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SIMULATION OF 3D SEISMIC ILLUMINATION AND ITS APPLICATION IN SEISMIC ACQUISITION SURVEY DESIGN - DUAL-SOURCE CONFIGURATION (FLIP-FLOP)

Ta Quang Minh, Pham The Hoang Ha, Nguyen Minh Quang, Nguyen Danh Lam, Bui Le Thu
Vietnam Petroleum Institute
Email: minhtq@vpi.pvn.vn
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Summary

An ideal seismic survey should produce an even seismic illumination on the subsurface horizons and adequately illuminate faults. Thus, in seismic acquisition survey design, simulated seismic illumination is usually among the first steps to perform. In this paper the authors discuss how to perform a 3D seismic illumination simulation on a model of the subsurface environment using the Ray tracing technology. The results of the seismic illumination process using the Ray-Tracing method (ray propagation model) for the study area generate various Illumination-related maps to help assessing and optimizing the effectiveness of any particular seismic survey configuration. The paper also applied this technology to models and real-field data with a dual-source (flip-flop) configuration, producing various illumination map results to illustrate the effectiveness.

Key words: Survey design, seismic illumination, wave propagation, simulation.

1. Introduction

Seismic surveys are the first stage of oil and gas exploration process, helping to identify potential hydrocarbon accumulation zones. Currently, seismic survey designs are mostly done by foreign contractors using foreign commercial software. Seismic illumination simulation [1] is a key part of seismic acquisition survey design. The goal is to ensure an even seismic illumination on the target area, so that any seismic amplitude anomalies can accurately reflect lithology/fluid anomalies in the geology. Optimizing the design minimizes signal quality issues in poorly illuminated areas like fault shadows or under salt domes. However, in practice, in areas with complex velocity fields or geological structures, wavefields become distorted, reducing illumination intensity and coverage. Seismic illumination maps can help predict anomalies and adjust acquisition designs accordingly. Currently, seismic illumination design and simulation are done using commercial software, which comes with licensing costs. Since a similar software in Vietnam is not yet available, the seismic processing team at the Vietnam Petroleum Institute (VPI) has carried out research and try to develop the seismic illumination technology, which will allow us to manage and control the process independently and design more complex acquisition geometries.

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Illumination maps are built based on the results of the seismic illumination process using the Ray-tracing [2], a method that simulates how seismic waves propagate through complex geological structures. It provides crucial information, such as hit map, incident angle, max offset … to evaluate and optimize the design of seismic acquisition configurations. The research results as well as the testing of 3D seismic illumination technology will be presented in detail in this paper.

2. Theoretical basis

Seismic waves propagate according to the wave equation, which is simplified into the ray equation (indicating the directions in which rays travel) and the transport equation (describing the variation of amplitude along the ray [3]). From these simple elements, an overall illumination map is constructed. To simulate seismic waves illuminating seismic objects, the Ray-tracing method is used, which is the core method employed in seismic illumination technology.

2.1. The Ray-tracing method

The Ray-tracing equation, also known as the eikonal equation, is a differential equation that describes the path of seismic wave rays as they propagate through a medium with slowly spatial varying velocity and reflection properties of surfaces. In other words, this equation simulates the propagation process of seismic waves in complex structures. It can be expressed as [2]:

$$[\bar{\nabla}T]^2 - \frac{1}{v(\vec{x})^2} = 0 \quad (1)$$

Where:

T: Is the wave travel time;

∇T: Is the gradient of the wave travel time (the change in wave travel time with respect to position);

v: Is the seismic wave velocity.

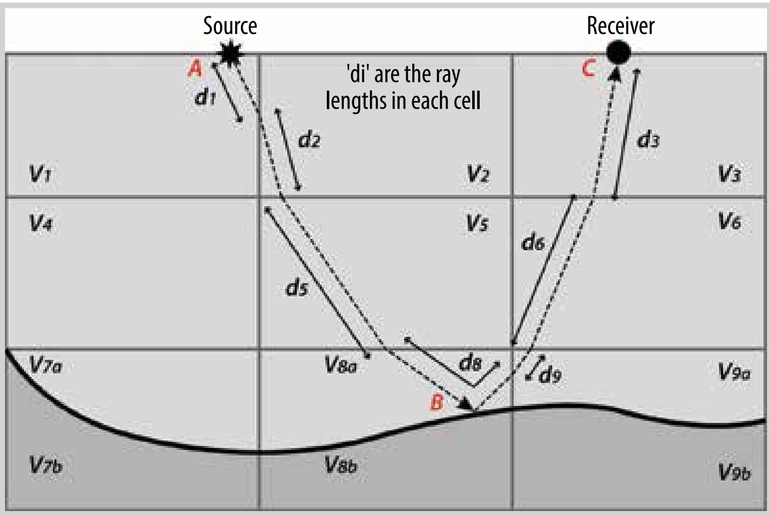


Figure 1. *Ray-tracing in the velocity field.*

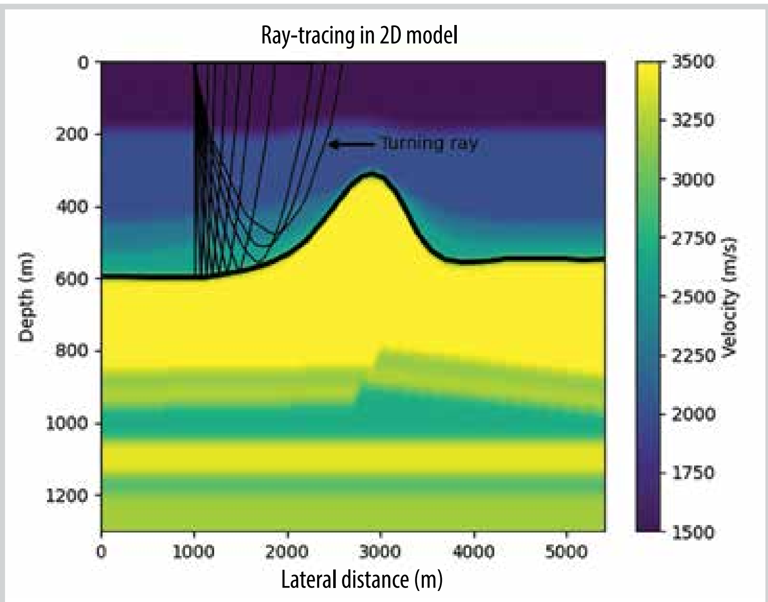


Figure 2. *Ray-tracing Runge-Kutta with a single reflector.*

The eikonal equation can be transformed into a system of stage-space equations:

$$\frac{d\vec{x}}{dt} = v^2(\vec{x})\vec{p} \quad (2)$$

$$\frac{d\vec{p}}{dt} = -\frac{\bar{\nabla}v(\vec{x})}{v(\vec{x})} \quad (3)$$

Where $\vec{p}$ is the slowness vector, representing the direction and magnitude of the ray velocity at the reference point; dt is the time step used to calculate the ray path.

