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The precision of the migration image of the depth section on the seismometry observations on northwestern Black Sea shelf

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For many years, the Institute of geophysics has been developing original versions of the finite-difference migration and wavefield modeling techniques for a valid reproduction of the geological cross-section. The modeling provides a practical test of the accuracy of the reproduction of various geological structure features on a migration result and a way to define, in the observed field, the waves which can be used to produce a migration image of the geologic environment efficiently.

In 2013, the Institute conducted a marine seismic investigation with reflection CDP (Common Deep Point) profiles on the continental slope of the NW part of the Black Sea. The registered wavefields were processed using full-wave finite-difference post-stack migration. The efficiency and validity of the processing methods for various geological structures were evaluated with the help of finite-difference modeling of the wavefield based on solving the wave equation on a grid with a seven-point pattern.

The study validates the precision of marine seismic data processing using full-wave finite-difference post-stack migration with the help of wavefield modeling.

Key words: Black Sea shelf, finite-difference post-stack migration, CDP-reflection data, seismic exploration.

Introduction. In 2013, the S.I. Subbotin Institute of geophysics conducted seismometry observations within the State Special Research Program "Comprehensive evaluation of the current state and a forecast of the dynamics of the marine environment and resources of the Azov-Black Sea Basin". The profiles were acquired by the reflection CDP method on the research vessel "Profesor Vodianytskyi". They were recorded by a digital seismic telemetry complex consisting of the central station (XZone® Bottom Fish) and overboard equipment (a system of air-gun shots and registration of the wavefield with a 72-channeltowed streamer 345 m long). The distance between hydrophones in the towed streamer was 3 m, and that between the sources (air-gun shots) was 12.5 m. The towed streamer was 90 m away from the excitation source at a depth of 3 m. The record time was 4 s long with a sampling of 0.5 ms [Kobolev et al., 2013].

The seismic reflection profiles recorded on the NW shelf of the Black Sea in 2013 were processed using the finite-difference full-wave post-stack migration [Verpakhovskaya et al., 2013]. The resulting wave images reflected the features of the upper crust structure in the Black Sea area. The method's rationale was proved to be mathematically correct earlier [Verpakhovskaya, 2017]. However, we had to test the practical validity of the obtained migration cross-sections along seismic profiles to confirm the imaged discontinuities for a quality interpretation.

The efficiency and the accuracy of specific details of the subsurface structure near a sea bed recovered with this version of seismic migration were tested by modeling the wavefield given the geological models corresponding to the deep structure of the study area. The modeling was done for a real observation system set up for the reflection survey on the NW shelf of the Black Sea in 2013. Marine seismic data should be processed taking into account the wavefield's specific features depending on the shots and receivers [Orlenok, 1997; Hutton et al., 1989].

The main task of the processing of marine seismic observations is filtering out the interference waves. They include, among others, reverberated and satellite waves [Orlenok, 1997; Hutton et al., 1989]. Reverberation is multiple reflections with short ray paths from the border of the water column; satellite waves can originate in the source as well as in the receivers themselves, and the time of their registration in the wavefield depends on the depths of the source and of the receiver. A general outline of the origin of the reverberation and satellite waves is given in Fig. 1.

Besides that, in the wavefield, there can be present waves that would yield a boundar profiled lower than the real one because of multiple reflections as the air-gun goes off in the water column (the double burst). In such a wavefield, all recorded elements are repeated at intervals of 0.1—0.4 s. Deconvolution is applied to quench the interference waves arising from the double burst and reverberation. Thus, pretreatment of the observed wavefield is one of the essentials which guarantee the valid application of the finite-difference migration to obtain the deep structure of a seismic profile.

A practical proof of the migration's validity can be done by wavefield modeling which allows defining the effective wave and the noise in an observed wavefield. Modeling a wavefield requires a velocity model of the real geological environment, which is used during imaging the deep cross-section by the finite-difference migration.

The finite-difference modeling of the wavefield, developed in the S.I. Subbotin Institute of geophysics, is based on the direct downward continuation of the field from a point source. Mathematically it is realized by solving the wave equation on a grid with a seven-point pattern. For the modeled example, we recreated the registration system employed during real marine observations and chose a velocity model typical for the deep structure of the upper part crust of the NW Black Sea shelf.

Processing marine seismic observations by the finite-difference full-wave post-stack migration method. The processing algorithm starts with data preparation (converting and editing trace passports), followed bypre-treatment (filtering, deconvolution, amplitude boosting, kinematic corrections, and stacked traces by the CDP method, which yields a CDP-stacked section. The last step is computing the finite-difference post-stack migration. It is the optimal way to produce an image of the geo-

