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Working in complex areas: New restoration workflow based on quality control, 2D and 3D restorations

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Abstract

When working in complex areas, the explorationist needs to construct 3D models and to check their coherency. Coherence can be analyzed on the current geometry but could also be quantified through restoration. To achieve this restoration, i.e. the search for an initial geometry with a realistic deformation pathway between the initial and the final geometries, appropriate tools are necessary. These include classical cross-section balancing, surface unfolding and volumetric restoration. In this paper, we will describe a workflow to do quantitative structural geology in complex areas. This includes the construction and quality control of the surfacic model, the line balancing, the cross-section, surface and multi-surface restoration and the volumic restoration. In addition to the quality control of the geometries, the restoration allows us to compute strain tensors. This can be done in the three types of restoration and visualized through ellipses and ellipsoids (resp. 2D and 3D) that represent the main strain or stress vectors. We shall discuss the relationship between these strain tensors and the expected fracture network, in density as in direction.

Keywords: 2D and 3D restoration; Structural geology; Complex areas

1. Introduction

1.1. Defining prospects in complex areas

Geomodelers have been used daily for about ten years in the oil industry to share data and ensure coherency between the various teams in oil and gas production. They allow loading subsurface data and building surfaces and grids from them. Upgrades when new data are recorded are getting easier and the major geomodelers have an increasing number of functionalities to interpret the surface data, propose correlations and quantify uncertainties and their influence on HC field development. In contrast, during the first phases of exploration, integration of data and modeling facilities in a common tool are still rare. They are rare not (only) because geologists are old-fashioned people who love to work with pens and artistically draw what they have in mind, but also and mainly because of the lack of dedicated tools. For years, specific software has use of surface data such as maps and digital elevation models, to do cross-section balancing, or to do surface unfolding. Integration, however, was not done. With the development of the KINE3D suite within the geomodeler Gocad, we have tried to fill this gap and to allow geologists working in exploration to have their own shared model in order to integrate data and to ensure that the proposed model is compatible with all of them (Fig. 1).

The goal of the explorationist is to identify prospects for drilling requiring definition of trap geometry, closure and size, and their potential infilling with hydrocarbon. It may depend on the age of the structure versus the age of the hydrocarbon maturation/migration process. The quantification of the petroleum system is done through basin modeling tools. In this paper we will concentrate on the issue of the definition of the geometry. The geometry of faults and horizons is the structural geologists' domain. For a long time, they have had a technique, known as section balancing, to ensure a first quality control of their

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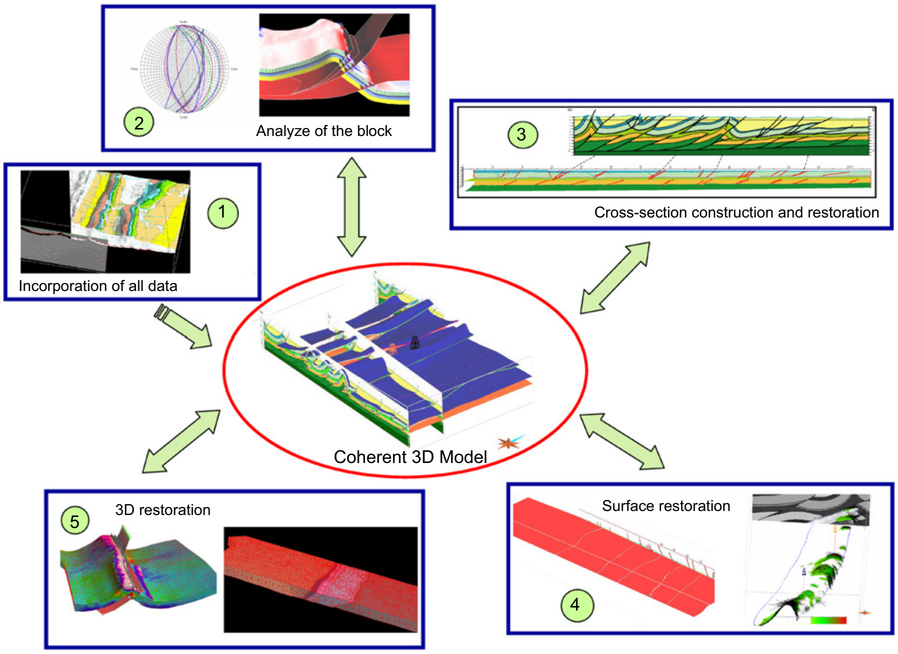

Fig. 1. Geomodeling and restoration tools. *Step* 1: Incorporation of the data and construction of a first model. The geomodeler allows us to integrate all the data and to construct surfaces that represent the horizons and faults, volume that represents the layers and to paint them with properties at different scales. *Step* 2: The quality control of the first model, that includes the check of the top–bottom coherency, the fault network analysis and the quantification of the amount of deformation, shortening or extension. Return to the model: improvement of the horizon surfaces (unfoldability) and of the top–bottom coherency. Output: surface model, amount of shortening or extension, cross-sections across the 3D data set. *Step* 3: Cross-section restoration. Return to the model: improvement of the horizon and fault geometries within the cross-section. Output: the pre-deformation geometry that may be the initial geometry for forward modeling (for temperature evolution, HC maturation/migration modeling, 2D mechanical modeling). *Step* 4: Surface restoration. Return to the model: improvement of the horizon and horizon fault intersection geometries. Output: main strain direction and intensity, dilatation, probability of fracture intensity. *Step* 5: Volumic restoration. Return to the model: improvement of the horizon and fault geometries. Output: main strain and stress directions and intensity, dilatation, probability of fracture intensity in 3D, pre-deformation geometry that may be the initial geometry for 3D forward modeling for temperature evolution, HC maturation/migration modeling, mechanical modeling.

interpretations. After a review of the concepts and algorithms hidden behind this generic word, we will describe how the use of an integrated tool, a geomodeler with dedicated plug-ins, may help to define the prospects.

1.2. Data and data representation

When speaking about software, the term *n*D, especially 3D and now 4D, is often used with an unclear meaning. Let us clarify what are the dimensions of the data and differentiate them from the degree of freedom of the algorithms used in restoration. The output and interpretation of a tool based on a 3D_algorithm applied to a volume are not at all the same as a simple shear flattening (1D algorithm) applied to a horizon (2D surface). The exploration data are in a 3D world, meaning in mathematical terms that we represent a point by 3 components (X, Y, and Z). However, when we stay on a line (a well, for instance, if we are not interested in its borehole) one component is enough to be located (the measured depth, for instance); so a line is a 1D object, a surface (a horizon or a fault) is a 2D object and a volume (a layer) is a 3D object. A 1D object has a length (in meters) a 2D object has an area in m^2, and a 3D object has a volume, in m^3.

A line could be represented by an ordered list of points, a curve, or by a function with one variable. Surfaces could be discretized by a list of triangles or a grid (rectangular mesh). Alternatively, they could be represented by a function with 2 variables. This is what we call a parameterization of the surface. The volumes could be also represented on a discrete mode by a mesh; for instance, a tetrahedral mesh or a 3D grid or on a continuous mode by a parameterization in 3D.

From these data, the geologist may wish to complete a cross-section: a set of curves in the same vertical plane where the intersections are computed and so the layering is automatic. This completion of the section corresponds to the mathematical concept of topology and/or graph. For the geologist, this means that the lines are oriented and support geological information. The surrounding data model of the software includes these informations and facilitates the task of the user. Similarly in 3D, the geologists need to build surfaces and volumes. All those who have tried to do it, know that a set of surfaces that represent the faults and horizons and a surface model are not the same. As for the cross-sections, the differences are the topology and the information included in the graph (surfaces + intersections). There are some difficulties in passing from a set of points to intersected curves and surfaces, which are eased by use of the geomodeler.

