Studying Long-term Earth Deformation Processes with Visual Analytics Methods

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Abstract
This paper points out the close correlation between scientific tasks, reasoning artefacts and visual analytics tools. Two concepts are introduced to describe and model the scientific research process, its tasks, and reasoning artefacts. They form the basis for an assessment of existing visual analytics tools which are used to assist the process of studying long-term earth deformation processes. An experts' reasoning process from interpretation of 2-D and 3-D reflection seismic data up to tectonic modelling as well as tool application was examined. The tools were evaluated in terms of their support on creating reasoning artefacts like hypothesis and model building; issues for developing advanced tools are specified.

Keywords: Geo-Visualization, Scientific reasoning, Artefacts, Long-term earth deformation process.

1. Introduction

Understanding long-term earth deformation processes is necessary especially in terms of their effects and impact on human life and activities. Knowledge about these processes may support decision making, for example finding the best location for a bridge in an area with high earth deformation potential. Studying and understanding log-term earth deformation processes requires models which describe these processes. For the modelling activity different approaches exist: numerical modelling which applies mainly mathematical methods, and analogues modelling which makes use of visual methods amongst others.

In the field of visualization a new research field gains more and more attention: visual analytics. The basic idea is to support the capabilities of the human visualization system in information processing by computer systems which extract and compile information from mostly large and heterogeneous databases. It wants to combine the strengths of human and machine (Encarnacao 2005, Andrienko &Andrienko 2006).

The goal of our research is to develop visual analytics methods and tools for all aspects of analogues modelling of long-term earth deformation processes. In a cooperative project located at GeoForschungsZentrum Potsdam (GFZ Potsdam) attended by Geophysicists, Geologists and visualization experts we want to examine following questions: a) What scientific tasks have to be supported by the tools? b) Which visual analytics methods and tools are suitable and necessary to support these tasks? c) How must these tools be designed that they can be part of an interoperable framework? In the first step of our work we take a closer look to the various scientific tasks that have to be assisted by the tools. Besides, we examine and assess visualization tools and methods which are applied already to assist the modelling process in the domain of long-term earth deformation processes. The development of advanced visual analytics methods and tools will be the main goal in the next step of the project.

2. Studying long-term earth deformation processes

Long-term deformation processes cannot be observed in-situ in real time. Only single situations from present or past times can be grasped. If we want to gain an understanding of the complex processes that have formed the current structure of the earth, we have to reconstruct them from material and data as observed today.

Geoscientists like Geophysicists, Geologists or Mineralogists, look at a variety of aspects to study geo-processes: minerals and their properties, geological small- and large-scale structures like bands, fractures or subduction zones, dynamic phenomena like volcanoes or seismic data as well as surface pattern. Only the combined view to all of these different but correlated aspects brings out a comprehensive understanding and modelling of the ongoing processes.

Scientists who work in this field have to handle very different data:

- Short- and long-term data that range from seconds and days to millions of years;
- small- and large-scale data covering an interval of millimetre and meter to some thousands of kilometres;
- one-, two- and three dimensional data like volcanoes as point data, surface patterns as two-dimensional data or data from highly complex three-dimensional geological structures;
- measured and interpretation-derived data, like seismic data as basic data and derived interpreted lineaments; or
- data with good and bad quality .

Also, one has to deal with data in different forms like tables, maps, graphs, pictures and even films.

Scientists have to analyse all the data, bring it together and correlate it, form assumptions, and, finally, develop models of geo-processes. In this scientific working and reasoning process different methods and tools are used, one group are visual analytic tools.

