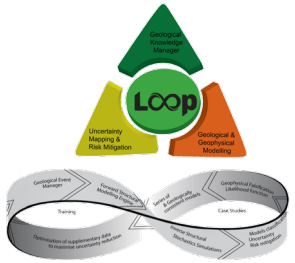
Imadeddine LAOUICI,

Postdoctoral fellow

A KNOWLEDGE-DRIVEN STRUCTURAL MODELING FORMALISM:

fresh perspective

Presentation at the 3D Geological modeling Conference Fremantle, Apr 9, 2025

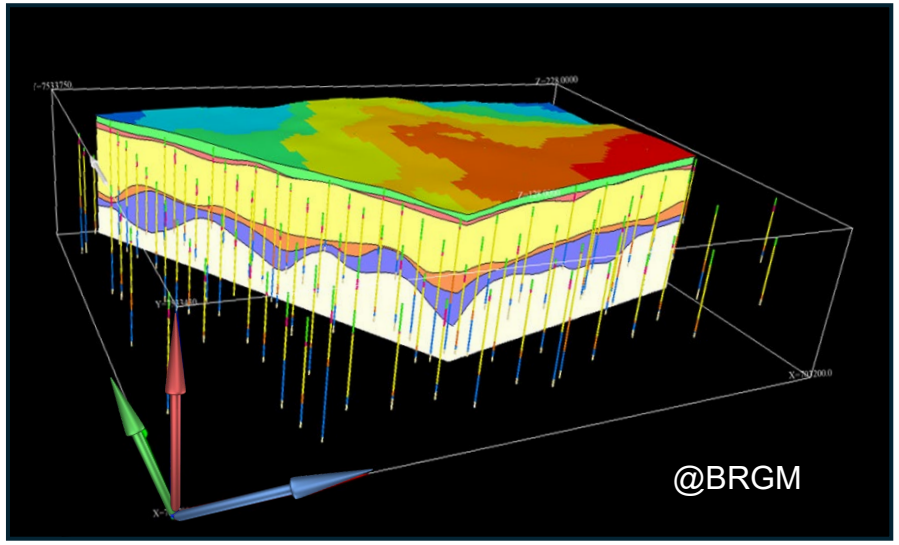


Geomodels: Overview

Structural models and their usage

Three-dimensional representations of the subsurface architecture (Wellmann and Caumon, 2018)

- Understanding Geological History
- Resource Exploration
- Groundwater Management
- Geological Hazard Assessment
- Engineering and Construction



~~This is a structural geomodel~~

This is a geometric representation of a structural geomodel

Software ?

GemPy

leapfrog | GEO

Loop3D/
LoopStructural

GEOMODELLER
Our Products > GeoMod

GOCAD® MINING SUITE

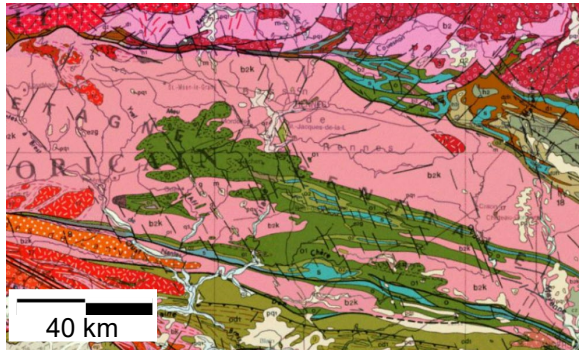
Petrel
Shared earth—critical insight

Information Géologique
Modélisation et visualisation

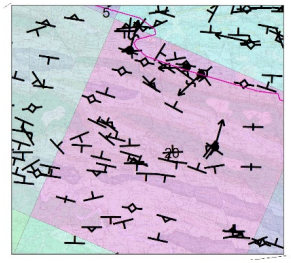
GDM SUITE

Geomodels: Systems & Interpolation-based paradigm

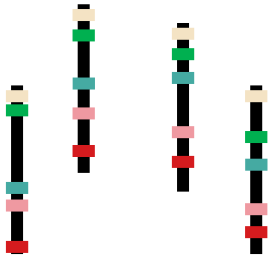
Typical geomodelling inputs



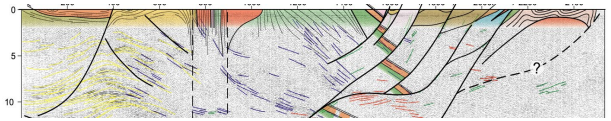
Geological map of the Central Armoricain Doamin at 1:1,000,000 scale (source BRGM)



Field measurements (ISTO report)



Borehole data



Seismic profile Armor2 interpreted (Gumiaux 2003)

Volume of inputs **< 0.1 %** volume of the model

3D geomodelling system

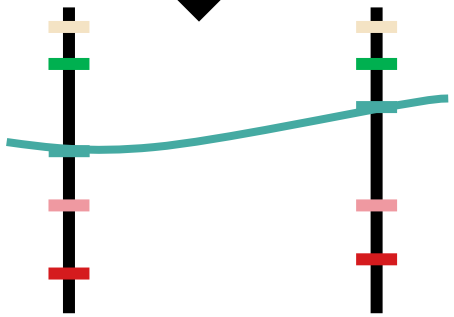
Infer & estimate properties

Interpolation

$$M = f(x, P)$$

Geological module

Engineering module



Conceptual model / Geological knowledge

- Stratigraphy: units and their ages.
- Relations between units, i.e., erosive/onlap.
- Structural Geology: Faults and *folds* with their structural parameters.

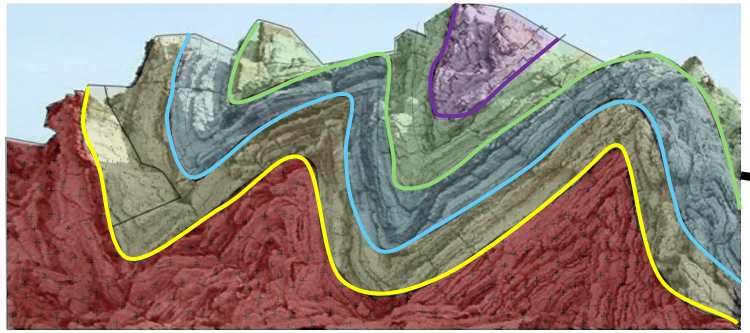
Interpolation algorithms

- Kriging (Lajaunie, 1997, Oliver and Webster, 1990)
- Radial Basis Functions (RBFs) Cowan et al., 2002)
- Discrete smooth interpolation (Mallet, 1989)
- …

Software toolbox

- Data management
- Perform operations
- Modeling functionalities

Geomodels: Knowledge incorporation & limitations

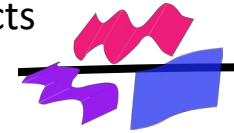


Folded layers (chevron folding)

Discrete objects

Explicit

(Hardy, 1971)



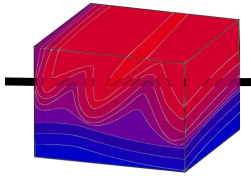
Interpolation

$M = f(x, P)$

Isovalues of a scalar field

Implicit

(Lajaunie et al., 1999)



Interpolation

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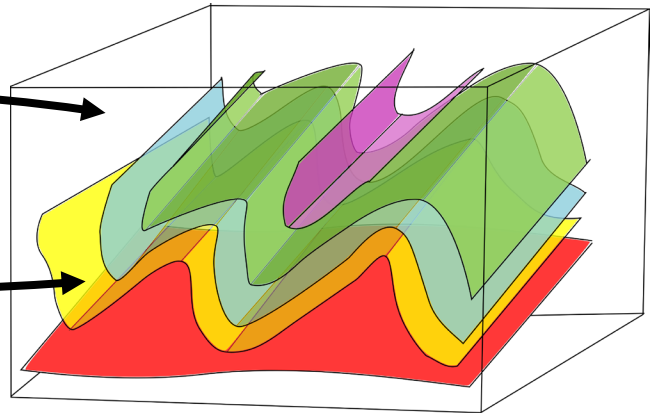


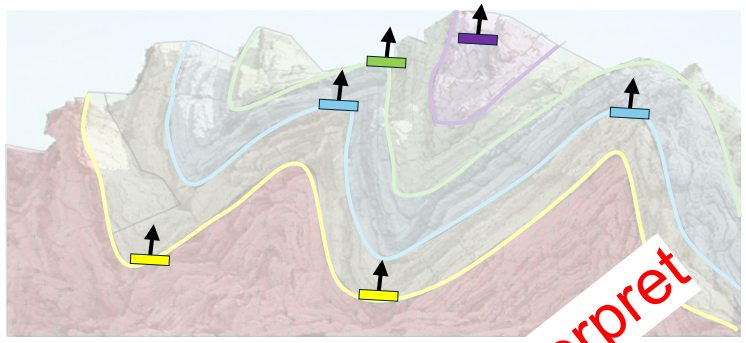
Geological aspects

- Succession of strata
- Continuity of surfaces (topology)
- Thickness (constant vs variable)
- **Folds**

