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3-D Geological Modeling and ‘Reservoir’ Flow Simulation of a Leveed-Channel Outcrop with Application to Deepwater Leveed-Channel Reservoirs*

Carlos A. Santacruz[2], Roger Slatt[1], Yucel Akkutlu[1], and Kurt J. Marfurt[1]

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[1]Geology and Geophyics, University of Oklahoma, Norman, OK.
[2]North America Division, Noble Energy Inc., Houston, TX. (casantac@yahoo.com.ar)

Abstract

This paper presents a 3D geological model of part of the Cretaceous Dad Sandstone (Lewis Shale) leveed-channel outcrop that was built from outcrop and ground-penetrating radar (GPR) data. Because this outcrop is an analog to deepwater leveed-channel systems, the goal was to evaluate possible hydrocarbon production problems related with sub-seismic scale stratigraphic heterogeneities. To accomplish this, the geological model was imported into Eclipse™ for well performance simulation under a number of drilling and geologic scenarios. For example, slumps which often line the bottoms of channel-fill are common in subsurface leveed-channel reservoirs, but they are likely to be deleted during the upscaling process for reservoir simulation. The objective of this paper was to demonstrate that deleting such small-scale features in an upscaled model may lead to erroneous simulation of reservoir performance.

The geological model was built by the integration of Ground Penetrating Radar (GPR), photomosaics and measured stratigraphic sections, and focused on sub-seismic scale continuity and connectivity of sandstones and mudstones. Petrophysical data such as porosity and permeability for the model were obtained from a 1700 ft well drilled and cored through the same strata 4.3 Km away. The shallow GPR data was scaled for input into Petrel™ and seismic attributes were applied to enhance GPR signal quality. Focus of the simulations was on channel-lining slumps and their effect as potential barriers or baffles to fluid flow into a wellbore. Five depletion simulations and fifteen waterflood simulations were generated, each with different permeability (1-40md) of the slumps and injector well locations. Low slump permeability was found to better maintain the water in the reservoir by reducing water coning in the depletion simulations. However, an increase in slump permeability improved oil production for the waterflood simulations.

Using flow simulation it was possible to conclude that the continuity, thickness, distribution and petrophysical properties of the base-channel slumps in reservoirs may result in different well performance than predicted by simulation in leveed-channel deposits.

Selected References

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http://www.searchanddiscovery.net/documents/2009/30075slatt/ndx_slatt.pdf

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3D GEOLOGICAL MODELING AND RESERVOIR FLOW SIMULATION OF A LEVEED-CHANNEL OUTCROP, LEWIS SHALE FORMATION, RATTLESNAKE RIDGE, WYOMING, WITH APPLICATION TO DEEPWATER LEVEED-CHANNEL RESERVOIRS.

By
GeoEngineer. Carlos Santacruz
Dr. Roger Slatt
Dr. Yucel Akkutlu
Dr. Kurt Marfurt

“Nature laughs at the difficulties of integration”

Pierre-Simon Laplace

Outline

- *Concepts*
- *Objective*
- *Area of Study and Regional Geology*
- *Previous Work*
- *Geological Model*
- *Flow Simulations*
- *Discussion*
- *Conclusions and Recommendations*

Outline

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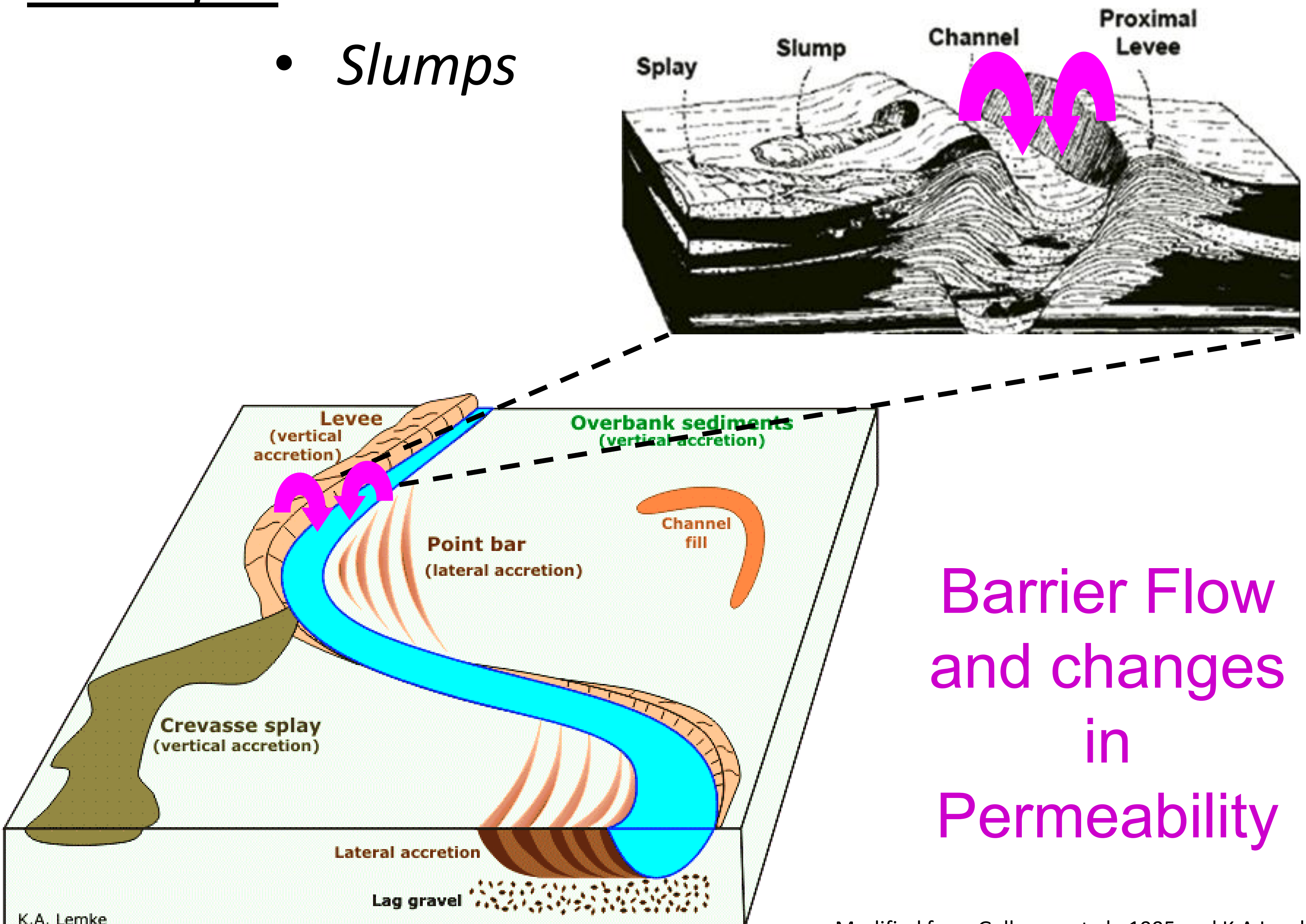
Concepts

- *Slumps*

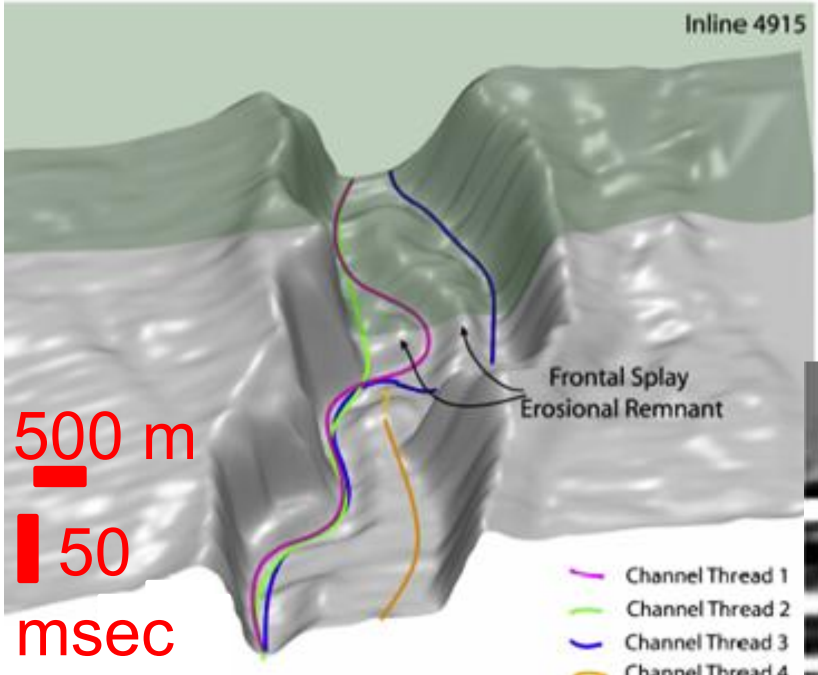


Barrier Flow and changes in Permeability

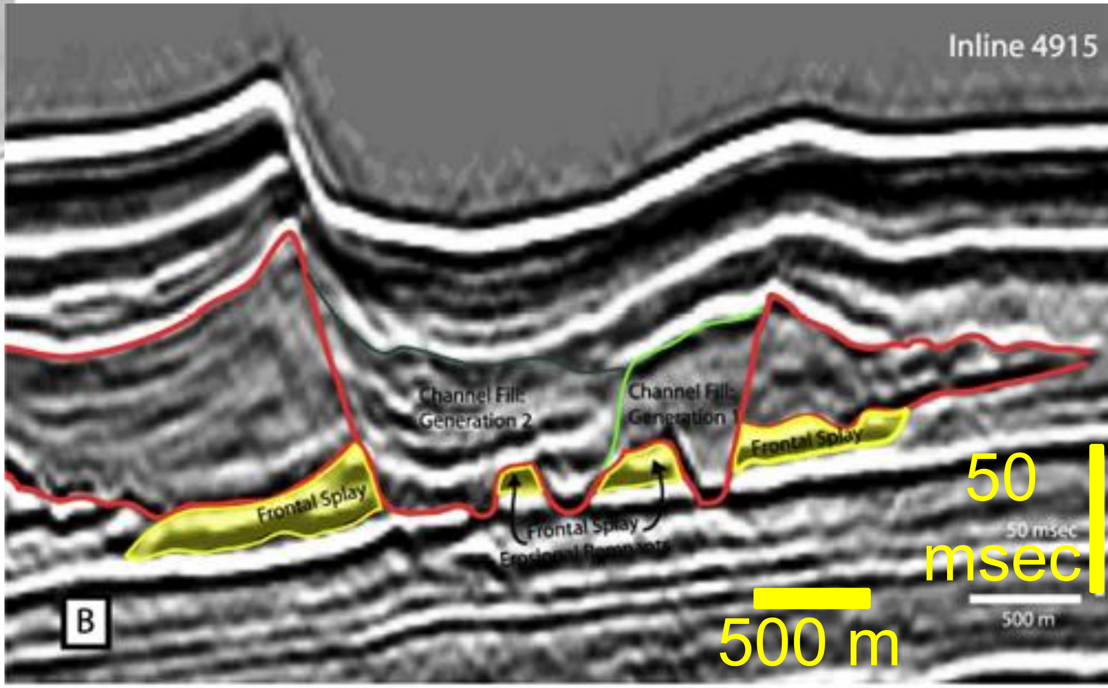
Modified from Galloway et al., 1995 and K.A Lemke 2009

Concepts

- *Erosional Remnants*



Interpretation



Modified from Minken et al., 2004

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Objective

The objective of this study was to build a geological model for flow simulation of leveed-channel deposits, displayed in outcrop, for comparison with analog reservoirs to evaluate production problems in this complex reservoir type.

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Area of Study and Regional Geology

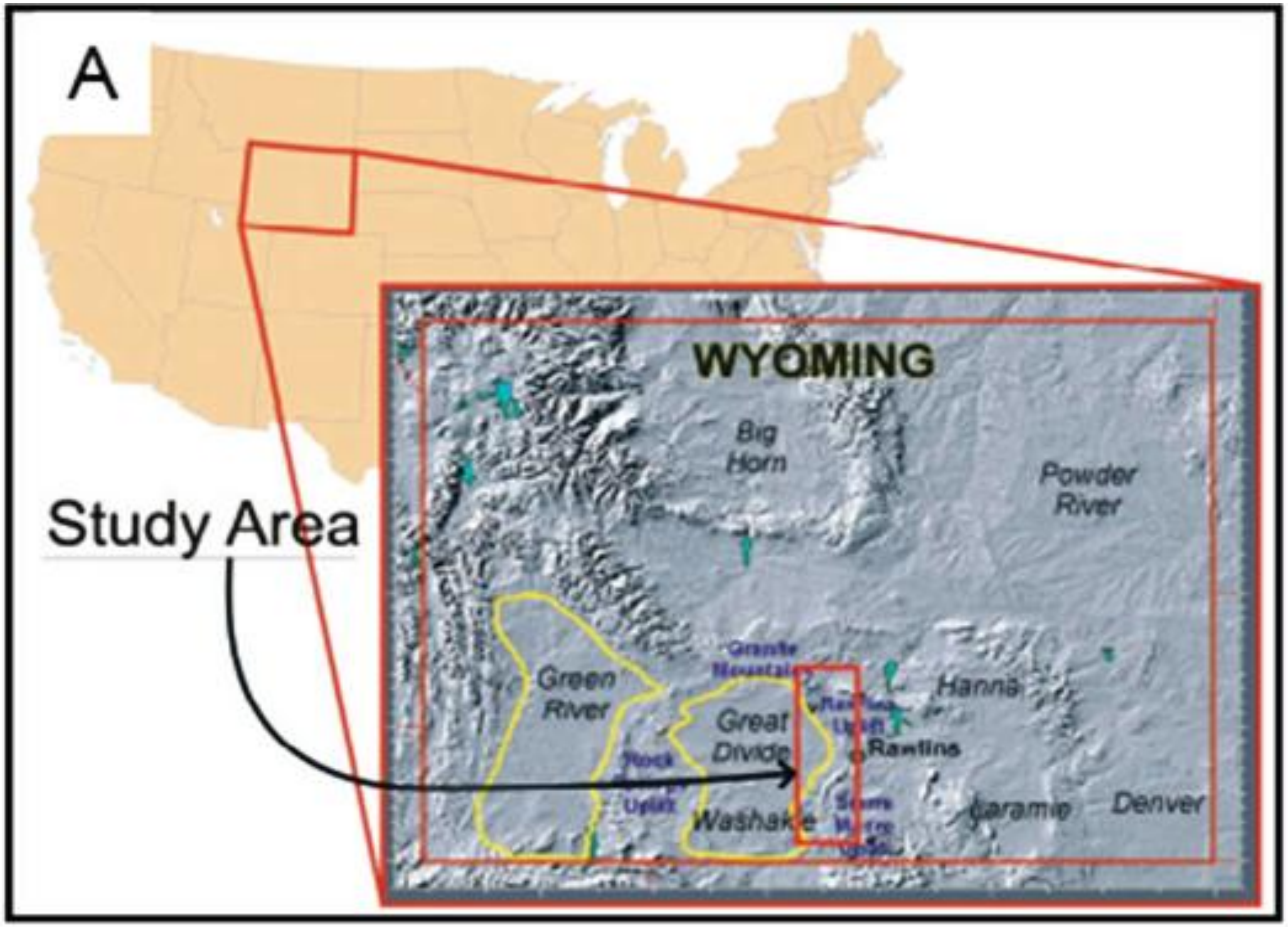

Figure 1. Location of the study area in southern Wyoming on the map of the United States of America (Van Dyke, et al., 2006).

Area of Study and Regional Geology

Figure 2. Map of the United States of America, showing the North American Interior Seaway (75 Ma).

Figure 3. Major seaway regression at 65.0 Ma (Blakey, 2006).

