

IDENTIFICATION OF LINEAMENTS ON THE SEABED BASED ON A DIGITAL RELIEF MODEL USING THE EXAMPLE OF THE CASPIAN SEA

Natalia Libina¹, Victoria Putans¹, Sergey Kovachev¹, Artem Krylov¹,
Sergey Mironyuk², Michail Tokarev²

¹Shirshov Institute of Oceanology, Russian Academy of Sciences, RUSSIA

²Lomonosov Moscow State University, RUSSIA

kovachev@ocean.ru

mironyuksg@gmail.com

Abstract

This paper focuses on the application of geomorphometric methods to analyze a digital model of the seabed to identify lineaments on a regional scale, using the Caspian region as an example. The active development of remote sensing methods and geoinformation technologies has led to lineament analysis becoming widespread in both scientific and applied geological and geophysical research. This work demonstrates the use of geomorphometric methods to identify regional-scale lineaments in the Caspian region, using the bathymetric model as the initial data. The study's results demonstrated the effectiveness of shadow analysis methods and the identification of keel shapes by calculating relief curvature to detect large-scale lineaments. Combining the results of geomorphometric analysis with data on the distribution of earthquake epicentres enables active fault zones to be identified, which could be very useful for assessing seismic hazards and identifying areas of possible earthquake source zones (PES zones) on the shelf. There are still issues to be resolved, such as verifying that the selected lineaments comply with active faults in aseismic areas, determining the block-hierarchical structure of the studied areas and determining the magnitude of the displacement of blocks, both vertically and horizontally. Methods for detecting lineaments based on the DRM of the bottom should be developed and combined with the selection of lineaments based on magnetic and gravitational field anomalies. Experiments should be conducted on filtration methods and geomorphometric analysis to select the optimal complex.

Keywords: Caspian Sea, lineaments, geomorphometric analysis, relief curvature, earthquake epicenters

I. Introduction

The active development of remote sensing methods and geoinformation technologies has led to the widespread use of lineament analysis, both in scientific research and in applied geological and geophysical research [4, 10, 12 and others].

The understanding of the term "lineament" is ambiguous. It was introduced at the beginning of the twentieth century by W. Hobbs, who formulated it as a rectilinear relief element depicted on a geographical map reflecting a deep fault [13]. Later, this concept expanded to such an extent that various researchers now use this term to understand the most diverse structures of the Earth's crust – from giant deep-seated faults on a planetary scale to weakly expressed local fracture zones. Lineaments are considered as linear and arc-shaped elements of the geological and geophysical environment, reflected in the relief and including a variety of objects: fractures and cracks, zones of increased concentration of deformations, gradient zones of geophysical fields, elements of structural

and material heterogeneity of the geological environment, they can also reflect the supply channels of various fluids and solutions. Accordingly, the allocation of lineaments according to relief maps is possible due to the fact that they represent the exits to the earth's surface of discontinuous faults and their direct mapping features: the actual faults and cracks.

Modern lineament analysis is one of the methods of processing and decrypting Earth remote sensing data in order to study the deep structure of a particular territory. The essence of the method is to identify extended linear elements – lineaments, both rectilinear and arcuate (ring structures) in the image of the earth's surface, usually associated with disjunctive disturbances of the earth's crust of various origins. Geo-indicators of decoding are mainly geomorphological and landscape heterogeneities formed at the latest stage of tectonic development.

The use of lineament analysis has shown that the lineaments expressed on the surface largely reflect violations of the foundation structure, even overlain by a powerful sedimentary cover. The features of the deep structure of the basement are projected onto the daytime surface through the sedimentary cover, controlling the relief shapes [3, 11, 14, 15, 17]. Large lineaments in most cases are the surface manifestation of active faults, including deep ones. This gave rise to the use of lineament analysis in identifying tectonic disturbances.

In marine conditions, it is not possible to use lineament analysis based on remote sensing data of the Earth's crust. The use of modeling methods based on the analysis of digital models of the bottom relief and geophysical fields can be considered promising. In particular, geomorphometric methods and high-frequency filters for selecting threshold, extreme, and gradient areas can be used.

Currently, the rapid development of computing hardware, geoinformation technologies, remote sensing methods and equipment, which led to the creation and development of databases on digital terrain models, has led to the active progress of geomorphometry, an interdisciplinary field that emerged at the end of the twentieth century. Geomorphometry is based on the principles of morphometric analysis implemented in computational modules of geoinformation systems. Geomorphometric methods are increasingly being used to solve various problems in land-based geo-surveys, including for detecting tectonic disturbances [2, 32].

Until recently, geomorphometric analysis based on the digital bottom relief model (DRM) was not widely used due to the lack or low reliability of digital bathymetry in most seas. Nevertheless, the regular updating of the General Bathymetric Chart of the Oceans – GEBCO [8], the creation of new bathymetric maps based on multipath sonar creates conditions for the application of geomorphometric analysis for a regional scale based on the bathymetric model. It should also be noted that the identification of lineaments (faults) on a regional scale does not require a high-level DRM. In this regard, it is possible to use a DEM with a low grid discreteness: from 1 to 5 km, or the detailed DRM of the bottom is pre-filtered with a low-frequency filter (low-pass filter) to smooth out local relief deviations.

For example, [37] presents the results of the identification of neotectonic disturbances on the shelf of the Barents Sea using geophysical (seismic) methods and morphometric characteristics of the curvature of the relief. The allocation of lineaments along the shadow relief made it possible to identify a series of rift volcanic formations and zones of large discontinuities in the continent-sea transit zone [6, 7]. Shadow analysis and a method for identifying morphometric characteristics of relief curvature were also used to locate faults in the Pechersk Sea [27] and in the Laptev Sea. The results of the lineament analysis showed their applicability for further use in the development of possible earthquake source zones (PES zones) and seismic hazard assessment [30].

