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Numerical modeling of influence of ice formations under seismic impacts based on grid-characteristic method

Polina Stognii[a,b], Dmitriy Petrov[a,b,c], Nikolay Khokhlov[a,c], Alena Favorskaya[a,c,]*

[a]*Moscow Institute of Physics and Technology, 9 Institytsky Pereylok st., Dolgoprudny, Moscow Region, 141700 Russian Federation*
[b]*Institute of Computer Aided Design of the Russian Academy of Sciences (ICAD RAS)*
[c]*Scientific Research Institute for System Studies of the Russian Academy of Sciences, 36(1) Nahimovskij av., Moscow, 117218 Russian Federation*

Abstract

Today the Arctic is one of the most important regions, where lots of oil and gas deposits are located. The Arctic contains different ice formations that give rise to problems of the North seas' exploring. The models ought to simulate the situations with the presence of ice constructions and oil slices. The main goal is to find the difference between responses from oil slices and ice formations. This paper represents the modeling results with ice cover and ice field. Wave patterns and seismograms are depicted for each model. Different cases of installing the source of impulse and receivers are examined.

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Keywords: grid-characteristic method; numerical modeling; Arctic seismic prospecting; ice cover; ice field.

1. Introduction

Development of the Arctic is caused by the necessity to elaborate many oil deposits; their supplies are estimated by approximately 7.8 billion tons[1]. The considerable barrier on the way of oil extraction in the North seas is the presence of different ice formations, ice cover, and icebergs, in particular[2]. Seismic exploration[3] with present ice constructions is more difficult and sparser in comparison with other oceans[4]. One of the main stages in planning the geological survey works is mathematical modeling which allows to bring down the cost of carrying out seismic

* Corresponding author. Tel.: +7-495-408-66-95; fax: +7-495-408–42–54.
E-mail address: aleanera@yandex.ru

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exploration significantly. In current research, the results of numerical experiments in seismic exploration in the conditions of the Arctic shelf[5] are depicted.

The main problems of development of the Northern Sea Route with the extent 2200-2900 nautical miles from the Novaya Zemlya to the Bering Strait are associated with difficult ice conditions and necessity of using powerful icebreakers that can move into the ice cover with thickness up to 2 m (now the track has 7 icebreakers, diesel-electric icebreakers and ice-class vessels). Ice hummocks, ice, and icebergs are often a serious impediment to these ships. Large ice formations also represent a danger to stationary ice-resistant platforms and sea bed pipelines[5-7].

The movement of ice masses occurs under the influence of winds and streams. The ice cover is characterized by the presence of icebergs, ice hummocks, drifting ice, cracks in the ice, and spring floods[8-10]. The presence of ice hummocks materially affects on the ice surface roughness and leads to the increase of friction forces from wind and streams. The average distance between sails of ice hummocks in various regions of the Arctic is about 200-300 m, the height of the hummock sail can reach several meters, and the depth can reach a few tens of meters. The problems of ice ridging are discussed in papers[11-15]. The characteristic dimensions of icebergs are more than several times bigger than the characteristic dimensions of ice hummocks. For example, during most part of the year the Pechora Sea and the Kara Sea are covered with drifting ices, the speed of such ices may exceed 5 m/s, the thickness of plane ice is up to 2 m, the thickness of draft ice hummocks is 20 m. Thus, the structure and parameters of ice cover of the Northern seas are significant parameters determining the extreme loads at fixed and floating offshore oil and gas industrial structures. Therefore, it is very important to model the dynamic processes in the air, water, and soil of the Arctic, as well as the processing of observation results, prediction of ice conditions, and the estimation of further stability of stationary platforms, sea bed pipelines, further security of icebreakers and ice-class vessels[16,17].

The hydrocarbon exploration in the Arctic area has its own specificity. In particular, one of the layers, through which the seismic signals propagate, is the sea[18-20], the other layer is the ice. The icebergs, ice hummocks, drifting ice, and ice cover have also contribution to the measured or calculated responses in seismic prospecting. During exploration work on land, one must take into account the effect from the permafrost. In addition to seismic technology, the electrical exploration of hydrocarbons is an effective approach. The review of studies on this topic is given in papers[21,22].

The paper is organized as follows. Section 2 describes the basic mathematical models, including the central equations and grid-characteristic method. Section 3 represents two models with ice cover and ice field and wave patterns for each model. Section 3 provides the analysis of seismograms for these two models with different cases of installation of source of impulse and receivers. Section 4 concludes the paper.

