



## Seismic Imaging Technology Advance in BGP

Dai Nanxun\*, BGP, CNPC

### Summary

In the 1980's when post-stack migration was still the dominant seismic imaging tool, BGP developed the algorithm of finite-difference migration with higher order approximation, which led the industry in high end imaging processing at the time. In the 1990's first the prestack time migration and then the prestack depth migration became productionized. However, the development of prestack migration software in BGP fell behind afterward, partially to blame the delay in acquiring advanced computer hardware. Fortunately, in the last ten years the situation has improved. Kirchhoff 3D prestack time/depth migration have been implemented on Linux clusters, and applied in production processes for more than two years now. In this paper I will report new advances in the development of software for wave equation prestack depth migration, including those based on full wave equation and one-way wave equation. We will focus more on the reverse time migration method for tilted transversely isotropic (TTI) media since it covers VTI and isotropic media. We will also discuss the creative design in parallel computation strategies of this software and its advantages.

### Introduction

Seismic subsurface imaging as the primary tool in search for oil and natural gas has been evolving from horizontal stacking in the 1970's, post-stack migration in the 1980's, and 3D prestack time migration (PSTM) in the late 1990's, all the way to today's full scale routine production run of 3D prestack depth migration (PSDM). Large size 3D prestack depth migration application with Kirchhoff

method started in the last couple of years in the last century since Linux clusters were first used in seismic data processing. It was soon replaced, in most cases, by one-way wave equation PSDM at the beginning of this century. In the last few years RTM became widely used as the preferred solution for subsurface imaging in the presence of strong velocity variation and complex, steeply dipping reflectors such as those found in thrust areas.

Kirchhoff PSDM relies on ray tracing to estimate the travel time of seismic events. In the cases of complex geology it faces challenges in handling multiple arrivals of waves and in improving poorly estimated travel time in the so-called shadow zones. One way wave equation techniques, on the other hand, extrapolate the wave fields from surface to subsurface based on the assumption that both the source wave field and reflected wave field propagate in only one direction, downward or upward. In cases of strong velocity variation and steeply dipping interfaces this assumption no longer holds and one way wave equation PSDM fails to produce high quality images.

Reverse time PSDM (RTM) is the current state-of-the-art in seismic imaging techniques. Based on the full acoustic wave equation it fully respects the physics of wave phenomenon in acoustic media and honors not only the primary reflections but also turning waves, prism waves, seismic ghosts and some other multiples. Since RTM is implemented in the space-time domain it naturally simulates wave propagation in heterogeneous velocity models as well as anisotropic media such as VTI and TTI, thus enable it to image most complex subsurface structures. To deal with the topography common in western China, in our implementation the source and



## Seismic Imaging Technology Advance in BGP

receives are accurately placed at their positions of right elevation, making the applications suitable for land seismic data processing.

In the next sections we present the implementation of RTM for TTI media. When symmetry axis is set to be vertical the algorithm then reduces to RTM of VTI media. If all the anisotropic parameters are vanished one gets the RTM of isotropic media.

### TTI RTM

Zhou et al (2006) derived a coupled partial derivative equation system in the time–space domain for pseudo–acoustic wave propagation in TTI media based on Tsvankin's (2000) phase velocity relationship:

$$\frac{v^2(\beta)}{v_0^2} = \frac{1}{2} + \varepsilon \sin^2 \beta + \frac{1}{2} \sqrt{(1 + 2\varepsilon \sin^2 \beta)^2 - 8(\varepsilon - \delta) \sin^2 \beta \cos^2 \beta} \quad (1)$$

where  $v$  and  $v_0$  are the phase velocity and group velocity along the symmetry axis, respectively.  $\delta$  and  $\varepsilon$  are the dimensionless weak anisotropic parameters defined by Thomsen (1986).  $\beta$  is the phase angle with respect to the anisotropy axis. Equation (1) implicitly assumes that the shear wave velocity along the symmetry axis is zero while  $\varepsilon - \delta$  positive. It was shown by Grechka et al (2004) that this condition is necessary to avoid non–physical negative shear velocities in other directions. After some algebraic manipulations the system obtained by Zhou et al (2006) can be written as

$$\begin{cases} \frac{1}{v_0^2} \frac{\partial^2 u}{\partial t^2} = (1 + 2\varepsilon)H_2 u + H_1 w \\ \frac{1}{v_0^2} \frac{\partial^2 w}{\partial t^2} = (1 + 2\delta)H_2 u + H_1 w \end{cases} \quad (2)$$