Area of Study and Regional Geology

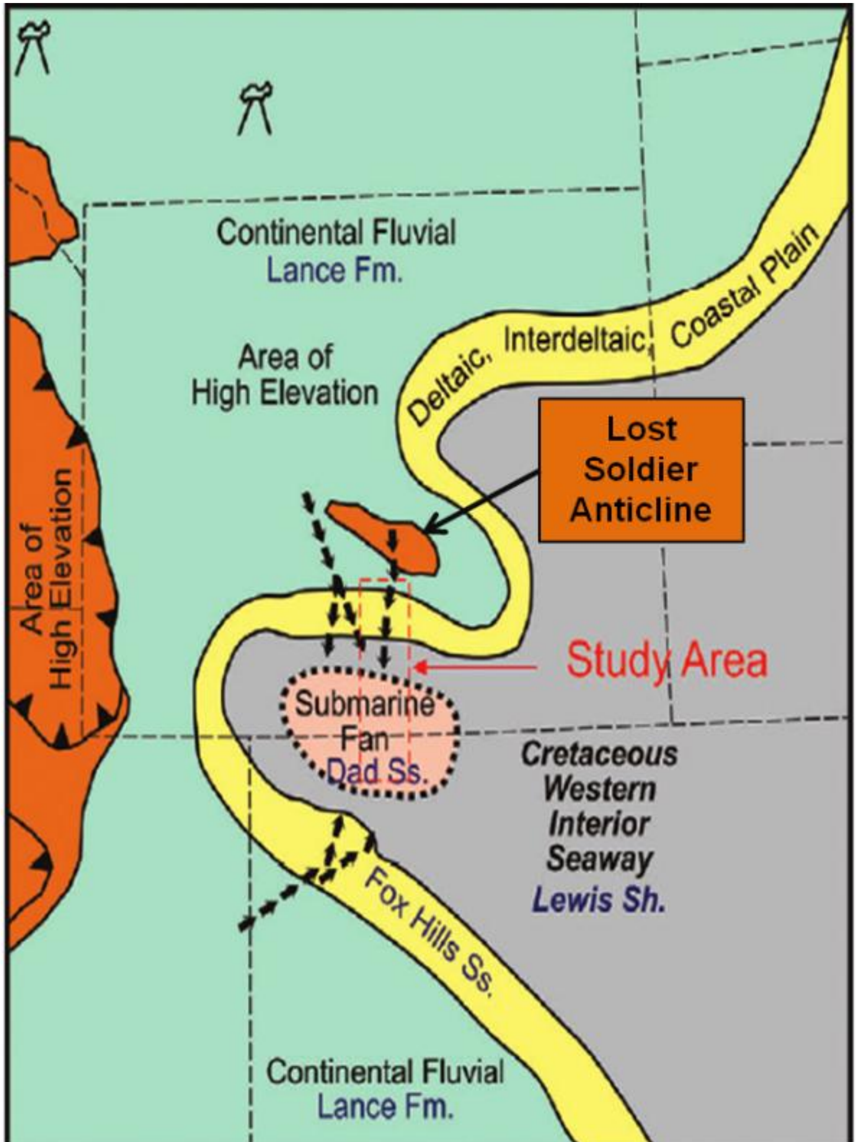

Figure 4. Paleogeographic reconstruction (modified from Slatt, et al., 2006)

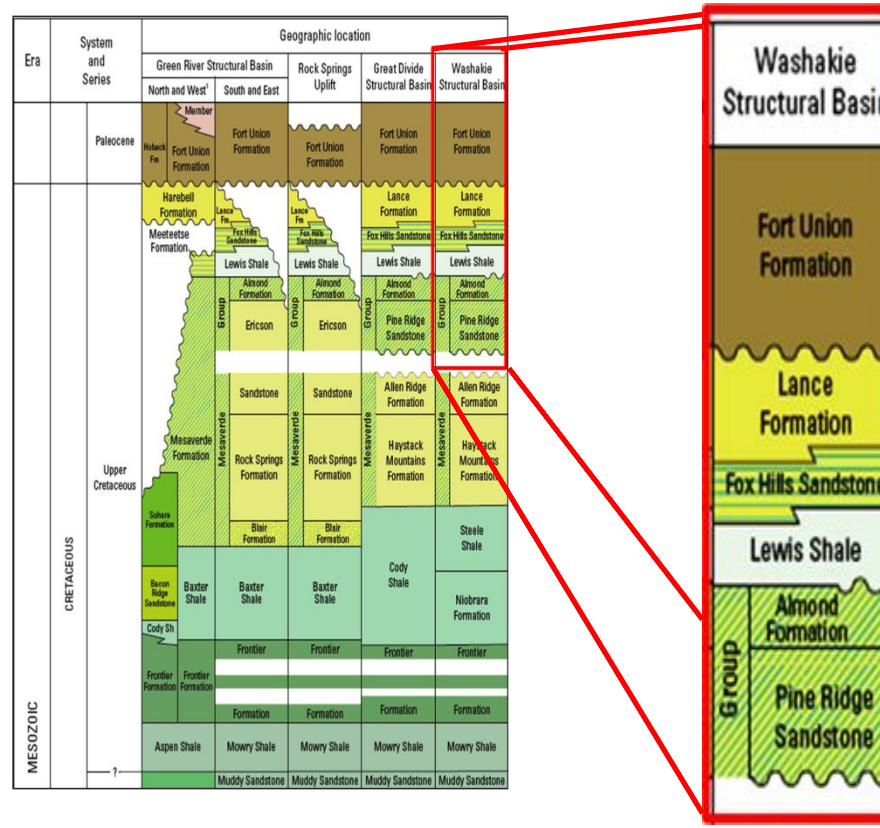

Figure 5. Stratigraphic Column

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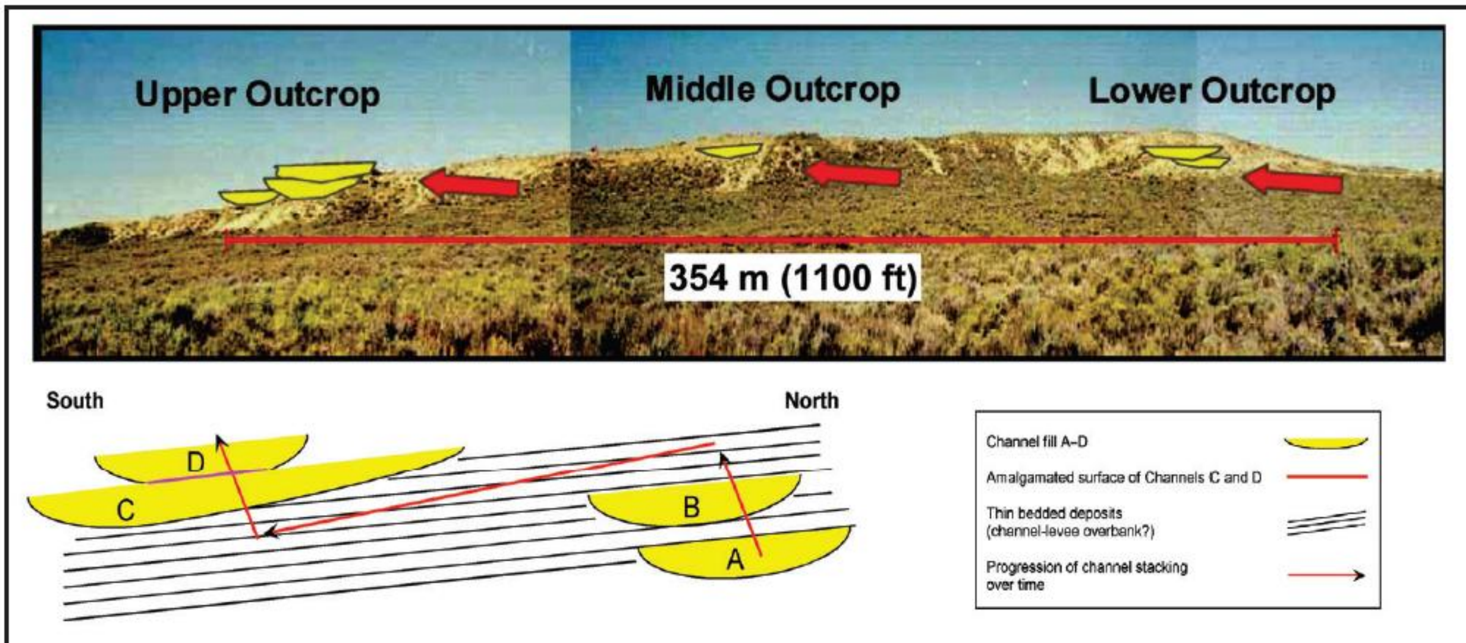
Previous Work

Tc, Td in Bouma sequence (in-2ft)

Ta, Tb in Bouma sequence (1-14ft)

Bracklein (2000) → **LDT, HDT,** mudstone, slump, debris flow, thin bedded facies → **From 16 measured sections**

Bracklein (2000) →



Previous Work

Staggs (2003) → 19 GPR lines. Including channel on spine 1 and Channels C and D on Rattlesnake ridge.

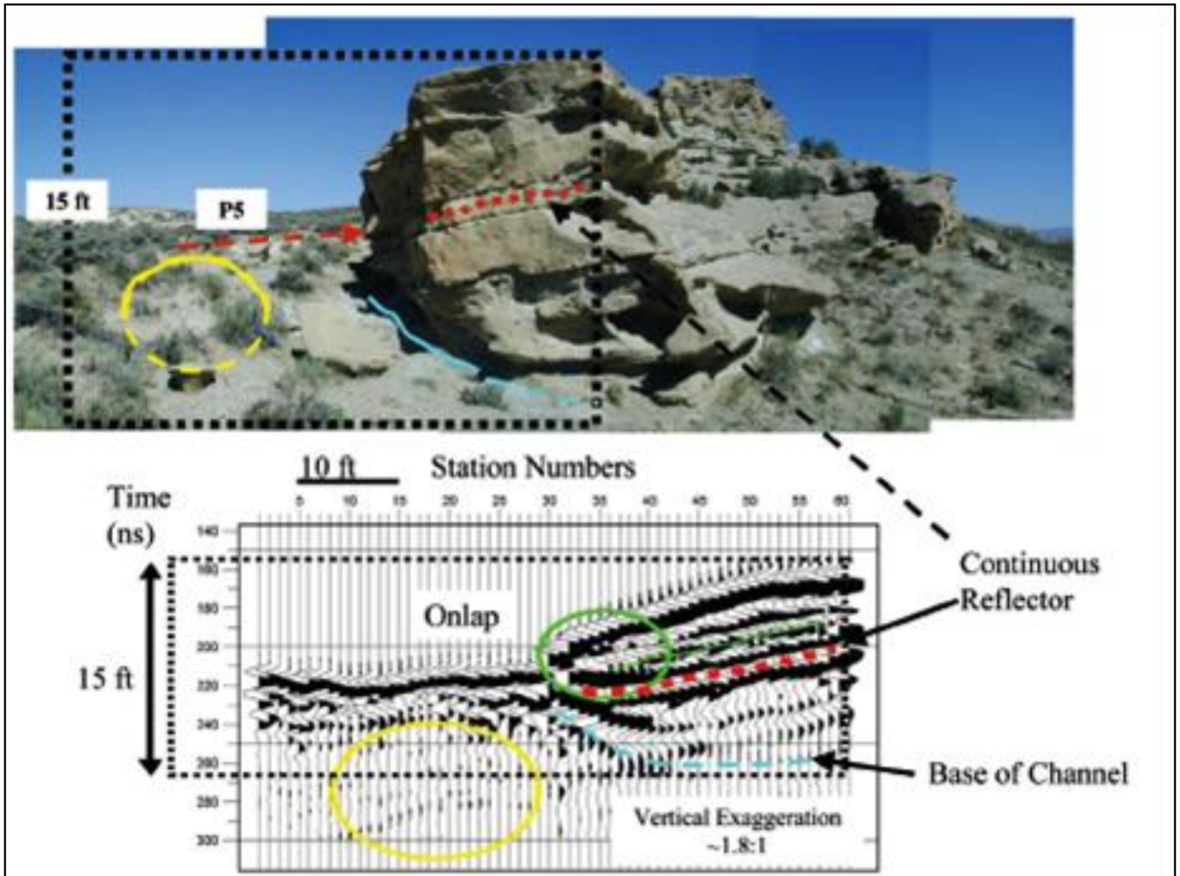
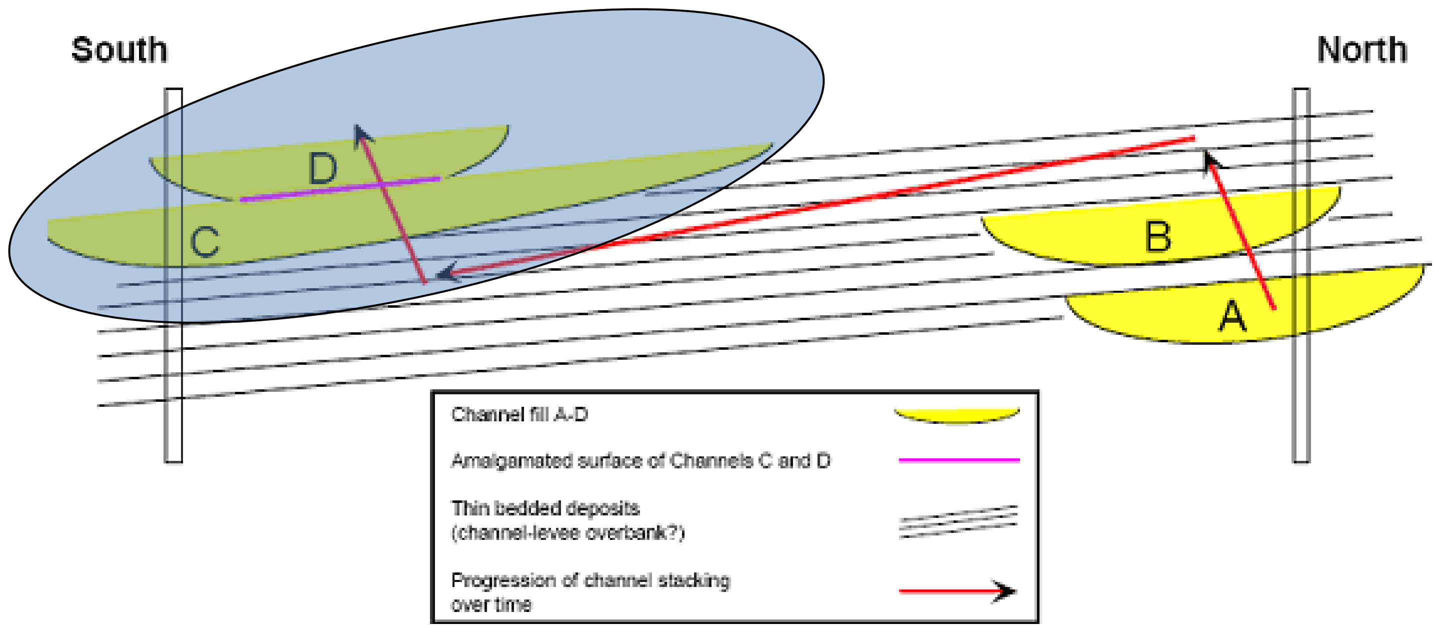


Figure 7. GPR line which identifies the base of the channel (Correa, 2007)

Previous Work

Correa (2007) →



Correa (2007) → 12 GPR lines

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Geological Model - Imported Data

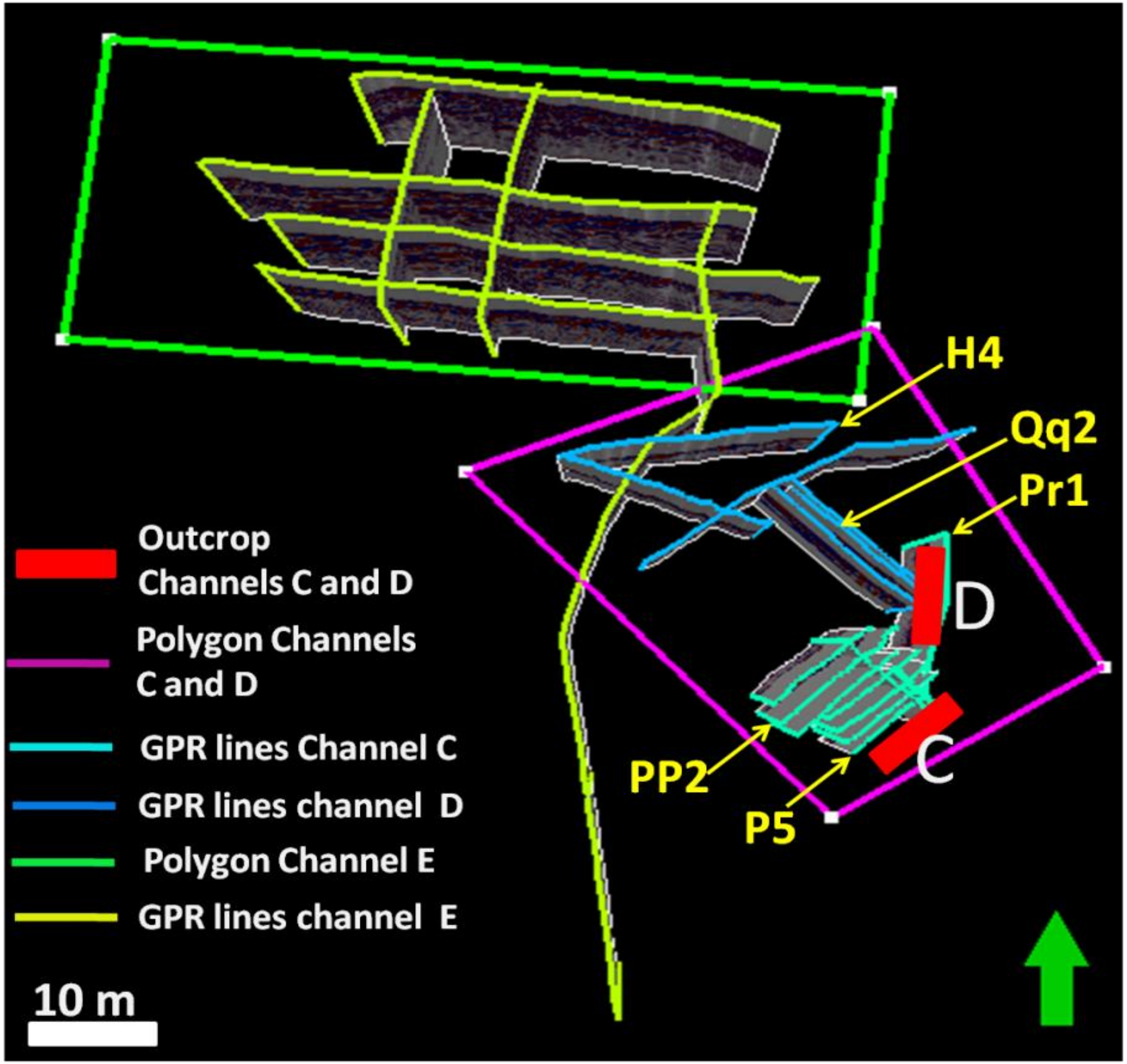


Figure 8. Plan view of the GPR lines, outcrops, and the polygons used to build the geological model.