2. Mathematical models

The models of continuum described by the linear-elastic statements[23,24] are represented by Eqs. 1-2, where ρ is the density of the material, c_p is the speed of P-waves into the material, c_s is the speed of S-waves into the material, $\vec{v}$ is the field of velocity in the material, $\boldsymbol{\sigma}$ is the field of the stress tensor.

$$\rho \frac{\partial \vec{v}}{\partial t} = \left(\nabla \cdot \boldsymbol{\sigma}\right)^{\mathrm{T}} \tag{1}$$

$$\frac{\partial \boldsymbol{\sigma}}{\partial t} = \rho\left(c_p^2 - 2c_s^2\right)\left(\nabla \cdot \vec{v}\right)\mathbf{I} + \rho c_s^2 \left(\nabla \otimes \vec{v} + \left(\nabla \otimes \vec{v}\right)^{\mathrm{T}}\right) \tag{2}$$

In order to simulate an oil slice and a slice of sea-water numerically, the approximation of perfect liquid[25] was used. The total set of equations, describing the acoustic field of pressure p and components of velocity v, was being tackled using Eqs. 3-4, where ρ is the density of the material, c is the speed of acoustic waves into the material.

$$\rho \frac{\partial \vec{v}}{\partial t} = -\nabla p \tag{3}$$

$$\frac{\partial p}{\partial t} = -c^2 \rho (\nabla \cdot \vec{v}) \tag{4}$$

Boundary conditions were realized with such given quantities as speed of boundary and outside force[26]. In addition, mixed boundary conditions[27], contact conditions of absolute adhesion, free slip[28], contact between liquid and solid body were used. The grid-characteristic method[10] was used for numerical solving of set of Eqs. 1-2 and Eqs. 3-4. This method allows to build correct numerical algorithms while calculating points on boundaries and also points, which lie on surfaces of division of two media with different densities and different Lame parameters. In all calculations, the grid-characteristic scheme with third order of accuracy was applied[29-33].

3. Models with ice cover and ice field

The great number of icebergs (almost uniformly arranged along the surface of water)[2,4] and simple slice of ice 2-3 m high are frequently met in the North seas. Their influence on wave patterns takes into account while searching the underwater part of sea on oil accumulations. In such a way, the numerical experiments of influence of ice cover and ice field (which means more or less uniform distribution of icebergs along all the surface of water) on wave responses in the Arctic conditions were carried out. In all cases (in number of four), the step in space was 1 m, step in time was 10^{-4} s. In whole, 15,000 steps in time were made. On each side, the non-reflective conditions[29-33] were considered. For all models, the impact was carried out with the help of Riker impulse.

In models, the slice of water 200 m high and a slice of soil 1000 m high were examined. The width of range of integration was equal to 2000 m. The density of water was 1000 kg/m^3 and the density of soil was 2100 kg/m^3. The velocity of sound in water was equal to 1500 m/s, in the ground the velocity of longitudinal waves was 3000 m/s, and the velocity of transverse waves was 1875 m/s.

First, two models with ice cover on surface of water and source of impulse both on the surface of ice and on bottom of sea were examined. The density of ice was 917 kg/m^3. The velocity of longitudinal waves in the ice slice was equal to 3940 m/s and the velocity of transverse waves achieved 2493 m/s. The source of impulse was situated in the center of all the range of integration. In addition, the model included (or didn't include) the oil slice at a depth of approximately 700 m under the ground, which was 20 m in width. The density of the slice was 1800 kg/m^3. The velocity of longitudinal waves in it was equal to 2500 m/s, and the velocity of transverse waves was 2000 m/s. Second, calculations of influence of ice field on wave responses and with a source of impulse situated both on the surface of water and on the bottom of the sea were made.

The oil slice, like in the first two models, was present under the ground in the same place (or wasn't present). All the parameters of ice and layer were taken the same. Icebergs in calculations were represented as triangular clutters of ice at distance of 30 m from each other along all the surface of water. The schematic representation of all four models is introduced in Fig. 1.

