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Analyzing the Illumination and Resolution in Seismic Survey Designing

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Abstract

Seismic modeling aids the geophysicists to have a better understanding of the subsurface image before the seismic acquisition, processing, and interpretation. In this regard, seismic survey modeling is employed to make a model close to the real structure and to obtain very realistic synthetic seismic data. The objective of this study is to analyze the resolution and illumination of the fault by designing appropriate 3D seismic survey parameters. The ray-based seismic modeling was built using 2D seismic data, geological reports, and the well logs in one of the oil fields in the southwest of Iran. A pre-stack depth migration simulator was used to evaluate the survey geometry on the resulting seismic image. The results proved that a survey designer could improve the image of the target in a seismic section by applying the ray-based analyses, with respect to illumination and resolution studies.

Keywords: Seismic Modeling, Ray Tracing, PSDM Simulator, Seismic Resolution, Illumination Analysis, Fault imaging

1. Introduction

Conventional acquisition geometry analysis methods are primarily based on common-midpoint (CMP) processing. These methods do not take into account the overburden effects on the data quality and image quality. Seismic survey modeling is needed to find the optimal acquisition and imaging solutions for particular geophysical objectives. The benefit of using modeling is that it enables geophysicists to test various scenarios and consequently analyze the positive and adverse effects of each parameter on the quality of seismic images. The ray-based modeling has its advantages and disadvantages too. The applicability to complex, isotropic and anisotropic, and laterally varying layered media is the main advantage. It makes possible to track the paths in the medium along which energy propagates, an aspect very significant in tomography. In comparison with other methods such as finite difference and physical modeling, the ray tracing can provide the robust and reliable results at a lower cost of computations. The ray technique also has some limitations; it is applicable only to

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smooth media, in which the characteristic dimensions of inhomogeneity are considerably larger than the prevailing wavelength of the considered waves (Cerveny and Psencik, 2010).

Seismic illumination and resolution analyses provide a quantitative description of survey parameters that can distort the image during migration in the data processing. Gibson and Tzimeas (2002) discussed quantitative measures of image resolution for seismic survey design. A proper illumination map can improve the imaging through reducing the cost of reshooting. Xie et al. (2006) discussed the illumination analysis and various illumination measurements at different levels of details. Mirsa et al. (2008) used subsurface illumination modeling to investigate the image quality, fold variation, and acquisition footprints in different survey designs. Lecomte et al. (2003) and Lecomte and Pochon-Guerin (2005) introduced a pre-stack depth migration (PSDM) simulator approach to handling 3D lateral resolution and illumination in PSDM images without the need to migrate synthetic data in the processing stage. This simulation process is a 3D spatial convolution procedure working in the depth domain and models PSDM point scatter responses and reflectors with computational times close to 1D convolution (Lecomte, 2004). In the faulted areas, the seismic resolution and the quality of resulting image can be controlled by seismic modeling. Therefore, to illuminate the fault structure, the seismic survey designer should try to determine the appropriate seismic survey parameters. Botter et al. (2014) presented a workflow to assess the impact of fault zone internal structure on the resulting seismic image by using the discrete element method (DEM) and the PSDM simulator. In faulted regions, the acquired seismic data often suffer from poor image quality due to the low illumination coverage, especially in the proximity of the fault planes. Saffarzadeh et al. (2017) used the illumination map for selecting the optimum survey direction in the target horizon.

In the present study, the seismic survey parameters such as bin size, migration aperture, and fold were pre-designed using the conventional method by the workflow of the 3D seismic survey. These parameters were employed in the seismic modeling to examine the effects of source frequencies and the direction of seismic survey geometry on the illumination and resolution of the resulting image.

2. Methodology

The analyses based on illumination and resolution attributes can be useful to modify the seismic survey parameters. First, key survey parameters should be pre-designed using a conventional method. In this method, the seismic survey designer is limited to a few choices regarding the basic parameters to be used. Some of the most significant onshore 3D seismic survey parameters are as follows:

Shot and receiver positions: The source interval (SI), receiver interval (RI), source line interval (SLI), receiver line interval (RLI), and the bearing of receiver lines are important factors in seismic survey design.

Fold: The 3D fold is the number of midpoints that are positioned inside a bin (Cordsen et al., 2000). This parameter mainly controls the quality of the seismic data.

Migration aperture (MA): The migration aperture has become more significant in the implementation of the pre-stack migration algorithm. It can be useful for repositioning the seismic events at their correct positions and collapsing the diffracted energy. To ensure a sufficient migration into the desired image area, the boundary of the survey must be expanded. Migration aperture (MA) for a zero offset traces can be written by (Cordsen et al., 2000):

$$MA = z \tan(\theta) \tag{1}$$

where, z is the depth, and θ is the dip of the target horizon.

