Automatic High-Density Constrained Velocity Picking

Emil Blias[1]

[1]SeisVS, Calgary, Alberta, Canada (emilb@shaw.ca)

Abstract

Velocity analysis is one of the main steps in seismic processing. A velocity model, beyond its initial purpose to obtain a seismic stack, is used for time and depth imaging, AVO analysis and inversion, pore pressure prediction and so on. In conventional processing, it is a highly costly procedure and it needs manual work. In this paper, I present a high-density automatic velocity analysis. Semblance-based coherency measures are commonly applied to perform velocity analysis (Taner and Koehler, 1969) on seismic reflection data. Velocities are estimated by maximizing a coherence measure with respect to the hyperbola parameter. The main idea is that we look for stacking velocities for each CDP gather and dense set of time samples using a threshold for the semblance. The program finds all constrained values of stacking velocities where it is possible (where the semblance value is larger than the threshold). To find the constraints for the stacking velocities, one may pick velocity manually at several points and determine the constraints. Then we take these CDP gathers as the reference points and extend picked velocities for the whole line area.

Introduction

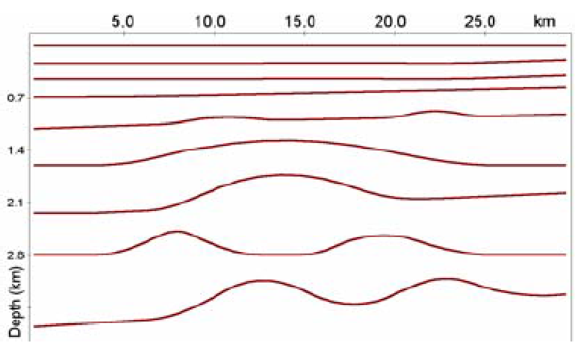
The velocity field is the most important factor in seismic processing. Accurate knowledge of seismic velocities is essential for transforming surface reflection time data into depth images of reflector locations. We should distinguish two kinds of velocity. From real data, we directly extract velocities in the time domain, which give us the best image (stack). We can call it stacking velocities or time-imaging velocities. If we want to obtain a depth image through depth migration or simply by time-to-depth transformation, we have to use depth velocity model. In this paper, we consider only stacking velocities. The conventional approach assumes manual velocity picking for several CDP gathers and interpolation for the line for 2-D data or over an area for 3-D data. For many procedures, such as time migration, AVO analysis or when the stacking velocities change rapidly, we need an accurate velocity field. Fast lateral fluctuations of stacking velocities may be caused by shallow velocity anomalies even in the subsurface with gentle dipping boundaries (Blias, 2005). At the same time, velocity is quite a damaging factor if we find it wrong and it is a time-consuming factor to determine it properly.

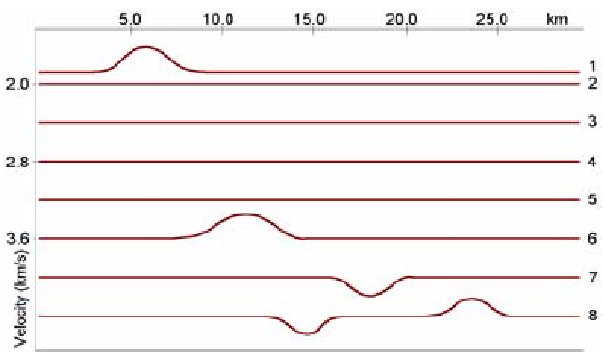
In addition to obtaining correct estimates of velocity, we also have a question of reliability related to the sampling density. From geological information and since CDP gathers are highly overlapped; we know that velocity cannot change rapidly within adjacent CDP gathers. It implies that to describe adequately lateral and vertical stacking velocity changes we can use much lesser number of parameters then input data. On the other hand, we know that we cannot expect to determine a reliable stacking velocity for each time sample of the CDP gather. This is because the coherence based approach (the same as any other) assumptions are not satisfied for most time samples. The main assumption in any automated velocity picking is that there is one event within the considered time window.

Let us shortly consider the restrictions on applying a locally 1-D model to velocity analysis. Strictly speaking, RMS velocity and Dix's formula have been derived for an infinitely small spread length for a 1-D layered velocity model that is for a model with horizontal homogeneous boundaries. That is why one can often read that conventional velocity analysis is based on a horizontally layered media assumption. In reality, we never have horizontal boundaries and homogeneous layers and if we had this subsurface, we would not need seismic exploration because for this kind of subsurface it is enough to know the velocity distribution at one point. Fortunately, we can use Dix's formulas in many real situations even when there are lateral changes in the subsurface velocities, as well as when we have a long spread length.

The practically important question is: How far can we go from this assumption? In other words, when can we assume that stacking velocities are close to RMS? Dix's formula gives a reasonable estimation of interval velocity when and only when stacking velocities are close to RMS. At first sight, the answer would be that we can use Dix's formula when the subsurface is close to a 1-D model, that is the medium has almost horizontal boundaries with almost homogeneous layers. But this is not completely right because we can see significant dips when Dix's formula gives reasonable interval velocity estimations and we can see that sometime even relatively small lateral velocity changes cause large deviations of stacking velocities from RMS, and, therefore, from average velocities.

