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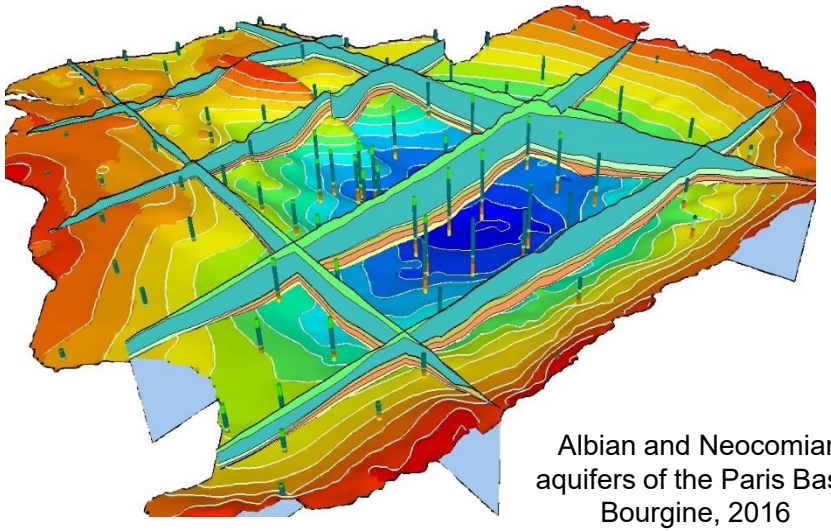
SCIENTIFIC CHALLENGES FOR A MULTISCALE, UPDATABLE NATIONAL GEOLOGICAL MODEL

Simon LOPEZ

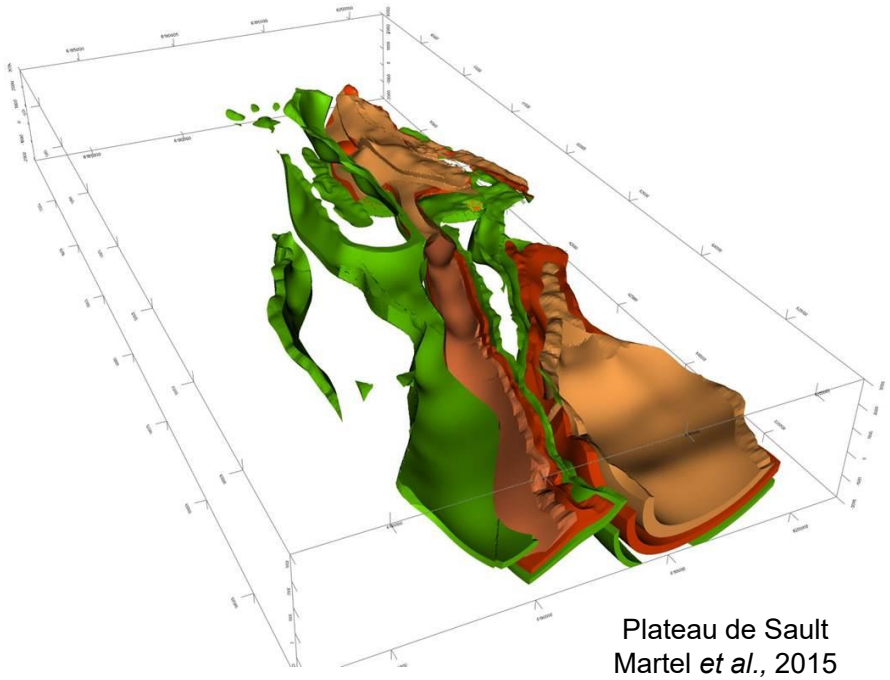


SCIENTIFIC CHALLENGES FOR A MULTISCALE, UPDATABLE NATIONAL GEOLOGICAL MODEL

Simon LOPEZ, …



Albian and Neocomian aquifers of the Paris Basin
Bourgine, 2016



Plateau de Sault
Martel *et al.*, 2015

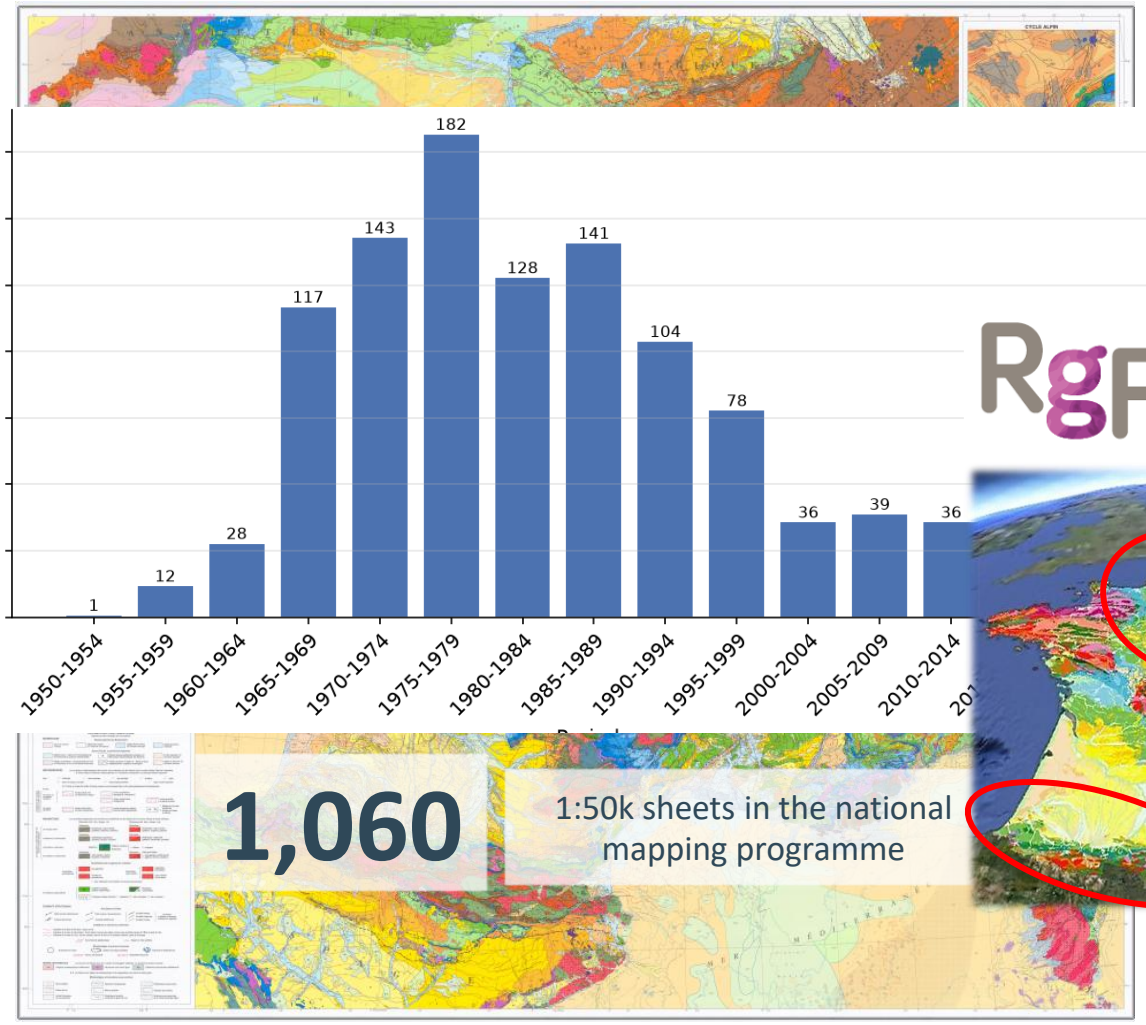
3D GEOLOGICAL MODELING AT BRGM

- >50 years of experience
- continuous production of multi-purpose 3D geological models
  - geological knowledge
  - applications towards predictive geosciences
- commercial tools (e.g. Gocad, Petrel, Isatis, Surpac…)
- « home-made » innovative (but legacy) solutions:
  GDM Suite and *GeoModeller*
- common DNA / characteristics:
  - operational purposes: tools implement both algorithms and practical know-how
    - field mapping
    - *downstream* (quantitative) applications
  - geostatistics
  - implicit modeling :
    the model can be regenerated if the data changed

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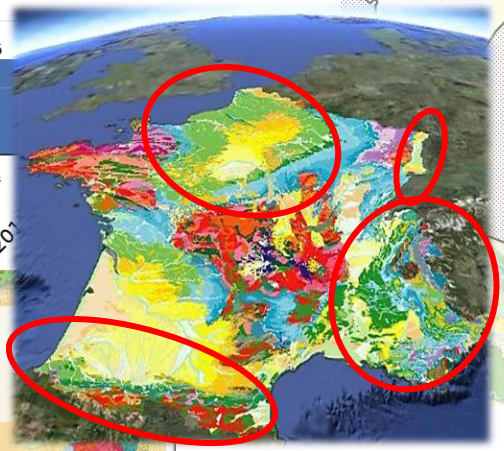
A vast legacy corpus