Limitations during model construction

- Restriction in integrating geological knowledge

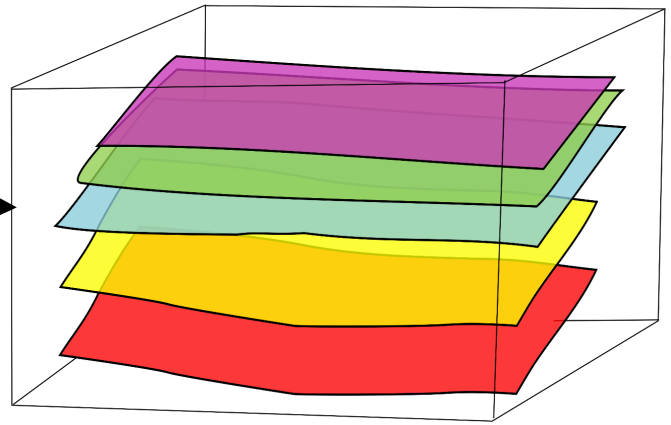
Geomodels: Knowledge incorporation & limitations



Folded layers (chevron [illegible]g)

Interpolation

$$M = f(x, P)$$



Geologic[illegible]pects

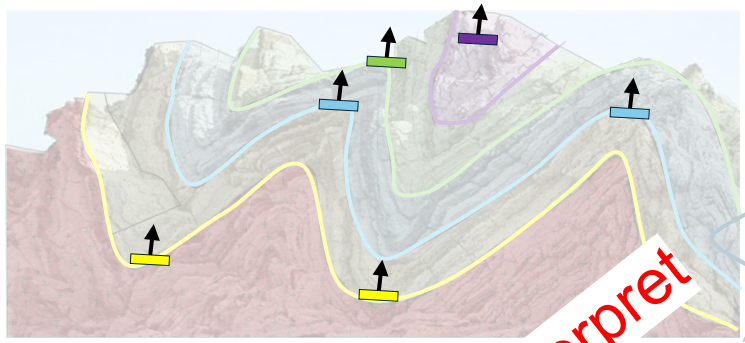
- Success[illegible] strata
- Con[illegible]y of surfaces (topology)
- [illegible]kness (constant vs variable)
- **Folds**

Expert's need to interpret

Limitations during model construction

- Restriction in integrating geological knowledge
- Expert centric (subjectivity, bias, loss of history)

Geomodels: Knowledge incorporation & limitations



Folded layers (chevron g)

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Geologic spects

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Interpolation

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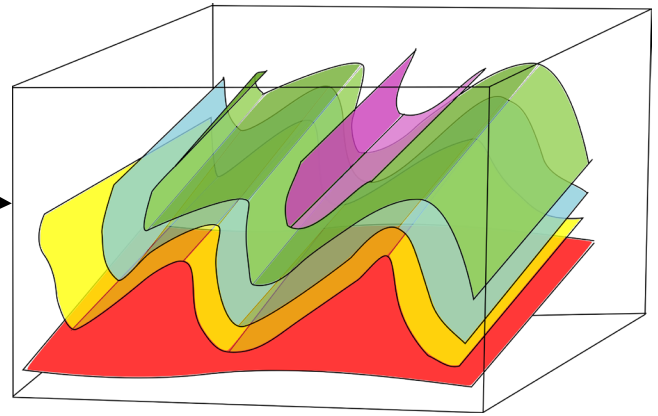
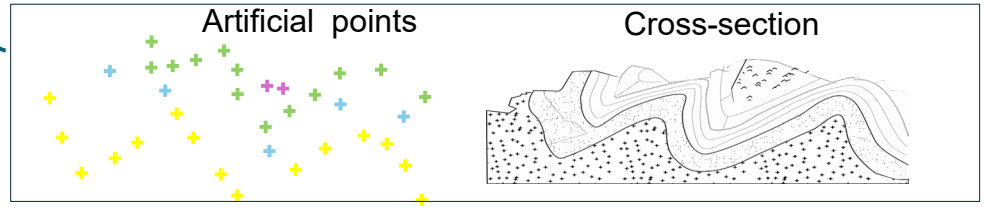




(1) Interpretations to constraints (Lemon & Jones 2003, Caumon, 2003)

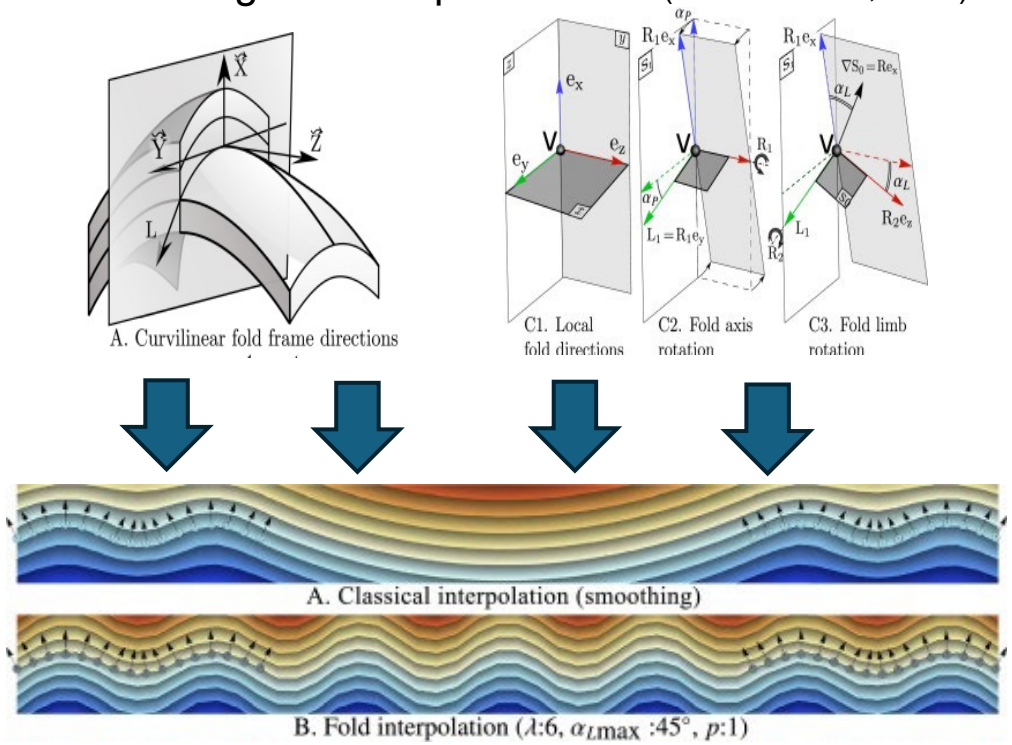
(2) Formulating geological concepts within the mathematical framwork (Wellmann & Caumon 2018)

Limitations during model construction

- Restriction in integrating geological knowledge
- Expert centric (subjectivity, bias, loss of history)
- Loss of the semantic content

Geomodels: Knowledge incorporation & limitations

Extraction of structure's properties and convert them to geometric parameters (Laurent et al ., 2016)



Interpolation with fold geometry constraints (wavelength, amplitude and tightness)

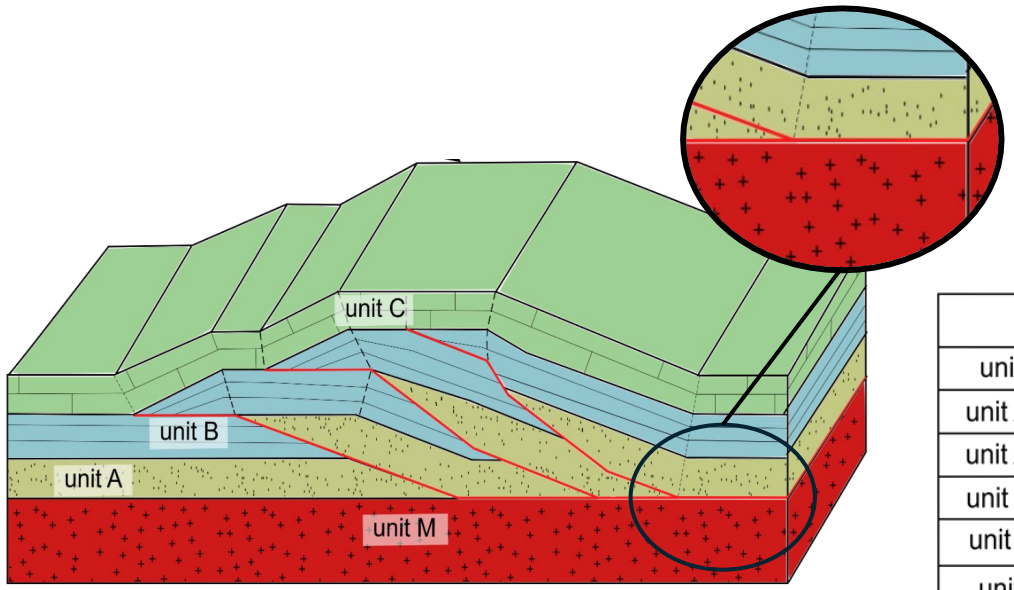
Literature :

