Structural uncertainty of time-migrated seismic images[a]

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ABSTRACT

Structural information in seismic images is uncertain. The main cause of this uncertainty is uncertainty in velocity estimation. We adopt the technique of velocity continuation for estimating velocity uncertainties and corresponding structural uncertainties in time-migrated images. Data experiments indicate that structural uncertainties can be significant even when both structure and velocity variations are mild.

INTRODUCTION

The usual outcome of seismic data processing is an image of the subsurface (Yilmaz, 2001). In the conventional data analysis workflow, the image is passed to the seismic interpreter, who makes geological interpretation, often by extracting structural information, such as positions of horizons and faults in the image. Hidden in this process is the fact that structural information is fundamentally uncertain, mainly because of uncertainties in estimating seismic velocity parameters, which are required for imaging. Apart from the trivial case of perfectly flat seismic reflectors, which are positioned correctly in time even when incorrect stacking or migration velocities are used, seismic images can be and usually are structurally distorted because of inevitable errors in velocity estimation (Glogovsky et al., 2009).

Understanding and quantifying uncertainty in geophysical information can be crucially important for resource exploration (Caers, 2011). The issue of structural uncertainty in seismic images was analyzed previously by Thore et al. (2002) and Pon and Lines (2005). Tura and Hanitzsch (2001) studied the impact of velocity uncertainties on migrated images and AVO attributes. Bube et al. (2004a,b) studied the influence of velocity and anisotropy uncertainties on structural uncertainties.

In this paper, we propose a constructive procedure for estimating the degree of structural uncertainty in seismic images obtained by prestack time migration. The basis for our approach is the method of velocity continuation (Fomel, 1994; Hubral et al., 1996; Fomel, 2003a,b; Burnett and Fomel, 2011), which constructs seismic

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images by an explicit continuation in migration velocity. Velocity continuation generalizes the earlier ideas of residual and cascaded migrations (Rocca and Salvador, 1982; Rothman et al., 1985; Larner and Beasley, 1987). In addition to generating accurate time-migration images, it provides a direct access to measuring the structural dependence (sensitivity) of these images on migration velocities. We define structural uncertainty as a product of velocity picking uncertainty and structural sensitivity.

We use a simple data example to illustrate our approach and to show that structural uncertainty can be significant even when both structure and velocity variations are mild. Although the proposed approach is directly applicable only to prestack time migration, it can be extended in principle to prestack depth migration using velocity-ray approaches for extending the velocity continuation concept (Adler, 2002; Iversen, 2006; Duchkov and De Hoop, 2009).

VELOCITY CONTINUATION AND STRUCTURAL SENSITIVITY

Velocity continuation is defined as the process of image transformation with changes in migration velocity (Fomel, 1994, 2003b). Its output is equivalent to the output of repeated migrations with different migration velocities (Yilmaz et al., 2001) but produced more efficiently by using propagation of images in velocity (Hubral et al., 1996). If we denote the output of velocity continuation as $C(t,x,v)$, where t and x are time-migration coordinates and v is migration velocity, the time-migrated image is simply

$$I(t,x) = C(t,x,v_M(t,x)) \; , \tag{1}$$

where $v_M(t,x)$ is the picked migration velocity. Figure 1 shows the velocity continuation cube $C(t,x,v)$ generated from a benchmark 2-D dataset from the Gulf of Mexico (Claerbout, 2005). Migration velocity $v_M(t,x)$ picked from the semblance analysis is shown in Figure 2. The velocity variations reflect a dominantly vertical gradient typical for the Gulf of Mexico and only mild lateral variations, which justifies the use of prestack time migration. The corresponding migration image $I(t,x)$ is shown in Figure 3 and exhibits mild, nearly-horizontal reflectors and sedimentary structures.

The structural sensitivity of an image can be described through derivatives $\partial t/\partial v$ and $\partial x/\partial v$, which correspond to slopes of events in the $C(t,x,v)$ volume evaluated at $v = v_M(t,x)$. These slopes are easy to measure experimentally from the $C(t,x,v_M)$ volume, using, for example, the plane-wave destruction algorithm (Fomel, 2002; Chen et al., 2013a,b). Figure 4 shows one common-image gather $G(t,v) = C(t,x_0,v)$ for $x_0 = 10\,\mathrm{km}$ and the time slice $S(x,v) = C(t_0,x,v)$ for $t_0 = 2\,\mathrm{s}$. Measuring the slope of events $\partial t/\partial v$ in this gather and evaluating it at the picked migration velocity produces the slope

$$p_t(t,x) = \left.\frac{\partial t}{\partial v}\right|_{v=v_M(t,x)} \; . \tag{2}$$

