# Knowledge– driven applications for geological modeling

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## Abstract

Oil and gas exploration relies for a good part on 3D earth modeling operated from raw seismic data and from information issued from drillings. At present, the resulting models have to be shared by various potential users, who must be able to possibly extend, update, revise or rebuild them in view of additional geological data or according to new geological interpretations.

The present paper proposes an knowledge-driven approach for "Shared Earth Models" (SEM 1998) building which ambitions to share throughout the workflow not only raw data and the various representations of the geometrical objects included in a definite model but also the geological interpretation related to this model. This approach rests on a Geo-Ontology that identifies and formalises the structural geologists' expert knowledge and on a derived abstract descriptor (Geological Evolution Scheme), which enables full sharing of the user's geological interpretation between the various applications.

Geological assemblages result from a definite history made of various successive events, which create geological objects. For this reason, the arrangement of these objects and, in consequence, the arrangement of the various geological surfaces present in 3D models verify specific rules, which define a "geological syntax" (M. Perrrin, 1998). The proposed Geo-Ontology takes into account this particular chrono-spatial structure of geological models. The paper describes the main concepts that are used and defines the syntactic rules to which they must obey. Moreover, it is possible to deduce from the Geo-Ontology, that we have defined, a standard geological descriptor (Geological Evolution Scheme = GES), which records the geologist's interpretation of any given geological assemblage and which can be used for automatically building the related 3D model. The resulting methodology ("geological pilot") is exposed and illustrated through an example, showing how a GES can be used all along the workflow that goes from raw data to shared structural and stratigraphical models fully exportable for reuse by other geologists.

The knowledge-driven approach presented and the resulting "geological pilot" methodology appear very promising for producing a new generation of earth models, able to be fully shared by multiple possibly distant users. 3D-model updating or revision will be much easier and the proposed methodology is also promising for kinematics (4D) modeling.

**Keywords**

3D geological modeling, Shared Earth Models, ontology, oil & gas exploration.

# 1 Introduction: data-driven and knowledge-driven models

## 1.1 Geological models for hydrocarbon exploration & production

During the last two decades, 3D geological models have progressively become a major instrument for hydrocarbon exploration and production. These 3D models are more or less conventional representations of a definite portion of underground, whose horizontal dimensions may be a few hundreds of meters or a few kilometers (reservoir models) or several tens of kilometers (basin models) and whose vertical dimensions reach a few thousands meters at the maximum. Reservoir models comprise various surfaces (sedimentary interfaces, faults...) which limit blocks of geological matter that are described by means 3D meshes populated with petrophysical properties.

The producing of fully documented reservoir or basin models starting from raw data involves various operations, that are operated by modeling chains operating complex workflow involving various software applications (J.L. Mallet 2002). Different types of modeling chains are available for research and geological exploration (J.L. Mallet 1992), (M. Floater & al., 1998, (Earthvision, 1999), (Landmark, 2002). These sophisticated software tools have a high running cost for companies since many people must be trained to use them. For this reason, companies will hardly be willing to change the modeling chain they use for another one. Improvement can then only be brought by adding to new compatible modular components existing modeling chains, that can be used as “plug and play” items.

The major differences existing between the various modeling chains currently used in industry are related to the type of surface representation chosen - generally triangular (EDS, 2004) or parametric (BEICIP, 1999)-, the method used for assembling them either manually or in a semi-automatic way and to the quality of the final result, which may be a topologically consistent 3D model or a mere assemblage of surfaces. Generally speaking, geological 3D models comprise very numerous data that induce important computing times. For this reason, their revision, in case of data or interpretation changes, is generally a delicate and lengthy operation.

Geometrically, a 3D geological model consists in a set of elementary surfaces, which bound elementary volumes (geological blocks), the global topology being that of a 3D jigsaw puzzle with no voids (Figure 1). The main peculiarity of this assemblage of surfaces and volumes is due to the fact that it is the result of a definite history, which affected the portion of underground represented through geological ages. Specific processes took place during various spans of time, generally millions of years, inducing creation, destruction or transformation of matter. Each definite surface of the model is the record of one remarkable geological event, which can be considered as having been instantaneous with respect to the geological time scale.

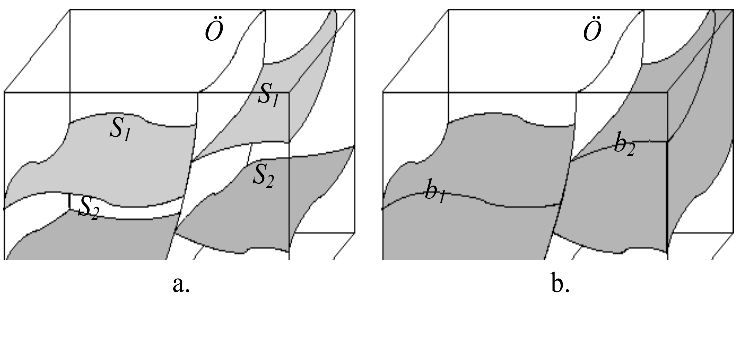



*Figure 1: a) $S_1$ and $S_2$ are two geological surfaces intersected by fault $\Phi$. b) $b_1$ and $b_2$ are two geological blocks between $S_1$ and $S_2$, which are belonging to one formation.*

A geologist cannot build a model unless he/she completes the raw data related to the surfaces entering into the model by an interpretion of the "geology" to be represented. This interpretation constitutes the added value brought by the geologist to the modeling in view of his/her expert knowledge. As it will be explained in part 2.2 of the present paper, geological interpretation consists in giving a geological qualification (stratigraphical surface, fault...) to the various surfaces entering into the model, and in implicitly or explicitly establishing a total or partial chronological order between the various geological events to which they correspond. Since an older geological event cannot modify a younger one, the chronological order defined by the geological interpretation has consequences on the geometry and on the topology of the model to be built. For this reason, the geological interpretation must be considered at the various stages of the workflow related to reservoir model building (cf. Figure 2) for deciding which surfaces should be modeled, how they should be assembled and which relations they should have with the internal stratification within each block of the model (M.Perrin, 1998).

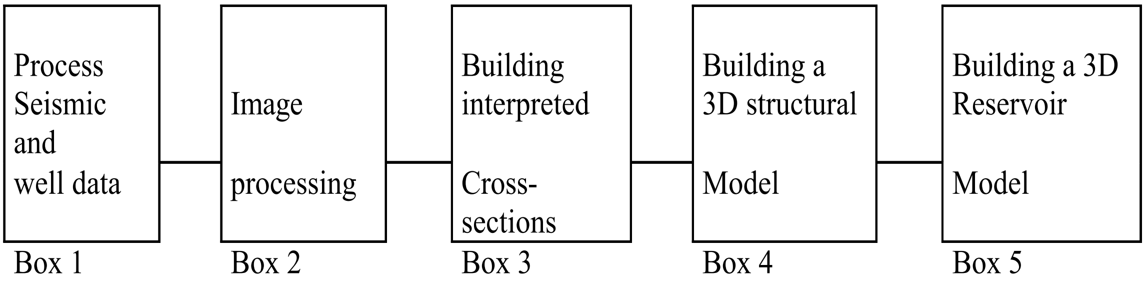



*Figure 2: Workflow for the building of a reservoir model.*

In the present paper, we will demonstrate that the specific structure of geological assemblages can easily be dealt with. Moreover, we will show that it can be the starting point for developing an knowledge-driven approach that can greatly facilitate geological model building.