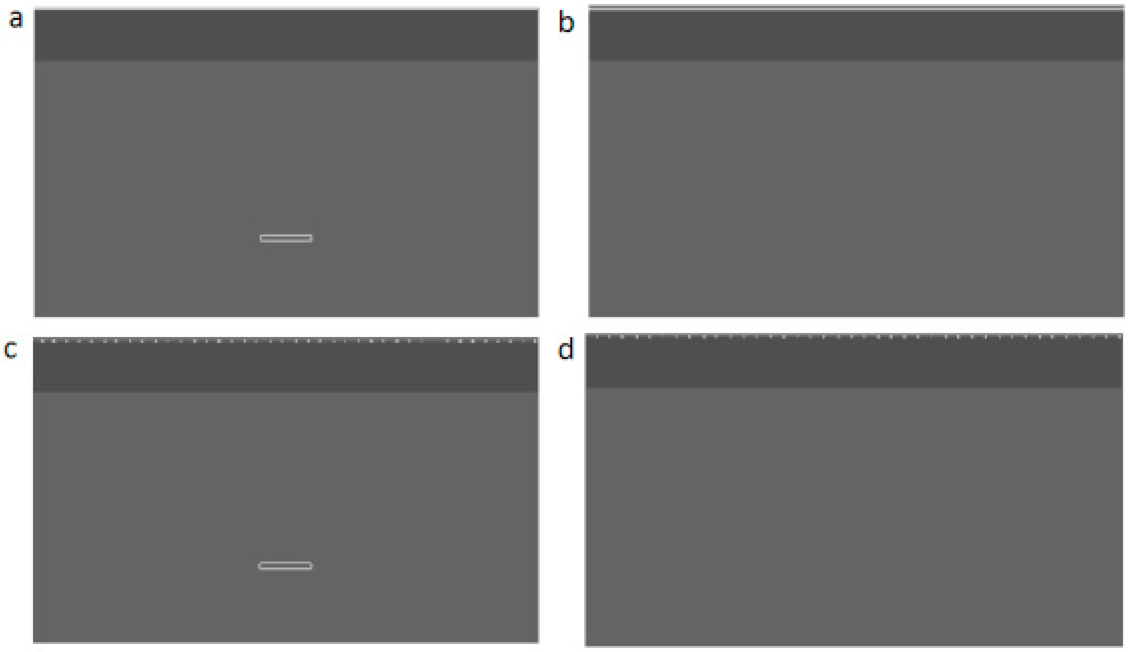

Fig. 1. (a) the model with an ice cover and oil slice; (b) the model with an ice cover without an oil slice; (c) the model with an ice field and oil slice; (d) the model with an ice field without an oil slice.

The wave patterns at time 0.5 s and 0.36 s are depicted in Fig. 2. The models with a slice of ice and ice field with a source of impulse on surface of ice and water at time 0.5 s are represented in Fig. 2a-2b, respectively. The models with a slice of ice and ice field and a source of impulse on the bottom of the sea at time 0.36 s are shown in Fig. 2c-2d, respectively. It is noticeable that a slice of ice, as well as an ice field, doesn't influence wave patterns significantly. Only in the case of ice field there are lots of responses (from each iceberg) but they are completely different from the response, coming from the oil slice.