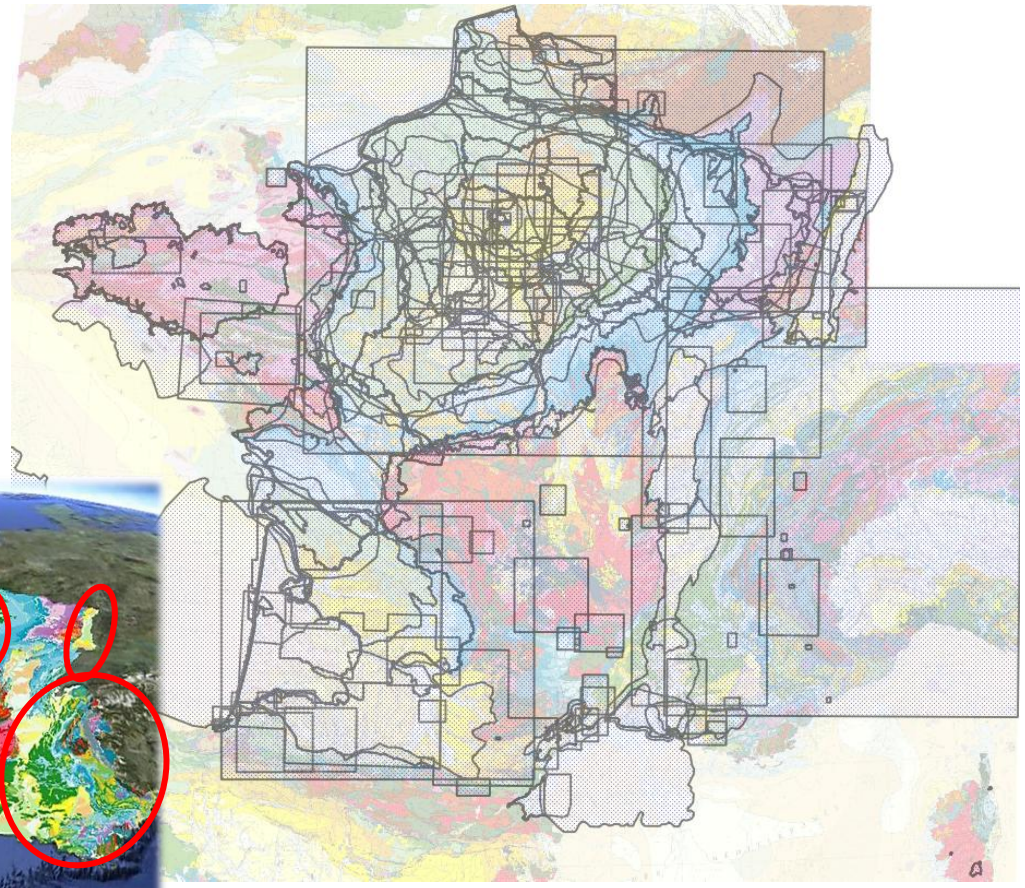
1:1M map 6th edition (2003)



1,060 1:50k sheets in the national mapping programme

RgF RÉFÉRENTIEL GÉOLOGIQUE DE LA FRANCE





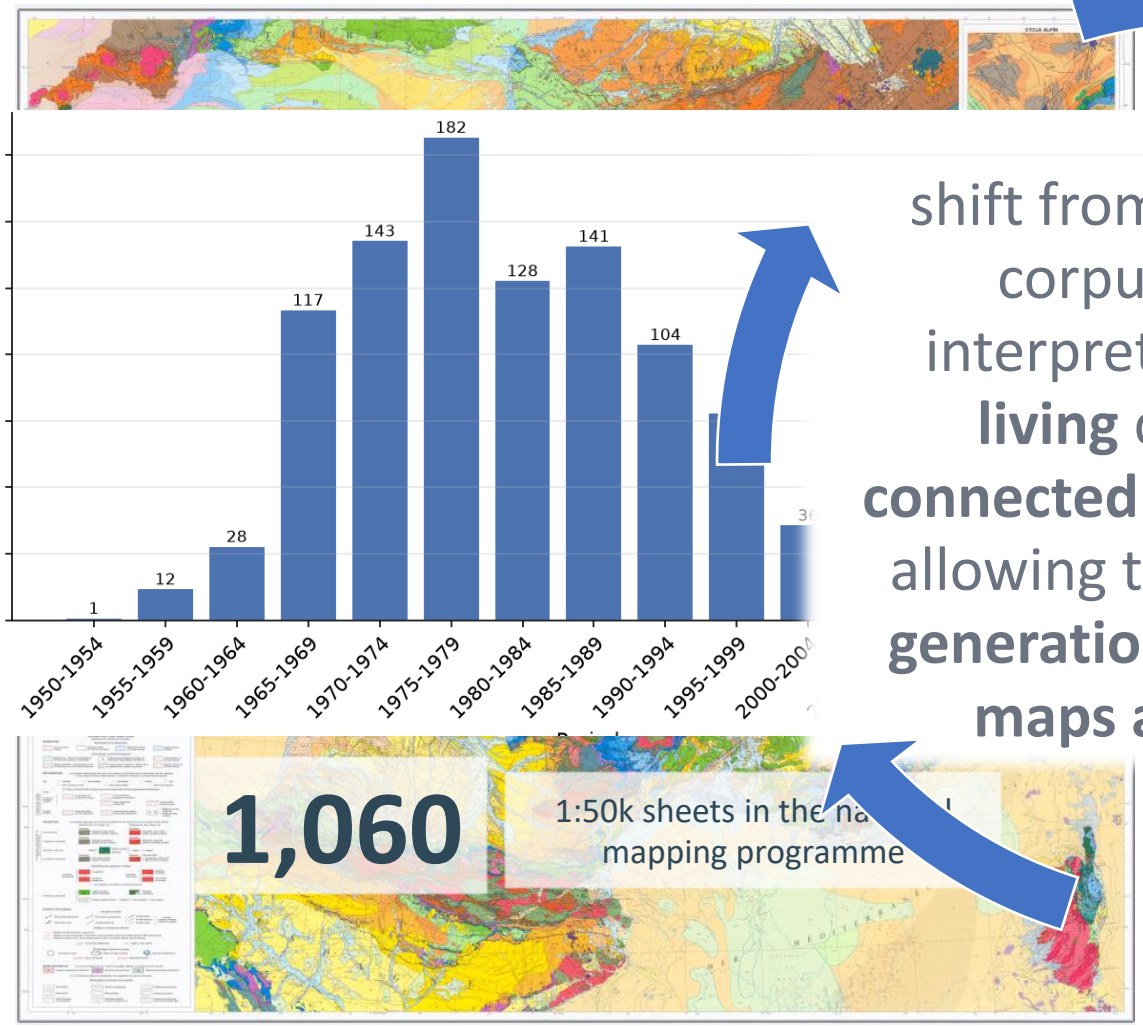
>200 legacy 3D geomodels, inventoried within PEPR Sous-sol

>1M boreholes

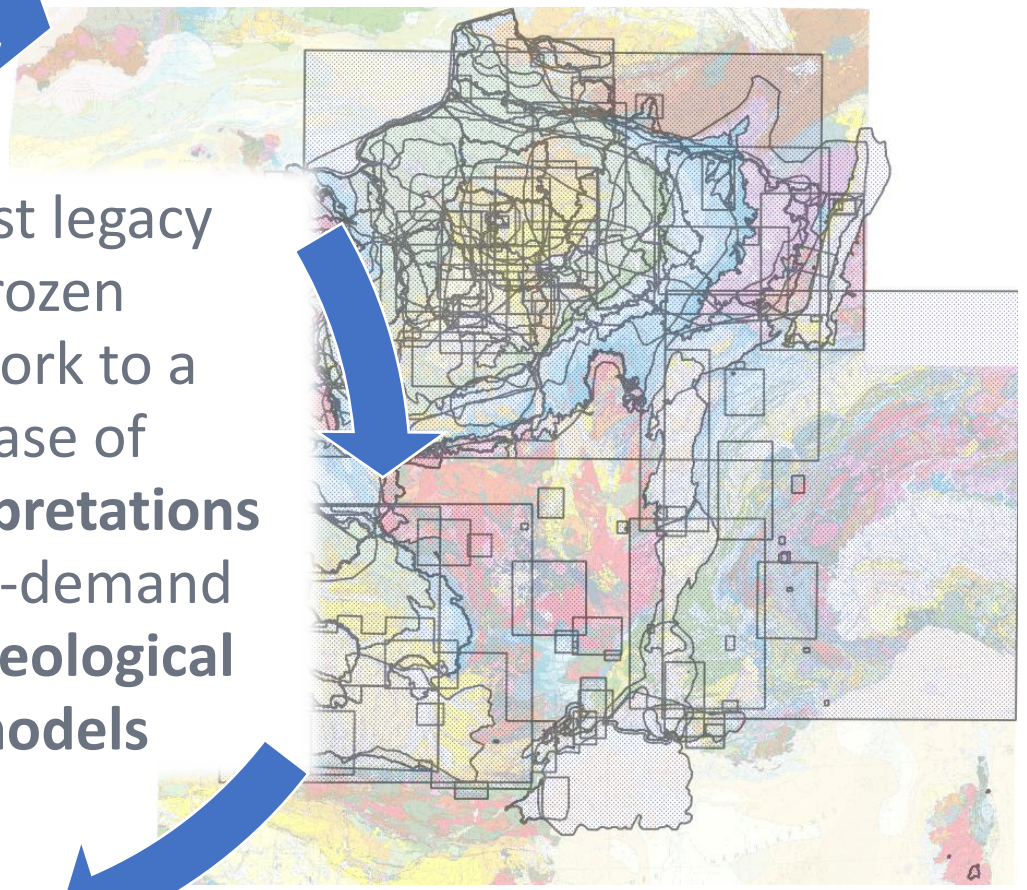
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A vast legacy corpus

1:1M map 6th edition (2003)



shift from a vast legacy corpus of frozen interpretive work to a **living** database of **connected interpretations** allowing the on-demand **generation of geological maps and models**