Geological Model - *Imported Data*

- *21 GPR lines (Staggs et al., 2003)*
- *8 Measured Sections (Bracklein, 2000)*
- *3 photos combined into a 3D photomosaic, Bracklein, 2000 and Correa, 2007)*
- *Porosity and Permeability values from Spine 1 (Slatt et al., 2006) and Tahoe field (White et al., 1992)*

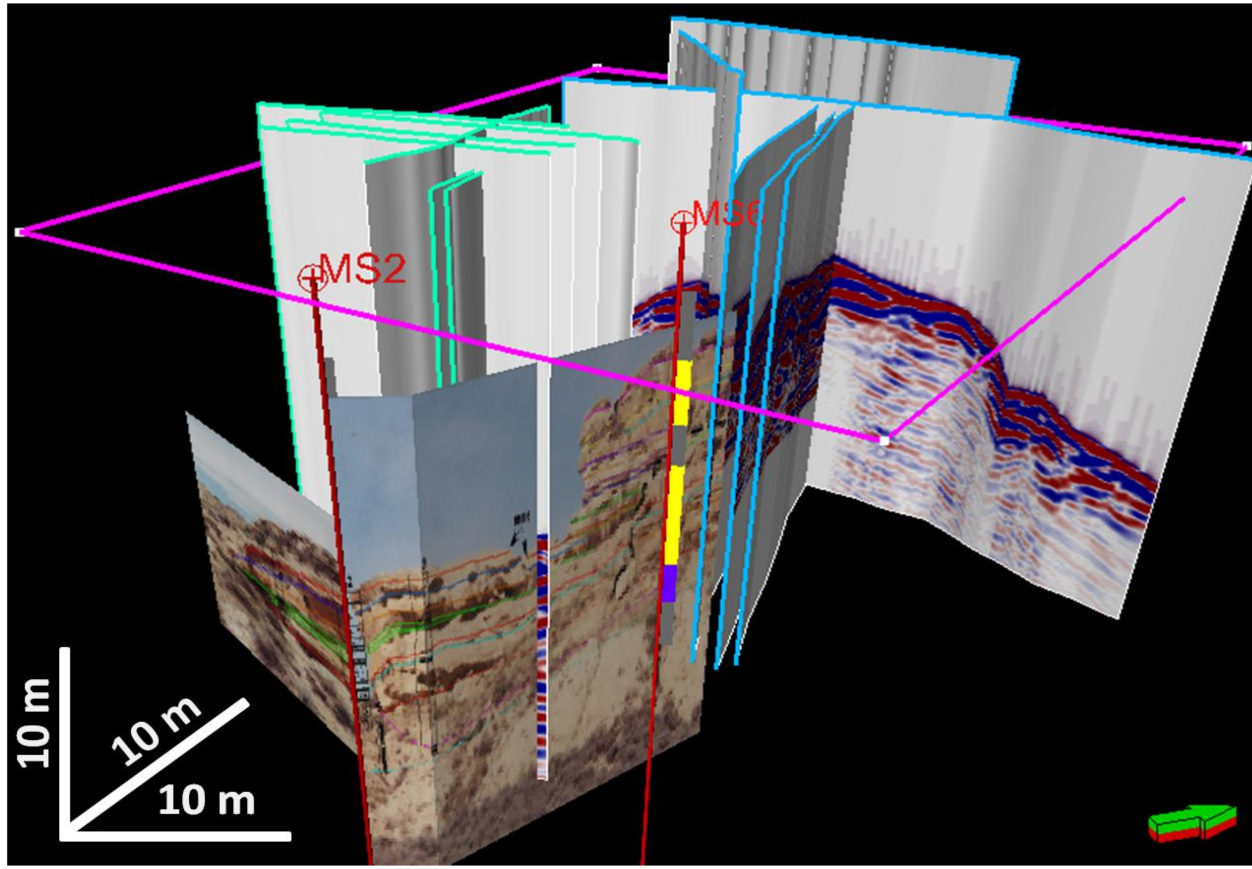
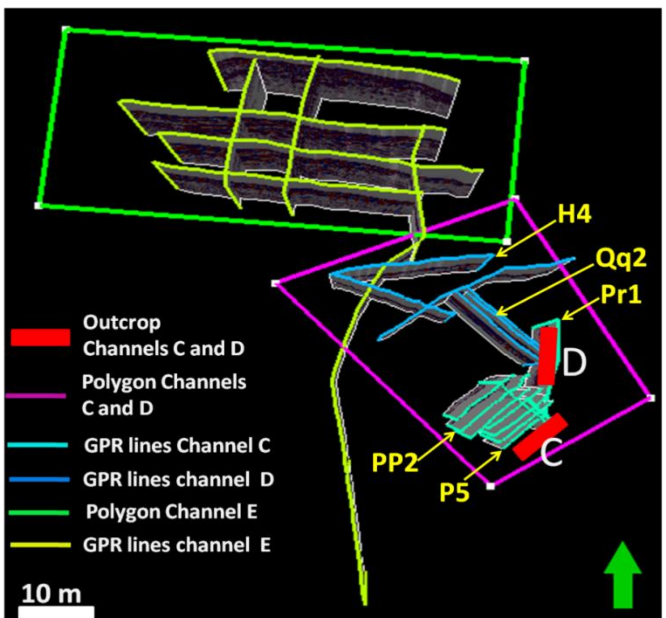
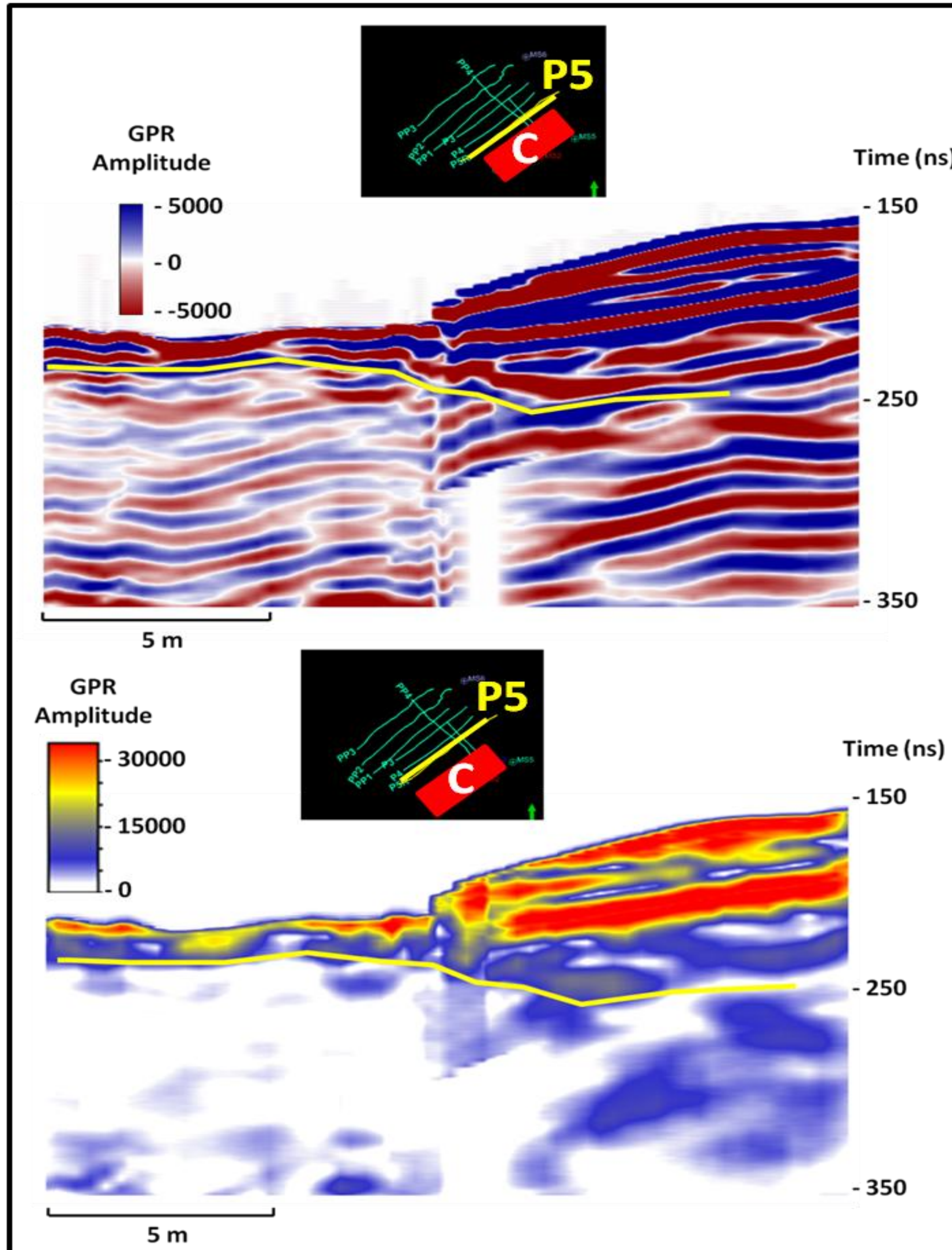


Figure 9. Some of the available data used to model Channels C and D.

Geological Model

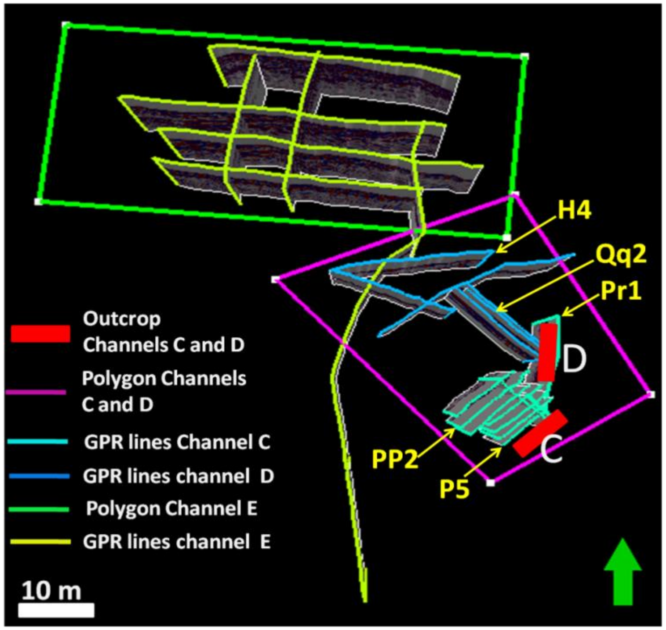
Figure 10. Quality control for Envelop GPR Attribute.

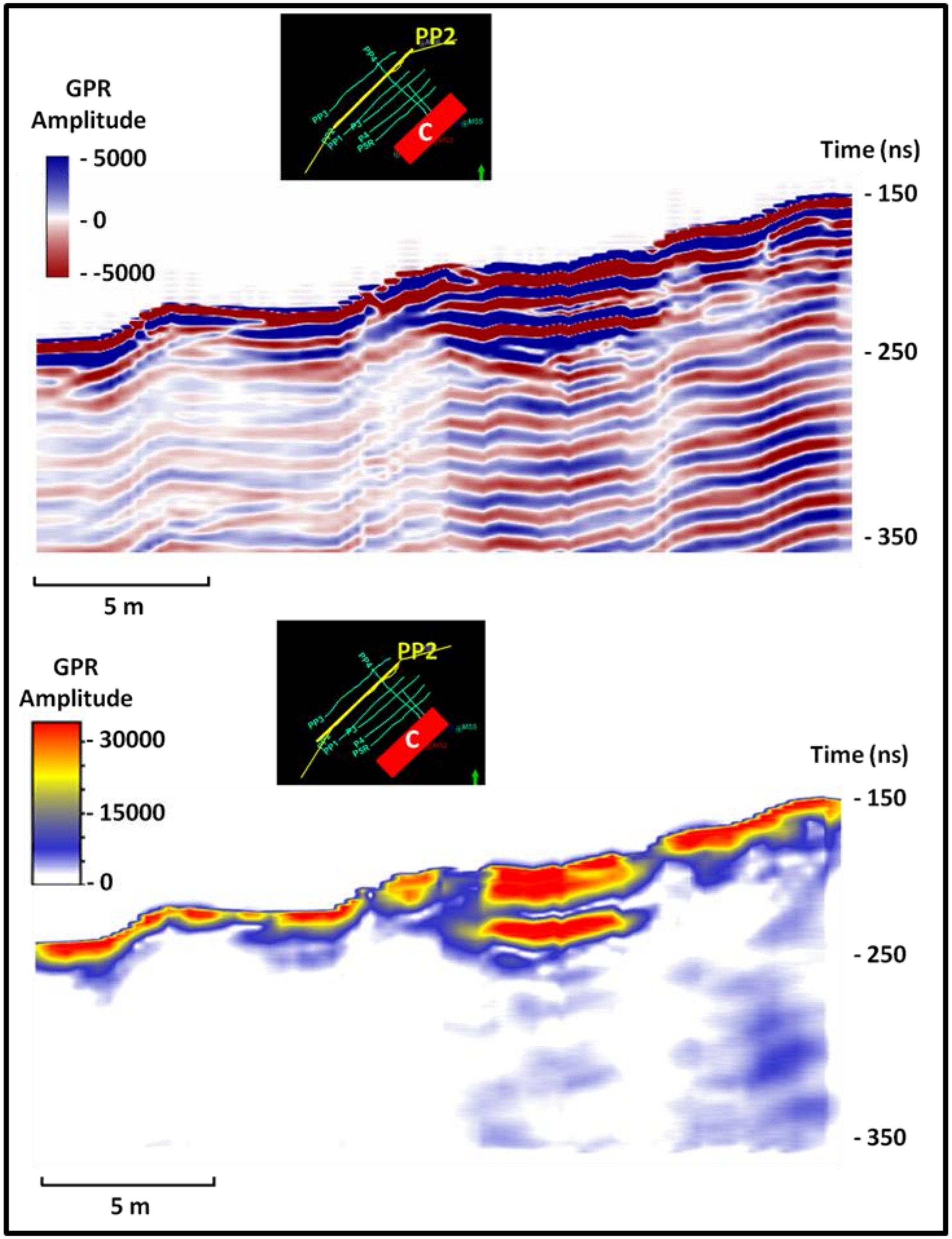




Geological Model

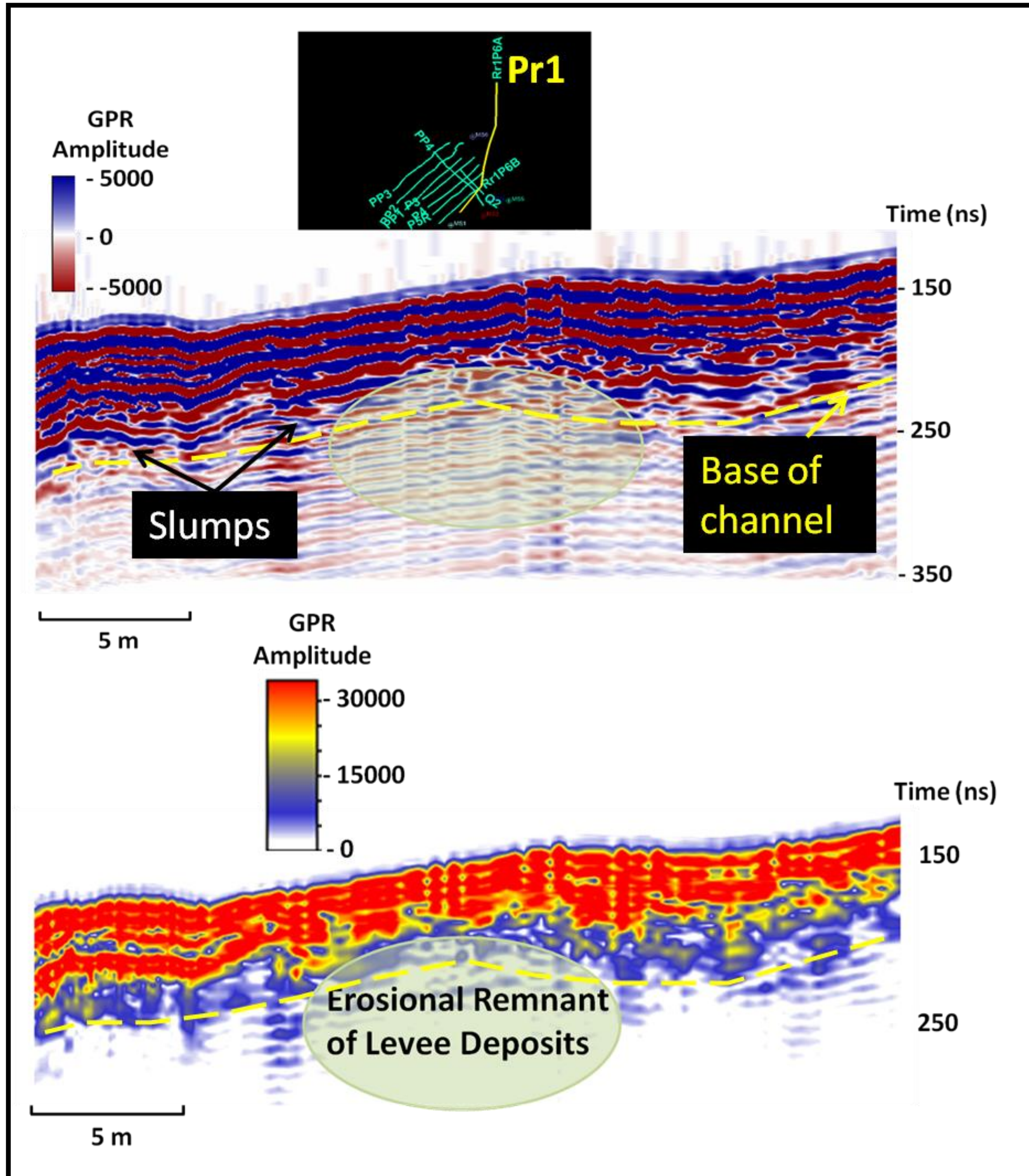
Figure 11. Envelop GPR Attribute highlights the base of the channel C.

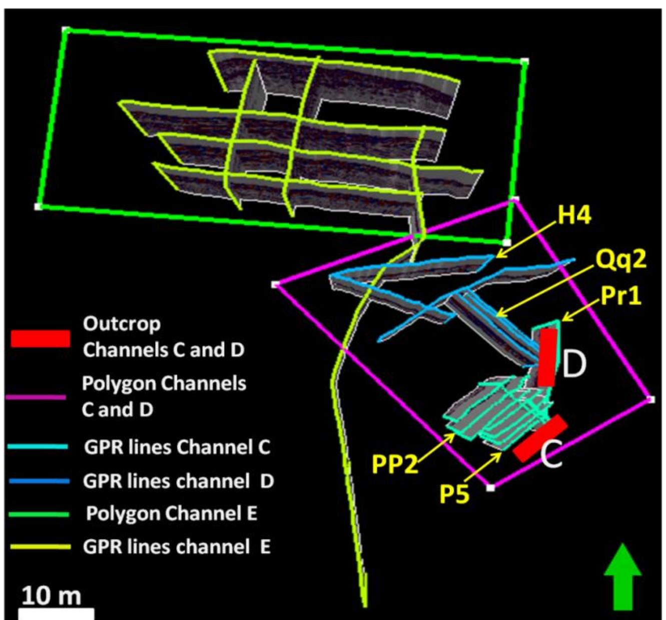




Geological Model

Figure 12. Erosional remnant of levee deposits identified on Pr1 GPR line.