The terminology 4D is commonly used referring to time as the fourth dimension. In geology, when the structural deformation is nil, the burial and thus the depth is linearly dependent on time; so trials to represent the geological world through a 3D parameterization exist (Mallet, 2004) and this is also what sedimentologists do when drawing a Wheeler diagram. However, up to now real 4D modeling in earth science are still rare, they work when deformation are vertical (deposition, compaction, erosion), TEMIS3D for basin modeling (Schneider et al., 2000). In complex areas, such as a model is still difficult to get, it requires backward 3D software (such as KINE3D_3) and a full 3D direct model able to deal with sedimentation, erosion and displacement around non-vertical faults. Research on these topics is active but commercial products have not yet been released.

2. Restoration: theory

2.1. Quantitative approach in structural geology

The ideas that form the foundation for section balancing have been present in the literature from the early 1900s. The theory that the section areas must be conserved during deformation was first used by Chamberlain (1910). Hossack (1979) determined that orogenic shortening could be calculated by reversing the Chamberlain technique. In 1969, Dahlstrom (1969) discussed the mechanics of section balancing in detail and it became widely used. In the years between 1970s and 1980s, the geologists, working by hand, mainly restrained the balancing technique to checking the length coherence along cross-sections (Bally et al., 1966). As Elliot (1983) postulated, if an admissible solution, that honors all the data, can be restored to its undeformed state, such a model represents a viable solution. Of course, a viable model is not a unique solution but, hopefully, if all the available data have been incorporated in the viable model, alternative interpretations are limited. In fact, Elliot (1983) postulated this for cross-sections at a time where balanced cross-sections were done manually with a limited number of length measures; now software allows us to apply these principles in real 2 and 3D increasing greatly the accuracy of the proposed geometry.

After the pick of the development of balanced cross-section tools in the 1990s, this has led to the release of various commercial products (Geosec_2D, Locace, 2D_Move; Kligfield et al., 1986; Moretti and Larrère, 1989); the research has continued with surface unfolding (Gratier and Guillier, 1993; Mallet and Massot, 2001). Commercial products have also been proposed (3D_Move and Geosec_3D in the late 1990s and more recently KINE3D_2) and software for real 3D restoration now exists (KINE3D_3; Moretti et al., 2006).

In these pages, we shall call "1D restoration" the line balancing technique; "surface restoration" or "2.5D_restoration" the processes that allow us to unfold and unfault a surface, which represents a horizon. This is a backward process that could be applied through the commercial products 3D_Move, Geosec_3D or KINE3D_2, among others since a few non-commercial prototypes also exist. We shall call 2D_restoration the cross-section balancing tools (which could be applied through LOCACE, GEOSEC or 2D_Move) and 3D_restoration the volumic restoration. The principles are summarized in Fig. 2. All the examples shown in this paper are done with KINE3D_1, 2 or 3 which allow the geologist to do, respectively, incorporation of data and line balancing (KINE3D_1), cross-section, surface and multi-surface restoration (KINE3D_2), and volumic restoration (KINE3D_3).

Considering that the mathematical and computer science problems linked to restoration are now solved, one may focus on the geological questions. There are different techniques, different algorithms and different ways to use these algorithms. The aim of this paper is to define the characteristics of each one and how to choose the more appropriated one, not based on software availability but on exploration issues, data quality and geological context.

2.2. Methods

Various deformation modes have been proposed for the upper crust: the main one is the flexural slip, the shear happens preferentially along the inter-bed weak layer (shale, silt), surface of the horizon and thickness are preserved, and the simple shear (Fig. 2). The simple shear deformation mode is known to be a good approximation of the deformation of the granular materials and therefore of the deformation of the poorly consolidated sediments of the extensive areas (Verrall, 1981; Gibbs, 1983; White et al., 1986). Ductile lower crust deformation can be also modeled using this approach. At the opposite, in the upper crust, the competent layers behave more typically with a flexural slip mode as widely discussed previously (Suppe, 1983; Moretti and Larrère, 1989). However, both exist and so useful tools need to propose at least the two options and allow them to be combined.

These deformation modes lead to various algorithms depending if they are applied in 1, 2 or 3D.

2.2.1. Line balancing

If the area of a horizon is preserved during the deformation, and if there is a major direction of transport, we may consider that the length of the horizon in this direction is constant. So by computing the gap between the length of a horizon and the horizontal distance between the tip points, we can quantify the shortening or extension. Historically with a curvimeter and now with a computer, it is possible to measure the length of the horizons between faults. It is the comparison of these lengths that corresponds to the line balancing technique; all the first

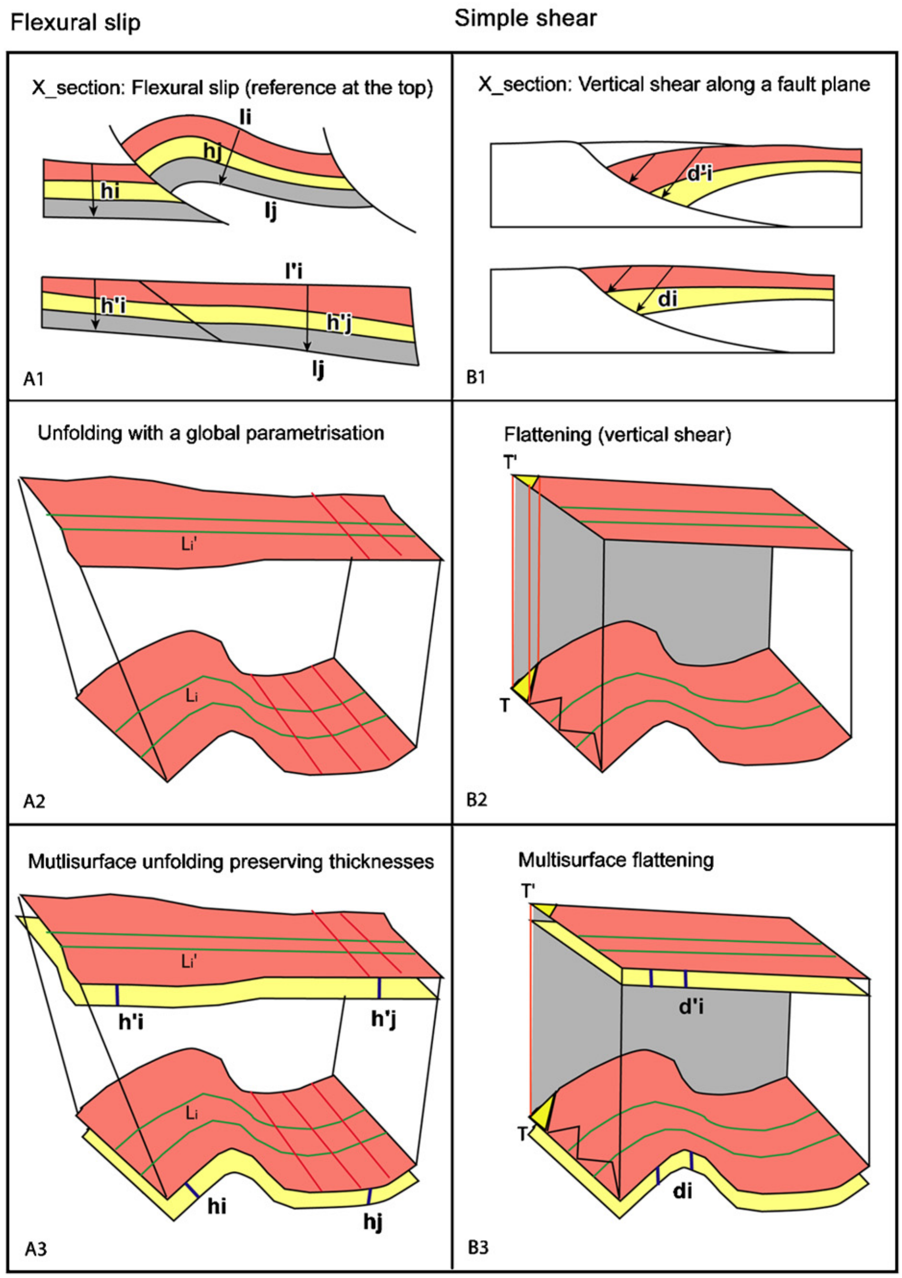

Fig. 2. Simple shear versus flexural slip in cross-section and in surface restorations. (A) 1. Flexural slip in cross-section, the lengths and the thicknesses of the layers are preserved as well as the areas in the plane of the sections. 2. Unfolding through a global parameterization, the global area is preserved, the lengths in the direction of the parameterization (green and red lines) are preserved. The restoration vectors could be in any direction. 3. Multisurface unfolding by flexural slip. The thicknesses between the reference level and the other ones are preserved. (B) 1. Simple shear in cross-section, the distances in the shear direction, d_i are preserved, thickness, lengths and areas change. 2. Unfolding by vertical shear, the area of each triangle changes, the global area changes. The restoration vectors are all parallel to the imposed shear direction. 3. Multisurface restoration by simple shear, the distances in the shear direction between the reference level and the other ones are preserved.

cross-sections were done using this approach (Bally et al., 1966). The geologist verifies if the shortening, or the extension, is the same for the various pre-deformation horizons and if this ratio of deformation is coherent on strike along the structure. He can check not only the length coherency but also the thickness variations.