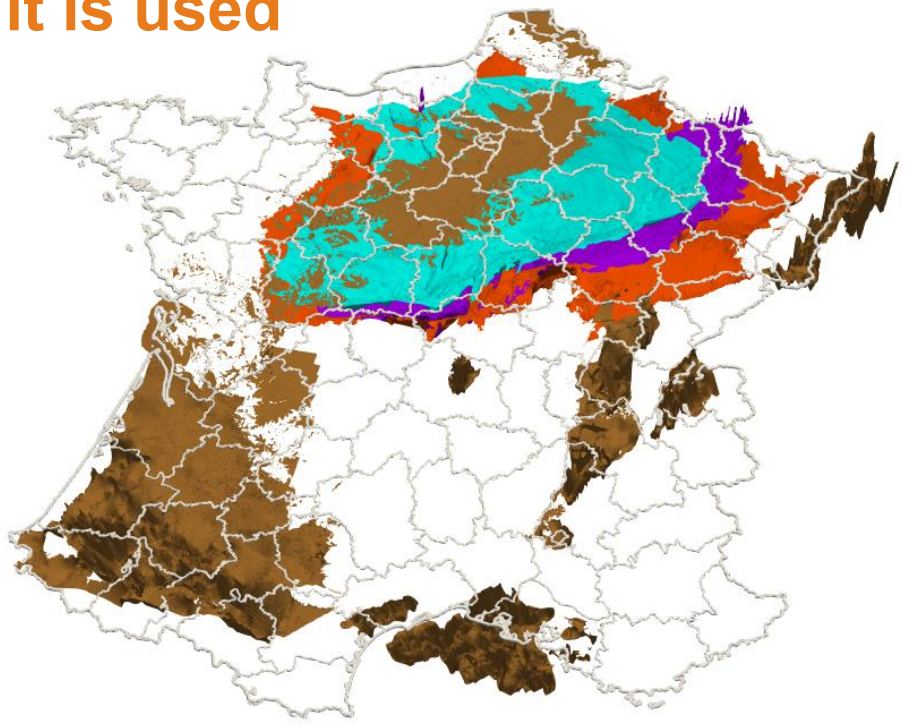


>200 legacy 3D geomodels, inventoried within PEPR Sous-sol

>1M boreholes

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A national geological model is a public asset — if it is used



What the “users” need :

- infrastructure and tunnelling: metre-scale detail, locally
- geothermal, CCS, hydrogen storage: basin-scale, regional
- groundwater, raw materials, hazards: everything between
- planning and policy: a coherent national picture
- …

The akward (but well known) part:

No single scale serves these needs.

(and the subsurface knowledge keeps changing — every borehole, every tunnel, every campaign).

A useful national model is therefore **multiscale and updatable**, or it is a snapshot.

Can we generate a model on demand at a given scale,
which could then be reused and improved for a specific study…
… and ideally the improvements made in this study would be tracked and banked.

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Bank the description, compute the product

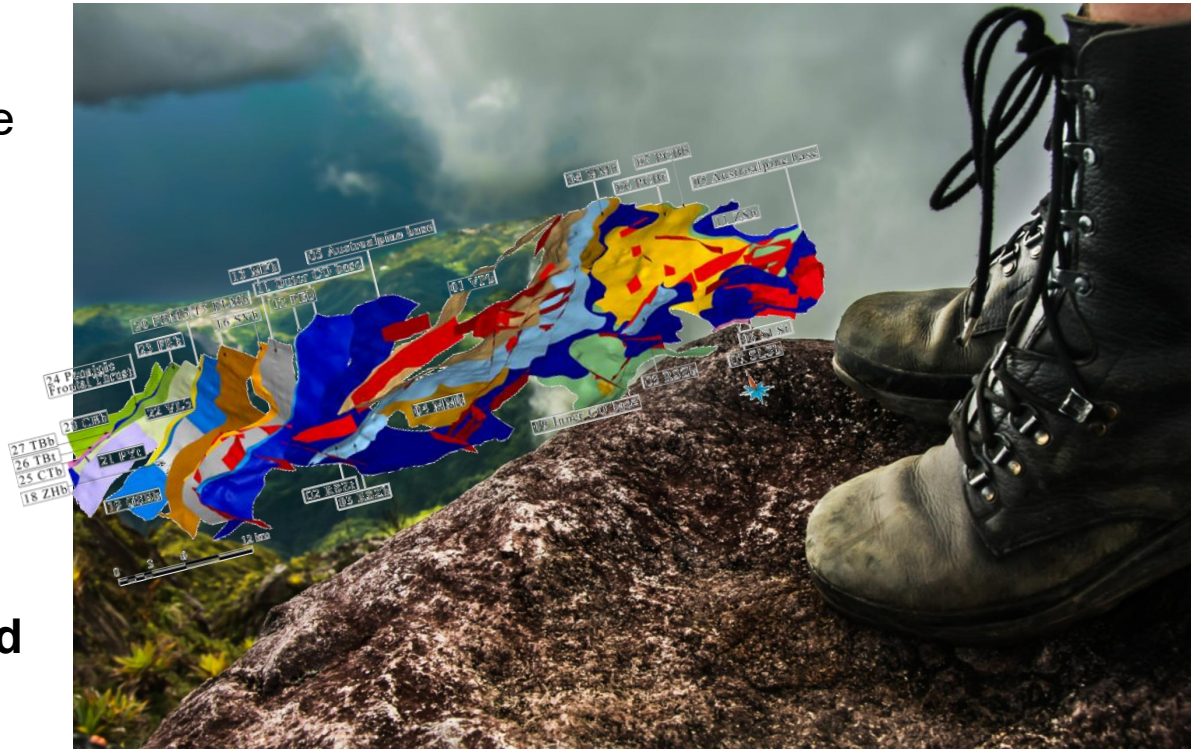
Maps, sections and models are views.
Current workflow is often:
build the product, archive the product.

A map or an explicit model encodes one interpretation at one scale. Changing the scale, or the interpretation, means redrawing by hand, so in practice neither gets done.

Store the observations, the geological rules and the interpretive decisions as data, with provenance.
Regenerate any representation, at the scale each use requires and whenever the knowledge changes.

Geostatistical models (e.g. GeoTOP), **implicit models and AI-based models are generative.**

Because uncertainty is everywhere in the subsurface, whatever generates the models, **we must be able to trace interpretive choices.** That traceability is what allows us to explain and discuss a model (cf. validation).



model by Arienti *et al.*, 2024


a few challenges…
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#01

OBSERVATIONS

RECOVERING THE EVIDENCE THAT LEGACY MAPS ABSORBED

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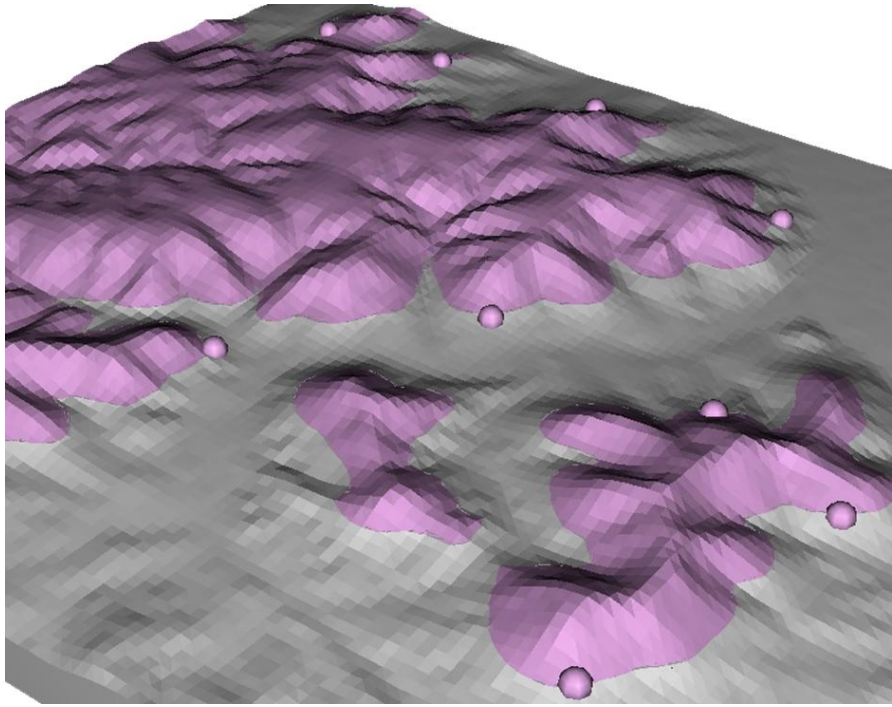
CHALLENGE 1 · OBSERVATIONS

Recovering the evidence that legacy maps absorbed

A map is interpretive linework; (in France) the measurements behind it were mostly discarded.



In France: around 4 million map polylines inherited from 70 years of mapping
The field observations that justified them were rarely archived:
the line survived but the evidence did not.



Courrioux et al., 2015

The approach

- Use all existing observations!
- Infer virtual field observations from the linework — contact points, orientations where a tangent plane can be fitted (in the spirit of map2loop)
- Keep them parsimonious: the minimum that regenerates the map, not a dense sampling.
- Flag every virtual observation as inferred.
- Place them where a geologist could actually go and check.

The long-term goal

Replace every virtual observation with a real one…
…**sending geologists back into the field** 🧐 **(or to study boreholes).**

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#02

RULES AND INTERPRETATIONS

BANKING GEOLOGICAL REASONING AS SOMETHING A COMPUTER CAN EXECUTE

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Banking geological reasoning as something a computer can execute

Combine two graphs: how to build a model and what is true.