Geological Model

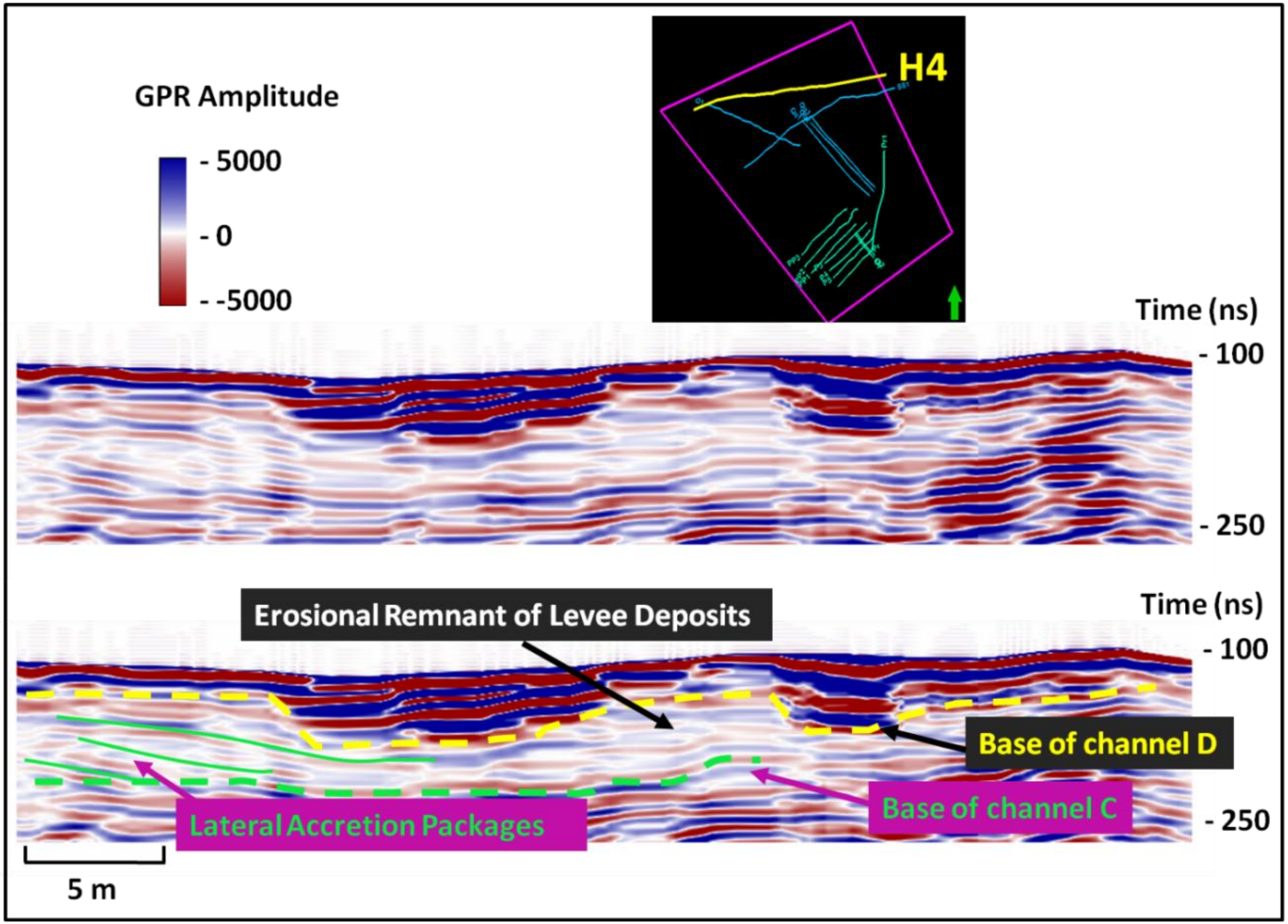


Figure 13. H4 GPR line shows erosional remnant of probable levee deposits. H4 location is shown in the black square.

Geological Model

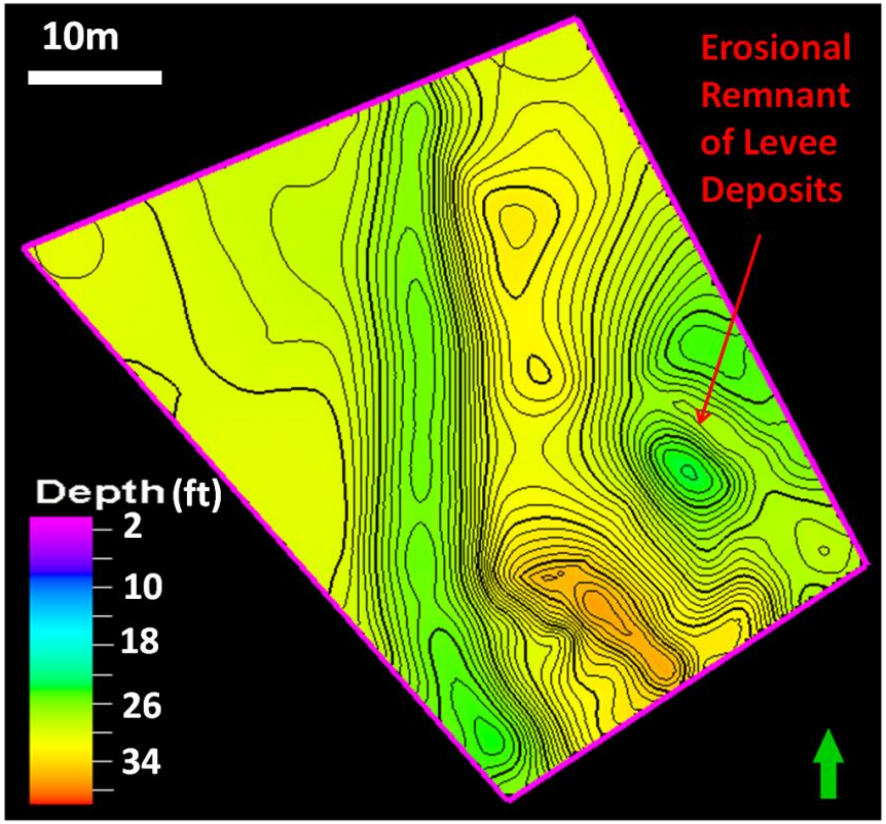


Figure 14. Depth surface of Channel C in a plan view.

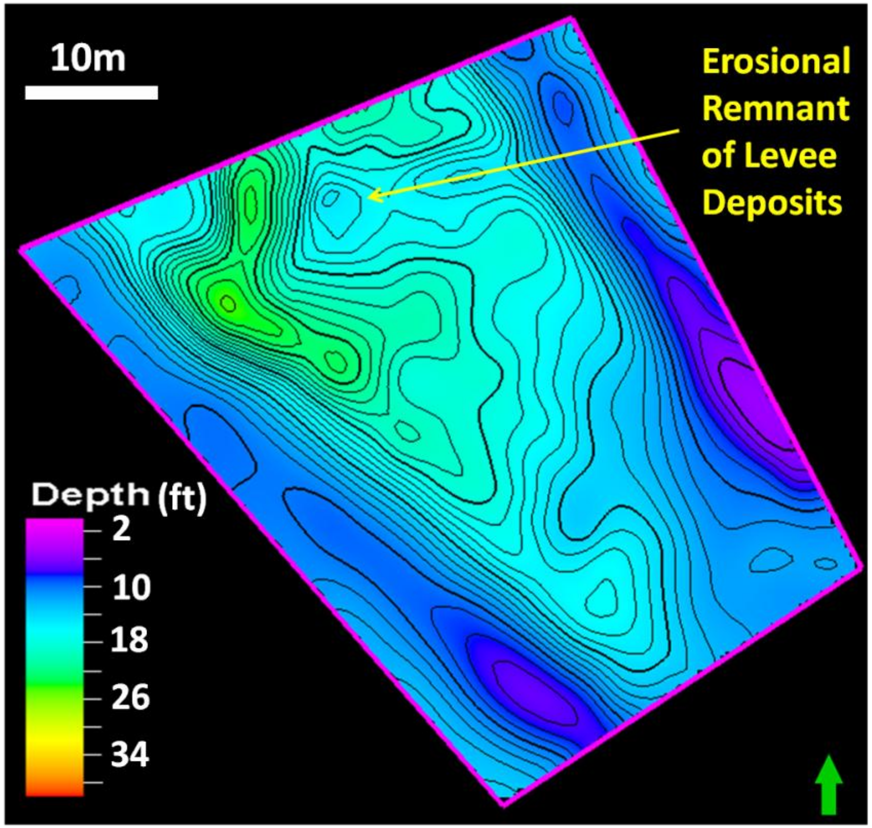


Figure 15. Depth surface of Channel D in a plan view.

Area	Width (m)	Thickness (m)	Dip of reflectors direction
Channel C	32	3.99	SW
Channel D	>30	8.82	SW

Geological Model

Figure 16. Base of Channel C and slumped beds are present beneath it. Modified from Correa (2007)

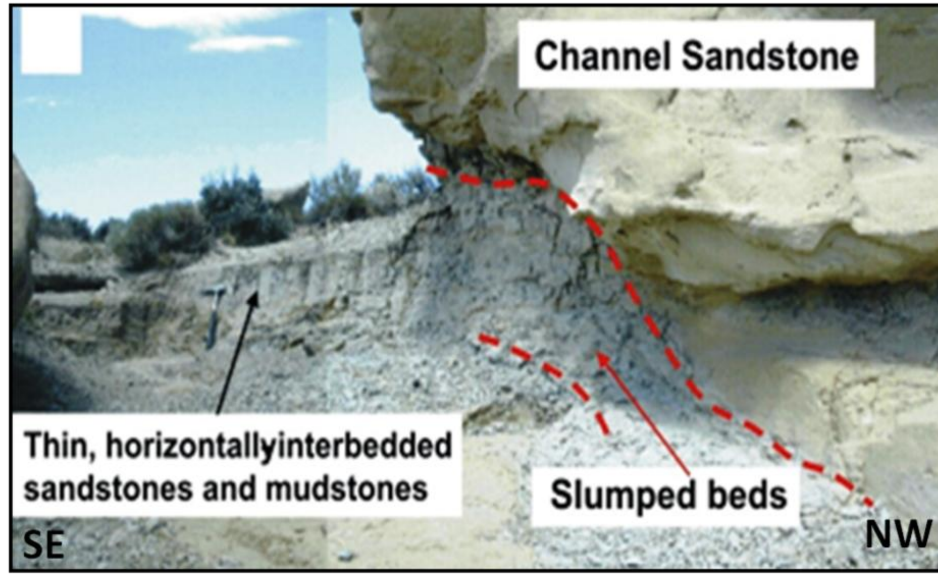
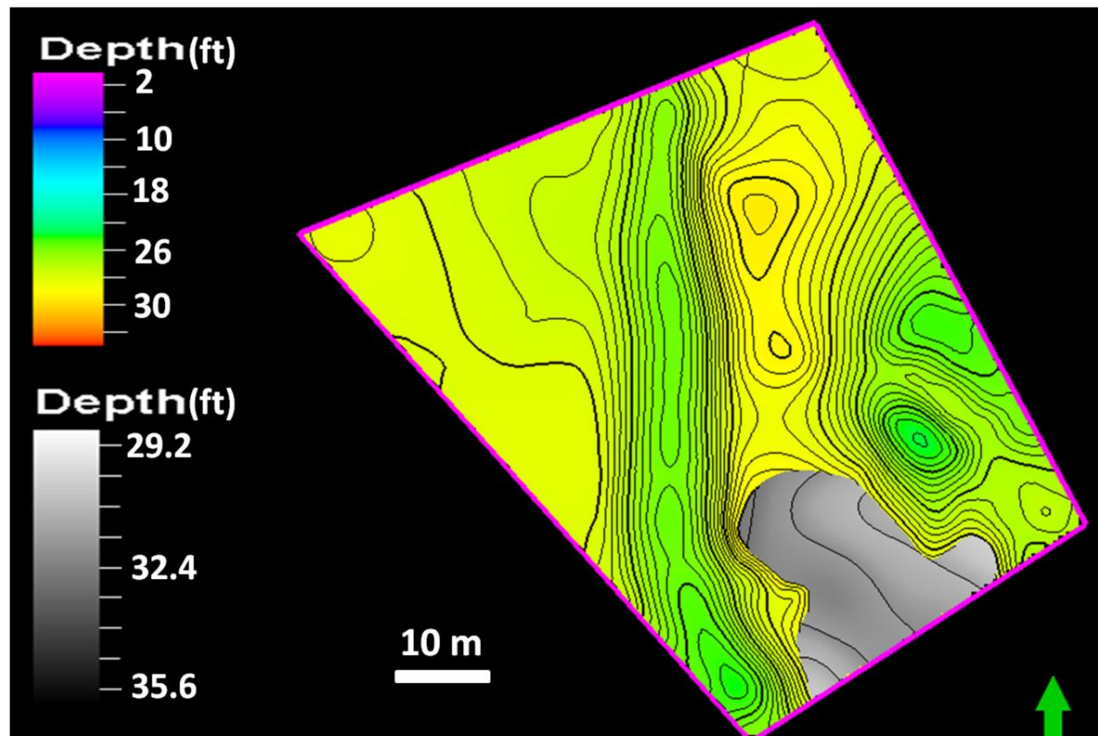


Figure 17. Depth surfaces corresponding to the margin of Channel C (color scale) and slumped beds (gray scale).



Geological Model

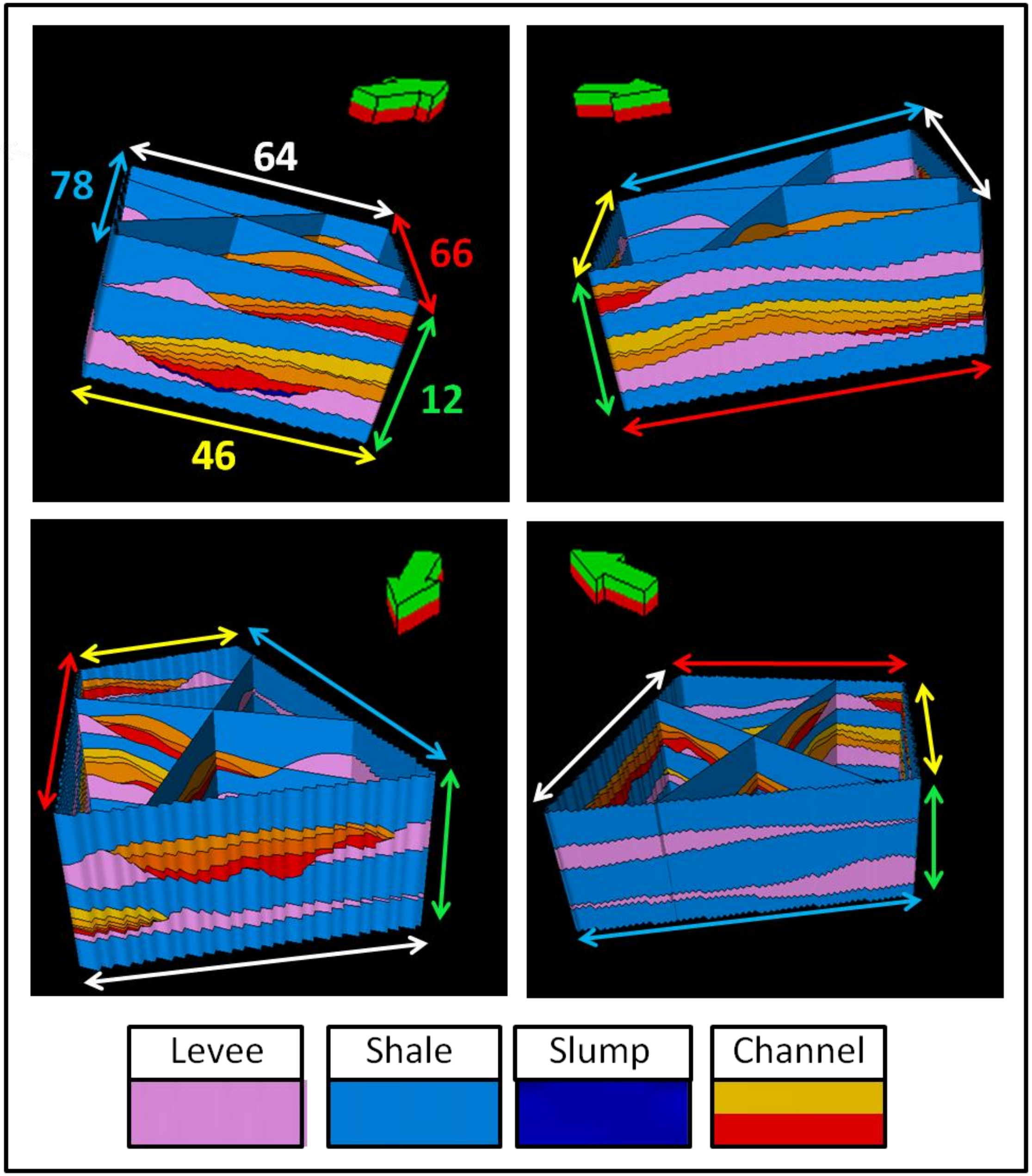


Figure 18. Edges and north-south /east-west intersections of the model; dimensions of the edges are expressed in meters.

