Implementation of the DIPSCAN method to estimate boundary dips in complicated structures by VSP data

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ABSTRACT

The knowledge of velocity model not even along well but at offset is key for building of VSP-CDP image and tie of VSP and surface seismic data. And the task is more difficult in situations of lateral variations of the media properties, that very typical for highlands. The quality of obtained image is in a straight dependence on quality of reference model. And it is the main reason to obtain adequate reference model for offset-VSP processing.

The common drawback of existent methods is in a necessity of ray propagation through the unknown media. The main idea of method suggested in this report is in reverse extrapolation of time-field of primary downing wave in the media based on first break hodograph and velocity model defined along the well with the specific dip for all layers of the model. Then back propagation seismic problem is solved based on extrapolated time-field and resulting wave field is stacked to primary reflectivity trace. In these calculations dip of layers is variable. Then one must make interpretation of obtained scope of reflectivity traces, using the following rule: largest amplitude in trace corresponds to the true layer dip at a given depth. After that discovered values can be stacked in one trace which is to correspond to the multi-dipped layer model.

In report examples of this technology working will be shown on modeled and real field data from various districts.

INTRODUCTION

One of the basic questions at construction of the near borehole space image by offset VSP data is selection of a priori model. The subsurface image reflects the real medium more reliably when a priori model is more accurately given. One of the basic results of zero-offset VSP data processing is evaluation of primary reflected waves trace. To correct calculate this trace it is necessary to take into account besides velocity model also well intersection angles of subsurface model interfaces.

Layer velocity model along well trajectory may be obtained as result VSP data processing. VSP also allows determine parameters of subsurface model in a vicinity of well for multi-dipped layered media: it is a set of velocities and dip angles of layers. So, for example, in case of known velocity model on a well and necessity of determination only angles of layer dips the problem was solved in work Lines, Bourgeois and Covey (1984). Authors used a technique of the least squares for minimization of discrepancy between observed and theoretical wave travel time from shot point to receiver point (method of optimization) to determine the dip angle of reflecting layer.

Essential disadvantage of similar techniques is necessity of manual seismic event picking to determine arrival times of reflected wave that in practice is hard and not always exact problem. One more disadvantage is necessity of tracing of a ray from source point to receiver point through the unknown media on distance from a well. As result, the estimations of dip angles for real media are unstable and computing expenses are significant.

The problem of estimation of subsurface interfaces dip angles when velocities are known is solved also in DIPSCAN technique (Tabakov etc., 2004). Its principal difference is that in the given approach does not use ray tracing from source point to receiver point that allows avoid accumulation of the errors connected to uncertainty of subsurface model on significant distances from a well. DIPSCAN technique bases on direct wave time field extrapolation in the nearest vicinity of a well and does not require a preliminary seismic events picking for estimation of arrival times of reflected waves.

In this paper it is considered mathematical aspects of the solution of 2D problem of layer dip angles determination for the reflected P-waves and converted incident and reflected PS-waves. Development of technique on a case of 3D model with plane borders is considered also.

MATHEMATICAL ASPECTS OF 2D PROBLEM

Let's consider a problem of estimation of dips of plane interfaces for 2D elastic layer-homogeneous transversely isotropic media by vector 3C field of upgoing reflected P-waves of offset VSP $\mathbf{u}(h,t)$. It is generally supposed, that well trajectory is deviated $w(z) = x(z), z \in [0, \overline{H}]$, where $\overline{H}$ - well bottom depth, the source $S(x_0, z_0)$ is in one plane with a well trajectory. Suppose also that the velocity model of medium in the vicinity of well, i.e. layer velocities and interface depths in the points of well trajectory intersection, and first arrival traveltimes of direct incident wave are known.

For an estimation of subsurface interface dips varied with depth $\varphi(h)$ by a real wave field of the reflected P-waves $\mathbf{u}(\xi,t)$ we use functional

$$J(h,\varphi)=\int_{t_-}^{t_+}\int_{h_-}^{h}\left\|\mathbf{u}(\xi,t)-\mathbf{u}_\varphi(\xi,t)\right\|_{\mathbf{R}^3}^2 d\xi\, dt \qquad (1)$$

where $\mathbf{u}_\varphi$ – the evaluated field of the reflected waves for model with interfaces dip φ, $t_-=t(h)-\Delta t$, $t_+=t(h)+\Delta t$, $t(h)$ – reflected wave arrival time for depth h, Δt - dip estimation time range, $h_-=h-\Delta$, h = h(z) – cable depth, depth along well trajectory, Δ - dip estimation depth aperture.

