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THREE-DIMENSIONAL GEOMETRIC MODELING OF A FAULTED DOMAIN: THE SOULTZ HORST EXAMPLE (ALSACE, FRANCE)

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Abstract—This paper describes an example of 3-D modeling using GOCAD software, a geometric modeler designed for geological surfaces. The problem is to build a geometrically consistent model of a fault and layers system starting from faults' traces on cross sections, cross sections derived from seismic profiles, and drillhole data. A methodology is proposed and discussed. The main problems in modeling faults are the multiplicity of solutions for linking traces, and the lack of knowledge about the morphology of the fault and their 3-D extrapolation. It is shown that GOCAD is a powerful tool for the geologist to (1) interactively identify the inconsistencies between the 2-D interpretation of initial cross-section profiles, (2) take into account complex morphologies such as the subdivision of a fault, (3) investigate as many hypotheses as needed, and (4) obtain a realistic geometric model of a system of faults and layers.

Key Words: 3-D modeling, GOCAD, Faults, Layers, Rhine Graben, Soultz Horst

INTRODUCTION

General context

Interest in three-dimensional (3-D) modeling comes from the fact that geological objects and processes are located naturally in space and that many questions earth scientists have to answer now cannot be solved easily in two dimensions, and thus require a real 3-D approach. Computer graphics make possible this approach.

Various types of modeling can be considered (geometric, kinematic, physical), but geometric models are of particular interest because they are generally a prerequisite for most others.

The third dimension of a geological object generally is accessed through the mental image that the geologist has of it. But this image of course is inaccurate and ephemeral (Kelk, 1992), difficult to communicate, and not necessarily the same for every geologist. Moreover, its consistency cannot be checked.

GOCAD

Computer-Aided Design (CAD) software initially developed for mechanics does not always give satisfactory answers to geological problems. For example, a goal of 3-D modeling in mechanics may be to design a motor from a given list of known characteristics and a series of plans. The way to proceed is to assemble a series of simple geometrical shapes (cylinders, rectangles, cones). The complexity comes from the number of elementary pieces to assemble. Let us transpose this example to geology and imagine this motor is hidden underground, known by some drillhole places and indirect geophysical investigation. From this partial information the geologist will have to (1) guess it is a motor and the brand of motor it is, (2) reconstitute its geometry, (3) calculate its characteristics, and (4) determine whether it would be safe to store toxic waste.

The goals thus are the reverse: mechanical CAD aims to design objects which do not yet exist, whereas geological CAD has to rebuild an existing body from partial, irregularly distributed, and more or less precise information. Moreover, the complexities of the objects treated are not the same for both disciplines.

Current research is based essentially on the transposition of traditional mechanical CAD methods to geological problems using interpolators such as B-splines (Auerbach and Schaben, 1990) or NURBS (Fisher and Wales, 1990), to model complex surfaces.

GOCAD is geometric modeling software being developed at the Nancy School of Geology (Mallet, Jacquemin, and Cheimanoff, 1989) especially suited to geological objects. Surfaces are described as 2-D graphs (sets of adjacent triangles), lines are described as 1-D graphs (sets of adjacent segments).

A set of interactive tools makes it possible to create and modify lines and surfaces in 3-D space. The user can build initial surfaces (triangulation between two lines, inside a closed line, building of isovalue surfaces) before fixing constraints and applying Discrete Smooth Interpolation (DSI). Some operators do exist

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to split, unsplit, improve, and beautify the triangular mesh. It also is possible to cut surfaces by other surfaces.

The 3-D position of the nodes of the segments or triangles are computed using the DSI interpolator (Mallet, 1989), which minimizes a global roughness criterion of the surface or line. Moreover, DSI is able to take into account many types of geological data and constraints (precise or fuzzy surface location, local dips, relative displacements along faults). A useful constraint in GOCAD is the capability to stick part of the border of a surface to another surface, and to oblige this border to remain stuck, so that it slides along this other surface when fitting its geometry to data applying DSI.

GOCAD software is developed in C language under Unix and X-window/Motif. Shaded 3-D views require a graphic processor. The work presented in this paper was performed on a Silicon Graphics IRIS-4D workstation.

Problem to solve

The general problem is to build a 3-D surface model of a system of faults and layers starting from cross sections and drillhole data. This is a problem usual for earth sciences (Zoraster and Ebisch, 1990). Verschuren (1991) describes a method in which the modeling of layers takes into account fault displacements without modeling fault themselves. An application to geological mapping is shown by Siehl and others (1992).

The method proposed and discussed in this paper is based on the use of GOCAD. It consists firstly of building the fault network by linking traces from section to section, then building layers taking into account the fault model. If the final model reveals inconsistencies, the initial interpretation of the fault is reconsidered until a satisfactory solution is obtained. The major problem of this approach is the nonunicity of solutions for linking fault traces and the fact that the initial interpretation of the fault system has great influence on the final layer model.

THE SOULTZ HORST

Geological context

The Soultz Horst is located on the western border of Rhine Graben (Alsace, France) on the old petroleum field of Pechelbron. It is made up of sedimentary Mesozoic rocks (Triassic to Middle Jurassic) lying on a Hercynian basement of porphyritic Soultz Granite. Both Mesozoic rocks and granite are affected by a series of subvertical north–south normal faults dipping westward or eastward. Two major tectonic phases have been recognized in the Rhine Graben: an initial north–south compression (Eocene) is followed by an important east–west Oligocene extensional phase (Villemin and Bergerat, 1987). The latter is responsible for most observed structures and the actual geometry of faults and layers.

