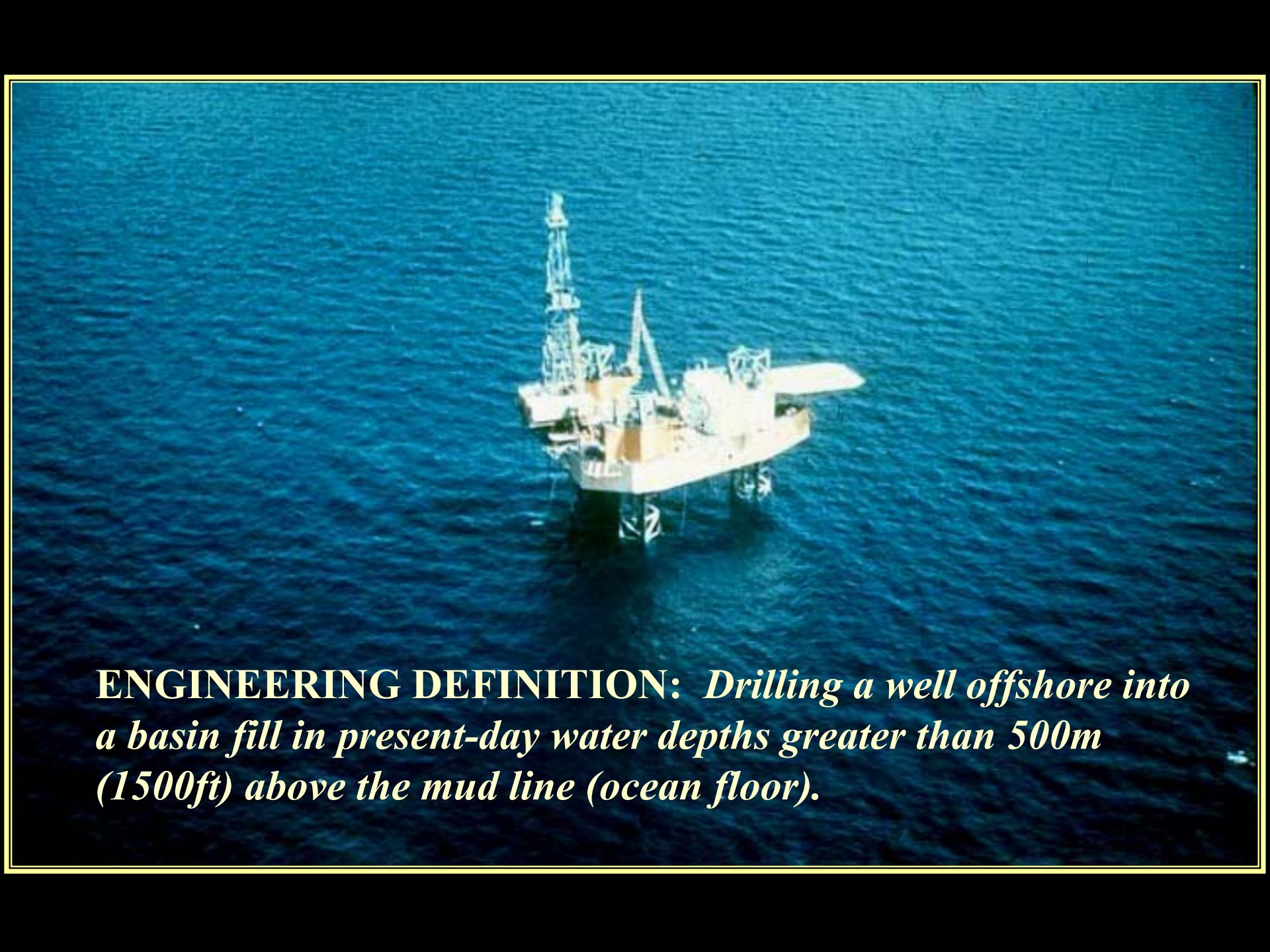
2001-02 AAPG Distinguished Lecture

Funded by the AAPG Foundation
through the J. Ben Carsey Memorial Endowment

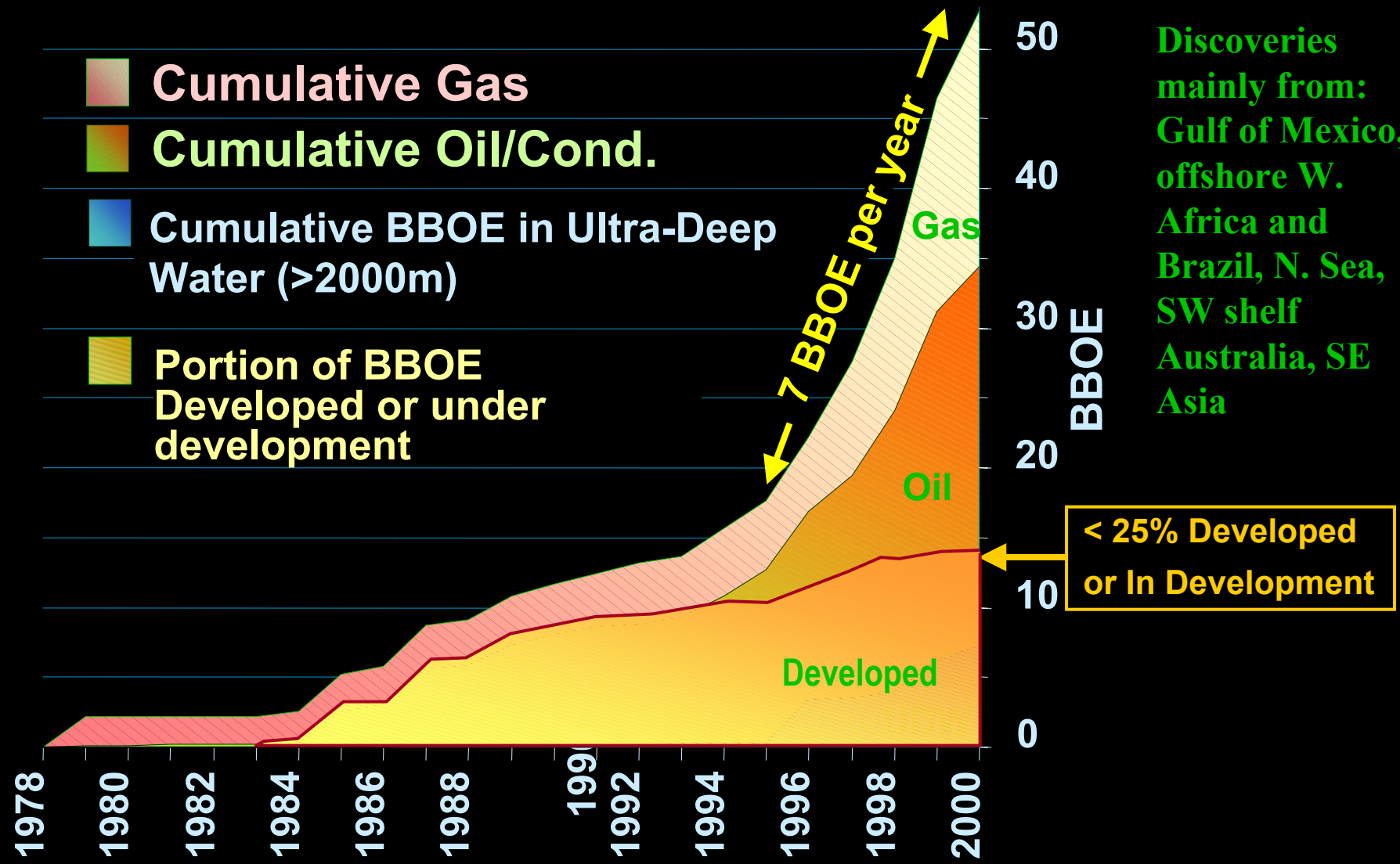
Outcrop/Behind Outcrop Characterization of Deepwater (Turbidite) Petroleum Reservoir Analogs: Why and How

Roger M. Slatt
University of Oklahoma
Norman, Oklahoma



ENGINEERING DEFINITION: ***Drilling a well offshore into a basin fill in present-day water depths greater than 500m (1500ft) above the mud line (ocean floor).***

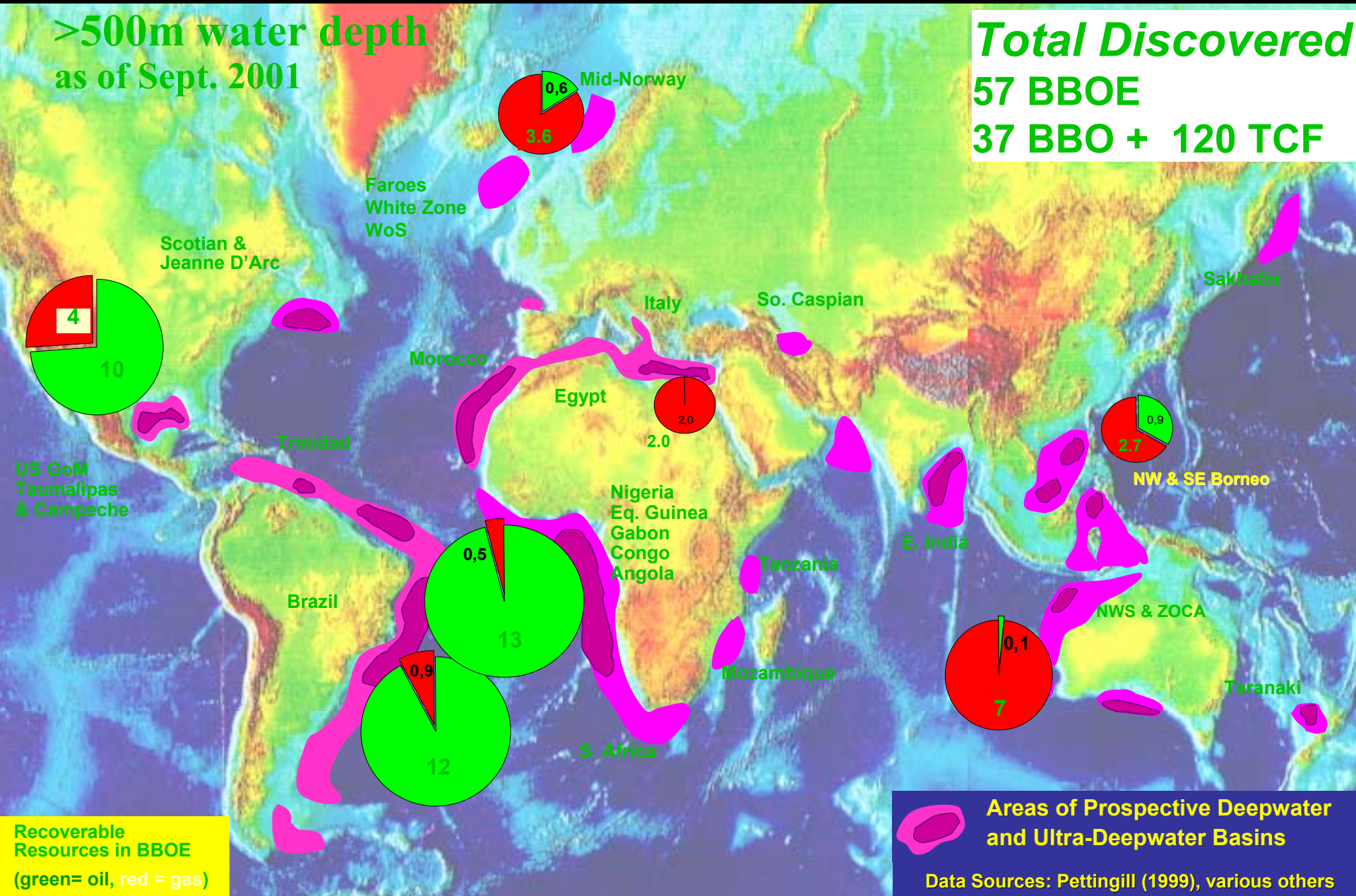
Deepwater (>500m) discovered reserves



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

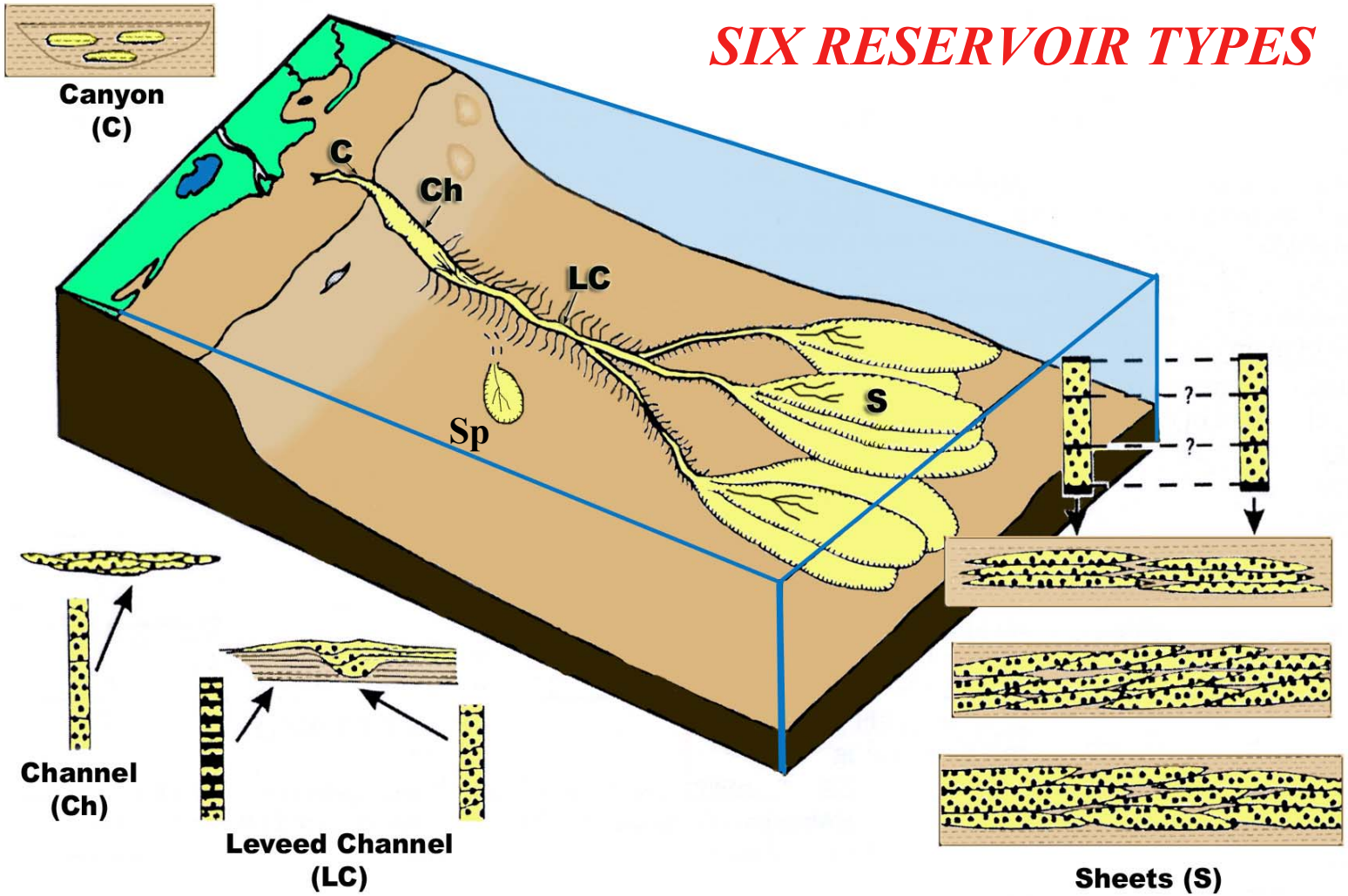
Source: Various

Deepwater Discovered Reserves

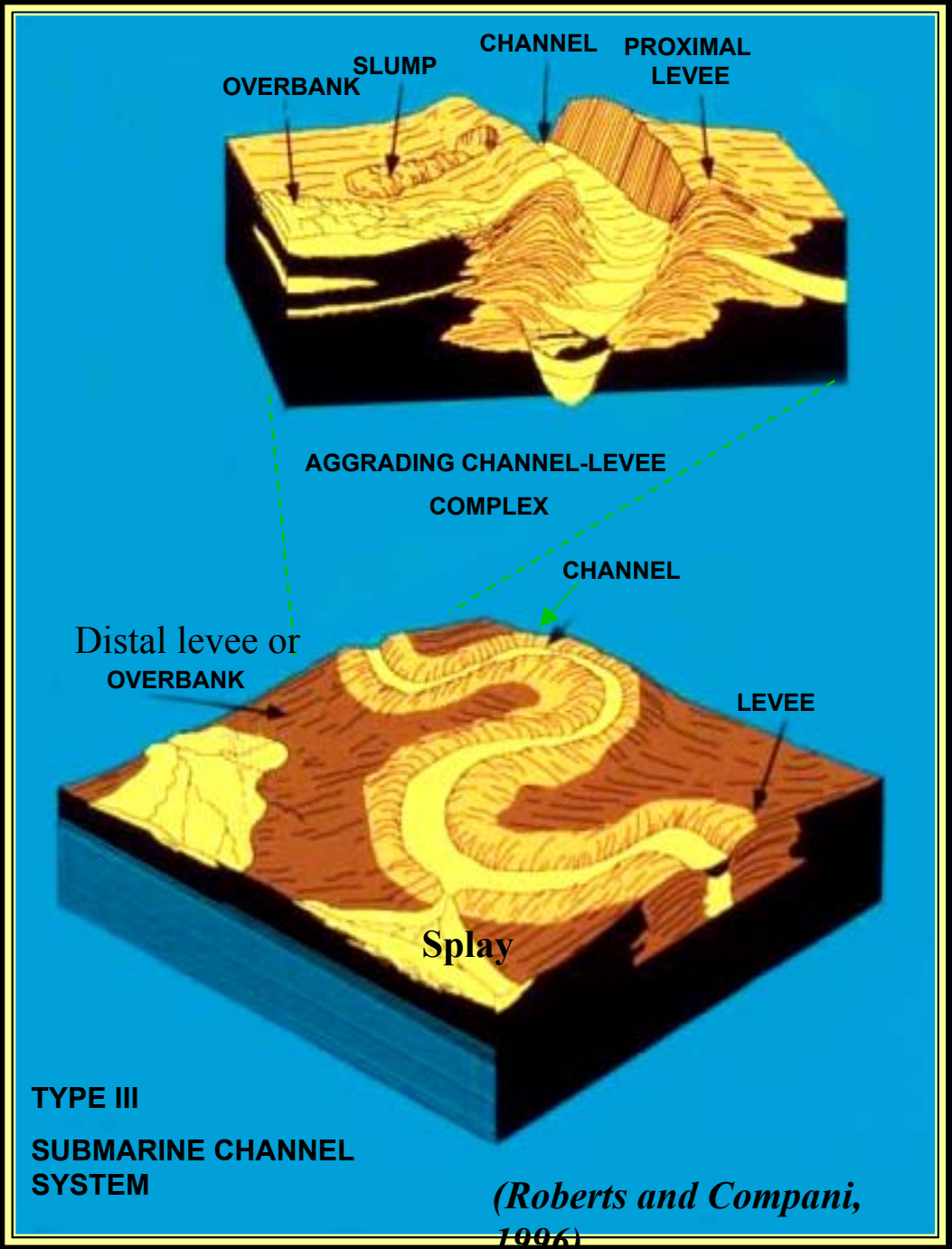


GEOLOGIC DEFINITION: Clastic sediments transported beyond the shelf edge into deep water by sediment gravity flow processes and deposited on the continental slope and in the basin. They are later buried and become part of a basin fill: ***Engineering and geologic 'deep water' are usually the same.***

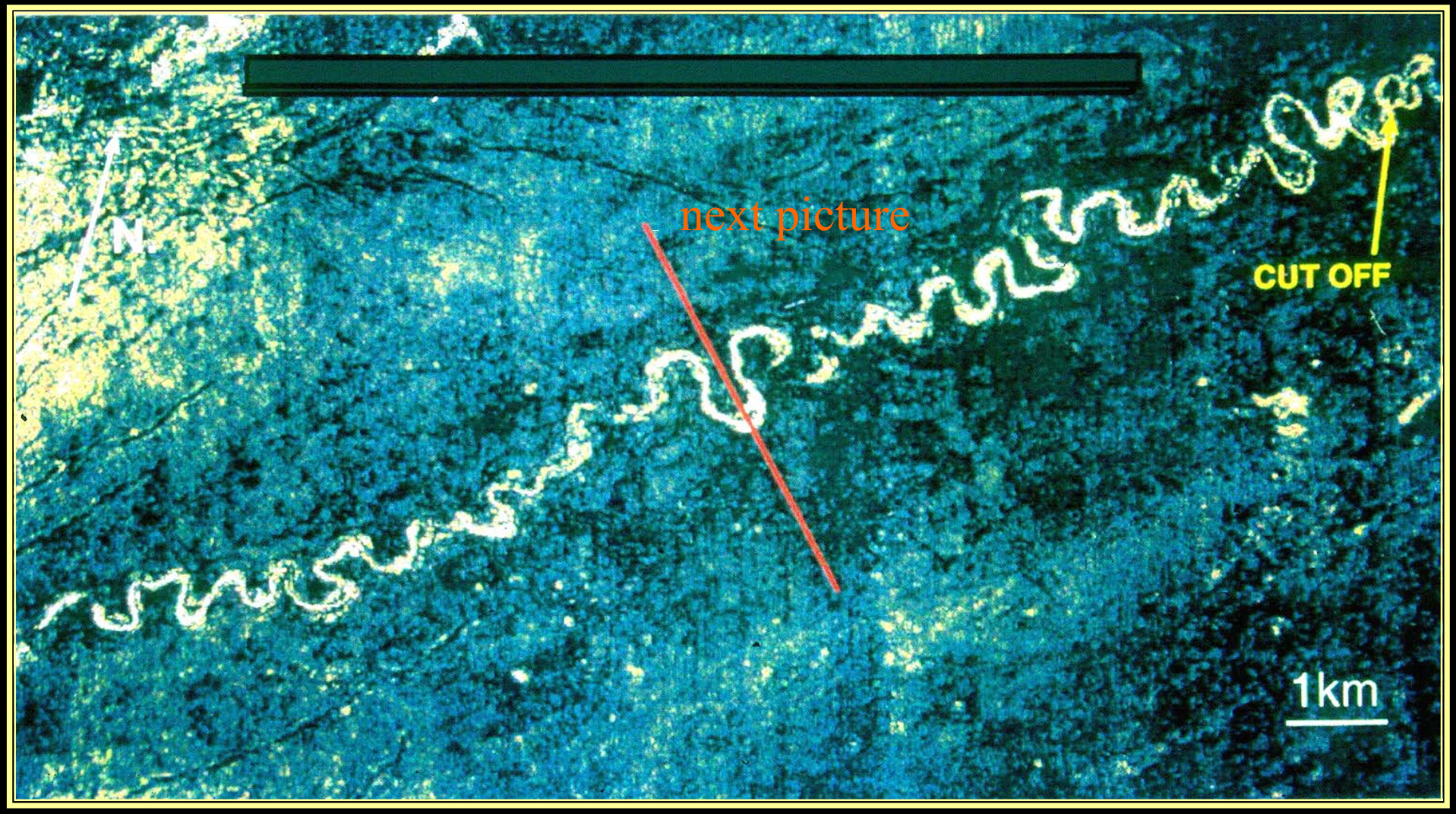
SIX RESERVOIR TYPES



Modified from Bouma (2000)


CHANNEL
PROXIMAL LEVEE
SLUMP
OVERBANK
AGGRADING CHANNEL-LEVEE COMPLEX
CHANNEL
Distal levee or
OVERBANK
LEVEE
Splay
TYPE III
SUBMARINE CHANNEL SYSTEM
(Roberts and Compani, 1996)

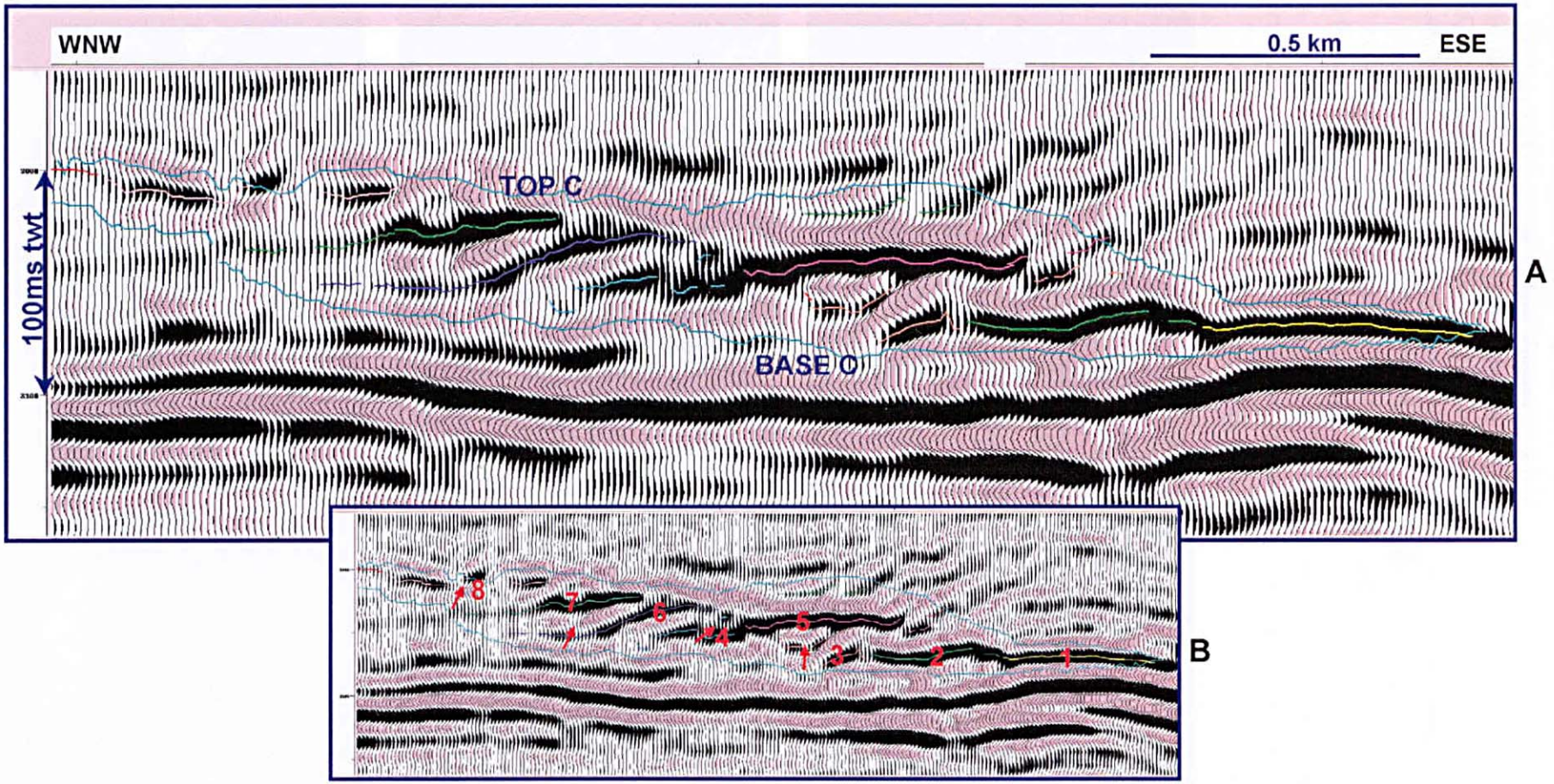
3D SEISMIC HORIZON SLICE



Offshore Angola

(Provided by Kolla)