Functional $J(h,\varphi)$ is a measure of closeness of observed and calculated fields on depth h at the given model interfaces dip φ. For finding of dip $\varphi(h)$ we shall minimize functional (1) by φ.

Opening subintegral expression in (1), we derive

$$J(h,\varphi)=\int_{t_-}^{t_+}\int_{h_-}^{h}\left\|\mathbf{u}\right\|_{\mathbf{R}^3}^2 d\xi\, dt+\int_{t_-}^{t_+}\int_{h_-}^{h}\left\|\mathbf{u}_\varphi\right\|_{\mathbf{R}^3}^2 d\xi\, dt-$$

$$2\int_{t_-}^{t_+}\int_{h_-}^{h}\langle\mathbf{u},\mathbf{u}_\varphi\rangle_{\mathbf{R}^3} d\xi\, dt = I(h)- \qquad (2)$$

$$2\int_{t_-}^{t_+}\int_{h_-}^{h}\langle\mathbf{u},\mathbf{u}_\varphi\rangle_{\mathbf{R}^3} d\xi\, dt = I(h)-2K(h,\varphi).$$

Item $I(h)$ weakly depends from φ. It is easy to see that dependence from φ function $K(h,\varphi)$ which is not that other as correlation coefficient of observed and evaluated fields much more strongly. It is obvious that $K(h,\varphi)$ achieves $\max_\varphi$, and $J(h,\varphi)$ - $\min_\varphi$ (at fixed h) when times of the first arrivals of waves $\mathbf{u}$ and $\mathbf{u}_\varphi$ coincide. At the same time the value $\mu(h)=\max_\varphi K(h,\varphi)$ is more than closer polarizations of these waves, i.e. than closer a dip φ to a true value. Thus, dip angle $\varphi(h)$ delivering maximum of $K(h,\varphi)$ is solution of formulated problem.

Let's consider

$$K(h,\varphi)=\int_{t_-}^{t_+}\int_{h-\Delta}^{h}(\mathbf{u}_{\varphi(h)}(z,t),\mathbf{u}(z,t))_{R^3}\,dz\,dt\,.$$

Scalar product means

$$(\mathbf{u}_{\varphi(h)}(z,t),\mathbf{u}(z,t))=$$

$$\|\mathbf{u}_{\varphi(h)}(z,t)\|\cdot\|\mathbf{u}(z,t)\|\cdot\cos\theta(z,t)\,,$$

where $\theta(z,t)$ - angle between vectors $\mathbf{u}_{\varphi(h)}(z,t)$ and $\mathbf{u}(z,t)$. Let's accept a signal of a modeled field $\mathbf{u}_{\varphi(h)}(z,t)$ as δ-function, so that $\|\mathbf{u}_{\varphi(h)}(z,t)\|=1$. Then scalar product of the registered vector of displacement $\mathbf{u}(z,t)$ and modeled one $\mathbf{u}_{\varphi(h)}(z,t)$ will mean a projection of vector $\mathbf{u}(z,t)$ on arrival direction of vector $\mathbf{u}_{\varphi(h)}(z,t)$ and expression for $K(h,\varphi)$ will look as

$$K(h,\varphi)=\int_{t_-}^{t_+}\int_{h-\Delta}^{h}\|\mathbf{u}(z,t)\|\cdot\cos\theta(z,t)\,dz\,dt\,. \qquad (3)$$

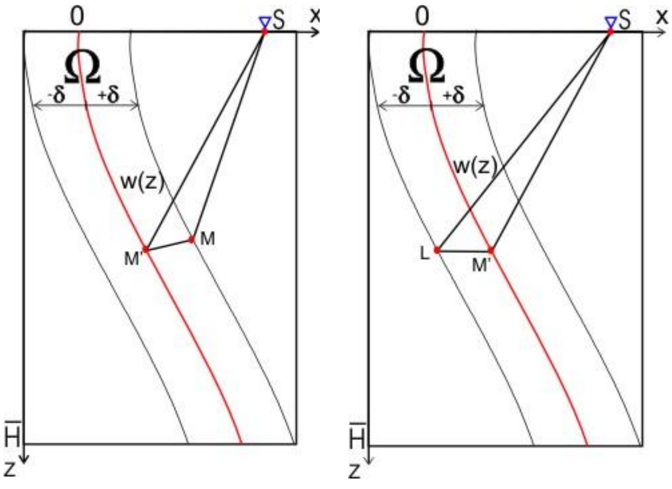
Hence, calculation of integral is reduced to stacking of amplitudes of observed field along model time-depth curves of reflected waves with taking in account of polarization of field $\mathbf{u}_{\varphi(h)}(z,t)$. In practice the account of polarization of model field $\mathbf{u}_{\varphi(h)}(z,t)$ means a turn of the registered vector field $\mathbf{u}(z,t)$ to a tracking component, which is understood as a projection of full vector of oscillations $\mathbf{u}(z,t)$ on the evaluated vector $\mathbf{u}_{\varphi(h)}(z,t)$ with known polarization (Bykov, 1984).