This method is simple but generally allows immediate elimination of many incoherent geometries. However, within this method the geometry of the faults between the intersections with the horizons does not influence the results; so this method is blind to improve the quality of the fault interpretation and/or the fault/horizon angle (called the cut-off angle). We may also add that taking into account the difficulty of computing thickness in steep anticlines, geologists often restrict this approach to constant thickness layers.

2.2.2. Cross-section balancing

In 2D restoration, the methods have been rather well established for several years; the basic assumption being the preservation of the areas in a vertical plane (plane strain hypothesis) corrected, or not, by the compaction/decompaction effects. The four main deformation modes are flexural slip, simple shear, ductile flow and rigid rotation. Fig. 2 and Table 1 synthesize the corresponding deformation modes and the quantities that are preserved for each method.

- With the *flexural slip method*, the principle is to preserve in a vertical plane layer areas, lengths and thicknesses. If the restored layer is isopach, the preservation of both thickness and length results in area conservation. If the thickness varies, the strict preservation of bed thickness and bed length may lead to area changes. In the commercial tool that proposes this method—flexural slip for non-isopach layer—LOCACE, the user may choose to give priority to the preservation of lengths or to the preservation of thicknesses (see Moretti and Larrère, 1989 for details). The combination of this deformation mode with the geometry of the faults and decollement level lead to a large variety of structures commonly described in the literature related to thrusts and folds (Mitra, 1990 among others).
- With the *simple shear method* we preserve the distances in the shear direction (neither the length, nor the thickness), areas are not preserved. The shear direction could be defined based on laboratory measurements for various granular materials, usually around 60°. For natural rocks, moving along pre-existing faults, at the time scale of the geological deformation and with an increasing compaction, and so a change in mechanical behavior, versus depth, the topic is not as simple and has been debated by various authors (Verrall, 1981; Gibbs, 1983; White et al., 1986; Faure and Chermette, 1989).
- With the *ductile flow*, the right method for decollement level, such as shale or salt, only the global area is preserved. This is a simplification of the 3D volume conservation.
- With the *rigid rotation*, also called domino style (Angelier and Colletta, 1983), within a given faulted block everything is preserved: bed lengths, thicknesses, areas and even cut-off angles between faults and horizons.

Table 1

Values	Flexural slip	Simple shear
Cross-section bed area	$XS\_S = XS\_S'$	$XS\_S \neq XS\_S'$
Cross-section horizon lengths	$li = l'i$	$li \neq l'i$
Cross-section thickness	$hi = h'i$	$hi \neq h'i$ $d_i = d'_i$ distance in the shear direction
Global surface	$S = S'$	$S \neq S'$, S always $> S'$
Area of one triangle	$Area\_T = Area\_T'$	$Area\_T \neq Area\_T'$
Length of the horizon in a given direction	$L_i \approx L_i'$	$L_0 = L_0'$
	If the surface is developable	$L_1 = L_1'$
Multi-surface thickness	$hi = h'i$	$hi \neq h'i$ $d_i = d'_i$ distance in the shear direction

Characteristic lengths: bed lengths li (in cross-section) L_i in 3D, thickness hi, distance in the shear direction d_i. Characteristic areas: bed area in cross-section: XS_S and horizon area: S. Triangle area: T.
Letter refers to initial geometry and prime to the unfolded one (see Fig. 2).

While balancing a cross-section, the geologist often has to use more than one deformation mode. For instance, in compressive areas, a combination of flexural slip for the competent layers and ductile flow for the poorly competent decollement levels is the most common and at smaller scale, the trishear concept combines the flexural slip and the simple shear methods. Sometimes, the final geometry of the layers as well as the fault shape and the horizon–fault cut-off help the geologist to choose the right deformation mode: concentric folds require flexural slip deformation when similar folds are compatible with a simple shear mode. In terms of degree of freedom of the algorithms, the flexural slip mode is 2D; the simple shear mode is 1D.

2.2.3. Surface balancing

In 2.5D_restoration, we need to unfold the structures and to erase the fault offsets. To restore a horizon the first step is to have a representation of this horizon through a surface, generally cut by faults. The representation of a surface could be deterministic, i.e. nodes on a triangular or rectangular mesh or implicit, a continuous equation allowing us to represent the surface at any scale. Similarly the unfolding could be based on a discrete or continuous approach, i.e. based on triangle (or square) or node displacements or to a global transformation. The details of the various existing methods can be found in Moretti et al. (2006, 2007); to summarize, there are three main techniques of unfolding.

- *Global approach (area preservation)*

  The aim of the global approach is to preserve the areas of the horizons by keeping as constant as possible the lengths in various directions (Fig. 2A). We will call this method "flexural slip" by extension since the flexural slip mode in cross-section also preserves the lengths of the horizon. After trial to work directly on the triangles (Gratier and Guiller, 1993), the major 2.5_restorations are now based on a parameterization of the surfaces (Bennis et al., 1991; Mallet, 2002). They allow preserving the lengths and the areas of the horizons if the surface is unfoldable and, when this is not 100% the case, to search for the best solution. In KINE3D_2, for instance, the user may choose their preference between preservation of lengths (red and green lines Fig. 2A2) and preservation of angle (between the red and green lines) in order to approach the global area conservation. One may refer to Mallet's (2002) for the algorithm description.

Another implementation of this global approach has been done using an elastic 2D code with the adequate elastic constants to get good area preservation; it leads to similar results.

- *Flattening-simple shear*

  Flattening is the simplest method (Fig. 2B): it exists on geophysical work-stations for instance and can be used on any surface representation. Mathematically, it is very simple, being in a 3D space, with z as vertical coordinate, the transformation of a point is given by

$$M[x, y, z] \geqslant M[x, y, Z\_\text{constant\_value\_user\_defined}]$$
$$\text{(vertical shear)}.$$

When picking seismic data, the explorationists use this method as a visualization functionality, not as a true restoration, especially when working with time scale seismic data. However, the principle of some 2.5D_ restoration tools is to combine the flattening with a choice of the shear angle, as in 2D restoration, and eventual translations.

To apply a simple shear method, a reference level is required; in flattening mode implementation as done in geophysical software, the reference is the selected horizon. Another possibility is to consider the fault as reference (Sanders et al., 2005); this concept was initially proposed by Verrall (1981) among others for the deformation of syntectonic sediment in extensive context. The reference level is, in this case, a listric fault and its decollement level. The use of this deformation mode when restoring competent bed in compressive areas remains highly questionable in 3D as in 2D: the horizon area is not preserved and, when more than one layer is restored, the thicknesses are not preserved.

- *Extrapolation of parallel cross-section restoration*

  An alternative approach is based on the extension of the cross-section restoration, the horizons and faults are restored in a vertical plane and the surfaces that correspond to the pre-deformation stage are built by linking the 2D cross-sections. The restoration in the cross-sections could have been done using flexural slip or simple shear deformation modes.

