4D GPR for Characterization of Fluid Flow in Carbonates: Insights from Structural- vs. Stratigraphic-Controlled Domains and Comparison with Eclipse Dynamic Modeling*

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Abstract

Time-lapse 3-D Ground Penetrating Radar (4-D GPR) was used to track fluid flow in two carbonate reservoir analogues: the fracture-controlled Madonna della Mazza grainstone quarry (Southern Italy) and the structurally undisturbed oolitic limestone of Ingraham Park (Miami, FL). The goals of this study are: 1) to assess the role of stratigraphic versus structural heterogeneities and to characterize fluid dynamics in gravity flow experiments; 2) to compare 4-D GPR results with dynamic flow simulation.

In Madonna della Mazza (MdM), 2,952 liters of water were infiltrated from the quarry surface into the host matrix (poro/perm, 35%/630mD) in a location with deformation bands and open faults. At Ingraham Park 3,200 liters were infiltrated in five hours (poro/perm, 60%/1,500mD). Both infiltrations were performed using 4 m-diameter, temporary ponds. Water decreases the speed of electromagnetic waves and, consequently, increases the traveltime of subsurface reflections. Timeshifts are extracted between pairs of time-lapse surveys with 3-D cross-correlation. The timeshifts volumes are converted to water content changes by applying the Topp petrophysical transfer function. Such 3-D water content change volumes provide snapshots of fluid flow over an observation period up to 15 hours after the end of the infiltration.

At the MdM quarry, the undisturbed matrix experiences higher water content changes (peak of 4%) than the deformation bands area (2%) indicating their active role in compartmentalizing fluids. In addition, the infiltrated water bulb shows a pronounced up-dip asymmetry along a fault plane due to preferential flow. At Ingraham, water content changes peak is 9% across the pond infiltration area. Here, higher porosity and permeability values of the host rock facilitate more rapid fluid migration compared to MdM. The upper water bulb boundary is within the pond perimeter while the lower boundary is shifted down-dip as fluid migration follows stratigraphy.

For dynamic flow modeling in Eclipse the detailed stratigraphic and structural interpretation of MdM 3-D GPR survey had to be simplified and downsampled for computational reasons. The dynamic model fails to capture and visualize the role of structural heterogeneities: the effect of deformation bands on the fluid migration is completely lost. Simplification and downsampling prevent dynamic modeling from reproducing realistic flow conditions observed in the 4-D GPR experiments.

4D GPR for Characterization of Fluid Flow in Carbonates:

Insights from Structural- vs. Stratigraphic-controlled Domains and Comparison with Eclipse Dynamic Modeling

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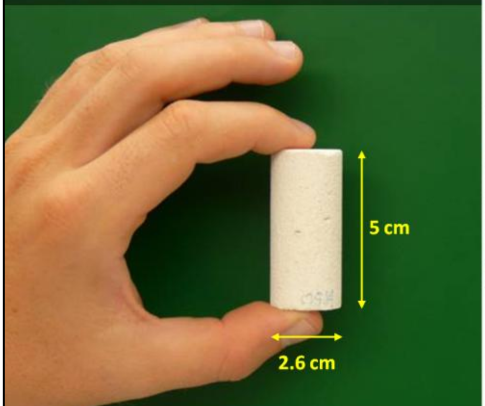
GOALS:

- Assess structural & stratigraphic controls on fluid flow
- Compare with dynamic flow modeling