## 1.2 Shared Earth models

A huge amount of models are permanently produced by oil & gas companies. These models must currently be extended, updated, revised or reused in the course of hydrocarbon exploration and production processes. These operations are likely to involve various professional people (geologists, reservoir engineers, computer scientists…), who are possibly located in various distant sites. For these reasons, a new challenge is to now produce "Shared Earth Models" (SEM) that can be accessed and possibly modified by any potential user.

“Shared Earth Modeling” can be operated using two different types of approach either “data-driven” or “knowledge-driven”, which can easily be described using the naïve example pictured on figure 3, which comprises an older surface A and a younger surface B. The raw data corresponding to these two surfaces are shown on figure 3a. They can be interpreted in two different ways. Figure 3b shows a “stratigraphical unconformity” corresponding to an interruption of the older surface A by the younger surface B. Figure 3c shows, on the contrary, an “on-lap” configuration ,in which the younger surface stops on the older one.

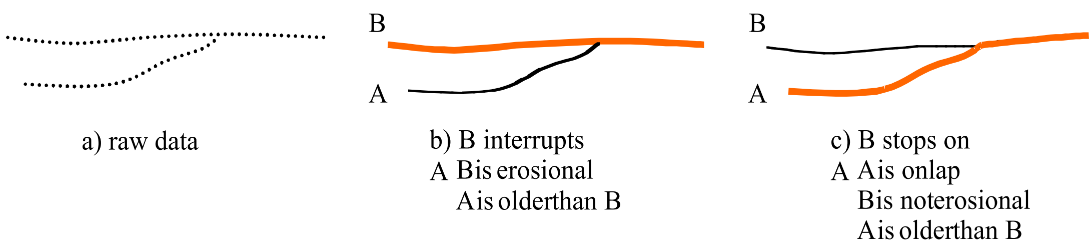



*Figure 3: Relationships between geology and topology : changes in the geological hypotheses induce in the topology and in the surface identification.*

In a **data-driven approach**, the configurations shown on figures 3b and 3c will be merely apprehended as a specific geometrical/topological assemblages. Efforts for producing SEM will then only be dedicated to making sure than these assemblages are correctly taken into account throughout the modeling chain. The main drawback of this approach is that it provides no possibility for changing the geological interpretation. Supposing that the raw data pictured on figure 3a have been interpreted as corresponding a stratigraphical unconformity, there is no way of producing an alternative model where this stratigraphical unconformity would be replaced by an on-lap configuration. This is due to the fact that the geological interpretation is not explicit but remains hidden behind its topological consequences ("B interrupts A" or "B stops on A"). The data-driven approach does not explicitly consider the specific geological dimension of the model .

The above difficulty can easily be overcome using a as **knowledge-driven approach**. Surfaces A and B will then be considered as two geological objects linked by specific geological relationships and the geometrical/topological relationships between these two surfaces will no longer be considered as intrinsic features of the model but as the consequence of geological interpretation. By assuming that B is an "erosional surface" younger than A, it will be possible to deduce a topology in which B interrupts A. Assuming, on the contrary, that the younger surface B is no longer erosional and that the older surface A is an "on-lap surface", we will deduce a topology in which A interrupts B. In this knowledge-driven approach, the topology of the geological model is the consequence of an explicite geological interpretation that is availabe within the modeling chain and which can thus be changed at any time in order to produce alternative models corresponding to different geometrical/topological assemblages.

Most modeling chains currently used by oil & gas companies provide highly interactive modeling tools, which enable the geologist to easily interpret the geology of the model they intend to build by deciding, for instance, with the help of the mouse, which surface stops on which other. However these interactive tools generally do not offer the possibility of expliciting the interpretation hypotheses that are implicitly made when using them. Worse, some of them provide the possibility for the geologist to produce geologically inconsistent models, displaying for instance intersections that cannot be correct in view of the ages of the surfaces involved. For these reasons, the modeling chains currently used by companies at present do not allow the use of a knowledge-driven approach.

# 2 An ontology for geological modeling

## 2.1 Defining a Geo-Ontology

An ontology is a formalism for providing standard descriptions of the languages used by various specialists for expressing their expert knowledge (T.R. Gruber, 1993b), (KSL, 2003). It provides to domain specialists a common vocabulary comprising **"concepts"** or **"classes"** (formal explicit descriptions of the concepts / entities in the domain considered), **"slots"** (properties of each concept describing its various features and attributes), and **"facets"** (restrictions on the slots like: cardinality, value type, etc.). Using such terminology, it is possible to describe the axioms and the constraints specific of the considered domain knowledge. By using this formalized description, domain specialists can easily share a common understanding by means of computer applications and possibly reuse or extend it within the domain considered. For these reasons, ontology has increasingly come out in the recent years as key artificial intelligence tool for semantic-driven information access.

Since it will be used in complex modular modeling chains, the Geo-Ontology that will be presented here should allow reasoning on symbolic objects, which can be used or reused by various applications. It should thus correspond to a system based on knowledge level modular in accordance with the knowledge model approaches developed by A. Gómez-Pérez and V.R Benjamins (1999) and by Velde (Velde 1993), and with the derived knowledge engineering methodology CommonKADS (Schreiber & al. 2000). Moreover, since it deals with geological events, the proposed Geo-Ontology belongs to the broad family of temporal representations studied by M. Abel (1991), C.S Jensen & al. (1998), Galante (2003), B Bennett and A.P.Galton (2004), which can extract relevant information from temporal events and from the order in which they occur.

The constraints of the geology domain knowledge, will be described in the “Knowledge Interchange Format” (KIF, 1998). KIF was one of the first knowledge representation languages. According to T.R. Gruber (1993a), “[it] provides for the representation of knowledge about knowledge, [allowing] the user to make knowledge representation decisions explicit and [...] to introduce new knowledge representations without changing the language”. KIF uses a logically comprehensive declarative semantics. It enables the capture of intuitive sets of axioms and of the related constraints by using definitional forms with ontological significance.

The Geo-Ontology hereafter defined is based on the “geological syntax” developed by M. Perrin, (1998), which provides a formal description of underground geological structures. Its goals are the following:

- provide meanings for the main geological terms and organize them;
- provide a common knowledge shared by professional geologists and various computer-based systems.
- enable software to be autonomous and suited to validate the results obtained.

This Geo-Ontology deals with the broad arrangements of geological objects which are described by “structural geology” (B.E. Hobbs & al., 1976). It is however compatible with more specialized ontology related to geology, such as the one that has been recently developed by M. Abel and her colleagues in the field of sedimentary petrology (M. Abel & al. 1998), (M. Abel 2001), (M. Abel & al. 2003). It constitutes a knowledge base able to be re-used and shared by all computer software dealing with geology and it opens the possibility of producing information enabling the representation of all kinds of underground models.

