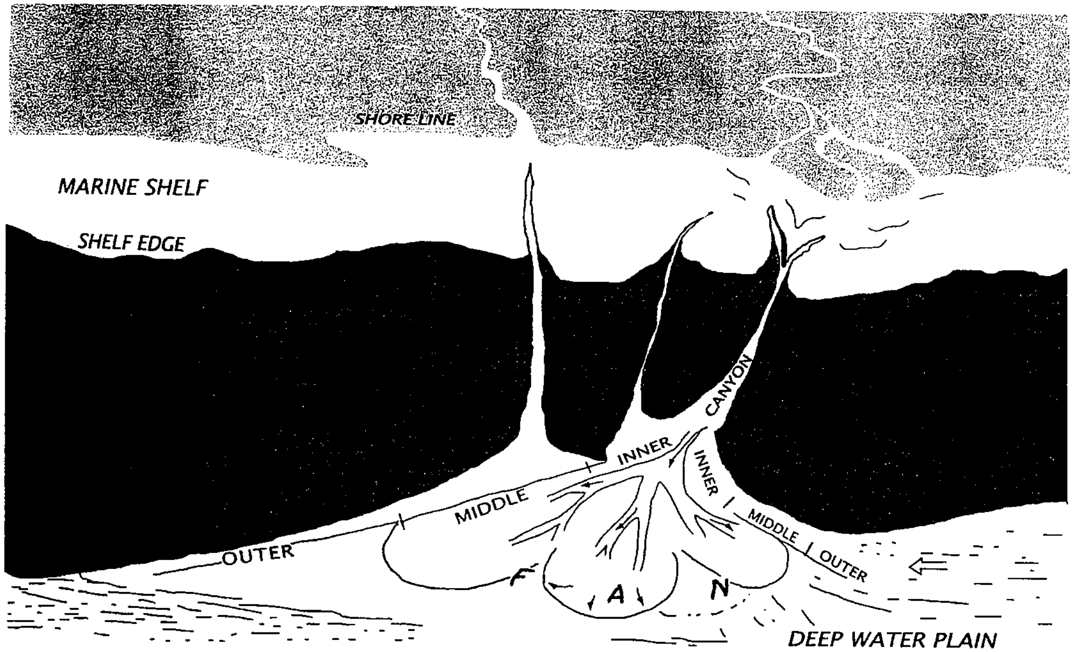
PRINCIPAL DELTA ENVIRONMENTS



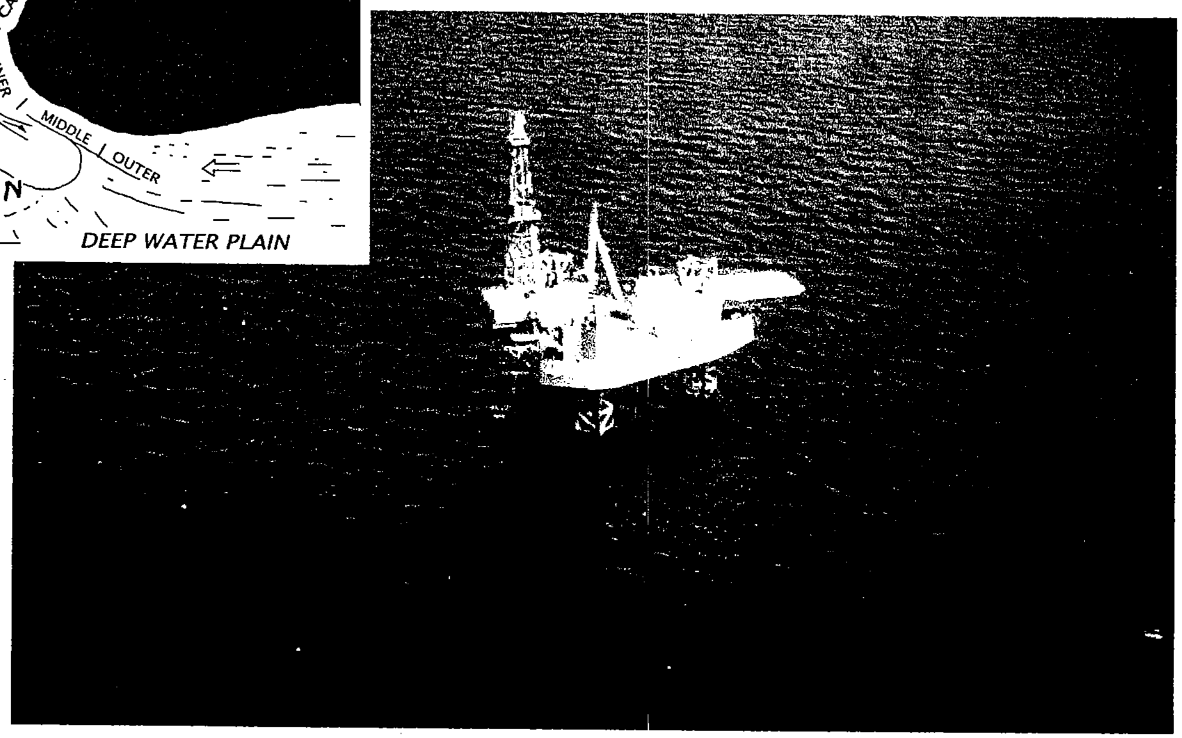


DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS

GEOLOGIC DEFINITION: ***Clastic sediments transported beyond the shelf edge into deep water by sediment gravity flow processes and deposited on the continental slope and in the basin. They are later buried and become part of a basin fill.***

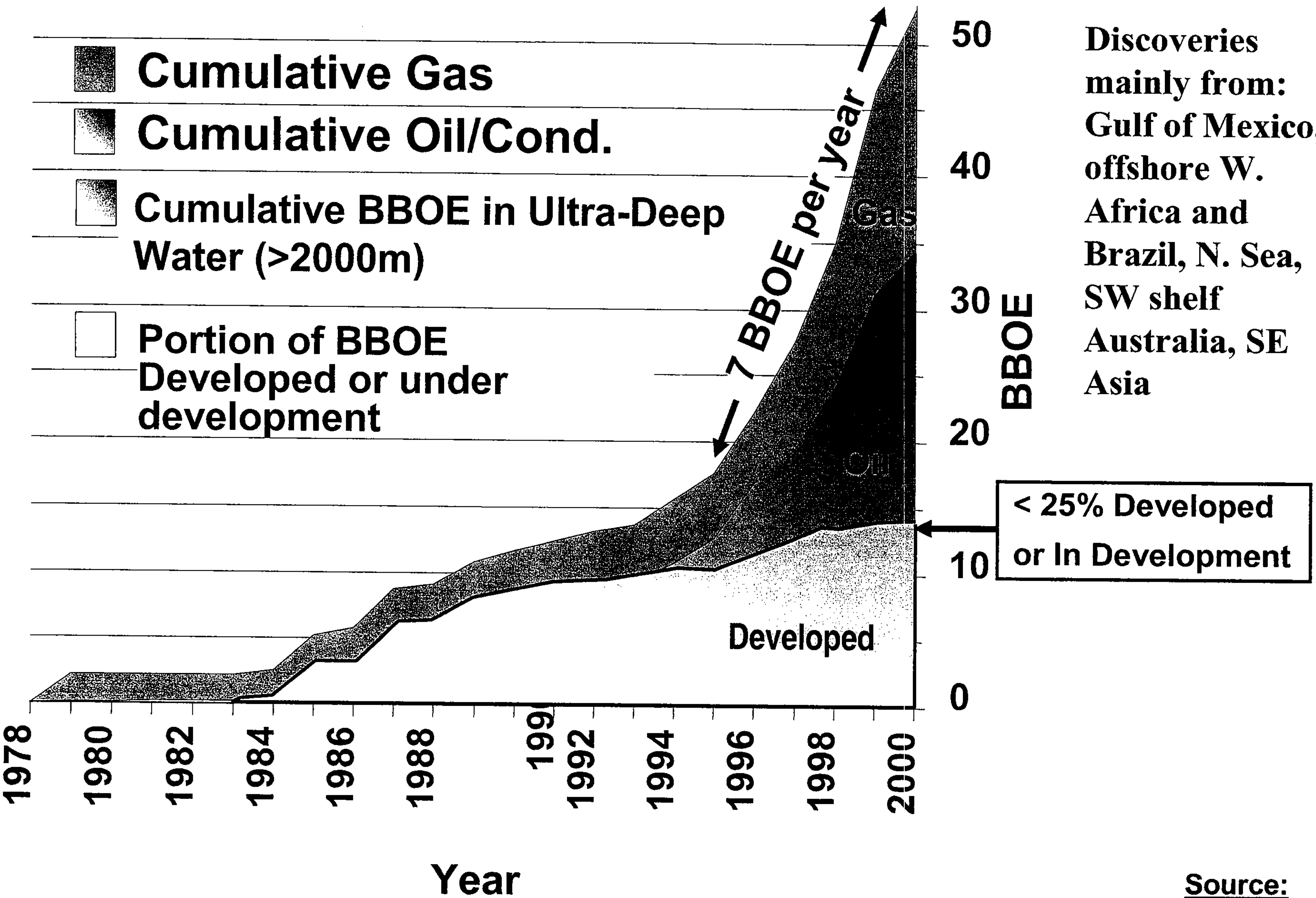


Engineering and geologic 'deep water' are usually the same, but for different reasons.



"DEEP WATER"

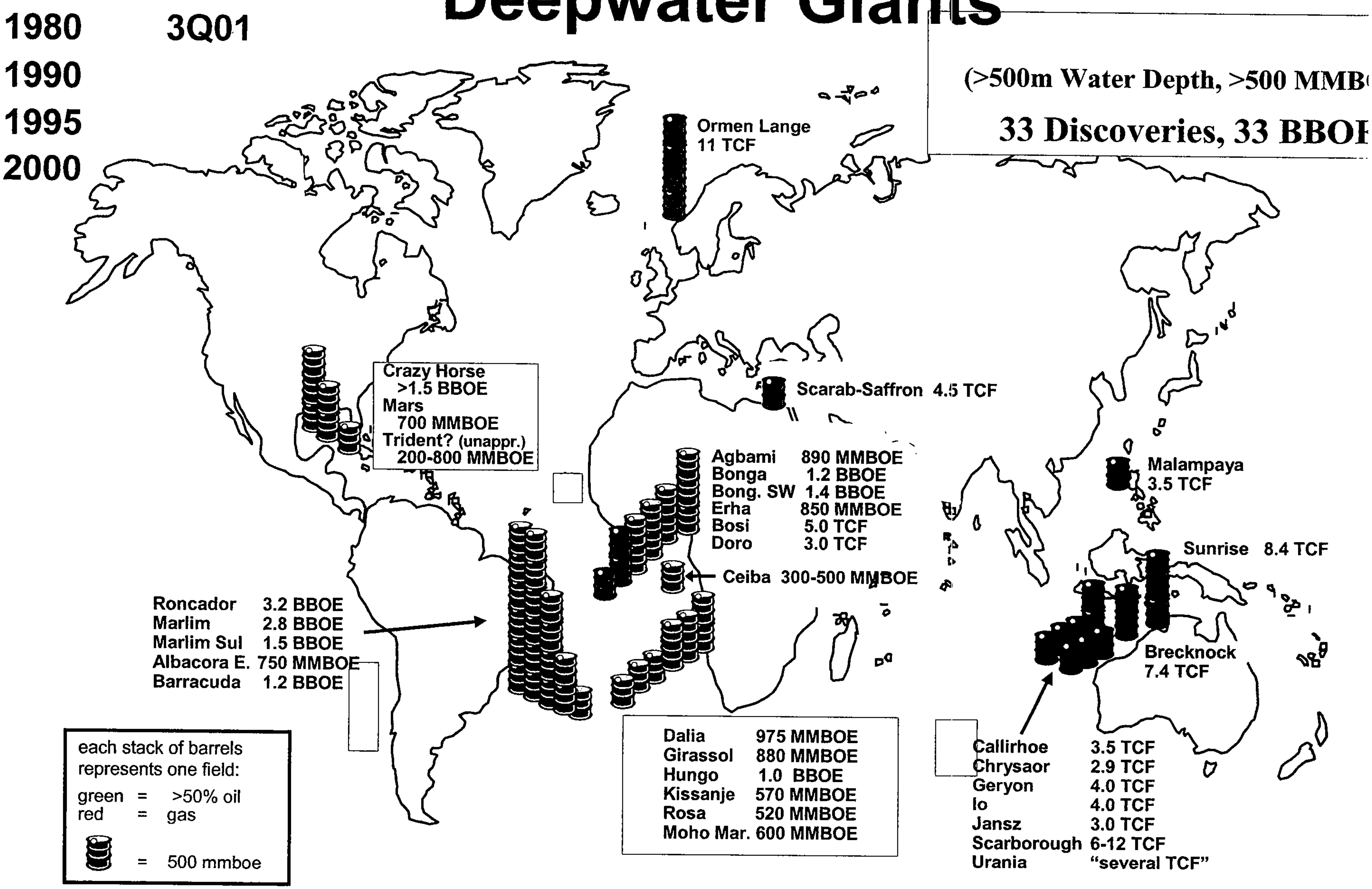
Deepwater (>500m) discovered reserves



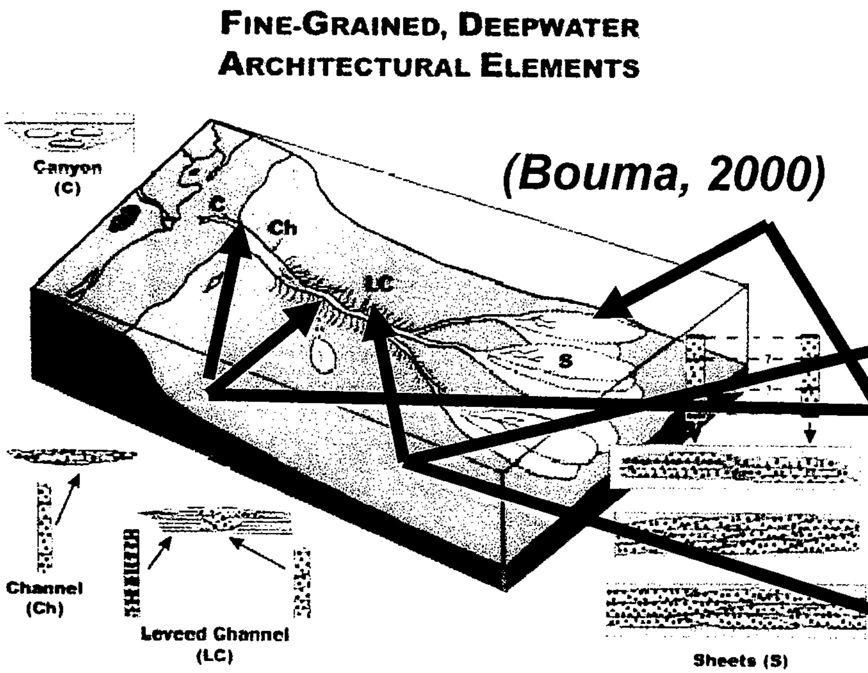
Discoveries mainly from: Gulf of Mexico, offshore W. Africa and Brazil, N. Sea, SW shelf Australia, SE Asia

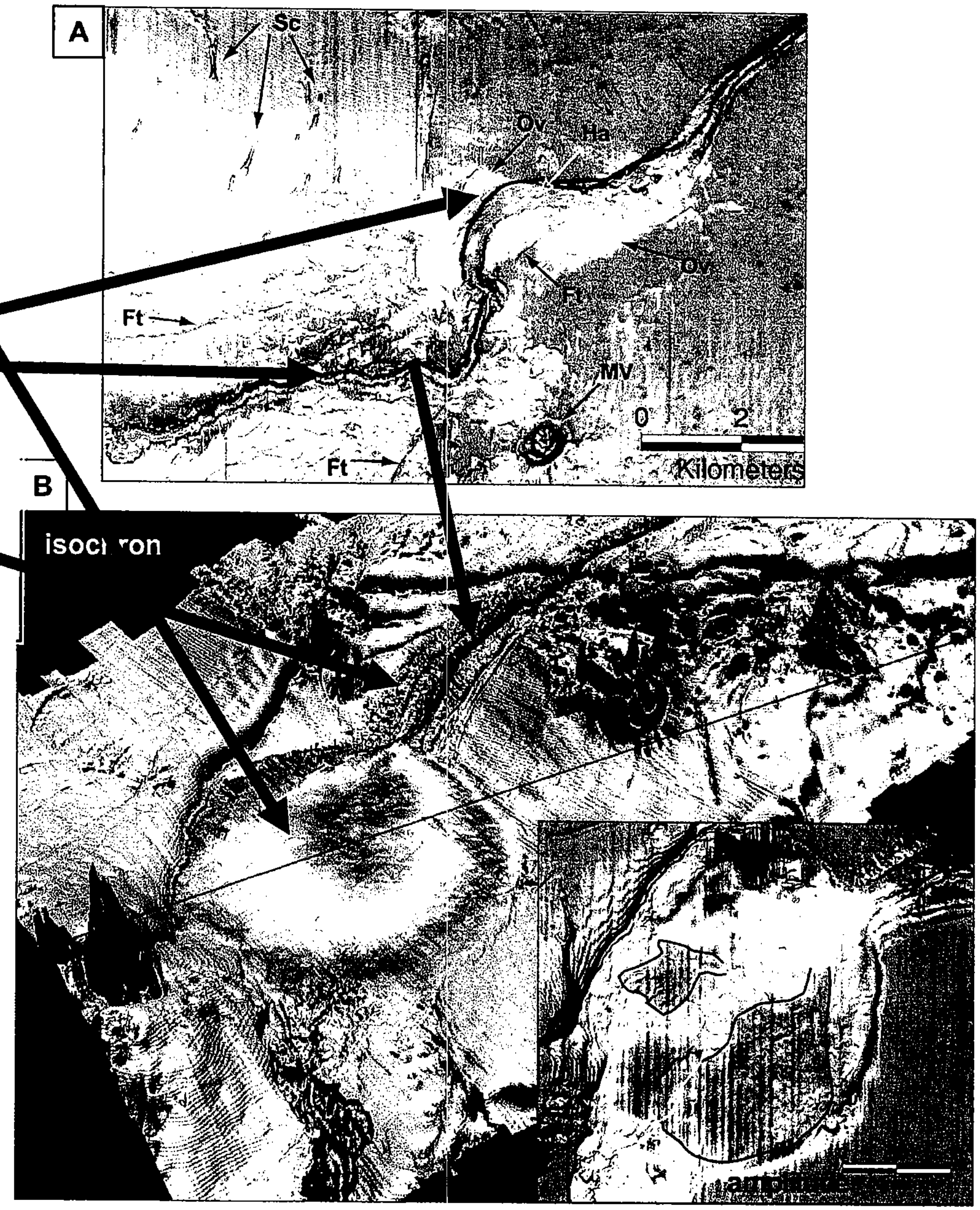
Source: Various

Deepwater Giants



Deepwater discoveries exceeding 500 MMBOE, announced as of September 2001. The South Atlantic and Gulf of Mexico are oil and gas; Europe, Asia and Australia are predominantly gas discoveries. Data from IHS Energy Group (2000, used with permission) and other published references as noted.





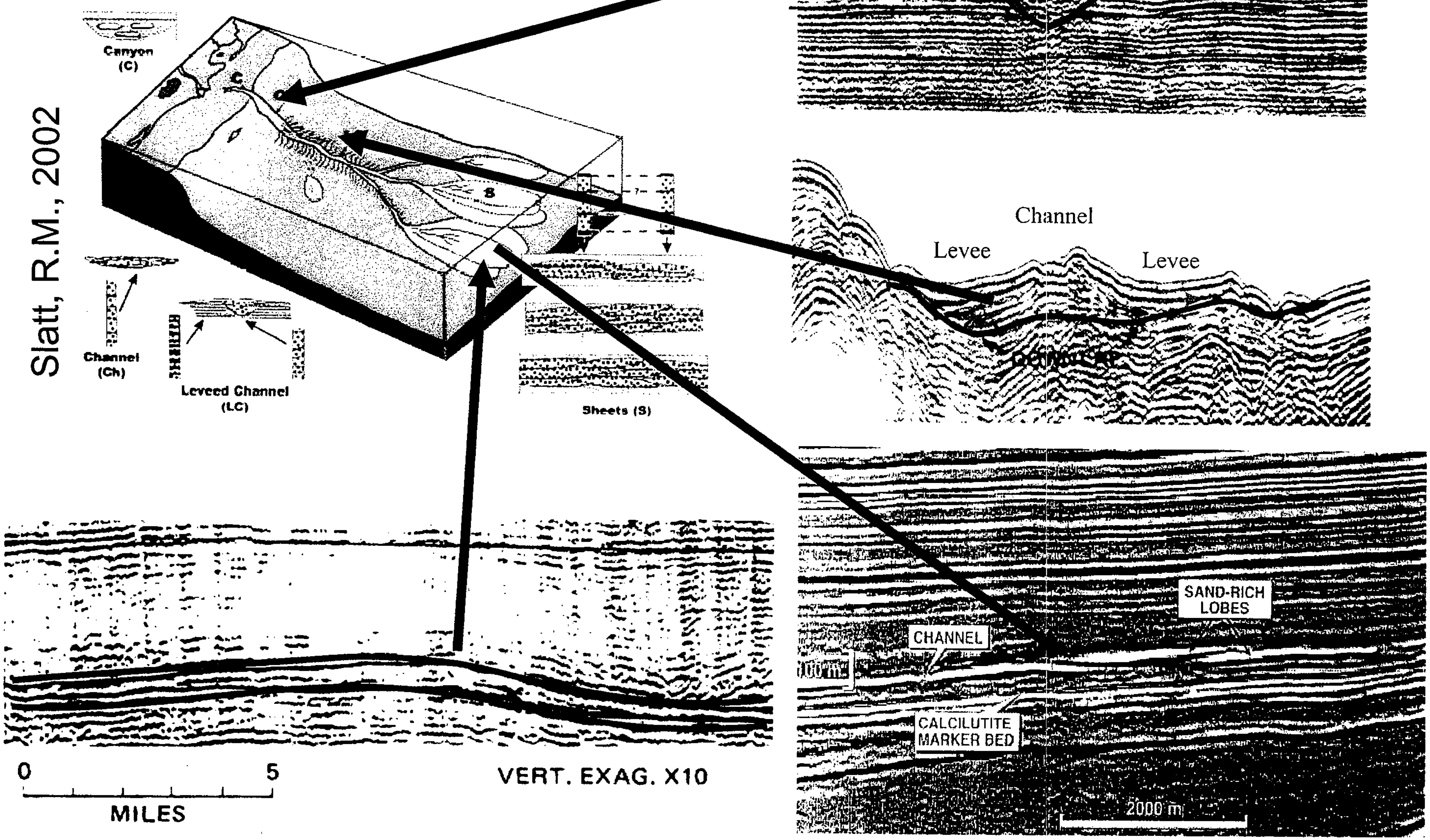
(Pirmez et al., 2000)

Three major elements:

- Sheets
- Channel-fill
- Levee/overbank

Seismic Facies Mapping: Turbidites

FINE-GRAINED, DEEPWATER ARCHITECTURAL ELEMENTS

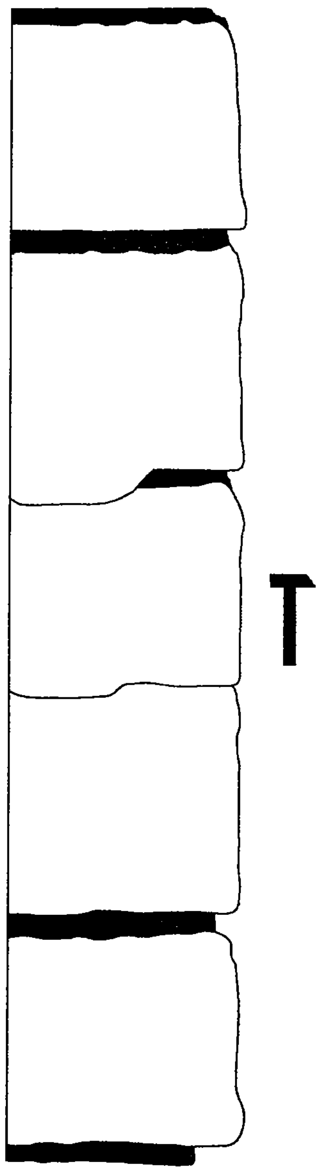


Slatt, R.M., 2002

Mitchum, R.M., 1985

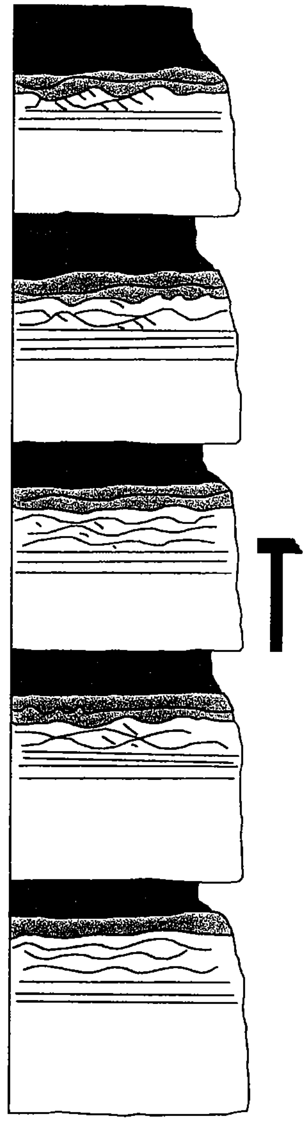
DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS:

Sheet Sandstones & Reservoirs



Amalgamated Sheets

(Mutti, 1979)

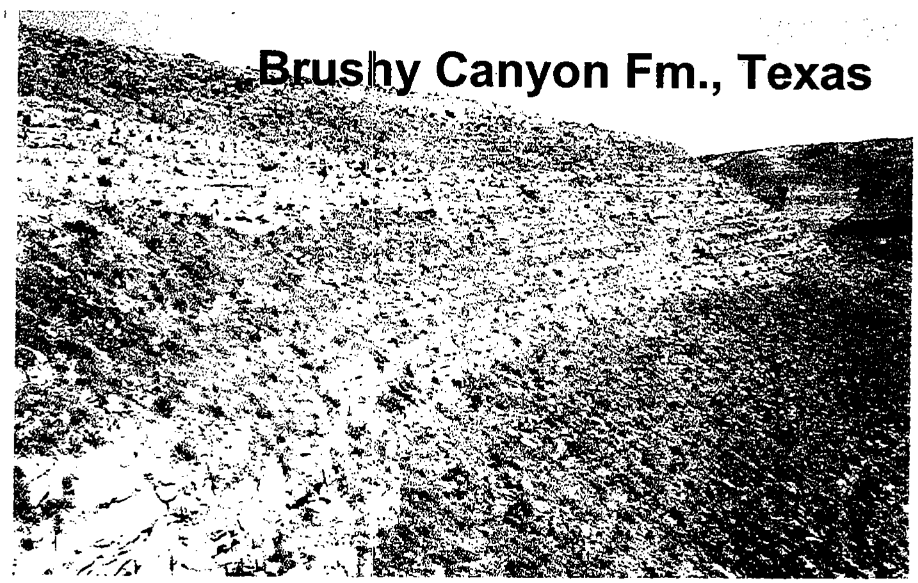


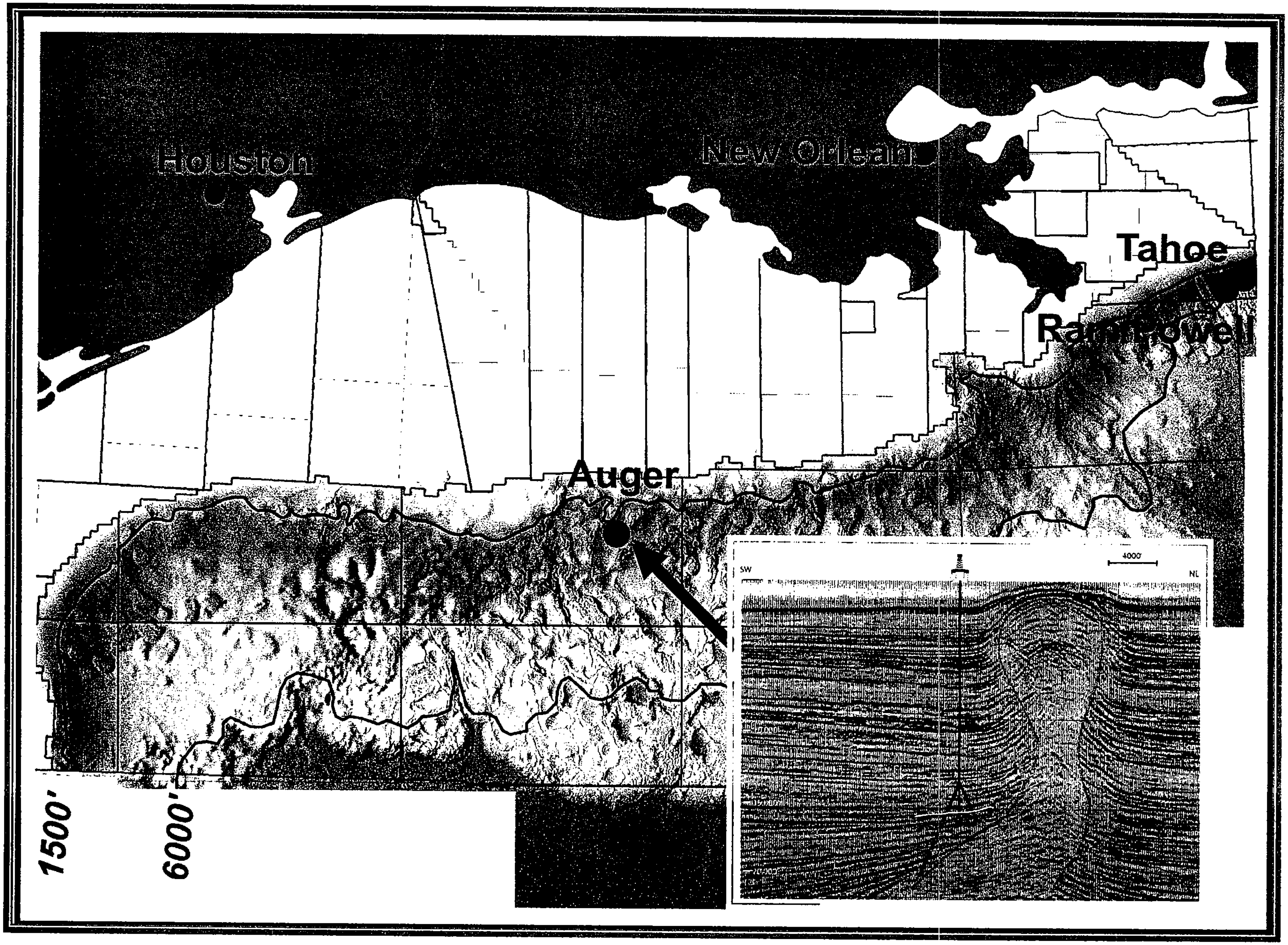
Layered
Sheets

Amalgamated sheets

Layered sheets

Brushy Canyon Fm., Texas



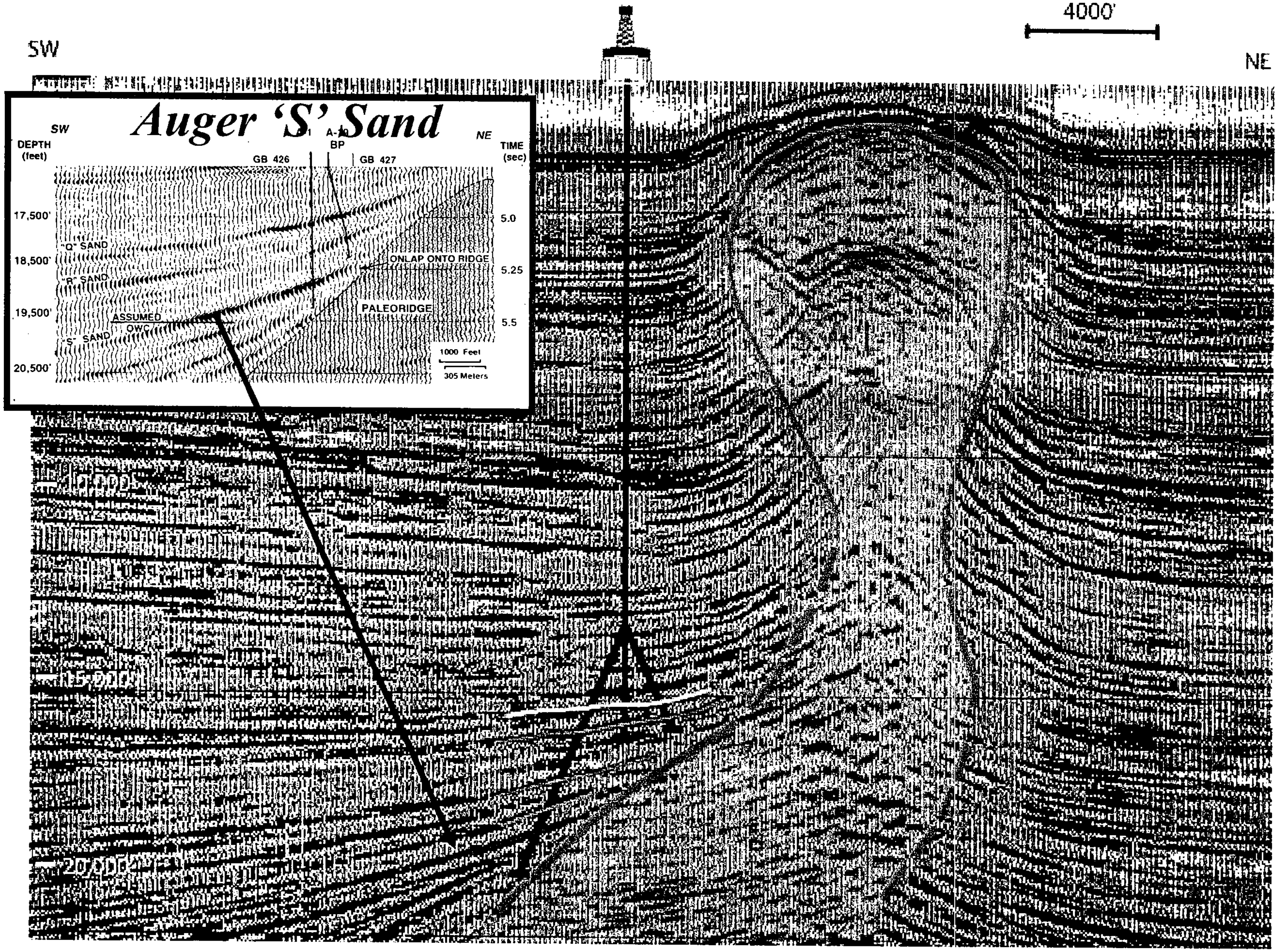


(Kendrick, 2000)

SHEET SANDSTONE EXAMPLES

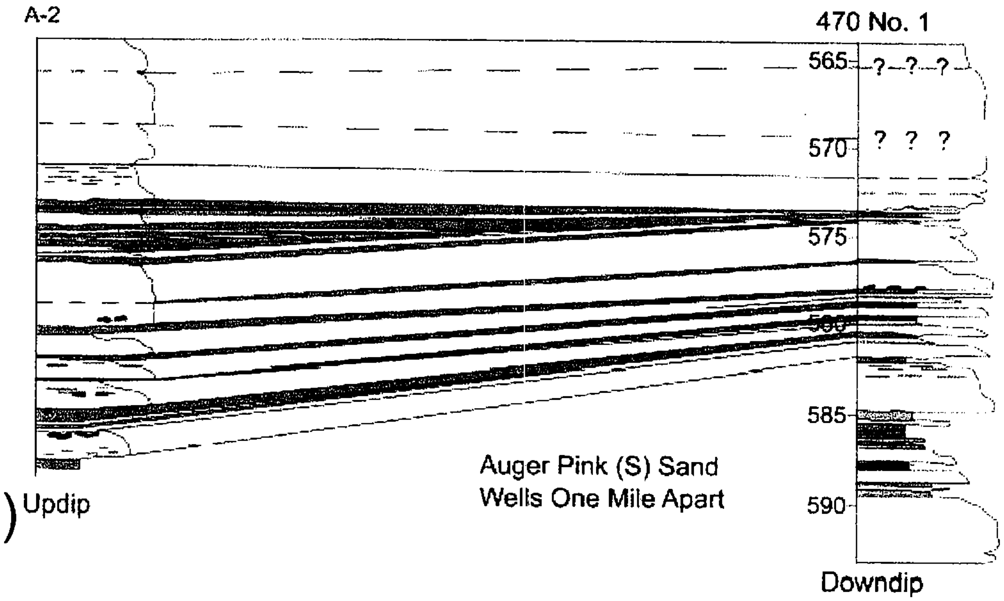
• *S Sand, Auger Field; Gulf of Mexico (Kendrick, 1998)*

-120MMBE assigned to S Sand
-As of 2000, 7 wells have produced 110 MMBE
-Field occurs within a salt-withdrawal mini-basin
-Combination fault-stratigraphic pinchout trap
-layered/amalgamated sheet sands , and shales extend across entire basin
-oil-bearing zones beneath water-bearing zones
-Excellent aquifer support
-Pulsed Neutron Capture (PNC) logs record replacement of oil by water during development; indicate that some shales isolate sands and others do not
-PNC data do not confirm that the 20ft. thick shale separating S1 and S2 sands is a barrier; however, other shales are barriers
-Different types of shales with different sealing potential?? Can these be recognized??

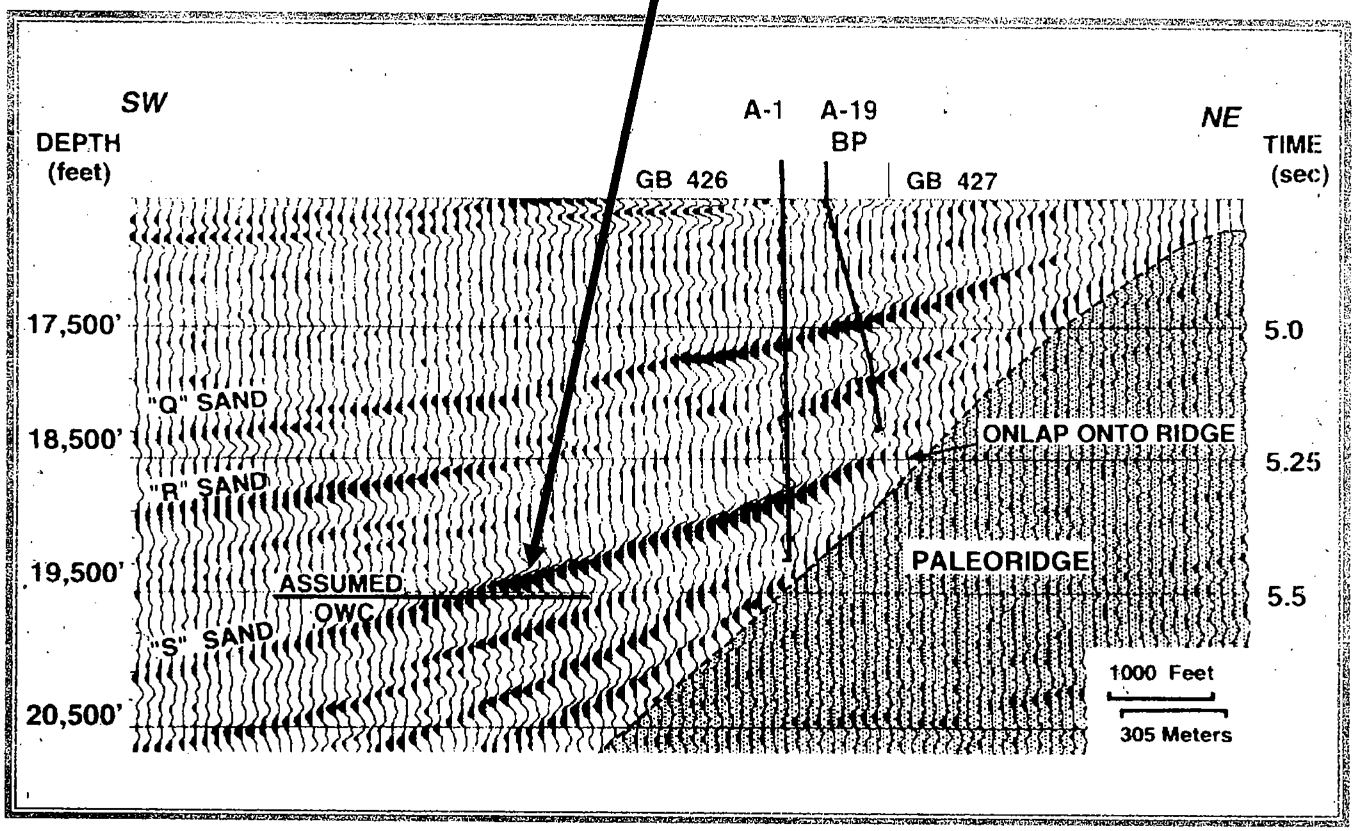


(Kendrick, 2000)

Auger Field: GoM



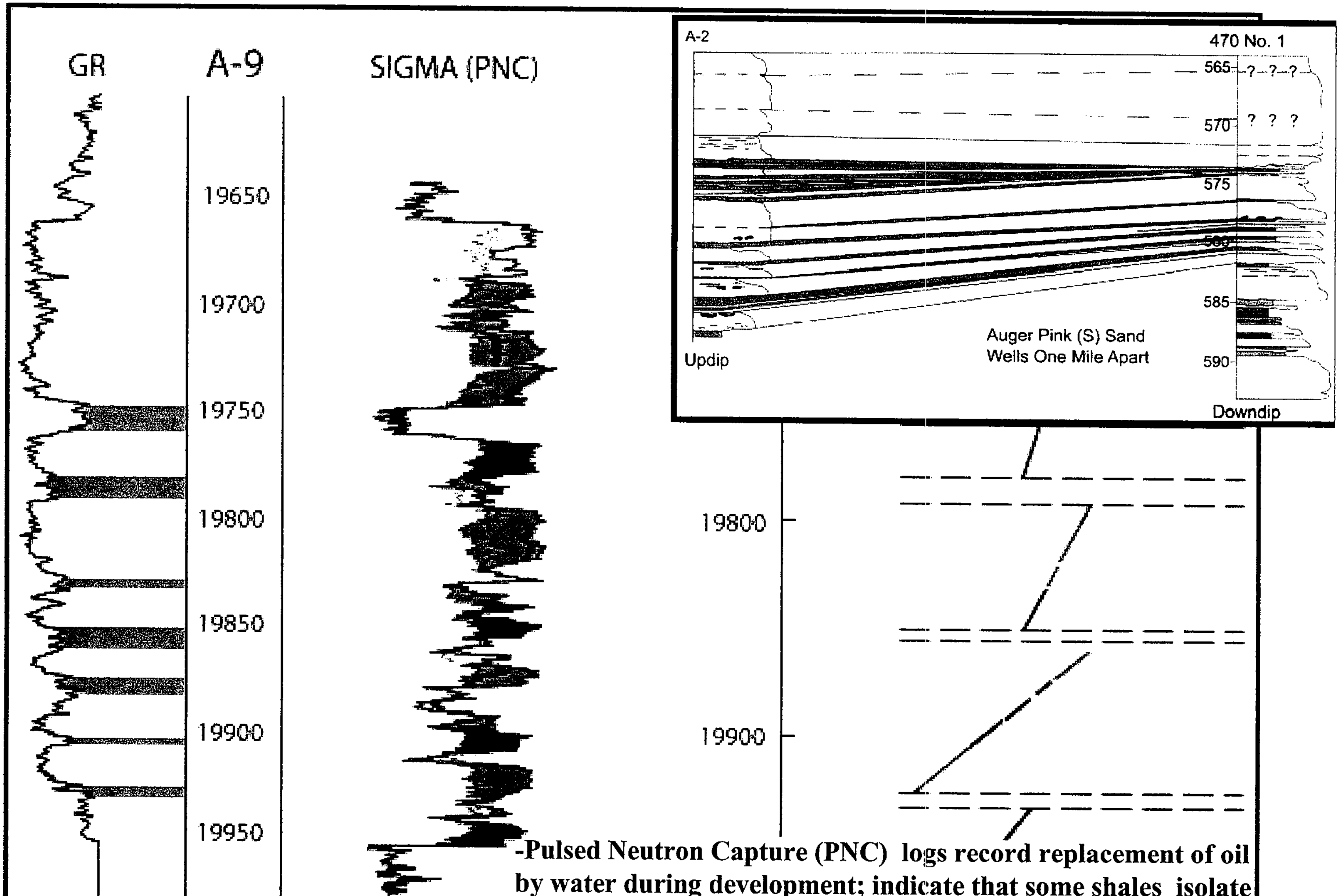
(Modified from Balinski et al., 1994)



(McGee et al., 1994)

Bilinski at al, 1995

Slatt and Weimer, 1999



-Pulsed Neutron Capture (PNC) logs record replacement of oil by water during development; indicate that some shales isolate sands and others do not