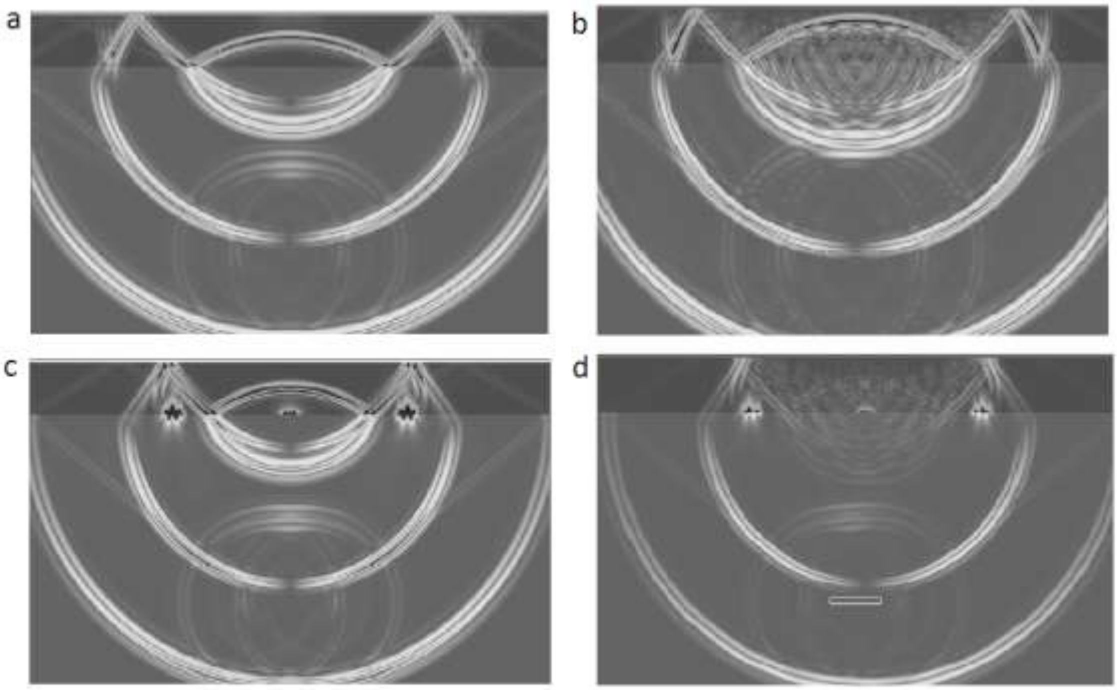

Fig. 2. (a) ice cover and oil slice, source of impulse on surface of ice; (b) ice field and oil slice, source of impulse on surface of water; (c) ice cover and oil slice, source of impulse on the bottom of the sea; (d) ice field and oil slice, source of impulse on the bottom of the sea.

4. Seismograms for models with ice cover and ice field

Seismograms based on models with an ice cover and present/absent oil slice are represented in Fig. 3. Detectors are situated both on the surface of water and on the bottom. In all cases, a source of impulse was on the surface of water. In case of oil slice being present and detectors on surface of water (Fig. 3a), the diagram turned out to be more distinct, and that's why it is easily distinguished from that without a slice (Fig. 3c). If detectors lie on the bottom (Fig. 3b-3d), the seismograms with present and absent oil slice differ much more than in case, when detectors are on the surface. As a result, the detectors on bottom are the most informative, while exploring underwater slices on oil.

Seismograms for the model with an ice cover with a source of impulse on bottom are introduced in Fig. 4. Detectors are situated only on surface of water. Diagrams in this case have a significant difference. In Fig. 4a, there are extra wave lines, which point out to the presence of an extra slice. Comparing this way of establishing equipment (source of impulse is on bottom, detectors are on surface), it will turn out to be more demonstrative while revealing an oil slice than in case, when both, a source of impulse and detectors, are situated on surface.

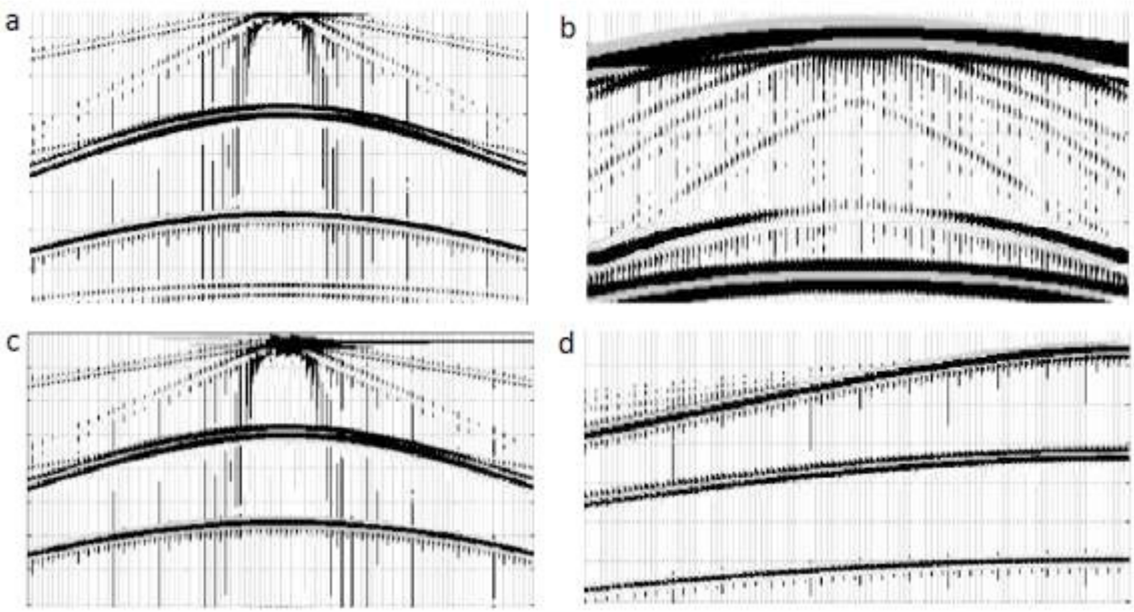

Fig. 3. (a) the oil slice is present, detectors are on the surface; (b) the oil slice is present, detectors are on the bottom; (c) no oil slice, detectors are on the surface; (d) no oil slice, detectors are on the bottom.