The Soultz Horst shows an important thermal anomaly and is currently the object of geothermal studies (Kappelmeyer and others, 1991; Le Masne and others, 1992). 3-D geometric modeling has been performed within the framework of these projects in order to define and understand better the geometry of potential hot dry-rock reservoirs and their boundaries.

Data

Data are located in Figure 1. They consist of 78 drillholes and five seismic profiles interpreted by J. P. Cautru (Menjoz and others, 1988) in terms of geological cross sections (Fig. 2).

FAULT MODELING

Building a fault network from traces is achieved in two steps: (1) select the traces that are to be linked from section to section and (2) build a surface network adjusted to the selected traces.

Trace correlation problems

The main problem comes from the many different ways to link traces. This is because of the nonsimi-

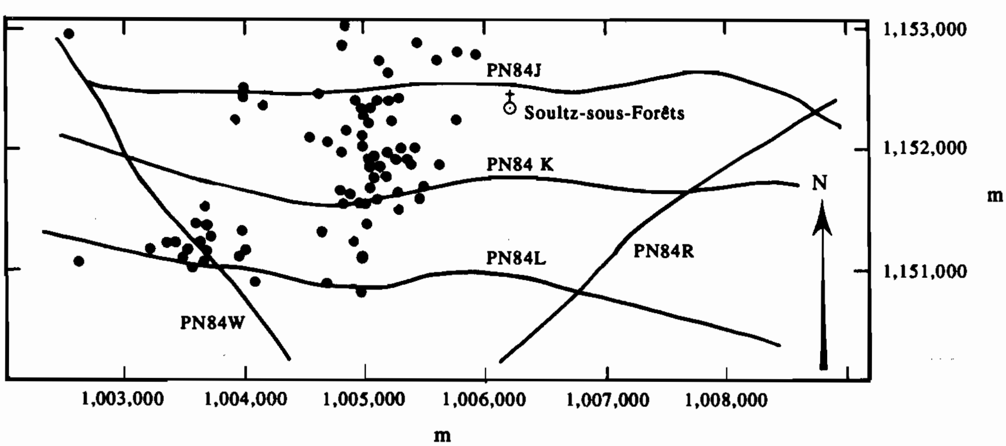

Figure 1. Location map of drillholes and seismic profiles. Lambert II coordinates (Alsace, France).

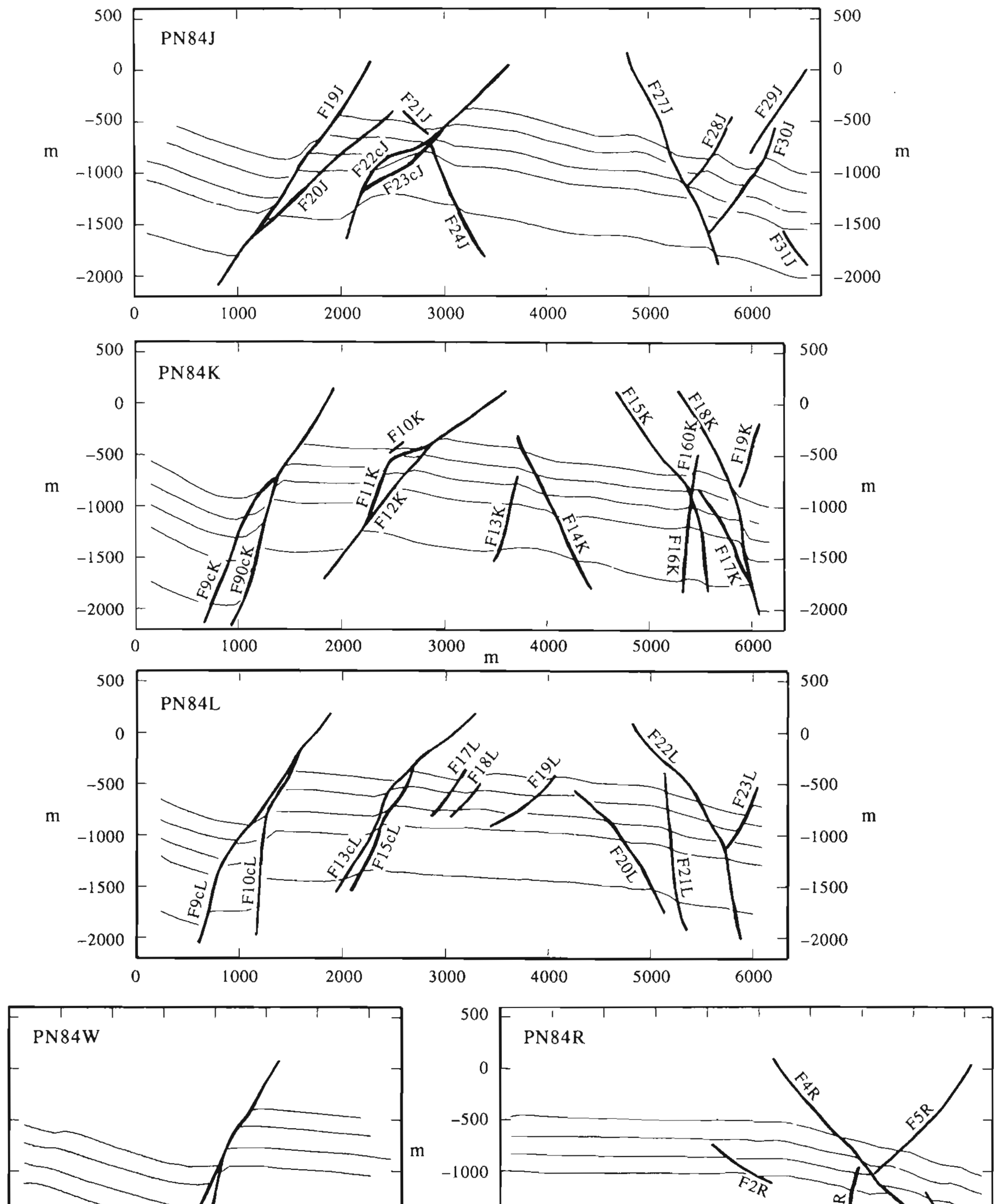

Figure 2. Interpreted seismic cross sections by J. P. Cautru (Menjoz and others, 1988). Data are displayed using GDM software from BRGM/Geomath.