- A 3D modeling approach to complex faults with multi-source data (Wu et al., 2015)
- Generating variable shapes of salt geobodies from seismic images and prior geological knowledge (Clausolles et al., 2019)
- Realistic modelling of faults in LoopStructural 1.0 (Grose et al., 2021)
- Inversion of geological maps for fault geometry (Grose et al., 2021)
- Spatial agents for geological surface modelling (De Kemp et al., 2021)
- Finite Difference Implicit Structural Modeling of Geological Structures (Irakarama et al., 2021)
- …

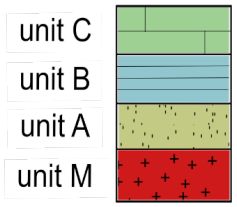
Limitations during model construction

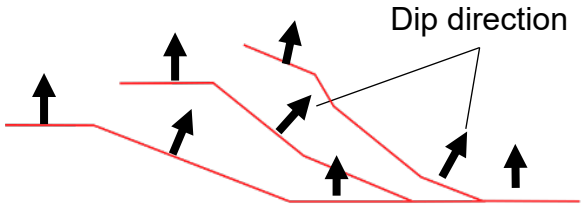
- Restriction in integrating geological knowledge
- Expert centric (subjectivity, bias, loss of history)
- Loss of the semantic content
- Focus on knowledge mathematically formulable
- Dependency on data
- Global parametrization

Geomodels: Knowledge incorporation & limitations



Duplex structure with folds, thrusts and flat ramps

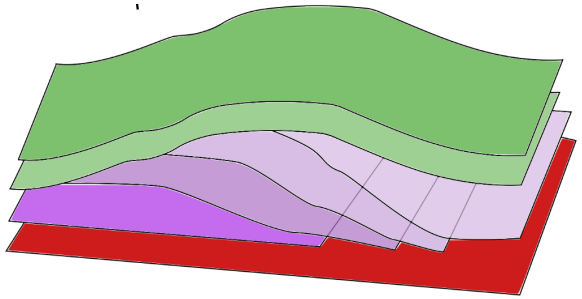




original model

Formation	Surf type
unit C	Erod
unit AB4	Onlap
unit AB3	Onlap
unit AB2	Onlap
unit AB1	Erod
unit M	

Alternative model (no faults)



Institutions database

Stored in

Geomodeller's hurdles

Institution's hurdles

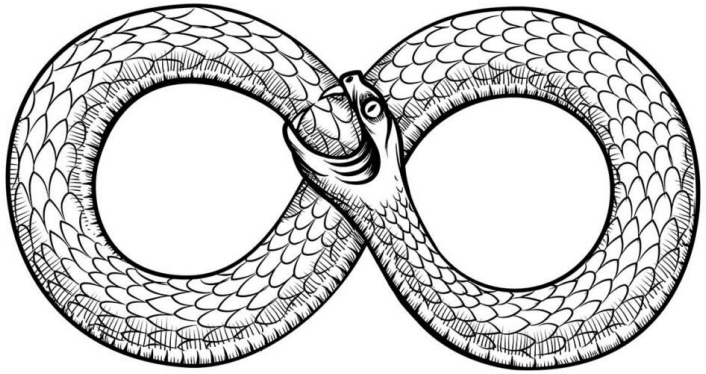
Limitations after model construction

- Knowledge sharing and querying
- Geomodels updating and reproducing

Limitations during model construction

- Restriction in integrating geological knowledge
- Expert centric (subjectivity, bias, loss of history)
- Loss of the semantic content
- Focus on knowledge mathematically formulable
- Dependency on data
- Global parametrization

Problem statement & proposed solution

Interpretation  **Knowledge**

PhD part 1

Formal interpretation

A **generic formalism** for the interpretation as a **distinct entity**

Tracing explicitly the **decision history**

PhD part 2

Knowledge formalization

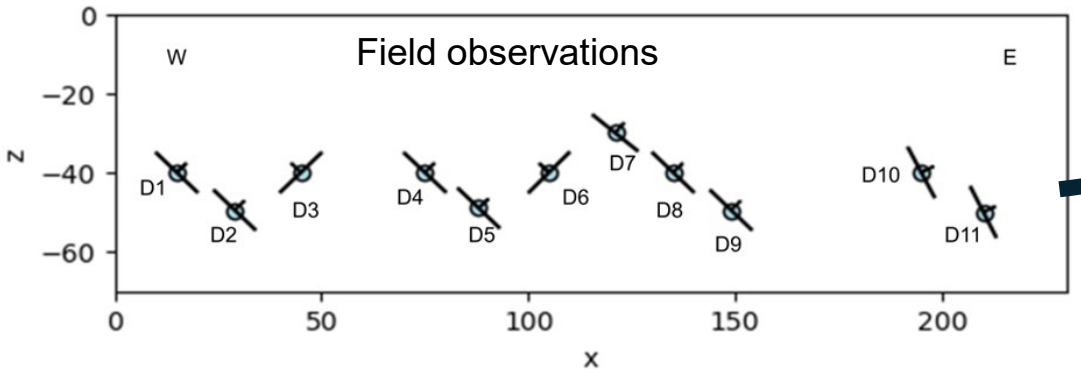
Introduction of knowledge in an **explicit** and **structured** way without loss of semantics

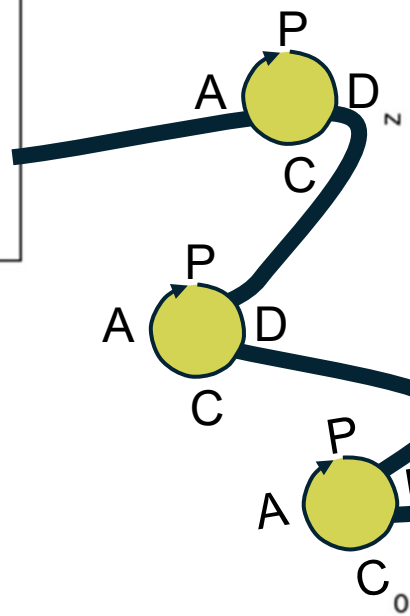
Making knowledge in the geomodel **independent** of its 3D geometric rendering