In complex structures such as faults, salt domes, and reefs, the determination of survey parameters is so challenging and critical due to the complicated wave field behavior involved in such structures. Hence, seismic survey modeling is employed to make a model close to the real structure and obtain very realistic synthetic seismic data via seismic modeling. The model-based approach often uses the background model and estimates the ray path by different survey settings. An appropriate velocity cube with some elastic assigned parameters is needed to build a reliable model for investigating the ray-based analysis. First, a reliable interval velocity model of structures is constructed through integrating the previous 2D seismic data, geological studies, and the data of the well. The illumination and resolution analyses can be useful to modify the seismic survey parameters determined by the conventional method.

Key survey parameters in complex structures are usually determined by illumination analyses, which can analyze the effects of various seismic survey designs (Prasad et al., 2008). Figure 1 shows a simple way to illustrate the generating of the illumination map. It is significant that, for any shot and receiver pairs, the reflection points on the target horizon be modeled. By cutting the objective horizon into bin cells, the number of common reflection points (CRP's) with their properties can be quantified. Counting the number of rays in each CRP bin yields fold, offset, and azimuth attributes related to the CRP's at the target rather than to the CMP's at the surface. Illumination maps show the number of the reflection points on the target horizon. Seismic illumination becomes more and more challenging in regions with rugged topography and complex geological structure having severe lateral velocity variations. Without enough illumination for the target reflectors, conventional seismic data cannot guarantee a quality image. In addition, resolution studies can examine the effect of target resolution on the resulting image using the source wavelet, the overburden model, and the survey geometry. The simulated PSDM image is used to explore the effects of fault structure on the resulting seismic image. Ray-based modeling can evaluate the 3D spatial pre-stack convolution operators called point spread functions (PSF's). The inputs to the PSDM simulator are an appropriate overburden velocity model, survey geometry, and the reflectivity. Rather than generating synthetic seismograms and processing these data to achieve the PSDM image (at a pretty high cost if a large volume of data must be modeled, processed, and imaged), this method applies the so-called PSDM filters to input reflectivity structure to produce the PSDM look-alike image. The reflectivity cube, which is obtained from acoustic properties of the model (Vp, Vs, and density), can be converted to the wavenumber domain and then combined with PSDM filter to produce the PSDM image. Figure 2 shows the flowchart of the generation of the simulated PSDM image. For each shot-receiver pairs, illumination vector could be generated by the ray-based method. The illumination vector I_{SR} is defined as the difference between two slowness vectors (P_S and P_R) at an illumination point (Figure 3). P_S and P_R are calculated by ray-tracing techniques, giving the high-frequency approximation of the solutions to the wave equation. At the considered illumination point, P_S is parallel to the incidence ray, and P_R is parallel to the scattered ray (Lecomte, 2008). The response of a scattered ray at a reference point can visualize the local imaging capability of the PSDM filter. This response in the spatial domain is called a point-spread function (PSF) and can be obtained based on ray tracing (Lecomte, 2008). To calculate the PSF at a point on the image, all K_{SR}'s in the wavenumber domain are mapped for a particular frequency band and pulse, and then an inverse Fourier transform is employed to gain the corresponding image. Briefly, the PSDM filter was generated by the illumination vectors in the wavenumber domain considering the proper source wavelet. Also, the inverse Fourier transform of the PSDM filter yields the PSF in the spatial domain. The simulated image constructed by combining a reflectivity model of the target with the PSDM filter in the wavenumber domain provides a direct prediction of the PSDM amplitude (Figure 2).

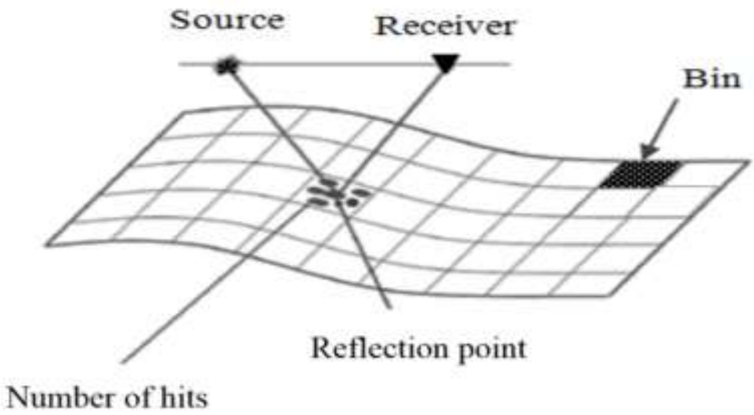


Figure 1
The principle of the generation of illumination map; in each bin cell, there is a reflection point related to each shot and receiver pair, and the number of hits shows the quantity of the illumination.