3D Seismic line, offshore Angola

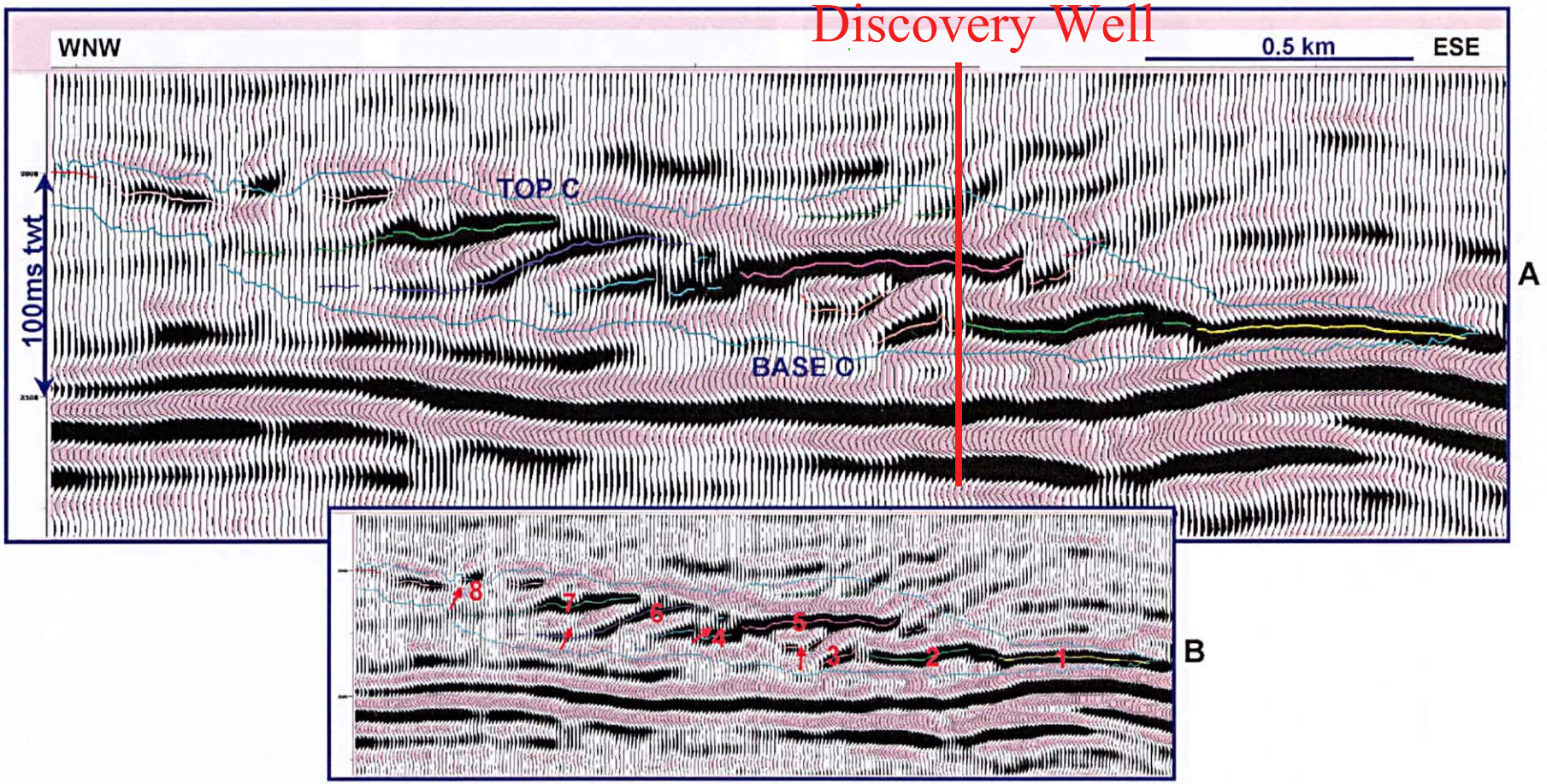


Black = positive seismic reflection

Purple = negative seismic reflection

Kolla et al., 2001

3D Seismic line, offshore Angola



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Kolla et al., 2001

APPRAISAL & DEVELOPMENT

- HOW BIG IS THE RESERVOIR?
- HOW WILL THIS RESERVOIR STYLE PERFORM?
- HOW WIDELY MUST WE SPACE OUR EXPENSIVE DEVELOPMENT WELLS?
- SHOULD WE DRILL A VERTICAL, SLANT, OR HORIZONTAL WELL??
- HOW CAN WE FAST-TRACK DEVELOPMENT OF THIS RESERVOIR?
- WHAT WENT WRONG?

HOW CAN OUTCROPS HELP ANSWER THOSE TOUGH QUESTIONS??

BUILDING A SCALED GEOLOGIC MODEL FROM OUTCROPS:

- **Sheet Sandstone Reservoirs**
- **Leveed Channel Sandstone Reservoirs**

Lets study the Cretacous Lewis Shale in Wyoming!!

TOOLS AND TECHNIQUES FOR OUTCROP CHARACTERIZATON

STANDARD

- Brunton Compass
- Hand Lens
- Jacobs Staff
- Tape Measure
- Rock Hammer
- Camera

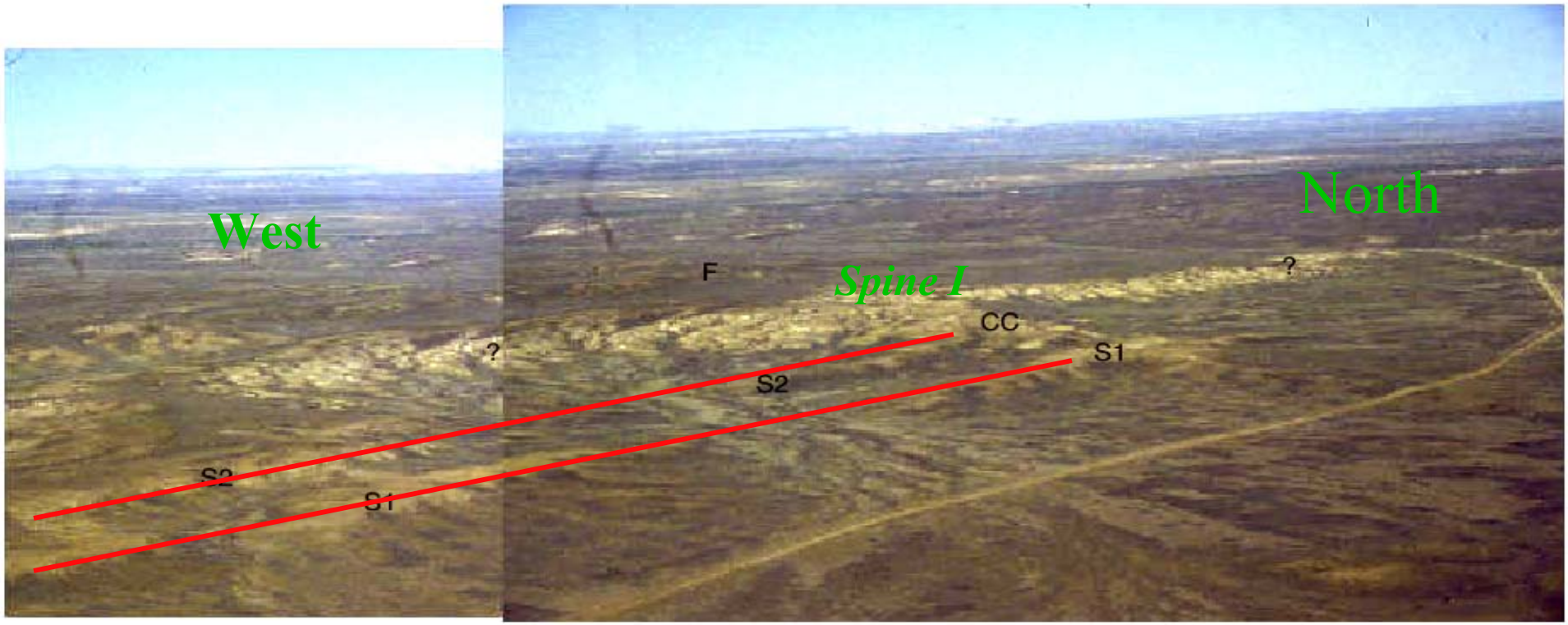
RECENT ADDITIONS

- Photomosaics on Workstation
- Outcrop gamma-ray/sonic logs
- Behind-outcrop logging/coring
- Ground Penetrating Radar (GPR)
- Global Positioning System (GPS)
- Ultra-shallow seismic behind outcrop
- Outcrop Minipermeameter
- 3D Imaging

Cretaceous Lewis Shale, Wyoming
"Bashful outcrops"

S1 and S2 are continuous Lewis sheet sandstones
CC is Lewis leveed channel complex on Spine I
F is shallow marine Fox Hills

Cretaceous Lewis Shale, Wyoming



S1 and S2 are continuous Lewis sheet sandstones

CC is Lewis leveed channel complex on Spine I

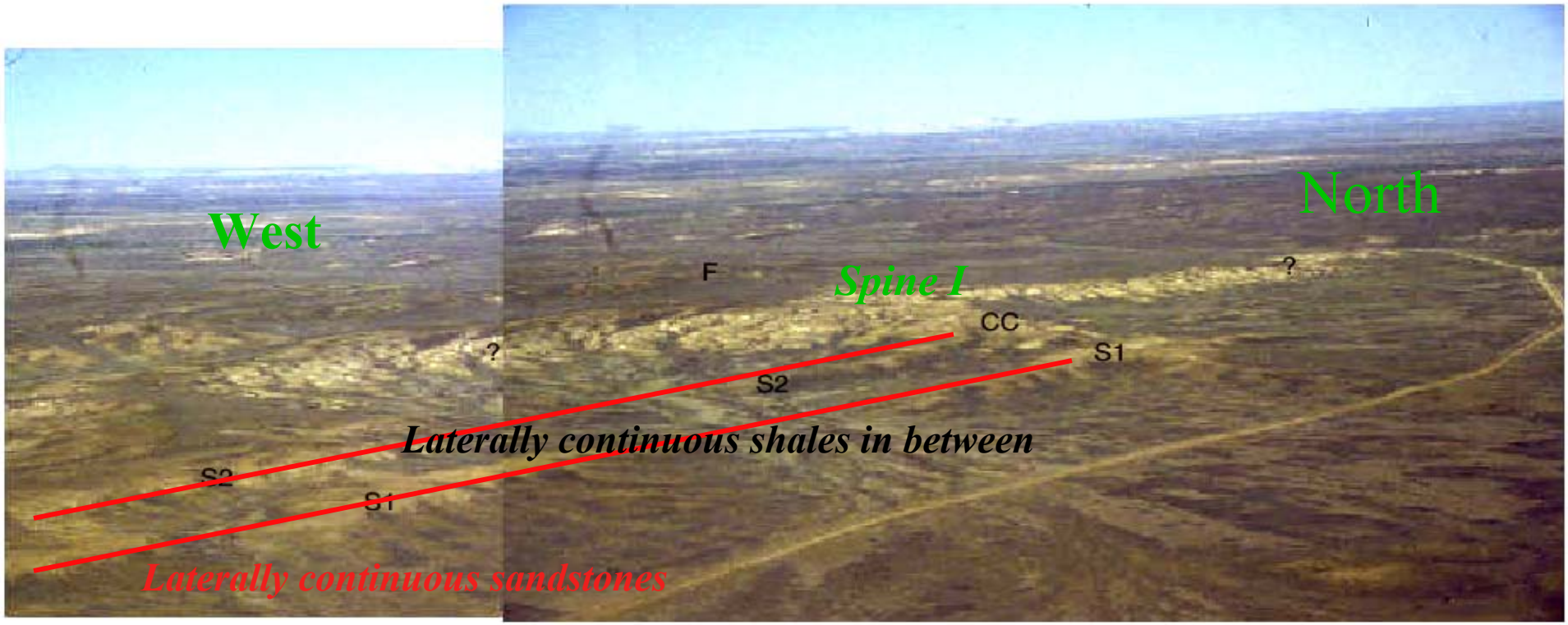
F is shallow marine Fox Hills

Sheet Sandstones: ***Laterally continuous for miles:*** ***i.e. good potential reservoir facies; individual sandstone intervals are separated by shales.***

(Witton, 1999)

Sheet Sandstones

Cretaceous Lewis Shale, Wyoming



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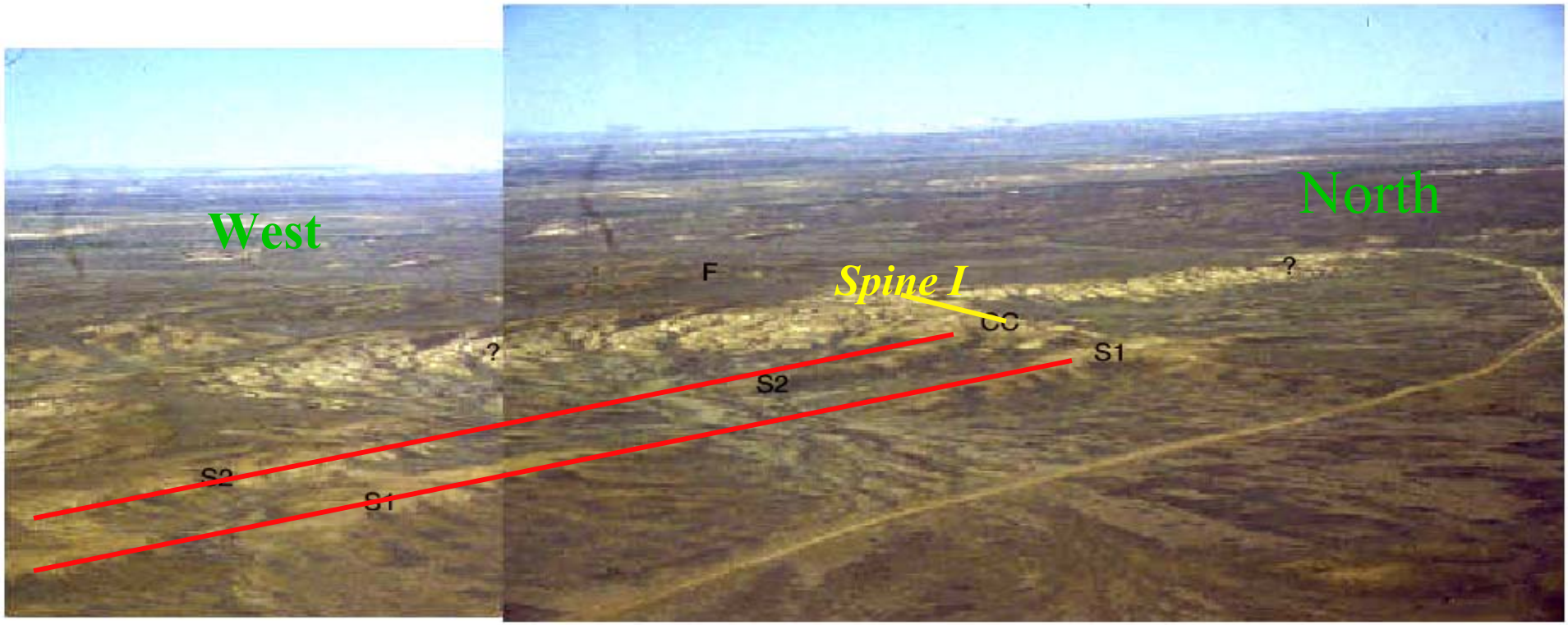
Cretaceous Lewis Shale, Wyoming



S1 and S2 are continuous Lewis sheet sandstones

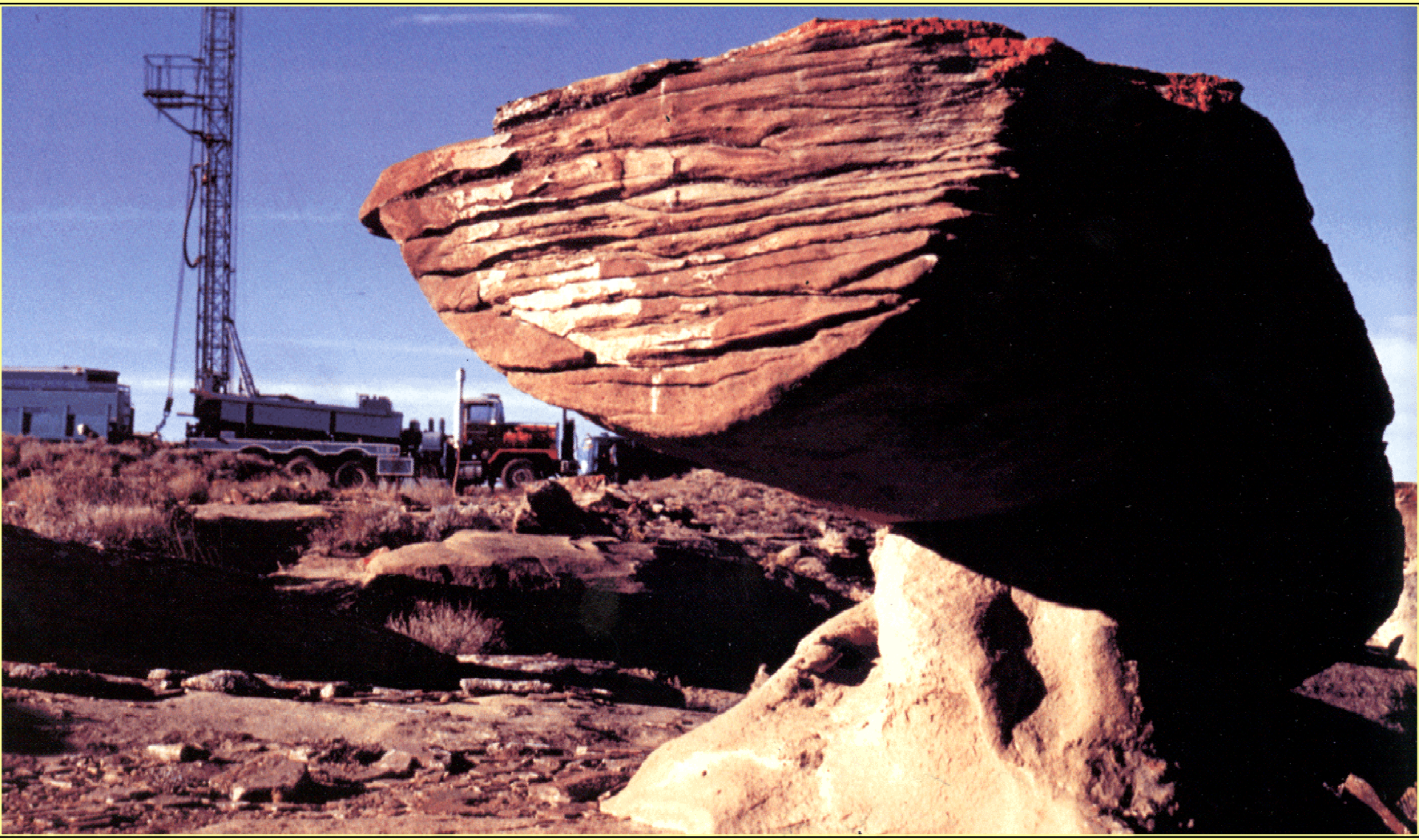
CC is Lewis leveed channel complex on Spine I

F is shallow marine Fox Hills

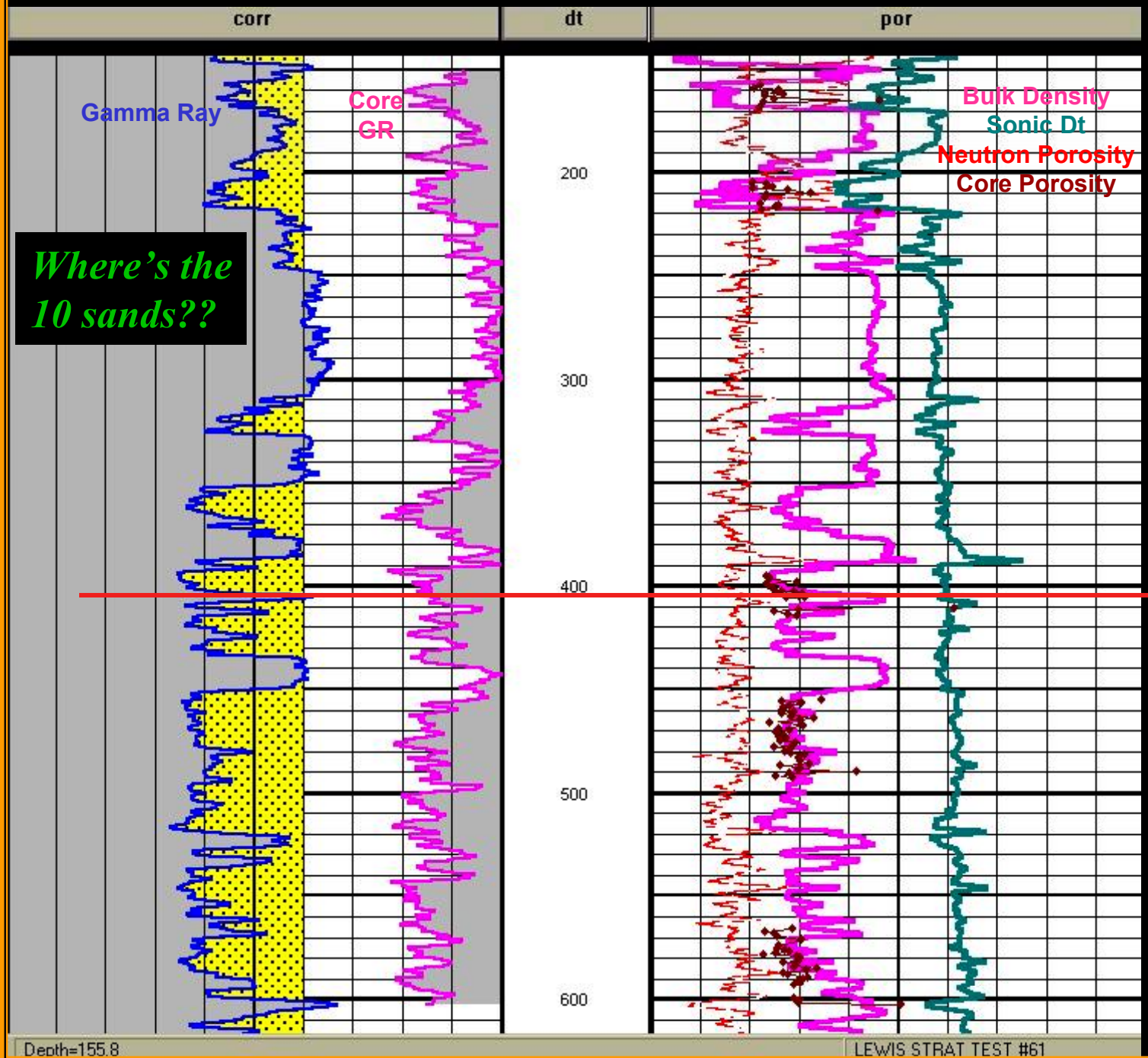
Spine I

(yellow line is app. 450m on ground; 120m of strat. section) **Well-------**

10 Channel-fill sandstones, each separated by shale/mudstone breaks:i.e. discontinuous reservoirs; not so easy to develop as reservoirs