Geological Model

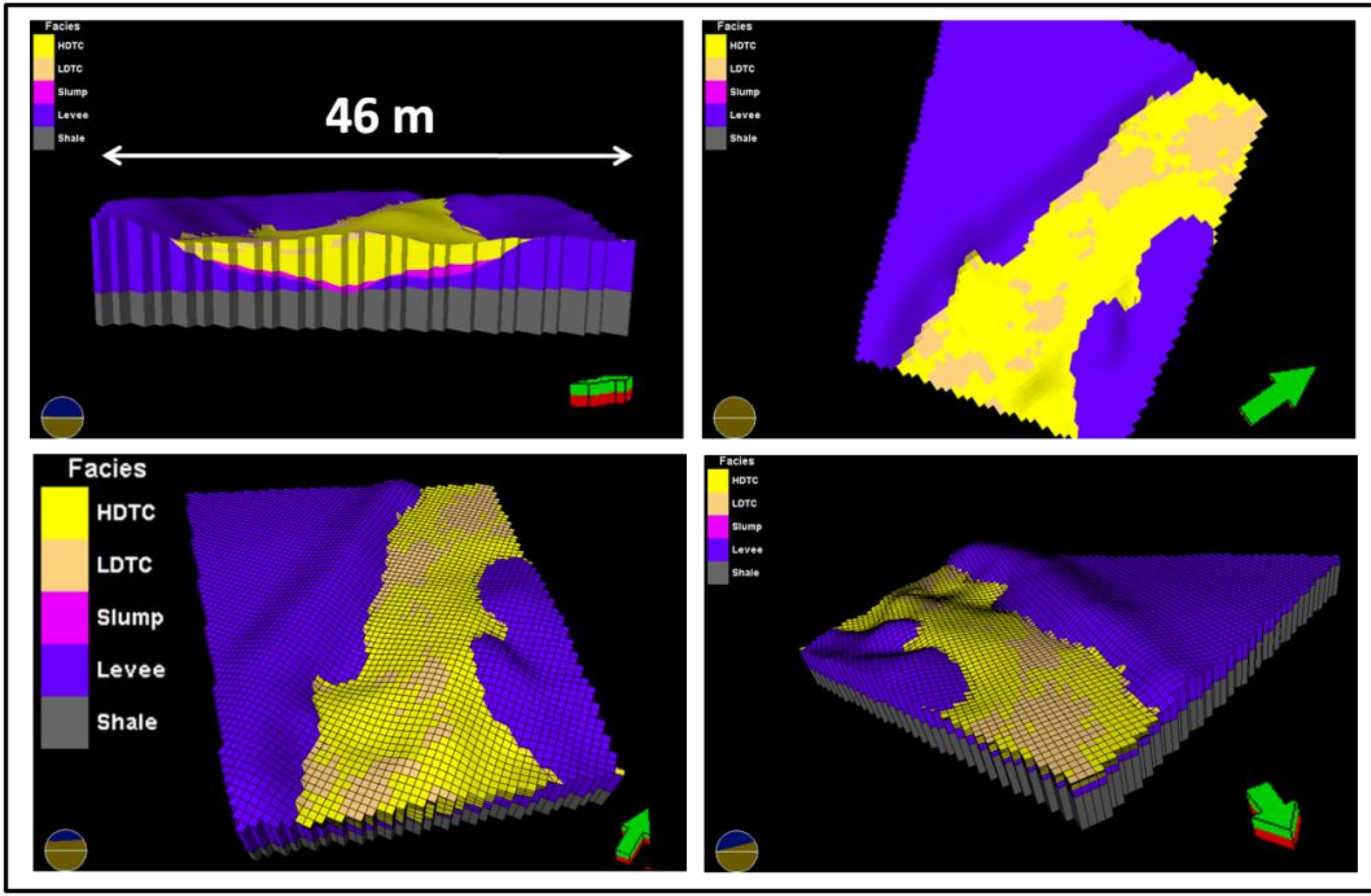


Figure 19. Stochastic model for the combination of facies.

Geological Model

Facies	Porosity		Permeablity	
	Mean (%)	Std. Deviation	Mean (md)	Std. Deviation
HDTC	29.5	1.1	415	293
LDTC	29	2.3	304	301
Shale	14.6	0.7	0.03	0.01
Levee	18.4	2	40	5
Slump	15	5	N/A	N/A

Geological Model

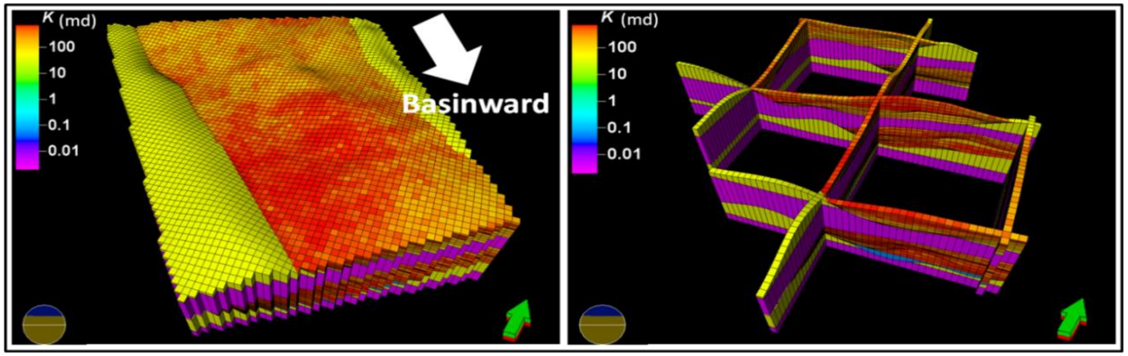


Figure 22. Petrophysical (permeability) model of Channel D showing that permeability improve basinward.

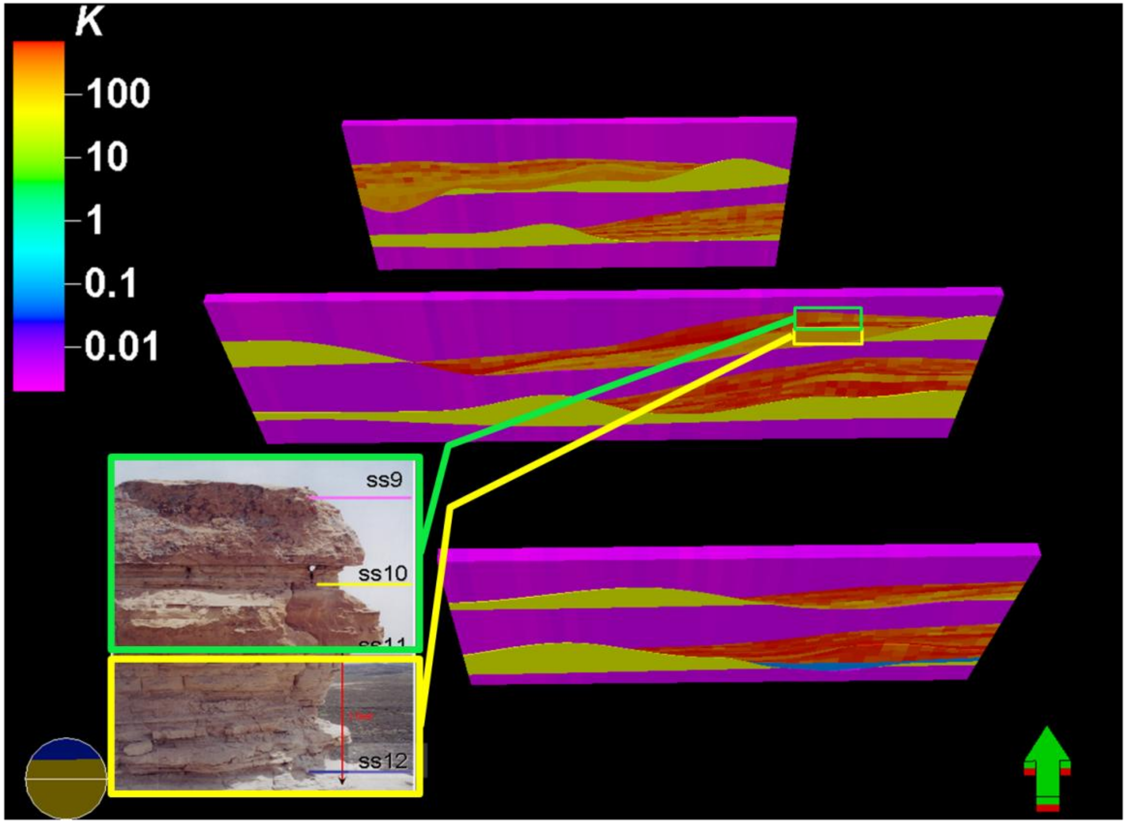


Figure 23. Fence diagram illustrates vertical variation in the different beds.

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- *Conclusions and Recommendations*

Flow Simulation

Volumetric calculations

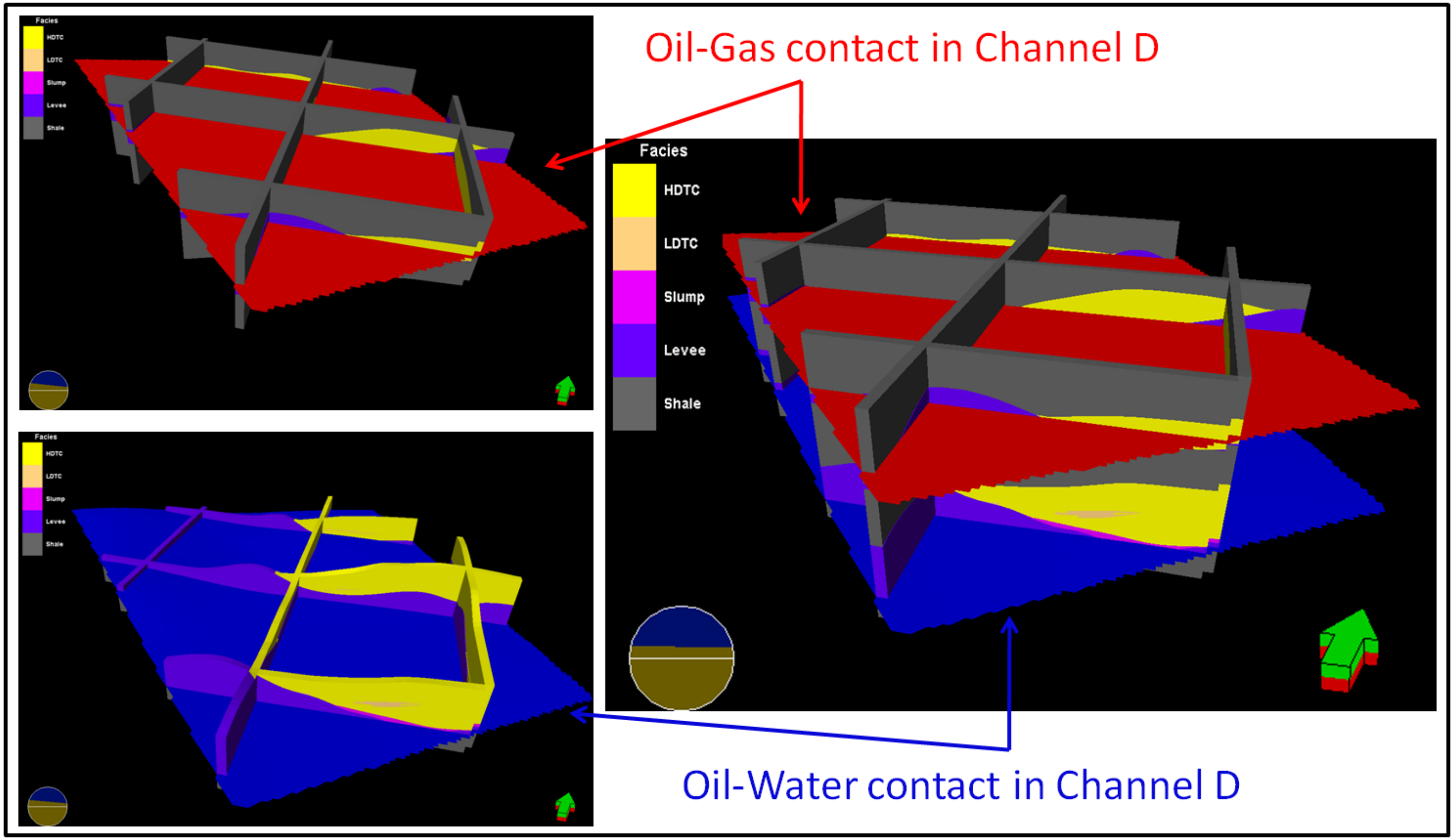
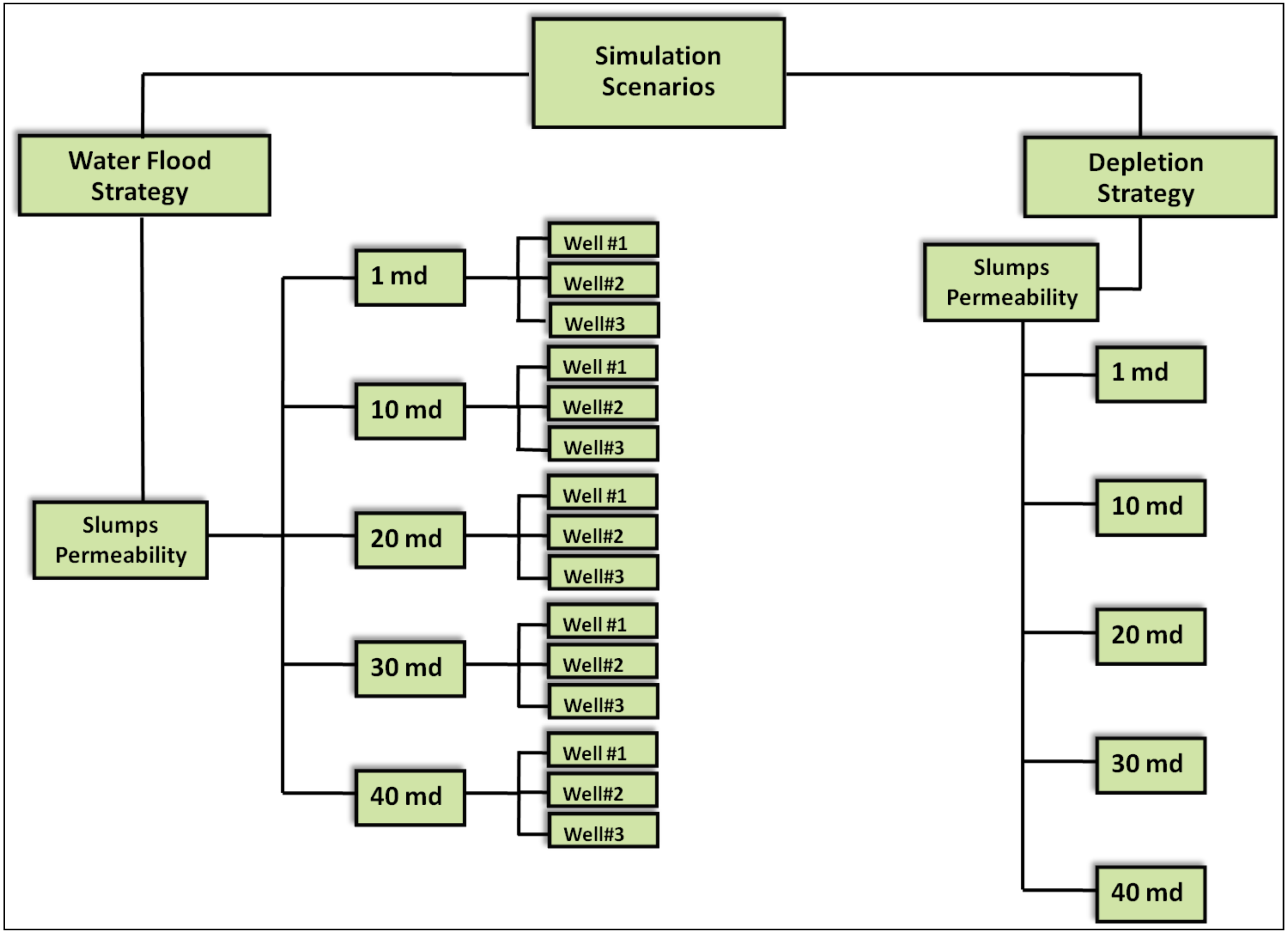


Figure 24. Oil-Water and Oil-Gas contacts in Channel C and Channel D respectively. Blue is water contact and red is gas contact

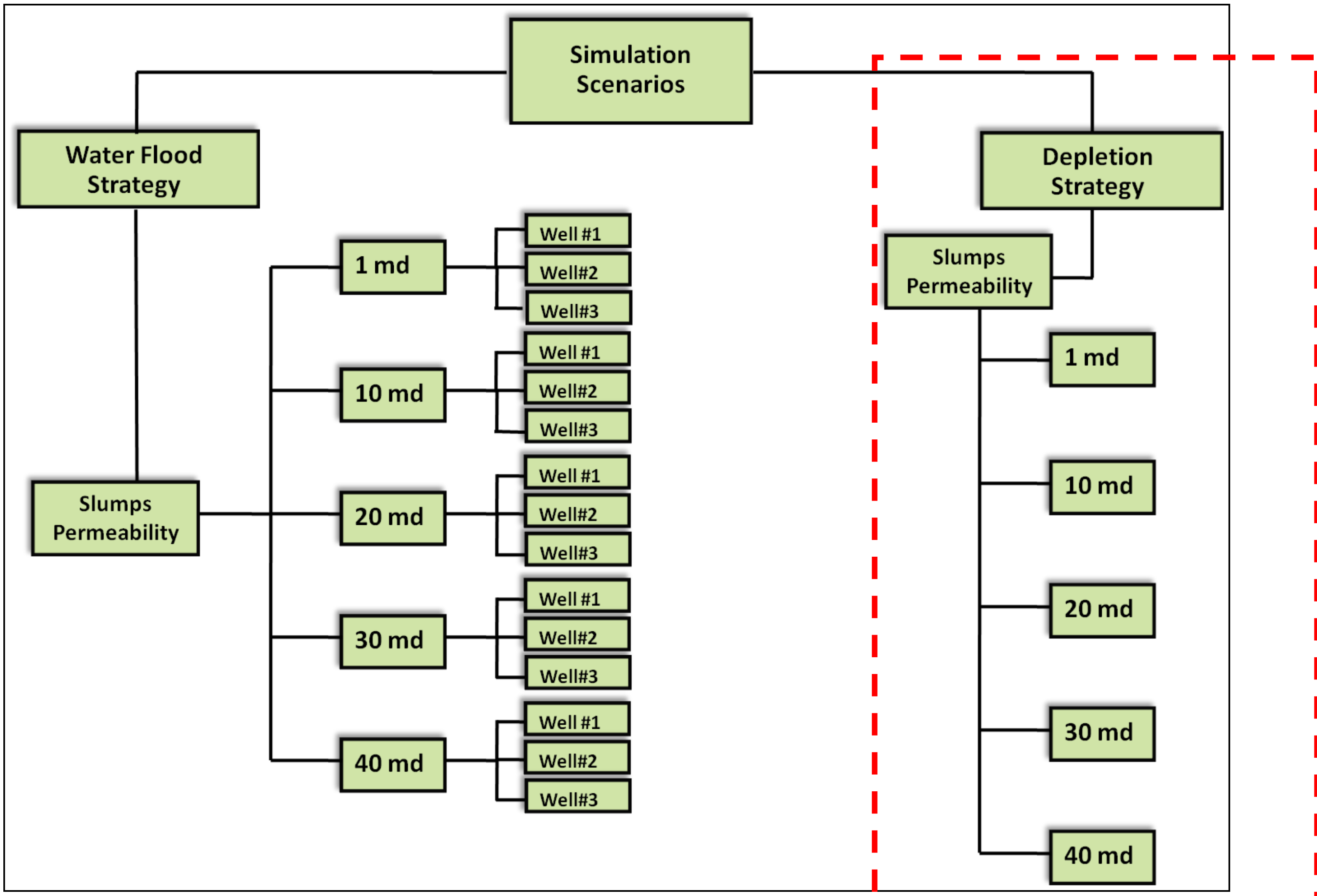
Flow Simulation

Simulation Scenarios



Flow Simulation

Simulation Scenarios



Flow Simulation

Eclipse flow simulation

Property	Value
Initial Reservoir Pressure (Pi)	350 bar (5080 psia)
Reservoir Temperature	250 (°F)
Bubblepoint Pressure (Pb)	275 bar (3990 psia)
Solution Gas oil ratio (GOR)	205 sm3/sm3 (863 scf/STB)
Oil FVF at Pi (Boi)	1.52 rm3/sm3 (bbl/STB)
Oil Viscosity at Pi (μoi)	0.86 cp
Oil Gravity (API)	35 API
Specific Gas gravity	0.75
Irreducible Water Saturation (Swi)	20%
Irreducible Oil Saturation (Soi)	10%

Table 25. Reservoir properties used in the flow simulations.