A constructive graph — how to build a model

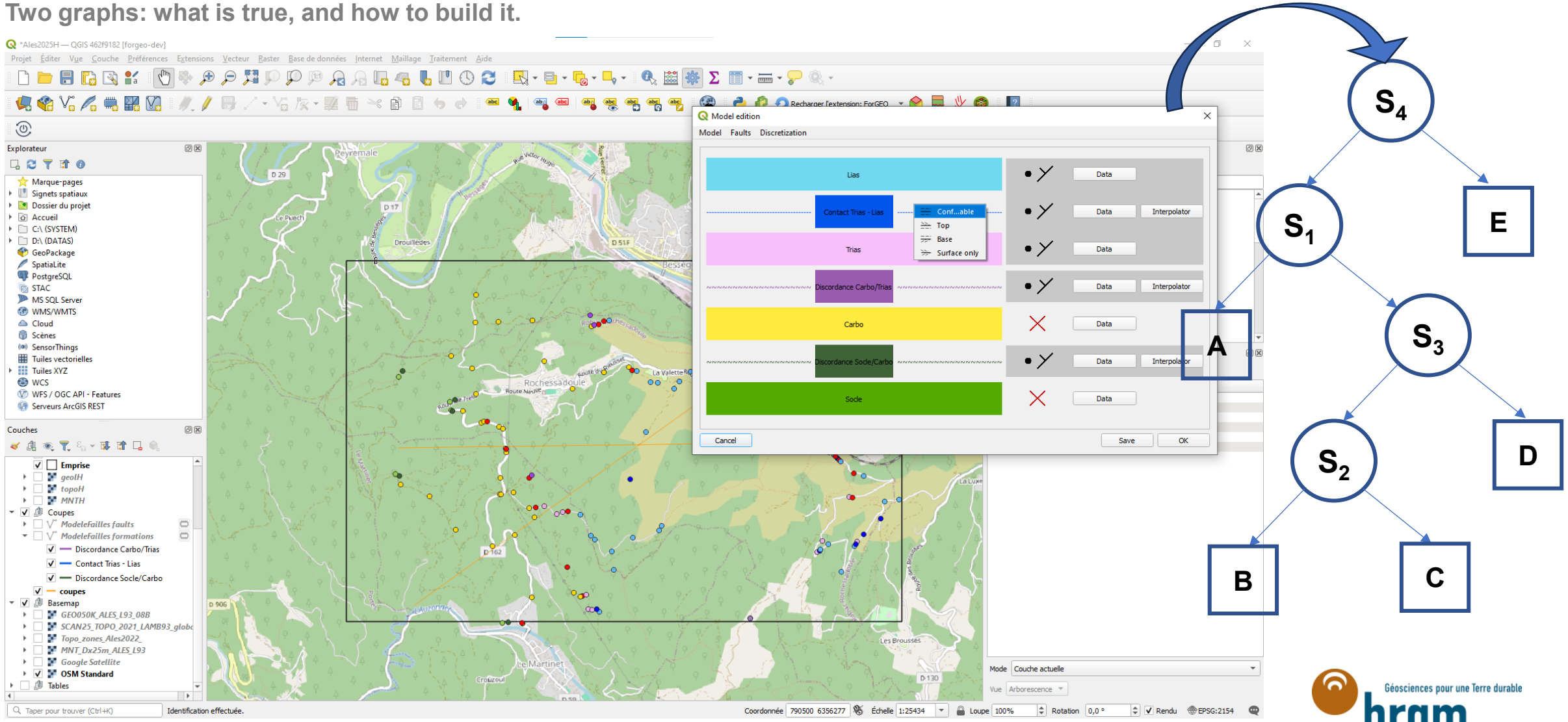
An ordered description of operations on primitives — this surface, cut by that fault, bounded by this unconformity. Geometry is computed from it, **so topological consistency holds by construction**, at any scale, every time.

Inherited from implicit modelling;
most current geomodelling can be recast this way

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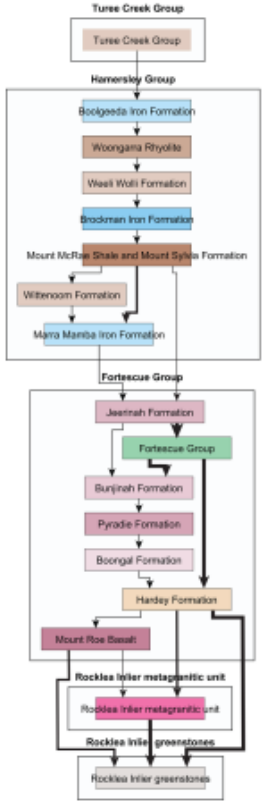
Banking geological reasoning as something a computer can execute

Two graphs: what is true, and how to build it.

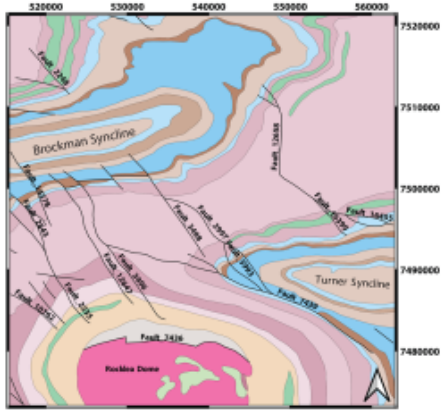


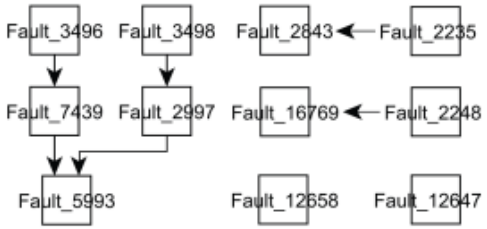
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(a) stratigraphy graph



(b) faults and fault-fault relationships

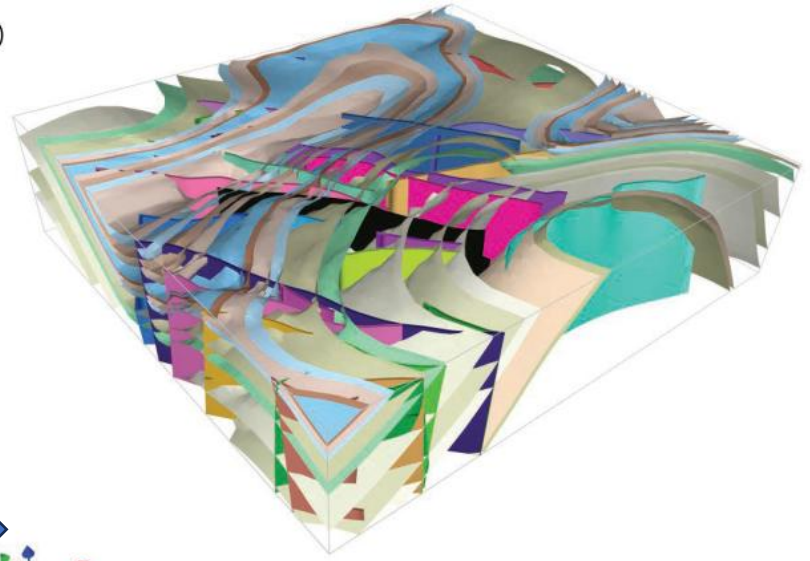




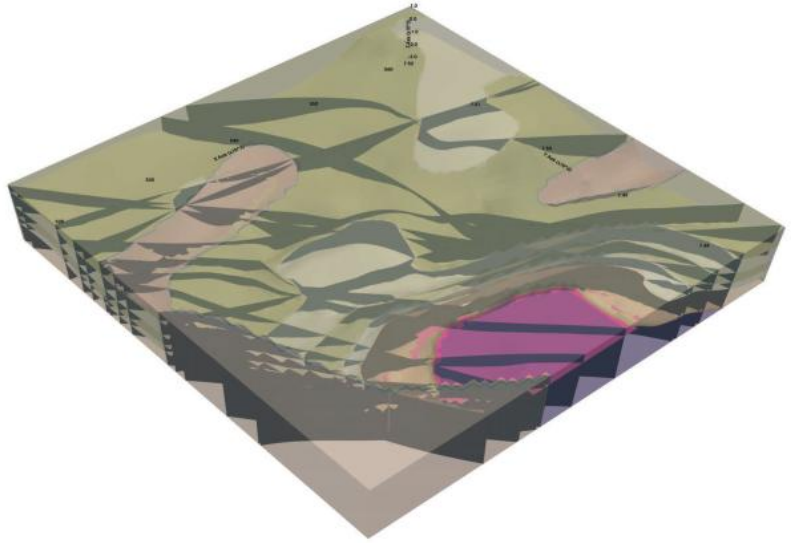
(c) fault-unit relationships

unit\fault	Fault_7436	Fault_7439	Fault_2235
Boolgeeda_Iron_Formation	0	0	0
Boongal_Formation	0	0	1
Brockman_Iron_Formation	0	1	0
Bunjinah_Formation	0	1	1
Fortescue_Group	0	0	1
Hardey_Formation	1	0	1
Jeerinah_Formation	0	1	1
Marra_Mamba_Iron_Formation	0	1	1
Mount_McRae_Shale_and_Mount_Sylvia_Formation	0	1	0
Pyradie_Formation	0	0	1
Rocklea_Inlier_greenstones	1	0	0
Rocklea_Inlier_metagranitic_unit	1	0	0
Turee_Creek_Group	0	0	0
Weeli_Wolli_Formation	0	0	0
Wittenoom_Formation	0	1	0
Woongarra_Rhyolite	0	0	0

(a)

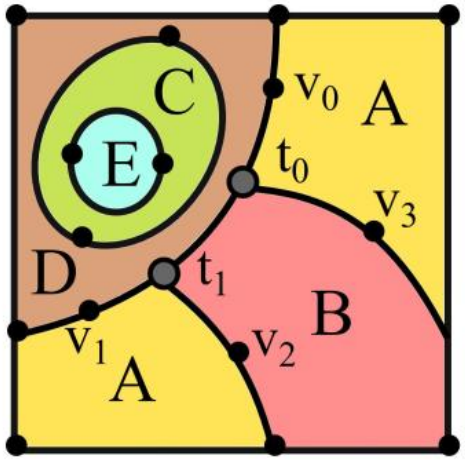


(b)