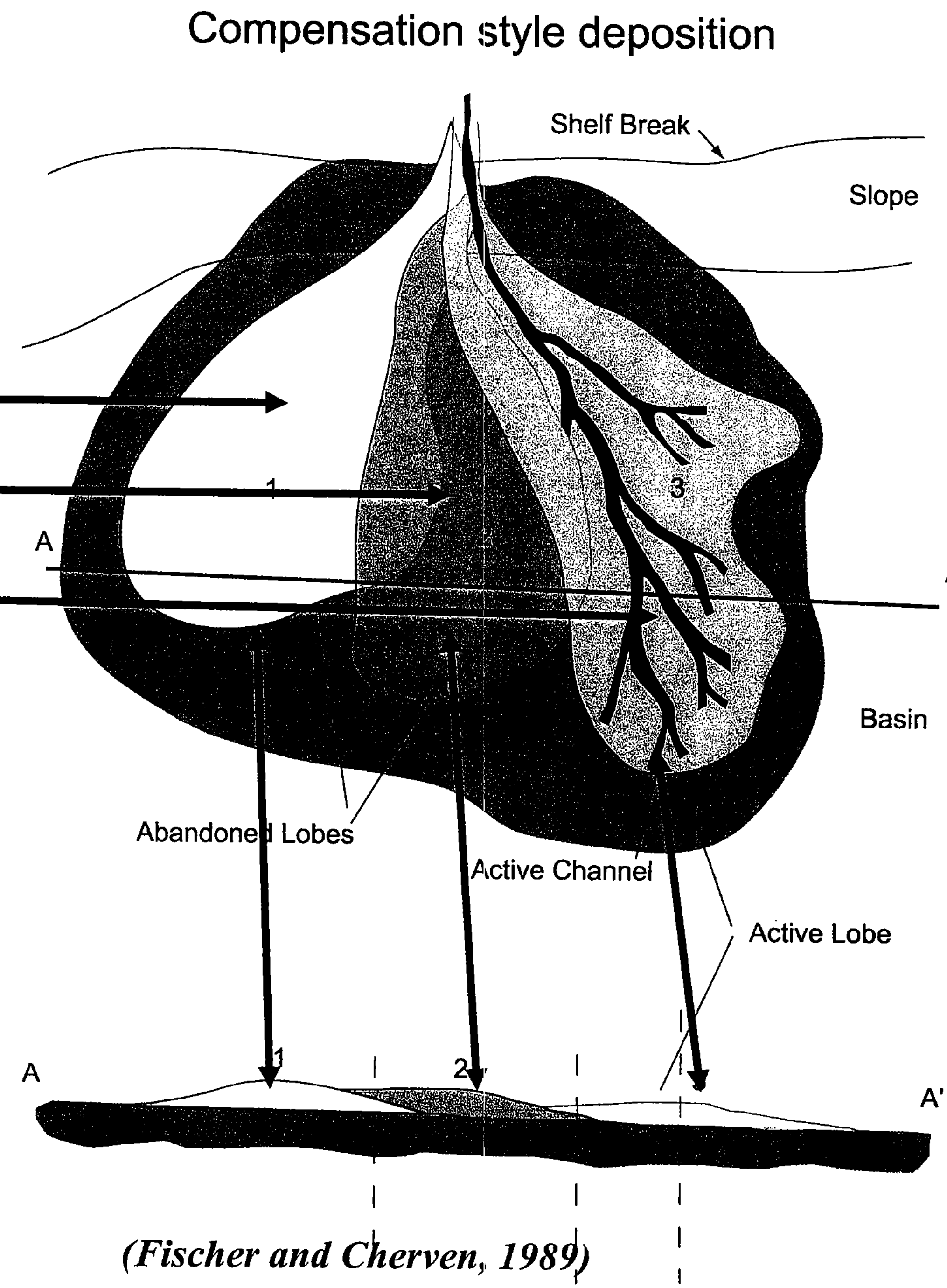
(Kendrick, 2000)

Axis of deposition

Time 1

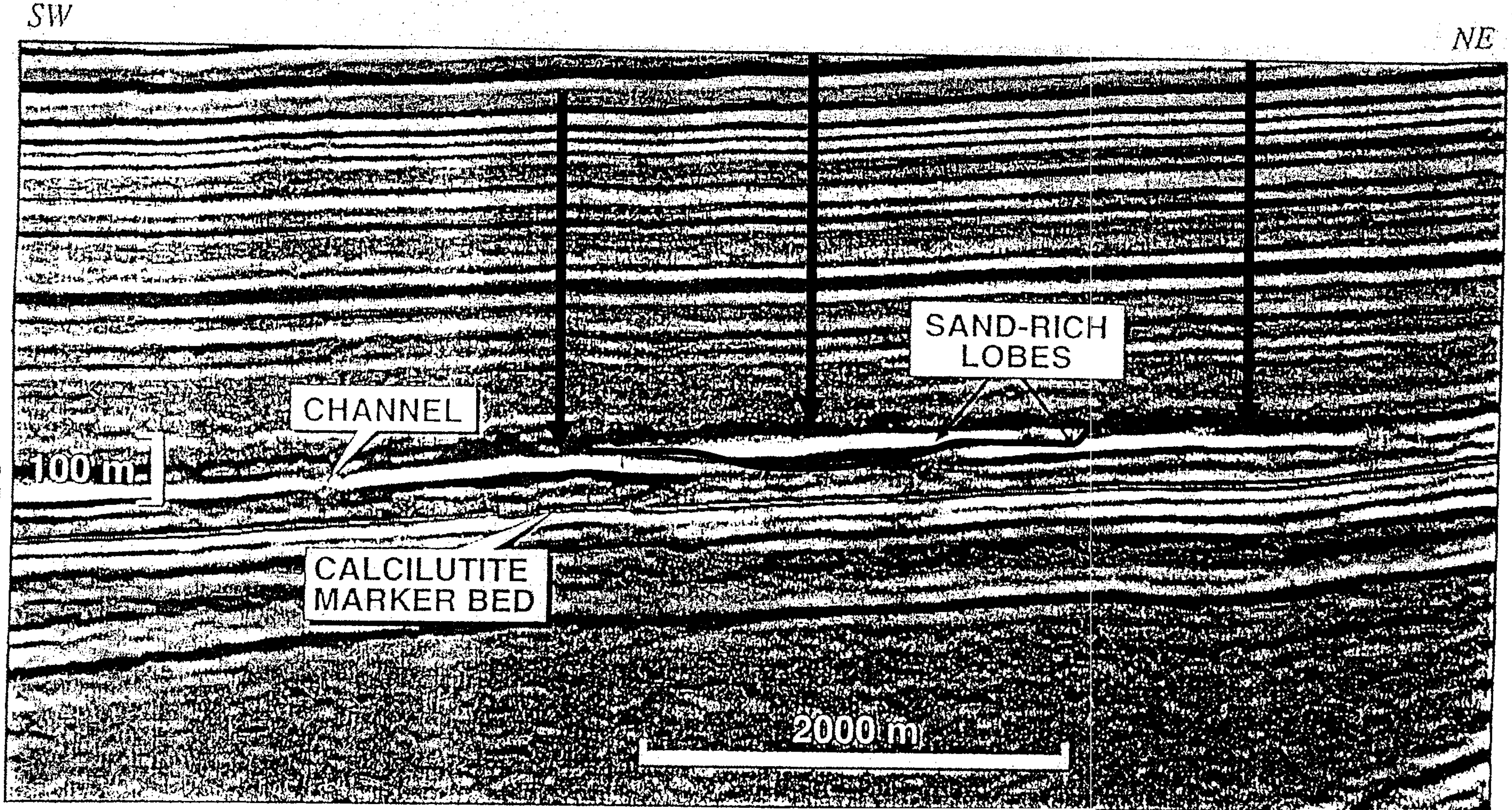
Time 2

Time 3



(Fischer and Cherven, 1989)

Time 1 **Time 2**



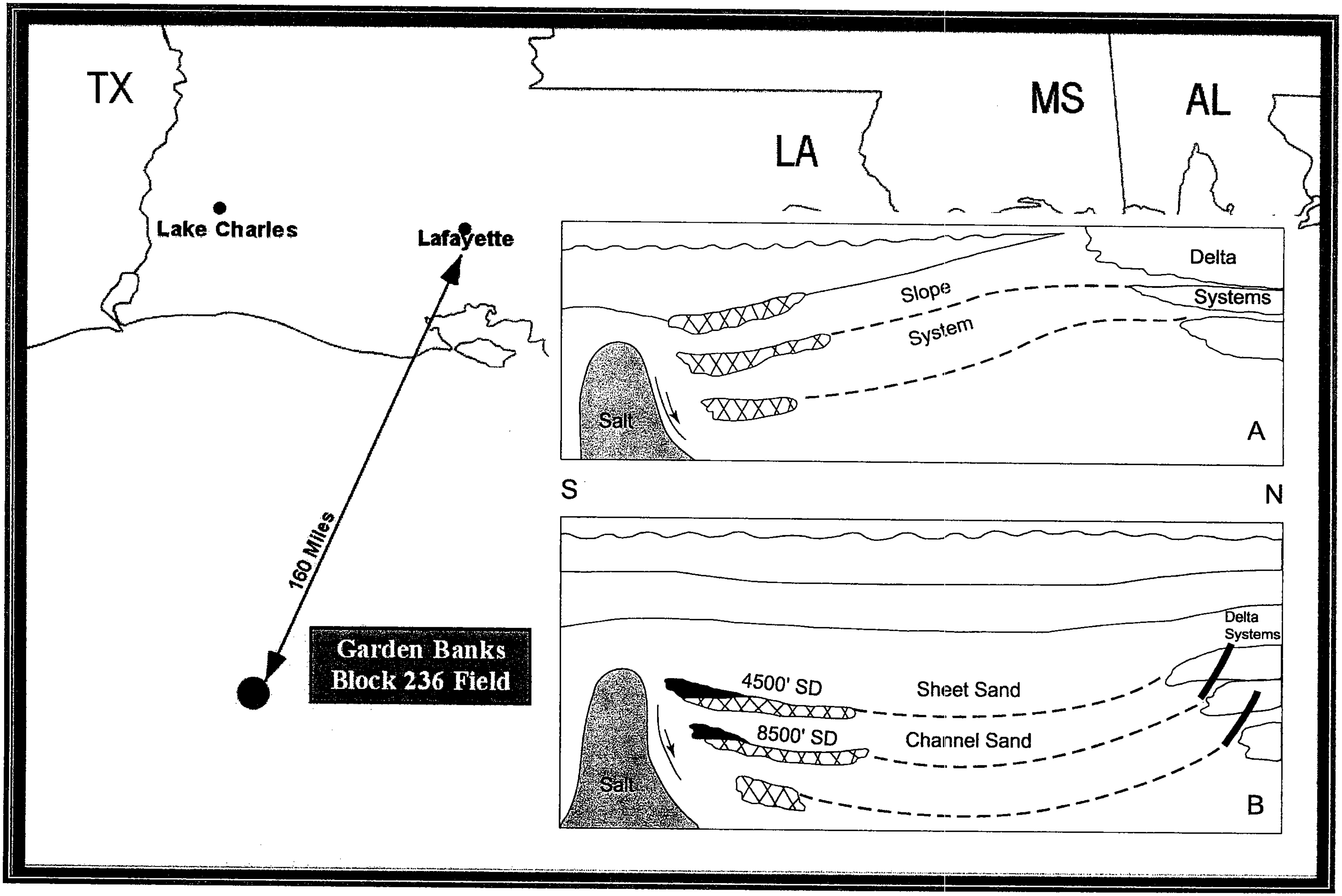
(Bruhn, 1998)

"Compensation style" deposition as seen on seismic; Brazil

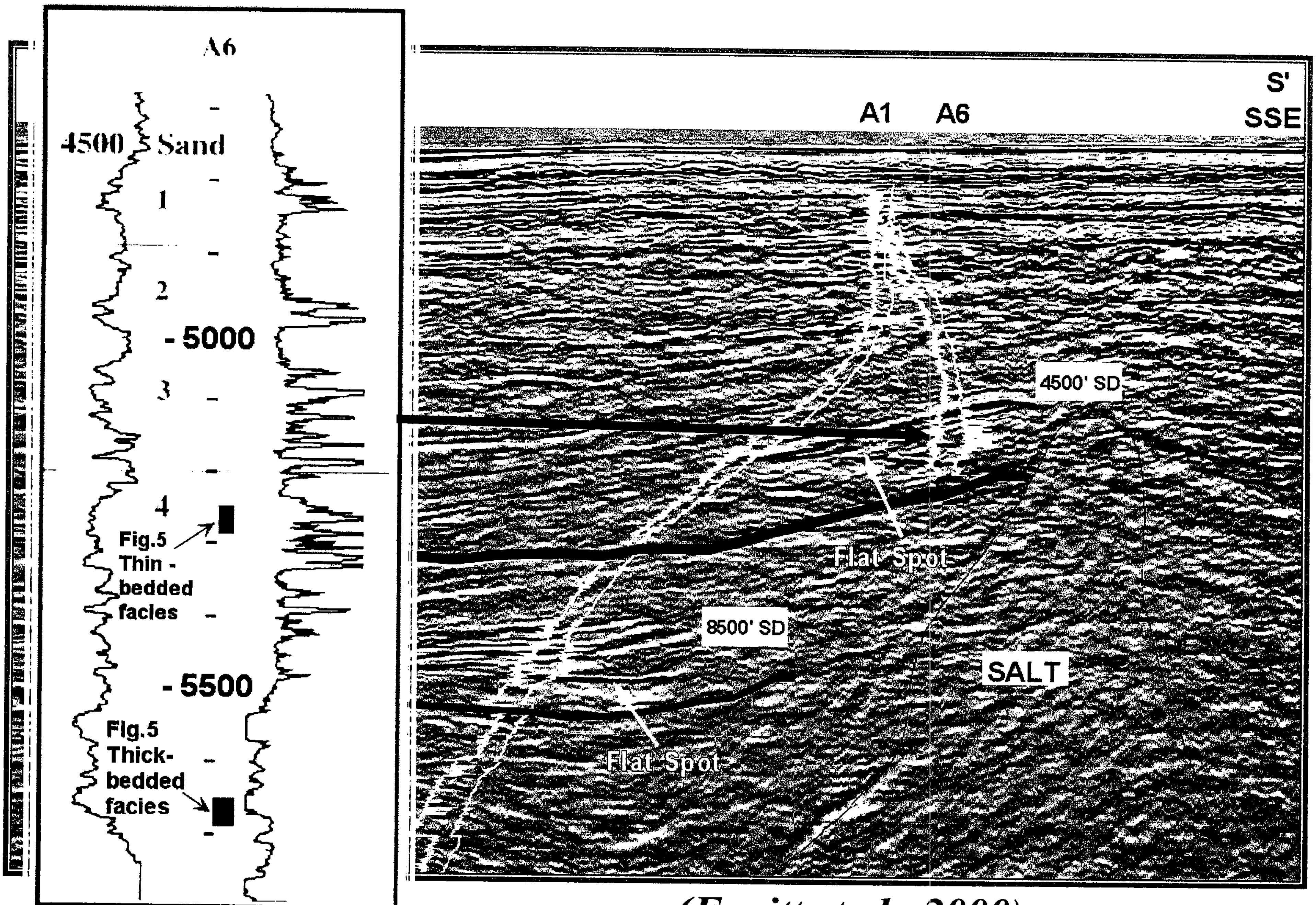
SHEET SANDSTONE EXAMPLES

- **4500' Sand, Garden Banks 236; Gulf of Mexico**
  (Fugitt et al., 2000)

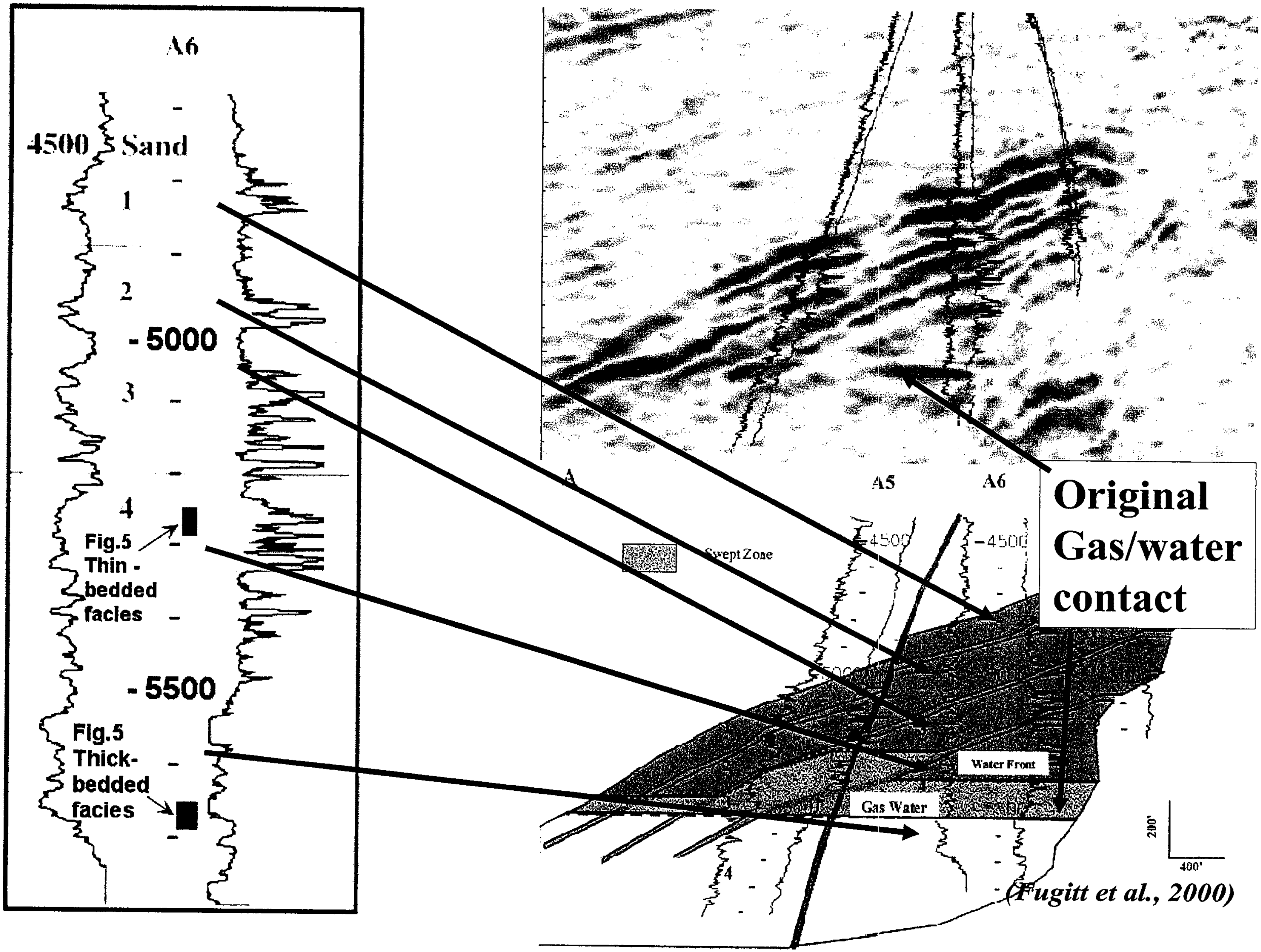
  -Since 6/94, 93BCFG produced
  -layered/amalgamated sheet sandstones
  -shaley intervals subdivide sandy intervals into different production zones
  -strong water drive
  -Porosity: 16.7-33.5%
  -Permeability: 0.6-2520md (Aver. = 427)
  -Porosity and permeability vary with grain size (best reservoir quality in thicker, cleaner sands)



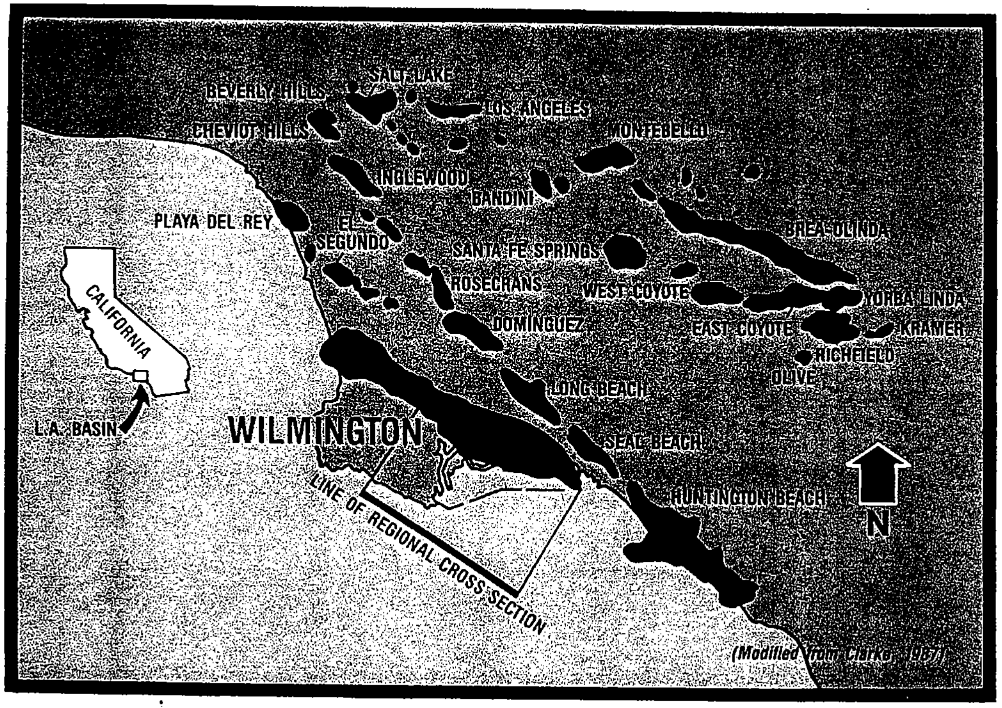
(Fugitt et al., 2000)

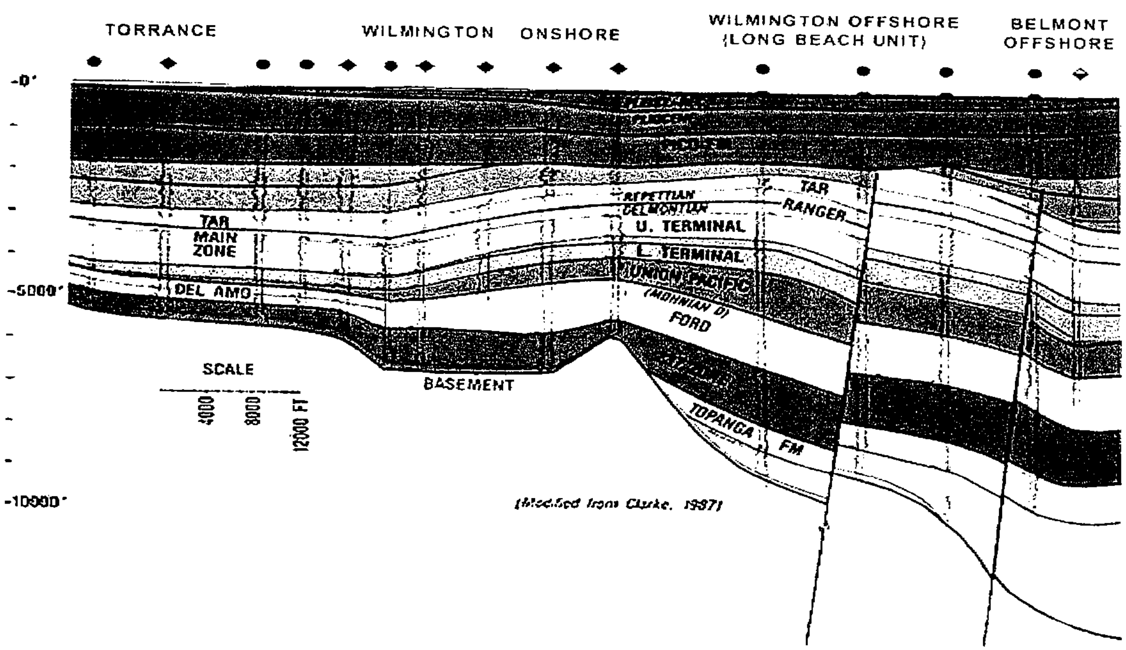


(Fugitt et al., 2000)



A6
4500 Sand
1
2
5000
3
4
Fig.5 Thin - bedded facies
5500
Fig.5 Thick- bedded facies
A
A5
A6
Original Gas/water contact
4500
4500
Swept Zone
Water Front
Gas Water
200'
400'
(Fugitt et al., 2000)





Long Beach Unit; S. California *(Slatt et al., 1993)*

-Part of the larger Wilmington Oil Field of southern California

-3.8BBOOIP

-Laterally continuous shales extend across fault blocks

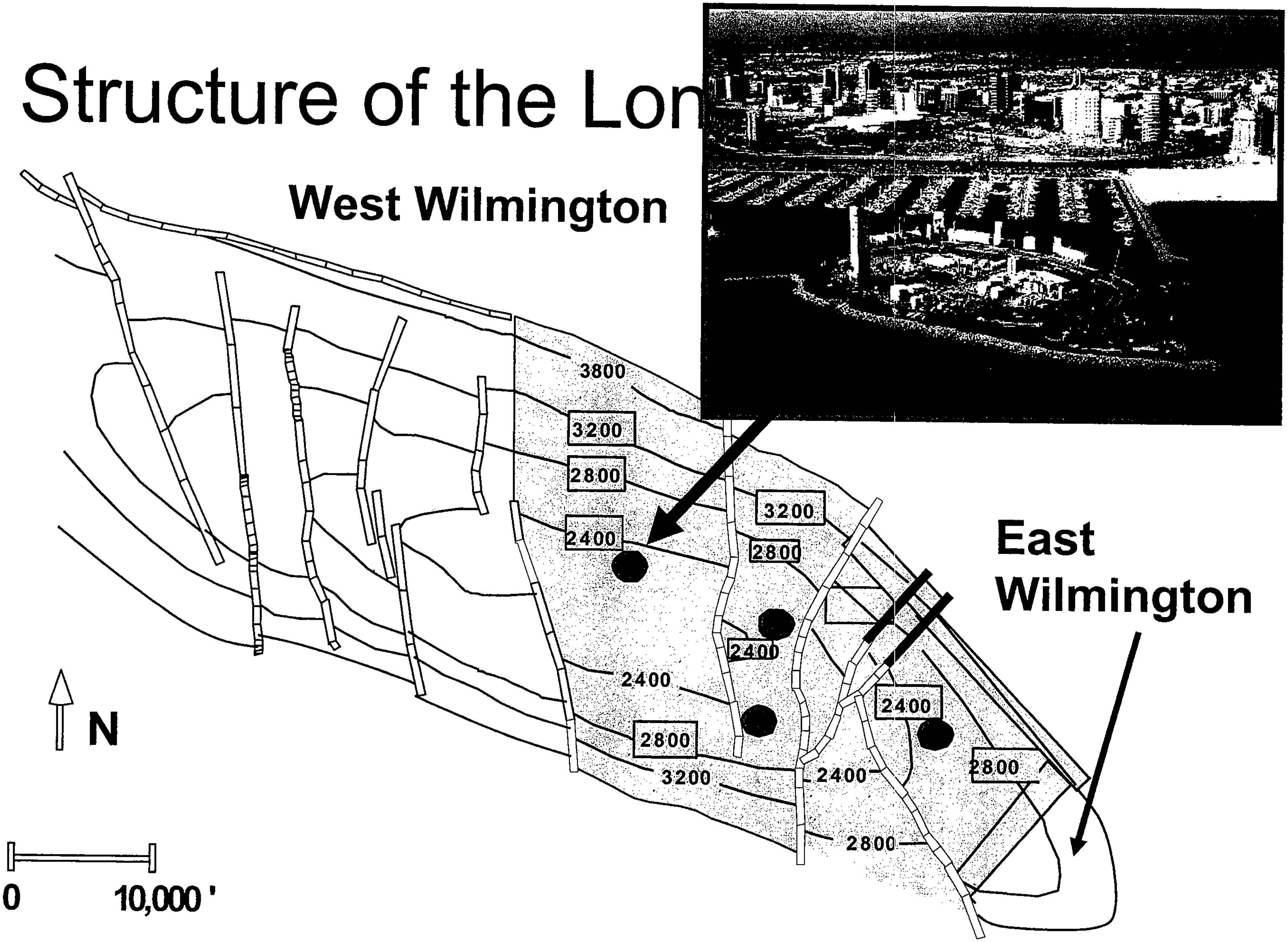
-Ranger Zone is most prolific unit

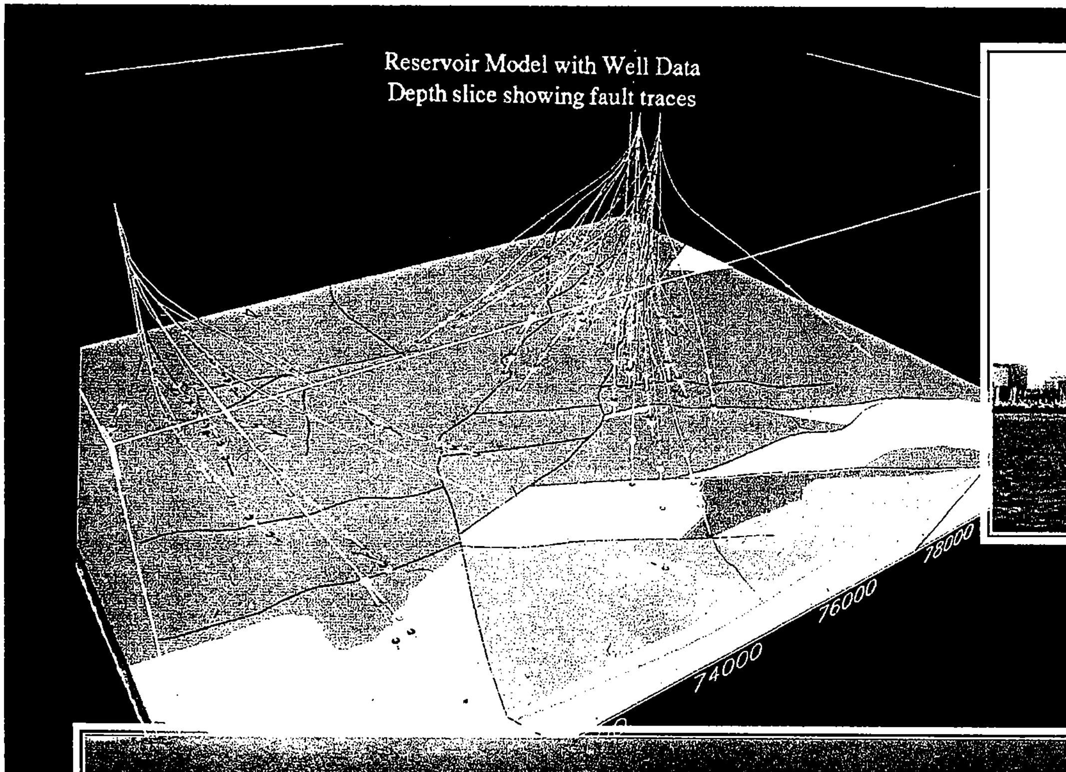
-Sands are unconsolidated except where held together by oil

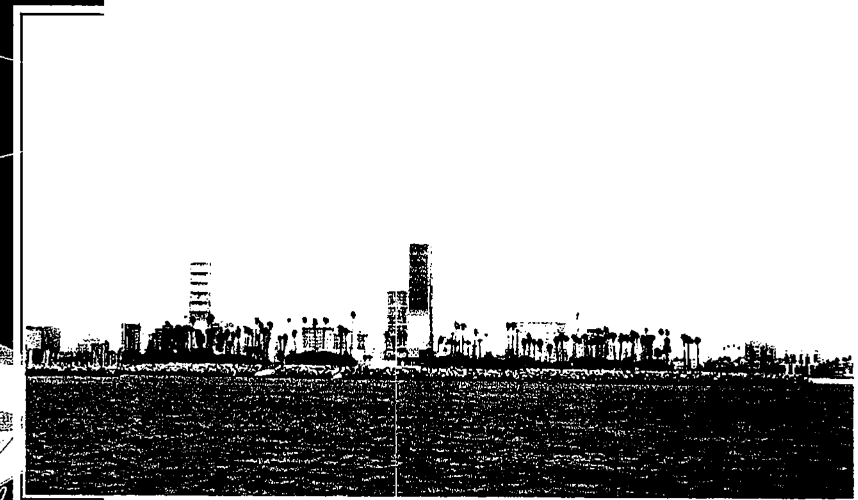
-Porosites and permeabilities are high

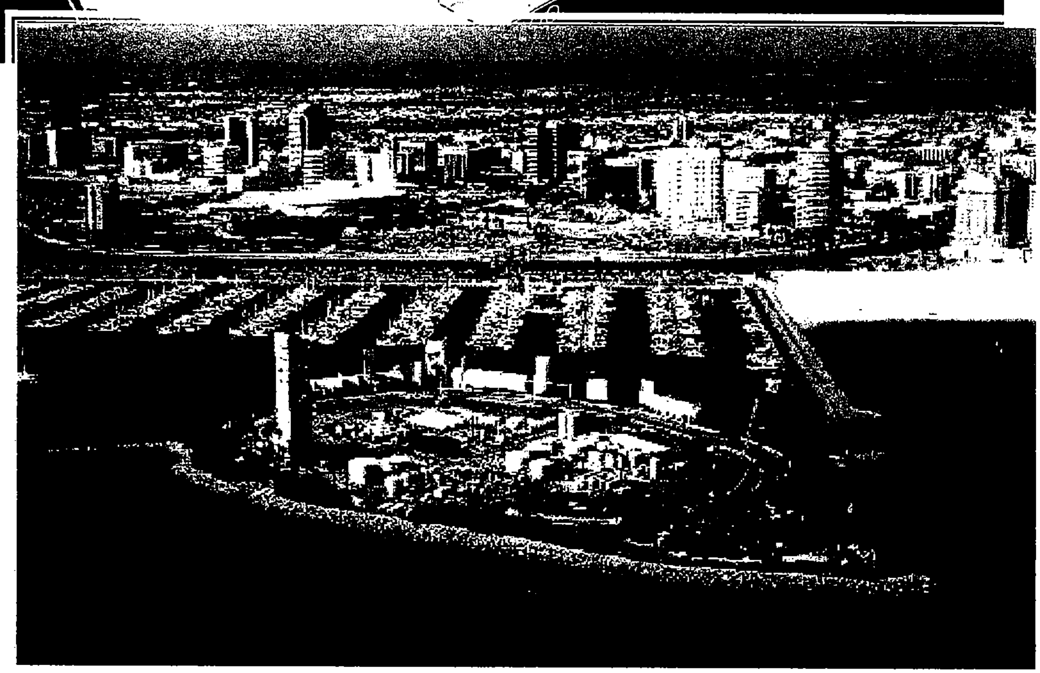
-Long distant continuity of sands

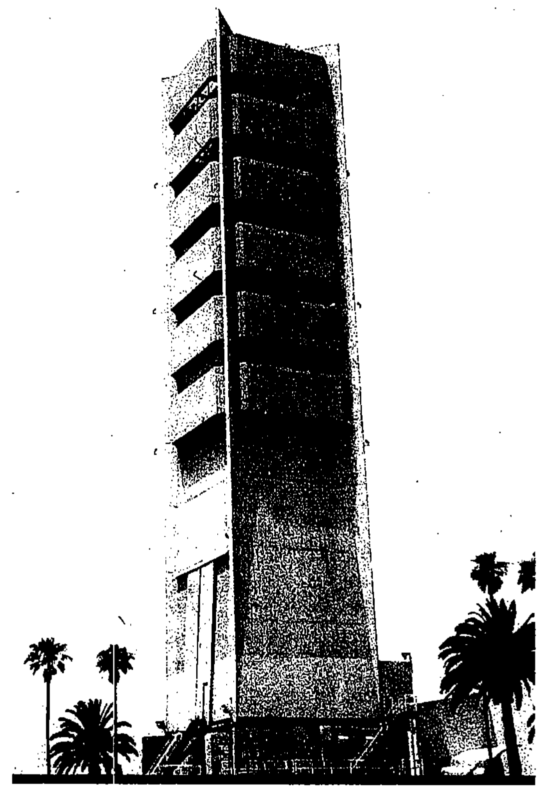
Structure of the Lon



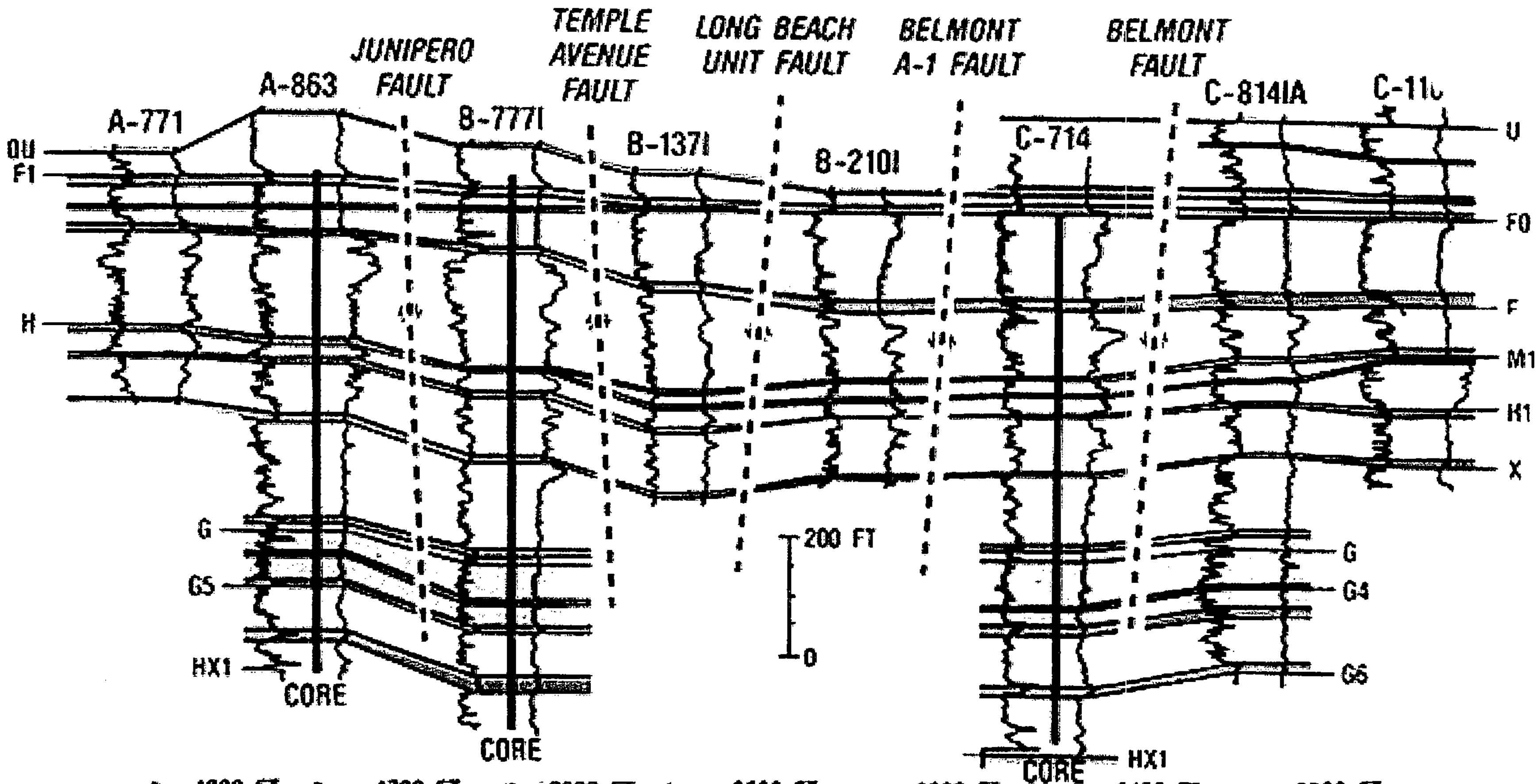

Reservoir Model with Well Data
Depth slice showing fault traces
74000
76000
78000







E-W REGIONAL CROSS SECTION

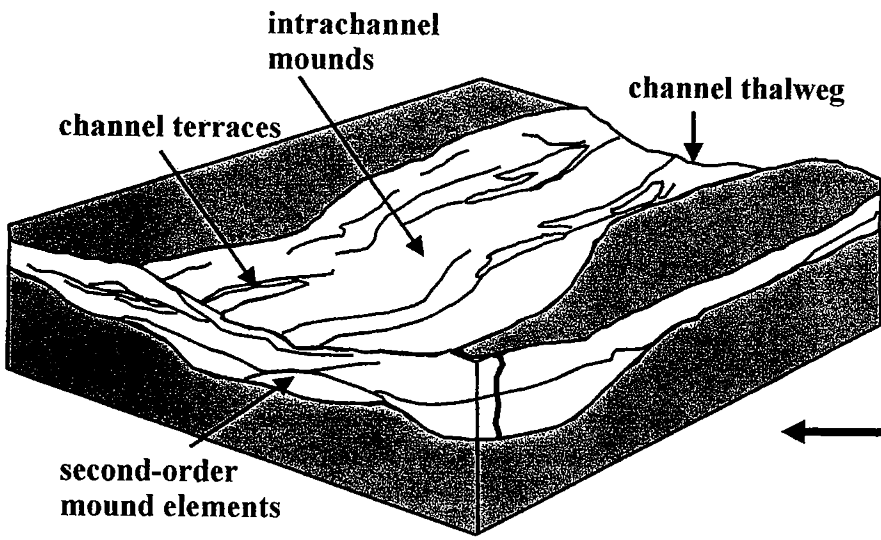


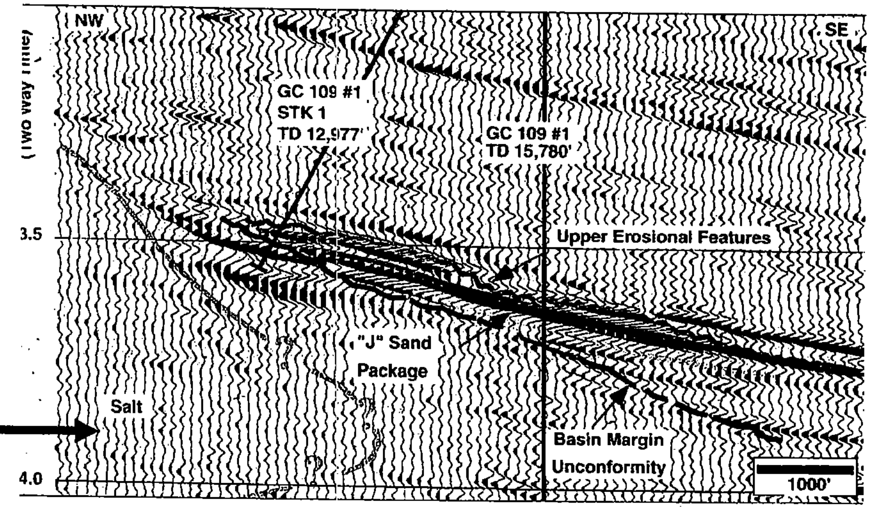
(Slatt et al., 1990)

DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS:

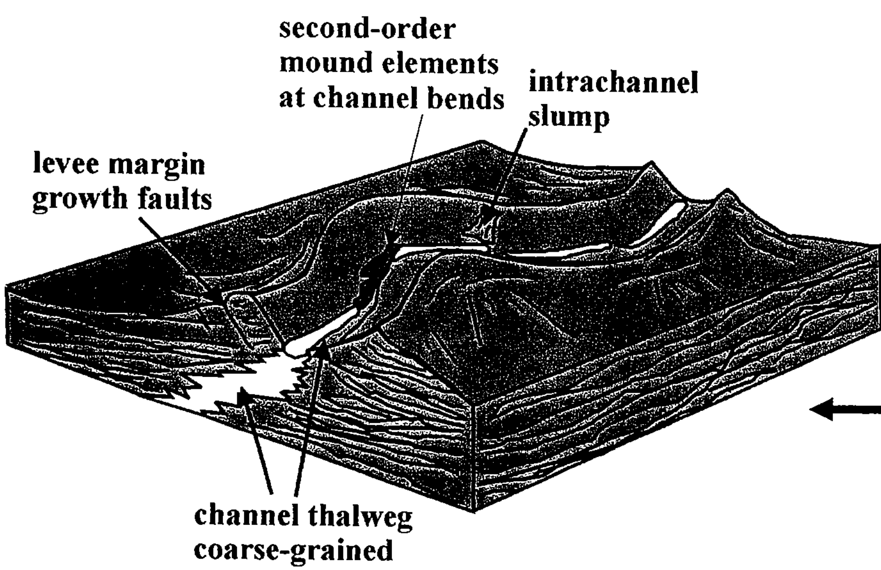
Channel-fill Sandstones & Reservoirs

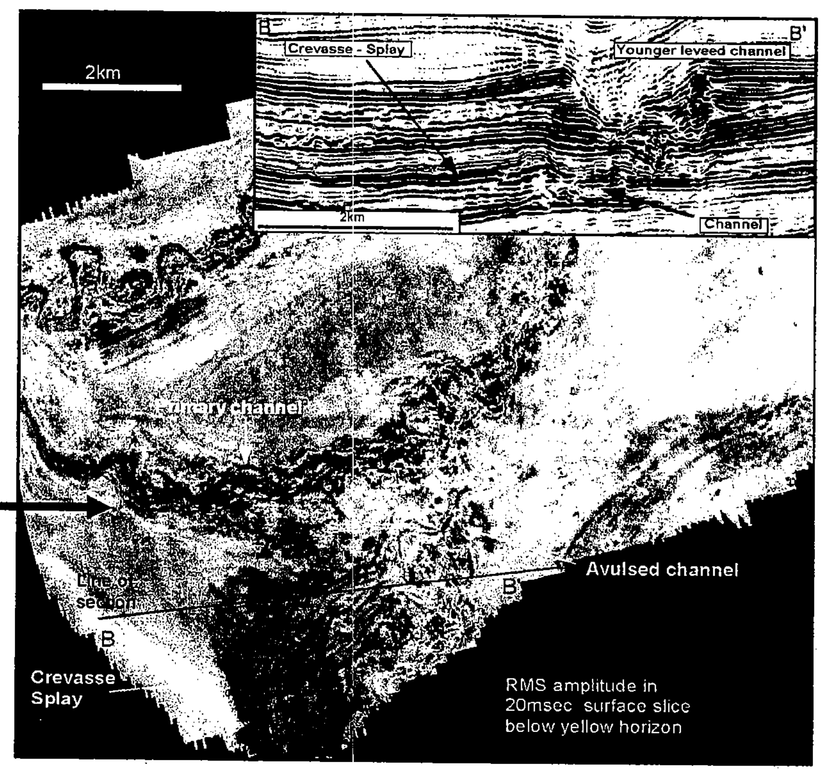
EROSIONAL CHANNELS





DEPOSITIONAL (AGGRADATIONAL) CHANNELS





(Clark & Pickering, 1996)

