Integrating outcrop fracture data and pressure transient data for constructing local scale flow models of the fractured and karstic Lez aquifer, Southern France

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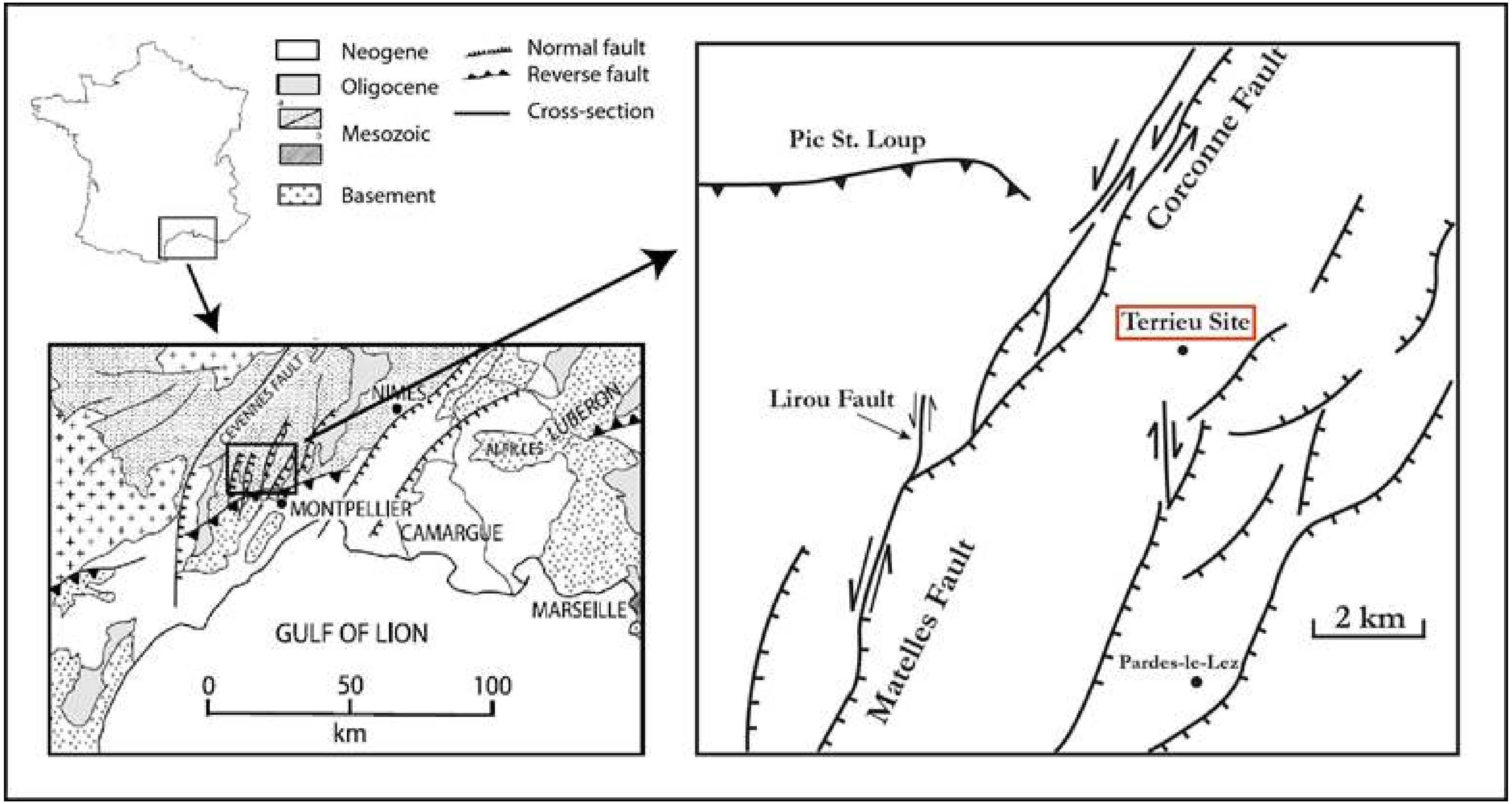
Karst without Boundaries
Trebinje, Bosnia and Herzegovina