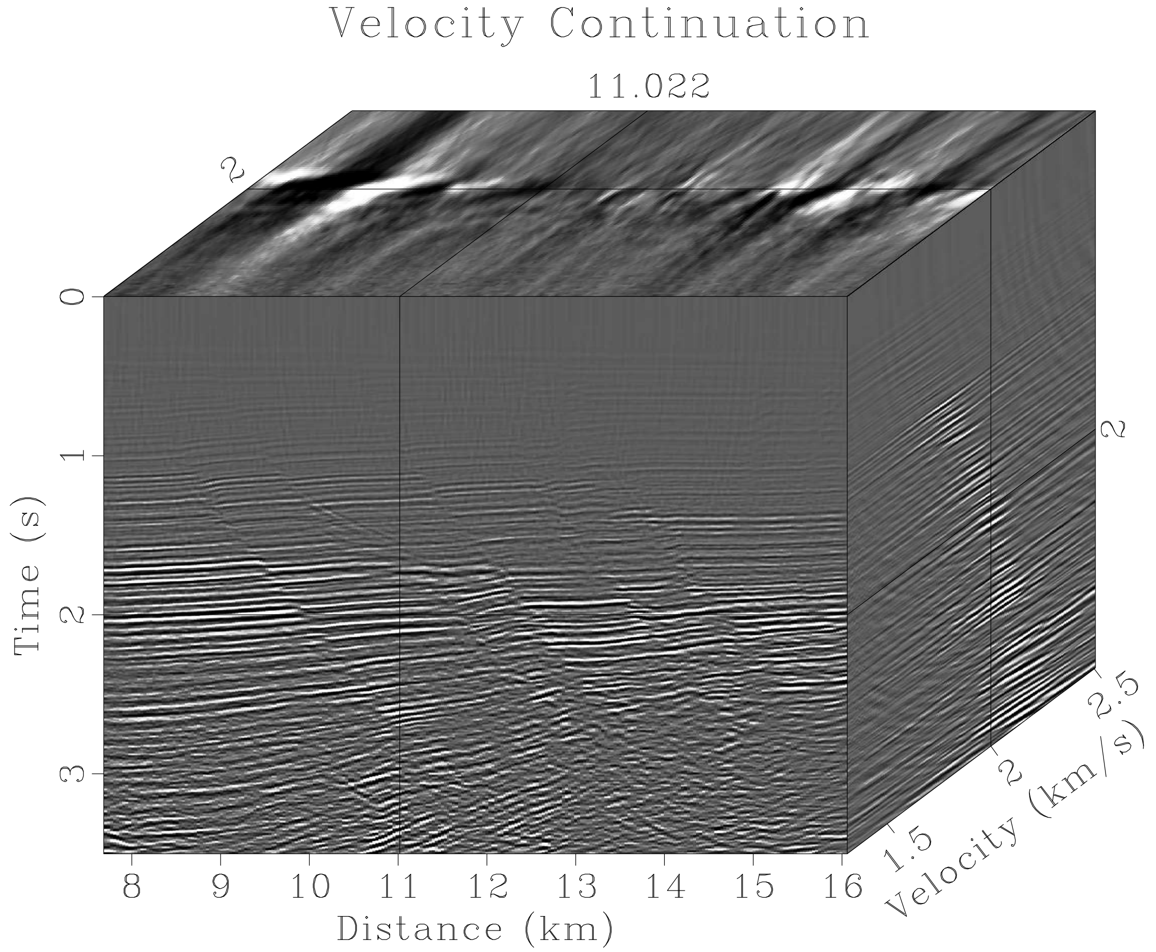


Figure 1: Velocity continuation cube for prestack time migration of the Gulf of Mexico dataset.