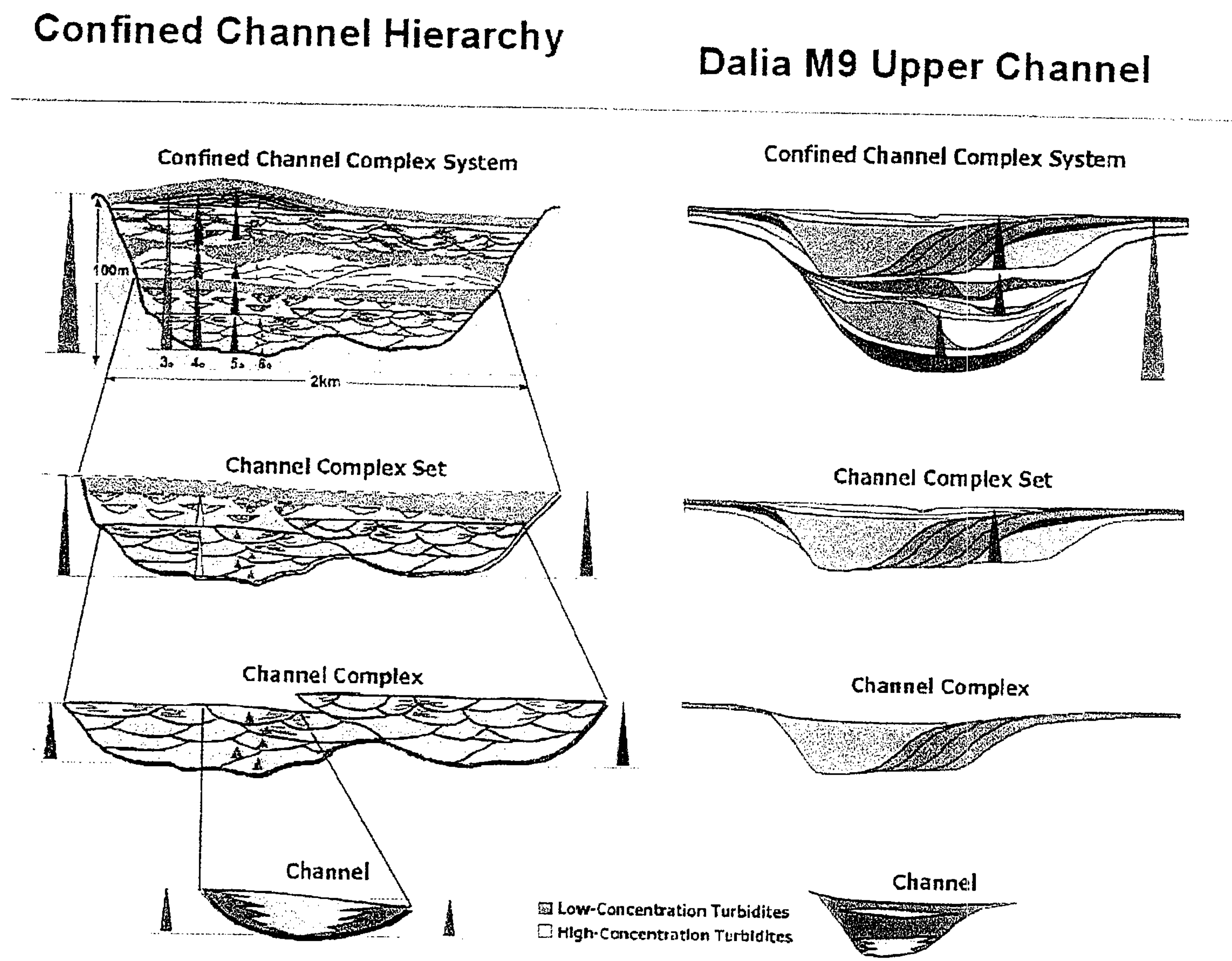
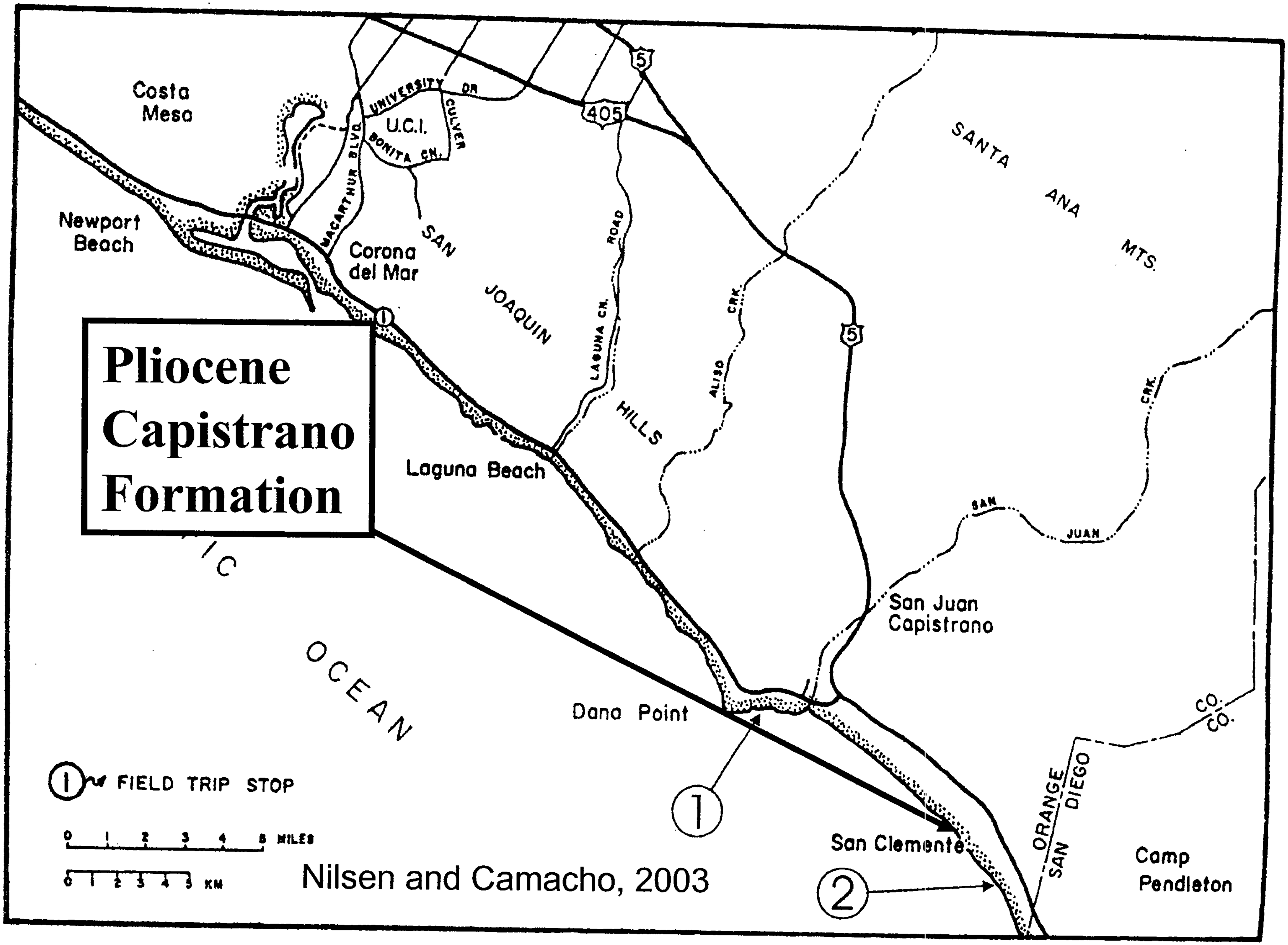
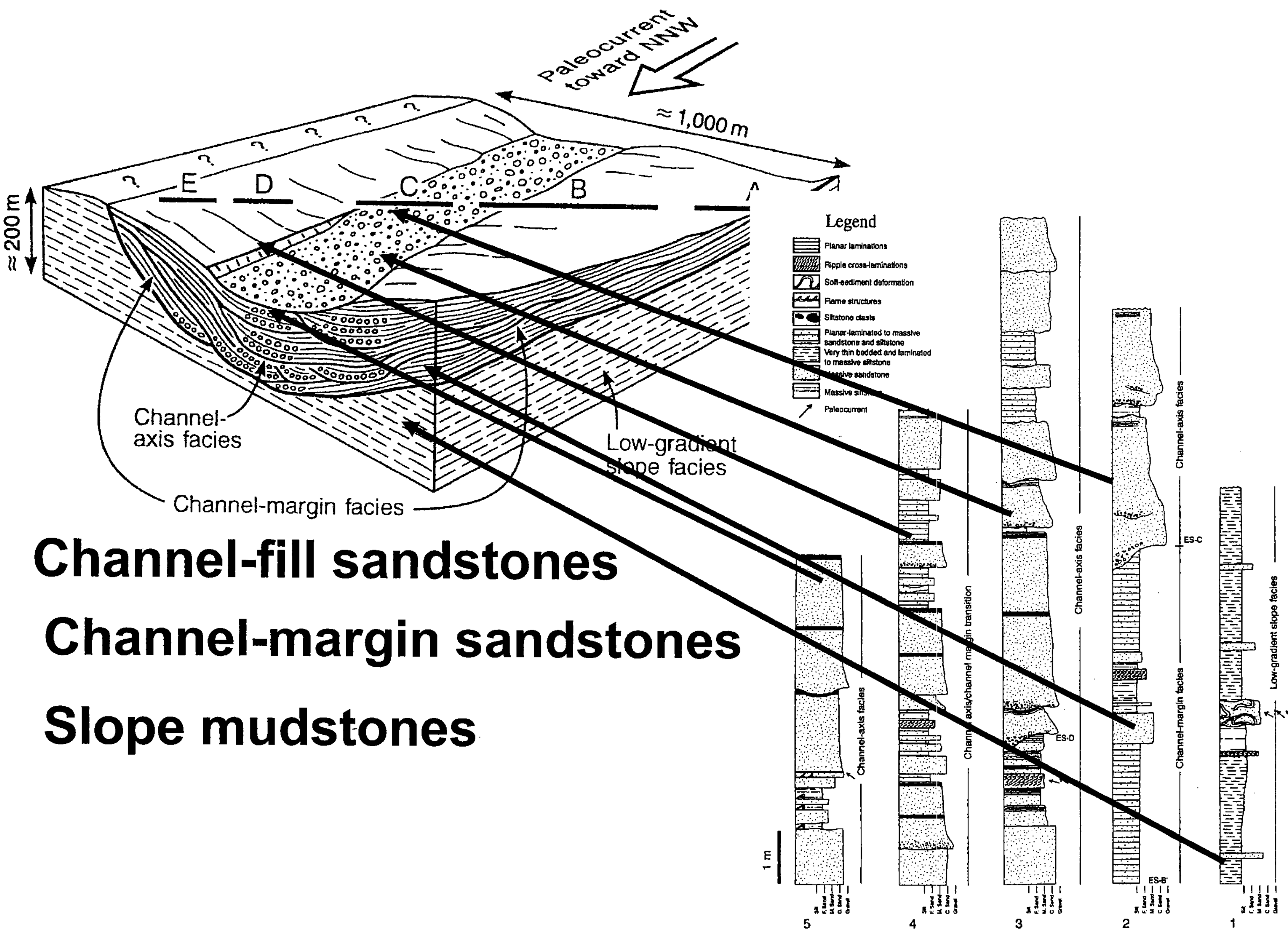


Figure 1: Comparison between the stratigraphic hierarchy of confined channels proposed by Sprague *et al.* (2002) and the stratigraphic hierarchy for the Dalia M9 Upper Channel System

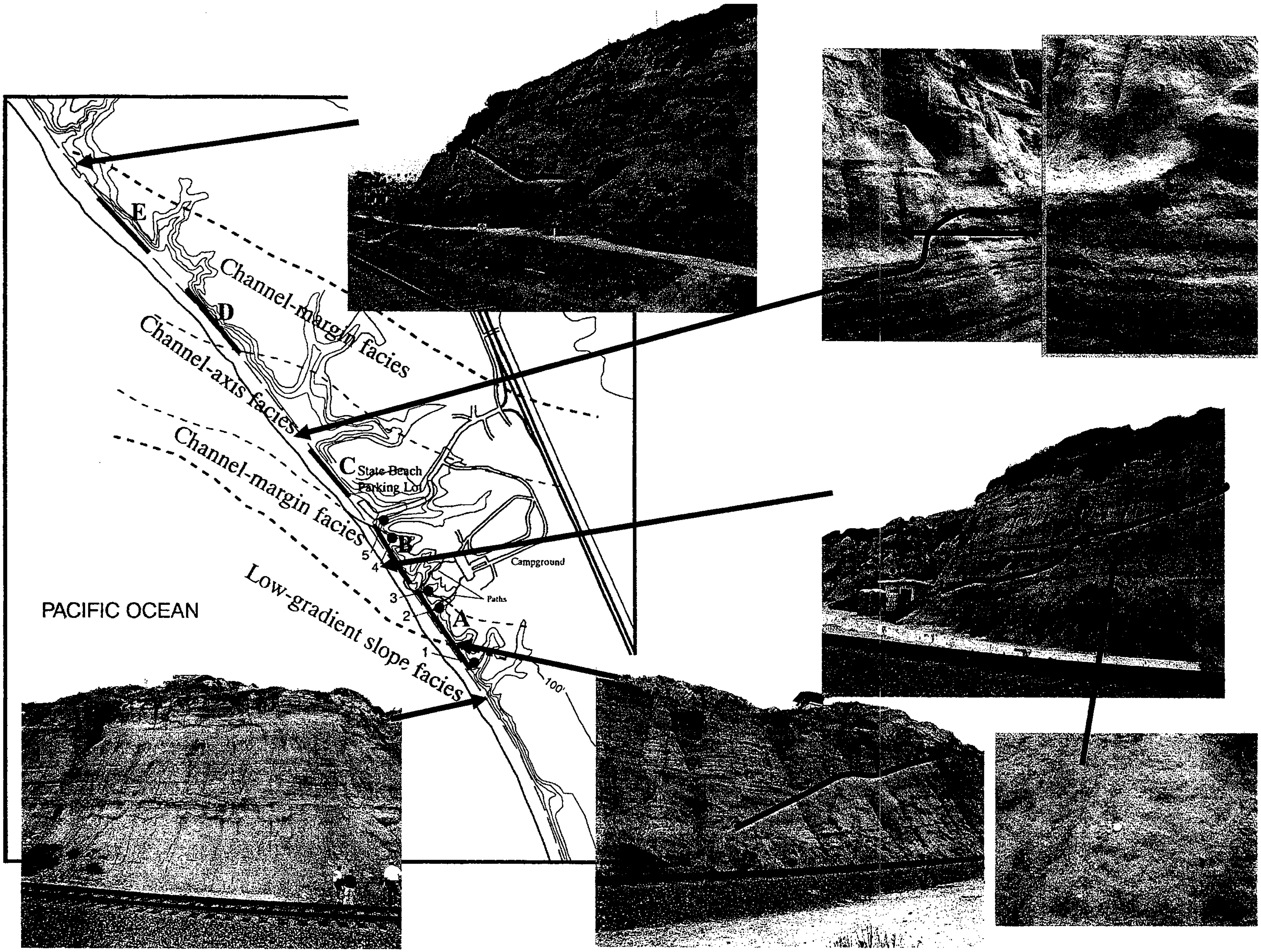
(Abreu et al., in press)



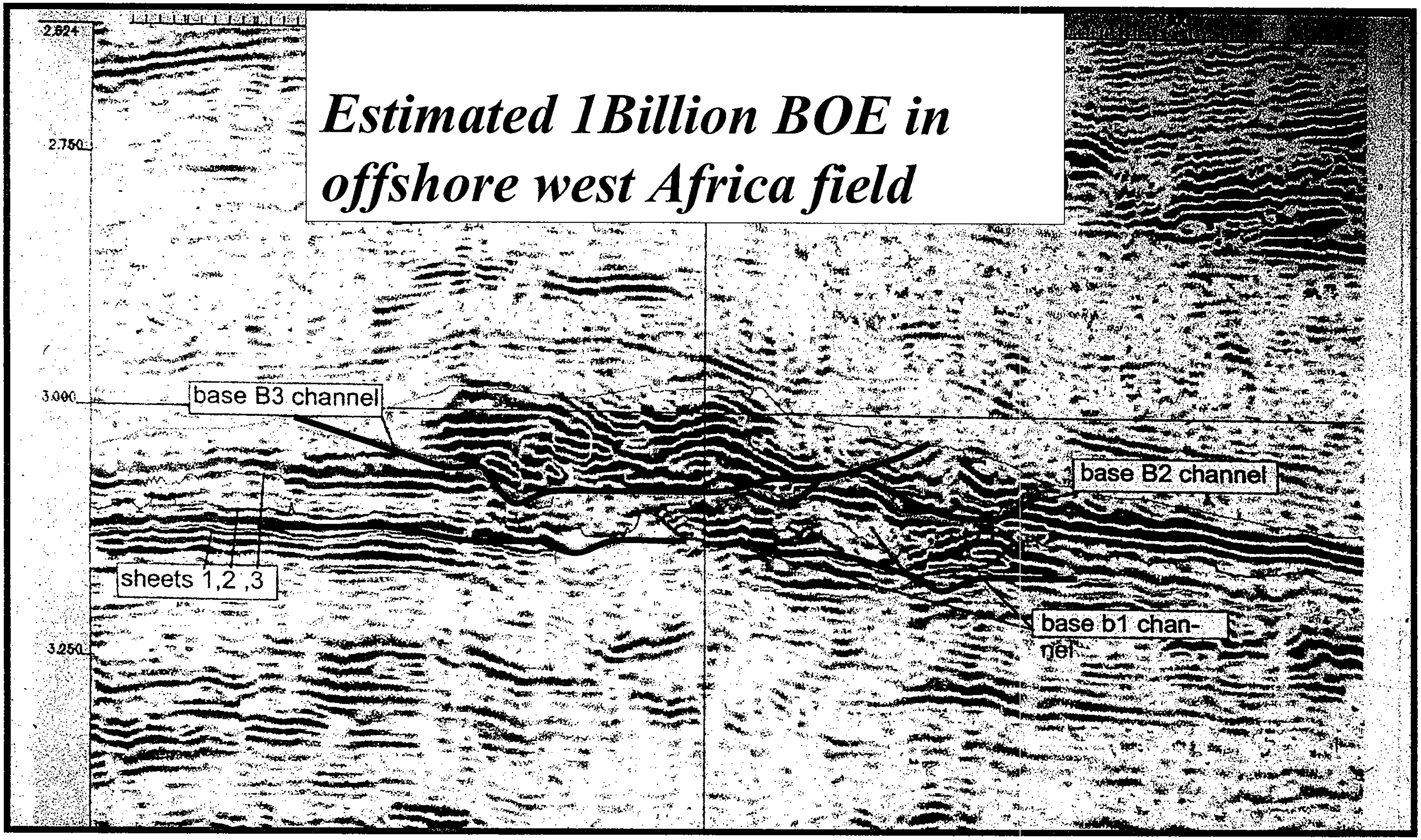
Pliocene Capistrano Formation
Costa Mesa
Newport Beach
Corona del Mar
U.C.I.
UNIVERSITY DR
CULVER
BONITA CN.
MACARTHUR BLVD.
SAN JOAQUIN HILLS
LAGUNA CN. ROAD
ALISO CRK.
SANTA ANA MTS.
SAN JUAN CRK.
5
405
Laguna Beach
San Juan Capistrano
Dana Point
San Clemente
ORANGE CO.
SAN DIEGO CO.
Camp Pendleton
PACIFIC OCEAN
1
2
FIELD TRIP STOP
0 1 2 3 4 5 MILES
0 1 2 3 4 5 KM
Nilsen and Camacho, 2003



Paleocurrent toward NNW
≈ 1,000 m
≈ 200 m
E
D
C
B
A
Channel-axis facies
Low-gradient slope facies
Channel-margin facies
Legend
Planar laminations
Ripple cross-laminations
Soft-sediment deformation
Flame structures
Siltstone clasts
Planar-laminated to massive sandstone and siltstone
Very thin bedded and laminated to massive siltstone
Massive sandstone
Paleocurrent
Channel-axis facies
Channel-axis/channel margin transition
Channel-axis facies
Channel-axis facies
Channel-margin facies
Low-gradient slope facies
ES-C
ES-D
ES-B'
1 m
5
4
3
2
1
Channel-fill sandstones
Channel-margin sandstones
Slope mudstones



E
D
Channel-margin facies
Channel-axis facies
C
State Beach
Parking Lot
Channel-margin facies
B
5
4
Campground
3
Paths
2
A
1
PACIFIC OCEAN
Low-gradient slope facies
100'


Estimated 1Billion BOE in offshore west Africa field
2.624
2.750
3.000
3.250
base B3 channel
base B2 channel
sheets 1,2 ,3
base b1 chan-
nel

CHANNEL-FILL SANDSTONE EXAMPLES

- *N Sand, Ram Powell, Gulf of Mexico (Kendricks, 2000)*

  -Cumulative production is 12MMBE

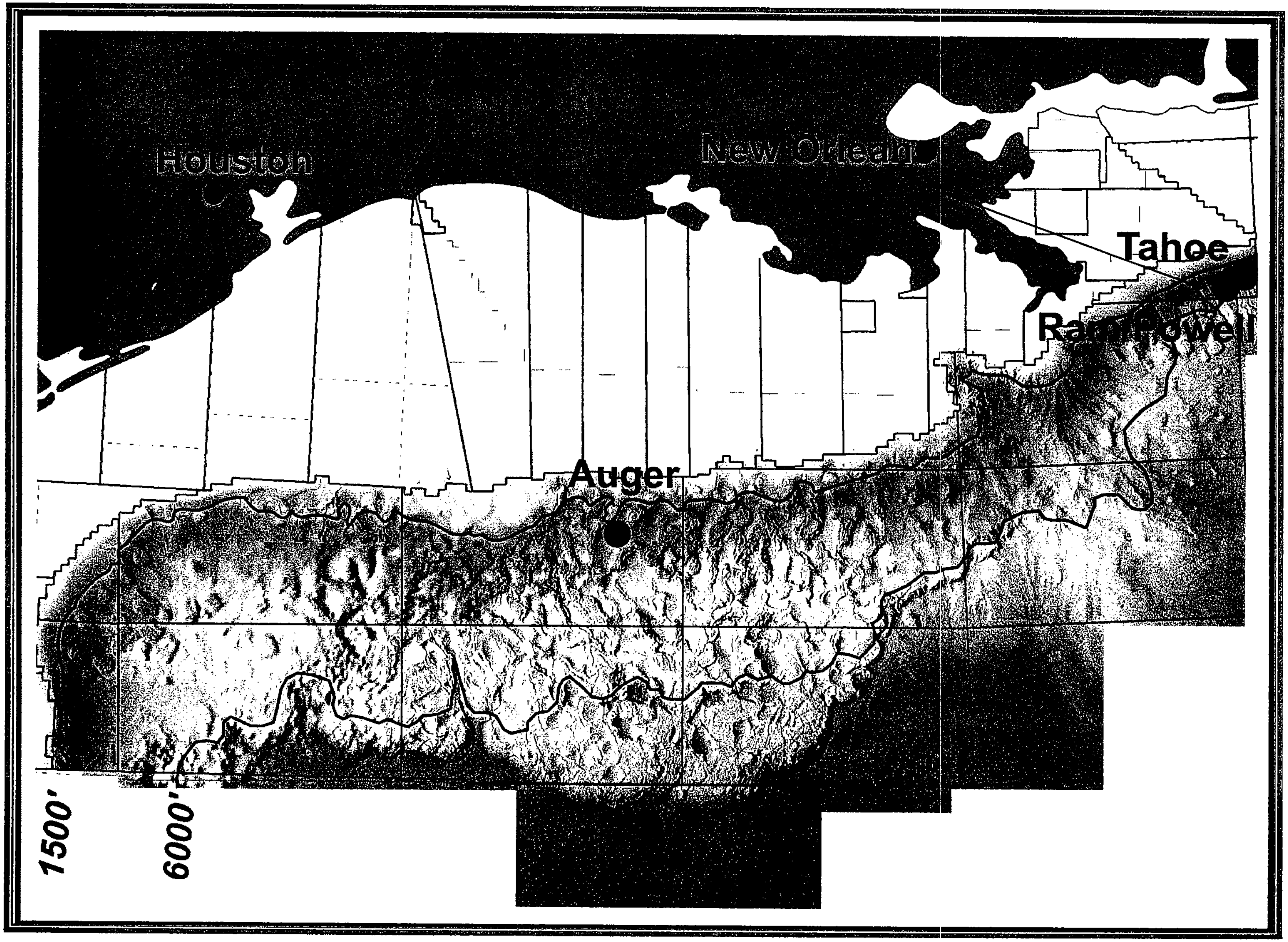
  -Elongate geometry of N sand and adjacent shales indicate sand was deposited in pre-existing erosional depression, with turbidity currents entering at the northern apex of the depression

  -Reservoir is composed of multiple, laterally offset stacked, lenticular channel-fill sandstones of variable thickness and numerous perched water levels

  -Pre-development geologic modeling indicated an amalgamated channel sand reservoir with a single oil-water contact

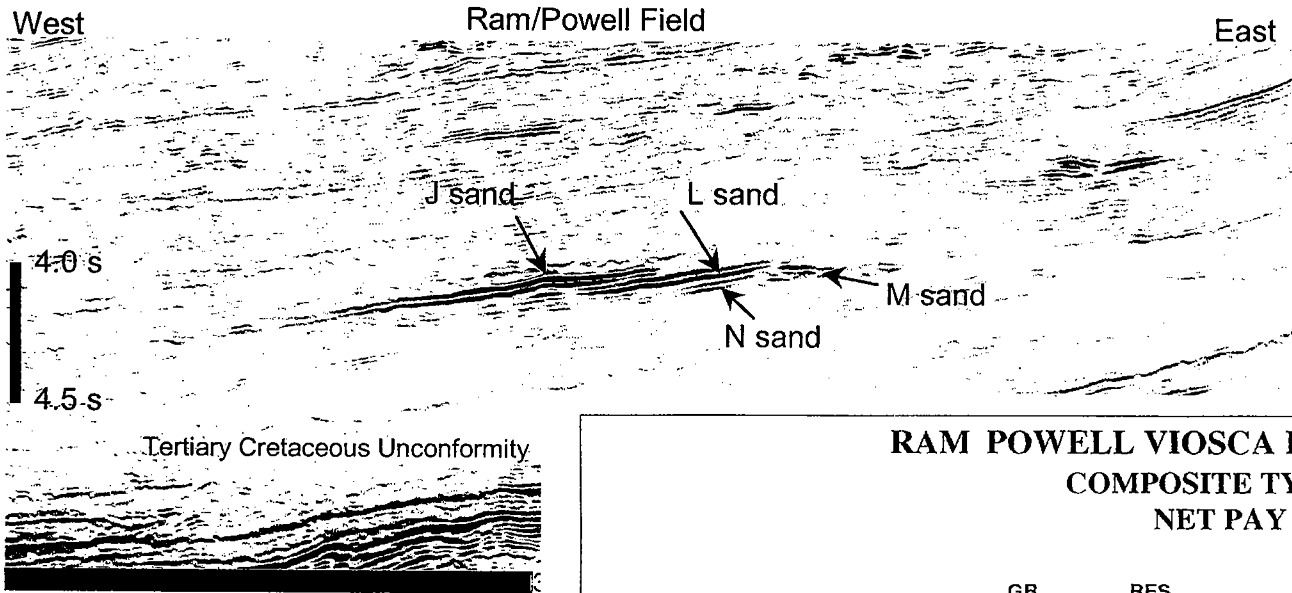
  -Development drilling and early production revealed water bearing sands beneath oil sands in individual wells updip of the presumed oil-water contact. Each development well encountered a perched water level.

  -Water legs occur in depressions within the field which could not be displaced by oil as it migrated in

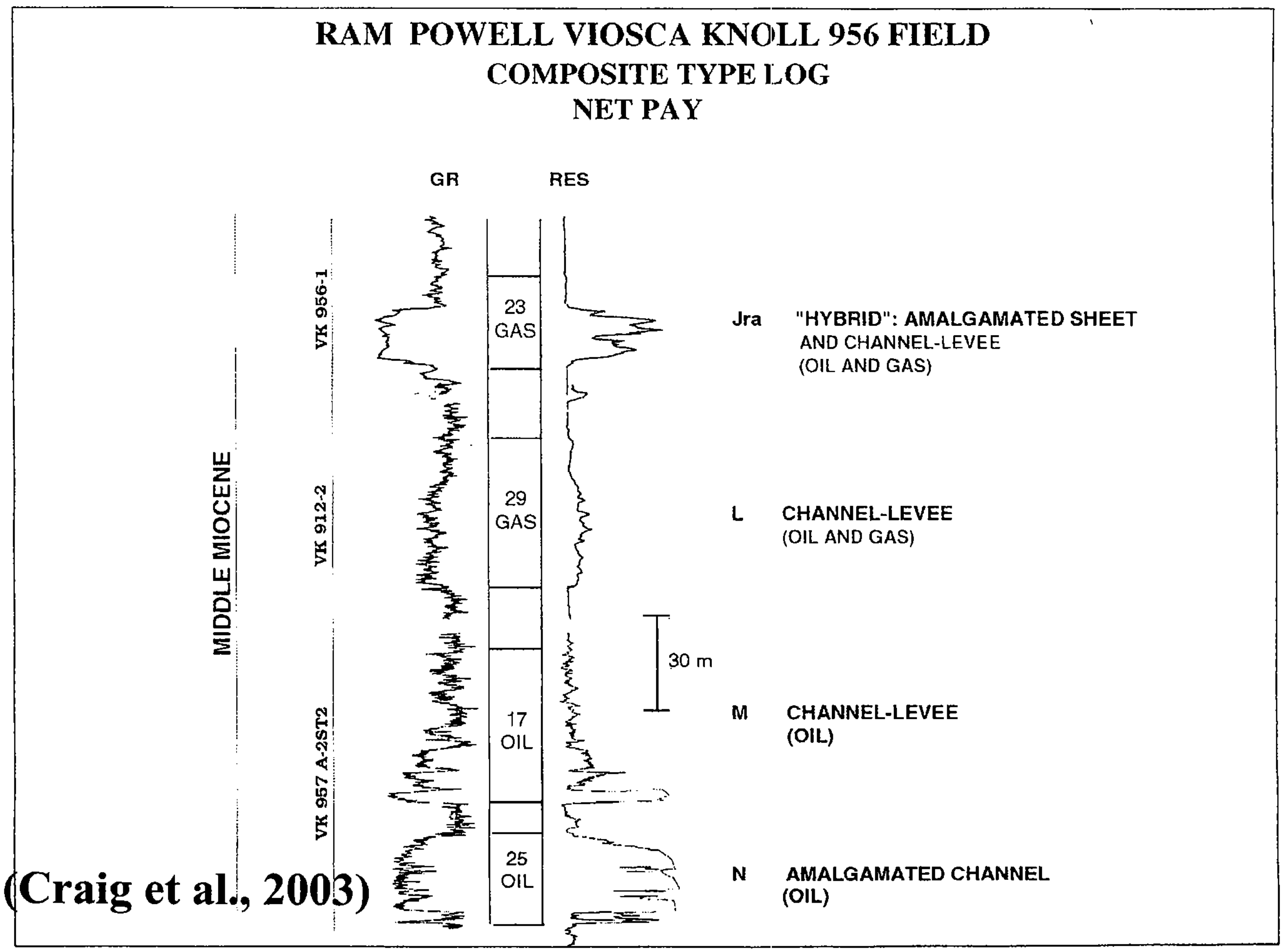


(Kendrick, 2000)

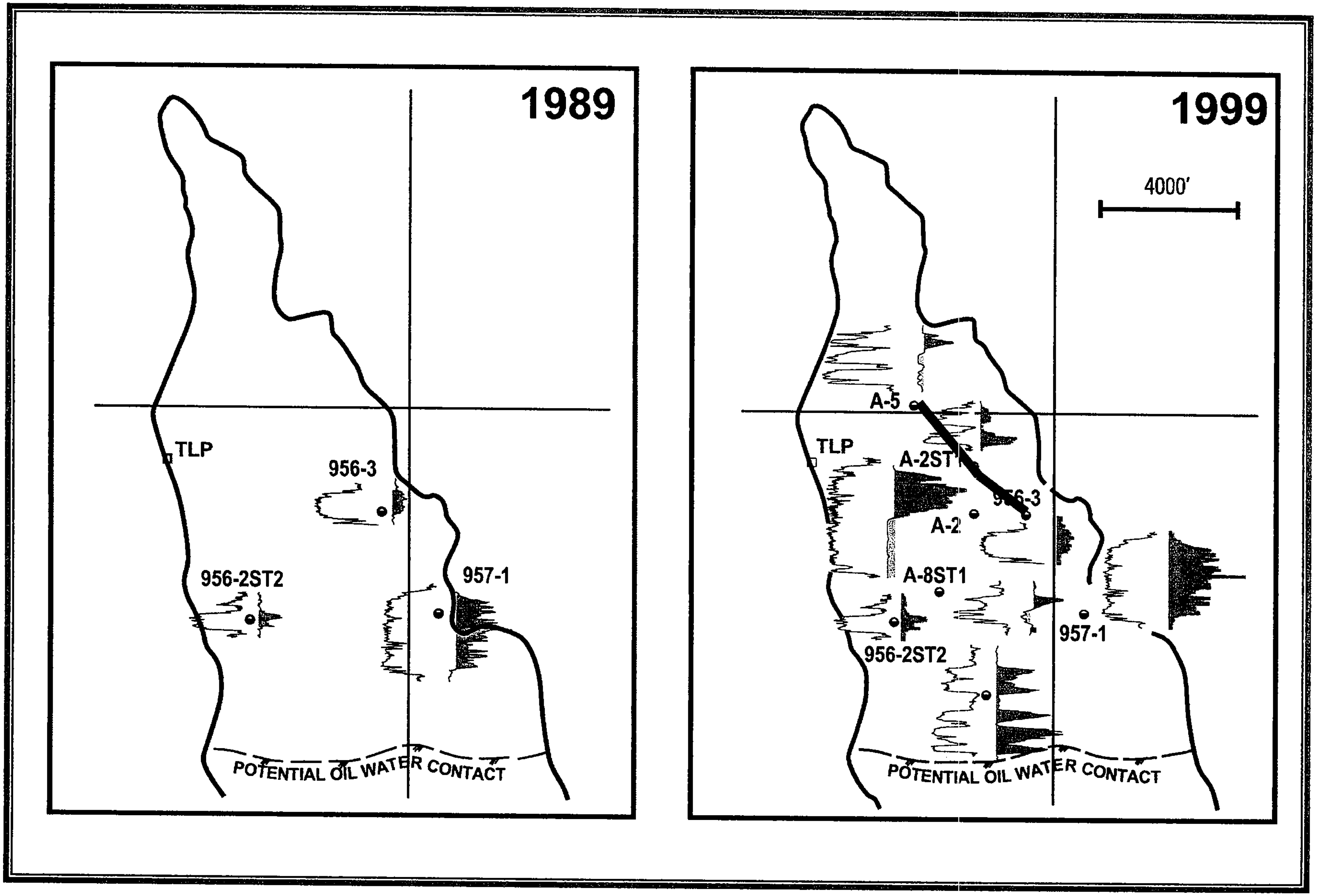
al., 2003



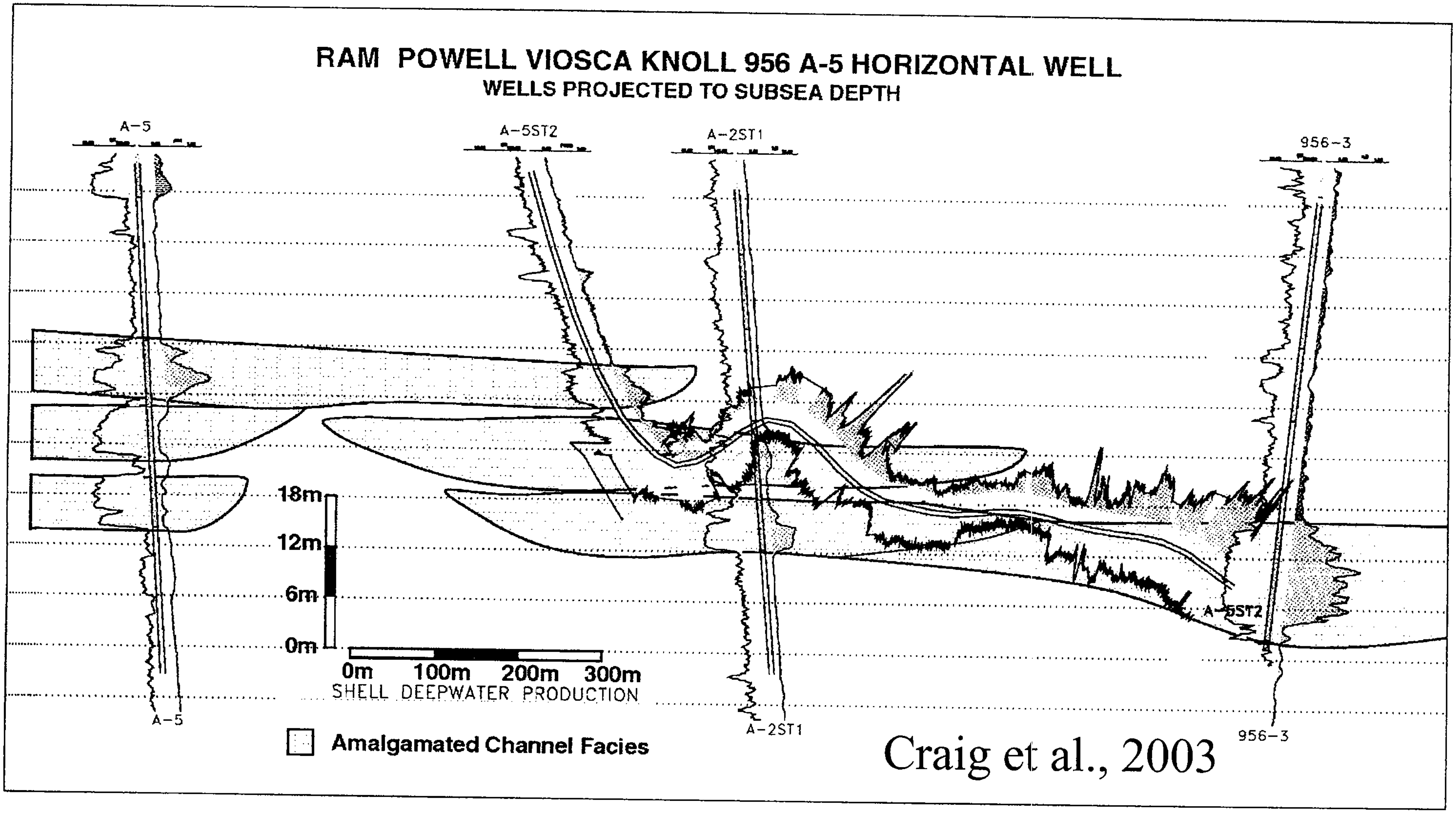
(Kendrick, 2000)



(Craig et al., 2003)



(Kendrick, 2000)

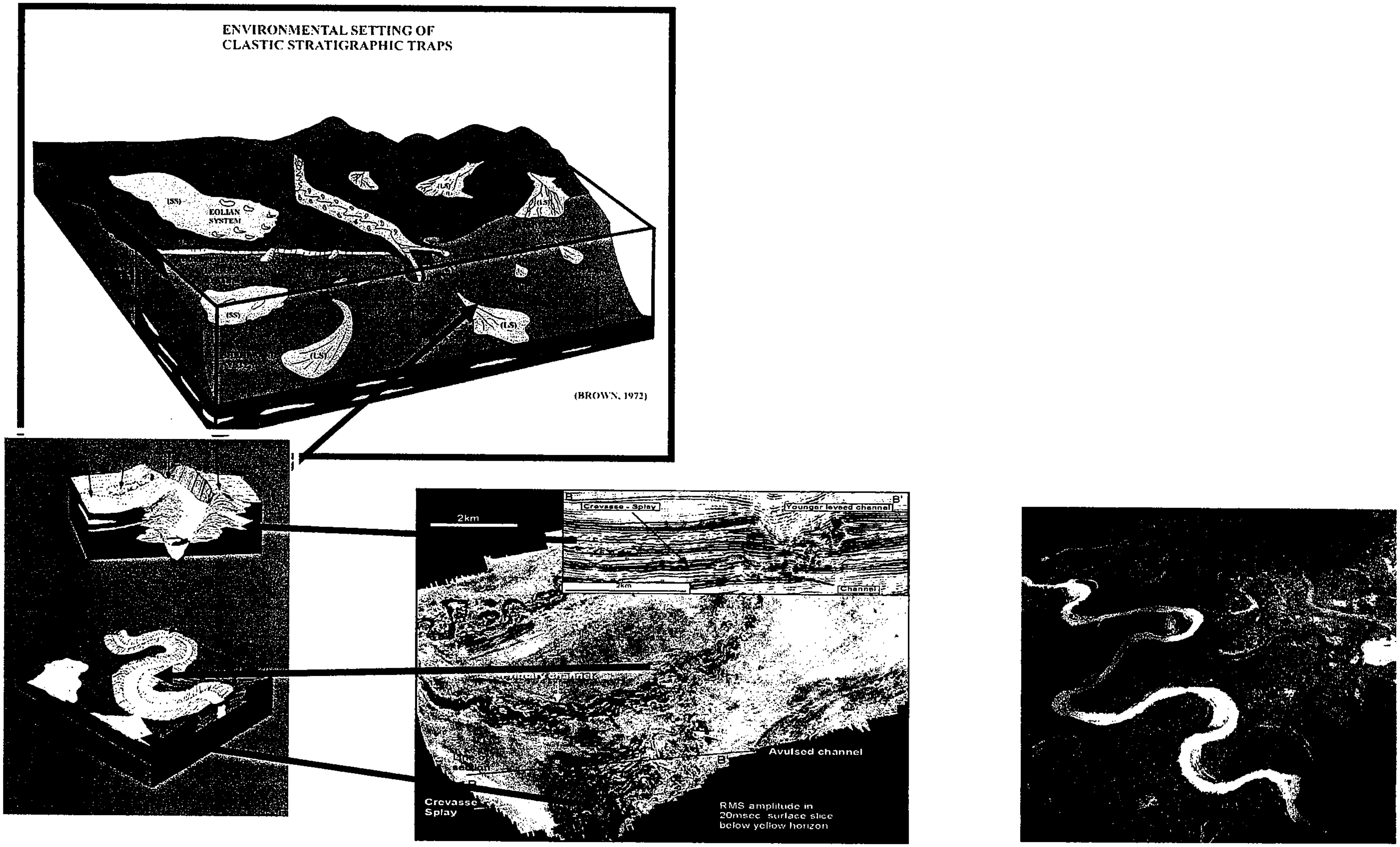


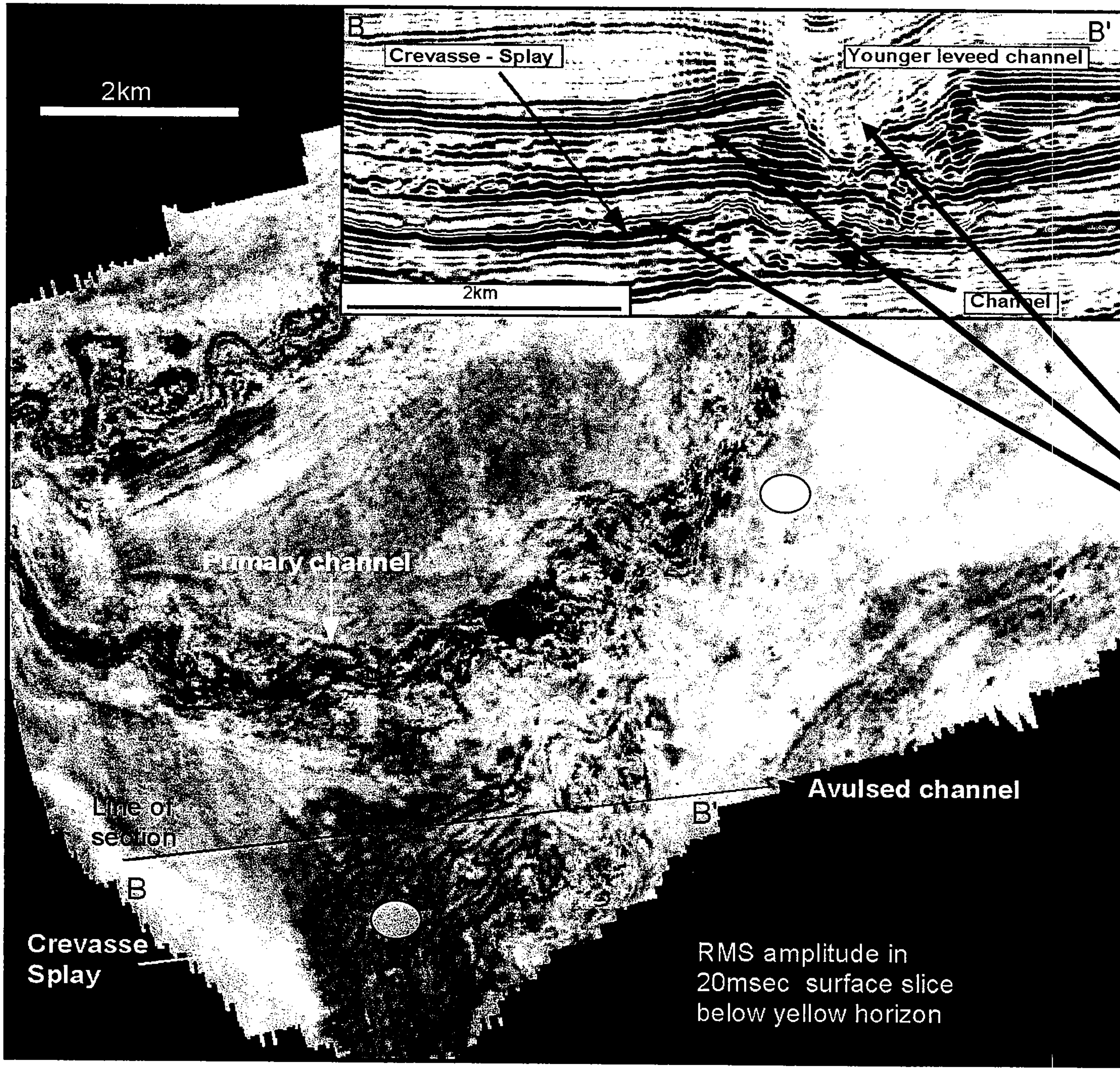
Craig et al., 2003

DEEPWATER (TURBIDITE) DEPOSITS & RESERVOIRS:

Levee Sandstones & Reservoirs

Leveed Channel deposits and reservoirs





Potential Reservoir:

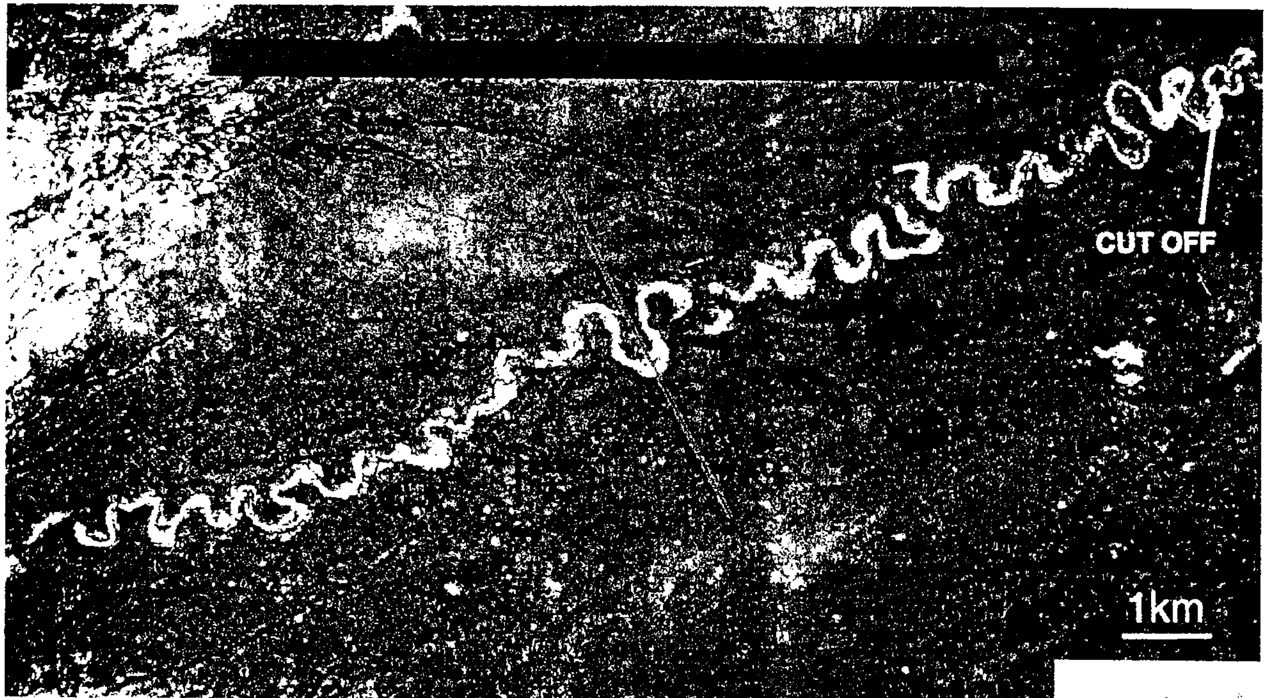
---Channel

---Levee

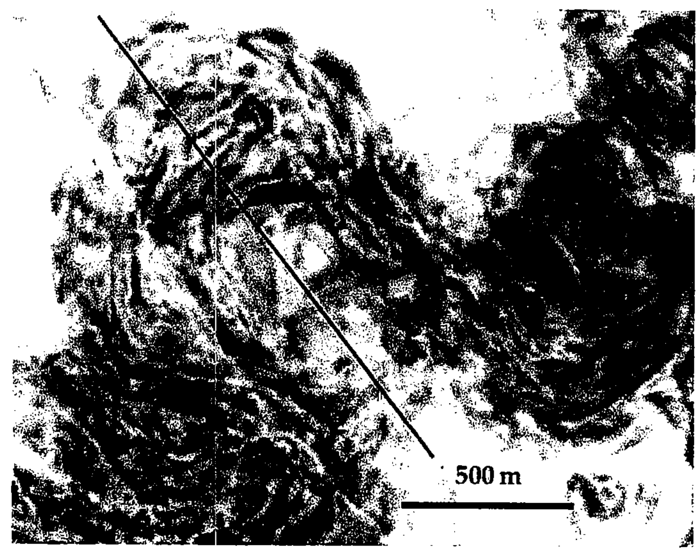
---Splay

(Mayall et al., 2000)

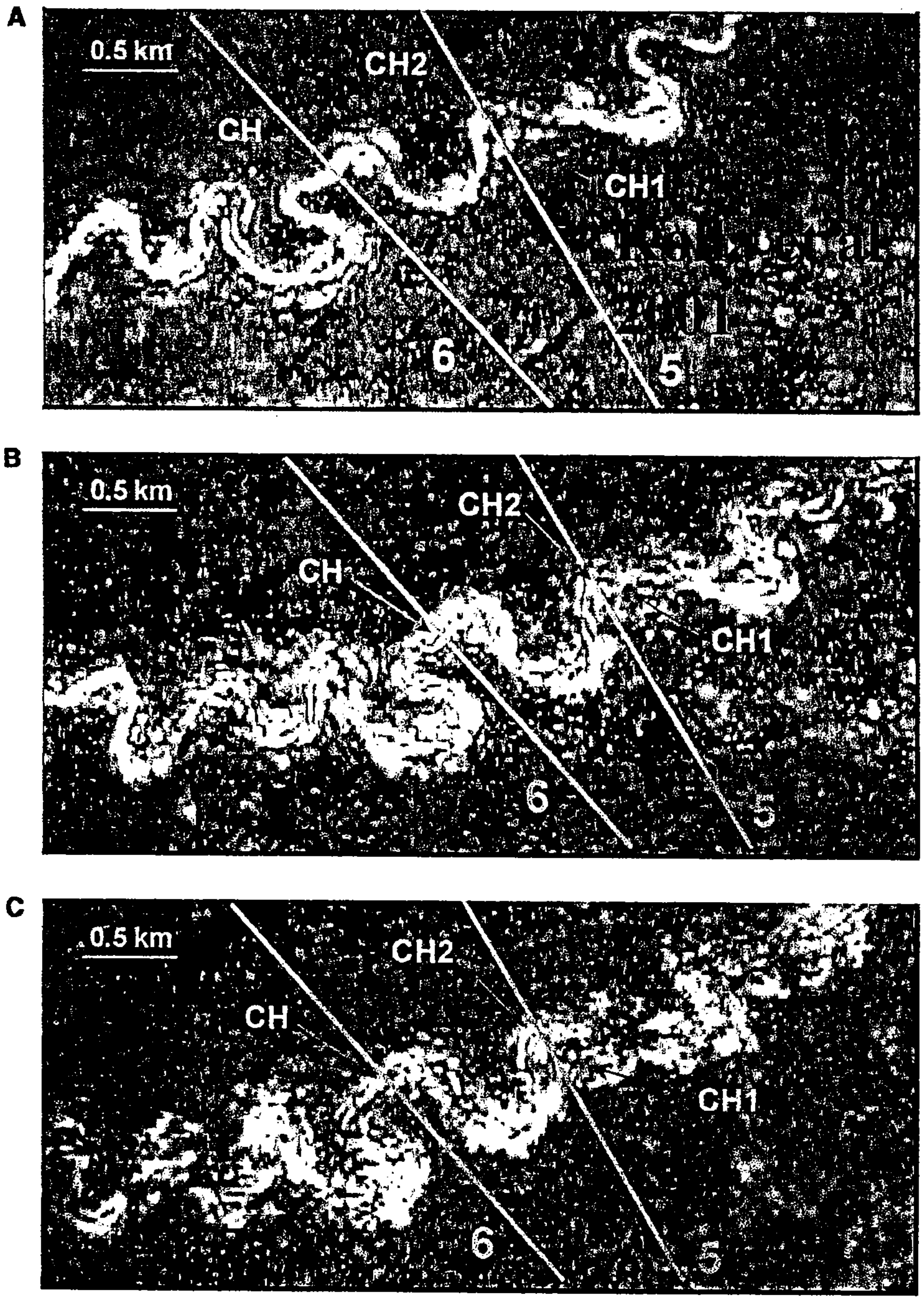
3D SEISMIC HORIZON SLICE

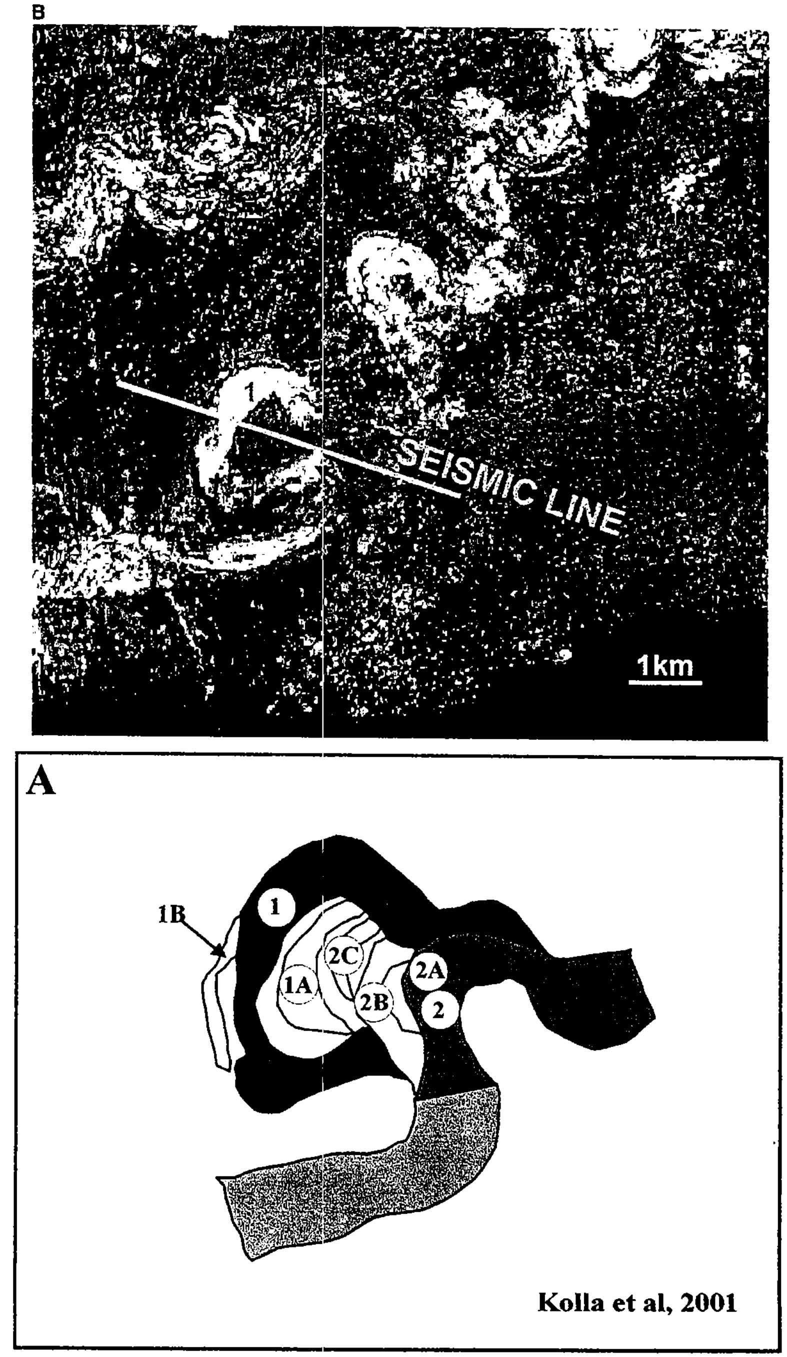


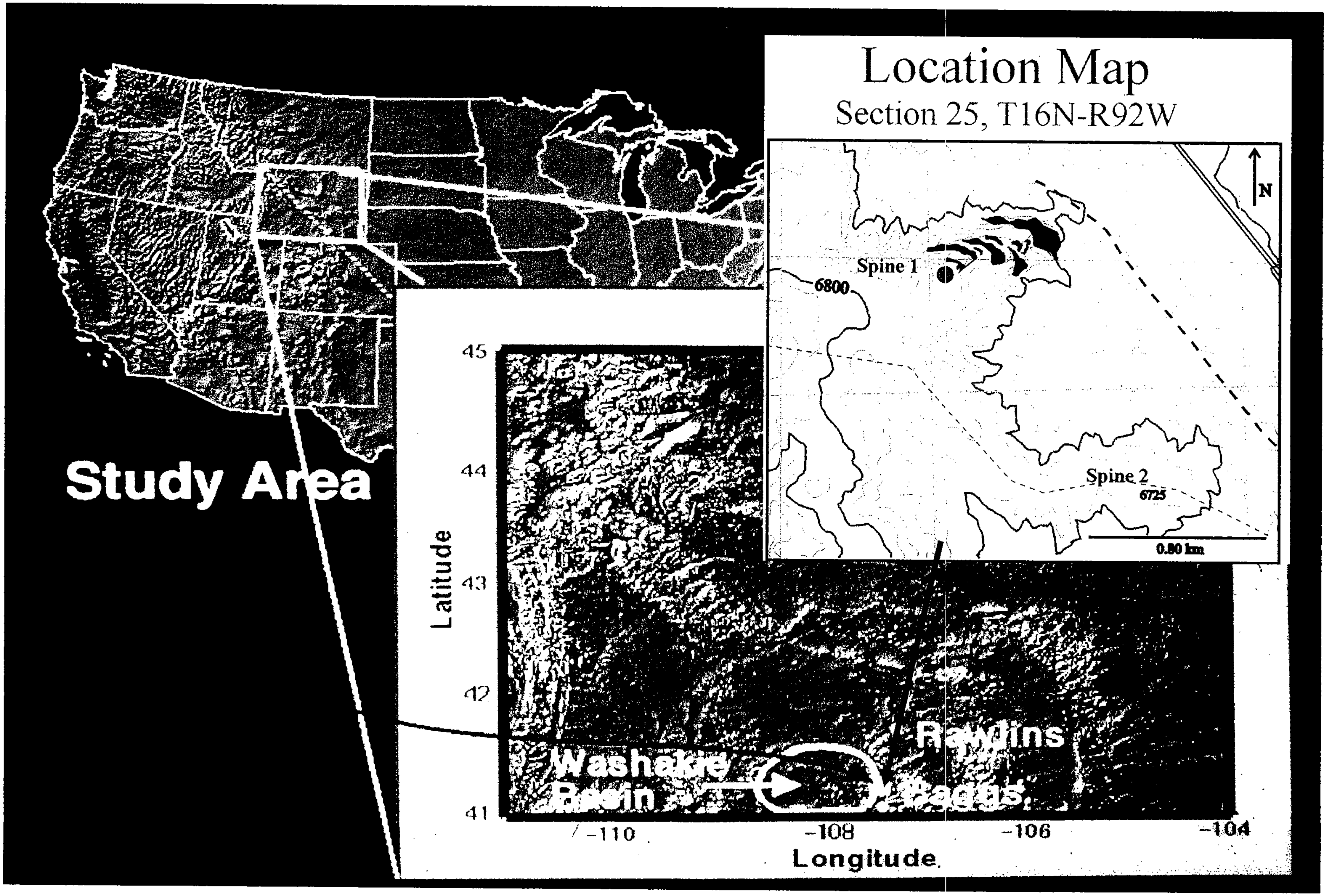
3D seismic horizon slice of leveed channel, offshore Angola (Kolla et al., 2001)



Offshore Angola

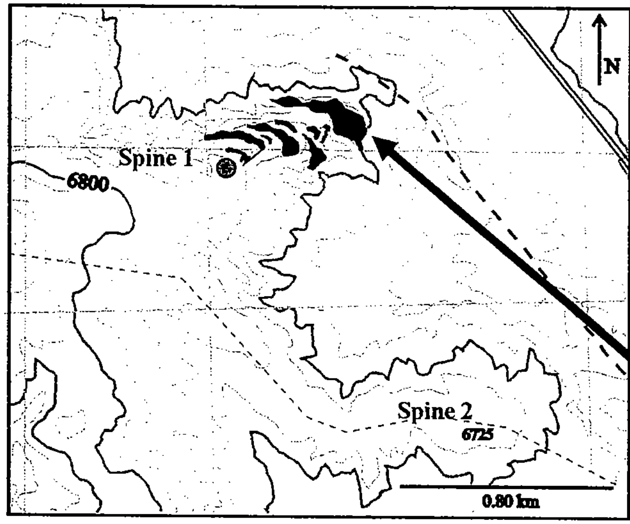

A
0.5 km
CH2
CH
CH1
6
5
B
0.5 km
CH2
CH
CH1
6
5
C
0.5 km
CH2
CH
CH1
6
5

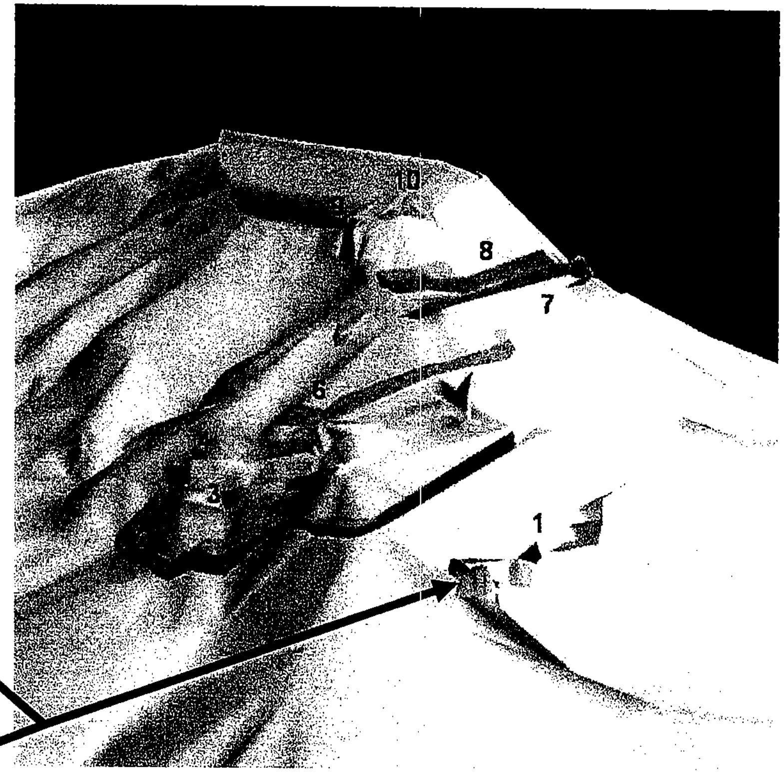

B
1
SEISMIC LINE
1km
A
1B
1
2C
1A
2A
2B
2
Kolla et al, 2001



Location Map
Section 25, T16N-R92W
Spine 1
6800
Spine 2
6725
0.80 km
N
Study Area
Latitude
45
44
43
42
41
Longitude
-110
-108
-106
-104
Washakie
Basin
Rawlins
Baggs

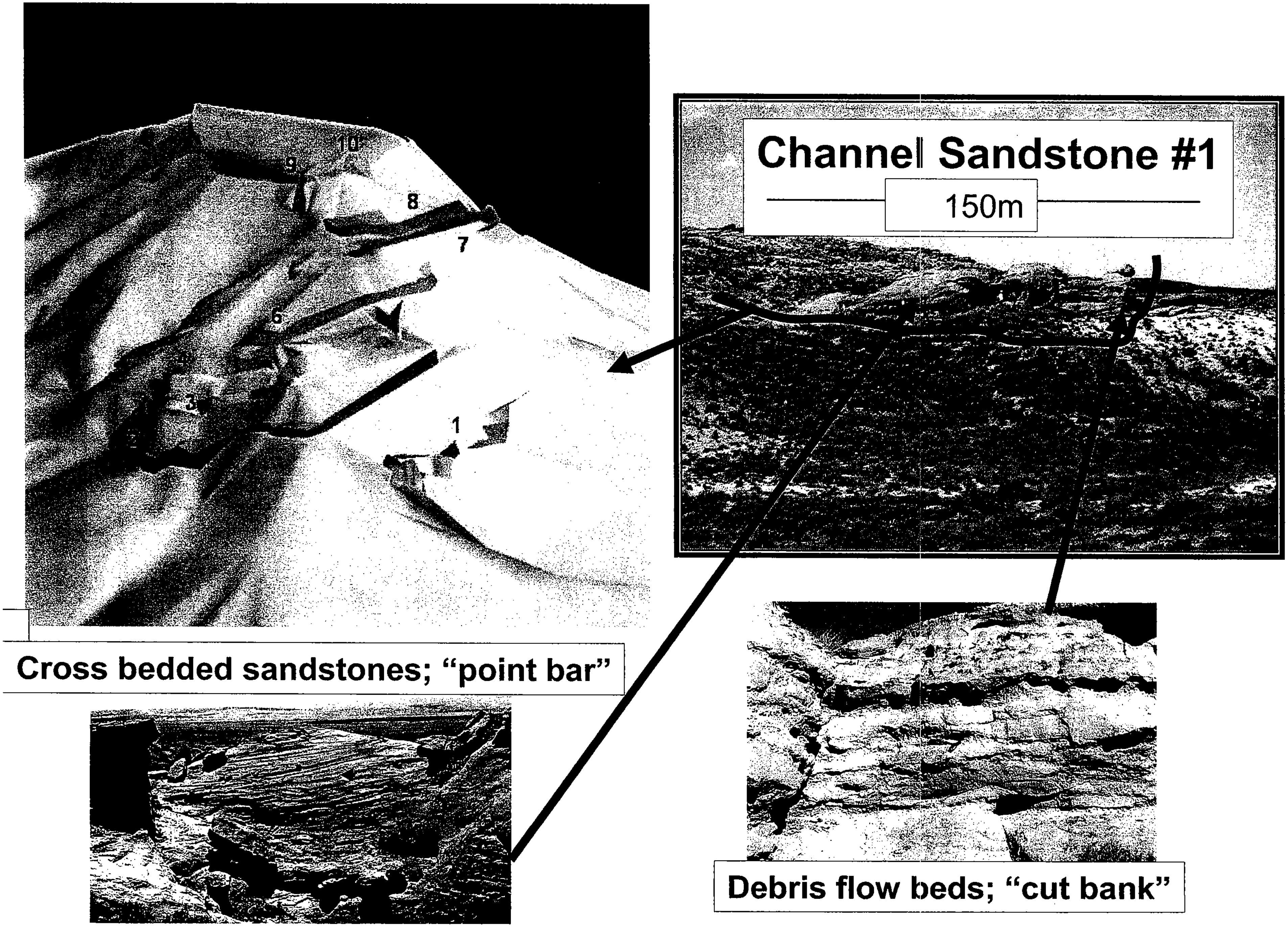
Location Map
Section 25, T16N-R92W

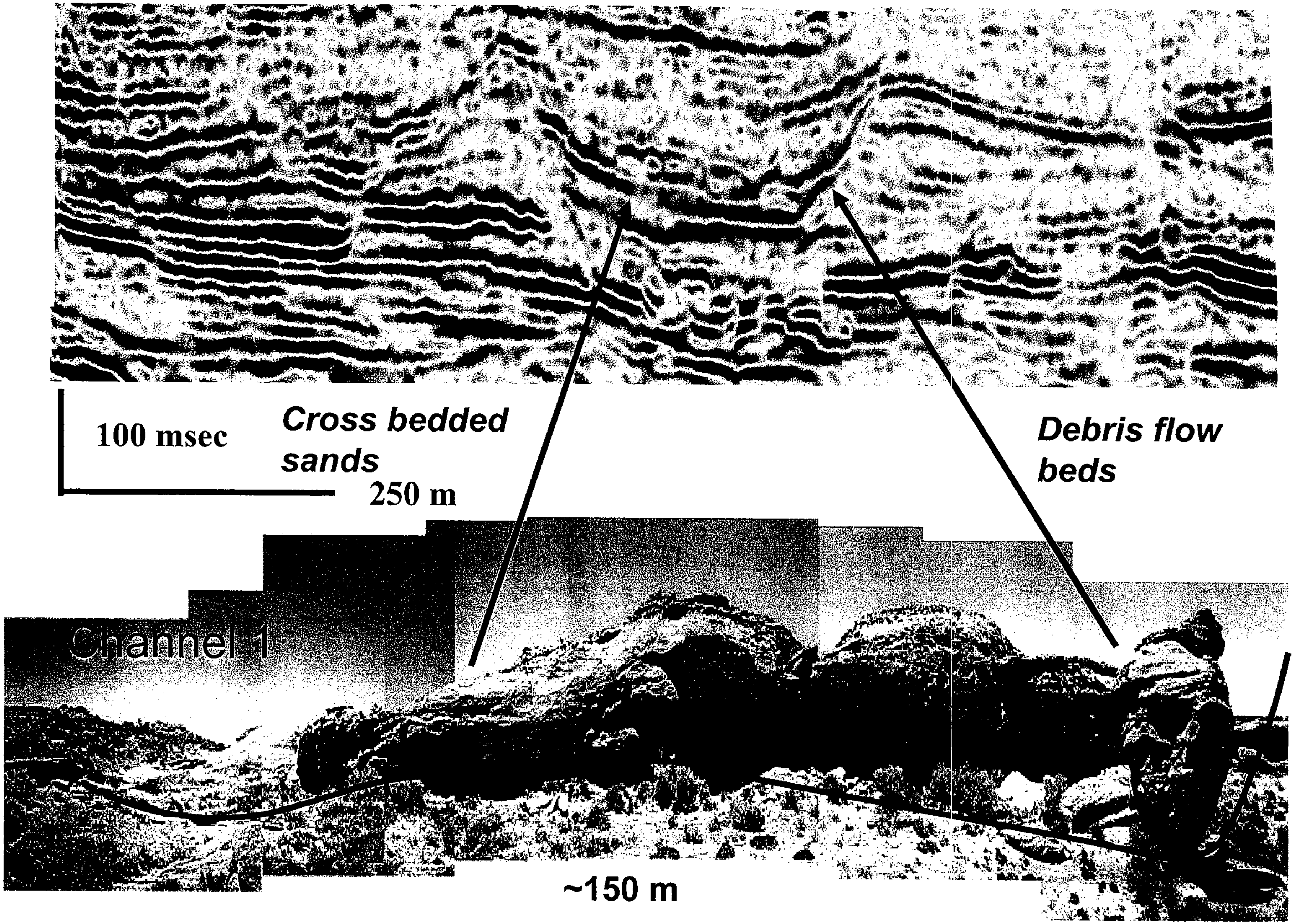


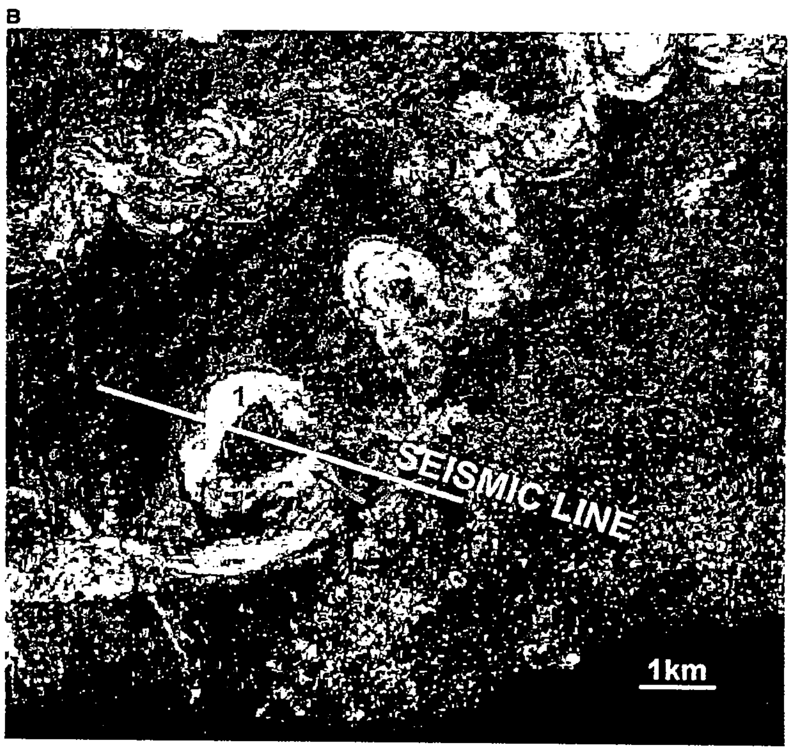


Channel-fill #1Sandstone

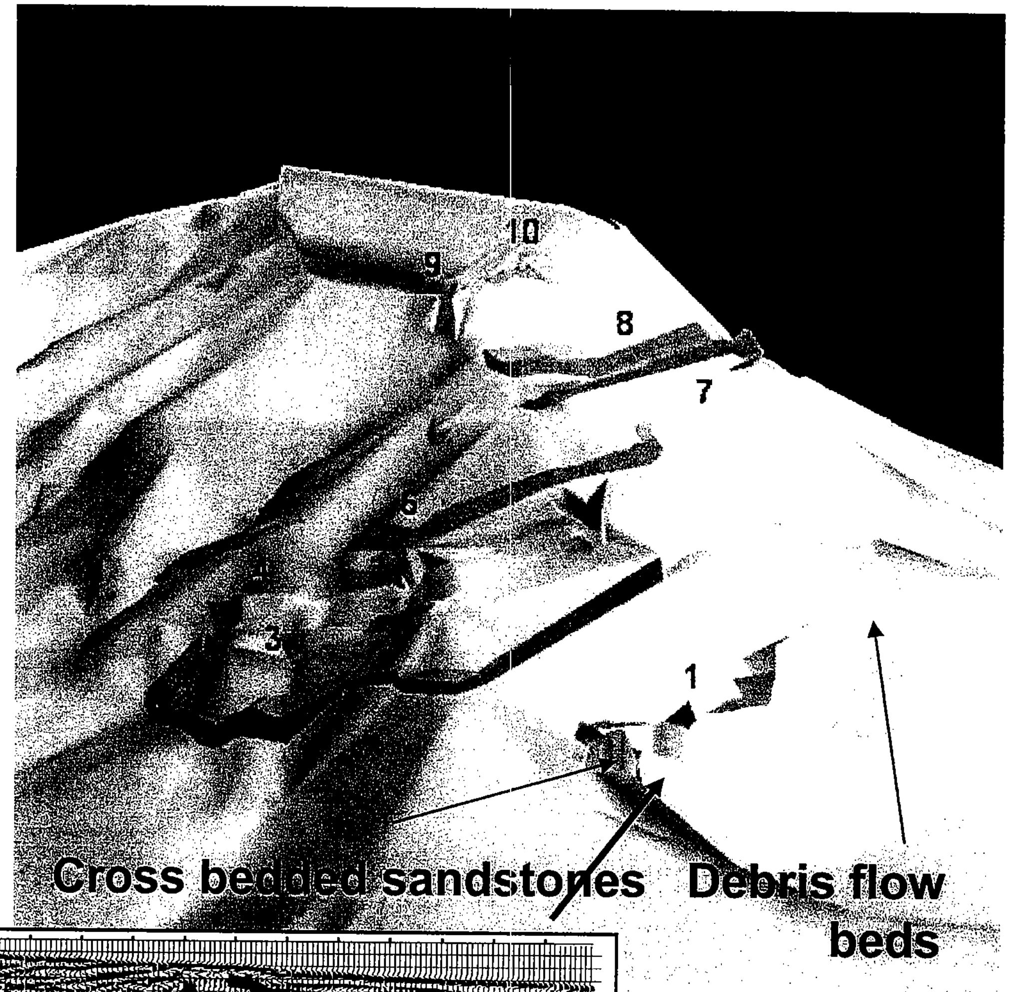
Spine 1

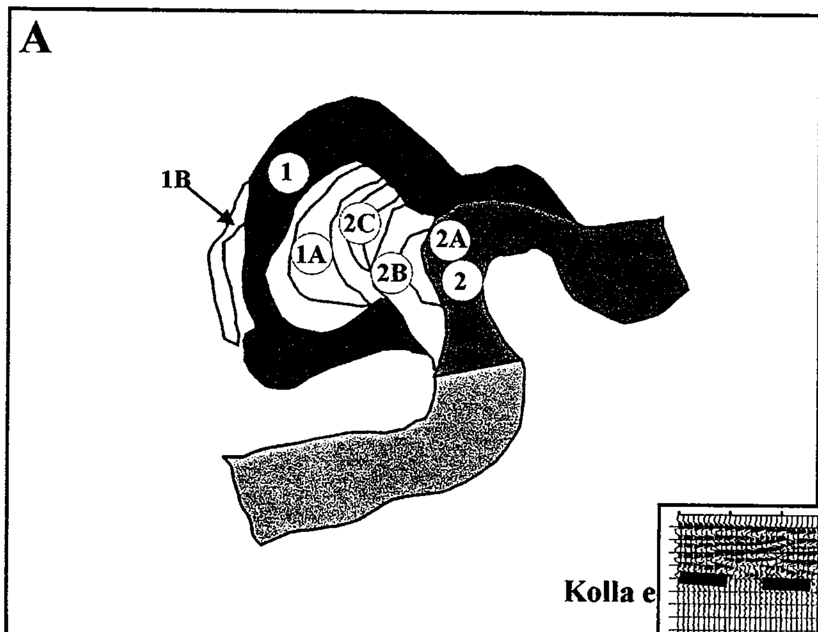

10
9
8
7
6
3
1
Channel Sandstone #1
150m
Cross bedded sandstones; “point bar”
Debris flow beds; “cut bank”

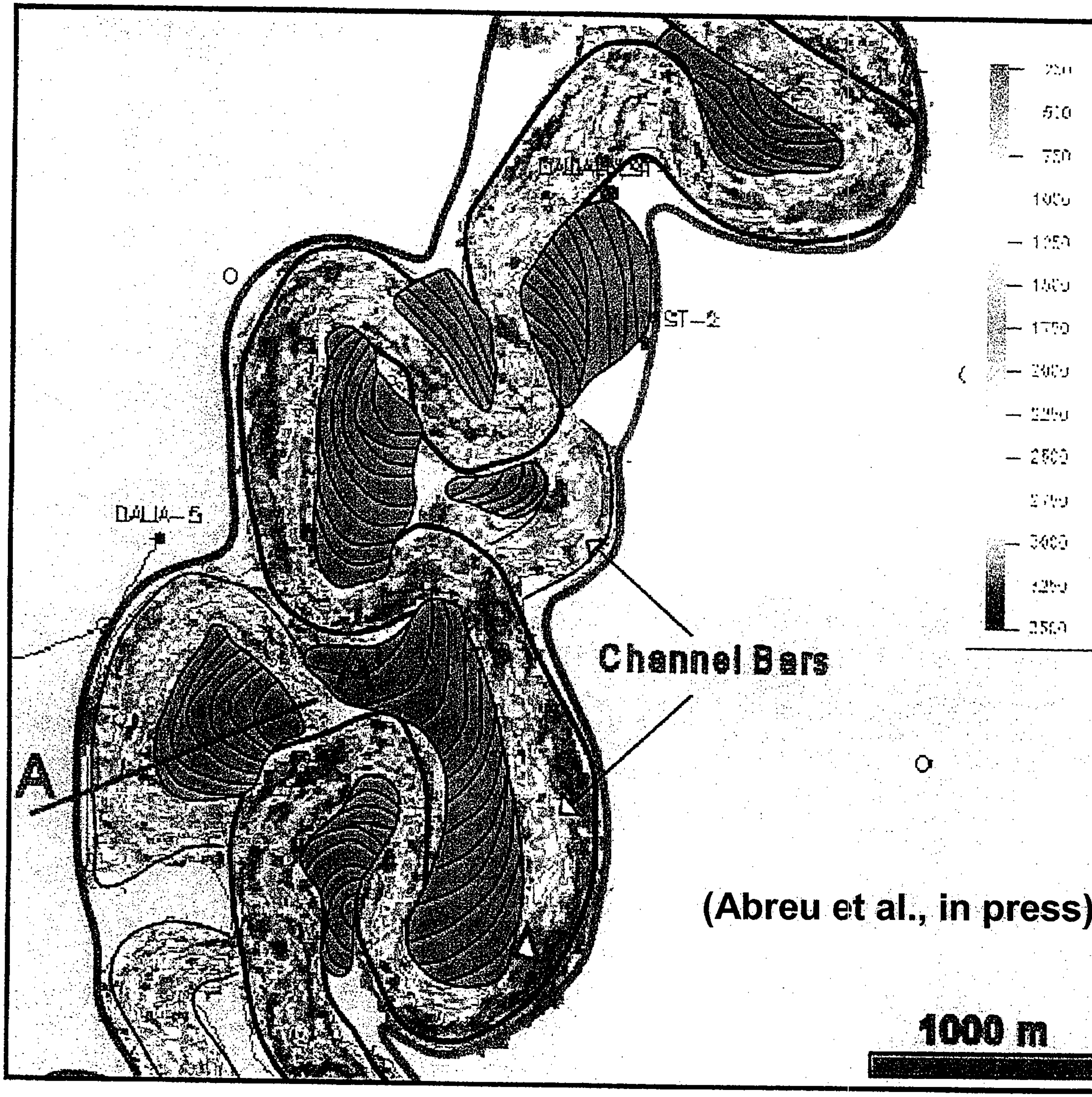

100 msec
Cross bedded sands
250 m
Debris flow beds
Channel 1
~150 m



Sandstones are various colors; shales are green.







DALIA-5
ST-2
Channel Bars
A
1000 m
(Abreu et al., in press)

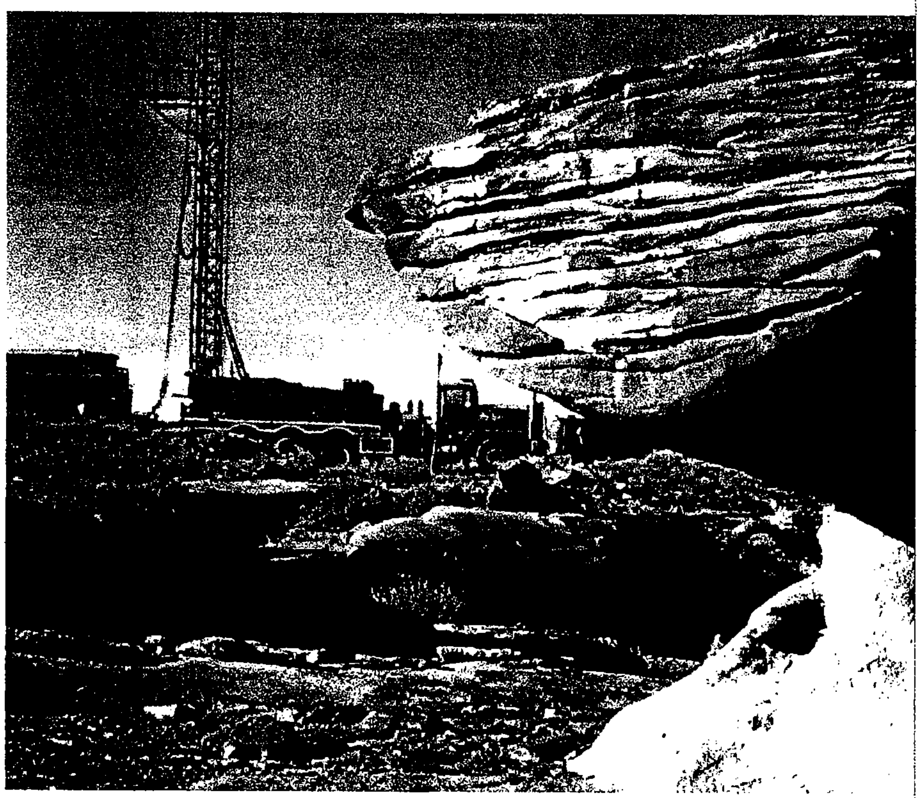
AAPG **EXPLORER** January 2003

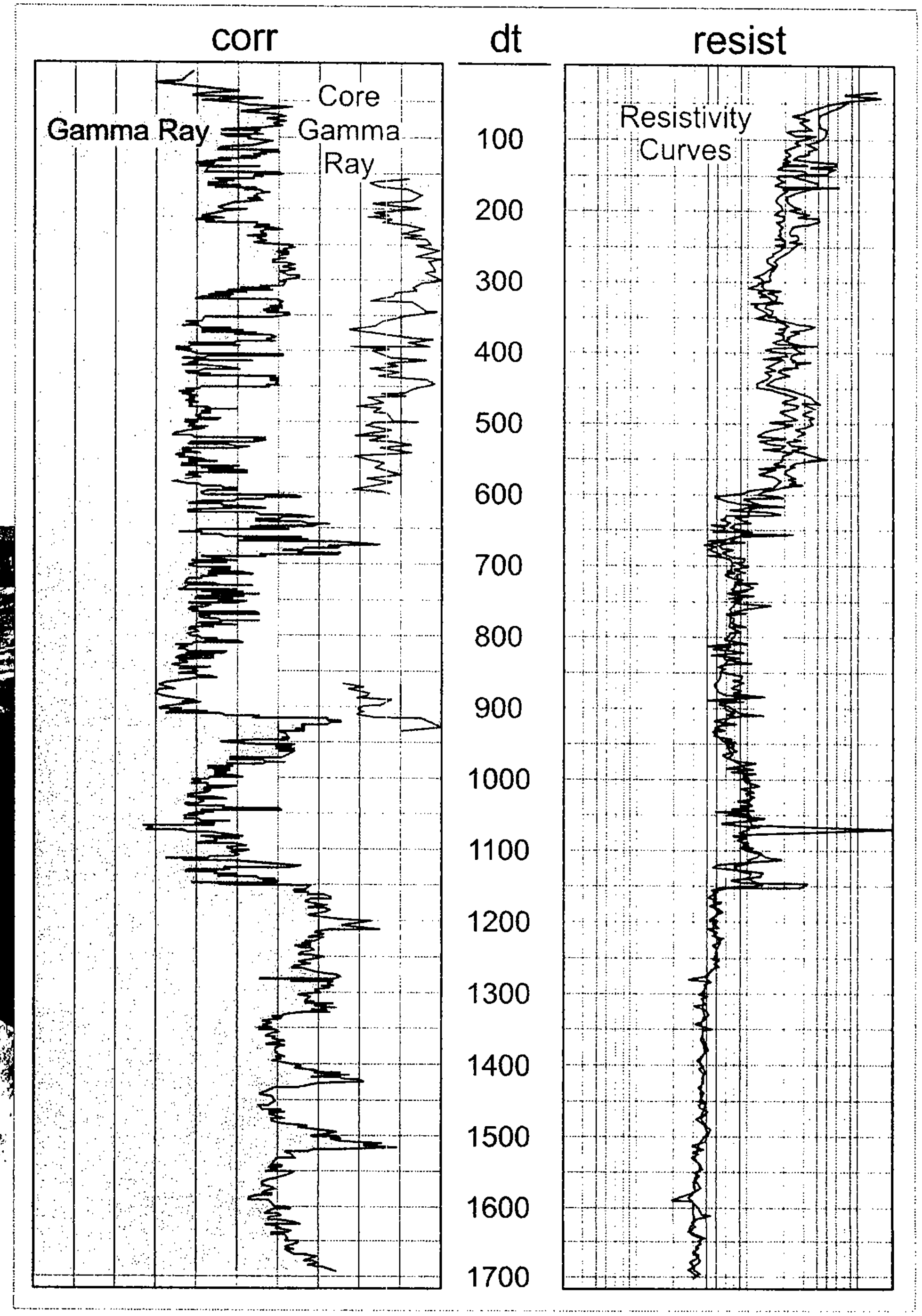
"I'd like to extend the life...

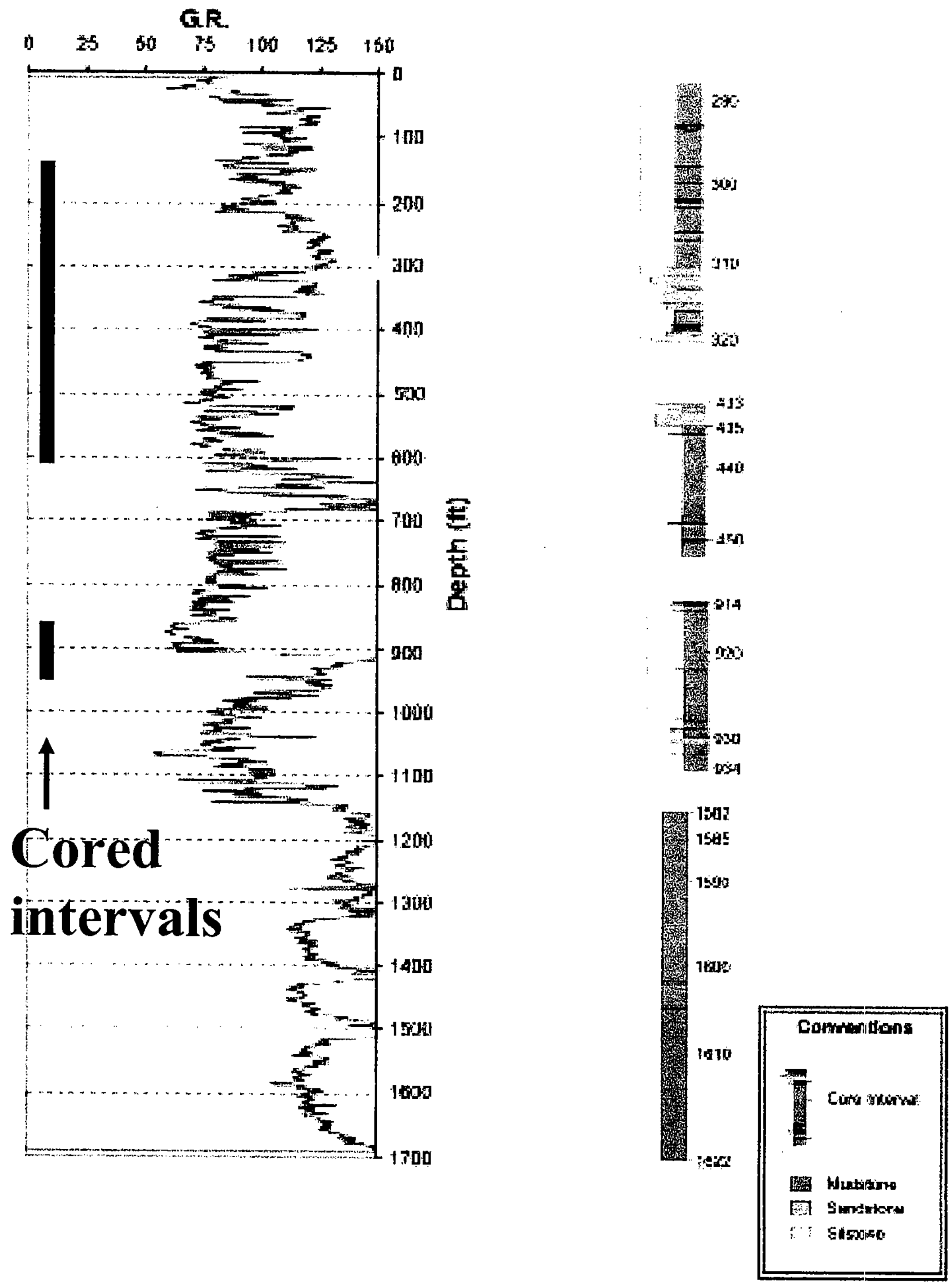
. . . of this field, because we know there is bypassed pay in thin sands. Conventional seismic can help identify the compartments, but its resolution isn't good enough for what we need.

What can we do to locate this pay and increase production?