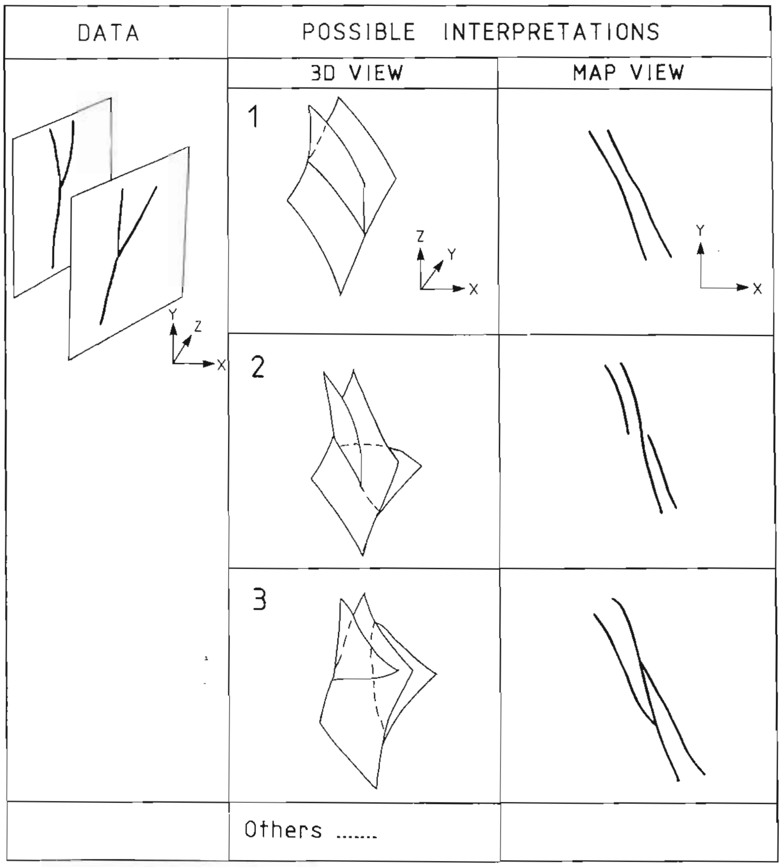

Figure 3. Example of fault correlation problem. From apparently simple data, several 3-D interpretations are possible. First interpretation is based on assumption of continuity of Y structure. Second and third interpretations assume existence of major and two secondary faults. Second interpretation assumes that there is only vertical displacement, whereas third one assumes combination of vertical and horizontal displacement. This determines shape of intersection line which is unknown when considering only trace data.

larity of the trace network from one profile to another and the inability to determine a priori which trace belongs to which fault. A typical example of this problem is illustrated in Figure 3. This example is relatively simple because it is usual to work on a network of tangled traces (10–20 traces/profile for example).

An initial interpretation has been selected among all the different possible solutions, based on geometri-

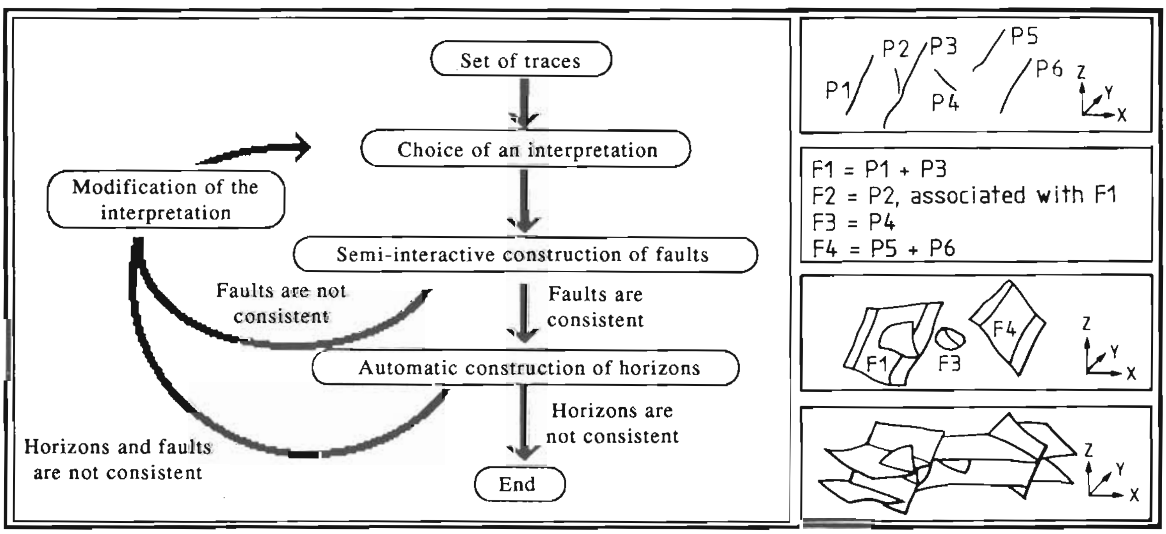

Figure 4. Steps in fault correlation sequence.

cal (proximity, similarity of shape or dimension) and geological criteria (same displacement, alignment along a well-known structural direction).