## 2.2 Geological rules

As we have already mentioned, each geological model depends from an interpretation. When building a model, one must define which surfaces one wishes to represent in accordance with a chosen scale and with one’s particular interest. By choosing to represent a definite number of surfaces, one also chooses to split the geological time into definite time entities (“geological periods”). Each period is bounded by single geological events and corresponds to a span of time during which various geological processes possibly took place corresponding to matter creation (sediment deposition, magma intrusion), matter destruction (erosion), matter transformation (diagenesis, metamorphism), matter deformation (folds, faults, thrusts). Geologists usually consider that the matter created during a definite geological period corresponds to one geological **formation**.

Till now, few authors have paid attention to the above peculiarities of geological models, either for reconstructing sedimentary piles (J. Hamburger, 1989) or for performing automatic geological mapping (M. Sakamoto & al. 1993) or for actual geological modeling (R. Mayoraz 1993), (Earthvision,1999),. Previous work operated in Ecole des Mines de Paris has shown that, in order to be geologically consistent, underground models should be built in accordance with a few chrono-spatial rules. These rules define a “geological syntax” (M.Perrin, 1998). We first assume that surfaces present in an underground model are of two types:

- polarized surfaces (POL) corresponding to limits of sedimentary formations or of intrusive granites; their two faces are geologically different: one faces older formations (= F-old), the other younger formations (= F-young);
- non polarized tectonic surfaces (TEC) which correspond to geological discontinuities, faults or thrust surfaces, whose two faces are geologically equivalent both facing older formations.

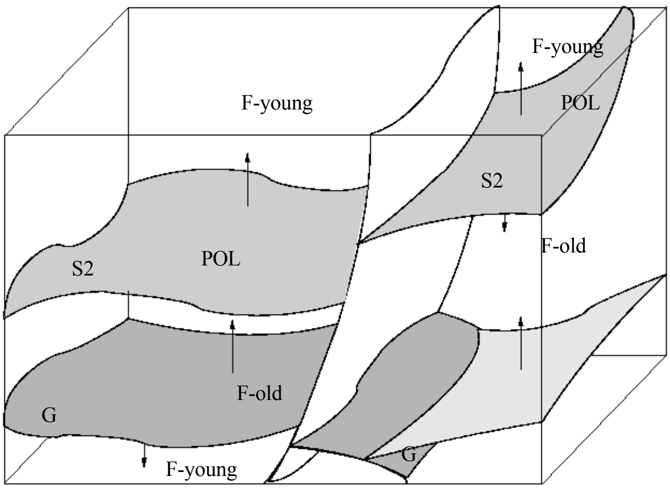



*Figure 4: POL and TEC surfaces. $S_1$, $S_2$ sedimentary POL surfaces (upper side corresponds to F-young); G granite limit POL surface (upper side corresponds to F-old); F fault TEC surface.*

The fundamental rules are that each surface, either POL or TEC has one well-determined age and that when two surfaces intersect, one of them is necessarily interrupted by the other Chrono-spatial relationships between intersecting surfaces can be of two types:

- on lap: when the older surface (B) is a POL (on lap surface), it interrupts the younger surface (A); intersection of (A) with a TEC is impossible;
- unconformity: the younger surface (B = unconformable surface) interrupts the older surface (A).

In order to deal with these cases in any geometric configuration, attributes **DISC/CONC** are given to F-old and F-young faces of each surface in the following way:

- defect values : F-old, F-young = CONC;
- on lap surface : F-young = DISC;
- unconformable surface : F-old = DISC;
- on lap + unconformable surface or fault surface : F-old, F-young = DISC.

Figure 5 provides an example of geological structure scene.

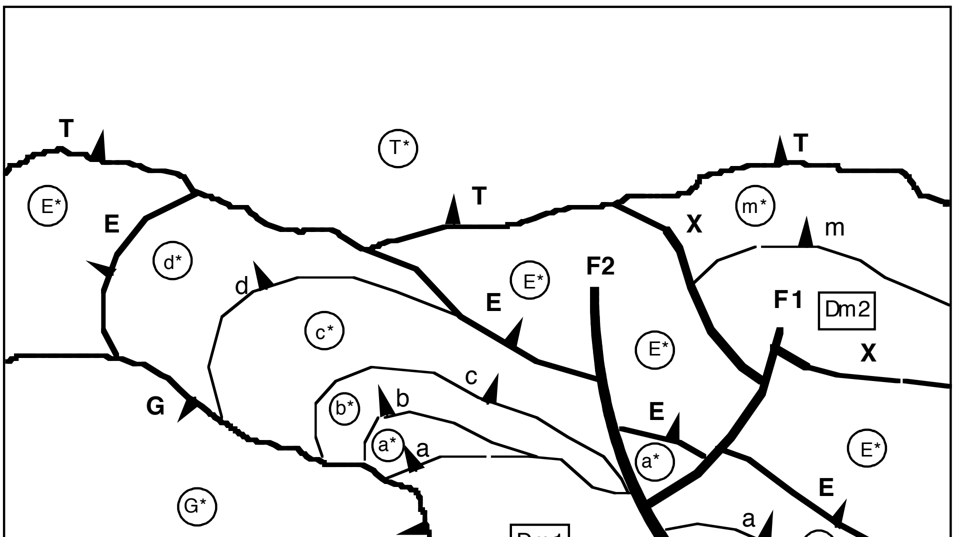


*Figure 5: Example of a geological scene*

This synthetic example records most of the features currently present in geological assemblages:

- POL surfaces (the arrow points towards F-young)
- TEC surfaces

POL surfaces **a, b, c, d, E, m** and **T** are sedimentary surfaces, which respectively underlie sedimentary formations **a**$^*$**, b**$^*$**, c**$^*$**, d**$^*$**, E**$^*$**, m**$^*$ and **T**$^*$ (**T**$^*$ actually corresponding to the atmosphere which overlies the topographical surface **T**)
POL surface **G** is a granite intrusion limit.
Surface **T** is an example of an erosional surface interrupting older surfaces **E** and **X**.
Surface **a** is an example of an on-lap surface, which interrupts younger surfaces **b** and **c**.
$\mathbf{F_1}$ and $\mathbf{F_2}$ are faults, which split older surfaces **E** and **a** into several disconnected parts. Fault $\mathbf{F_1}$ stops on fault $\mathbf{F_2}$ .

Thrust surface **X** separates two different sedimentary assemblages consisting in:

- Assemblage 1: formations **Dm1, a**$^*$**, b**$^*$**, c**$^*$**, d**$^*$**, E**$^*$**)**
- Assemblage 2: formations **Dm2** and **m***.

