Fast geometric restoration of complex 3D structural models for seismic interpretation validation
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SUMMARY

Three-dimensional (3D) model restoration is a powerful model validation technique which typically requires knowledge of rock mechanical parameters for every layer in the model, as well as boundary conditions. These may be difficult to evaluate and to input into restoration software. In this paper, we present a method which geometrically restores complex 3D structural models without relying on mechanical parameters. In an adaptation of the mathematical GeoChrom framework, we compute a restoration transformation for each horizon in the initial model from present day geometry and the uvt deposition coordinates, providing innovative consistency constraints and validation metrics. No user intervention is required at any time during the process and faults are automatically taken into account in the computation with no added steps to eliminate gaps and overlaps. Once the restoration transformations are associated to the input model, the 3D structure can be restored to any intermediate state quickly enough to enable browsing through its geological history. We compare our results to previous flattening techniques and show the potential of our method for interpretation validation.

INTRODUCTION

Seismic flattening is a way of checking interpretations against seismic data. For complex, 3D structural models, viewing flattened cross sections may not be enough to detect inconsistencies linked to interpretation. Restoring the model to a geometry in the past may be a better way to understand how the interpretations relate to one another as a whole.

Restoration emerged as an interpretation validation technique when the only available data were in situ observations. At the beginning of the twentieth century, Chamberlin (1910) described how, by following the Pennsylvania rail road which cuts across folded Devonian sandstone, precise dip measurements at regular locations could be gathered in cross sections and used to piece together the local Appalachian folding tectonic story. Dahlstrom (1969) laid out the ground rules for cross section restoration in the marginal part of an orogenetic belt, reasoning that a cross section which can be restored according to these rules has a better chance of being accurate than a cross section that fails the restoration test.

Modern numerical modelling techniques have progressed to cross section (Maerten and Maerten, 2006), 3D surface (Maerten and Maerten, 2015) and full 3D structural model (Muron, 2005; Chauvin et al., 2018) restoration, which help model validation. Most methods compute transformations by running finite-element codes on grids that conform to geological structures, i.e. faults and horizons, using physical attributes of the different layers in the model, user-defined boundary conditions and mechanical considerations (Moretti et al., 2006). Complex structures can benefit from implicit horizon representation (Durand-Riard et al., 2010; Chauvin et al., 2018), which relieves constraints on the mesh required by finite-element methods. Structural model validation tools and workflows build upon these techniques (Moretti, 2008) but they may still be too complex to be routinely used in the oil and gas industry.

Also based on an implicit approach, the (u,v,r) space defined by the GeoChrom framework (Mallet, 2004; Moyen, 2005) provides a glimpse at geological structures as they were deposited but does not map the geological space to a true deposition space as the vertical dimension is a geological time, not deposition depth. Labrunye et al. (2009) show how seismic data can be flattened to the (u,v,r) space and displayed along with interpretations to help with validation but working with an abstract, deposition time-related vertical axis deforms layers in an unrealistic way, which may hide inconsistencies.

Mallet (2014) suggested that a new generation of geometric restoration techniques could be based on the GeoChrom framework and Lovely et al. (2018) presented the very first. Using algorithms developed to compute the GeoChrom (u,v,r) functions, Lovely et al. (2018) adapted the transformation from geological to depositional space to provide a restoration that preserves layer thickness.

In this paper, we present an evolution of the mathematical GeoChrom framework aimed at restoring complex 3D structural models without any user input. Our solution addresses problems encountered by Lovely et al. (2018) and the effect of our new equations are illustrated by the restoration of a faulted structural model.

![Figure 1: Restoration of a simple model with lateral variation in layer thickness. (A) Horizons in the present-day geological space. (B) Restored space where model is restored to the deposition time of middle (yellow) horizon. Reference horizon Hz is flat and the layer underneath deforms passively, changing the geometry of the green horizon.](image-url)
Fast geometric restoration of complex 3D structural models

Figure 2: Principle of GeoChron Based Restoration (GBR) - Minimal deformation tectonic style. From the present-day geometry of reference horizon \( H_0 \) in the geological space (A), a restoration transformation is computed based on a family of curved surfaces \( S_r(d) \) parallel to horizon \( H_0 = S_r(0) \) (B). Transforming \( G_T \) to the restored space at time \( r \), denoted \( \tilde{G}_T \) (C), restores reference horizon \( H_0 \) to its geometry at deposition time \( r \) whilst preserving the thickness of older layers.