Lab Measurements vs. Pond Experiment

STANDARD PLUG

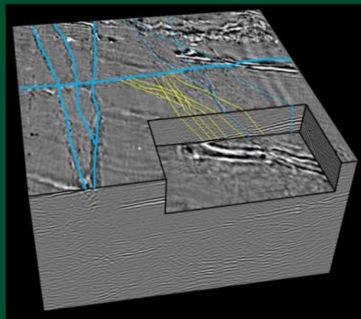


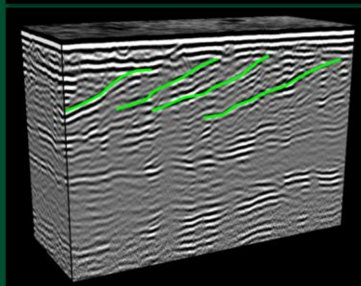
MEGA PLUG

* max penetration depth on GPR datasets

X 5.000.000 volume increment

Field Sites Overview



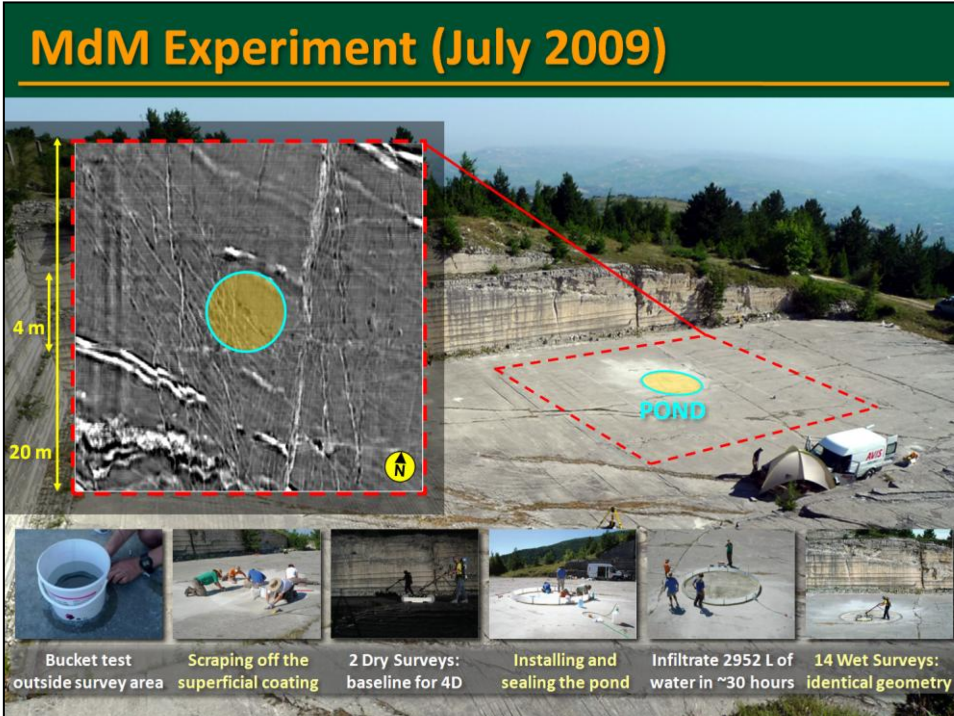


Madonna della Mazza quarry (MdM)

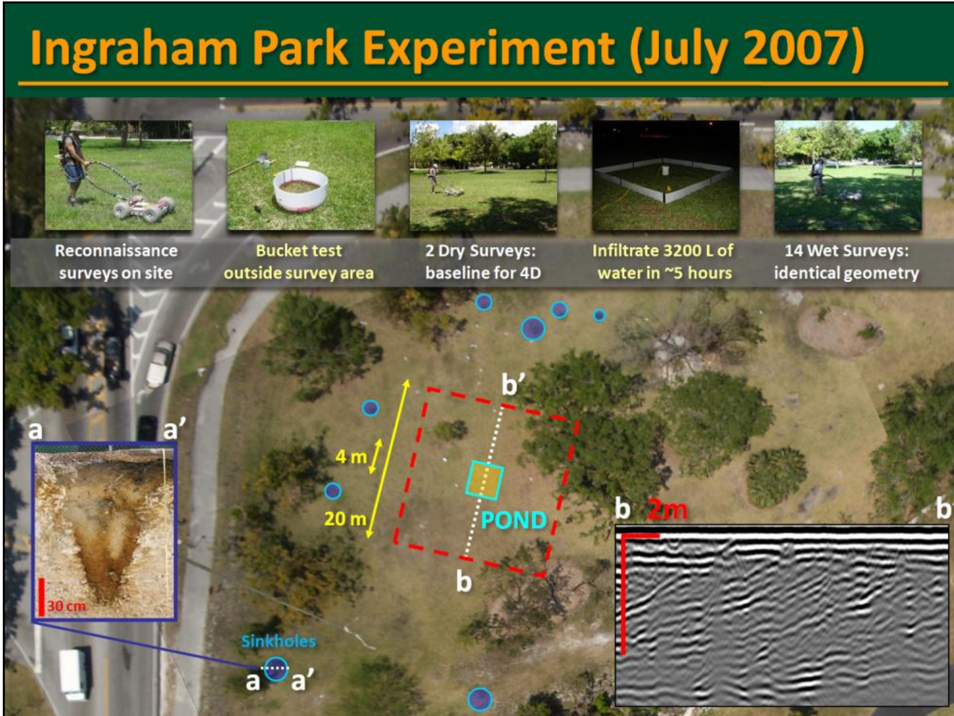
- Upper-Cretaceous rudist grainstones
- Poro/Perm: 25-35 % / 150-630 mD
- Faults and Deformation Bands

Ingraham Park

- Pleistocene oolitic shoal system
- Poro/Perm: 40-60 % / 600-1500 mD
- Heterogeneities:
  1) grain size distribution
  2) geometry of depositional bodies
  3) stratigraphy

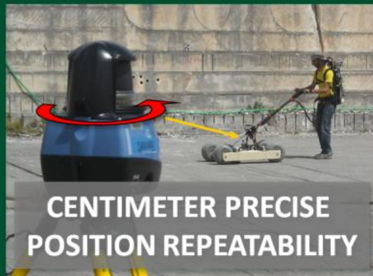


Presenter's notes: The picture shows MdM quarry.



Presenter's notes: In Ingraham Park, the survey area was chosen to avoid sinkholes.