It was analytically shown and illustrated with modeling (Blias, 1981, 1988, 2003, 2005a, 2005b) that deviation between stacking and RMS velocity depends on where lateral velocity changes occur. The main reason for the stacking velocity anomalous behaviour (for large deviations from average velocity) is non-linear lateral variations of the overburden interval velocities or the boundaries.





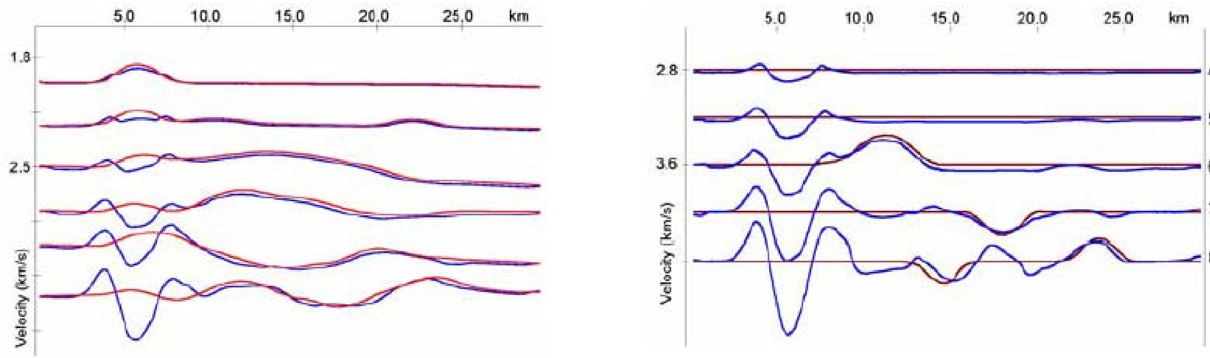


Figure 1. A) Depth velocity model. Boundaries; B) Interval velocities; C) RMS (blue) and stacking (red) velocities; D) Interval velocities (brown) and their Dix's estimations (blue).

The dipping boundaries and linear changes in interval velocities (boundary and velocity gradients) do not cause large changes in the stacking velocities. They do not prevent the use of the Dix formula to find interval velocities. To demonstrate this, let us consider a depth velocity model with significant deep structures and lateral changes in interval velocities.

Fig. 1a displays boundaries of the depth velocity model; interval velocities for this model are shown on fig. 1b. For this model, zero-offset times and NMO functions (travel times) have been calculated via ray tracing. These time arrivals have been approximated by hyperbolas using a spread length equal to 0.8 of the reflector depth. Fig. 1b shows zero-offset times for five deep boundaries. Stacking and RMS velocities are displayed on fig. 3c. We see that even though the model has significant deep structures (600 m depth difference for the 5km) and essential lateral variations in deep interval velocities, stacking velocities are close to RMS. It implies that Dix's formula should give a reasonable estimation of interval velocities.

Dix's formula has been applied to these stacking velocities and zero-offset times. The result for five deep layers is shown on fig. 3d. We see that even though the subsurface model contains curvilinear boundaries and interval velocities with lateral changes, the Dix's formula gives quite accurate results everywhere except in the interval 2 – 8 km. The large difference between stacking and RMS velocities is caused by the shallow velocity anomaly in the first layer (Blias, 2005a,b). It implies that for this model, stacking velocities are close to RMS velocities and we can use a locally 1-D velocity model when considering interval velocity determination. This modeling proves that lateral velocity changes do not have to cause anomalous stacking velocity behaviour.

From this model example and the results by Blias (1981, 1987, 2003, 2005) it follows that we should care about possible significant lateral velocity changes even in relatively simple geology if we did not remove effects of lateral shallow velocity changes. In case when first break assumptions do not work, we can use deep reflections to recover shallow velocity anomalies (Blias, 2005b,c). For this, we have to pick horizon-based stacking velocities with high density, preferably for each CDP point because we have to follow all high-amplitude lateral variations of stacking velocities, caused by shallow velocity anomalies. That is why high-density automatic velocity analysis is needed in many cases not only to speed up highly time-consuming velocity picking procedure, but also to determine more accurate time and depth velocity models, which are used for time and depth prestack migrations.

Automated Velocity Picking

We can ask ourselves several important questions. First, do we need automatic high-density velocity picker? We already know the answer to this question: we need it in a situation with essential lateral changes of stacking velocities. We need it for large 3-D data sets to save time in velocity picking. We also need it to improve velocity models for AVO, for better seismic imaging quality. The second question might be: can we trust the results of automatic velocity picking? This question has an easy answer: we have several QC controls, namely NMO gathers (flat reflections), better imaging quality, more reasonable depth velocity model, which is determined from NMO curves. We use coherence measure to estimate an NMO function. The main problems with this approach are:

(i) Non-uniqueness because of coherence semblances. Often there are more than one local maximum for the one zero-offset time value, mostly caused by multiples. To solve this problem, we use constraints, which allow us to separate primaries from multiples. To calculate area constraints, we create supergathers at several points of the area, usually from 10 to 100 reference points, depending on geology. At these points, we stack thousands of traces to create supergathers, which reflect velocity properties around a reference point. Usually the subarea covered by the supergather, is about 2 – 4 km^2. For each supergather, we pick stacking velocities and this manual or automatic picking is an easy one. Then the program analyzes these velocities and calculates constraints for the high-density automatic velocity analysis.