The description of this method is easy from an algorithmic point of view; the geological meaning of the subjacent hypotheses is less clear and may even appear contradictory: on one side, we suppose that the deformation happens along a main direction, on the other we allow the horizon length to change in the perpendicular direction. As a result the horizon areas are not preserved except if the case is purely cylindrical.

In term of degree of freedom of the algorithms, the global parameterization mode is 2D; the simple shear mode is 1D.

Unfaulting. In addition to the unfolding, to restore horizons the user generally needs to erase the fault offsets. This process could be done "a posteriori", by zipping the fault lips (rotation, translation and internal deformation could be necessary) or jointly with the unfolding by imposing the continuity of the parameterizations across the faults. Alternatively we can accept void and overlap to avoid imposing internal deformation. When using a method based on parallel cross-sections, the contact fault/horizon is constrained on the cross-section and then imposed by construction on the surfaces.

2.2.4. Multimap restoration

To restore a set of surfaces we can unfold jointly each one but this will not help to check the coherency between the top and the bottom of the layers. So it is better to choose a reference level and to maintain characteristic lengths between the series below, and sometime above, during restoration. In order to remain coherent, and with the general exception of the decollement levels, thicknesses have to be preserved with a flexural slip approach and distance in the shear direction with the simple shear. These are the two options proposed in KINE3D_2. Figs. 2A and B sketch the two methods applied to multi-surface restoration and examples of use will be discussed later one. These methods are really the 3D extension of the methods used in cross-section balancing. The thickness conservation is imposed for the flexural slip; respectively the distance is the shear direction. Note that the results of a multisurface unfolding following the flexural slip hypothesis are not the same as an unfolding of each layer; in the case of an isopach layer, the geometries will be rather similar but the computed dilatation will be different.

2.2.5. Volume restoration

Research into 3D restoration has been active for about 10 years. The difficulties reside in the meshing of complex structural zones and in the choice of adequate algorithms.

Surface representations allow us to follow in detail the geometry of horizons, main facies boundaries and faults; however, to solve equation in 3D, we need 3D meshes. It seems to be a simple problem except that computer memories are limited, solvers need some quality of the mesh to be able to converge and CPU is also bounded. Meshing in earth science is so a constant research topic (Prévost et al., 2005). The constant quandary is related to the fact that fluid flow specialists like grids, even just structured grids for some of them, when nature could be too complicated to be represented by a list of adjacent cubes. The advantages and disadvantages of the various meshes are out of the scope of this paper and even of the project. To avoid having to choose, the technical solution that we have selected, allows us to work with both: tetrahedral meshes and structured grids.

For the restoration process, 3D extension of the discrete equation of the flexural slip has been tested (Cornu et al.,

2000) without great success. So more classical approaches have been tested, developed in other fields such as strain minimization (Mallet, 2002) and elastic relaxation (Muron, 2005). We have also tested a link with a finite element code of mechanics, *Code_Aster* (Moretti et al., 2006). This solution appears to be the most robust and it is the one preferentially proposed in the commercial version of KINE3D_3.

In 3D restoration, as in 2D, target geometry has to be partially given by the user: fault offsets could be erased and a specific horizon unfolded for instance. This information, translated in imposed or forbidden displacements, is sent to *Code_Aster* along with the mesh coordinates and the rheology of the material (restricted to elastic constitutive law, with Young modulus and Poisson ratio). We mainly used elasticity hypothesis for reversibility purpose. The unfaulting is imposed through linked displacements between the fault lips of the horizons (Moretti et al., 2007) or by gliding along the fault plane. The outputs contain the new geometry, as well as the strain and the stress tensors. The area conservation of the horizons is not imposed and neither the thickness conservation; however, as long as the restoration is possible without changing them, they appear to remain constant.

Since *Code_Aster* is a finite element code, the resolution of the equation is done in the volume and so, as long as the meshing is fine enough to ensure the representativity of the surfaces, the results are not greatly affected by either the type or the coarseness of the mesh. In Fig. 3, we can see the strain aspect ratio computed on the restoration of the displayed faulted anticline with a grid of 4000 cells (left) and the tetrahedral mesh of 26 000 cells (right). The boundary conditions and the rheologies are the same. The geometry of the areas submitted to extension, compression or no internal deformation is roughly the same.

3. The outputs of the restoration processes

3.1. Nomenclature

Concerning names, to make it easy, we shall call *Dilatation* the local area variation on the surfaces as well as the volume variations of the mesh cells. So, for a surface the computed *Dilatation* of each triangle is

$$2D\_Dilatation = (\text{Area}_{\text{to\_day}} - \text{Area}_{\text{at previous step}})/\text{Area}_{\text{to\_day}}.$$

For a volume for each cell of the mesh the formula will be similar

$$3D\_Dilatation = (\text{Volume}_{\text{to\_day}} - \text{Volume}_{\text{at previous step}})/\text{Volume}_{\text{to\_day}}.$$

When doing restoration we compute a new geometry; the individual displacement of each node is stored with a vector called *Restoration.* Each cell of the initial geometry in 2D as in 3D is deformed, the tensor of deformation could be represented by their eigenvalues in terms of direction and intensity, they are the *main strain directions*: Max, Medium (in 3D) and Min. When working with a constitutive law, strain and stress are linked so the 3D restoration allows also computation of the *main stress directions*: Max, Medium and Min. We can also compute some invariants of the strain and stress tensors as their *trace* and *aspect ratio*. Following the definition proposed by Sassi and Faure (1997) the *aspect ratio* is given by $(L_2-L_3)/(L_1-L_3)$, L_i being the eigenvalues of the strain (resp. stress) tensor (Maximum, Intermediate and Minimum). The *trace* is $(L_1+L_2+L_3)/3$.

The curvature of a surface quantifies the difference between the tangent plane at a given point and the surface. It is the same definition then for a curve, in this case the curvature is easily represented by the inverse of the radius

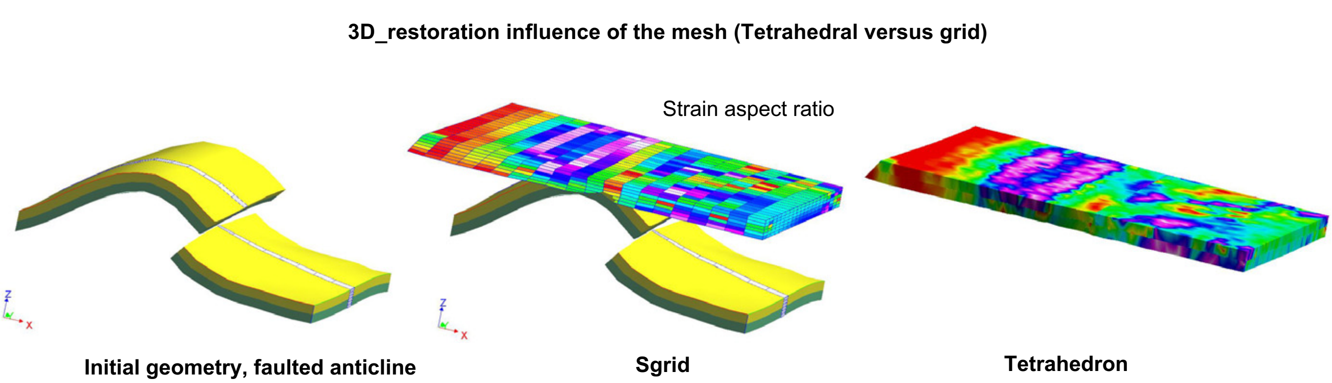

Fig. 3. Volume restoration, influence of the mesh. Restoration of a faulted anticline. In the center the mesh is a grid that follows the horizons, the number of cells is 4000. Right of the mesh consists of tetrahedron, they also honor the horizons but are much more numerous (26 000). The displayed property is the strain aspect ratio; it represents the areas with deviatoric strain. We can note that the difference between both simulations is close to zero. Due to the finite element approach there is no need to increase the number of cells to obtain better results as long as the mesh allows representing the geometry of the layers and faults.

