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New Methods for Extracting and Constructing Fault Surfaces from 3D Seismic Data

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Introduction

The description of a fault model includes the fault surfaces and associated tip lines, the fault network geometry, and the displacement geometry of faults. Fault surfaces are usually observed from seismic discontinuities, which include reflector breaks, flexures, and amplitude changes. These discontinuities can often have a regular appearance that corresponds to fault geometries found in rock analogues. Coherency-type cubes, hereafter referred to as discontinuity cubes, are often used to highlight faults in structurally complex areas. In despite of this, methods for automatic tracking of fault surfaces have often failed because of the ambiguous appearance of these discontinuities. Extracted objects from raw discontinuity cubes will usually not appear like fault surfaces and need heavy editing before they are put into a fault model. As a result, fault interpretation is generally performed by interpretations on seismic sections with no use of automatic extraction of seismic discontinuities.

The paper will demonstrate advanced use of image processing and object extraction, which aid in a fast interpretation of fault surfaces from full-stack seismic volumes. Furthermore, it suggests a workflow for refining the extracted surface objects into a complete fault model using surface modelling facilities.

Common problems associated with fault surface extraction

Discontinuity cubes highlight seismic discontinuities but these are very rarely in a condition that serves direct extraction of fault surfaces. Fig. 1 illustrates the typical features that are highlighted in discontinuity cubes. Firstly, the attributes commonly show clusters of voxels that correspond to stratigraphic features, faults, or low-coherent seismic signals. To extract faults from attribute cubes, ways to distinguish faults from other features needs to be implemented. Secondly, the attributes associated with faults commonly appear as irregular bodies, which are several voxels thick. Algorithm for fast thinning and extraction should detect the optimal position of the fault surface. Thirdly, faults are often connected, where secondary faults are linked to primary ones and show crosscutting relationships. To represent individual faults correctly, the extraction method needs to distinguish faults at linkage points and to correlate them across each other. Finally, the extracted faults have a displacement geometry, which is indicated by the offset of the seismic events. This geometry needs to be consistent with the modelled displacements of the stratigraphic objects.

Solutions

The abovementioned problems suggest that fault surface extraction may succeed if the extraction is user-guided. An initial extraction of seismic voxels that can constrain the fault surfaces must consider the following; (1) a conceptual model of the tectonic style and structural position of the area, (2) the position of fault surface and displacement of horizons and other stratigraphic objects, and (3) the linkage and geometry of several fault surfaces in a full network model.

The workflow proposed in this paper emphasise the use of computer-driven methods for surface extraction and, when the surfaces are being constructed, manual editing becomes important where the model needs modification.

Fault surface extraction

Seismic volumes often show clusters of discontinuities, which are associated with stratigraphic features, such as reflector layers, channels and sequence boundaries. Faults often cut at a high angle to reflectors and are relatively planar. To distinguish faults from stratigraphic features, the geometrical attributes, such as dip and trend, can be used.

Randen et al. [1] and Pedersen et al. [2] took use of the principals for "swarm intelligence" to highlight faults in attribute volumes. By encoding fault properties expectations as behaviour of intelligent software agents, they were able to enhance and extract responses to fault geometries in the attribute (Fig. 2). This method, which is termed Ant-Track, assumes that faults have approximately constant local dip and azimuth. During the attribute detection the orientation estimate and the attribute value are stored in the surface property. These properties can in turn be used to extract surfaces on the basis of orientation and the strength of the attribute.

The method allows us to highlight faults with similar dip and azimuth, thus giving the opportunity to visualise sets of faults in complex fault systems (Fig. 3). The stored orientation estimate can be used to plot the fault surface normal onto a stereo net.

The orientation estimate is used to extract individual surfaces and avoid wrong extraction at places where faults are intersecting. This is obtained by conditioning the attribute to highlight parallel faults that are not intersecting (Fig. 3). Before surfaces are extracted, the attributes are thinned to a single voxel, which is at the centre of the cluster or at the highest attribute value.

Fault network construction

Further work needs to ensure that the fault surfaces are consistent with both fault criteria observed from the seismic and the expected fault geometries based on a structural model. In new datasets, where the structural model is less known, the extracted surfaces can provide information to subdivide major and minor faults. The seismic on either side of the fault surface can be displayed and will indicate the displacement geometries. Such information, together with seismic plane slicing along the trend of the fault segments, is useful to assess the confidence of the extracted fault surfaces.