Flow Simulation

Eclipse flow simulation

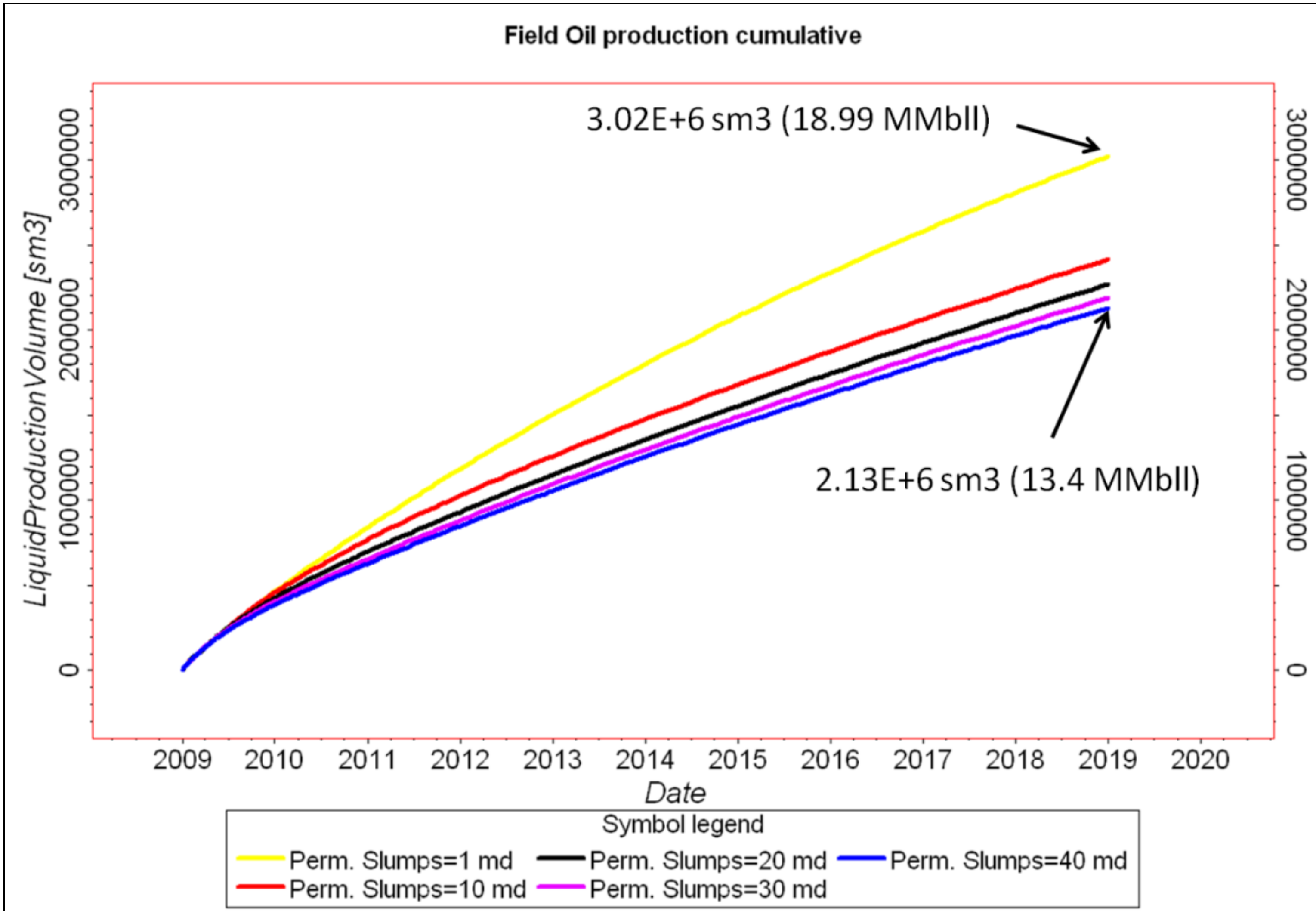


Figure 26. Field oil cumulative production for the different depletion cases.

Flow Simulation

Eclipse flow simulation

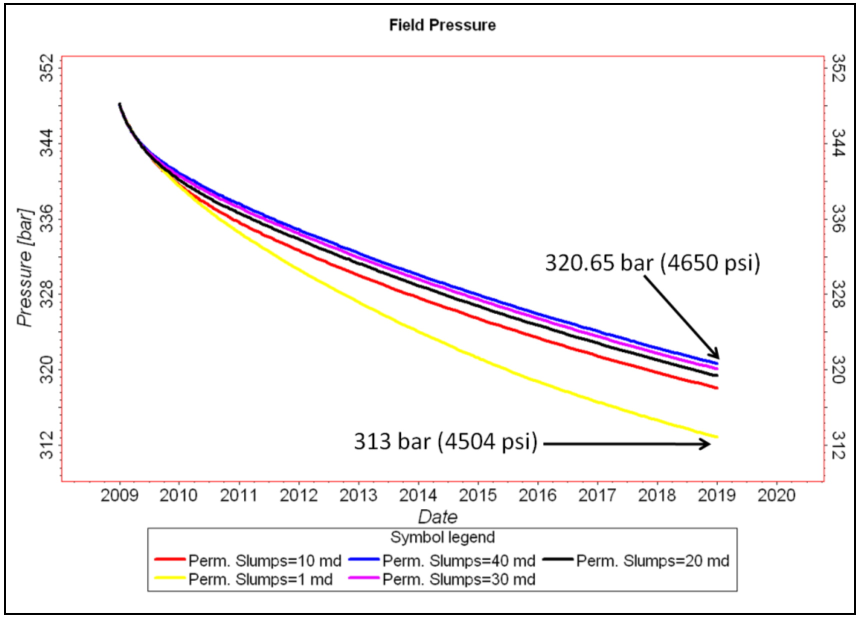


Figure 27. Field pressure for the different simulation cases.

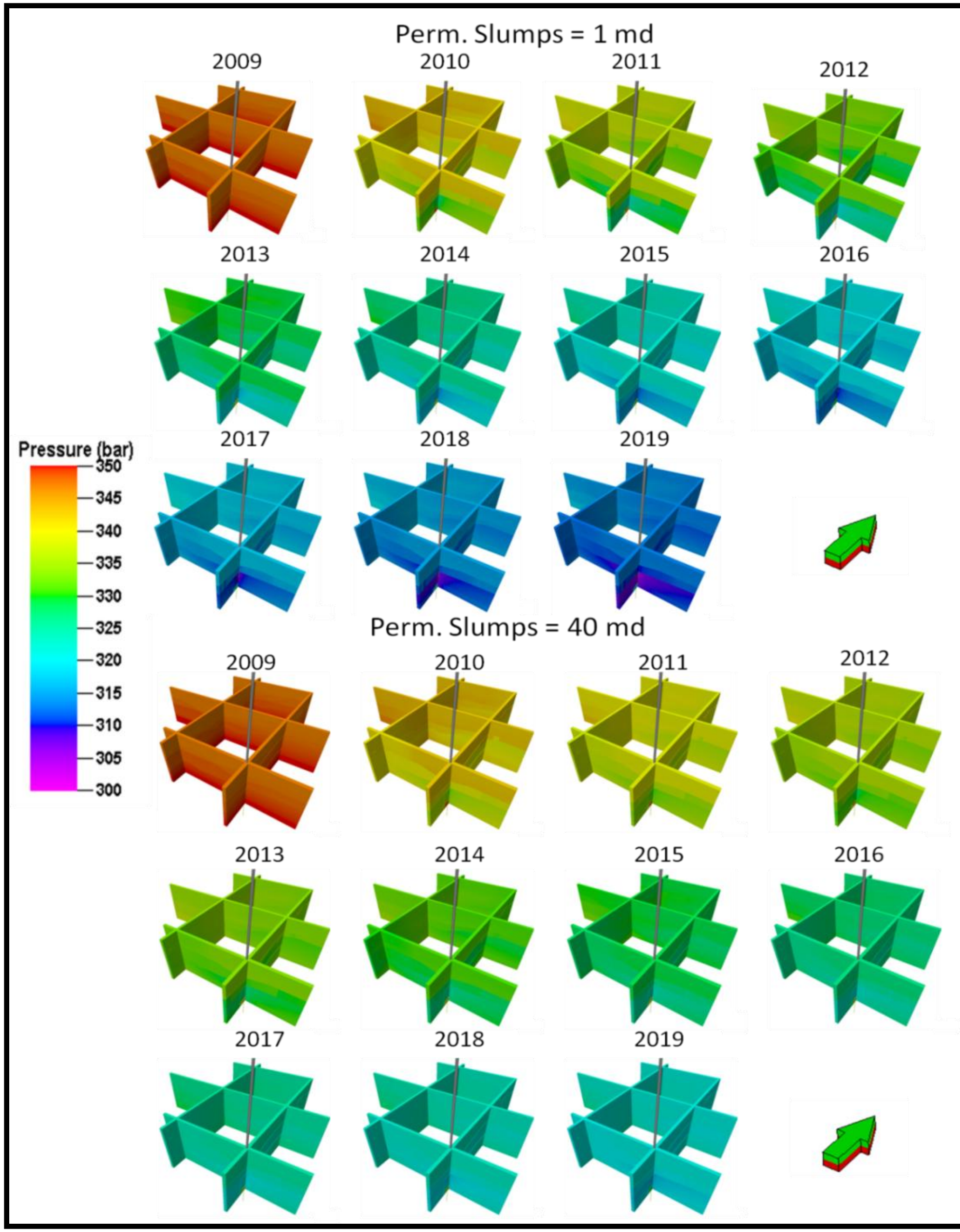


Figure 28. Pressure fence diagrams (Perm. Slumps = 1 md) and (Perm. Slumps = 40 md).

Flow Simulation

Eclipse flow simulation

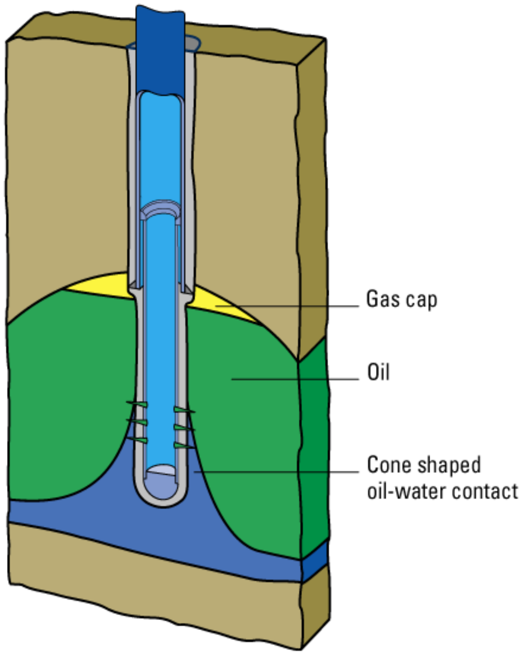


Figure 29. Water coning diagram. SLB, 2006.

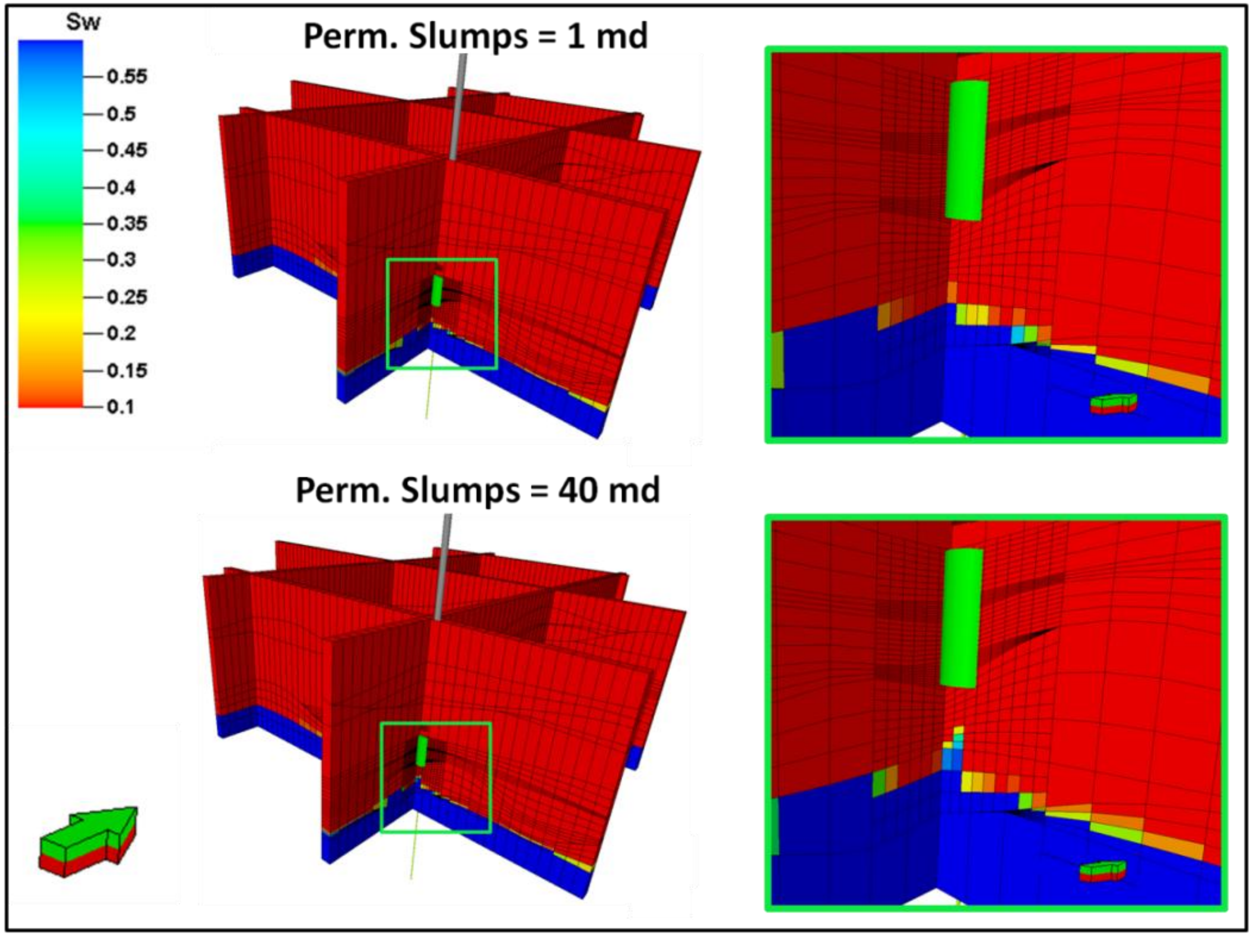
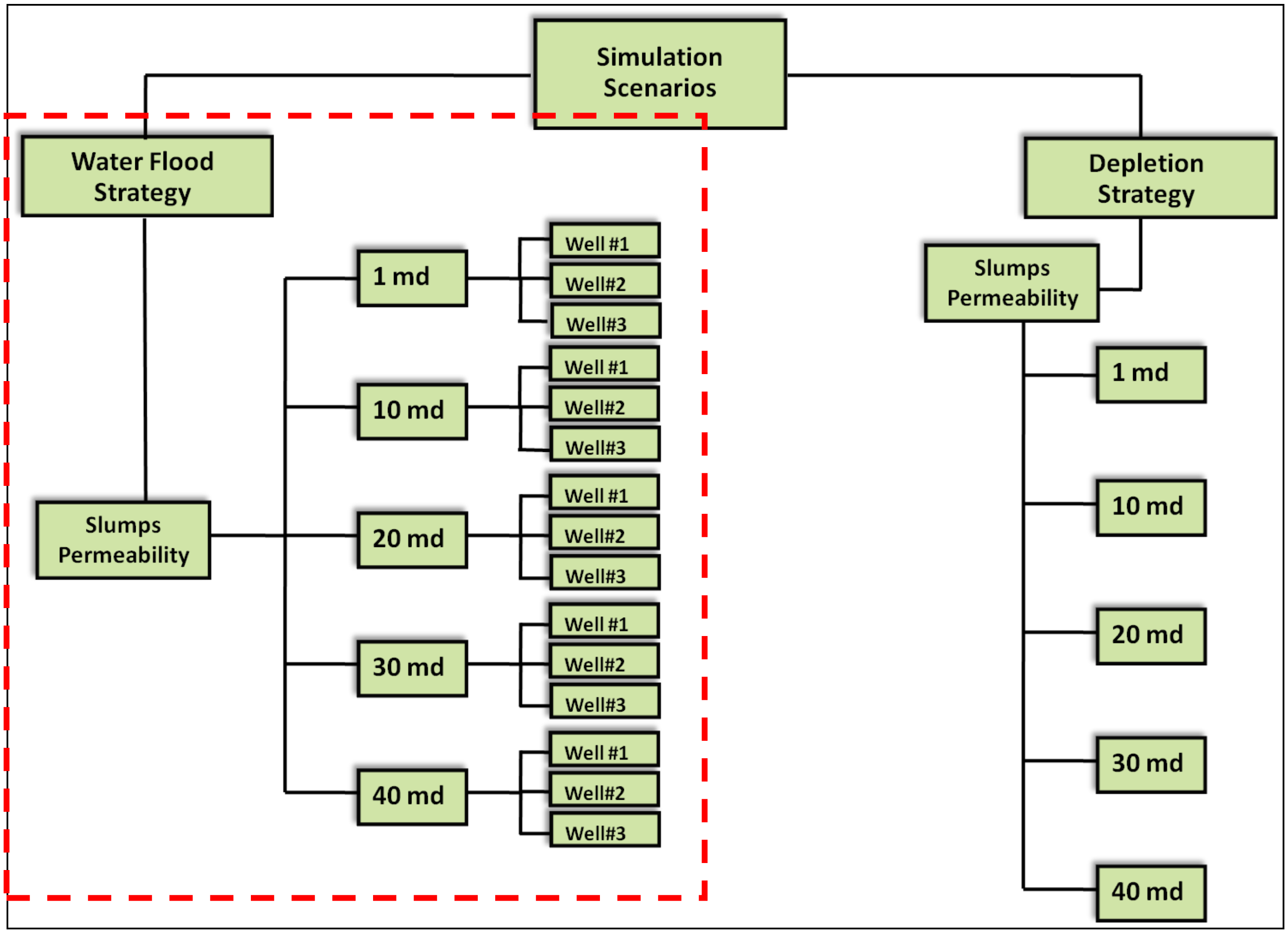


Figure 30. Water coning process in the low and high cases at year 2010.