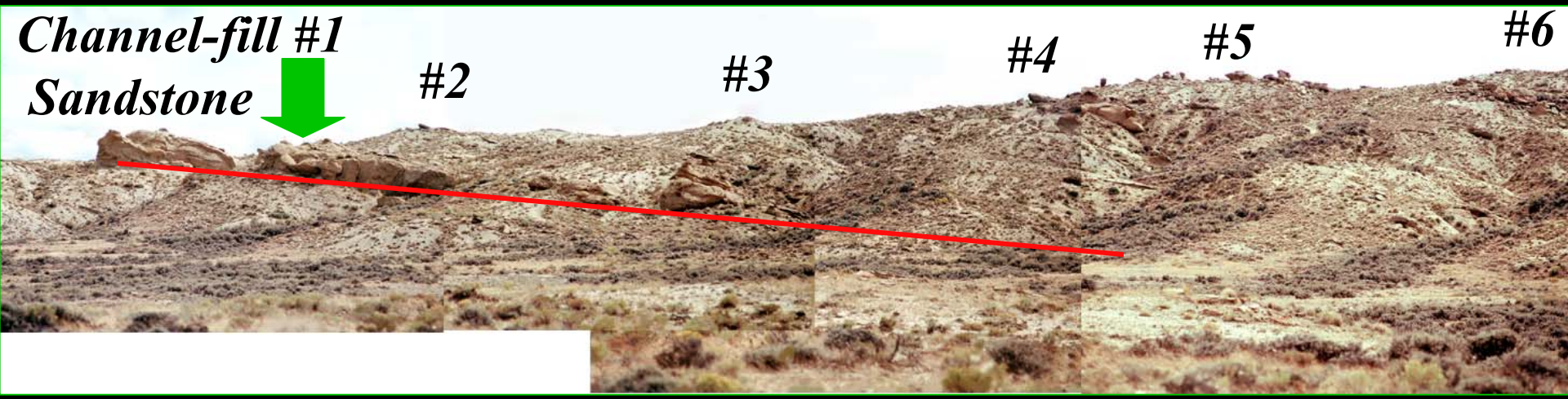


Behind-outcrop drilling for logs and core



CSM Strat Test #61 Core and Log Data

Well-------

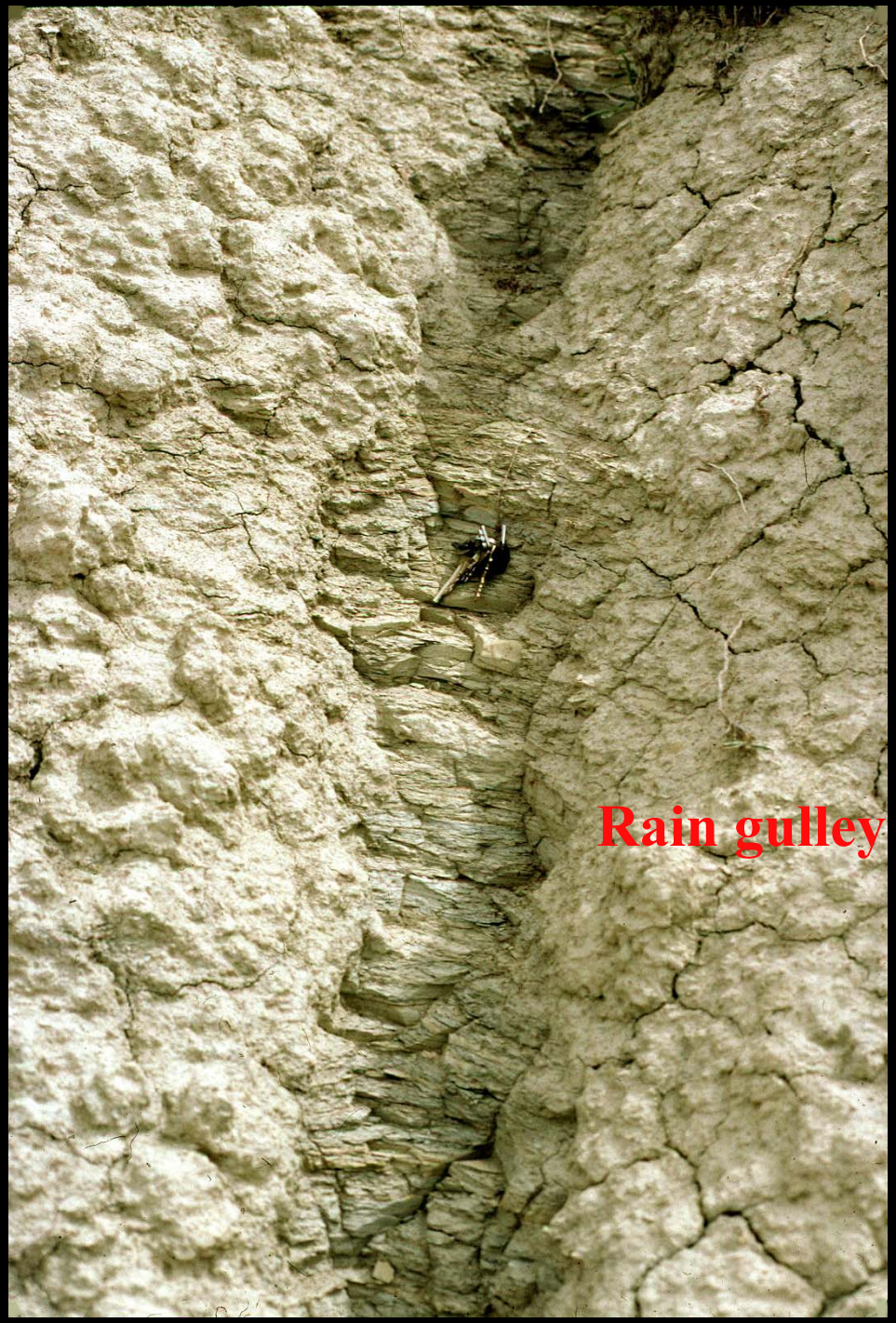


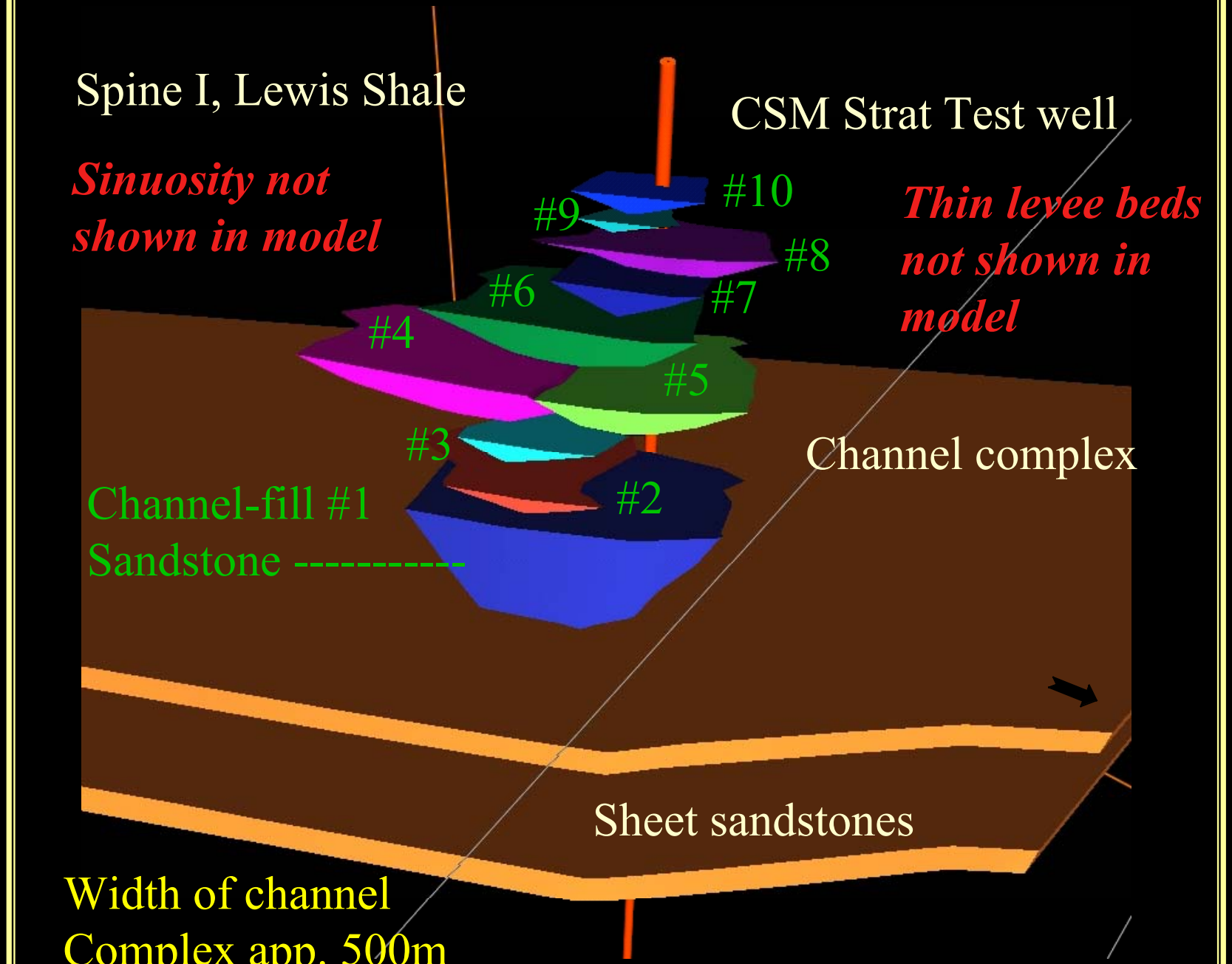
Where did the Channel-fill #1 Sandstone go?? Meander loop of sinuous channel??

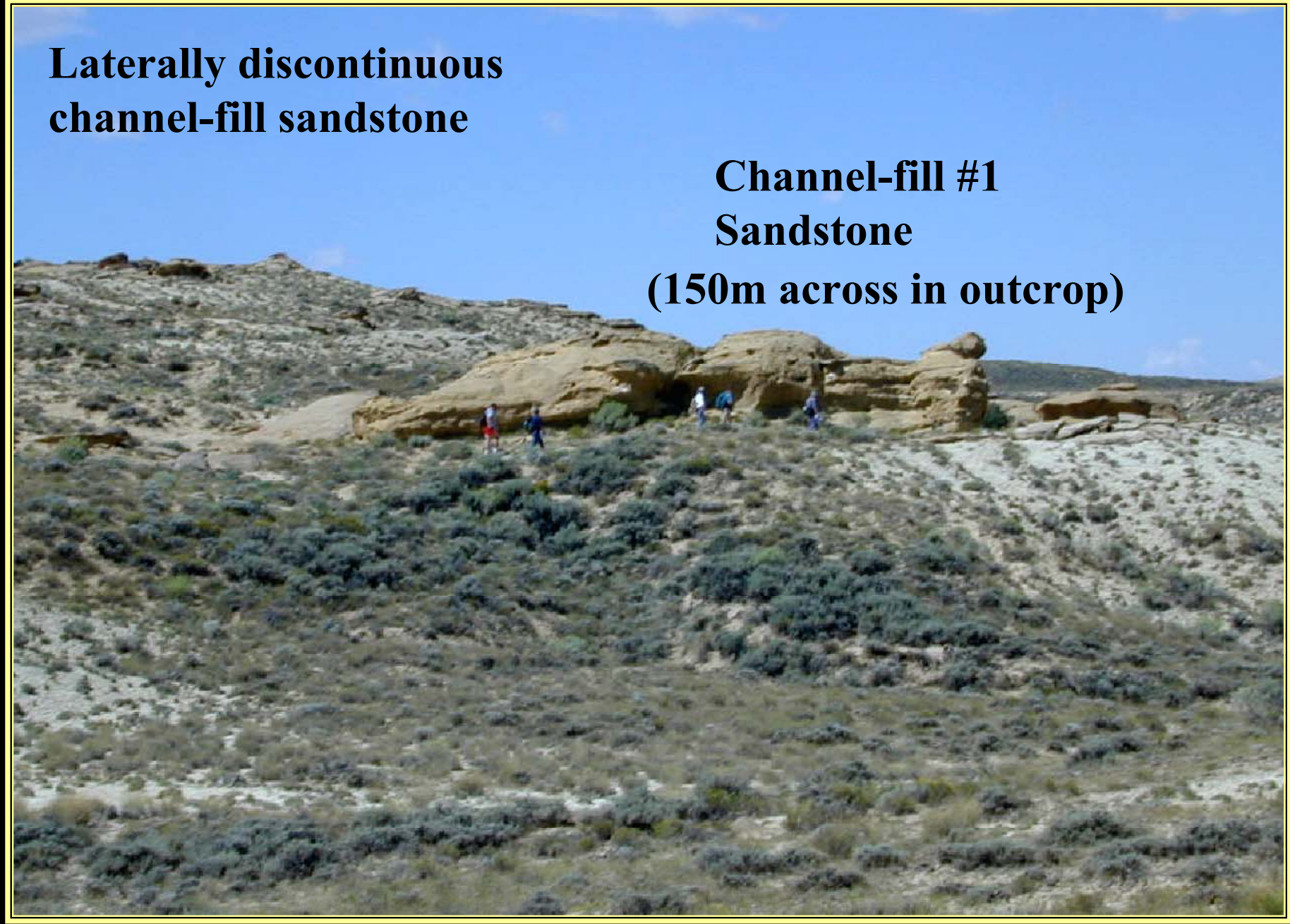
Well-------

Where did the Channel-fill #1 Sandstone go?? Meander loop of sinuous channel??

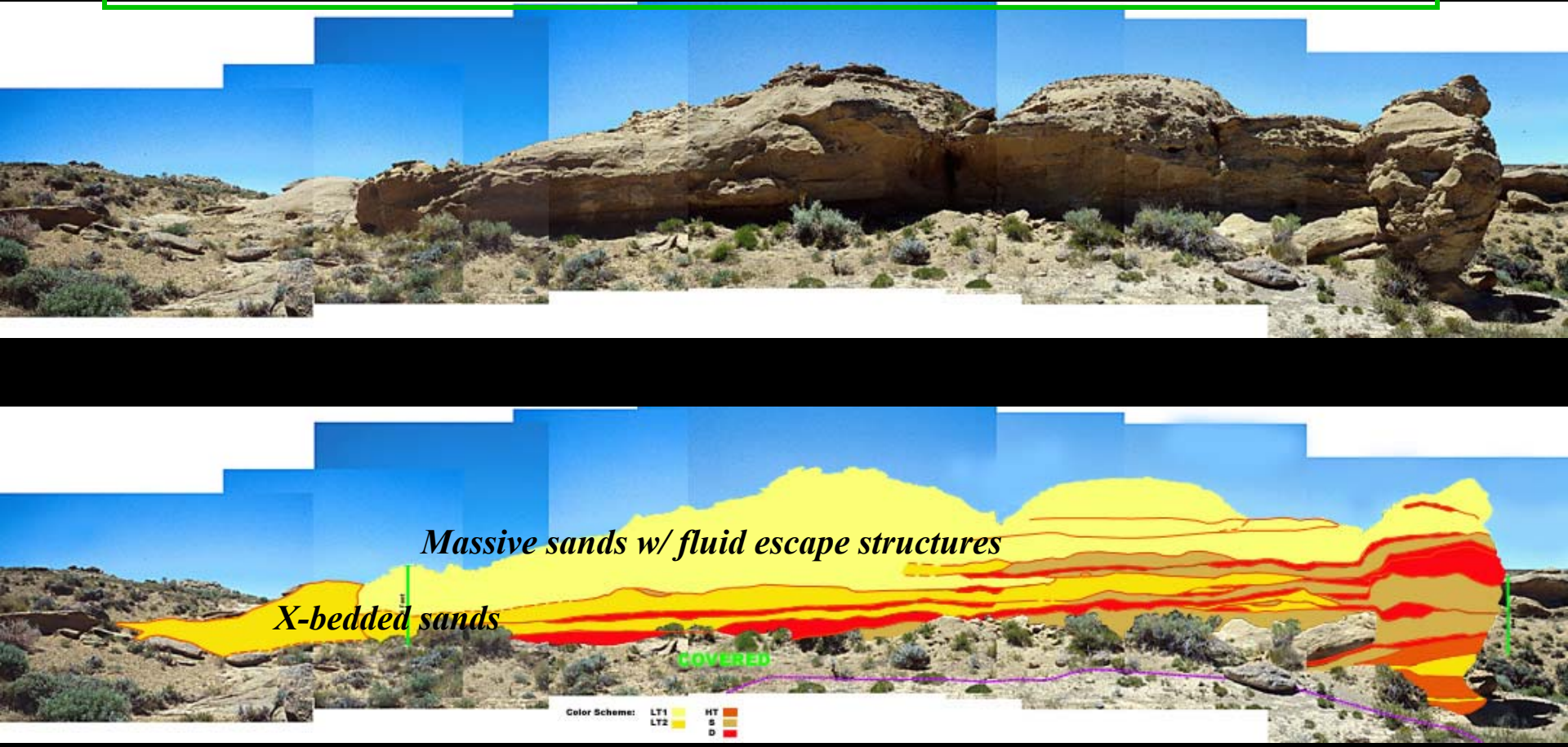
Thin-bedded, extra-channel or levee facies




Spine I, Lewis Shale
CSM Strat Test well
Sinuosity not shown in model
Thin levee beds not shown in model
#10
#9
#8
#7
#6
#5
#4
#3
#2
Channel-fill #1 Sandstone ----------
Channel complex
Sheet sandstones
Width of channel Complex app. 500m


Laterally discontinuous
channel-fill sandstone
Channel-fill #1
Sandstone
(150m across in outcrop)

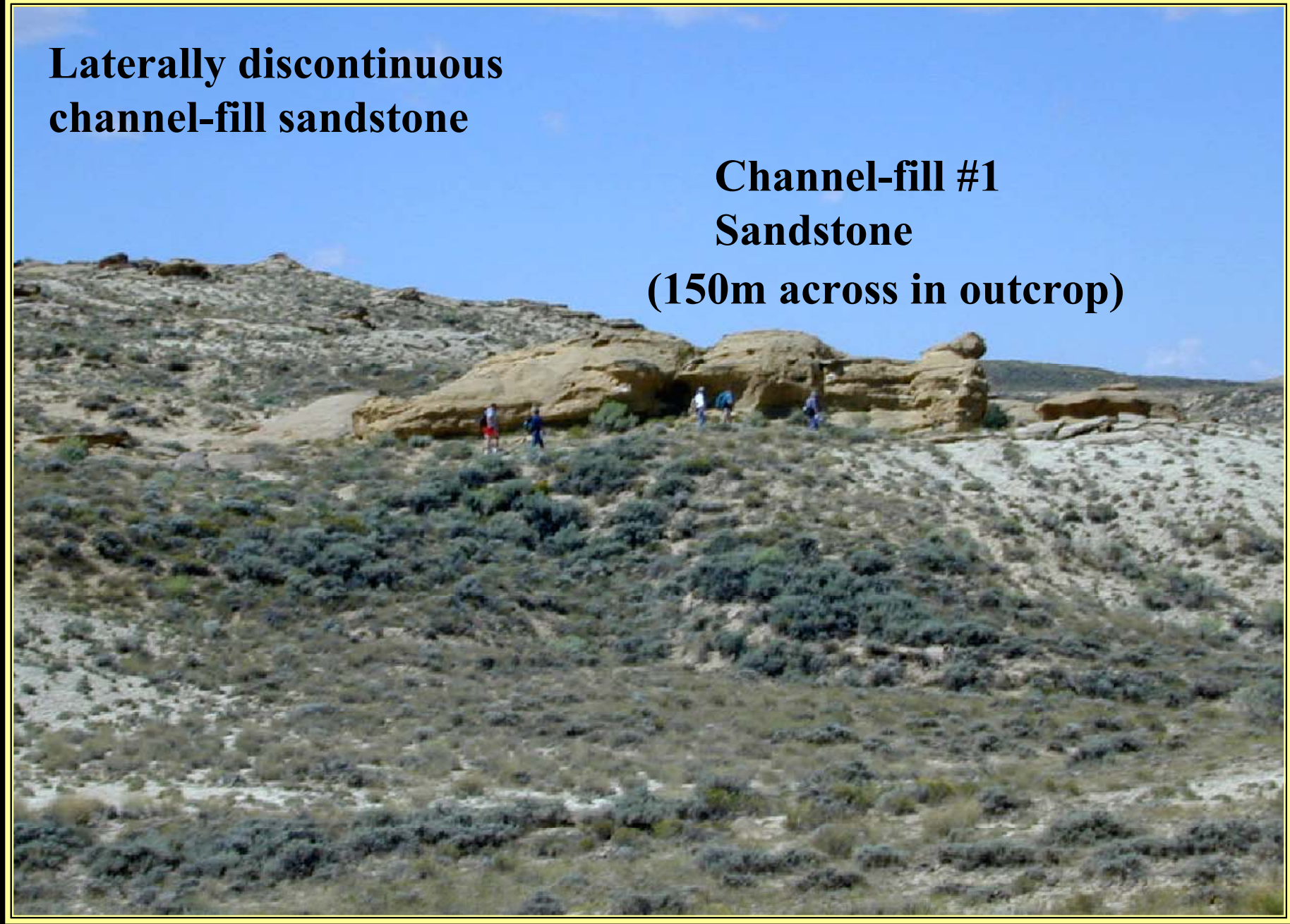
Channel-fill #1 Sandstone; oblique view across channel-fill



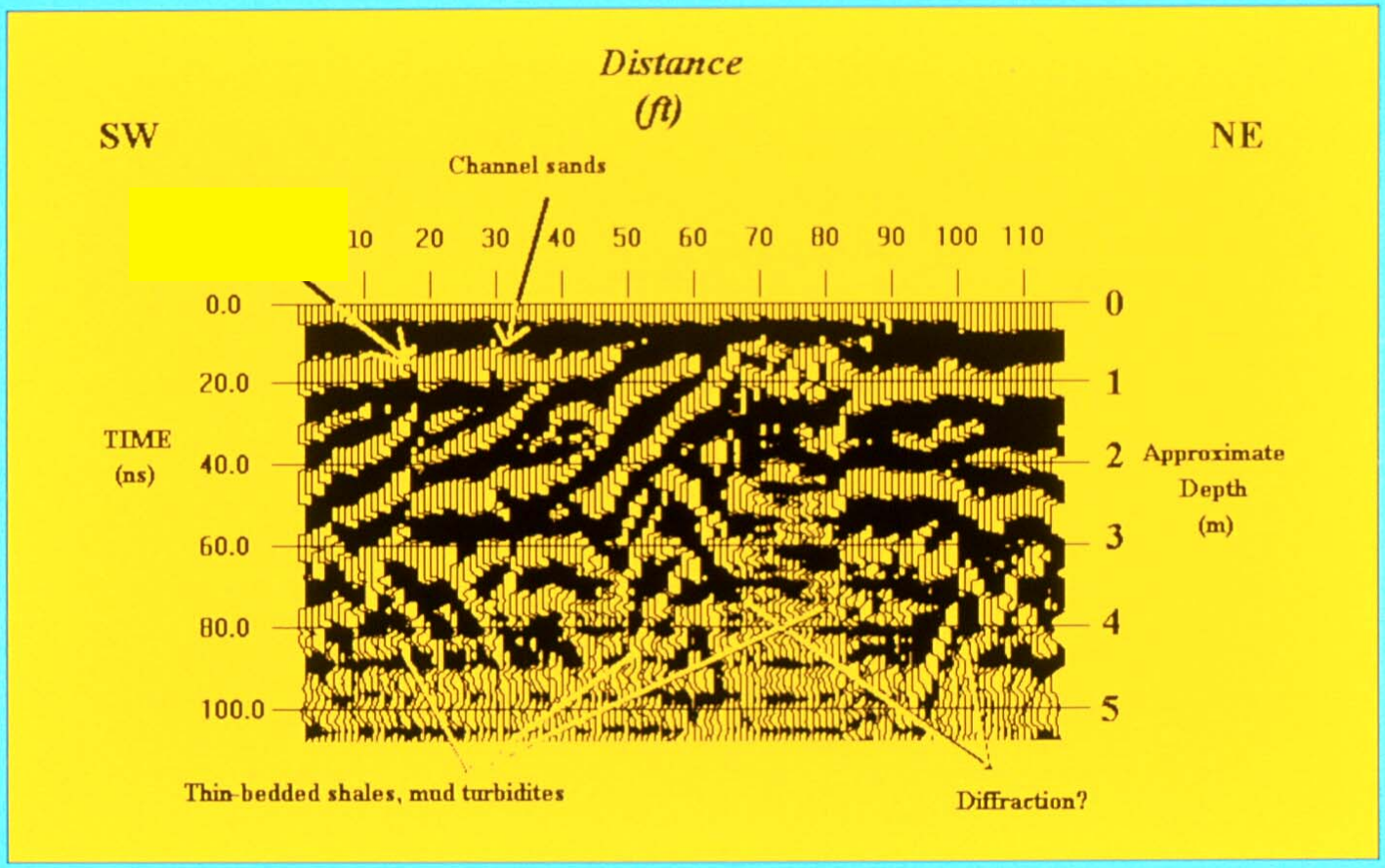
Red = shale clast cong. Brown = sandy debrites


Cross-bedded sandstone

Interbedded turbidites and debrites


Laterally discontinuous
channel-fill sandstone
Channel-fill #1
Sandstone
(150m across in outcrop)