A first model of the faults and layers is created from this interpretation. Then the model is examined for inconsistencies, the interpretations are modified, and the model is rebuilt until the result is consistent (Fig. 4). The interpretation of a fault is rejected if the fault or the layers that are affected by the fault show deformations which are thought to be unacceptable with reference to the geological and tectonical context of the studied zone.

Return to the initial data may be necessary in critical situations. For example, linking traces on profiles K and W close to their intersection was impossible without creating aberrant surfaces. The solution has been to return to the seismic profiles and notice that an additional trace could be drawn on each one (F9CK and F30W on Fig. 2), leading to a more reasonable interpretation by adding a fault to the system. This emphasizes the role of 3-D geometric modeling as an aid in interpretation.

Single fault modeling

General case— The goal is to build a triangulated surface that passes at best through the existing data and whose geometry agrees with the geological knowledge.

Barnett and others (1987) have shown that the form of isolated normal faults can be considered as elliptic; displacement decreases roughly linearly from a maximum at the fault center, to zero along the fault border line termed the "Tip-line". Therefore the form of all the isolated faults is assumed to be elliptic.

The fault is built in two steps. Firstly the Tip-line, which is supposed to pass through the extremities, is created (Fig. 5A). DSI is used to give the Tip-line a general elliptic form while passing through the

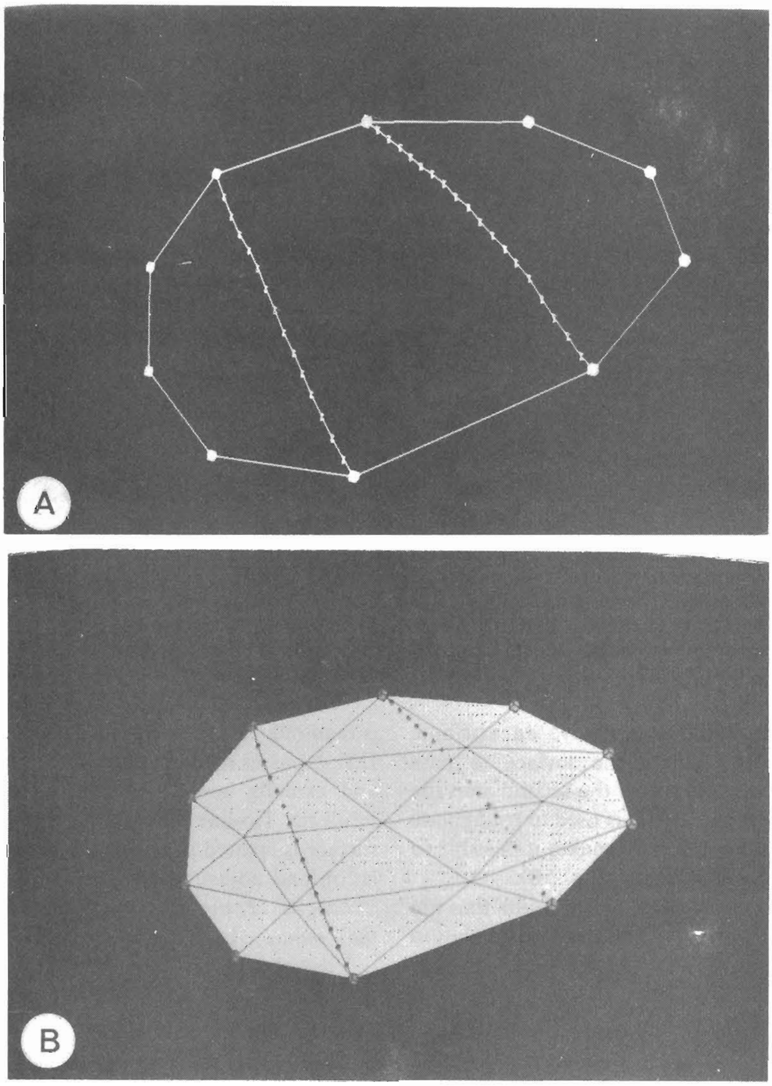

Figure 5. Steps in building single isolated fault from two traces. A, Tip-line is created which passes through extremities of traces; B, final result: "patch" function is applied to Tip-line and DSI is used to adjust surface to traces.

