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SALT-DOME STRUCTURES MODELING IN DEPTH DOMAIN USING RAY TRACING AND SEISMIC ATTRIBUTE ANALYSIS

(Представлено членом редакційної колегії д-ром геол. наук, доц. О. В. Шабатурою)

B a c k g r o u n d . *Increasing the resource base and hydrocarbon exploration is the main goal of performing seismic data acquisition. Due to the presence of salt diapirs, normal and reverse faults as well as other discontinuities in the geological subsurface, there appear characteristic features of seismic signals – a break in phase continuity and significant attenuation of the amplitude without a break in phase continuity. These geological features are sometimes distinguished by attenuation of the seismic signal or even an absence of wave field reflections. In areas of salt-dome tectonics, it is often completely impossible to trace any reflective horizons. To accurately map the fault location, deep or vertical horizons, it is necessary to improve the approach to obtaining and interpreting data in faulted areas with complex geology.*

M e t h o d s . *The research presents an integrated approach to modeling the rays from each receiver of seismic signals to each bin on the reflective boundary. The reflected beams then propagate from the reflective boundary to the simulated position of the seismic receiver. Since the nature and velocity of beam propagation vary, it is possible to obtain additional information from zones shielded by faults or sub-vertical horizons, to trace the trajectories of seismic energy propagation and its focusing/defocusing zones. Verification of the seismic image and its geological content was performed using seismic attribute analysis.*

R e s u l t s . *Ray tracing allowed analyzing poor illumination zones below salt wings. During further steps such as processing and interpretation, ray tracing provided additional information for diapir mapping. Seismic attribute analysis was used as an additional tool to define the boundaries of the salt structure. This makes it possible to analyze the dynamic and kinematic parameters of the seismic field and map the salt body's boundaries based on these characteristics.*

C o n c l u s i o n s . *An integrated approach involving several methods will solve the problem of mapping seismic horizons in areas surrounding fault zones with a weak seismic signal. A more reliable geological image can only be obtained by using complex sequences, including seismic processing, ray tracing, and seismic attribute analysis. The integrated application of the techniques demonstrates consistent geological results and has implications for discovering new deposits and hydrocarbon traps confined to the zones of development of salt-dome tectonics in the Dnipro-Donets basin.*

K e y w o r d s : *ray tracing, seismic data processing, seismic attribute analysis, interpretation, salt tectonics, diapir, hydrocarbons, oil, gas.*

Background

The Dnipro-Donets Basin (DDB) is a large oil and gas-bearing province of Ukraine with extensive deposits of oil and gas, rock and potassium salt, sulfur, mercury, polymetals, mineral water sources, which has led to a wide variety of geological and geophysical studies undertaken here over the years, contributing to the region's high level of exploration.

Despite the use of modern processing algorithms, previous studies did not prove sufficient to accurately reproduce the geological environment in areas with prospects for hydrocarbon deposits, although, at the same time, complicated by salt diapirism. Therefore, it is important to develop an integrated approach to modeling seismological characteristics and methods for the seismic wave field analysis in a geological section complicated by salt-dome tectonics.

To test the effectiveness of the technology of seismic research on salt diapirs and their adjacent zones, the authors selected a number of objects within the gas condensate field in the Mashivsko-Shebelinskiy gas-bearing district of the Eastern oil and gas-bearing region of Ukraine, located in the central part of the periaxial zone of the Dnipro-Donets basin.

The geological structure of the research area was studied using drilling and seismic data. The shield is covered by Paleozoic, Mesozoic, and Cenozoic sedimentary formations. The oldest formations to make the sedimentary complex of the studied area are the Devonian sediments, which lie on a weathered shield transgressively with angular and stratigraphic discordance. Devonian deposits are composed of terrigenous and halogenated formations. Sandstones, limestones, siltstones, and mudstones represent terrigenous formations above the salt. In terms of age, the overlying Devonian stratum is an unsegmented complex of Upper Famennian sediments. Below the terrigenous Devonian formations, lies a saline stratum represented by salt with interlayers of anhydrites, dolomites, and terrigenous rocks. With a sufficient thickness, the salt layer creates salt domes rising up to the bottom of the Paleogene.