The Caspian region seems to be a successful scientific platform for the further development of the methodology: the area is seismically active, has been studied extensively for a long time, and there is a significant amount of data available to verify the modeling results.

II. Methods and data

A relief map of the bottom of the Caspian Sea and the adjacent territory with data used to verify the proposed method of lineament extraction is shown in Fig. 1. The map shows the distribution of earthquake foci, shows previously identified [35] geo-fluido-dynamic objects "pipes", some of the fault detection points according to continuous seismic profiling (CSP), as well as the results of the actual manifestation of active fault zones [16]. Data on active faults from the Active Faults of Eurasia Database (AFEAD) [1] are also presented.

Geomorphometric analysis

In this work, the Caspy-30 DEM was used as the initial data for the geomorphometric analysis of the Caspian Sea bottom relief [5]. The sampling step of the 5000 m grid corresponded to the task of selecting regional-level lineaments.

To identify the faults according to the DRM, methods of geomorphometric terrain analysis were applied: shadow analysis and identification of keel shapes using the calculation of the curvature of the bottom relief. All calculations and constructions of possible fault lines were performed using the Surfer Golden Software V.16 software package. Data analysis modules of geographic information systems (GIS) software complexes can also be used for geomorphometric calculations.

Shadow analysis of the bottom morphology is performed visually using grayscale images (shadow maps) The DRM with its conditional illumination is sequentially illuminated at different azimuths of the virtual light source so that all linear elements of the relief deflections are clearly distinguishable. The vertical illumination angle was 45°, and the azimuths were equal 45°, 135°, 225°, 315°. The supposed lineaments (faults) were manually highlighted on each shadow map. As a result, all the lineaments highlighted at different positions of the conditional light source were reduced to one map. This approach allows you to quickly perform a preliminary analysis of the shape of the bottom relief and identify the most pronounced gradient zones.

To identify regional scale lineaments, you can use a DRM with a grid discreteness of 1 to 5 km. When using a detailed grid, the bottom DRM is pre-filtered with a low-pass filter (low-pass filter) to smooth out local relief deviations and artifacts possible due to the fact that the bottom DRM is formed based on data from various sources. Calculations are performed on a rectangular grid.

The keel shapes of the bottom relief were identified after calculating the profile (vertical) and planned (horizontal) curvature, morphometric values based on second-order derivatives of the DRM function and describing curved and concave relief shapes, i.e. ridge and keel shapes [36]. The profile (vertical) curvature is the curvature of the surface in the direction of the maximum slope (the curvature of the profile line laid along the direction of the stream line), and the horizontal (planned) curvature is the curvature of the line formed by the intersection of the earth's surface with a plane perpendicular to the direction of orientation of the maximum gradient (exposure).

Only the values of negative curvature shapes corresponding to the keel shapes of the relief were plotted on the curvature map. Next, the proposed lineaments were highlighted.

Seismological data

Fig. 1 shows data from long-term seismological observations (pink circles, [40] and data from bottom seismological observations of the Institute of Oceanology of the Russian Academy of Sciences (red circles) [18, 21, 22; 33]. The size of the circle determines the magnitude of the earthquake.

In 2004 and 2006 the Institute of Oceanology of the Russian Academy of Sciences conducted detailed seismological observations with bottom stations near the coast of Dagestan (Middle Caspian). In 2004 bottom stations were installed on the Yalamo-Samur structure to assess the seismic

hazard of the studied area. 10 bottom seismographs of different types of were used, including pop-up [19, 23, 29, 31] and buoy devices [20, 26, 33]. The structure of the seismometric network took the form of two nested squares with a central station in the middle. The duration of registration was 75 days [26]. In 2006 buoy-type devices were installed in the water area of the Middle Caspian Sea on the beam of the Izberbash. The seismic network had the shape of a square with a side of about 50 km and an additional seismograph in the center. Registration lasted 90 days. As a result of these two experiments, records of more than 550 micro- and weak earthquakes with magnitudes $M_L = 0.1-4.7$ ($MLH = 0.7-4.3$) were obtained, one fifth of which originated in the upper mantle at depths of 50-200 km. The method of magnitude determination is in the articles [22, 25, 38, 39]. At the same time, for the entire period of instrumental observations since the 1930 last century, regional land-based stations recorded only 10 mantle earthquakes with $MLH = 3.5-6.3$.