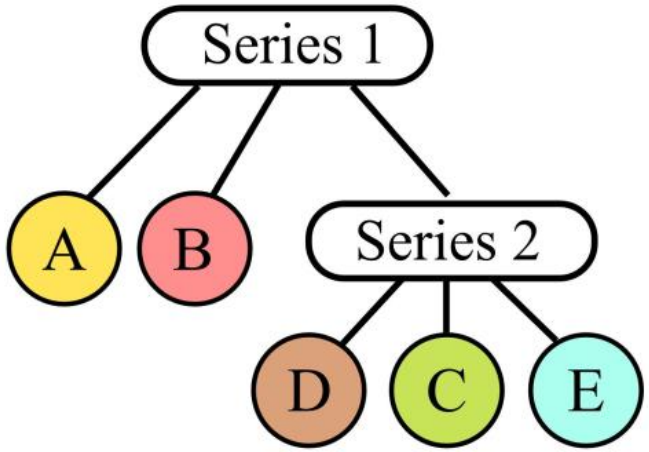


map2loop
Jessel *et al.*,
2021

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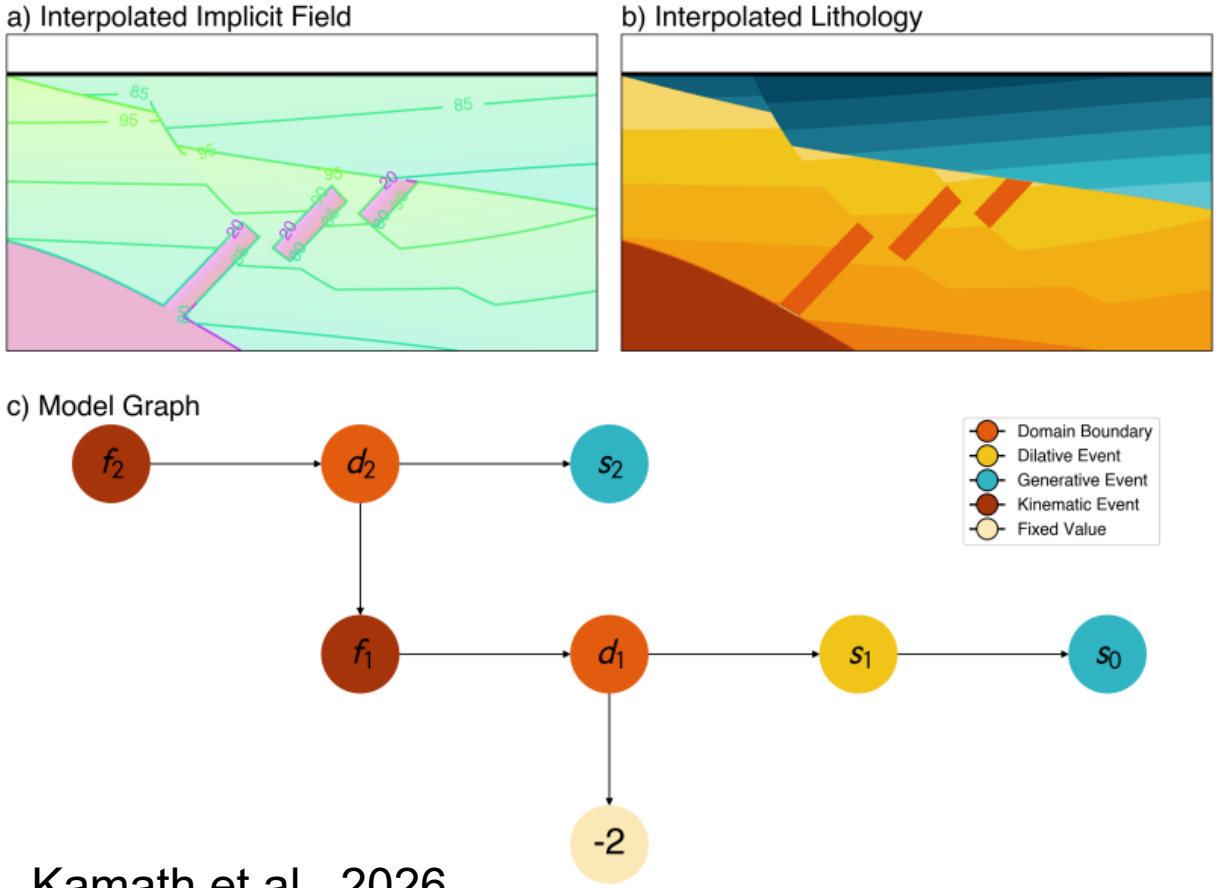


Contacts-Graph



Series Tree

Amorim et al., 2023
sketch-based geological modeling



Kamath et al., 2026
semi-supervised learing using neural fields

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Banking geological reasoning as something a computer can execute

Combine two graphs: how to build a model and what is true.

A constructive graph — how to build a model

An ordered description of operations on primitives — this surface, cut by that fault, bounded by this unconformity. Geometry is computed from it, **so topological consistency holds by construction**, at any scale, every time.

Inherited from implicit modelling;
most current geomodelling can be recast this way

A knowledge graph — what is true

A domain ontology encodes the vocabulary and the rules — stratigraphic order, cross-cutting relations, how formations group into coarser units. It allows inference (reasoning): a stated relation implies others, and contradictions are detectable.

e.g. POKIMON ontology, Laouici et al., 2025
(tested on both maps and 3D models)

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CHALLENGE 2 · RULES AND INTERPRETATIONS

Banking geological reasoning as something a computer can execute

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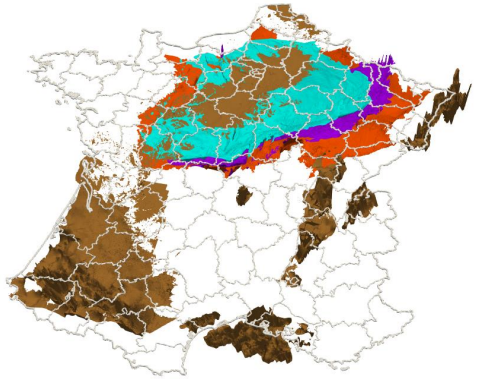
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e.g. POKIMON ontology, Laouici et al., 2025
(tested on both maps and 3D models)

The hard part

Deriving a constructive graph from descriptive data is ill-posed: several graphs are always admissible.
The residual ambiguity grows with the area covered.
This represents a bottleneck at a national scale, one that probably cannot be resolved by algorithms alone.



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SCALE

CHANGING SCALE IS A GEOLOGICAL OPERATION,
NOT (ONLY) A GEOMETRIC ONE

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CHALLENGE 3 · SCALE

Changing scale is a geological operation, not (only) a geometric one

Cartographic generalisation has formal levels of detail; 3D geomodelling does not yet.

The skeleton — faults

Simplify fault networks by hierarchy and cumulative displacement, so what survives at a coarser scale is what matters mechanically.

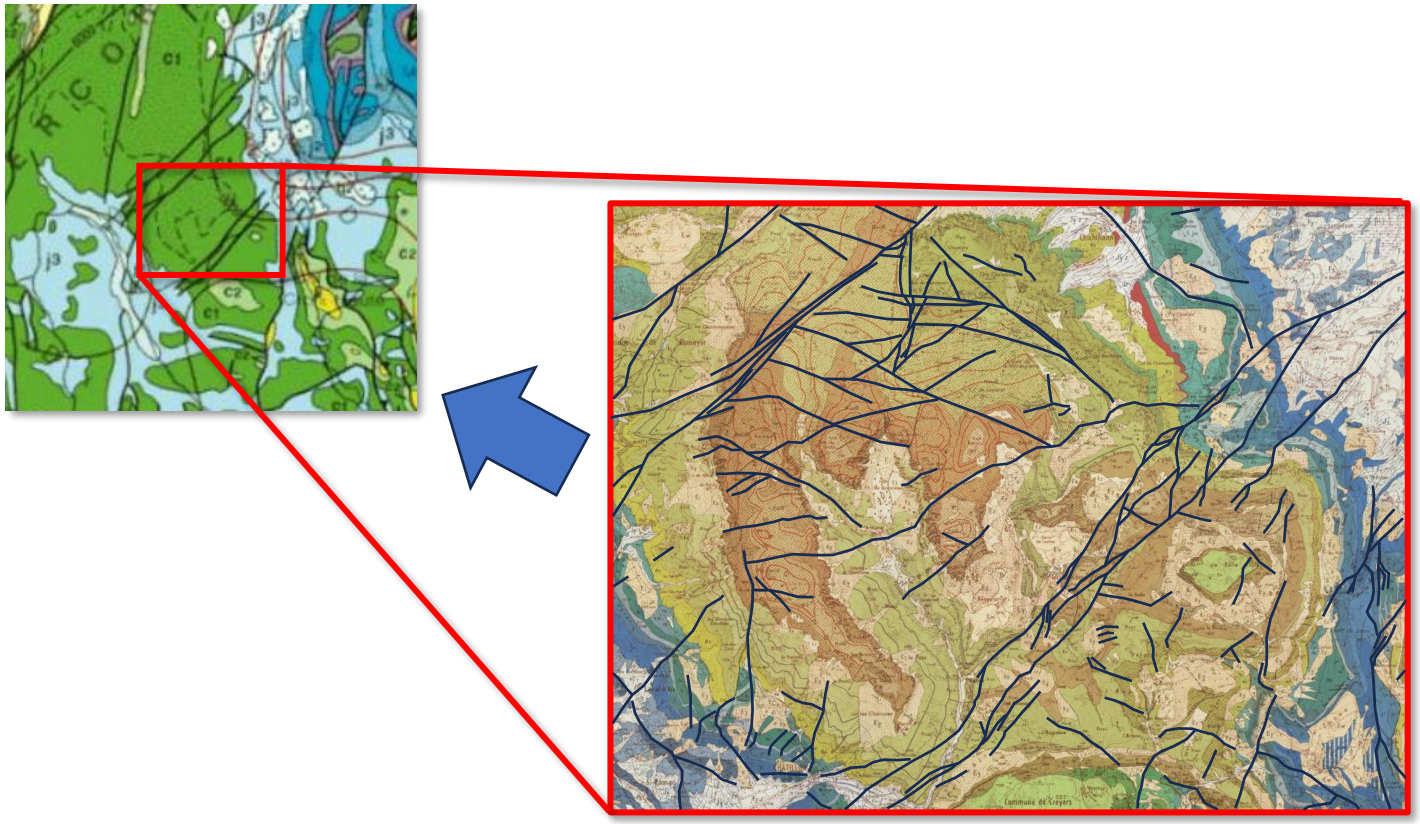


figure by G. Caumon

CHALLENGE 3 · SCALE

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The flesh — strata

Upscale horizons with multi-resolution or discontinuous interpolation bases, or with Stochastic PDE formulations that make resolution an explicit parameter.