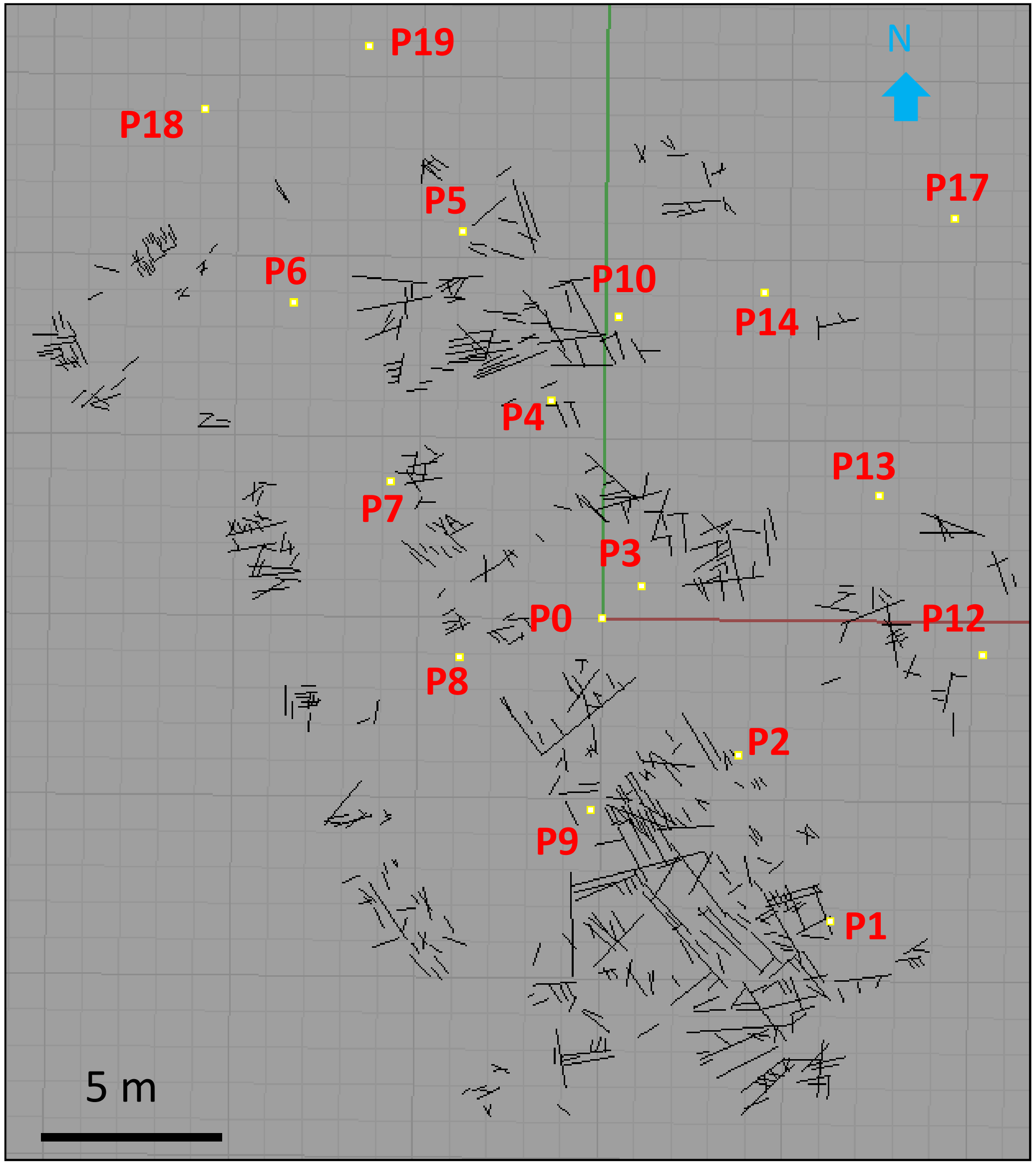
Talk outline

- Geological and hydrogeological background
- New & existing fracture and borehole data
- Numerical modelling approach
- Preliminary simulation results
- Conclusions