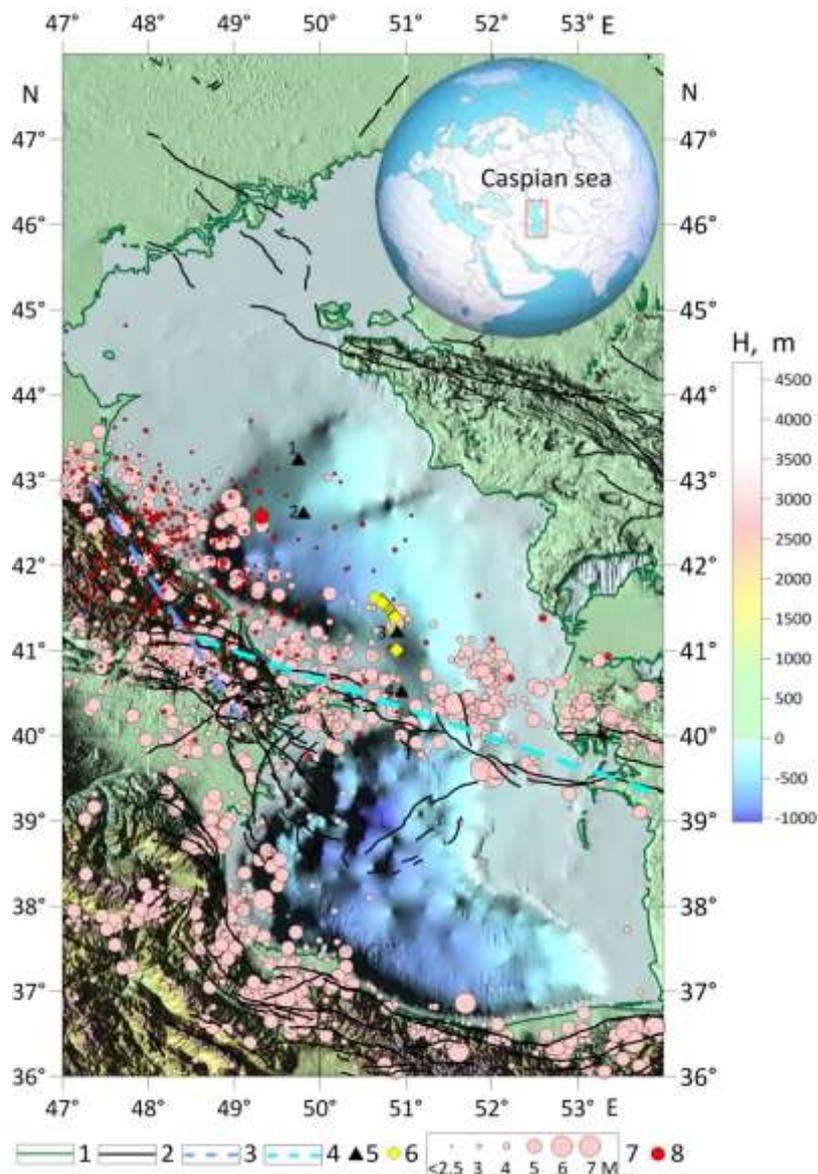


Fig. 1: Map of the distribution of earthquake epicenters and active fault zones in the Caspian Sea region. 1) The coastline; 2) Active fault zones according to the Active Faults of Eurasia Database (AFEAD) [1]; 3) The West Caspian Fault; 4) The Absheron threshold; 5) The position of the detected faults according to continuous seismic profiling (CSP) data; 6) "pipes" according to the CSP; 7) Earthquake epicenters according to the USGS catalog; 8) epicenters of earthquakes recorded by bottom stations of IO RAS in 2004 – 2006

Active fault diagram

The Active Faults of Eurasia Database (AFEAD) data for the Caspian region [1] were chosen as the active fault diagram, shown in Fig. 1 with black lines.

Seismic profiling data

Seismo-acoustic data were obtained in expeditions of the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences in the period 2004-2015 using the Geont Shelf single-channel continuous seismo-acoustic profiling system and Sparker source (300 Hz).

The seismic and acoustic data was processed in specialized software packages RadExPro 2012.3, ISE 3.2 and Chirp-II, and the software package Kingdom Suite 2d/3d was used for interpretation.

III. Results and discussion

As a result of the analysis of the shadow maps of the DRM and the calculation of the profile and planned curvature, lineaments of a regional scale were identified, expressed in the relief of the bottom. Presumably, most of them are associated with fault zones. The separation of smaller structures is complicated by the fact that the sedimentary cover smooths out the manifestation of the basement structure on the seabed surface.

Highlighted by grayscale images (shadow maps) DRM bottom lineaments are shown in Fig. 2. There were no lineaments in the coastal part of the DRM. The linear relief elements become clearly distinguishable at different illumination azimuths. Thus, the variation of the illumination azimuths allows us to obtain the most complete picture of the lineament distribution, reflected on the summary map (Fig. 2e).

The results of the lineament selection according to the distribution of the profile and planned curvature of the relief are shown in Fig. 3. The figure shows that the most pronounced and extended lineaments in conditions of slightly gradient relief are highlighted mainly on the planned curvature map, and the profile curvature map for these sections is less informative. In the conditions of sharply rugged relief of mountainous areas of the coastal part of the DRM, the characteristics of planned and profile curvature are equally effective.

Fig. 4 shows a summary diagram showing the lineaments obtained from the DEM analysis, earthquake epicenters from the catalog [40], data from bottom seismological observations of the Institute of Oceanology of the Russian Academy of Sciences [18, 21, 22], the location of the geo-fluido-dynamic structures of the "pipe" [35], locations of faults identified according to the CSP data, active fault zones according to [1].

Judging by Fig.1 and 4, both sets of earthquake epicenters are confined to fault concentration zones identified by data on the curvature of the relief. The epicentral field under consideration is characterized by the presence of lineaments and clusters. The main and densest group of earthquake epicenters stretched from NORTH to SOUTH from about 42.6 to 41.3°n along the Dagestan coast on land (depths of foci 10-40 km) and in the Caspian Sea (depths of foci 10-50 km) along the steeply falling side of the Derbent depression to the northeast.