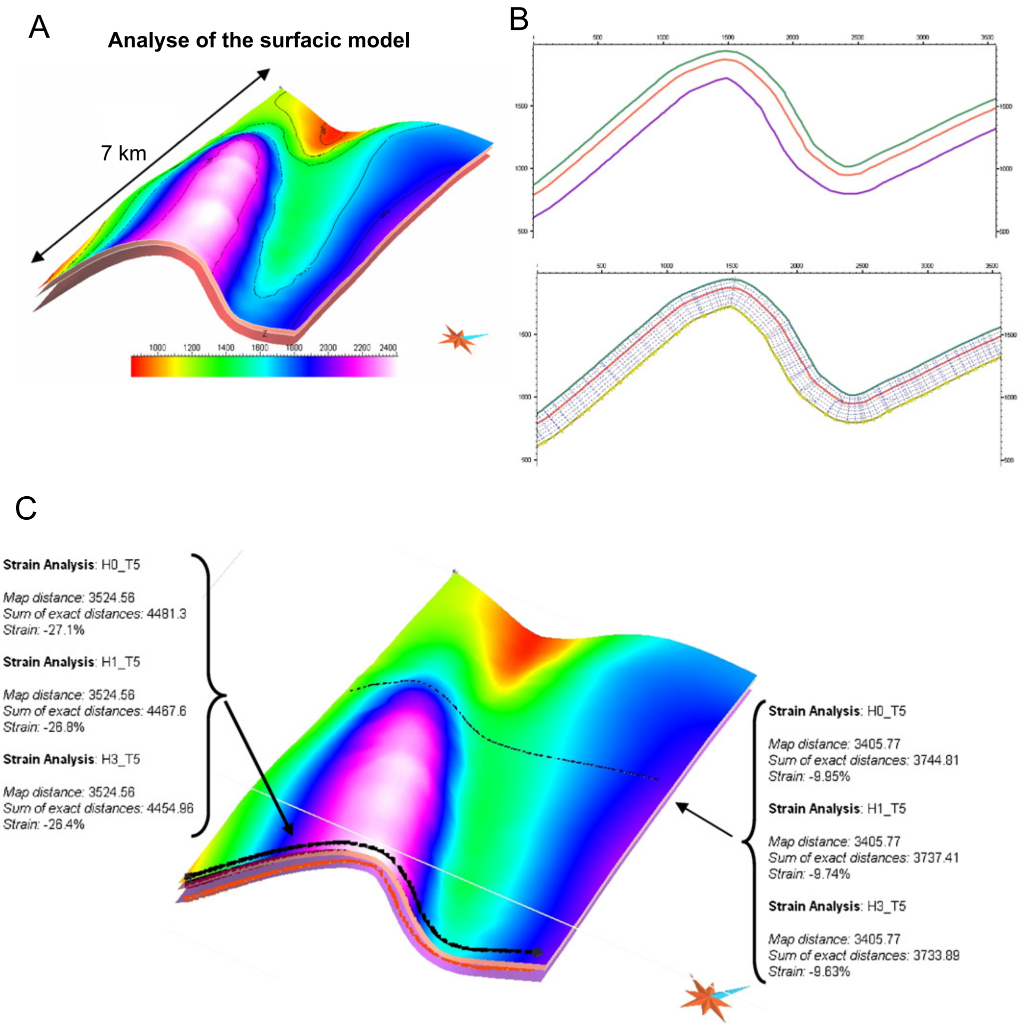

Fig. 4. Static analysis of the plunge extremity of an anticline. (A) Initial geometry, the color code is the elevation (between 1000 and 2500 m). (B) Analysis of the model, extraction of cross-section, check if the top–bottom relationship using a kink-band grid automatically computed by the software from the selected horizon (here the top). (C) Computation of the shortening to check the coherency of the shortening between the various horizons and on strike evolution along the anticline.

of the circle tangent at the curve on the given point. If the curve is planar the radius is infinite and its inverse is null. We differentiate the *Min_Curvature* and the *Max_Curvature*. The *mean curvature* is half of the sum and the *Gaussian curvature* the product of both. A surface is unfoldable if its *Gaussian curvature* is close to zero, which is the case if one of the curvatures is null.

3.2. Workflow

The three main outputs of a restoration process are:

- a quality control of the geometry and often improvements of the initial geometries;
- a computed pre-deformation geometry;
- a quantification of the internal deformation required for the restoration.

A comparison of the results of the different steps will be done on a fold (Fig. 4). This structure is the tip of an asymmetric anticline which corresponds to the Sheep Mountain anticline (Bellahsen et al., 2006). A complete analysis of this case study is in preparation, and so here we shall just present the results on the western tip of the plunging anticline to discuss the results of the various restorations. The anticline plunges west-northwestward (about 20° NW) and presents a northern steep flank (dip from 40° to 90°) and a smoother southern flank (dip from 10° to 40°). The shown part of the structure is about 7 km long and the thickness of the restored series 220 m. One of the horizons is known by surface data while the other ones have been constructed using thickness data. They are isopach. We might consider that the surfaces are correct as confirmed by the analysis of the model. Fig. 4 shows the coherency of the shortening across the structure for the

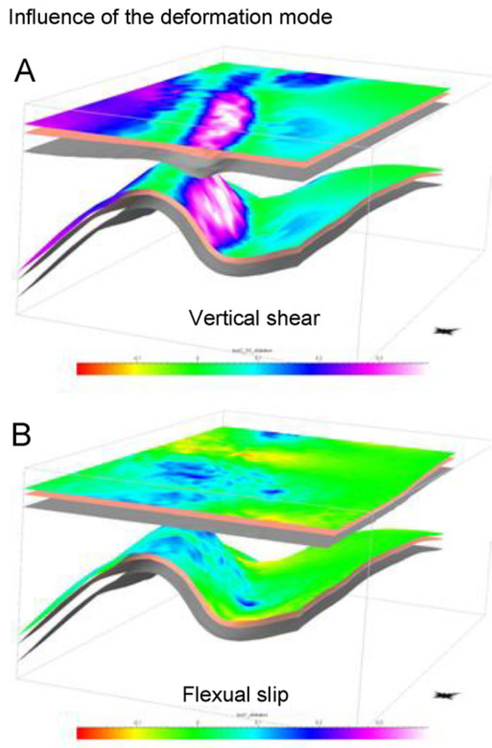

Fig. 5. Multisurface restorations with different deformation modes. (A) Vertical shear (distances in the shear direction are preserved between the horizons). (B) Flexural slip (areas and thicknesses are preserved). The upper horizon is colored with the dilatation. In the case of the simple shear, the dilatations are always positive and rather large. They are larger in the flanks of the anticline where the dip is steep and minimum in the horizontal part including the top of the anticline. In the flexural slip case, the dilatation is smaller and the larger values highlight the parts with a low unfoldability. High dilatation zones correspond to high internal deformation zone, i.e. zones with a larger probability of fracture density.

various horizons and the accuracy of the thickness values. In the central part of the fold the shortening is 22% (N70°).

Obviously, when restoring, if the chosen mode of deformation is inadequate, the results are questionable. Fig. 5 shows multisurface restorations with two different deformation modes: the simple shear (5A) and the flexural slip (5B). The restored geometries are different, in both cases, the upper layer is flat since it is an imposed boundary condition but its area is different and the computed geometries of the two other layers are very different: with the simple shear the distances in the shear direction (here vertical) have been preserved whereas in the case of the flexural slip the thicknesses have been preserved, as sketched on Fig. 2. As a result, restoration with the simple shear hypothesis computes non-isopach initial layers with a thicker part on the flank of the structures. At the opposite the restoration with the flexural slip hypothesis is coherent. The computed dilatations also differ. The choice of the right mode of deformation function of the geological context and of the rheology of the layer is out of the scope of this paper, comparisons between the different modes can be seen in Moretti et al. (2007). We shall focus on the following comparison what we learn from the different restorations (1D, 2D and 3D) with the same hypothesis of flexural slip mode, i.e. conservation of horizon lengths, thicknesses and areas.