3. Scientific tasks and visual analytics artefacts

To design visual analytic tools which are suitable in a great extent to support a scientist’s work, the scientific research process with its tasks has to be regarded more closely. In the field of GIScience Gahegan (2005) has introduced an approach of the research process where he combined the core activities exploration, synthesis, analysis, evaluation, and presentation, with several further components: conceptual structures, like hypothesis or concept; concretized representations, like category or model; scientific activities, like induction or deduction; as well as visual and computational methods. This model gives a goof overview about involved components and their relations. A further approach to describe the research process comes from analytic reasoning. This approach focus on *reasoning artefacts*, which are tangible pieces of information that are identified or created by a scientist during the reasoning process and contribute to reaching defensible judgements (Thomas & Cook, 2005). The reasoning artefacts range from simple pieces of raw data to high-level constructs that represent large parts of analytic solution. They are (after Thomas & Cook, 2005):

- Source data: an individual piece of data or media, that has to come to the analyst's attention
- Relevant information: source data that is believed to be relevant to the issue and usable for constructing arguments and judgements
- Assumption: An asserted fact and its basis that will be used for reasoning
- Evidence: The information or assumption takes on argument value when the analyst assesses its quality, accuracy, strength, certainty, and utility against higher-level knowledge artefacts.
- Patterns and Structures: Relationships among pieces of information
- Arguments: logical inferences linking evidence and other reasoning artefacts into defensible judgements
- Causality: Inference that forms the argument that an event or action caused a second one.
- Models: A means of encoding a complex phenomenon with its structure, behaviour or appearance
- Hypothesis: A conjectured explanation, assessment or forecast
- Scenarios: Sequences of information in explaining or defending part of a judgement chain.

Both approaches should be combined to get a comprehensive framework for scientific task description. The first approach deals with the whole scientific process, and identifies the involved components; the second elaborates the cognitive artefacts used in the process.

Artefacts are tools that help a person to fulfil a task. The artefacts mentioned above can be described as cognitive or reasoning artefacts. If the analytical reasoning process should be supported by visual analytics tools a further group of artefacts comes up and has to be considered: visual artefacts. Artefacts have a specific role in accomplishing tasks; they contribute decisively to if a task can be fulfilled successfully or not. Artefacts receive high attention in Activity Theory where they are considered as mediators between the intended and the achieved activity goal (Nardi, 1996; Dransch, 2001; 2002). Only a well designed artefact can act as a good bridge, first to pass successfully through the execution of all necessary activities and actions and second to evaluate the attained goal against the intended goal.

If the scientific process with its diverse tasks is to be supported by visual analytics tools two groups of artefacts have to be considered: the reasoning artefacts and the visual artefacts. Thus, the question arises: how are both types of artefacts to be combined to get suitable tools? Reasoning artefacts as well as the related visual artefacts are highly determined by the application field; therefore, they have to be analyzed and realized in a domain context. The next chapter gives an example for a domain specific reasoning process assisted by visual tools.

4. Visual analytics artefacts for analysing long-term geoprocesses

Studying long-term geoprocesses is one of the main research fields at GeoForschungsZentrum Potsdam (GFZ Potsdam). In earth sciences, we currently lack a deeper understanding of how structures and the responsible deformation processes relate to each other across the range of scales between lithospheric faults and grain-scale fractures. The understanding of the structural inventory as observed today requires an integrated approach over such a large range of scales to understand the above complexity and to provide appropriate predictions. In a study in the North German Basin, the 3-D structural inventory is examined by the interpretation of seismic and borehole data; the resulting structural model will be later validated by retro-deformation (e.g. Lohr et al., subm.). To classify fractures, faults and deformation, coherency and neural network analyses will be fed by outcrop and core data. The accumulation and scaling of deformation will also be addressed by analogue experiments. The complete process of analysis, interpretation and modelling is assisted by following visual methods and tools:

With 2-D and 3-D reflection seismic data, insight into the subsurface structure is gained, ranging between few metres to 10s of kilometres in depth penetration and with variable lateral and vertical resolution. After processing of the measured data, interpretation and tectonic modelling follow (e.g. Krawczyk et al., 2006). The visualized seismic data (Fig. 1) will be inspected for 2-D or 3-D structures like lineaments, slip zones or faults. For the interpretation the seismic data are combined with other information like data from drill holes. The interpretation results are constructed in different views and perspectives as two and three dimensional cross sections and horizontal slices (Figs 2 - 5). From the original seismic data not only one single interpretation can be derived, it is a various amount of interpretations which are possible. For that reason all conceivable interpretations are to be evaluated if they fit into the overall geotectonic structure, this is also done with the help of visual comparison

