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Illustrative Multivariate Visualization for Geological Modelling – Supplementary Material

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Abstract

In this paper, we present a novel illustrative multivariate visualization for geological modelling to assist geologists and reservoir engineers in visualizing multivariate datasets in superimposed representations, in contrast to the single-attribute visualizations supported by commercial software. Our approach extends the use of decals from a single surface to 3D irregular grids, using the layering concept in order to represent multiple attributes. We also build upon prior work to augment the design and implementation of different geological attributes (namely, rock type, porosity, and permeability). More specifically, we propose a new sampling strategy to generate decals for porosity on the deformed grid; a hybrid visualization for permeability, which combines 2D decals and 3D ellipsoid glyphs; and a perceptually-based design that allows for visualizing additional attributes (e.g., oil saturation), while avoiding visual interference between layers. Furthermore, our visual design draws from traditional geological illustrations, facilitating the understanding and communication between interdisciplinary teams. An evaluation by domain experts highlights the potential of our approach for geological modelling and interpretation in this complex domain.

In this additional material, we present an overview of workflows, task analyses and challenges in the oil and gas domain. This characterization comes from our long-term collaboration with domain experts, literature review as well as previous studies conducted in this domain, and aims at informing visualization practitioners new to this domain.

For our characterization, we use the *multi-level typology framework* [BM13]. This typology allows "the translation of empirically observable domain problems into abstract tasks and subsequently into design choices" [BM13]. For a given task, we first identify *why* the task is performed, and then *how* the task will be supported. *What* connects these two stages and refers to the *input* and *output* (if applicable) of a task. For more details we refer the reader to [BM13,Mun14]. We use the labels **`black`** and **`purple`** bold to refer to **`action`** and **`targets`** under the *why* category, whereas **`green`** bold refers to the *how* category (in the paper).

1 Domain Problem Characterization

In the domain of oil and gas, the process of exploration, development and production (E, D&P) consists of complex tasks and workflows that require the processing of large volumes of data coming from multidisciplinary sources [SBS15] (Figure 1). The ultimate goal is to obtain optimal recovery from the subsurface pools of hydrocarbons encompassed by rock formations. For this purpose, several data processing and analysis tasks are conducted by multidisciplinary teams to create a reliable version of the target geological reservoir. In the next subsections, we provide details on some of the challenges faced during the modelling and exploration of these datasets.

1.1 Exploration Stage

The main part of the understanding of the geological reservoir happens during the *exploration stage*. In this stage, geophysicists and geologists aim to **`discover`** potential areas of exploration from a set of seismic images from the field — classified as prestack (raw data) or post-stack (post-processed data) — produced by the process of seismic echography. They aim to **`discover`** geological scenarios and potential reservoirs for exploration called *prospects* [WKC14]. To achieve this goal, exploration wells are drilled and physical and digital data such as *rock core* (pieces of rock) and *well log* (physical measurements made by instruments lowered into the hole that capture certain frequencies (logs) referring to specific lithologies (rock types)) are collected from the wellbore. This process is known as *coring* [GA11].

1.2 Development Stage

After the reserves are confirmed, the goal now is to **`generate`** a 3D geological representation of the underground reservoir. For this purpose, seismic images are used (generally post-stack images, after the noise and over corrections are made) as a basis to **`generate`** the topological part of the reservoir (gridding process). Each layer of the reservoir is **`derived`** from a series of geological interpretations on the seismic images conducted by geologists – e.g., by sketching horizon lines and faults [PGT*08]. Due to noise and lack of precision from the seismology acquisition, the process of defining the layering of the subsurfaces of the field, named *horizons*, relies on the expertise of geologists and their ability to conceptualize geological scenarios [LNP*13]. This process is known as *seismic interpretation* [NLP*13].

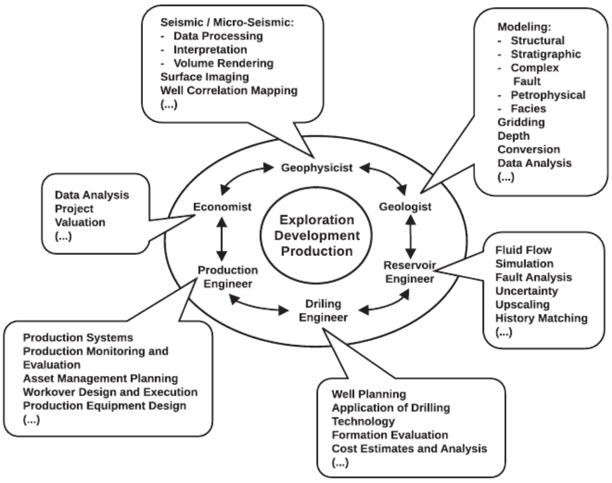

Figure 1: *Multidisciplinary disciplines and tasks throughout the exploration, development and production stages [SBS15].*