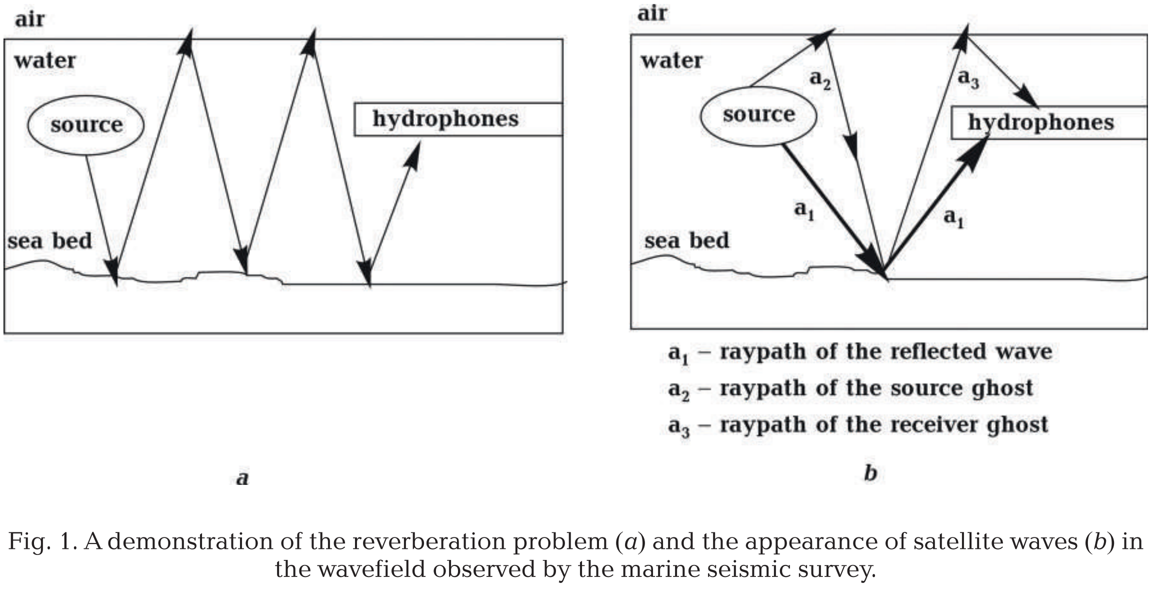

Fig. 1. A demonstration of the reverberation problem (*a*) and the appearance of satellite waves (*b*) in the wavefield observed by the marine seismic survey.

logical cross-section to interpret the seismic observations. The mathematical rationale of this version of migration was proved in [Verpakhovskaya et al., 2013], studying the stability of the solution and the degree to which the differential equation is approximated by the finite-difference one. Thus, it remained to test the accuracy with which the details of the deep structure of the environment are recovered in the resulting migration image.

The most prominent feature of the marine seismic data of 2013 is the presence of very strong low-frequency interference waves. Although they are probably an artifact created by the equipment fixing the receivers at a certain depth, their origin still needs a more thorough consideration. Given the interference, it was necessary to filter the data to isolate and boost the signal. Fig. 2 shows the observed wavefield for a single excitation source before (*a*) and after the procedure (*b*). It can be seen that the chosen settings allowed discarding the low-frequency component. After the data were formatted, the traces' passports edited, and the obtained set filtered, all records of separate excitation sources were compiled for further treatment. Fig. 3, *a* presents the collective wavefield of all shot gathers for one profile observed in 2013.

The next, more demanding treatment procedure of the reflection seismic data processing is stacking the traces by CDP. It is necessary to enter a kinematic correction into the observed wavefield as computed for a given wave velocity in the geological environment. Thus, to stack the traces by CDP correctly, one needs to determine the wave velocity in the region as precisely as possible. Fig. 4 shows most clearly the extent to which the CDP stack of traces results depend on the chosen wave velocity.

A CDP-stacked section is a standard result of data treatment by the reflection seismic survey technique. A CDP-stacked section for

