Geostatistical Analysis of the Data Sets on the Mariana Trench, Pacific Ocean

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Research Goals

Research Objective
– is an application of R programming language for geostatistical data processing. The impact of the geographic location and geological factors on its geomorphology has been studied by methods of statistical analysis and data visualization using R libraries.

Research Aim
– is to identify main impact factors affecting variations in the geomorphology of the Mariana Trench: steepness angle and structure of the sediment compression.

Research Focus
– is upon understanding variability of factors responsible for the deep ocean trench formation and comparative analysis of its geomorphic structure. It contributes towards investigations of the geology of the Pacific Ocean and the interplay between geomorphic, geological, tectonic and volcanic factors affecting submarine landform formation.

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Mindmap

Figure 1: *Project mindmap: methods, concepts, approaches and tools. Plotting: LATEX [22]*

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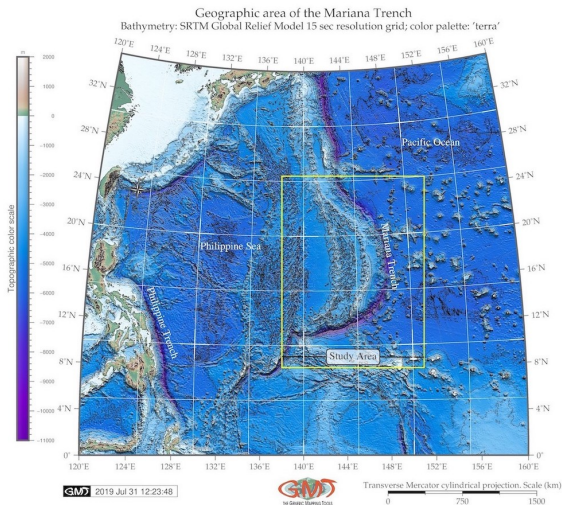
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Mariana Trench

Figure 2: Topographic map and location of the Mariana Trench. [24]

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Introduction - I

Mariana Trench is one of the 37 known deep-water trenches of the World Ocean, 28 of which located in the margin areas of the tectonic plates of the Pacific Ocean. It forms the peripheral framing, of which five are located in the Atlantic [3] and four in Indian Ocean [42].

Mariana Trench creates a complex of the deeply interrelated factors, determinants and processes. Factors affecting formation, geomorphic development and bathymetric patterns of the Mariana Trench are diverse:

- ▶ geological
- ▶ hydro-chemical
- ▶ biological
- ▶ geothermal
- ▶ climatic
- ▶ tectonic
- ▶ bathymetric
- ▶ geomorphological

Introduction - II

The seafloor of the Mariana Trench is a background, on which all the processes occurring in the Mariana Trench are reflected [6]:

- ▶ The hydrosphere influence on the Mariana Trench is reflected by deep ocean currents bringing sediments to the trench bottom and contributing towards accumulation of the sedimental thickness layer [13].
- ▶ The impact of lithosphere is illustrated by a constant exchange of matter and energy between the submarine volcanoes located nearby [14].
- ▶ The structure of the Mariana Trench and the nature of its relief are greatly complicated by the multiple secondary tectonic disturbances, i.e. by the occurrence of faults and displacements on of grabens, horsts and lateral geologic shifts.
- ▶ Among other trenches, Mariana Trench is distinct for its edge type associated with the marginal tectonic plate subduction processes [4].

Geography

Study area: Mariana Trench: the deepest place of the Earth, located in the west Pacific Ocean. Mariana Trench is a long and narrow topographic depression of the sea floor, the deepest among all hadal trenches, 200 km to the east of the Mariana Islands, eastwards of the Philippine Islands.
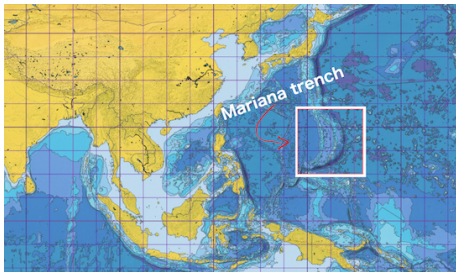

Figure 3: Mariana Trench: square of the study area

Mariana Trench:
Geological characteristics

Bathymetry
- transverse profile is strongly asymmetric: the slopes are higher on the side of the island arc. The slopes are dissected by deep underwater canyons. Various narrow steps are often found on the slopes of the trench.

Geomorphology
- complicated steps of various shapes and sizes, caused by active tectonic and sedimental processes. Hence, it is the largest structural trap located in the continental margins of the Pacific Ocean.
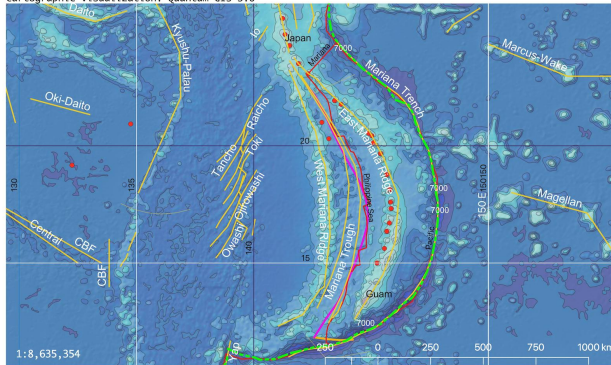
Sediments
- the sediments are being carrying by the ocean waves in a clockwise direction, passing through the trenches on the west of the Pacific, i.e. the Kermadec Trench, Tonga Trench, Samoan Passage.

Map of the Mariana Trench

Figure 4: Enlarged map of the Mariana Trench

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Tectonics - I

▶ Mariana Trench crosses four tectonic plates: Mariana, Caroline, Pacific and Philippine.

▶ The formation of the Mariana Trench is caused by complex and diverse geomorphic factors.

▶ Mariana Trench presents a complex system with highly interconnected factors:
  ▶ geology (sediment thickness across 4 tectonic plates),
  ▶ bathymetry (coordinates, depth values in the observation points),
  ▶ geometry of the slopes: angle and steepness,
  ▶ oceanography (deep sea currents),
  ▶ volcanology,
  ▶ deep sea marine biology.

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Tectonics - II

The system of the Mariana trench is complicated and consists of the interrelated factors forming its tectonic structure:

▶ The main part of the seabed of the Mariana Trench is composed by the oceanic crust forming rift zones of the mid-ocean ridges with a capacity of 5 to 10 km [45].

▶ The deformations of the trench respond to the coupling between the upper and lower plates relating to the continental slab age-buoyancy [47],

▶ The back-arc deformation roughly correlate with upper continental tectonic plate velocity [12].

▶ The trench migration rates are chiefly controlled by the lower continental tectonic plate velocity [19],

▶ In turn, tectonic plate velocity depends on the tectonic slab age buoyancy [5].

Technical Approach

To study such a complex system as Mariana Trench, an objective method combining various approaches (statistics, R, GIS, descriptive analysis and graphical plotting) was performed.
Thus, the methodology includes following steps:

► Data capture in GIS, vector thematic data were processed in QGIS: tectonics, bathymetry, geomorphology and geology.
► Programming on R language
    ► statistics
    ► descriptive analysis
    ► graphical plotting
► Geospatial comparative analysis of variables by 4 tectonic plates

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Methodology (Brief)

The methodology includes following steps.