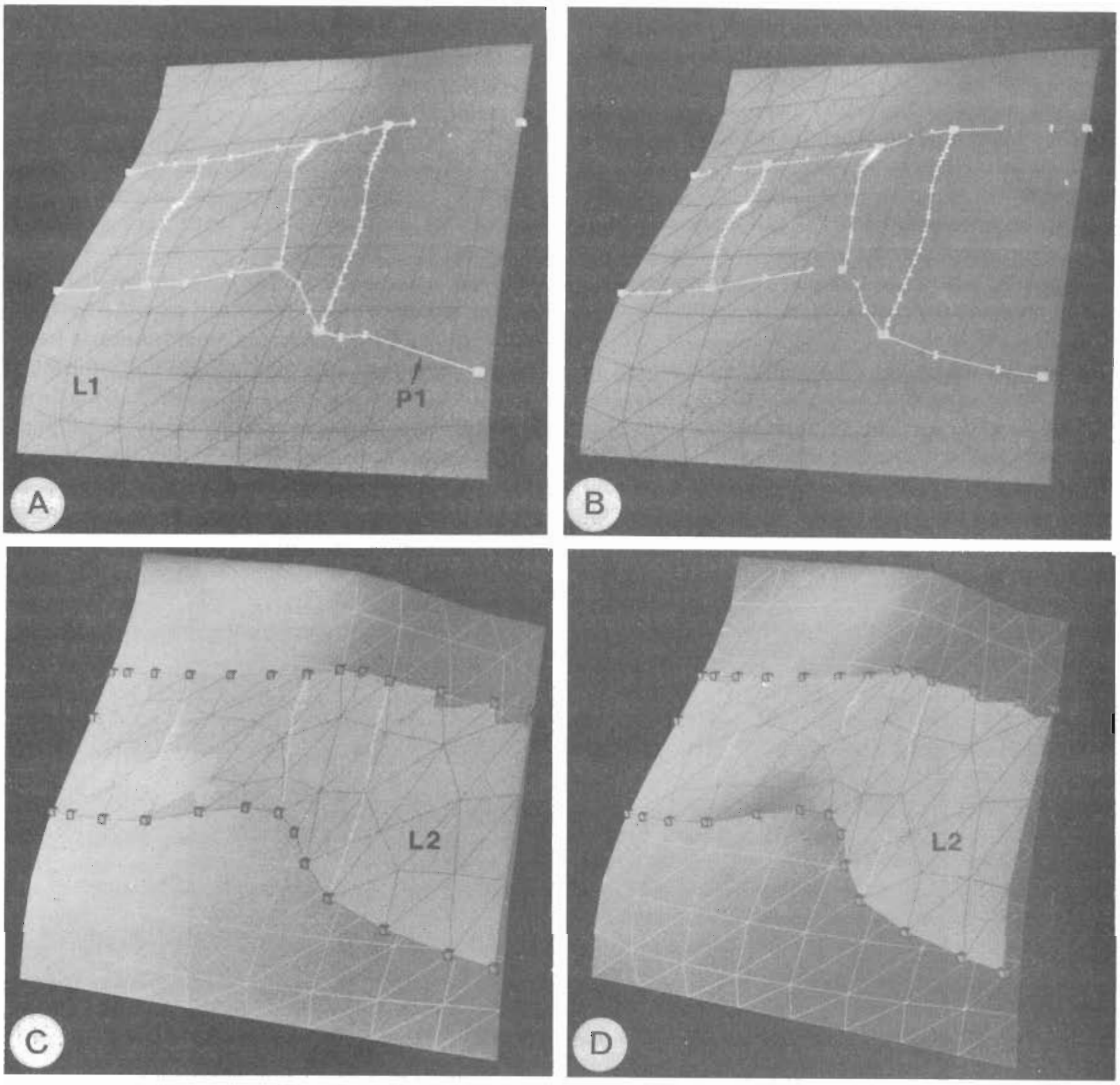

Figure 6. Steps in building two faults associated as half-opened lens. A, Surface L1 represents major fault. Data of L2 consist of three traces. Line termed P1 linking traces edges is created. "On-Tsurf" constraint is imposed on this line so that it adheres to major surface when running DSI. This constraint is displayed by small white segments from nodes of P1 to L1. B, Line P1 is modified after running DSI. Part of P1 adheres now perfectly to L1. C, L2 surface is created by triangulation between two parts of P1. Control nodes are imposed on border of L2. "Fuzzy-control-line" constraint is set from surface L2 to line P1. L2 does not fit data traces yet. D, Surface L2 fits globally to line P1 after running DSI.

traces's extremities (some nodes have an attribute "control node" which forces the surface to pass exactly through these nodes). In the second step the "patch" function (Chipot, 1991) is used to triangulate inside the closed tip line and DSI makes it possible to adjust this surface to the traces (Fig. 5B).

Fault known by a single trace— For faults that are known by one trace only, an azimuth of extrapolation is required. The form of the Tip-line is obtained using DSI; it passes through the two extremities of the trace and extends laterally in the given direction. The resulting Tip-line has an elliptic shape. Then the surface is created as in the general situation (triangulation and adjustment).

Length of the fault is larger than the size of the model—In some situations, especially for

(Figure 7 Opposite)

Figure 7. Steps in building horizon. A, Initial surface, globally adjusted to available data, is created. Important deformations are visible because fault displacements are not taken into account. B, Initial surface then is cut by each fault and reajusted using DSI. Each border is attached to its own fault with "On-Tsurf" constraint. Displacements of horizon on each side faults is visible clearly. C, View of whole set of faults cutting horizon.