## 2.3 General concepts

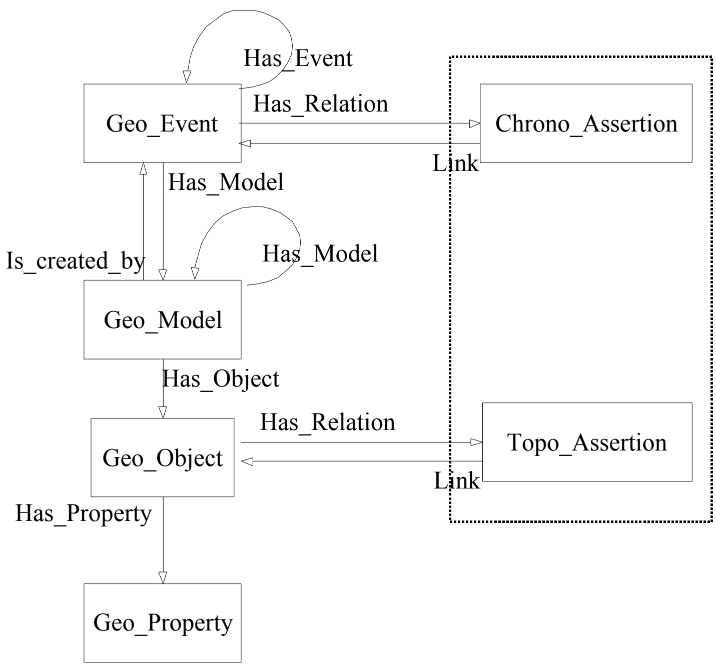



*Figure 6: Geo-Ontology overview*

In the Geo-Ontology, we have defined five basic concepts:

- Geo_Event, which refers to a geological process occurring during a definite span of time or to a combination of such processes. The result of a Geo_Event is a Geo_Model.
- Geo_Model corresponds to a geological assemblage created by a definite Geo_Event. It comprises various Geo_Objects.
- Geo_Objects correspond to actual physical geological objects such as formations, stratigraphical or fault surfaces…. Geo_Objects are described using the Geo_Property package.
- Geo_Assertions are chrono-spatial relationships linking two definite Geo_Events or Geo_Objects.
- Geo_Property refer to any geological or technical property associated to a Geo_Object.

Geo_models can be specified i.e. correspond to a definite physical geological assemblage or be templates. The following examples illustrate the practical meaning of the above defined concepts:

The result of the Geo_Event "deposition of sediments" is a Geo-model **"strata pile",** which can be either an abstract concept (template) or a set of sedimentary layers deposited during a definite span of time. Refering to the example given in figure 2, an elementary Geo_model for a strata pile may consist in 2 stratigraphical surfaces S1 and S2 (i.e. 2 Geo-Objects being given the Geo_Property "**stratigraphical interface"**) linked by the Geo_Assertion: "S2 younger than S1". This Geo_Object can be divided into 3 different templates:

- **"Parallel_Stratification"** where the Geo-Property **"parallel surface"** is given to S1 and S2,
- **"Unconformity"** where the Geo-Property **"erosional surface"** is given to S2,
- **"On-lap"**, where the Geo-Property **"erosional surface"** is removed from S2 and where the Geo-Property **"on lap surface"** is given to S1.

The Geo_Model "fault network" will consist in various Geo-Objects F1, …., Fn possessing the Geo_Property **"fault surface"** linked by the spatial Geo_Assertion **"stopsOn":** specified by the relation: F1 stopsOn F2, F2 stopsOn F3, …, Fn-1 stopsOn Fn.

## 2.4 Related sub-concepts

For each of the basic concepts, we have defined domain sub-concepts and related taxonomies.

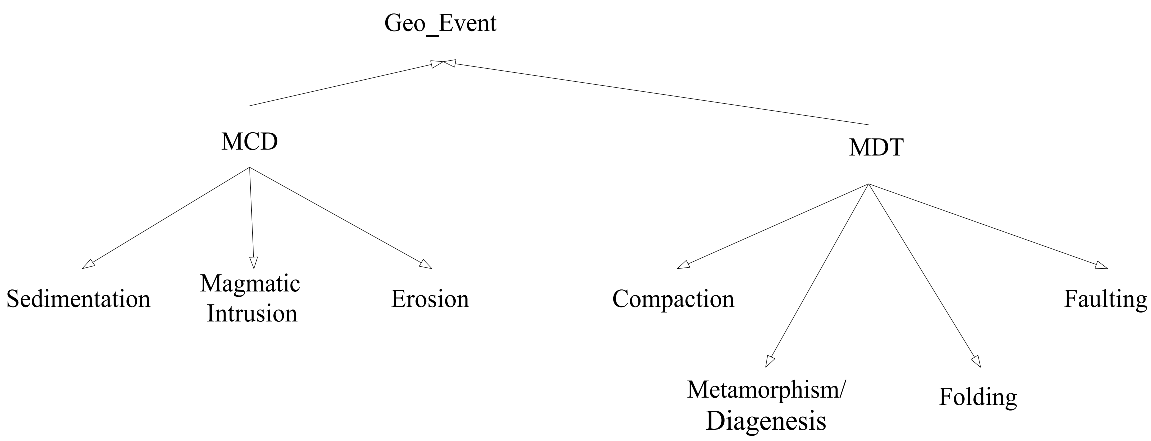



*Figure 7: Geo_Event taxonomy*

As shown on Figure 7, the Geo_Event concept is inherited by two sub-concepts named **MCD** (for Matter Creation and/or Destruction) and **MDT** (for Matter Deformation or Transformation). MCD represents geological processes of matter creation (sedimentation), matter destruction (erosion) and matter destruction and creation (magmatic intrusion). MDT corresponds to matter deformation (folding or faulting) or to matter transformation (compaction, diagenesis/metamorphism).

Each Geo_Event has three slots:

- **rank,** corresponding to a definite scale of representation,
- **duration**, which corresponds to the geological period during which the event was operating,
- **beginsAt**, which refers to the date at which the event started.

In order to specify whether a definite MCD corresponds to matter creation or matter destruction or both, we use three boolean attributes: sedimentation, magmaticIntrusion and erosion. These three attributes must obey to the following rule:

```
( /= (and (MCD ?m).erosion  (and ?m.magmaticIntrusion ?m.sedimentation)) 0)
```

meaning that at least one of the two processes of erosion and sedimentation is necessarily operating in any MCD event.