1.2.1 Geological Modelling

After the structural grid is created, the next step is to **discover** the overall geological **trends** of the underground reservoir. Since reservoir models are generally built to be input to flow simulators that are used by reservoir engineers in order to **verify** flow behavior, in order to achieve success, these models have to capture the essential heterogeneity of properties (**trends**) that will impact reservoir simulation performance. Because the information from small scales (e.g., coring data and lab measurements) are interpolated/extrapolated to several meters following some geostatistical model [GA11], the amount of uncertainty that is inserted makes this task highly difficult. Moreover, if these static models fail to model the reservoir heterogeneity, the simulation forecasts conducted by the reservoir engineers can be useless. For this reason, geologists and geophysicists **explore** the **distribution** of these properties (within the reservoir model) to **verify** if the property modelling is appropriate or if it has features (**outliers**) that were introduced which are contrary to the knowledge of the well data (e.g., core data, well log). During these studies, they **explore** and **compare** geological attributes to **identify** **correlations** between properties and geological or petrophysical **trends** [RB15]. This task is even more challenging since attributes have different data types (e.g., scalar, tensor) and semantics.

To model geological attributes, geologists begin with the goal of **generating** the attribute *facies*, which are distinct sedimentary areas that correspond to rock types. In the literature, there are several methods available aiming to generate a good initial distribution of facies along the reservoir from the sampled data. These methods are typically based on geostatistical models such as sequential-indicator simulation [JH03], object-based modelling (OBM) [HD*90], truncated Gaussian simulation (TGSIM) [MA94], or multiple point statistics (MPS) [Str02]. After facies are defined, unique property values are assigned in each grid cell describing its geology (geological attributes) such as *rock type*, *permeability* and *porosity* (where these **depend** on facies). The property distribution typically uses interpolation or a combination of geostatistical methods such as kriging [OW90], sequential-Gaussian simulation (SGS) [DJ98], or multiple-point statistics (MPS), within each of the facies previously modelled. After the geological attributes are populated, the three-dimensional model is now known as a fine-scale (high resolution) geological or static reservoir model.

1.2.2 Static Uncertainty and Quality Control

In the previous scenarios, the process of creating a reliable geological model involves a lot of uncertainty and depends on statistical models and methods for extrapolating/interpolation information. Indeed, uncertainty exists in all stages: in raw data measurements, raw data processing and interpretation, structural modelling, stratigraphic modelling, facies modelling, property modelling, among others. These methods cannot guarantee that the attributes' heterogeneity match the underneath reservoir.

The uncertainty involved in this domain negatively affects the ability to fully understand the reservoir behavior thereby affecting reliable production forecasts and drilling planning in the next stages. To reduce uncertainty during geological modelling, a common approach is to **generate** several alternative models, which are called *geological realizations*. In this process, geostatistical techniques are used to model uncertainty through stochastic simulations [MM99]. This method **generates** equally-probable spatial distributions of properties, called realizations. After this process, the problem of data interpretation and understanding scales from one to hundreds of geological models. From these sets of models, it is necessary to **identify** the ones that better represent the reservoir heterogeneity, generally based on some attribute **similarity** criteria. Some methods to rank geo-realizations consider volume-based measures of oil or gas in place (OOIP or OGIP), the net porous volume (NPV), the gross rock volume (GRV), or the connected volume using various connectivity criteria [RA13]. After the models are **identified**, the best ones still need to be **verified** and **explored** for the aforementioned reasons, which leads to a time-consuming process.

1.2.3 The Simulation Model

Once the geological model contains the geological attributes, reservoir engineers are responsible to **generate** a dynamic model from the static model by integrating production data (e.g., pressure) and laboratory data (e.g., fluid properties analysis) [GA11, RB15]. From the geological model, they **produce** the *simulation model* or *dynamic model* through a process called *upscaling* [RB15] that yields a coarser version of the geological model. The upscaled models can be several times smaller than the geological model in terms of resolution, which makes the capture of detailed reservoir descriptions difficult. Big cell sizes (simulation grid) cause modeling processes to be performed using average values which often mask situations dominated by the **extremes**, not by average **distributions** [GA11]. An example is an area of very low permeability in the geological model that acts as a barrier to the flow of fluids; after the averaging process this barrier may disappear. Therefore, the flow behavior is not captured adequately in a model that has a coarser grid. For this reason, reservoir engineers also **browse** detail cells or small regions (**outliers**), since a single cell may be responsible for situations such as leaking. Some recent research has emphasized further how the transition between scales is one of the reasons why reservoir simulations can fail in predicting fluid flow behavior [AG*13, ACG*14].