Margin of Channel Sandstone #1



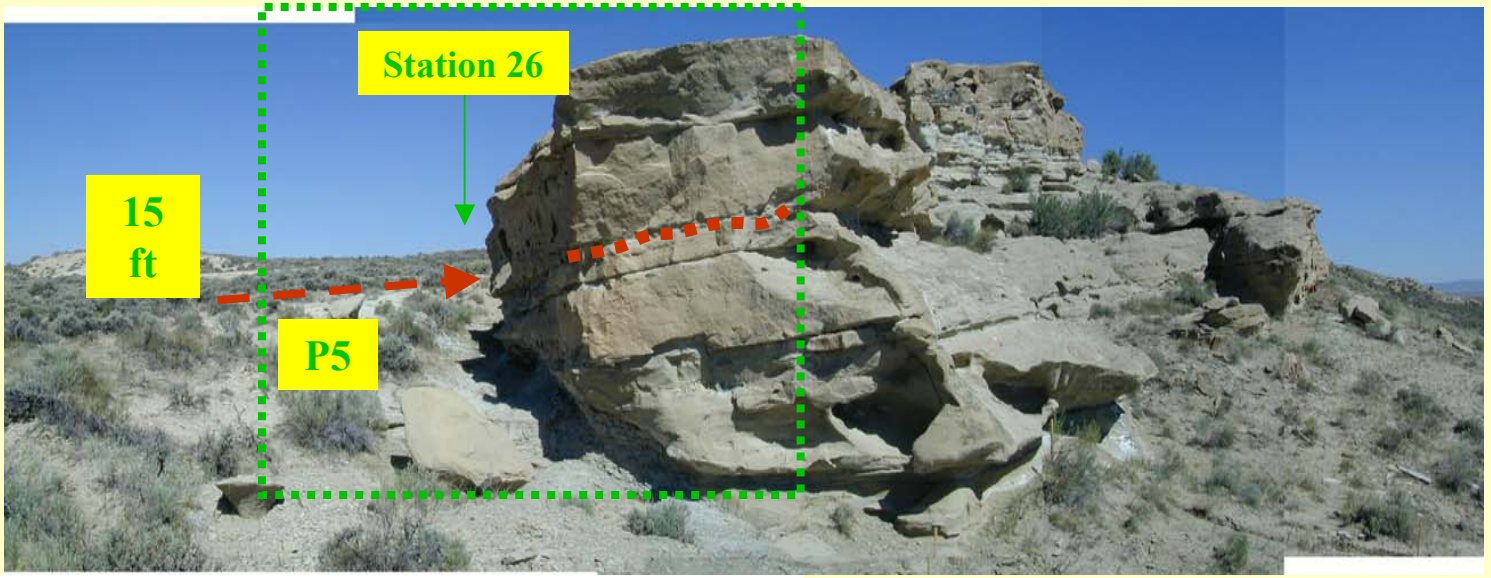
Ground-penetrating radar (GPR) line across channel margin showing sharp channel boundary and internal channel-slump features

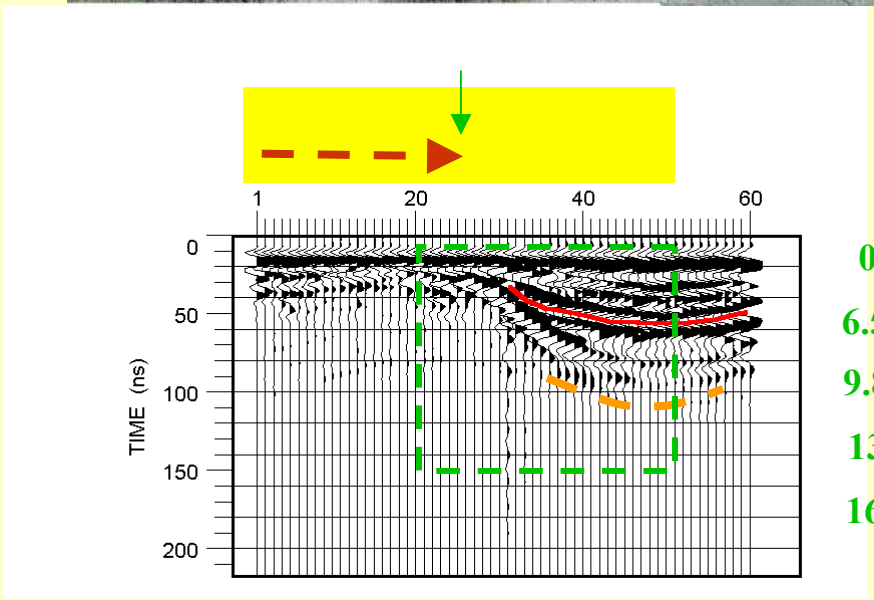
(Young et al,, 1999)

S

Complex Channel margin

N



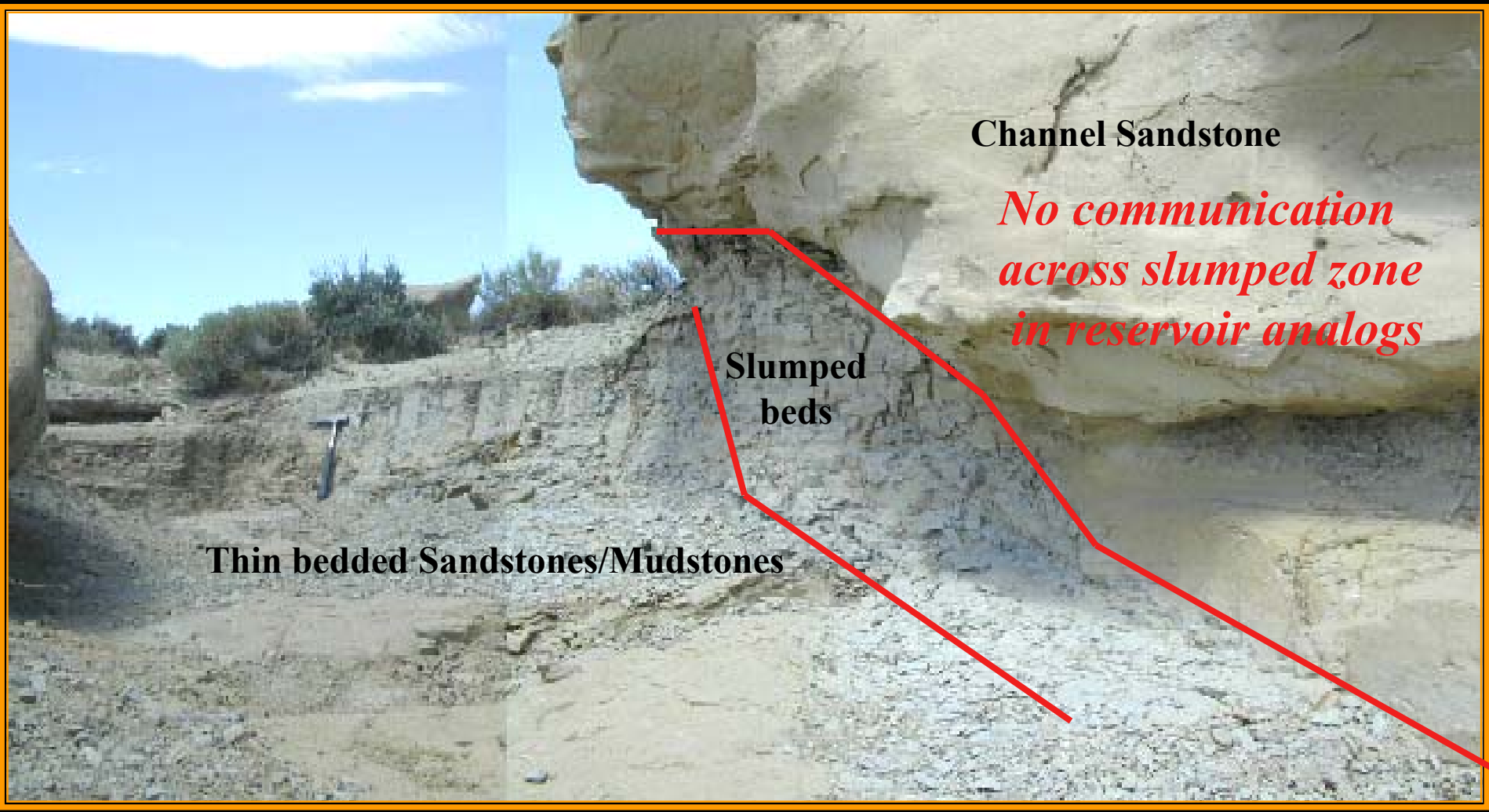


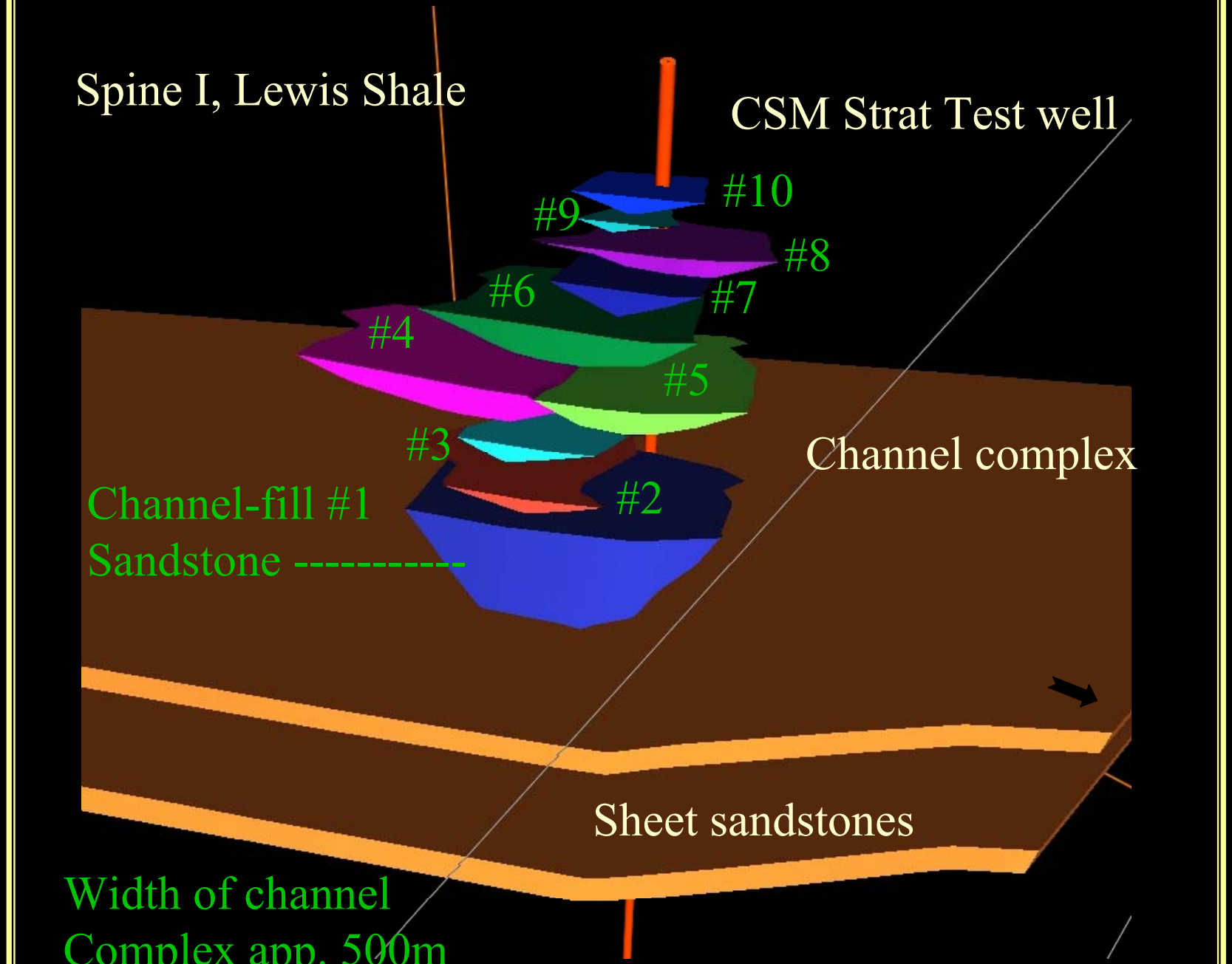
Channel margin is slumped, with channel sand injections into adjacent thin-beds

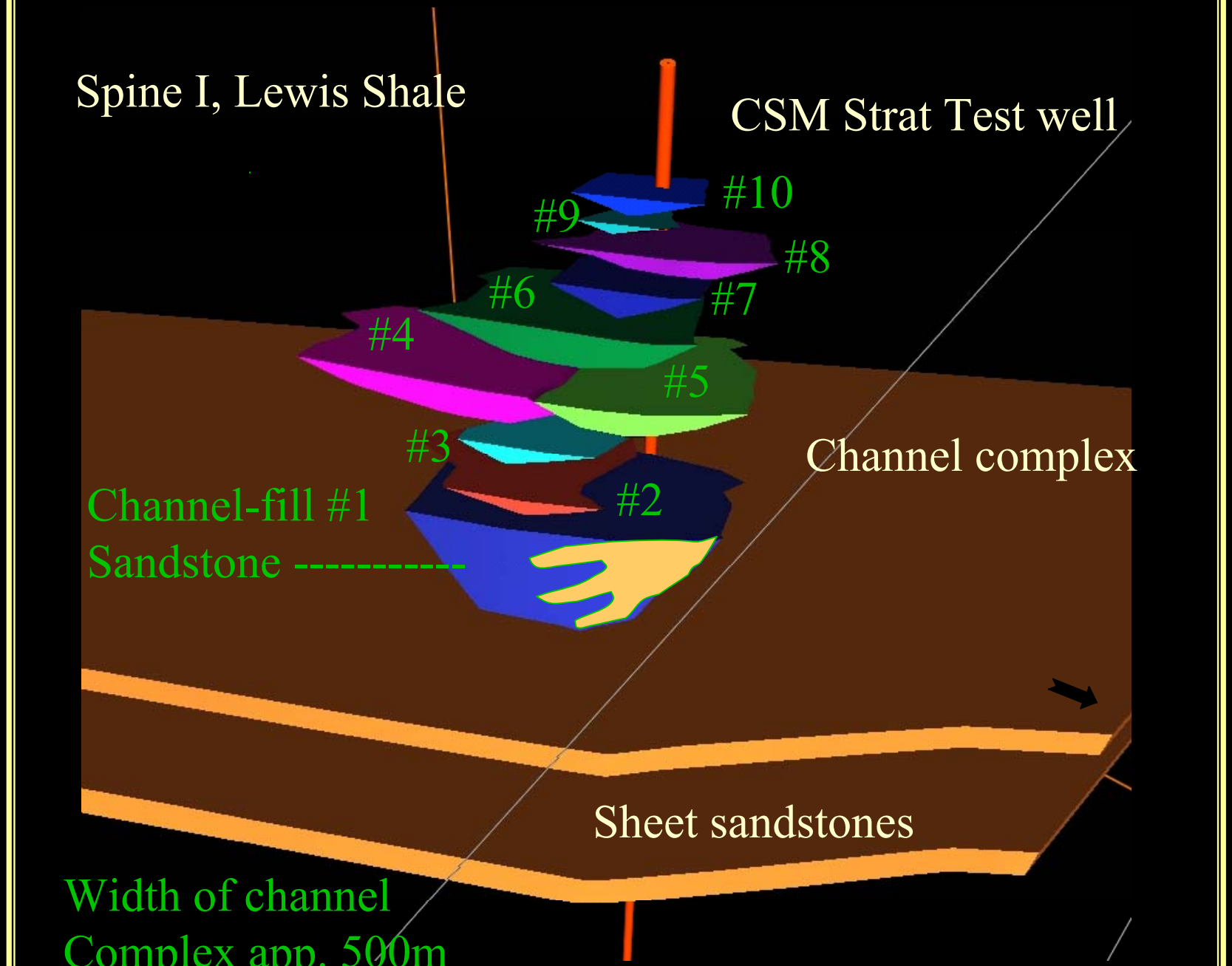
Approximate depth (ft)

H:V ~ 1:1


Channel Sandstone
Slumped beds
Thin bedded Sandstones/Mudstones


Channel Sandstone
No communication across slumped zone in reservoir analogs
Slumped beds
Thin bedded Sandstones/Mudstones


Spine I, Lewis Shale
CSM Strat Test well
#10
#9
#8
#6
#7
#4
#5
#3
#2
Channel-fill #1
Sandstone ----------
Channel complex
Sheet sandstones
Width of channel
Complex app. 500m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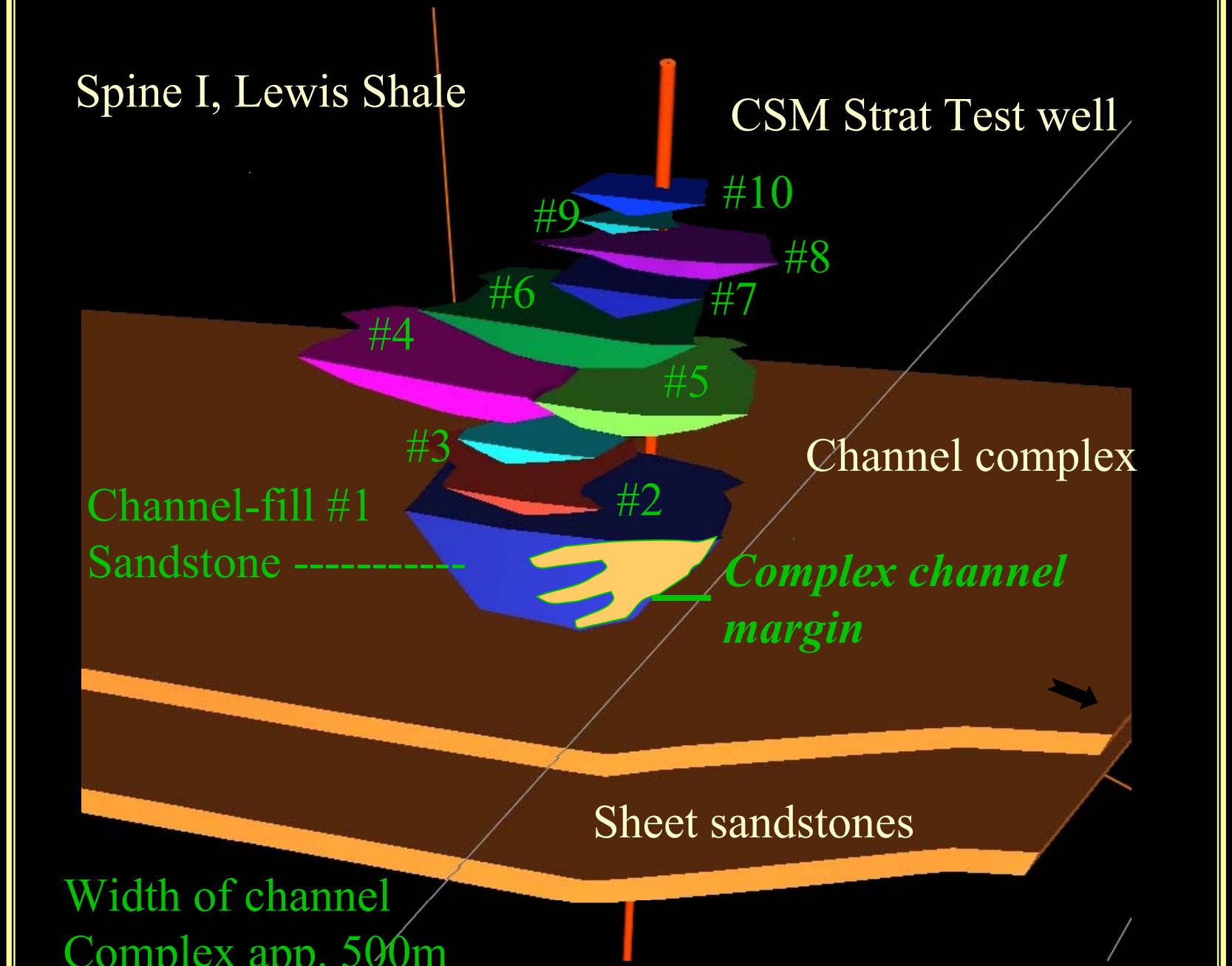
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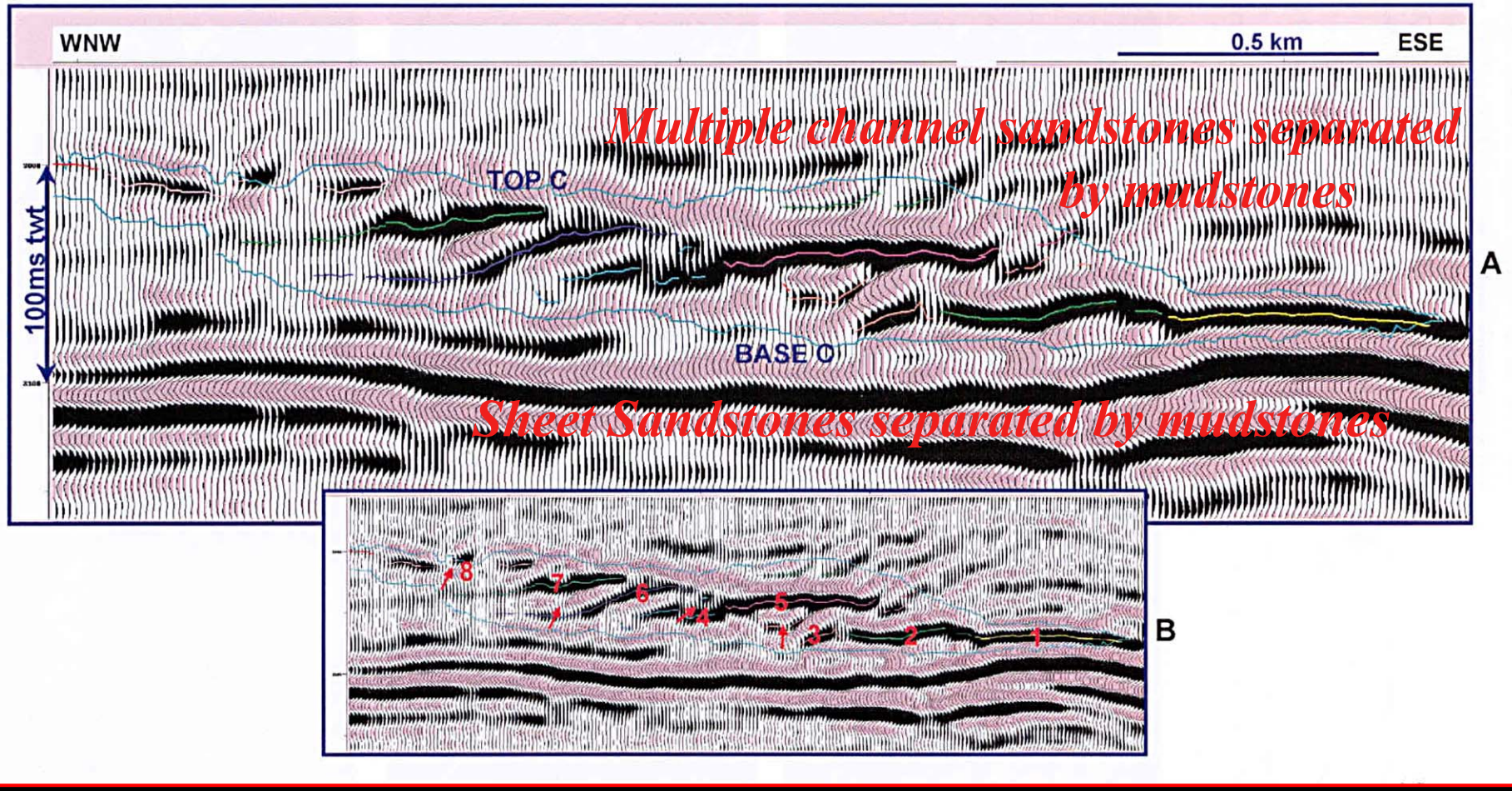
Channel complex
Channel-fill #1
Sandstone ----------
Complex channel margin
Sheet sandstones
Width of channel
Complex app. 500m

3D Seismic line, offshore Angola



Black = positive seismic reflection

Purple = negative seismic reflection

Kolla et al., 2001

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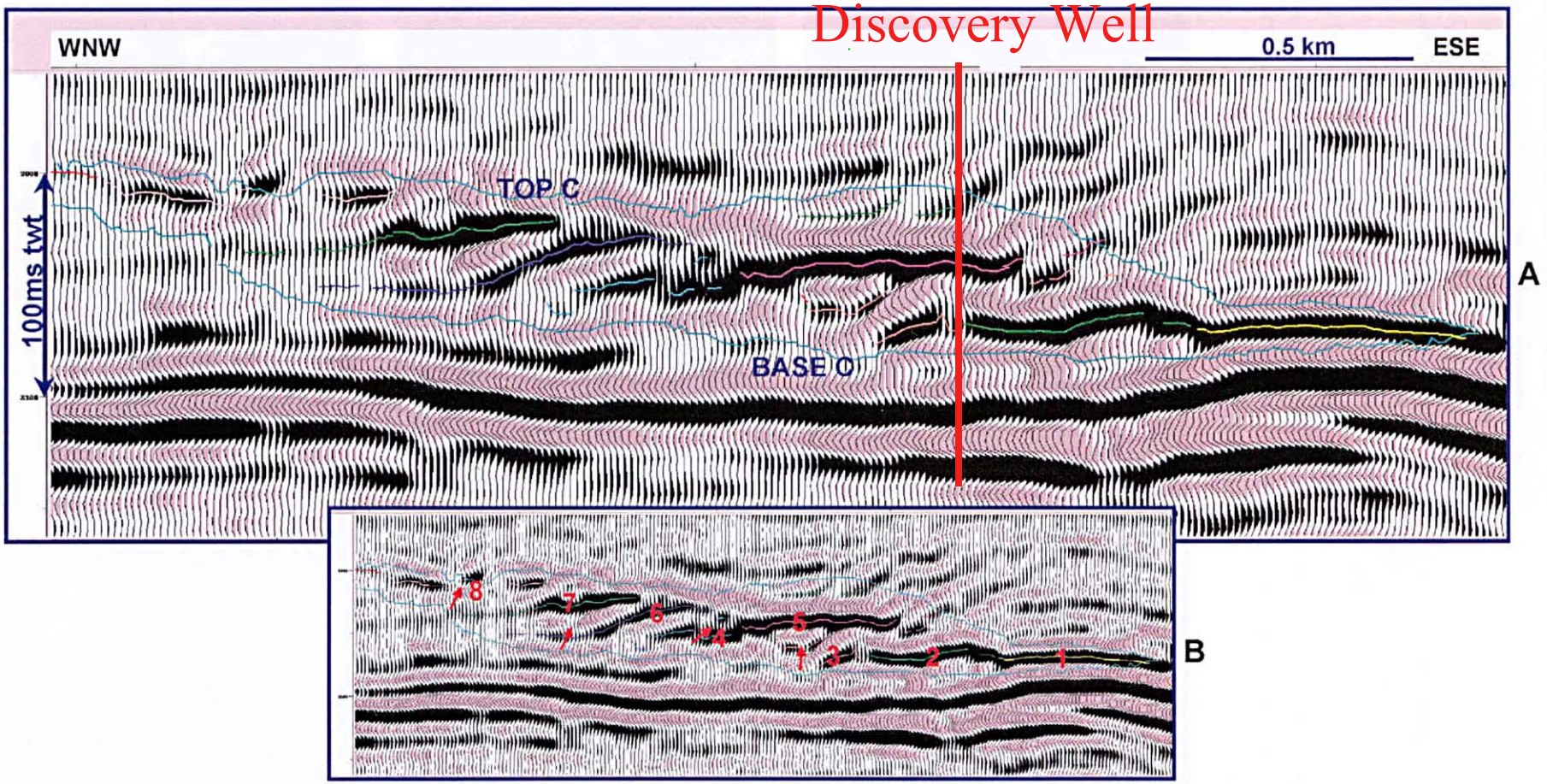