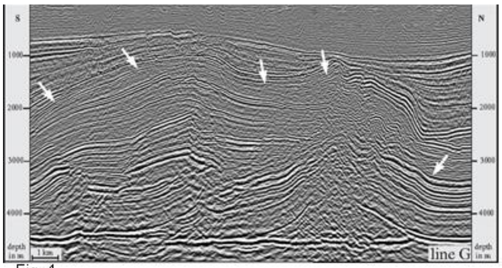


Fig. 1

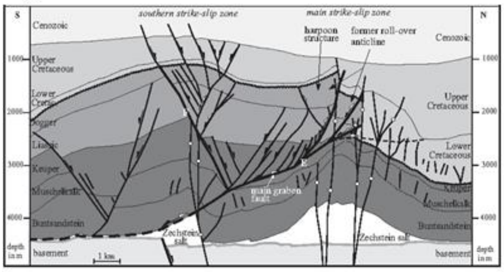
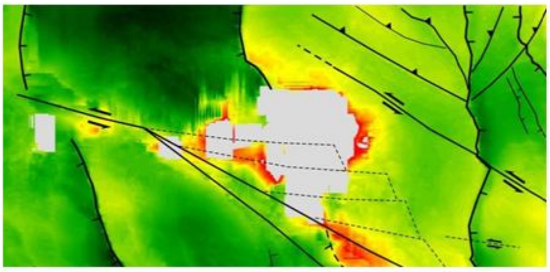


Fig. 2



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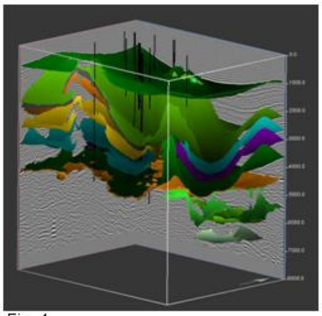

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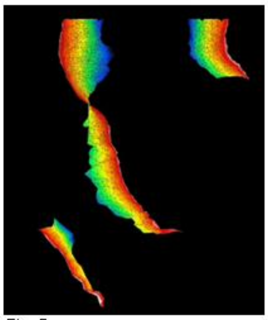

Fig. 5

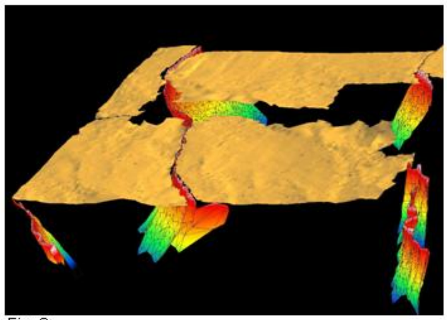

Fig. 6

Fig. 1: 2-D reflection seismic profile cut in N-S direction through a 3-D pre-stack depth-migrated reflection seismic volume (after Lohr et al., subm.). The white arrows mark a prominent unconformity.
Fig. 2: Interpretation of the reflection seismic profile shown in Figure 1 (after Lohr et al., subm.)
Fig. 3: Map view of a horizon interpreted from a 3-D seismic volume with main fault traces and colour-coded for depth (Lohr et al., unpublished).
Fig. 4: 3-D view of the interpreted reflection seismic volume (after Lohr et al., subm.) with wells (black lines) and interpreted horizons.
Fig. 5: 3-D view of fault traces picked from the reflection seismic volume (cf. Fig. 3).
Fig. 6: Combination of fault surfaces and interpreted horizon.

and assessment. After this iterative process of interpretation and assessment the various visual presentations with their manifold insight in the tectonic structure facilitate the creation of a tectonic model (Fig. 6). Finally, in a last step the generated tectonic model has to be evaluated. For this purpose a 3-D retro-deformation is applied to the model. The interpreted model state will be deformed by software according to physical rules up to a state where all layers are in a horizontal non-deformed position. The different steps will be visualized to follow the deformation, and with it the evaluation process, to recognize misinterpretations (Fig. 7).