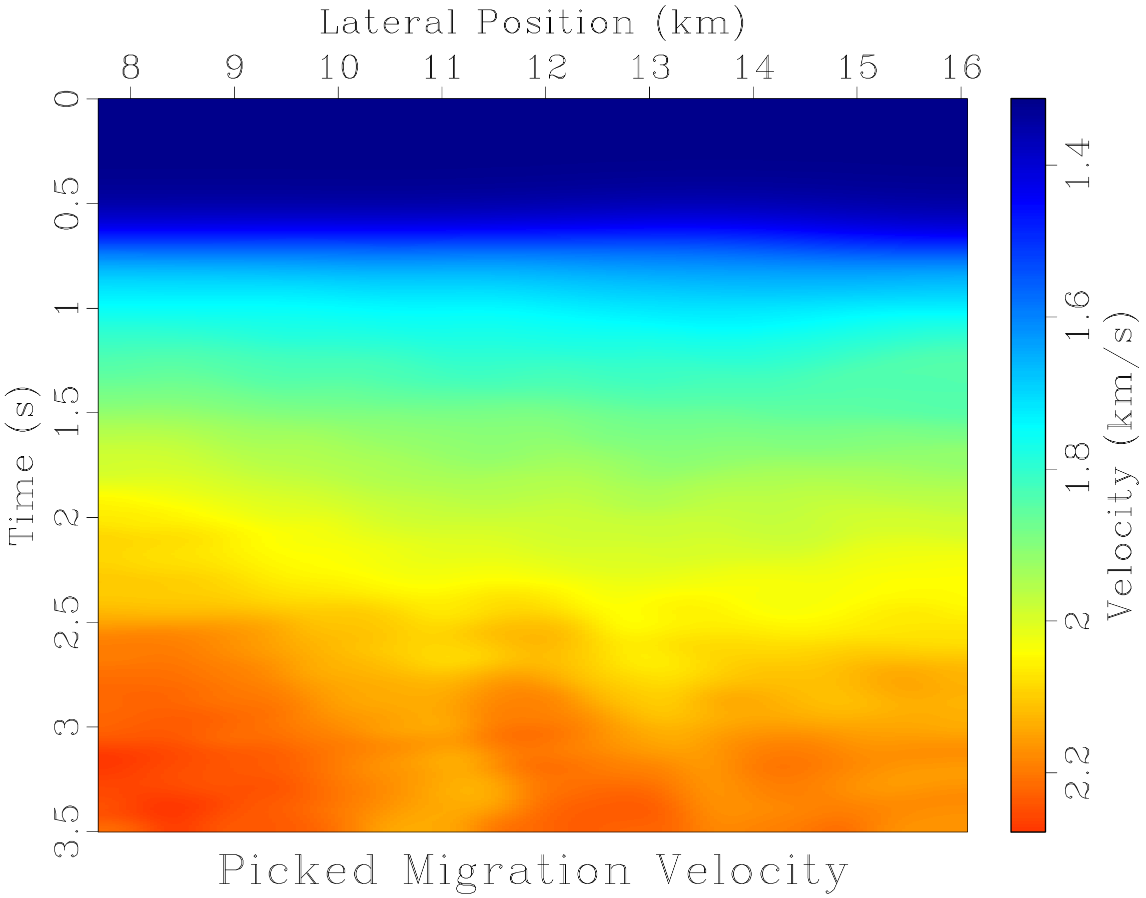


Figure 2: Migration velocity picked from velocity continuation.