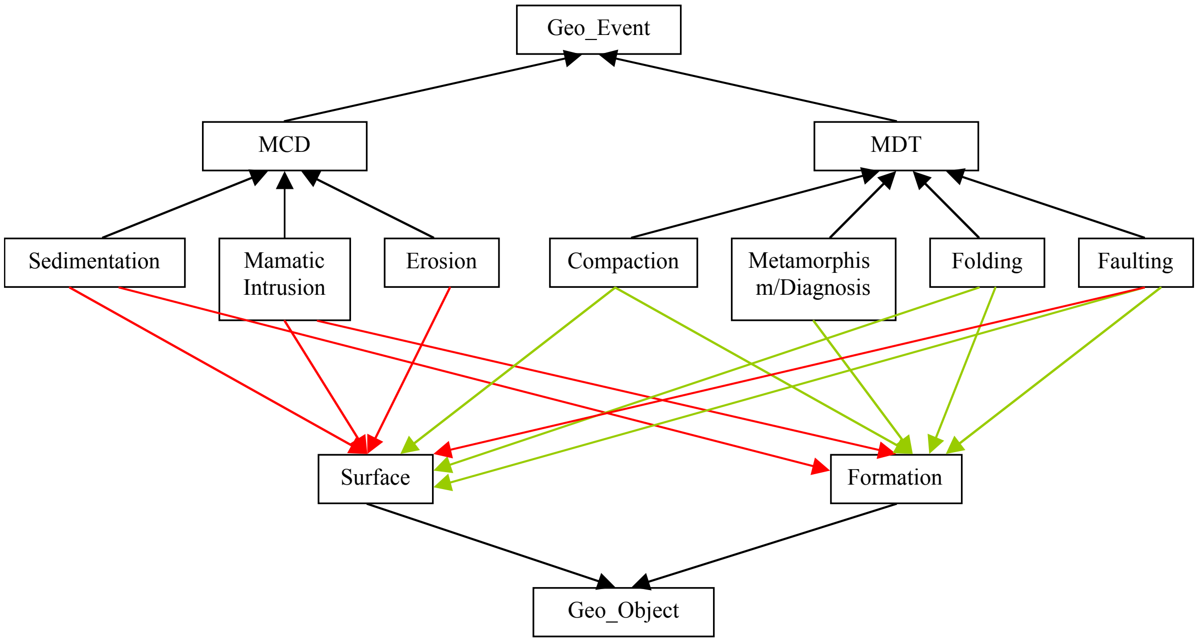



*Figure 8: Relations between Geo_Event and Geo_Object. The red links are the "**Create_Object**" relation; the green links are the "**Transform_Object**" relation; and the black ones are referred to the heritage between the concepts.*

Moreover, as shown in Figure 8, Geo_Events refer to Geo_Objects. We define **"Create_Object"** as the Geo_Event's property, to refer to the Geo_Object's created by all types of the MCD event and faulting event. We also define **"Transform_Object"** as the Geo_Event's property, to refer to the Geo_Object's transformed by all types of the MDT events.

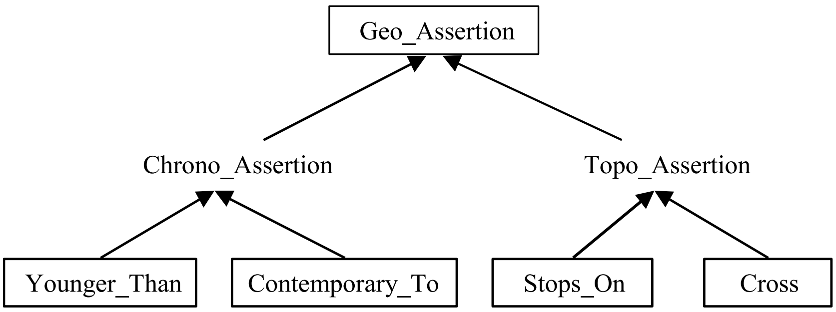



*Figure 9: Geo_Assertion taxonomy*

**Geo_Assertion** concepts represent the relations, which can occur between Geo_Events. They are specified in sub-concepts as shown on Figure 7. Each assertion is linked to two events, respectively by "from" and "to" attributes.

A definite Geo_Assertion embeds the following constraints with respect to the events that it relates.

```
(if (Younger_Than (Geo_Event ?a) (Geo_Event ?b) ) ( < (?a.hasObject).age (?b.hasObject).age))
```

meaning that, if an event a is younger than an event b, the age of a is less than the age of b.

```
(if (Stops_On (Geo_Object ?f1) (Geo-Object ?f2) ) (and ( = ?f1 (TectonicBLS ?t).hasObject ) ( = ?f2 (?t.hasObject))))
```

meaning that, if a Geo_Object F1 stops on a Geo_Object F2, then F1 and F2 are tectonic BLS's.

| |
|---|
| ( if (instance-of (Geo_Assertion ?r) Younger_Than) (< (?r.from).beginsAt (?r.to).beginsAt))(( instance-of (Geo_Assertion ?r) Older_Than ) (> (?r.from).beginsAt (?r.to).beginsAt ) ( ( instance-of (Geo_Assertion ?r) Stops_On ) (= (?r.from).beginsAt (?r.to).beginsAt )))) |

meaning that Geo_Assertions can only be of one of the three types: "younger than", older than" or "stops on".

The **Geo_Object** concept is used to model the various objects met in structural geology.

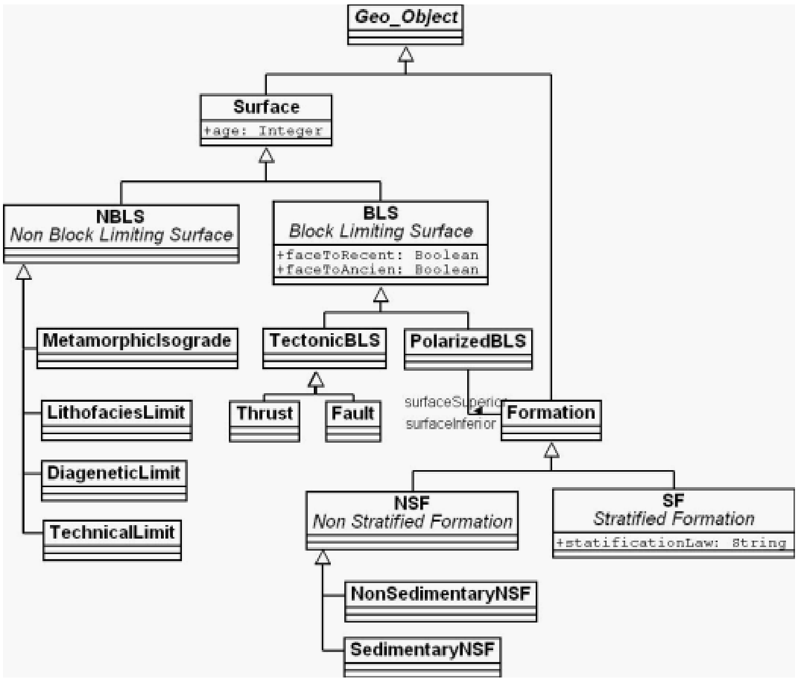



*Figure 10: Geo_Object taxonomy*

According to the geological syntax to which we refer, there are two types of geological objects : "Surface" and "Formation". A formation is limited by at least two POL surfaces, which correspond to **"surfaceSuperior"** and **"surfaceInferior"** attributes (cf. Figure 10). The geological syntax defined by [Per98] only considers "Block Limiting Surfaces" and all the related sub-concepts. However, there also exit in geology "Non Block Limiting Surfaces" such as:

- LithofaciesLimit separating volumes occupied by different types of rocks within a given formation,
- MetamorphicIsograde corresponding notably to paleotemperature limits possibly cross-cutting BLS's,
- DiageneticLimit separating soft and consolidated sediments,
- TechnicalLimit considered in oil and gas exploration such as gas-oil limit, oil-water limit…

The "Formation" sub-concept is specialized in the two sub-concepts: **"StratifiedFormation"** and **"NonStratifiedFormation"**. Each StratifiedFormation is given a stratification law, which represents the geometry of the stratified rocks resulting from sedimentation, sediment compaction and folding.