Flow Simulation

Simulation Scenarios



Flow Simulation

Well Engineering

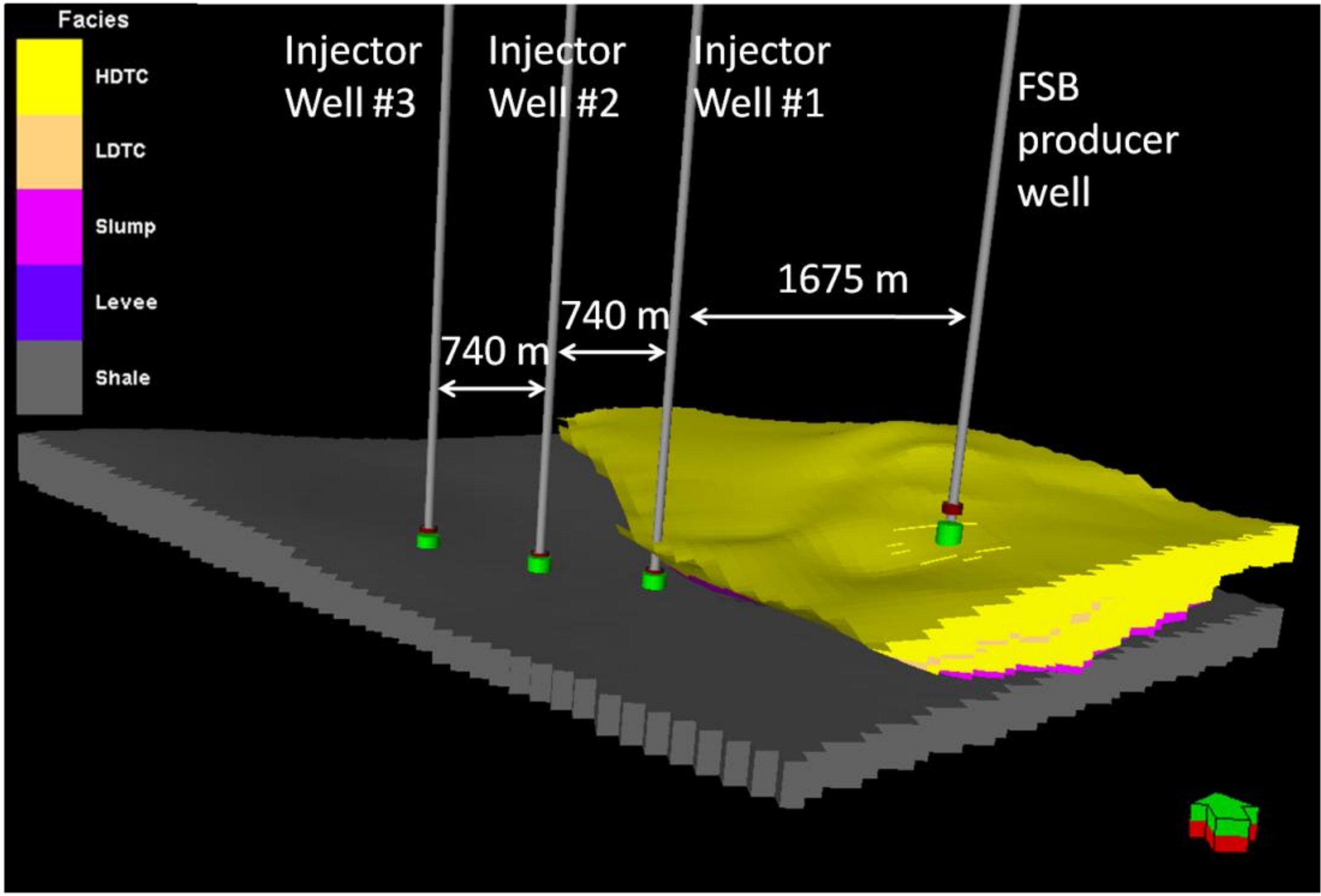


Figure 31. Location of the 3 injector wells in the levees of Channel C.

Flow Simulation

Streamline flow simulation

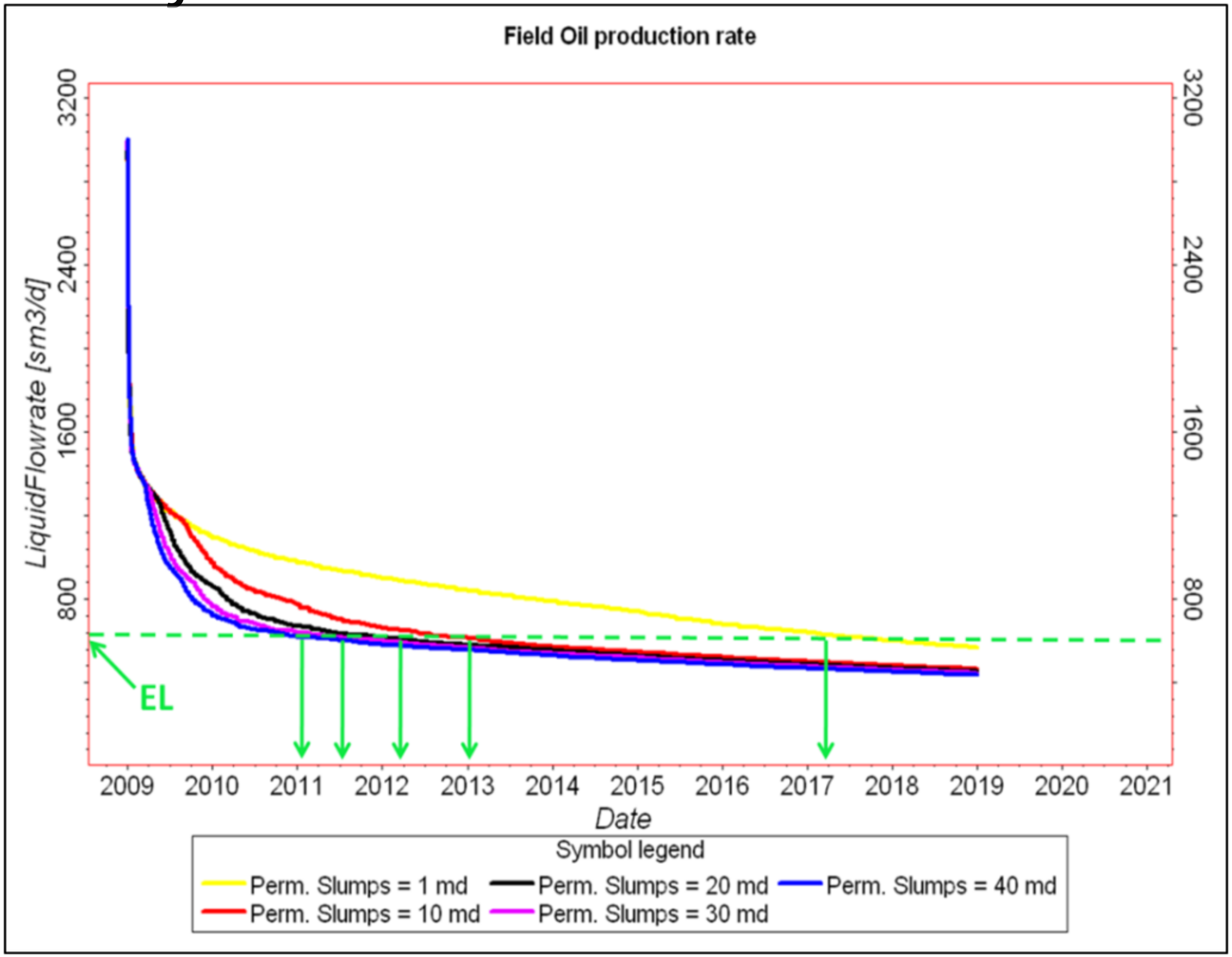


Figure 32. Determination of a date to apply waterflood strategy from the economic limit (EL).

Flow Simulation

Streamline flow simulation

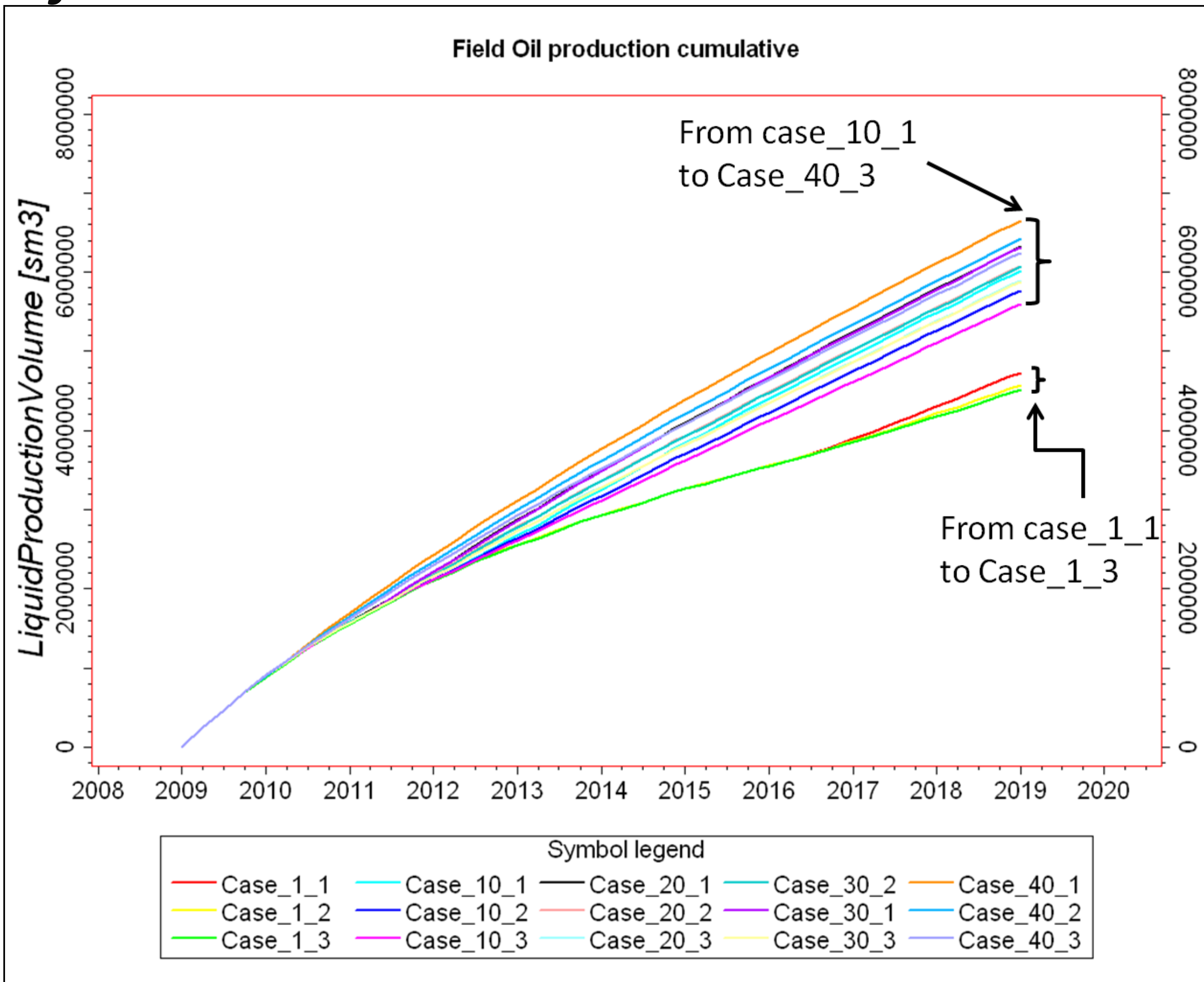
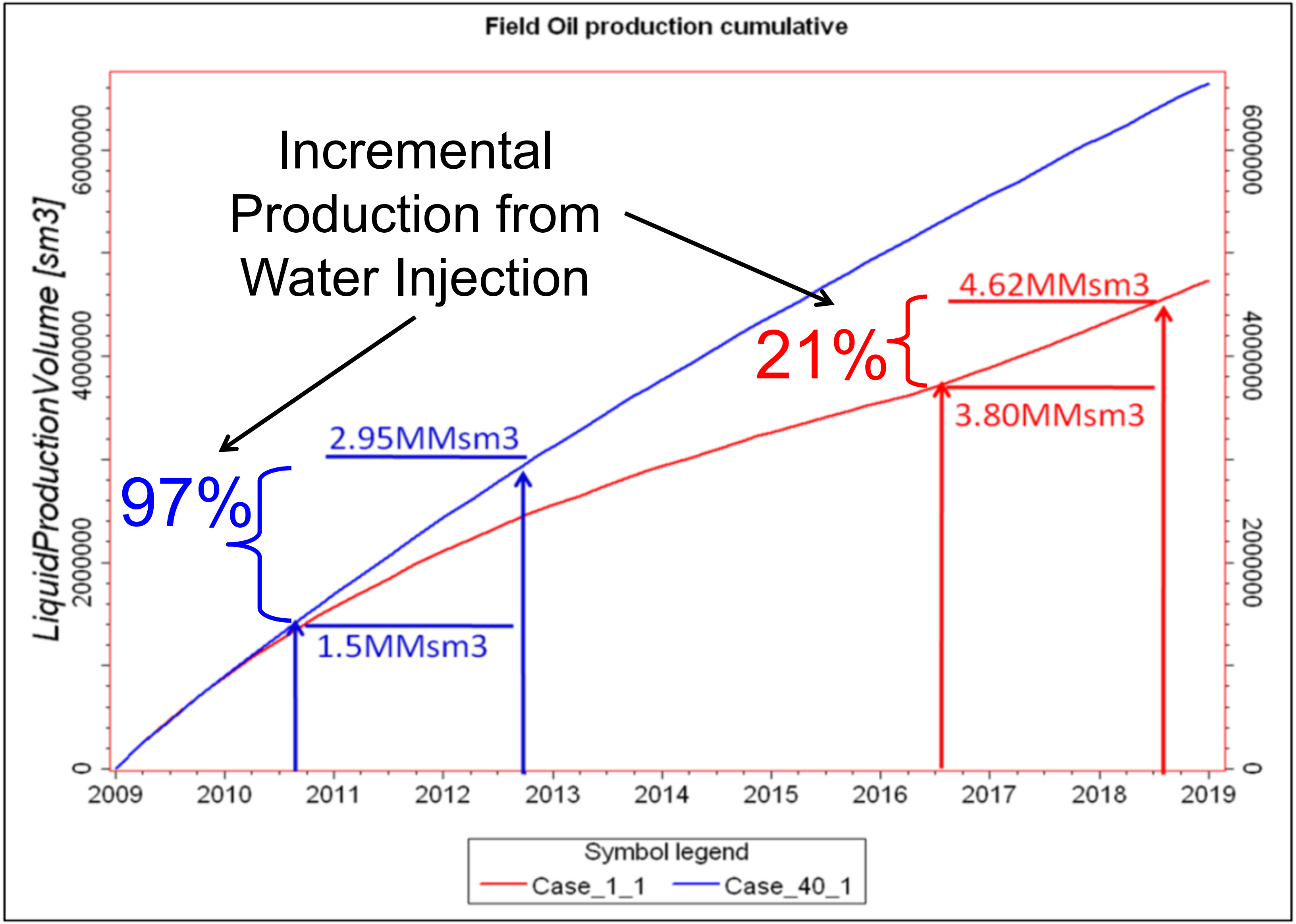


Figure 33. Field oil production for all the 15 waterflood simulation cases.