GPR Systems



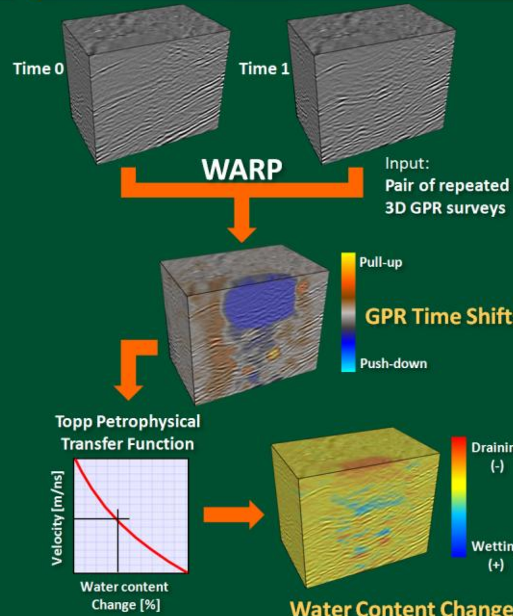
MdM → 16 surveys

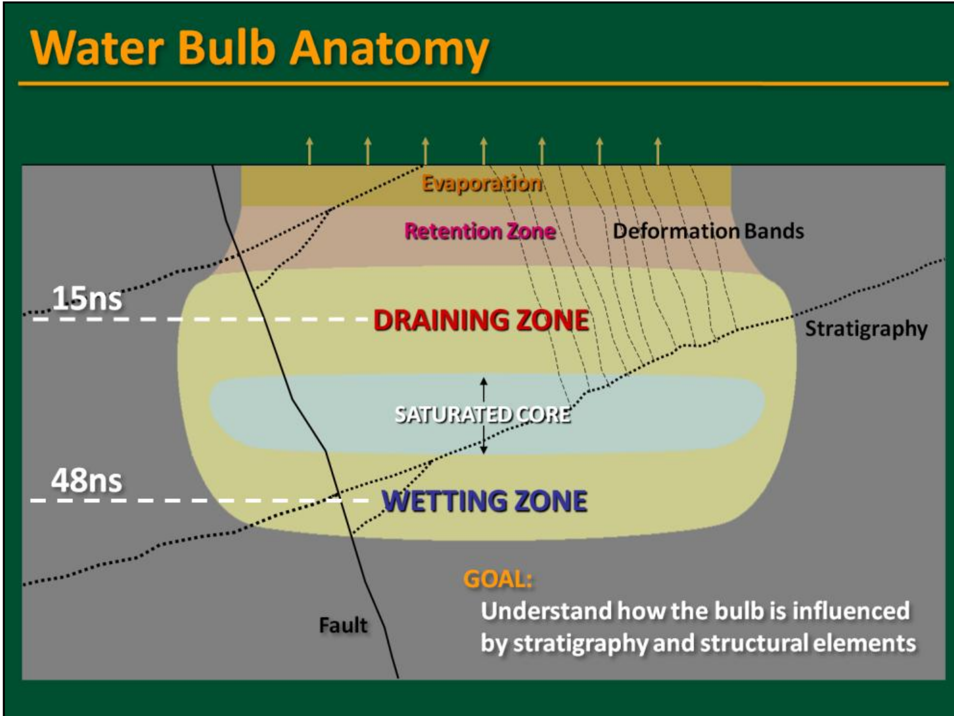
- 200 MHz dual-channel GPR
- 401 InLines (5cm spacing)
- 801 CrossLines (2.5cm spacing)
- 20x20x~12m survey volume

Ingraham Park → 16 surveys

- 250 MHz single-channel GPR
- 181 InLines (10cm spacing)
- 401 CrossLines (2.5cm spacing)
- 18x20x~8m survey volume