Thus, for calculation of function $K(h,\varphi)$ it is necessary to determine polarization angles and arrival times of reflected P-waves of field $\mathbf{u}_{\varphi(h)}(z,t)$ along which stacking of amplitudes of reflected wavefield $\mathbf{u}(z,t)$ will be made.

Let's show, that required characteristics of the reflected waves are easy for defining for known model by computed direct wave times field in a vicinity of a well.

First of all we should calculate direct wave time field in a vicinity of a well. To not trace rays through unknown media from a source to receivers we apply procedure of extrapolation of this time field.

Assuming that the field of times of a direct wave in points of well is known to us from first arrival times, we make extrapolation of this field in some vicinity of well Ω, where $\Omega=[w(z)-\delta,\ w(z)+\delta],\quad z\in\overline{[0,H]}$ (figure 1), and $0<\delta\le x_0$, where x_0 - source coordinate. The medium in the extrapolation area of time field is supposed parallel - layered with dip φ.



(a) (b)

Figure 1. Direct wave times field extrapolation where (a) considered point M is before well, (b) considered point L is behind well

Let's define arrival time of direct wave front in some point M belonging to area $\Omega^{+} = [w(z), w(z)+\delta], \quad z \in [0, \bar{H}]$ (figure 1b), assuming, that times of the first arrivals $t(S, M'(h))$ of a direct wave on a well (i.e. in points $M'(h)$, where *h* - depth along a well) and velocity model of media in a vicinity Ω are known.

From Fermat's principle follows, that the ray is propagated from source point *S* to receiver point $M'(h)$ over minimal time, i.e. the inequation $t(S, M) + t(M, M'(h)) \geq t(S, M'(h))$, in which $t(S, M)$ - ray travel time from point S to point M, $t(M, M'(h))$ - a transit time from point M to point $M'(h)$, is right.

It follows that $t(S, M) \geq t(S, M'(h)) - t(M, M'(h))$ and $t(S, M)$ can be determined from the optimization problem solution

$$t(S, M) = \max_{h} \{ t(S, M'(h)) - t(M, M'(h)) \}. \quad (4)$$

From problem definition, it is obvious, that ray tracing is applied only in the nearest vicinity of a well for calculation of $t(M, M'(h))$ time.

Similarly, for point L (figure 1b) belonging area $\Omega^{-} = [w(z), w(z)-\delta], \quad z \in [0, \bar{H}]$ we obtain: $t(S, L) \leq t(S, M'(h)) + t(L, M'(h))$ from which it follows that

$$t(S, L) = \min_{h} \{ t(S, M'(h)) + t(L, M'(h)) \}. \quad (5)$$

The computed field of times, in practice, is smoothed to weaken errors of the extrapolation connected to receiving sampling along a well and approximation of the real medium by a discrete grid of parameters also.

The scalar field of direct wave times can be characterized family of lines orthogonal to fronts of wave which are rays following in direction of time field gradient.

Thus, in area Ω it is possible to calculate a vector of direct wave polarization as gradient of this wave front scalar field:

$$\mathbf{p}_{dp}(x,z) \equiv \{\sin\theta_{dp}(x,z), \cos\theta_{dp}(x,z)\} = \nabla t(x,z), \quad (6)$$

where θ_{dp} - polarization parameter specifying angle between vector $\mathbf{p}_{dp}$ and normal to interface.