Seismograms for the model with an ice field and present/absent oil slice are introduced in Fig. 5. The source of impulse was situated on surface of water. In case, when detectors lie on the bottom (Fig. 5a-5c), the difference between present oil slice and its absence is better noticed than in case, when detectors are on the surface of water (Fig. 5b-5d). Yet it is possible to differentiate cases of present and absent oil slice from all the seismograms, that's why we can conclude that even great number of icebergs on surface of water (called an ice field) doesn't influence spotting places of oil deposits considerably.

Seismograms for the model with an ice field and a source of impulse on the bottom are introduced in Fig. 6. The detectors are situated on the surface. In this case the diagrams differ much more, concerning present/absent oil slice than in the situation, when both, the source of impulse and detectors, are on the surface of water.

5. Conclusions

In this paper, the results of numerical modeling of wave propagation with the acoustic and linear-elastic slices were represented. The problems of seismic exploration in the Arctic under different conditions were examined. In particular, the results of computation of models with ice cover and ice field were represented through wave patterns and seismograms for each model. In addition, cases of different installation of source of impulse and receivers were examined. Based on the calculations obtained, it is possible to distinguish responses from different ice formations from those from oil slices, avoiding the high cost of field experiments.

Acknowledgements

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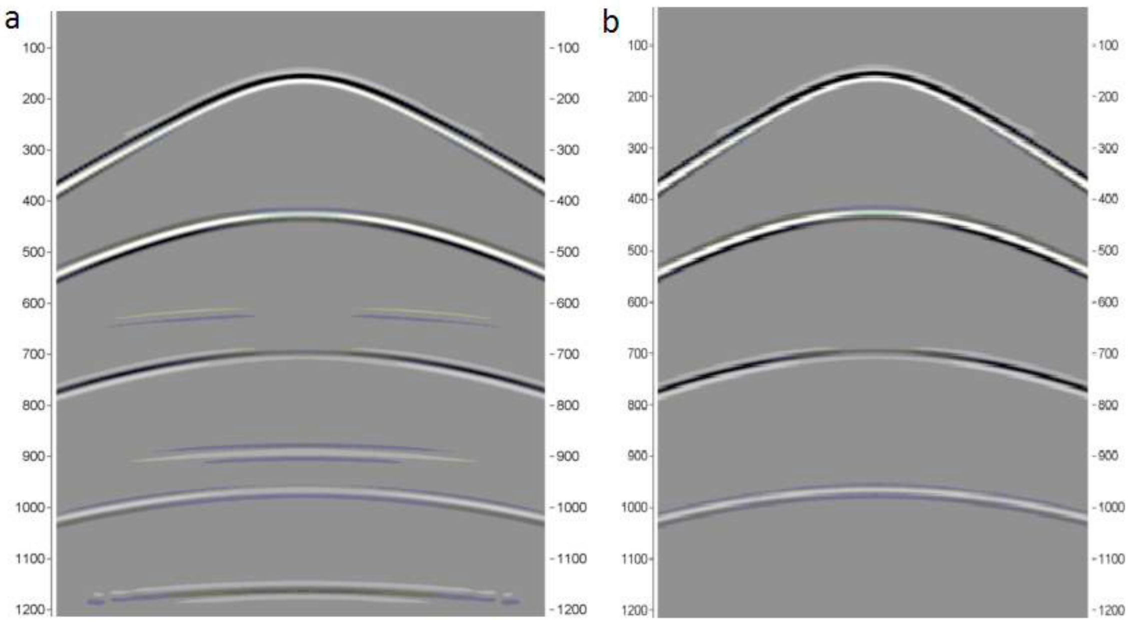

Fig. 4. (a) seismogram with an oil slice is present; (b) seismogram without an oil slice.