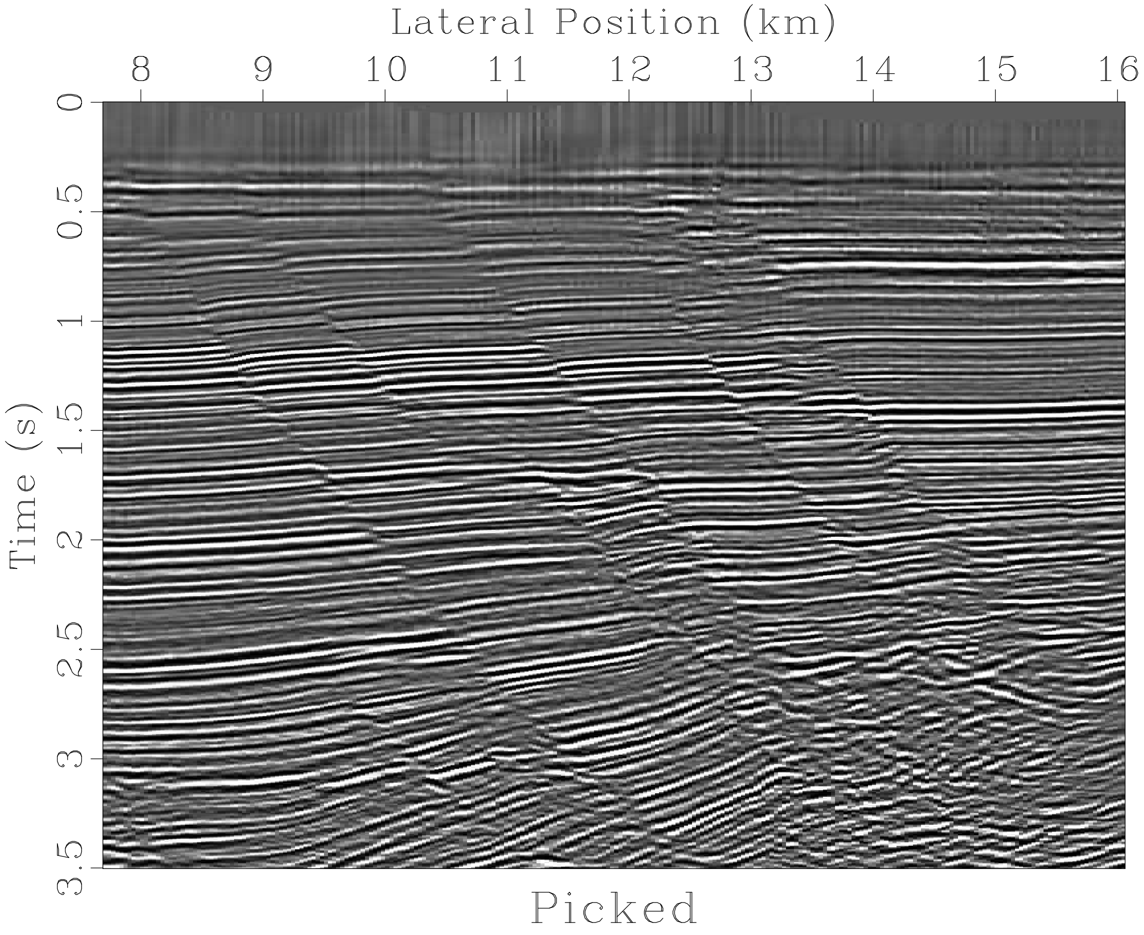
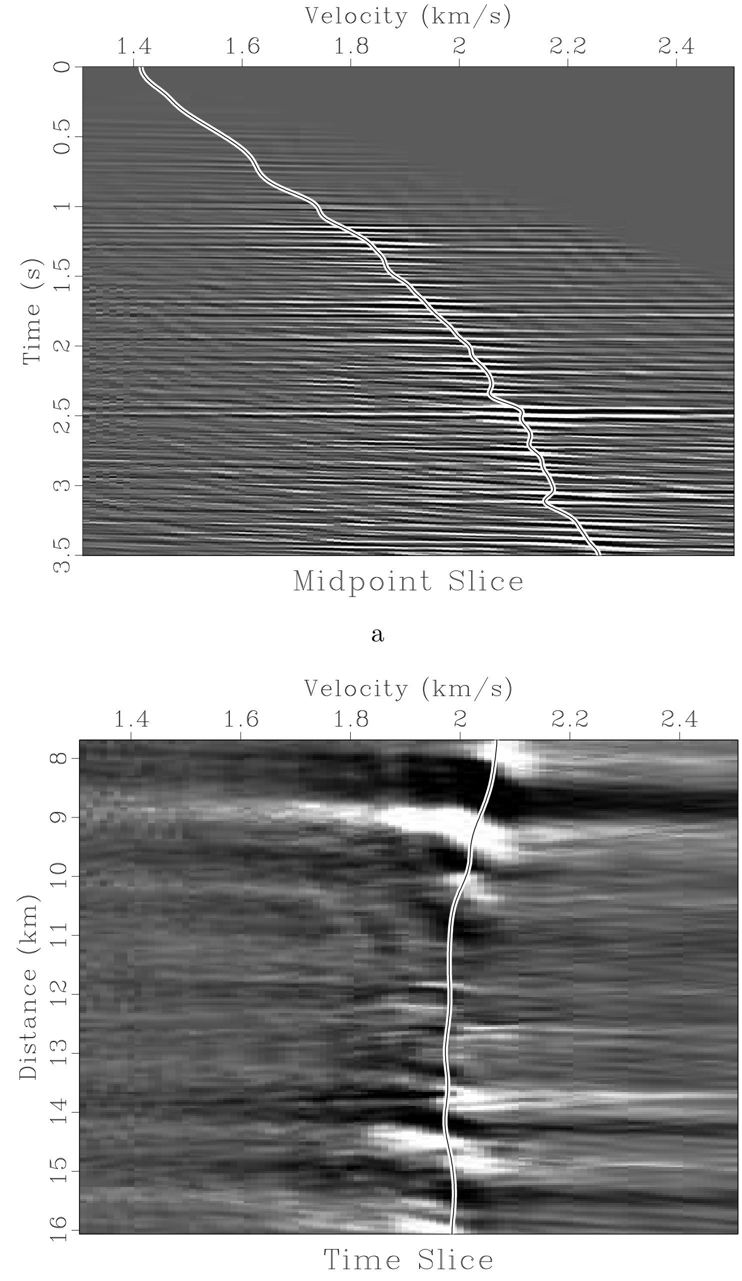


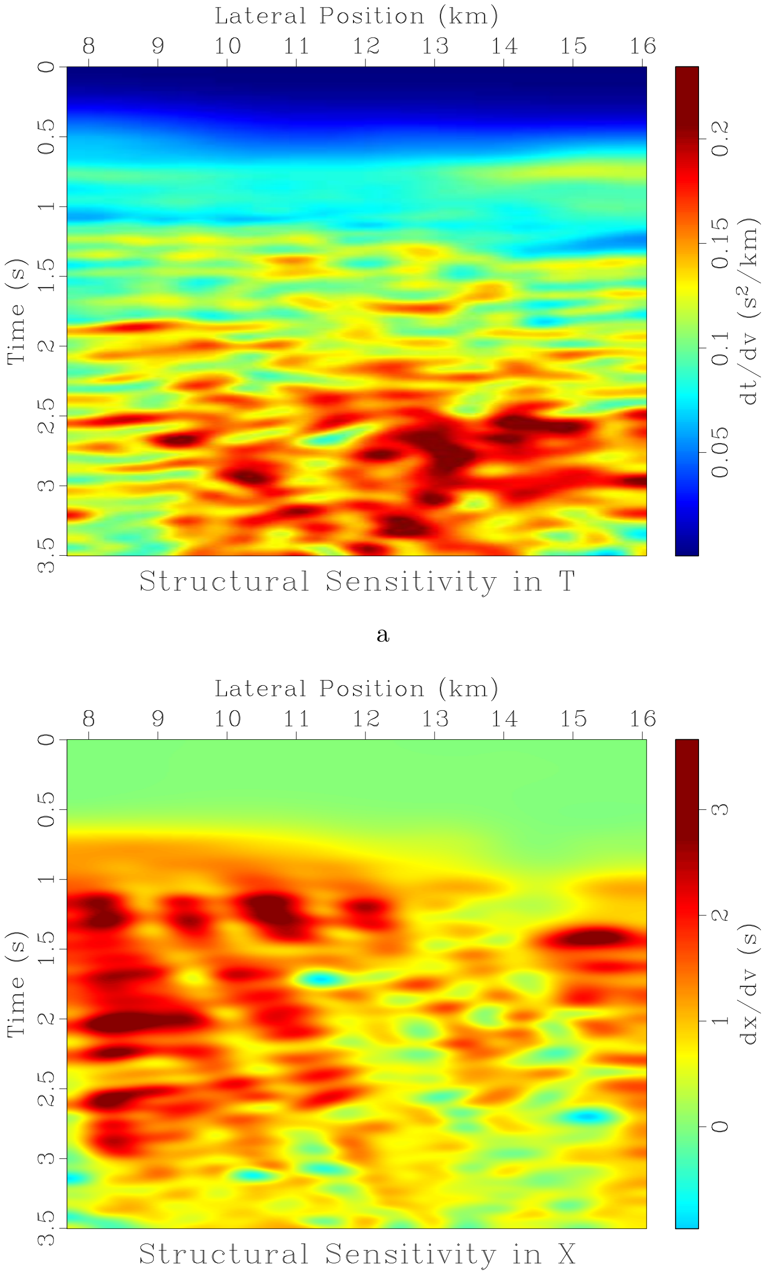
Figure 3: Seismic prestack time-migration image generated by velocity continuation.