Knowing polarization parameter of incident wave $\theta_{dp}(x,z)$ and dip φ of reflecting boundary according to the law of reflection we can determine polarization parameter of the reflected wave by formula:

$$\theta_{up}(x,z) = \theta_{dp}(x,z) - 2\varphi - \pi.$$

The vector of the reflected wave polarization will look as:

$$\mathbf{p}_{up}(x,z) \equiv \{\sin\theta_{up}(x,z), \cos\theta_{up}(x,z)\}. \quad (7)$$

To estimate arrival times $t_{\varphi(h)}(h)$ and polarization angles $\theta_{\varphi(h)}(h,t)$ of model reflected wave field $\mathbf{u}_{\varphi(h)}(z,t)$ in (2) for the current depth *h* from each cell $(x,z) \in \Omega$ of the current fictitious boundary zc crossing a well at depth *h* the ray under angle $\theta_{up}(x,z)$ is shoot (figure 2). Arrival times $t_{\varphi(h)}(h)$ is sum of direct wave times in points (x, z) of boundary zc known as result of extrapolation of direct wave time field and the estimated transit time of the rays shoot from these points up to their crossing of well. Fictitious boundaries are located from the well top downward with step of a grid.

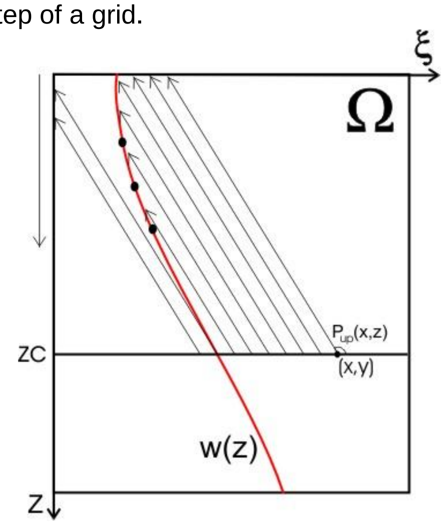


Figure 2. Calculation of reflected waves model field parameters

Now to calculate $K(h,\varphi(h))$ for the current depth h it is necessary to make stacking of amplitudes of observed vector field $\mathbf{u}(z,t)$, projected on direction of model field $\mathbf{u}_{\varphi(h)}(z,t)$ according to its polarization $\theta_{\varphi(h)}(h,t)$, along arrival times $t_{\varphi(h)}(h)$ in range of the given aperture Δ.

Finally it is necessary to calculate $\mu(h) = \max_{\varphi} K(h,\varphi)$ and, as result, to determine dips of model $\varphi(h)$. For this purpose, in practice, the approach at which is computed the set of traces $K(h,\varphi_i)$ (figure 6) for dips φ_i, $i=0,1,\ldots$ from the given range of its allowable values is optimum. Dips of model $\varphi(h)$ are determined as result of estimation $\max_{\varphi_i} K(h,\varphi_i)$ for each depth h (in practice, only for the depths appropriate to interfaces of layered model). Moreover, the trace of primary reflections $\mu(h) = \max_{\varphi_i} K(h,\varphi_i)$, corresponding to found multi-dip model is computed. And, if dips were determined for selective depths values in intervals between them are obtained as a result of interpolation

The problem concerned of estimation of dips of multi-dip 2D model of media with plane interfaces also can be solved using converted PS-waves.

The main feature in this case is other formulas for estimation of polarization parameters.

Polarization parameters of the reflected shear $\theta_{us}(x,z)$ and incident converted $\theta_{ds}(x,z)$ wave are expressed through polarization parameter of incident P-wave $\theta_{dp}(x,z)$ and subsurface interface dip φ taking in account conversion law as follows:

$$\theta_{us}(x,z) = \varphi - \pi - \arcsin((V_s/V_p)\sin(\theta_{dp}(x,z) - \varphi)),$$
$$\theta_{ds}(x,z) = \varphi + \arcsin((V_s/V_p)\sin(\theta_{dp}(x,z) - \varphi)), \quad (8)$$

where V_p - velocity of P-wave propagation, V_s - velocity of S-wave propagation.

In the rest, the algorithm, basically, is similar to the considered algorithm of the solution of problem for the reflected P-waves.

DEVELOPMENT OF METHOD FOR 3D MEDIA

Let's consider the solution of problem of estimation of dips and azimuths of plane interfaces of elastic homogeneous transversal-isotropic 3D model of medium. Similarly to 2D case, this problem can be solved by minimization of functional of root-mean-square discrepancy between observed $\mathbf{u}$ (z, t) and model $\mathbf{u}_{\varphi,\theta}(z,t)$ wavefields by two parameters dip φ and azimuth θ:

$$J(\varphi,\theta,h) = \int_{t(h)-\delta}^{t(h)+\delta}\int_{h-\Delta}^{h+\Delta} \|\mathbf{u}_{\varphi,\theta}(z,t) - \mathbf{u}(z,t)\|^2_{\mathbf{R}^3}\, dz\, dt =$$
$$\int_{t^-}^{t^+}\int_{h^-}^{h} \|\mathbf{u}\|^2_{\mathbf{R}^3}\, d\xi\, dt + \int_{t^-}^{t^+}\int_{h^-}^{h} \|\mathbf{u}_{\varphi\theta}\|^2_{\mathbf{R}^3}\, d\xi\, dt -$$
$$2\int_{t^-}^{t^+}\int_{h^-}^{h} \langle \mathbf{u}, \mathbf{u}_{\varphi\theta}\rangle_{\mathbf{R}^3}\, d\xi\, dt =$$
$$I(h) - 2\int_{t^-}^{t^+}\int_{h^-}^{h} \langle \mathbf{u}, \mathbf{u}_{\varphi\theta}\rangle_{\mathbf{R}^3}\, d\xi\, dt = I(h) - 2K(h,\varphi,\theta), \quad (9)$$

where parameters δ and Δ determine range of wavefield stacking .

The problem, as well as in 2D case, is reduced to determination $\max_{\varphi,\theta} K(h,\varphi(h),\theta(h))z$ for all observation depths h.

Problem of time-field extrapolation in 3D domain using only one survey line is very hard and not correct. Thus it is expedient to simplify this problem to 2D case. To do this let us realize the following coordinate transformation.

Let's set some absolute system of coordinates (for example, geographical) X, Y, Z which origin is in a point O - well mouth (figure 3). The equation of well, generally speaking, curvilinear, we shall write down as $X(Z), Y(Z), Z \in [0,\overline{H}]$, where $\overline{H}$ - well bottom depth. The source is located in point $S(X_0, Y_0, Z_0)$. We shall consider a plane π (interface of layer) with dip φ, azimuth θ and intersecting well on depth $h4$ (figure 3).

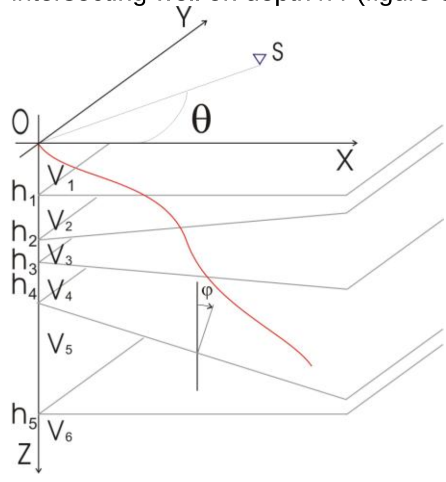


Figure 3. 3D model of medium with different layers dips

Turn of initial system of coordinates around of point O so that the plane XOY became parallel to a plane π, and the axis OY has remained in a plane $Z=0$.

The tie of new coordinate system with old one will look as:

$$(x,y,z)^T = \mathbf{A}(\varphi,\theta)(X,Y,Z)^T, \quad (10)$$

where coordinate transformation matrix is

$$\mathbf{A}(\varphi,\theta)=\begin{pmatrix} \cos\varphi\cos\theta & -\cos\varphi\sin\theta & \sin\varphi \\ \sin\theta & \cos\theta & 0 \\ -\sin\varphi\cos\theta & \sin\varphi\sin\theta & \cos\varphi \end{pmatrix},$$

$(.)^T$ - vector-column of the appropriate coordinates in 3D space. The equation of well trajectory in the new coordinate system becomes $\{x(z), y(z), z \in [0,\overline{h}]\}$ and source coordinates are $\{x_0, y_0, z_0\}$. Notice that both the equation of well and source coordinates thus become dependent from angles φ, θ, and to real depth H corresponds $h = h(\varphi,\theta)$.

If now we shall consider set of layers with the interfaces parallel to plane π the matrix of turn $\mathbf{A}(\varphi,\theta)$ for them will be same. Now, for reduction our problem to 2D case, we only need to turn a vertical plane so that it passed through a source and axis Oz.

The final reduction of initial problem to 2D case is implemented with the help of construction of well image in the plane ξOz, containing point S and axis Oz. Projections of rays and well trajectory on plane xOy are shown on figure 4a.