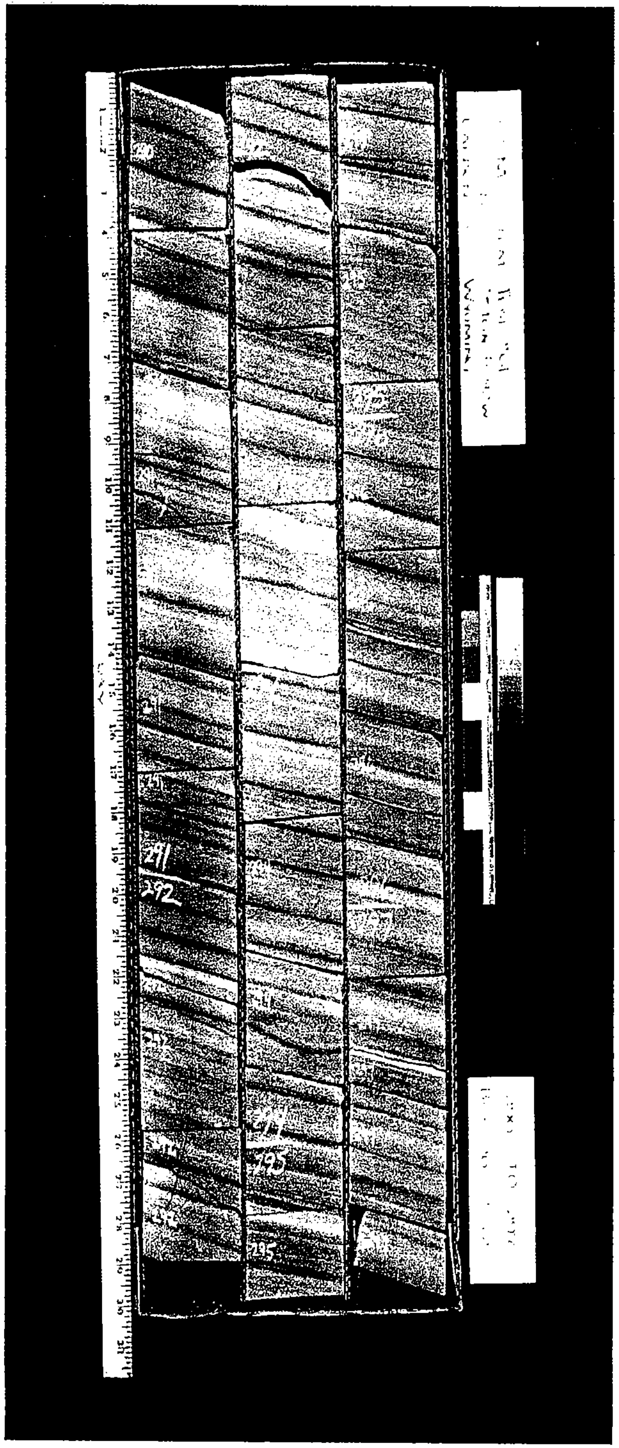
Behind-outcrop well on Spine I

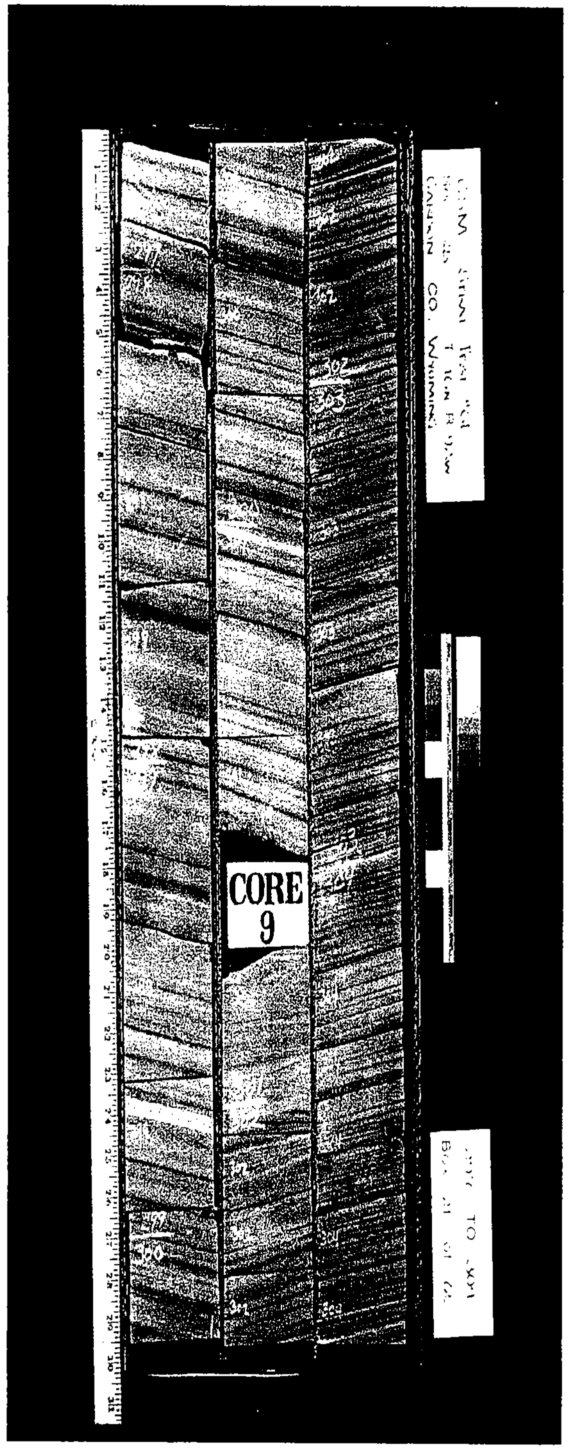


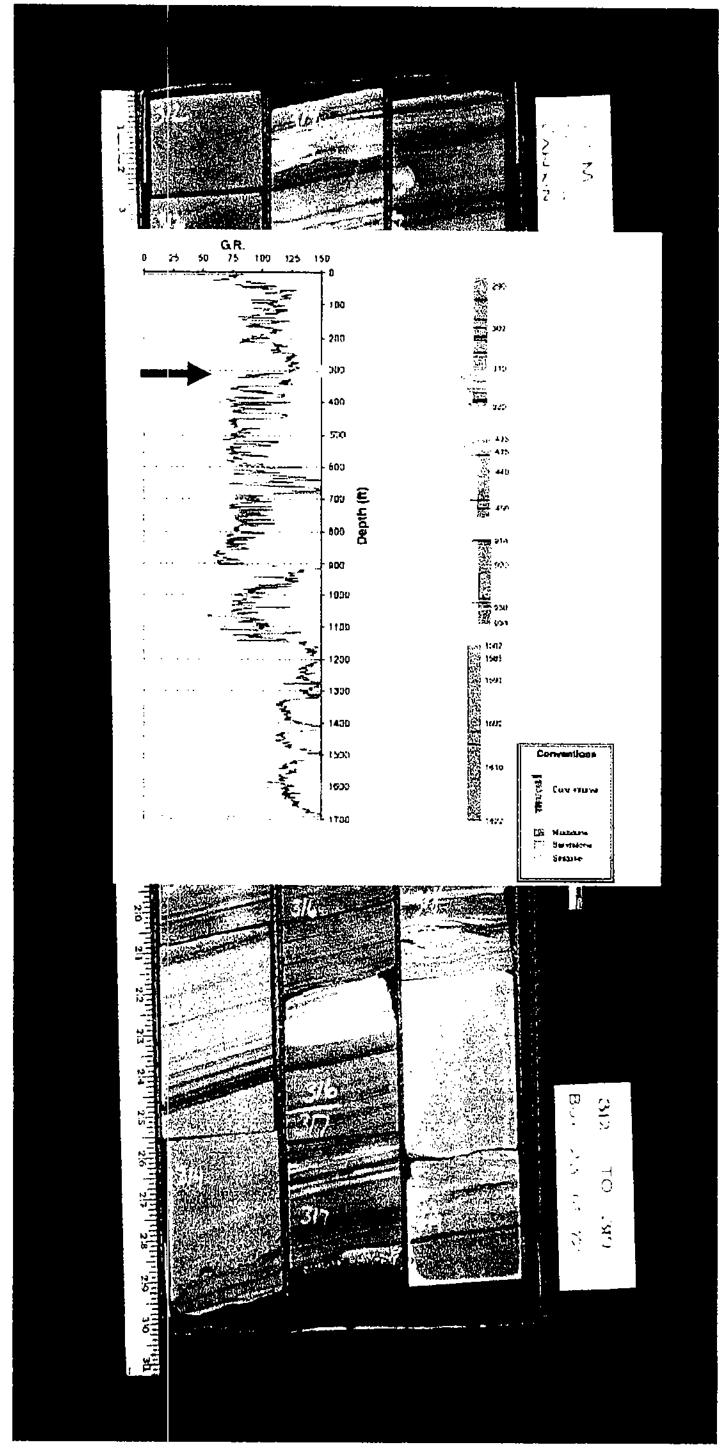


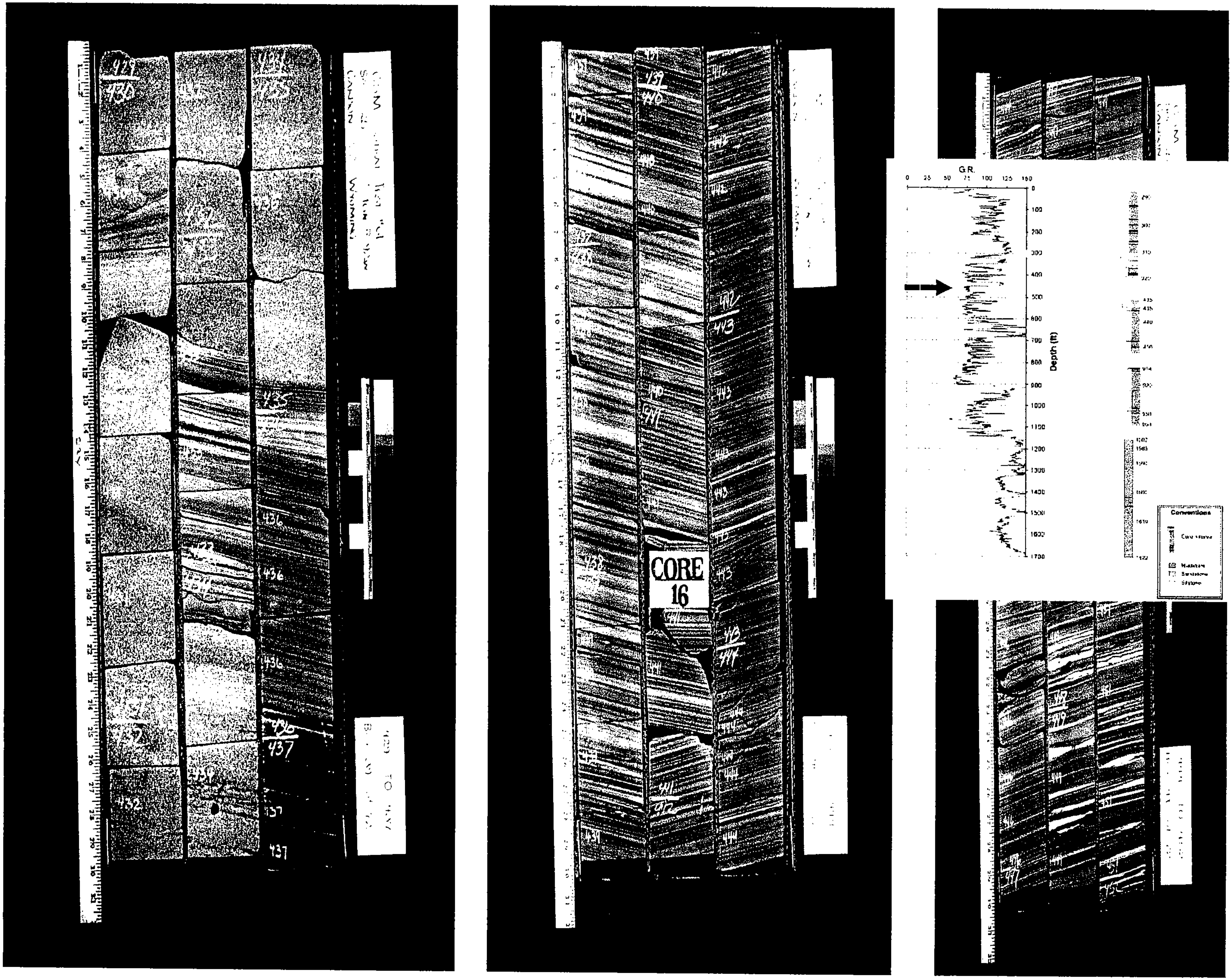


G.R.
0
25
50
75
100
125
150
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Depth (ft)
Cored
intervals
Conventions



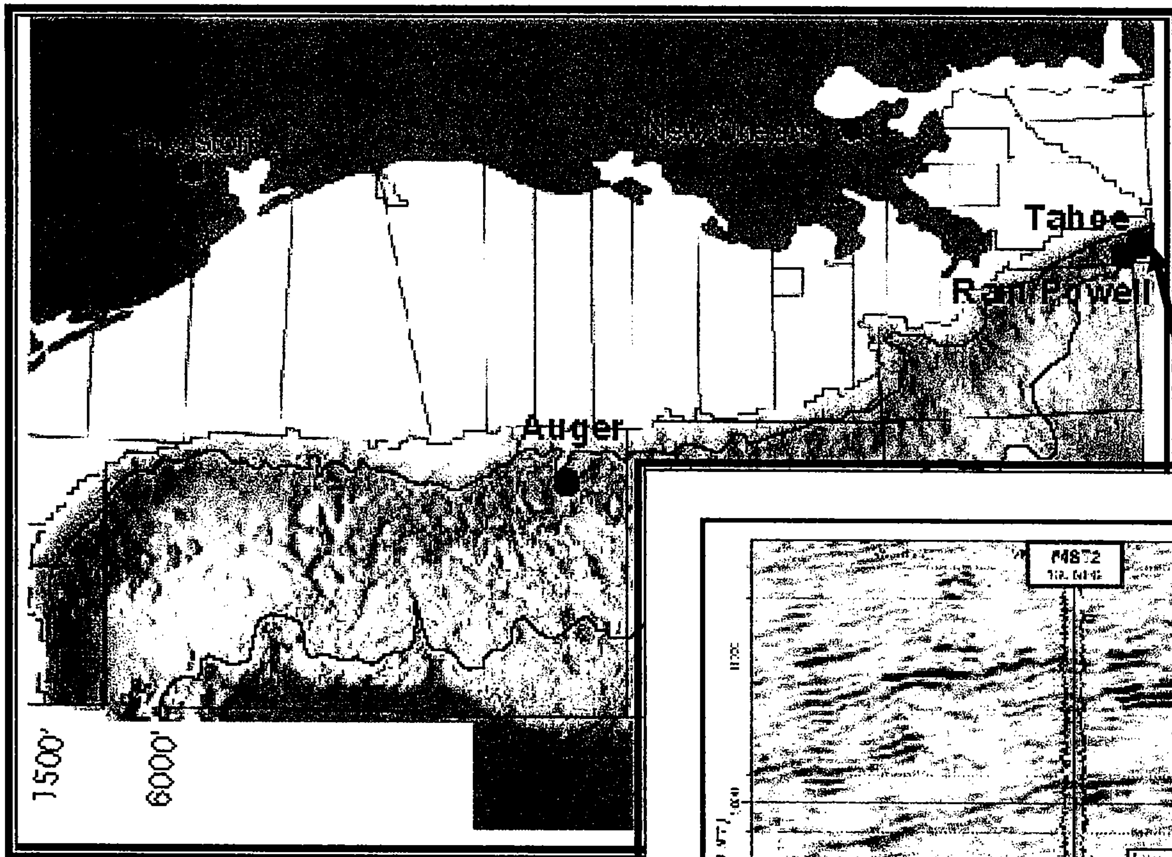

CORE
9

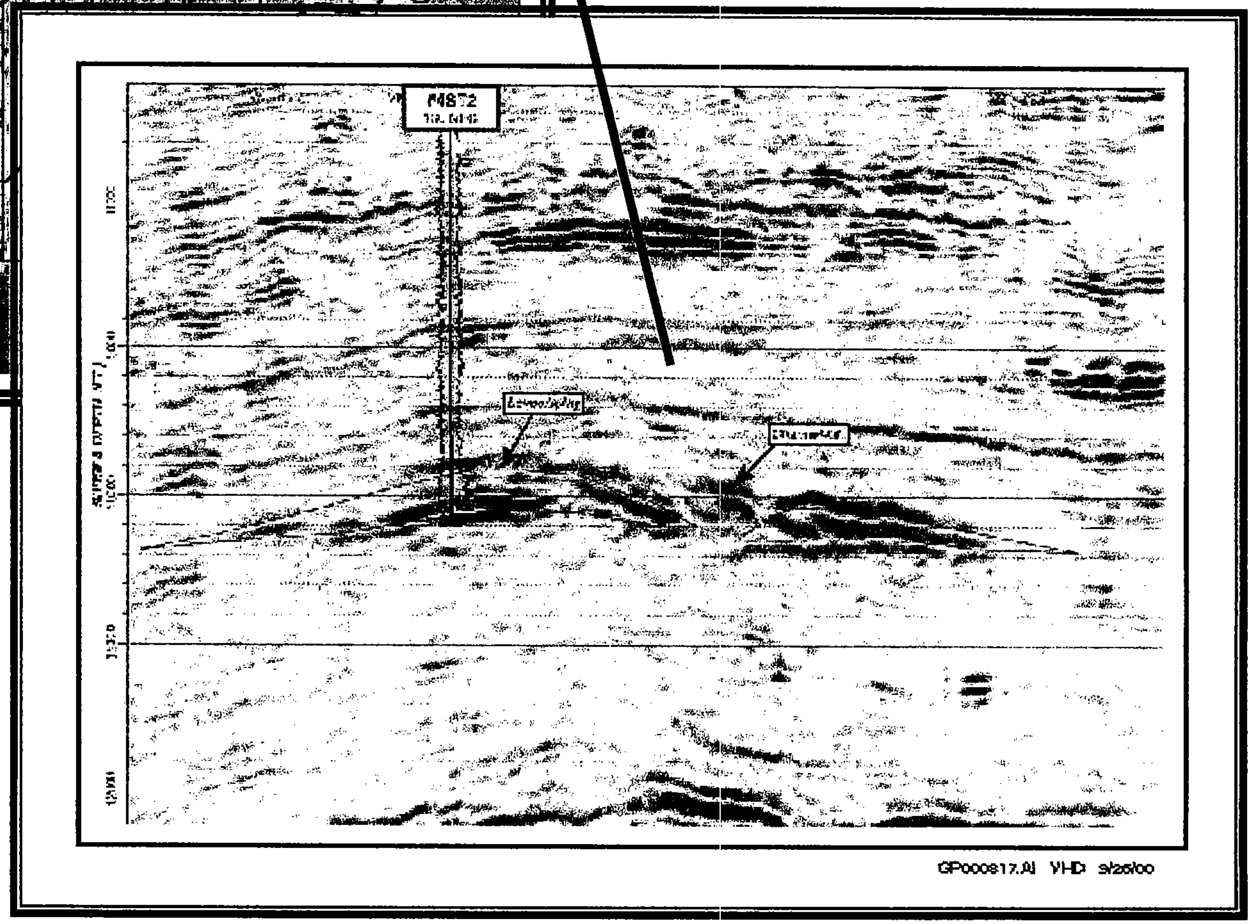

G.R.
Depth (ft)
Conventions


CORE
16
G.R.
Depth (ft)
Conventions

CHANNEL LEVEE/OVERBANK EXAMPLES

- *M4.1 Sand, Tahoe, Gulf of Mexico (Kendrick, 2000)*
  - Upper Miocene
  - Field is on faulted structural nose
  - Characteristic 'gull wing' on seismic
  - Channel is elongate dim area on horizon slice
  - >17MMBE gas and condensate from 4 wells
  - Single well flow rates from thin bedded levees tested 29MMCFGPD and 950BCPD
  - Pressures in west levee depleted over time over entire stratigraphic interval; Pressures in east levee only depleted in upper part; lower part at original pressures, indicating disconnect with west levee.
  - Oil-water contact is shallower in west, than east levee.
  - Early production from upper levees provided optimism that was lost when production began from lower levee interval

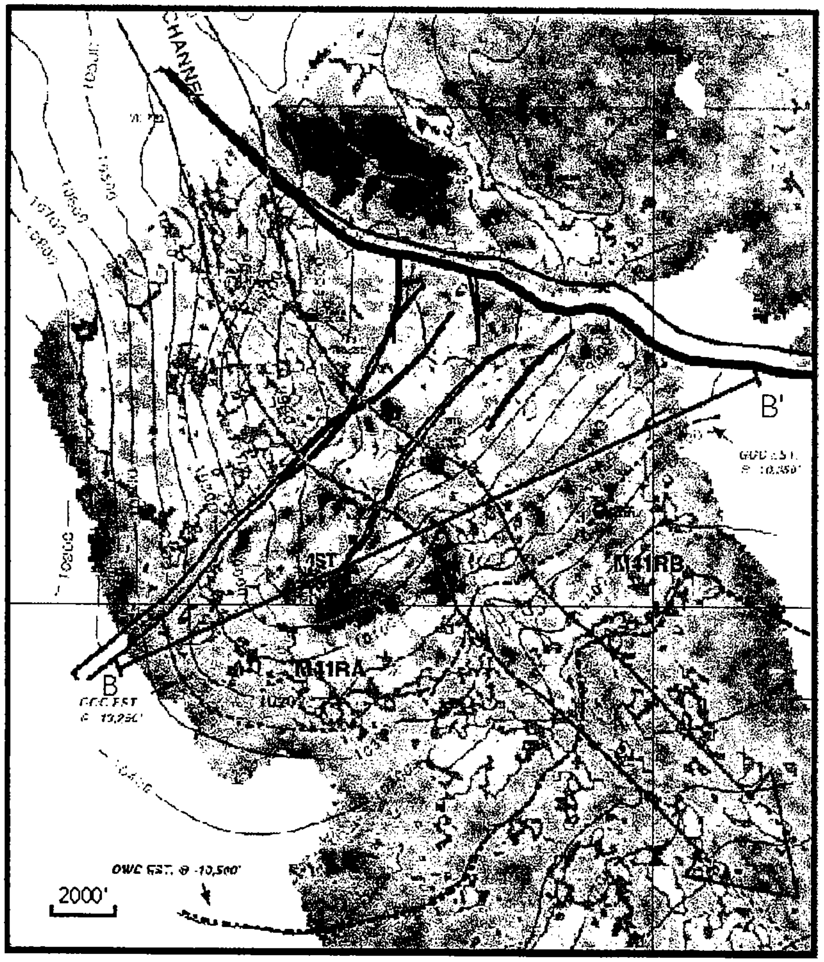


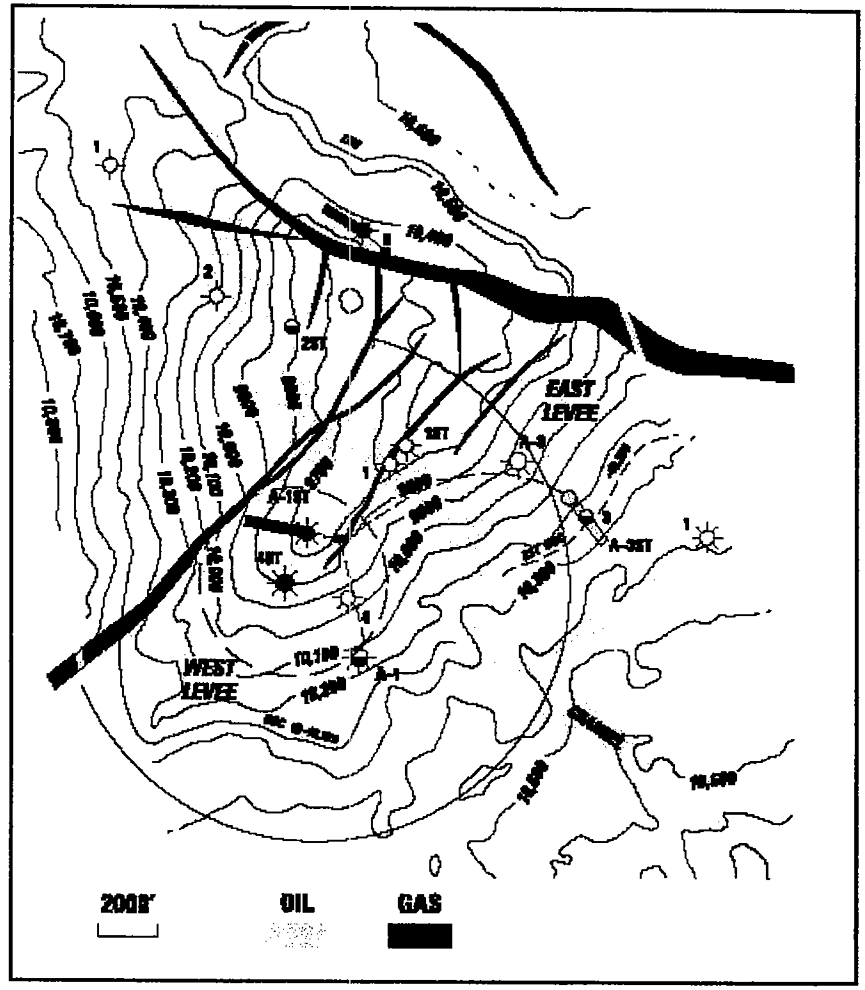


M4.1 Sand, Tahoe

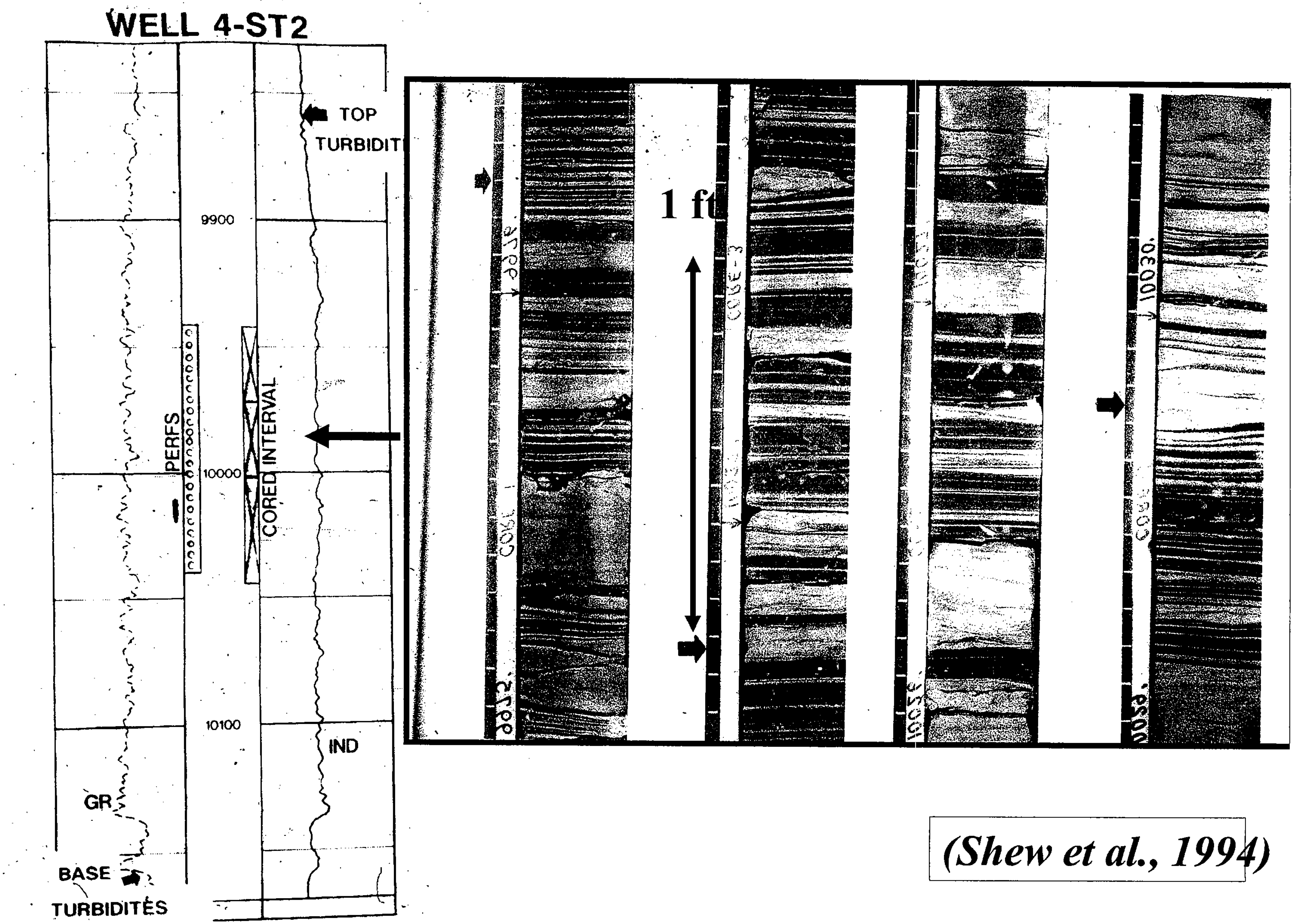
(Kendrick, 2000)

M4.1 Sand, Tahoe





(Kendrick, 2000)



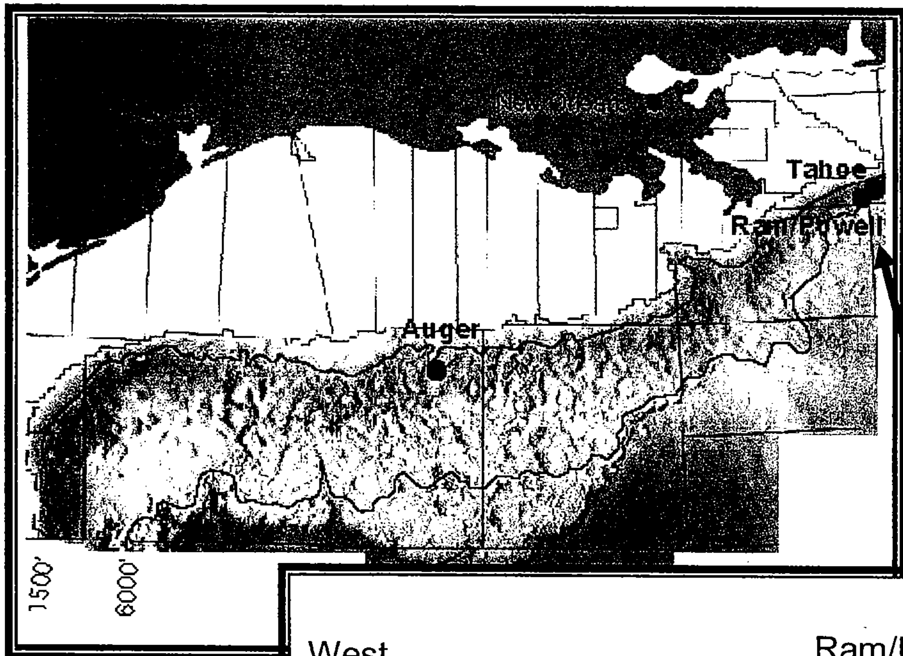
(Shew et al., 1994)

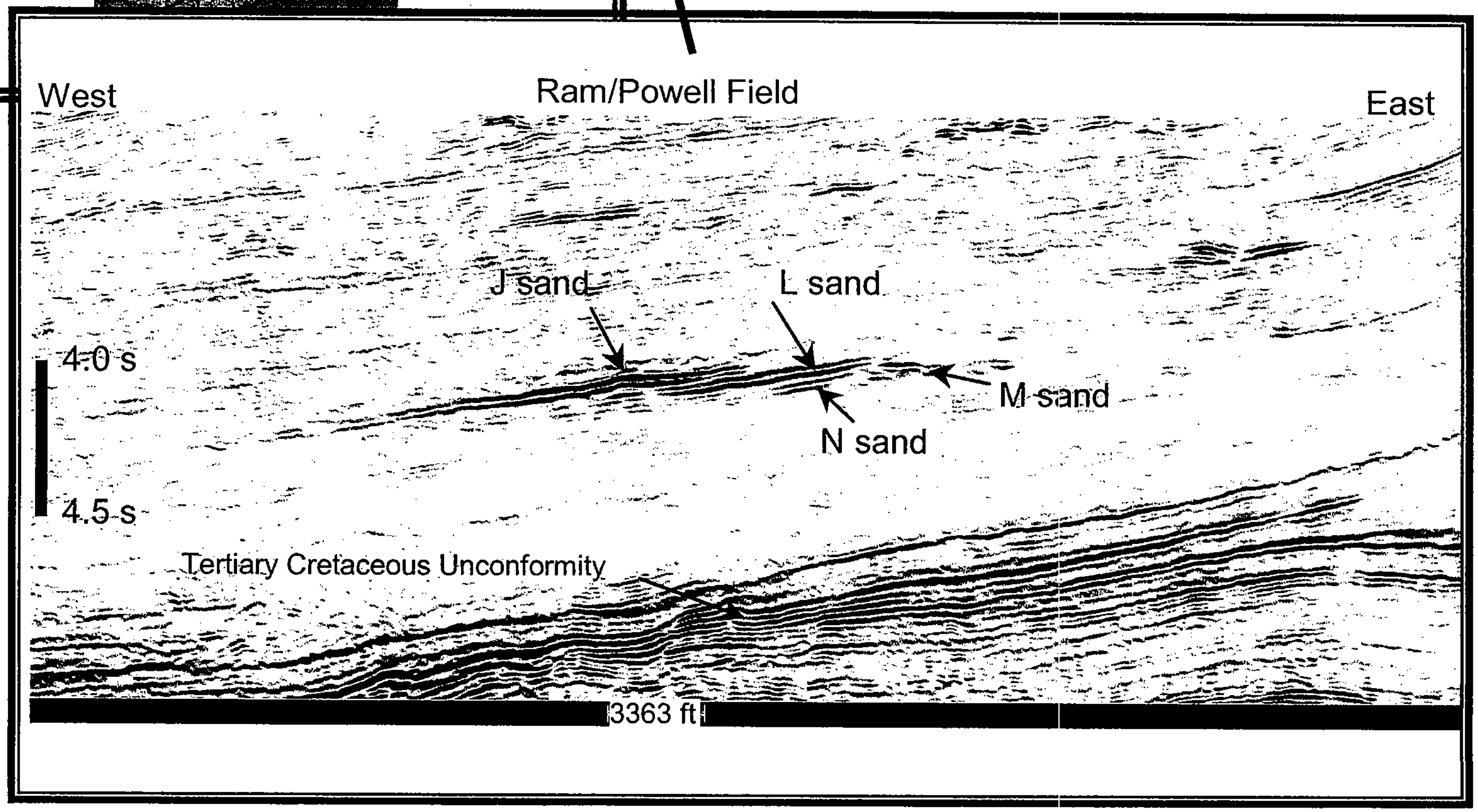
• *Ram/Powell, L Sand, Gulf of Mexico (Clemenceau et al., 2000)*

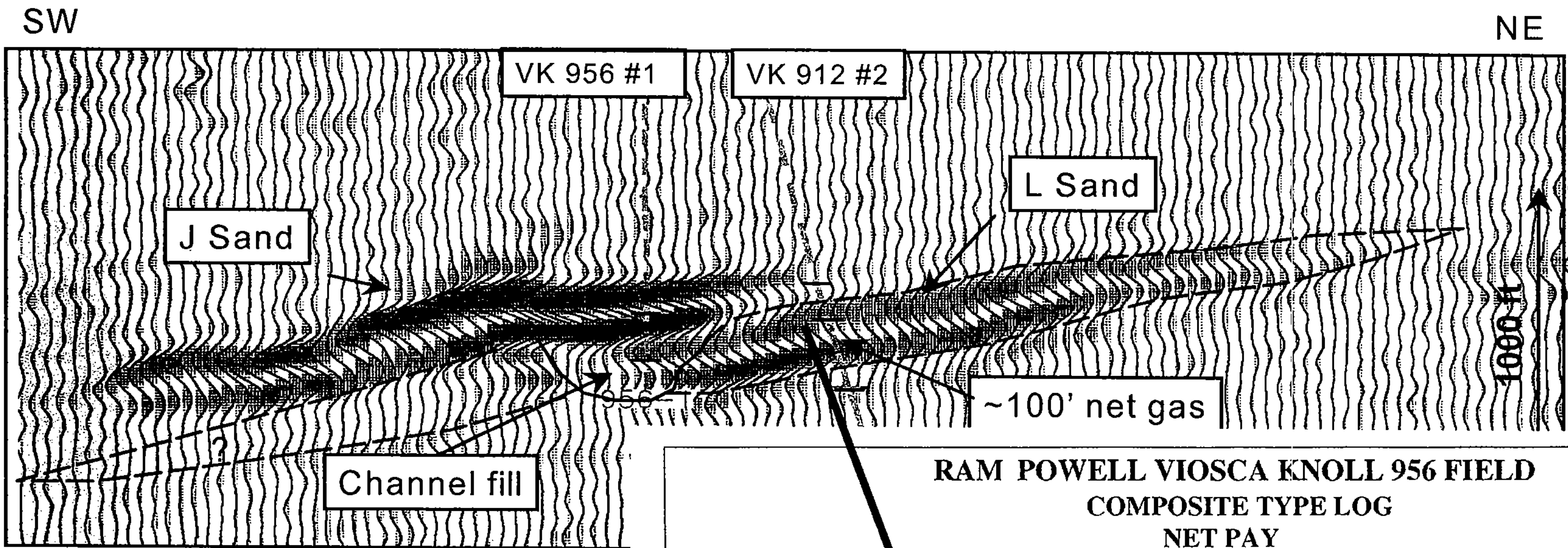
- L Sand comprised of *channel, proximal* and *distal levee* facies
- Channel is 1500-2000ft. wide, contains 25-100ft. water wet sand
- Gas charged, east levee extends 15,000 ft. to east of channel
- Reservoir is thin-bedded levee/overbank facies; individual sands are 0.04-1 inch thick!!
- Sand porosities = 15-32%(X=28%); k = <10-1000md (X=300)
- Single 2,500ft. horizontal well in proximal levee facies peaked at 8.8MBOPD & 108MMCFGD. This well has produced 4.8MMBO & 61.5BCF (15.4MMBOE from 9/97(?)-5/00.
- 4 day well test in 50ft. thick distal levee flowed 23MMCFGD and 2700BC/D with PTA perms of 143md.
- Good lateral continuity and pressure communication across entire 4000 acre proximal levee reservoir
- Channel and levee sands are NOT in communication, as determined from pressure data
- Gas sands give good seismic amplitudes. water sands do

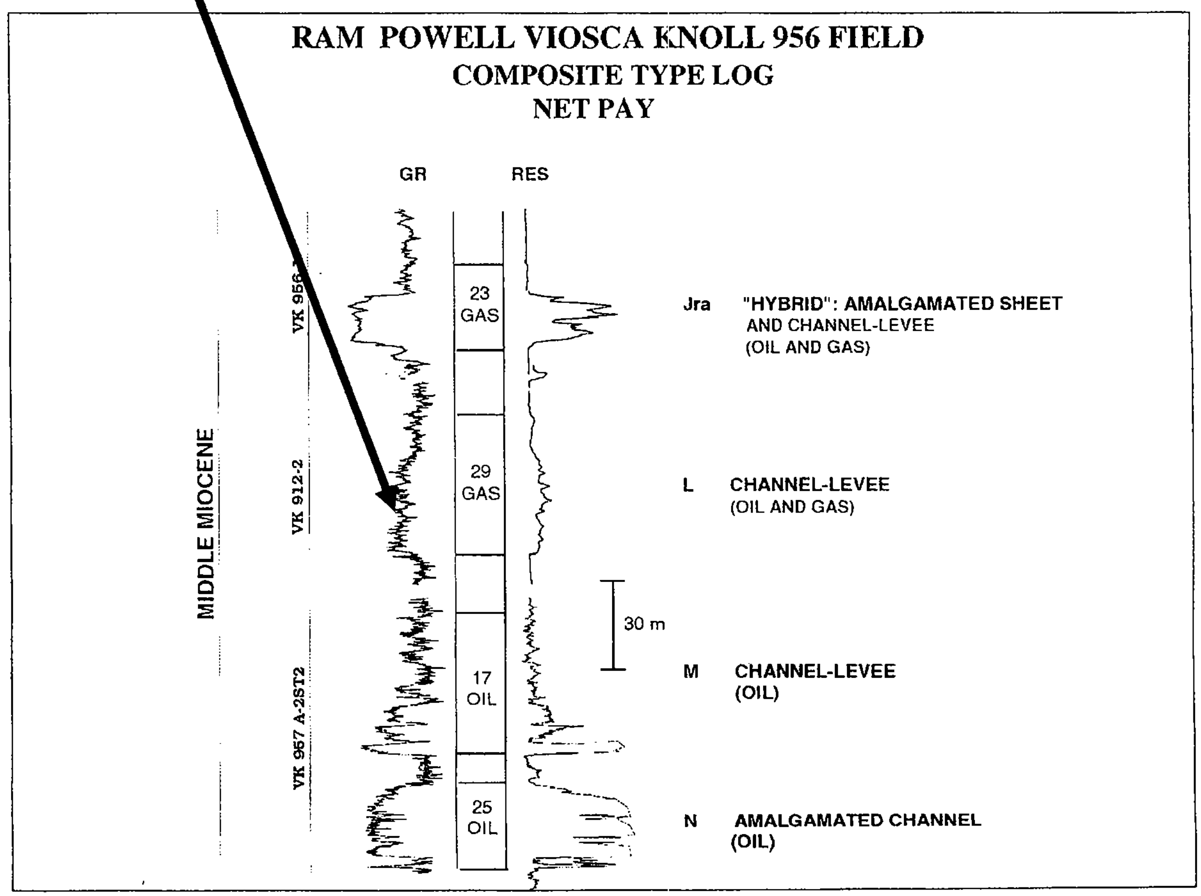
Ram-Powell 'L' Sand

(Clemenceau et al., 1995; Kendrick, 2000)





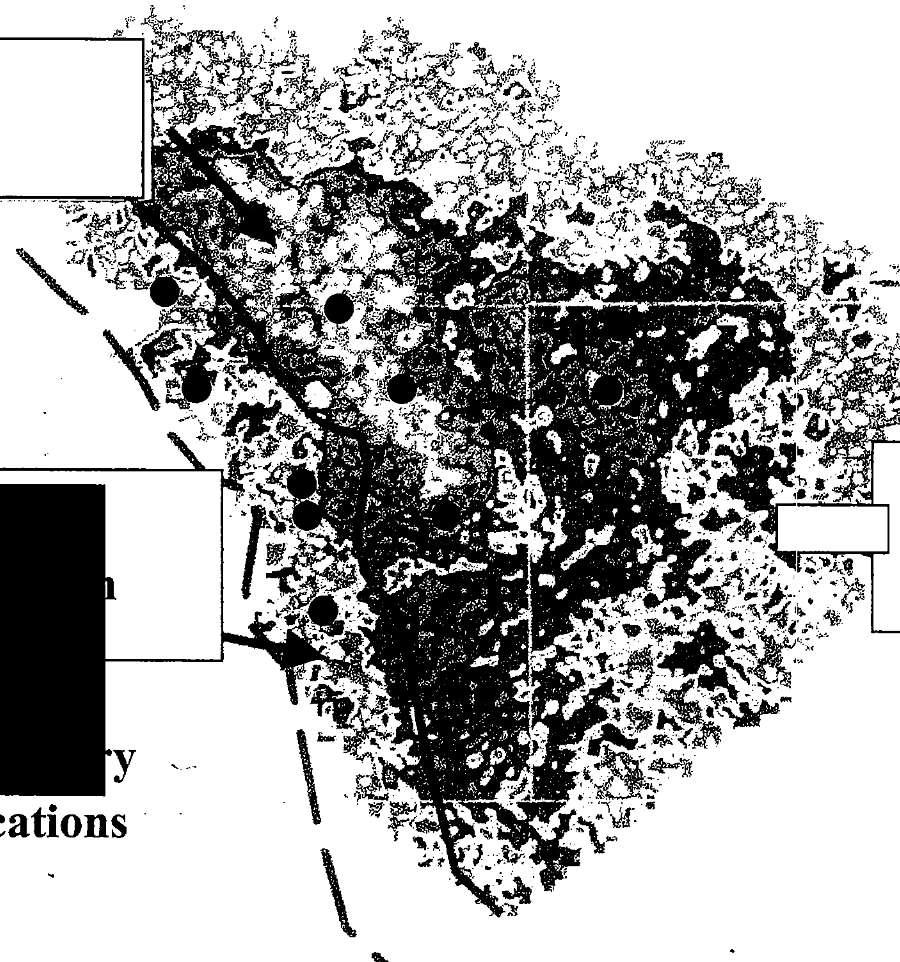




L Sand

(Craig et al., 2003)

