Merging chronostratigraphic modeling and global horizon tracking
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Abstract
We have determined to combine the automatic interpretation of horizons in a seismic cube with a space/time framework to construct a chronostratigraphic model that matched seismic events and could be used later, without having to rework it in reservoir modeling and seismic characterization. A large number of single seismic events were automatically extracted from the cube as horizon patches. Each patch was associated to an individual isogeologic time constraint. An optimization process then proposed a geologically coherent model in the volume, filling the gaps in the area where no patch was extracted, and taking into account additional geologic information, such as unconformities, fault displacement, or well information. Furthermore, this process generated a seismic flattened volume used to check the quality of the model and revealed some geologic features such as unpicked faults, channels, lobes, and splays. We evaluated a use case in which this method was successfully tested on a complex faulted data set.

Introduction
Traditionally, 3D seismic interpretation is based on the recognition of some particular seismic events, which are automatically or manually tracked throughout the seismic cube. This task is painstaking and time consuming, particularly when some regions of the seismic data are noisy. As a consequence, the interpretation is generally limited to major horizons and a significant part of the seismic information is ignored when the geologic and reservoir models are built. Indeed, such models are generally built with simple depositional rules, such as proportional and parallel to the top or bottom without taking into account the fine intraformational variations seen via the seismic events. Therefore, seismic stratigraphy is typically inconsistent with reservoir model stratigraphy. When seismic data are used in a reservoir model, it is with the assumption that the reservoir grid stratigraphy should follow seismic events.

In the past 15 years, several techniques have emerged to build a chronostratigraphic model from a 3D seismic cube. Zeng et al. (1998) propose the stratal slicing approach, based on proportional slicing between picked surfaces. To fully exploit the information of the seismic data, more automatic or more global approaches have then been developed. Stark (2004, 2005) introduces the notion of relative geologic time volume (also called age volume), in which each seismic sample can be associated with a relative age value. Dip-driven methods (e.g., de Groot et al., 2006; Lomask et al., 2006; Guillou et al., 2013) use local dip and azimuth information at each grid position within the volume. Horizon-patch methods (e.g., Borgos et al., 2003; Monsen et al., 2007) are based on the classification of the topological relationships between small surfaces of similar seismic attributes. Global optimization methods (e.g., Pauget et al., 2009) minimize a cost function built from links between seismic samples. Besides Monsen et al. (2007), these methods all produce a relative geologic time volume as defined by Stark.

The proposed approach in this paper is based on the concept of the space/time mathematical framework introduced by Mallet (2004) for geomodeling purposes. This framework consists in computing a 3D transformation, called the uvt-transform, between the geologic space and a depositional space, where the effects of erosion and of tectonic forces are removed. Contrary to Dorn et al. (2011), it does not rely on proportional slicing between horizons, but on a full 3D interpolation of the relative geologic time throughout the volume constrained by geologic information, such as picked horizon or fault points.
If we can automatically provide enough interpreted seismic events, and if it is assumed, as in most of the other methods, that fault and salt surfaces have already been interpreted, this framework allows us to build a precise chronostratigraphic model from a 3D seismic cube with as little manual interaction as possible, while ensuring a good match between seismic chronostratigraphy and reservoir stratigraphy. For that purpose, we propose the following workflow:

- automatically interpret as many seismic events as possible
- build the \(uvt\)-transform from this interpretation
- use the \(uvt\)-transform for interpretation.

The key steps of this workflow will be illustrated on two different data sets.

### Automatic interpretation of seismic events

The goal of this first step is to automatically extract as much information as possible from the seismic cube and to deliberately ignore the chaotic zones.

#### Seed selection

First of all, a set of seismic traces is selected in the seismic cube, such that no two seismic traces are closer than a user-specified horizontal distance. This distance may be different for the inline and crossline directions, but it should be chosen so as to select at least one trace per fault block. Then, a series of points is generated from each trace such that:

- No two points are closer than a user-specified vertical distance. This distance corresponds to the smallest distance between two vertically consecutive seismic events we want to catch. To track a maximum of different seismic events, the number of seismic samples between two consecutive points along the vertical direction is generally chosen as much smaller than the one along the horizontal direction.
- A point must match the strongest seismic event of the portion of the seismic trace between the previous and the next point along the vertical direction. The points are automatically adjusted to either the signal peak or the signal trough, consistently in the whole cube. The goal is to focus the horizon tracking on the most visible and continuous seismic events.