where

$$\begin{aligned} H_1 &= \sin^2 \theta \cos^2 \phi \frac{\partial^2}{\partial x^2} + \sin^2 \theta \sin^2 \phi \frac{\partial^2}{\partial y^2} + \cos^2 \theta \frac{\partial^2}{\partial z^2} + \\ &\sin^2 \theta \sin 2\phi \frac{\partial^2}{\partial x \partial y} + \sin 2\theta \sin \phi \frac{\partial^2}{\partial y \partial z} + \sin 2\theta \cos \phi \frac{\partial^2}{\partial x \partial z} \\ H_2 &= \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} - H_1 \end{aligned} \quad (3)$$

Here  $\theta$  and  $\phi$  are the dip and azimuth angle of the tilted symmetry axis, respectively. This system gives accurate approximation for VTI media when the symmetry axis is fixed and vertical. In TTI media, however, it was shown to be unstable by numerical experiments, particularly, in the presence of rapid variation in orientation of the symmetry axis (Fletcher et al., 2009, Zhang et al, 2009). Fletcher et al (2009) pointed out that these instabilities appear to arise from the interaction of the SV–wave artifact with sharp contrasts in symmetry axis orientation models. Fletcher et al (2009) proposed to stabilize the simulation of wave propagation by adding finite  $v_{sz}$  velocity terms. Their system reads

$$\begin{cases} \frac{1}{v_0^2} \frac{\partial^2 u}{\partial t^2} = (1 + 2\varepsilon)H_2 u + H_1 w + \frac{\varepsilon - \delta}{\sigma} H_1 (u - w) \\ \frac{1}{v_0^2} \frac{\partial^2 w}{\partial t^2} = (1 + 2\delta)H_2 u + H_1 w - \frac{\varepsilon - \delta}{\sigma} H_2 (u - w) \end{cases} \quad (4)$$

where

$$\sigma = \frac{v_0^2}{v_{s0}^2} (\varepsilon - \delta) \quad (5)$$



## Seismic Imaging Technology Advance in BGP

largely demonstrates the kinematic signatures of SV-waves in TTI media (Tsvankin, 2001). To remove SV wavefront triplications and thus stabilize the wave propagation in media with rapid variation in dip field of tilt-axis, Fletcher et al (2009) recommended to choose  $\sigma$  smaller than 0.8.

Alternative systems were also proposed to mitigate the instability problem, such as the one by Zhang et al (2009). In our numerical experiments the system along with the described implementation avoids instability but unfortunately introduces additional unwanted coherent noises that propagate much faster than the qP waves. These noises also demand specially designed absorbing boundaries to prevent them from bouncing back and forth into the imaging space from the computation boundaries.

The color coded background in Figure 1 is the tilted symmetry axis dip  $\theta$  model of the 2D BP TTI model. As an example Figure 1 shows the source wave field, that is computed based on system (4) with  $\sigma = 0.75$ , propagating through the area where the high contrast exist in dip field. The wave propagation simulation is unstable in this area when system (2) is used.

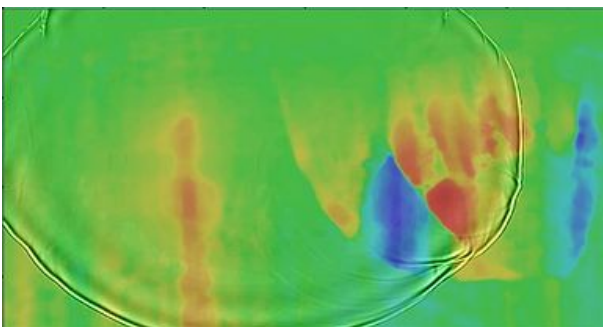


Figure 1. A snapshot of source wave field with the color coded  $\theta$  field of the 2D BP TTI model.

### Autonomous Parallel Model

RTM or other shot-profile migration is commonly implemented on a distributed memory/process parallel system using MPI (Message Passing Interface) or PVM (Parallel Virtual Machine). Typically a master/slaves model is employed. In such a model tasks (shots to be migrated) are pre-assigned by a master node to slave nodes. The master is slated to read input data and pass it to the slave nodes as well as to collect partial results from them.