Equations (2) and (3) can be numerically solved using the Runge-Kutta method (RK4) [4]. This is a classical method used to solve differential equations. Therefore, it is applied in seismic raytracing to solve the first-order system of equations (2) and (3), thereby determining the path of seismic wave rays in a velocity-varying medium.

Figure 1 illustrates how ray-tracing is performed in velocity field by this method [5]. The field is discretized into samples for computational simulation. In this field, the ray trajectory is estimated repeatedly after every fixed time interval or step. At the end of each step, the current position of a tracing ray is updated and the values of the velocity and ray parameters at the nearest sample to this position are used to define the next position of the ray.

An important characteristic in seismic wave simulation is that the wave will be reflected at horizon surfaces before returning to the receiver. Additionally, the reflected wave shown in Figure 1 can travel in various ways and may even bend before hitting the reflection boundary, as illustrated in Figure 2 (turning ray). This occurs due to total internal reflection at shallower interfaces (when the angle of incidence is greater than the critical angle). This phenomenon can affect the construction of the illumination map, particularly in areas with velocity anomalies.

2.2. The dual-source configuration (flip-flop shooting)

Flip-flop shooting is a widely used technique in seismic surveys that alternates between two seismic sources. While one source is being recharged, the other is actively acquiring data. This dual-source configuration enhances seismic coverage and resolution by increasing the number of subsurface inlines, thereby improving the overall data quality. Figure 3a shows the acquisition geometry. Figure 3b shows a map view of the trajectory of the shots used in this study.

2.3. The results - counting the hits

As the seismic acquisition vessel travel through the area, typically planned by a route optimization software such as SURVOPT, the acquisition configuration were simulated to regularly deploy a source, ray-trace the seismic wave to the target horizons and reflect the ray back to the receiver arrays. For those rays that arrive to the receiver array, the ray's corresponding hit to the subsurface horizon were counted and tally at the end of the vessel run. Thus, a hit map can be generated which can be used to assess:

- Which region of the subsurface receive more or less hits.

- Whether the illumination is even.

- Ability of the particular survey configuration to shine on a particular fault, i.e. the ability to provide enough strength of the seismic wave on the fault.

Since the history of the travel rays were traced, a number of other useful indices can be tallied such as:

- Offsets - The distance between the receiver that receives the traced ray and the originated source.

- Azimuth: Source-receiver's azimuth.

- Incident angle: The angle that the seismic wave arrive to a particular surface

- Travel time: The time that the seismic wave travels along the ray from the source to the receiver.

From these indices, corresponding maps can be generated (section 4).

3. Experiments in 3D synthetic model

Ray tracing and seismic illumination experiments on various 3D synthetic model were conducted to assess the performance of the method.

3.1. 3D single ray simulation

3D synthetic model experiments were conducted to assess the performance of the ray-tracing method, as shown in Figure 4. The results align with the expected behavior of wave rays in an inhomogeneous medium. Both reflection and turning rays were successfully simulated (Figure 4b).

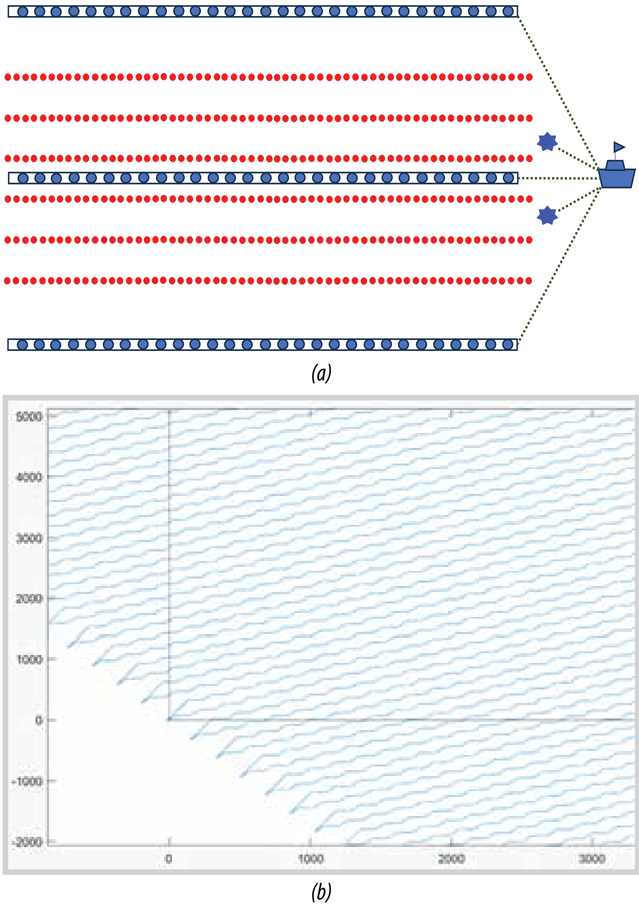


Figure 3. *(a) Acquisition geometry with flip-flop shooting, (b) Trajectory of the shots in flip-flop shooting.*