3.3. Improving the model

All the processes that have been described previously—the static analysis of the surfaces, the lines balancing, the cross-section and surface restorations as well as the volumic restoration—can potentially improve the accuracy of the horizon and fault geometry.

Quality control on the thickness maps will allow us to correct directly on the current geometry the top–bottom incoherencies that may lead to unexpected thickness changes. Similarly, the curvature analysis may allow improving the area of no-developability. In both cases automatic tools correct the surfaces. Layers compatible with the flexural slip deformation mode, isopach or with thickness variation may be drawn automatically and unfoldability based on curvature may be imposed (Galera et al., 2003).

The lines balancing allow highlighting the major errors, for instance, a missing duplex above a decollement level will result in a gap of shortening between the series above and below this decollement. However, the final length of the horizons is not directly influenced by the fault geometry, so the fault geometry itself will be only improved with the 2D and 2.5D restoration. The cross-section restoration appears to be very constraining in terms of horizon–fault angle and top–bottom coherency especially when using flexural slip. Unexpected back-shear appears immediately when the initial cut-off is wrong or when the length of the top and bottom of each part (faulted block or thrust sheet) is incoherent. Then, the surface restoration allows us to check, and potentially improve the consistency of the fault lips and of the horizon surface. To finish the volume restoration will help to constrain horizons and fault surfaces. Note that only the volume restoration is influenced by the complete surface of the fault and so can potentially help to improve it.

It is important to keep in mind the difference of algorithms between the cross-section restoration and the surface and volume restoration. In cross-section the algorithms are determinists: for each layer, all lengths and thicknesses are preserved, with the chosen sampling. In contrast, the conservation of lengths and areas in the surface restoration is a minimization of a global function; so the results of the surface unfolding will be a flat surface, if the target geometry is flat, and the fault lip will be closed if this constraint is imposed. The program will impose internal dilatation to reach these targets, and eventually the area conservation will not be perfectly achieved. In the same way, for the volume deformation, incorrect geometry may result in a high computed internal deformation and bad global volume conservation. Interpretation of unexpected geometries is much easier than unexpected amounts of internal deformation. So when the uncertainties of the horizon and fault geometry are large it is necessary to first correct the geometry and so pass through the various steps: quality control, X-Section and 2D restoration and then 3D_restoration.

Another way to better visualize the geometrical inconsistencies when doing surface restoration and volume restoration is to minimize the imposed geometrical constraints. If the contact on the faults is only imposed on few points and not all along the fault lips, incoherent geometries between the two blocks bounded by this fault will result in gap and overlap, such a feature is much easier to interpret than an amount of internal deformation.

3.4. Quantification of the pre-deformation geometry

Fig. 6 shows the restoration with the various approaches: cross-section, multi-surface and volume.

With a cross-section restoration, initial geometry is an isopach layer, relative shear happens between the three layers that could be visualized in different ways. In the present case, the lateral borders being without geological meaning, we imposed a vertical pin line in the North-eastward syncline.

The multisurface restoration leads to three almost parallel horizons when using the flexural slip hypothesis (Figs. 5B and 6B).

The volume restoration also results in an isopach layer even if the thickness conservation is not imposed by the algorithms. The areas of the top and bottom horizons are almost the same and so the chosen method (FE code, elasticity) appears to be a good approximation of the flexural slip in 3D. Backshear could be quantified as in the case here on the left side (SW) of the model.

In the case of surface restoration (Fig. 6B), the global area change of the surfaces with our algorithm is low, for instance for H3: Initial Area: $2.938 \times 10^7\,m^2$, Final Area: $2.927 \times 10^7\,m^2$, variation 1%. In the case of volume restoration (Fig. 6C), the global area conservation is not imposed but the variation is low V_initial: $6.3 \times 10^9\,m^3$, V_final: $6.4 \times 10^9\,m^3$, and the area conservation of the top and bottom horizon (also not imposed) is good (for H3, Final Area: $2.894 \times 10^7\,m^2$, variation 1.5%).

3.5. Quantification of the internal deformation

Internal deformation, dilatation, i.e. local change of area and volume, as well as main strain directions are computed during the restoration. As explained previously, these values, especially if the dilatation is high could reflect the errors on the initial model. If we overpass this step, when the geometry is close enough to the true one, what can be concluded from these values?

Figs. 7 and 8 show some of the properties that could be computed and a comparison with the *Gaussian curvature* that is usually used when working only with the current geometry to infer a probability map of fracture density. Fig. 7 zooms on the northern tip of the anticline for the upper layer while Fig. 8 shows a comparison between the computed values for the top and the bottom depending on the restoration (surface or volume). As expected only the volume restoration shows a strong variation between the computed internal deformation for the top and the bottom of the layer (Fig. 8C).

With the surface restoration, a *2D_Dilatation* and two main strain vectors are computed (Figs. 7B and 8B). With the volume restoration since we use a mechanical approach, the rheology described the relationship between strain and stress and so a stress tensor is also computed. In addition to the *3D_Dilatation* that measured the volume change for each cell of the mesh, we can compute the aspect ratio and the trace of the matrix.

Fig. 8 shows the dilation computed for the H3 (top) and H0 (bottom) horizons in both cases (surface and volume restoration) as well as the *Gaussian curvature*. Common sense, as often data, suggests that on a folded rigid material increase of curvature induces an increase in new fractures, so the *Gaussian curvatures* of the horizons have been used to predict fracture density (Hennings et al., 2000). Fig. 8A shows the *Gaussian curvature*, the axis of the anticline and

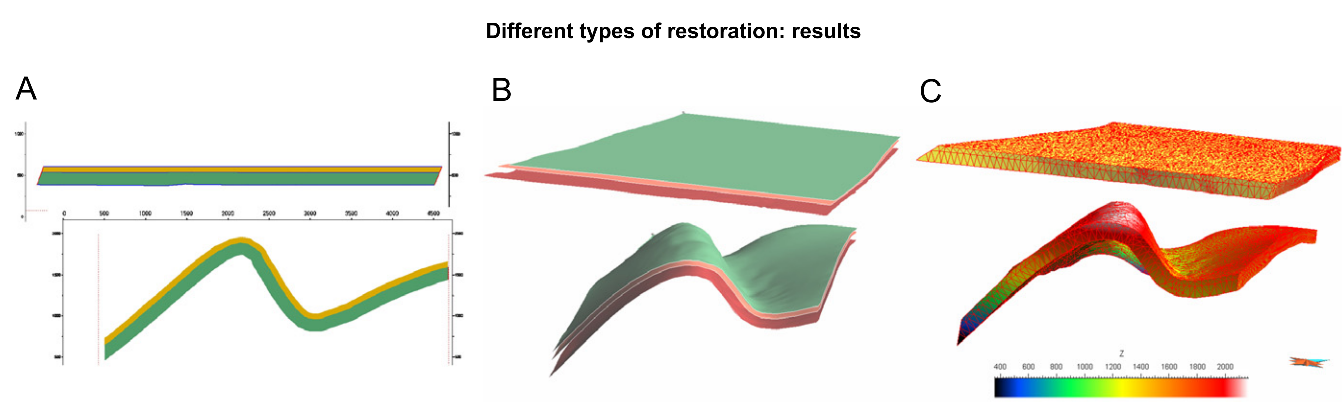

Fig. 6. Various modes of restoration applied to this structure. (A) Cross-section restoration with the flexural slip mode of deformation. The top horizon has been chosen as reference and a pin line has been imposed (red line on the figure). (B) Multisurface restoration using the flexural slip approach as described Fig. 2. (C) Volumic restoration with an FE mechanical approach, the chosen rheology is elastic with a large deformation hypothesis (GREEN).