a

b

Figure 4: Common-image gather (a) and time slice (b) from velocity continuation with overlaid time-migration velocity.



a

b

Figure 5: Estimated structural sensitivity in time (a) and lateral position (b) with respect to velocity.

We measure the slope $p_x(t,x)$ analogously by evaluating local slopes in time slices of constant t:

$$p_x(t,x) = \left.\frac{\partial x}{\partial v}\right|_{v=v_M(t,x)} . \tag{3}$$

Figure 5 shows the estimated p_t and p_x, which comprise the structural sensitivity of our image.

Theoretically, structural sensitivity can be inferred from the zero-offset velocity ray equations (Chun and Jacewitz, 1981; Fomel, 2003b)

$$\begin{aligned} \frac{dt}{dv} &= v_M\, t\, t_x^2 = \frac{t}{v_M}\, \tan^2\theta \,, && (4) \\ \frac{dx}{dv} &= -2\, v_M\, t\, t_x = -2\, t \frac{t}{v_M}\, \tan^2\theta \,, && (5) \end{aligned}$$

where t_x corresponds to the slope of the reflector, and θ is the reflector dip angle. According to equations 4-5, the reflector dip is the dominant factor in structural sensitivity.

UNCERTAINTY IN VELOCITY PICKING

Figure 6a shows a semblance scan produced in the process of velocity continuation. A common procedure in migration velocity analysis is picking a velocity trend from the semblance, either manually or automatically. In this example, we use automatic picking with the algorithm described by Fomel (2009).

While picking may select the most probable velocity function, its probability is less than 100%. If we view normalized semblance as a probability distribution and determine a confidence interval corresponding roughly to one standard deviation, it provides an approximate range of uncertainty in velocity determination. This range is shown in Figure 6b and computed according to

$$\delta v(t,x) = \sqrt{\frac{\int\limits_{v_{min}}^{v_{max}} \left[v - v_M(t,x)\right]^2\, S(t,x,v)\, dv}{\int\limits_{v_{min}}^{v_{max}} S(t,x,v)\, dv}} \,, \tag{6}$$

where $S(t,x,v)$ is the semblance volume that corresponds to $C(t,x,v)$, and $[v_{min}, v_{max}]$ is the full range of velociies. The interpretation of semblance picks as probability distributions is heuristic but helps in quantifying uncertainties in velocity picking.

STRUCTURE UNCERTAINTY

Putting structural sensitivity and velocity uncertainty together, we can define *structural uncertainty* simply as their product:

$$\delta t \;=\; \frac{\partial t}{\partial v}\, \delta v \,, \tag{7}$$

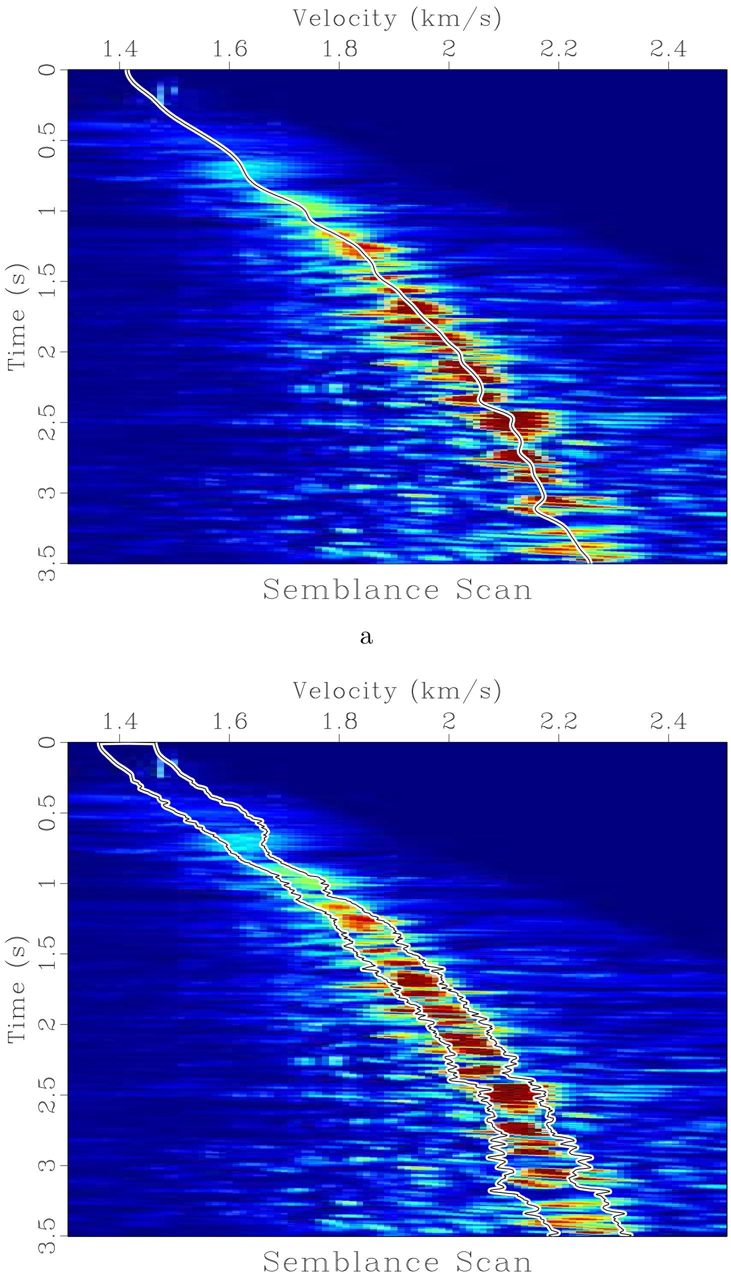


Figure 6: Velocity scan at 10 km image gather. The curve in (a) corresponds to the automatically picked velocity trend. The curves in (b) identify an approximate range of velocity uncertainty around the picked trend.

