Geospatial Analysis by Python and R: Geomorphology of the Philippine Trench, Pacific Ocean

Polina LEMENKOVA[1*]

[1]Ocean University of China, College of Marine Geo-sciences, 238 Songling Rd., Laoshan, 266100, Qingdao, Shandong Province, China (P.R.C.), ORCID ID: 0000-0002-5759-1089

Abstract: The study area is focused on the Philippine Trench, a hadal trench located in the axe of the collision of the Philippine Sea Plate and Sunda Plate, west Pacific Ocean. The research is aimed at the analysis of the trench geomorphology by a correlation between changes in slope steepness and environmental variables. The methodology consists in modeling data by statistical libraries of Python and R programming languages. The results revealed that variations in the slope steepness correlate with the sediment thickness across the Philippine Trench. Variations in the landform are caused by a combination of various factors that include geology, tectonic slab dynamics, and increasing depths in bathymetry. Algorithms of the advanced machine learning and graph-based analysis applied for the marine geological data set demonstrated in this research enabled to gain insights into the seafloor geomorphology that can only be accessible by remote sensing methods and modeling. Application of the statistical methods of the data analysis by Python and R packages has broad applicability to similar research aimed at modeling landform variations in the submarine geomorphology of the hadal trenches.

Keywords: Philippine Trench, Python, R, computing, programming, Philippines, Pacific Ocean, geomorphology, geospatial analysis, statistical analysis, data modeling, oceanology

1.   Introduction

The relationship between the submarine geomorphology, bathymetry, and the tectonic settings of the ocean trenches can be derived by comparing geomorphic features (such as the steepness of the slope angles across the profiles) and geological conditions (e.g., sediment thickness). To evaluate relationships between various factors affecting the structure of the hadal trenches, methods of the advanced modeling and statistical analysis can be successfully applied [1], [2], [3].

Examples of the studies of the understanding the correlation between various factors influencing ocean ecosystems and functioning are presented in various works [4], [5], [6], [7]. Their work aims to understand how the interconnections between geology, sedimentation, and ocean landforms can be explained using available methods of the geospatial analysis. Variations in the structure of the submarine geomorphology have origin in the palaeologic geological time caused by the variety of impact factors [8]. From the more recent publications on Philippine Trench dynamics, it has been noted [9] that fluctuations in the trench dynamics affect slab morphology and character. [10] keep track of the lateral fluctuations in the upper mantle structure of the Philippine Sea basin, which is later more detailed studied by [11] with a more close focus on the geophysics across the Philippine Sea. However, clear and exact modeling of the structure and functioning of the deep ocean areas has not proposed yet. Some attempts are given [12], [13], [14] to analyze the evolution of the ocean as a marine ecosystem and factors affecting its structure and functioning, aimed at the environmental monitoring and ecological communities.

Therefore, modeling of the hadal areas of the oceans, in particular ocean trenches, is an actual challenge in the modern oceanology and marine geology. Using advanced methods of Python computing for processing data arrays enables to develop models of the submarine geomorphology in the hadal areas of the ocean [15]. Using R language allows assessment as to how do various factors affect the actual shape of the trench and to what extent the trench migration and continuous development may be influenced because of the complex interplay of the multiple geospatial factors [16]. Advanced data analysis and precise computing enabled by combinations of R and Python provide additional possibilities on the data modeling and estimation of the geomorphic landforms in comparison with geological factors and bathymetric elevations.

Corresponding author; Tel.: +86-1768-554-1605, pauline.lemenkova@gmail.com

In some previous case studies [17], [18], [19], using available methods of the oceanographic mapping existing at that time, the geomorphic patterns of the deep-sea channels, submarine fans and their topography were analyzed with regards to the deep-water sedimentation [20], mid-ocean ridge tectonics and volcanism, dynamics of the Philippine back-arc [21], [22], [23].