The constraint corresponding to the fact that the two surfaces of a "TectonicBLS" are Disc can be represented in the following way:

| |
|---|
| ( = (and ((TectonicBLS ?f).faceToRecent) ((TectonicBLS ?f).faceToAncient) ) 0 ) |

In addition, the "Formation" sub-concept involves the two following constraints on the surfaces that limit it:

( = ( – ((Formation ?f).surfaceSuperior).age ( ?f.surfaceInferior).age ) ?f.duration )

Moreover, the NSF concept can be specified to two sub-concepts according to their surfaceSuperior attributes respectively. We define them as follows:

(define-class NonSedimentaryNSF (?x) def: (and (subclass-of NonSedimentaryNSF NSF) ((?x.surfaceSuperior).facetoRecent) (not ((?x.surfaceSuperior).facetoAncient))))

corresponding to an intrusive formation (e.g. granite)

(define-class SedimentaryNSF (?x) def: (and (subclass-of SedimentaryNSF NSF) ((?x.surfaceSuperior).facetoAncient) (not ((?x.surfaceSuperior).facetoRecent))))

corresponding to a non stratified sedimentary formation (e.g. re-formation)

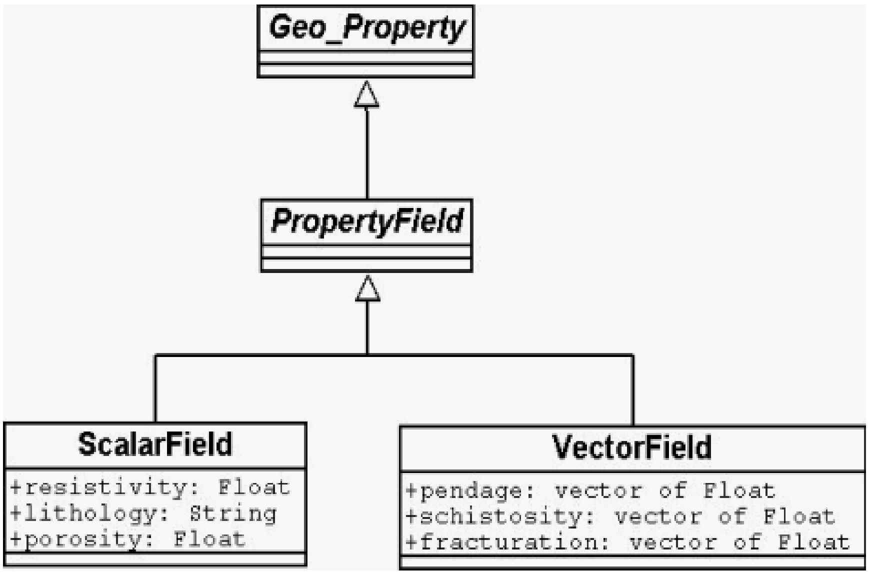



*Figure 11: Geo_Property taxonomy*

The **Geo_Property** concept is used to attach to a given Geo_Object domain oriented properties of various type. As shown on Figure 11, we refine this concept in our case by introducing the PropertyField sub-concept in order to fill geological volumes with attributes such as lithology porosity, resistivity (corresponding to the "ScalarField" slot) or such as dip, tectonic cleavage (corresponding to the VectorField" slot.

### 2.4.1 Additional constraints

Different levels of details can be represented by events of different ranks. This induces **additional constraints**:

- between event of rank(n) and event of rank(n+1).

(>= ((iota (?x) (hasEvent (Geo_Event ?e) ?x)).beginsAt) ?e.beginsAt)

```
(<= ?e.duration (+ (setof ((?x) (hasEvent (Geo_Event ?e) ?x)))))
```

- between Geo_Events and Geo_Objects, if we define:

```
( = ?x (Geo-Event ?e).hasObject )
```

These constraints are the following:

```
(if (instance-of  ?x Formation) (= ?e.beginsAt  (?x.surfaceSuperior).age) ) (if (instance-of  ?x Formation)  (=  ?e.duration  (–  (?x.surfaceSuperior).age  (?x.surfaceInferior).age)  ))  (if (instance-of ?x Surface) (= ?e.beginsAt ?x.age) )
```

meaning that the total duration of the events of rank n+1 corresponding to an event of rank n must be inferior or equal to the duration of this rank n event and that the surfaceInferior of the older of the rank n+1 event is the same as the surfaceInferior of the corresponding rank n event.

# 3 Application: building "Shared Earth Models" by using the "geological pilot" methodology

## 3.1 Presentation of the demonstration

In order to illustrate the use of the Geo-Ontology that we have defined, we have operated a demonstration on an example extracted from a real case study operated at IFP. The necessary IT tools to realize this demonstration have already been produced and experienced by the EpiSEM Action project (EPISEM, 2000).

The raw data consist in 7 unsegmented geological surfaces which have been imported as an unstructured RESCUE model (RESCUE 2004). Our demonstration involves the workflow illustrated on Figure 12, which consists:

- in putting geological attributes to each of the imported surfaces through a "Geological Knowledge Editor" (GKE) and in gathering the resulting information in a geological descriptor, the "Geological Evolution Scheme" (GES). This stage corresponds to geological interpretation.
- in building a 3D model by intersecting and segmenting the various surfaces in a definite order determined by reading the GES (Geological Pilot Methodology).

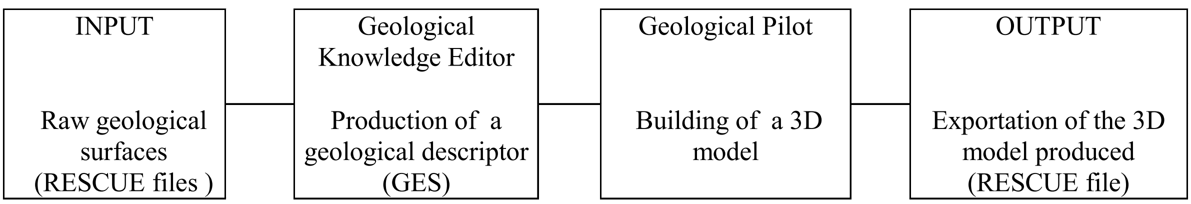



*Figure 12: A real case of building 3D earth model demonstrated in the EpisemAction project.*

The result is a fully consistent geological model that can be exported as a structured RESCUE model.

We will expose then methodology used for the demonstration in sections 3.2 and 3.3, and present the obtained result in section 3.4.

