Outcrops as Analog of Fractured Reservoirs: Capture Explicit Geometries, Derive Statistics and Model Behaviour*

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Introduction

Predicting the mechanical response of specific geologic complex structures from the field has increasing societal and industry interest. For instance, what are the risks of fault re-activation from the production or injection fluids or gas in (abandoned) reservoirs and how can these risks be mitigated? Or, how can small-scale fractures be mechanically extended to enhance reservoir properties while the activation of bigger faults (seismic hazards) is avoided? Although these are practical concerns in regard to subsurface reservoirs, addressing the failure potential of fractures or faults in complex structural settings is a recurring research theme surrounded with numerous fundamental questions. Outcrops serve as learning ground which offer hands-on access to fault-fracture network geometries and which form ideal input for numerical modeling of fluid flow behaviour or for mechanical simulations of re-activation of pre-existing deformation structures.

Our capabilities to capture geologic structures from the field have become much more quantitative with the help of digital acquisition hardware like tablet or handheld devices and tools like LiDAR-scan and photogrammetry. On the computational side, major advance has been made in discretizing realistic geometries with refined and hybrid meshes and mesh adaption to account for complex deformation structures (e.g., Paluszny and Matthäi, 2009). Despite these great advances in digital acquisition of geologic structures and the meshing and numerical modeling of complex geometries, no functional workflow exists that captures the complexity of field-derived structures as direct input for numerical experiments. With lack of a fitting modeling workflow, complex structural models can only be built with arduous effort and is typically avoided.

The conventional approach is to conceptualize a deformation structure into simplified geometries before using them as input in numerical experiments. While conceptual models helped us in establishing fundamental principles, they cannot predict the deformation response of actual structures under stress. Addressing the failure potential of fractures or faults in such specific and complex structural settings is a recurring research theme. Explicit description of a geologic structure can be done with a discrete geometric representation. Geologic software, such as Paradigm's gOcad/SKUA, Baker Hudges JewelSuite™ or MV Move Suite, provide necessary tools to build coherent 3D geologic geometry models, but they require geometric field descriptions that make-up the structure in order to start. The building of models from field data requires a tool for collecting discrete geologic features immediately in the field.

Geographic Information Systems (GIS) provide key functionality for digitizing geometries and assigning attribute information, and its user interface is increasingly adapted to tablet PCs and use in the field. On the other hand, the design of advanced geometry models requires Computer-Aided Design software, which typically lack adaptation for use in the field. The geologic structural model design software have several tools in common with true CAD software and have the added advantage that functionality supports specific geologic feature types, such as faults and horizons and which acknowledge geologic rules. However, these software are not adapted for use in the field and do not (yet) support the entire 'life-cycle' of a structural description from field acquisition to numerical modeling.

Data Acquisition

The choice for capturing explicitly a geologic structure as discrete geometric representation is, however, not evident. Natural fracture networks, for instance, are traditionally up-scaled as effective parameters in many continuum finite element models, whether for fluid flow or mechanical simulations. Characterization of natural fracture networks is important for the description of rock strength and slope stability in geo-engineering and for the description of surface analogues of buried fractured aquifers in hydrogeology and hydrocarbon reservoirs in petroleum geology (e.g., Nelson, 1987). Up-scaled fracture network properties may be acquired directly in the field, for instance, by means of counting the number of and distance between fractures along a physical scan-line (e.g., Eyal et al., 2001). Such a 1D sampling may be fit to a specific purpose and statistically sound; it also has the inherent limitation that the geometric arrangement of the fracture network cannot be retrieved from such surveys.

Explicit representations of a fracture network require the mapping of fracture geometries and spatial relationships of the network and the assignment of attributes. The explicit geometric descriptions come in the form of poly-lines/gones or spline curves and surfaces. Geologic attributes include the infill of veins, the aperture of joints and displacement indicators, for shear fractures specify distinct structural features. The length or spacing between fractures constitutes intrinsic information of the mapped fracture network. Ideally, field acquisition achieves an accurate mapping of structures and delivery of a statistically sound dataset for deriving up-scaled properties.

Our capabilities to capture geometries of geologic features from outcrops have greatly improved with optical remote sensing technologies, such as LiDAR and photogrammetry (e.g., Enge et al., 2007). With the advance of such high-resolution 3D-textured surface representations, the observational quality of field surveys can be greatly improved, and both (semi-)automatic tracing of discontinuities and data collection from virtual outcrops (McCaffrey et al., 2010) have, in principle, become possible. However, many key observations and interpretation decisions still need to be made by the geologist in the field with direct 'hands-on' access to the outcrop. These include, but are not restricted to, observations such as the infill or displacement indicators of fractures. Critical aspects of fracture networks are the intersection between fractures and abutment relationship relative to bedding or mechanical unit interfaces. In particular, we consider that such critical constraints should be hard observations and not left to (semi-)automatic algorithms, especially because terminations typically do not stand-out in the textured surface. Therefore, the tracing of geometries also require decisions, for instance that of fracture terminations, which are best made in the field.