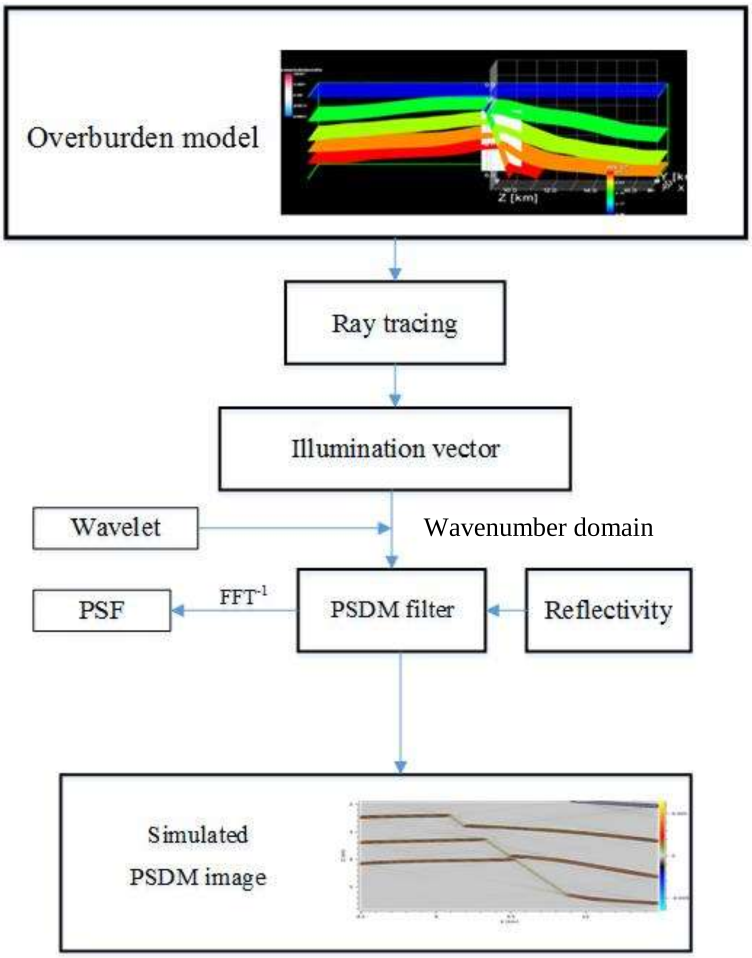


Figure 2
The flowchart of PSDM image generation; illumination vectors were calculated by ray tracing using the background model within the target cube. The PSDM filter was created by combining the illumination vectors with the source wavelet; the filter was finally convolved with the reflectivity to simulate the PSDM seismic image.

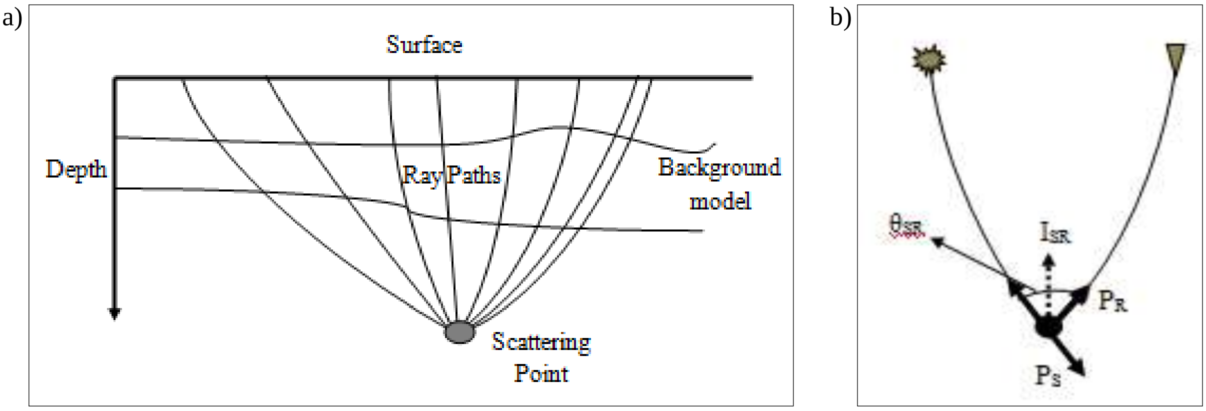


Figure 3
a) The scattering point and its related ray paths in the background model; b) Illumination vector (ISR) calculated by P_R (parallel to the scattered ray) and P_S (parallel to the incidence ray).

3. Example

The study area is a faulted structure in Dezful embayment in the southwest of Iran. The Zagros basin was a part of the stable supercontinent of Gowndwana and a passive margin in Paleozoic and Mesozoic times. Oligocene–Miocene Asmari formation, the most productive oil rock reservoir, was deposited in the foreland of Zagros Fold-Trust Belt (Kavoosi and Sherkati, 2012). Mid Miocene Gachsaran formation consists of competent and incompetent units with anhydrite, marl, salt, and limestone lithology deposited over Asmari formation. The thickness of Gachsaran formation in Dezful embayment increases from the southwest to the northeast (Ghanadian et al., 2017). It can act as a seal for hydrocarbon trap. Asmari and Sarvak formations are the main reservoir units in the area studied. Figure 4 shows the stratigraphic column of the studied area.