4D GPR Method



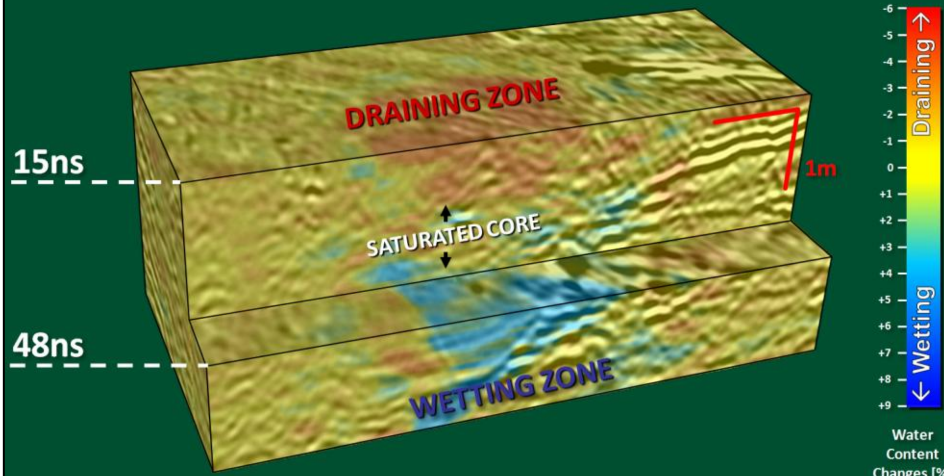


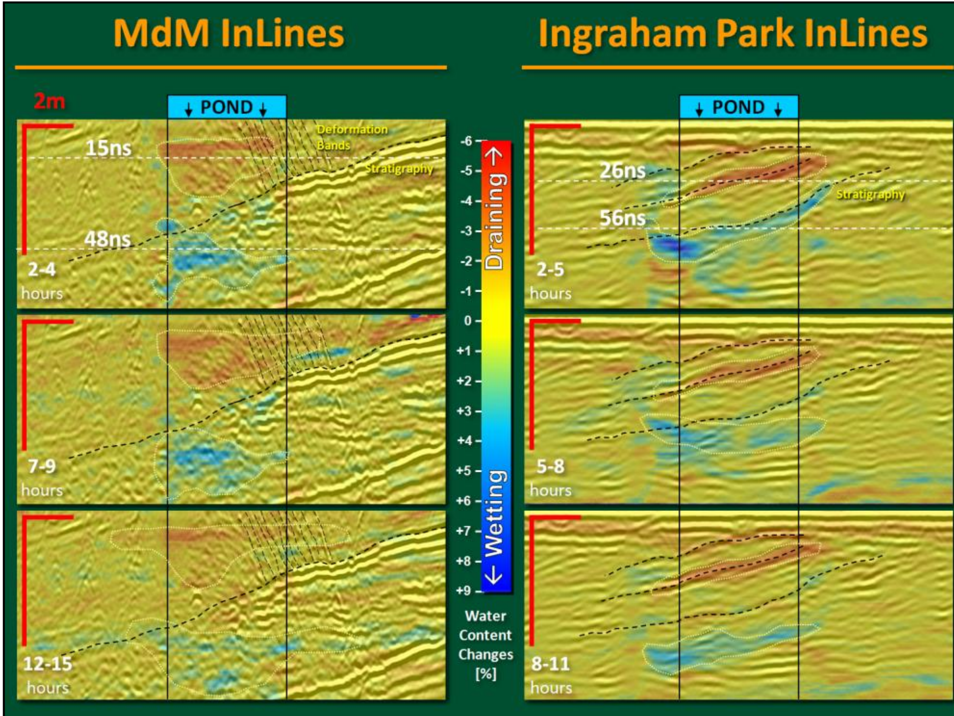
Presenter's notes: The cartoon shows a representation of the injected water mass. The water bulb in the host rock can be subdivided into zones.

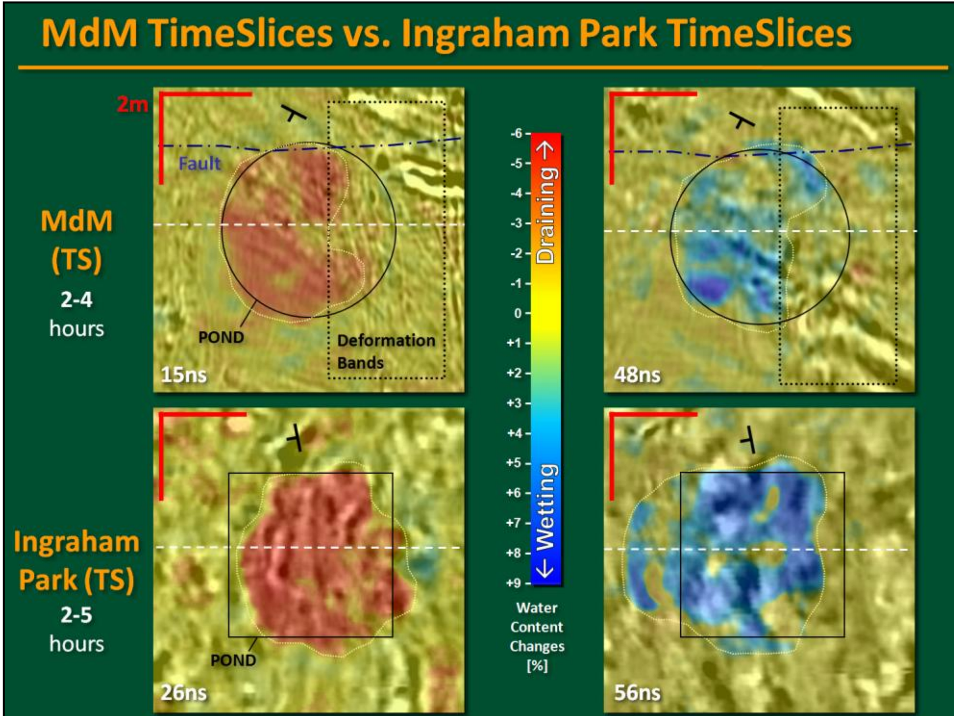
The Hydraulic Head

Hydraulic Head:
Measure of the gravitational force that causes the groundwater to flow