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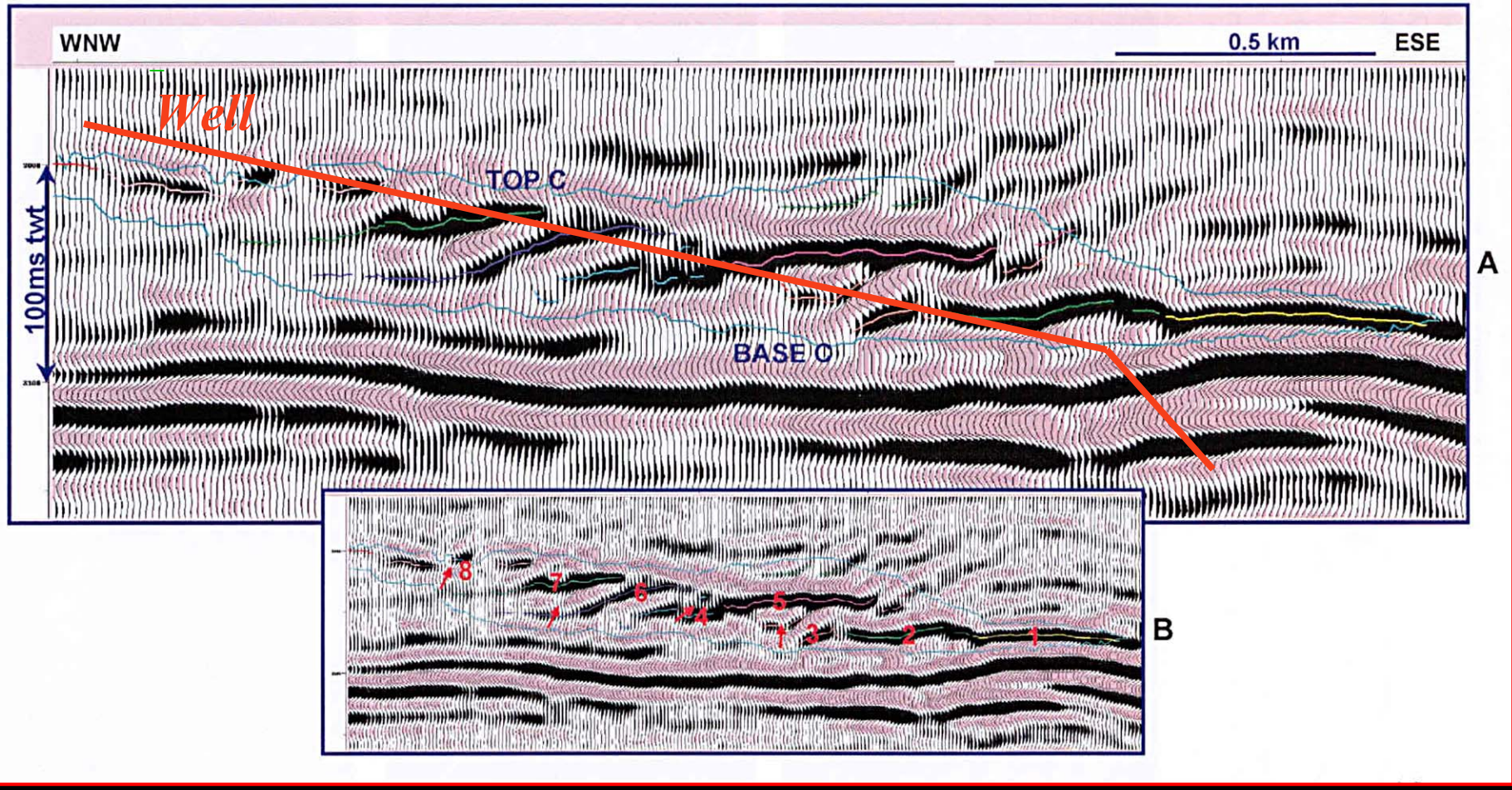

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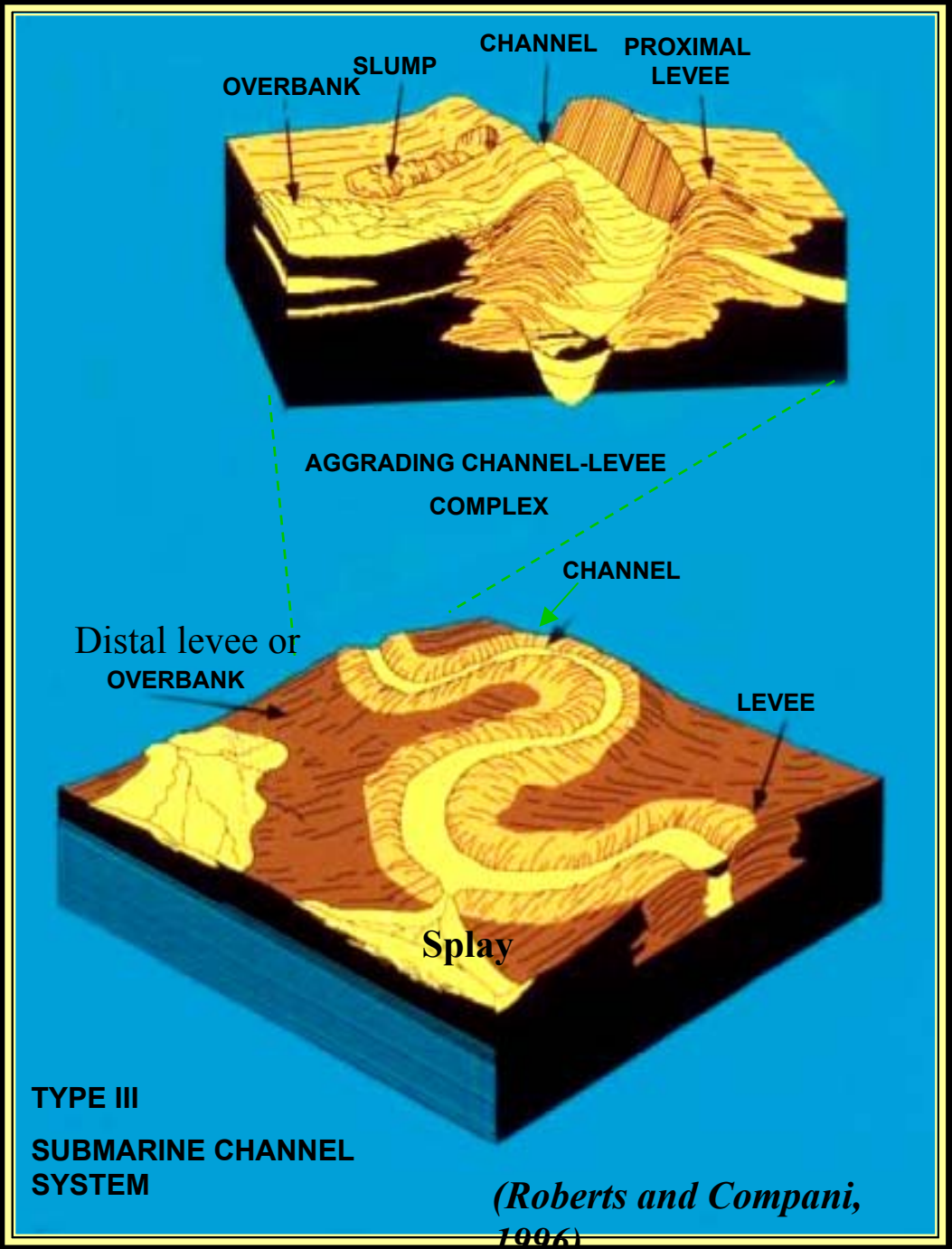
Kolla et al., 2001

HOW CAN OUTCROPS HELP ANSWER THOSE TOUGH QUESTIONS??

BUILDING A SCALED GEOLOGIC MODEL FROM OUTCROPS:

- **Thin-bedded levee reservoirs**

Lets study the Miocene Mt. Messenger Formation in New Zealand!!


OVERBANK
SLUMP
CHANNEL
PROXIMAL LEVEE
AGGRADING CHANNEL-LEVEE COMPLEX
CHANNEL
Distal levee or OVERBANK
LEVEE
Splay
TYPE III
SUBMARINE CHANNEL SYSTEM
(Roberts and Compani, 1996)

Miocene Mt. Messenger Formation, Taranaki Basin, New Zealand: *Cliff is 250m high and several km long*

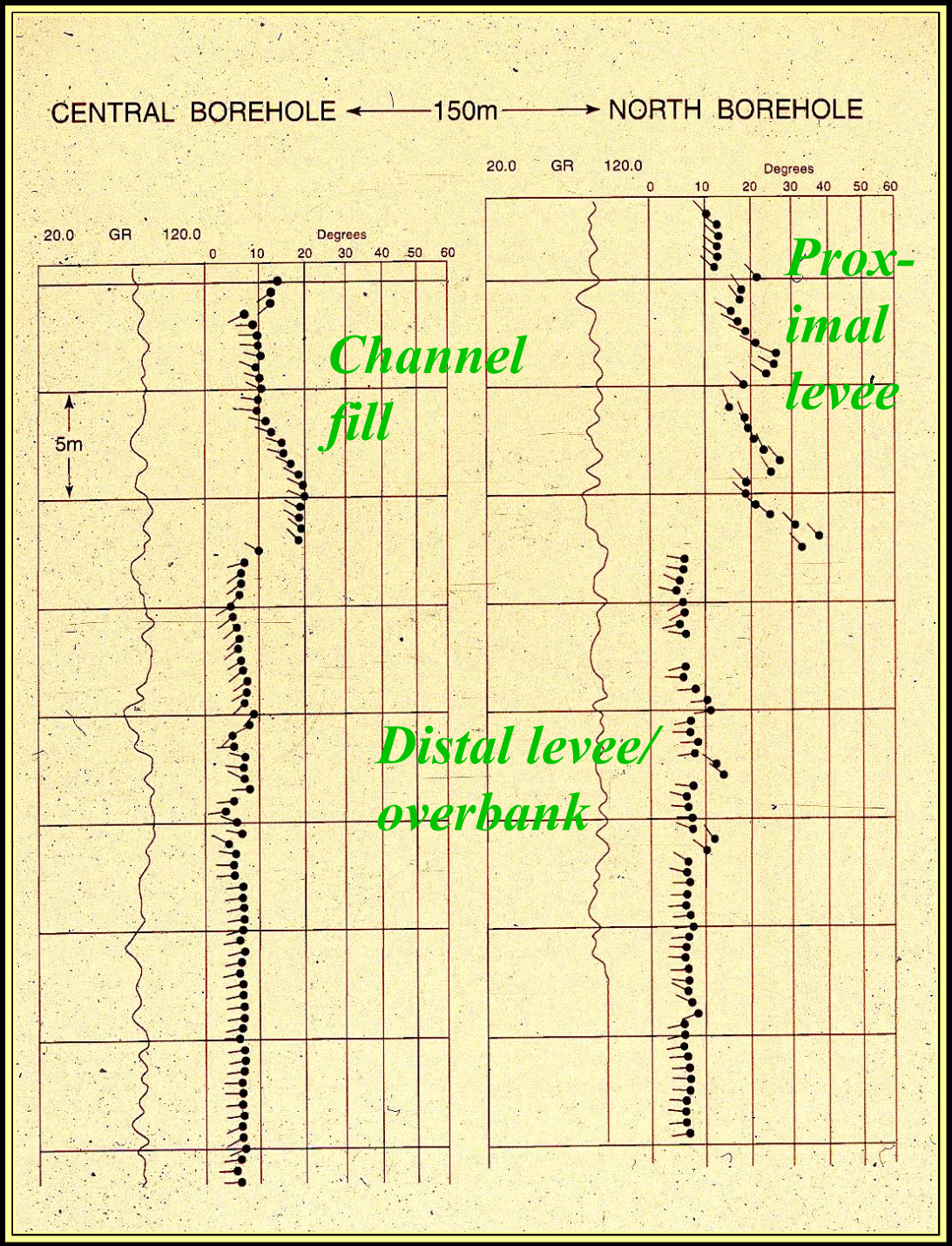
PHOTOMOSAICS FROM HELICOPTER; WELLS; CORES; LOGS; HIGH-RESOLUTION SHALLOW SEISMIC; MEASURED SECTIONS

Depositional interval or bed scale

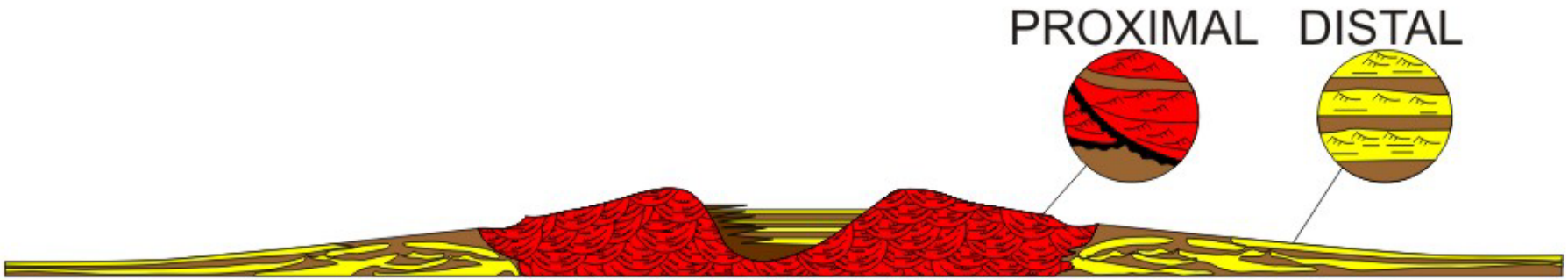
C = channel fill (upward dip decrease); P = proximal levee (high & variable angle dips); D = distal levee;

Distal levee bed sets (lower & uniform dip angles)

Behind-outcrop dipmeter logs (by Schlumberger)



(Slatt et al., 1998)



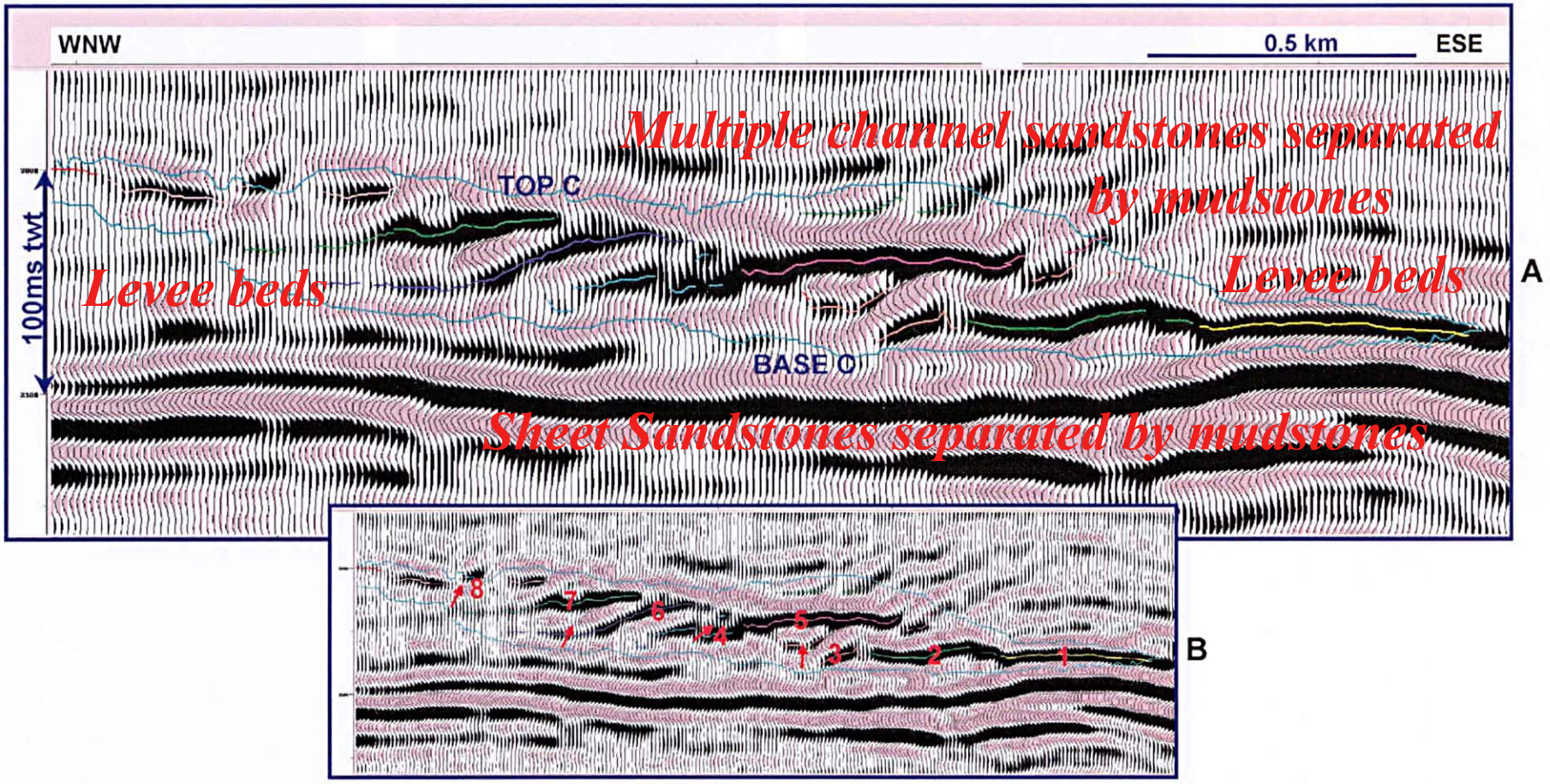
LEVEE FACIES

Proximal levee: Higher net sand; thin bedded; cut-and-fill; mud-lined scours; climbing ripples; good connectivity; high angle and variable dips of beds.

Distal levee: Lower net sand; thin bedded; interbedded sand/silt; good continuity; low angle and uniform dips of beds

Channel margins: Complex: slumps, discontinuities, mud-lined; variable fluid communication in leveed channel reservoirs

3D Seismic line, offshore Angola



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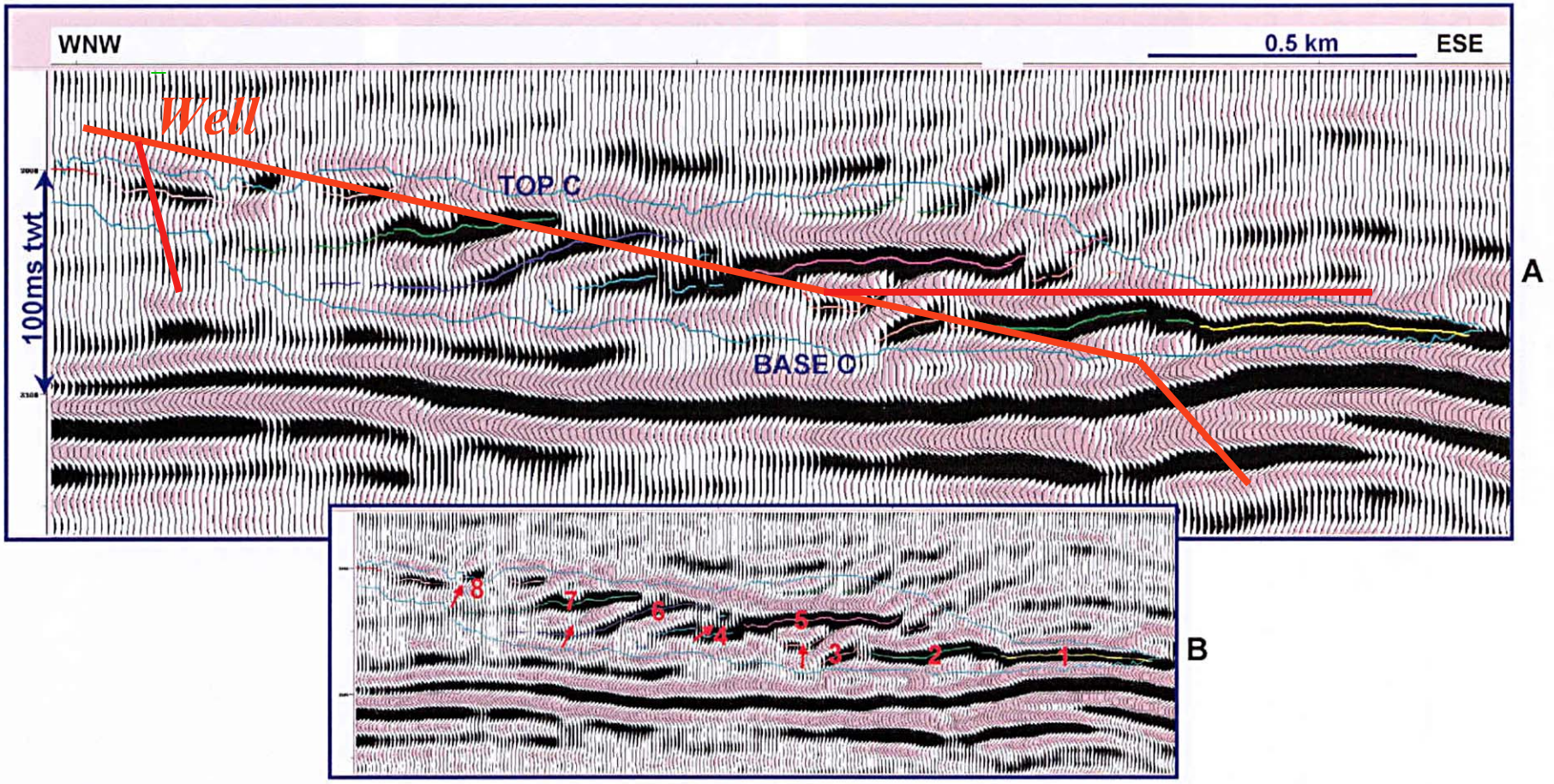
Kolla et al., 2001



