Predictive painting of 3-D seismic volumes[a]

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ABSTRACT

Structural information is the most important content of seismic images. I introduce a numerical algorithm for spreading information in 3-D volumes according to the local structure of seismic events. The algorithm consists of two steps. First, local spatially-variable inline and crossline slopes of seismic events are estimated by the plane-wave-destruction method. Next, a seed trace is inserted in the volume, and the information contained in that trace is spread inside the volume, thus automatically "painting" the data space. Immediate applications of this technique include automatic horizon picking and flattening in applications to both prestack and post-stack seismic data analysis. Synthetic and field data tests demonstrate the effectiveness of predictive painting.

INTRODUCTION

Structural information is the most important content of seismic images. One way to characterize structure is to assign a dominant local slope attribute to all elements in a volume. Claerbout (1992) proposed the method of plane-wave destruction for detecting local slopes of seismic events. Closely related ideas were developed in the differential semblance optimization framework (Symes, 1994; Kim and Symes, 1998). Plane-wave destruction finds many important applications in seismic data analysis, including data regularization, noise attenuation, and velocity-independent imaging (Fomel, 2002, 2007b; Fomel et al., 2007; Burnett and Fomel, 2009).

The main principle of plane-wave destruction is prediction: each seismic trace gets predicted from its neighbors that are shifted along the event slopes, and the prediction error gets minimized to estimate optimal slopes. In this paper, I propose to extract the prediction operator from the plane-wave destruction process and to use it for recursive spreading of information inside the seismic volume. I call this spreading *predictive painting*.

One particular kind of information that becomes meaningful when spread in a volume is *relative geologic age*, in the terminology of Stark (2004): seismic layers arranged according to the relative age of sedimentation. Once relative geological age is established everywhere in the volume, it is possible to flatten seismic images by extracting *stratal slices* (Zeng et al., 1998a) without manual picking of horizons. Even though flattened seismic horizons do not necessarily correspond to equivalent true geologic ages, flattening improves the interpreter's ability to understand and quantify the structural architecture of sedimentary layers (Zeng et al., 1998b). The idea of using local shifts for automatic picking was introduced by Bienati and Spagnolini (2001) and Lomask et al. (2006). Stark (2003) presents an alternative approach involving instantaneous phase unwrapping. Analogous techniques are implemented by (de Groot et al., 2006; Bruin et al., 2007).

Flattening and automatic picking of horizons are important not only for final structural interpretation but also for prestack imaging and data analysis and for extracting prestack amplitude attributes. The idea of prestack gather flattening using local cross-correlations was developed previously by a number of authors (Hinkley et al., 2004; Duveneck and Traub, 2006; Gulunay et al., 2007a,b).

The predictive painting method, introduced in this paper, provides a new approach for extracting and applying structural patterns, with superior computational performance. The advantages of the proposed method include both conceptual simplicity and computational efficiency. In the next sections, I describe the basic algorithm for automatic painting and demonstrate its performance with synthetic and field data examples.

DESTRUCTION AND PREDICTION OF PLANE WAVES

Plane-wave destruction originates from a local plane-wave model for characterizing seismic data (Fomel, 2002). The mathematical basis is the local plane differential equation

$$\frac{\partial P}{\partial x} + \sigma \, \frac{\partial P}{\partial t} = 0 \; , \tag{1}$$

where $P(t,x)$ is the wave field and σ is the local slope, which may also depend on t and x (Claerbout, 1992). In the case of a constant slope, equation 1 has the simple general solution

$$P(t,x) = f(t - \sigma x) \; , \tag{2}$$

where $f(t)$ is an arbitrary waveform. Equation 2 is nothing more than a mathematical description of a plane wave. Assuming that the slope $\sigma(t,x)$ varies in time and space, one can design a local operator to propagate each trace to its neighbors.