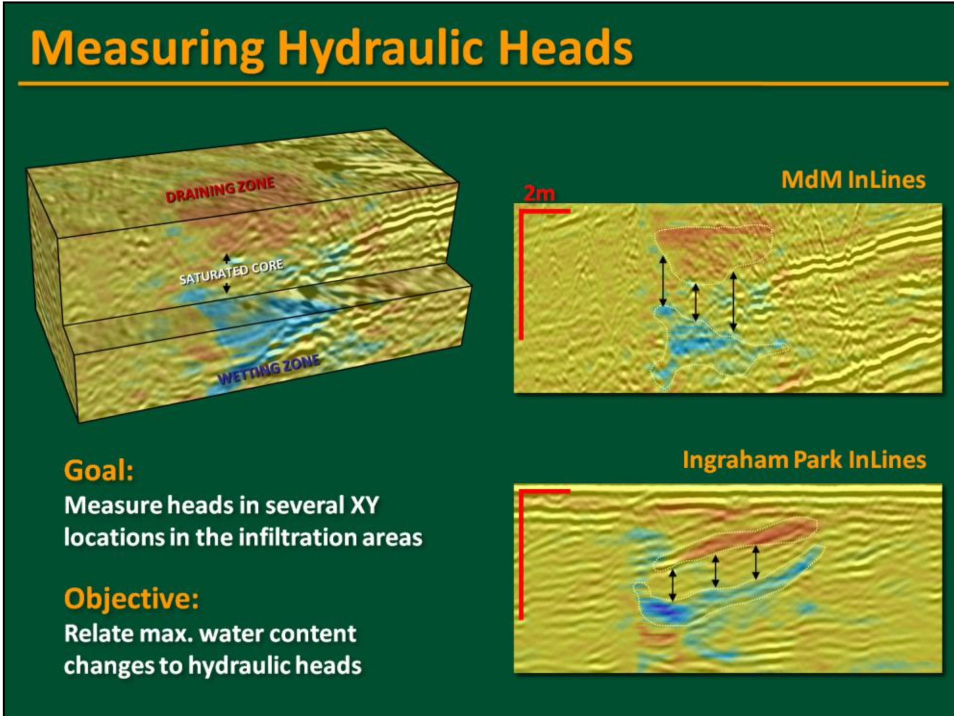
In the water bulb:
Difference in depth between the draining and the wetting zone



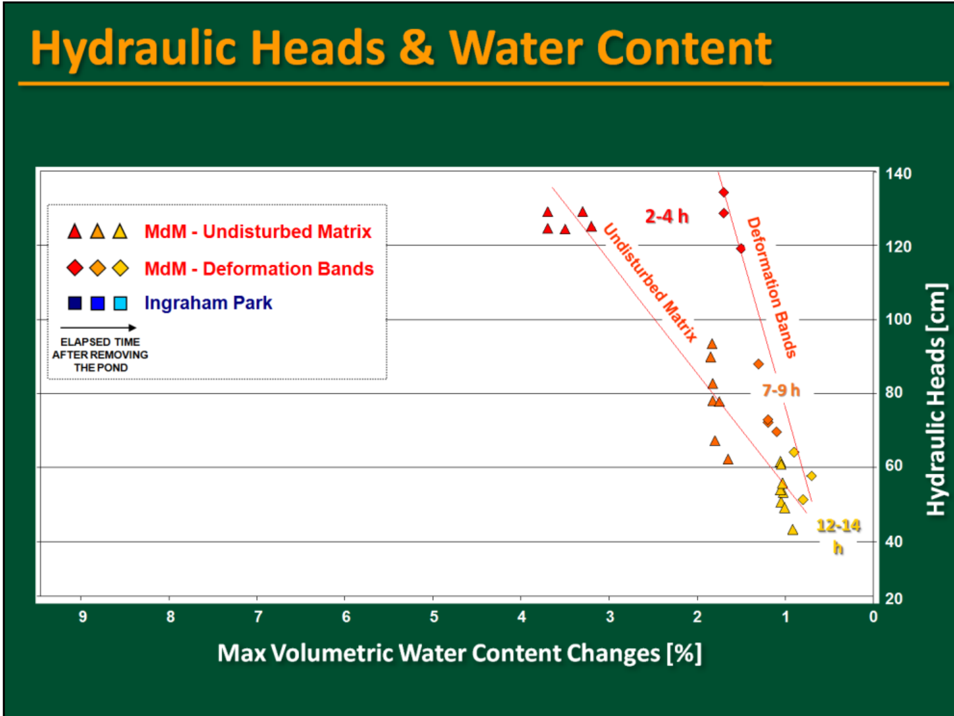

MdM InLines
Ingraham Park InLines
2m
POND
POND
Deformation Bands
Stratigraphy
15ns
48ns
26ns
56ns
Stratigraphy
2-4 hours
7-9 hours
12-15 hours
2-5 hours
5-8 hours
8-11 hours
-6
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
+7
+8
+9
Draining
Wetting
Water Content Changes [%]