The morphology of pre-Triassic salt domes is either mushroom-shaped or columnar, which is determined by the presence or absence of the Lower Permian sulfate-halogen deposits in their section. In the areas of the Dnieper-Donets depression with widely-developed sulfate-halogen deposits, salt diapirs will exhibit a mushroom-like shape. Salt domes mainly complicate adjacent Paleozoic anticlinal folds; and in the Mesozoic stratum, they are responsible for the formation of folds that cover the buried Paleozoic uplifts.

The Upper Serpukhovian deposits consist of rhythmic layers of sandstones, siltstones, mudstones, and occasional limestones. Sandstones are light-gray, gray, layered, in some places turning into gray, thin-layered siltstones.

Sandstones have good filtration and permeability properties and are usually considered as hydrocarbon reservoirs.

In such cases, the overhanging Lower Permian salt wings can make the most effective shield. An example of such an object is shown in Fig. 1a, which shows a cross-section through the Chutivske gas condensate field. Fig. 1c demonstrates a seismic section with a diapir intersected by wells 1 and 2. The first well shows industrial gas inflows from the Upper Visean sand reservoir, and the second one is drilled into watered-saturated sandstone. A comprehensive analysis suggests that well 1 opened a trap shielded by a salt wing and one of the faults. In addition to the above objects, it should be noted that many diapirs in the DDB are accompanied by specific accumulative bodies in the Slavic formation, partially or completely covered by Lower Permian salt wings. These bodies are composed predominantly of carbonate rocks and have good reservoir properties. Fig. 1b shows one of these objects associated with the Khrestishchenskiy salt dome.

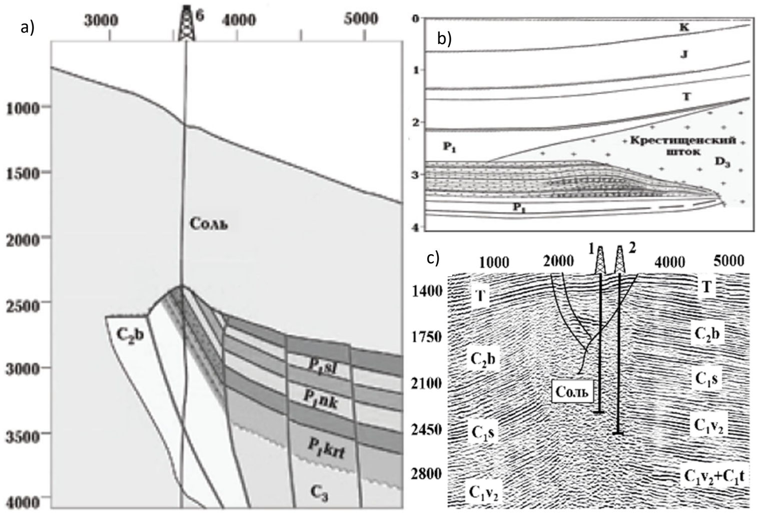

Fig. 1. Cross-section

(through: a) Chutivske gas condensate field; b) Khrestishchenskiy salt dome; c) Bakeiskiy salt dome located in DDB) obtained from pre-stack depth migration

Analysis of recent research and publications reveals attempts to visualize the geological environment near the salt diapir. In many publications, the authors give a detailed analysis of individual methods, without using an integrated approach. For example, (Jurado, Sinoquet, & Ehinger, 1996) describe the usage of 3D reflection tomography in their study of complex geological structures. In addition, (Jones, 2008) in "Effects of pre-processing on reverse time migration: the North Sea" studies diffracted multiples and back-scattered noise, developing an apex-shifted approach and more recently using 3D SRME. In their study of diapirism, (Shafiq et al., 2017) use phase congruency to detect salt domes within migrated seismic volumes. (Soleimani, Aghajani, & Heydari-Nejad, 2018) place importance on applying the normalized full gradient (NFG) method in the processing of potential field data to detect salt dome boundaries. The papers above propose new individual approaches to mapping salt domes. Unfortunately, every method has its disadvantages. Thus, the relevance of further research is driven by the additional benefits of a complex approach that will integrate methods the effectiveness of which has been particularly proven and which will therefore be effective for the study of specific geological structures.