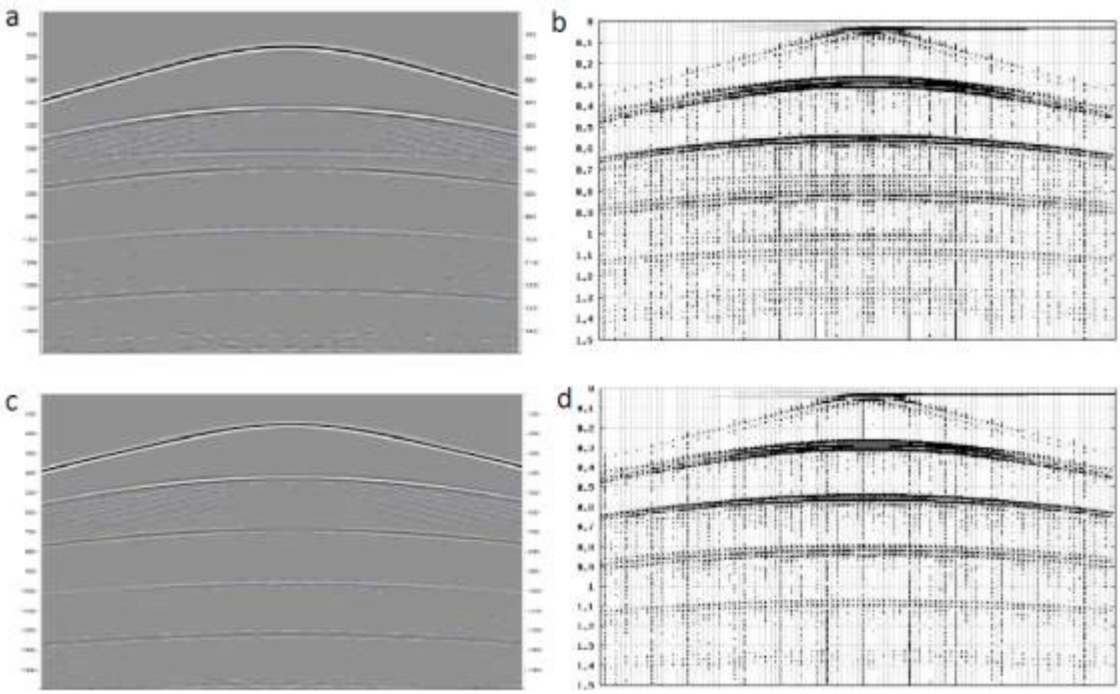

Fig. 5. (a) the oil slice is present, detectors are on the bottom; (b) the oil slice is present, detectors are on the surface; (c) no oil slice, detectors are on the bottom; (d) no oil slice, detectors are on the surface.

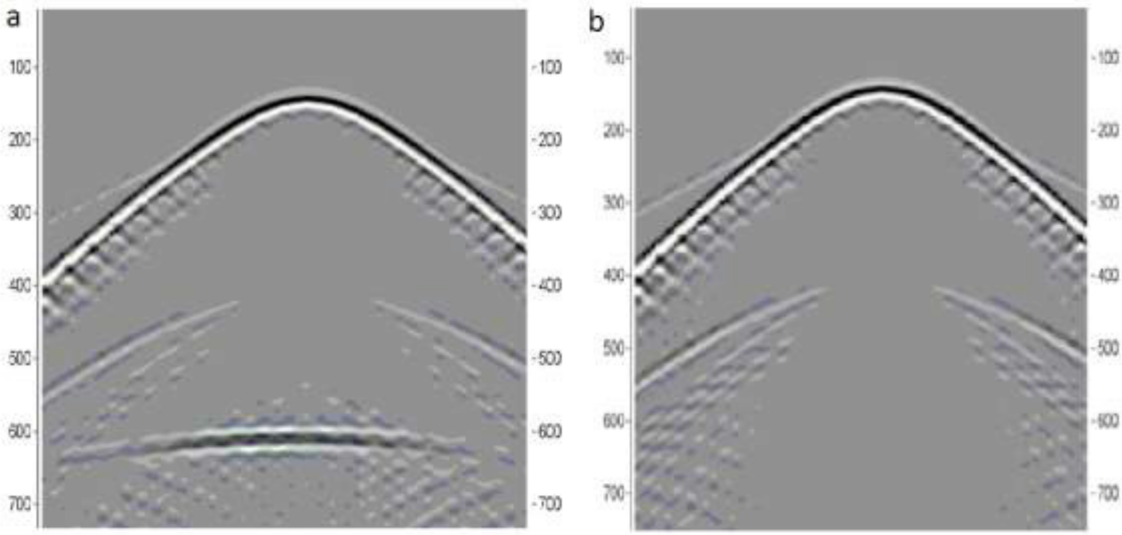

Fig. 6. (a) seismogram with the oil slice; (b) seismogram without oil slice.

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