Figure 1a shows some of the seeds extracted along an inline section of our first seismic cube. This small data set comprises 300 inlines and 801 crosslines with a 500 4-ms time sample and covers an area of 75 km². The seeds were extracted at signal peaks every 45 inlines and 45 crosslines, with a maximum vertical distance of 36 ms generating about 5000 points. Figure 1a' magnifies a portion of the inline section highlighting...
how seed points are adjusted to the local peaks of the seismic.

**Patch extraction and filtering**

Each point is then used as a seed by a conventional 3D horizon tracker such as the one described in Dorn (1998). Typical autotracking parameters control the results: correlation threshold, automatic stop at fault or salt crossing, etc. Each of the seed points generates its own horizon surface. Most of the surfaces will present holes and will not cover the whole seismic cube, which is why we refer to them as *patches*. It must be noticed that this approach can be easily parallelized, each thread processing its own set of seed points.

Several filtering operations are required to prepare the patches for the subsequent modeling steps:

- Several seed points may correspond to the same seismic event, which may be tracked several times. If the tracker is robust enough, the corresponding patches partially or totally overlap. This configuration is automatically detected, and the overlapping patches are merged two by two, in decreasing size order. For each pair of patches to be merged, only the biggest patch is kept. Then for each seismic trace where it has no point, the biggest patch receives the point of the smallest one. There is currently no automatic merge of the disconnected (or nonoverlapping) patches, which correspond to the same seismic event. The patch extraction method proposed by Borgos et al. (2003) and Monsen et al. (2007), based on attribute classification instead of simple signal correlations, could be useful to improve that point. However, it is probably much more time consuming. The interpolation process discussed in the second part of this paper is robust enough to handle disconnected patches.

- When faults are available in the model, there are often some discrepancies between the position of the loosely interpreted fault surfaces and the real position of faults in the seismic cube. These errors disrupt the modeling process. In that case, patch points that are close to faults (typically two or three seismic samples away from the fault surface) can be automatically discarded. To improve the quality of the final model, it is nevertheless better to have faults interpreted at the right location and keep the patch data point that are close to the faults.

- Patches that are smaller than a user-defined size are automatically discarded (typically between one and a few hundred points). They generally correspond to chaotic zones. They bring no or little valuable information for the computation of the chronostratigraphic model and would uselessly slow the process.

As a result, we obtain a set of nonredundant horizon patches, whose sizes vary according to the quality of the seismic and to the complexity of the structures. Figure 1b shows the 700 patches obtained from the 5000 seeds and the seismic cube from Figure 1a. The merging process alone divided the number of patches by four. Improving seismic event continuity using a structural filter similar to the one presented in Labrunye and Mallet (2004) before running the tracker may help to increase patch continuity and reduce tracking errors, such as jumps to a wrong seismic event.

**Chronostratigraphic model building using intraformational constraints**

If, as Vail et al. (1977), we assume that “primary seismic reflections follow chronostratigraphic (time-stratigraphic) correlation patterns rather than time-transgressive lithostratigraphic (rock-stratigraphic) units,” then horizon patches can be considered as isosurfaces of the relative geologic time volume. As discussed in Zeng (2013), this assumption may not always be true. However, as most of the authors cited in the “Introduction” section, we will consider it as a generally valid approximation. In the second step of the workflow, geomodeling techniques are used to convert the patches into a chronostratigraphic model.

**The uvt-transform**

The space/time mathematical framework of Mallet (2004, 2014) consists of a curvilinear parameterization with three components (called $u$, $v$, and $t$) of a 3D volume, which represents a zone of interest of the subsurface. This volume is topologically cut by the fault surfaces, and it is not necessarily the seismic cube. It may be, for example, an unstructured mesh with any polyhedral shape with a user-defined resolution, depending on the user’s objectives and on the computer’s specifications. The goal of this 3D parameterization is to generate a new space, in which the effects of erosion and structures are removed.

The $t$ component is analogous to a relative geologic time volume. As shown in Figure 2, it is built such that:

- An iso-$t$ surface corresponds to a stratigraphic horizon.
- An iso-$t$ surface is topologically cut by the fault surfaces.

The $u$ and $v$ components define the paleogeographic coordinates. As shown in Figure 2, they are built such that:

- The gradients of $u$ and $v$ are orthogonal.
- The norm of the gradients of $u$ and $v$ is approximately equal.
- Along an iso-$t$ surface, the $u$ and $v$ components are continuous across the faults.