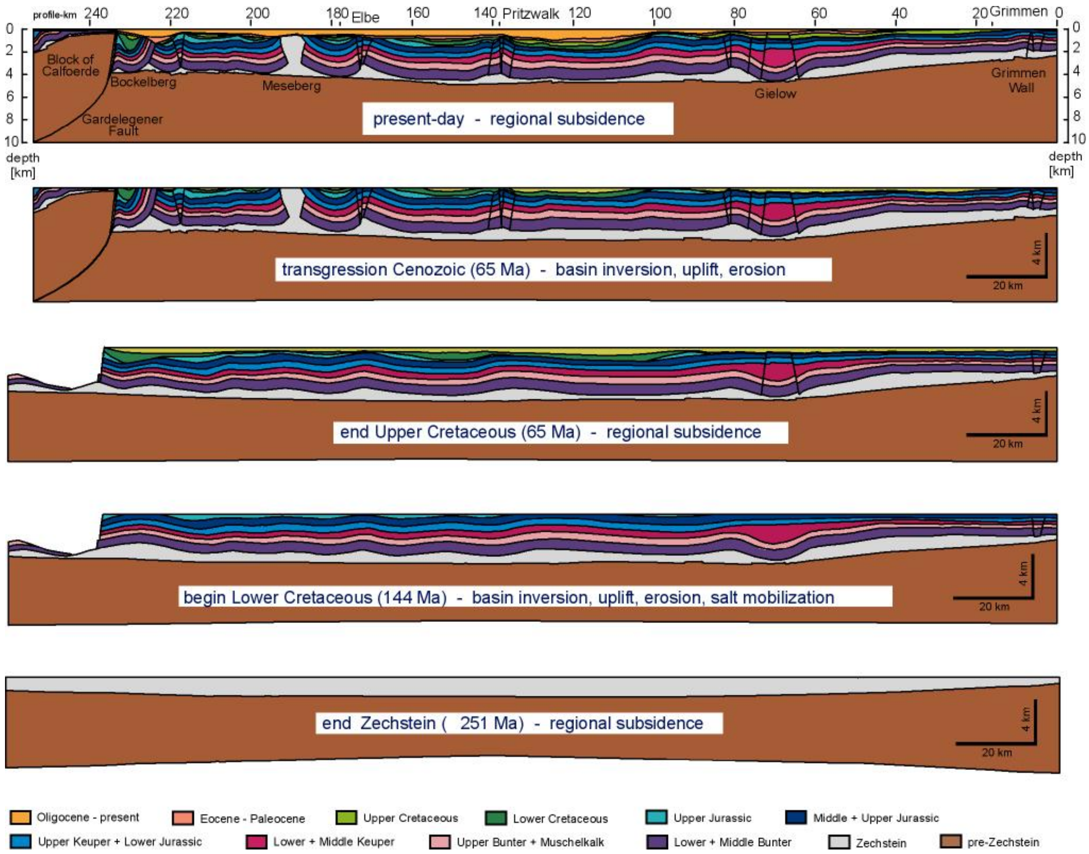

Fig. 7: Sequence of a retro-deformed seismic cross-section, showing the evolution along a distinct profile through time (after Kossow & Krawczyk, 2002). Lowermost panel represents undeformed stage, uppermost panel is present-day geometry of subsurface structures.