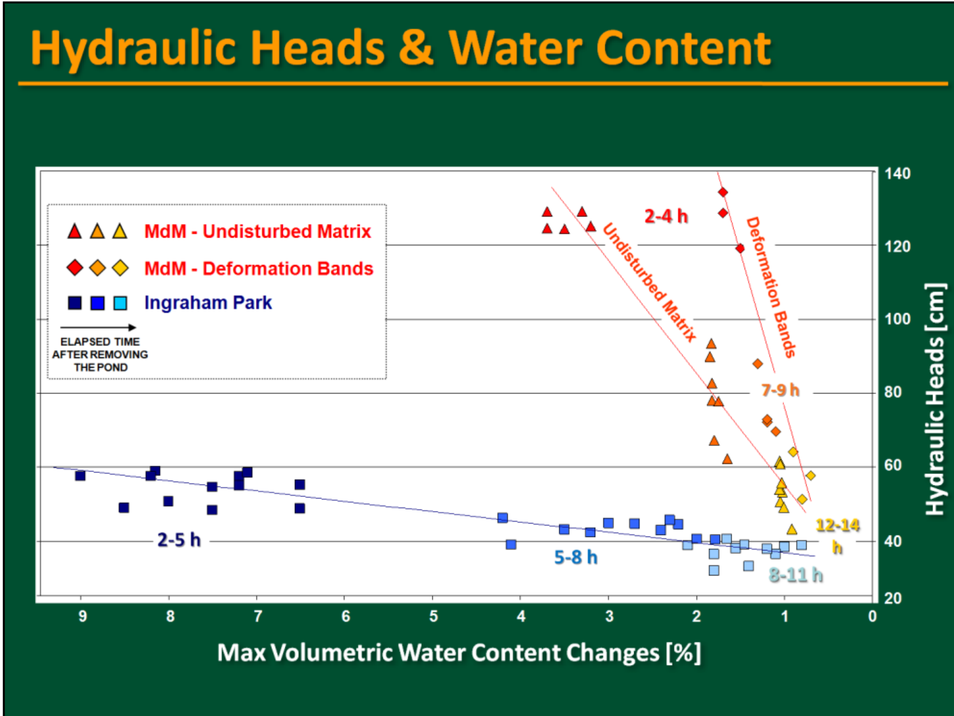
Presenter's notes: In MdM, TS show a pronounced asymmetry of both draining and wetting zones.



Presenter’s notes: For both field sites, we measured hydraulic heads over time.



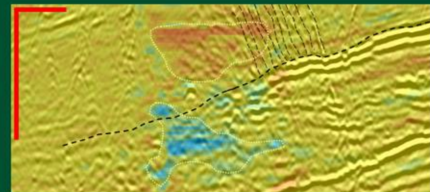
Presenter's notes: In MdM, data show that, on a 1-10m scale, there is a sharp difference in magnitude of water content changes.

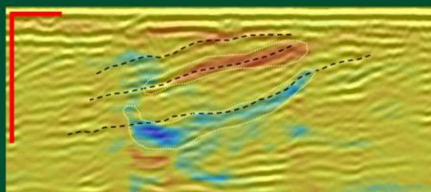


Presenter's notes: In Ingraham Park, there are no separate trends of 4D GPR derived water content changes.

Learning Points

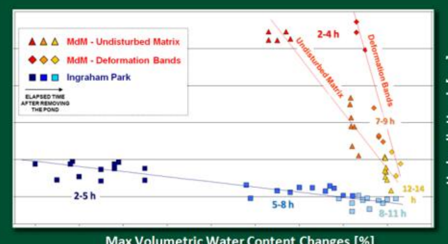
- In structural-controlled domains, faults and deformation bands influence the fluid dynamics