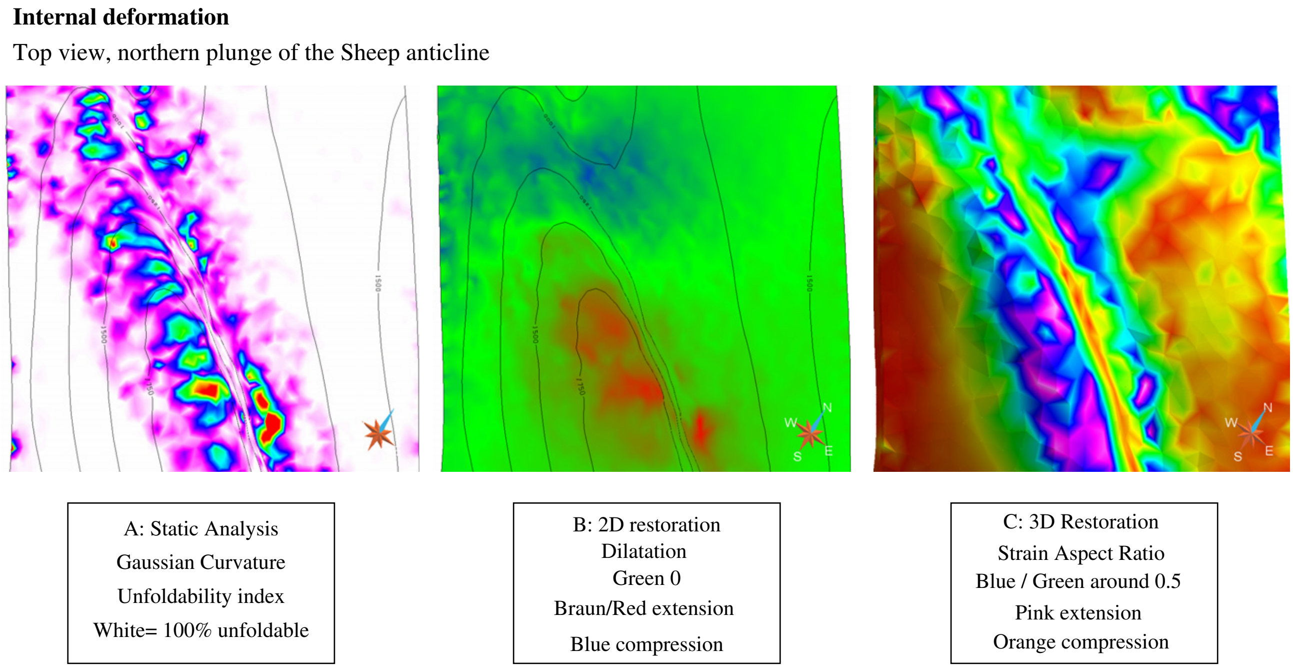

Fig. 7. Comparison on the outputs of the restoration_1. (A) For comparison *Gaussian curvature* of the top horizon. (B) 2D_Dilatation computed for the surface unfolding. (C) 3D restoration volumetric changes displayed through the trace of the stress tensor.

of the syncline northward present areas with low unfoldability index and so a potential need for internal deformation to be unfolded. The curvature is only dependent on the local surface geometry. Figs. 7 and 8 show clearly that the areas of major abnormal *Gaussian curvature* (yellow and red, Figs. 7A and B) correspond to high *2D_Dilatation* (Figs. 7B and 8B) but the *3D_Dilatation* highlights also other zones of large internal deformation.

We saw that the global dilatation of the surface is close to zero, locally, the *2D_Dilatation* computed from the surface restoration (Figs. 7B and 8B) shows an area of extension that covers part of the hinge of the anticline and extends northward to the flank. The maximum of *2D_Dilatation* is less than 3% and the minimum (the maximum of compression) is 2%. In the case of the volume restoration, there is a global volume conservation, the *3D_Dilatation* as a medium value of less than 1% but on few tetrahedrons they may pass 10%. We consider this zone as erroneous in the initial geometry of the surfaces.

Joins are supposed to develop, or to be reopened, parallel to the minimum strain vectors. Fig. 9 shows this minimum strain direction computed in surface and volume restoration (zoom on the same area as on Fig. 7). Both of the surface and the volume restorations show a rotation of the main strain direction around the tip of the anticline; the computed directions are rather close (at point A-southwest flank, for instance, N135°). On Fig. 10, the minimum strain and so the potential fracture direction have been highlighted with a threshold on the *2D_Dilatation* (left) or with the ellipsoid of strains. Comparing Figs. 10 and 8A, one can note the difference of prediction on the probability of fractures. The *Gaussian curvature* approach will never suggest extensional fractures in a vertical flank since only the local geometry is taken into account; by contrast the restoration approach, even in 2D, may quantify such a set of potential fractures.

4. Discussion

The 3D restoration with the mechanical approach is an important step, even if some physical phenomena have not yet been quantified. The current features on the available tools and potential directions of research could be summarized as follow:

4.1. Improvement of the initial geometry

Especially for the oil industry, since an error of just few hundred meters on a culmination may result in a dry well, the first output of the restoration is a more accurate initial geometry. Structural geology principles are integrated to correct the geometry on the current stage and the restoration could be used on a trial-and-error mode to eliminate unrealistic geometries in 2D, 2.5D as well as in 3D.

An automatic approach to reach an admissible solution honoring the data may be a desirable objective. Since restoration quantifies the dilatation, a minimization of this parameter may help to propose a new geometry. Such an approach has been already developed for other parameters in the GOCAD environment. For the 2.5D restoration, Caumon and Muron (2006) proposed a research of the

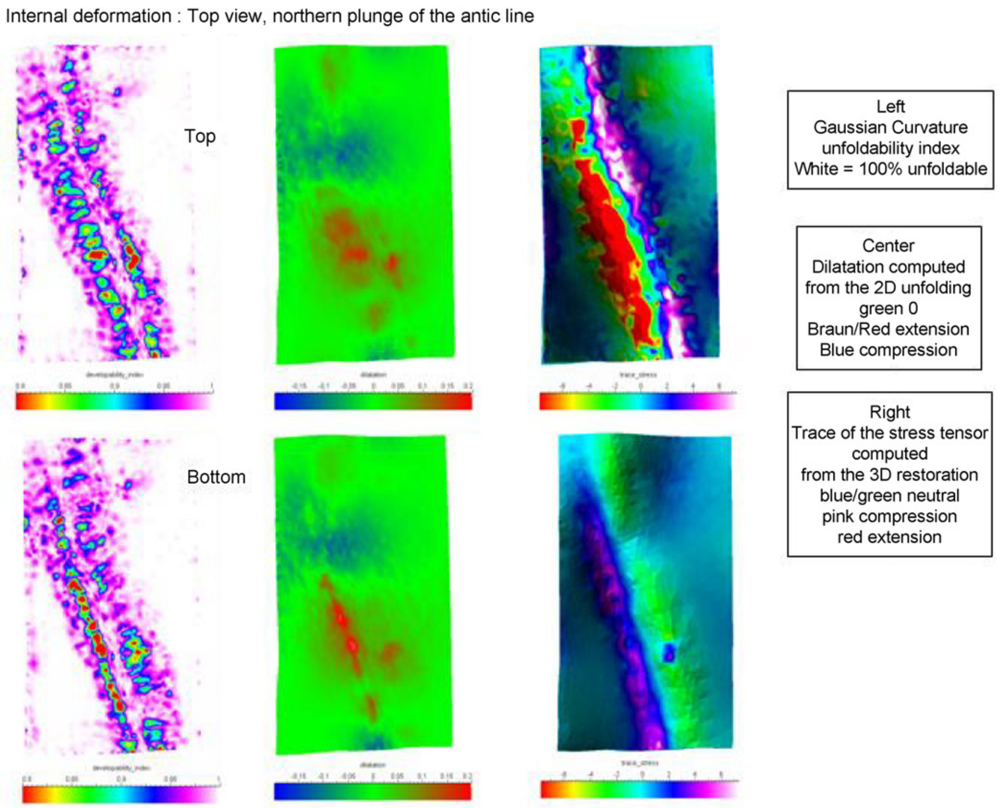

Fig. 8. Comparison on the outputs of the restoration_2. The three images are the same properties as displayed in Fig. 7 but for the top and the bottom of the layer. (A) For comparison *Gaussian curvature* of the top horizon. (B) 2D_Dilatation computed for the surface unfolding. (C) 3D_Dilatation, i.e. volume changes during the restoration, displayed through the trace of the stress tensor. The 2.5D_restoration does not see a major difference between the top and the bottom since the geometries of the two horizons are rather equivalent. In 3D the results are different, the top horizon shows extension in the anticline and compression between the vertical flank and the northward syncline, whereas the bottom horizon shows the opposite (extrado versus intrado).