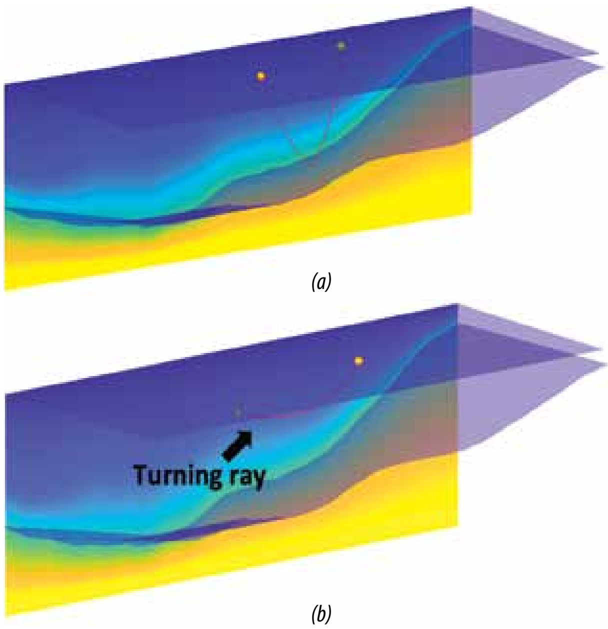


Figure 4. *Ray-tracing in 3D synthetic model: (a) ray reflects at the horizon, (b) turning ray.*

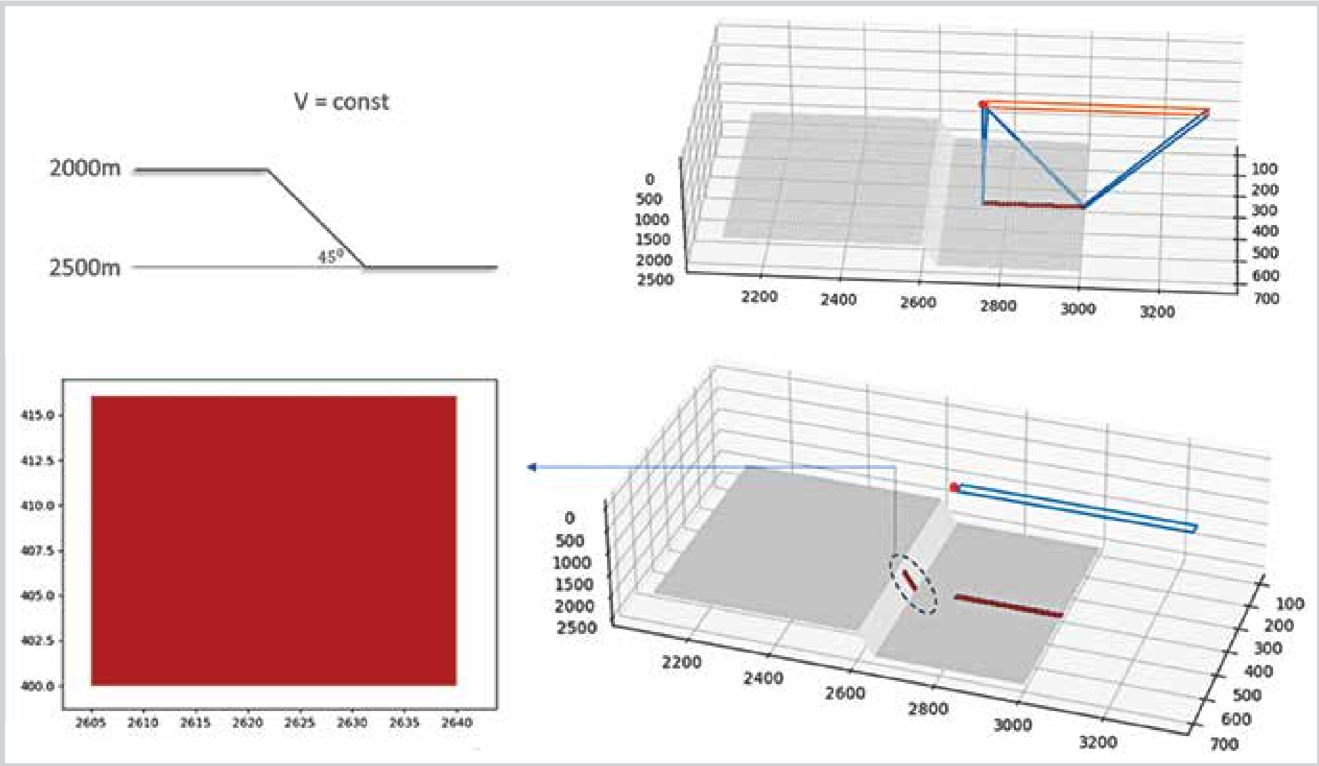


Figure 5. *Ray-tracing in an isotropic velocity model.*

3.2. 3D single shot simulation in a constant velocity model

Note that if the velocity is a constant, the horizon is a plane, and the source/receiver configuration is known then the number of hit to a grid point in the horizon can be calculated beforehand. To validate the method's accuracy for seismic illumination, a single-shot illumination experiment was conducted in a simple 3D dipping horizon model (constant velocity model and 45° horizon to simulate a fault) and the results were compared with theoretical calculations (Figure 5). The aquisition configuration is demonstrated in Table 1.

The illuminated area on the 45° horizon, is depicted in Figure 5. As shown in Table 2, the theoretically illuminated area, which is 34.5 grid cells, while the simulated illumination area spans 35 grid cells (with an error of less than 1 grid cell due to the discretization of the model). That implies an excellent match. Similar experiments on various models show the reliability of our illumination software.

Table 1. *Acquisition configuration for single shot simulation in a constant velocity model*

Source distance (m)	25
Source depth (m)	6
Number of cables	8
Cable distance (m)	50
Cable depth	15
Number of receivers/cable	281
Receiver interval (m)	25
Minimum offset (m)	150

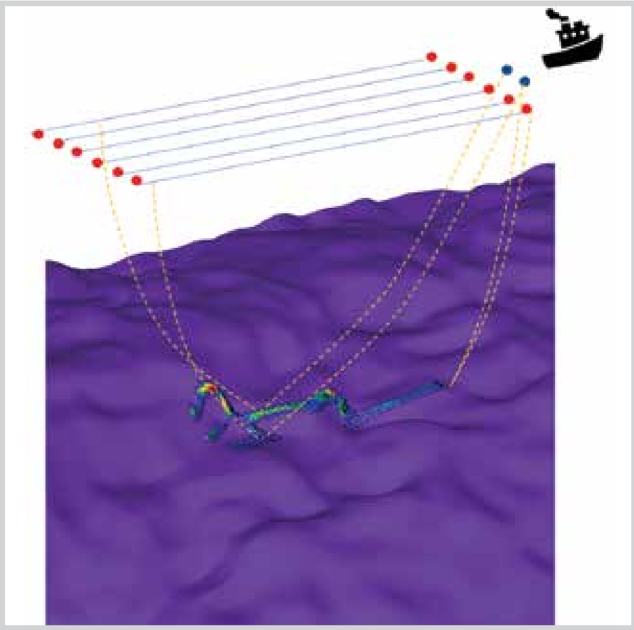
Table 2. *Comparison of illuminated area on the 45° horizon*