Field Acquisition Tool Development

We developed our DigiFract software (Hardebol and Bertotti, 2013) for structural field data acquisition, focusing particularly on fracture networks. The software has been used by a variety of researchers and students during various projects, including acquisition on a siliciclastic succession in Jordan (Strijker et al., 2012) and on the Latemar carbonate platform in the Dolomites in North Italy (Boro et al., 2012). Our experience is that a strongly customized acquisition and processing workflow can be designed on top of user-friendly and intuitive open source Quantum GIS software (www.qgis.org) and by using a variety of open source C++ and python libraries. Our DigiFract software (e.g., Figure 1) enables us to capture fracture geometries during the acquisition stage and derive distribution statistics during subsequent data processing. Digitizing fractures as 2D GIS geometries helps in performing scan-line and scan-window analyses by using a variety of spatial and topological operations from open-source geometry libraries. This meets well the aim to enhance the acquisition and processing workflow of outcrop data as proxy for fractured reservoir characterization.

We propose a set of new developments. Firstly, describing structures by discrete geometries requires digitizing and typically involves cross-mapping from 2D views or slices to an underlying 3D reality. Secondly, capturing a geologic structure involves both discrete geometries and a data-structure that specifies the (spatial) arrangement between the structural elements. This requires a coherent organization of data across the entire tool chain from acquisition to numerical simulation and post-processing (Figure 2).

1. Cross-dimension mapping (between 2D and 3D space) of geometries and translations or extrusions are recurring operations in the acquisition workflow. Software for handling data sources that are intrinsically 3D, e.g., seismic data, provide 3D mapping tools. Instead, field observations of structures are typically collected on 2D exposure surfaces, and translation to an underlying 3D representation is complicated. New functionality will need to combine the strengths of GIS with its *Feature* relational data model of data attribute assigned to geometries and CAD software with complex 3D spline geometry definitions.
2. Central in the digital abstraction and consistent bookkeeping of a geologic structure will be adopting the Feature definition. A Feature can serve as a persistent data container for storing both Geometry and Attribute aspects of structural elements. Spatio-relational arrangements of the different features and their geometric parts form the digital description of a deformation structure. The implementation of a ‘structural feature’ will also involve the definition of groupings, hierarchies or topological relationships between the digitized geometries. The handling of typology during digitizing must occur in a manner that it foresees and circumvents later meshing issues and will involve distance thresholds and tolerance levels.

Results and Conclusions

The demands to understand the geomechanical response of our deeper subsurface are paramount and require adopting novel modeling techniques to better capture the actual response of already complex deformed rocks. The stress distributions may be calculated for various quasi-static loading scenarios of a subsurface reservoir fed with input model of an outcrop-based fracture network analogue. The benefits of new proposed developments will be the capability of discrete geometric descriptions being more easily meshed and adjusted in exploration of the range of uncertainties of subsurface fault networks. Currently, geometries are rarely re-visited because of the cumbersome work. Because the models will be fed by real-world observations, the predictive value of model output will improve and be better applied to specific scenarios.

Especially, the simulations will significantly better predict the response of already deformed rock mass to stresses as initial structures will be accounted as discrete geometric descriptions.