▶ firstly, vector thematic data were processed in QGIS: tectonics, bathymetry, geomorphology and geology.

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Methodology (Brief)

The methodology includes following steps.

▶ firstly, vector thematic data were processed in QGIS: tectonics, bathymetry, geomorphology and geology.

▶ secondly, 25 cross-section profiles were drawn across the trench. The length of each profile is 1000-km.

　　▶ the attribute information has been derived from each profile and stored in a table containing coordinates, depths and thematic information.

　　▶ this table was processed by methods of the statistical analysis on R

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  ▶ the attribute information has been derived from each profile and stored in a table containing coordinates, depths and thematic information.
  ▶ this table was processed by methods of the statistical analysis on R

▶ thirdly, performed geospatial comparative analysis to estimate effects of the data distribution by 4 tectonic plates: slope angle, igneous volcanic areas and depths.

Data Capture in GIS

The GIS part of the research is performed in the QGIS 3.0. Geospatial tasks by QGIS plugins: reading coordinates, crossing profile lines, reading data from attribute table into .csv format. Various geospatial data have been uploaded into the GIS project: bathymetry (depths), sediment thickness, location of igneous volcanic zones, tectonic plates, etc. The GIS project: UTM cartesian coordinate system (square N-55).
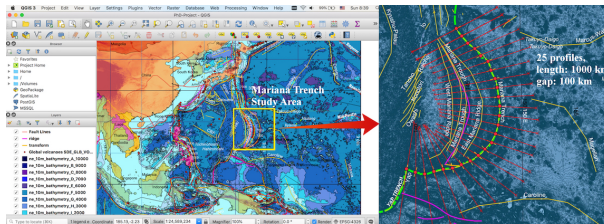
Figure 5: *Study area. Methodological approach using QGIS: digitizing profiles across the Mariana Trench. Source:* [23]

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Digitizing bathymetric profiles
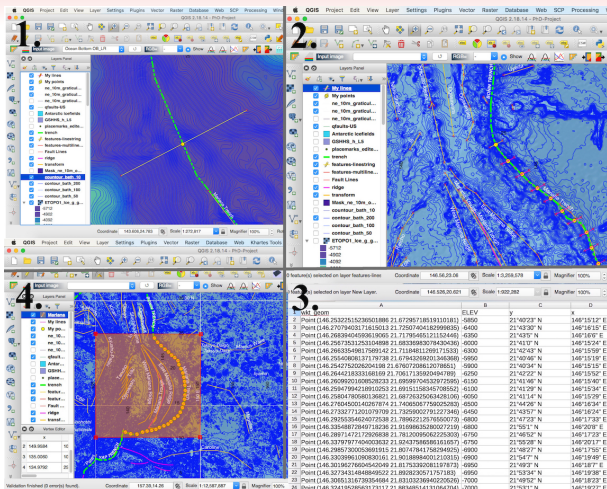
Figure 6: *Digitizing 25 bathymetric profiles across the Mariana Trench.* [23]

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TₑX macro language code for bathymetric plotting. Example for profile 16, 17, 18.

```
\begin{filecontents*}{MyTab18.csv}
ELEV ,y2,x2
145.528246366,47.0433461696,-7800 # bathymetric data here in 3 columns
\end{filecontents*}
\begin{tikzpicture}
\begin{axis}[grid=major,minor x tick num=10,minor y tick num=10,
      colorbar sampled line,colormap name=bluered,
      title={Mariana Trench. Bathymetric Profiles Nr.16,17,18},
      ylabel={Depth (m)},
      legend entries={Profile18,Profile17,Profile16,},
      scaled ticks=false,
      yticklabel style={/pgf/number format/fixed,/pgf/number format/fixed zerofill,}]
\addplot+ [scatter,only marks,mark=Mercedes star flipped,colormap name=bluered,]
table [x=x, y=d, col sep=comma] {MyTab16.csv};
\addplot+ [scatter, colorbar sampled line,only marks,mark=asterisk,colormap
name=bluered,]
table [x=long, y=d, col sep=comma] {MyTab17.csv};
\addplot+ [scatter, colorbar sampled line,only marks,mark=10-pointed star,colormap
name=bluered,]
table [x=y2,y=ELEV, col sep=comma] {MyTab18.csv};
\end{axis}
\end{tikzpicture}
```
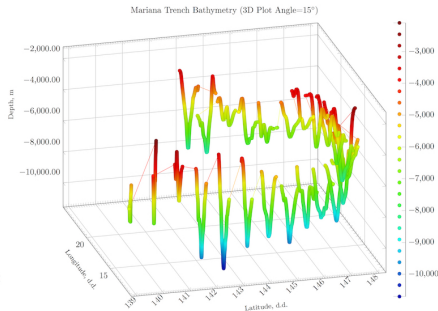
LATEX for bathymetry

Figure 7: *LATEX Plotting: two selected profiles, 2D View. Source: [32]*

LaTeX for bathymetry: 3D plotting

Figure 8: *LaTeX Plotting: Marina Arc, 3D View. Source: [32]*

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Graph: bathymetric profiles
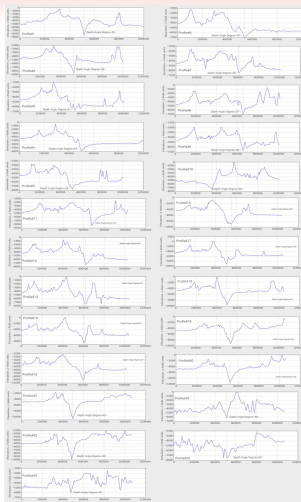
Figure 9: Graphs of the 25 bathymetric profiles, Mariana Trench. Source: [23]

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Statistical box plots
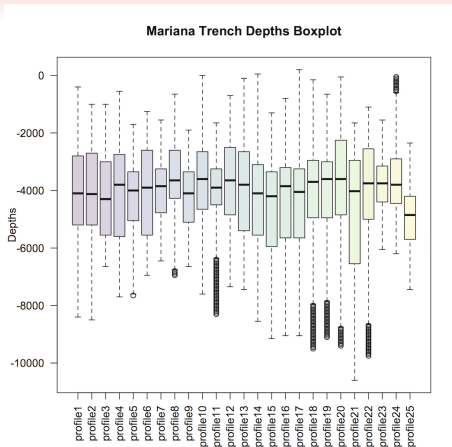
Figure 10: Boxplots of the cross-section profiles: R based statistical analysis. [32]

'Violin' Plots

The violin plots show Kernel probability density distribution of the bathymetric observations, as multimodal distributions with multiple peaks. Kernel density distribution plot was created using library {violinmplot} of R in a combined plot, which includes calculated quantiles for 0.25 and 0.75 of the data pool.
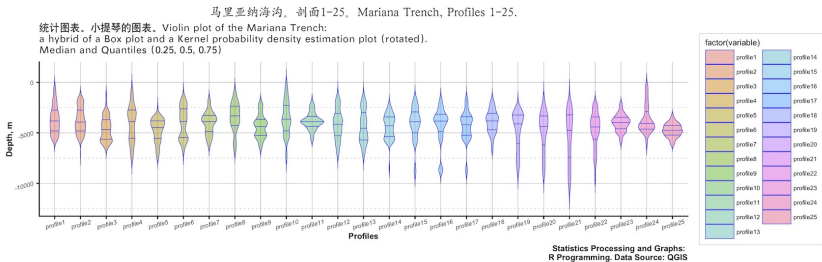
Figure 11: Violin plots of the profiles: R based statistical plotting. [31]