3D Seismic Horizon Slice through a reservoir



N

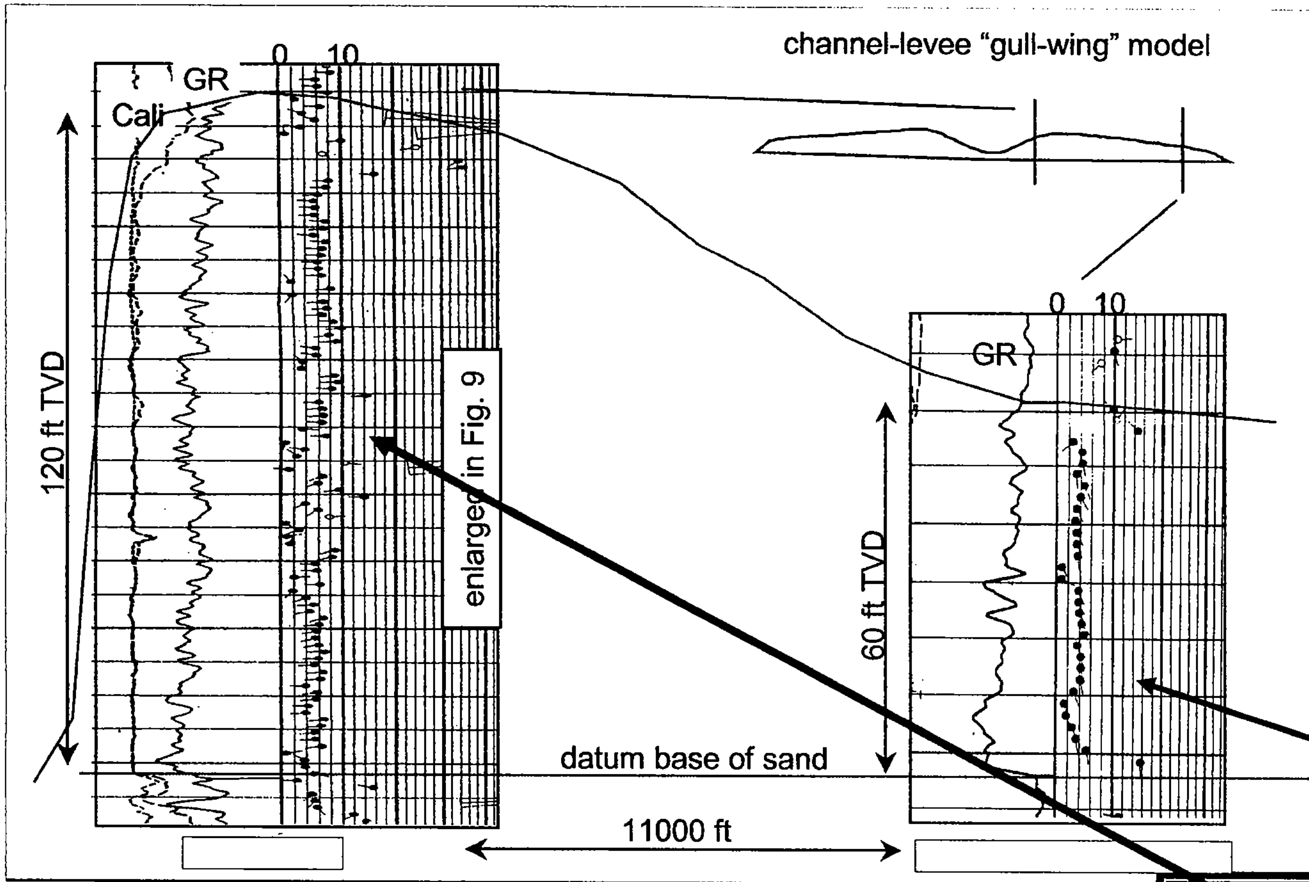
[redacted]

● App. Well locations

3 Miles

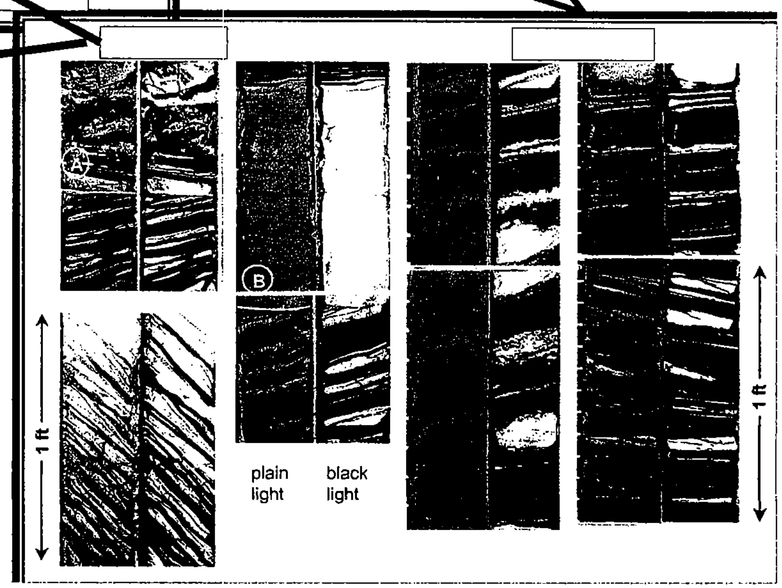
(Clemenceau et al., 1995)

Ram-Powell L Sand



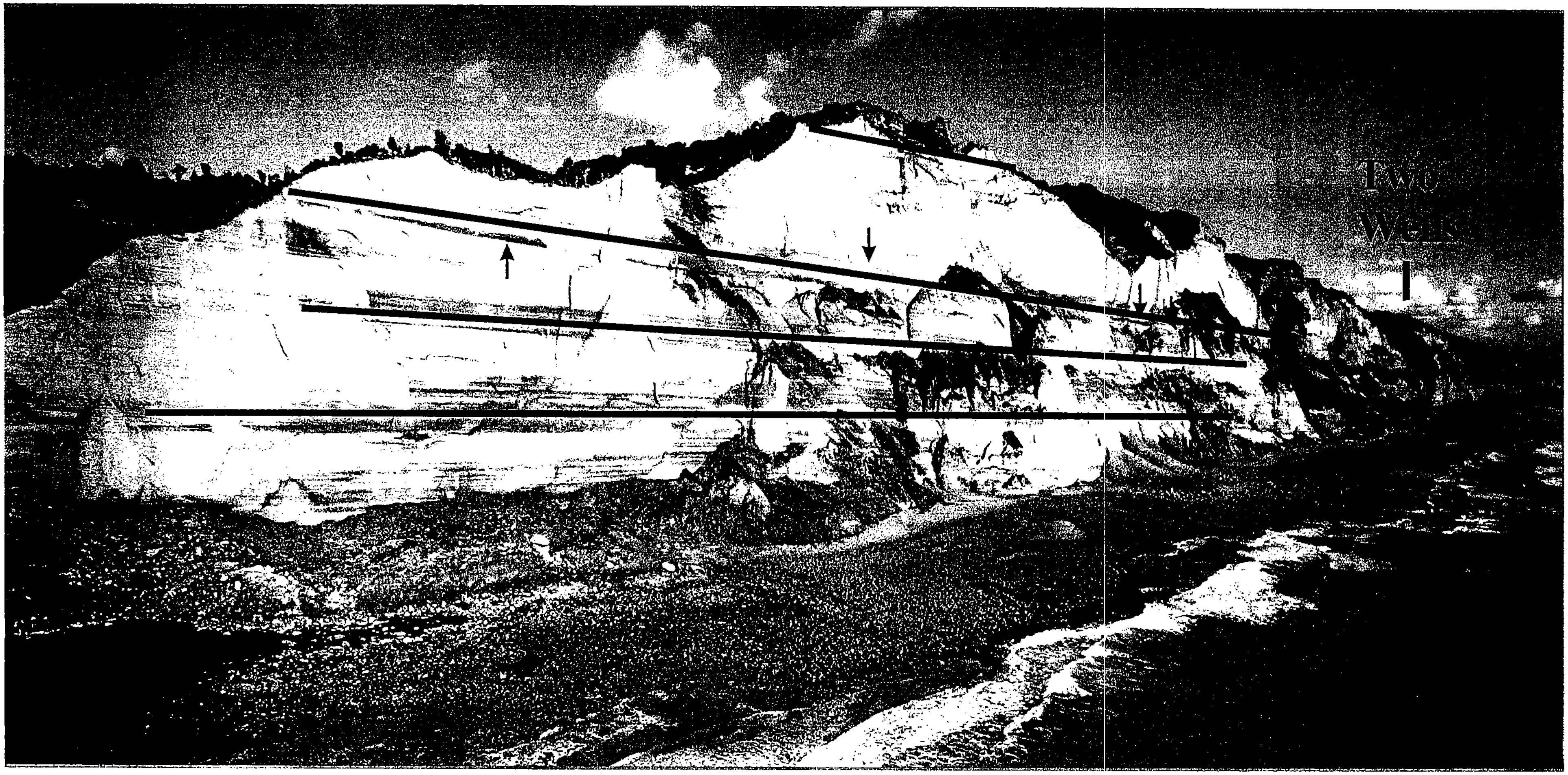
Low and uniform dip magnitudes of beds

High and variable dip Magnitude of beds



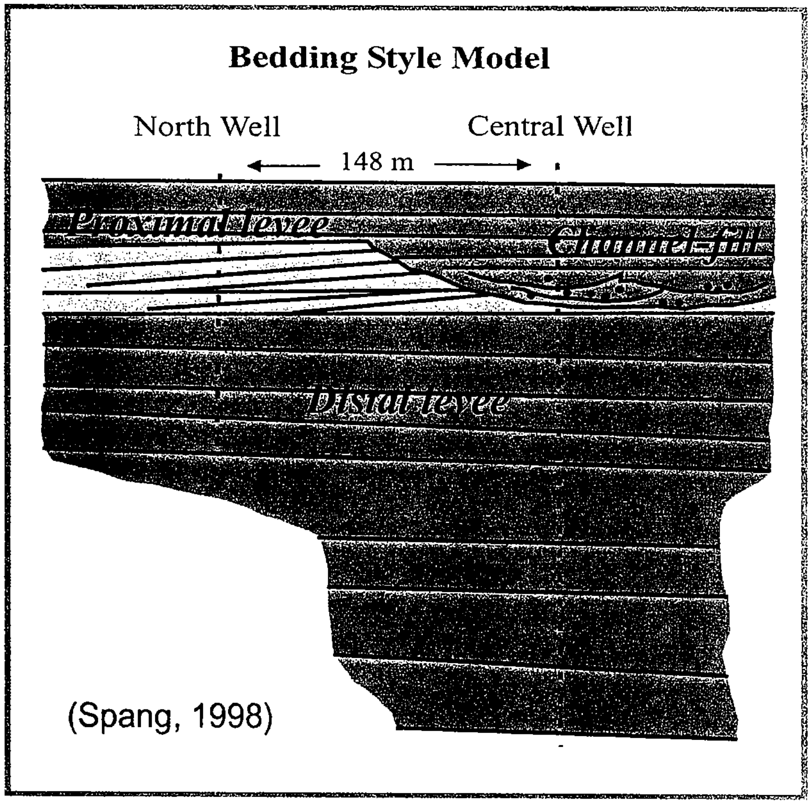
(Clemenceau et al., 2000)

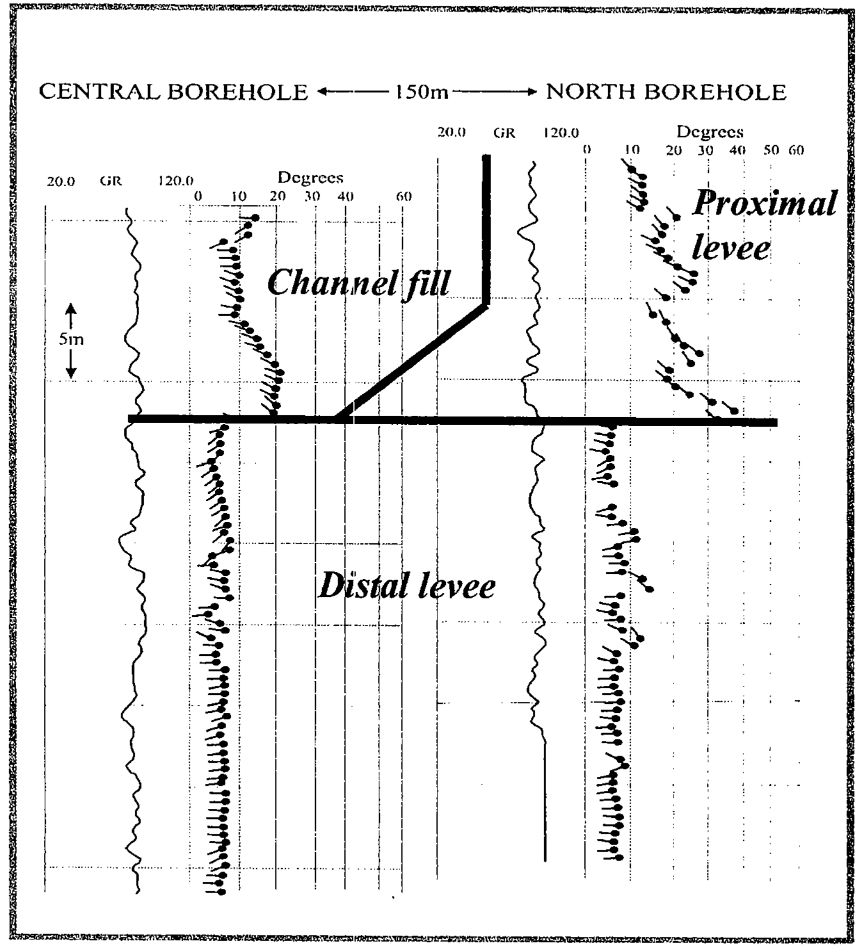
Miocene Mt. Messenger Formation, Taranaki Basin of New Zealand



PHOTOMOSAICS FROM HELICOPTER; WELLS; CORES; LOGS; HIGH-RESOLUTION SHALLOW SEISMIC; MEASURED SECTIONS

Mt. Messenger Fm., New Zealand Bedding style and Dipmeter example





Dip Patterns

Channel-fill

* Variable Dip
* Decrease Upward

Proximal Levee

* Variable Dip & Azimuth
* Relatively High Dip Angles

High net/gross

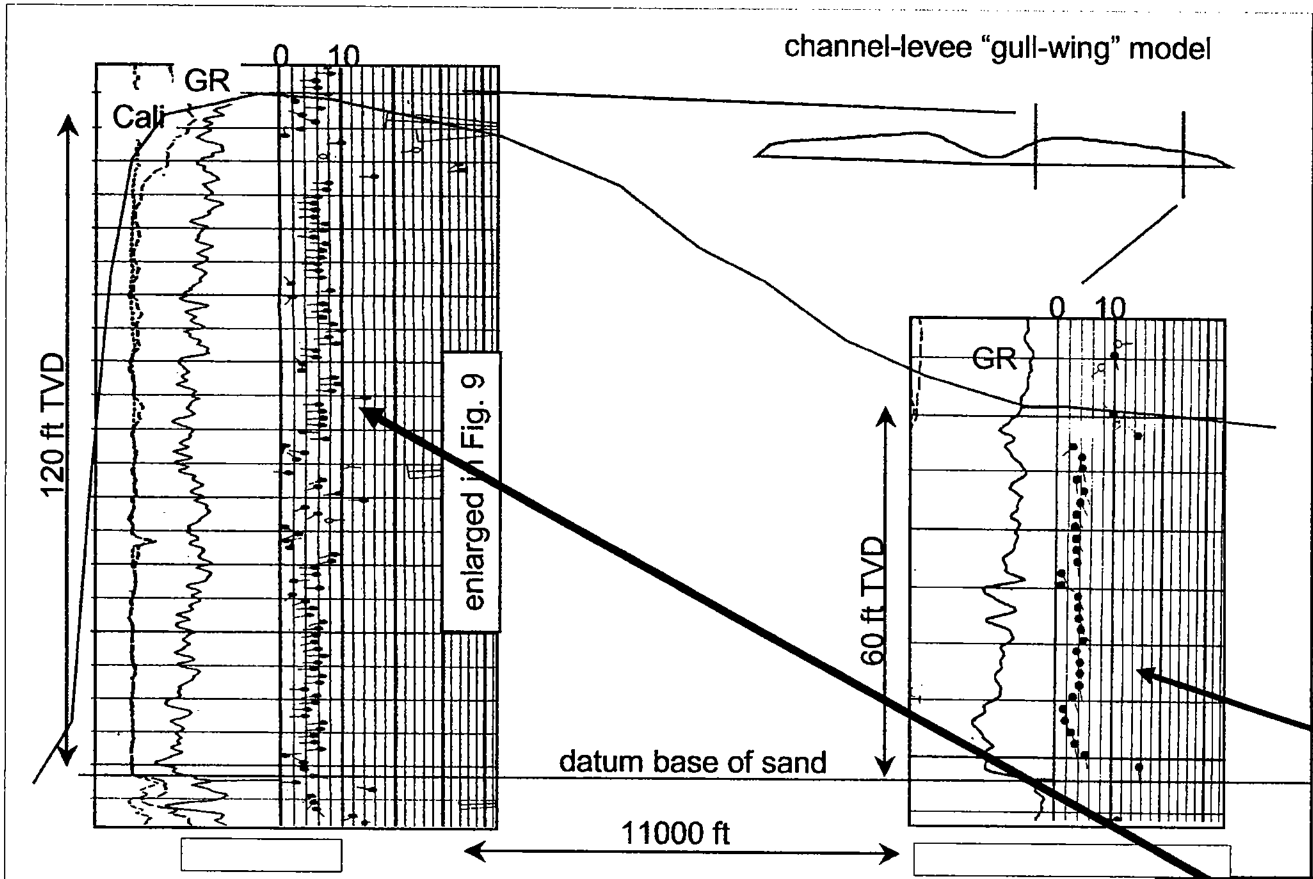
Distal Levee

* Constant Dip & Azimuth
* Relatively Low Dip Angles

Lower net/gross

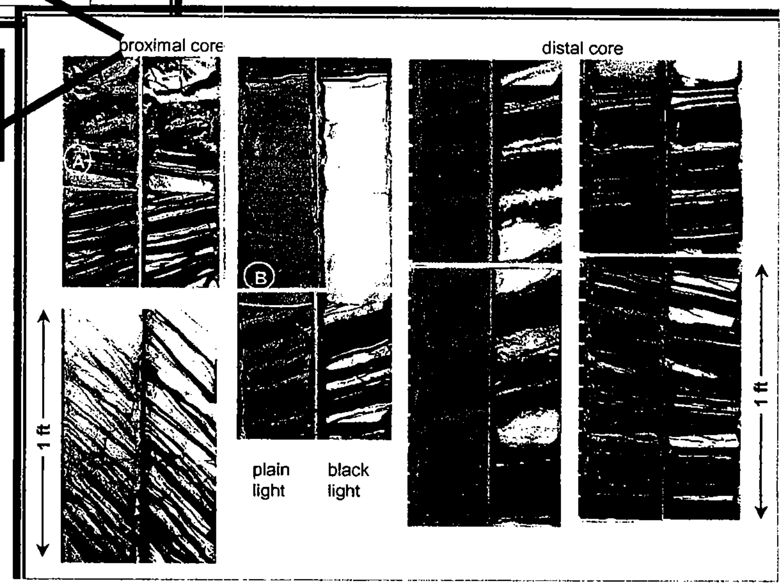
Ram-Powell L Sand

Low and uniform dip magnitudes of beds



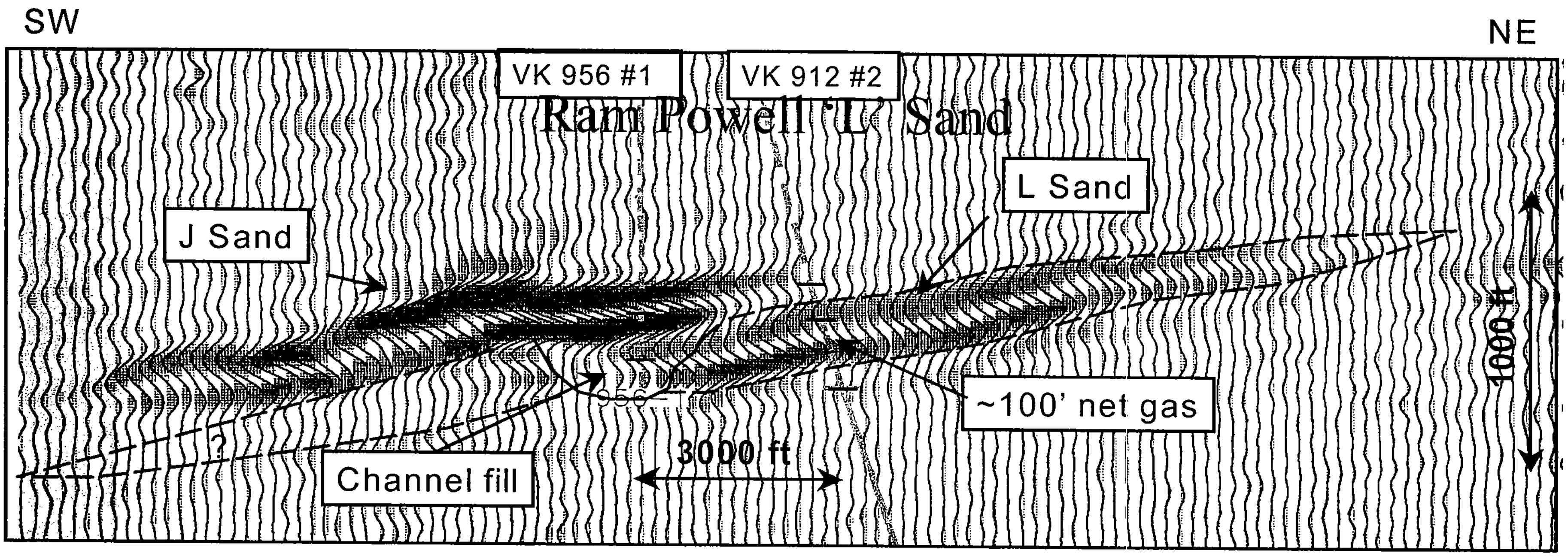
Proximal levee

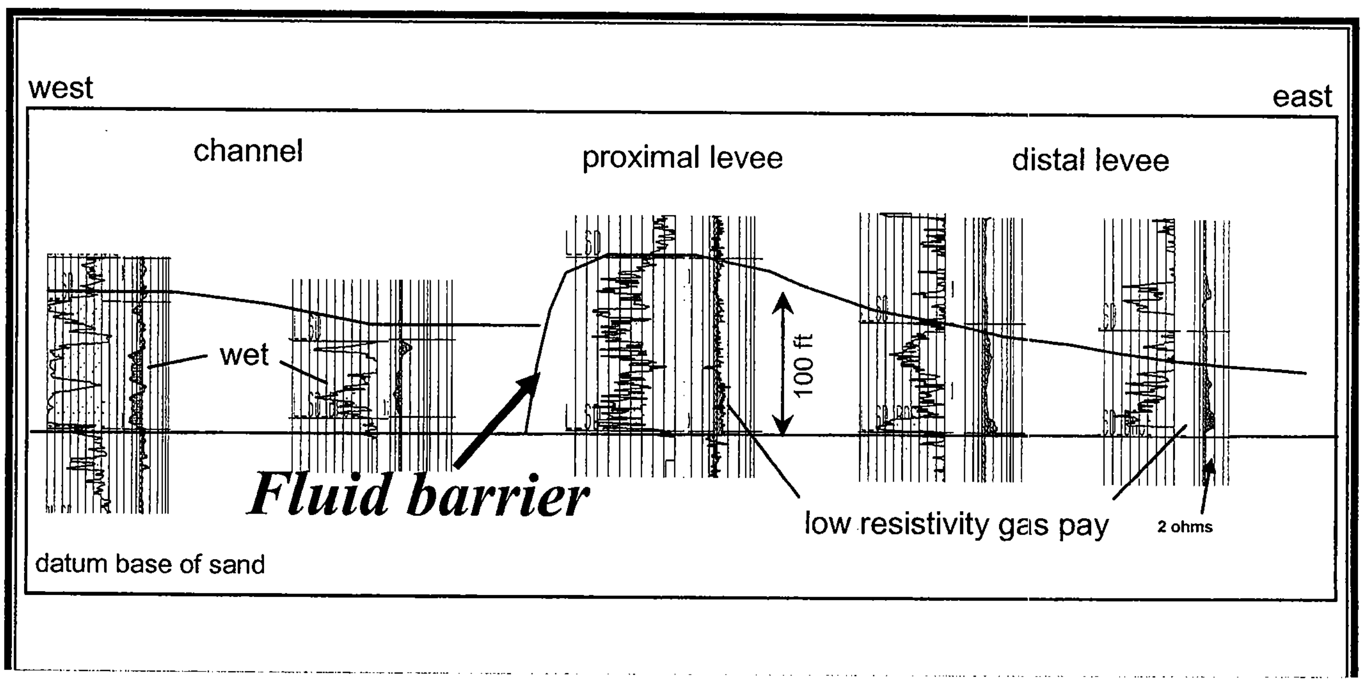
Distal levee



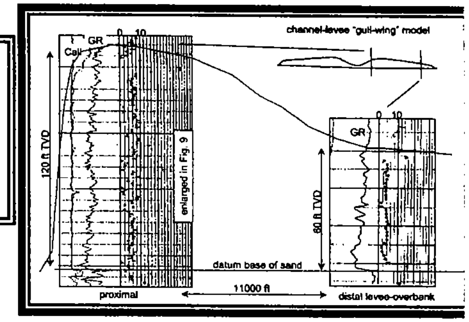
High and variable dip magnitudes of beds

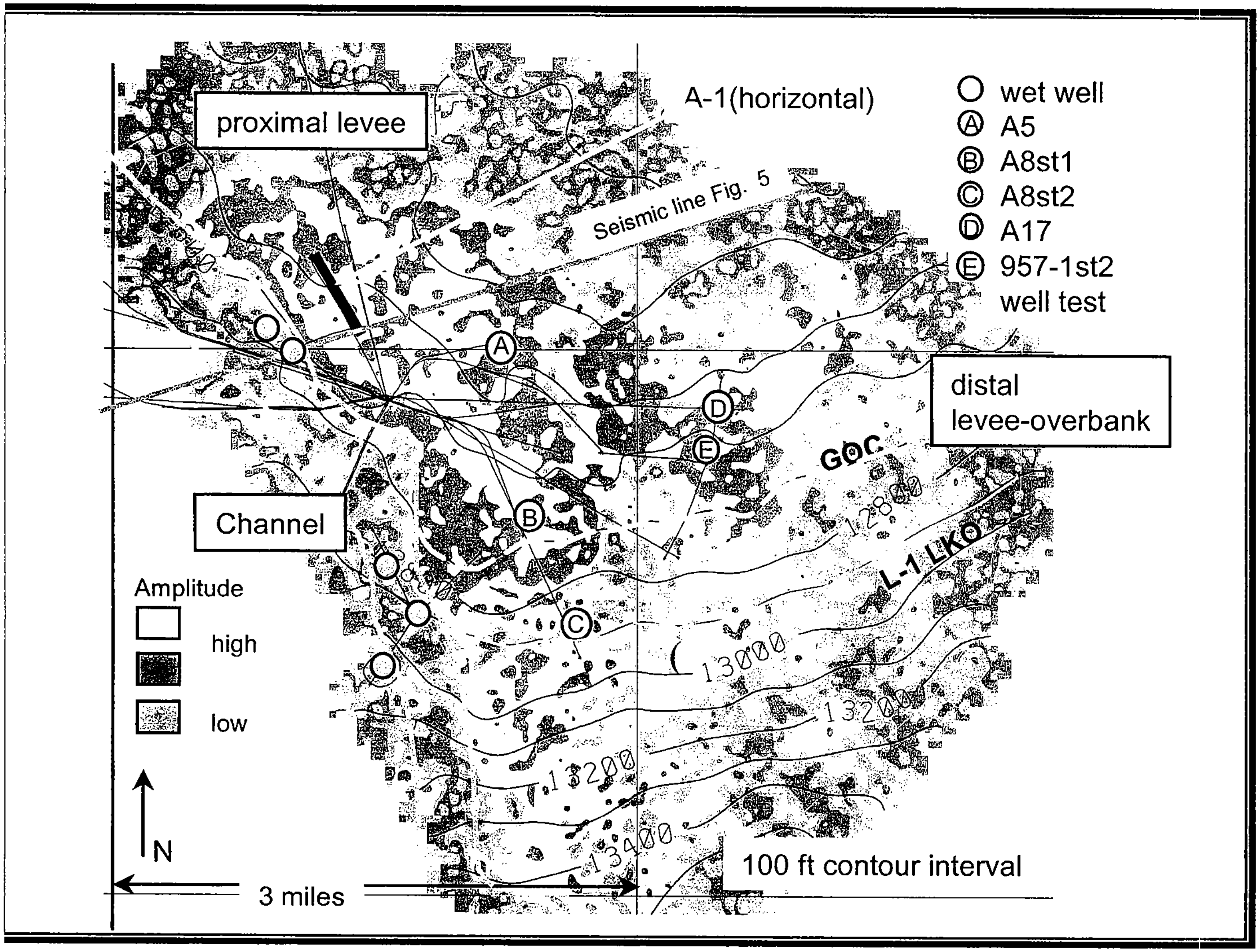
(Clemenceau et al., 2000)


SW
NE
VK 956 #1
VK 912 #2
Ram Powell 'L' Sand
L Sand
J Sand
~100' net gas
Channel fill
3000 ft
1000 ft
?


west
east
channel
proximal levee
distal levee
wet
100 ft
Fluid barrier
low resistivity gas pay
2 ohms
datum base of sand

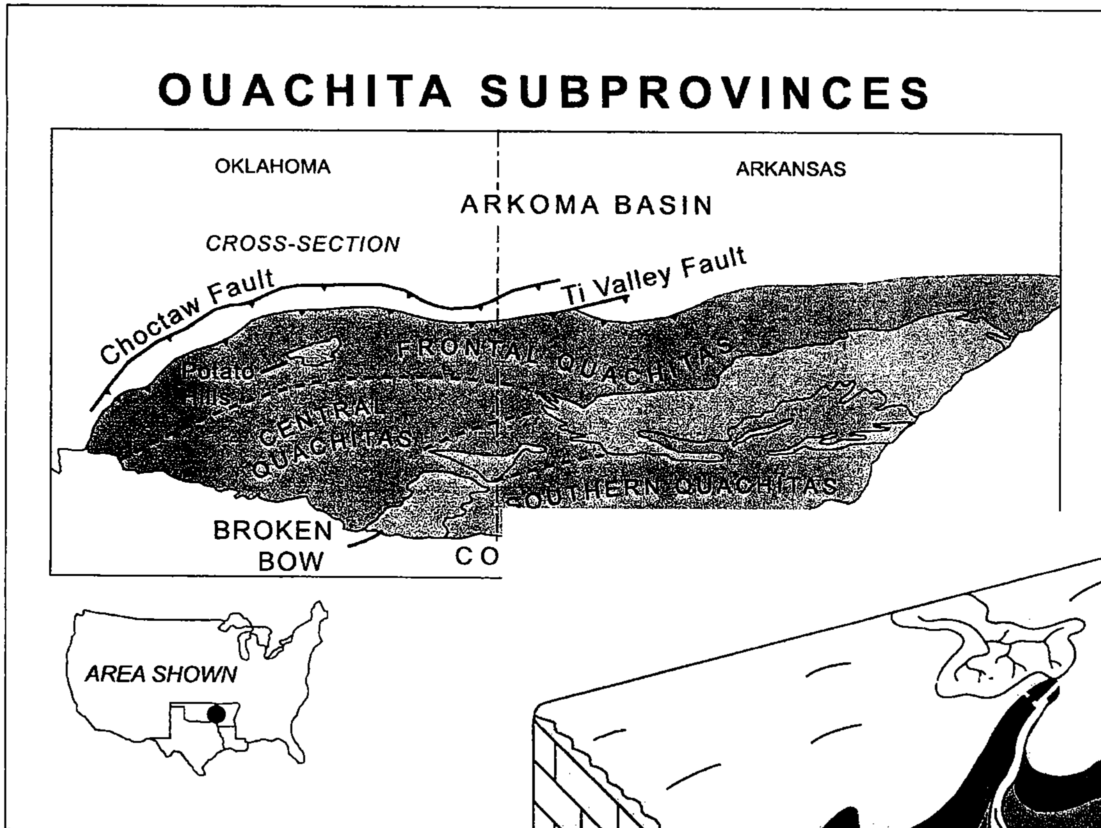
Drilling Strategy: Horizontal well in proximal levee beds, parallel to channel: "Well performance exceeded expectations with a peak flow rate of 105mmcfgd and 9600 bopd"

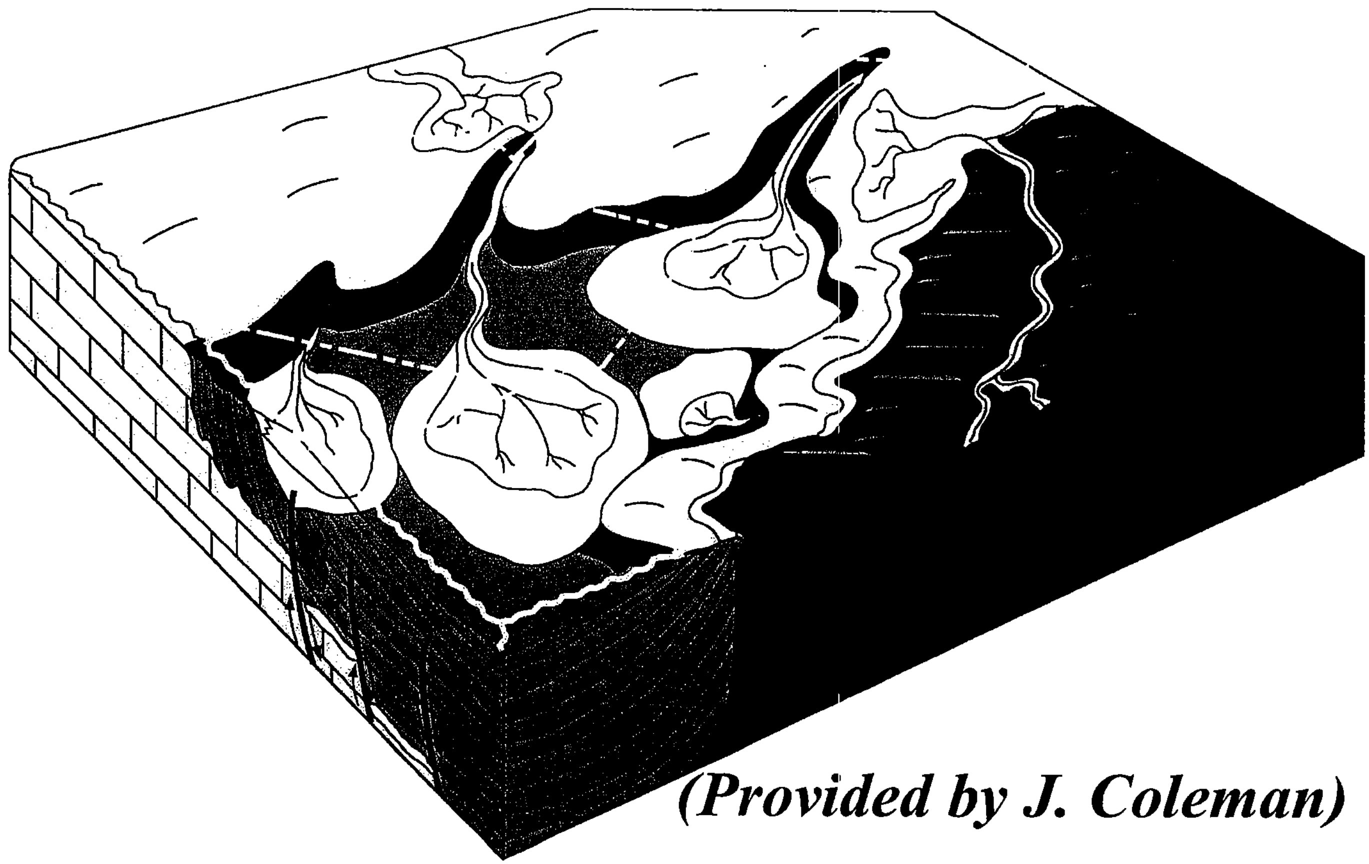




Horiz. well in proximal levee

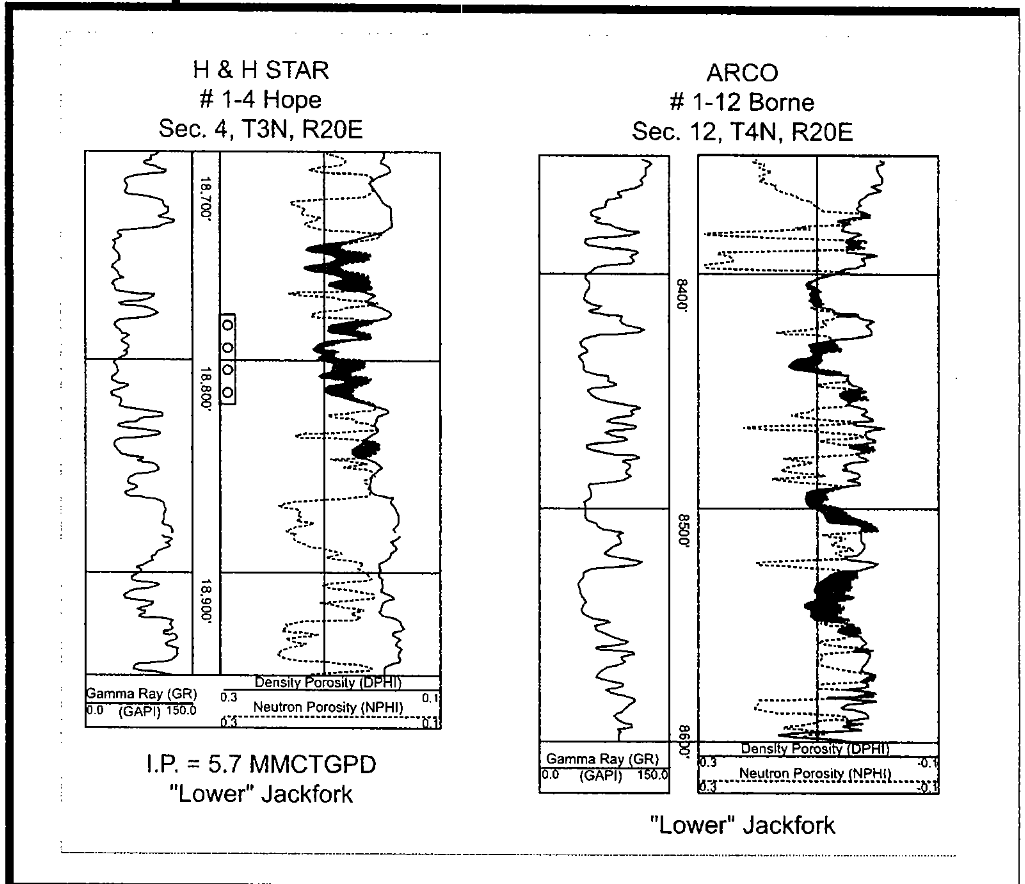
(Clemenceau et al, 2000)



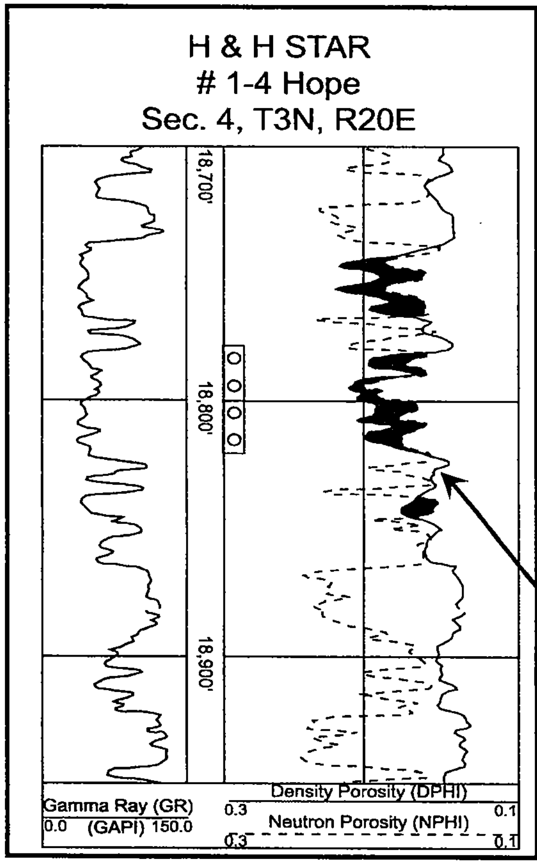


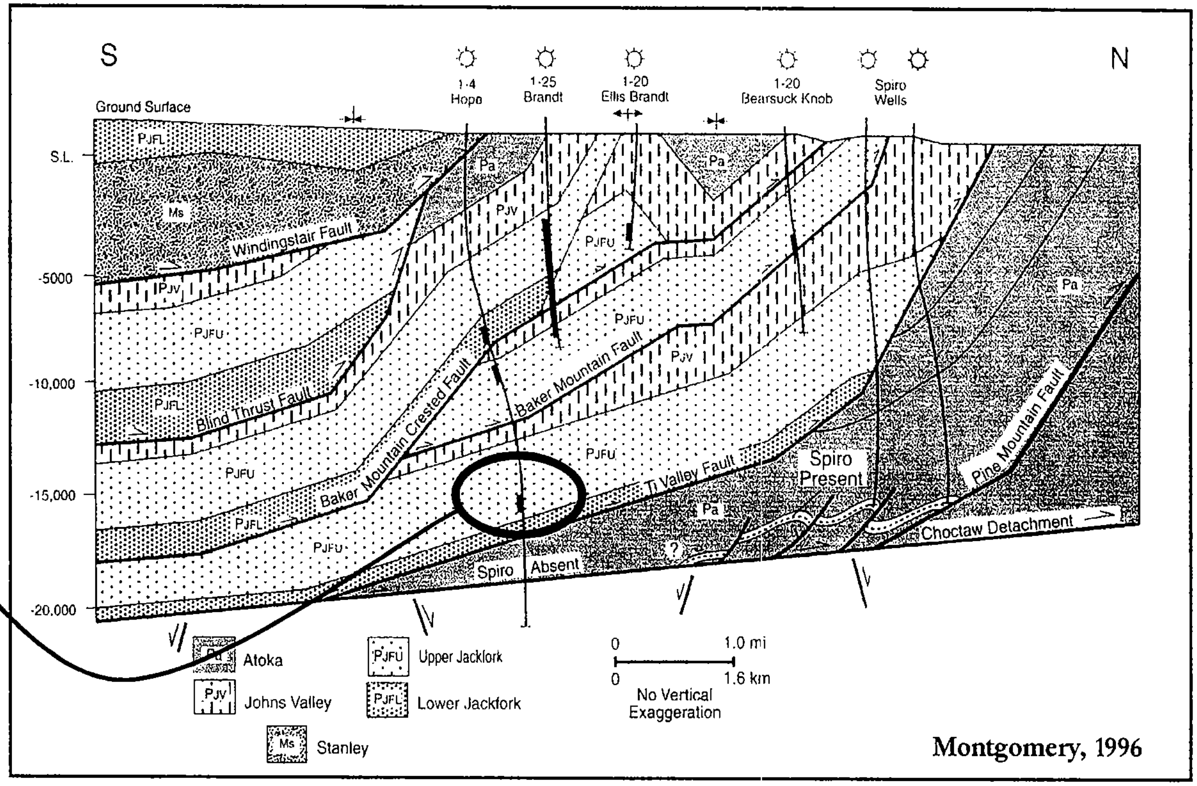
(Provided by J. Coleman)

Jackfork Gas



Jackfork Group Reservoir Potential





I.P. = 5.7 MMCTGPD
"Lower Jackfork"

Gamma ray and neutron & density porosity logs for productive Jackfork strata in two eastern Oklahoma wells

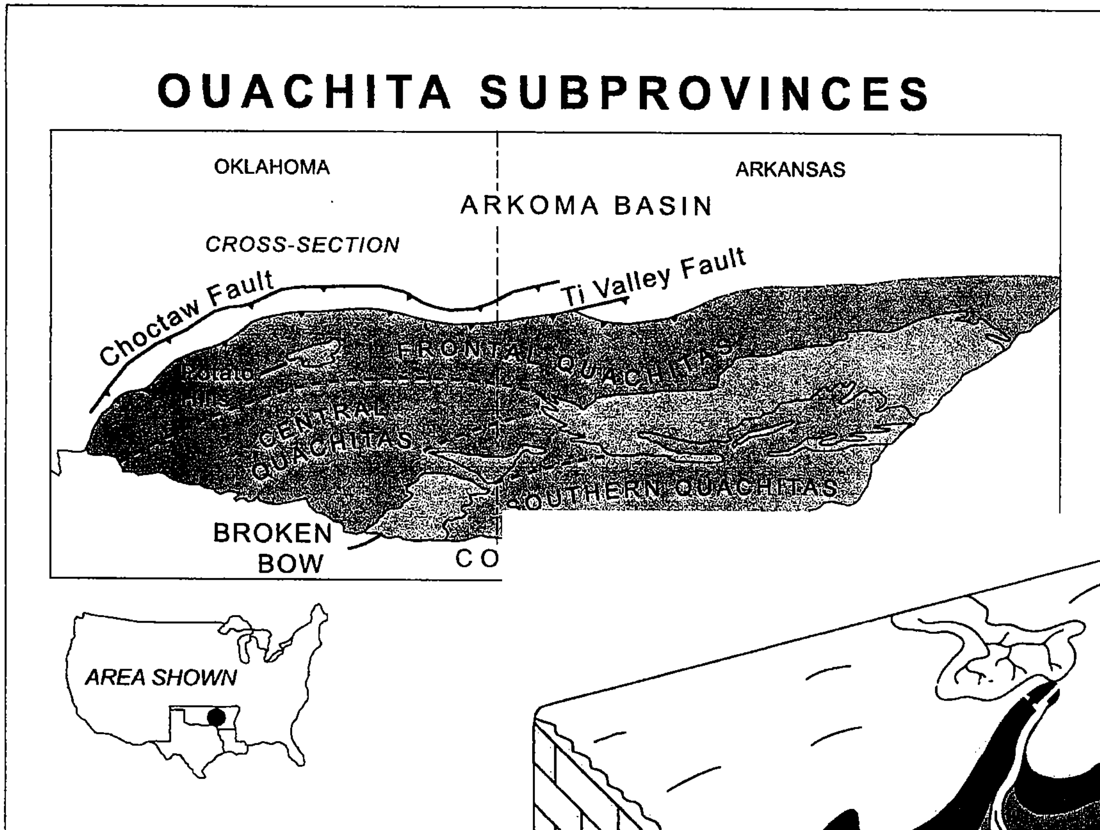
(modified from Pauli, 1994).