Table 1
3D acquisition parameters using the conventional method.

Receiver line bearing (azimuth)	N29E
Receiver lines	12
Active channel per line	200
Receiver interval	40 m
Receiver line interval	360 m
Rolling	3
Source interval	40 m
Source line interval	400 m
Cross-line fold	6
Inline fold	10
Bin size	20 m × 20 m
Nominal fold	60
Recording length	6 s
Sampling interval	4 ms
Aspect ratio	0.54

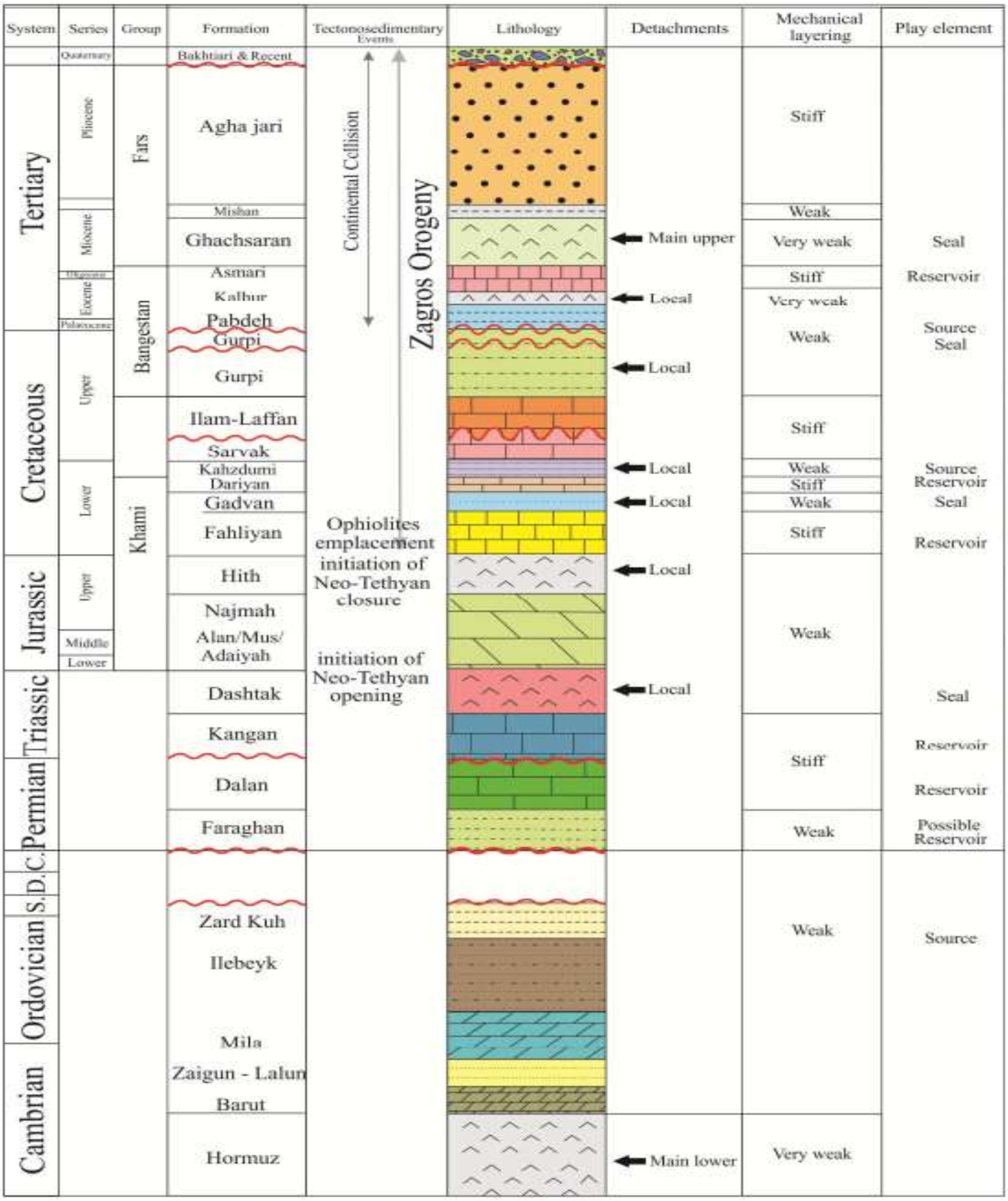
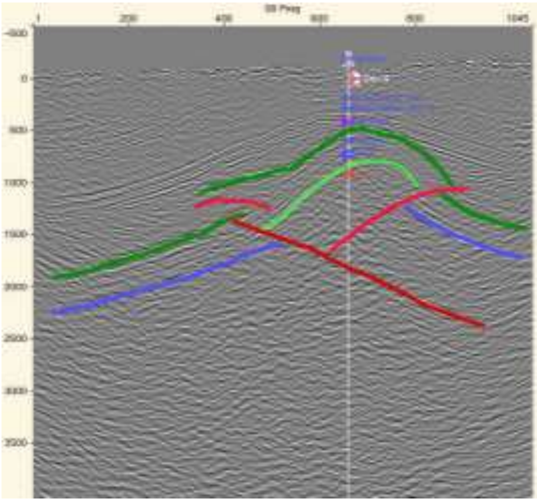