Theoretical illuminated area	34.5 grid cells
Simulated illuminated area	35 grid cells

3.3. 3D single shot simulation in a spatially-varying velocity model and a real horizon with comparison to the result from a commercial software

Another single-shot illumination experiment was conducted in a spatial varying velocity model and compared with results from a leading commercial seismic illumination software. Figure 6 demonstrates a high degree of consistency between the hitmap of the single-shot illumination produced by the VPI software (Figure 6b) and that from commercial software (Figure 6c). This confirms that the VPI software can be reliably used for multiple-shot testing, providing a viable alternative for large-scale seismic illumination experiments.

A single-shot illumination experiment was also conducted near a complex geological structure, specifically a large fault, to further assess the method's reliability. Figure 7 shows the illuminated part of the horizon (red grids) near the fault.



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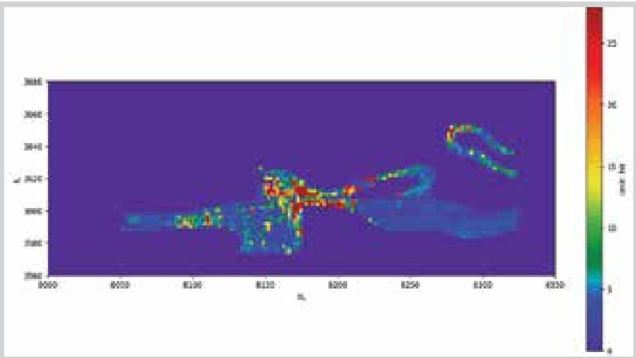

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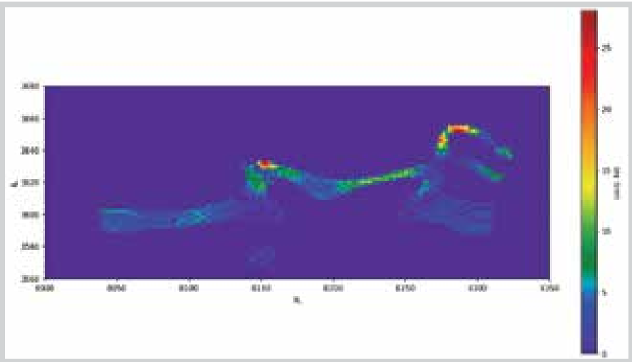


(c)

Figure 6. (a) Single-shot illumination in 3D model with spatially-varying velocity model and a real horizon. Illumination hitmap of single-shot illumination produced by (b) VPI software, (c) commercial software.

4. Field application

In this study, a set of illumination maps are constructed by using VPI software and compared with those created by a foreign contractor for an operational block in the Malay - Tho Chu basin. The seismic acquisition configuration was chosen to align with that used by the foreign contractor to facilitate a direct comparison of the results (Table 3). The suitable selection of data acquisition parameters in 3D seismic surveys has a significant impact on the quality of the data collected [6].

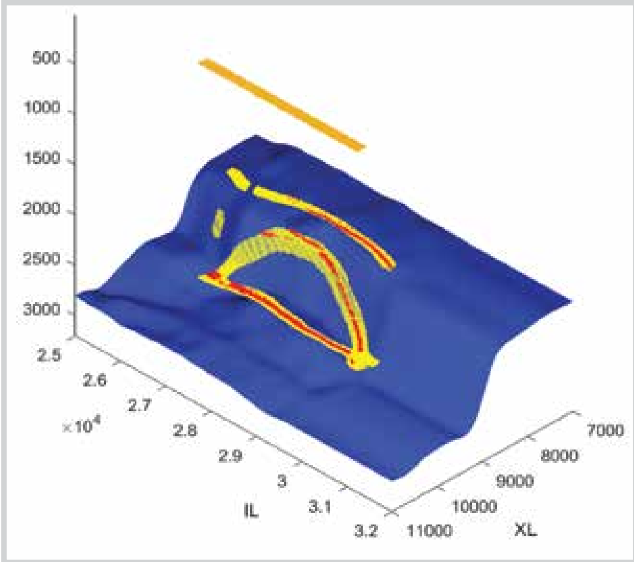
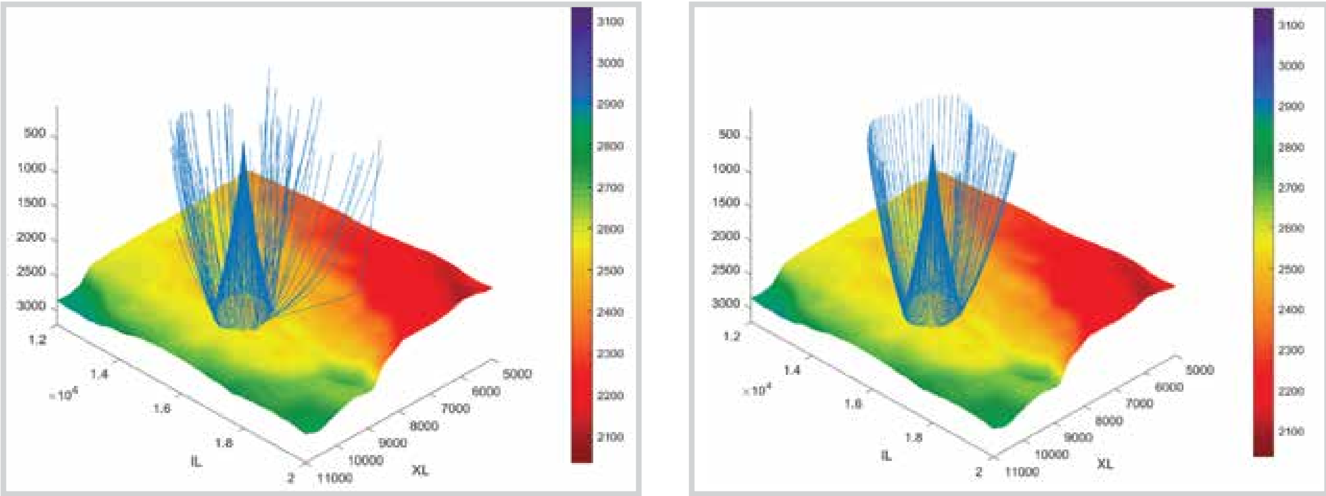


Figure 7. Illuminated part of complex horizon (fault).