These definitions of the $u$, $v$, and $t$ components can be expressed with a mathematical formula, which
becomes a constraint to be honored by a linear solver such as the one described by Mallet (2004). As a result, it is possible to map every \((x, y, z)\) point in the geologic space to a \((u, v, t)\) point in the parametric space. This transformation is called the \(uvt\)-transform. Although the transform in Dorn et al. (2011) is computed stratigraphic unit by stratigraphic unit from a geometric analysis of the interpreted horizon along the seismic traces, the \(uvt\)-transform is computed conformable sequence by conformable sequence, from a 3D interpolation honoring any kind of geologic information given to the solver as constraints, such as interpreted major horizons surfaces, well markers, stratigraphic relationships, unconformities, and, in the context of our workflow, horizon patches. Moreover, it is possible to weight the constraints to promote some geologic information compared with others considered as more uncertain.

By construction, the stratigraphic horizons in the parametric space are unfolded and unfaulted whatever the fault type (normal, reverse, and strike-slip). Missing or eroded deposits will appear as hiatuses. For these reasons, the parametric space is called the paleospace. As illustrated in Figure 3, the reverse \(uvt\)-transform maps the paleospace point into the geologic space, which makes it easy to go back and forth between both spaces.

The \(uvt\)-transform is different from the simpler \(xyt\)-transform, in which the transformation of horizon surfaces leads to overlaps of volume elements in the parametric space around reverse faults and a loss of continuity across normal faults (Figure 4). Such problems are not considered in the previously cited methods, except by Dorn et al. (2011), who solve it by a horizontal translation of the horizons in the \((x, y, t)\) domain. However, this simple operation may become difficult when the fault network is complex.

**The intraformational constraint**

The usual way of building the \(t\) component of the \(uvt\)-transform is to assign a geologic time value to every interpreted horizon according to a given stratigraphic

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**Figure 2.** The \(uvt\)-transform, a curvilinear parameterization of a reservoir. The \(t\) component of the parameterization is a type of relative geologic age: iso-\(t\) surfaces follow the geologic horizons and are cut by the faults. The \(u\) and \(v\) components of the parameterization are perpendicular and continuous across the faults. The three small pictures on the right show an example of each of these components painted on the same geologic model. Courtesy of EAGE Publications Bv (Mallet, 2014).

**Figure 3.** Direct and reverse \(uvt\)-transform. The gray and white boxes illustrate the discretized parametric domain. Any \((x, y, z)\) point of the geologic space can be transformed into the paleospace with the direct \(uvt\)-transform. Any \((u, v, t)\) point of the paleospace can be transformed back to the geologic space with the reverse \(uvt\)-transform. Courtesy of EAGE Publications Bv (Mallet, 2014).

**Figure 4.** Processing fault displacements in the \(xyt\)-transform and in the \(uvt\)-transform. \(H\) is the horizon to be flattened, \(F_1\) is a reverse fault, and \(F_2\) is a normal fault. The red arrows show how the horizon \(H\) contacts with faults \(F_1\) and \(F_2\) are shifted as a result of the different transformation methods. In the \(xyt\)-transform, the horizon overlaps close to the reverse fault \(F_1\) and there is a gap in the location of the normal fault \(F_2\). The \(uvt\)-transform takes into account the horizontal and vertical fault displacements to restore the continuity of horizon \(H\).
column and to interpolate the values throughout the volume (Mallet, 2004). However, when the geologic structure is complex, for example, with numerous fault blocks, consistently defining the relative age of thousands of patches may be challenging. Monsen et al. (2007) propose a solution based on a directed cyclic graph.

We prefer to take advantage of the ability of the uvt-transform framework to integrate a new kind of geologic information. This leads us to define a new constraint, which specifies that all points in each patch must belong to a single unspecified iso-t surface. The filtering operations previously defined should ensure the validity of this assumption. Because a patch is not associated to a particular stratigraphic boundary, we call this constraint the intraformational isovalue constraint.

Relative geologic time interpolation

The modeler then computes the uvt-transform, interpolating the geologic time values by considering all the intraformational constraints globally in 3D and at the same time. In addition to the intraformational constraints, the following constraints are required to compute the geologic time:

- An arbitrary iso-t-value is given to at least two of the patches, typically one at the top and one at the bottom of the model. To compute an age that increases with the depth, the top patch iso-t-value is chosen as smaller than the bottom patch iso-t-value.
- The gradient of t remains more or less constant throughout the model. This constraint has a relatively low weight and may be balanced by the intraformational constraint in case of stratigraphic layers with uneven thickness.
- Patches corresponding to nonconformable stratigraphic boundaries (erosion or baselap, for example) must be flagged as such by the user to define particular constraints. They are used to predict the location of hiatuses in the relative geologic time.