We designed an autonomous parallel model for our shot-profile migration. In this model a master node's job is only to establish a micro database of task pool and to issue remote shell commands to activate compute nodes. Each compute node then works independently to fetch a task from the task pool, load input, compute migration and then store output locally. Once a node is activated there is no more direct inter-node communications. Since each node works independently when a node fails it does not affect other nodes. As long as the local partial result is not damaged its task can be resumed by the user. On the other hand, if the local disk is down or the node ceases to be responsive the node may be deleted from the machine list. The tasks that have been performed by the deleted node will be reset to initial status in the task pool and will be picked up later by other compute nodes. This model allows heterogeneous nodes/clusters to work together on a large project and the natural load balancing mechanism ensures that all nodes will finish computing in about the same time when the task pool is emptied regardless of the variation in computation capacity among the working nodes. There are other benefits from this autonomous model. For example,



## Seismic Imaging Technology Advance in BGP

users are free to pause some nodes or to add more nodes to the project while other nodes continue their normal computation without any interruptions. Table 1 summarizes the features and benefits of the autonomous parallel model.

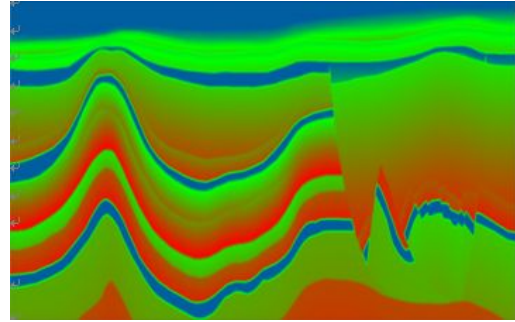
Table 1: The features and benefits of Autonomous Parallel Model

|                          | <b>Master/Slave Model</b>                                   | <b>Autonomous Model</b>  |
|--------------------------|---|--|
| <b>Task control</b>      | Master assigns tasks to nodes                               | Master creates task pool for heterogeneous nodes to fetch                      |
| <b>Work model</b>        | Master passes input to nodes and collects results from node | Master activates nodes, while each node works independently                    |
| <b>A node is down</b>    | All nodes are paused and then resumed                       | Only one node is paused and then resumed                                       |
| <b>A node is damaged</b> | Project needs to restart                                    | The node gets deleted from the pool  |
| <b>Node manage</b>       |   | Flexible to pause and/or add nodes while the program is running on other nodes |

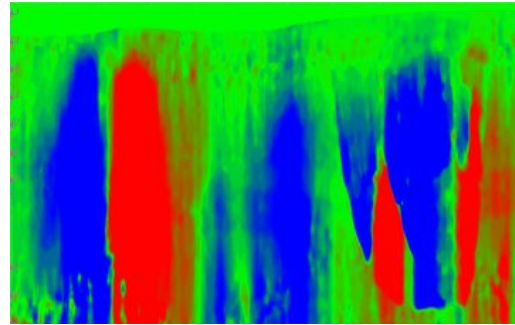
### Examples

Figure 2 shows a partial region of the 2D BP TTI model with only the  $\delta$  parameter and  $\theta$  parameter present in Figure 2 (a) and Figure 2 (b). The right region of the model represents a challenge to a TTI RTM algorithm. Testing of this model has revealed that some of the previously popular formulas have some degree of instability problems when wave front reaches the area where  $\theta$  changes abruptly, as discussed by Fletcher et al (2009) and Zhang et al (2009). Figure 2(c) shows the TTI reverse time PSDM image generated by using system (4).

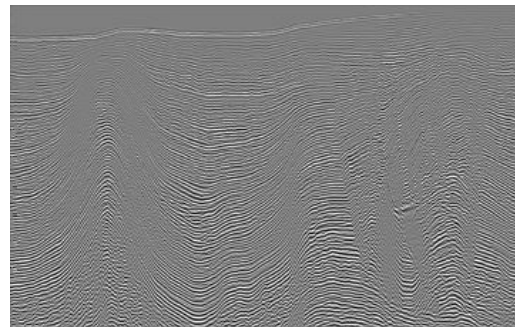
Figure 3 shows comparison of TTI RTM image to VTI RTM and isotropic RTM images of a zoomed-in part of the 2D BP TTI model. The VTI image is obtained by ignoring the  $\theta$  parameter. And the isotropic image is computed by an isotropic RTM program with only the velocity model being used. It shows that if anisotropy truly presents but is partly or totally ignored the PSDM results will be poorly focused and the images will be distorted.