Regression Analysis: Enlarged Selected Profiles.
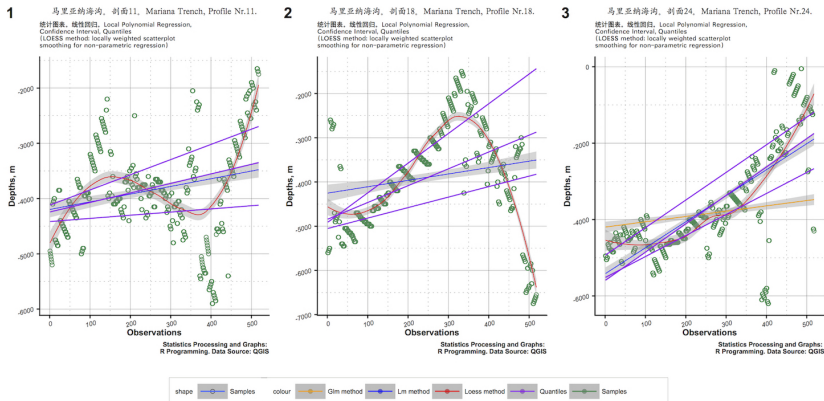
Figure 12: Regression Analysis: 3 selected profiles. Source: [29]

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Normalized steepness slope calculation of the cross-section profiles
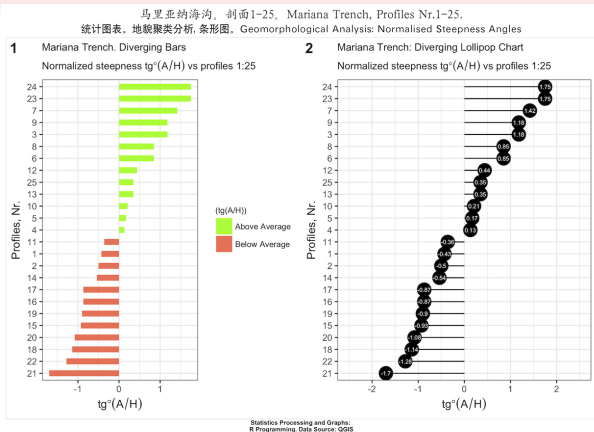
Figure 13: Normalized steepness slope calculation of the cross-section profiles: R library {ggplot}, [52]. [32]. Visualization of the plot for normalized steepness: R.

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Ranking dot plots by data grouping
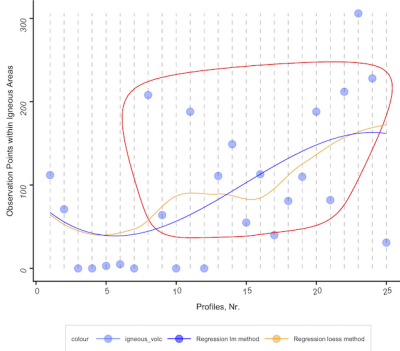
Figure 14: *Ranking dot plots by data grouping: Left: distribution of data points by profiles across igneous areas. Right: variation of steepness angles by 25 profiles. R based visualization and statistical analysis, libraries {ggalt} and {ggplot}.* [29]

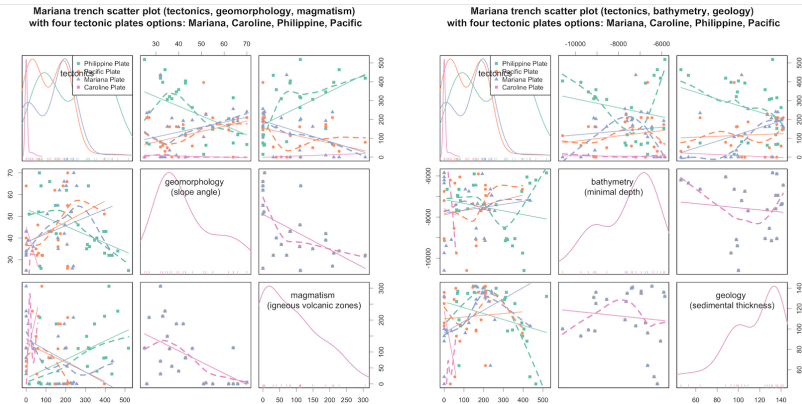Compiled in LuaLATEX by Polina Lemenkova for: the Seminar at OUC.
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Scatterplot matrices

Figure 15: *Scatterplot matrices.* [30]

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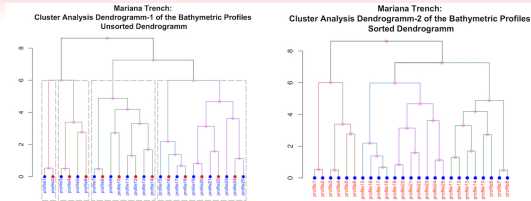
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Python

Figure 16: *R based dendrogram tree of the 25 profiles. Left: unsorted, right: sorted. [33]*
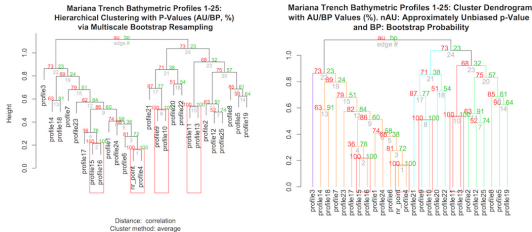
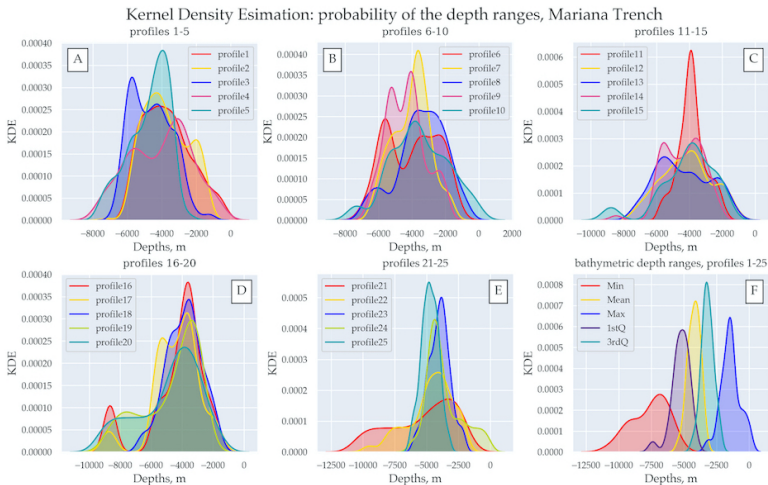Figure 17: *Hierarchical clustering with p-values using multiscale bootstrap probability, R. [33]*

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Python (Matplotlib)

Figure 18: *Kernel Density Estimation (KDE) for the profiles bathymetry. Python libraries: Matplotlib, Seaborn, Pandas [46]. [28]*