The surface construction takes place preferably while the individual faults are edited and checked against the seismic. The cleaning-up of fault structures may include changes in fault tip lines and intersections, linkage of fault segments, and smoothing of the surface. Examples of making these changes in a gOcad model are shown in Fig. 4. Also useful are filters, which sort the objects on the basis of position, direction and size. Such filters may easily take away noise (acquisition tracks, coherent noise) from the model.

Integration with horizons

The tying of fault- and horizon surfaces is often difficult because of poor interpretation quality close to faults. The horizons and other stratigraphic objects needs to be separated across the faults in a consistent way corresponding to geologically sensible displacement patterns of faults. If the horizons have wrong picks it may lead to time-consuming editing before the displacement geometry is made consistent. There are both automatic and semi-automatic methods, which are proposed here, depending on the quality of the interpretation and the level of accuracy that is aimed.

The automatic method extrapolates and connects horizons towards the faults, a method similar as in several modelling tools. The horizon control points at a given distance away from the fault are used for extrapolation. The surface is smoothed towards the fault, thus avoiding the erratic intersections that can be caused by poor picks.

The semi-automatic method uses fault-parallel displays and manual picking to refine the fault- to horizon intersections (Fig. 5). This method will ensure a consistent displacement geometry that can be controlled by the user.

The first method is recommended for early phase interpretation whereas the second method can be used to refine detailed horizon displacements in for example reservoir compartments.

Further research examines how to use fault displacement contours on surfaces for automatic generation of horizon intersections. Displacement patterns are unique features of faults, which can provide quality control and fast integration of faults and horizons.

Summary
Ant-Track processing is considered efficient tool for extracting faults from seismic volumes. Selection of attributes on the basis orientation provides for, not only fast extraction of faults, but also for a better understanding of fault patterns during seismic screening.

Surface construction needs to be tightly integrated with other techniques, such as filtering of objects and interpretation of lines and points.

References
[1] T. Randen, S. I. Pedersen, L. Sønneland "Automatic Extraction of Fault Surfaces from Three-Dimensional Seismic Data"., Ann, Int. Mtg., Soc. Expl. Geophys., Exp. Abstr, 2001

[2] S. I. Pedersen, T. Randen, L. Sønneland, Ø. Steen "Automatic Fault Extraction using Artificial Ants" SEG 2002.