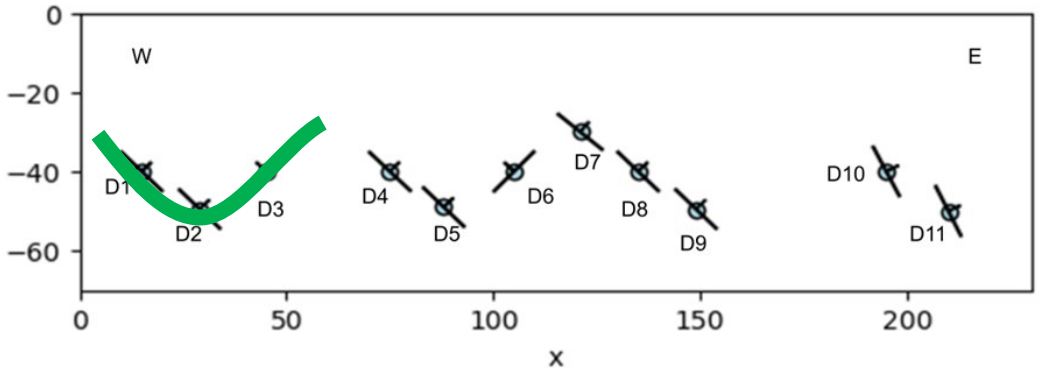
Semantics in geomodels

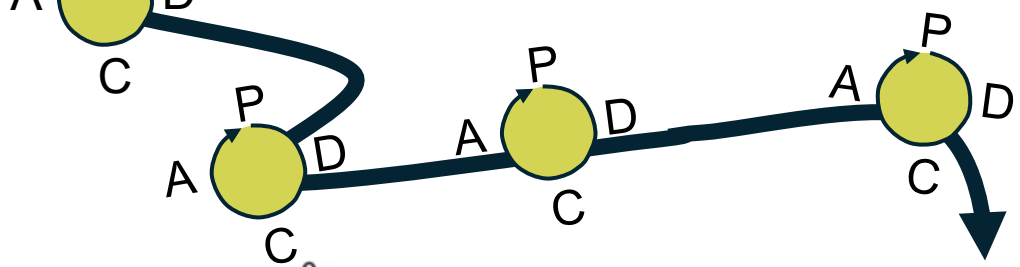
Post-doc

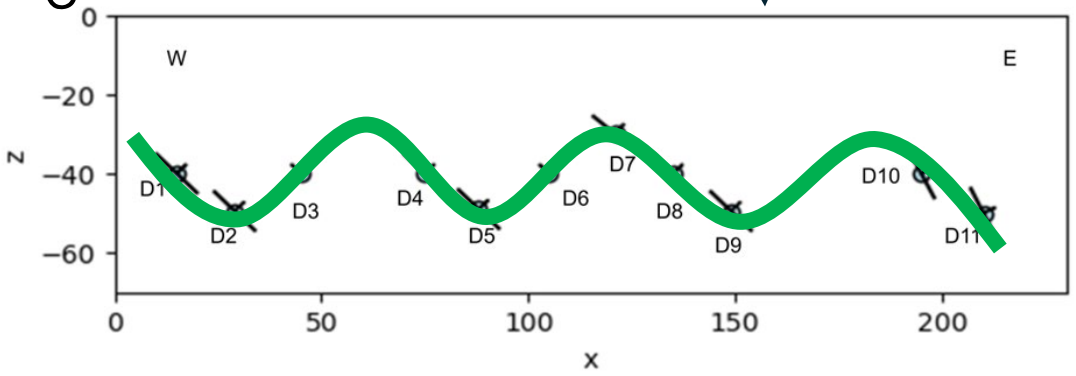
Theory: Analyzing the interpretation process





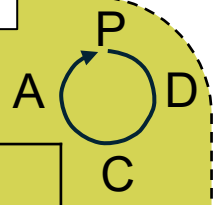






Generic interpretation process

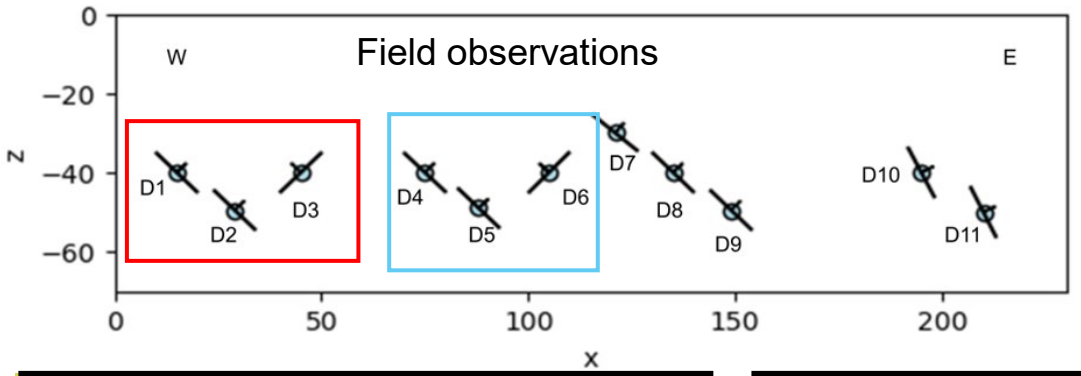
Interpretative Tasks	
Interrogate information Select situation to interpret	Plan
Choose hypothesis Estimating and Assigning values	Do
Evaluate the hypothesis	Check
Decide about the hypothesis Update initial understanding	Act

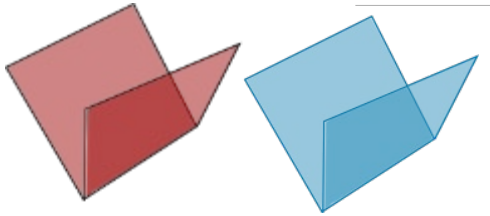


Iterative

Incremental

Theory: Required knowledge





Instance
fold_1

fold_1 has limbs:
L1 and L2

Instance
fold_2

fold_2 has limbs:
L3 and L4

Generic interpretation process

Plan

Do

Check

Act

Iterative

Incremental

Updatable

Geological knowledge

Situations to interpret

- Missing properties of geological entities
- Structural relations between geological entities
- …

Descriptions of geological entities

Representation knowledge

The interpretation process is independent of the 3D digital representation

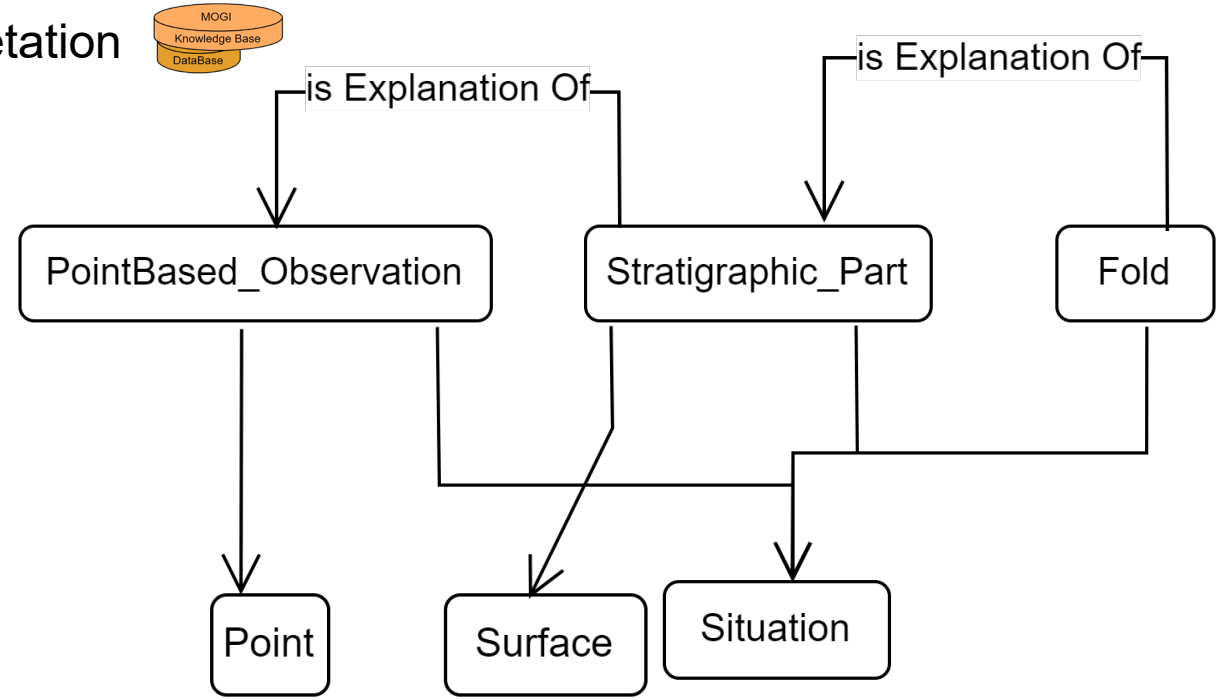
Operational system

Knowledge model (MOGI)