THEORY

For a horizon \( H_0 \) deposited at geological time \( r \), the GeoChron Based Restoration (GBR) method presented in this paper consists in computing a 3D transformation which restores horizon \( H_0 \) to its geometry at the time \( r \) it was deposited, i.e. the geometry of the sea floor. The part of the subsurface that is older than horizon \( H_0 \) is passively deformed in a consistent way. In order to ensure consistency, the GBR method honours a tectonic style particular to the area being studied, keeps fault blocks in contact so as not to generate any gaps or overlaps in the restored model and minimises horizon area and layer volume variations.

Figure 1 shows the restoration of a simple model with two layers to the time when the middle horizon was deposited. The structural model is deformed as a whole in a consistent manner and lateral variation in thickness of the layer under the restored horizon is preserved.

The GBR method is based on a robust mathematical framework which requires specific notations, illustrated in Figure 2 for clarity. Starting from the geological space \( G_T \) as it is observed and modelled in the present day (Figure 2A), a family of curved surfaces \( \{S_r(d) : d \geq 0\} \) parallel to horizon \( \{H_r \equiv S_r(0)\} \) is built as iso-values of a scalar function \( r \) which monotonously decreases with depth \( B \). In the restored space \( \tilde{G}_T \) at time \( r \), containing a direct frame of orthogonal unit vectors \( \{\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z\} \), the family of curved surfaces becomes horizontal \( \{S_r(0) : d \geq 0\} \) parallel to \( \{\mathbf{e}_x, \mathbf{e}_y\} \). Reference horizon \( H_0 \) is restored to \( \tilde{H}_r \), its state at time \( r \), and older horizons \( H_r \), and \( H_r \), deform passively into \( \tilde{H}_r \) and \( \tilde{H}_r \), preserving the thickness of the layers in-between.

According to these principles, the \((u_r, v_r, \tau_r)\) functions required to build \( \tilde{G}_T \) from \( G_T \) differ from the classic \((u, v, t)\) functions used in the GeoChron framework. First, \( \tau_r \) is not computed from all horizons in a stratigraphic sequence but is constrained so that restored horizon \( H_0 \) in \( \tilde{G}_T \) coincides with the sea floor \( S_r(0) \) which, at geological time \( r \), is considered to be a continuous, unfaulted surface with given topography \( \mathcal{Z}_r \) as a function of the GeoChron model \( u, v \) coordinates:

\[
\tau_r(\mathbf{r}) = \mathcal{Z}_r(\mathbf{u}(\mathbf{r}), \mathbf{v}(\mathbf{r})) \quad \forall \mathbf{r} \in H_r.
\]

Next, as any restoration technique must minimise deformation and volume variation, if surfaces \( \{S_r(d) : d \geq 0\} \) are level sets of function \( \tau_r \), for any infinitesimally small increment \( \varepsilon \), the thickness of the thin layer between \( S_r(d) \) and \( S_r(d + \varepsilon) \) must be, as consistently as possible, equal to \( \varepsilon \). This makes surfaces \( S_r(d) \) and \( S_r(d + \varepsilon) \) as parallel as possible. These requirements lead to the following, general constraint on \( \tau_r \):

\[
\|\mathbf{grad} \tau_r(\mathbf{r})\| = 1 \quad \forall \mathbf{r} \in G_T \tag{1}
\]

Honouring this non-linear equation is not straightforward. Lovely et al. (2018) first approximate \( \tau_r \) based on the \( t \) function of a GeoChron model built from only horizon \( H_r \) to restore and then apply a post-processing to scale this approximation “to depth in a manner that preserves volume or vertical thickness in the restored space”. This local, computationally-intensive process becomes even more complex close to faults. Rather than locally correcting our first approximation, we compute a global correction function \( C_r \) on \( G_T \) which, once added to the initial \( \tau_r \), yields an improved function \( \tau_r = \tau_r + C_r \) which satisfactorily honours equation 2.

Figure 3 shows the distribution of \( \|\mathbf{grad} \tau_r\| \) over the \( G_T \) space for the restoration of yellow horizon in Figure 1. Histogram (A) is the distribution of \( \|\mathbf{grad} \tau_r\| \) prior to correction, obtained from a regular \((u, v, t)\) computation performed using only data from the middle horizon. This initial version of \( \tau_r \) does not honour equation 2 as the mode of \( \|\mathbf{grad} \tau_r\| \) deviates from 1 and the distribution is widely dispersed. After adding our global correction function \( C_r \), \( \tau_r \) honour equation 2 much more closely (B), which ensures the \( \tau_r \) component of our restoration transformation keeps deformation and volume variation to a minimum.