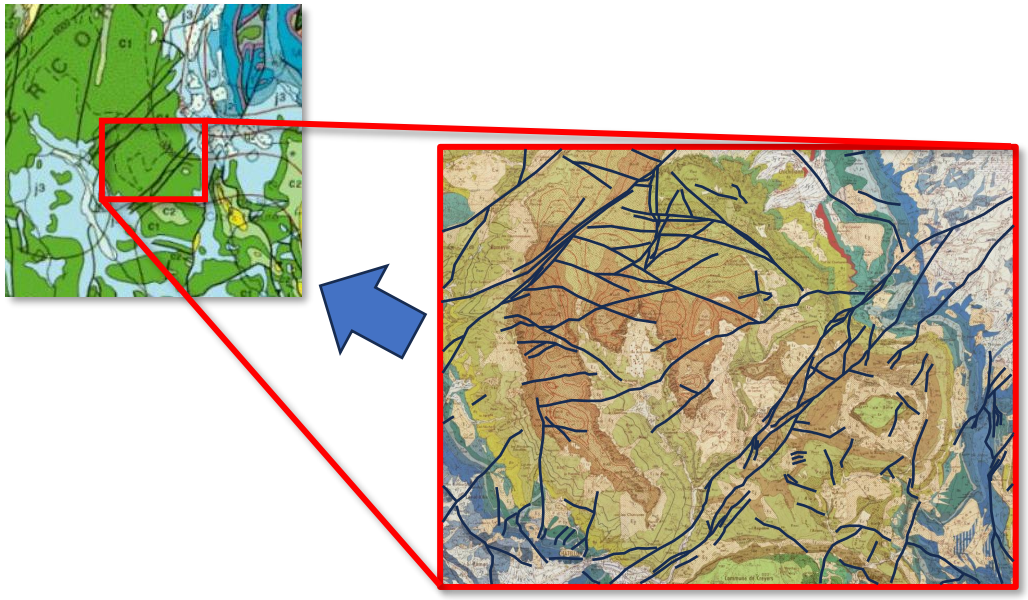


figure by G. Caumon

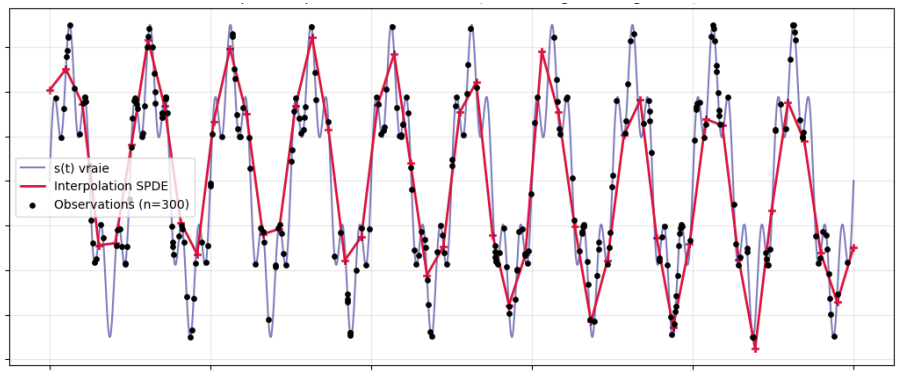


figure by C. Garayt

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The flesh — strata

Upscale horizons with multi-resolution or discontinuous interpolation bases, or with Stochastic PDE formulations that make resolution an explicit parameter.

Embed this into the graph — branching

Encode in the constructive graph how a sub-graph simplifies between scales, so one banked description serves 1:50k, 1:250k and 1:1M without three models.

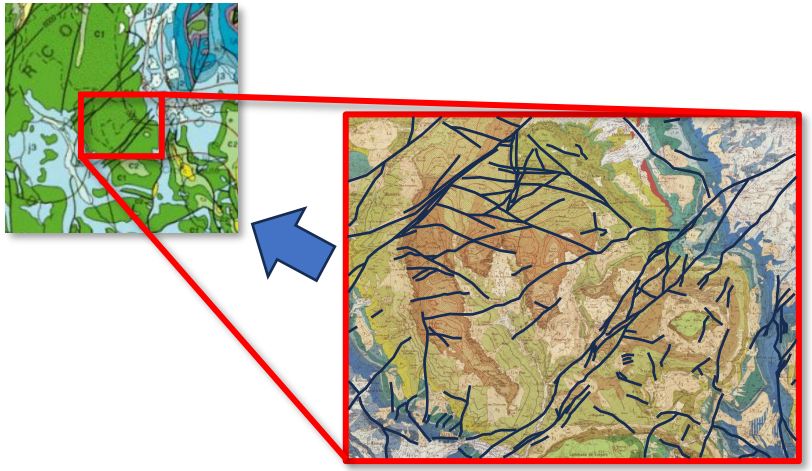


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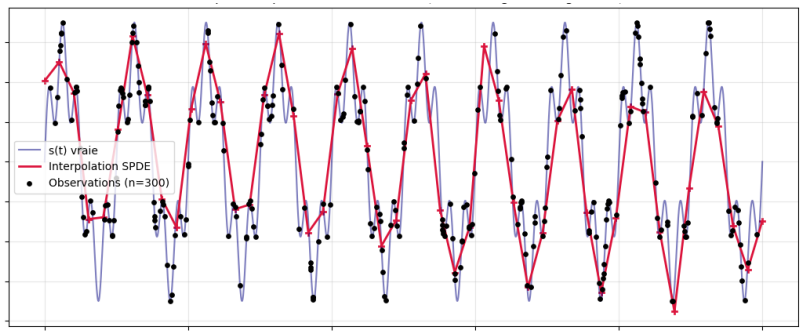
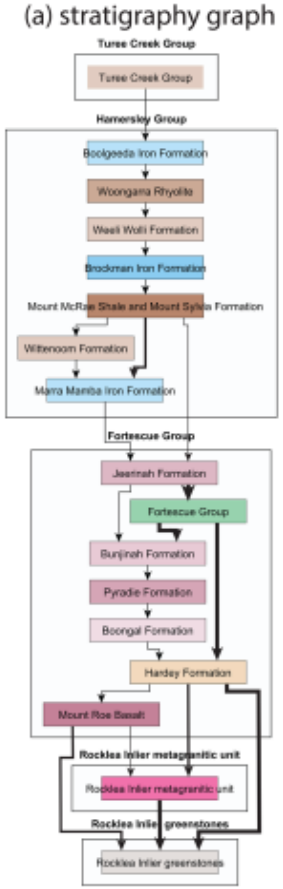


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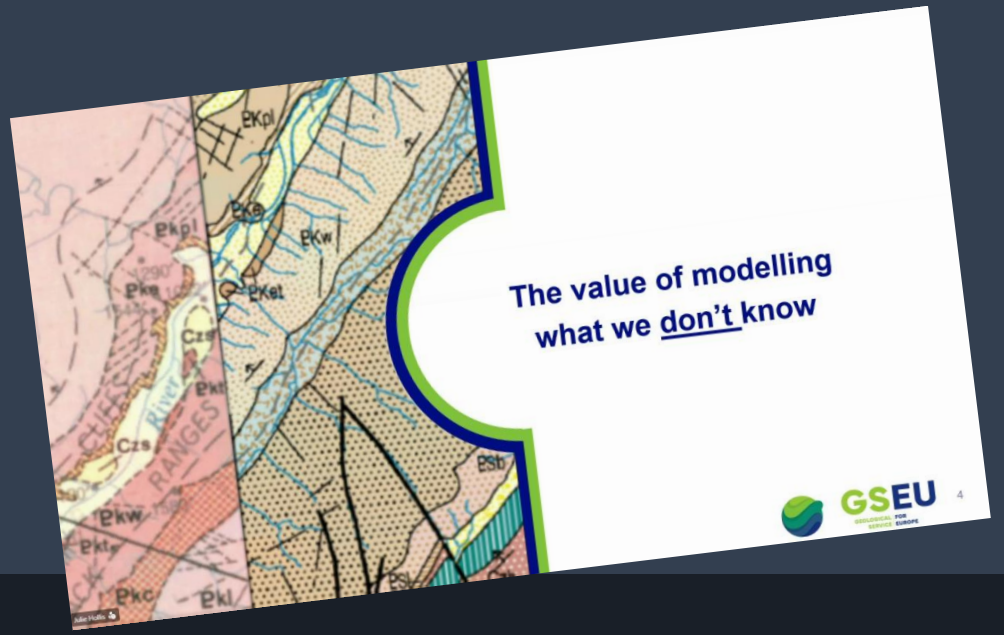


map2loop
Jessel *et al.*, 2021

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#04



A NATIONAL SCALE GRAPH

NOBODY CAN WRITE IT BY HAND

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CHALLENGE 4 · AMBIGUITY AND THE EXPERT

Nobody can write the graph by hand for complex national scale systems and no algorithm should

Let the machine find the ambiguities/alternatives; let the geologist resolve them.

Elicitation, not automation

- **Computer Supported Collaborative Work** : an AI agent proposes justified hypotheses, in text, image or sketch; a geologist accepts, rejects or amends
- Ambiguities are rendered as paired 2D and 3D views the geologist arbitrates on visual evidence, never on graph operations
- **Each decision is recorded with its justification and uncertainty** — alternatives stay in the graph, bounded to where they apply,
- **Natural interaction**: prompting, comparing pictures, sketching (not a form to fill).