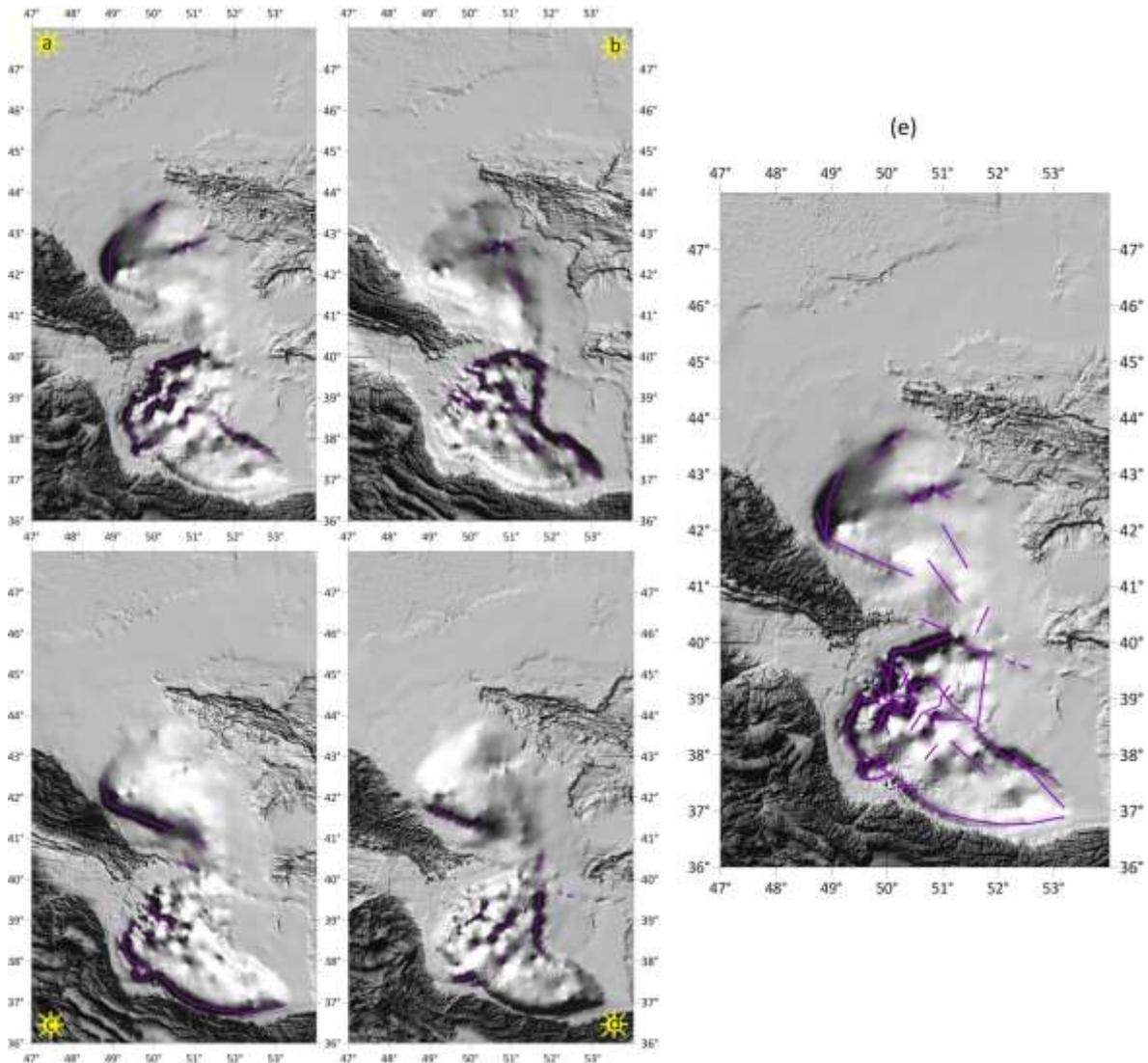


Fig. 2: Highlighting lineaments in grayscale images (shadow maps) DEM of the bottom of the Caspian Sea at a vertical illumination angle of 45° and various azimuths: (a) 135° ; (b) 45° ; (c) 225° ; (d) 315° ; (e) – Summary map. The coastline is shown in black, and the highlighted lineaments are shown in purple color

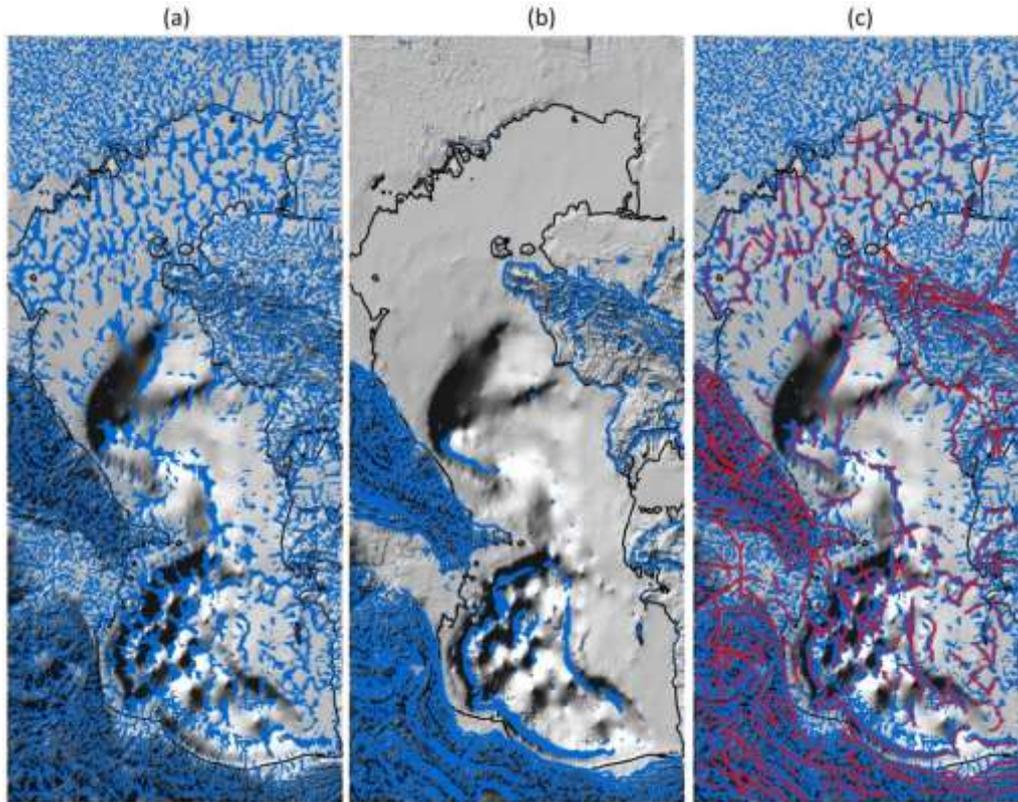


Fig. 3: Lineament selection based on maps of keel shapes of the Caspian Sea bottom relief. The keel shapes are shown on shadow maps plotted in the Mercator projection. a) keel shapes on the map of the planned curvature of the relief; b) keel shapes on the profile curvature map of the relief; c) highlighted lineaments according to keel shapes on the map of the general curvature of the relief

At the same time, both crustal and mantle earthquakes with foci at depths from 100-150 to 200 km were observed in the latter group. Fig. 1 and 4 show that earthquake epicenters are concentrated mainly along two linear structures: the well-known deep structure – the Absheron threshold and the proposed structure - the deep West Caspian Fault (WCF).