Let $\mathbf{s}$ represent a seismic section as a collection of traces: $\mathbf{s} = \left[\mathbf{s}_1 \; \mathbf{s}_2 \; \ldots \; \mathbf{s}_N\right]^T$, where $\mathbf{s}_k$ corresponds to $P(t,x_k)$ for $k = 1, 2, \ldots$ A plane-wave destruction operator (Fomel, 2002) effectively predicts each trace from its neighbor and subtracts the prediction from the original trace. In the linear operator notation, the plane-wave destruction operation can be defined as

$$\mathbf{r} = \mathbf{D}\,\mathbf{s} \; , \tag{3}$$

where $\mathbf{r}$ is the destruction residual, and $\mathbf{D}$ is the destruction operator defined as

$$\mathbf{D} = \left[\begin{array}{ccccc} \mathbf{I} & 0 & 0 & \cdots & 0 \\ -\mathbf{P}_{1,2} & \mathbf{I} & 0 & \cdots & 0 \\ 0 & -\mathbf{P}_{2,3} & \mathbf{I} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & -\mathbf{P}_{N-1,N} & \mathbf{I} \end{array}\right] , \tag{4}$$

where $\mathbf{I}$ stands for the identity operator, and $\mathbf{P}_{i,j}$ describes prediction of trace j from trace i. Prediction of a trace consists of shifting the original trace along dominant event slopes. The prediction operator is a numerical solution of equation 1 for local plane wave propagation in the x direction. The dominant slopes are estimated by minimizing the prediction residual $\mathbf{r}$ using regularized least-squares optimization. I employ shaping regularization (Fomel, 2007a) for controlling the smoothness of the estimated slope fields. In the 3-D case, a pair of inline and crossline slopes, $\sigma_x(t,x,y)$ and $\sigma_y(t,x,y)$, and a pair of destruction operators, $\mathbf{D}_x$ and $\mathbf{D}_y$, are required to characterize the 3-D structure. Each prediction in 3-D occurs in either inline or crossline direction and thus conforms to equation 4. However, as explained below in the discussion of Dijkstra's algorithm, it is possible to arrange all 3-D traces in a sequence for further processing.

Prediction of a trace from a distant neighbor can be accomplished by simple recursion. Predicting trace k from trace 1 is simply

$$\mathbf{P}_{1,k} = \mathbf{P}_{k-1,k} \cdots \mathbf{P}_{2,3}\,\mathbf{P}_{1,2} \; . \tag{5}$$

If $\mathbf{s}_r$ is a reference trace, then the prediction of trace $\mathbf{s}_k$ is $\mathbf{P}_{r,k}\,\mathbf{s}_r$. I call the recursive operator $\mathbf{P}_{r,k}$ *predictive painting*. Once the elementary prediction operators in equation 4 are determined by plane-wave destruction, predictive painting can spread information from a given trace to its neighbors recursively by following the local structure of seismic events. The next section illustrates the painting concept using 2-D examples.

PREDICTIVE PAINTING IN 2-D

The input for the first example is borrowed from Claerbout (2006) and shown in Figure 1a. It is a synthetic seismic image containing dipping beds, an uncomformity, and a fault. Figure 1b shows local dips measured by the plane-wave destruction algorithm. The slope estimate correctly depicts the constant dip in the top part of the image and the sinusoidal variation of the dip in the bottom. Figure 2a shows the output of predictive painting: I assign the reference trace, selected in the middle of the image, with several horizon picks, which are then automatically spread into the image space by using prediction operators from equation 5. Figure 2b shows another kind of painting: This time, the reference trace contains simply the time values along this trace. When spread by predictive painting, it turns into the *relative geologic age* attribute, as defined by Stark (2004). Relative age indicates how much a given trace