(ii) High-frequency velocity oscillations. To remove this kind of deviations, we use median smoothing.

(iii) Non-hyperblic NMO curves. To pick non-hyperbolic NMOs, we use additional parameters to describe the NMO curve τ(k):

$$\tau(k) = t(k) = \sqrt{t_0^2 + \frac{x_k^2}{V_{Stk}^2}} + \sum_{i=1}^{J} \alpha_j f_j(k)$$

where x_k is an offset for the k-th trace in the CDP gather, V_{Stk} is a stacking velocity, α_i are unknown parameters to be calculated, $f_j(k)$, j = 1, 2, …, J, J stands for the number of basis even functions f_j; usually, j = 1 or 2.

(iv) Class II AVO response. We can use a method, similar to the approach suggested by Sarkar et al. (2001). We can consider a generalization of the semlance method to include AVO effects. We use an objective function to find stacking velocity V_{stk} as:

$$E(A,B,v) = 1 - \frac{\sum_{t=t_0-\Delta}^{t=t_0+\Delta} \sum_{i=1}^{n} \left(A(t) + B(t)x_i^2 - U_i(t - \tau_i(V_{Stk}))\right)^2}{\sum_t \sum_i U_i^2(t)} \qquad (1)$$

where $U_i(t)$ is a seismic trace at the offset x_i, $\tau_I(v)$ is an NMO function, A(t) and B(t) are AVO parameters; t_0 is zero offset time for which we find stacking velocity $V_{Stk}(t_0)$. Parameters A and B can be found from the system of equations:

$$\frac{\partial E}{\partial A(t)} = \frac{\partial E}{\partial B(t)} = 0$$

This can be written as two linear equations with respect to A and B:

$$A(t)\sum_{i=1}^{n} 1 + B(t)\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} U_i(t - \tau_i(v))$$

$$A(t)\sum_{i=1}^{n} x_i^2 + B(t)\sum_{i=1}^{n} x_i^4 = \sum_{i=1}^{n} U_i(t - \tau_i(v)) * x_i^2$$

It can be shown analytically that if we consider B(t) = 0, then (1) is the same as the conventional coherence measure, introduced by Taner and Koehler (1969).

(v) Sparse geometry and fast lateral velocity changes. Caused by either shallow velocity anomalies or steep dipping boundaries. In this case, we can use another generalization of the coherence measure:

$$E(\vec{\alpha}) = \frac{\sum_{x}\sum_{t_0(x)-\Delta}^{t_0(x)+\Delta}\left[\sum_{i=1}^{N} U_i(t - \tau(l_i, \vec{\alpha}, x), x)\right]^2}{N\sum_{x}\sum_{t_0(x)-\Delta}^{t_0(x)+\Delta}\sum_{i=1}^{N} y_i^2(t - \tau(l_i, \vec{\alpha}, x), x)}$$

where NMO function $\tau(x)$ is written as:

$$\tau(l, \vec{\alpha}, x) = \sqrt{[T_0(x_0) + d(x - x_0)]^2 + l^2[a + b(x - x_0) + c(x - x_0)^2]}$$

and α is a vector with coordinates (a,b,c,d).

Interval Velocity Analysis

Conventional velocity analysis works in two steps:

(i) We scan CDP gathers with a coherence measure (velocity spectrum or semblance) using hyperbolas. These hyperbolas are parameterized with two parameters: zero-offset time T_0 and a stacking velocity V_S. We measure semblance for a set of hyperbolas and transform the CDP gather traces from the offset and time coordinates into coordinates of time and stacking velocities for the coherence semblances.

(ii) Then we pick local maximums of these coherence semblances and assign zero-offset time and corresponding stacking velocities. The method, presented by Toldi (1989), assumes that we can use RMS velocity as a reasonable estimation of stacking velocity. Then we can scan CDP gather not for stacking but for interval velocity and calculating RMS velocity for each value of the interval velocity. As was shown by Blias (1981, 2005a, 2005b) in the subsurface with modest dipping boundaries and moderate deep interval velocity changes, we can consider the RMS velocity as close to stacking velocities and use this approach. In the presence of not properly accounted shallow or overburden velocity anomalies, the difference between stacking and interval velocities can bee large (up to 30% and more) so before using this approach we have to remove the effects of the lateral changes in overburden.

Automated Velocity Analysis in the Presence of Shallow Velocity Anomalies

Shallow velocity anomalies cause fast lateral variations in stacking velocity, increasing with depth. As was shown by Blias (1988, 2003, 2005a) and on the model example (Fig. 1d), application of Dix's formula to laterally inhomogeneous layer gives reasonable interval velocity estimation. Then we can include analytical traveltime inversion into automated velocity analysis. For this, the program automatically picks a velocity for the shallowest horizon, determines interval velocity in the first layer and then predicts stacking velocities, using formulas developed by Blias (1981, 1988, 2003, 2005). Then the automated velocity picker determines stacking velocities in a layer stripping manner around predicted values.