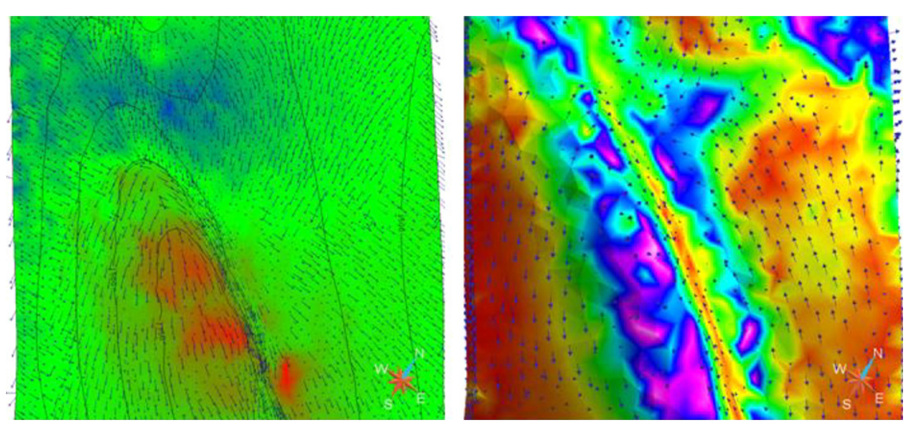

Fig. 9. Main strain directions. Comparison of the main strain directions computed with the surface restoration (left) and the volume restoration (right). Note that the triangle size and the tetrahedron face size are not the same, so the apparent display, especially the number of arrows, of the strain field is different.

ideal fault slip direction based on the minimization of the dilatation and Maerten et al. (2006) have proposed an optimization of the horizon geometries to minimize the dilatation. In KINE3D_1 one may also constrain the horizon surfaces to be unfoldable. Here, unfoldable means that the Gaussian curvature will be zero and as a result the dilatation is null when restoring except where the fault lip geometry is erroneous. However, the minimization of the dilatation is not a definitive criterion of quality for a surface near the faults; damaged zones exist as well as fracture corridors. A systematic research of the perfectly unfoldable horizon will result in the construction of horizons with smooth geometry, and faults with no asperity. Geologist with field experience will not consider

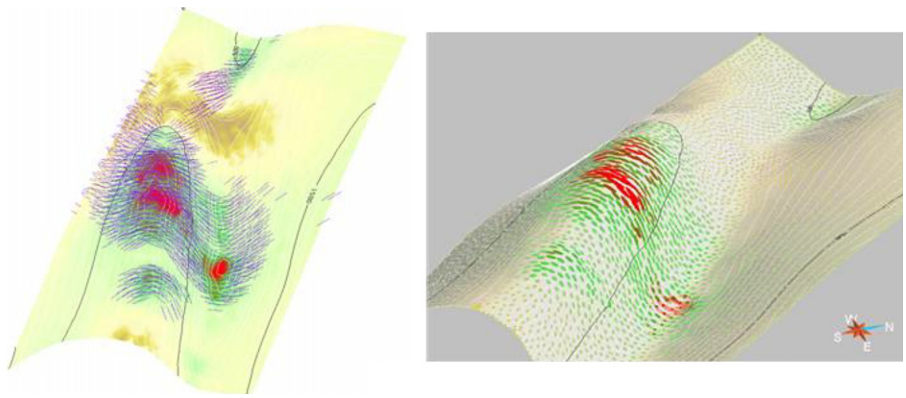

Fig. 10. Areas of computed high internal deformation and fracture direction. On the left the direction of the minimum strain and so the potential fracture direction is highlighted. On the right, the ellipsoids of strain are painted by the dilatation.

that as a must, additional criterion would have to be added. Since rock material is not elastic, the horizon that represents the top of a geological layer is not a sheet of elastic material; so claims that the computed dilatation is a real physical parameter that may constrain precisely the horizon geometry are questionable. The author is more in favor of the use a discriminatory threshold, i.e. to consider the high dilatation values as unrealistic and so to eliminate unrealistic geometry, thanks to them. The systematic minimization of the dilatation, especially 2D_dilatation, to find the best geometry of a horizon seems poorly geologically founded.

4.2. Representativeness of the computed strain and stress tensor

The geological material is never homogeneous, and inheritance exists in terms of fractures. There is no limitation on the described workflow for the material property and each cell of the mesh may have its own characteristics. However, in the shown examples, constant properties by layer are practically and commonly chosen since there is no easy way to better define the initial characteristic. Changes in these properties versus time (i.e. versus burial, temperature, etc.) should be also realistic. *Code_Aster* allows the user to make all these changes but their influence on the results of the restoration has not been systematically tested yet. One may infer that their influence on the pre-deformation geometry will be very small. However, this may not be so on the stress tensor and dilatation values if the contrast between the material elastic properties is large.

However, even if more sophisticated rheology is used, a backward restoration with "free" borders will never constitute a mechanically admissible way to compute a stress tensor. KINE3D will rather be used by the mechanics as a preprocessing to compute the initial geometry before doing a direct, i.e. forward, mechanical and kinematical modeling. Working with this kind of approach, the use of a mechanical code, even with simple hypotheses, to do the backward restoration is a huge advantage. The direct modeling could then be done immediately with the same mesh but imposing other boundary conditions and more realistic mechanical behaviors. One may even use strictly the same approach and the same algorithms in forward modeling. For instance, in 2.5D (Moretti et al., 2003) as in 3D (Moretti et al., 2006) the "restoration" tools used for a forward modeling allow us to test how the rheological contrasts influence the main stress directions. In the two previously cited papers, we modeled the stress reorientation in a sandy channel interbedded in a silty or shaley environment. Whatever the theoretical limitations of the method, the results were in agreement with the field and subsurface observations and with the analogical models (Calassou and Moretti, 2003; Moretti et al., 2003). Such a result leads us to be optimistic on the quality of the internal strain pattern computed with the restoration tools.

5. Conclusions

A full suite of tools now exists to do structural geology and restoration in a geomodeler. This is clearly an important step since one of the goals of the structural geologist is to improve the accuracy of the proposed horizon and fault geometry through the restoration. Up to now, the stand-alone products that have existed fail to allow for fast incorporation of all the data and constant comparison with them during the trial and error inherent to the restoration process. As a plug-in of a geomodeler, the new suite allows the user to have constant access to the data and the data uncertainties. This proximity results in a huge saving of time and also increases the precision of the results. As indicated on Fig. 1, the coherent surface model is both an input and an output for the various restoration steps.

The highlight and correction of the error could, and has to be done at each step: the analysis of the block, the cross-section balancing the surfaces unfolding and the volume restoration. Each step corresponds to an increase of complexity that makes the interpretation more difficult. Internal deformation will be proposed which will tend to compensate for error on the geometry by compression or dilatation of the neighboring material during the deformation. So all the tools are useful and they have to be used jointly.

After correction of the geometry, the restoration helps to compute paleogeometry, pathway of deformation and internal deformation within the material, especially the reservoirs. The restoration with an FE code of mechanics in elasticity appears to be an adequate choice to unfold layers preserving areas, thicknesses and volume. Both surface and volume restoration allow us to compute dilatation and main strain direction.

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KINE3D is marketed by Paradigm-EarthDecision.

Code_Aster

Code_Aster has been developed and used internally by *Électricité de France (EDF)* for more than 15 years. Since 1997 and every two years, *EDF* releases a fully documented free version of the source code of *Code_Aster*, available online (http://www.code-aster.org) and managed by a group of 20 permanent developers. This version is updated every six months. A "development" version can also be downloaded on the website (version used for the restoration shown in this paper is *Code_Aster* v. 8.1).

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