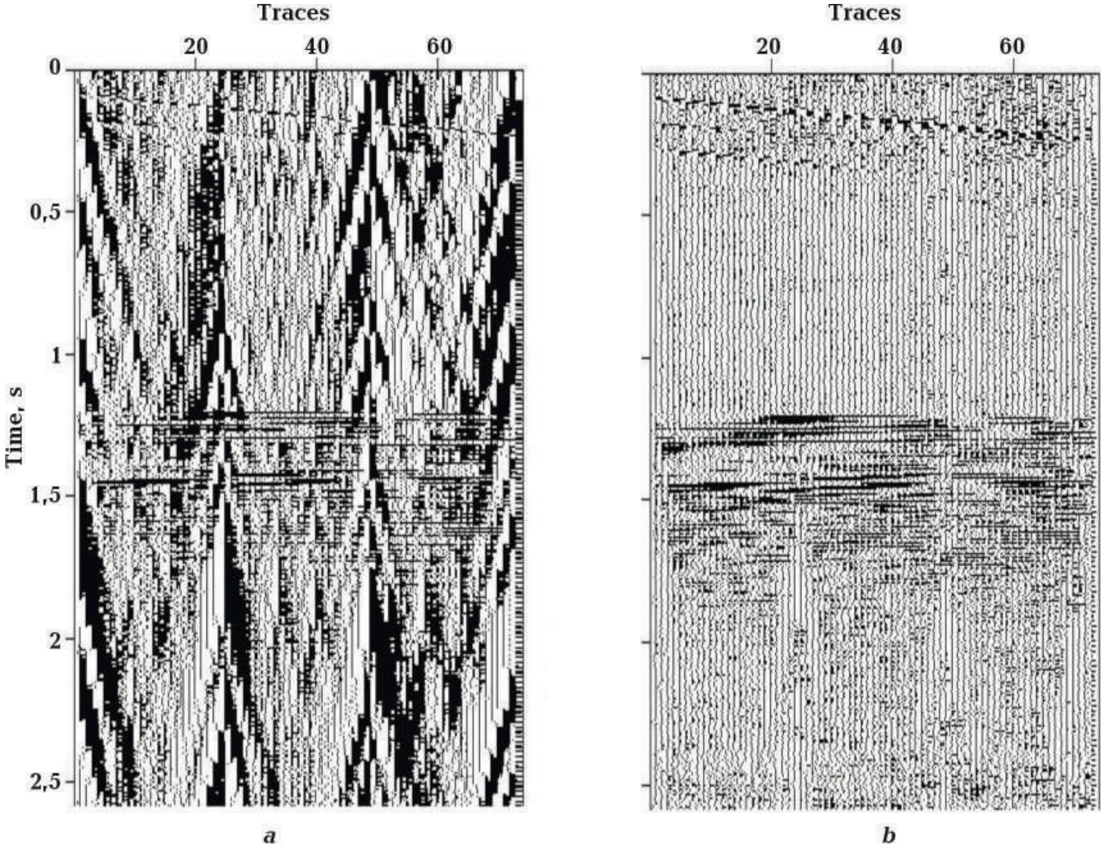

Fig. 2. The observed wavefield for a single shot point before filtering (*a*) and after (*b*).

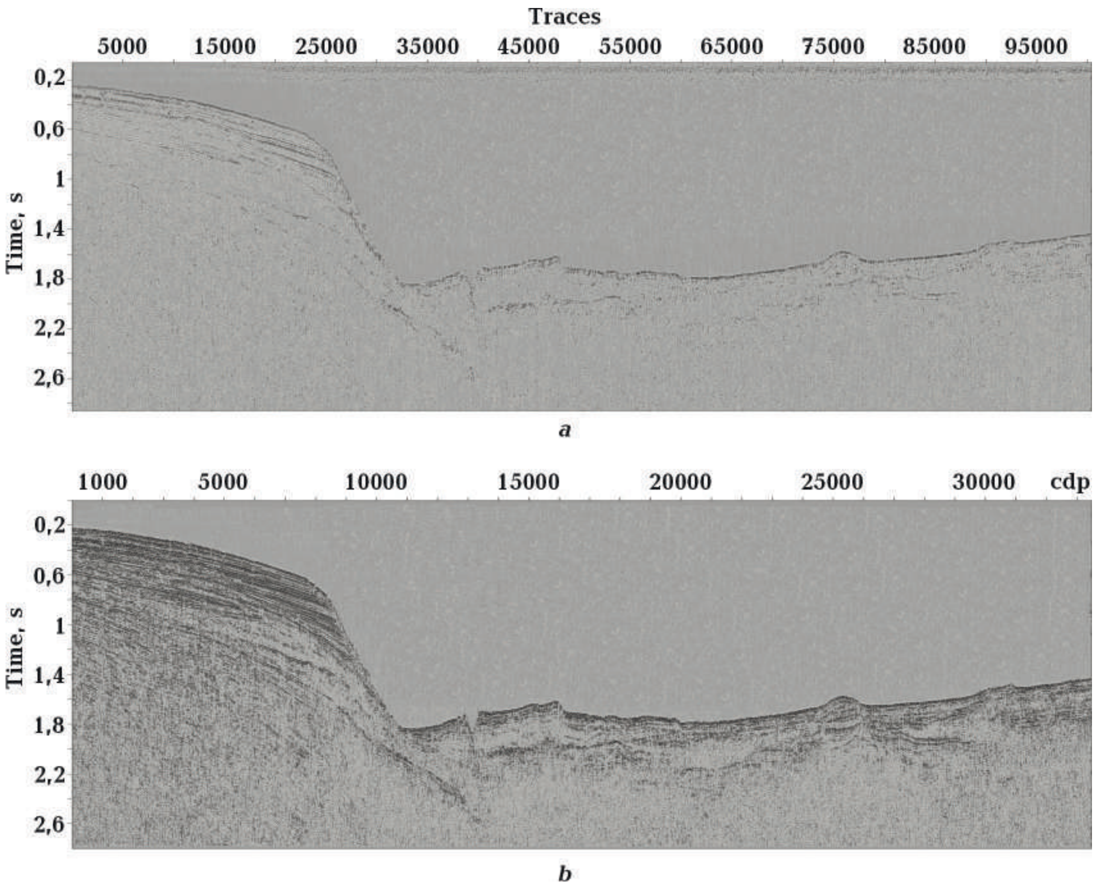

Fig. 3. An example of the normalized wavefield for all observation points and the CDP-stacked section for one of the profiles observed in 2013 on the Black Sea shelf.