Results: Knowledge model

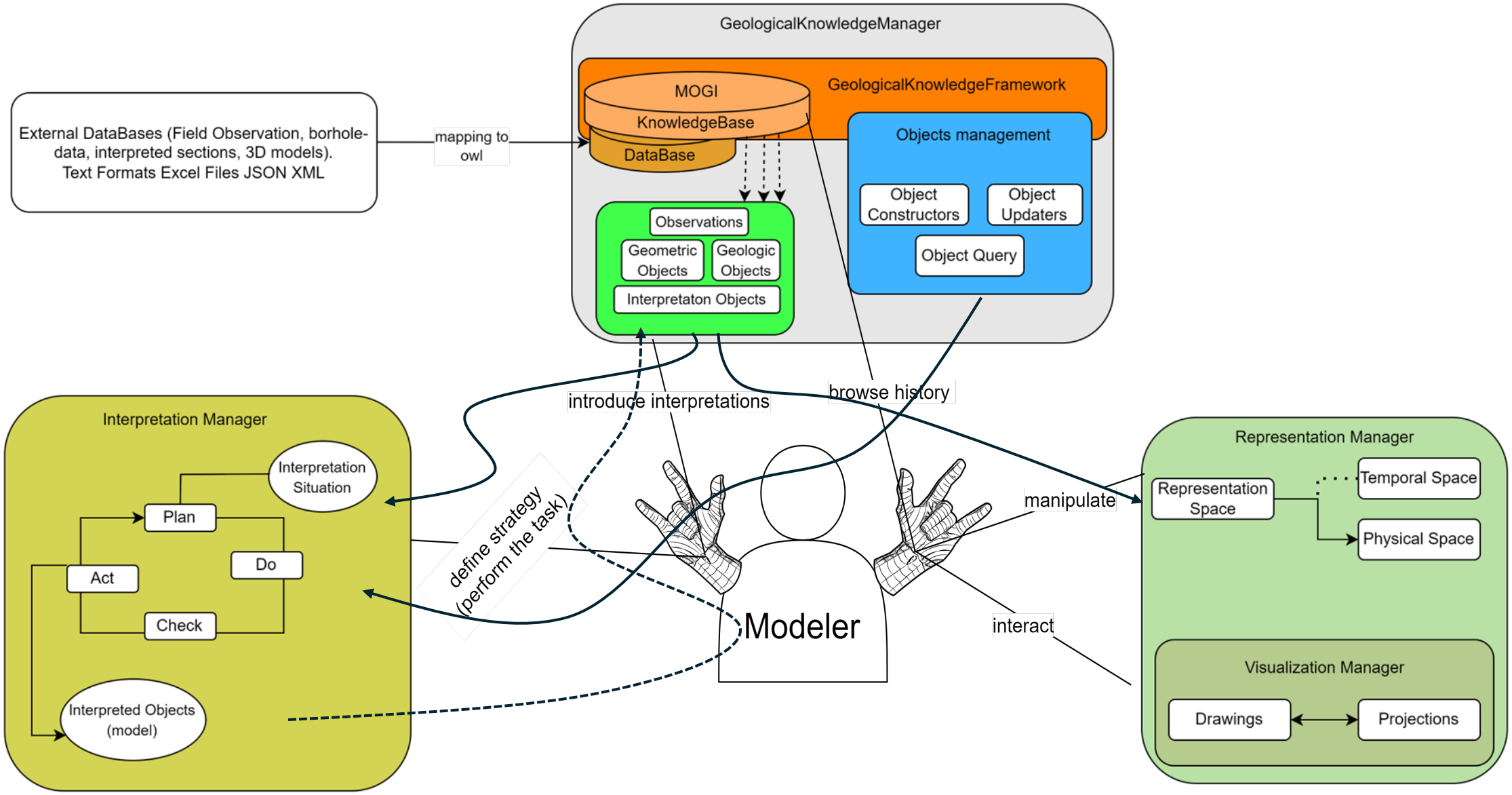
MOGI Minimal Ontology for Geological Interpretation

- owl:Thing
  - Geological Concept
  - **Observation**

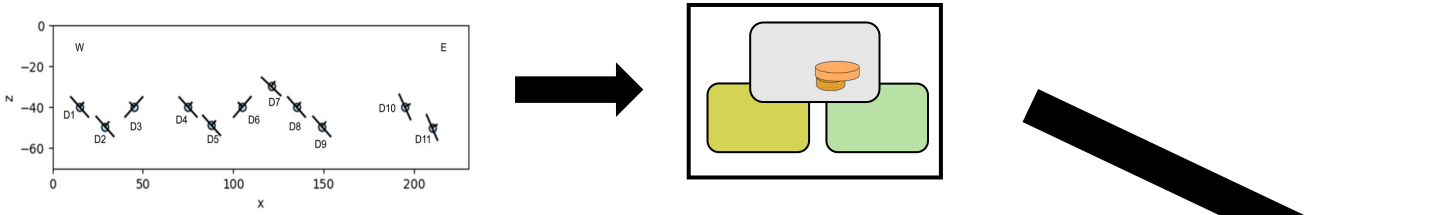


- Observations and geological entities
- Situations and relations between explaining and candidate entities
- Geological concepts are related but independent from representational concepts

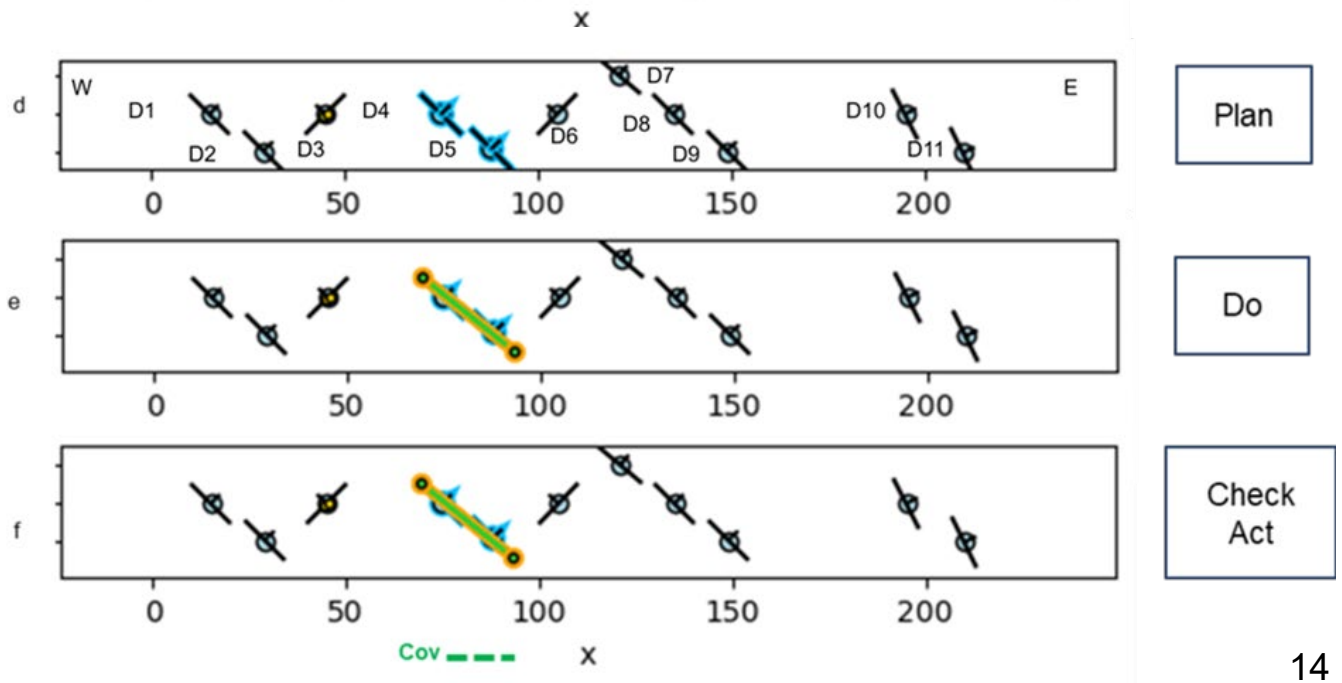
Results: Operational system's components



Results: Application on synthetic data



- Plan:
  - Selection of inputs ➔ random selection
  - Querying inputs and listing their possible explaining objects
- Do:
  - Selection of the interpretation hypothesis ➔ random selection (Stratigraphic_Part)
  - Assigning parameters (mean value of spatial coordinates)
- Check:
  - Evaluating the hypothesis ➔ strict alliance with criteria (conform)
- Act:
  - Updating the knowledge base with the new accepted interpretation



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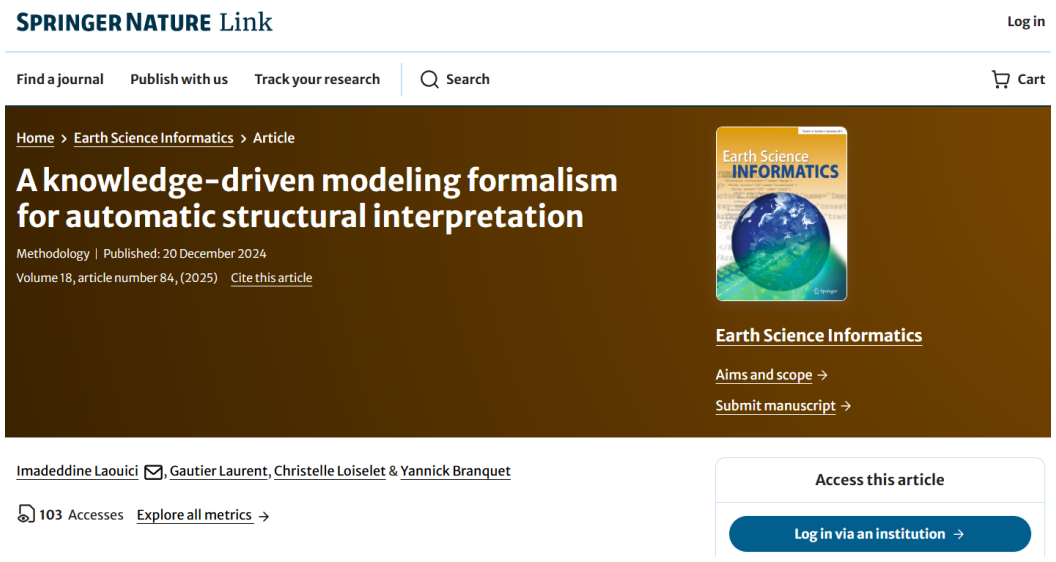
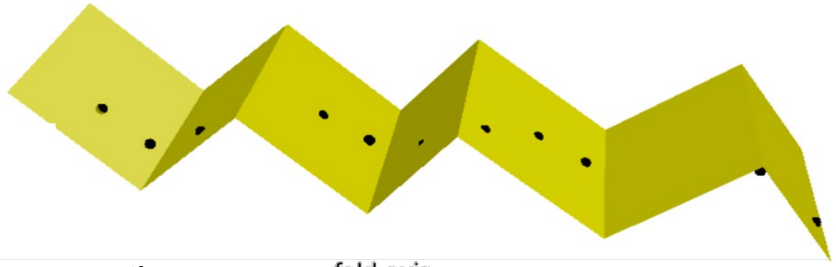