Table 3. Seismic acquisition configuration for studied block

Parameter	Value
Number of cables	8
Cable distance (m)	50
Receiver interval (m)	12.5
Cable depth (m)	10
Cable length (m)	7,000
Minimum offset (m)	100
Numbers of explosive sources	2 (flip-flop)
Explosive interval (m)	18.75
Source depth (m)	6
Distance between 2 sail line (m)	175

Experience in building models for ray-tracing indicates that horizons and attribute blocks must be adequately smoothed to prevent anomalies that may arise during the ray tracing process. This smoothing is particularly important when simulated seismic waves encounter rough or angular surfaces of boundary layers, or when wave paths become overly complex due to abrupt changes in attribute values (such as Vp and Rho). Figure 8 illustrates the results of a ray-tracing test conducted on the horizon X in studied block, highlighting the differences before and after the smoothing process.



(a) (b)

Figure 8. *The ray-tracing results on horizon X: (a) before and (b) after smoothing with a filter length of 20 sample points.*

Table 4. *Definition of output maps*

No.	Map	Definition
1	Hit map	Map of Horizon's grid points with the value of each grid point proportional to th e Number of Sources and Receivers that the wave can reach that particular grid point and returning to the receiver array.
2	Max.angle map	Map of Horizon's grid points with the value of each grid point proportional to th e maximum incident angle of the rays that a source can reach this grid point and the reflection ray returns to the receiver array.
3	Max.offset map	Map of Horizon's grid points with the value of each grid point proportional to th e maximum offset of all receivers that receive the reflection ray from the particular grid point.
4	Max.travel time map	Map of Horizon's grid points with the value of each grid point proportional to th e maximum travel time of any rays that can reach that particular point and return to the receiver array.
5	SMA map	Map of Horizon's grid points with the value of each grid point proportional to th e Simulated Migration Amplitude [7].

In the final step, illumination maps will be generated by performing ray-tracing within the established model using the selected configuration. The process requires a mildly smoothed illuminated horizon and an input velocity model, which is also smoothed.

The creation of illumination maps involves aggregating the number of reflected rays that reached receiver array at each point on the horizon, along with key parameters (offset, incident angle, travel time…). For each source-receiver pair, the wave ray is simulated as it reflects off the horizon and returns to the receiver. By summing the reflections at each horizon point, a hitmap is produced, showing the intensity of illumination for a given acquisition setup. Besides the hit map, a set of output maps are also built in illumination process as shown in Table 4.

To enable comparison, the illumination results generated using VPI software will be labeled as VPI, while those obtained from the foreign contractor will be designated as FC. Figure 9 presents the hitmap of horizon X, located in the Malay-Tho Chu basin, allowing for a direct comparison of the illumination patterns produced by both methods. Some key observations can be made as follows:

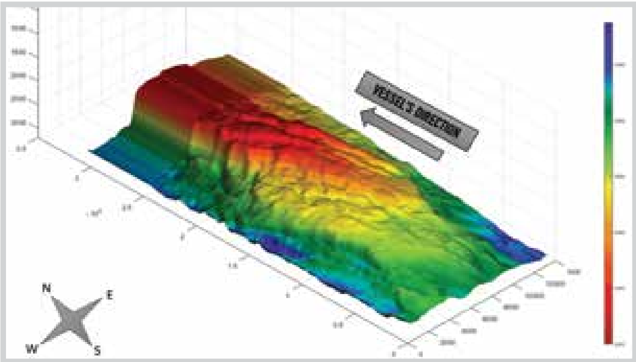
- The FC results show lower resolution but good illumination of larger faults. However, smaller faults are not clearly distinguished from the surrounding areas.

- The VPI results, with higher resolution, reveal variations in brightness according to the fault size, offering clearer differentiation between large and small faults.

Figure 10 demonstrates other output illumination maps by using VPI software. The following observations can be made from these results:

- The maximum offset values are relatively uniform across the horizon surface, except at locations where faults are present. This observation aligns with the hitmap results, as areas with flat terrain exhibit similar brightness, even though they are located at different depths.

- The maximum travel time map shows no clear variation with the depth of the horizon; however, it is noted that the shallow terrain in the northern region has



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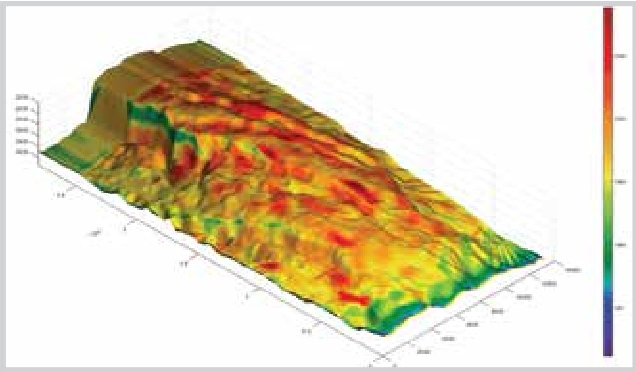

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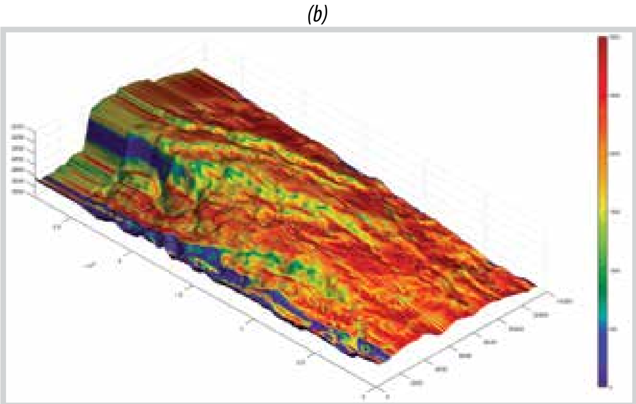