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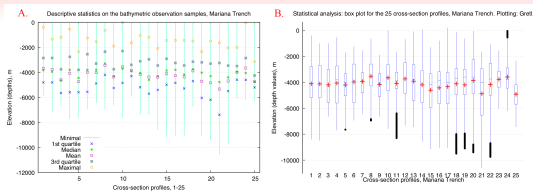
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Gretl

Figure 19: Descriptive statistical analysis of the bathymetry in the study area: minimal, mean, median and maximal values (A); box plots of the cross-sectional profiles (B). Plotting: Gretl . Source: [27]
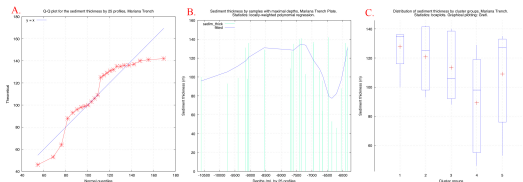

Figure 20: Statistical analysis of the sediment thickness: QQ plot (A), locally-weighted polynomial regression (B); box plots ranked by clusters (C). Source: [27]
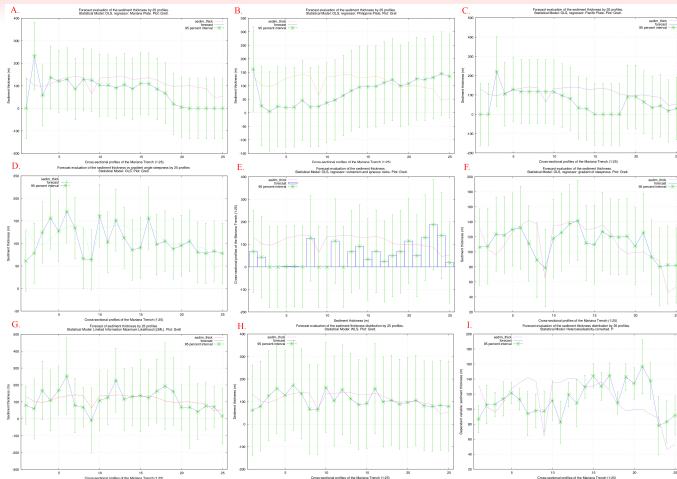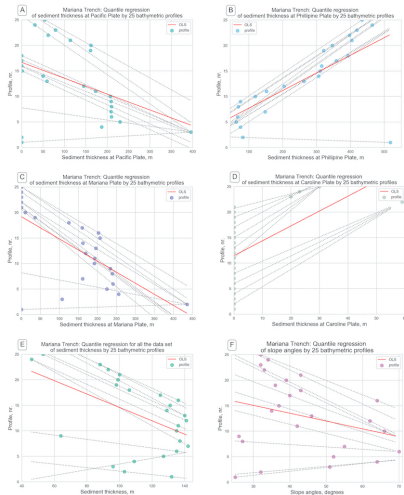
Gretl

Figure 21: Forecast evaluation of the spatial variations in sediment thickness. Modelling methods: OLS (A-F); LML (G); WLS (H); Heteroskedastisity-corrected (I). Plotting: Gretl. [27]

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Python (StatsModel)

Quantile regression tested by Python library StatsModel. [25]

▶ quantile regression is tested by Python library StatsModel [46] for sediment thickness (m) versus geologic parameters [25]

▶ quantile regression (approach of the linear regression) shows the estimated conditional median and other quantiles of the response geological variables:

▶ the upper two rows of the plot show (subplots A, B, C, D) data distribution across tectonic plates: A) Pacific Plate; B) Philippine Plate; C) Mariana Plate; D) Caroline Plate; E) Cumulative sediment thickness; F) Slope angle degree by profiles

▶ the lower row of the plot (subplots E, F) shows data distribution for the cumulative sediment thickness and slope angle degree by profiles.

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Results - I. Bathymetry: north, profiles 1-19

Statistical analysis revealed following findings:

▶ The major depth observation points of the Mariana Trench are located in between the -3000 and -5000 m.

▶ The widths of the confidence intervals are expanding rapidly by the profiles 12 to 15 thus indicating on the large amplitude of the depths variations in this part of the Mariana Trench.

▶ The profile depths are affected by the local geographic features caused by the location on 4 tectonic plates with varying environmental conditions.

▶ Conversely, profiles from 1 to 16 have gradual decrease in absolute depths, which can be noted in outliers sample location.

▶ A slight increase in absolute depths of the profiles № 4-8.

Results - II. Bathymetry: south, profiles 20-25

Summaries of the variations of the local polynomial regression of the bathymetric depths of the measured samples are presented.

▶ The maximal depths reach up to -10000 in the current dataset: profiles №20, 21, 22 crossing mostly Philippine tectonic plate (t.p.).

▶ The widths of the confidence intervals expand rapidly by the profiles 19 to 22 indicating on the large amplitude of the depths variations in this part of the trench.

▶ Decrease of depth: profiles №23, 24, 25, Caroline t.p.

▶ Profiles №23 and 24 demonstrate the deepest depth values.

▶ The absolute depths in the profiles 22 to 25 on the Caroline t.p. become shallower than those on Philippine and Pacific t.p.

▶ The majority of the observation points: Pacific and Philippine t.p., following by Mariana t.p. Caroline t.p. only covers a few points.

▶ Variability in the geological factors of the underlying t.p. triggers changes in bathymetric settings

Results - III. Sediment thickness

The sediment thickness changes notably both within the trench by profiles (1:25) and between four tectonic plates that Mariana Trench crosses: Philippine, Pacific, Mariana and Caroline. Since the tectonic properties and attribute values of them are not identical. The comparative analysis of how the data vary across four distinctive plates revealed that the middle part of the Mariana Trench (profiles: 14 up to 17) has roughly equal proportions of the sediment thickness layer, which indicates that

▶ spatial locations and distributions of the volcanic areas and slope angle of the ocean trench are closely interrelated;

▶ geographic distributions of the volcanic areas and steepness of the slope angles of the ocean trench affect sedimental thickness.

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Results - IV. Angle steepness (1)

Analysis of the angle steepness of the cross-section profiles along Mariana Trench revealed following findings:

▶ The major trend of the trench angles located on the Pacific plate has downward general line trend.

▶ The Philippine tectonic plate, on the contrary, has a minimal peak by profiles № 14-21, and then moving upwards.

▶ The highest value for the trench angle steepness is within Caroline t.p.

▶ Mariana plate has the highest density of depth distribution values, followed by the Philippine plate, then Pacific and Caroline, respectively.

▶ From two multiple panel graphs by groups one can compare the slope angles and depth distributions by tectonic plates.

Results - V. Angle steepness (2)

- ▶ A bunch of bathymetric cross-section profiles form a cluster groups with similar geomorphic properties divided into five groups over the study area.
- ▶ Thus, profiles: 21, 22, 18 and 20 have all strong slope tg°angle degree, which is an average of 0.05.
- ▶ Similarly, profiles: 15, 19, 16, 17, 14 and 2, belonging to class very strong slope, have an tg°angle of 0.057 to 0.058 (Figure 19).
- ▶ When compared with third group in the study area, such as class extreme slope (profiles: 1, 11, 4, 5, 10 and 13), the average slope tg°angle fluctuating from 0.060 to 0.070.
- ▶ The fourth group is class steep slope (profiles: 25, 12, 6, 8 3) with a slope tg°angle values from 0.070 to 0.075.
- ▶ Finally, the last group is notable for the highest steepness (profiles: 9, 7, 23, 24), with average slope tg°angle degree up to 0.079.