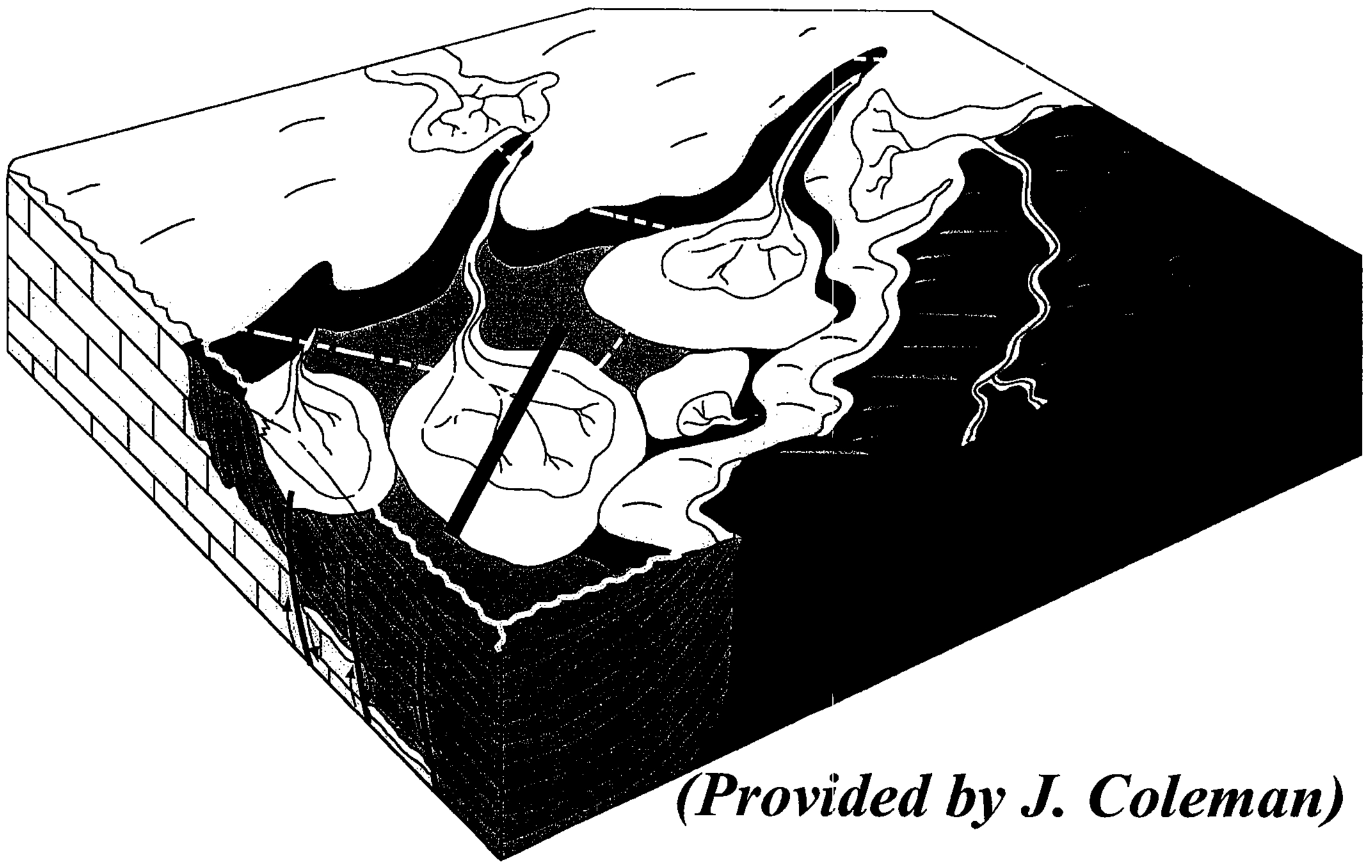
- **Well**
  - **Monthly Production (Mcf)**
- **GHK/Amoco Ratcliff 1-33**
  - **200,000+**
- **GHK Thompson 1-4**
  - **350,000+**

- **Well**
  - **Monthly Production (Mcf)**
- **GHK Morgan 1-5**
  - **900,000**
- **GHK Guggenheim 1-6**
  - **50,000**

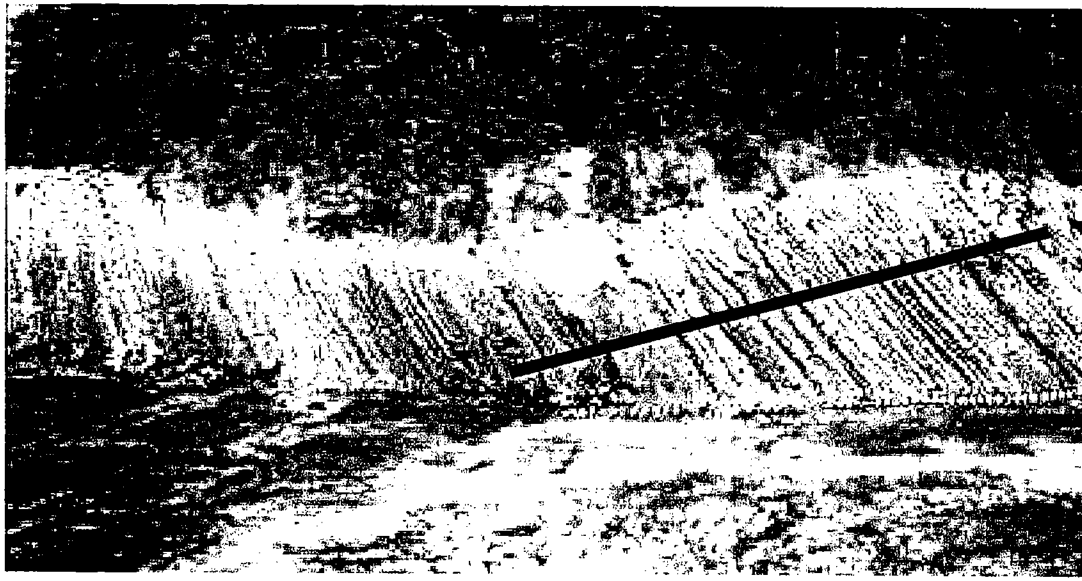
JACKFORK GROUP HYDROCARBON RESERVOIR/TRAP TYPES

- LARGE-SCALE STRUCTURES
- FRACTURES
- STRATIGRAPHIC PINCHOUTS??
- UNCONFORMITY??
- DIAGENETIC??
- STRATIGRAPHICALLY CONTROLLED FRACTURE FREQUENCY??





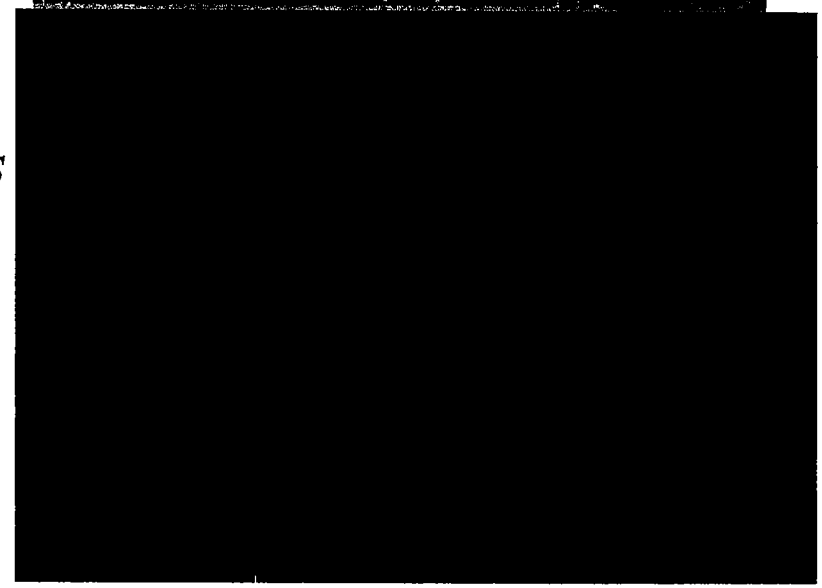
(Provided by J. Coleman)

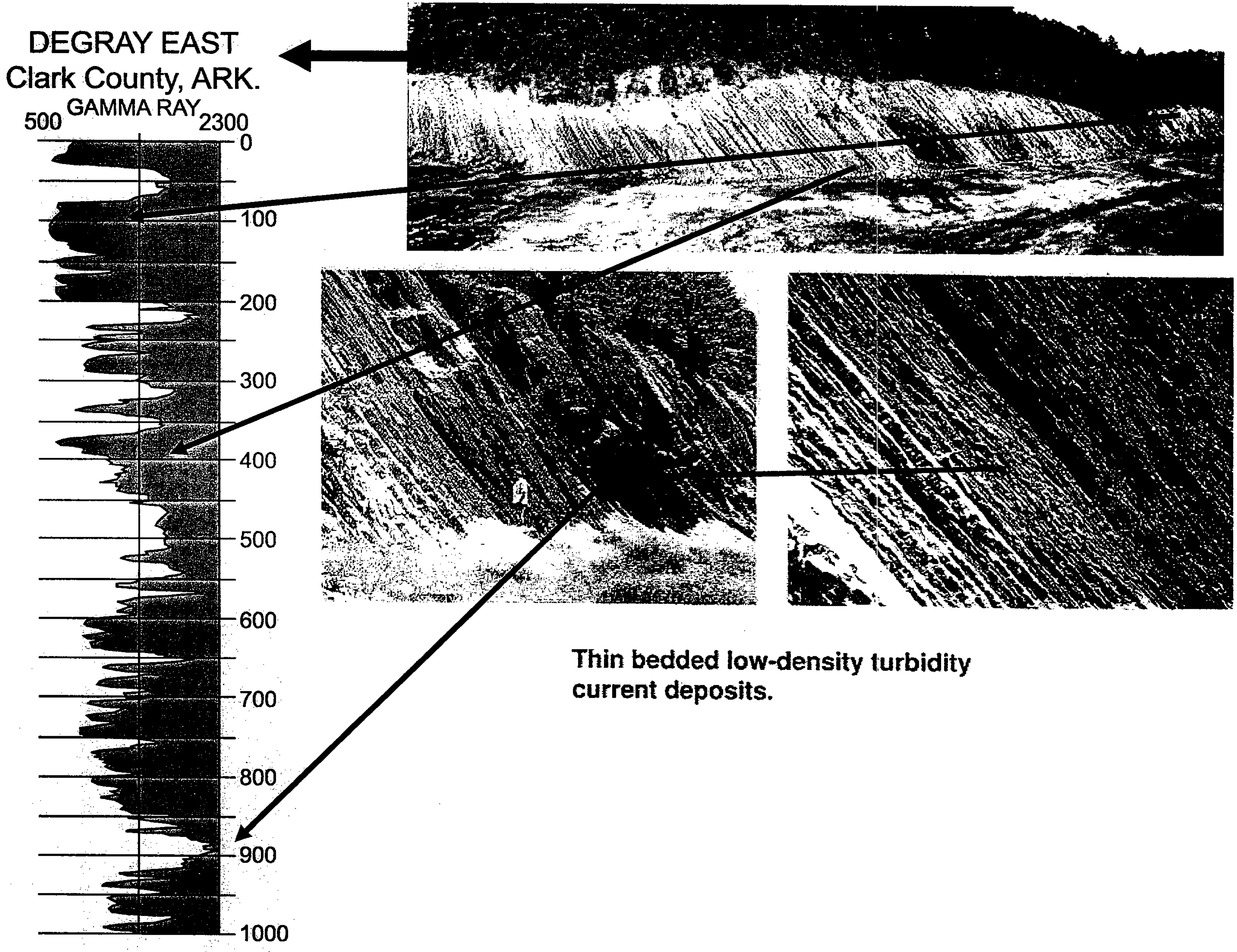


DeGray Lake Spillway, Arkansas

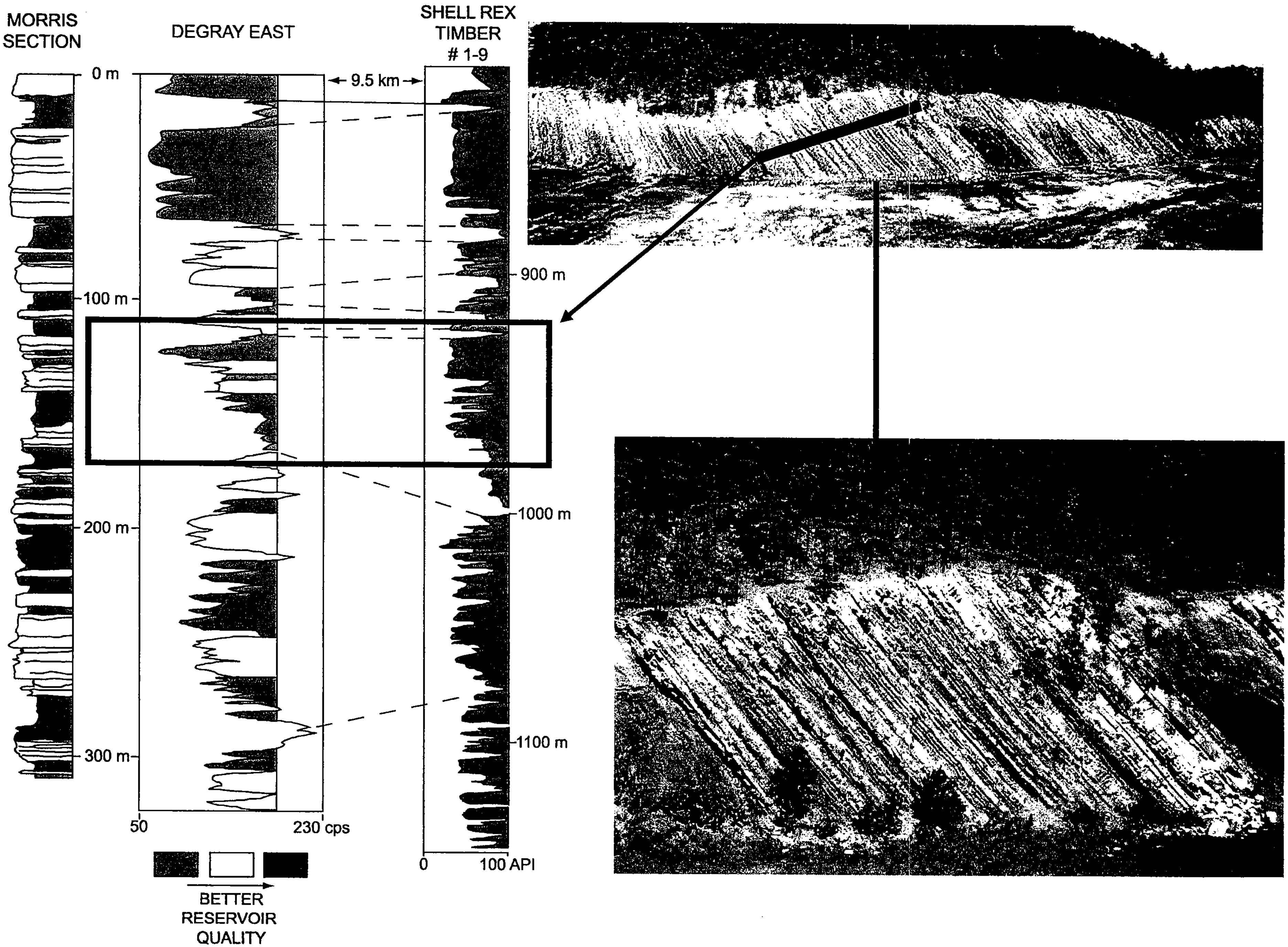
Jackfork Group, mainly sheet sandstones

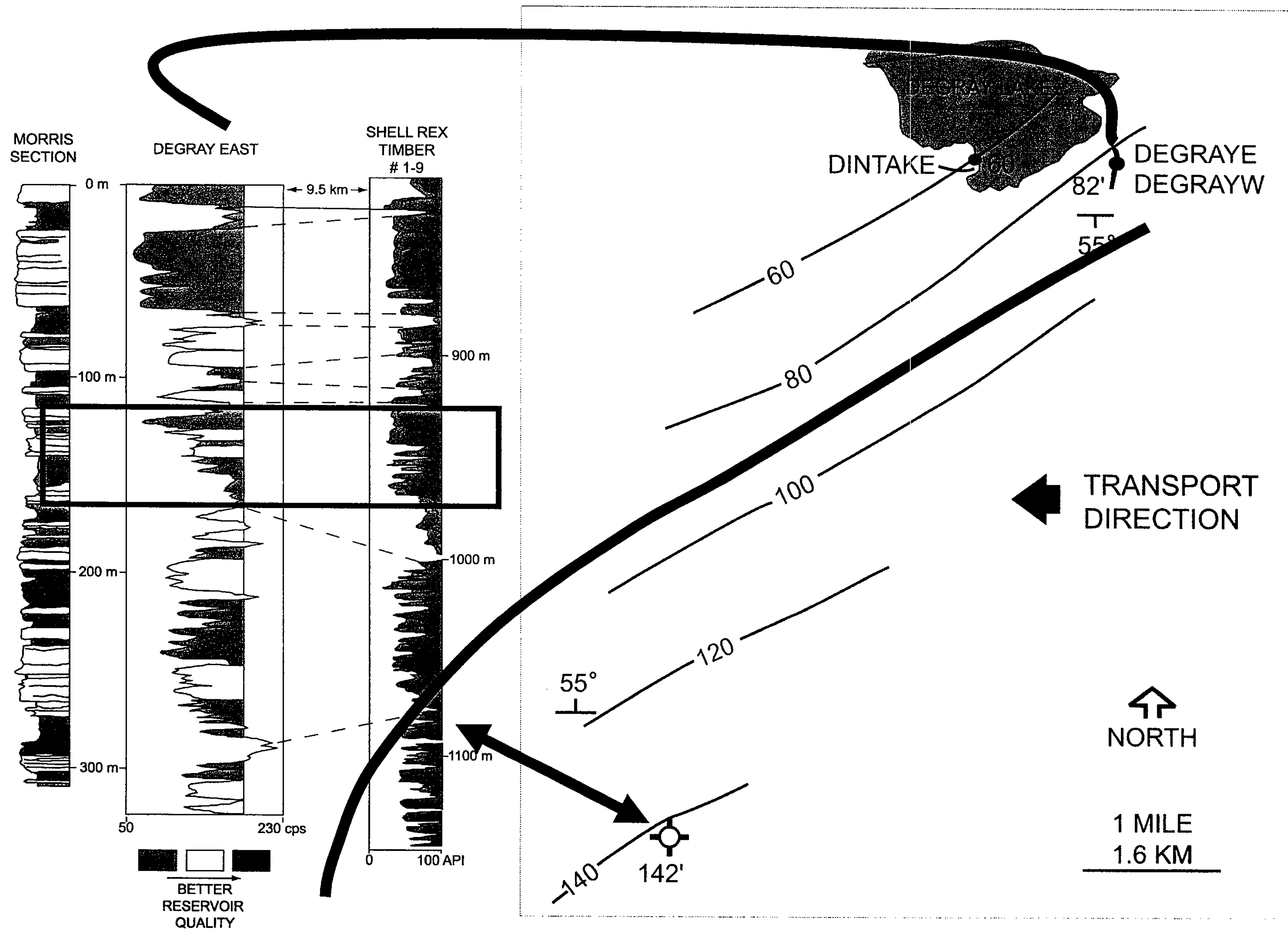
(Slatt et al., 2000)



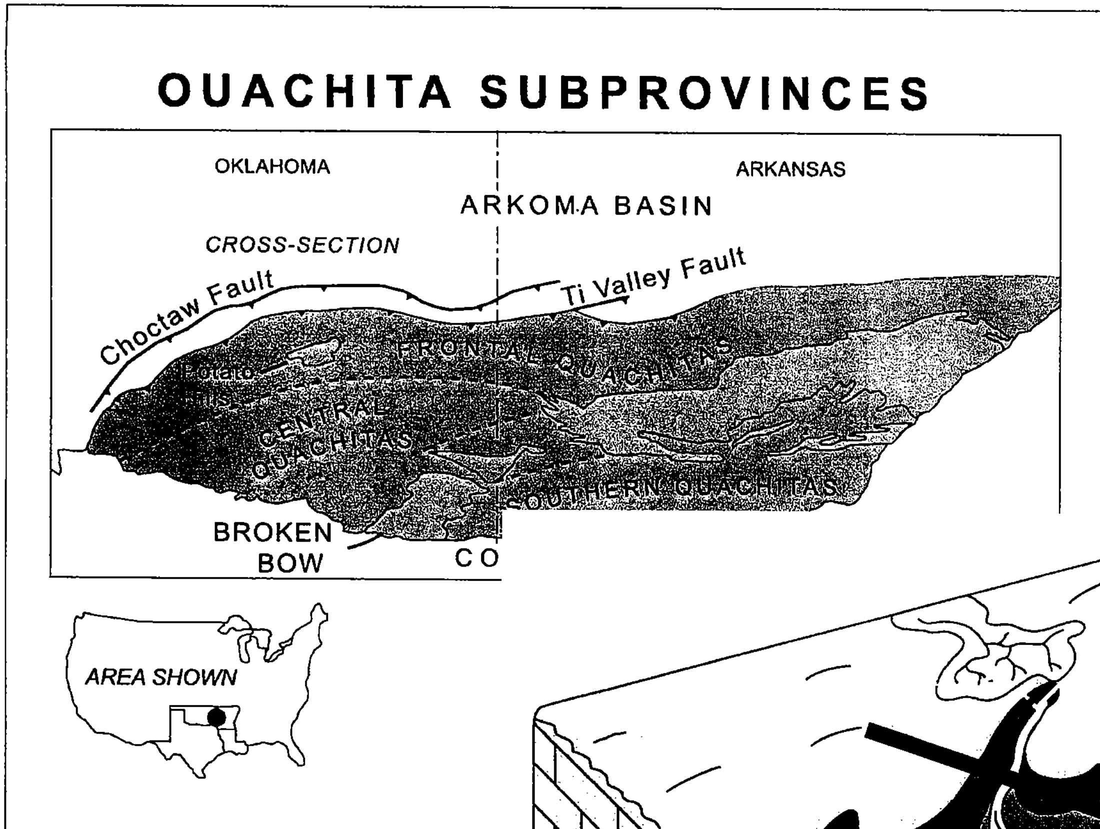


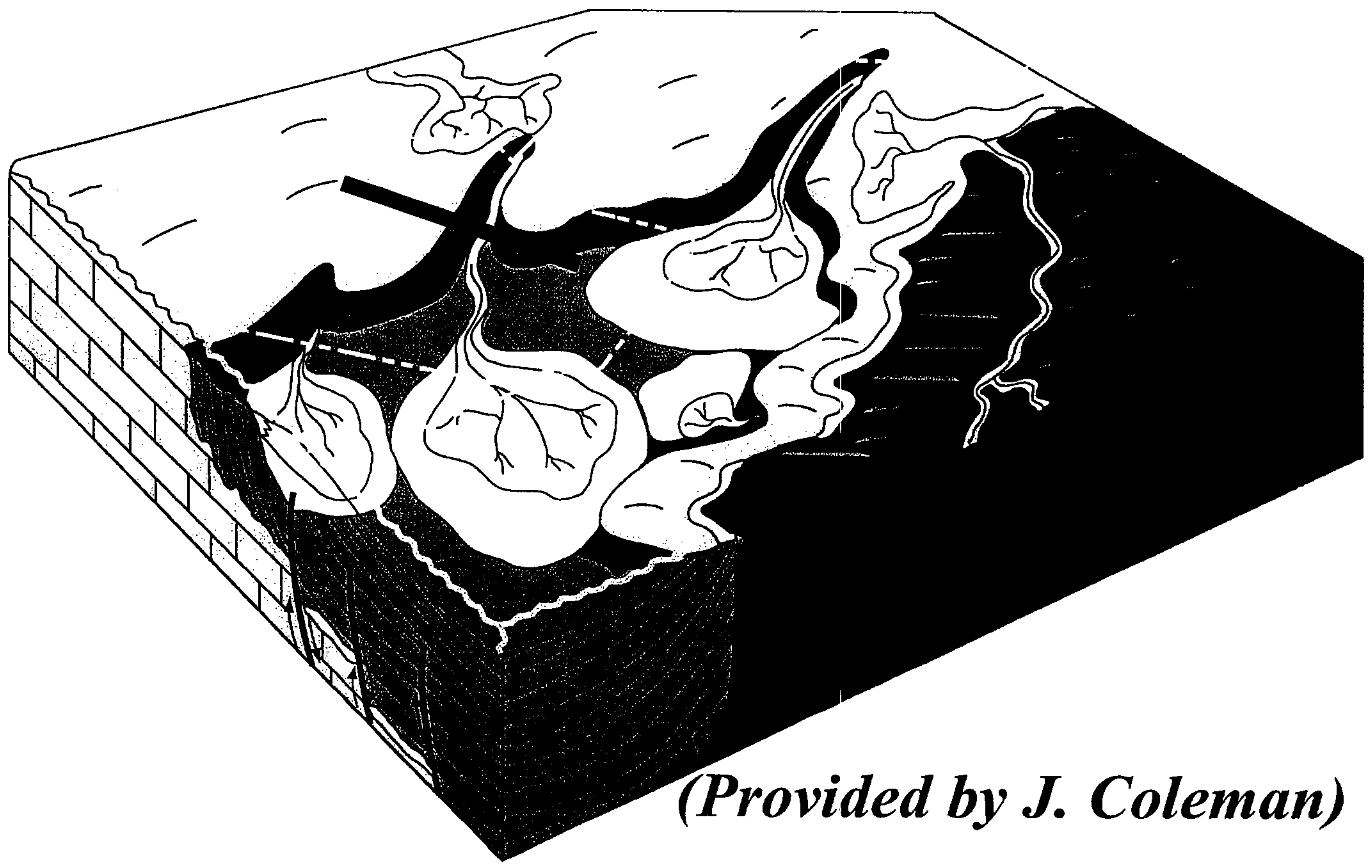
Thin bedded low-density turbidity current deposits.


MORRIS SECTION
DEGRAY EAST
SHELL REX TIMBER # 1-9
0 m
9.5 km
900 m
100 m
1000 m
200 m
1100 m
300 m
50
230 cps
0
100 API
BETTER RESERVOIR QUALITY



MORRIS SECTION
DEGRAY EAST
SHELL REX TIMBER # 1-9
9.5 km
0 m
100 m
200 m
300 m
900 m
1000 m
1100 m
50
230 cps
0
100 API
BETTER RESERVOIR QUALITY
DINTAKE
DEGRAYE
DEGRAYW
82'
55°
60
80
100
120
140
142'
TRANSPORT DIRECTION
NORTH
1 MILE
1.6 KM

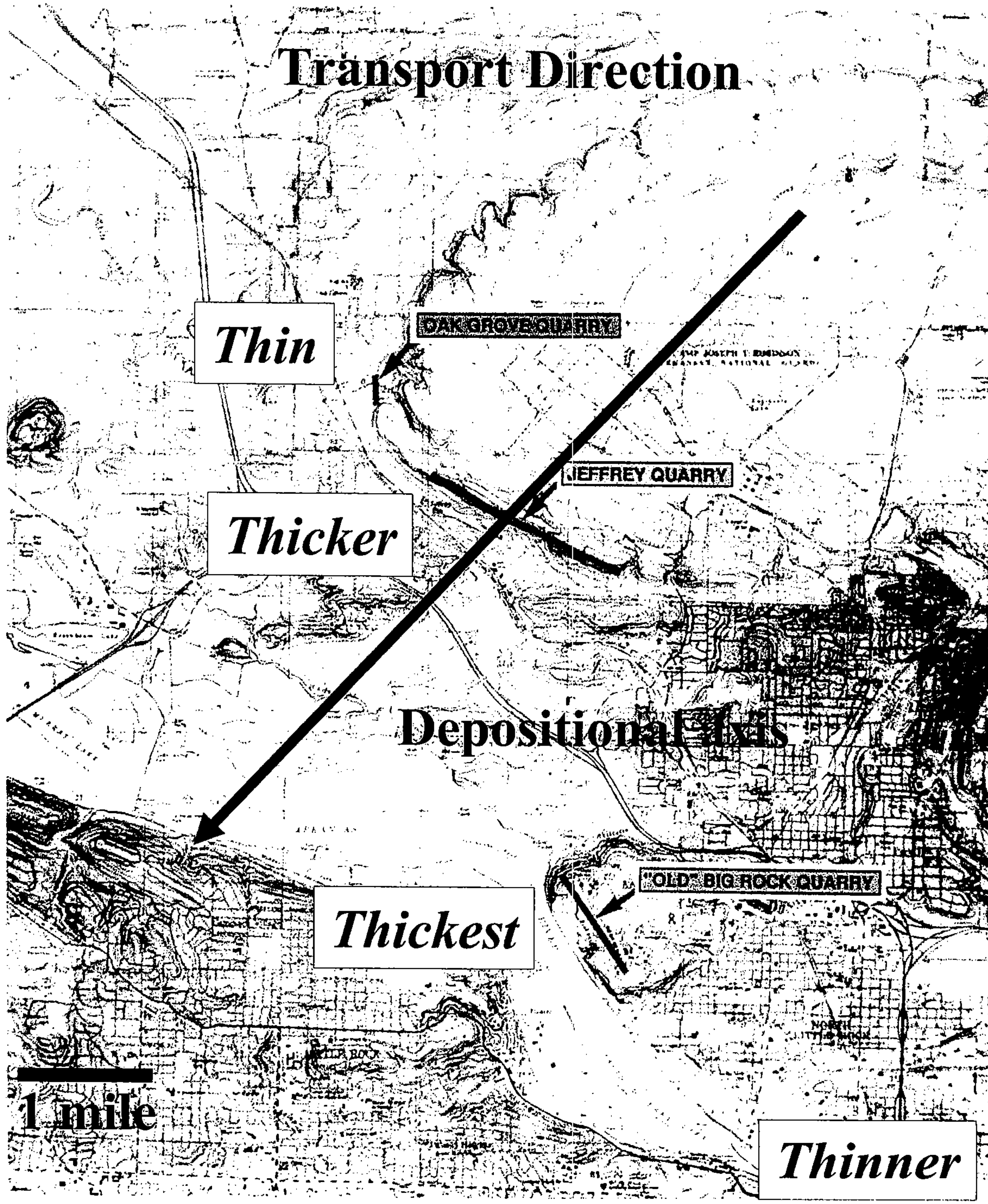




(Provided by J. Coleman)

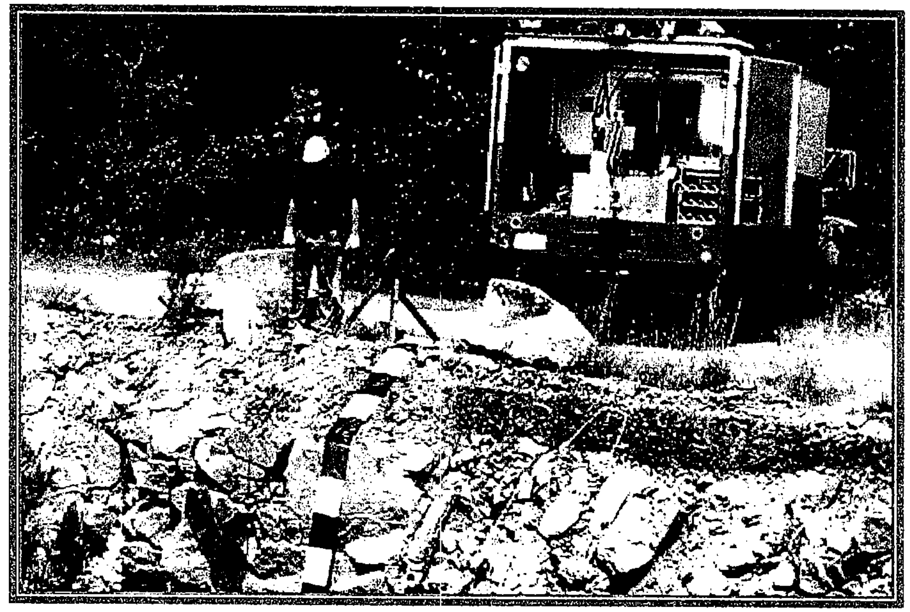
Upper Jackfork near Little Rock, Arkansas

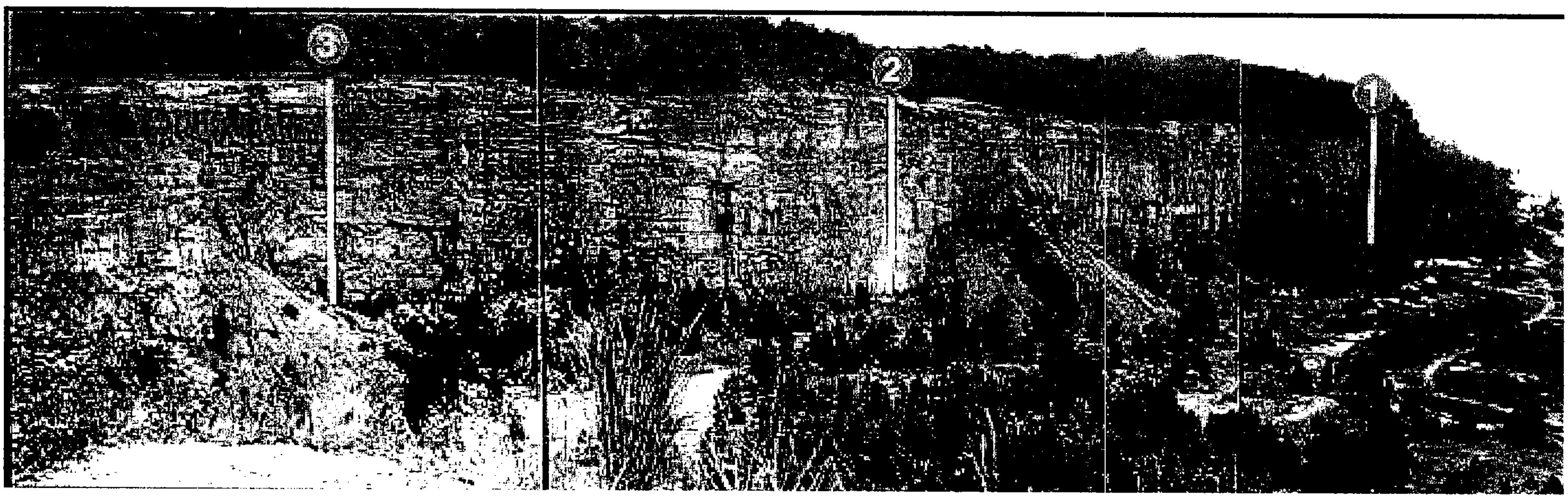
(Jordan et al. 1993)



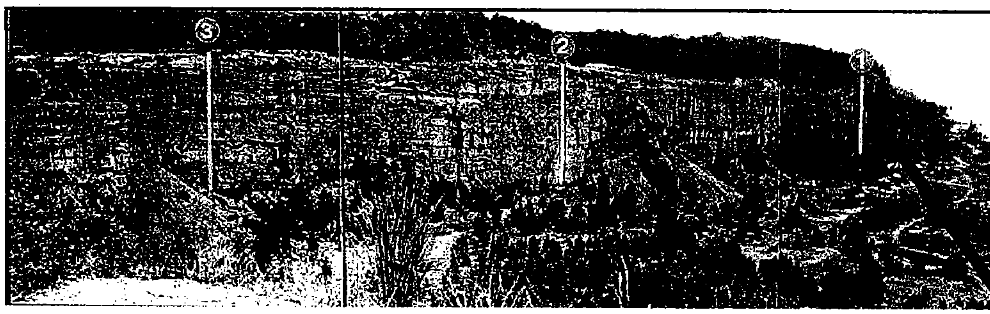
Big Rock Quarry

North Little Rock, Arkansas



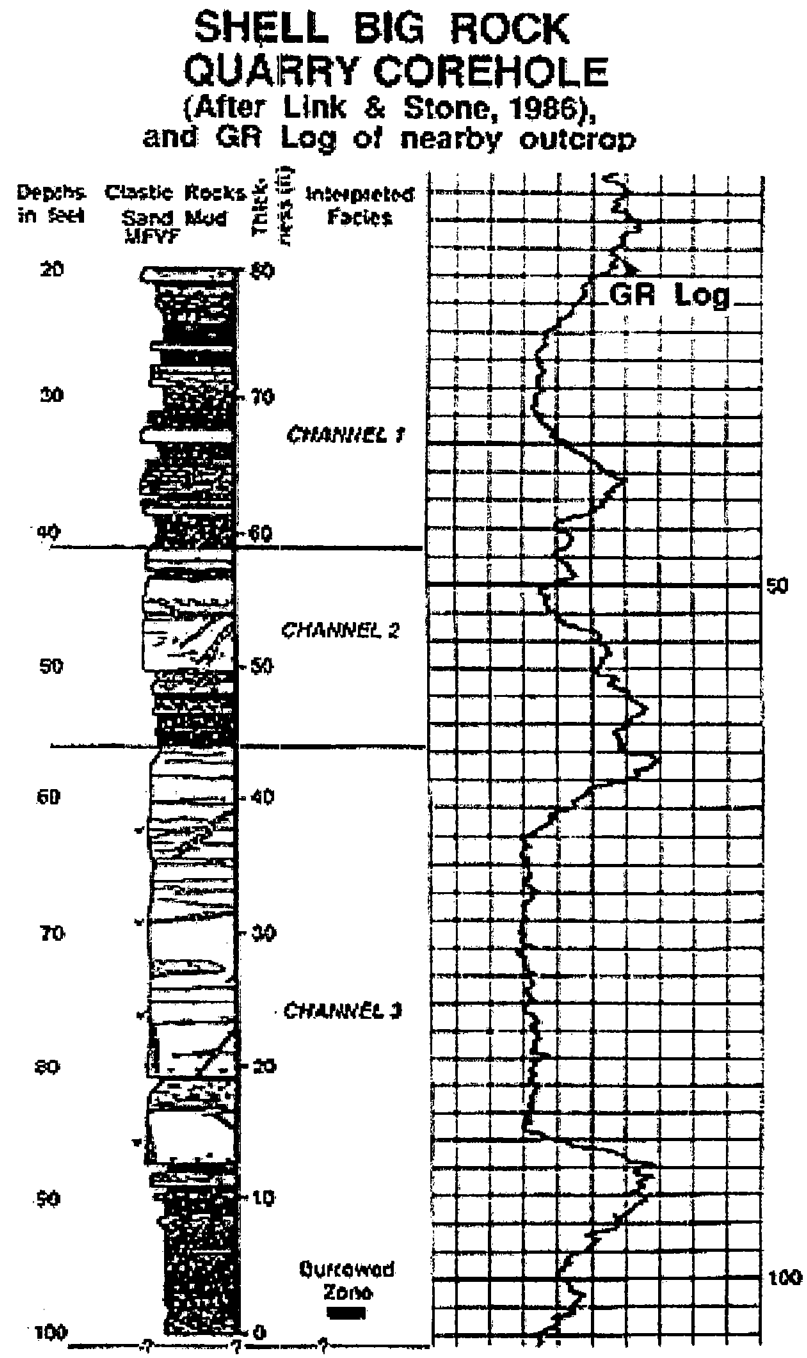


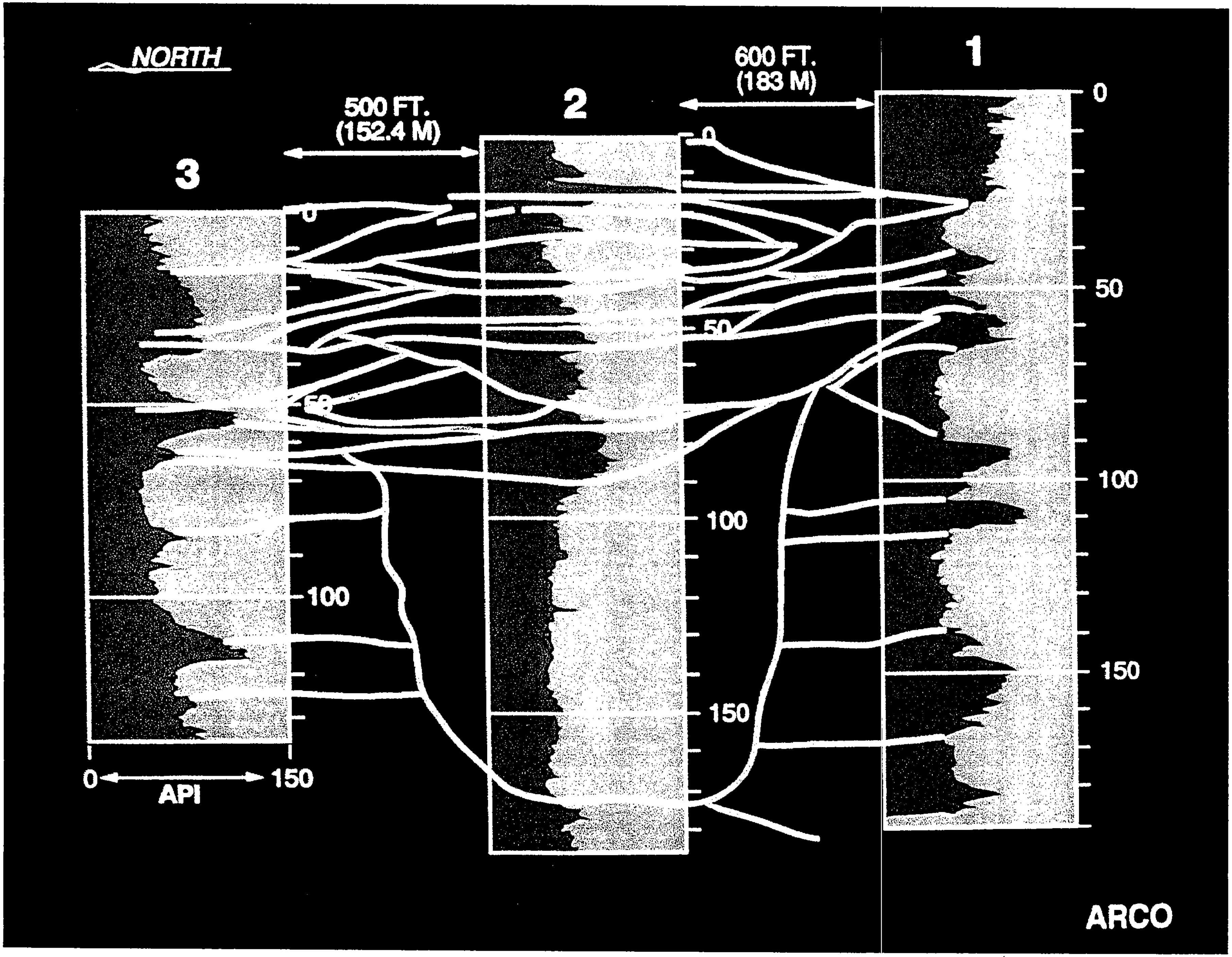
The three numbered vertical yellow lines are locations of outcrop gamma ray logs. Each log is spaced about 200m apart.



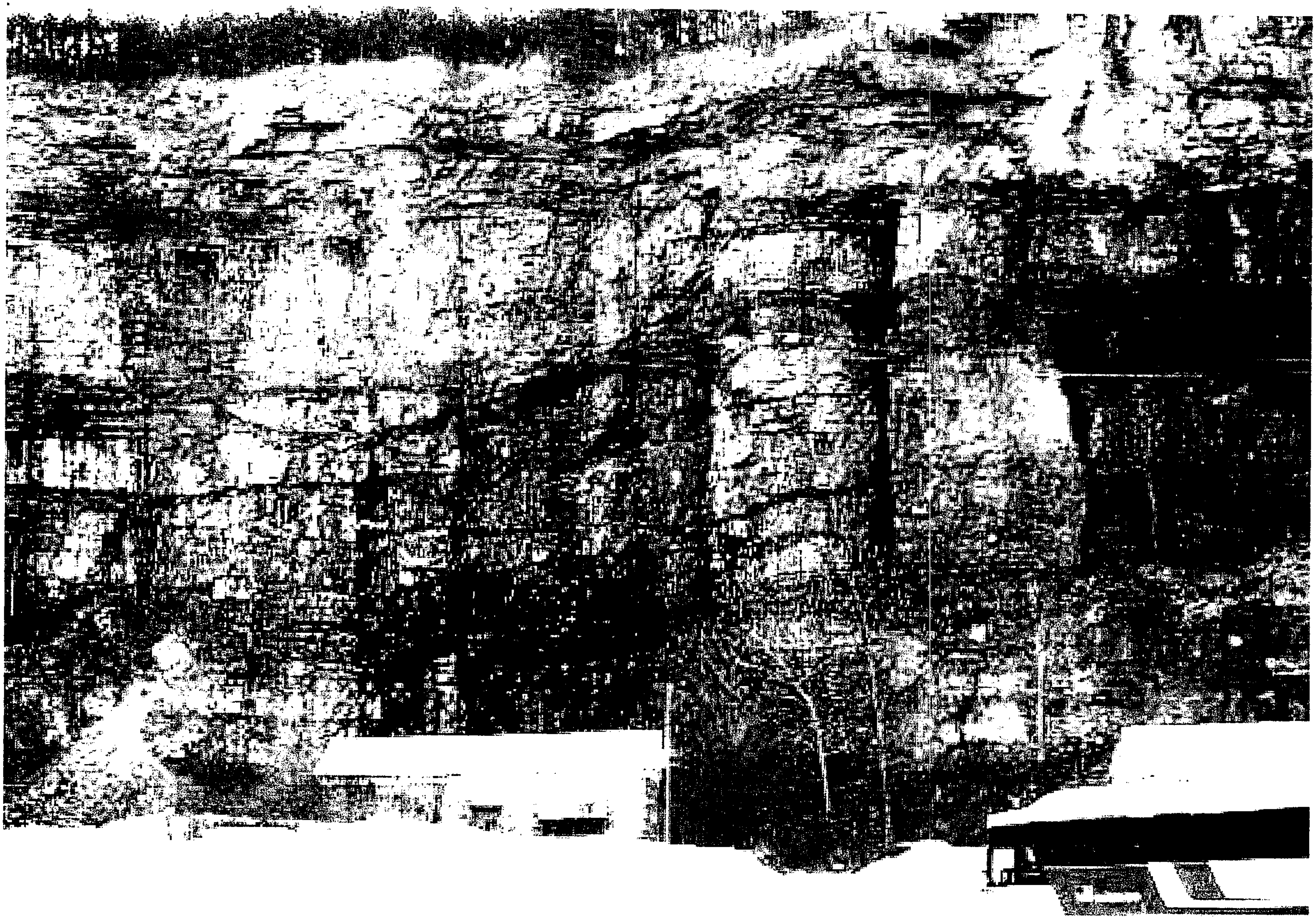
Outcrop gamma ray log from location 1. Shell Oil Co. drilled a core behind this outcrop location. Core description is shown alongside outcrop gamma ray log.