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Figure 9. *(a) Depth map of horizon X, (b) FC hitmap, (c) VPI hitmap.*

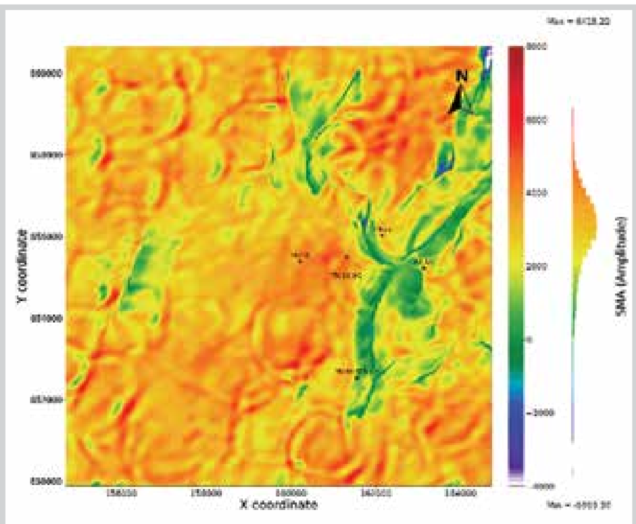
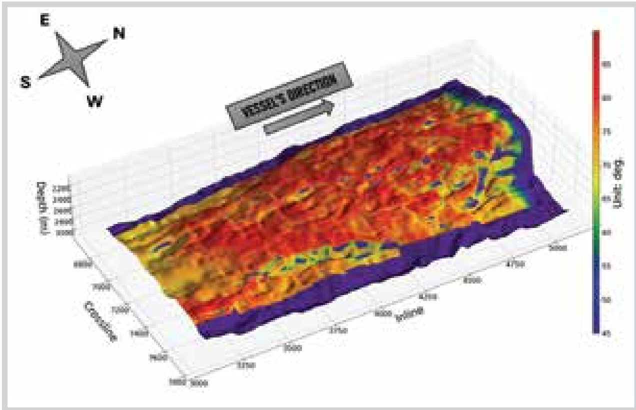


Figure 11. *SMA map of a small region.*



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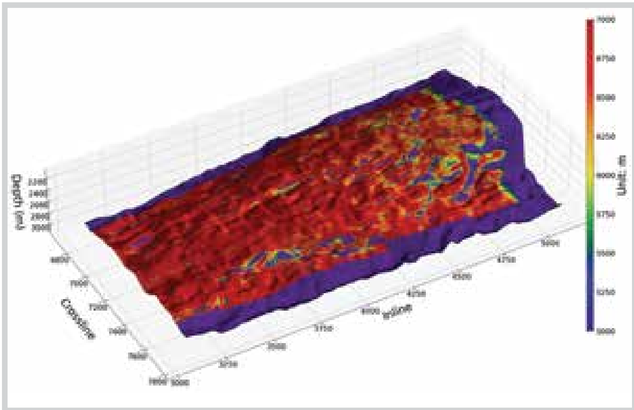

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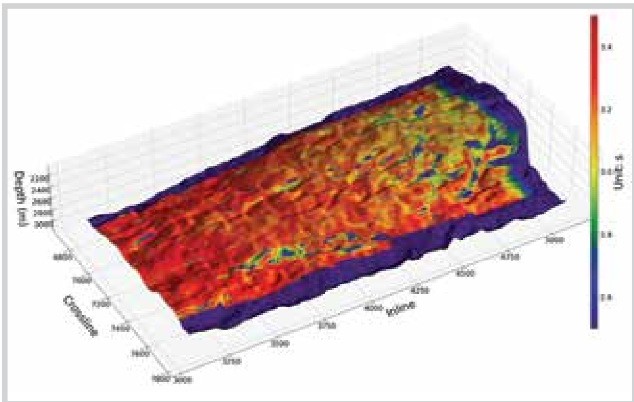


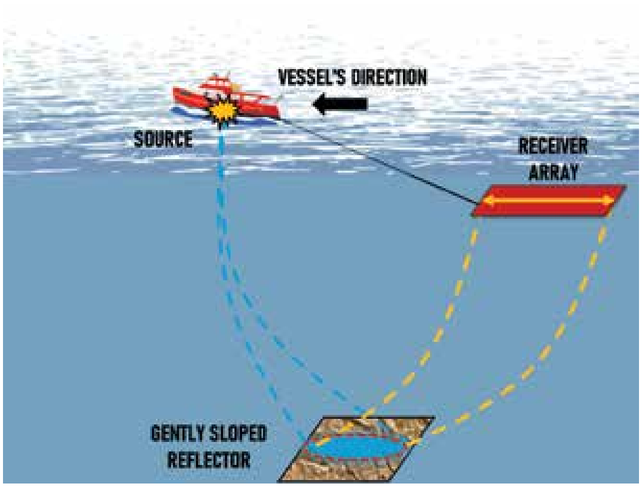
(c)

Figure 10. *(a) Max.angle map (b) Max.offset map (c) Max.travel time map.*

smaller travel time values compared to the deeper areas in the southern and southwestern regions.

- The maximum incident angle map clearly varies with the depth of the horizon and is consistent with theoretical expectations, as the shallow area exhibits larger incident angles compared to the deeper region.