## 3.2 Performing and recording a geological interpretation

In order for the geologist to perform and record his/her geological interpretation, we have created two specific items the **Geological Knowledge Editor (GKE**) and the **Geological Evolution Scheme (GES).**

The **GKE** is a tool for facilitating the geologist's interpretation. Thanks to the GKE's user friendly interface, the geologist can put geological attributes to each of the geological surface. The imported RESCUE model is thus transformed in a Geo_Model consisting in various Geo_Objects, which are given Geo_Properties (POL surfaces of various types, faults etc...) and which are linked by various Geo_Assertions, which record their chrono-spatial relationships.

By referring to the Geo-Ontology the GKE automatically records these Geo_Assertions in a logical structure the "Geological Evolution Scheme", that will be described hereafter. Doing so, the GKE acts as a compiler: a surface having age relationships incompatible with the surfaces previously introduced will not be accepted as a new valid GES node and an error message will be given to the user. The knowledge recorded in the GES can thus be used to check the consistency of the geological structure that is created.

The **GES** is a descriptor of the geological interpretation performed by using the GKE. It consists in a graph, which classifies the Geo_Objects corresponding to the various surfaces of the model according to their relative ages. The GES can be seen as a specific case of the above defined Geo-Ontology representing the structure and the history of the geological assemblage to be modeled. Examples of GES are given on Figures 13 and 14.

The GES data structure is an oriented acyclic not necessarily connex graph which may have several root nodes (S. Schneider, 2002). For a GES of rank *i*, nodes can be of four types :

- **SED PILE** ***S*** = sedimentary pile, which can be a single POL surface or a pile of POL surfaces described by a GES of rank *i+1* and having the same bottom surface as *S*;
- **FAULT NET** ***N*** = fault network, which can be a single fault or thrust surface or a set a faults described by a GES of rank *i+1*. The various faults have all one age and are linked by "stops on" relationships.
- **FOLD** ***F*** = folding geological transformation; it modifies the stratification laws from the preceding POL nodes.
- any **SEG of rank** ***i+1***, corresponding to an increased level of detail.

With the help of the GKE, the user builds a GES in accordance with his/her interpretation of the available geological data. He / She creates nodes of the graph corresponding to various geological events and arcs which link these nodes according to chronology (a definite event is anterior/posterior to another) or to specific spatial relationships (a definite fault stops on another definite one).These relationships enable to deduce the topology of all surface intersections by specifying in each case which surface interrupts the other.

As an example, using the geological editor, it is possible to deduce from the scene shown on Figure 5 the GES represented on Figure 13. The various concept instances that are involved in the construction of this GES are represented on Table 1.

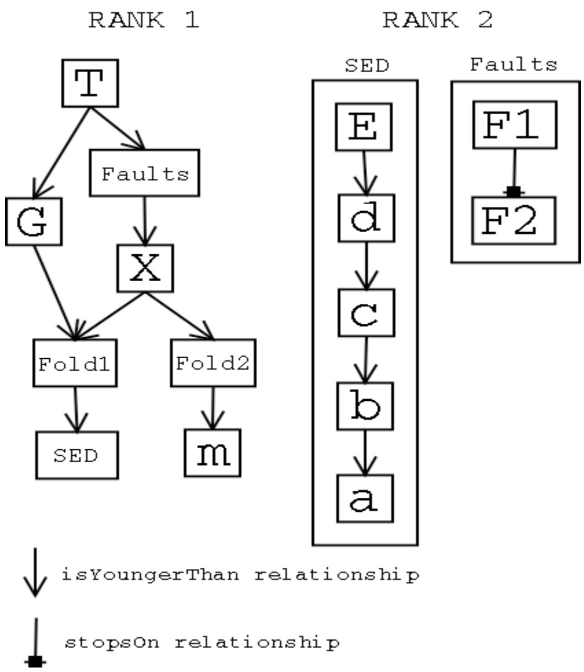



*Figure 13: GES corresponding to the scene shown on figure 5.*

| Surface | Formation | Instance-of |
|---|---|---|
| T | T* | POL (unconformity) |
| G | G* | POL (intrusive) |
| F1 | | Fault |
| F2 | | Fault |
| X | | Thrust |
| M | M* | POL (conformity) |
| E | E* | POL (unconformity) |
| D | D* | POL (conformity) |
| C | C* | POL (conformity) |
| B | B* | POL (conformity) |
| A | A* | POL (onlap) |

*Table 1: Concepts instances involved in the construction of the GES represented on Figure 5.*

## 3.3 Automatic building of a 3D model

In 2001, Institut Français du Pétrole and Ecole des Mines have developed a prototype of **"Geological Pilot",** which can be coupled to most currently used geological modelers (S. Brandel et al., 2001) and which is still being improved (S. Brandel et al., 2004). It enables to automatically build from unsegmented geological surfaces a 3D geological model fully consistent both topologically and geologically by using the geologic interpretation recorded in the GES. In addition, the resulting model can easily be revised in case of changes of the data and/or the interpretation made by the user. The algorithms used in the Geological Pilot are described in (S. Schneider, 2002).

The "geological pilot methodology" consists in considering partial order relationships established between the various geological surfaces by means of the GES and in using them for building a consistent model step by step. The various raw surfaces are identified using 3G-maps (P. Lienhardt, 1994), an optimized data structure designed for describing and managing the 3D scene topology (Y. Halbwachs, Ø. Hjelle, 1999). The rule is that an older geological event cannot modify a younger one. In consequence, the various intersections that must be operated are identified by running through the GES graph from top to bottom (interpretation course) and, for each node met, from this very node to the top (intersection courses). The second course is launched if and only if all the ascendants of the current node have already been interpreted. Otherwise, we recursively go back to process the upper following branch of the graph that has not already been interpreted (cf. Figure 14).

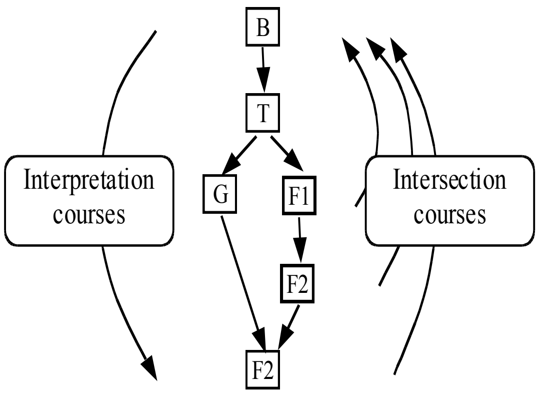
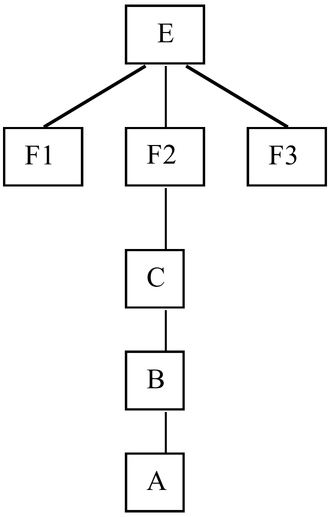



*Figure 14: Determination of the intersections to compute by going through the GES with imbricated interpretation and intersection courses; for each step of the interpretation course, we run an intersection course.*

## 3.4 Results

The unsegmented surfaces corresponding to the input rescue model used for the demonstration are pictured on Figure 15. The geological interpretation has consisted in considering that all subvertical surfaces are faults (F1, F2, F3) and all the others surfaces. Moreover, surface E has been considered as erosional since it interrupts surface c, while surfaces a, b, c have been considered as regular parallel stratigraphical surfaces. In addition, we have made the assumption that the upper located stratigraphical surfaces are the younger. The GES corresponding to this interpretation is pictured on Figure 16.