(Jordan et al., 1991)

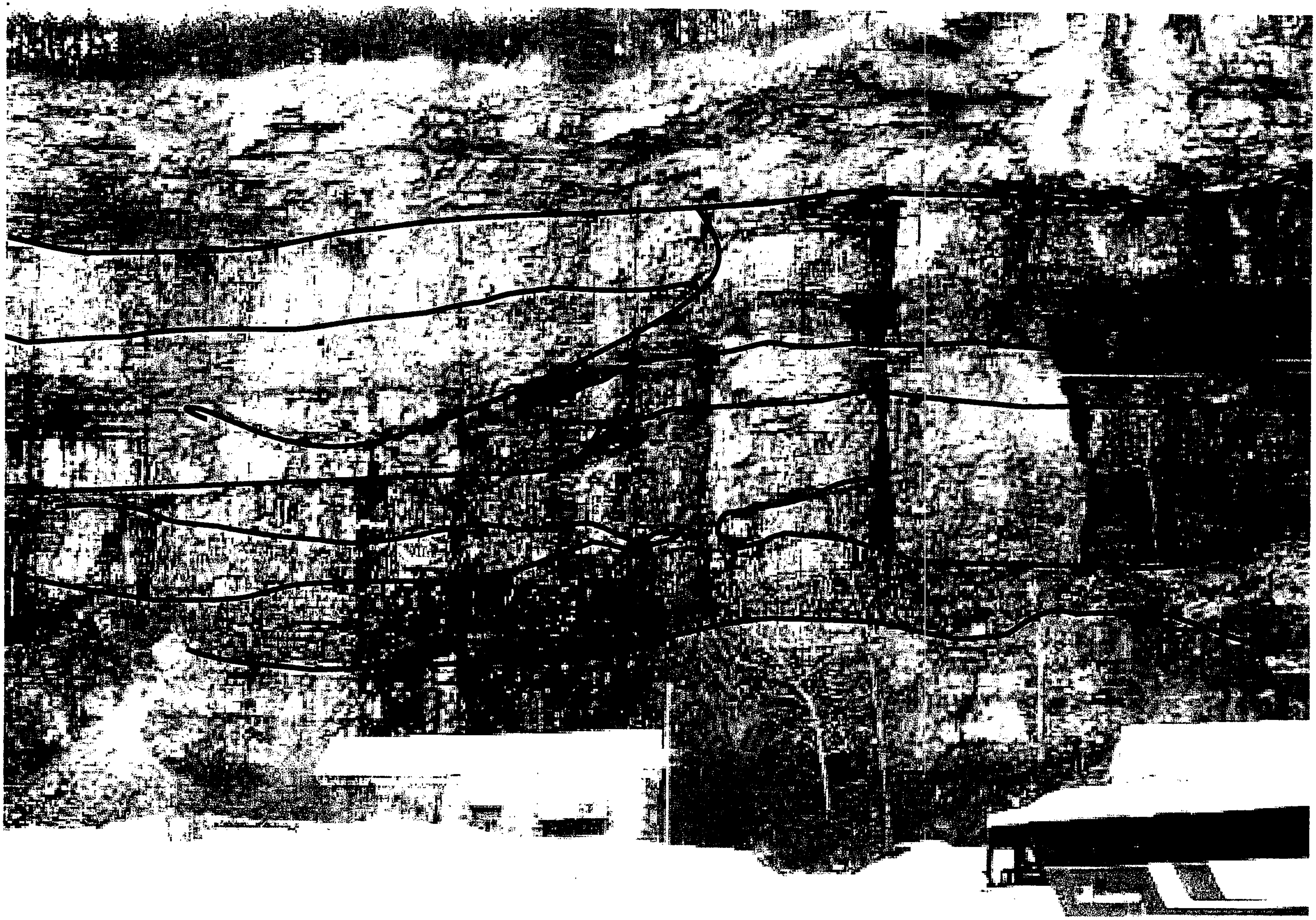




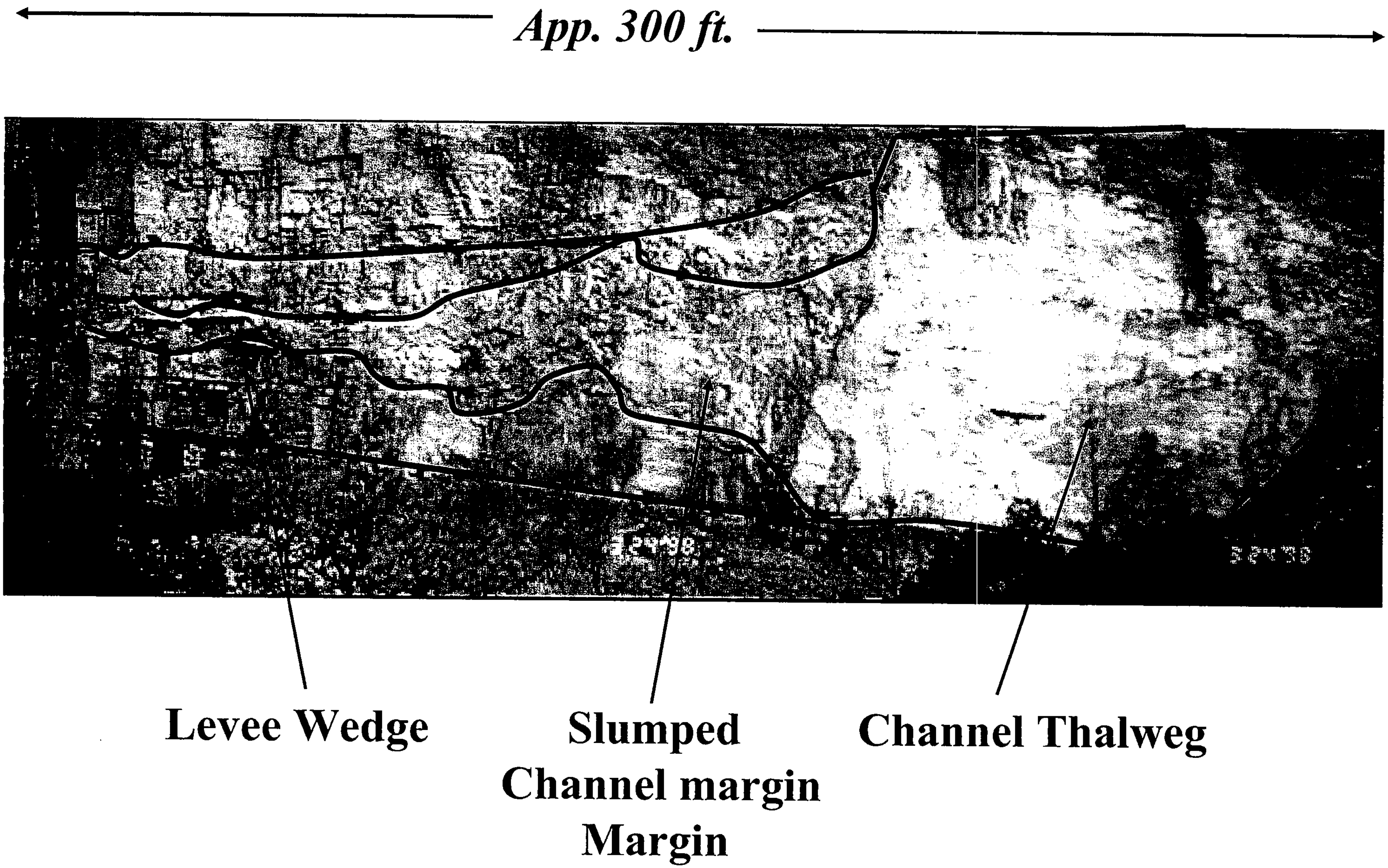
NORTH
500 FT.
(152.4 M)
600 FT.
(183 M)
3
2
1
0
50
100
150
0
50
100
150
0
50
100
150
0
API
150
ARCO

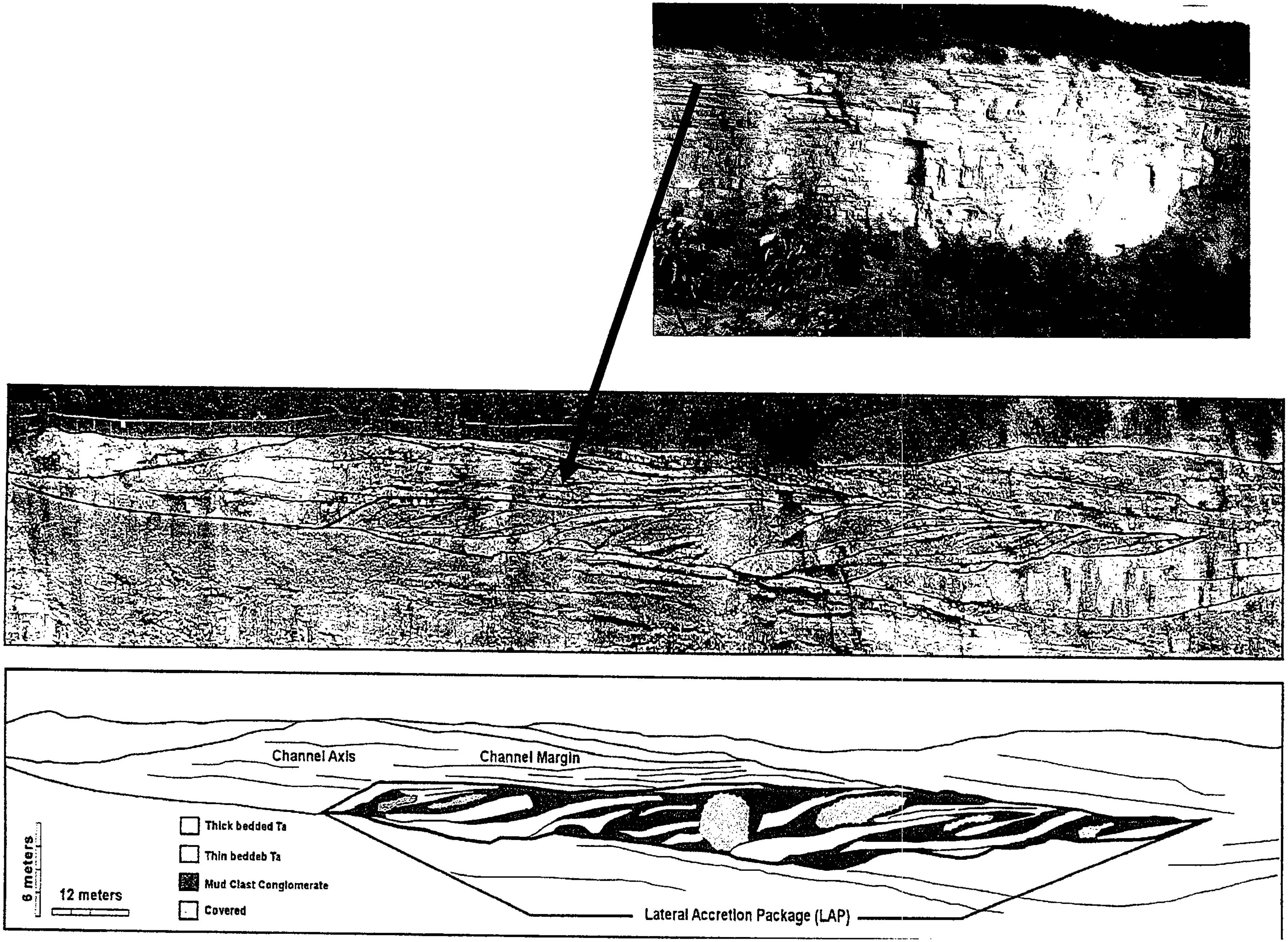


Cut-and-fill structures. Most cuts are mud-lined

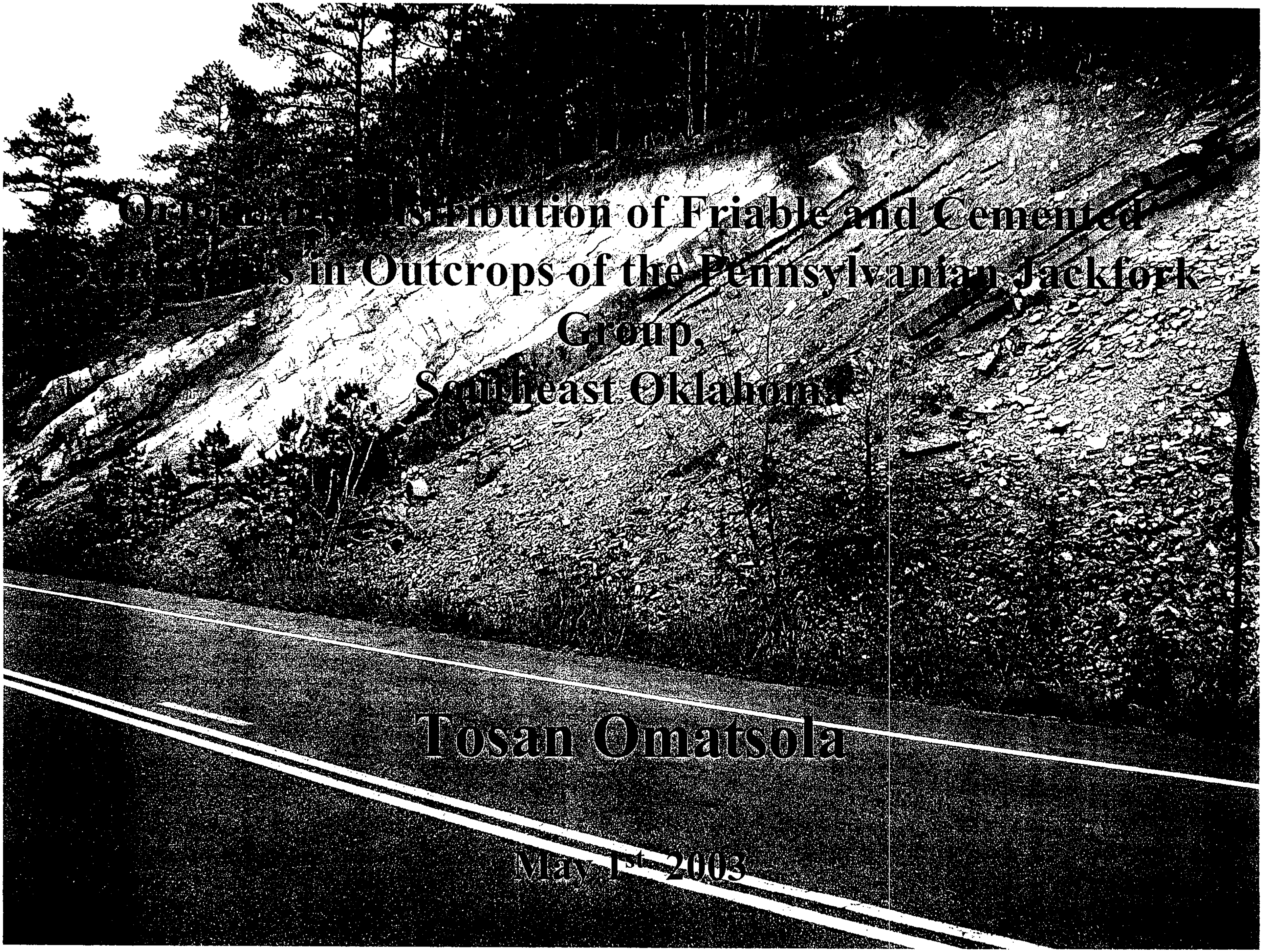


Cut-and-fill structures. Most cuts are mud-lined


App. 300 ft.
Levee Wedge
Slumped
Channel margin
Margin
Channel Thalweg



(Abreu et al., in press)

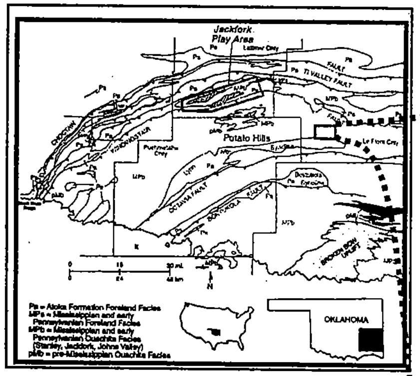

Origin and Distribution of Friable and Cemented
Sandstones in Outcrops of the Pennsylvanian Jackfork
Group,
Southeast Oklahoma
Tosan Omatsola
May 1st 2003

Sandstones in study area are dominated by two main sandstone types:

- **Friable sandstones**
- **Quartz cemented sandstones**

The two sandstones are representative of different porosity, permeability and facies types

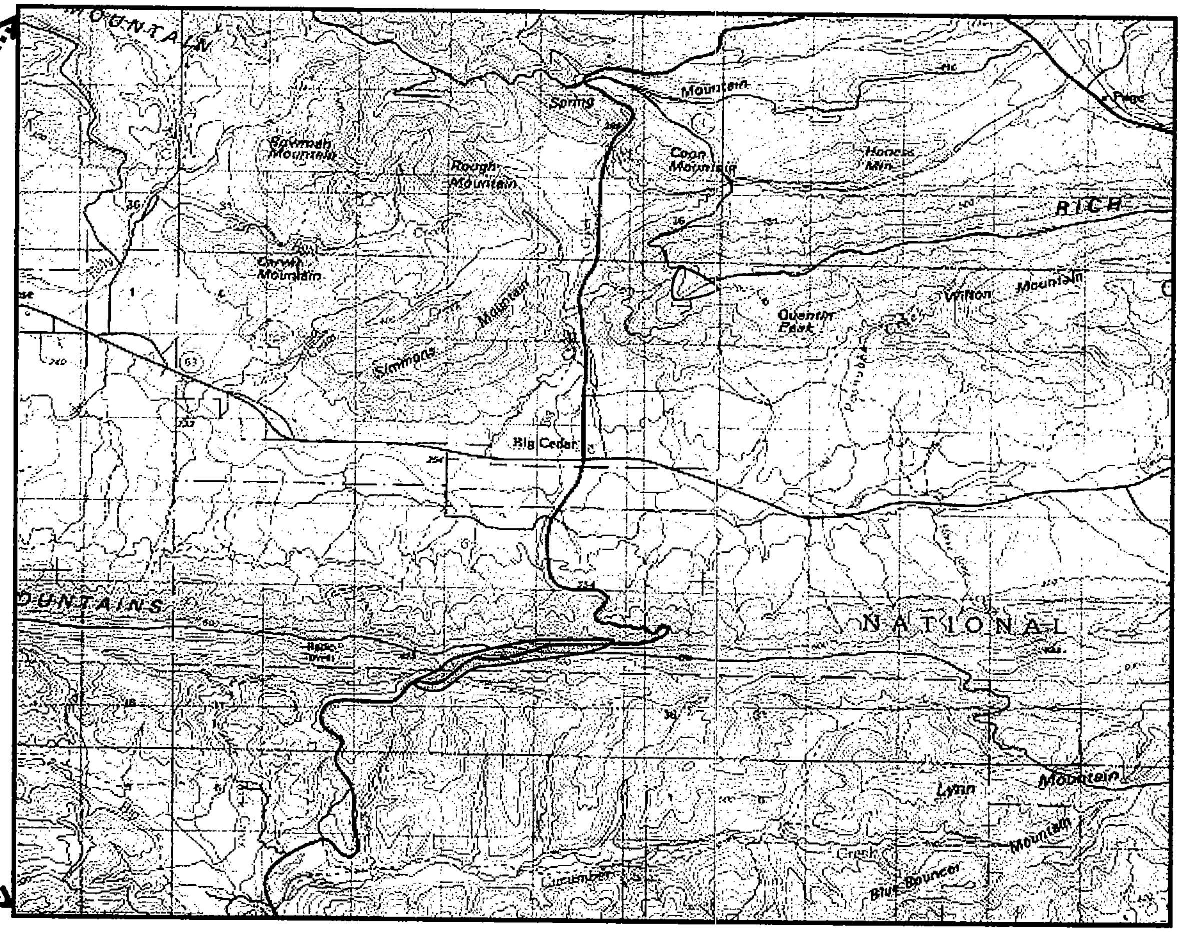
Study Area Location



(Modified from Montgomery, 1996)

- Arkoma Basin
- Frontal Ouachitas
- Central Ouachitas
- Broken Bow Uplift
- Study Area

The area of investigation is in the Ouachita Mountains, southeast Oklahoma; ~4 miles (6.5km) from the Oklahoma – Arkansas border



N

2 miles

Outcrop B along U.S Highway 1 (Talimena/Scenic Drive)

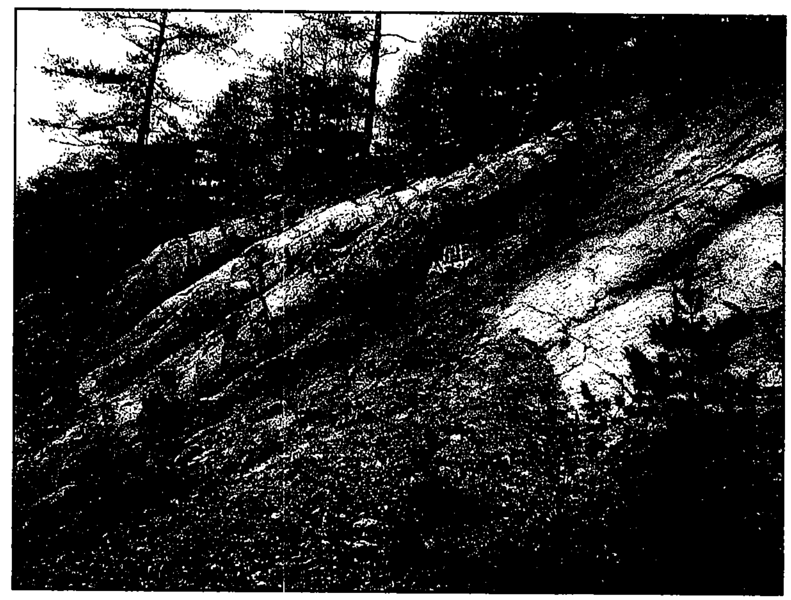
Outcrop A along U.S Highway 259

Lithostratigraphy

- Quartz cemented sandstones
  - Gray – tan (fresh) and light gray – medium brown (when weathered)
  - Very fine to fine-grained; moderately - well sorted
  - Planar-tabular bedded; bulbous contacts, scoured bedding (occasionally)
  - Thick & thin bedded (0.5 – 5ft), (0.8m-1.5m); massive, amalgamated or layered; Bouma Ta-Tc beds
  - Various sedimentary structures and deepwater ichnofacies
  - Highly fractured

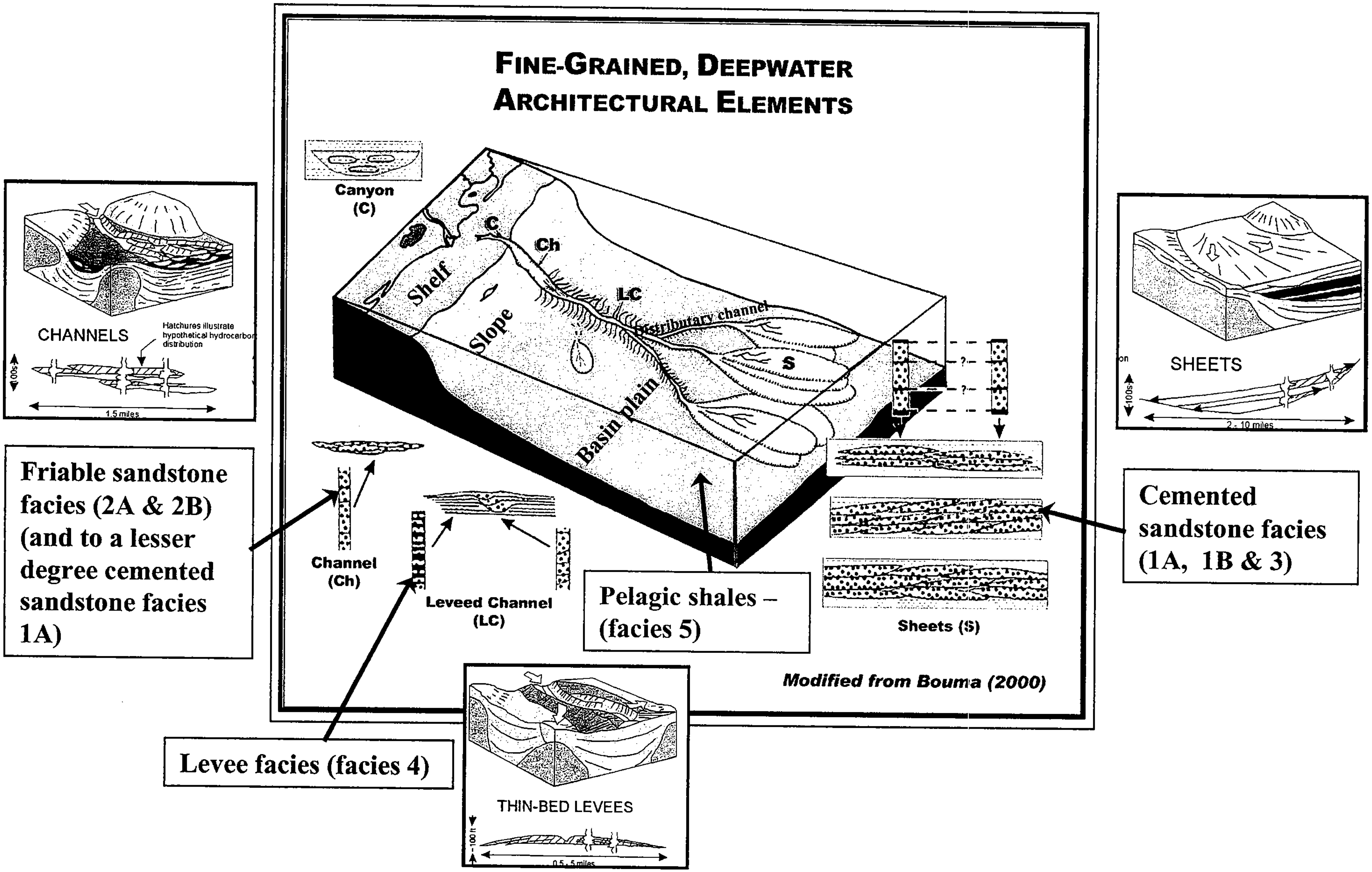
Lithostratigraphy

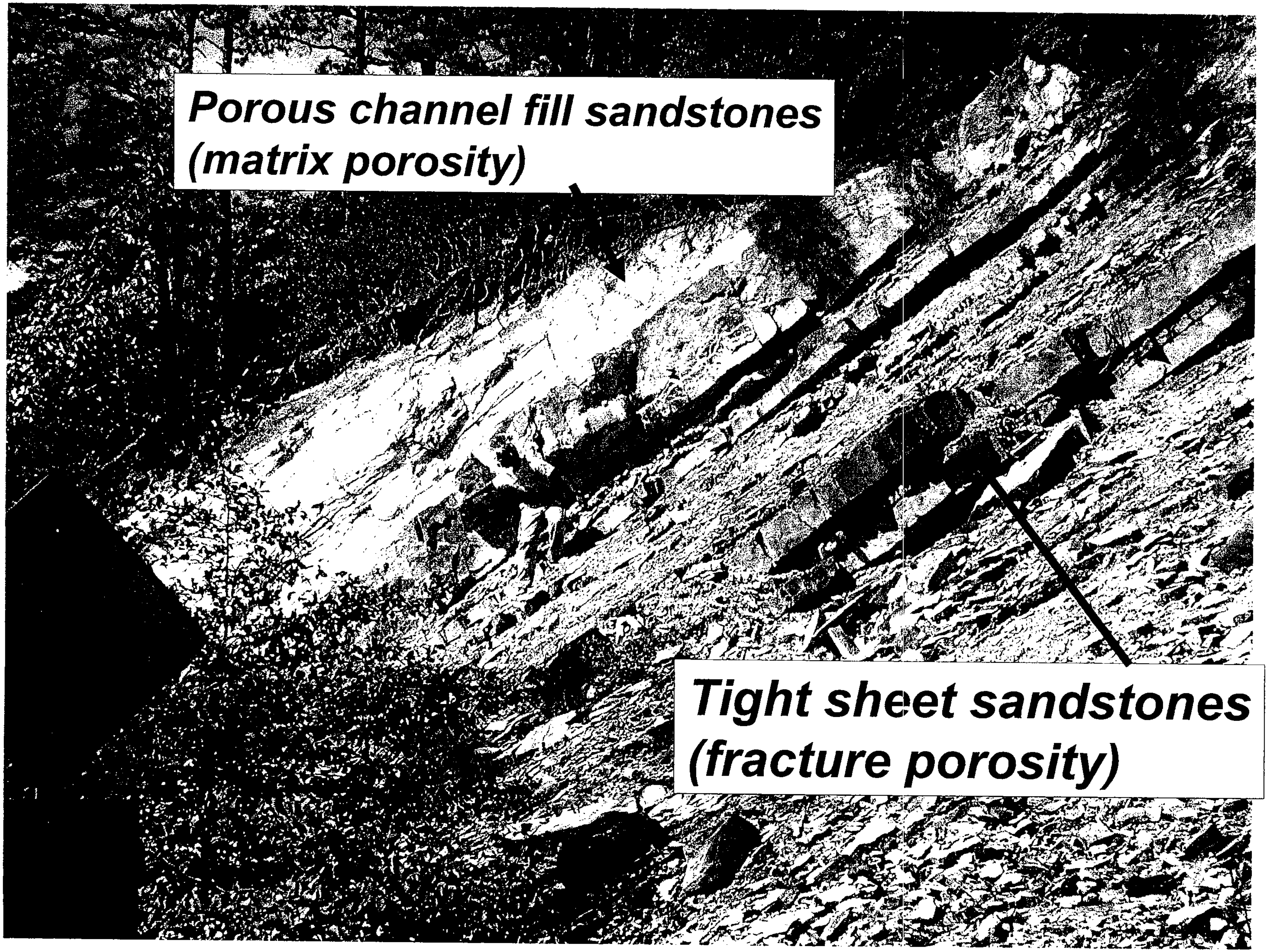
- Friable sandstones
  - Gray – whitish (fresh) and yellow – orange (when weathered)
  - Fine to medium-grained; poorly - moderately sorted
  - Bulbous contacts/bedding; planar bedded (occasionally)
  - Thick & thin bedded (0.5 – 7ft), (0.8m-2.1m); massive, amalgamated or layered (occasionally)
  - Various sedimentary structures
  - Highly porous (and also fractured)



Sedimentary Environment –

Jackfork Group Depositional and Facies Model

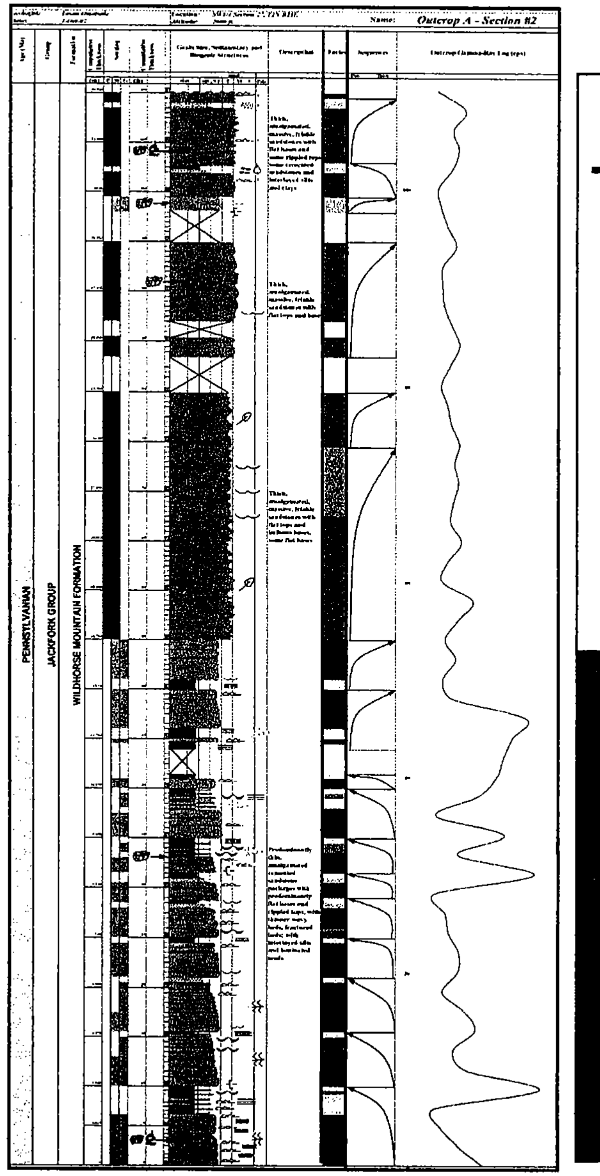



Porous channel fill sandstones
(matrix porosity)
Tight sheet sandstones
(fracture porosity)

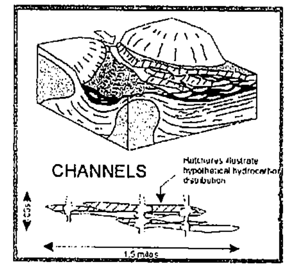
Jackfork Reservoir Potential - *Facies*

- Sequence stratigraphy, ***where applicable*** provides a predictive tool for the lateral and vertical distribution of facies

- By identifying channelized (matrix porosity) and non-channelized strata (fracture porosity) explorationists may better predict where these facies may exist and tailor exploration and production plans accordingly.

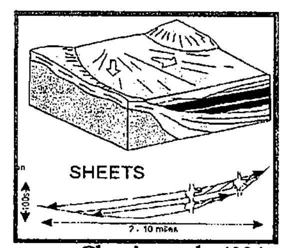


Friable Sandstones (channel Facies) Matrix porosity



Chapin et al., 1994.

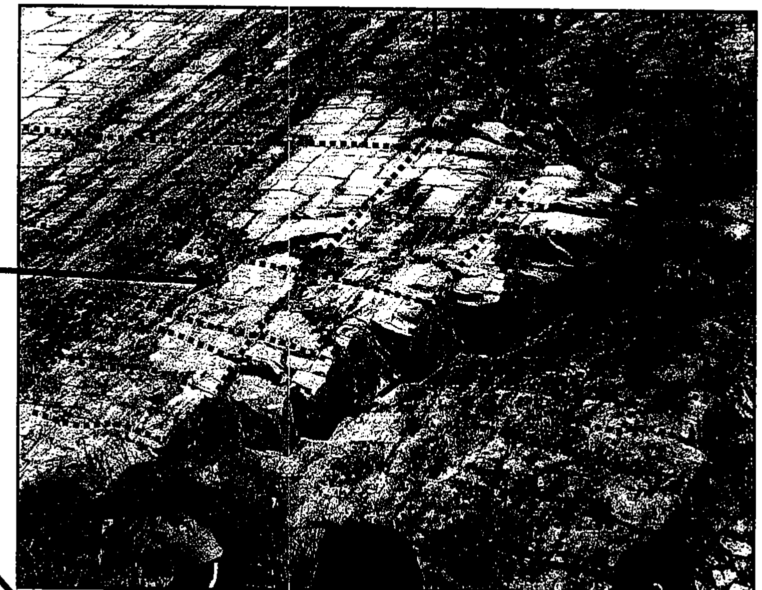
Quartz Cemented Sandstones (sheet facies) Fracture porosity

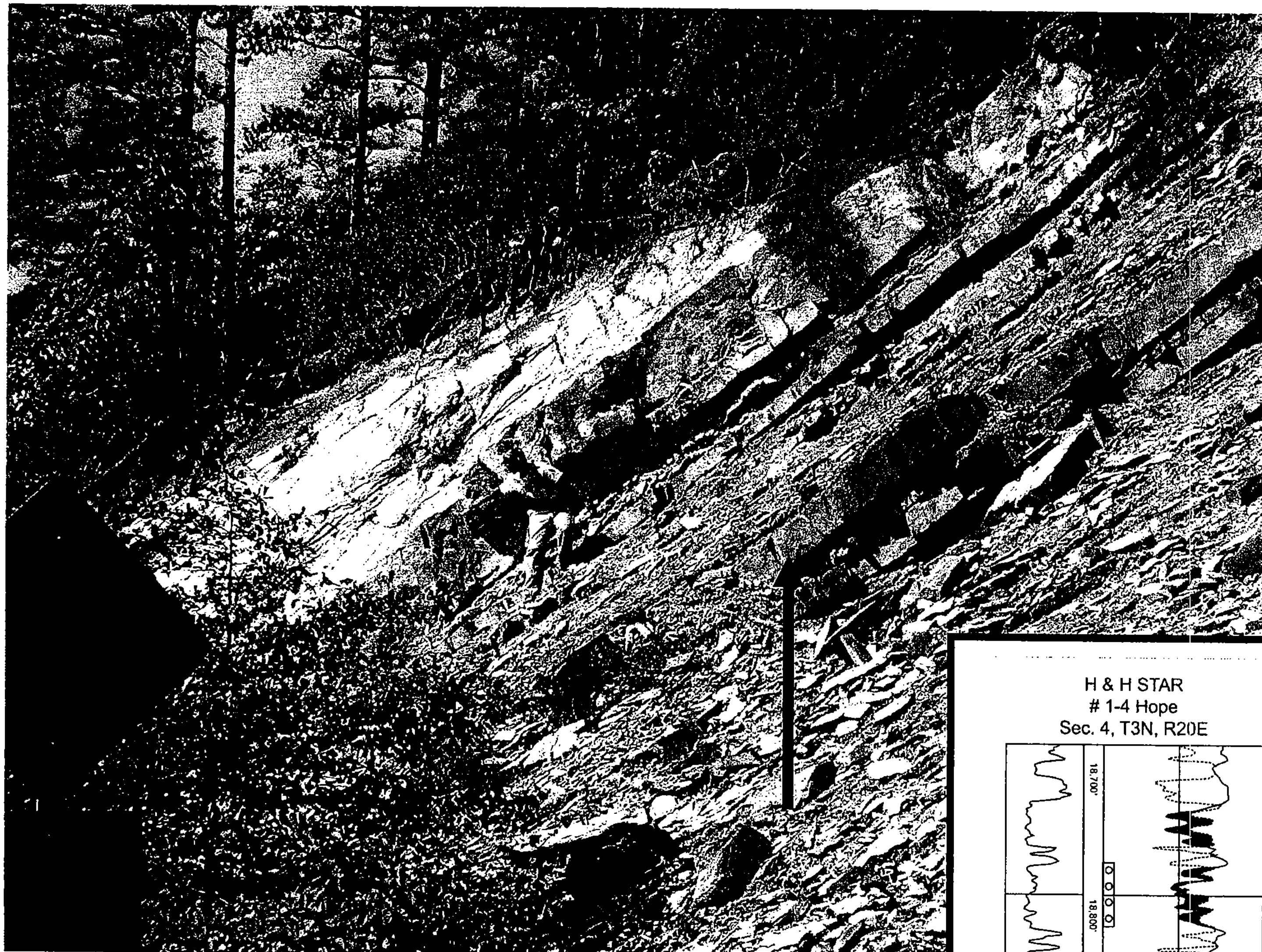


Chapin et al., 1994.

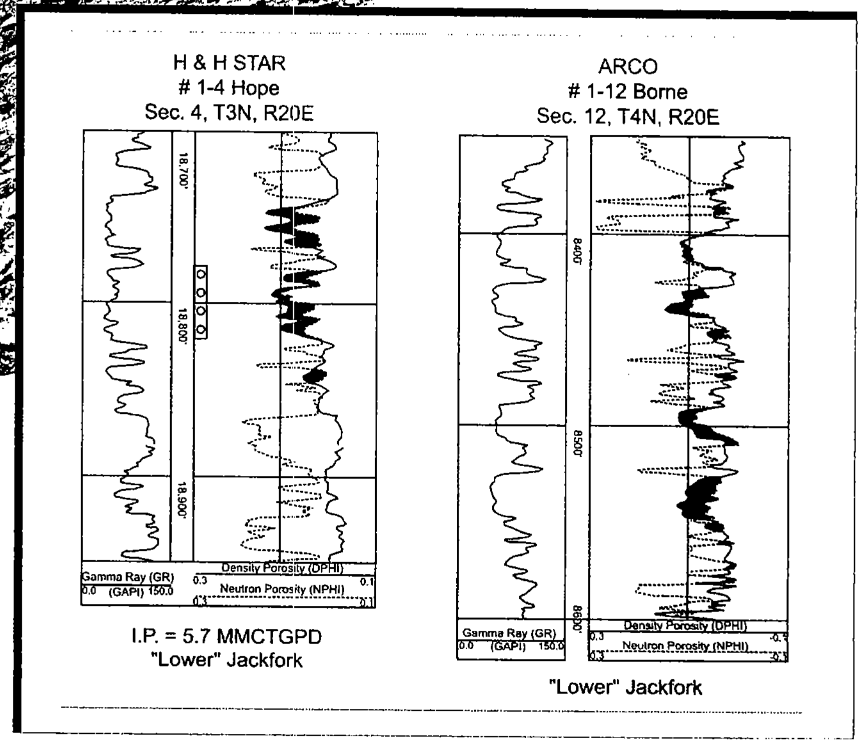
Jackfork Reservoir Potential - *Porosity*

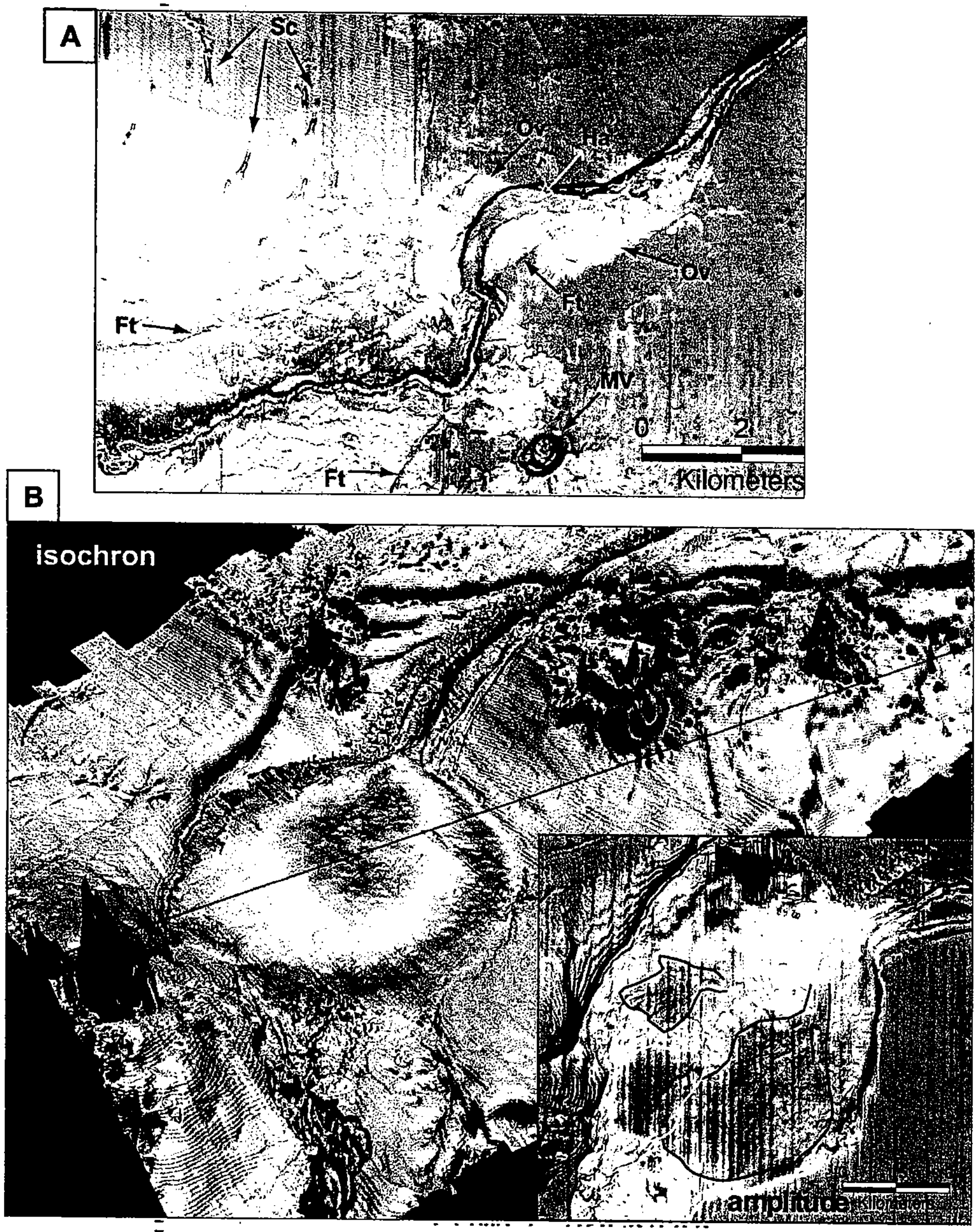
- **Studies show that:**
  - **Fracture porosity dominates in the cemented sandstones**
  - **Friable sandstones matrix porosity is dominant.**
- **In subsurface analog reservoirs, juxtaposition of the different sandstone types with their associated differences in reservoir quality may result in among others:**
  - **Varying production rates and development operational hazards**
  - **Challenging development economics for an analog reservoir.**



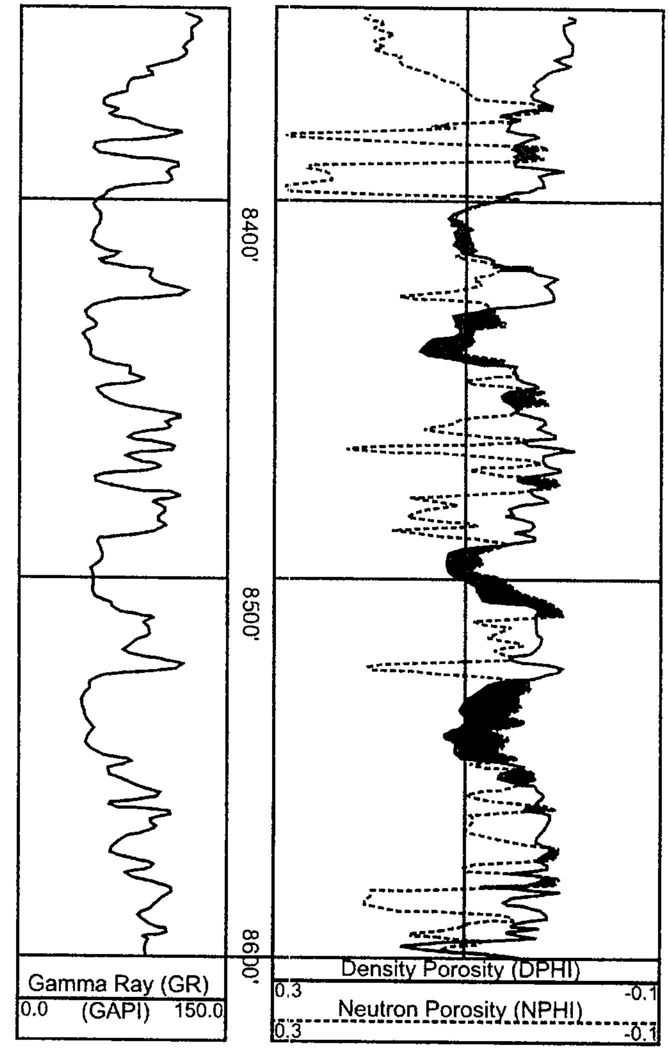


Sheets or channels????
Does it matter????





ARCO
1-12 Borne
Sec. 12, T4N, R20E



"Lower" Jackfork

Sheet or channel-fill sandstones????? Does it matter???