A further method to get insight in tectonic processes is the analogue or scaled sandbox experiment. In these experiments appropriate analogue materials simulate the mechanical behaviour of different tectonic domains in the brittle part of the upper crust. Here, deformation processes which take place in nature over millions of years can be simulated fast and efficiently in the lab (e.g. Lohrmann et al., 2003). Initially undeformed experiment set-ups consist of coloured sand layers and other markers that can be inspected visually during deformation. In the sandbox experiment the simulated deformation process can be analyzed visually in two different ways. First the deformation of the different layers and their structure becomes visible and therewith the understanding of the type of distortion increases (Fig. 8). Second a high-resolution monitoring system allows the description and visualization of physical parameters inherent in the system and at the surface (Adam et al., 2004). This gives also insight in the physical behaviour of the simulated scenario (Fig. 9).

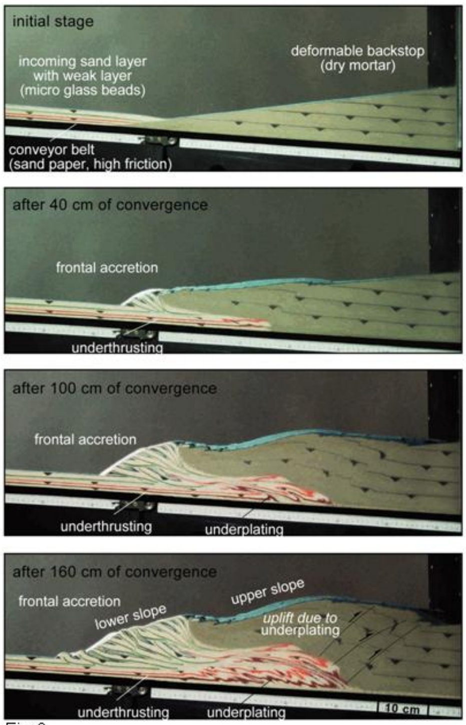

Fig 8

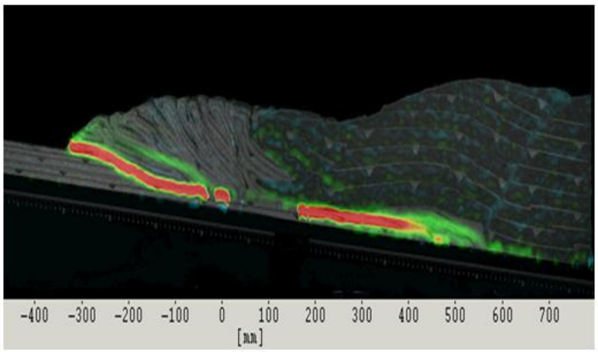

Fig 9

Fig. 8: Sandbox simulation of deformation in a compressive regime. The uppermost panel shows the undeformed stage, the three lower ones different deformation stages (after Lohrmann et al., 2006).
Fig. 9: Example of deformation localisation during a sandbox experiment using the particle imaging velocimetry technology (cf. Adam et al., 2005).

The combination of those physical experiments with geophysical images yielded by reflection seismic will enable to combine lab and natural studies, thus aims at transferability to natural systems.

5. Assessment of Visual Artefacts

To assess the usefulness of existing tools they have to be verified in terms of how they assist the creation and handling of reasoning artefacts. In the first example of visual analytics methods mentioned above a scientist has to recognize pattern in the seismic data, enrich it with information from other sources, interpret the appreciated information as particular structure, and correlate them with the overall geotectonic structure. He also has to evaluate the different conceivable interpretations and to confirm or discard them. Finally, he has to create a geotectonic model which also has to be evaluated.

In terms of reasoning artefacts the scientist applies *relevant information* from different sources, has to find *patterns and structures*, makes *assumptions*, finds *evidences* for or against the assumptions, formulates *arguments* and *causality*, generates *models* and uses *scenarios* for model assessment.

Visual analytics tools or artefacts should help to derive, manipulate, and understand reasoning artefacts. How is this realized in our context?