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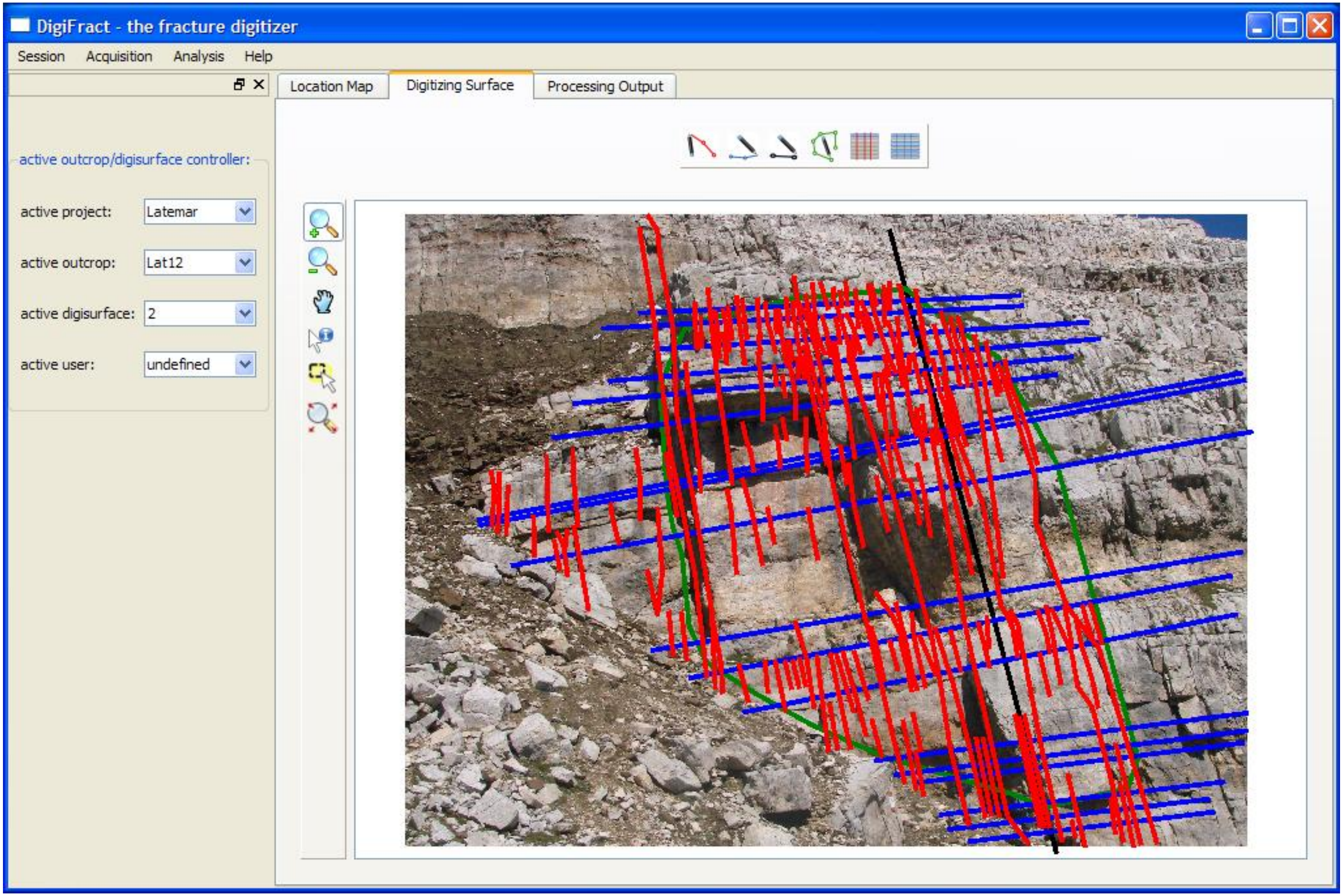

active outcrop/digisurface controller:

active project: Latemar

active outcrop: Lat12

active digisurface: 2

active user: undefined

Figure 1. The graphical user interface of DigiFract containing two map canvasses: (1) the Location Map, a map view like any conventional GIS and (2) the Digitizing Surface canvas, that displays the outcrop surface onto which structural features are digitized.

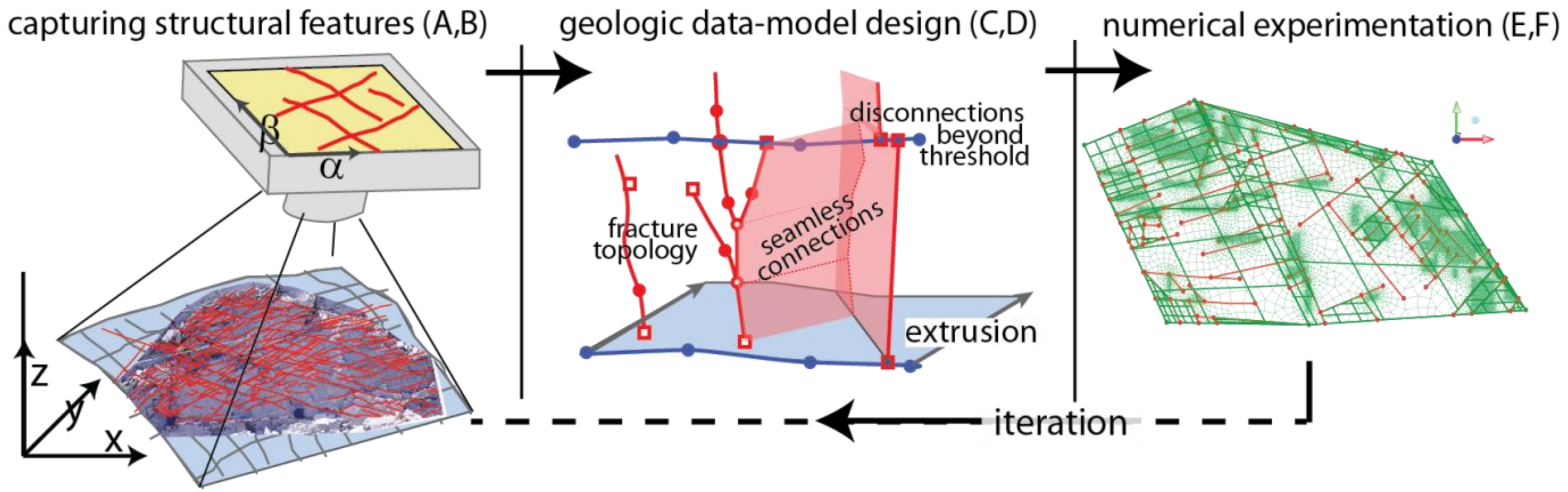

Figure 2. The main steps for new functionality to complement geologic model building software to capture structural descriptions from the field as input to numerical experiments.