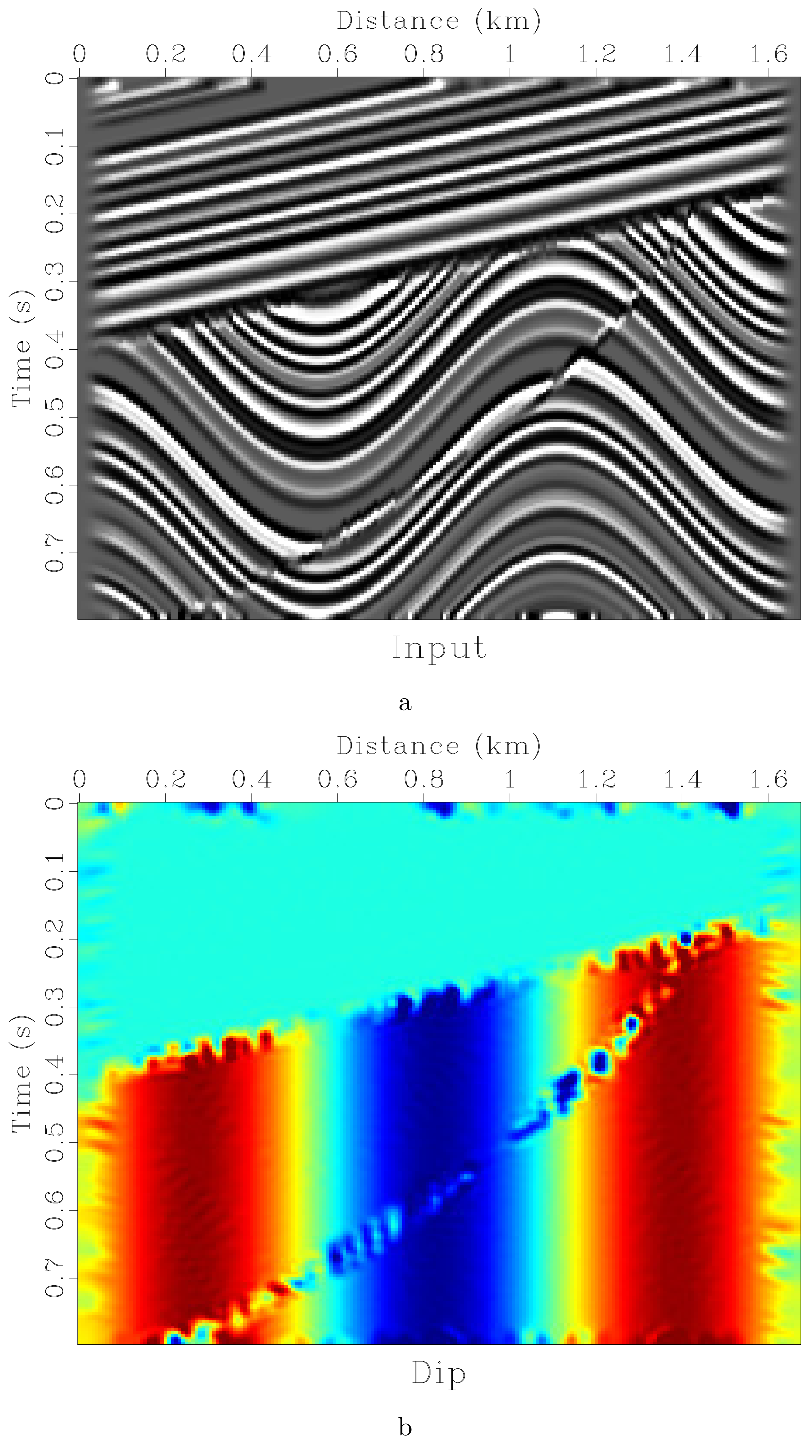
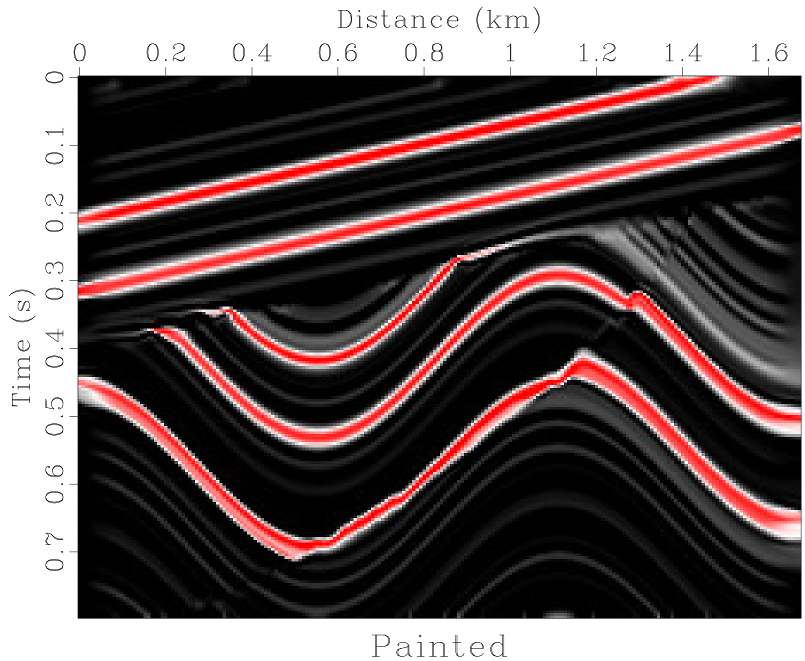


Figure 1: (a) Synthetic image from Claerbout (2006). (b) Local dip estimate.