Figure 4

The stratigraphic column of the studied area (Ghanadian et al., 2017).

Figure 5 displays the interpreted 2D seismic stacks with the well location on the crest of the anticline of Line A. The exploratory objective of the present research is to illuminate the fault structures by the determination of the optimum wavelet frequency and to survey geometry azimuth in the area of study. Appropriate survey parameters were obtained using conventional processing techniques applied to the available 2D seismic data and well log data. Moreover, the workflow of the 3D land seismic survey (Vermeer, 2012) in the presence of technical and financial limitations was used for this purpose. Table 1 shows the seismic survey parameters determined by the conventional method in the investigated area.

Line A



Line B

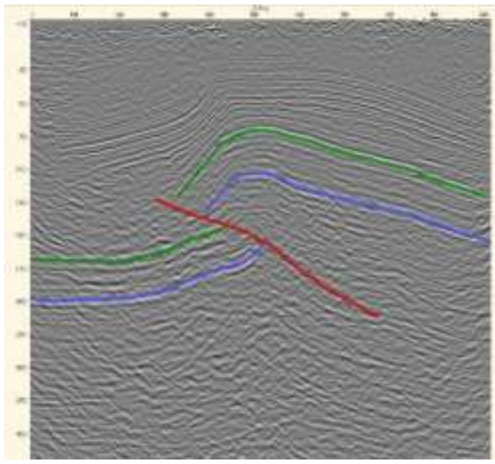


Figure 5
The interpreted 2D seismic sections which show the presence of the complex fault structures; the location of well is in the left section.

For the ray-based modeling, the interval velocity function was obtained through a detailed velocity analysis of the 2D seismic data and was correlated with the data of the well (Figure 6). We used PARADIGM software to create the velocity model. Seismic stacking velocities are mainly processing velocities, which can be converted into the interval and average velocities using the Dix's equation (Dix, 1955). The used workflow of building a velocity model in the current case is illustrated below:

- Converting root mean square (RMS) velocity sections to interval velocity sections.
- Scaling-up the interval velocities from processing to the geocells in the structural model between time horizons.
- Gridding the scaled-up processing interval velocities using an interpolation method.
- Scaling-up the velocities from wells to the geocells in the structural model between time horizons.
- Gridding the scaled-up well interval velocities using an interpolation method.
- Scaling the processing velocities based on the well velocities in all the cells in the structural model.

For investigating the effect of different parameters on the seismic resolution, a 2.5D homogeneous overburden model (velocity and density) was built from the actual model information by considering the horizons and their related velocities between each other (Figure 7). This 2.5D homogenous model was created by SeisRox software.