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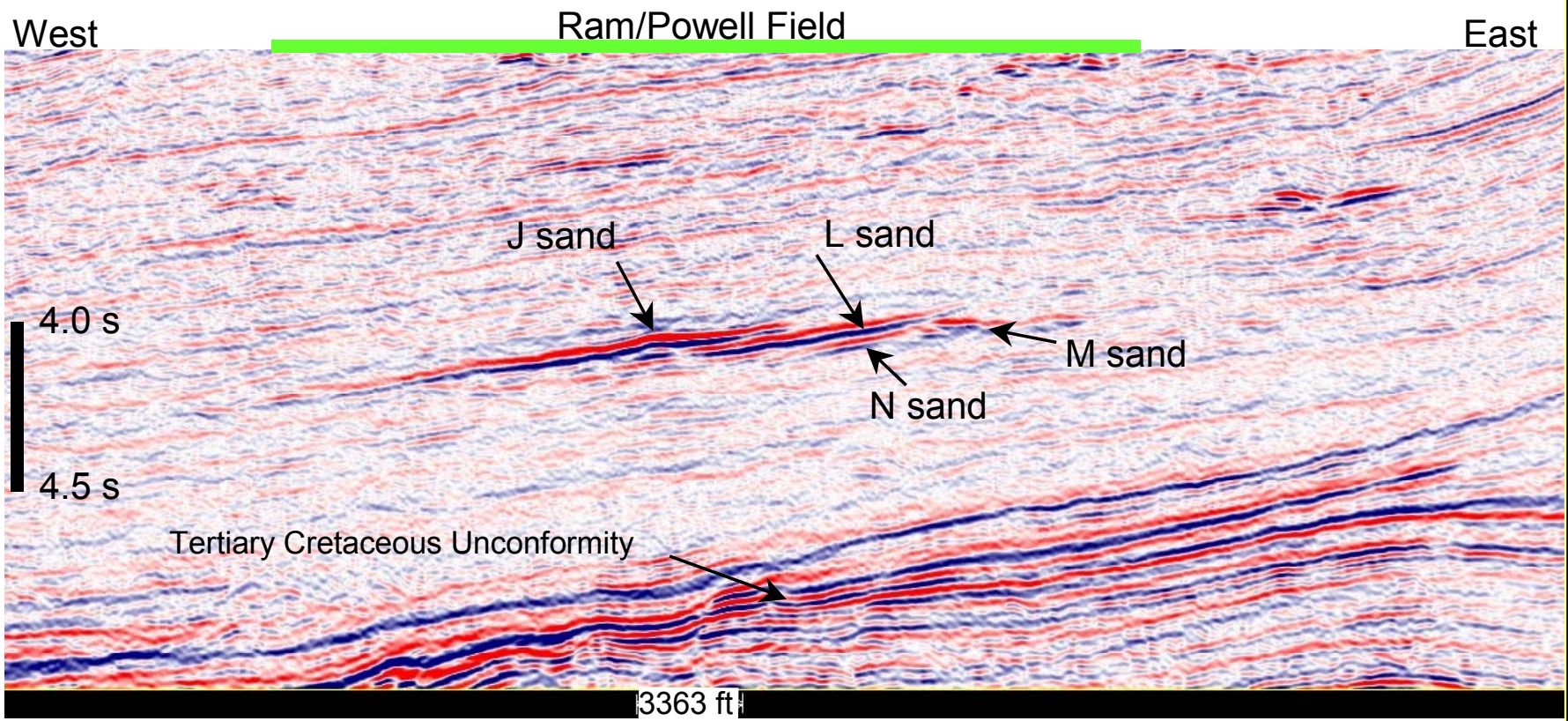
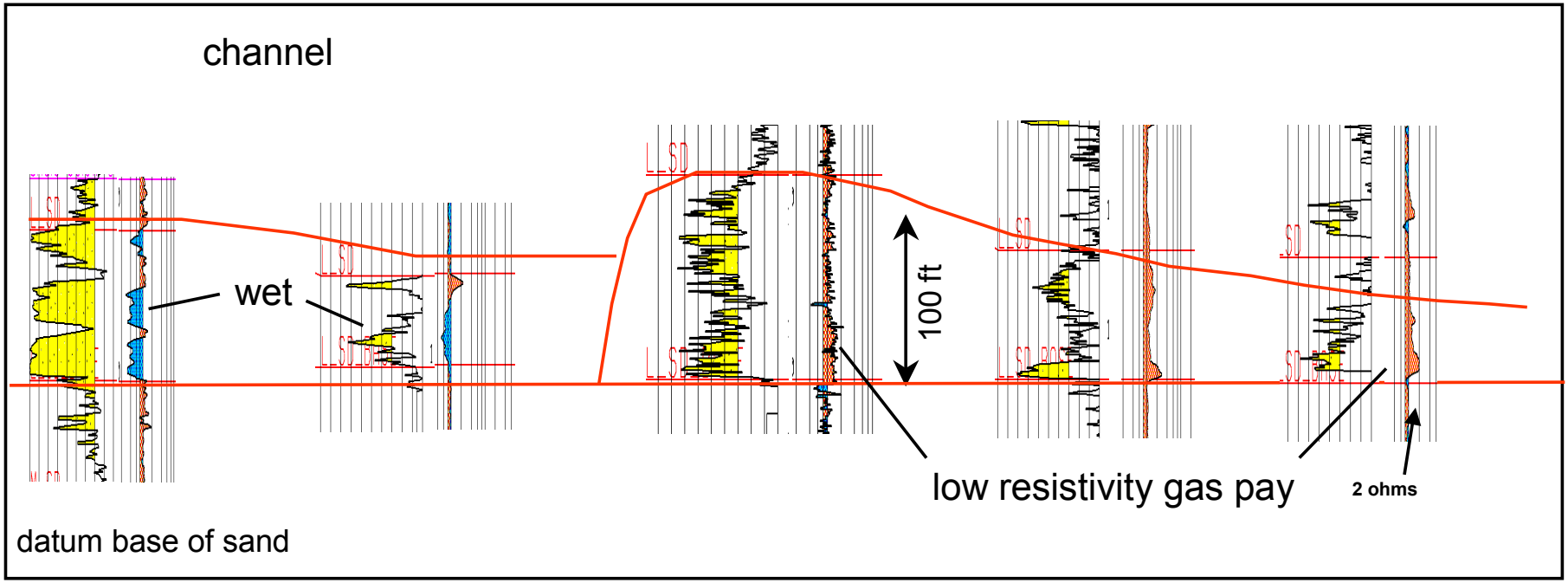
Kolla et al., 2001

L Sand, Ram/Powell Field, Gulf of Mexico: comprises channel, proximal, & distal levee facies.



(Clemenceau et al., 2000)

Ram Powell 'L' Sand



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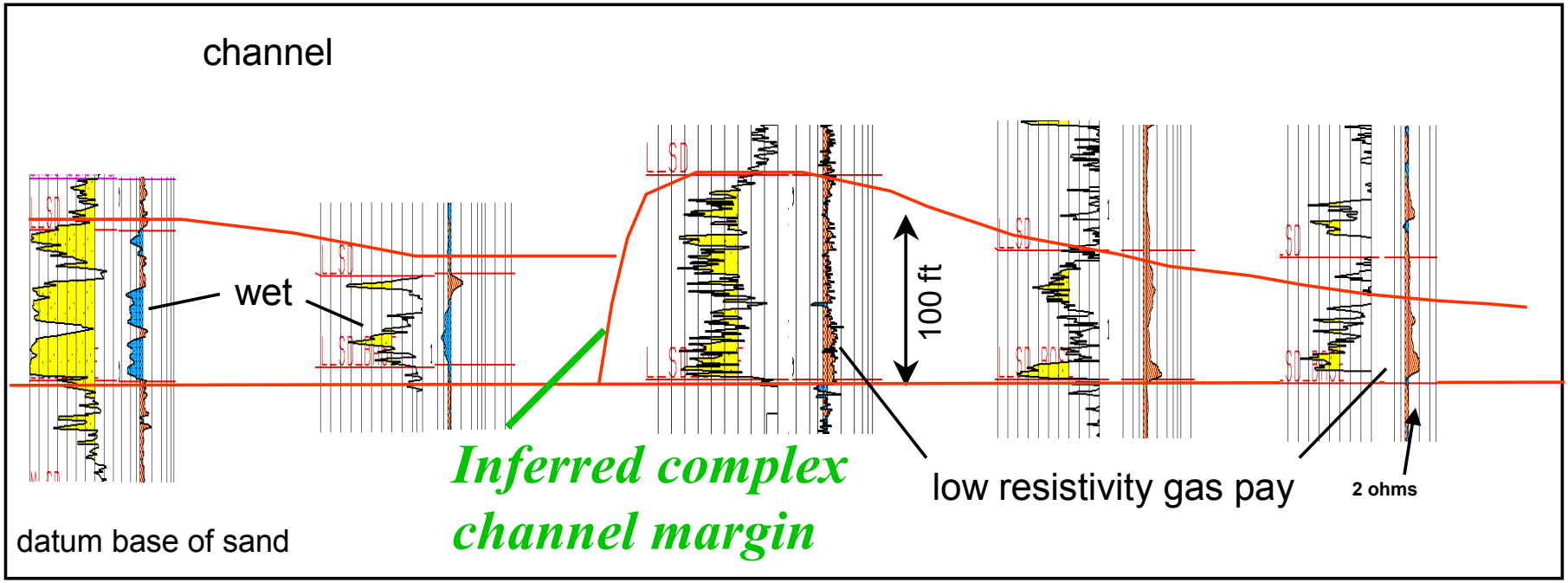

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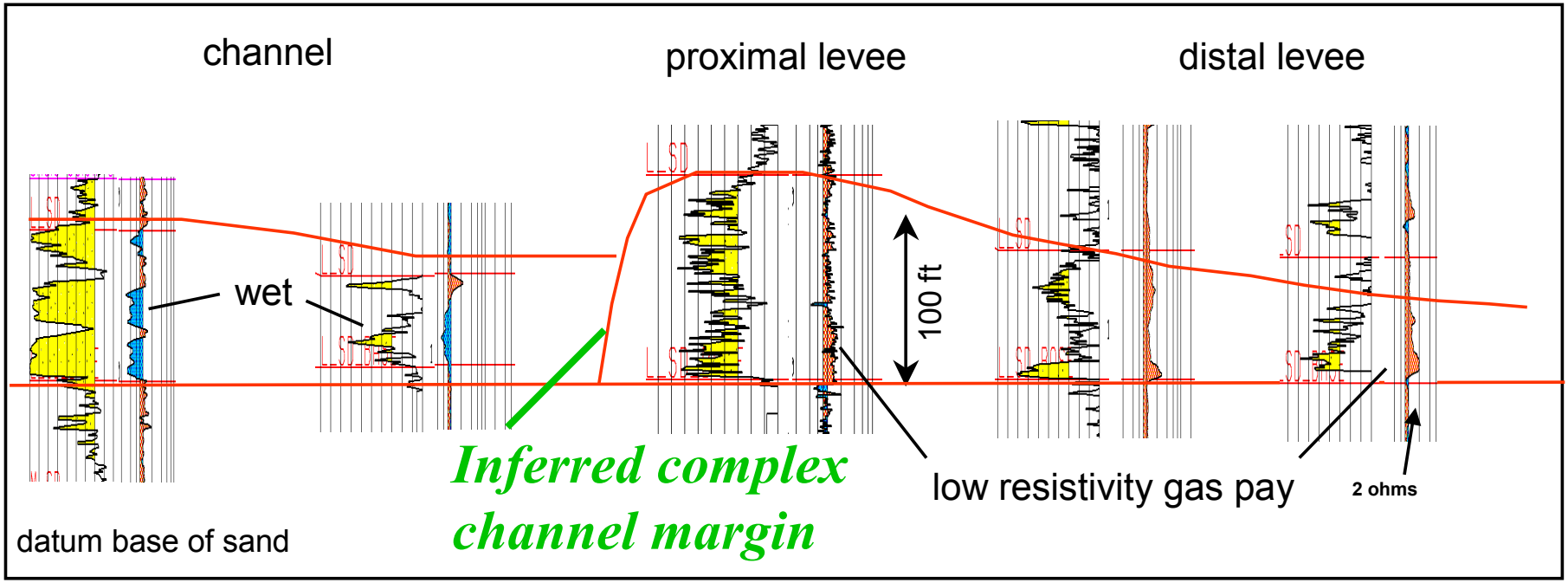

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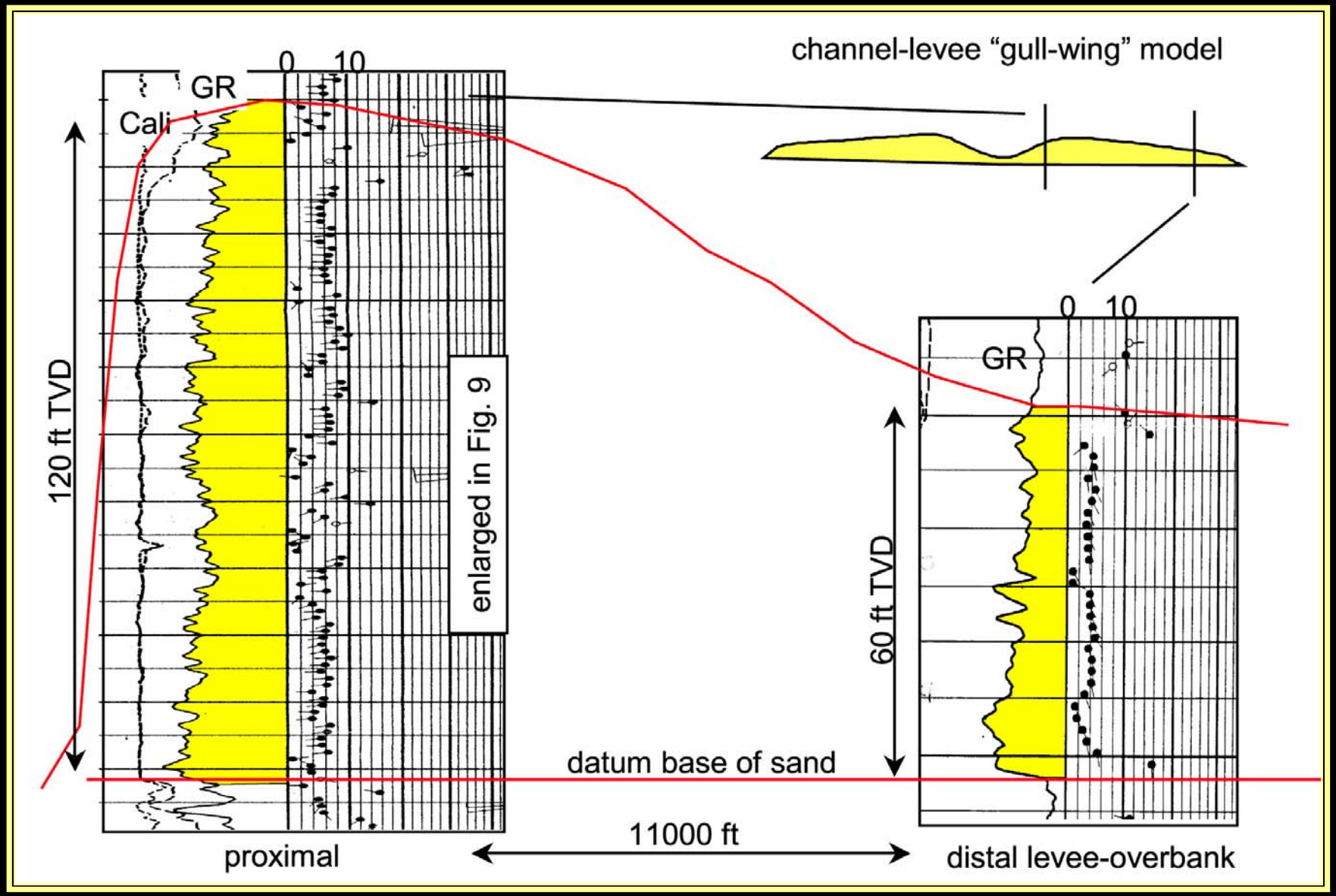

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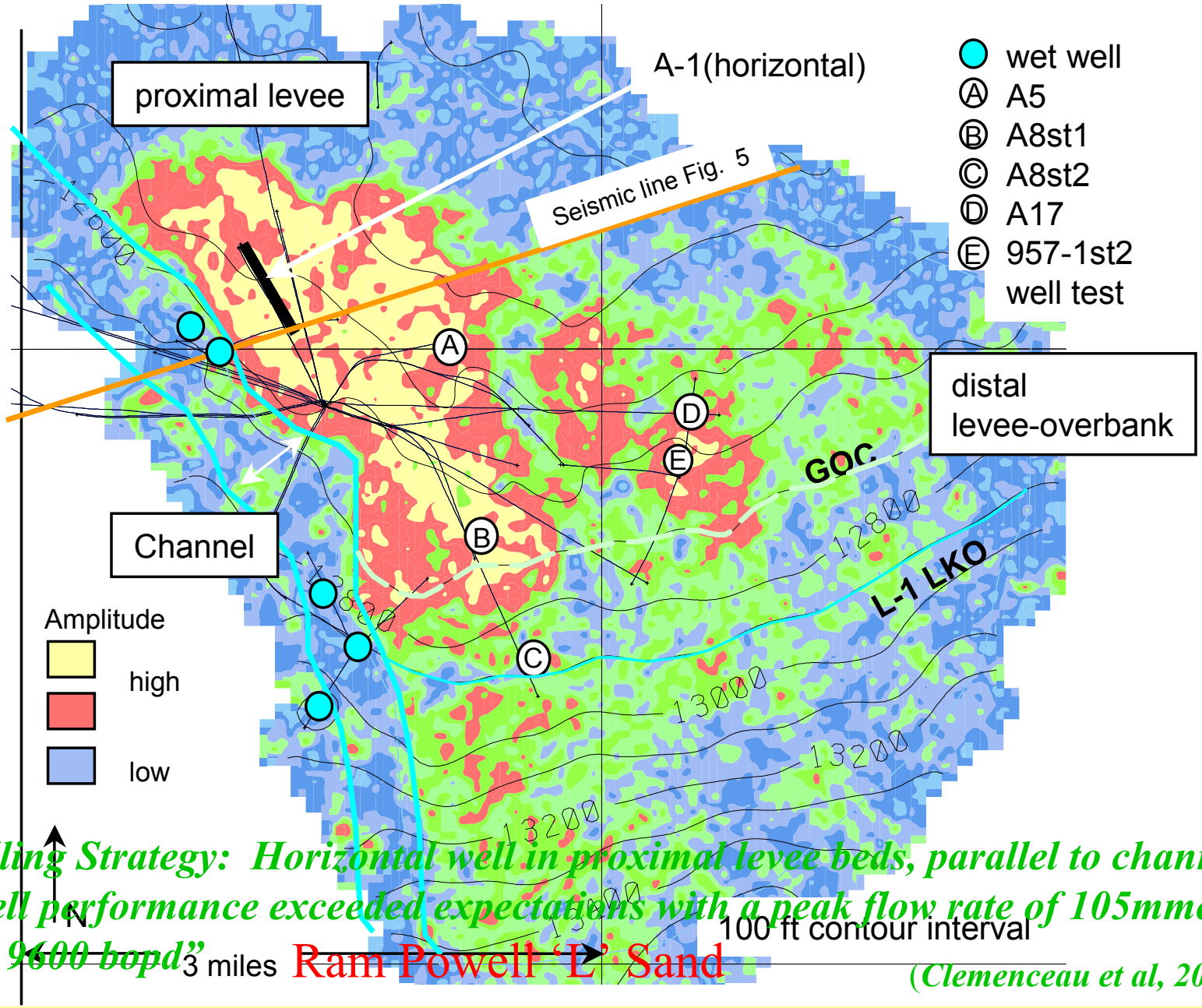


Drilling Strategy: Horizontal well in proximal levee beds, parallel to channel: "Well performance exceeded expectations with a peak flow rate of 105mmcfgd and 9600 bopd"

Ram Powell 'L' Sand

(Clemenceau et al, 2000)

WHAT IF YOU DON'T HAVE SEISMIC????

BOREHOLE IMAGE LOGS WILL ALLOW YOU TO DIFFERENTIATE FACIES FOR VOLUMETRICS AND DRILLING STRATEGY (i.e. conventional well logs won't differentiate facies with any degree of certainty)

-Wellbore and behind-outcrop borehole image logs (STAR™ and FMI™) verify this in Lewis Shale and Mt. Messenger!!

™ Baker-Hughes

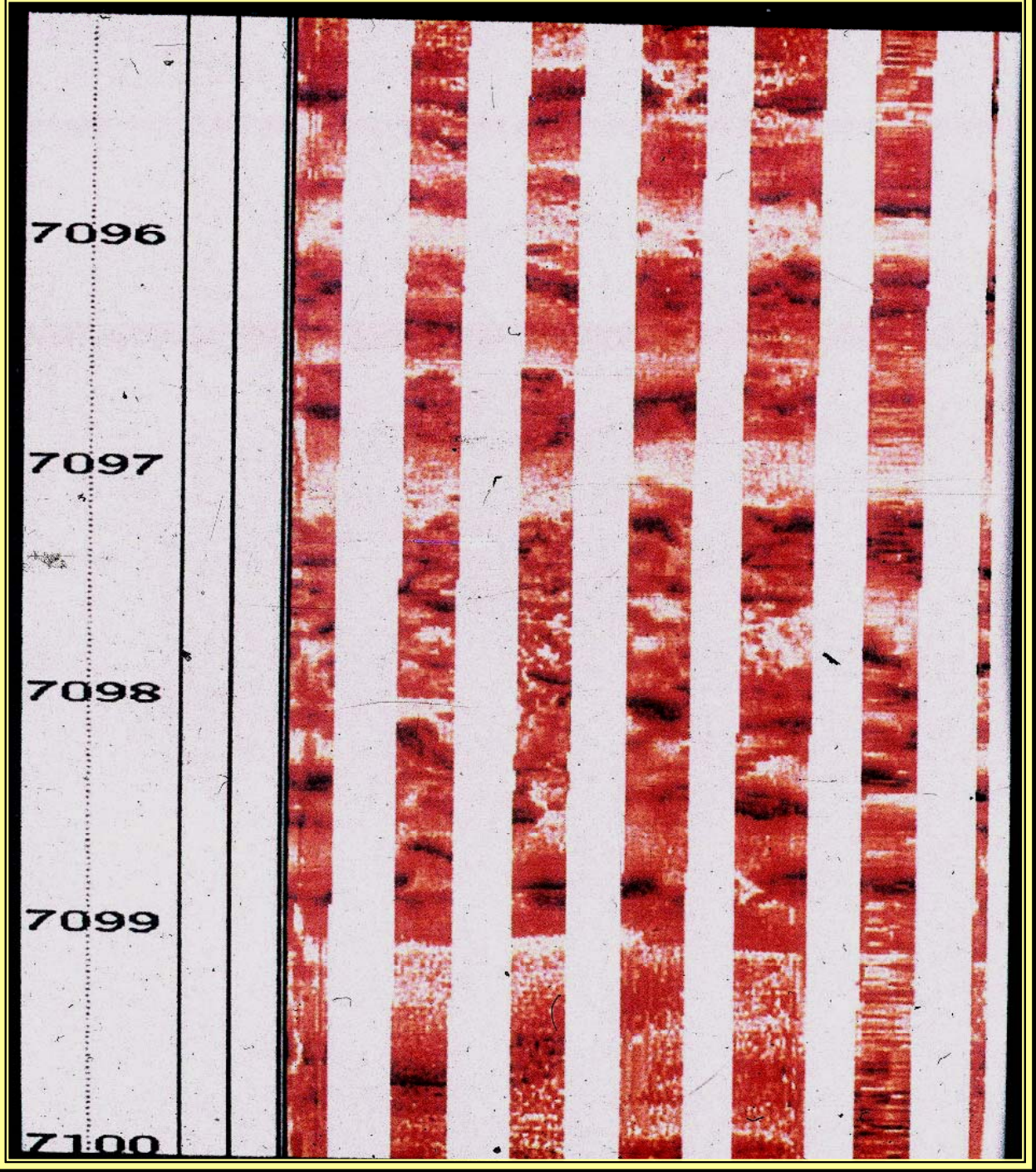
™ Schlumberger

Borehole Image Log, Lewis Sh.

Debrites and Turbidites =

Channel -fill sandstones

(Witton, 2000)

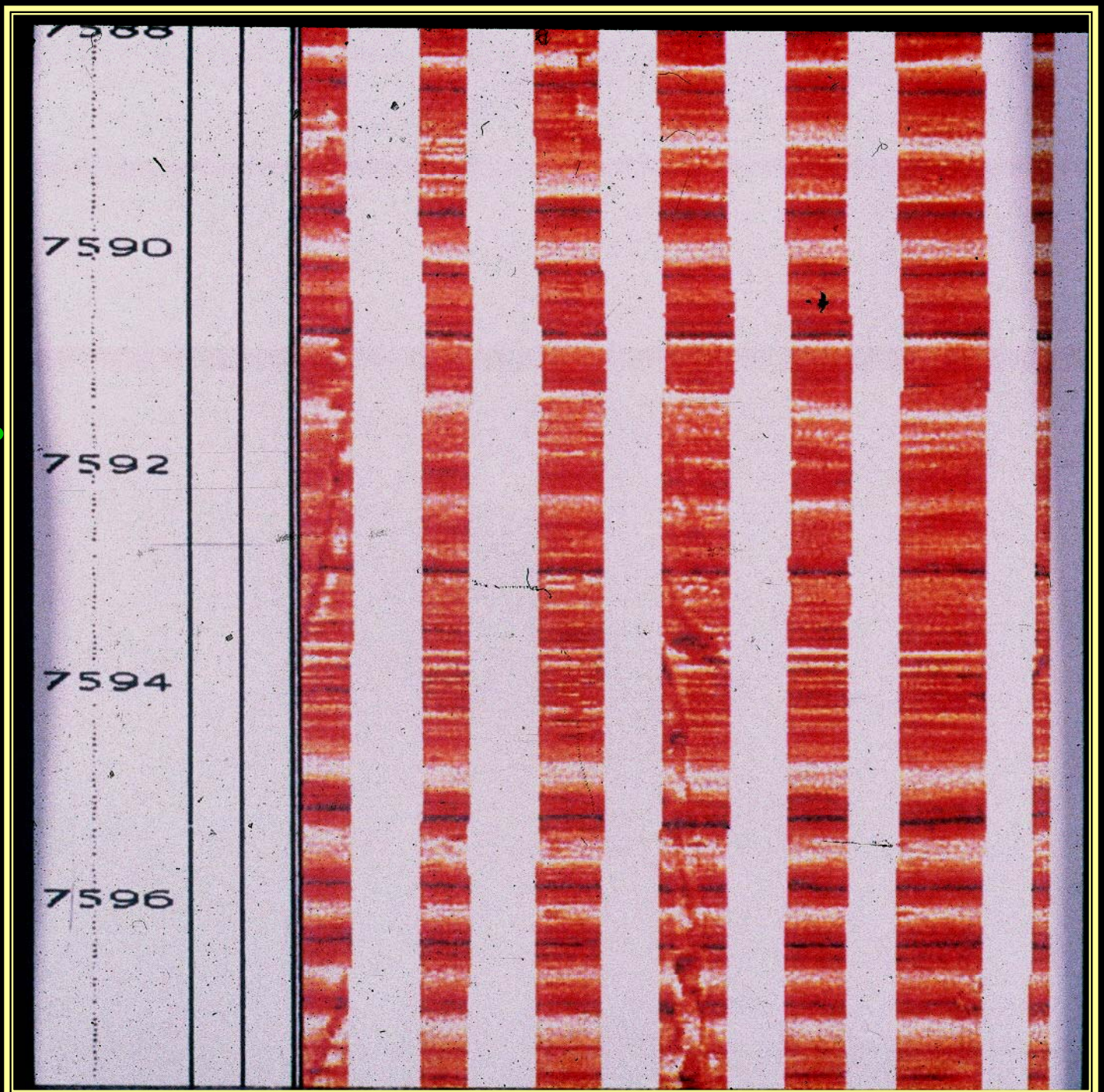


Borehole Image Log, Lewis Sh.