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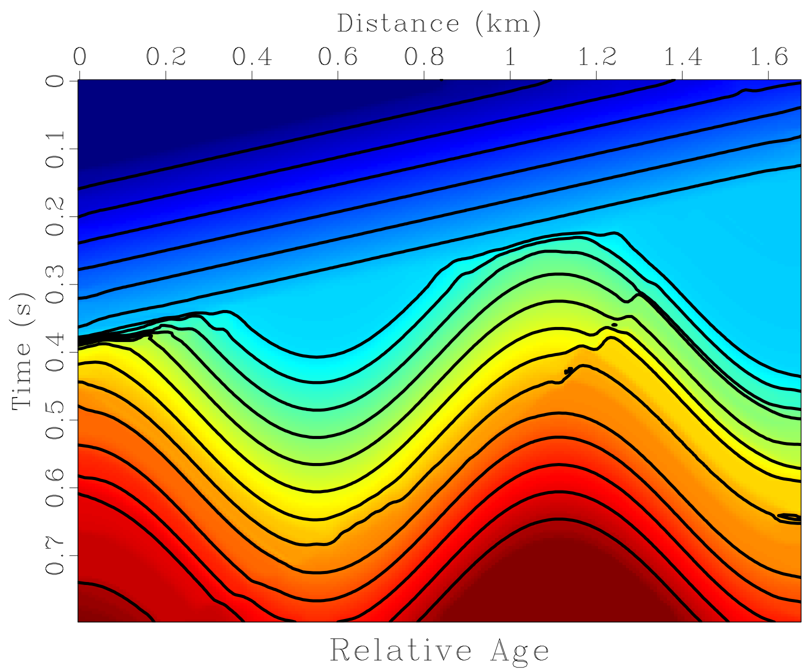

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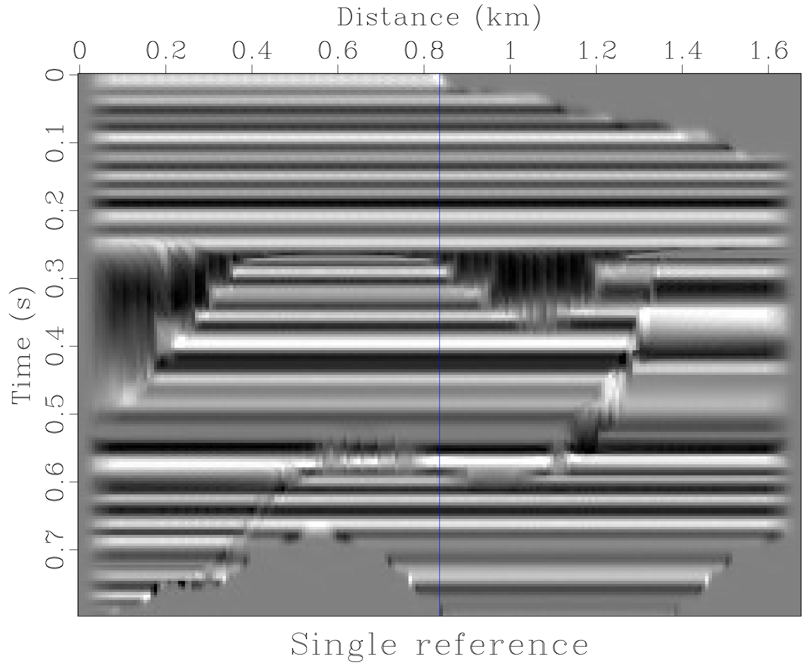
Figure 2: Predictive painting using synthetic image from Figure 1a. (a) Painted horizons. (b) Painted relative age. The reference trace is in the center of the image.



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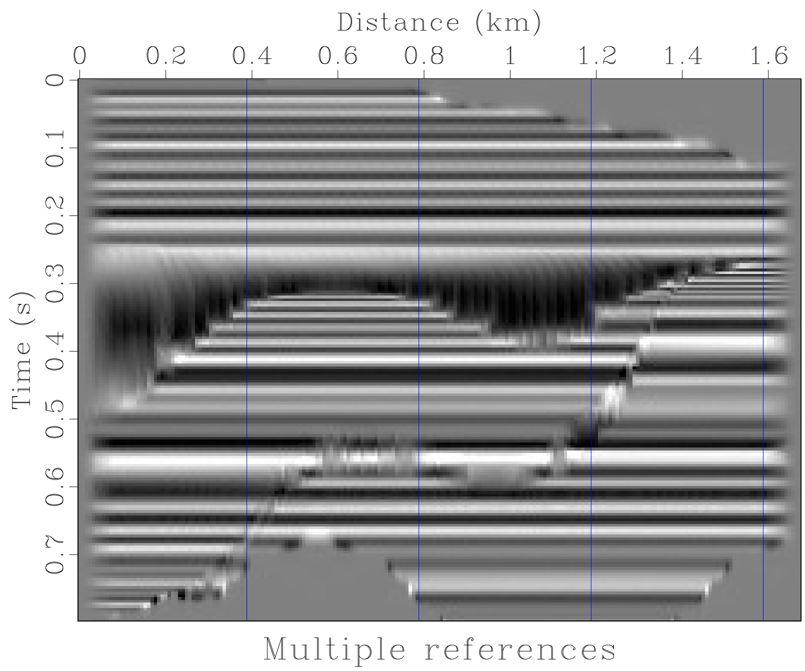