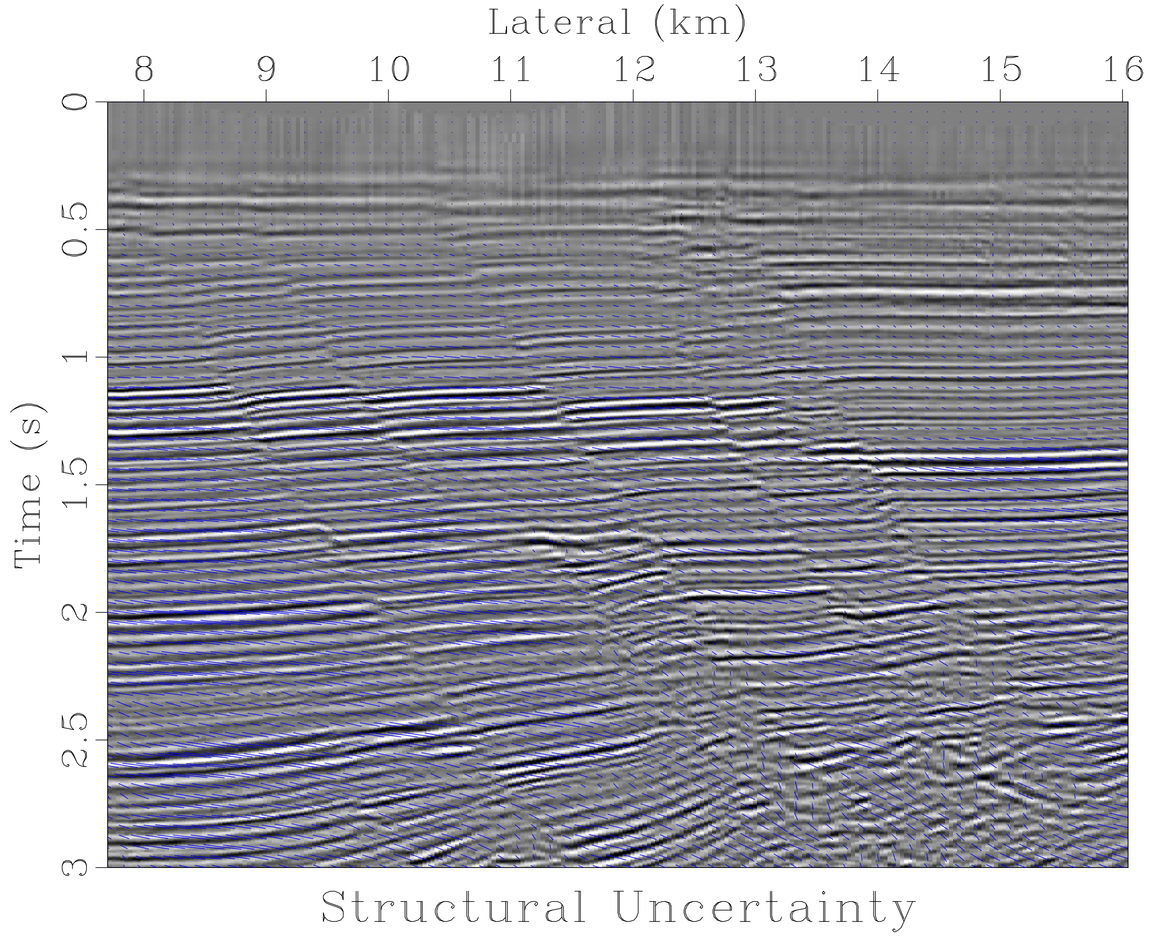


Figure 7: Estimated structural uncertainty in the seismic image from Figure 3, displayed as displacements.

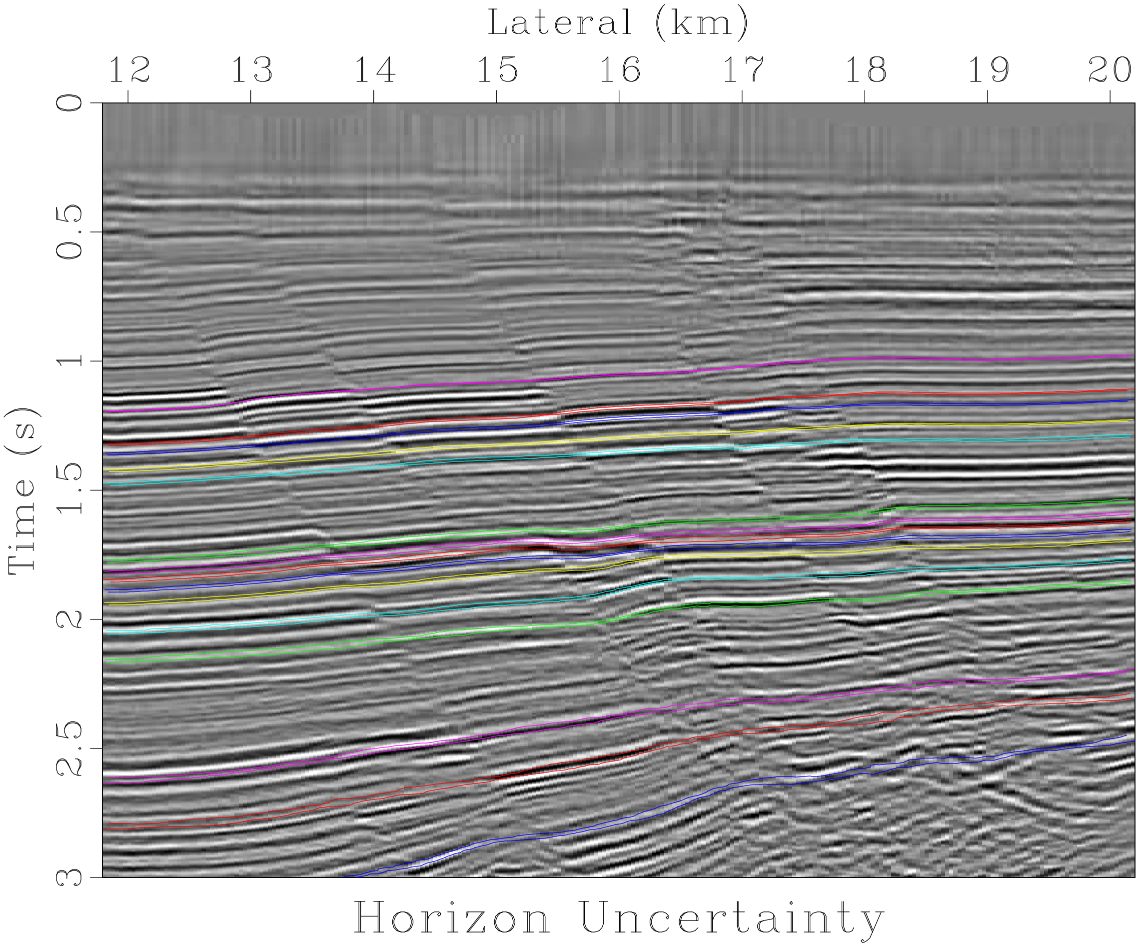


Figure 8: Estimated structural uncertainty in the seismic image from Figure 3, displayed as horizon uncertainties.

$$\delta x \;=\; \frac{\partial x}{\partial v}\,\delta v\;. \tag{8}$$

The uncertainty $\{\delta t, \delta x\}$ is the main output of our study. It is shown as small line segments in Figure 7 and as uncertainty in horizons in Figure 8. The estimated uncertainty varies inside the image space and generally increases with depth. It is surprisingly large, given the mild variations in structure and velocity. We believe that, when making quantitative estimates related to structural interpretation, it is important to take this kind of uncertainty into account.