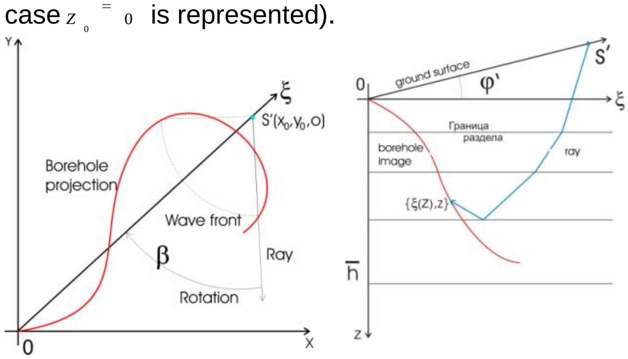
Condition of construction of well image is preservation of distances from well trajectory points up to a source. The deviated well image in the plane ξOz is the curve:

$$\{\xi(z), z \in [0,\overline{h}]\},$$

where

$$\xi(z) = \sqrt{x_0^2 + y_0^2} - \sqrt{(x(z)-x_0)^2 + (y(z)-y_0)^2}. \quad (11)$$

The example of construction of well trajectory image is shown on figure 4b (for simplicity the case $z_0 = 0$ is represented).



(a) (b)

Figure 4. 3D well trajectory and rays projection on the plane where (a) projection of rays and well trajectory on the plane xOy, (b) well trajectory and rays construction in the plane ξOz

The assumption necessary for construction of incident wave front is that the vector of direct wave polarization weakly depends on orientation of boundaries of layers (in comparison with the reflected wave). It makes possible jump in a vicinity of well to a plane of the reflected wave propagation with the help of the described transformation of coordinates and construction in this plane of direct wave time field in the assumption of its symmetry to axis Oz.

After initial statement is reduced to case of 2D plane-parallel subsurface model, the solution of problem of estimation of dips and azimuths of interfaces exactly repeats the 2D problem solution.

Dependence $\mathbf{u}_{\varphi,\theta}$ on angles is caused by dependence of the equation of well and coordinates of point S on φ and θ. Thus, at scanning parameters φ and θ model will not change, and the relative position of well and shot point will vary only. As result of minimization of $J(\varphi,\theta,h)$ in (9) we find the functions $\varphi(h), \theta(h)$, determining required dips and azimuths, and correlation coefficient

$$K(\varphi,\theta,h) = \int_{t(h)-\delta}^{t(h)+\delta}\int_{h-\Delta}^{h} (\mathbf{u}_{\varphi(h),\theta(h)}(z,t), \mathbf{u}(z,t))_{R^3}\, dz\, dt$$

which is a measure of presence on the given depth of reflector with dip φ and azimuth θ. Estimation $K(h)$ is implemented by the same way, as well as in 2D case, only with that simplification, that as a result of coordinate transformation, the dip of medium interfaces in system ξOz becomes equal to zero. Notice that observed vector displacements field $\mathbf{u}$ also should be multiplied on matrix of turn $\mathbf{A}(\varphi,\theta)$. It is necessary for making to transform observed and model wavefields in one system of coordinates.

It is necessary to take into account that for the found value $\varphi(h)$ we should to recount depth of layer h in real depth H. For this purpose it is necessary to transform coordinate system to initial one.

In result we obtain trace of primary reflections in initial system of coordinates (initial depths), describing layered 3D media with dips φ and azimuths θ of its interfaces.

APPLICATION EXAMPLES

Let's show results of application of method DIPSCAN for dip interfaces estimation in the limits of 2D models on the model and real data.

For the given layered model (figure 5) with 5 degrees dip of interface on depth of 1200 m and 10 degrees dip of interface on depth of 1800 m and shot point offset 150m we shall calculate a field of VSP P-waves and apply DIPSCAN for estimation of dips.

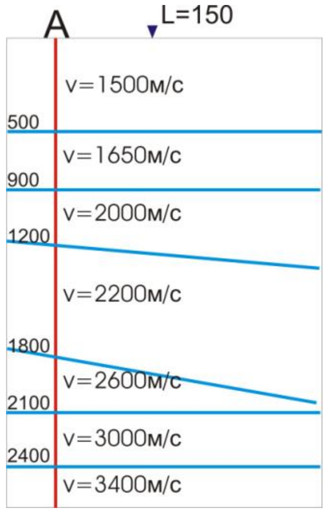


Figure 5. 2D model of medium with the given dips of interfaces

Figure 6 shows the set of traces of primary reflections evaluated for various model layers dips φ . In figure the maximal amplitudes for each interface are marked. Apparently, the outlined reflections correspond to the given model dips.