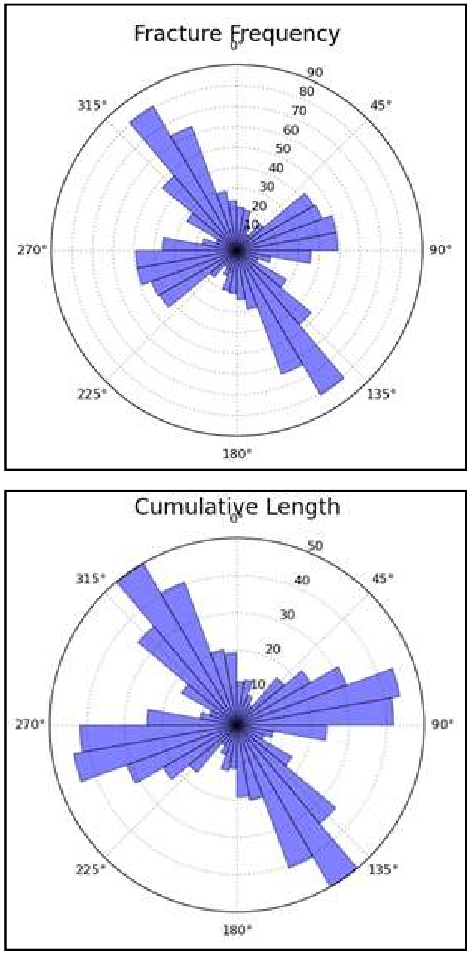
Study location – the Lez aquifer



Study location – the Terrieu drill site



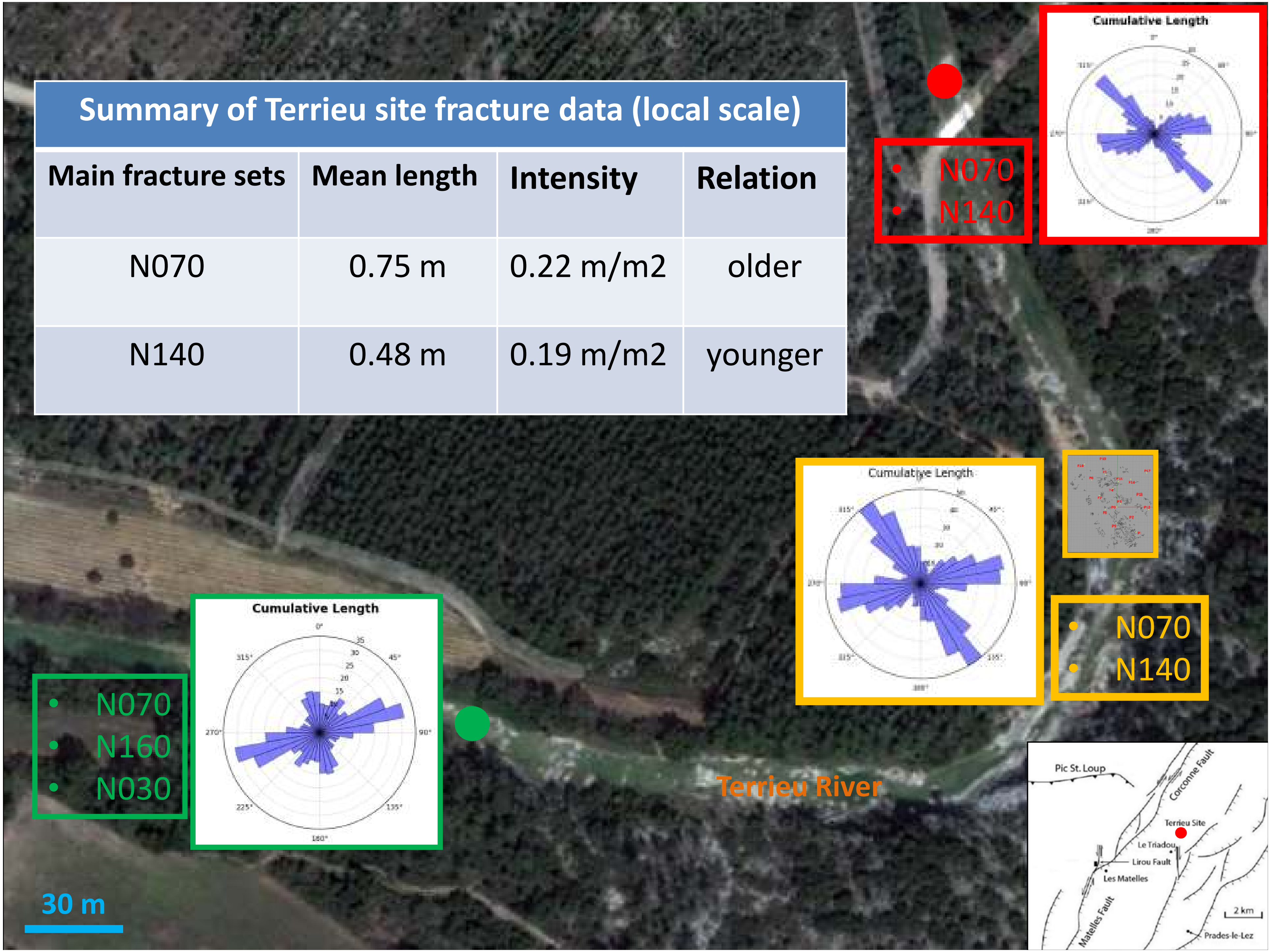
Two major fracture sets



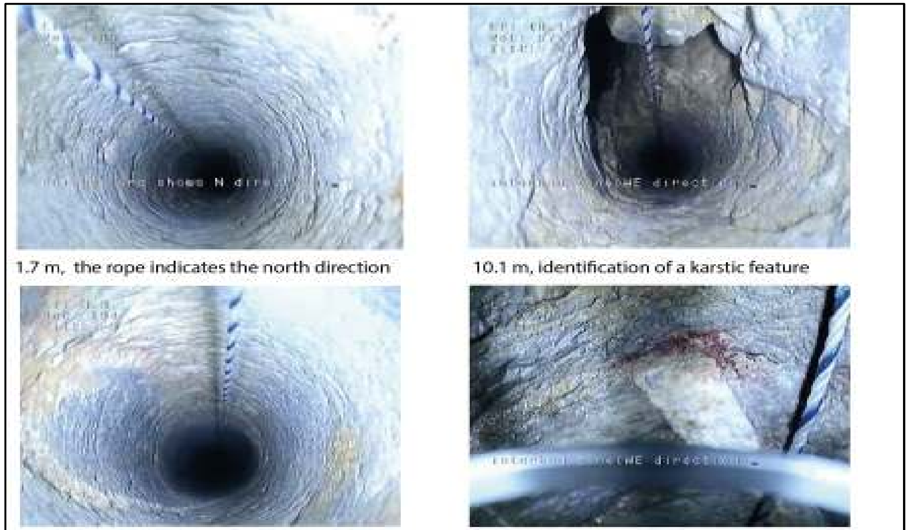
Terrieu site pavement fracture data
– corrected from M. Jazayeri Noushabadi, 2009

Summary of Terrieu site fracture data (local scale)

Main fracture sets	Mean length	Intensity	Relation
N070	0.75 m	0.22 m/m2	older
N140	0.48 m	0.19 m/m2	younger



Review of Terrieu site database



1.7 m, the rope indicates the north direction

10.1 m, identification of a karstic feature

3.9 m, observation of a partly-filled fracture

21.4 m, cemented fracture terminating against a bedding surface

Well logging data:

1. Temperature log
2. Conductivity log
3. Borehole video (blue dots)

Well test data:

1. Single-borehole - PIs
2. Interference – Inter-well Perm

Fractures detected in boreholes:

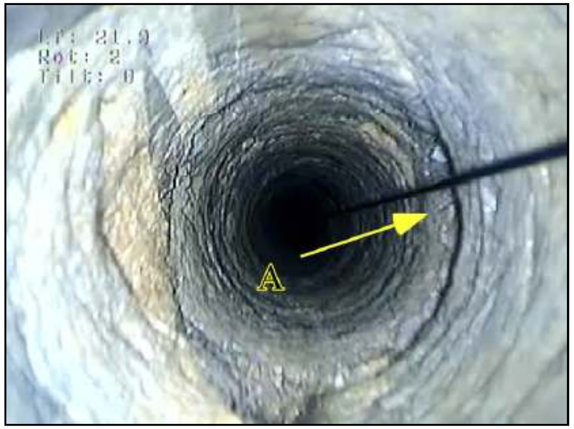
- Most are steep, strata-bound
- N070 – generally open
- N140 – mostly calcite filled
- Karst along the bedding planes

Justifies using pavement fracture data to characterize fracture network within the underlying units

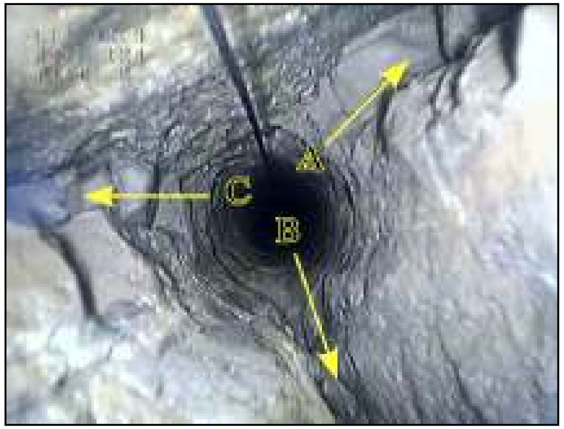
The importance of karstified bedding surface and pipes

Conductive features observed in the boreholes

1. Some karstification along bedding planes – sheet karst
2. Enhanced karstification at the intersections of vertical fractures with bedding planes – pipe karst
3. Fractures (partly calcite cemented)