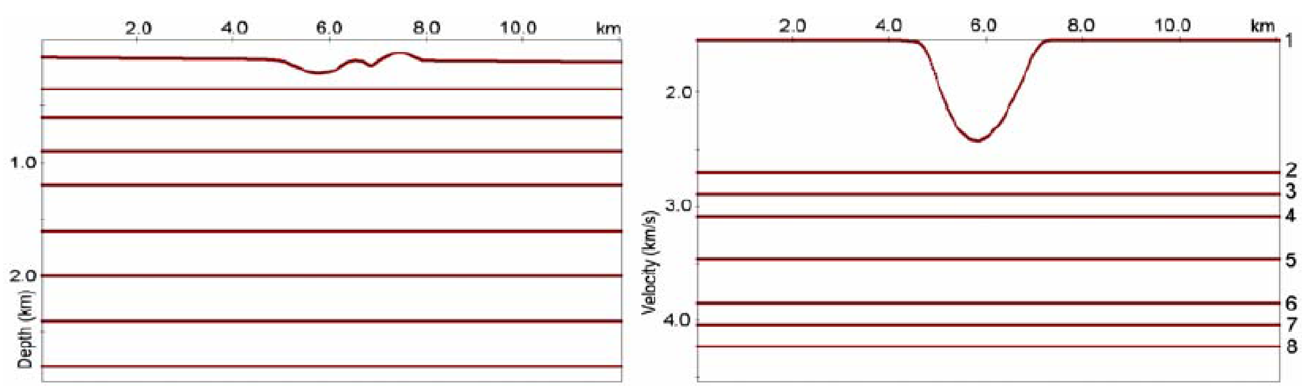


Figure 2. Depth velocity model. A – boundaries, B – interval velocities.

Model Data Example

To test automated high-density velocity analysis for data with fast lateral changes of stacking velocities and non-hyperbolic NMO curves, we created a depth velocity model. Fig. 2a shows this model. All boundaries except the bottom of the first layer and all interval velocities except the first one are constant. A shallow velocity anomaly is created by a curvilinear boundary and first interval velocity that increases from 1.6 km/s to 2.5 km/s. For this model synthetic CDP gathers have been calculated with maximum offset/ reflector depth = 1.25. Shot interval = receiver interval = 20 m. Random noise has been added to the gathers. All 5 steps have been run on this synthetic data. Fig. 3 shows the velocity field after automatic continuous velocity analysis. We see large lateral stacking velocity oscillations increasing with depth.

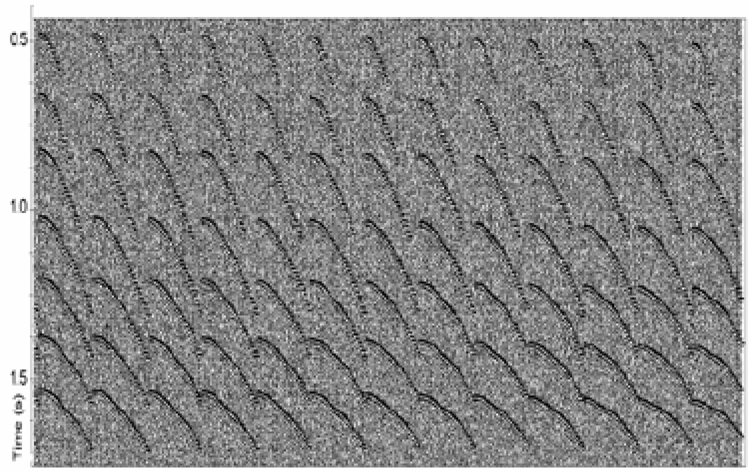


Figure 3. Synthetic CDP gathers.

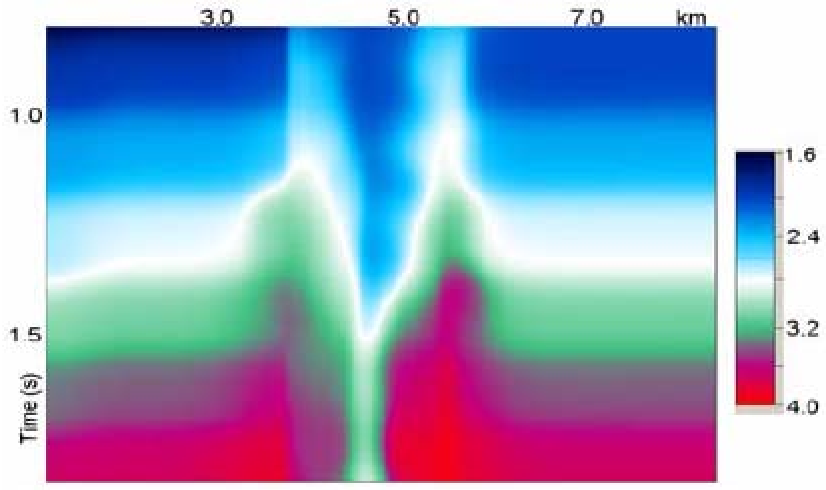


Figure 4. Stacking velocities.