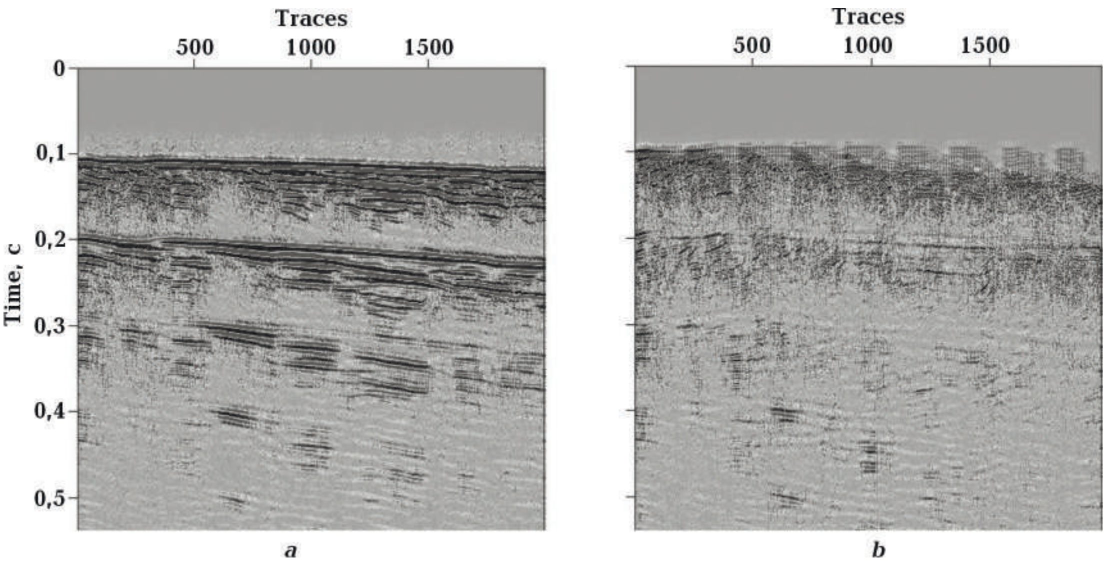

Fig. 4. A demonstration of the velocity's effect on CDP: real velocity (*a*) and false velocity (*b*).

one marine profile observed on the NW shelf of the Black Sea in 2013 is given in Fig. 3, *b*. However, to interpret the seismic observations accurately, one has to execute post-stack migration, which allows more precise mapping of the boundaries and other features of a geological section along the profile. As our research has shown, to process the data of a marine seismic survey with reflection CDP profiles, the optimal version of migration is the finite-difference fullwave post-stack migration. It yields a stable and accurate result because the differential wave equation is well-approximated by a finite-difference one given a special grid with a 12-point space-time pattern [Verpakhovskaya et al., 2013].

A finite-difference fullwave post-stack migration provides a more detailed structure of the vertical profile than the CDP-stacked section. Fig. 5 displays the comparison of two sections. The migration (Fig. 5, *b*) includes details of some boundaries present in the profile which are absent or unclear in the CDP-stacked section (Fig. 5, *a*).

Modeling the efficiency and validity of the finite-difference fullwave migration after trace summation by the CDP method. Wavefield modeling is based on the direct downward continuation of a point source field based on the finite-difference solution of the scalar wave equation. The latter has the following appearance in the Cartesian coordinates:

$$\frac{d^2 u}{d x^2} + \frac{d^2 u}{d y^2} + \Psi = \frac{1}{V^2(x, z)} \frac{d^2 u}{d t^2}, \quad (1)$$

where u is the amplitude of the wavefield, $V(x, y)$ — velocity of the seismic waves in the point with coordinates x, z, ψ — the external source. Thus the wave field is a function of the spatial coordinate and time.

The external source is presumed in the point x_0, z_0 which belongs to the computation

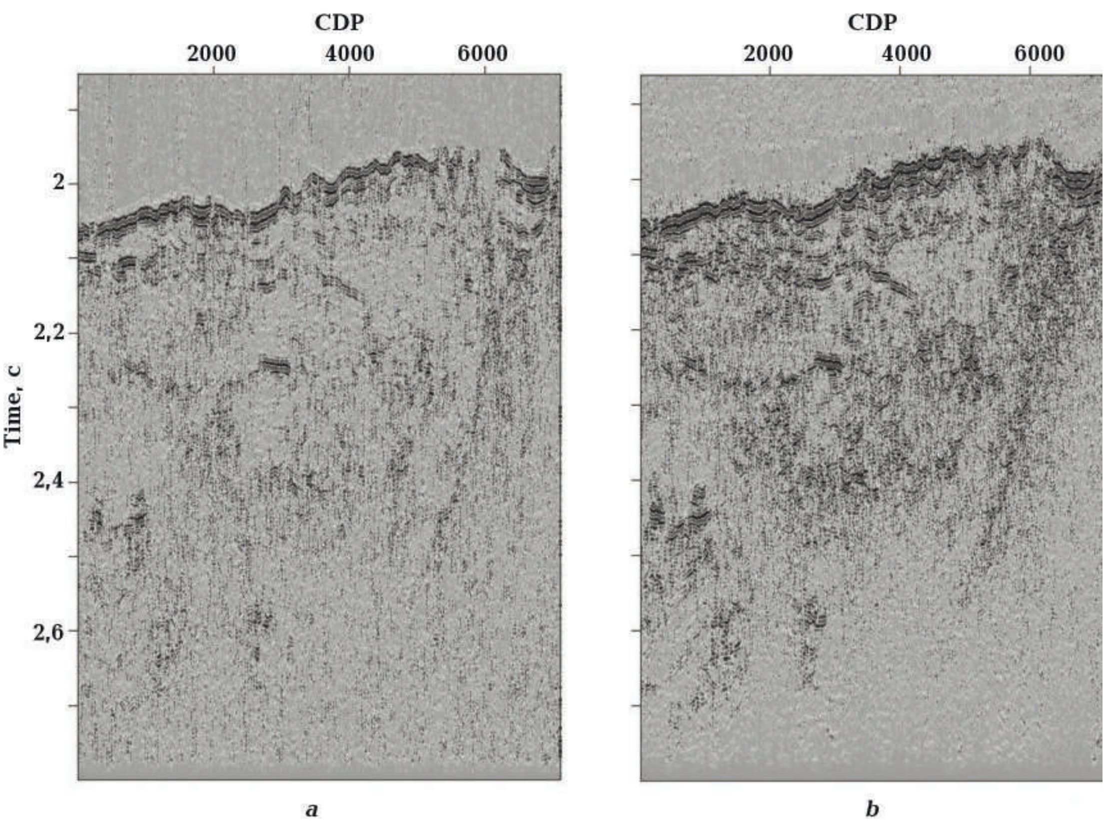

Fig. 5. CDP-stacked section (*a*) and the result of fullwave finite-difference post-stack migration (*b*).