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Figure 3: Synthetic image from Figure 1a flattened using a single reference trace (a) and multiple references (b). The reference traces are marked by vertical lines.

is shifted with respect to the reference trace. Unshifting each trace accomplishes automatic flattening. The result is shown in Figure 3a. Most of the horizons are successfully flattened, although the algorithm fails to "heal" some of events across the fault because of significant structural discontinuities. In cases like that, the geological insight of the interpreter is invaluable and cannot be easily replaced by an automatic algorithm.

One reference trace is not necessarily structurally connected to all events in the volume. By using multiple references and averaging the relative age among all of them, one can obtain a more accurate extraction of stratal slice information. The result of using multiple references, shown in Figure 3b, contains more detailed information about horizons that are not structurally visible from the single reference trace.

As mentioned in the introduction, flattening and automatic picking of horizons are useful not only for post-stack structural interpretation but also for prestack data analysis. Figure 4 shows an application of 2-D predictive painting to a marine CMP (common midpoint) gather. After the field of local slopes has been found (Figure 4b), predictive painting is applied to mark individual events (Figure 4c) or to flatten them (Figure 4d), which effectively accomplishes moveout correction. This processing is automatic and does not require manual picking or any prior assumption on the moveout shape. After extracting the moveout information, the moveout parameters can be estimated by least-squares fitting, as described by Burnett and Fomel (2009). It is important to note that the gather flattening method is prone to errors in the presence of crossing events, such as multiple reflections, since only the dominant slopes of the strongest events are going to be picked up by the slope estimation procedure.

PREDICTIVE PAINTING IN 3-D

The challenge of predictive flattening in 3-D is in selecting a recursive path that the reference trace should follow to paint its neighbors. For choosing this path, I adopt a version of Dijkstra's shortest path algorithm (Dijkstra, 1959; Cormen et al., 2001). Dijkstra's algorithm finds the path between two nodes in a network of nodes, where there is a cost associated in connecting each node with its neighbors. In our case, the nodes are seismic traces in a 3-D cube. I use the semblance between neighboring traces as a cost function. Dijkstra's algorithm finds the shortest (minimum-cost) path by effectively arranging all nodes in a sequence from low to high cost and evaluating each new node using the information from previous nodes. I run the shortest-path algorithm starting from the reference trace and paint other traces in a recursive sequence using the information from previously painted traces. Using semblance as a cost function helps avoiding 3-D misties by forcing the shortest path to go around possible fault areas.

The 3-D data test is reproduced from Lomask et al. (2006). It uses a portion of a depth-migrated 3-D image with structural folding and angular unconformities (Figure 5a). Inline and crossline dips are measured automatically from the image using