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#05

VALIDATION
THERE IS NO GROUND TRUTH FOR INTERPRETATIONS

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CHALLENGE 5 · VALIDATION

There is no ground truth for interpretations

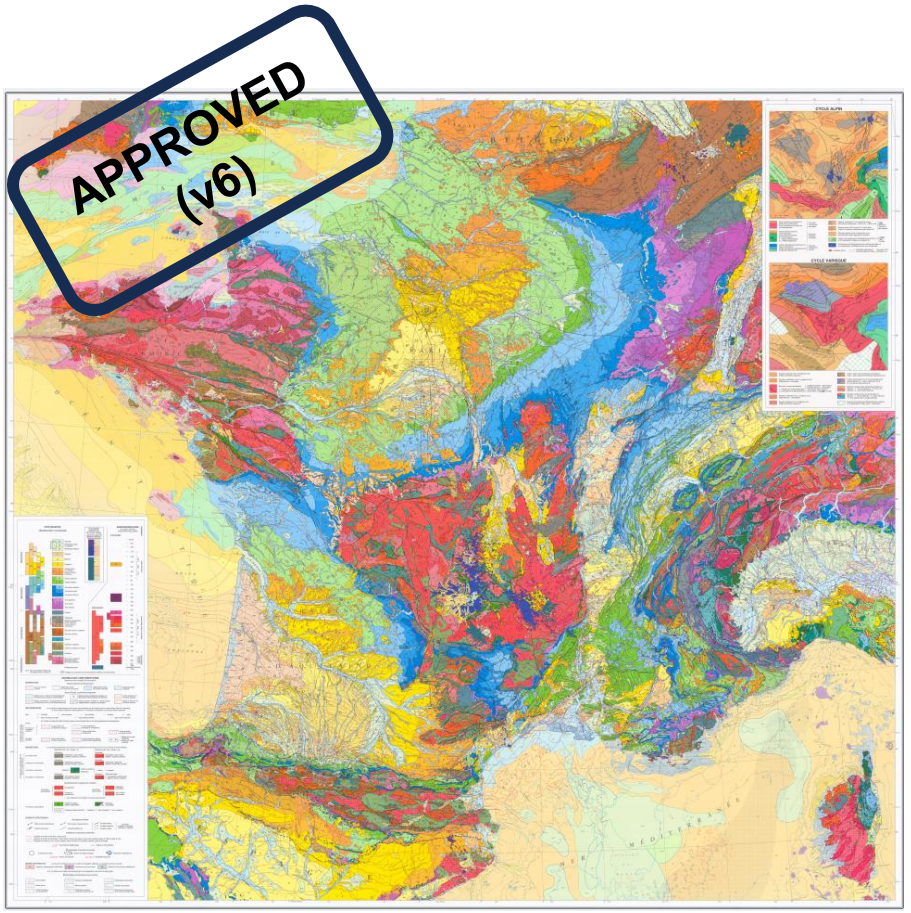
Verification can be automated; validation is a matter of expert judgement.

Verification — automatable

Topology holds by construction.
Semantics are checked against the ontology.
Consistency can be checked (e.g. Parquer *et al.* 2025).

Validation — judgement and consensus

Experts given the same data interpret it differently
(Bond et al. 2007…).
A map or model is right only in the sense that a community of experts accepts it.
Structured elicitation and expert panels are the method…
… **which is why the links between data, interpretation and model must stay explicit**.



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#06

TRACTABILITY

UPDATABLE MEANS RECOMPUTING (AT NATIONAL SCALE)

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CHALLENGE 6 · TRACTABILITY

"Updatable" means recomputing — at national scale

If geometry is computed rather than stored, performance decides whether on-demand generation is feasible

Raw compute

National coverage, several nominal scales, regeneration frequent enough to follow new observations…
New methods (learning based or SPDE formulations) help because they scale to very large datasets while keeping field-scale observations.

Graph tractability

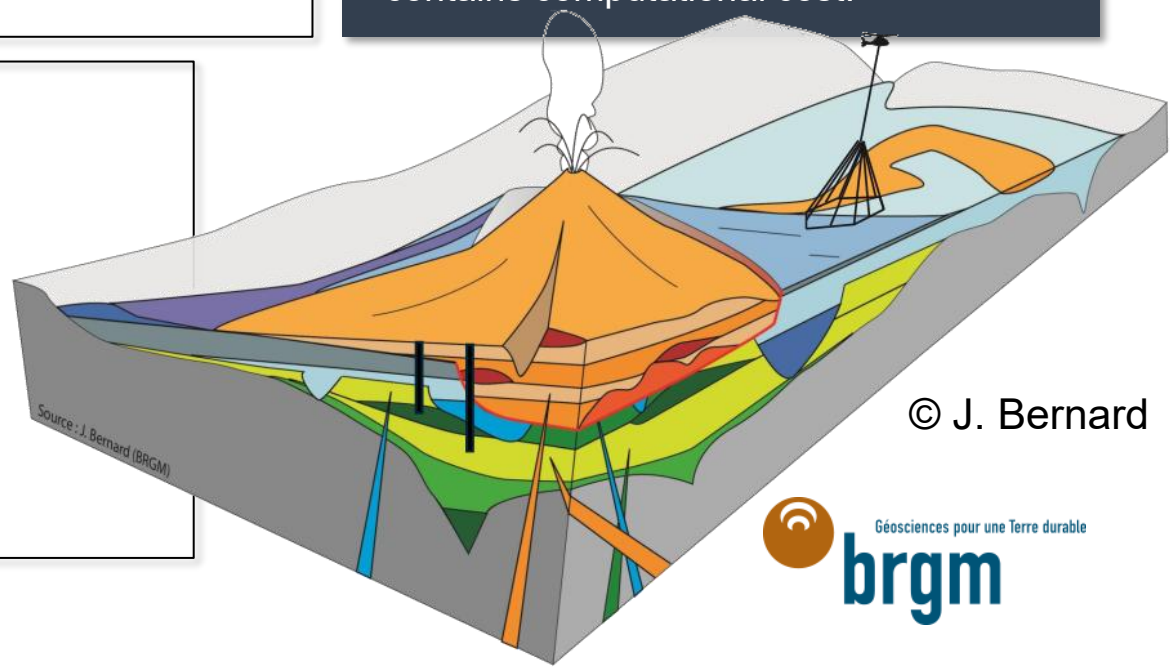
A hierarchical graph that stays queryable and reasonable-over at every scale.
Ontological reasoning is prone to combinatorial explosion; **the containment is reasoning over bounded sub-graphs**, never the whole country at once.

Locality as a design answer

The graph decomposes into spatially bounded validity domains (geological domains).
Recomputation of one sub-graph, not the national model: the compartmentalisation that contains interpretive ambiguity also contains computational cost.

Geology may remain (highly) uncertain

3D modelling may remain a challenge in its own right.
In some contexts, **the available observations cannot constrain a unique geometry.** We must accept interpretations in the form geologists actually produce them, as sketches and conceptual schemes, and treat them as data in their own right.
Above all, it needs **communication suited to each audience**, so that users understand how uncertain these models are and **do not read a well-rendered geometry as established fact.**



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#07



BEYOND GEOMETRY

BRINGING IN GEOPHYSICS (WITHOUT BLURRING OBSERVATION, PROPERTY AND INTERPRETATION)

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Bringing in geophysics without blurring observation, property and interpretation

Geophysics constrains geometry through a property layer and should never overwrite interpretation.

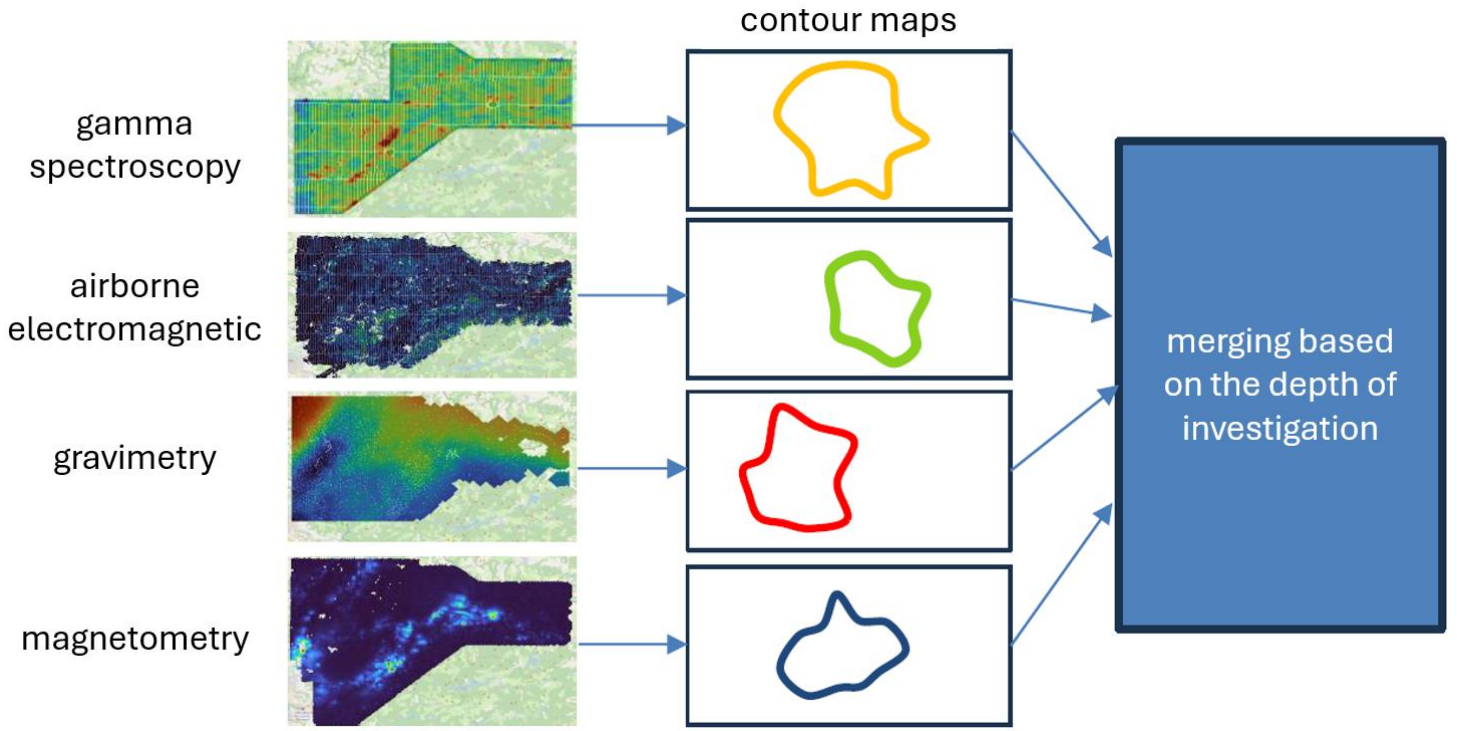
Interpretation
The constructive graph: objects, chronology, topology — what a geologist decided