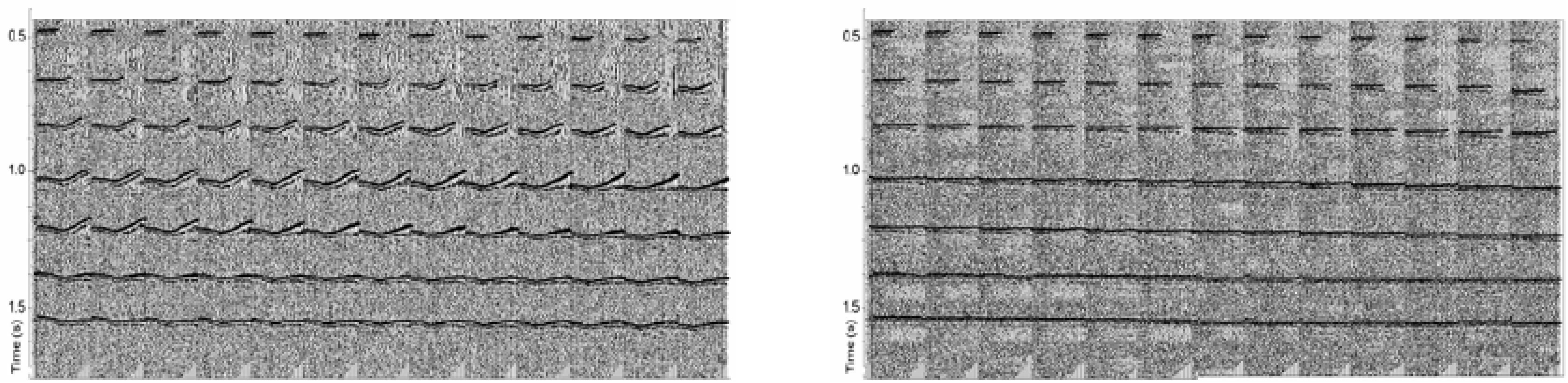


Figure 5. A) Hyperbolic NMO gathers; B) Non-hyperbolic NMO gathers.

Fig. 5 shows CDP gathers after hyperbolic automated high-density velocity analysis (a) and nonhyperbolic (b) close to the center of the velocity anomaly. We see that for this model NMO curves differ significantly from hyperbolas.

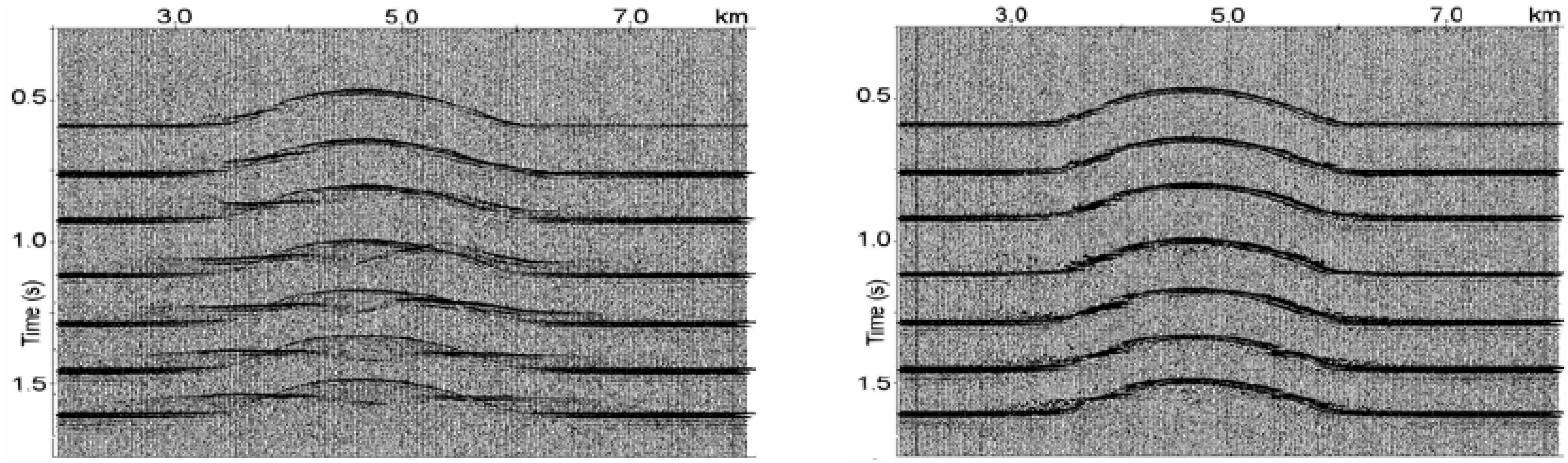


Figure 6. A) Post-stack data from hyperbolic NMO gathers; B) Post-stack data from non-hyperbolic NMO gathers.