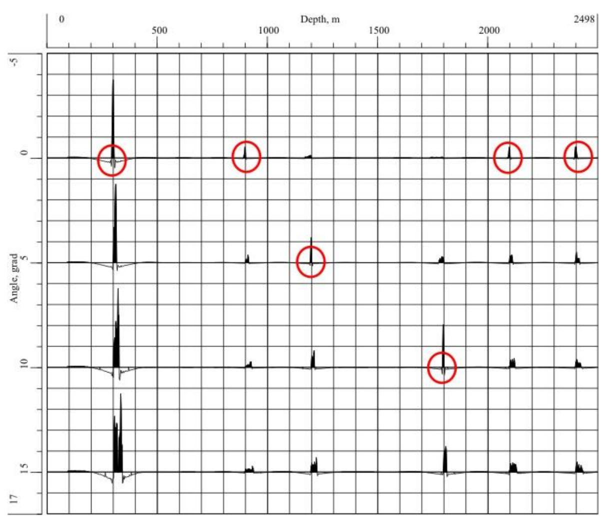


Figure 6. Set of traces of primary reflections for various medium dips of given model

Figure 7 shows traces of primary reflections obtained by model wavefield as result of corridor stacking and DIPSCAN technique application correspondingly.

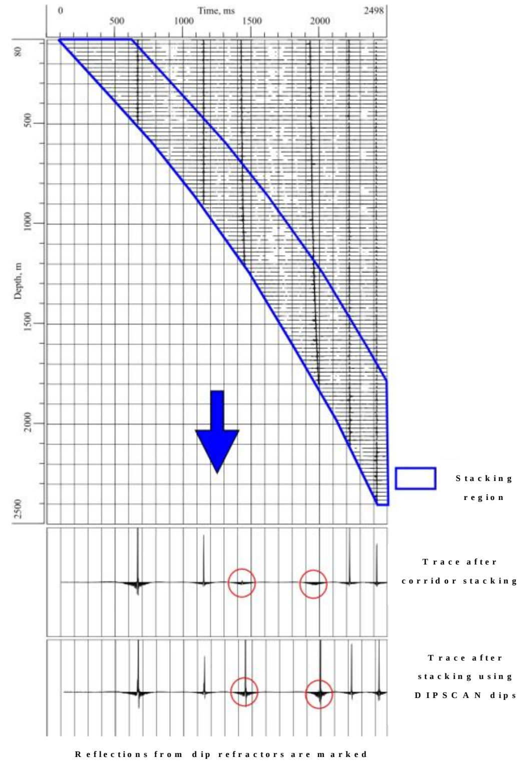


Figure 7. The result of corridor stacking in comparison with the result of DIPSCAN technique

It is obvious that for reflection events corresponding to dip interfaces (on depths 1200m and 1800m) corridor stacking was not in phase and result is not correct.

As the second example we use result of DIPSCAN technique application to the real data. Figure 8 shows the field of upgoing P-waves of offset VSP moved to a vertical to show better that there is dip interfaces in the model of medium corresponding to this wavefield.

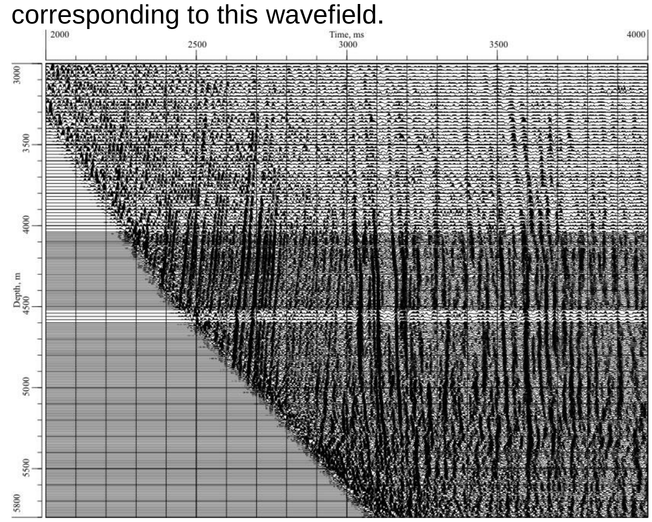


Figure 8. Wavefield of reflected P-waves of offset shot point after NMO corrections application

To estimate interfaces dip were calculated traces of primary reflections in range of dips from -50 up to 50 degrees with step of 5 degrees (figure 9) by DIPSCAN technique. Scanning has revealed presence of the dipped horizons described by dips up to 15 degrees.