Karstified bedding plane

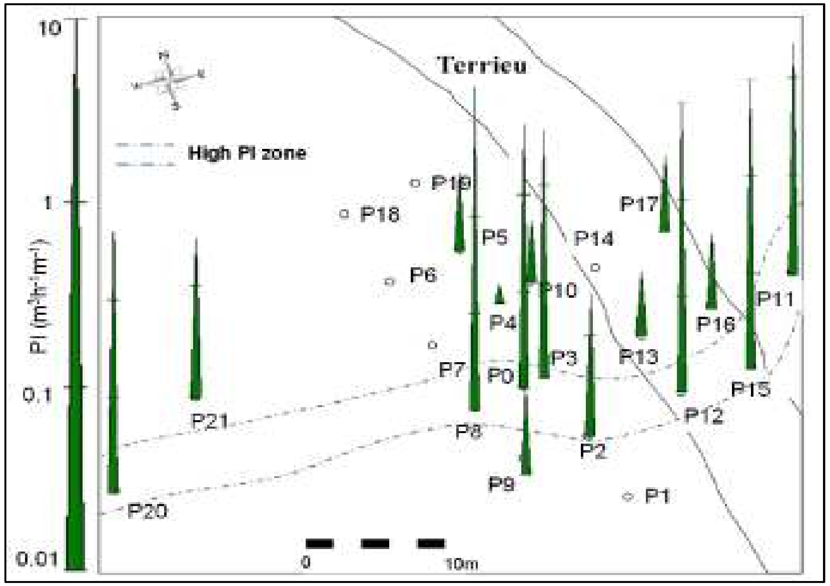


Fracture/bedding Intersection

Sub-vertical fractures

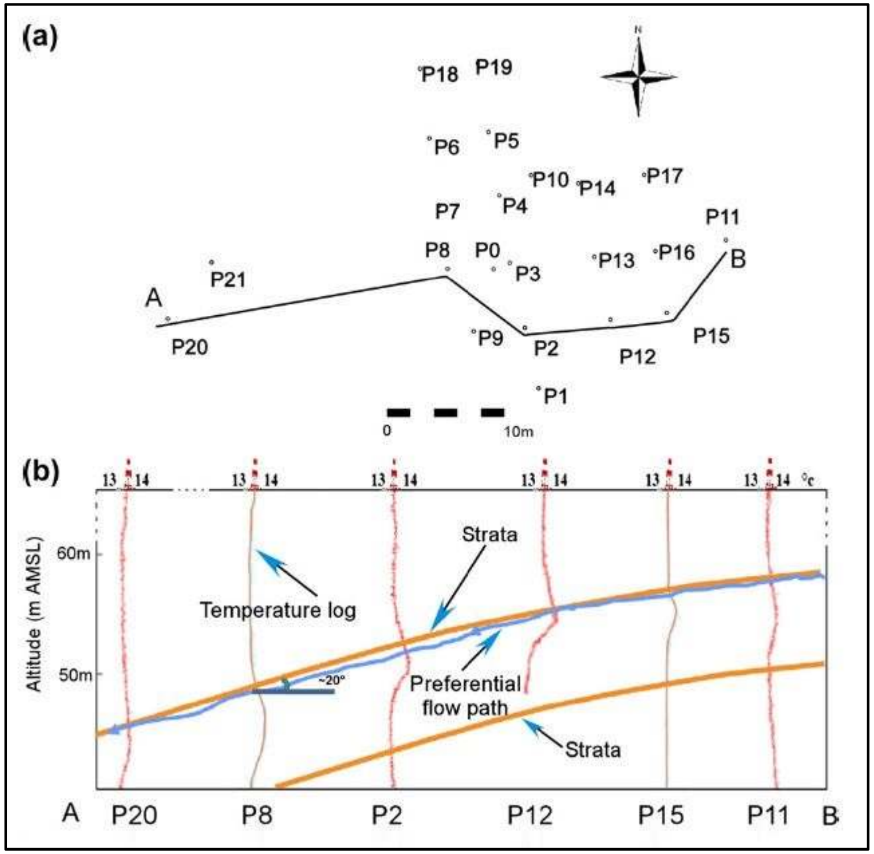
Karstification along bedding planes is very important for flow. However, the extent of karstification is unknown (channels are a min of 10 cm wide).

Integration of well test and well logging data



PI values interpreted from well tests

High PI zone indicates the main flow path at the test site;
Lateral location and connectivity



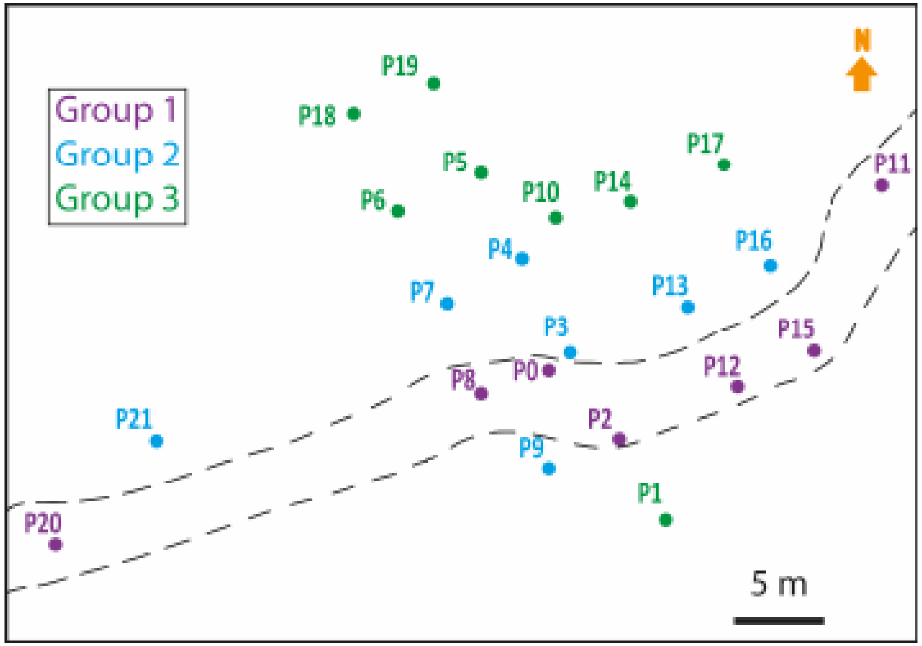
Correlation of temperature log profiles

Vertical distribution and connectivity

3D spatial location of the main bedding plane can be determined

M. Jazayeri Noushabadi, 2009

Classification of well models



Three well groups at the Terrieu site

Initial step for model construction;
Basis for determining hydraulic properties.

Well grouping based on:

- Productivity Indices (PIs);
- Interference behaviours;
- Presence or absence of flow features;
- Proximity to main karst channel.

Group 1 – Intersects the main flow path

- Extremely high PIs; open features presenting; rapid response to pumping
- P0, P2, P8, P11, P12, P15 and P20

Group 2 – Proximal to the main flow path

- Intermediate PIs; in-filled fractures presenting
- P3, P4, P7, P9, P13 and P21

Group 3 – Far from the main flow path

- Low PIs; Delayed responses to pumping
- P5, P6, P10, P14, P17, P18 and P19

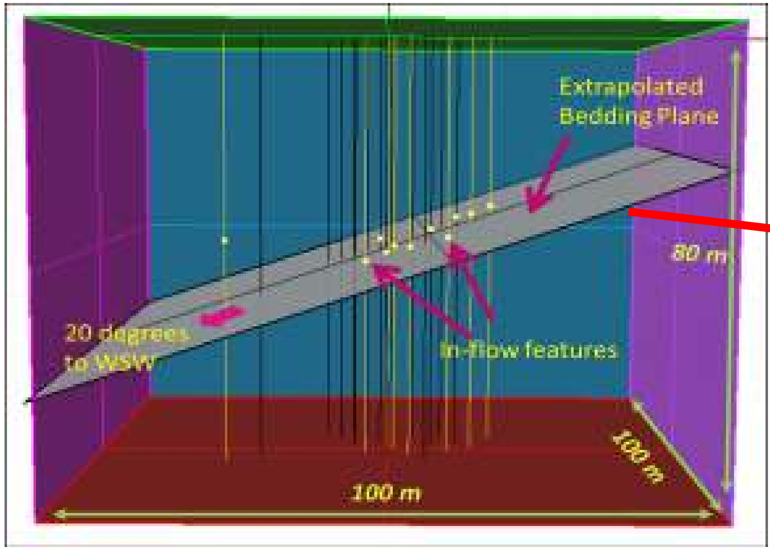
Multi-scale conceptual flow model

Generalised flow paths:

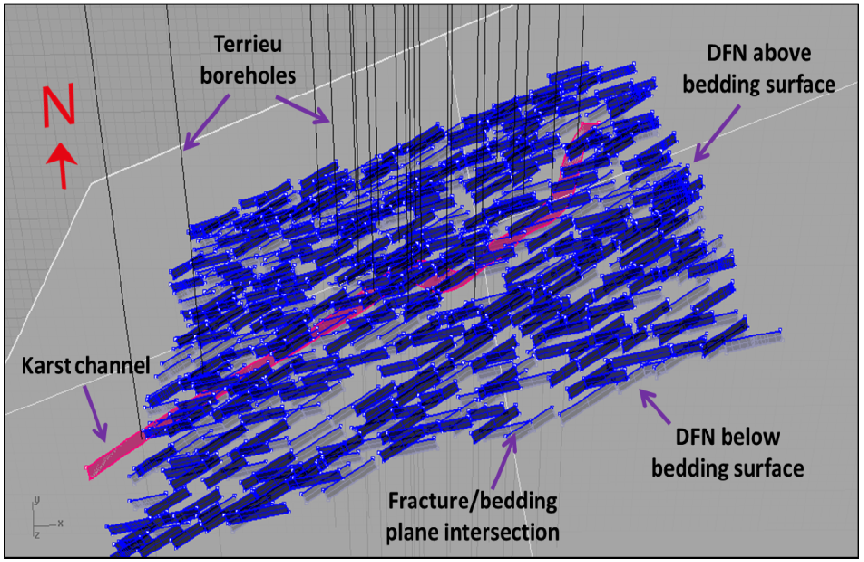
1. Karstification along bedding plane generates **sheet features** – **the most important**!
2. Un-karstified bedding plane – **low permeability but good lateral connectivity**
3. Metre-scale fractures that terminate at main bedding plane, are sites of **pipe** karst (**linear** features) that connect the boreholes to the main karst channel (intersections enhanced by dissolution) – **enhanced permeability**
4. Fractures away from bedding plane and matrix are dynamically combined into pseudo-matrix, providing most storage – **very low permeability**