area of the field continuation, according to the Berlage pulse formula:

$$u\left(x_0, y_0\right) = \alpha \sin\left(2\pi \frac{t}{p}\right) t \exp\left(-\frac{t}{r}\right),$$

where p is dominant pulse period, r — decay factor, t — time, α — amplitude.

The finite-difference wavefield continuation is done using a three-dimensional space-time grid with grid coordinates i, j, k, which correspond to the coordinates x, z, t with the grid steps Δx, Δz, Δt.

The wavefield is continued by an explicit scheme on the special difference grid with a seven-point pattern (Fig. 6):

$$u_{i,j}^{k+1} = 2u_{i,j}^{k} - u_{i,j}^{k-1} +$$

$$+ V_{i,j}^2 \left[\frac{\Delta t^2}{\Delta x^2} \left(u_{i+1,j}^{k} + u_{i-1,j}^{k} \right) + \right.$$

$$+ \frac{\Delta t^2}{\Delta z^2} \left(u_{i,j+1}^{k} + u_{i,j-1}^{k} \right) -$$

$$\left. - 2u_{i,j}^{k} \left(\frac{\Delta t^2}{\Delta x^2} + \frac{\Delta t^2}{\Delta z^2} \right) \right], \qquad (2)$$

where $u_{i,j}^{k}$ is the wavefield value in a grid point with the coordinates (i, j, k); $V_{i,j}$ — velocity in the point (i, j).

The boundary conditions of the direct wavefield continuation are:

$$u_{i,j} = 0 \quad \text{for} \quad i = 0; \quad i = n; \quad j = m;$$

$$u_{1,j} = u_{-1,j}\,, \qquad (3)$$

where $n + 1$ — number of nodes along the axis X; $m + 1$ — number of nodes along the axis Z.

At the boundaries of the grid area, it is assumed that: $u = 0$.

The wavefield is computed according to equation (2) in all points at the timelevel $k + 1$ given the wavefield values at time levels k and $k - 1$.

The explicit finite-difference scheme (2), (3) has conditional stability under the quadratic approximation of the original differential equation (1). The stability condition was determined by studying the stability of the solution, and it establishes the relationship between the grid steps Δx, Δz, Δt [Samarskiy, 1983]:

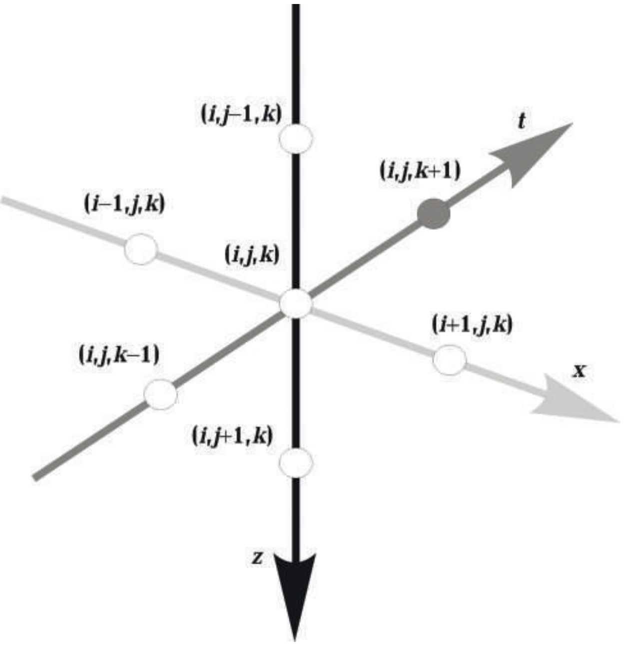

Fig. 6. The 7-point grid template for inverse continuation of the wavefield.

$$\Delta t\, V_{\max} \le \frac{\Delta x^2 + \Delta z^2}{\sqrt{\Delta x^2 + \Delta z^2}}.$$

A velocity model of the geological environment is described by a set of boundaries unbroken along the seismic profile and unambiguous relative to the profile line. The velocity parameters of a column section between two described limits are set by additional parameters according to the profile coordinates.

The algorithm of the wavefield modeling of the reflection CDP profile presumes entering observation system parameters: the number of shot points, start profile coordinates, step between shot points, step between receivers, maximum offset, maximum calculation time, and step for time. This way, the wavefield is modeled for the profile with a given number of shot points.