First of all, it has to be mentioned that several tools exist which are developed in the petrol industry. However, scientists cannot work within an integrated, homogeneous visualization tool during the reasoning process; they have to apply different software packages which make the analytical process less comfortable. The single sub-processes are supported as following:

- Combining relevant information from different sources is less supported.
- Finding patterns and structures in the seismic data is not assisted by software, the scientist has to recognize them visually only by using one's expert knowledge; automatically pattern recognition as additional help to find all possible options is not sufficiently realized, since the automatic tools need thresholds which are not fully reliable on all scales.
- Formulating evidences for or against assumptions about geotectonic structures like lineaments or faults is assisted in a graphical way. A scientist visualizes the interpreted geotectonic structures and proves them according to their consistency and logic in the overall geotectonic situation. (This is only possible with 3D data.) The graphical presentation can answer the question if the assumption fits and why or why not. It is a suitable visual artefact to confirm or discard assumptions.
- Formulating arguments and causalities concerning the overall geotectonic structure. These higher level reasoning artefacts consist of related confirmed assumptions and evidences. For their creation the process of graphical construction and assessment as described before is applied. A further development could include physical plausibility rules in the graphical construction software to have additional criteria for assessing complex geotectonic arguments and causalities.
- Model generation. All arguments and causalities derived before are combined in a visual tectonic model. This visual artefact gives a useful expression about the geotectonic situation.
- Model assessment. This sub-process is supported by a highly sophisticated tool where a retro-deformation is applied to the model from the present state to the origin. All steps are visualized to recognize wrong assumptions, arguments and causalities. The tool works with plausibility rules. It compiles a sequence of retro-deformation levels from the tectonic model, which was created in the process before, and compares the levels with plausibility rules incorporated in the software. All levels are visualized; mismatches between the rules and the retro-deformation levels are indicated.

In the case of the scaled sandbox experiment analogue visualizations as well as digital visualization of physical parameters created by a high-resolution camera system help to form assumptions, evidences, arguments and causalities about geotectonic structures and processes of an experimental setting. The high- resolution camera system has its origin in the car industry, especially in crash tests. It creates a dynamic database from deformation processes, extracts deformation parameters from that database, and visualizes them. Since recording every single grain of sand it can show which grain is moving, when it is moving, and where it is moving. Additionally, physical parameters, like friction, can be derived and depicted. It is a good completion to the analytic method and tools mentioned before and in combination they bring together lab and natural studies.

Altogether a well designed framework of tools exists to support the scientific process of studying long term earth deformation processes. They range from plain visualization tools to tools that combine data analysis, plausibility assessment, and graphical representation. Some improvements are possible concerning more computational support, e.g. by including more complex plausibility rules. However, there is one gap that can be observed: dealing with processes. Most tools for hypothesis formulation and model building have their origin in petrol industry, where petrol deposits are the most important subject and not the geoprocess itself. Therefore, the majority of existing tools handles and depicts states; the dynamic dimension of processes is often neglected. Creating and assessing reasoning artefacts which are necessary to understand a process and its dynamic is not supported suitably for that reason.

6. Further Research

To overcome the limitations of existing tools we want to develop a framework of visual analytics methods and tools that is able to depict the process itself and transforms the discrete space-time slices into a space-time continuum. It should combine and analyse different long-term time-series data from geology, geophysics and satellite geodesy to get different aspects of geo-processes. A dynamic visualization of the processes is necessary to recognize the structures that are responsible for earth deformation as well as the temporal relations between different effects.

The research focus on the close relationship between tasks, reasoning artefacts and visual artefacts. For that reason the visual analytics tools will be directed to the reasoning artefacts which are used by scientists when studying long-term earth deformation processes like assumptions, evidence, arguments, causalities, hypothesis, and models. To meet this goal, the research work will be done in close cooperation between experts from geoscience, geoinformation sciences and visualization.

7. Conclusion

Studying long-term earth deformation processes requires different analytics and visualization tools that assist different scientific tasks like hypothesis or model building. Suitable tools exist from petroleum industry or automobile industry, especially from the field of crash tests; however, they have to be improved in terms of time dimension. Essential are tools for analysing space-time structures and pattern combined with dynamic visualization. For the development of advanced visual analytics tools it is also necessary to investigate the scientific tasks researchers have to fulfil and related reasoning artefacts.

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