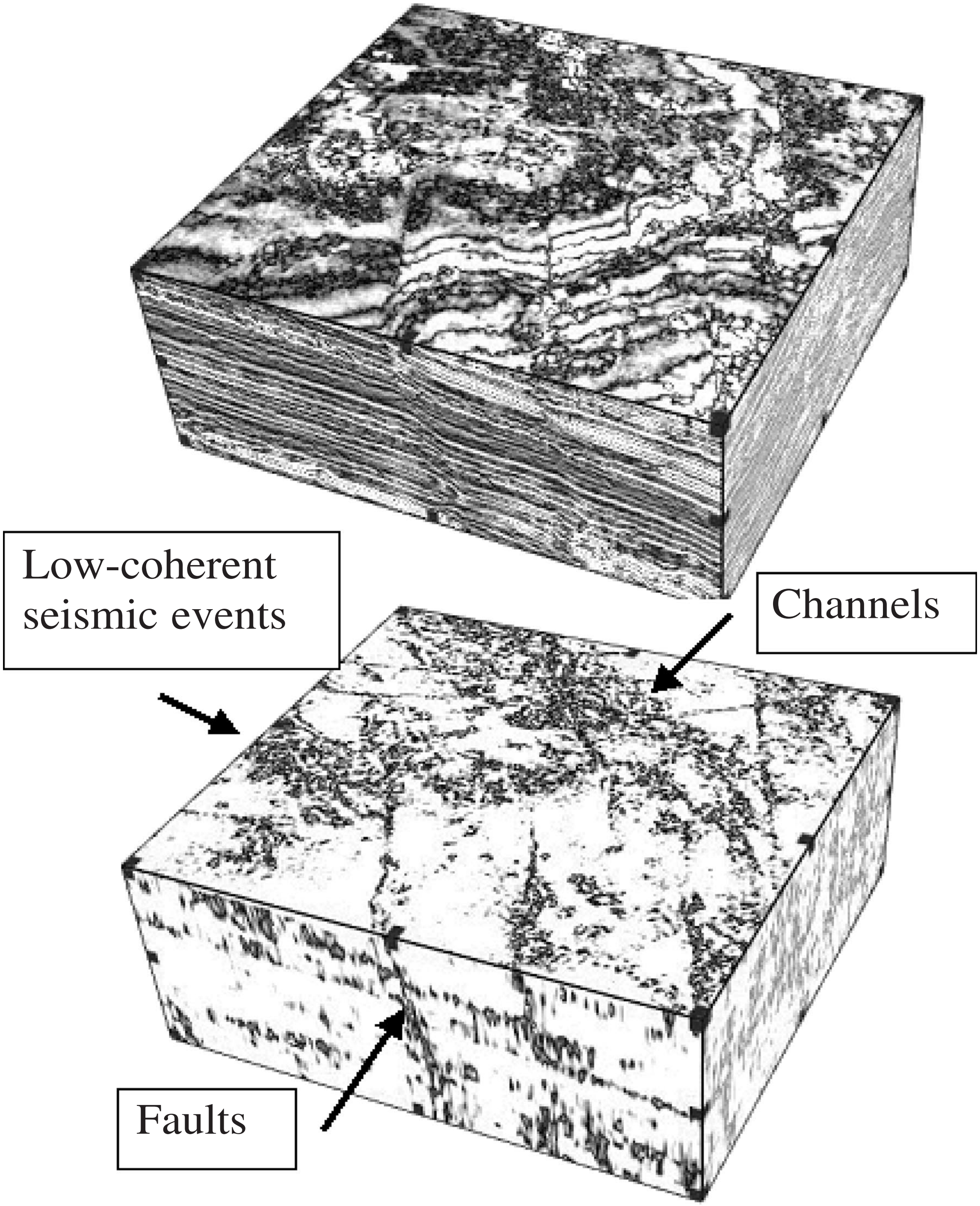

Figure 1. Seismic full-stack cube (above) and a corresponding discontinuity cube (below). Faults are highlighted but are connected with stratigraphic features.

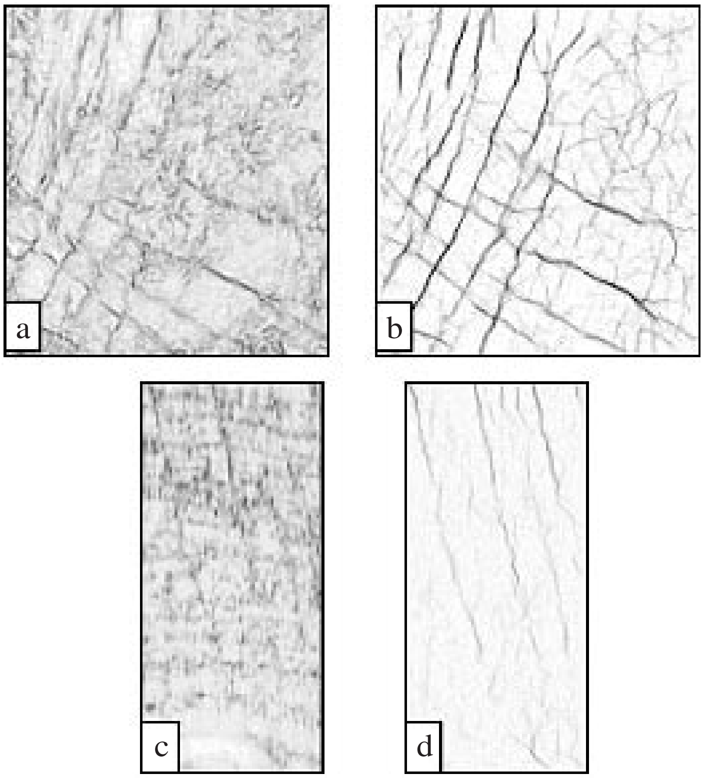

Figure 2. a) Time slice of discontinuity cube (Variance) with corresponding Ant Track result (b). c) Vertical section of the same cube with Ant Track result (d).