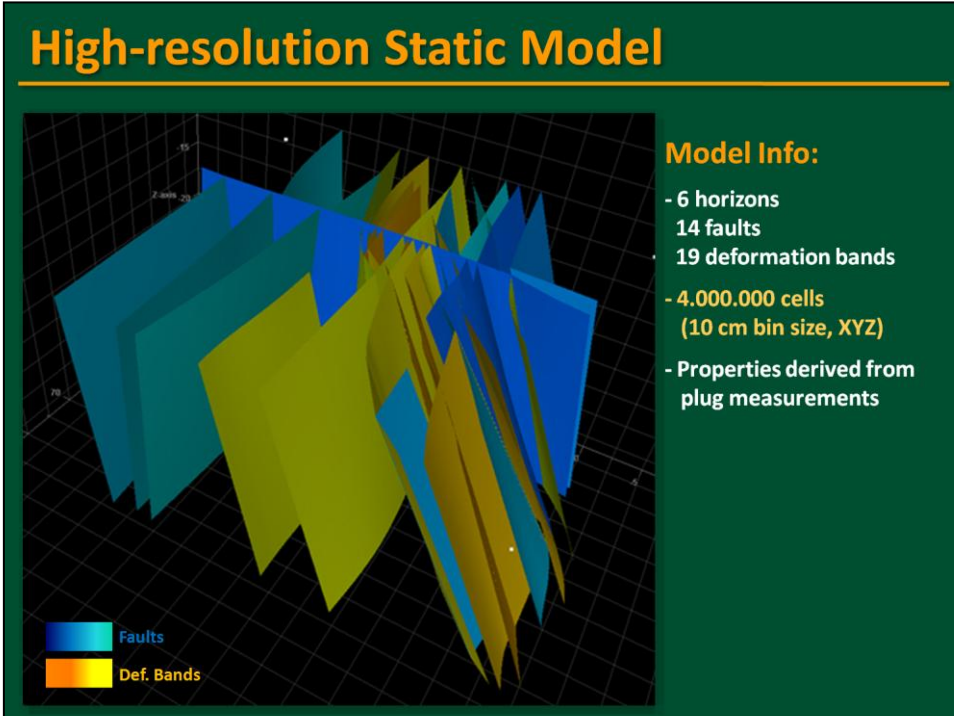




- Stratigraphic control is dominant in undisturbed domains

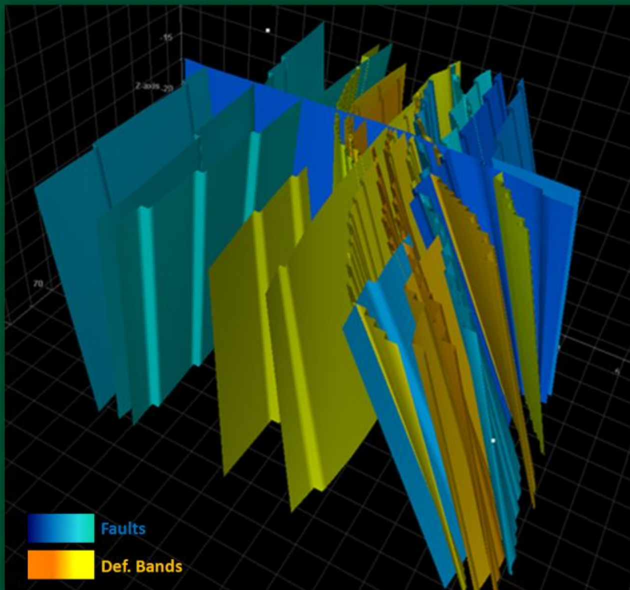
- MdM: different trends at 1-10m scale for matrix and def. bands
- Ingraham: larger water content changes with smaller heads





Presenter's notes: For the dynamic modeling, a static reservoir model of the surveyed portion of the MdM quarry was constructed.

Simplified Static Model

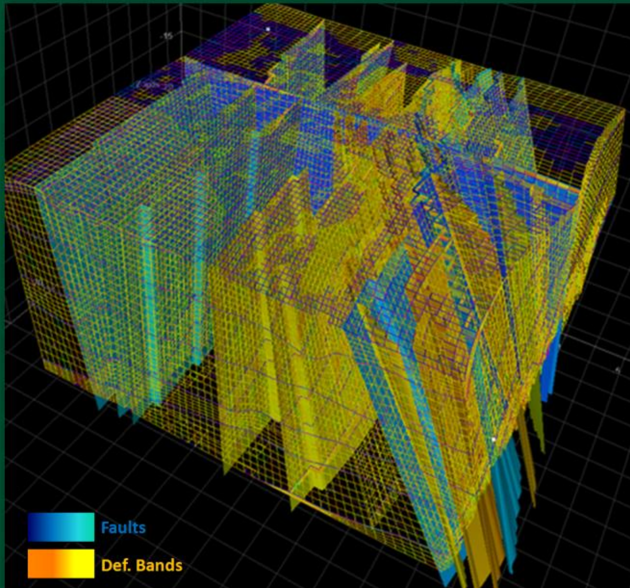


Simplifications:

- Zig-zag shape for faults and deformation bands (avoid sharp angles at cell boundaries)

Presenter's notes: As a preparation for the dynamic simulation, the original 3D stratigraphic and structural interpretation had to be adapted.