Combining with the Kirchhoff migration equation [8], a simulated migration amplitude map can be constructed to predict the effect of illumination on the final migrated seismic cube. An evenly illuminated SMA map means that



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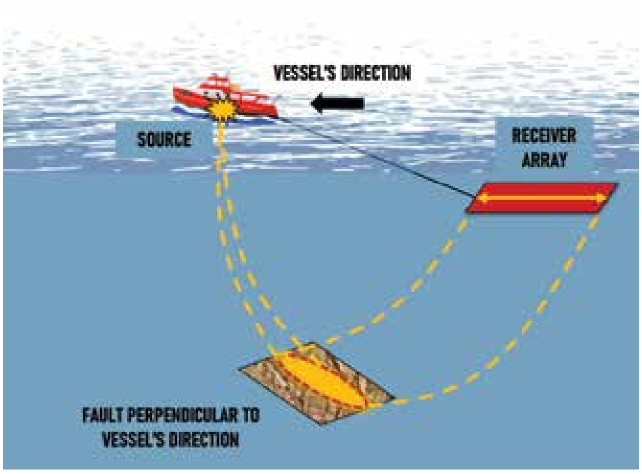

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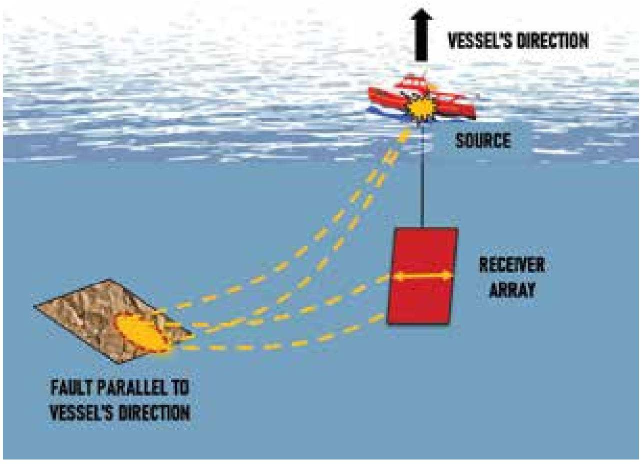


(c)

Figure 12. *Different reflector topographies.*

any seismic anomaly extracted from the future seismic cube is due to the change in the actual lithology and fluid of the target geology, not an artifact of the illumination. In this study, an SMA map for a small region was constructed as part of the analysis (Figure 11).

5. Discussion

The design of a seismic survey plays a critical role in determining the quality and accuracy of illumination results. Factors such as source-receiver geometry, source spacing, and acquisition aperture directly affect the ability to image subsurface structures. Poorly designed surveys can lead to incomplete coverage, reduced resolution, and significant shadow zones, particularly in complex geological settings. Conversely, optimized survey designs enhance the illumination of key target areas, ensuring higher resolution and more accurate imaging of subsurface features.

- Effect of vessel's direction relative to horizon's dip direction

In practice, the size of the receiver array is constrained by the number of cables and the length of each cable. Additionally, spatial sampling of signals is limited by the spacing between the cables and the receivers on each cable. Consequently, different topographies, which influence the propagation of reflected seismic waves, will yield varying illumination results. Reflector topographies categorized into three primary types (Figure 12):

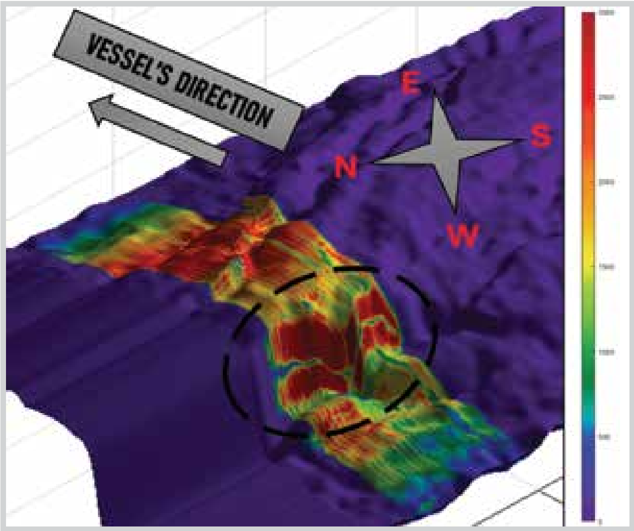
- Gently sloped reflectors;
- Faults perpendicular to the vessel's direction;
- Faults parallel to the vessel's direction.

A gently sloped reflector represents the most favorable topography for illumination (Figure 12a). This topography simplifies the calculations and design of the receiver system, facilitating optimal illumination conditions. As a result, it enhances the accuracy of planning and data collection in seismic surveys.

In case of a fault, it is necessary to consider influence of the vessel's direction relative to the horizon's dip direction. The effectiveness of illumination can vary significantly depending on the interaction between seismic wave propagation and reflector orientation.

When the vessel's direction is perpendicular to the faults (Figure 12b), seismic waves can effectively illuminate the fault, producing clearer and more coherent reflections. This alignment enhances the likelihood of capturing direct wave paths, thereby improving the quality of the seismic data.

In contrast, when the vessel's direction is parallel to the faults (Figure 12), the illumination may be less



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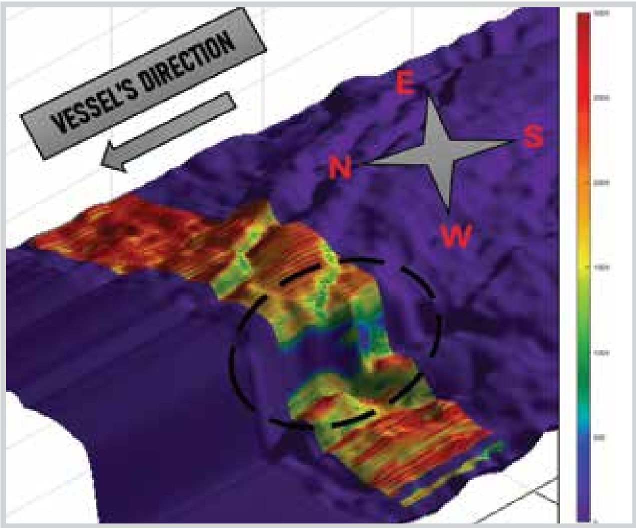


(b)

Figure 13. *Hitmap of a fault in two case: (a) fault perpendicular to the vessel's direction, (b) fault parallel to the vessel's direction.*

effective. The seismic waves may encounter more complex reflection patterns and potential shadow zones, leading to weaker signals and less distinct reflections from the dipped horizon.

Figure 13 shows the hitmaps of a big fault illuminated by 2 different vessel's directions. The fault is better illuminated when the vessel's direction is perpendicular to the fault (Figure 13).