Fig. 6 shows post-stack data obtained from hyperbolic NMO gathers (a) and non- hyperbolic (b). We see that non-hyperbolic NMO significantly improves post-stack image within the intervals around the shallow velocity anomaly. Here we should mention that the shallow velocity anomalies may not cause non-hyperbolic NMO but they always cause significant lateral variations of stacking velocities from deep reflectors (Blias, 2005a, 2005b).

Real Data Examples

Let's first consider a seismic line with shallow velocity anomalies. Non-first-break approach of determination and removal effects of these anomalies (Blias, 2005) needs horizon-based stacking velocity information. Fig. 7 shows a CDP gather after automated high-density velocity analysis: a – hyperbolic NMO and b – non-hyperbolic NMO.

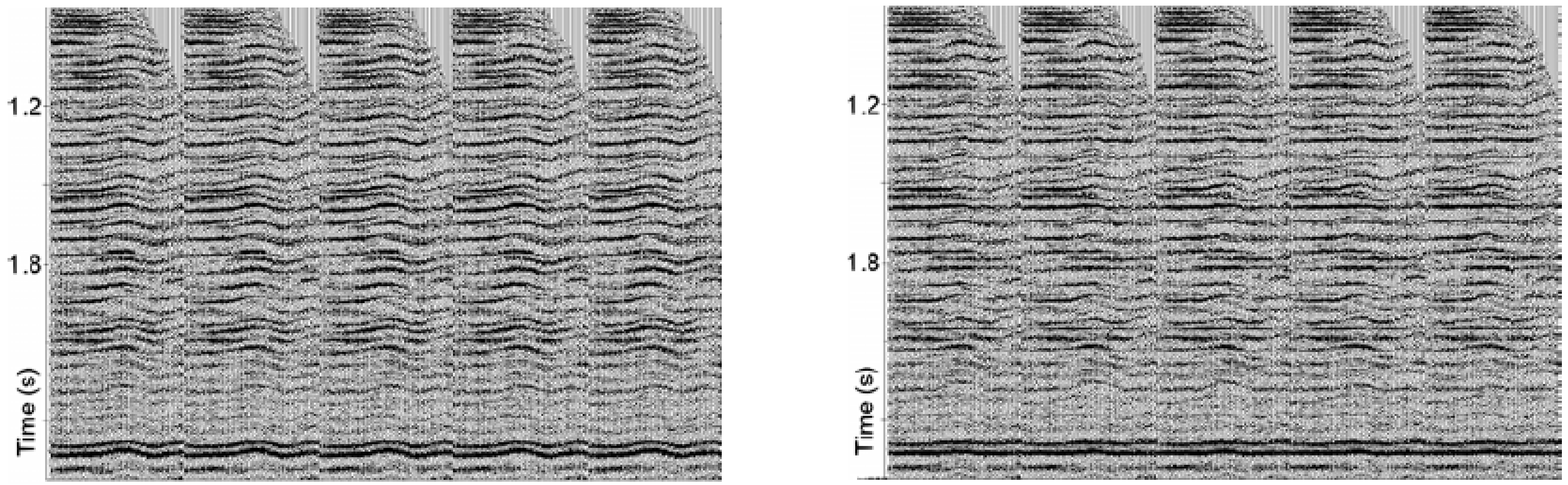


Figure 7. A) CDP gathers after hyperbolic NMO; B) CDP gathers after nonhyperbolic NMO.

Shallow velocity anomalies are the origin of non-hyperbolic NMO curves as well as of lateral variations of stacking velocities, increasing with depth, and poor imaging quality. To determine and remove effects of shallow velocity anomalies, we applied a non-first-break approach (Blias, 2005). In this method, we use the results of horizon-based high-density automated velocity analysis to build a depth velocity model. We use this depth velocity model to remove the influence of the shallow velocity anomalies. For this we run raytracing for the obtained depth velocity model and calculate prestack reflection time arrivals for all boundaries.