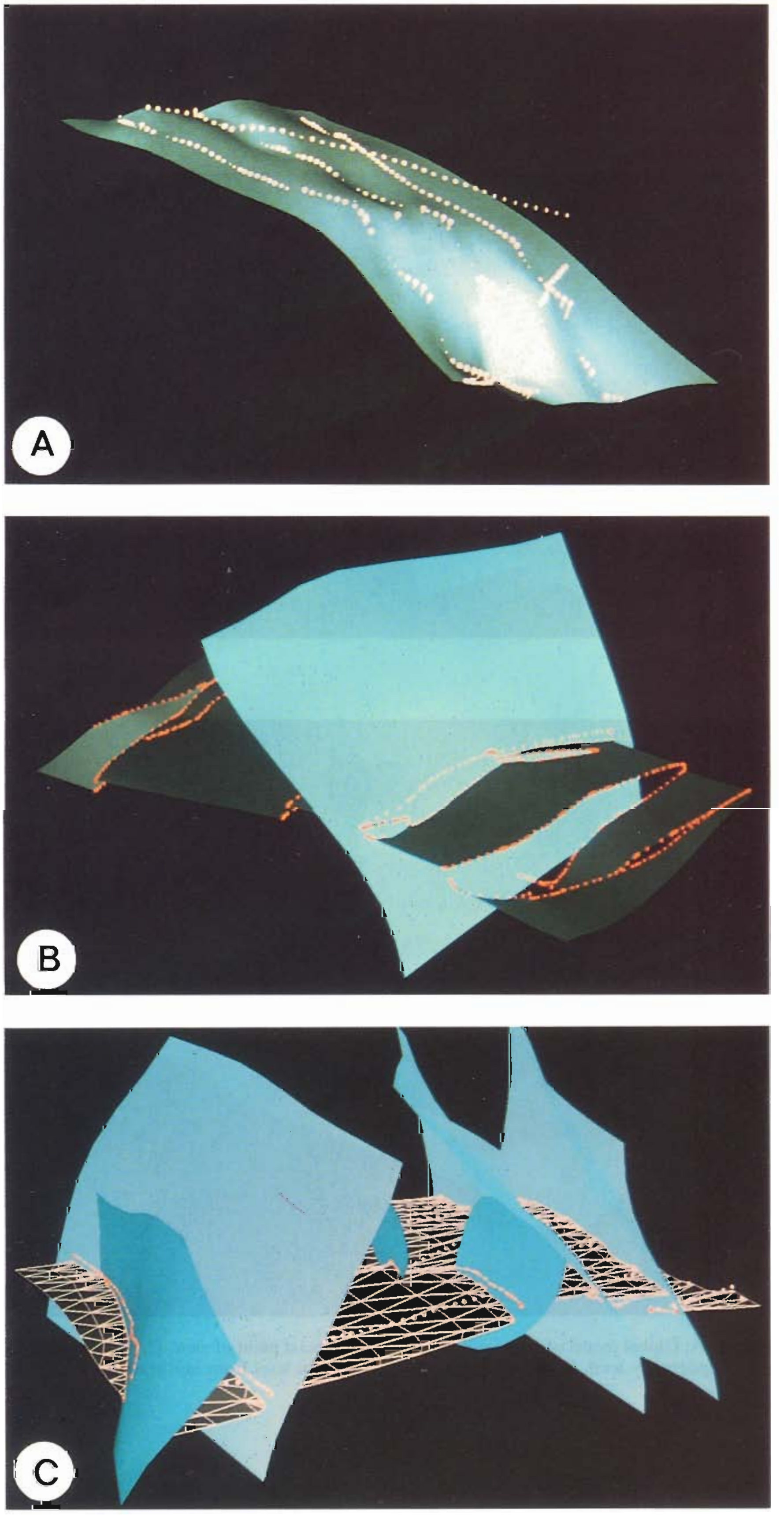

Figure 7—*caption opposite.*

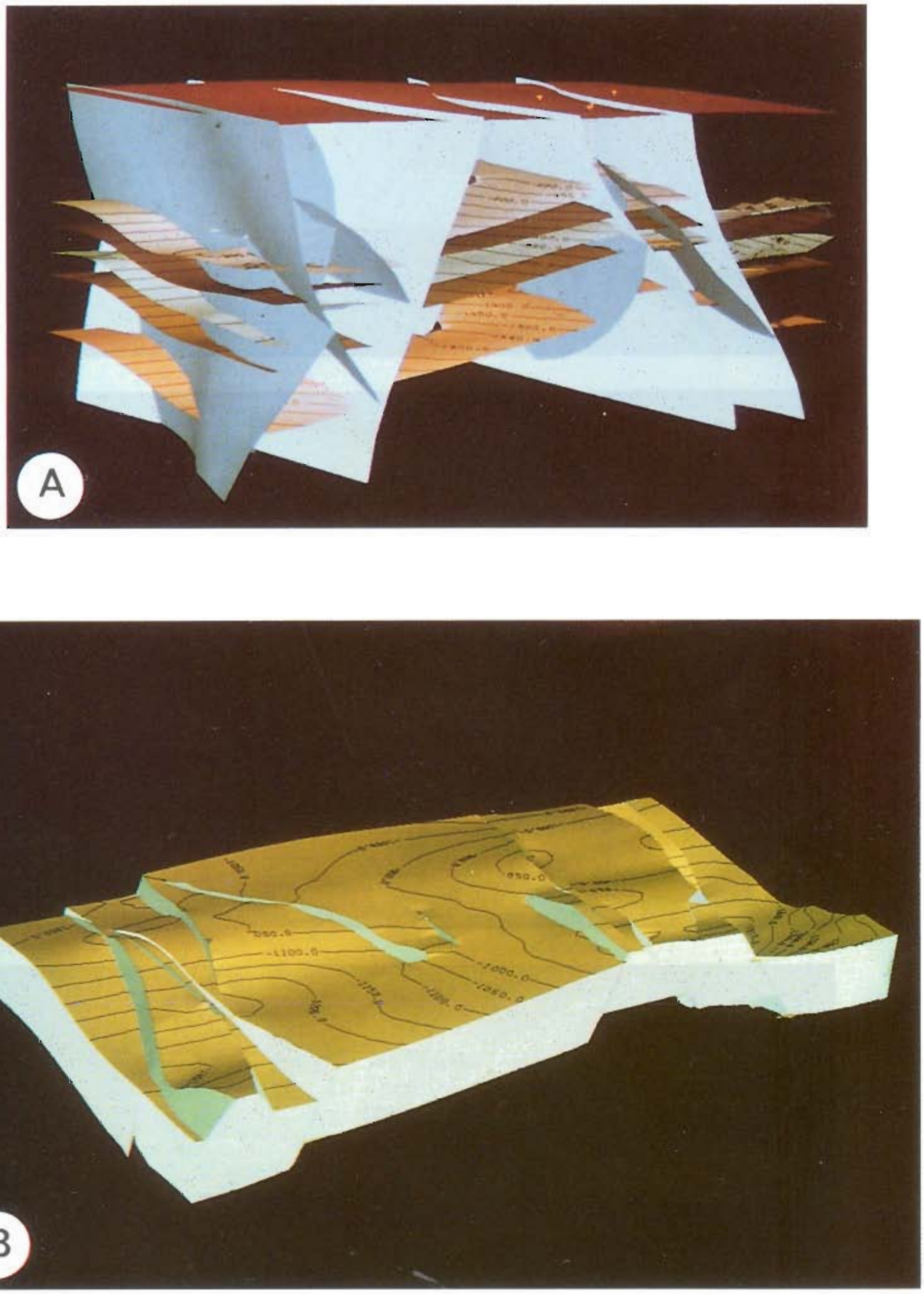

Figure 8. A, Global model of faults and layers from northeast point of view. Upper red surface indicates topography level, B, Box-diagram of Bundsandstein level from northeast point of view.

Table 1. Soultz Horst final fault interpretation.

FAULT NAME	LIST OF TRACES	ASSOCIATED WITH
F1	F19J / F9cK / F10cL / F30W	
F2	F90cK / Fc9L / F31W	F1
F3	F20J	F1
L1	F23cJ / F12K / F15cL	
L2	F22cJ / F11K / F13cL	L2
L3	F24J	L2
L4	F21J	
S1	F27J / F15K / F22L	
S2	F18K / F31J / F6R	S1 and S3
S3	F5R / F30J / F23L / F19K	S1
S4	F18K	S3
S5	F160K / F28J	S1
S6	F21L / F16K / F3R	S1
f1	F14K / F20L	
f2	F13K	
f3	F17L	
f4	F18L	
f5	F19L	

major regional faults, the Tip-line is outside the area of study and thus unknown. The surface border no longer corresponds to the Tip-line but rather to the border of the study area. The algorithm then is simpler. An initial vertical planar surface whose size corresponds to the area of the studied domain extension is built (triangulated vertical grid). Then it is adjusted globally to the traces using DSI.

Fault network modeling

Let us consider now the link between two intersecting faults. More precisely, let S1 be an already modeled surface. The problem now is to build a new surface, S2, that partially adheres to S1.

Surface S2 is built in two steps: determine the geometry of the border line, then create a surface as in the general situation.

A problem is that part of the S2 border line must adhere to S1 and that is geometry cannot be inferred only from available trace data. The border line will have to be constrained too by the geological knowledge of the faults relations and kinematics in this area. Therefore, it has been decided to define interactively the form of this line and select the parts of the border that must adhere to S1. The operator must interactively manipulate the line, incorporate constraints, and run DSI.

As an example, construction of one of the major faults named the "Soultz fault" is illustrated in Figure 6. This fault is divided into two branches that enclose a lens of sedimentary materials. Data consist of traces F23cJ, F22cJ, F12K, F11K, F15cL, and F13cL (Fig. 2). Traces F15cL and F13cL show that the lens opens itself toward the south and the bottom. Two surfaces have