Hypocenters of mantle earthquakes at depths up to 100 km are concentrated at distances up to 170 km from the conventional line of the Absheron threshold and northwest of Makhachkala.

Taking into account the data obtained using bottom seismological observations, it turned out that the area of mantle earthquake propagation is clearly divided into the western (Caucasian) and eastern (Caspian) sectors, separated by the West Caspian system of sub-meridional faults. These faults are characterized by large (several kilometers) vertical displacements with the eastern wing lowered, as well as right-thrust displacements. In the western sector, the continental lithosphere of the Transcaucasian massif is shifting under the folded belt of the Greater Caucasus.

In the eastern sector the dominant process is, apparently, the displacement of the lithosphere of the South Caspian basin under the southern margin of the Scythian platform. The West Caspian fault controls the location of the foci of several deep earthquakes. The fault zone is subvertical or slightly inclined to the west, which excludes the previously assumed displacement of the Caspian structures under the Caucasus [22]. In the process of subduction of the South Caspian lithosphere, the West Caspian fault plays the role of a transform fault.

According to bottom seismological observations, mantle earthquake foci are completely absent in the Western Sector. All of them are located to the east of the WCF.

In the process of the data analysis a spatial comparison of the position of the selected lineaments (faults) with the profiles of the CSP was carried out. This aggregation has shown that the lineaments (faults) identified by us on the CSP profiles are displayed as anomalies of the wave

field, which correspond to disturbances in the fine structure of precipitation. As an example, Fig. 5 shows four temporary sections of the CSP (position in Fig. 1 and 4) located exactly above the fault.

Fig. 4-1 and 4-2 clearly show the undulating anomalies extending to the surface of the bottom in the upper part of the section. In Fig. 4-1, in the enlarged fragment, along with the "creep" type formations identified and described earlier in [35], small-amplitude discontinuous disturbances are visible above. It is also worth noting the seismic and acoustic anomalies of the "bright spot" type, which most often correspond to local manifestations of gas saturation. Fig. 4-2 clearly shows the sediment column, penetrated by thin signal attenuation zones, which are localized in the local undulation of the bottom relief. The enlarged fragment shows small discontinuities directly below the bottom surface.

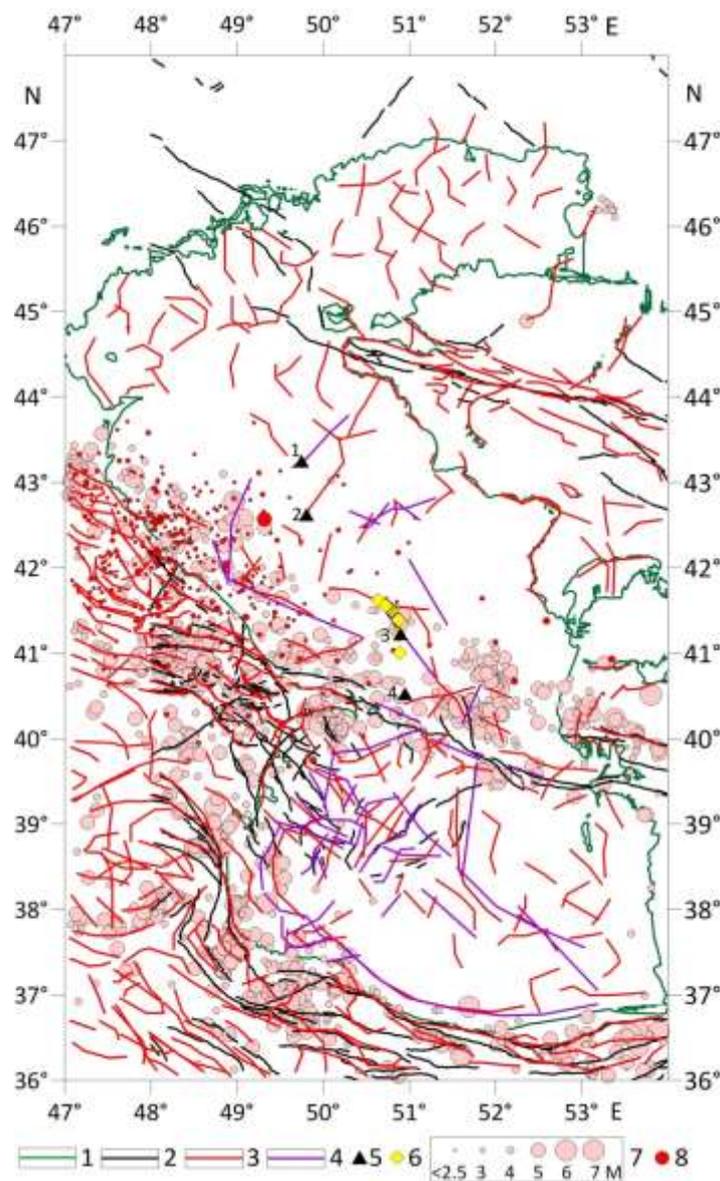


Fig. 4: Summary diagram of the distribution of lineaments, earthquake epicenters, and active fault zones identified by DRM. 1) the coastline; 2) active fault zones according to GIN RAS data; 3) lineaments identified by analyzing the curvature of the relief; 4) lineaments identified by shadow relief analysis; 5) fault detection points according to CSP data; 6) "pipes"; 7) Earthquake epicenters according to the USGS catalog; 8) epicenters of earthquakes recorded by bottom stations of IO RAS in 2004 – 2006