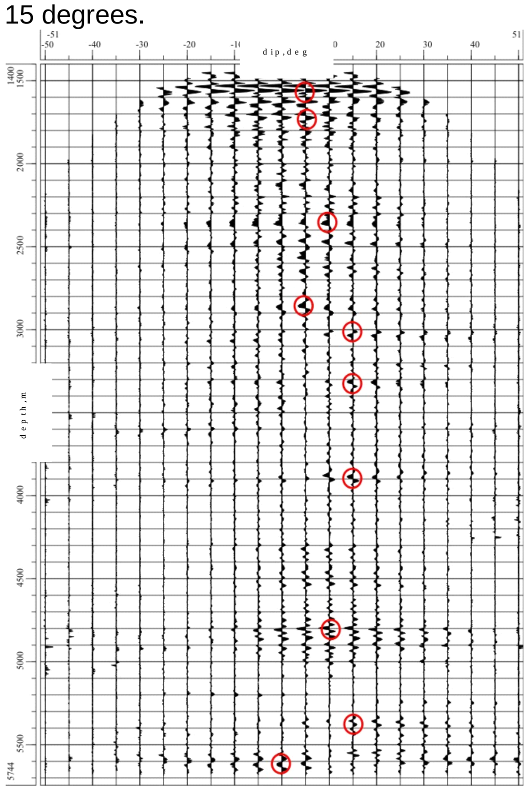


Figure 9. Set of primary reflections traces for various dips of media. Circles draw round the most outstanding reflections describing dips of layers

Results of the analysis of layers dips became a basis for building of multi-dipped model of media (figure 10) used for construction of near borehole space image.

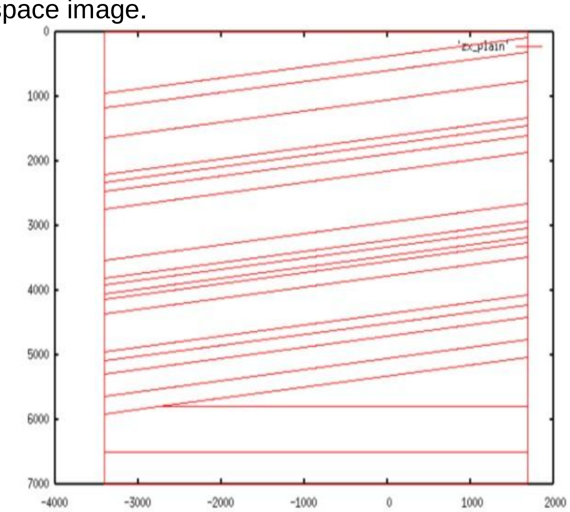


Figure 10. Multi-dipped model of medium constructed by DIPSCAN analysis results

Figure 11 shows the result of comparison of the image obtained by VSP data with a seismic section. It is necessary to note good coincidence for the main horizons of VSP migration result with using of subsurface model obtained by DIPSCAN technique with CDP data.

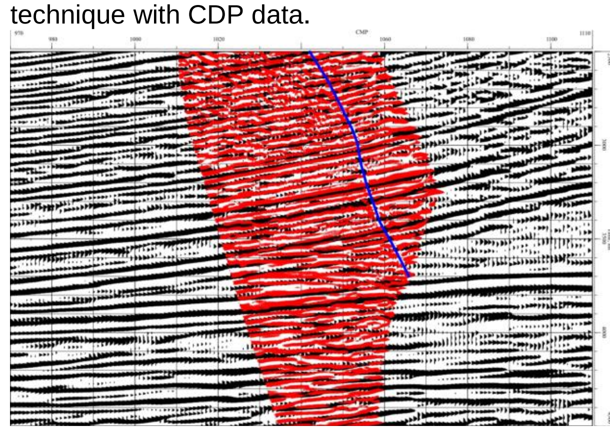


Figure 11. VSP image of near borehole space imposed on CDP section. The curve represents a well trajectory

CONCLUSIONS

1. The developed technique and program package of estimation of dips and azimuths of layers occurrence and the subsurface reflectivity raises quality and reliability of subsurface images obtained by VSP data due to determination of more exact model, and also allows to receive traces of primary reflections in that case when it is inapplicable corridor stacking.
2. Results of processing of real data in various geological areas indicate stability of estimations of parameters of multi-dipped subsurface model in a vicinity of a well at application of DIPSCAN method.
3. DIPSCAN method uses principles and opens prospects for development of such approach to construction of the image of media within the limits of which possibly is successful to work without attraction of the information about velocity model of media at a great distance from a well.

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