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Conclusion

Impact Factors
The slope steepness is generally related to the slab subduction (tectonic settings) in the particular area, but may also be associated with other factors: topography, submarine volcanism, geology, oceanology.

Enevenness
As a result of the undertaken study, a strong spatial geomorphic unevenness of the Mariana Trench has been revealed: the middle part (profiles: 14 up to 17) has very strong slopes and roughly equal proportions of the sediment thickness layer, while other parts differ.
Five unique regions across the trench length have been classified.

Applied statistics using R
The impact of various factors (oceanology, geology, submarine volcanism, tectonics) affecting structure and geomorphology of the Mariana Trench were studied by means of R programming language.

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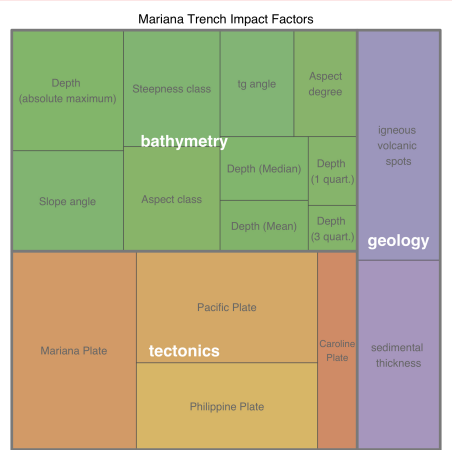
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Impact Factors

Figure 22: Treemap for impact factors affecting Mariana Trench formation, R visualization. Source: [32]
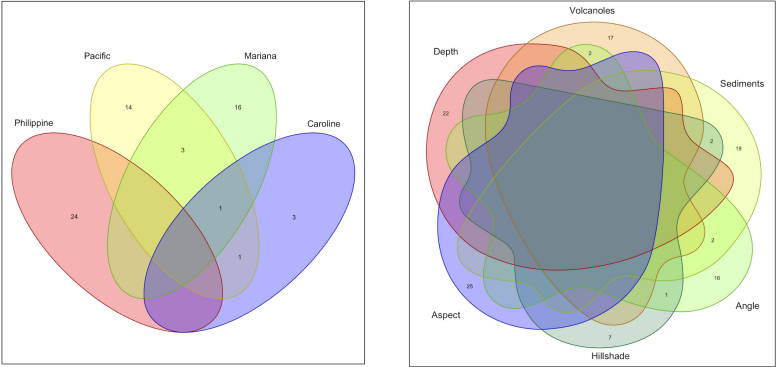
Euler-Venn diagrams: 4 and 6 petals

*Figure 23: Possible correlations of the impact factors affecting Mariana Trench.
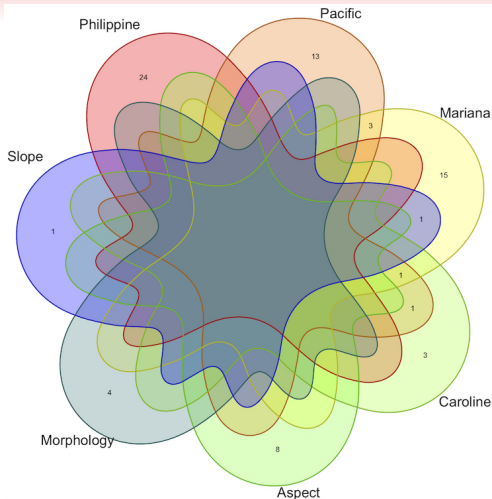Left: four tectonic plates. Right: environmental factors*

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Euler-Venn diagrams: 7 petals

Figure 24: Correlations of the impact factors
affecting Mariana Trench, R

Research Innovation

There are both theoretical and practical innovations of the presented research.

- ▶ The theoretical novelty lies in the comparative geomorphological mapping of the Mariana hadal trench that does not exists in the available literature.
- ▶ The practical novelty consists in the developed methodology of the sequential technological chain of processes: QGIS plugins, R, Python.
- ▶ Cartographic novelty consists in the developed and presented algorithm of the cross-section profiles digitizing and geomorphic modelling of the hadal trench modelling using QGIS plugins. Other methods include Gretle, SPSS [26], GMT [20], [21].
- ▶ Hadal trench present a complex system with highly interconnected factors affecting geomorphological structure, formation and development of the trench: slabs and tectonics plates, bathymetry, geographic location, geologic structure of the underlying basement and sediment thickness.
- ▶ Therefore, comparative analysis of the Mariana trench requires advanced methods of data analysis for operating with large data sets, structuring, organizing and managing thematic information in a GIS database, linking data and creating map overlays [36], [34].
- ▶ Integrating multi-source data supports verification of the data precision and control. The most important geodata include GEBCO [43]; [44], SRTM [2], ETOPO1 [1], Goole Earth [37], CryoSat-2, Envisat, Jason-1 [48].

Research Significance and Justification

The significance and justification of this works consist in the following:

▶ Although ML has been significantly increased recently, using scripting and ML in cartography still remains lower comparing to the traditional GIS used in geosciences (e.g. [51], [15], [17], [16], [38], [50], [41], [7], [40], [39]).

▶ Seafloor mapping includes multiple steps in technological process which may include: Hydrosweep DS sonar echo-sounding [35], CARIS HIPS data processing [8], ArcGIS/ArcCatalog database management, QGIS data processing.

▶ Accurate digitizing cross-section profiles using QGIS is effective. Modelling is important for accurate geomorphological data analysis and crucial for better understanding of the seafloor landforms.

▶ QGIS-based mapping provides accurate visualization of the seafloor.

▶ QGIS-based mapping provides enables cartographic digitizing.

▶ Efforts in developing methodology in automatization in bathymetric mapping exists [49].

Conclusion

▶ Precise, correct and up-to-date information about the geomorphology Mariana trench is necessary understanding marine geology, tectonics, seismicity, processes of sedimentation and geodynamic evolution of the seafloor [10], [11], [18], [9].

▶ Submarine geomorphological and bathymetric mapping plays a critical role in analysis of the geological structures of the seafloor, marine benthic habitats, navigation, geological drilling, modelling marine environment and other aspects of geosciences.

▶ Current studies contributed to the methodological testing and technical application of the advanced algorithms for seafloor modelling and mapping and to the geomorphological modelling.

▶ Tested, presented and explained functionality of the several QGIS plugins enables to do automated digitizing of the orthogonal profiles crossing trenches in the perpendicular direction. Through this modelling, the shape of the landforms and steepness gradient of the trenches were visualized, compared and statistically analyzed.

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References

[1] C. Amante and B. W. Eakins. *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis*. NOAA Technical Memorandum, 2009, p. 19. DOI: 10.7289/V5C8276M (cit. on p. 42).