Domestic scientists have explored integrated approaches to obtain highly informative seismic images. For instance, in their paper on advanced seismic imaging techniques, (Tiapkina, Tyapkin, & Okrepkyi, 2014) analyzed various types of hydrocarbon traps associated with salt domes in the Dnieper-Donets basin. Moreover, a classification of methods for seismic imaging was developed. Using examples from other sedimentary basins, the authors showed the benefits of pre-stack migration, the importance of multipathing of seismic energy, and the application of converted waves in imaging of near salt domes.

*The **relevance*** of this research is determined by the fact that, depending on the nature of the tectonic discontinuities of the synchronization axis, they can be traced on both sides of the axis. Tectonic discontinuities can either overlap or form a zone of the absence of wave field reflections. Sometimes, the areas of discontinuity are distinguished by the damping of oscillations. Often, in such areas, it is impossible to trace any reflective horizons, which made it necessary to improve the approach to obtaining and interpreting data in areas shielded by faults.

*The **purpose*** of the research is to develop a comprehensive approach to obtaining and interpreting data in areas shielded by faults or steep horizons associated with salt diapirism to enhance horizon visualization and obtain a geological section representing the real environment as accurately as possible.

Methods

In seismic survey planning and during ray tracing analysis, the principal objective is often to model the seismic response of a given target reflector in the depth domain. In particular, when the overburden geology is complex, e.g., with salt structures between the acquisition level and the reservoir zone, it is of special interest to try to simulate the target response, reflection and refraction of seismic rays for given acquisition geometries. A salt dome may cause distortion of seismic reflection beneath it in the time domain due to the tremendous wave transit velocity difference between salt rock and its surrounding rocks, giving rise to fake structures and fake faults in seismic interpretation (Fig. 2). If there are several paths of seismic energy propagation in the strata, it is necessary to select the option most suitable for depicting the target boundaries. Typically, trajectories are selected that have the minimum travel time or maximum calculated energy (Legott, Cowley, & Williams, 2004).

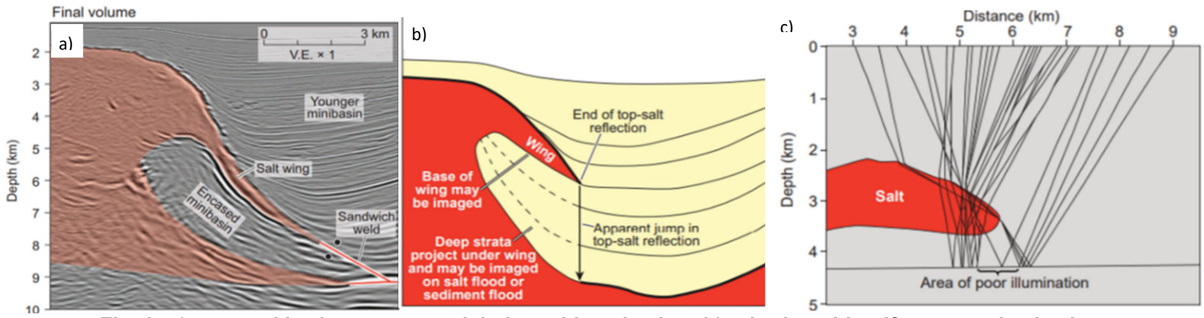

Fig. 2: a) encased horizons are overlain by a thin salt wing; b) criteria to identify a rotated salt wing; c) poor illumination zone below the salt wing (Jackson, & Hudec, 2017)

Ray tracing. Over the past twenty years, 3D seismic ray tracing has evolved from a research tool to a more operational tool in the petroleum industry. Simulated rays can be used to create ray attributes and synthetic seismograms for real 3D surveys with a large number of source and receiver points. The ray theory belongs to the methods most frequently used in seismology and seismic exploration for forward and inverse modelling of high-frequency seismic body waves and studying the propagation of seismic waves in layered subsurface with varying elastic parameters. In the case of applying a point source in the starting point of the ray, various attributes could be calculated by ray tracing travel time, amplitude, geometric spreading, etc. as Green's function attributes. Typically, each ray must be tested for intersection with a certain subset of all the objects in the model. A complex structural and tectonic model of the research area results in the creation of field zones poorly illuminated by seismic waves. Additionally, for subsalt reflections, the wavefield can be reflected back into the salt. Therefore, only a small amount of energy can reach the surface even if the seismic waves have reached the subsalt horizons (Cao, & Brewer, 2013).