An example is shown in Figure 5a, in which the iso-t-values computed from the patches of Figure 1b are superimposed on the seismic amplitude. For this particular data set, three patches have been used to initialize the t-values: the water bottom, a patch in the far bottom part, and a patch in the middle part that corresponds to an unconformable horizon.

The portions of the chronostratigraphic model without any constraint, typically within noisy seismic areas or holes inside the patches, are built from the constraints of the nearest patches. So a series of small patches may be sufficient to build a complete and accurate chronostratigraphic model. Figure 6 shows an inline section of the bottom of a migrated seismic cube. Deep seismic events are not well differentiated because of the low signal-to-noise ratio (S/N). The horizon autotracker managed to extract few patches, but they are quite small and discontinuous. However, this was sufficient for the modeler to yield a reasonable estimation of the relative geologic time throughout the volume. For zones without a patch, the time is computed from surrounding seismic events.

The displacement along a fault is approximated by the interpolation process from the patches, which are either above or below the fault, or which have points on both sides of the fault, when the tracker was able to skirt the fault. When it is not sufficient, however, the user can manually correlate patches across the faults and rerun the interpolation process to improve the fault displacement computation.

Refinement of the relative geologic time

Once the chronostratigraphic model is built, a relative geologic time is estimated at every point of the volume. It becomes possible to associate each patch to its iso-t-value, for example, by taking the mean time value of all its points. To build a stratigraphic column and define stratigraphic units, the user can select the patches corresponding to the major stratigraphic boundaries. It is even possible to insert a new horizon surface extracted from a selected iso-t and not associated to a patch. Each boundary is thus associated to its t-value, which enables the automatic association of each patch to its stratigraphic unit by a simple t-value comparison. Figure 5b, 5b′, and 5b″ shows the patches classified per stratigraphic unit thanks to the relative geologic time visible in Figure 5a.

The whole process can be repeated inside a particular stratigraphic unit to locally refine the interpretation and the chronostratigraphic model. The patch extraction is performed inside the unit boundaries, but with a smaller vertical and/or horizontal step between seed points, and the chronostratigraphic model is locally updated with the new patches. If required, manually picked horizons can be inserted at any time to better constrain the uvt-transform, where the autotracker fails. Phantom horizons, not necessarily matching the seismic data but defining recognized iso-t surfaces (as used by Zeng et al., 1998), could also be inserted in this way.

Quality control and interpretation in the paleospace

Our relative geologic time is not carried by the seismic cube, but the uvt-transform can be applied to the seismic cube itself. In practice, the (u, v, t) paleospace is meshed by a regular and structured grid with a resolution close to the one of the seismic cube and each (u, v, t) point of this grid is painted with the value of the seismic amplitude at its corresponding (x, y, z) point. If the transform has been accurately computed, all the transformed seismic events should be perfectly flat by construction. The interpreter can transform the seismic data into the 3D paleospace to check the quality of the u, v, and t parameterizations. If some seismic events are not flat, it is likely due to a missing interpreted hori-
zon or fault as shown in Labrunye et al. (2009) and Dorn (2011). Eroded deposits appear as gaps because they are not associated to any seismic data. Figure 5c is a \((u, t)\) section of the paleospace computed from the \((u, v, \text{and} t)\) transform from Figure 5a. The gap visible in the middle of the picture corresponds to the missing deposits of the eroded orange unit.

Coupled with the visualization technique, the paleospace (or any similar space) is known to be very useful to reveal some geologic features such as channels (Stark, 2006). Because the effect of the faults and folds can be correctly taken into account by the \(uvt\)-transform, a channel is much more obvious in the paleospace than in the traditional flattening methods. Thanks to the reverse \(uvt\)-transform, it is possible to interpret the channel in the paleospace and to transfer the interpretation back to the geologic space, as shown by Labrunye et al. (2009) and Dorn (2011).