[2] J. J. Becker, D. T. Sandwell, W. H. F. Smith, J. Braud, B. Binder, J. Depner, D. Fabre, J. Factor, S. Ingalls, S. H. Kim, R. Ladner, K. Marks, S. Nelson, A. Pharaoh, R. Trimmer, J. Von Rosenberg, G. Wallace, and P. Weatherall. "Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS". In: *Marine Geodesy* 32 (4 Nov. 2009), pp. 355–371. ISSN: 0149-0419. DOI: 10.1080/01490410903297766 (cit. on p. 42).

[3] J. L. Bogdanov. *Gidrotermal'nye rudoprojavlenija riftov Sredinno-Atlanticheskogo hrebta (Hydrothermal deposits of rift in the Mid-Atlantic ridge)*. Russian. Ed. by Bogdanov. Moscow: Nauchnyi mir, 1997. 167 pp. (cit. on p. 5).

[4] D. Boutelier, O. Oncken, and A. R. Cruden. "Trench-parallel shortening in the forearc caused by subduction along a seaward-concave plate boundary: Insights from analogue modelling experiments". In: *Tectonophysics* 611 (2014), pp. 192–203. ISSN: 0040-1951. DOI: 10.1016/j.tecto.2013.11.028 (cit. on p. 6).

[5] C. G. Chase. "Extension behind island arcs and motions relative to hot spots". In: *Journal of Geophysical Research* 83 (1978), pp. 5385–5388. ISSN: 0148-0227 (cit. on p. 11).

[6] R. Dic. "Novaja global'naja tektonika (New global tectonics)". Russian. In: Moscow: Mir, 1974. Chap. Jevoljucija kontinentov i okeanicheskih basseinov kak rezul'tat spredinga okeanicheskogo dna (the Evolution of continents and ocean basins as a result of the spreading ocean floor), pp. 26–32 (cit. on p. 6).

[7] A. D. Dumnov et al. *Nacional'nyj Atlas Rossii. Priroda. Jekologija. (National Atlas of Russia. Nature. Ecology)*. Russian. Ed. by V. M. Kotlyakov. Vol. 2. Institute of Geography, Russian Academy of Science (RAS), Moscow, Russia: PKO Kartografiya, 2007. 496 pp. ISBN: 5-85120-250-5. URL: https://elibrary.ru/item.asp?id=23676880 (cit. on p. 43).

[8] S. Gauger et al. "Swath-bathymetric mapping". In: *The expedition ANTARKTIS-XXIII/4 of the Res. Vessel 'Polarstern' in 2006. Berichte zur Polar- und Meeresforschung // Reports on Polar and Marine Research* 557 (2007). Ed. by K. Gohl, pp. 38–45. ISSN: 1618-3193. DOI: 10.6084/m9.figshare.7439231. HAL: hal-02022076. URL: https://www.coldregions.org/vufind/Record/288392. In English Ant. Acc. No.: 85104. CRREL Acc. No.: 63000887; illus., incl. sketch maps (cit. on p. 43).

[9] K. Gohl et al. *Deep crustal refraction and reflection seismics. Crustal and sedimentary structure and geodynamic evolution of the West Antarctic continental margin and Pine Island Bay*. Bremerhaven, Germany: Alfred Wegener Institute, 2006, pp. 20–30. DOI: 10.6084/m9.figshare.7439243. URL: https://epic.awi.de/29852/1/PE_75.pdf. Expedition program No. 75 of ANT-XXIII/4 Cruise 11-12 (cit. on p. 44).

[10] K. Gohl et al. "Tectonic and Sedimentary Processes of the West Antarctic Margin of the Amundsen Sea Embayment and Pine Island Bay". In: 2nd *Open Science Conference and 29th SCAR on 'Antarctica in the Earth System'* (July 12–14, 2006). Hobart, Tasmania, Australia, July 2006. DOI: 10.6084/m9.figshare.7435484.v1. URL: https://www.scar.org/events/ (cit. on p. 44).

[11] K. Gohl et al. *Crustal and Sedimentary Structures and Geodynamic Evolution of the West Antarctic Continental Margin and Pine Island Bay*. Bremerhaven, Germany, 2006. DOI: 10.13140/RG.2.2.16473.36961. URL: https://epic.Alfred%20Wegener%20Institute.de/29852/1/PE_75.pdf (cit. on p. 44).

[12] A. Heuret and S. Lallemand. "Plate motions, slab dynamics and back-arc deformation". In: *Physics of the Earth and Planetary Interiors* 149 (2005), pp. 31–51. ISSN: 0031-9201. DOI: 10.1016/j.pepi.2004.08.022 (cit. on p. 11).

[13] A. C. Horleston and G. R. Helffrich. "Constraining sediment subduction: A converted phase study of the Aleutians and Marianas". In: *Earth and Planetary Science Letters* 359–360 (2012), pp. 141–151. ISSN: 0012-821X. DOI: 10.1016/j.epsl.2012.10.019 (cit. on p. 6).

[14] D. M. Hussong and S. Uyeda. *Tectonic process and the history of the Mariana Arc: A synthesis of the results of deep sea drilling project leg 60*. p. 909–929. 1982 (cit. on p. 6).

[15] M. Klauo et al. "Land Planning as a Support for Sustainable Development Based on Tourism: A Case Study of Slovak Rural Region". In: *Environmental Engineering and Management Journal* 16.2 (2017), pp. 449–458. DOI: 10.30638/eemj.2017.045. URL: http://www.ecozone.ro/reviste.php?revista=12&volum=57&numar=174&RID=1199 (cit. on p. 43).

[16] M. Klauo et al. "Landscape metrics as indicator for ecological significance: assessment of Sitno Natura 2000 sites, Slovakia". In: *Ecology and Environmental Protection*. Proceedings of the Int'l Conference (Belarusian State University, Mar. 19–20, 2014). Minsk, Belarus: BSU Press, Mar. 2014, pp. 85–90. DOI: 10.6084/m9.figshare.7434200. HAL: hal-01972864. URL: http://elib.bsu.by/handle/123456789/103362 (cit. on p. 43).

[17] M. Klauo et al. "Determination of ecological significance based on geostatistical assessment: a case study from the Slovak Natura 2000 protected area". In: *Central European Journal of Geosciences* 5.1 (2013), pp. 28–42. ISSN: 1896-1517. DOI: 10.2478/s13533-012-0120-0. URL: https://www.degruyter.com/view/j/geo.2013.5.issue-1/s13533-012-0120-0/s13533-012-0120-0.xml?format=INT (cit. on p. 43).

[18] G. Kuhn et al. *The response of quaternary climatic cycles in the South-East Pacific: development of the opal belt and dynamics behavior of the West Antarctic ice sheet*. Bremerhaven, Germany, 2006. DOI: 10.13140/RG.2.2.11468.87687. URL: https://epic.Alfred%20Wegener%20Institute.de/29852/1/PE_75.pdf (cit. on p. 44).

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[19]   S. Lallemand, A. Heuret, C. Faccenna, and F. F. "Subduction dynamics as revealed by trench migration". In: *Tectonics* 27 (2008), p. 3014. ISSN: 1944-9194. DOI: 10.1029/2007tc002212 (cit. on p. 11).

[20]   P. Lemenkova. "Topographic surface modelling using raster grid datasets by GMT: example of the Kuril-Kamchatka Trench, Pacific Ocean". In: *Reports on Geodesy and Geoinformatics* 108 (Nov. 2019). **Scopus Q3, WoS**, pp. 9–22. ISSN: 2391-8365. DOI: 10.2478/rgg-2019-0008 (cit. on p. 42).