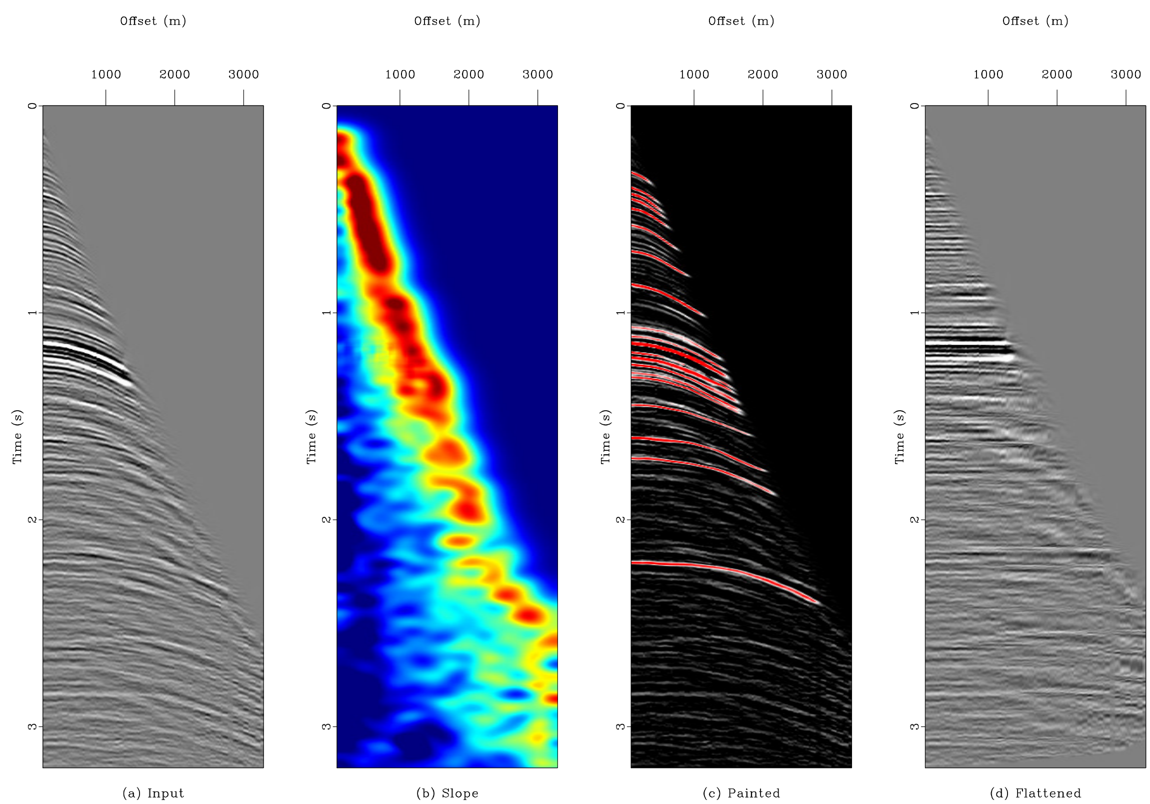

Figure 4: A marine CMP gather (a), estimated local slopes (b), events marked by predictive painting (c), and flattening (d).

plane-wave destruction (Figures 6a and 6b). Figure 7a shows painting of individual strong horizons in the volume. Figure 5b displays automatic flattening using predictive painting of the relative geologic age. Figure 7b shows some of the corresponding equal-relative-age horizons displayed on top of the original image. Predictive painting is able to correctly identify the most significant three-dimensional structural features.

CONCLUSIONS

I have introduced predictive painting, a numerical algorithm for automatic spreading of information in 3-D seismic volumes according to the local structure of seismic events. The structure is extracted using plane-wave destruction, which operates by predicting each trace in the volume from its inline and crossline neighbors. In the second step, prediction operators are used to spread information inside the volume. This procedure is automatic and computationally fast because it requires only a small fixed number of operations per each trace or data sample. Synthetic and field data tests demonstrate the effectiveness of predictive painting in accomplishing such tasks as automatic flattening and horizon picking.

Further research should concentrate on combining automatic tools with interactive interpretation to allow the information extracted from seismic data to be integrated with the geological insight of the interpreter.

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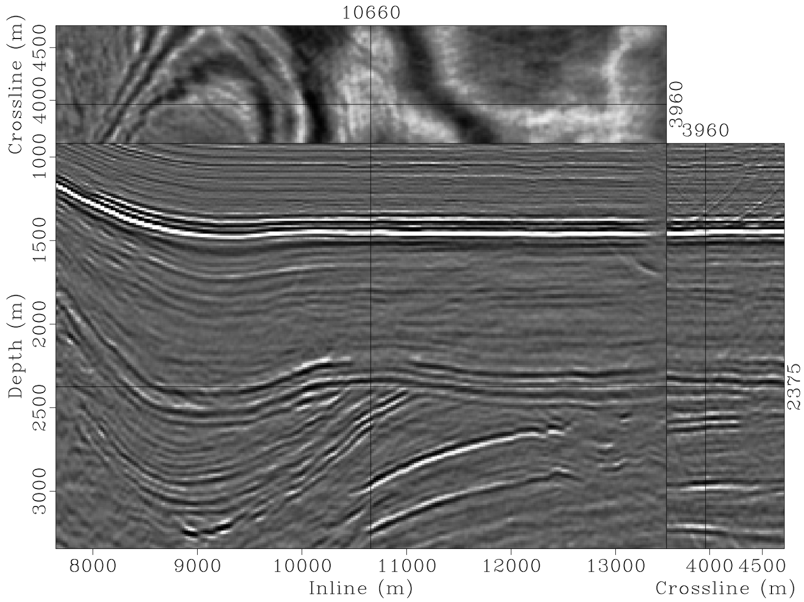