(a)



(b)



(c)

Figure 2. A part of the 2D BP TTI model: (a)  $\delta$ ; (b)  $\theta$ ; and (c) TTI reverse time PSDM image



## Seismic Imaging Technology Advance in BGP

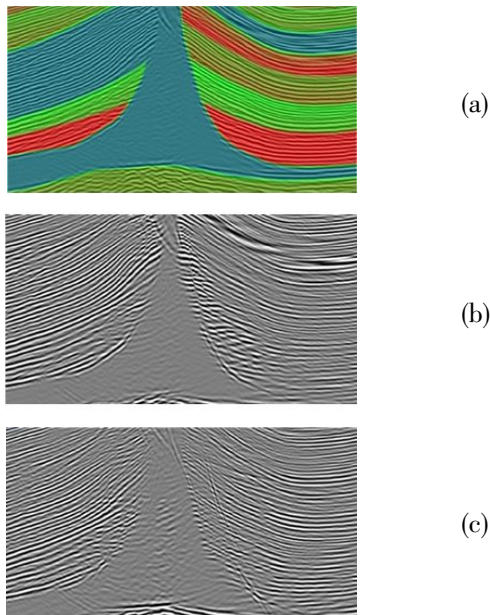


Figure 3. A part of 2D BP TTI model: (a) TTI RTM image color coded by  $\delta$  field; (b) VTI RTM image with  $\theta$  parameter ignored and (c) Isotropic RTM image.

Figure 4 shows a comparison of Kirchhoff 3D PSDM with 3D reverse time PSDM images. This case demonstrates that the RTM image displays higher signal to noise ratio and clearly defines the steeply dipped fault on the right hand side of the section.

### Conclusions

Recently developed wave equation PSDM programs, particularly the RTM algorithms, are robust tools to image complex subsurface structures, including those in strongly varying tilted transversely isotropic media. Our autonomous parallel model designed for heterogeneous Linux clusters improves use of the computer resources and adds flexibility in management of computation facilities as well as the migration project. The migration programs work on topographic surface making it particularly suitable for land seismic data processing.

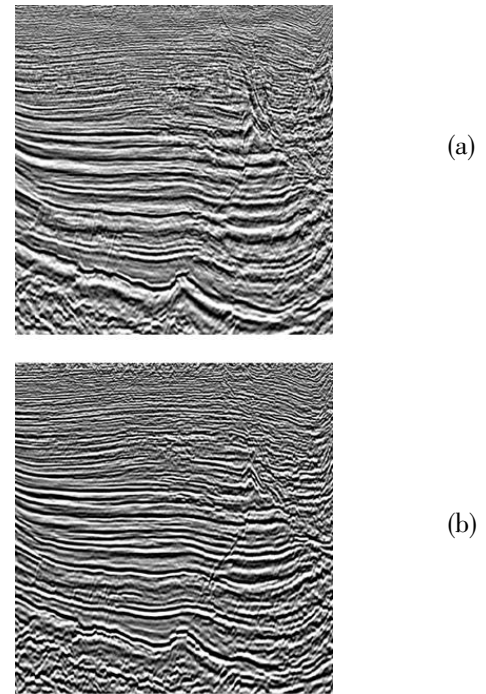


Figure 4. (a) 3D Kirchhoff PSDM image and (b) 3D reverse time PSDM image.

### References

- Fletcher, R. P., X. Du, and P. J. Fowler, 2009, Reverse time migration in tilted transversely isotropic (TTI) media: *Geophysics*, 74, 179–187.
- Grechka, V., L. Zhang, and J. W. Rector, 2004, Shear waves in acoustic anisotropic media: *Geophysics*, 69, 576–582.
- Thomsen, L., 1986, Weak elastic anisotropy: *Geophysics*, 51, 1954–1996
- Tsvankin, I., 2001, *Seismic signatures and analysis of reflection data in anisotropy media*: Elsevier.
- Zhang, Y., and H. Zhang, 2009, A stable reverse time migration and its implementation: 79th Annual International Meeting, SEG, Expanded Abstracts, 2794–2798.
- Zhou, H., G. Zhang, and R. Bloor, 2006, An anisotropic acoustic wave equation for modeling and migration in 2D TTI media: 76th Annual International Meeting, SEG, Expanded Abstracts, 194–198.