been built. The first one, named L1, large in extension, has been built from the traces F23cJ, F12K, and F15cL according to the method exposed in the section "Length of the fault is larger than the size of the model". The second one, named L2, adhering to the first, has been built from the traces F22cJ, F11K, and F13cL according to the method described next.

First, a line termed P1, which links the extremities of the traces, is created (Fig. 6A). It is formed by two disjointed parts which correspond to the top and bottom of the traces. The positions of P1's extremities are determined interactively. Some points of P1 are made to adhere to L1 using the "On-Tsurf" constraint (Lemelinaire, 1992). This constraint links a point of a surface or a line to another surface, and using DSI, forces this point to slide along the other surface. Points corresponding to the extremities of the traces are fixed as "control nodes". DSI is run on P1 to make it adhere exactly on L1 (Fig. 6B).

It then is possible to triangulate between these two parts of lines as shown in Figure 6C ("skin" function) and use DSI with the following constraints: not changing the border and passing at best through the three traces. Figure 6D shows the final result.

LAYER MODELING

Available data for each layer are its traces on every cross section and a set of points coming from wells. The traces can be discontinuous (cross a fault), secant, and of differing geometry from one trace to another. The triangulation method between traces is difficult to apply in such a situation.

This is why it has been decided to build an initial surface first which does not take into account the faults; it is adjusted globally to the available set of data points (traces and wells) (Fig. 7A). The surface then is cut by each of the faults, creating two identical borders at each intersection. Each created border is attached independently to its own fault using the On-Tsurf constraint. Lastly, the surface is adjusted again with DSI (Fig. 7B). This allows the border to slide and be readjusted along the faults (Fig. 7C). It can be seen that final surface better fits the data.

RESULTS

The fault network and five geological limits have been modeled, covering a 6 × 3 km surface for a 3 km depth. These are the tops of granitic basement, Buntsandstein, Muschelkalk, Keuper, and Jurassic.