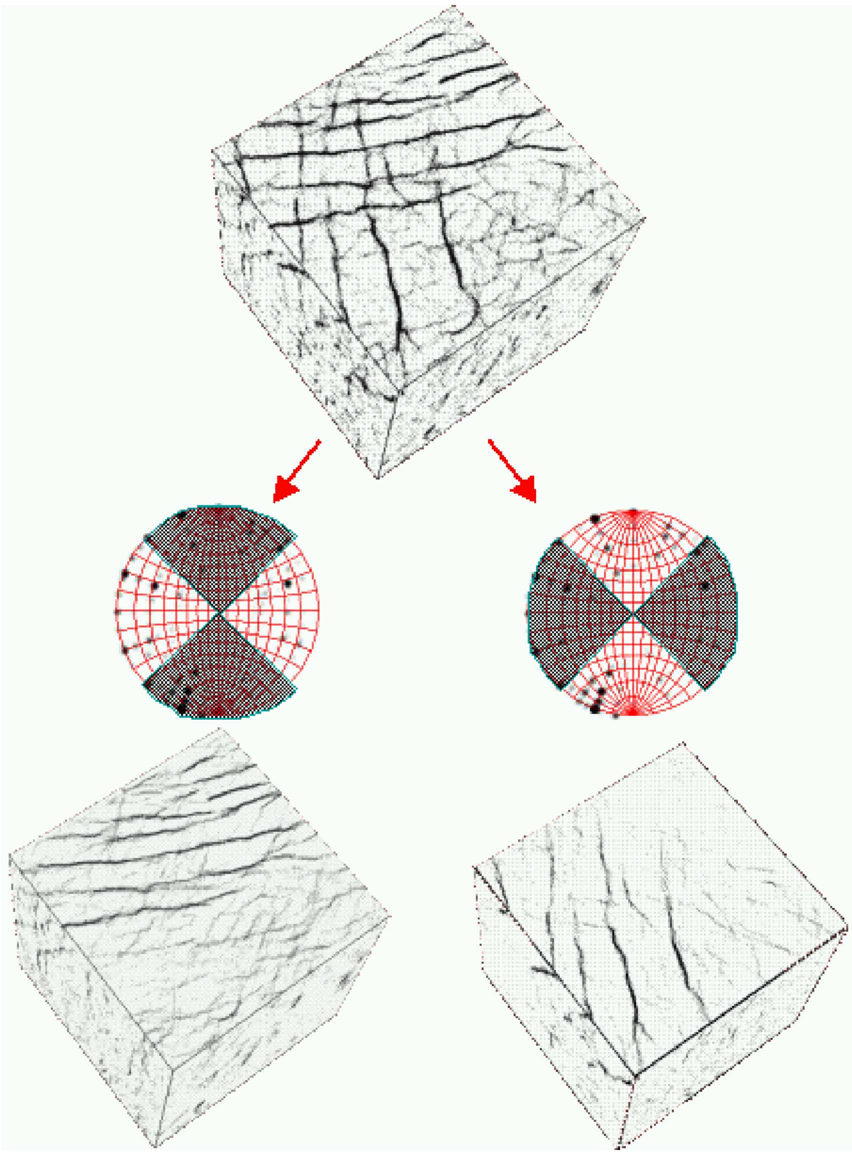

Figure 3. Ant-Track results showing the selection of fault sets using stereo plots (N-S and E-W trends, respectively).