The workflow started with locating sources and receivers, creating a structural model, and implementing a velocity model. Ray tracing modeling was performed in the survey to image the salt dome. A geological model was built to simulate the effects of salt domes on pre-salt reflection and to investigate the effect of salt dome thickness on pre-salt seismic reflection. The aim of ray tracing is to obtain a model of propagation, reflection, and refraction of seismic rays in a geological environment, modeled based on the available seismic data. The complete geologic environment model used for ray tracing consists of horizons, faults, and interval velocities. The next step was to analyze the target horizon below the salt wings selected as the reflection horizon. A combination of the rays' paths as a minimum distance from the source and receiver to the reflective horizon allows modeling the path of the reflected wave. The focus was on showing the effect of the wave transit velocity in the salt dome on pre-salt seismic reflection and the effect of low velocity interbeds in the salt dome on pre-salt seismic reflection. In addition, to illustrate the poor illumination zone, the multiplicity was calculated according to the coordinates of the intersection points of the ray trajectories.

Fig. 3 shows the results of an illumination survey from a series of uniformly spaced sources on the surface, shooting at a series of uniformly spaced receivers distributed over a 50 × 50 m grid (Fig. 3a). Even with a high resolution seismic, the geometry of the salt body (Fig. 3b-c) leads to the appearance of a poorly illuminated area in the target location (Fig. 3d-e). Images resulting from ray tracing will be overburden by migration artifacts in the target area, so ray tracing results help the interpreter with salt diapir mapping.

Unfortunately, the structure under the salt body is almost invisible, which is probably the result of insufficient ray density under the salt. Nevertheless, the main advantage of ray tracing is its realistic rendering of reflections, refractions, and shadows.

Seismic attribute analysis. The presence of salt bodies causes numerous challenges both at the stage of processing and at the stage of seismic data interpretation. One of the tools demonstrating a good result is the seismic attribute analysis, which allows qualitative assessment of dynamic and kinematic parameters of the seismic field and contouring the salt body according to the characteristics of the seismic signal.

Seismic attributes are important because they enable interpreters to extract more information from seismic data; they can facilitate spotting geological features and simplify seismic interpretation. Different seismic attributes are used for different geological problems. The following attributes are most often used when working with a salt dome: chaos helps to delineate salt extents; instantaneous phase determines the continuity boundary of sediments at the salt face; dip illumination is used to detect and highlight chaotic/noisy areas; amplitude contrast helps highlight and isolate salt structures among other types of rocks. The best approach is to use a number of complementing attributes, for instance, analysis of noisy areas, amplitude contrast, and fracturing zones. The result of an integrated attribute analysis can be seen in Fig. 4b, where the salt dome contour can be clearly observed. The result of migration is shown in Fig. 4a. Obviously, the layers which are closer to the surface are better visualized than the deeper ones, so the contour of the salt body can be recognized.

Results

Classical Kirchhoff migration is based on a single-ray scheme and, therefore, is usually not efficient enough in conditions of intense salt tectonics. An integrated use of ray tracing results and seismic attribute analysis provides good results in delineating hidden stratigraphic features that are not present in the legacy data. Analysis results shown in Fig. 4 confirm the presence of a narrower salt body below the wider upper part. This confirms the effectiveness of the proposed approach, which allows a more accurate determination of the geometry of the geological target. The application of the proposed strategy on the seismic data with an irregularly-shaped salt dome provided an appropriate image for the final structural and stratigraphic interpretation.

In Fig. 5, the colored lines were used to outline the salt dome. An integrated approach made it possible to prevent the impact of structural-tectonic features on the formation of the poor illumination zone. Thus, the reason for the weak seismic signal is not the tectonically shielded faults but the poor illumination zone below the salt caused by the seismic acquisition parameters. The location of the shadow zone was derived from the ray tracing results. The following step was to identify the presence of seismic signals after migration in the poor illumination zone. For this purpose, the seismic attribute analysis was used (in particular, Chaos, which maps the chaotic behavior of the local seismic signal from the statistical analysis of dip/azimuth estimate) as an additional source of information for salt dome detection.