Our flow model aims to capture this **hierarchical organization** of flow pathways (1, 2, 3 and partly 4)

Numerical model



Side view of the box-shaped model



Side view of the main bedding plane

The spatial distribution of the main bedding surface is determined through extrapolation using locations of in-flow features detected from well log data

Generalised distribution ~ dipping 20° towards WSW

1. Sheet karst is placed deterministically
2. Network of joints
   - Two main sets (N070 and N140) are controlled by density (modified length)
   - 70% N140 joints abut N070 set
   - Two layers are placed above/below the bedding plane
3. Pipe karst - bedding/fracture intersections

Assignment of hydrogeological properties to the model

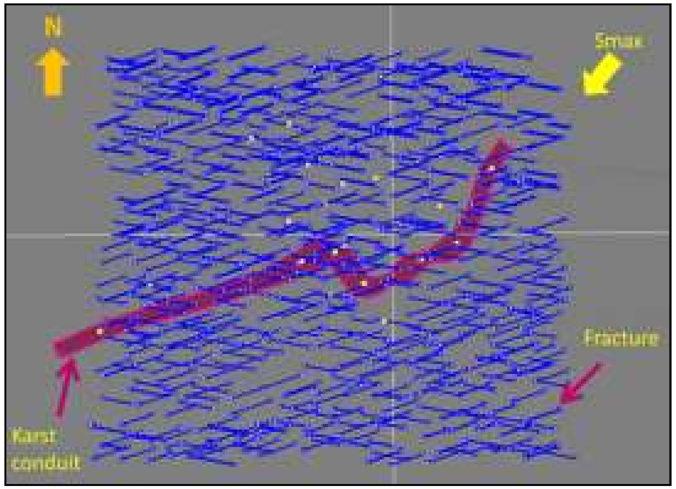
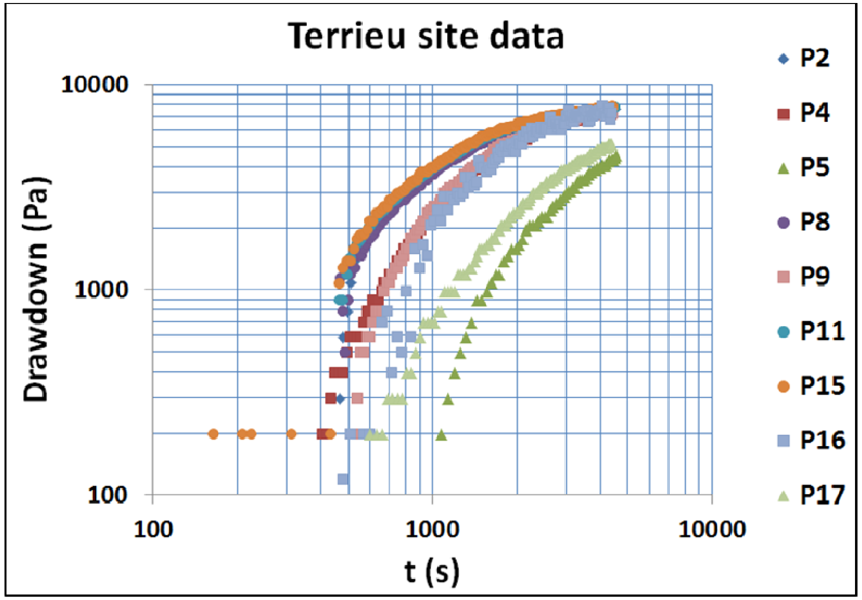
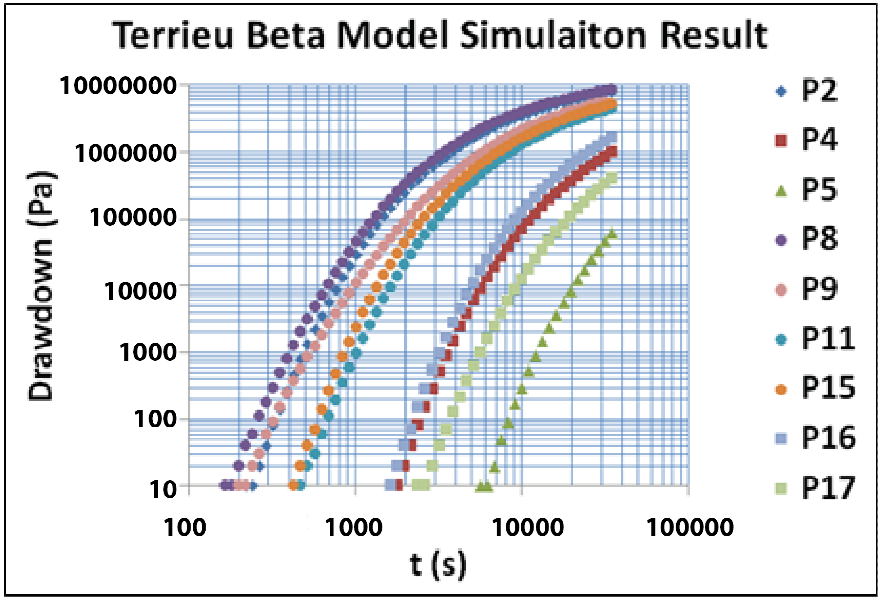


Table 1 - Hydraulic properties considered in the simulation model					
Flow region	Aperture (m)	Permeability (m^2)	Porosity (-)	Specific storage (Pa^{-1})	Initial pressure
Pseudo-matrix	NA	1.00E-15	0.01	1.00E-11	2.95e+05 Pa
Sheet karst	3.00E-03	2.00E-09	1	5.00E-07	
Pipe karst	7.50E-02	4.70E-04	1	1.00E-06	Production Rate
Unkarstified bedding	5.00E-05	1.00E-14	1	1.00E-08	
N070 fractures	5.00E-04	1.00E-11	1	1.00E-08	
N140 fractures	1.00E-04	2.00E-12	1	1.00E-08	100 m^3/day

- The major karst channel on the bedding plane (‘strip’) is 3 to 4 orders of magnitude more permeable than the fractures and matrix
- Low permeability for un-karstified portion of the bedding plane
- N140 set is less permeable than N070 set due to the orientation of present day maximum horizontal stress; N140 partly/completely closed
- Pseudo-matrix (fracture + matrix) is assigned with enhanced properties compared to the original background matrix
- Closed-boundary condition is assigned to all box surfaces
- Mesh created in ANSYS ICEM; simulations run in CSMP++

Preliminary simulation result – interference test





Similar clustering behaviour of the pressure curves indicates the flow model can preserve the expected hierarchical flow behaviour!