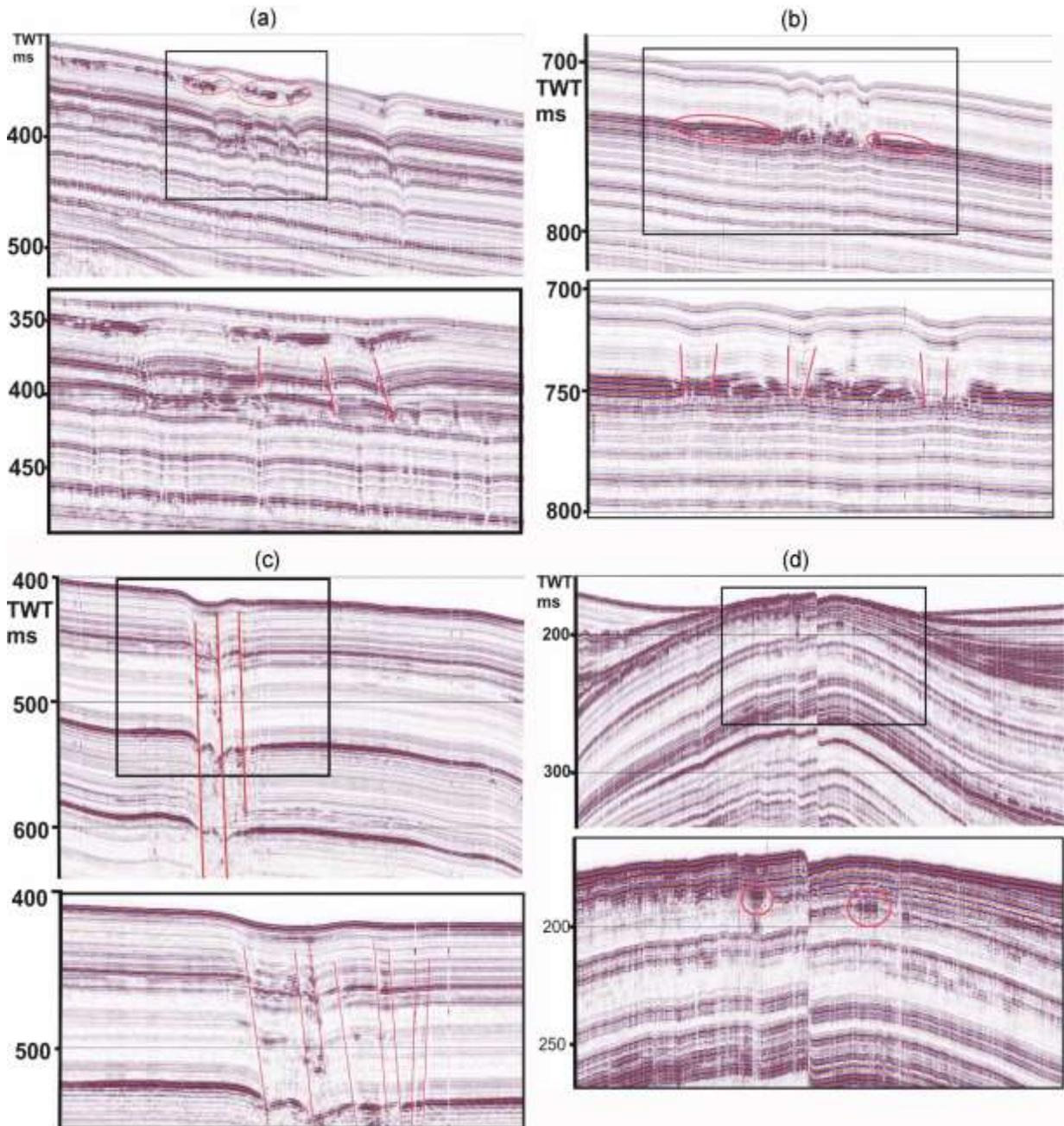


Fig. 5: Sections of NPS intersecting faults at the points shown in Fig. 4 by triangles. The bottom of the figures shows an enlarged framed section fragment. a) An incision crossing the fault at point 1; b) An incision crossing the fault at point 2; c) An incision crossing the fault at point 3; d) An incision crossing the fault at point 4.

It should be noted that the sections intersected by the highlighted lineaments shown in Fig. 4-1 and 4-2 are located in the northern part of the Derbent basin near the Tsentralnaya oil and gas structure. In general, the wave pattern is similar to them: parallel stratified strata, which becomes wavy closer to the bottom surface, and wave anomalies are expressed by local small breaks in reflective boundaries and bright spots.

Further south, the wave pattern changes. Wave anomalies and faults become more pronounced and permeate the entire observed precipitation column. Thus, in Fig. 4-3, several subvertical faults with a relatively large amplitude offset and associated wave field anomalies such as "bright spot" and "chaotic recording" are observed. This characteristic pattern corresponds to the "growing" gas pipe identified earlier in the area [9]. The subvertical "Tube" reaches the bottom surface and is clearly marked by a local decrease in relief. Further south, on the Absheron threshold, a vertical fault with

an amplitude of 30 meters is "cut" by the profile of the CSP (Fig. 5-4). The fault is pronounced in the bottom relief and in the entire thickness of the visible sediments and extends beyond the record. The enlarged fragment shows vertical signal attenuation anomalies, which are associated with small areas of the "bright spot" type.