**Toward the reservoir grid**

As stated earlier in this paper, the \(uvt\)-transform was first designed to build geologic models. It can

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**Figure 5.** Computation and use of the chronostratigraphic model on the same line section as in Figure 1. (a) \(uvt\)-transform computation. Each continuous colored subhorizontal line is an iso-\(t\) surface of the chronostratigraphic model, (b) semiautomatic patch classification. Each stratigraphic unit is painted with a specific color, (b′) 3D view of the classified patches, (b″) stratigraphic column, and (c) seismic visualization in the paleospace on a \((u\text{ and }t)\) section: The seismic events are unfolded and unfaulted. The gap in the middle of the section is due to eroded deposits from the orange unit.

**Figure 6.** Geologic time interpolation from a set of patches autotracked in the deepest part of a seismic cube with a low S/N. The black line is a fault. The discontinuous cool-colored lines are the autotracked patches (one color per patch). The continuous warm-colored lines are the iso-\(t\) lines of the chronostratigraphic model, interpolated between the top and bottom patches in this picture. Notice how the interpolation fills the gaps between the patches.
be directly used to build the reservoir grid (Jayr et al., 2008), and any improvement of the quality of the chronostratigraphic model leads to a direct improvement of the associated reservoir model. Any new patch, either automatically or manually interpreted, can be directly taken into account to define the geometry of the reservoir grid after a reinterpolation of the $uvt$-transform. This is a major difference to the other approaches, which stay at the interpretation level and require, to move on to the reservoir grid, additional work, such as data format conversion, with the risk of losing information.

Figure 7. Processing a complex data set with the workflow. (a) Input data: inline section of the 3D seismic and interpreted fault surfaces displayed as subvertical colored lines and (b) extracted patches. Patches representing the stratigraphic unit boundaries H1, H2, etc., each have a specific color; the others are blue. (c) 3D chronostratigraphic model iso-$t$ contours. (d) The resulting 3D paleospace. Gaps in H2 and H5 are caused by eroded deposits.
We validate our approach on a second 3D seismic cube with a good-quality poststack seismic signal migrated in the depth domain. This 9.5 GB volume comprises 851 inlines and 1160 crosslines with 2450 2-m samples, and it covers an area of 150 km$^2$. A horst sits in the center of the data set, and a series of conjugate faults define several half-grabens. Approximately 70 faults were already interpreted and modeled as surfaces (Figure 7a).

We first generate the seeds on the whole cube at the signal trough, every 50 inlines/crosslines horizontally and every 50 m vertically. Approximately 12,000 seeds were generated. As expected, the number of patches is correlated to the quality of the seismic and it decreases when going deeper within the model. After the filtering operations, approximately 2800 patches remained in the full volume. We select nine major seismic events (named H1, H2, . . ., H9), including the water bottom. For each one of these major horizons, we collect the automatically picked patches across the fault blocks and gather them in a single horizon. This ensures the continuity of the $uvt$-transform across the fault blocks and to define the unconformities (H2 and H5). Figure 7b shows the final result, highlighting the nine major seismic events among the other patches. The H5 boundary could not be automatically interpreted, so it had to be manually interpreted.

In the next step, the $uvt$-transform was computed from the faults and the patches on a tetrahedral mesh with 50 m/25 samples vertical resolution and 100 m/8 samples horizontal resolution to catch the smaller patch geometry variations and keep the computation time down. Figure 7c shows the resulting geologic time, and Figure 7d shows the corresponding paleospace. Two gaps can be seen for H2 and H5: They correspond to eroded materials for these two units.

Figure 8a shows a $(u, v)$ slice of the paleospace. The effect of the fault displacement has been removed by the $uvt$-transform, and the channel continuity is restored. However, the fault network is complex in this area and the result with our semiautomatic method could still be improved by adding new patches. Seismic attributes, such as semblance and instantaneous amplitude, can be transformed into the paleospace and corendered to better reveal channel contours, as shown in Figure 8b.

**Conclusion**

The workflow we have described combines a global interpretation technique that automatically picks as many horizon patches as possible with chronostratigraphic modeling based on the $uvt$-transform. The resulting chronostratigraphic model can take into account most of the clear seismic events while still incorporating all user inputs, such as manually picked unconformities. In chaotic zones where no event can be picked, the construction of the chronostratigraphic model relies on interpolation using the surrounding interpreted patches.

The workflow produces a paleospace where the stratigraphic horizons should be unfolded and unfaulted even for complex structures. This paleospace is a very powerful tool to control the quality of the interpretation, e.g., detecting missing faults or unconformities or erroneous horizon interpretation. It also helps to interpret complex features, such as channels or poorly defined horizons. The resulting $uvt$-transform can also be used as is to build a geologic model of the reservoir, closing the gap between interpretation and modeling.

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