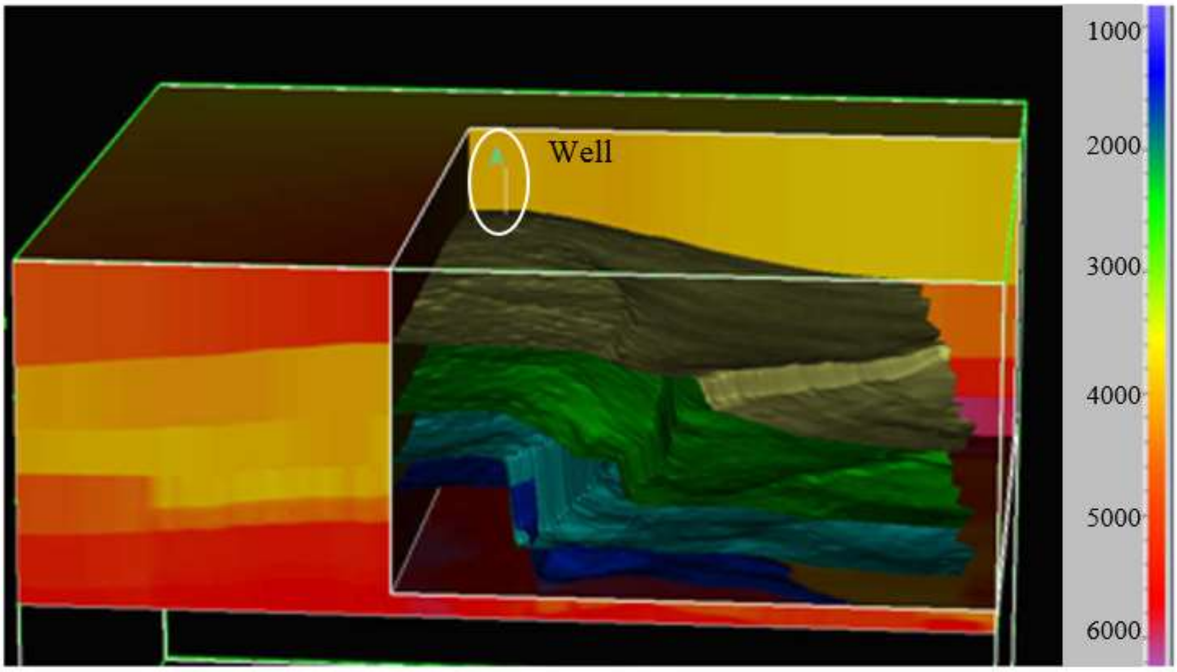


Figure 6
The horizons of the studied area for the ray-tracing modeling; the interval velocity model was built from the 2D seismic data and correlated with the well data.

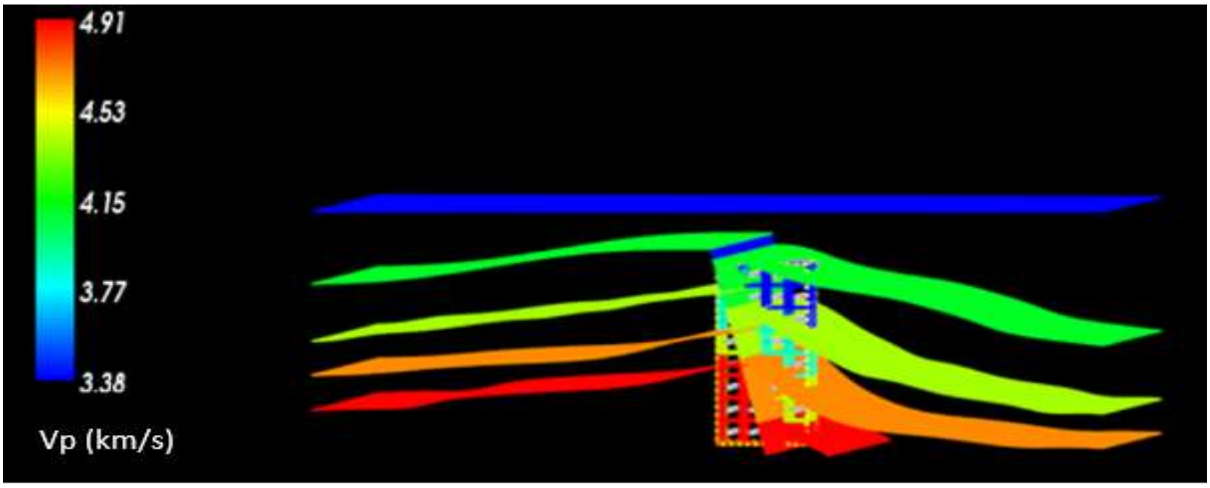


Figure 7
A 2.5D homogeneous overburden model (velocity and density); the grid cube shows the studied fault plane.

4. Results and discussion

Illumination hit maps were created using 3D ray tracing to the target horizon to analyze the effect of the direction of survey geometry on subsurface imaging by NORSAR 3D software. Figure 8a is the illumination map of the target horizon of the generated ray-tracing model. The illumination hole explains the poor coverage in the fault zone, which can be caused by improper shooting direction. The seismic survey designer can investigate the effects of different survey directions on the seismic quality in the model by using the generated illumination maps and some hit-based studies. The flower plot analysis is a useful survey design tool to analyze the acquisition requirements and to illuminate the particular target. This analysis can be used to find the appropriate offset, azimuths, and recording time regarding a specific point on the target. Figure 8b indicates that the best azimuth of the survey direction is N15E, while N29E is determined by the conventional seismic survey designing. Figure 8c shows the change in receiver line bearing; according to Figure 8d, it can fill the illumination hole on the fault plane. Also, the effect of various pulses on the PSDM image was studied in detail through the resulting PSDM images. Figure 9 depicts the effects of using source frequencies of 20, 60, and 80 Hz on the PSF and seismic sections. The results show that the lateral and vertical resolutions of PSF at a frequency of 80 Hz is better than those at other frequencies, but the frequency should be selected based on available instrument and different limitation consideration. The high frequency can improve the imaging; however, it is not always true since the role of illumination may not be seen for the parts that are not illuminated. The significant point is that when a 20 Hz source frequency is used, it is not wise to anticipate imaging the fault plane.