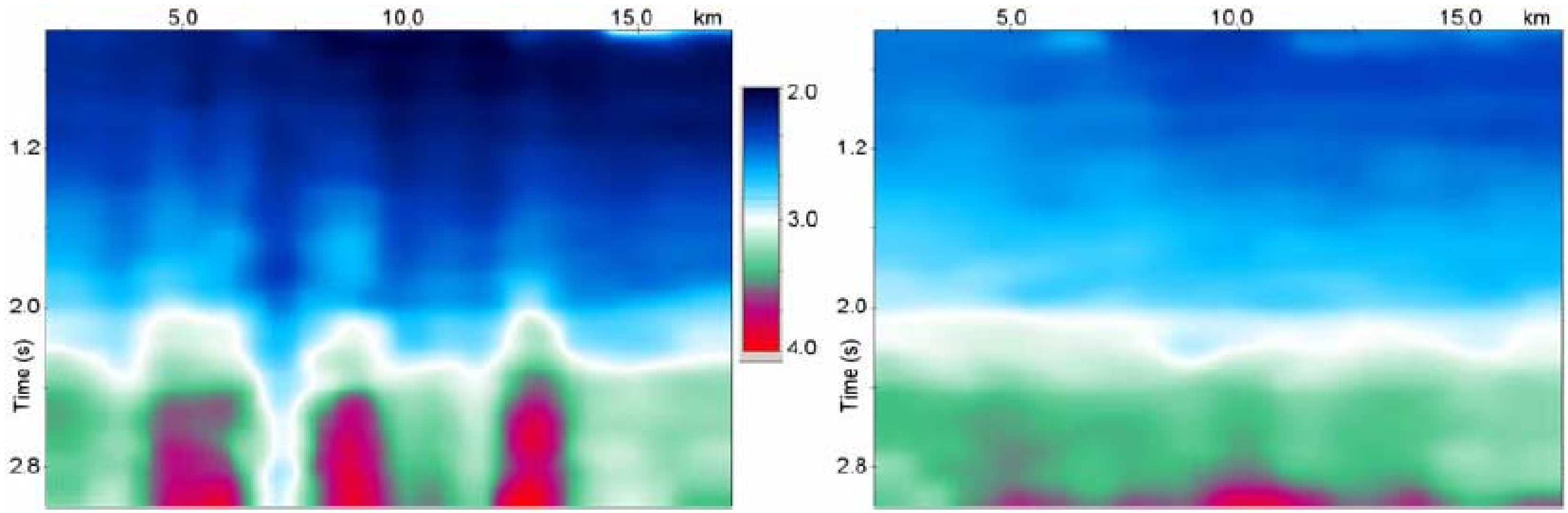


Figure 8. A) Stacking velocities before VR; B) Stacking velocities after VR.

Then we replace the shallow inhomogeneous layer with a homogeneous one and calculate time arrivals for this model. The difference between the first and the second set of times is applied to CDP gathers. This procedure moves events on prestack data to the position where they would be if the shallow layer were homogeneous. Fig. 9 shows post-stack data before (a) and after (b) shallow velocity replacement. We can see that VR significantly improved post-stack quality as well as the velocity field.

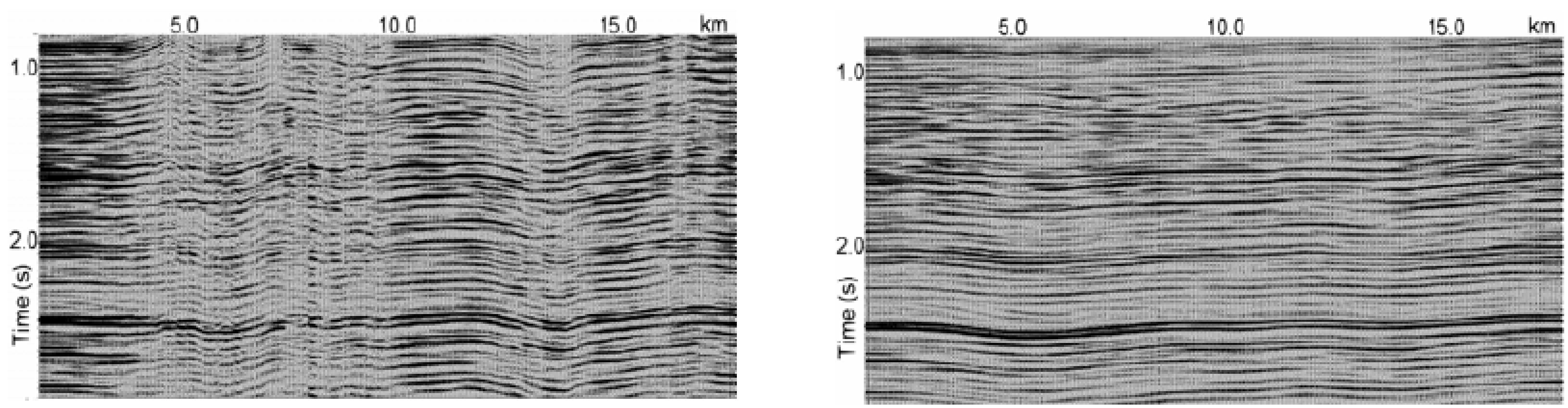


Figure 9. A) Post-stack data before VR; B) Post-stack data after VR.

Marine Data

Let us consider a marine data example with high noise level. Fig 10 shows initial CDP gathers (a), the same gathers after hyperbolic NMO (b) and non-hyperbolic NMO (c). Fig. 11 displays a supergather, calculated from 16,000 traces to pick velocities and create constraints for automated high-density velocity analysis.