Paper

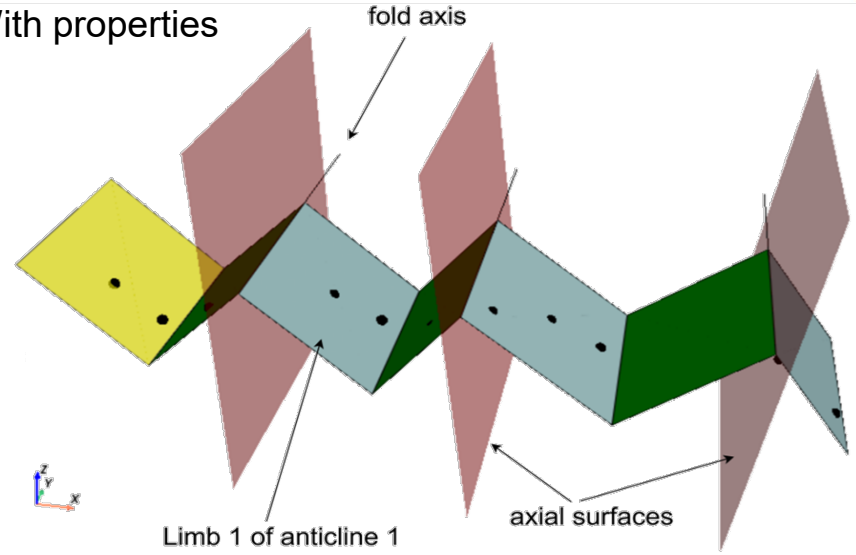
Repository of the script

10k lines of code

General view



With properties



- ✓ Preservation of the semantics of the described objects
  - ✓ Automation of various interpretative tasks
  - ✓ In depth interaction with the interpretation process
- ✓ Preservation of the interpretation history and the decisions made

Motivation

Multidisciplinarity

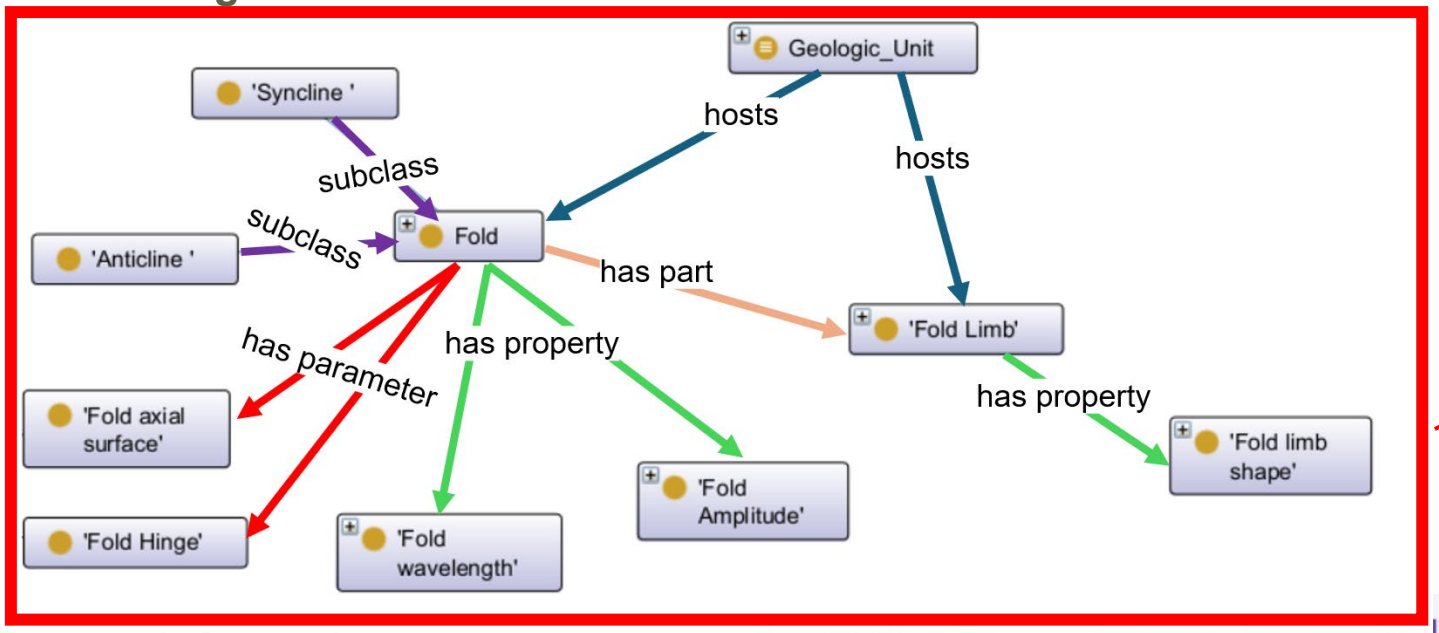
(e.g., geology, knowledge representation)

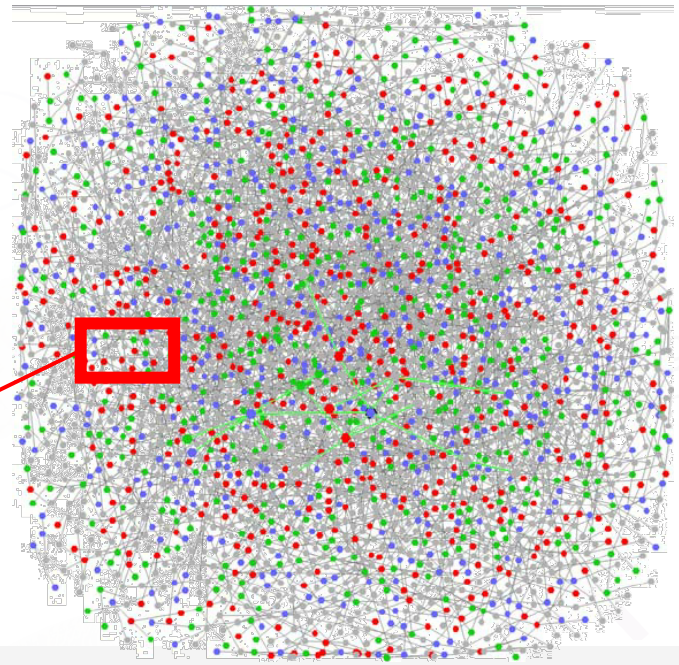
Knowledge modeling at different levels

(i.e., modeling models)

Need for better knowledge formalization (**ontologies** !!)

Ontologies





Ontology metrics:

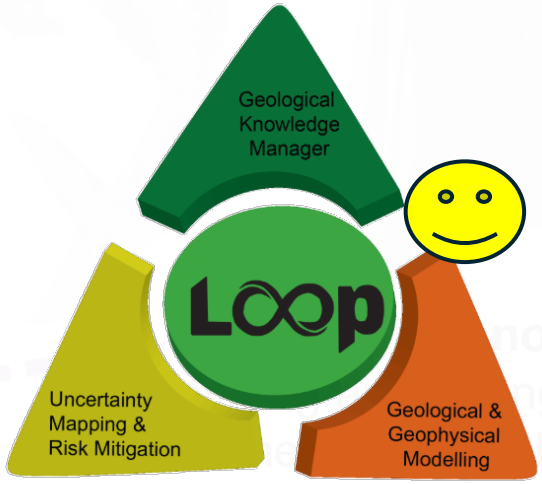
Metrics

Axiom	121 478
Logical axiom count	16 491
Declaration axioms count	6 893
Class count	6 700
Object property count	178
Data property count	1
Individual count	1 042
Annotation Property count	61

Class axioms

SubClassOf	7 500
EquivalentClasses	74

Subset from the GeoScience Ontology (Brodaric & Richards, 2020)



Ontologies

Application level

Proposed ontology

POKIMON
(Processes, Observation, Knowledge, Information, Modeling ONtology)

Domain level

Specifications for the ontology

GSO
(GeoScience Ontology)
(Brodaric and Rcihards 2019)

- Geological entities (objects, structures)
- Geological principles, laws, and rules.