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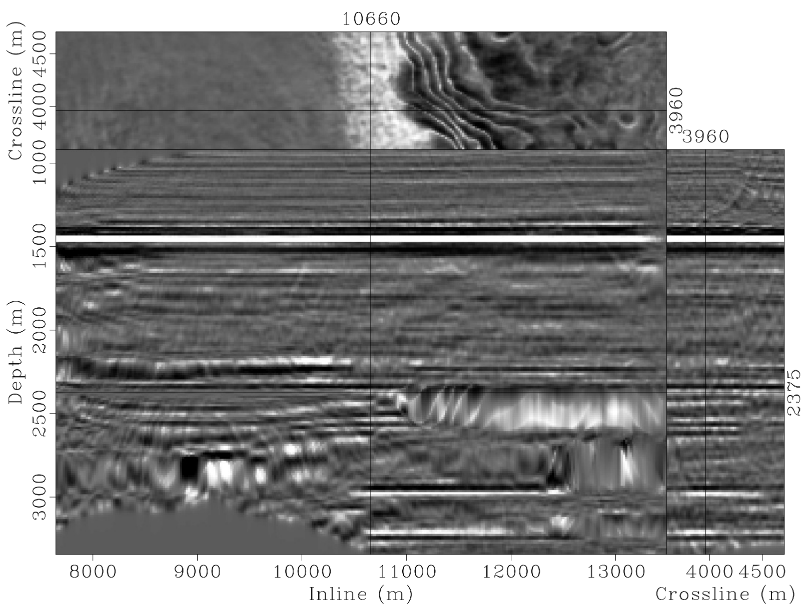
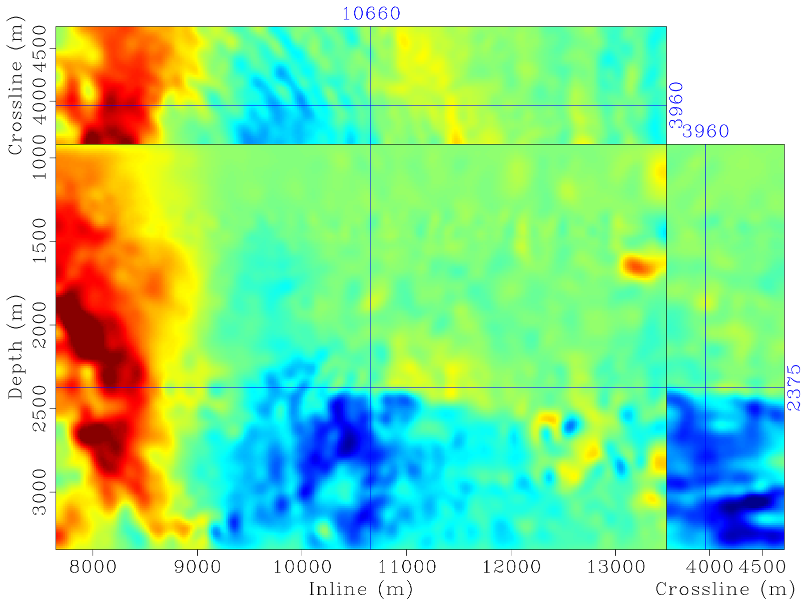


b

Figure 5: A North Sea image from Lomask et al. (2006) (a) and its predictive flattening (b).