Misfits

- The data range (drawdown pressure) is different;
- Larger dispersion of drawdown curves in simulation data;
- Some interference curves are not in the same order.

Acceptable at this stage since used simplified input;
could be adjusted by sensitivity analysis and history matching.

Conclusions

1. The hierarchical flow behaviour at the Terrieu site can be reproduced by integrating all available static and dynamic data.
   - Compatibility between static and dynamic data
   - Validity of proposed geological conceptual model

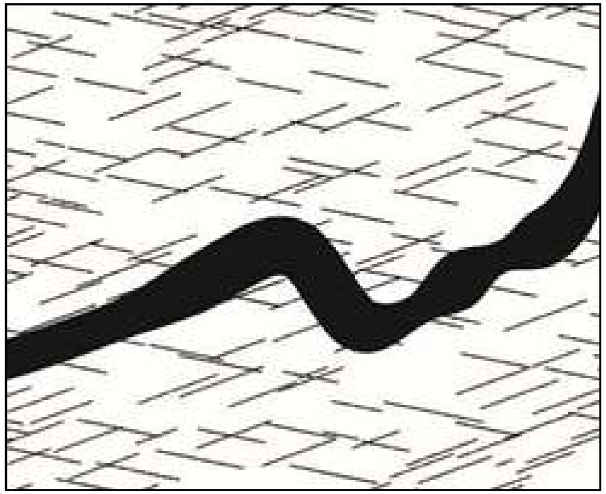
2. The modelling approach presented in this work has assisted to improve our understanding of the fluid flow in a highly fractured and karstified system, and it can be **extended** to other similar applications.
   - Realistic surface-based reservoir geometries (bedding and fracture network) – Rhino + FraX/REZO3D + ICEM
   - High flexibility in hydrological properties assignments
   - High resolution numerical flow calculation - CSMP++

Questions?

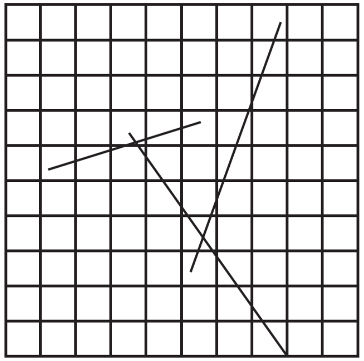
Your comments and questions are important to us!

Thank you!

Validation of the existence of the main flow channel



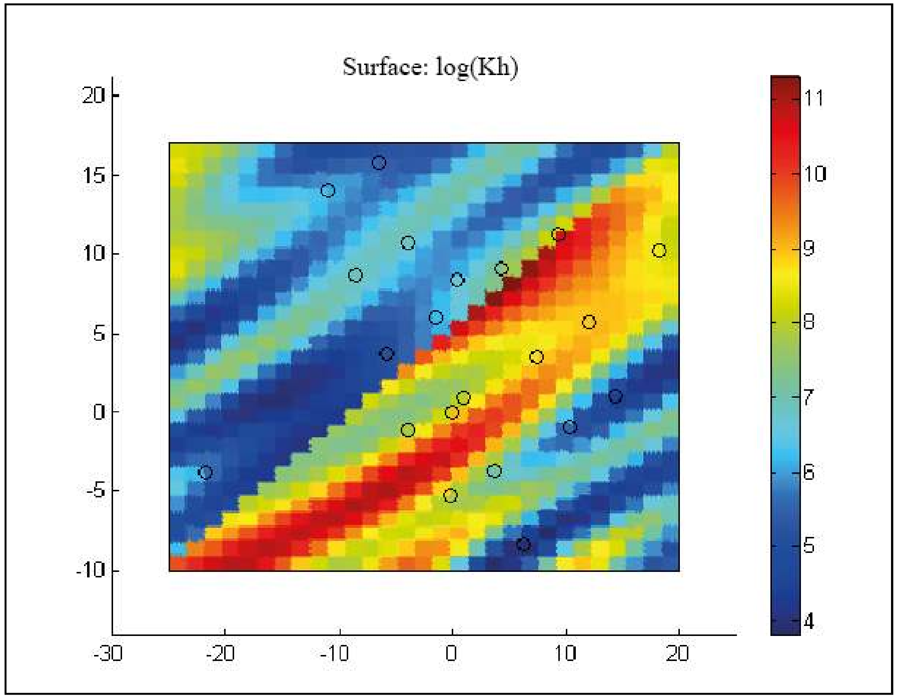
2D Terrieu DFN as initial prediction



0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	1	0	0	0
0	0	0	1	1	1	1	0	0	0
0	1	1	1	1	0	1	0	0	0
0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	1	1	0	0	0
0	0	0	0	0	0	1	1	0	0
0	0	0	0	0	0	0	1	0	0

Binary representation

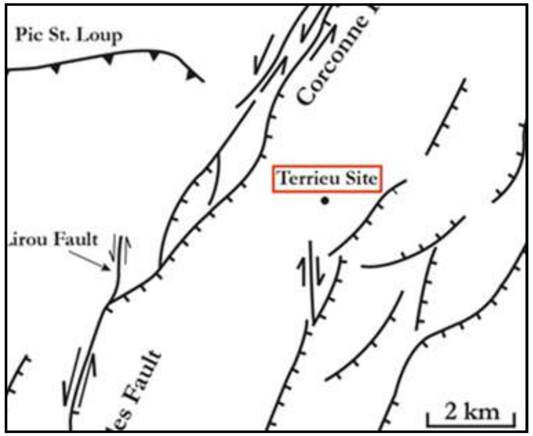
MCMC Inversion of Hydraulic Conductivity

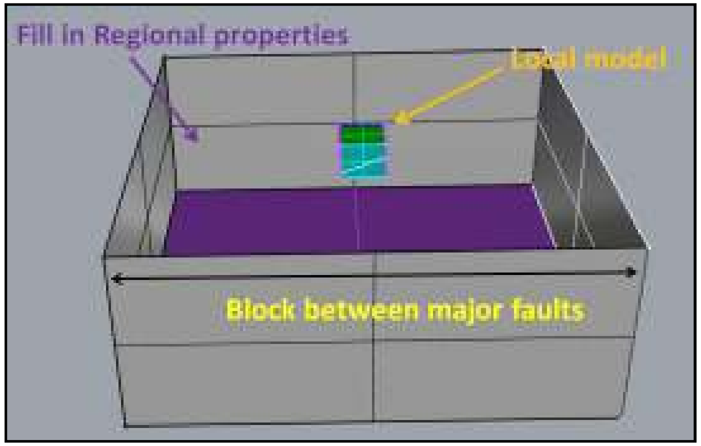


Considering steady-state pumping data of Terrieu borehole as constraints;
Adjusting conductivity values in each grid.