The simulation grid resolution is defined according to the **distribution** of the reservoir properties [RB15]. The reason for upscaling is that simulations are time and cost intensive when run in large models. Also, reservoir engineers need to run these simulations (which can take hours, days or even months) in several geological conditions which make this task even more complex.

1.2.4 Static Connectivity Analysis and Parameter Tuning

Reservoir engineers **explore** geological attributes as parameters for better prediction of oil recovery. They **identify** spatial configurations of static properties, e.g., *data* **correlations** and *geological* **features** (structures), in order to **summarize** optimal reservoir development strategies and to better **discover** the dynamic reservoir performance prior to running costly and time intensive fluid flow simulations. Due to its reliability, this task is better conducted on the static geological models.

Much research has been devoted to developing fast performance estimators as surrogates for flow simulation such as *time of flight* [ZGR*17]. These estimators do not aim to replace a full flow simulation; rather, their value lies in rapidly determining parameter sensitivities and screening reservoir models or production scenarios [dJVDJL09]. In particular, some efforts focus on using a combination of static geological information to quantify reservoir connectivity, a **derived** property that has already been proven to have a strong correlation with the efficiency of hydrocarbon recovery [HL10]. These *static connectivity estimators* (e.g., [MHS*16]) are easy in concept, inexpensive in execution, and create an important intermediate level between the reservoir characterization and simulation studies for the assessment of reservoir productivity.

In a primary recovery, if a part of a reservoir is not connected to a producing well, then the hydrocarbon present in that region cannot be recovered. In secondary recovery using water injection, both producing and injection wells need to connect to the same reservoir geobody in order to create better sweep zones. Therefore, there is a need to **identify** these regions. Connectivity is a necessary condition for reservoir productivity. In particular, for the assessment of optimum well placements, static connectivity analysis can be used by engineers to **identify** multiple production scenarios, **locate** promising candidates, and to **identify** only the most promising scenarios for running dynamic simulations. Metrics to define connectivity are commonly referenced as the so-called geobody and reservoir-to-well connectivity and are **derived** in terms of multiple geological properties such as facies, permeability and/or porosity cut-off(s), as well as propagation algorithms to **identify** connected grid cells.

All in all, engineers must define and assess a number of different well placement and recovery scenarios to select optimal outcomes. This procedure is called *well placement optimization* and involves a highly exploratory process, where engineers progress through different stages such as geological analysis (e.g., connectivity), incorporating gradual changes in parameters, **locating** the well trajectories, **verifying** connected areas, **generating** fluid flow simulations, and **verifying** the predicted reservoir performance.

1.3 Team Collaboration and Decision Making

Despite the aid of automated tools and methods, the process of **locating** optimal placement scenarios and recovery still remains heavily exploratory and relies on the analysis and interpretation of a series of specialists, who are the true driving force behind geological modeling and well optimization. Group work and analysis are also common for improving awareness of the data and reaching better decision making. Teams of engineers, geologists, geophysicists, and potentially other specialists may **summarize** recovery strategies; **summarize** the results from flow simulations, **identify** inconsistencies or interdependencies on the data, and finally **present** optimal strategies for project managers and stakeholders.

2 Abstract Tasks

WHY	Abstract tasks related to geological models
Analyse	
Discover potential areas of exploration from seismic images	
Discover overall geological scenarios	
Generate the 3D geological model topology	
Generate geological attribute distributions	
Generate geo realizations to deal with uncertainty	
Generate the dynamic simulation model and its fluid flow attributes	
Present results to managers and stakeholders and other multidisciplinary teams	
Present geological attributes considering data type and semantics	
Derive attributes or/and metrics that quantifies connectivity	
Verify possibilities for flow behavior prior to run simulations	
Search	
Explore distribution of attributes	
Browse cells and small regions (details)	
Locate promising candidate scenarios for well placement	
Locate optimal placement strategies	
Browse prospects for future exploration	
Locate well trajectories	
Queries	
Identify potential areas of exploration	
Identify geo realizations that better represent the reservoir heterogeneities	
Identify correlations between dynamic attributes	
Identify correlations between static properties	
Identify correlations between dynamic and static properties	
Identify geological features and structures	
Identify production scenarioes	
Identify connected regions	
Identify inconsistencies or interdependencies on the data	
Identify if well trajectories go through connected areas	
Identify wrong property values	
Identify parameters for the simulation	
Identify geogical trends	
Compare geological attributes	
Compare geological structures	
Summarize optimal development strategies	
Summarize geological trends	
Summarize recovery strategies	

Figure 2: *Abstract visualization tasks using the multi-level typology introduced by Brehmer and Munzner [BM13].*

Figure 2 describes a list of abstract tasks identified from our domain characterization. Our intention here is to provide an initial characterization that can be used and further refined in subsequent works.

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