IV. Conclusion

In this paper, using the example of the Caspian region, the use of geomorphometric methods to identify lineaments of a regional scale is demonstrated, in which the bottom DEM (bathymetric model) is used as the initial data. The results of the study showed the effectiveness of using methods of shadow analysis and the allocation of keel shapes by calculating the curvature of the relief to identify large lineaments. The combined use of the results of geomorphometric analysis with data on the distribution of earthquake epicenters makes it possible to identify active fault zones and may prove very promising in assessing seismic hazards on the shelf to identify areas of possible earthquake foci (PES zones).

There are still issues to be resolved: verification of the selected lineaments for compliance with active faults in aseismic areas, determination of the block-hierarchical structure of the studied areas, and determination of the magnitude of block displacement.

The prospects for the development of methods for detecting lineaments based on the DRM of the bottom should be considered to combine with the selection of lineaments based on magnetic and gravitational field anomalies; experiments in the selection of filtration methods and geomorphometric analysis to select the optimal complex.

The interpretation of the DRM data was carried out within the framework of the State assignment no. FMWE-2024-0019, the analysis of the seismicity of the studied region was carried out with the support of a grant from the State program of the Federal Territory "Sirius" "Scientific and Technological Development of the Federal Territory "Sirius" (Agreement no. 18-03 dated 09/10/2024).

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

References

[1] Active Faults of Eurasia Database (AFEAD). URL: http://neotec.ginras.ru/index/datamap/AFEAD_J39_Map.html; [/AFEAD_K39_Map.html](http://neotec.ginras.ru/index/datamap/AFEAD_K39_Map.html); [/AFEAD_L39_Map.html](http://neotec.ginras.ru/index/datamap/AFEAD_L39_Map.html). Date of access: 20.08.2024.

[2] Anokhin V.M., Maslov L.A. Experience in studying the patterns of direction and extent of lineaments and faults in the regions // Bulletin of KRAUNC. Geosciences. 2015. Issue N. 25. N. 1. P. 7-18.

[3] Bondur V.G., Zverev A.T. Physical nature of lineaments recorded on satellite images during monitoring of seismically hazardous areas // Modern problems of remote sensing of the earth from space. 2006. V. 3. N. 2. P. 177-183.

[4] Bondur V.G., Zverev A.T., Gaponova E.V. Lineament analysis of space images of seismically hazardous territories in Russia // Modern problems of remote sensing of the Earth from space. 2012. V. 9. N. 4. P. 213-222.

[5] Caspy-30. URL: <http://caspi.ru/HTML/025/ind-02.html>. Дата обращения 17.03.2020.

[6] Gavrillov A.A. Cosmogeological indication of morphostructural elements of the coasts and bottom of adjacent water areas (Peter the Great Bay, Sea of Japan) // Oceanology. 2021. V. 61. N. 4. P. 555-568. DOI: 10.1134/S0001437021040044.

- [7] Gavrillov A.A. New data on the structure of the underwater elevations of Bogorov, Toyama and adjacent areas of the bottom of the Sea of Japan (based on the results of geomorphological and cosmo-geological studies) // *Izvestiya, Atmospheric and Oceanic Physics*. 2022. V. 58. N 9. P. 1049-1058. DOI: 10.1134/S0001433822090080.
- [8] GEBCO: General Bathymetric Chart of the Oceans. URL: <https://www.gebco.net/>. Date of access: 15.02.2024.
- [9] Gerivani H., Putans V.A., Merklin L.R., Modarres M.H. Characteristics of features formed by gas hydrate and free gas in the continental slope and abyssal plain of the Middle Caspian Sea // *Marine Georesources & Geotechnology*. 2023. N 39(4). P. 419-430. DOI:10.1080/1064119X.2019.1709585.
- [10] Gilmanova G.Z., Rybas O.V., Goroshko M.V. Application of converted digital relief models for geological and structural zoning of large blocks of the earth's crust // *Pacific Geology*. 2011. V. 5. N 6. P. 509-517. DOI: 10.1134/S1819714011060042.
- [11] Gorbunova E.M., Ivanchenko G.N. Using remote sensing data from areas of the earth's crust to analyze the geodynamic situation. Moscow: GEOS, 2015. 108 p.
- [12] Grimmer J.C., Becker A., Schill E., Kohl T. Comparison of different digital elevation models and satellite imagery for lineament analysis: Implications for identification and spatial arrangement of fault zones in crystalline basement rocks of the southern Black Forest (Germany) // *Journal of Structural Geology*. 2018. V. 108. March 2018. P. 256-268. <https://doi.org/10.1016/j.jsg.2017.11.006>.
- [13] Hobbs W. N. Lineaments of the Atlantic border region // *Bull. Geol. Soc Amer*. 1904. V. 15. P. 483-506.
- [14] Ivanchenko G.N., Gorbunova E.M., Cheremnykh A.V. Some Possibilities of Lineament Analysis in Mapping Faults of Different Ranks: Case Study of the Baikal Region // *Izvestiya Atmospheric and Oceanic Physics*. 2023. V. 58(9). P. 1086-1099. DOI:10.1134/S0001433822090092.
- [15] Kats Ya.G., Poletaev A.I., Rumyantseva E.F. Fundamentals of lineament tectonics. Moscow: Nedra, 1986. 144 p.
- [16] Kaz'min V.G., Lobkovsky L.I., Bush V.A. Role of transverse strike-slip faults in the structure of the Karpinsky ridge and their kinematics. // *Geotectonics*. 2008. V. 42. N 3. P. 176-185. DOI: 10.1134/S0016852108030023.
- [17] Kocharyan G.G. Geomechanics of faults. Moscow: GEOS, 2016. 424 p.
- [18] Kovachev S.A. Microseismicity of the middle Caspian Sea based on the results of bottom seismological observations // In Proceedings: Proceedings of the Caspian Branch of IO RAS. Astrakhan. 2016. P. 9-37.
- [19] Kovachev S.A. Results of seismological observations in the Western Kaliningrad Region and in the Baltic Sea water area // *Izvestiya, Physics of the Solid Earth*. 2008. V. 44. N 9. P. 706-716.
- [20] Kovachev S.A., Ganzha O.Yu. Structure of the earth's crust of the Persian Gulf according to deep seismic sounding results // *Oceanology*. 2023. V. 63. N 5. P. 719-732.
- [21] Kovachev S.A., Kaz'min V.G., Kuzin I.P., Lobkovsky L.I. New data on mantle seismicity of the Caspian region and their geological interpretation // *Geotectonics*. 2009. V. 43. N 3. P. 208-220. DOI: 10.1134/S0016852109030030.
- [22] Kovachev S.A., Kaz'min V.G., Kuzin I.P., Lobkovsky L.I. New data on seismicity of the middle Caspian basin and their possible tectonic interpretation // *Geotectonics*. 2006. V. 40. N 5. P. 367-376. DOI: 10.1134/S0016852106050049.
- [23] Kovachev S.A., Krylov A.A. Microseismicity of the Persian Gulf and the Zagros Mountain Massif According to Bottom Seismological Observations // *Vulkanologiya i Seismologiya*. 2023. V. 17. N. 6. P. 41-59.
- [24] Kovachev S.A., Krylov A.A. Results of seismological monitoring in the Baltic Sea and western part of the Kaliningrad oblast using bottom seismographs // *Izvestiya Physics of the Solid Earth*. 2023. V. 59. N 2. P. 94-114.