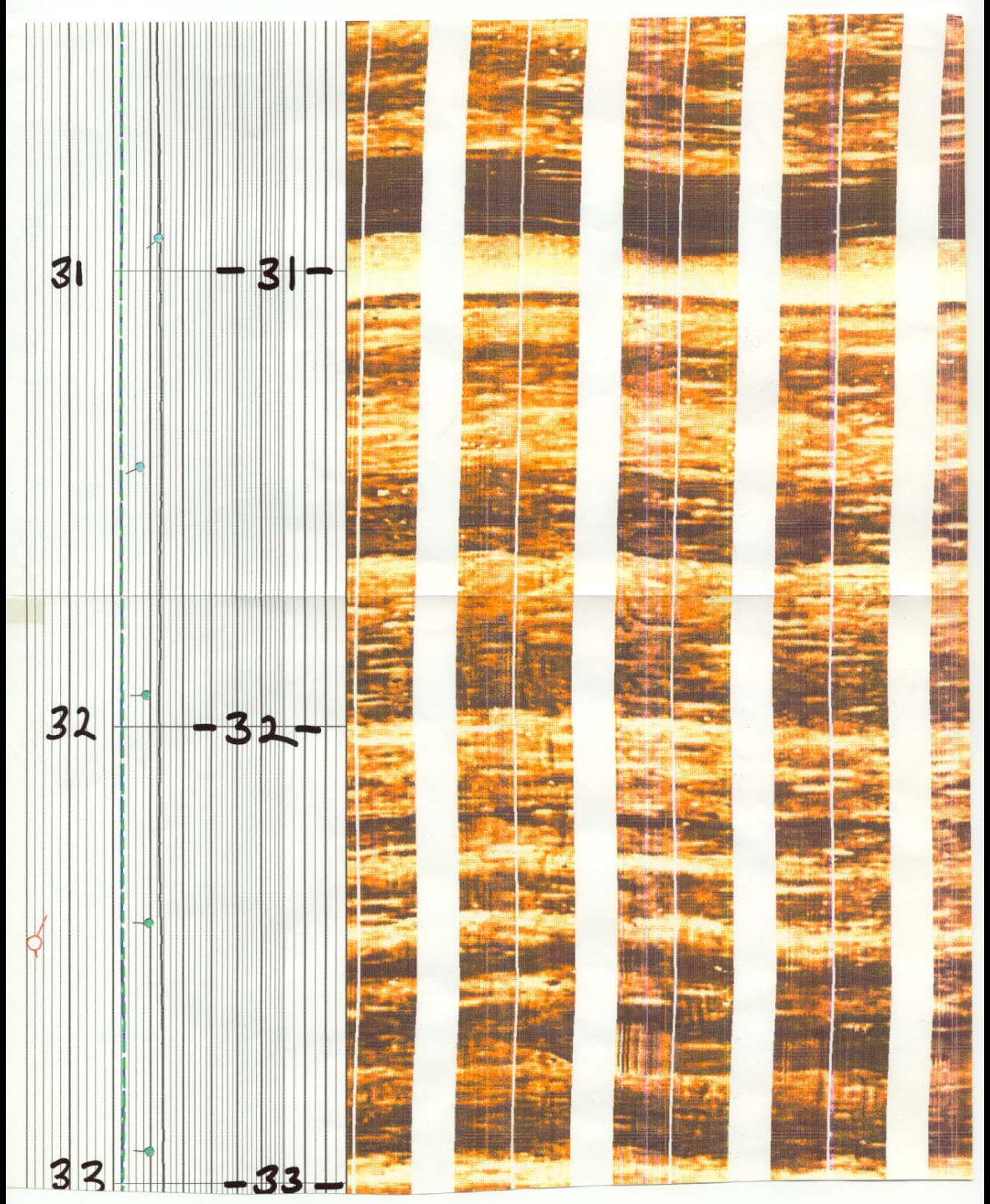
Turbidites only =

Sheet Sandstones

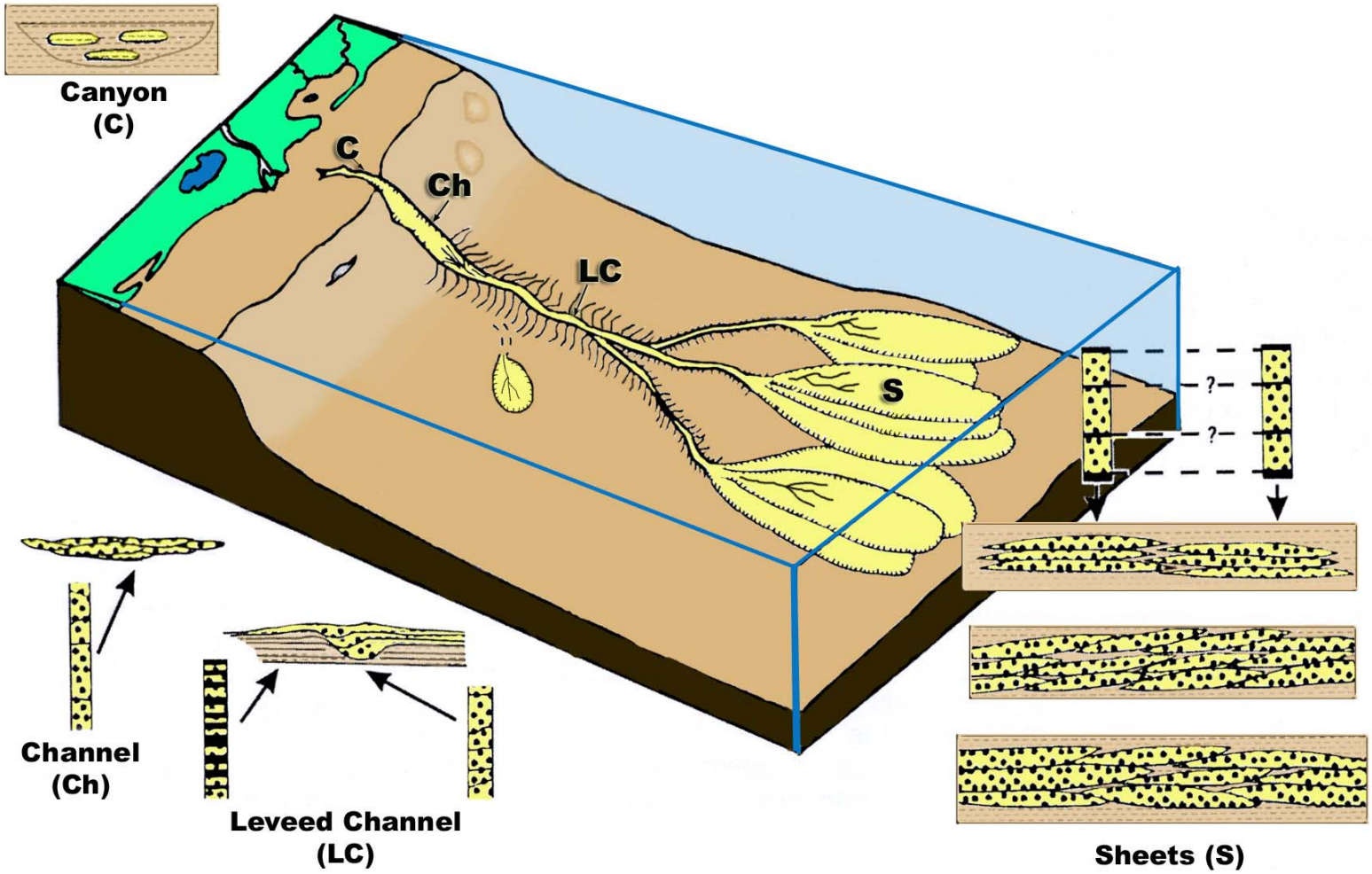
(Witton, 2000)



Levee beds from Mt. Messenger Fm. New Zealand

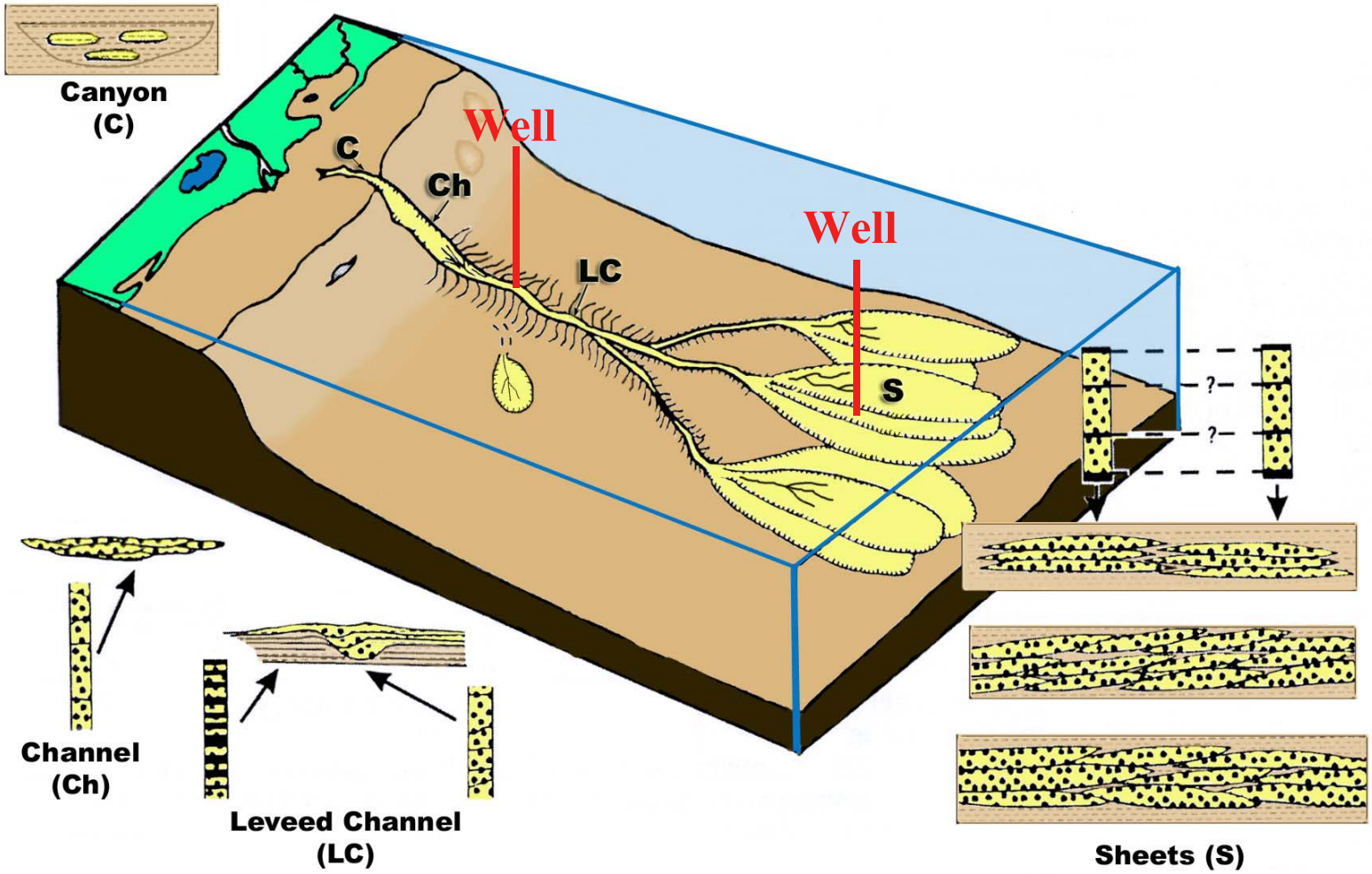


Fine-Grained, Deepwater Architectural Elements



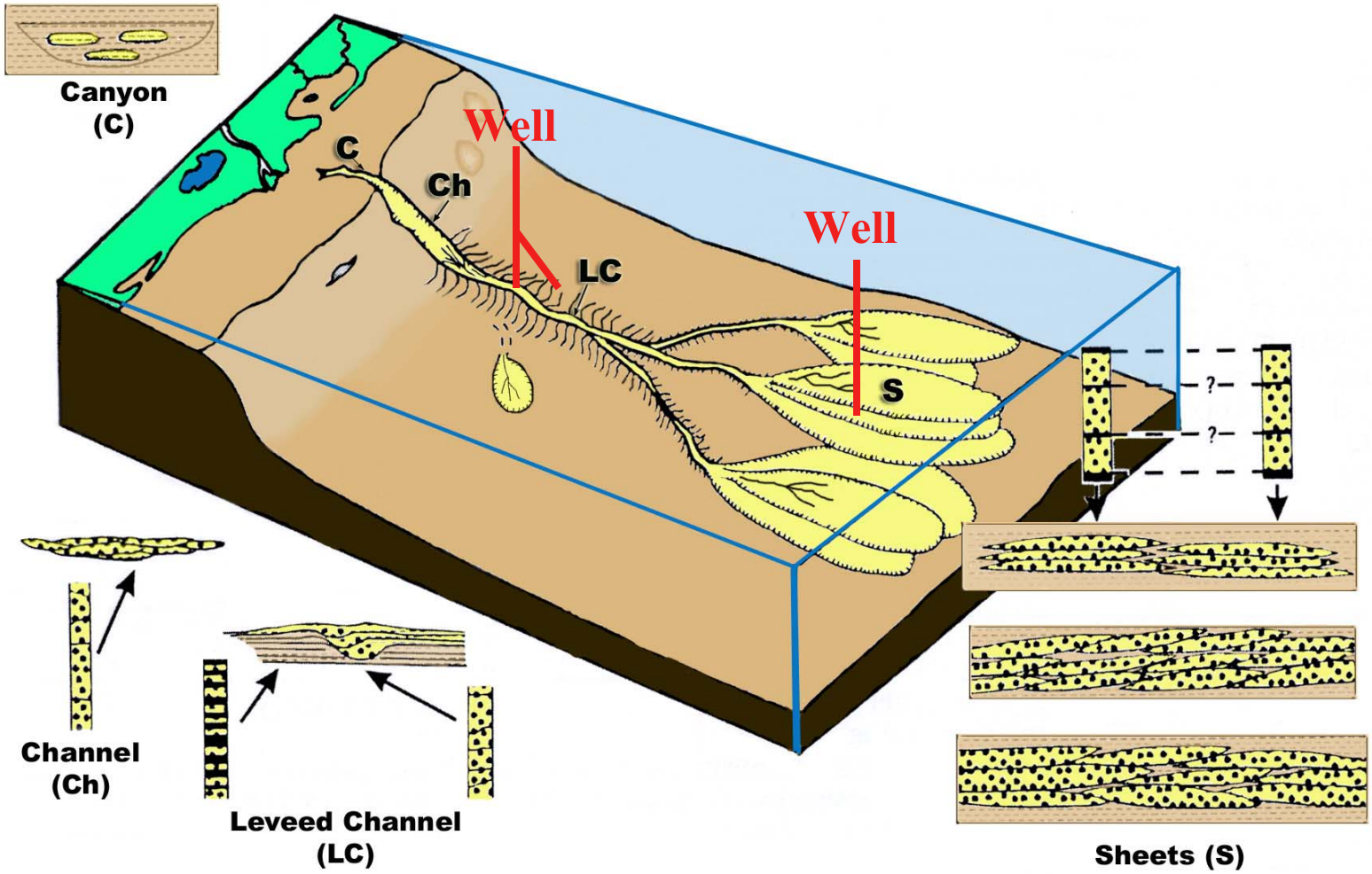
Modified from Bouma (2000)

Fine-Grained, Deepwater Architectural Elements



Modified from Bouma (2000)

Fine-Grained, Deepwater Architectural Elements

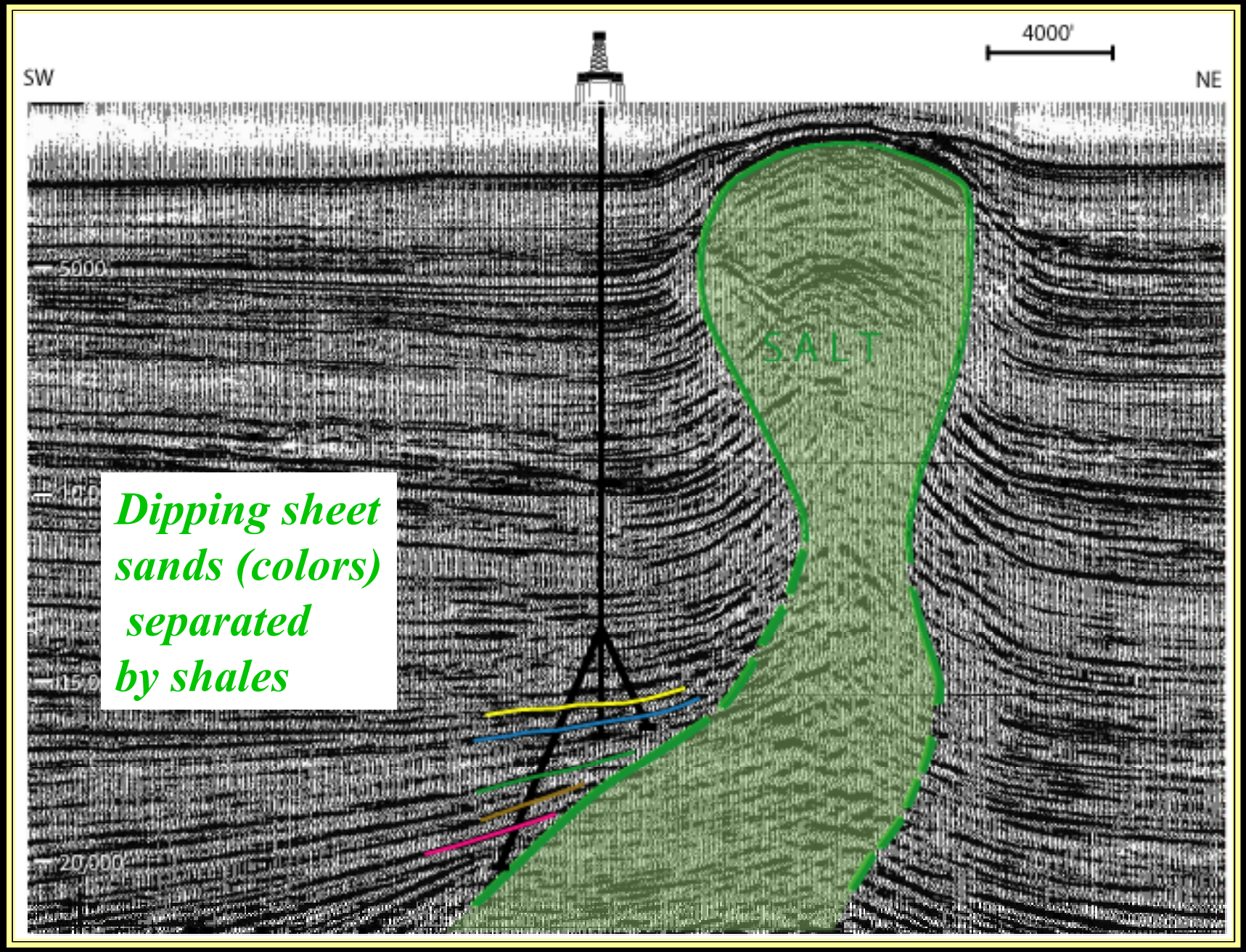


Modified from Bouma (2000)

YET ANOTHER USE OF OUTCROPS

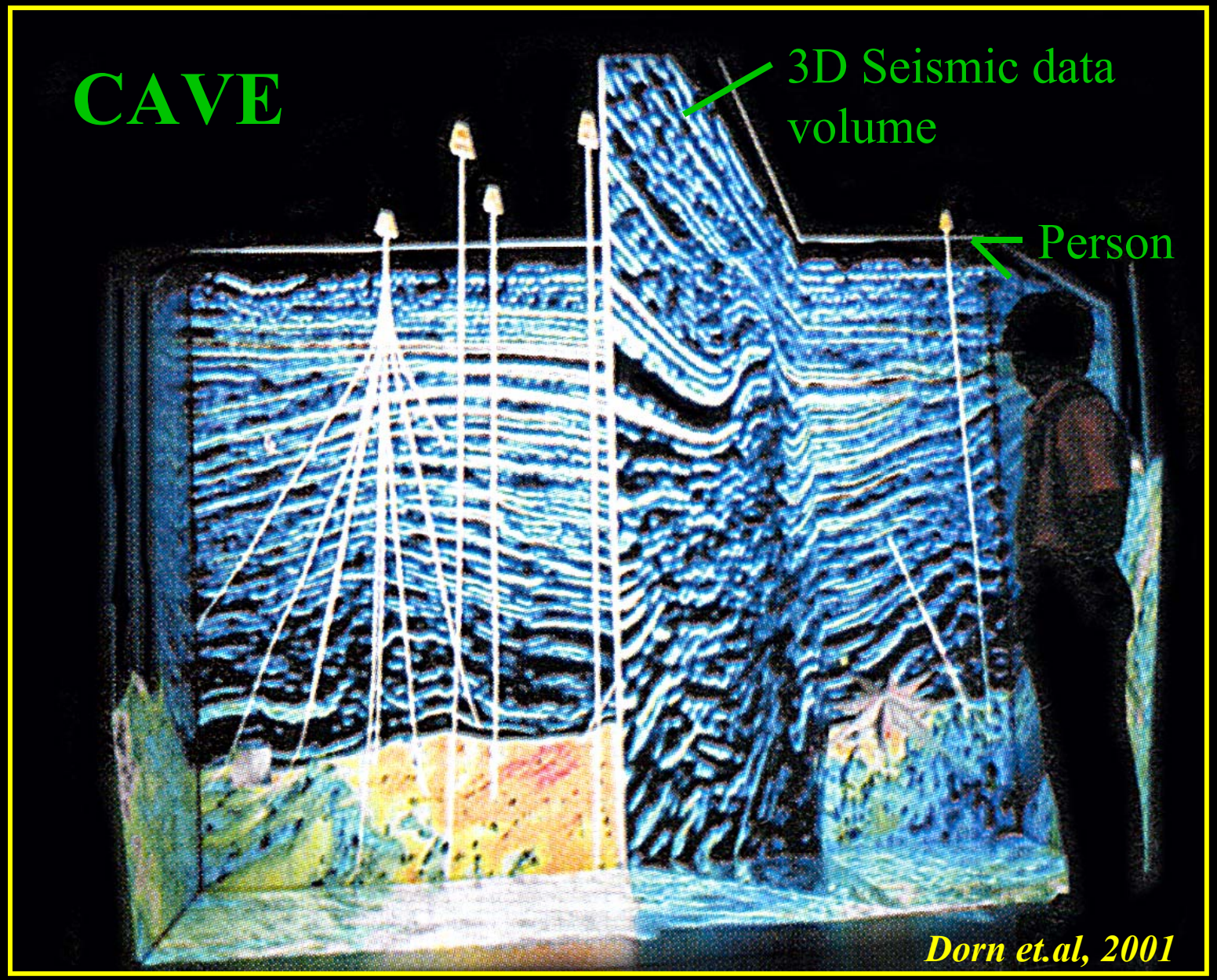
- **3D GEOLOGIC MODELING FOR VISUALIZATION, RESERVOIR PERFORMANCE PREDICTION & WELL PLACEMENT**

Lets study the Penn. Jackfork Group in Arkansas!!