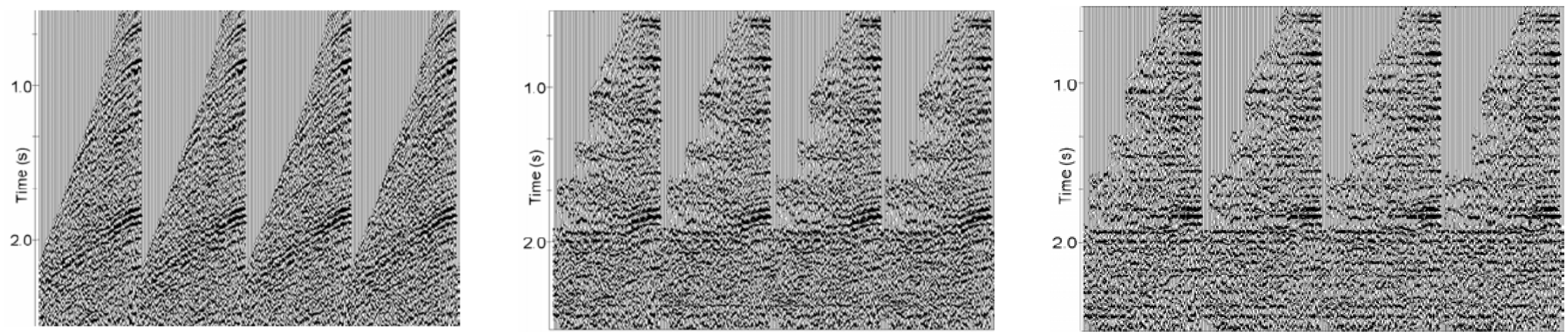


Figure 10. A) Initial CDP gathers, B) Gathers after hyperbolic NMO, C) Gathers after non-hyperbolic NMO.

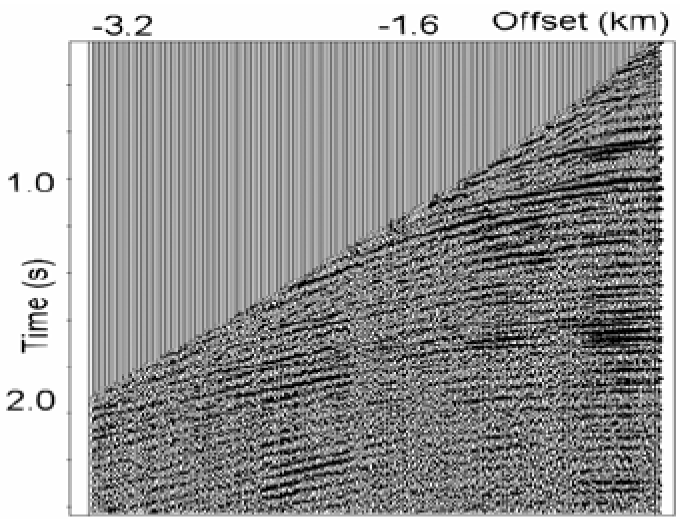


Figure 11. Supergather.

Conclusions

For some problems (time migration, depth velocity model building, AVO, pore pressure prediction) we need high-density reliable stacking velocities in each CDP gather. To utilize the advantage of high-density automatic velocity analysis, we have to determine and use geologically consistent constraints. Several generalizations for automatic velocity analysis have been developed for different cases. They take into account fast lateral velocity changes and AVO effects. The automatic high-density velocity picker can be applied to prestack data with different quality. It allows us to obtain reliable stacking velocities and non-hyperbolic NMO curves. NMO functions can be used to build a depth velocity model for pre-stack and post-stack depth migration.

Acknowledgements

I would like to thank Valentina Khatchatrian who developed most of the software, Ronald Hinds (Talisman) for helping me with this paper and Samvel Khatchatrian for useful discussion.

References Cited

Blias, E.A, 1981, Approximation of CDP traveltime for a layered medium with curved interfaces and variable layer velocities: Soviet Geology and Geophysics, N 11, p. 79-86.

Blias, E.A., A.N. Levit, and V.N. Ferentsi, 1985, Method of taking into account shallow anomalies while processing CDP data: Directions and methodology in Oil and Gas Exploration: Nauka, (in Russian), p. 71-74.

Blias E., 1988, Time fields in 3D medium with curvilinear inhomogeneous layers: Mathematic problems in seismic: Novosibirsk, p. 98-127 (in Russian)

Blias, E., 2003, Dix's type formulae for a medium with laterally changing velocity: 73rd Intern., SEG Annual Meeting, Expanded Abstracts, p. 706-709.

Blias, E., 2005a, Stacking and Interval Velocities in the presence of Overburden Velocity Anomalies: 67th EAGE Conference, Expanded abstracts, p. 175.

Blias, E., 2005b, Stacking velocities in the presence of shallow velocity anomalies: 75th Intern., SEG Meeting, Meeting, Expanded Abstracts, p. 2193-2196.

Blias, E., 2005c, Determination of shallow velocity anomalies using deep reflections: 75th Intern., SEG Meeting, Expanded Abstracts, p. 2585-2588.

Sarkar, D., J.P. Castagna, and W.J. Lamb, 2001, AVO and velocity analysis: Geophysics, v. 66/4, p. 1284-1293.

Taner, M.T., and F. Koehler, 1969, Velocity spectra—Digital computer derivation and applications of velocity functions: Geophysics, v. 34, p. 859-881.

Toldi, J.L., 1989, Velocity analysis without picking: Geophysics, v. 54, p. 191-199.