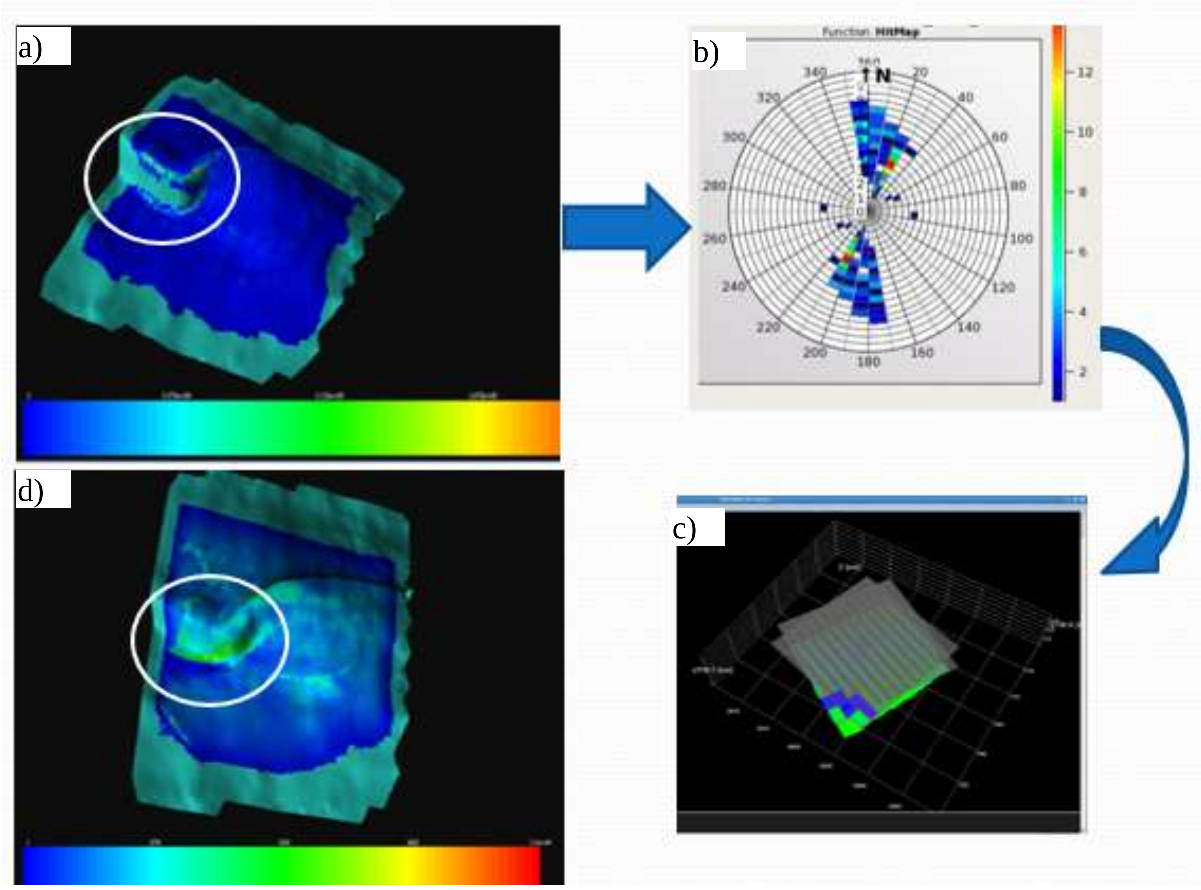


Figure 8
a) The illumination map of the initial survey using the conventional method; the ellipse reveals insufficient coverage of the fault plane; b) the flower plot generated by ray tracing to determine the optimum survey direction; c) changing the survey direction from N29E to N15E; d) the illumination map using the proposed survey; the ellipse reveals better coverage of the fault plane.