Similarly, restoration functions \((u_r, v_r)\) are based on the \((u, v)\) functions of the GeoChron framework but requirements for restoration differ. For consistency with the initial model and between the different stages of restoration, functions \((u, v)\) and \((u_r, v_r)\) must be identical on reference horizon \( H_r \). This is achieved by constraining each point \( \mathbf{r} \) on horizon \( H_r \) such that:

\[
\begin{align*}
1) u_r(\mathbf{r}) &= u(\mathbf{r}) \\
2) v_r(\mathbf{r}) &= v(\mathbf{r}) \\
3) \mathbf{grad} u_r(\mathbf{r}) &= \mathbf{grad} u(\mathbf{r}) \\
4) \mathbf{grad} v_r(\mathbf{r}) &= \mathbf{grad} v(\mathbf{r}).
\end{align*}
\]


Note: The document appears to be a page from a technical report or a scientific paper discussing the method of GeoChron Based Restoration for 3D structural models in geology. The text describes the principles and mathematical formulations involved in the restoration process, focusing on the minimization of deformation and volume variation. The figures illustrate the application of this method to a specific geological scenario, showing the transformation from the present-day geometry to the restored state at an earlier geological time.
Fast geometric restoration of complex 3D structural models

Once functions \( (u_\tau, v_\tau, t_\tau) \) are computed over \( G_\tau \), the restored model at time step \( \tau \) is obtained by moving each point \( r \) of \( G_\tau \) to its restored coordinates \( (u_\tau(r), v_\tau(r), t_\tau(r)) \) in the restored space \( G_\tau \).

APPLICATION TO 3D STRUCTURAL MODEL

Figure 4 shows our restoration technique applied to the model shown in Labruyé et al. (2009). First, restoration coordinates \( (u_\tau(r), v_\tau(r), t_\tau(r)) \) are computed for restoration times \( \tau \) matching the seven interpreted horizons in a total of 33 seconds of user time on a standard workstation. The model can then be shown in any of its restored states with each update requiring about three seconds of user time.

The central, red fault on Figure 4 is a strike-slip fault which separates regions with different sedimentation rates. White arrows highlight the thickness of one particular layer, between the yellow and light brown horizons, which is 44.1% higher in the right-hand side region (Figure 4 A. d2) than in the left-hand side region (A. d1). Flattening based on the GeoChron transform as presented in Labruyé et al. (2009) makes this layer the same thickness in both regions (B. d1 and d4). The seismic amplitude attribute is visibly deformed from one side of the fault to the other, which may make identifying interpretation errors more difficult. Geometric restoration using our GBR method preserves the initial thickness of the layer (C. d3 and d4) and the difference in both regions is 44.6%, which is close to the initial value. The seismic amplitude attribute displayed on the cross section does not show any deformation and the quality of the interpretation can be more easily controlled than in the flattened space.

Further analysis of restoration quality and accuracy, as well as possible interpretation errors pointed out by our results, shall be discussed in other publications.

Similarly to Labruyé et al. (2009), the next step in our restoration workflow is to develop tools to correct interpretations from the restored space and push those edits automatically to the structural model in the present day geological space.

CONCLUSIONS

Our full, mathematical adaptation of the GeoChron model principles to 3D restoration enables restoration of complex structural models to any time step with no user interaction. Required boundary conditions and strong consistency constraints based on the initial GeoChron functions are set automatically. All time steps are computed in a reasonable amount of time and updating the model to any of those restored states is fast enough for the user to scroll through the geological history of the model in real time, checking interpretation validity at any step.
Fast geometric restoration of complex 3D structural models

Figure 4: Comparison of 3D flattening and geometric restoration on cross sections in a 3D structural model with seven horizons and 22 faults modelled in a grid containing 135,526 tetrahedra. (A) Present-day geological space, overlain with seismic amplitude attribute. (B) GeoChron based flattened space, as introduced by Labrunye et al. (2009). (C) Model restored at deposition time of green horizon. White arrows show apparent thickness of one layer in each of the three spaces.
REFERENCES