IAO
Information Artefact Ontology (Ceusters and Smith, 2015)

- Geomodels, their characteristics, and their relations to interpretation
- Interpretation processes

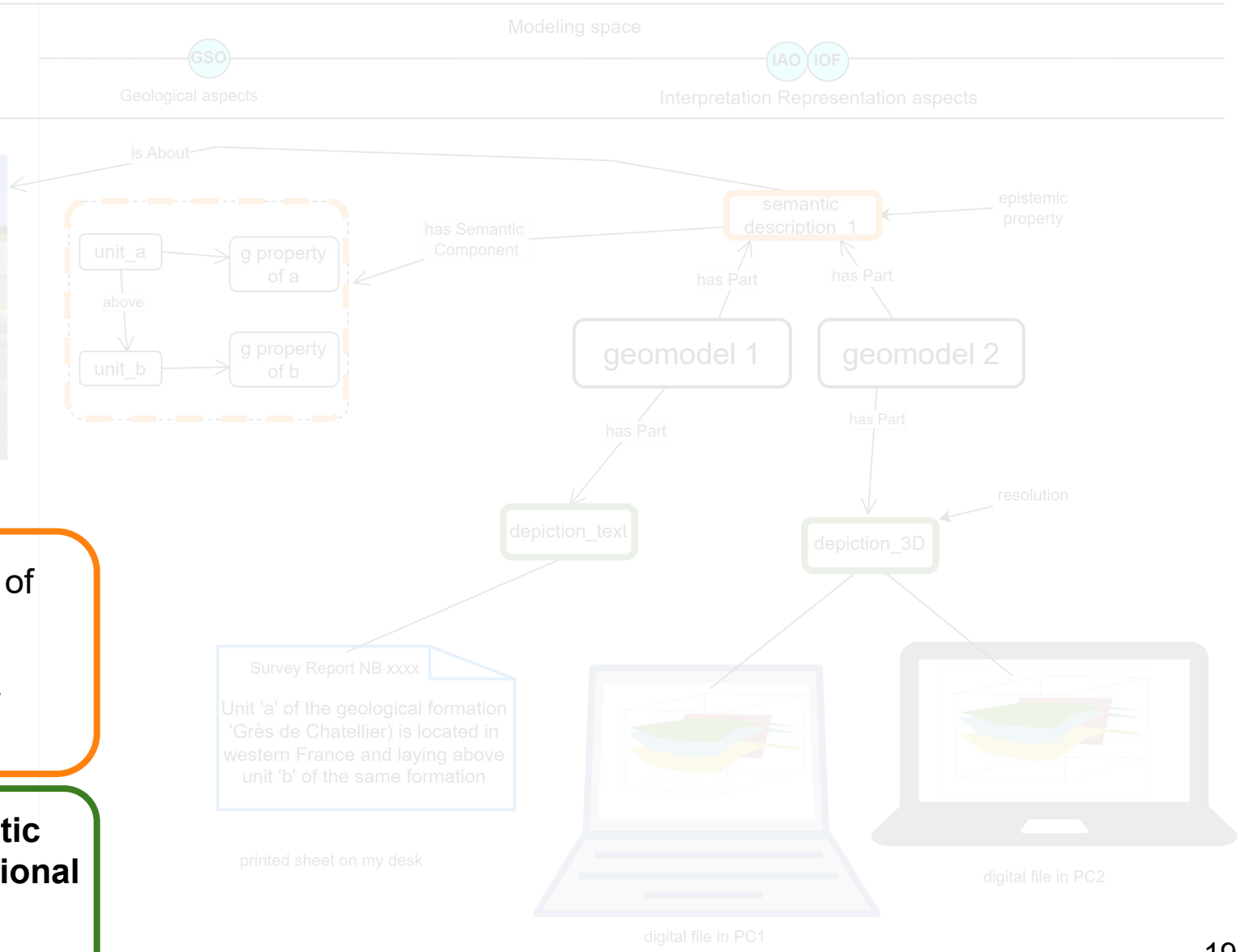
IOF
Information Ontology Foundry (Drobnjakovic et al., 2022)

- Representational entities

Proposed ontology: Definition & main entities

The geomodel:

- **Copyable entity ➔ represented** in **different** physical artefacts



The geomodel has two components:

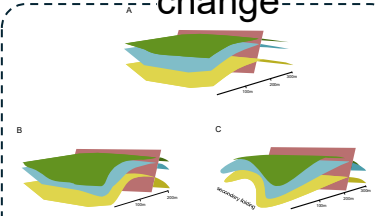
- Semantic Content Entity : **abstract description** of geological entities.
  - Modeled ➔ ontological representation
  - Attributes ➔ epistemic uncertainty, origin of information...

- Depiction Content Entity : **casting** of the **semantic component** into a specific **external representational paradigm**
  - Attributes ➔ resolution, colors …etc.