Fig. 7 provides a fragment of a wavefield along a marine profile registered in 2013, demonstrating a transitional zone from the Black

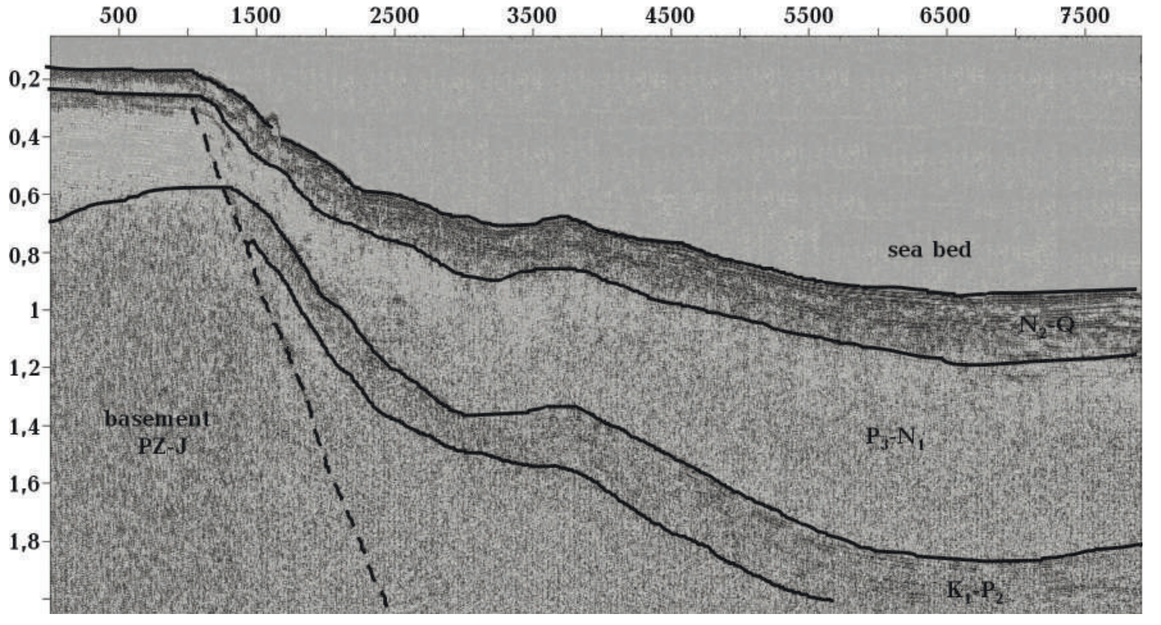

Fig. 7. Fragment of the wavefield with conditional elements of the stratigraphic interpretation in the transitional area between the NW Black Sea shelf and the continental slope together with the adjacent area of the W Black Sea depression. Pz-J — Paleozoic-Mesozoic foundational rocks; K_1-P_2 — non-partitioned sediments from the Lower Cretaceous to Eocene; P_3-N_1 — clayey sediments of the Maikop series; N_2-Q — intermittent strata of clays and sands from Middle Miocene to the Quaternary.

Sea's NW shelf to the continental slope, and the adjacent part of the West Black Sea Depression. The sea bed there is 1200—2000 m deep. In the continental slope area, the seismic material's informational value plunges as it includes chaotic areas and steep inclination angles of the imaged boundaries leading to ambiguous stratigraphic interpretation. It is also a fact that primaries and multiples are hard to separate at shallow depths. Thus, we considered it optimal to apply the finite-difference wavefield modeling.

The area of the continental slope and the adjacent part of the West Black Sea depression is not characterized by boring, which is why the sedimentary deposits shown in Fig. 7 are dated only approximately. From the Late Cretaceous to the end of Eocene the prevailing sediments accumulated on the sea floor were mostly carbonate and silicate-carbonate. This was succeeded by a terrigenous sediment accumulation regime, and from Oligocene to the end of the Early Miocene, the whole area accumulated clayey sediments of the Maikop series, a fairly monotonous stratum. It grows gradually thicker towards the West Black Sea depression, reaching almost 1000 m. From Middle Miocene to the Quaternary (inclusive), the sediments are represented by intermittent layers of clays and sands, with the fine-grained material prevalent [Pinus et al., 2014].

Since the modeling's goal this time was to confirm the efficiency and validity of the chosen migration method, the velocity characteristics of the environment and observation system had to be chosen as realistically as possible. The depth of the boundaries was somewhat adjusted to cut down the computation time. Meanwhile, some structure disturbances were entered into the model to determine the accuracy of their recovery in the migration section. For these settings was obtained a velocity model of the subsurface structure near the sea bed (Fig. 8, *a*). The velocity in the water layer was 1500 m/s, rising to 2200 m/s at the sea floor boundary, at the first boundary to 2600 m/s, and at the second boundary to 3000 m/s. The velocity is held constant within each layer.

There was chosen a profile 18 km long. The observation system imitated the one used for