Figure 17 shows the resulting structural model. It has been realized in an entirely automatic way by introducing the surfaces one by one and by intersecting and segmenting each surface with those previously introduced into the model as explained in section 3.3. The result shows correct topologies, surface E cutting all older surfaces and faults F1, F2, F3 inducing off-sets in all the stratigraphical surfaces that they cut.



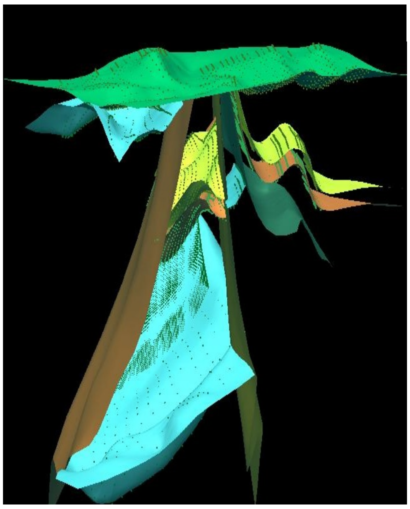



*Figure 15: Original structural model* *Figure 16: A GES view*

*Figure 17: Resulting structural model*

# 4 Conclusion

## 4.1 Further application of the Geo-Ontology to model building

The above given example of application corresponds to the very specific case of a 3D geological modeling starting from existing unsegmented geological surfaces, which uses a rather simple workflow . We presently study the much broader problem of building reservoir models starting from 3D seismic data, which directly concerns the everyday activity oil & gas companies. For this we consider more complicated workflow such as the one represented on Figure 18.

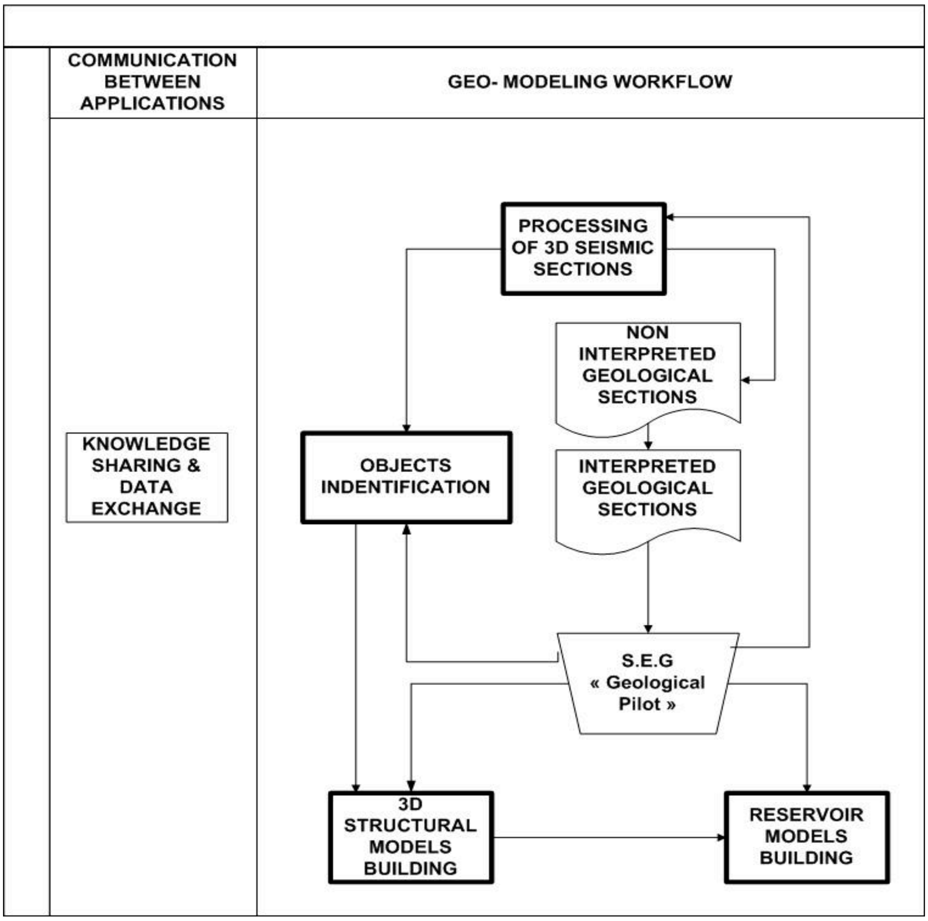



*Figure 18: A more complicated workflow using GES and Geological Pilot.*

This workflow shows that, in this case, the geological knowledge recorded in the GES will be used in four different types of applications dealing with:

- object identification, i.e. the reconstruction of unsegmented surfaces from clouds of points,
- building of 3D structural models using the geological pilot methodology,
- deriving reservoir models from structural models by adding stratigraphical meshes in the various geological blocks,
- improving the processing of the original seismic data before a possible replay of the model building for an improved result.

This is just given in order to show how the Geo-Ontology that we have defined and the derived GES, can actually be used in a realistic knowledge-driven approach for the geological model building.

## 4.2 Conclusion

Since raw geophysical and geological data are intrinsically ambiguous and frequently ill-distributed, no geological representation can be deduced from the data without a previous geological interpretation. In the case of 3D modeling, the geologist often implicitly provides his/her interpretation while building model. However these interpretation hypotheses are not recorded as such. This induces a major difficulty for the Earth Model sharing since there is no easy means for recovering the geological knowledge implicitly attached to a definite model.

The present paper has coped with this difficulty by proposing a formalism for explicitly expressing the geological knowledge attached to any geological assemblage. This opens the possibility of substituting the present data-driven modeling approach by a knowledge-driven approach. The abstract geological interpretation encapsulated in the GES makes possible an easy communication between the various software applications operating for the model building. This opens the way for performing 3D models in a largely automated way and for model updating, extension or revision by any user through internet or intranet networks.

The Geo-Ontology presented appears as an adequate potential standard to represent the most important knowledge used by geologists for representing current assemblages of terrain. It can be seen as a kernel of knowledge that can be shared by most geologists involved in modeling for various purposes: oil exploration, underground storage, civil engineering, etc. It can easily be re-used or extended for particular software development.

Since the defined GEO-Ontology rests on the basic assumption that any particular terrain assemblage is the result of a definite history , it appears to be particularly suitable for modeling step by step the various stages of the corresponding geological evolution.  We intend to devote much work in the near future to such “kinematic” modeling.

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