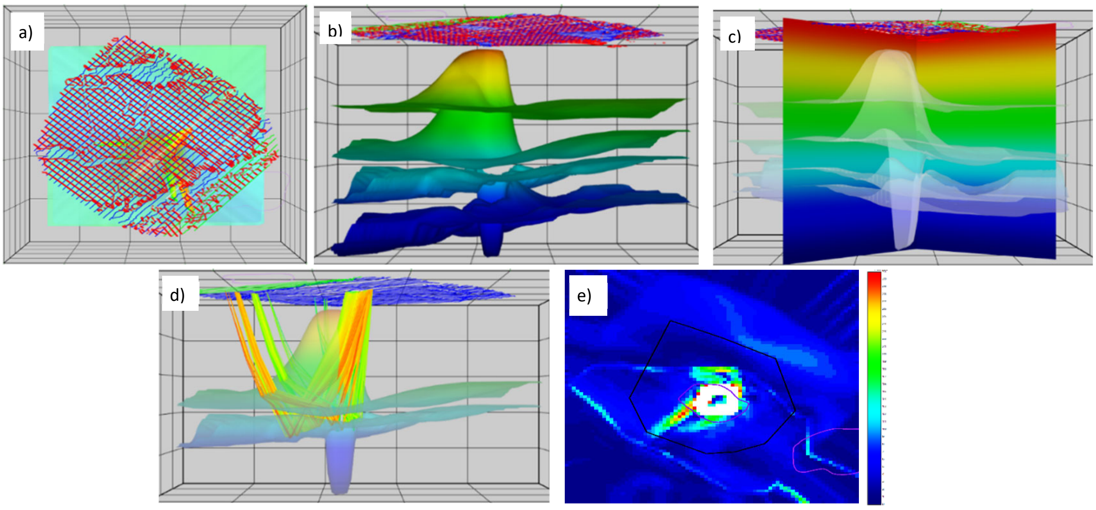

Fig. 3: a) Source and receiver points in the survey area; b) Structural model for the survey with a salt dome; c) velocity model over key horizons; d) ray tracing modeling from the target horizon below salt wings; e) dip angle attribute map

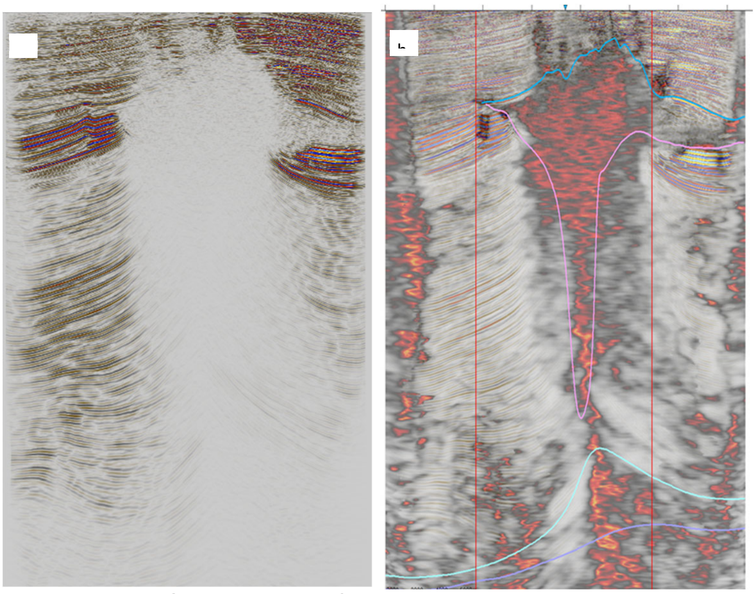

Fig. 4: a) Migrated PSDM section; b) Chaos attribute computed on the seismic after the salt body modeling confirms the approximate shape of the salt diapir

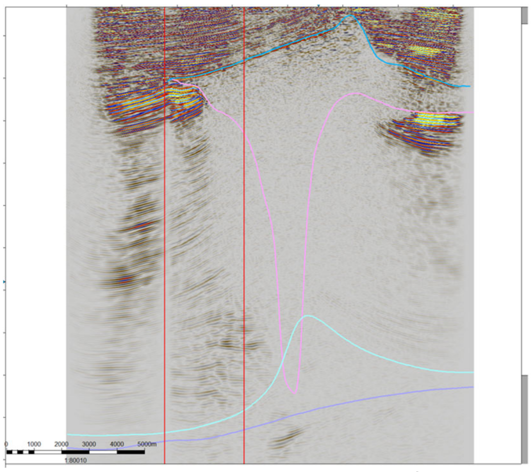

Fig. 5. Seismic cube cross section with the salt dome contour after applying an integrated method (ray tracing and seismic attribute analysis)