A final interpretation of the fault network is presented in terms of the links between the traces and the faults in Table 1.

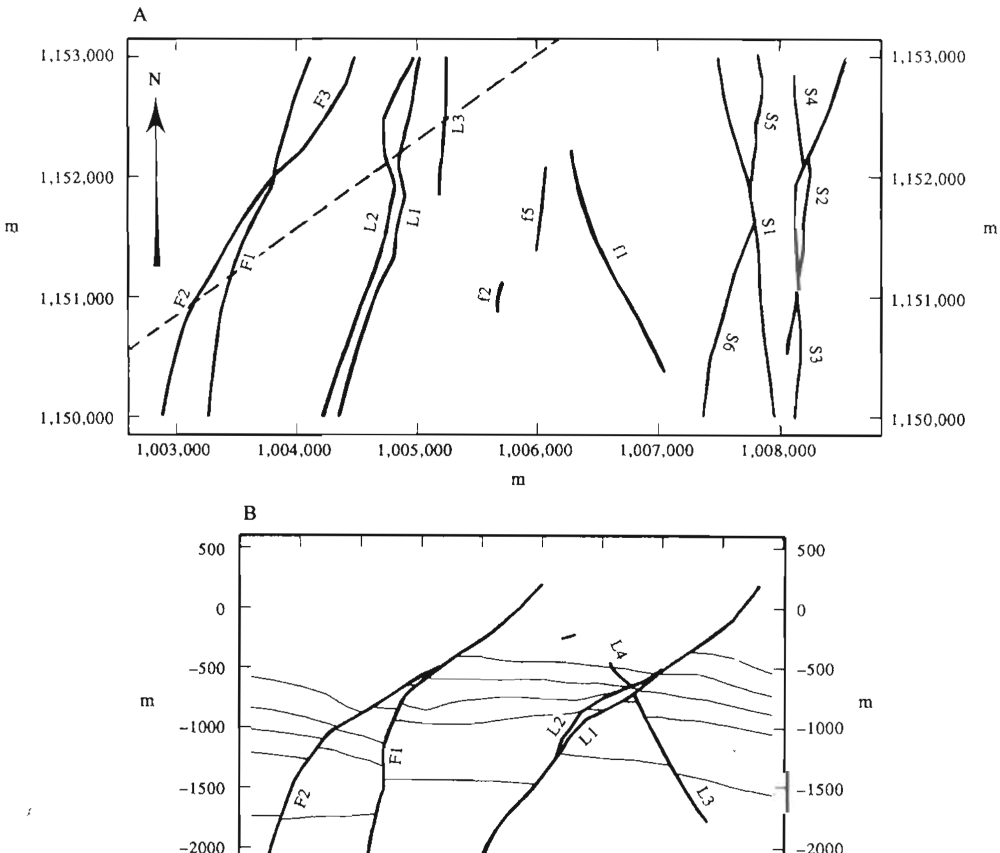

Figure 9. Two examples of sections through model. A, Horizontal section of fault network at level $Z = -700$ m. B, Vertical cross section. See location with dashed lines on horizontal section A.

The global model taking into account faults and horizons can be visualized and rotated in realtime. Figure 8A shows it from a northeast point of view. The block-diagram representation displayed in Figure 8B illustrates clearly the Horst structures with major normal movements of faults. Likewise, it shows the existence of tilted blocks along the north–south direction.

DISCUSSION

Currently, the validity of such a model can be tested only by whether it fits the data, and by its good coherence to geological features. It is clear that additional tests such as analysis of fault displacements (Freeman, Badley, and Yielding, 1989) or 3-D restoration (Rouby and others, 1993) of surfaces should be performed in order to check the global consistency of the model.

Presently, this model constitutes a reference for further investigation. Particular problems are detectable, well identified and precisely located in space. It becomes easier to define the location of new drillholes or new seismic profiles. As an example, possible geometrical exploitations of the model are done through provisional maps or cross sections (Fig. 9). These can be used as guides for interpreting new seismic profiles.

For further investigation, it should be possible to isolate specific volumic domains limited by faults or layers. These should be used as geometric framework for other simulations (geostatistics, heat transfer, flow, etc.).

3-D modeling of faults, testing as many hypotheses as needed, helps to isolate and remove some inconsistencies in the interpretation of the initial traces. It is clear that this type of inconsistency cannot be solved simply when only a mental correlation of traces is made. Interpretation of horizons on seismic profiles has not been questioned in this work, but likewise it may seem to be a problem. In this situation, the methodology applied to faults can be transposed to any reflector and therefore can be helpful in identifying reflectors to be linked from one profile to another, or on each side of discontinuities. Generally speaking, this emphasizes the interest in 3-D modeling as an aid is seismic profile interpretation.

Nevertheless, we must admit that changing interpretations leads to rebuilding the whole model, which can be time-consuming in some instances. Improvements to the method are thus necessary. Semiautomatic construction of a fault network must be developed, starting from the description of links between traces and relations between faults. This will lead the user to focus on geological interpretation rather than on model construction.

CONCLUSIONS

(1) Through this case study, the viability of GOCAD is demonstrated for use in the geometric modeling of complex fault networks and layers.

(2) Currently, it is unreasonable to envisage an automatic reconstruction of faults and layers. Nevertheless, tools for aiding in the reconstruction and interpretation process should be developed, leading to a semiautomatic approach.

(3) 3-D geometric modeling through GOCAD is a powerful tool for understanding geological objects, it is a real aid in interpretation, decision making, and planning further investigations.

(4) 3-D geometric models are not a final goal but are a step for other types of simulation.

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