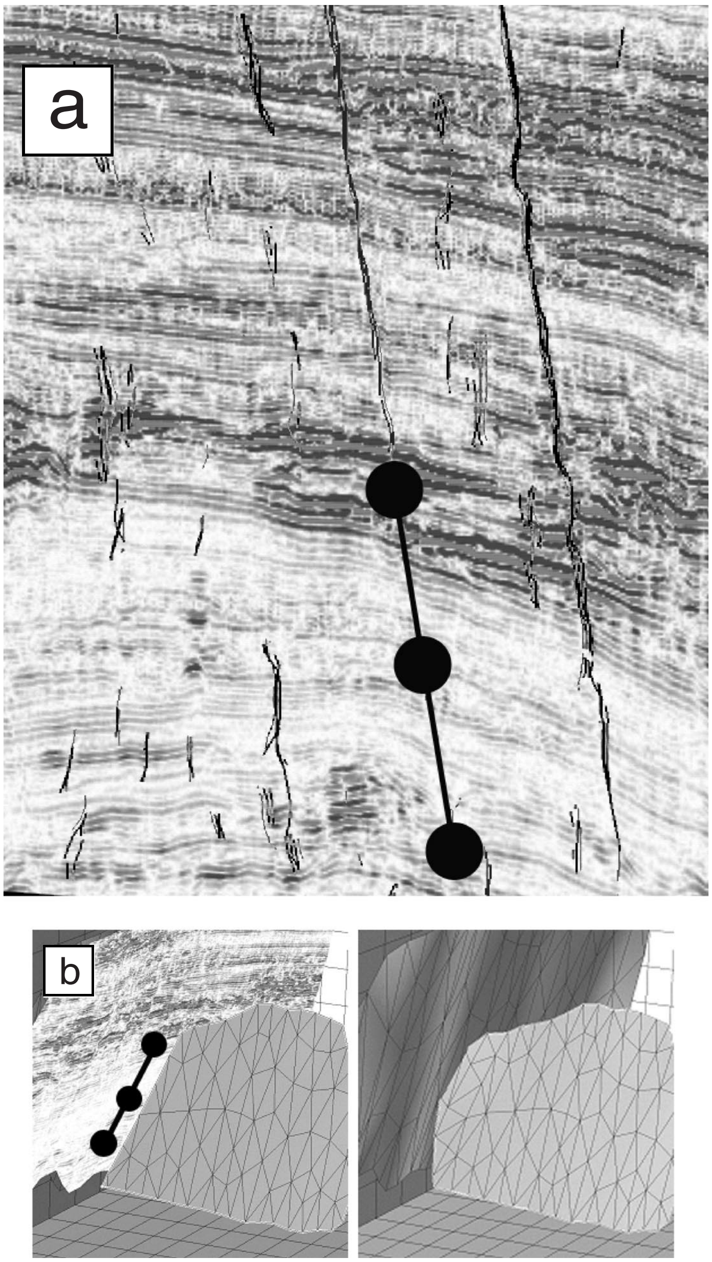

Figure 4. (a) Extracted fault surfaces displayed on seismic and manual line picking to add interpretation. (b) Seismic slices parallel to fault surface is used to construct fault intersections.

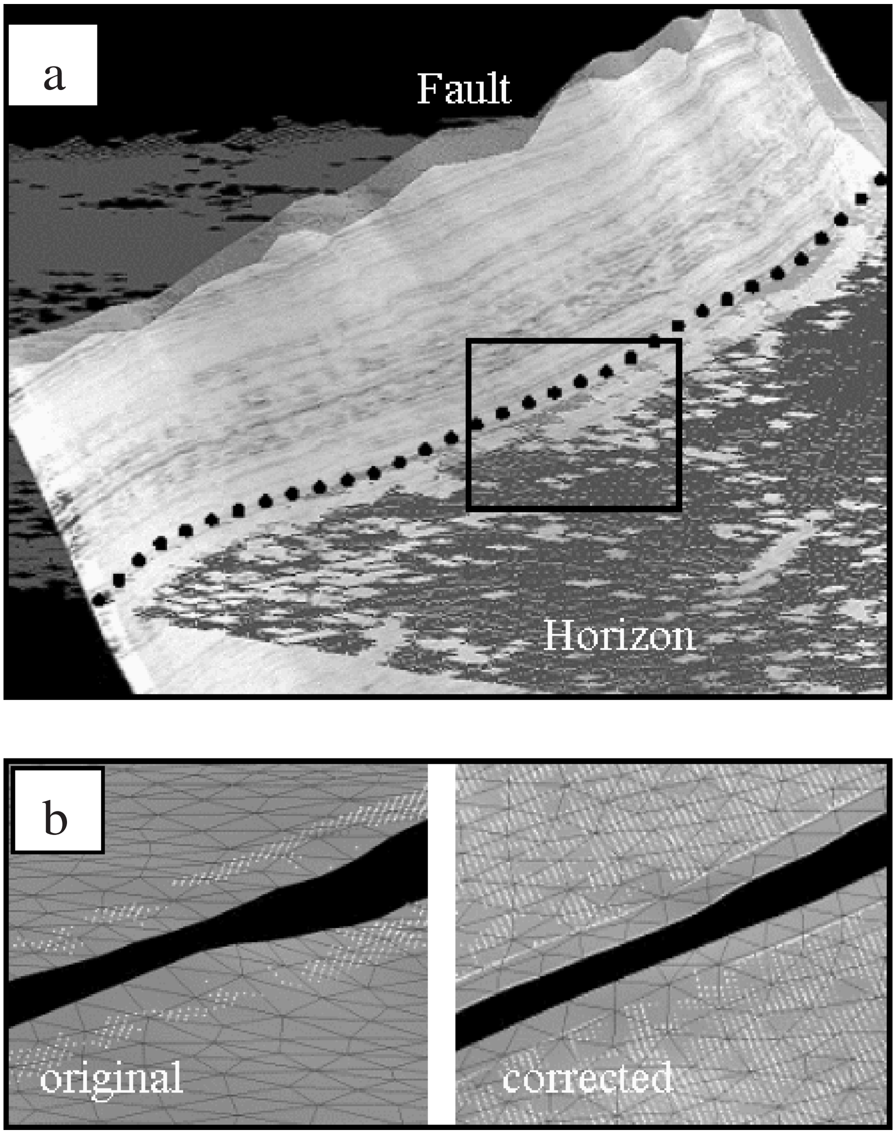

Figure 5. (a) A fault to horizon cut-off is interpreted on a seismic slice parallel to fault, and (b) is used to constrain the horizon surface towards the fault.