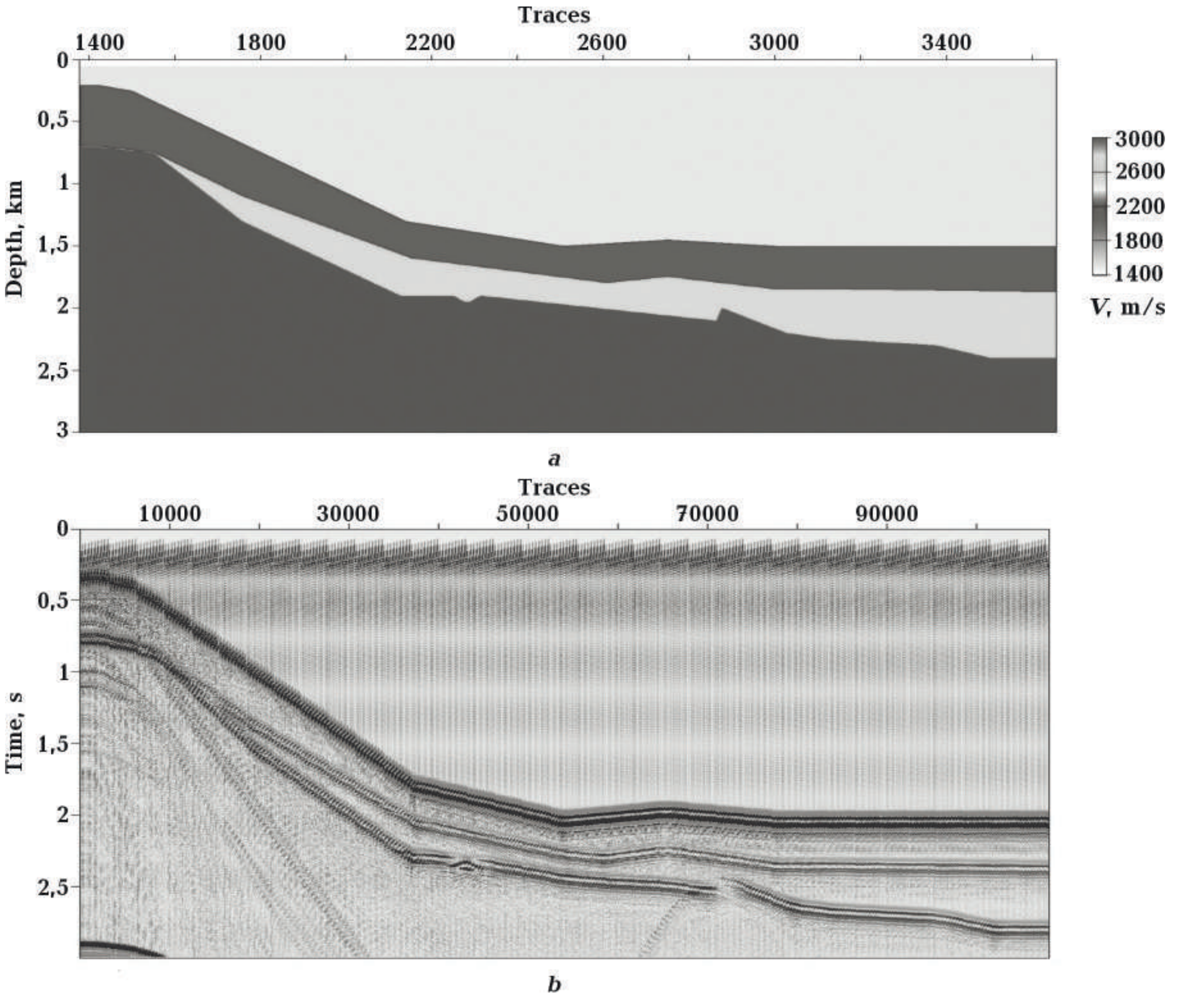

Fig. 8. Geological environment's velocity model (*a*) and the wavefield modeled for 1500 shots, recovering the observations by the CDP reflection survey system (*b*).

the seismic survey with a reflection CDP profile on the NW Black Sea shelf in 2013. The placement of the shot points (1500 in total) was every 12 m. The receivers (72 in total) were set 3 m apart. Since the first receiver was placed 90 m away from the source and the total record length for an excitation source was 216 m, the maximum offset was 306 m.

Fig. 8, *b* demonstrates the normalized wavefield for all shot points gathers along the profile. This is a standard view of the observed marine seismic reflection CDP profile. Here the wavefield was modeled with a time sampling of 0.5 m sand a total length of 3.0 s.

The modeled wavefield was processed according to the standard algorithm of seismic data processing, the main steps being trace editing (here, calculating and entering CDP numbers into trace passports), kinematic corrections, and stack traces by CDP. Fig. 9, *a* shows the CDP-stack section obtained for the modeled wavefield presented in Fig. 8, *b*.

The main task of the modeling was to evaluate how efficiently the finite-difference fullwave post-stack migration images all features of a subsurface structure near the sea bed. For this reason, the modeled CDP-stack section (Fig. 9, *a*) was used the fullwave finite-difference post-stack migration [Verpakhovskaya et al., 2013]. The result of the migration is given in Fig. 9, *b*.

Comparison of the velocity model (see Fig. 8, *a*), time CDP-stack section (see Fig. 9, *a*) and the fullwave finite-difference post-