Physical properties
Density, velocity, resistivity — each at its own support, resolution and uncertainty

Observations
Outcrops, boreholes, virtual observations — and gravity, magnetics, seismic, EM…

One interesting aspect of geophysics

Geophysical methods constrain the model *at a known scale,* carrying their own level of detail. (Potential-field data average over a volume, wavelength maps onto source depth and extent…)



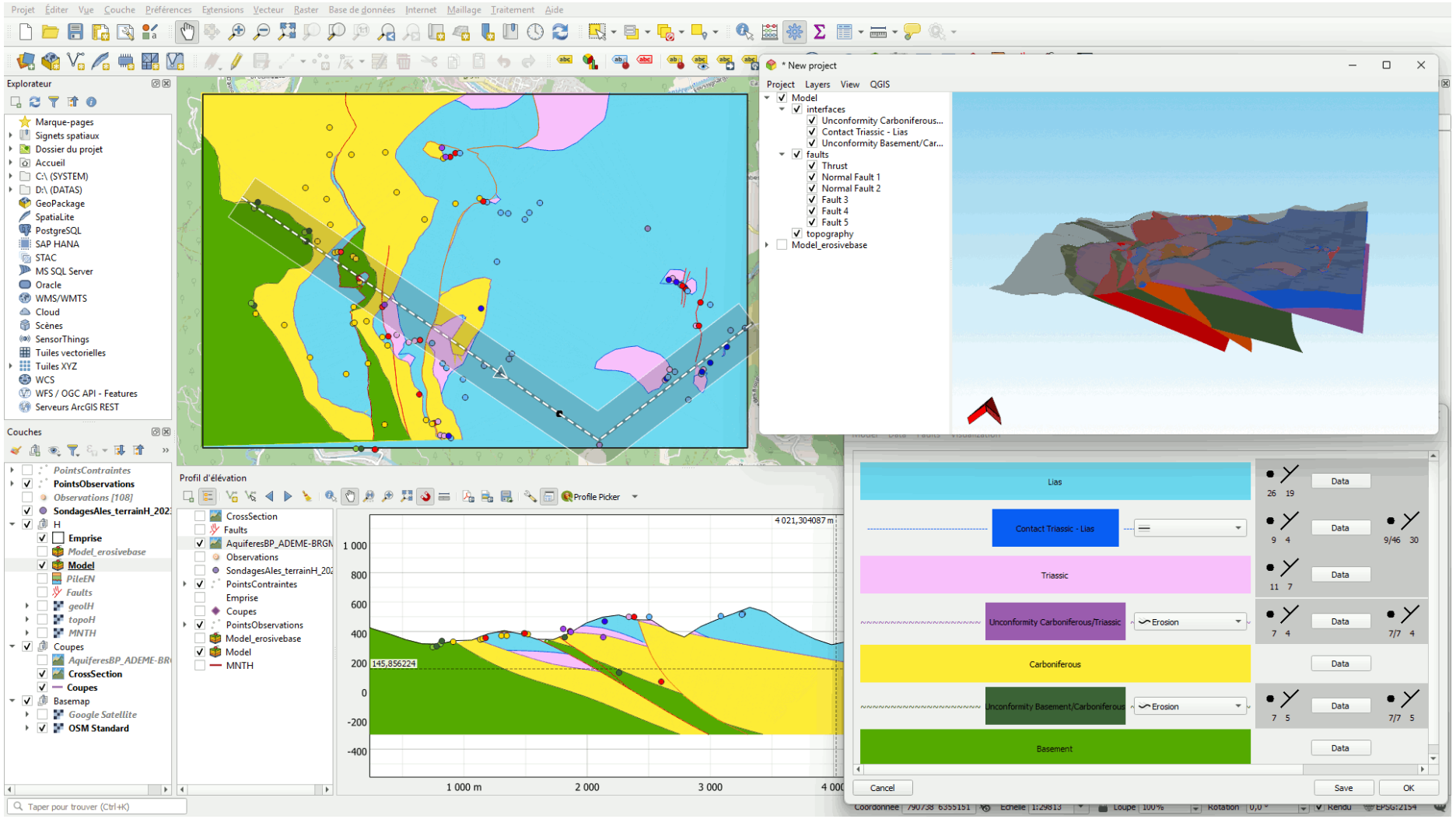
recovering interfaces as topological objects (Le Teurnier et al.)



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Computer Supported Collaborative Work

open FAIR data
open standards
open tools
e.g. QGis as a working environment for 3D geosciences



https://brgm.gitlab.io/geomodelling/forgeo

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CONCLUSIONS

3D modelling is, and always was, the fusion of multimodal data under uncertainty.
What changes is that machines and algorithms increasingly help us do it.

The human geologist stays at the centre of the process.

Accept spatially variable quality. Get something unfinished out fast, then improve it step by step.

Build the language of uncertainty.
Model users must understand how uncertain a model is, and why they need to engage with expert geologists.

Huge amount of work ahead!

Géosciences pour une Terre durable
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FRENCH NATIONAL GEOLOGICAL SURVEY

Geoscience for a sustainable Earth

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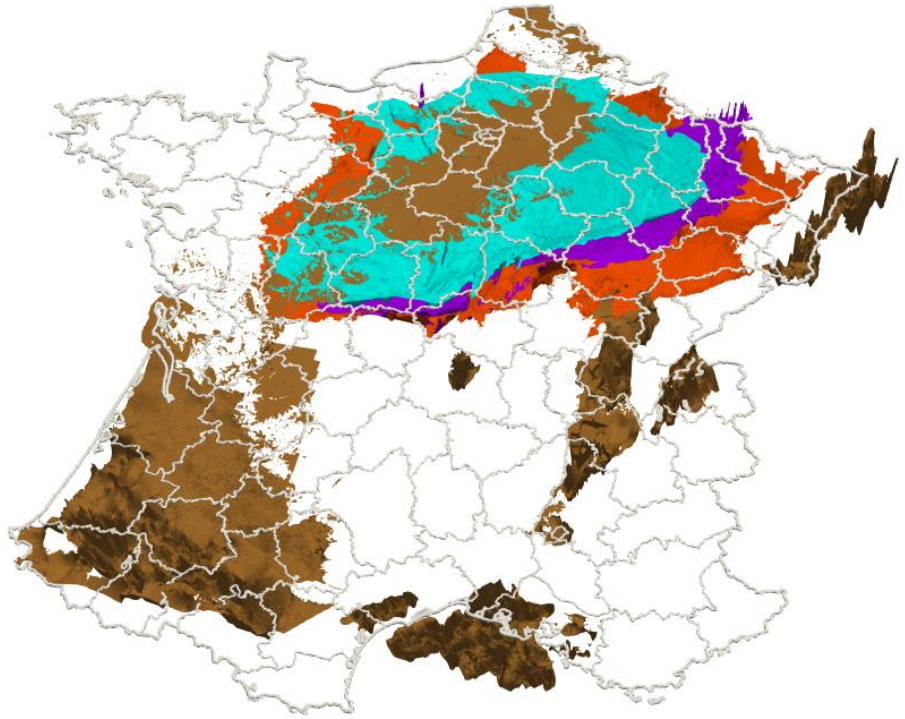
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RÉPUBLIQUE FRANÇAISE
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towards a National Geoscience Reference Framework (RGN)

The return on investment in geological knowledge ranges from 2 to 20 (reduced uncertainty, avoided costs, risk management…) (cf. R. Baumberger's talk)

An RGN to:
capitalise on and pool all subsurface knowledge, interconnected with national data infrastructures within a FAIR framework,
continuously update this knowledge, from geometries to properties,
deliver it on demand as multi-scale subsurface models tailored to the issues at stake, from local to national scale, in support of local policies.



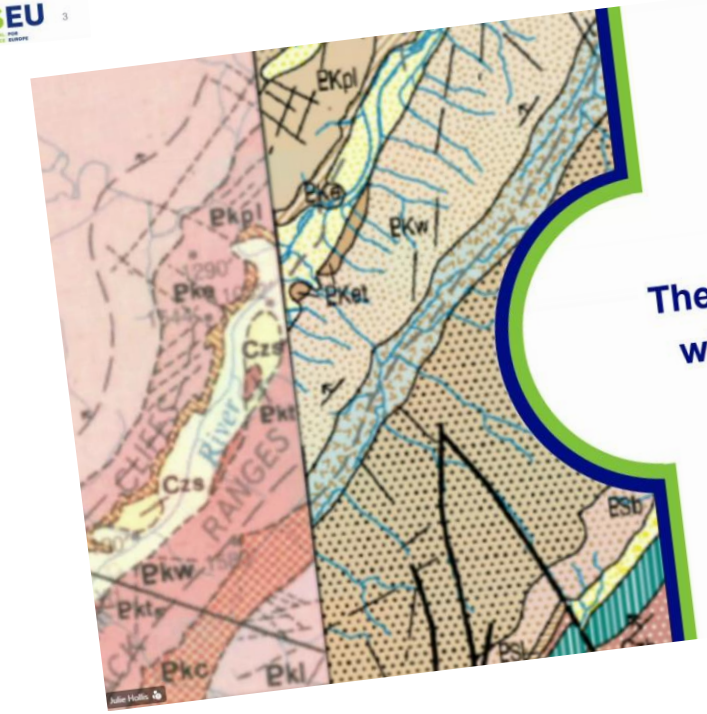
Building on:
a collaboration with CNRS and other partners (Inria, IGN…),
the ongoing transition towards an ecosystem of sovereign platforms that bring together data and services from BRGM and its partners (PEPRs).

A gradual transformation:
building a baseline model linked to data flows (recomputed as needed),
progressively improved by capitalising on project results and through targeted data acquisition (data gaps, or "white zones"),
easier access through a redesign of dissemination tools (InfoTerre 2.0),
local demonstrators refining the model, with priority given to high-stakes areas.



Geological reality is always more complicated than our representation of it

GSEU 3



The value of modelling what we don't know

GSEU 4

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