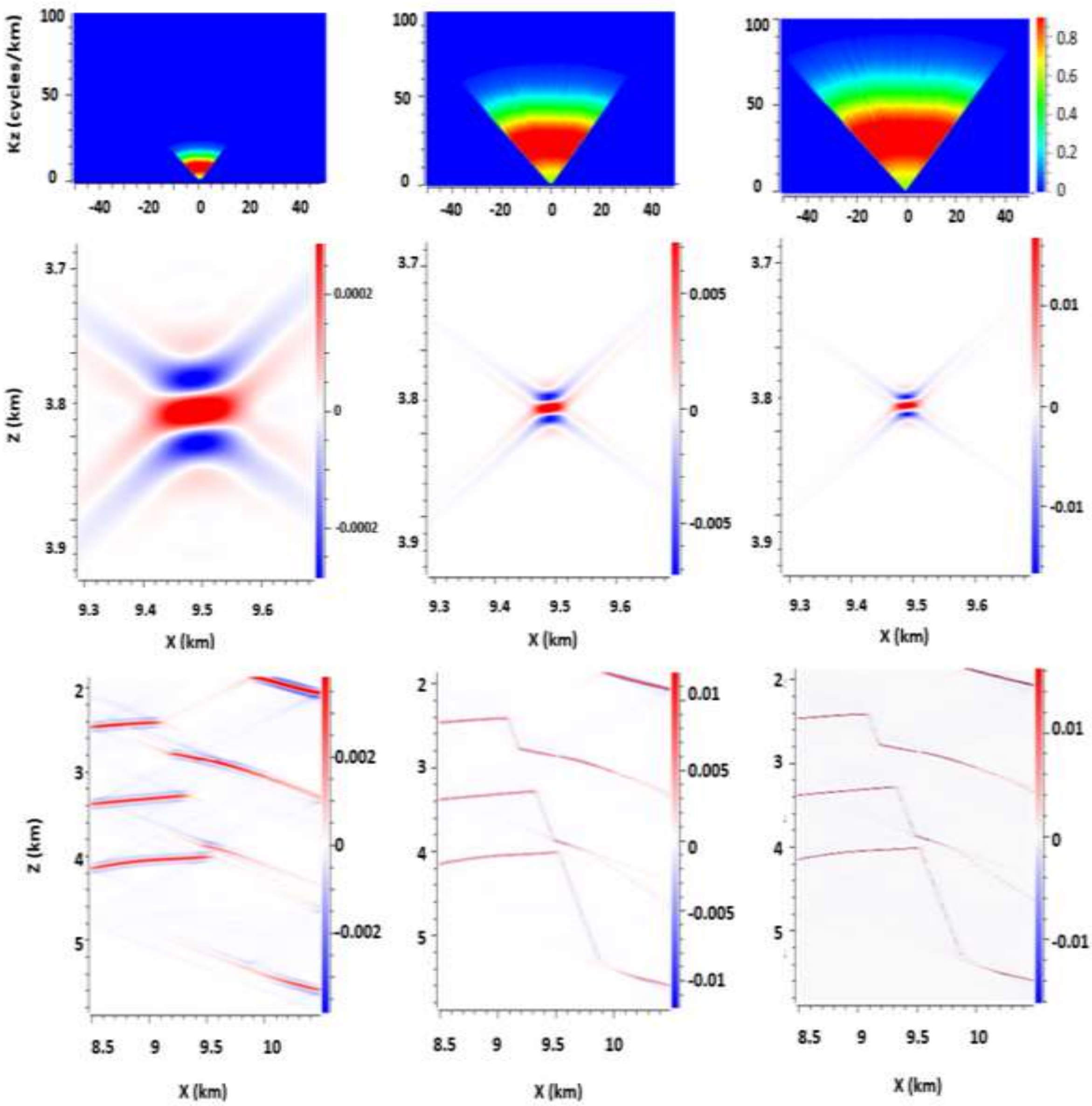


Figure 9

The PSDM filters (top row), PSF (middle row), and the PSDM images (bottom row) for Ricker zero-phase source wavelet at 20 Hz (left column), at 60 Hz (middle column), and at 80 Hz (right column). The 20 Hz source wavelet has a low resolution on the PSF, and the fault plane could not illuminate the PSDM image. The 80 Hz wavelet has a higher resolution compared to the others.

5. Conclusions

The conventional method in the complex structures is not able to provide sufficient results to determine the 3D seismic survey parameters. The model-based method often uses the background ray tracing model and pre-designed survey parameters to estimate the ray path in complex structures. The flower plot and ray-based analyses help the seismic designer optimize the seismic survey orientation so as to illuminate the specific target horizons. In this study, the initial azimuth of the survey direction determined by the conventional seismic survey design was N29E, which was modified to N15E by the proposed ray-based approach. Illumination and resolution analyses were the essential components for optimizing the seismic survey parameters. PSDM simulator was used to investigate the effects of source frequencies and survey geometry direction on the resulting seismic images. We concluded that the 20 Hz source wavelet could not image the target fault plane, but higher frequencies results showed a higher resolution and better recognition of the fault plane. This paper proved that a survey designer could enhance the image of fault planes by better understanding the effects of different survey parameters on the resulting image and through the illumination and resolution analysis of the target horizon.

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Nomenclature

CMP	: Common mid-point
CRP	: Common reflection point
FFT	: Fast Fourier transform
I_{SR}	: Illumination vector
MA	: Migration aperture
P_R	: Parallel to the scattered ray
P_S	: Parallel to the incidence ray
PSDM	: Pre-stack depth migration
PSF	: Point spread function
RI	: Receiver interval
RLI	: Receiver line interval
RMS	: Root mean square
SI	: Source interval
SLI	: Source line interval
z	: Depth
θ	: Related to incident angle θ

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