- Impact of depth

Flat reflective surfaces positioned at varying depths will generally experience similar illumination under ideal conditions, assuming there are no velocity anomalies or obstacles in the wave field's path. However, in practice, reflective surfaces frequently exhibit continuous depth variations and can display abrupt changes in areas affected

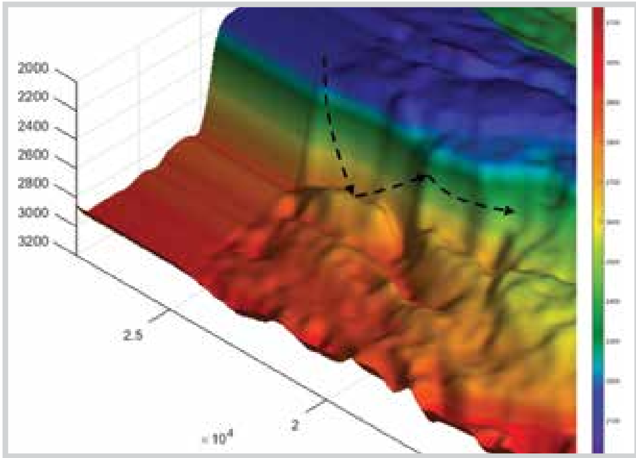
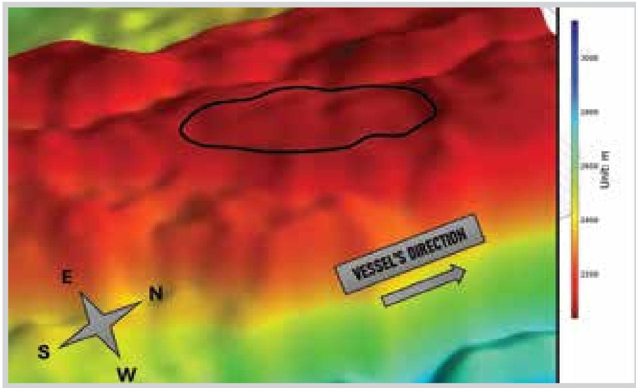


Figure 14. *Big fault obstructs the signal's return to the surface.*



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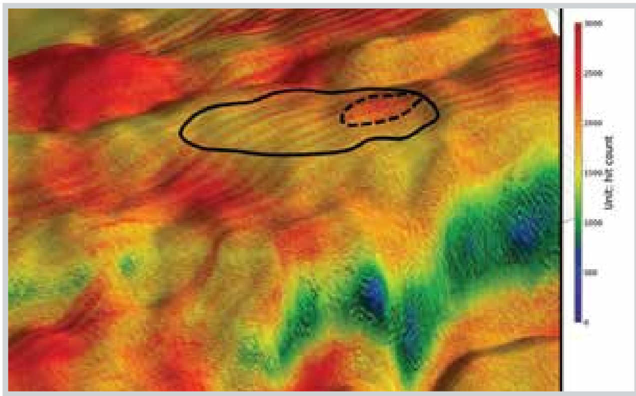

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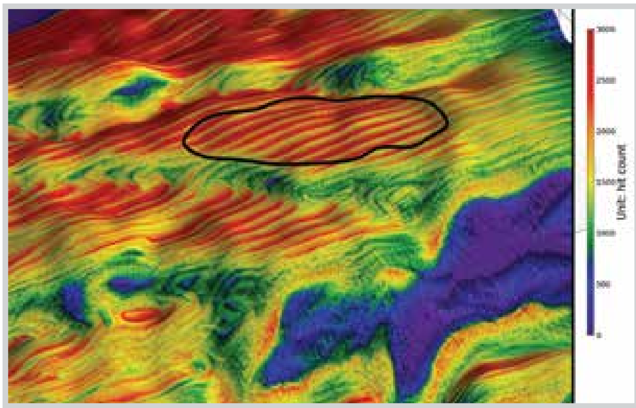

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Figure 15. *(a) Depth map of horizon X, (b) FC hitmap, (c) VPI hitmap.*

by faulting. Consequently, regions located at greater depths are often less effectively illuminated, as higher terrain can obstruct the signal's return to the surface. This effect is especially pronounced in proximity to big faults, where the complex topography further complicates wave propagation and reflection (Figure 14).

- Comparison on shallow flat zone

Figure 15 is a zoomed-in version of Figure 9, focusing on the solid black outlined area that represents the flattest and shallowest part of Horizon X. Within this region, the FC results reveal an unusually bright area, indicated by the dashed black line. the nearby large fault is illuminated weakly in both results, reflecting the impact of the vessel's direction relative to the horizon's dip direction. This observation underscores the influence of acquisition geometry on illumination quality.

6. Computational workload analysis

In addition to the algorithms used in seismic illumination technology, the application of parallel programming also plays a crucial role in this research. For studied horizon, the terrain's complexity and significant depth posed challenges in terms of calculation time. To illuminate the entire area of 350 km² with the current acquisition configuration, 112,500 shots need to be carried out. If only one CPU is used, the total computation time for all the shots would be huge.

For that reason, parallel programming has been applied, utilizing a total of 600 CPUs (50 nodes x 12 CPUs/node). As a result, the time required to create an illumination map for horizon X has been reduced to just over 4 days.

7. Conclusion

As presented in this paper, 3D seismic illumination is an important step needed to be performed before the actual roll-out of a seismic survey. This step provides a critical information regarding the amount and quality of seismic illumination that can reach any subsurface region, i.e. a more uniform illumination implies the future acquired seismic data can truly reflect the changes in lithology and fluid, regions that lacks illumination, such as under a fault, should require attention from survey design to seismic processing to balance out the results.

Theoretical research and technology development for the 3D seismic illumination method has been presented. The results on model data have shown the sensibility and accuracy of the developed technology. Application to the field data with the flip-flop acquisition configuration has shown promising results that at least comparable to results from a foreign contractor. Technology optimization such as parallel computing has been mentioned too.

In addition to the research and development, mastering seismic illumination technology also serves as the basis for simulating more complex configuration (such as three-source configuration) or arbitrary vessel trajectories. Developing this technology independently at the VPI allows for reduced reliance on commercial software, lowers implementation costs, allows more control of the process and enhances the capability for future support and quality control of survey design.

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