[21]   P. Lemenkova. "GMT Based Comparative Analysis and Geomorphological Mapping of the Kermadec and Tonga Trenches, Southwest Pacific Ocean". In: *Geographia Technica* 14 (2 Oct. 2019). **Scopus Q3, WoS**, pp. 39–48. ISSN: 1842-5135. DOI: 10.21163/GT_2019.142.04. URL: http://technicalgeography.org/index.php/latest-issue-2-2019/289-04_lemenkova (cit. on p. 42).

[22]   P. Lemenkova. "Computing and Plotting Correlograms by Python and R Libraries for Correlation Analysis of the Environmental Data in Marine Geomorphology". In: *Jeomorfolojik Aratrmalar Dergisi / Journal of Geomorphological Researches* 3 (Oct. 2019), pp. 1–16. ISSN: 2667-4238. DOI: 10.6084/m9.figshare.10012808. URL: https://dergipark.org.tr/tr/pub/jader/issue/49634/555979 (cit. on p. 3).

[23]   P. Lemenkova. "Statistical Analysis of the Mariana Trench Geomorphology Using R Programming Language". In: *Geodesy and Cartography* 45 (2 Sept. 2019). **Scopus Q3**, pp. 57–84. ISSN: 2029-6991. DOI: 10.3846/gac.2019.3785. URL: https://journals.vgtu.lt/index.php/GAC/article/view/3785 (cit. on pp. 16, 17, 21).

[24]   P. Lemenkova. "K-means Clustering in R Libraries {cluster} and {factoextra} for Grouping Oceanographic Data". In: *International Journal of Informatics and Applied Mathematics* 2 (1 Sept. 2019), pp. 1–26. ISSN: 2667-6990. DOI: 10.6084/m9.figshare.9891203. URL: https://dergipark.org.tr/tr/pub/ijiam/issue/48898/556356 (cit. on p. 4).

[25]   P. Lemenkova. "Testing Linear Regressions by StatsModel Library of Python for Oceanological Data Interpretation". In: *Aquatic Sciences and Engineering* 34 (2 June 2019), pp. 51–60. ISSN: 2602-473X. DOI: 10.26650/ASE2019547010. URL: https://dergipark.org.tr/ase/issue/45427/547010 (cit. on p. 32).

[26]   P. Lemenkova. "Numerical Data Modelling and Classification in Marine Geology by the SPSS Statistics". In: *International Journal of Engineering Technologies* 5 (2 June 2019), pp. 90–99. ISSN: 2149-0104. DOI: 10.5281/zenodo.3270949. URL: https://dergipark.org.tr/ijet/issue/45163/585830 (cit. on p. 42).

[27]   P. Lemenkova. "Regression Models by Gretl and R Statistical Packages for Data Analysis in Marine Geology". In: *International Journal of Environmental Trends* 3 (1 June 2019), pp. 39–59. ISSN: 2602-4160. DOI: 10.5281/zenodo.3253803. URL: https://dergipark.org.tr/ijent/issue/46279/560239 (cit. on pp. 30, 31).

中国海洋大学
OCEAN UNIVERSITY OF CHINA

[28] P. Lemenkova. "Processing oceanographic data by Python libraries NumPy, SciPy and Pandas". In: *Aquatic Research* 2 (2 Apr. 2019), pp. 73–91. ISSN: 2618-6365. DOI: 10.3153/AR19009. URL: http://aquatres.scientificwebjournals.com/issue/43060/543881 (cit. on p. 29).

[29] P. Lemenkova. "An Empirical Study of R Applications for Data Analysis in Marine Geology". In: *Marine Science and Technology Bulletin* 8 (1 Mar. 2019), pp. 1–9. ISSN: 2147-9666. DOI: 10.33714/masteb.486678. URL: http://dergipark.gov.tr/masteb/issue/41105/486678 (cit. on p. 24, 26).

[30] P. Lemenkova. "Scatterplot Matrices of the Geomorphic Structure of the Mariana Trench at Four Tectonic Plates (Pacific, Philippine, Mariana and Caroline): a Geostatistical Analysis by R". In: *Problems of Tectonics of Continents and Oceans*. Proceeding 51st Tectonics Meeting (Jan. 29–Feb. 2, 2019). Ed. by K. E. Degtyarev. Vol. 1. venue: Lomonosov Moscow State University, Faculty of Geology. Institute of Geology Russian Academy of Science (RAS). Moscow: GEOS, Jan. 2019, pp. 347–352. DOI: 10.6084/m9.figshare.7699787.v1. URL: http://www.ginras.ru/struct/5/20/index.php (cit. on p. 27).

[31] P. Lemenkova. "Factor Analysis by R Programming to Assess Variability Among Environmental Determinants of the Mariana Trench". In: *Turkish Journal of Maritime and Marine Sciences* 4 (2 Dec. 2018), pp. 146–155. ISSN: 2564-7016. DOI: 10.6084/m9.figshare.7358207. arXiv: 1812.00989v1 [physics.geo-ph]. URL: http://edergi.odu.edu.tr/ojs/index.php/JMMS/article/view/426 (cit. on p. 23).

[32] P. Lemenkova. "R scripting libraries for comparative analysis of the correlation methods to identify factors affecting Mariana Trench formation". In: *Journal of Marine Technology and Environment* 2 (Nov. 2018). Ed. by M. Panaitescu and F. Memet, pp. 35–42. ISSN: 1844-6116. DOI: 10.6084/m9.figshare.7434167. arXiv: 1812.01099 [physics.geo-ph]. URL: http://cmu-edu.eu/jmte (cit. on pp. 19, 20, 22, 25, 39).

[33] P. Lemenkova. "Hierarchical Cluster Analysis by R language for Pattern Recognition in the Bathymetric Data Frame: a Case Study of the Mariana Trench, Pacific Ocean". In: *Virtual Simulation, Prototyping and Industrial Design*. Proc. 5th Int'l Conf. Issue 5 (TSTU), Nov. 14–16, 2018). Ed. by M. N. Krasnyansky. Vol. 2. Tambov: TSTU Press, Nov. 2018, pp. 147–152. ISBN: 978-5-8265-1997-4. DOI: 10.6084/m9.figshare.7531550. URL: http://go.tstu.ru/meroprijatija.php?id=46&lang=ru (cit. on p. 28).

[34] P. Lemenkova. "Linking Data Between the Worksheets and GIS Databases for Effective Management of the Environmental Projects". In: *3rd International Farabi Readings. Green Bridge Through Generations*. Materials of the 5th International Student Forum (Al-Farabi Kazakh National University, Apr. 11–12, 2016). Ed. by V. G. Salnikov. Almaty, Kazakhstan: Al-Farabi KNU Press, Apr. 2016, pp. 349–353. ISBN: 978-601-04-1958-2. DOI: 10.6084/m9.figshare.7210238. HAL: hal-01973112 (cit. on p. 42).

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[35] P. Lemenkova. "Smart Seafloor Mapping in Real Time Regime Using Deep-Sea Multibeam Echosounder Hydrosweep DS". Russian. In: *Izvestiya MGTU 'MAMI'* 5.4 (26 Dec. 2015), pp. 23–27. ISSN: 2074-0530. DOI: 10.6084/m9.figshare.7434185. HAL: hal-02021995. URL: https://elibrary.ru/item.asp?id=25449856 (cit. on p. 43).