Discussion and conclusions

Hydrocarbon traps associated with salt domes cannot be accurately detected and further confirmed by drilling without obtaining a reliable structural-tectonic model. We have proposed a comprehensive approach to salt tectonics analysis involving a combination of methods to solve the problem of mapping seismic horizons in areas adjacent to fault zones with a weak seismic signal. This incorporates techniques such as ray tracing and seismic attribute analysis to create a more robust geological image. An integrated application of these methods demonstrates consistent geological results and has implications for the discovery of new deposits and hydrocarbon traps confined to the zones of salt dome tectonics within the Dnipro-Donets basin.

Authors' contribution: Natalia Rusachenko – conceptualization, formal analysis, methodology, writing (original draft); Tetiana Pastushenko – writing (review and editing); Serhiy Vyzhva – data validation, writing (review and editing).

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МОДЕЛЮВАННЯ СОЛЯНО-КУПОЛЬНИХ СТРУКТУР У ГЛИБИННОМУ ДОМЕНІ З ВИКОРИСТАННЯМ ТРАСУВАННЯ ПРОМЕНІВ ТА АНАЛІЗУ СЕЙСМІЧНИХ АТРИБУТІВ

В с т у п . ***Збільшення ресурсної бази та видобутку вуглеводнів є основною метою сейсморозвідувальних робіт. У зв'язку з наявністю в геологічному середовищі соляних діапірів, розломів, скидів і підкидів з'являються характерні особливості сейсмічного сигналу – розрив суцільності фази і значне згасання амплітуди без розриву суцільності фаз. Іноді такі геологічні утворення ідентифікуються ослабленням сейсмічного сигналу або навіть відсутністю відбиттів у сейсмо-хвильовому полі. Часто на ділянках розвитку солянокупольної тектоніки взагалі неможливо простежити відбивальні горизонти. Для достовірного відображення місця розлому, крутопадаючих чи вертикальних контактів необхідно вдосконалити підхід до роботи з даними на ділянках з густою сіткою розломів і складною геологією.***

М е т о д и . ***У дослідженні представлено комплексний підхід моделювання променів від кожного приймача сейсмічних сигналів до кожного біна на відбивальній границі. Потім відбиті промені поширювалися в геологічному середовищі від відбивальної границі до заданого положення сейсмічного приймача. Оскільки характер і швидкість їхнього поширення різні, то є можливість отримати додаткову інформацію із зон, екранованих розломами чи вертикальними контактами, дослідити траєкторії поширення сейсмічної енергії та зони її фокусування/дефокусування. Перевірка сейсмічного зображення та його геологічної змістовності була виконана за допомогою аналізу сейсмічних атрибутів.***

Р е з у л ь т а т и . ***Трасування променів дало змогу проаналізувати зону поганого освітлення під соляними крилами. Під час подальших кроків, таких як обробка та інтерпретація, трасування променів надало додаткову інформацію для оконтурення діапіру. Як додатковий інструмент для визначення меж соляної структури використано аналіз сейсмічних атрибутів. Це сприяло аналізу динамічних і кінематичних параметрів сейсмічного поля та на основі цих характеристик картографуванню меж соляного тіла.***

В и с н о в к и . ***Комплексний підхід із залученням кількох методів допоможе розв'язати завдання простеження сейсмічних горизонтів на ділянках, що оточують зони розломів зі слабким сейсмічним сигналом. Достовірніше геологічне зображення можна отримати, лише використовуючи комплексні підходи, що передбачають не тільки сейсмічне оброблення, але й трасування променів, аналіз сейсмічних атрибутів. Комплексне застосування методик демонструє геологічно змістовні результати та створює передумови для відкриття нових родовищ і пасток вуглеводнів, які приурочені до зон розвитку солянокупольної тектоніки Дніпровсько-Донецької западини.***

К л ю ч о в і   с л о в а : ***трасування променів, оброблення сейсмічних даних, аналіз сейсмічних атрибутів, інтерпретація, соляна тектоніка, діапір.***

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні пропублікацію результатів.

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