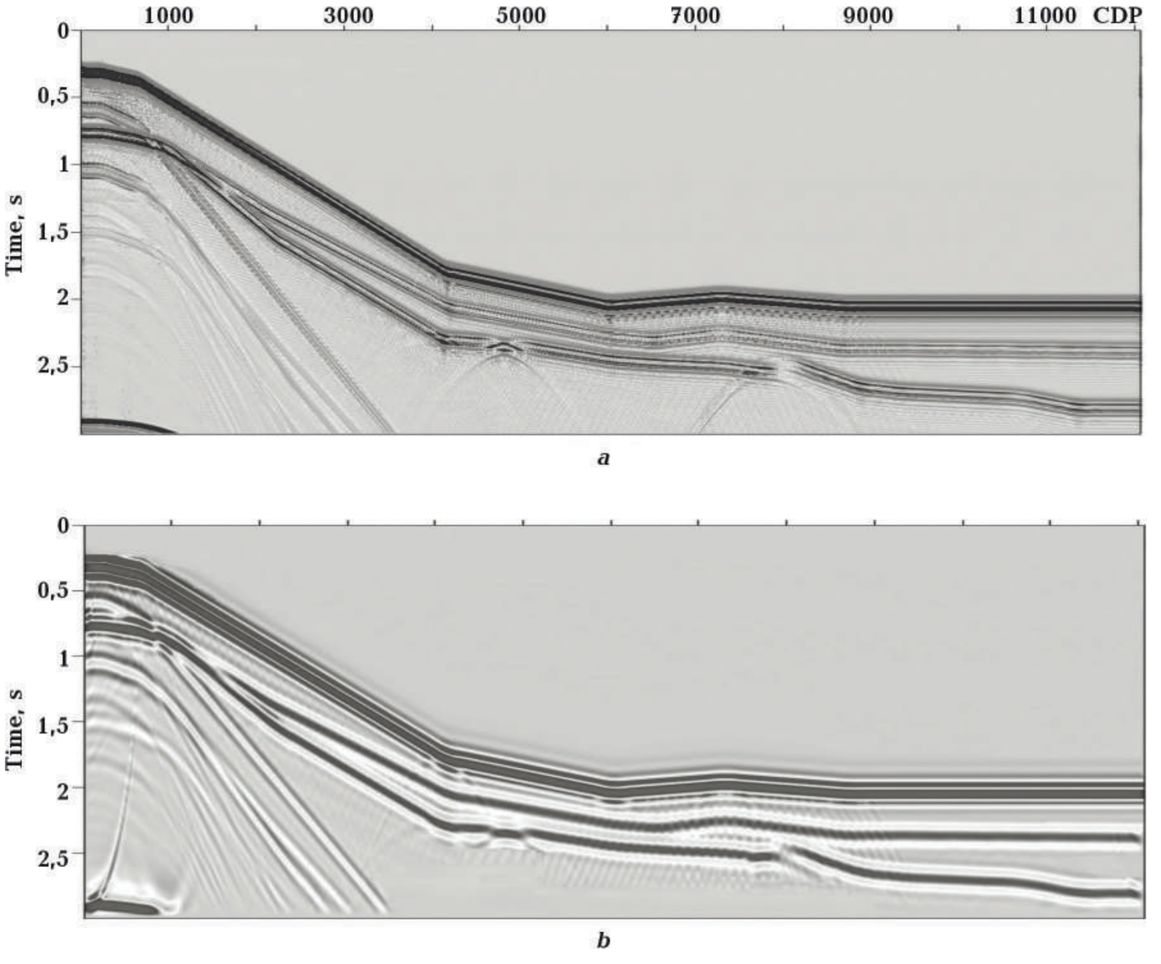

Fig. 9. CDP traces summation before wavefield modeling (*a*) and finite-difference fullwave post-stack migration (*b*).

stack migration (see Fig. 9, *b*) shows that the migration section has all the inhomogeneities on the boundaries of the velocity model in sharper relief. At the foot of the slope, there are multi-scale areas of dislocations and faults. However, the fault, which appears to be a steep incline, is not quite well-resolved at the rising side. This is probably caused by the one-sided observation system and requires a more thorough study, which we consider in our future work.

Conclusion. The seismic profile registered in 2013 on the NW Black Sea shelf were processed using the fullwave finite-difference post-stack migration. However, for the efficient interpretation of the obtained migration depth section, one has to be certain of the practical validity of the recovered deep geological structure. In practice, the migration results can be proved valid using the finite-difference modeling of the wavefield, which is based on solving the scalar wave equation using a grid with a 7-point pattern.

The results for a wavefield fully corresponding to the real velocity characteristics of the geological environment and the system of seismic observations carried out in 2013 on the NW Black Sea shelf confirm the validity of applying the fullwave finite-difference post-stack migration and the accuracy of recovery of the geological structural features along the profile in the migration image.

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Коректність міграційного зображення розрізу за матеріалами сейсмометричних спостережень на північно-західному шельфі Чорного моря

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Протягом багатьох років Інститут геофізики ім. С.І. Субботіна НАН України розробляв оригінальні версії скінченно-різницевих методів міграції та моделювання хвильового поля для достовірного відтворення геологічного розрізу. Моделювання забезпечує практичну перевірку точності відтворення різних особливостей геологічної будови на результаті міграції та може розглядатися як спосіб визначення в спостережуваному полі хвиль, які будуть корисними для побудови міграційного зображення геологічного середовища.

В 2013 р. на континентальному схилі північно-західної частини Чорного моря Інститутом геофізики ім. С.І. Субботіна НАН України були виконані сейсмометричні спостереження методом відбитих хвиль багатократними перекриттями. При обробці зареєстрованих хвильових полів використовувалася повнохвильова скінченно-різницева міграція після підсумовування трас методом спільної глибинної точки. З метою оцінки ефективності і коректності методів обробки за різних умов будови геологічного середовища використано скінченно-різницеве моделювання хвильового поля, яке базується на вирішенні хвильового рівняння на сітці з семиточковим шаблоном.

Дослідження підтверджує коректність обробки морських сейсмічних даних за допомогою повнохвильової скінченно-різницевої міграції після підсумування за допомогою моделювання хвильового поля.

Ключові слова: шельф Чорного моря, скінченно-різницева міграція суми СГТ, метод відбитих хвиль багатократними перекриттями, сейсморозвідка.