- [25] Kovachev S.A., Krylov A.A., Libina N.V. Determination of earthquake magnitudes based on the records of ocean bottom seismographs // *Vulkanologîa i Seizmologîa*. 2025. N. 5. P. 19-38.
- [26] Kovachev S.A., Kuzin I.P., Lobkovskii L.I. Detailed seismological observations on the central shelf and continental slope of the Northeastern Black Sea using sea-bottom stations // *Izvestiya, Physics of the Solid Earth*. 2003. V. 39. N 1. P. 19-24.
- [27] Kovachev S.A., Libina N.V. Assessment of initial seismicity for offshore platforms: a case study of the Pechora Sea // *Oceanology*. 2024. V. 64. N 1. P. 139-148. DOI: 10.1134/S0001437024010065.
- [28] Kovachev S.A., Kuzin I.P., Soloviev S.L. Microseismicity of the frontal Hellenic arc according to OBS observations // *Tectonophysics*. 1992. V. 201, Issues 3-4, P. 317-327.
- [29] Krylov A.A., Ananiev R.A., Chernykh D.V., Alekseev D.A., Balikhin E.I., Dmitrevsky N.N., Novikov M.A., Radiuk E.A., Domanyuk A.V., Kovachev S.A., Timashkevich G.K., Ivanov V.N., Ilinsky D.A., Ganzha O.Yu., Gunar A.Yu., Pushkarev P.Yu., Koshurnikov A.V., Lobkovsky L.I. A complex of marine geophysical methods for studying gas emission process on the arctic shelf // *Sensors*. 2023. V. 23. N 8. C. 3872.
- [30] Krylov A.A., Ivashchenko A.I., Kovachev S.A. Seismic hazard assessment for oil-and-gas-bearing shelf zones: a case study of the North Caspian region // *Oceanology*. 2015. V. 55. N 6. P. 910-915.
- [31] Krylov A.A., Kovachev S.A. et al. Ocean-bottom seismographs based on broadband met sensors: architecture and deployment case study in the Arctic // *Sensors*. 2021. V. 21. N 12.
- [32] Kuptsova O.V. Interpretation of faults in the southwestern part of Sakhalin Island // *Vestnik SGUGiT*. 2022. V. 27. N 1. P. 52-60.
- [33] Lobkovskii L.I., Kuzin I.P., Kovachev S.A., Krylov A.A. Seismicity of the Central Kuril islands before and after the catastrophic $M = 8.3$ (November 15, 2006) and $M = 8.1$ (January 13, 2007) earthquakes // *Doklady Earth Sciences*. 2015. V. 464. N 2. P. 1101-1105.
- [34] Lobkovsky L.I., Merklin L.R., Kovachev S.A. et al. Principal goals and preliminary results of the studies from r/v Rift in the Caspian Sea (April-May, 2006) // *Oceanology*. 2007. V. 47. N 5. P. 741-745.
- [35] Putans V., Trimonova M., Merklin L. Hidden hydrosphere under the Caspian Sea: Geophysical evidence and sea-level influence // *Interpretation*. 2023. V. 11 (1) P.: 1F-Z4 ISSN (print): 2324-8858 ISSN (online): 2324-8866. DOI:10.1190/int-2021-0102.1
- [36] Shary P.A. Geomorphometry in earth sciences and ecology, review of methods and applications // *News of the Samara Scientific Center of the Russian Academy of Sciences*. 2006. N 8(2). P. 458-473.
- [37] Sokolov S.Yu., Abramova A.S., Shkarubo S.I. Neotectonic disturbances of the Barents Sea shelf and their genesis according to the morphometry of the bottom topography, seismic surveys and the deep structure of the mantle // *Reports of the Russian Academy of Sciences. Geosciences*. 2023. V. 509. N 1. P. 62-68. <https://doi.org/10.31857/S2686739722602484> .
- [38] Soloviev S.L., Kovachev S.A. On the determination of local magnitude of near earthquakes from OBS observations // *Acta Geophysica Polonica*. 1994. V. XLII. № 4. P. 274.
- [39] Soloviev S.L., Kovachev S.A. On determining the local magnitude of local earthquakes based on observations of bottom seismographs // *Physics of the Earth*. 1996. N. 5. P. 26.
- [40] USGS. Search Earthquake Catalog. URL: <https://earthquake.usgs.gov/earthquakes/search/> . Date of access: 15.02.2024 .