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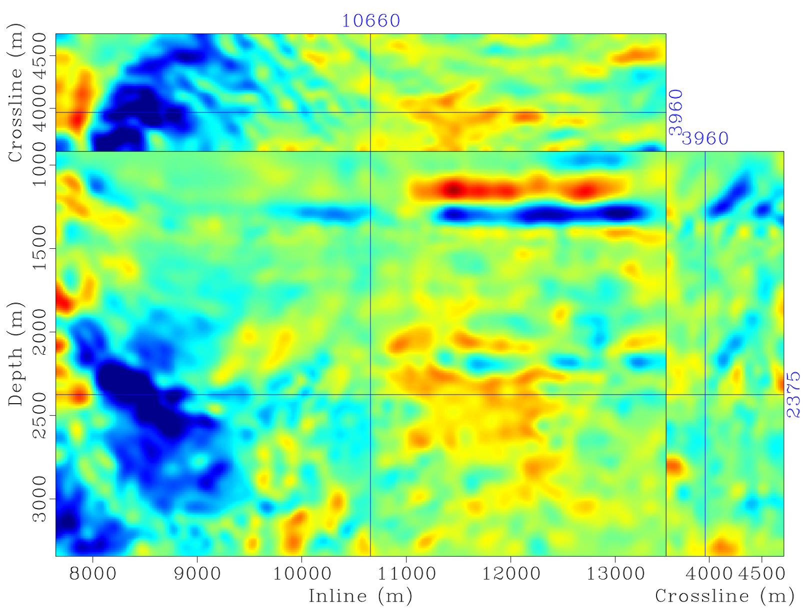

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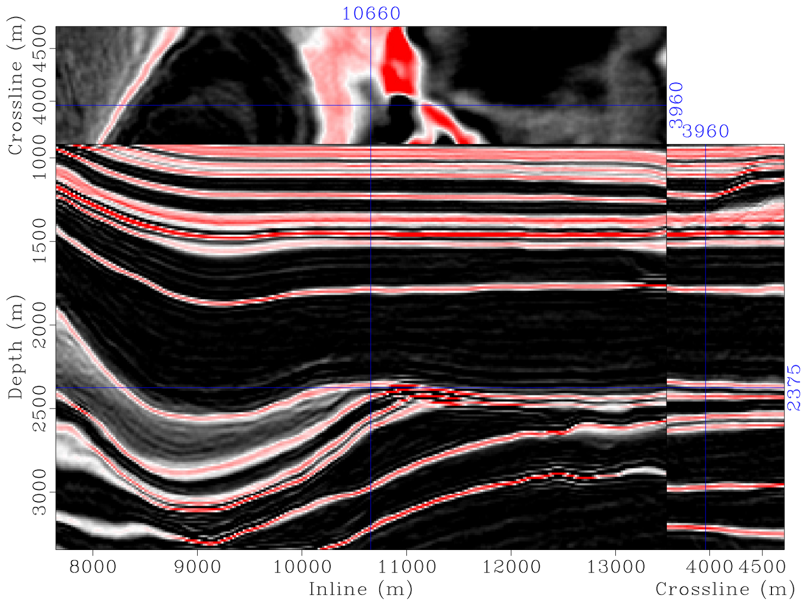
Figure 6: Inline (a) and crossline (b) slopes in the North Sea Image estimated by plane-wave destruction. Blue colors indicate negative slope; red colors, positive slope.



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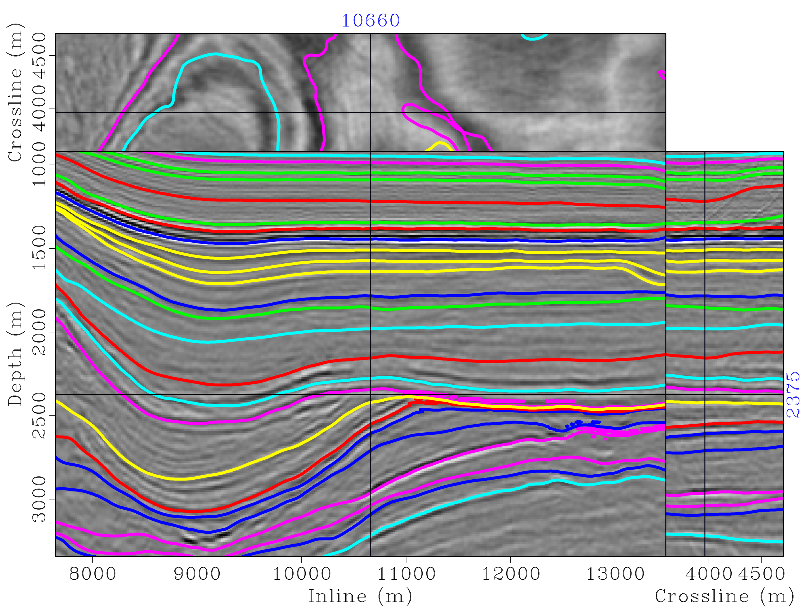

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Figure 7: Predictive painting (a) and automatic picking (b) of major horizons in the North Sea Image.

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