Flow Simulation

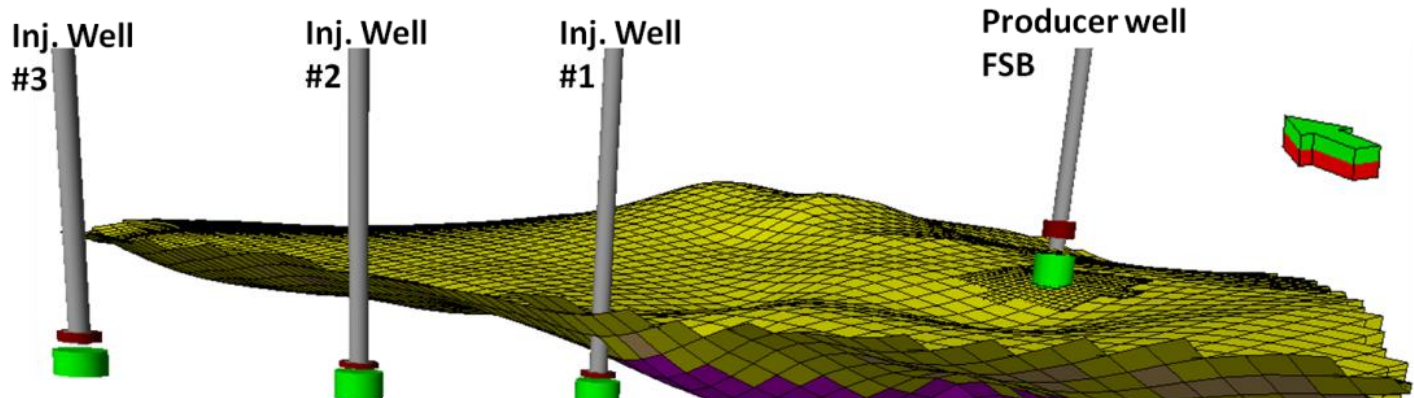
Streamline flow simulation

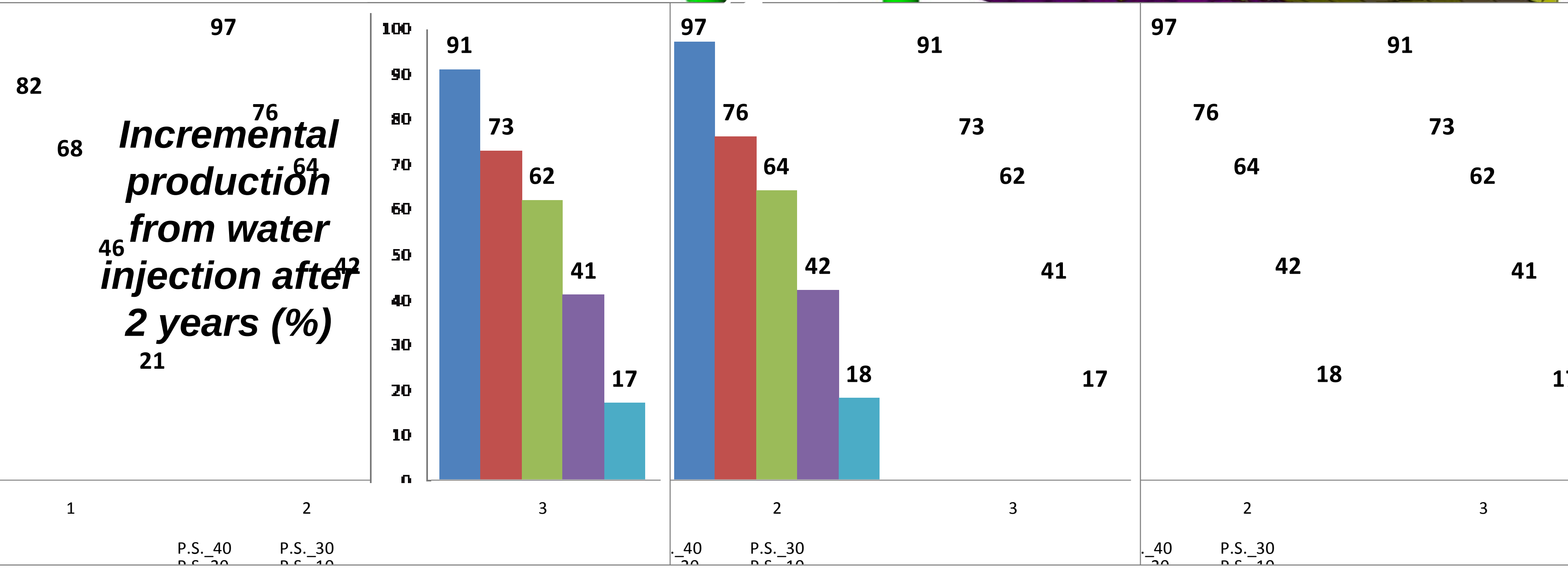
Figure 34. Oil cumulative production curve.



Flow Simulation

Streamline flow simulation

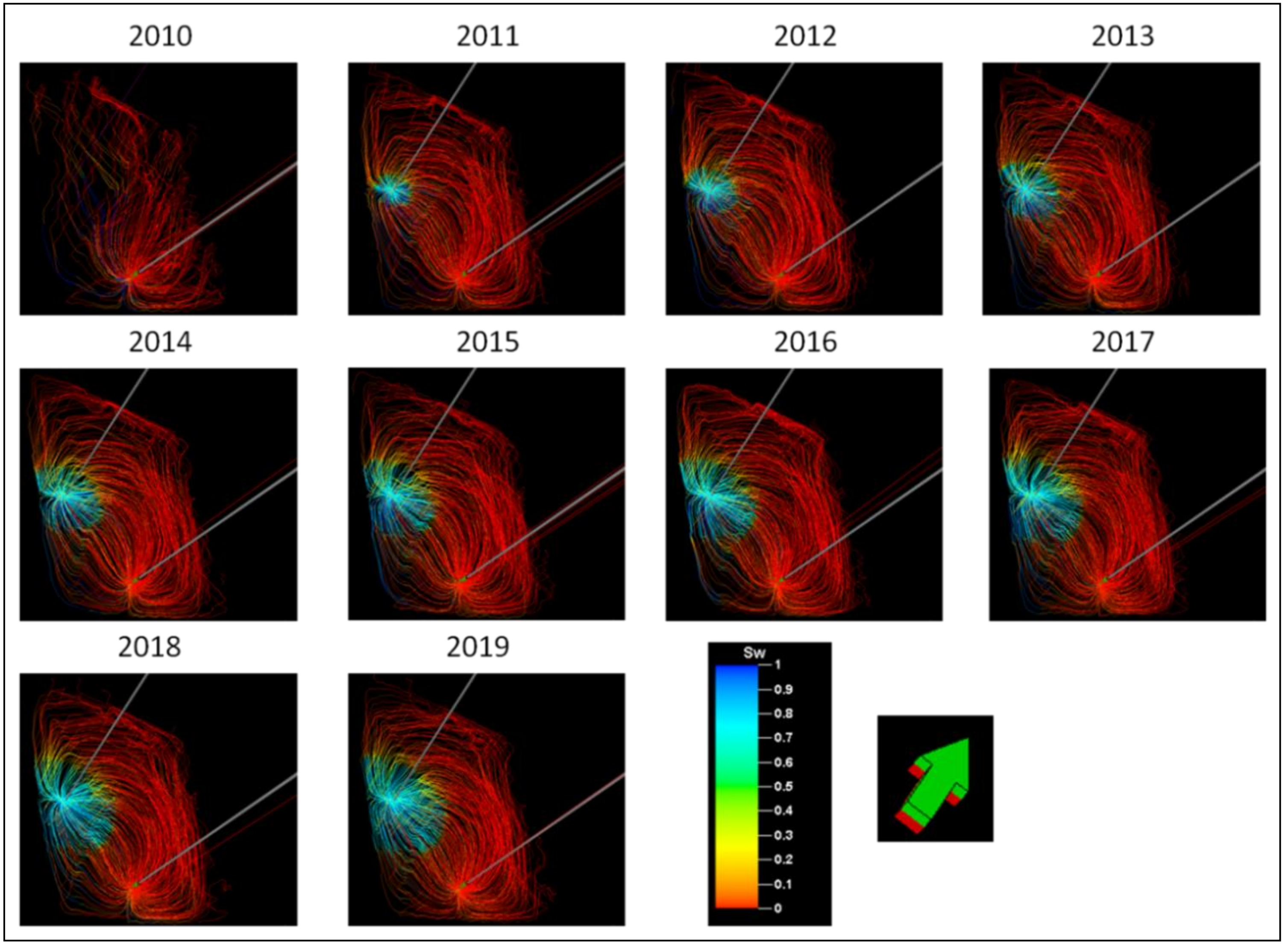




Flow Simulation

Streamline flow simulation

Figure 36. Streamline simulation of the water saturation for case_40_3.



Flow Simulation

Streamline flow simulation

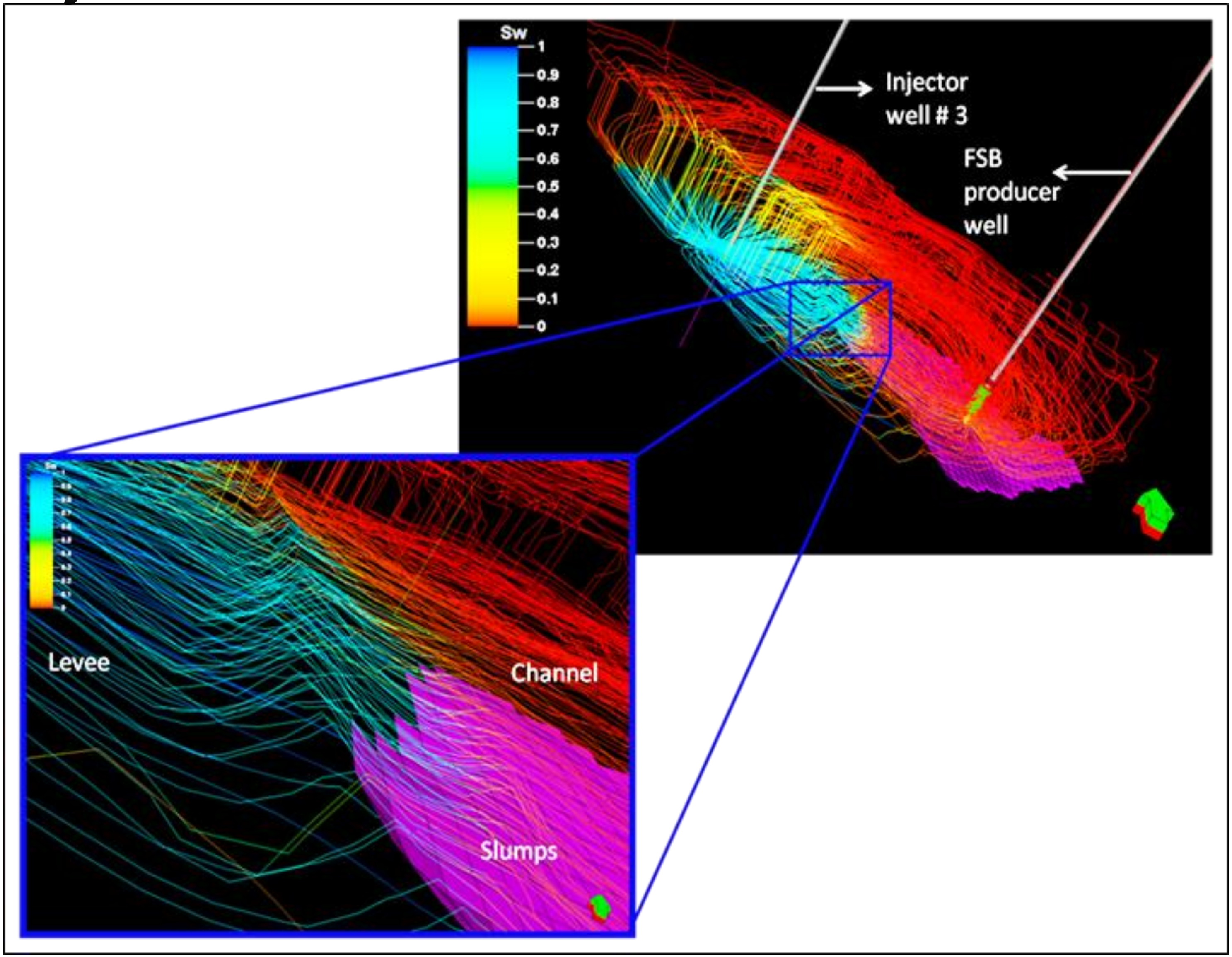


Figure 37. Injected water tries to overlap the slumps.

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Conclusions and Recommendations

1. *Slumps affect the flow of the fluids in the leveed-channel reservoirs.*

2. *Twenty flow simulation cases were developed based upon varying the production strategy and the permeability of the slumps, with the purpose to analyze production problems related with slumps in leveed-channel deposits.*

3. *The continuity, thickness, distribution and petrophysics of the slumps are fundamental for production problems in leveed-channel deposits, which contain these kinds of geological features.*

4. *Integration of disciplines is important, isn't?*

Conclusions and Recommendations

1. Future studies could analyze the thickness, continuity and especially the petrophysics of the slumps.

2. Mainly, the flow simulation was concentrated in Channel C, but connectivity between Channels C and D could provide future study, similar to the study by Stright et al., (2006).

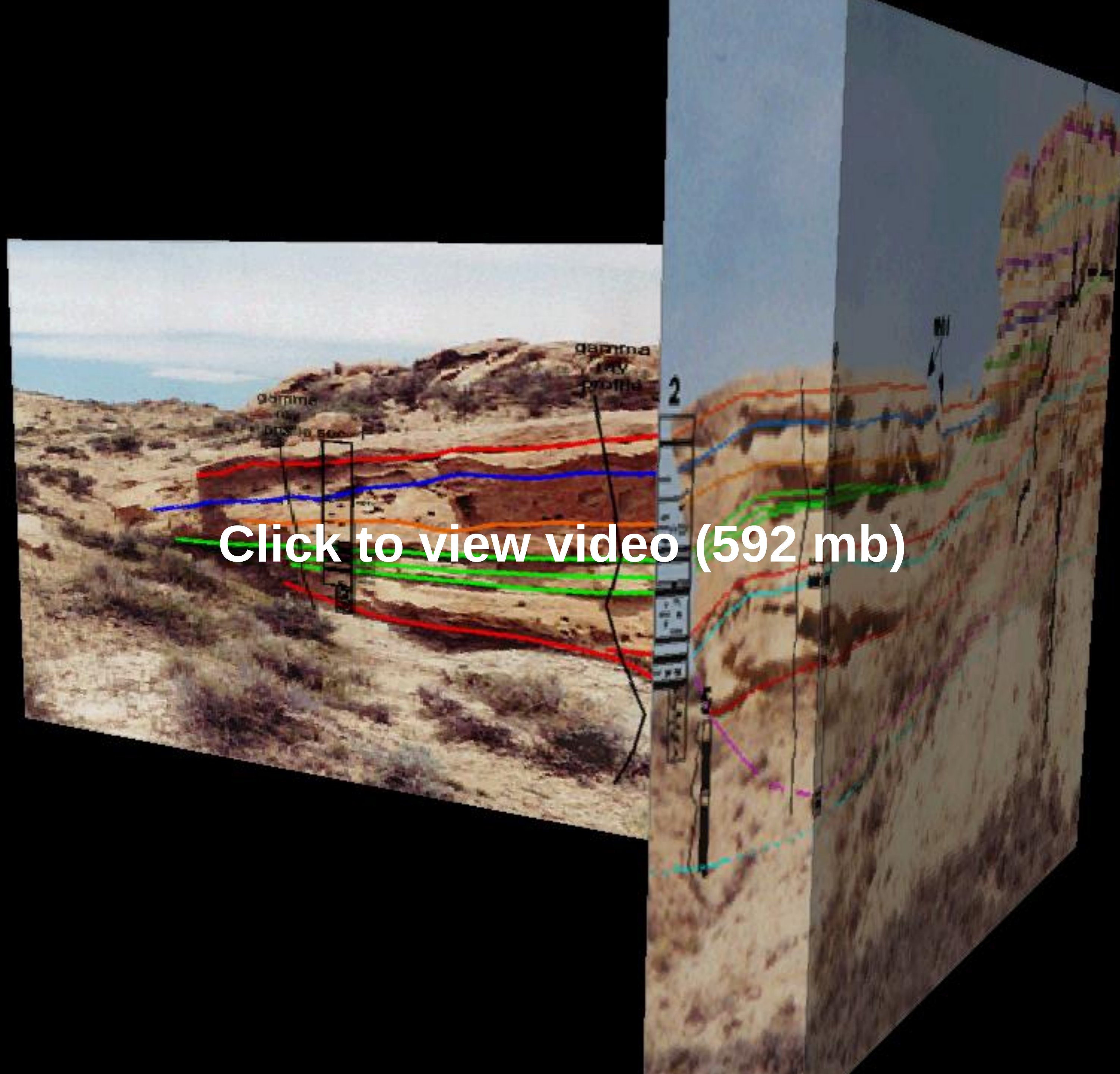
3. The lack of 3D GPR data provides possibilities for additional interpretations in the outcrop.

4. Water injection rates could be analyzed to define the best water injection rate depending on the distance between the injector and the producer wells.

Conclusions and ***Recommendations***

5. Oil production rate studies could help to prevent water coning and to obtain different results in similar simulation cases to the ones presented in this thesis.

6. Different grid arrangements could be used to model the leveed-channel deposits. It is recommended to avoid pinch-out grids in order to develop several flow simulations; however streamline simulations are highly recommended to observe the flow pattern of the water injected.


Click to view video (592 mb)

Flow Simulation

Streamline flow simulation

$$ELoil = \frac{WI * LOE}{NRI\left[Po * (1 - To) + Pg * (\frac{GOR}{1000})\right] * (1 - T)}$$

Where:

ELoil = economic limit for oil well, bbls/month

Po = oil price, $/Sbbl

LOE = lease operating expenses, $/well/month

WI = working interest, fraction

NRI = net revenue interest, fraction

GOR = gas-oil ratio, Scf/Mscf

To = oil severance/production taxes, fraction

T = Advalorem tax, fraction

Taken from Mian (2002).

EL (bbls/month)	138635
WI(Working interest fraction)	0.78
LOE (lease operating expenses, $well/month)	5’523.750
NRI (Net revenue interest) fraction	0.875
Po (oil prices) $/Stbbl	30
To (Oil and Gas severance/production taxes) fraction	0.04
Pg (Gas prices) $ Mscf	2.5
GOR (Scf/Stb)	3372.216
T (Advalorem tax) fraction	0.046

Table 5.5.1. Values used to calculate EL for the different flow simulations.

Flow Simulation

Streamline flow simulation

$$r_{inv} = 0.0325 * \sqrt{\frac{k * t}{\text{Ø} * \mu * c_t}}$$

$t_{(avg)} = 100$ days

where:

t = time, hours

k = permeability, md

c_t *= compressibility, psi*$^{-1}$

μ *= viscosity, cp*

Ø *= porosity, fraction*

Taken from Tarek, et al., 2005.

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