Simplified Static Model

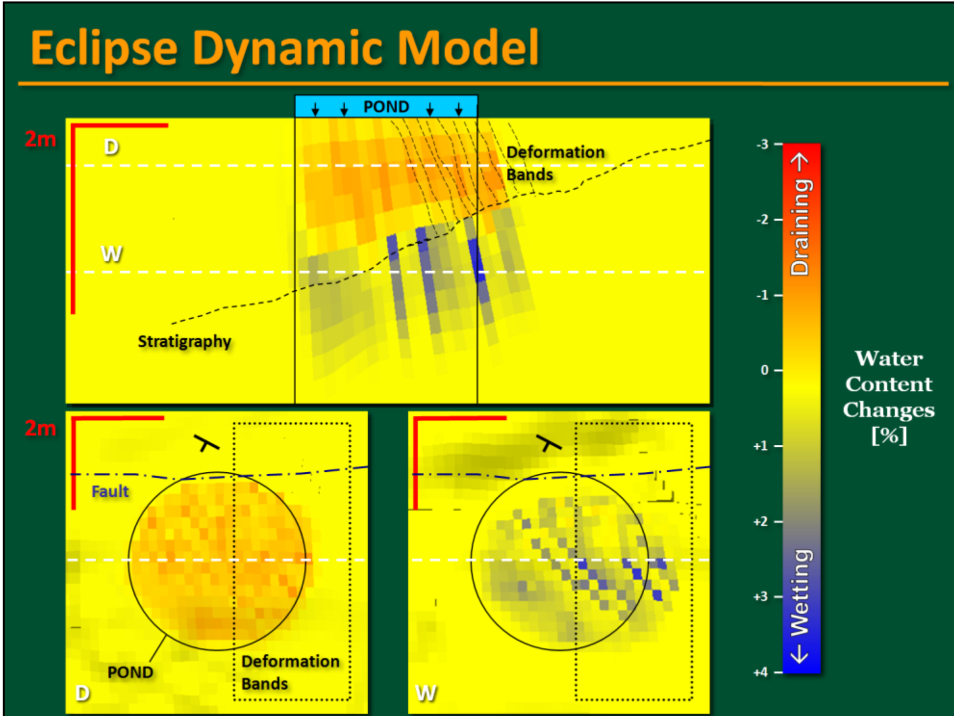


Simplifications:

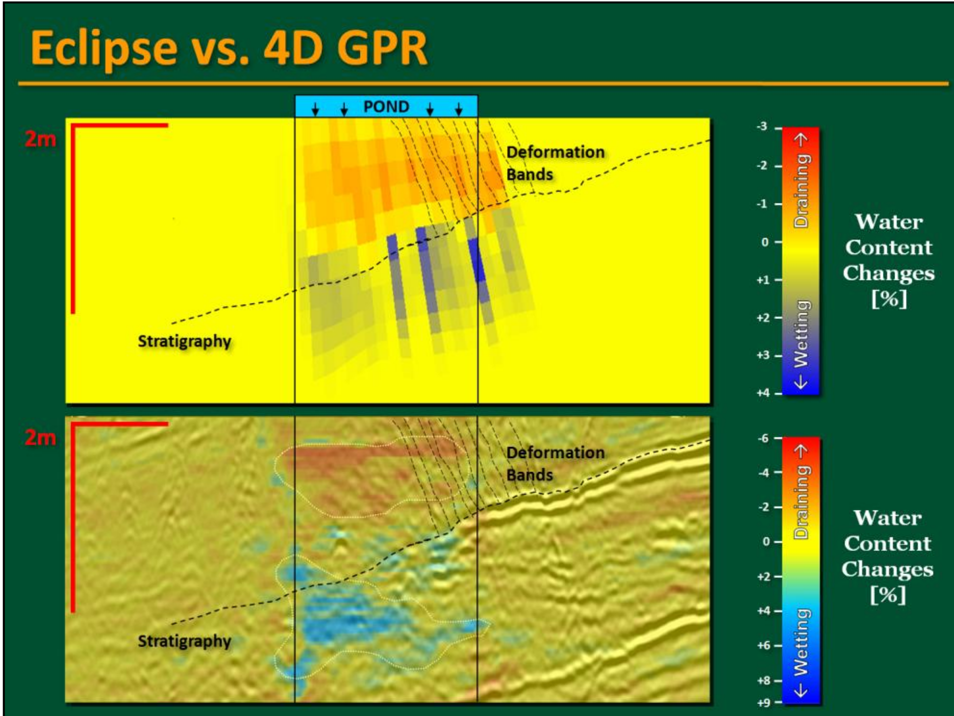
- Zig-zag shape for faults and deformation bands (avoid sharp angles at cell boundaries)

Dynamic model input:

- 150.000 cells (30 cm bin size, XYZ)
- Transmissibility= 0 for faults and deformation bands in cross-flow direction
- Vertical permeability = horizontal permeability



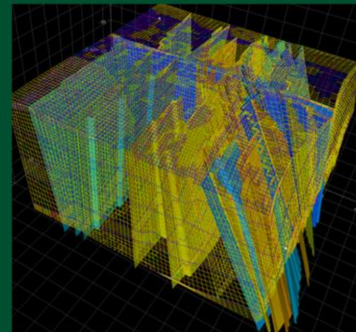
Presenter's notes: In the deformation bands, area higher values of water content changes are experienced.

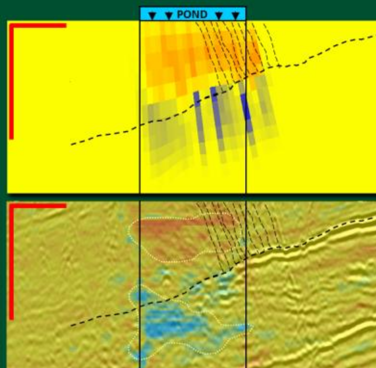


Presenter's notes: The effect of deformation bands is completely lost in the dynamic model results.

Learning Points

- Simplified model differs from original 3D interpretation in terms of precision and resolution





- Opposite flow behavior when comparing dynamic model and 4D GPR experiment

Conclusions + Implications

- Faults and deformation bands influence fluid migration in structural-controlled domains

- Stratigraphic boundaries control fluid flow in undisturbed, high-porosity domains

IMPLICATION: 4D GPR in gravity flow experiments offers insights on how to reduce uncertainties when upscaling from plug to reservoir scale

- Simplification and downsampling in dynamic modeling = effect of small-scale lateral variations is lost

IMPLICATION: realistic flow models should always include small-scale heterogeneities to improve reservoir characterization and residual fluid recovery