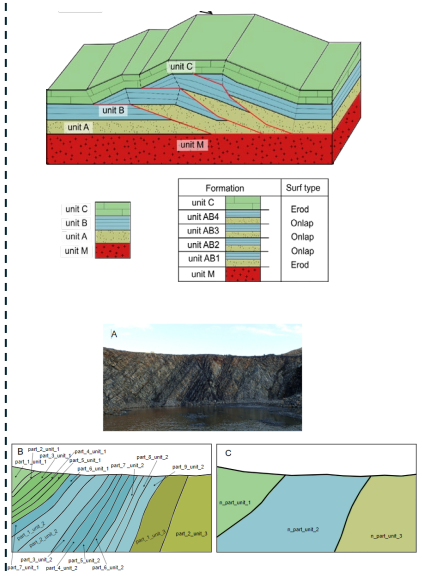
Proposed model: Application

uses cases

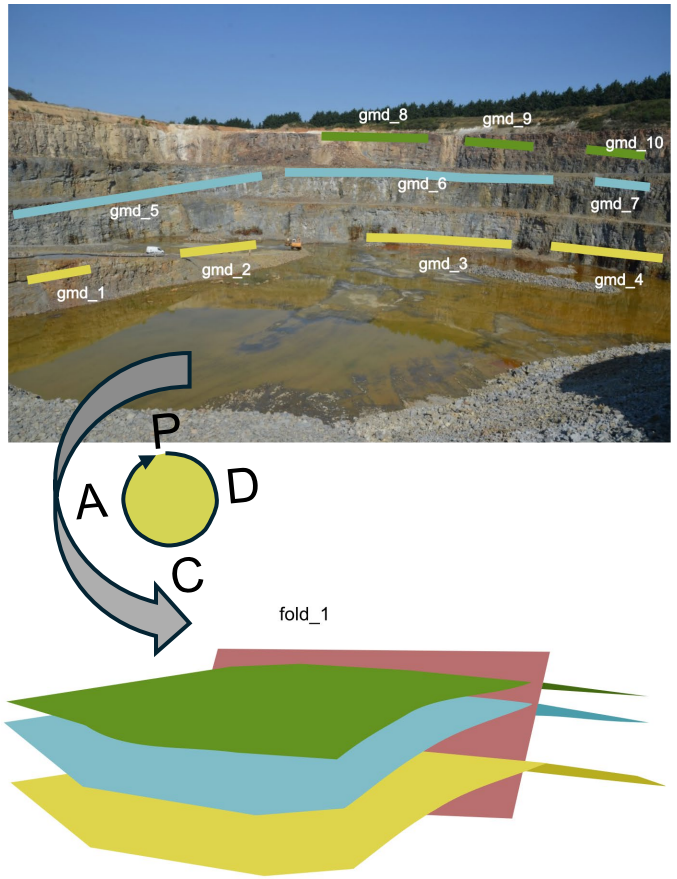
When geomodels change



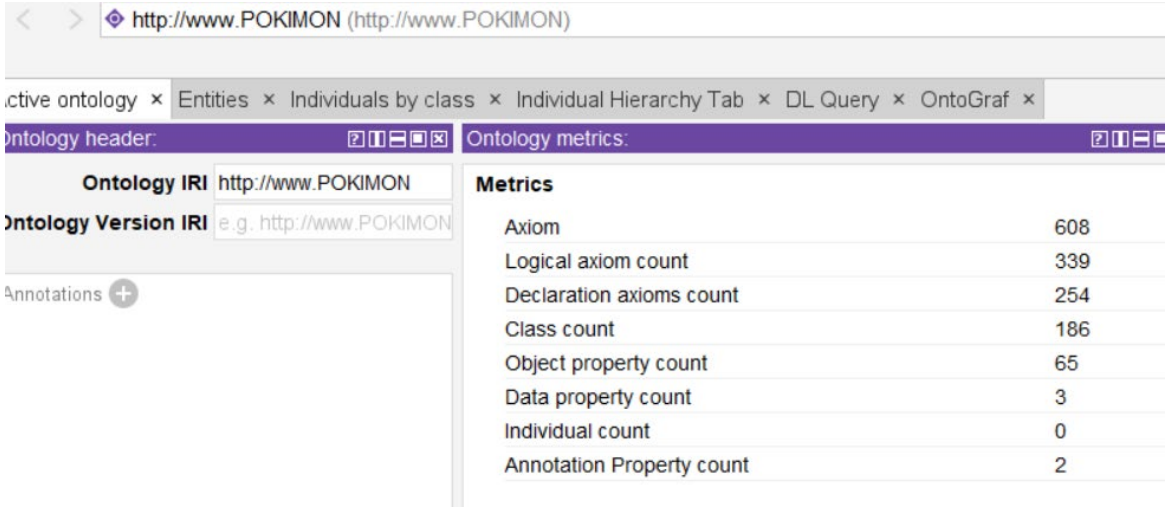
Modeling geomodels relations



Modeling the interpretation process



Implementation

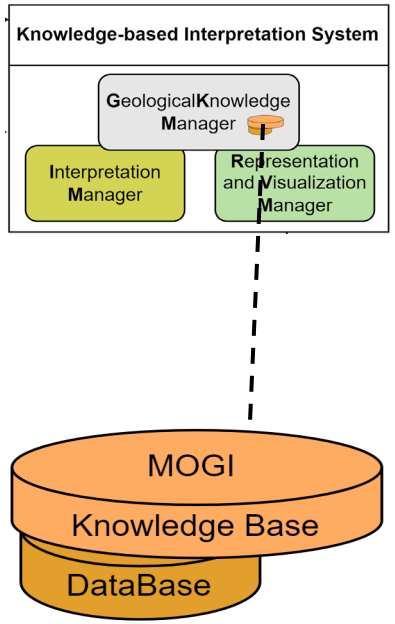


Paper 2: POKIMON: an ontology for geological interpretation in 3D geo-modelling
(in preparation for submission)

Motivation

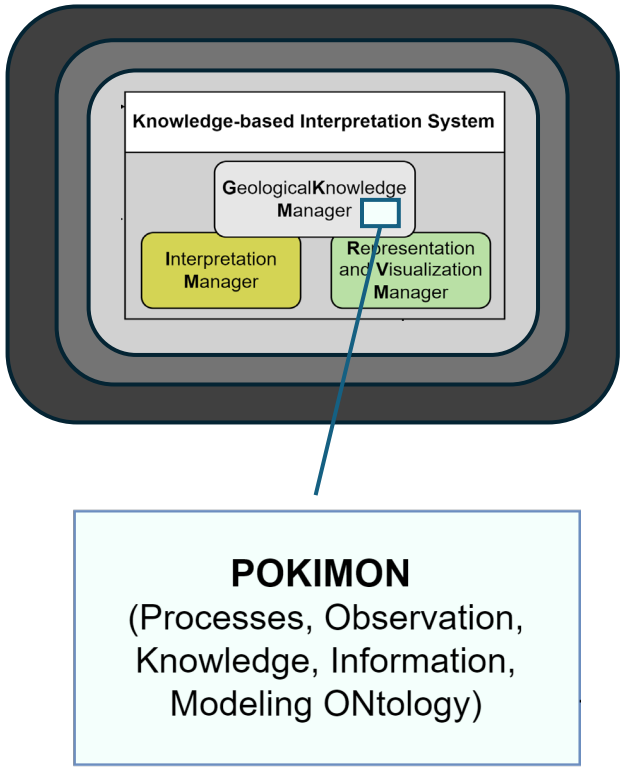
State of the art

Prototype v0



Next ……..?

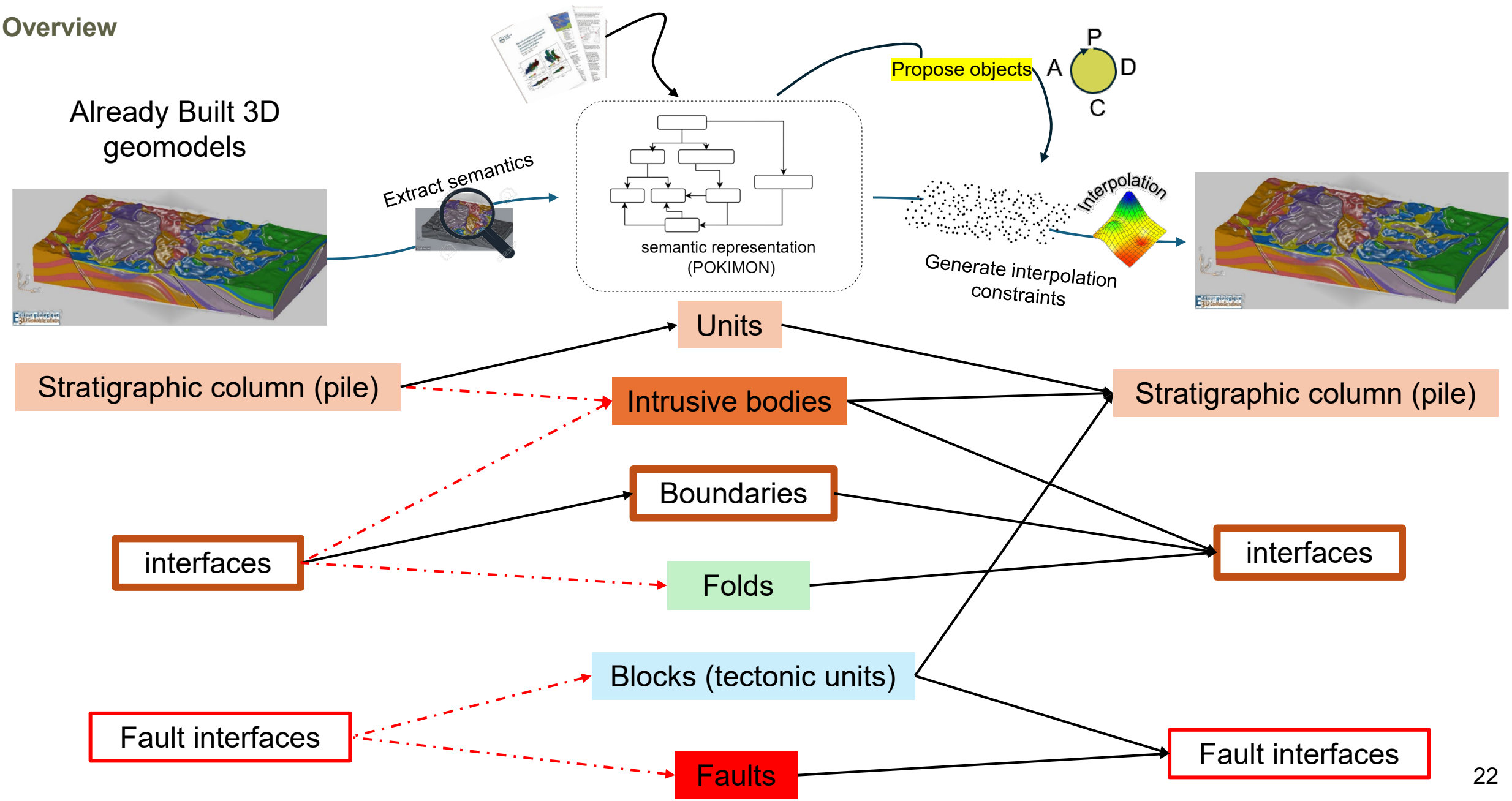
Prototype v1.0



Deployment within geomodelling systems ?!

Human-based geomodelling systems

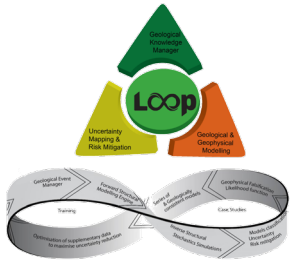
Overview


Already Built 3D geomodels
Extract semantics
semantic representation (POKIMON)
Propose objects
P
A
D
C
Interpolation
Generate interpolation constraints
Units
Stratigraphic column (pile)
Intrusive bodies
Stratigraphic column (pile)
Boundaries
interfaces
interfaces
Folds
Blocks (tectonic units)
Fault interfaces
Faults
Fault interfaces

THANK YOU FOR THE ATTENTION

Imadeddine LAOUICI

i.laouici@brgm.fr



Presentation at the 3D Geological modeling Conference Fremantle, Apr 9, 2025

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