[36] P. Lemenkova. "Thematic Information Clusters for Integrated GIS Mapping of the Marine Ecosystems". Russian. In: *Bulletin of the Yugra State University* S2.37 (Nov. 2015): *The 6th Technological Structures. Mechanisms and Perspectives of the Development*. Ed. by T. D. Karminskaya et al., pp. 48–50. ISSN: 1816-9228. DOI: 10.6084/m9.figshare.7439222. URL: https://elibrary.ru/item.asp?id=24989152. YSU Press (cit. on p. 42).

[37] P. Lemenkova. "Google Earth web service as a support for GIS mapping in geospatial research at universities". Russian and English. In: *Web-Technologies in the Educational Space. Problems, Approaches, Perspectives*. Proceedings Int'l Conference (Mar. 26–27, 2015). Ed. by S. V. Aryutkina and S. V. Napalkov. Arzamas, Russia: OOO Rastr-NN, Mar. 2015, pp. 460–464. ISBN: 978-5-9906469-1-9. DOI: 10.6084/m9.figshare.7211798. HAL: hal-01973680. URL: https://elibrary.ru/item.asp?id=23426340. EarthArXiv: ebyjq (cit. on p. 42).

[38] P. Lemenkova. "Seagrass Mapping and Monitoring Along the Coasts of Crete, Greece". M.Sc. Thesis. Enschede, Netherands: University of Twente, Faculty of Earth Observation and Geoinformation (ITC), Mar. 8, 2011. 158 pp. DOI: 10.13140/RG.2.2.16945.22881. URL: https://thesiscommons.org/p4h9v (cit. on p. 43).

[39] P. Lemenkova and I. Elek. "Clustering Algorithm in ILWIS GIS for Classification of Landsat TM Scenes: a Case Study of Mecsek Hills Region, Hungary". In: *Geosciences and Environment. Near-Surface Geophysics*. Proceedings of the 3rd International Conference (Association of Geophysicists & Environmentalists of Serbia (AGES), May 27–29, 2012). Ed. by S. Komatina-Petrovic. Belgrade, Serbia, May 2012. DOI: 10.6084/m9.figshare.7434218.v1. HAL: hal-02000222 (cit. on p. 43).

[40] P. Lemenkova, B. Forbes, and T. Kumpula. "Mapping Land Cover Changes Using Landsat TM: A Case Study of Yamal Ecosystems, Arctic Russia". In: *Geoinformatics: Theoretical and Applied Aspects*. Proc. 11th Int'l Conf. (May 14–17, 2012). Kiev, Ukraine, May 2012. DOI: 10.6084/m9.figshare.7434242.v1. HAL: hal-02022108. URL: https://elibrary.ru/item.asp?id=24527736 (cit. on p. 43).

[41] P. Lemenkova, C. Promper, and T. Glade. "Economic Assessment of Landslide Risk for the Waidhofen a.d. Ybbs Region, Alpine Foreland, Lower Austria". In: *Protecting Society through Improved Understanding*. 11th Int'l Symposium on Landslides & the 2nd North American Symposium on Landslides & Engineered Slopes. NASL (June 2–8, 2012). Ed. by E. Eberhardt, C. Froese, A. K. Turner, and S. Leroueil. Banff, AB, Canada, June 2012, pp. 279–285. DOI: 10.6084/m9.figshare.7434230. HAL: hal-01972877 (cit. on p. 43).

[42] A. P. Lisicyn, J. A. Bogdanov, and E. G. Gurvich. *Gidrotermal'nye obrazovanija riftovyh zon okeana (Hydrothermal formation of rift zones of the ocean)*. Russian. Ed. by V. M. Kupcov. Moscow, Institute of Oceanology. n.a. P. P. Shirshov: Nauka, 1990. 341 pp. (cit. on p. **5**).

[43] L. Mayer, M. Jakobsson, G. Allen, B. Dorschel, R. Falconer, V. Ferrini, G. Lamarche, H. Snaith, and P. Weatherall. "The Nippon Foundation – GEBCO Seabed 2030 Project: The Quest to See the Worlds Oceans Completely Mapped by 2030". In: *Geosciences* 8 (2 2018), p. 63. DOI: 10.3390/geosciences8020063 (cit. on p. 42).

[44] D. Monahan. "GEBCO: the Second Century". In: *Hydro International* 8 (9 2004). University of New Hampshire, pp. 1–10 (cit. on p. 42).

[45] W. J. Morgan. "Rises, trenches, great faults, and crustal blocks". In: *Journal of Geophysical Research Atmospheres* 73 (1968), pp. 1959–1982. ISSN: 0148-0227 (cit. on p. 11).

[46] G. v. Rossum and P. development team. *Python Tutorial Release 3.6.4*. Python Software Foundation, 2018. 446 pp. (cit. on pp. **29**, **32**).

[47] L. Ruff and H. Kanamori. "Seismicity and the subduction process". In: *Physics of the Earth and Planetary Interiors* 23 (1980), pp. 240–252. ISSN: 0031-9201. DOI: 10.1016/0031-9201(80)90117-X (cit. on p. 11).

[48] D. T. Sandwell, E. Garcia, K. Soofi, P. Wessel, and W. H. F. Smith. "Towards 1 mGal Global Marine Gravity from CryoSat-2, Envisat, and Jason-1". In: *The Leading Edge* 32 (8 2013), pp. 892–899. DOI: 10.1190/tle32080892.1 (cit. on p. 42).

[49] H. W. Schenke and P. Lemenkova. "Zur Frage der Meeresboden-Kartographie: Die Nutzung von AutoTrace Digitizer für die Vektorisierung der Bathymetrischen Daten in der Petschora-See". German. In: *Hydrographische Nachrichten* 25.81 (June 2008), pp. 16–21. ISSN: 0934-7747. DOI: 10.6084/m9.figshare.7435538.v2. HAL: hal-01964403 (cit. on p. 43).

[50] I. Suetova, L. Ushakova, and P. Lemenkova. "Geoinformation mapping of the Barents and Pechora Seas". In: *Geography and Natural Resources* 4 (2005). Ed. by V. A. Snytko, pp. 138–142. ISSN: 1875-3728. DOI: 10.6084/m9.figshare.7435535 (cit. on p. 43).

[51] I. Suetova, L. Ushakova, and P. Lemenkova. "Geoecological Mapping of the Barents Sea Using GIS". In: *Int'l Cartographic Conf. ICC. Theme 5 Digital Cartography & GIS for Sustainable Develop. of Territories. Session 4 'Land Management (3)'*. La Coruña, España, July 12, 2005. DOI: 10.6084/m9.figshare.7435529. HAL: hal-01974744. URL: https://icaci.org/files/documents/ICC_Proc./ICC2005/htm/oral.htm (cit. on p. 43).

[52] R. D. C. Team. *R: a Language and Environment for Statistical Computing*. Available at http://www.R-project.org. Vienna, Austria: R Foundation for Statistical Computing, 2014 (cit. on p. 25).

Compiled in LuaLATEX by Polina Lemenkova for: the Seminar at OUC.
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