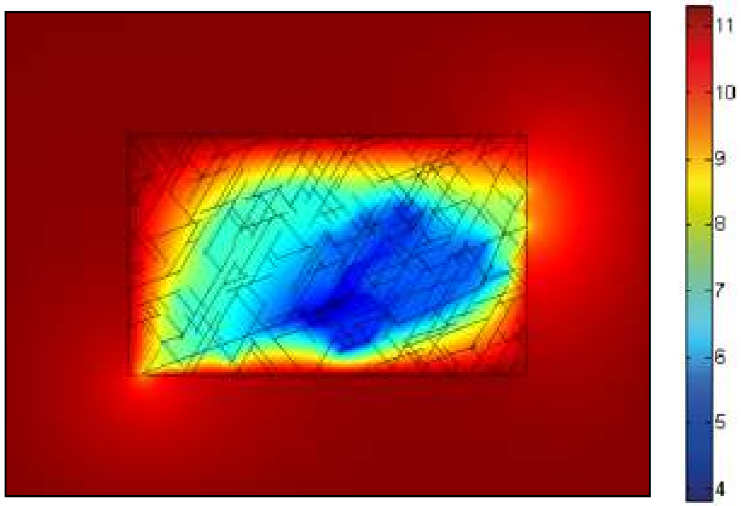
Way forward

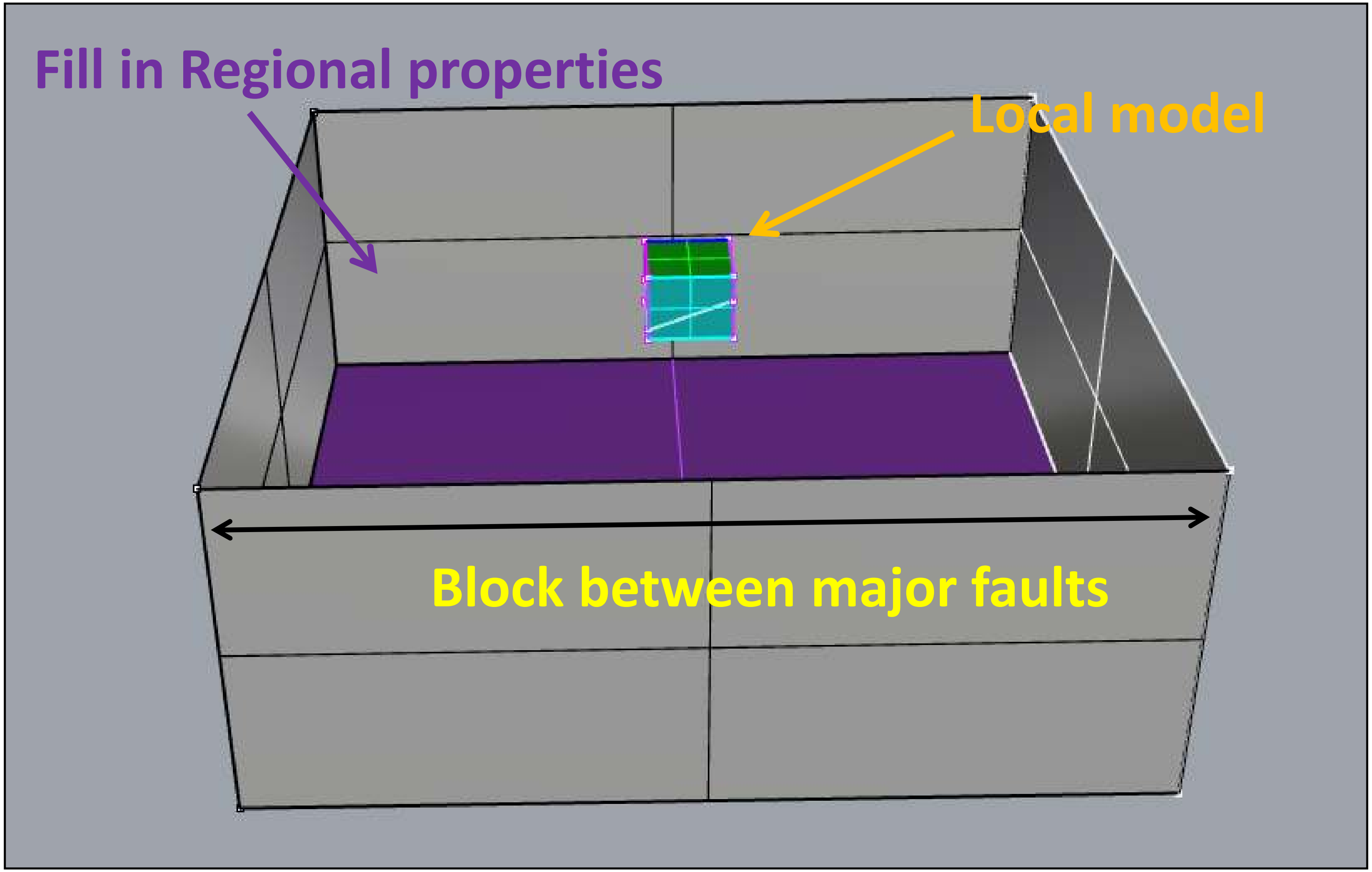
1. Reduce the impact from uncertainties associated with the **boundary conditions** by immersing the local model within the regional model