When converting seismic images from time to depth, it is also important to realize that the time-to-depth conversion itself is a mathematically ill-posed problem (Cameron et al., 2007) and has its own significant uncertainties.

CONCLUSIONS

We have estimated structural uncertainty in seismic time-domain images simultaneously with performing prestack time migration. To accomplish this task, we projected the uncertainty in migration velocity picking into the structural uncertainty by measuring the structural sensitivity of seismic images to velocity. The latter measure is provided by velocity continuation, which serves both as an imaging tool and as a tool for sensitivity analysis. Field data examples show that structural uncertainties can be significant even in the case of mild structures and slow velocity variations. Taking these uncertainties into account should improve the practice of seismic structural interpretation by making it more compliant with risk-management assessment in reservoir characterization.

REFERENCES

Adler, F., 2002, Kirchhoff image propagation: Geophysics, **67**, 126–134.

Bube, K. P., J. A. Kane, T. Nemeth, D. Medwedeff, and O. Mikhailov, 2004a, The influence of stacking velocity uncertainties on structural uncertainties: 74th Ann. Internat. Mtg., Soc. of Expl. Geophys., 2188–2191.

Bube, K. P., T. Nemeth, O. Mikhailov, D. Medwedeff, and J. A. Kane, 2004b, The influence of uncertainties in anisotropy on structural uncertainties: 74th Ann. Internat. Mtg., Soc. of Expl. Geophys., 2192–2195.

Burnett, W., and S. Fomel, 2011, Azimuthally anisotropic 3D velocity continuation: International Journal of Geophysics, **2011**, Article ID 484653.

Caers, J., 2011, Modeling uncertainty in the Earth sciences: Wiley.

Cameron, M. K., S. Fomel, and J. A. Sethian, 2007, Seismic velocity estimation from time migration velocities: Inverse Problems, **23**, 1329–1369.

Chen, Z., S. Fomel, and W. Lu, 2013a, Accelerated plane-wave destruction: Geophysics, **78**, V1–V9.

———, 2013b, Omnidirectional plane-wave destruction: Geophysics, **78**, V171–V179.

Chun, J. H., and C. A. Jacewitz, 1981, Fundamentals of frequency-domain migration: Geophysics, **46**, 717–733.

Claerbout, J. F., 2005, Basic Earth imaging: Stanford Exploration Project, `http://sepwww.stanford.edu/sep/prof/`.

Duchkov, A. A., and M. V. De Hoop, 2009, Velocity continuation in the downward continuation approach to seismic imaging: Geophysical Journal International, **176**, 909–924.

Fomel, S., 1994, Method of velocity continuation in the problem of seismic time migration: Russian Geology and Geophysics, **35**, 100–111.

———, 2002, Applications of plane-wave destruction filters: Geophysics, **67**, 1946–1960.

———, 2003a, Time-migration velocity analysis by velocity continuation: Geophysics, **68**, 1662–1672.

———, 2003b, Velocity continuation and the anatomy of residual prestack time migration: Geophysics, **68**, 1650–1661.

———, 2009, Velocity analysis using AB semblance: Geophysical Prospecting, **57**, 311–321.

Glogovsky, V., E. Landa, S. Langman, and T. J. Moser, 2009, Validating the velocity mode: the Hamburg Score: First Break, **27**, 77–85.

Hubral, P., M. Tygel, and J. Schleicher, 1996, Seismic image waves: Geophysical Journal International, **125**, 431–442.

Iversen, E., 2006, Velocity rays for heterogeneous anisotropic media: Theory and implementation: Geophysics, **71**, T117–T127.

Larner, K., and C. Beasley, 1987, Cascaded migrations - Improving the accuracy of finite-difference migration: Geophysics, **52**, 618–643. (Errata in GEO-52-8-1165).

Pon, S., and L. R. Lines, 2005, Sensitivity analysis of seismic depth migrations: Geophysics, **70**, S39–S42.

Rocca, F., and L. Salvador, 1982, Residual migration: 52nd Ann. Internat. Mtg, Soc. of Expl. Geophys., Session:S1.4.

Rothman, D. H., S. A. Levin, and F. Rocca, 1985, Residual migration - Applications and limitations: Geophysics, **50**, 110–126.

Thore, P., A. Shtuka, M. A. Lecour, T. Ait-Ettajer, and R. Cognot, 2002, Structural uncertainties: Determination, management, and applications: Geophysics, **67**, 840–852.

Tura, A., and C. Hanitzsch, 2001, Estimating and interpreting velocity uncertainty in migrated images and AvO attributes: Geophysics, **66**, 1208–1216.

Yilmaz, O., 2001, Seismic data analysis: Soc. of Expl. Geophys.

Yilmaz, O., I. Tanir, and C. Gregory, 2001, A unified 3-D seismic workflow: Geophysics, **66**, 1699–1713.