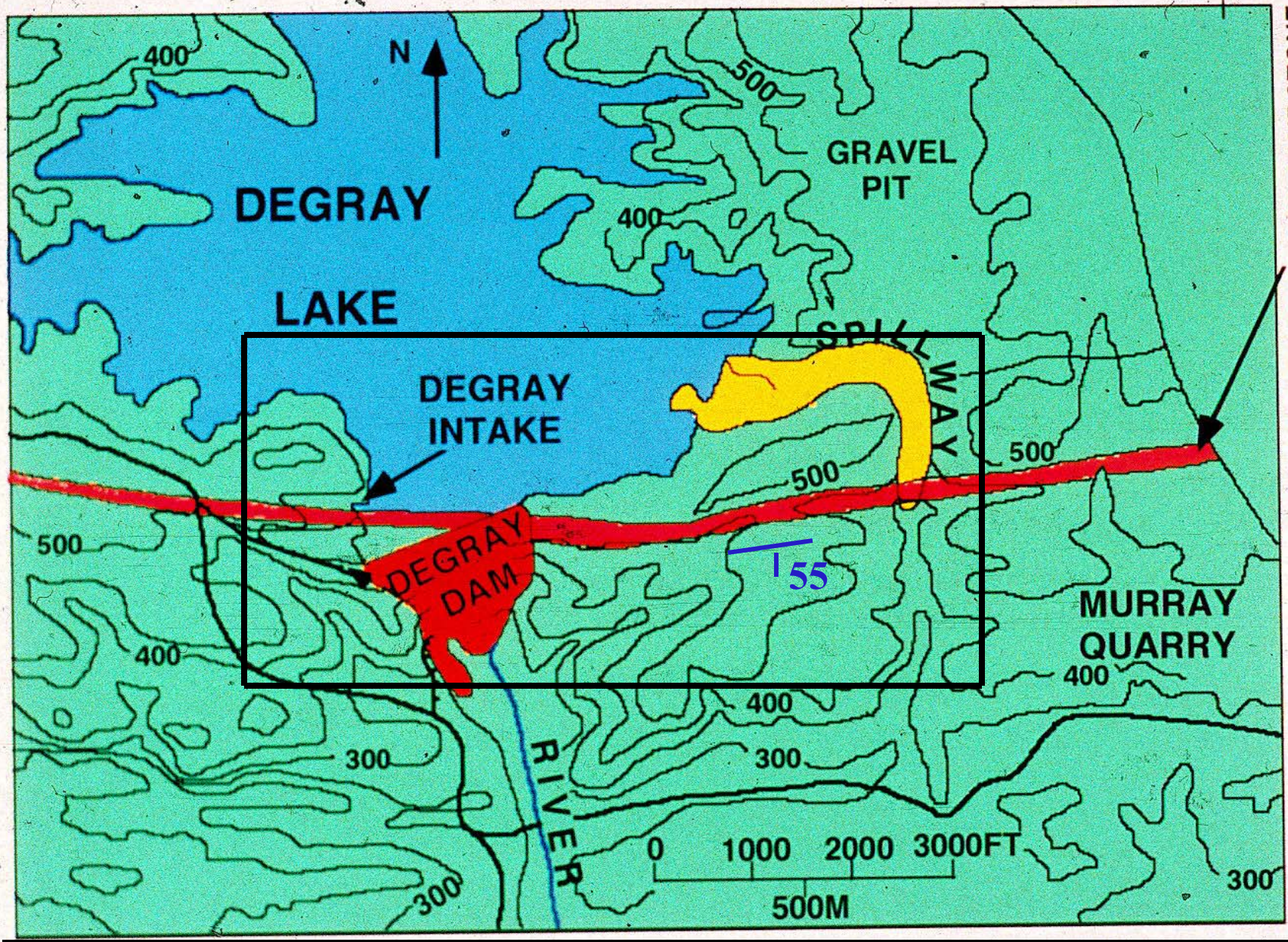


Gulf of Mexico stacked sheet sand reservoirs *(Kendrick, 2000)*

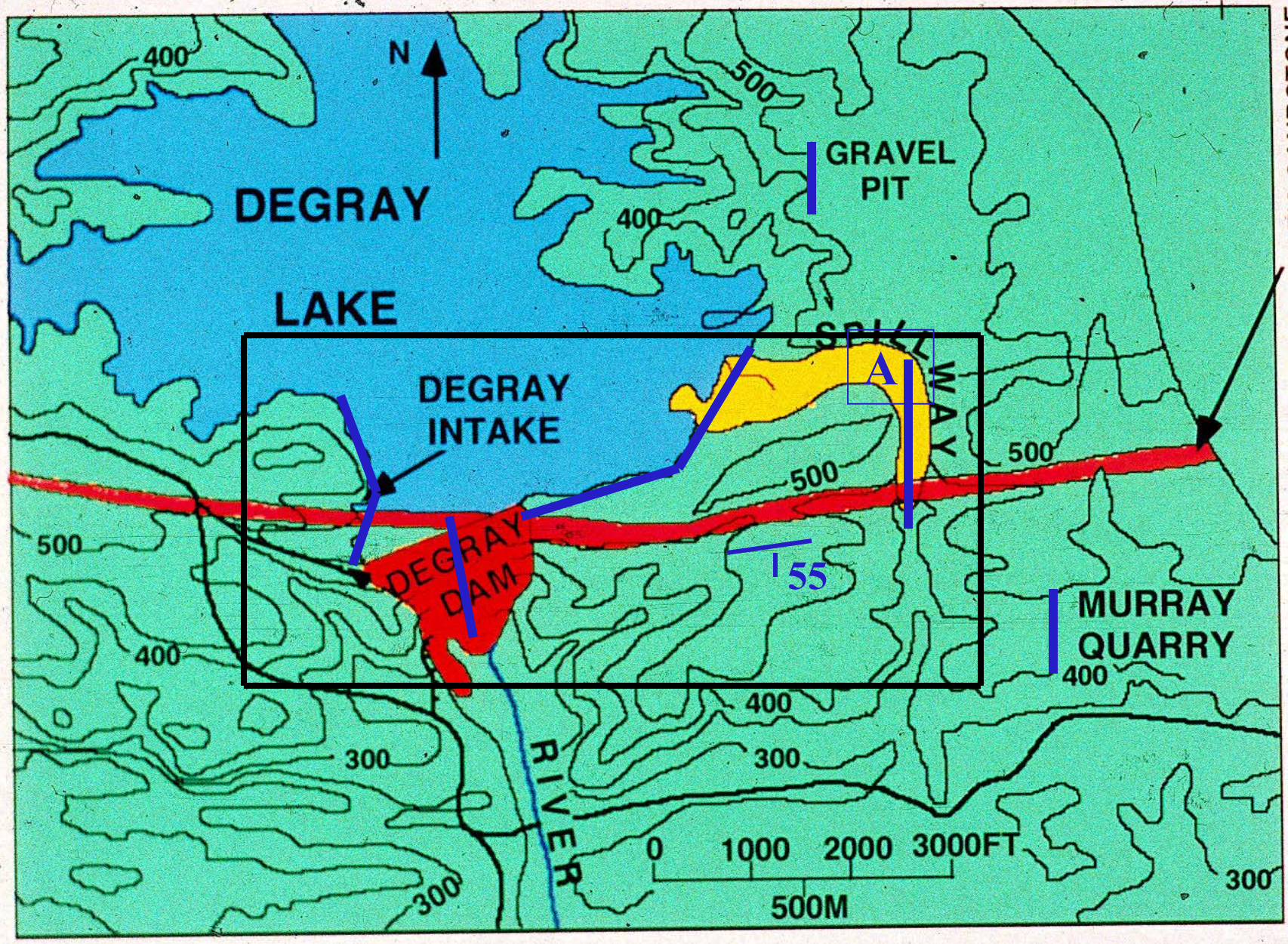
CAVE



Walk-in CAVE's are excellent, but expensive!!

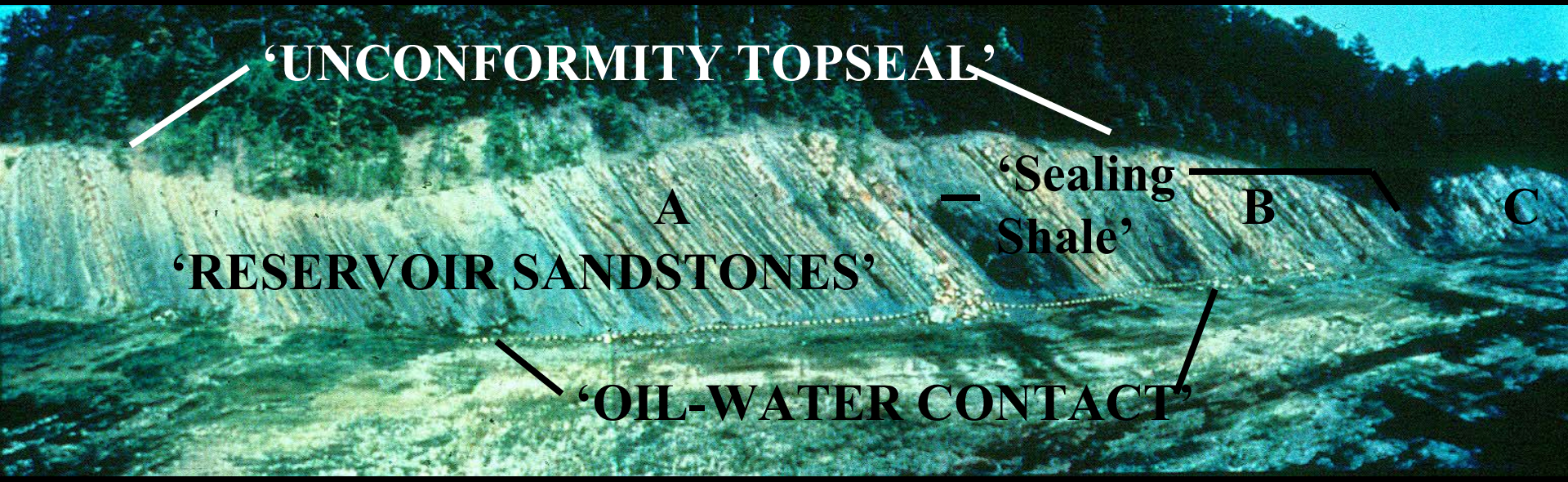


GEOLOGIC MODELING AREA, ARKANSAS: THE INEXPENSIVE CAVE IS CALLED AN OUTCROP!!!



OUTCROP GEOLOGIC MODELING AREA, ARKANSAS

OUTCROP GEOLOGIC ‘RESERVOIR’ MODEL



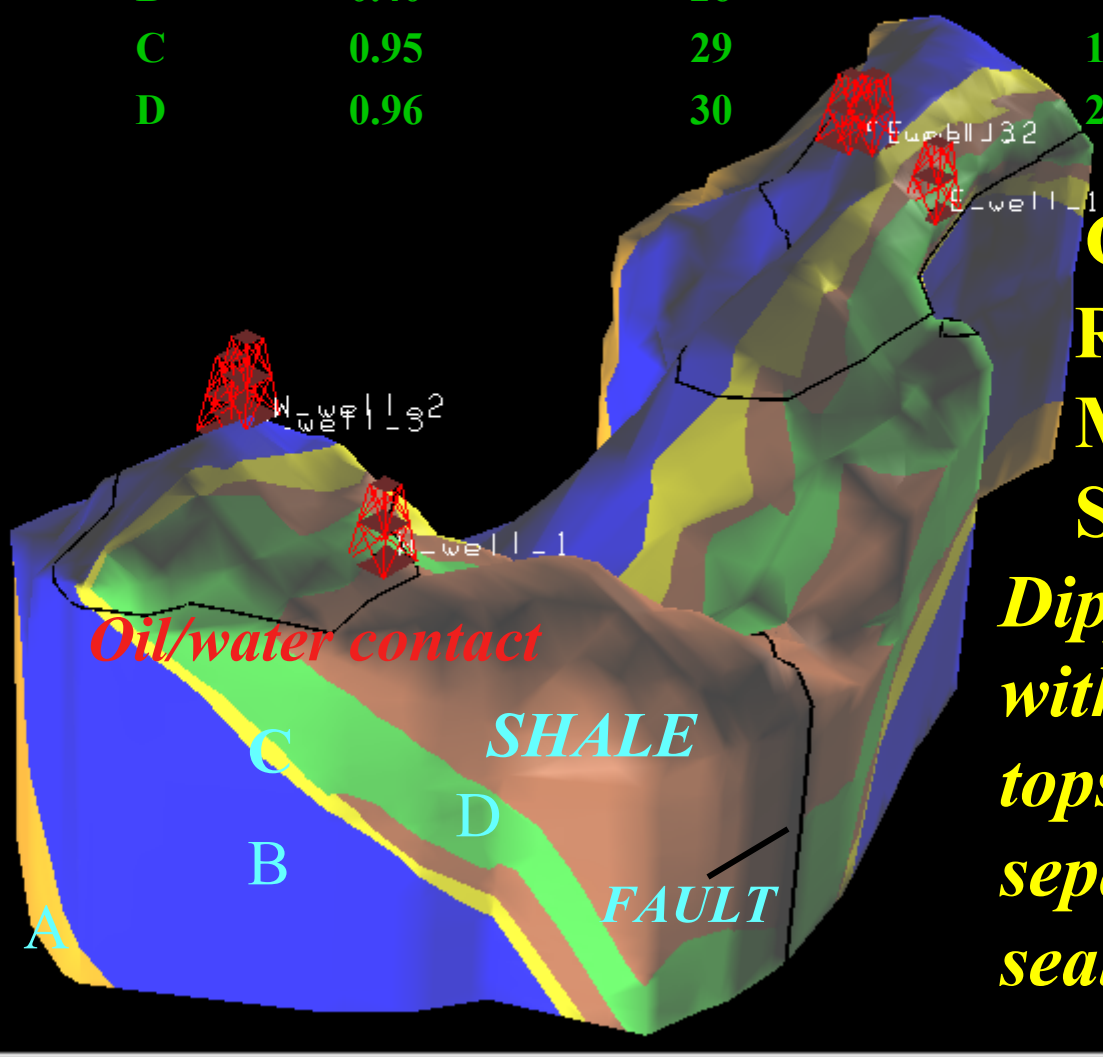
OUTCROP ‘A’

“Imagination is more powerful than knowledge”
Albert Einstein

Gocad - Camera (2)

View Display Settings Windows Help

Zone	Net/Gross	Por.(%)	Perm.(md)	Sw (%)
A	0.70	29	1000	20
B	0.40	26	300	20
C	0.95	29	1000	20
D	0.96	30	2000	20



GEOLOGIC RESERVOIR MODEL FOR SIMULATION:

Dipping sandstones with unconformity topseal; Layers separated by sealing shales

Orbit increment

20

All

west_2mounta
west_2mounta
west_2mounta
west_2mounta
west_mountain
west_mountain
west_mountain
west_mountain
west_mountain
west_mountain

Immediate

Clone

Info:

Gocad - Camera (1)

View Display Settings Windows Help

Orbit increment

2.86241

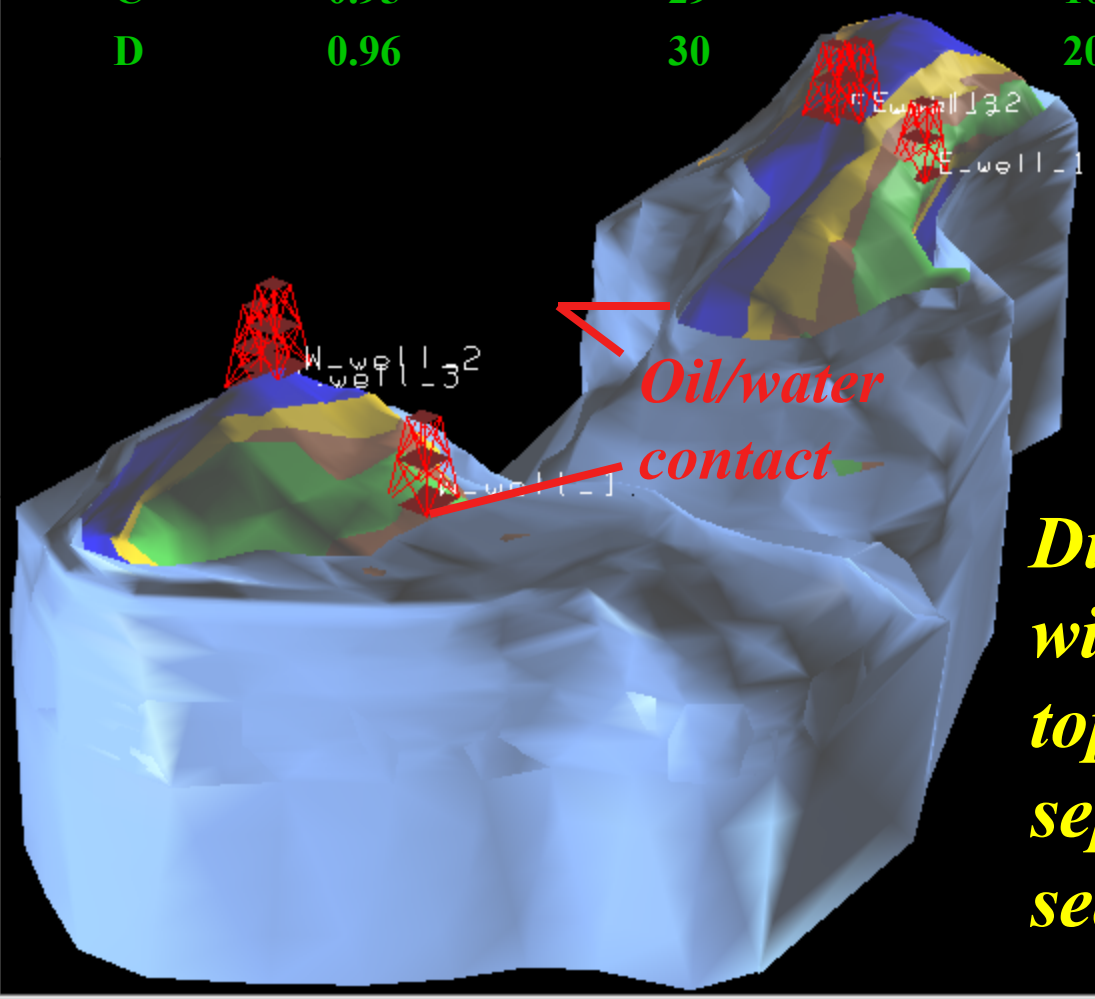
All

east_mountain
east_mountain
man_flt
min_flt
mountain
oil_water_con
unconformity
water_E_1
water_E_10
water_E_2

Immediate

Clone

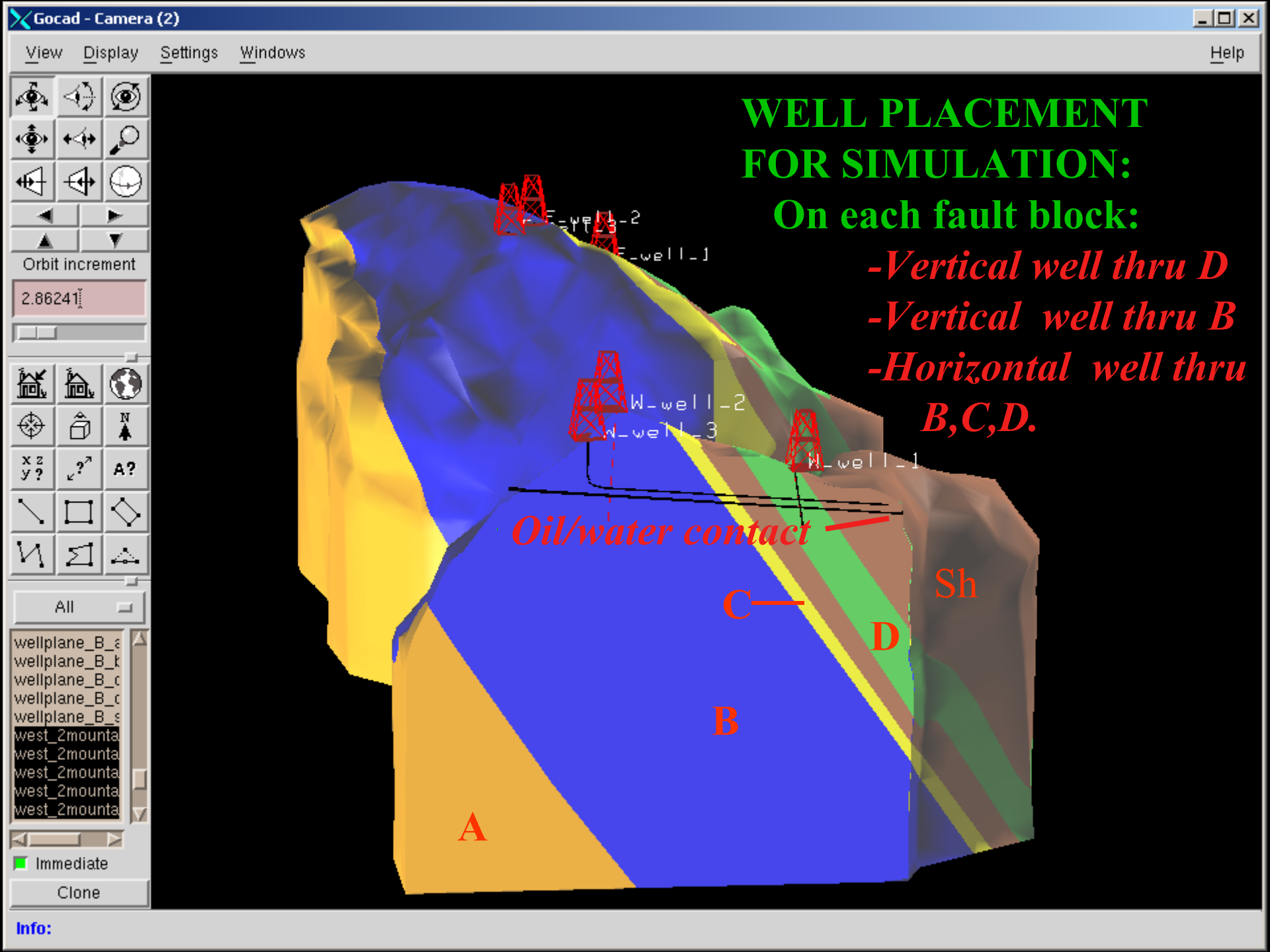
Zone	Net/Gross	Por.(%)	Perm.(md)	Sw (%)
A	0.70	29	1000	20
B	0.40	26	300	20
C	0.95	29	1000	20
D	0.96	30	2000	20

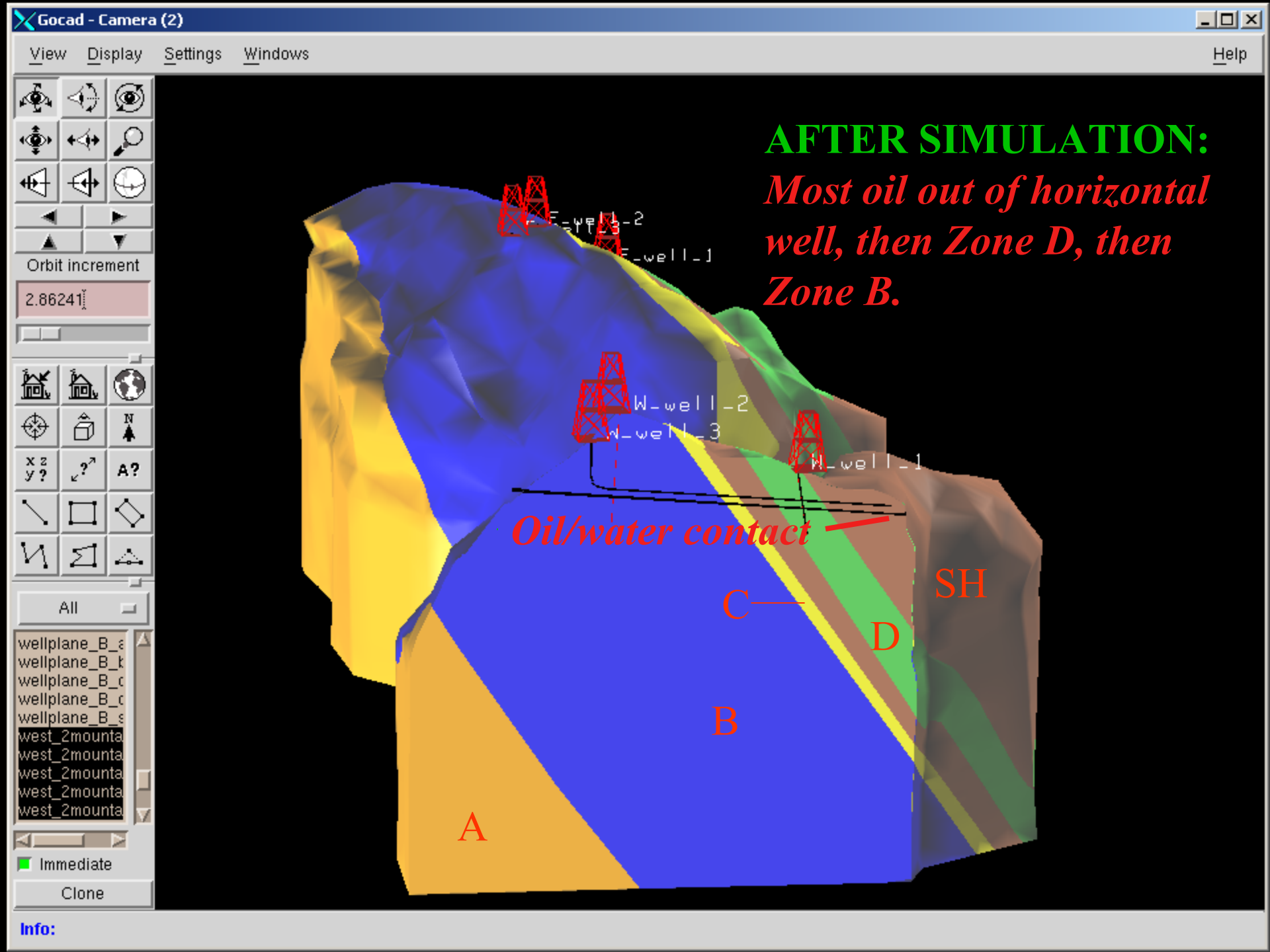


GEOLOGIC RESERVOIR MODEL FOR SIMULATION:

Dipping sandstones with unconformity topseal; Layers separated by sealing shales

Info:


Gocad - Camera (2)
View
Display
Settings
Windows
Help
Orbit increment
2.86241
All
wellplane_B_a
wellplane_B_b
wellplane_B_c
wellplane_B_c
wellplane_B_s
west_2mounta
west_2mounta
west_2mounta
west_2mounta
west_2mounta
Immediate
Clone
Info:
WELL PLACEMENT
FOR SIMULATION:
On each fault block:
-Vertical well thru D
-Vertical well thru B
-Horizontal well thru
B,C,D.
E_well_2
E_well_1
W_well_2
W_well_3
W_well_1
Oil/water contact
Sh
C
D
B
A


Gocad - Camera (2)
View
Display
Settings
Windows
Help
Orbit increment
2.86241
All
wellplane_B_a
wellplane_B_b
wellplane_B_c
wellplane_B_d
wellplane_B_e
west_2mounta
west_2mounta
west_2mounta
west_2mounta
west_2mounta
Immediate
Clone
Info:
AFTER SIMULATION:
Most oil out of horizontal well, then Zone D, then Zone B.
W_well_2
W_well_3
W_well_1
Oil/water contact
SH
C
D
B
A

VALUE OF OUTCROPS

- **SEEING IS BELIEVING**
- **BUILD SCALED GEOLOGIC MODEL FOR SUBSURFACE PREDICTION:**
  - **-FACIES**
  - **-TRENDS**
  - **-GEOMETRIES**
  - **-DIMENSIONS**
  - **-CONTINUITY/CONNECTIVITY**
- **3D GEOLOGIC MODELING FOR SIMULATION**
- ***IMPROVED & MORE ECONOMIC:***
  - ***-WELL SPACING & PLACEMENT***
  - ***-RESERVOIR PERFORMANCE PREDICTION***

2001-02 AAPG Distinguished Lecture

Funded by the AAPG Foundation
through the J. Ben Carsey Memorial Endowment

Outcrop/Behind Outcrop Characterization of Deepwater (Turbidite) Petroleum Reservoir Analogs: Why and How

Roger M. Slatt
University of Oklahoma
Norman, Oklahoma