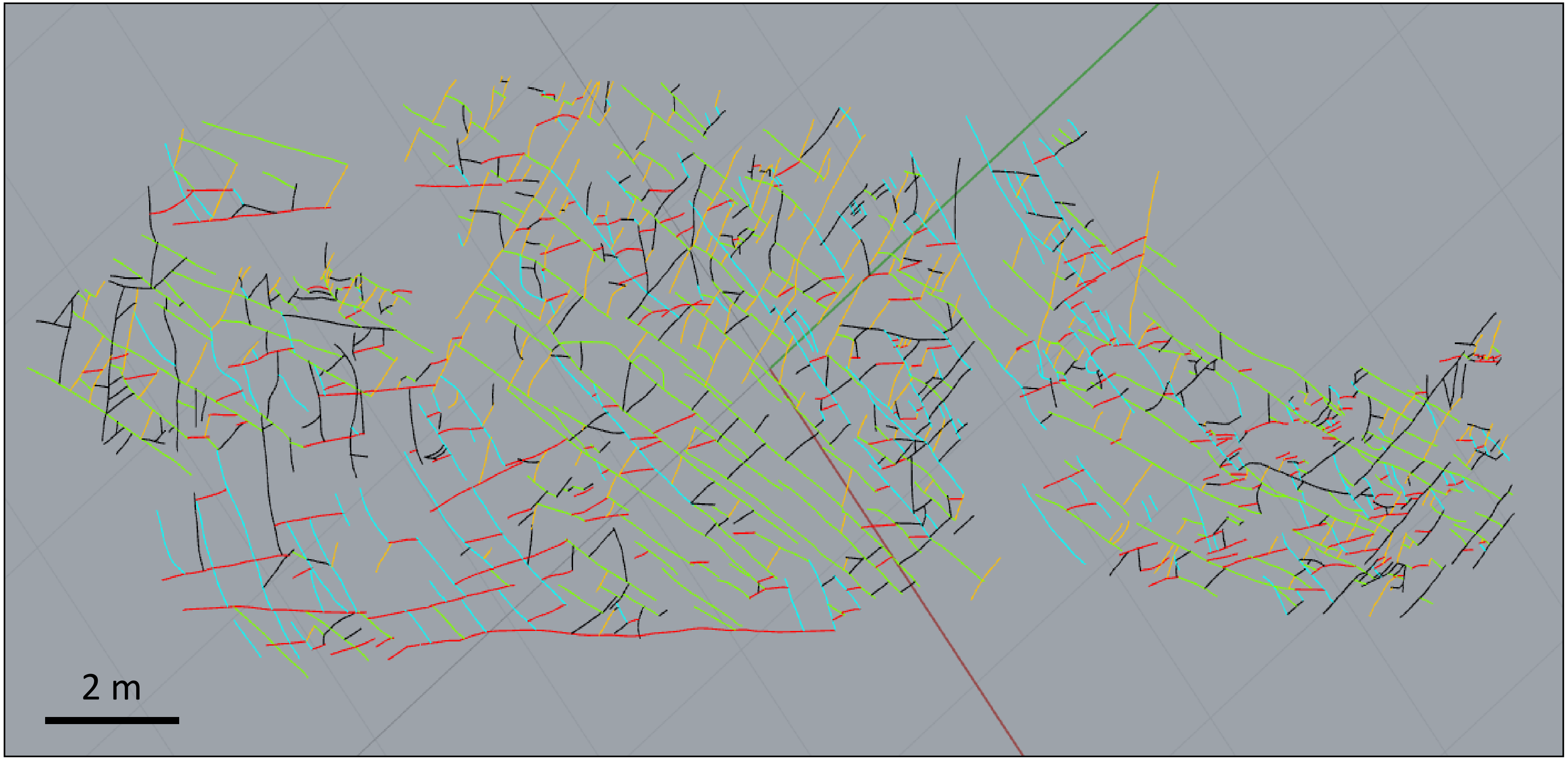


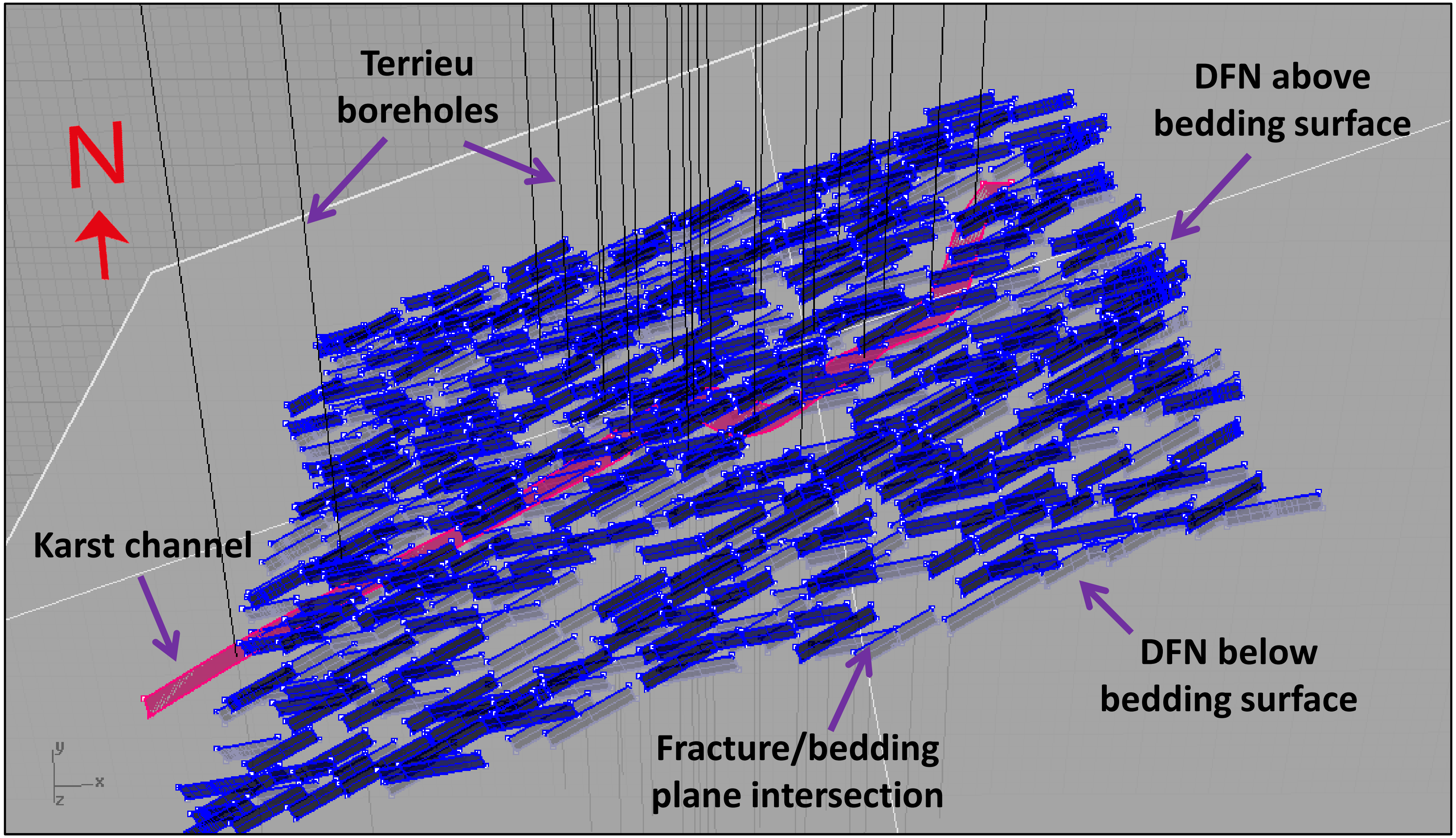


2. Reduce the impact from uncertainties associated with **hydraulic parameter assignments** by using a MCMC algorithm to inverse the their distributions (e.g. aperture) in the fracture network




Fill in Regional properties
Local model
Block between major faults


2 m


Terrieu
boreholes
N
DFN above
bedding surface
Karst channel
DFN below
bedding surface
Fracture/bedding
plane intersection