However, given the non-available tools of machine learning and operating with numerical data in oceanography, current studies significantly lack numerical data analysis and visualization that become possible with the rapid development of the programming algorithms applied in oceanography nowadays [24]. There are proven relationships between the geomorphic structure of the submarine landforms and sedimentation in the selected parts of the Ocean [25]. Other factors include oceanology as underwater currents [26], geology [27], tectonics [28], accumulation of the sedimentation that goes into the hadal trenches through the canyon-channel systems [29].
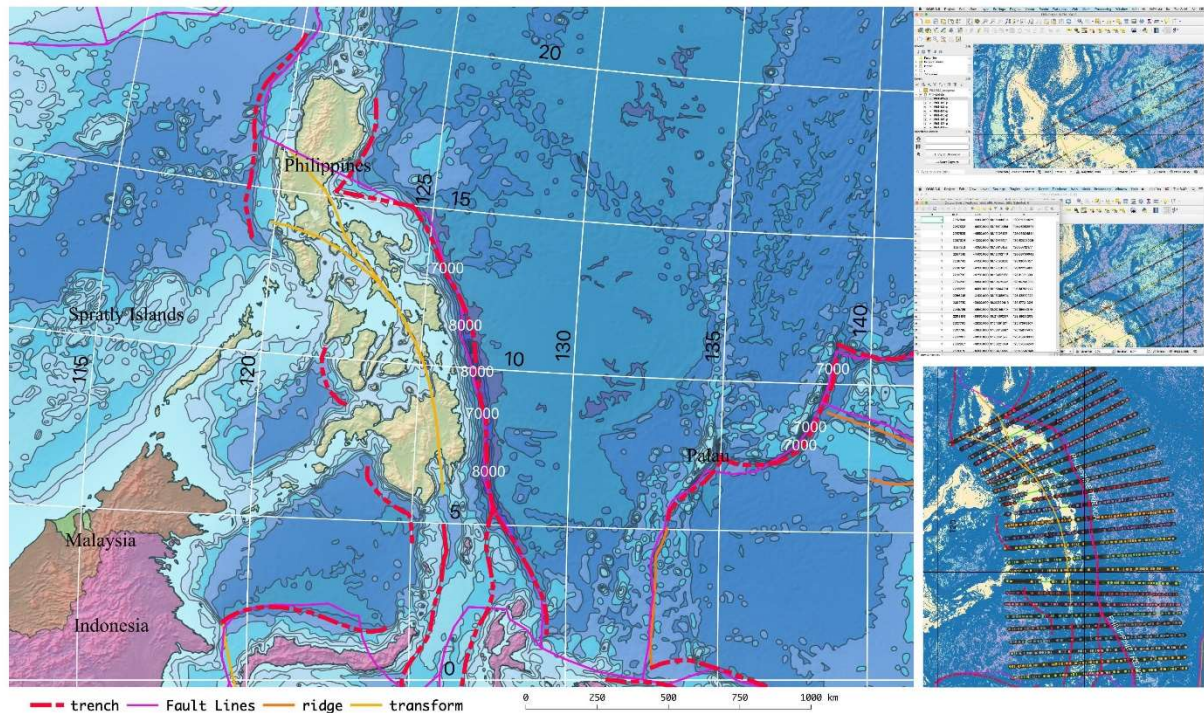

Fig. 1. Study area and digitizing cross-section profiles of the Philippine Trench and the Philippine archipelago area. Mapping: QGIS.

Active usage of numerical computing provided by R programming language enables to widely use statistical methods for marine geological and data modeling [30]. Possible applications include analysis of the interplay between the elements of the submarine ecosystem using cluster analysis [31]. Others include predicting changes in the structure of the marine ecosystem, reconstruct origin and evolution of the trench dynamics, interpretation of the existing slab motions in the Philippine Plate area [32], [33], [34], [35].

The Philippine Trench is located along the eastern edge of the Philippine archipelago, which is a deformed orogenic belt resulting from the collision of oceanic and continental blocks [36]. Because of the location in the Philippine and Sunda tectonic slabs collision, the Philippine Fault is proven to have motion in its dynamics [37], [38], [39], [40], [41], [42]. The northwestward motion of the Philippine Sea Plate is partially absorbed by the subduction of first, the Philippine Trench moving westwards, second, the East Luzon Trough located in the north-east, and third, by the Philippine Fault. Along with geologic factors, tectonic instability of the Philippine Sea Trench necessarily causes variations in the structure of its geomorphology, which is studied in this paper.

2.   Materials and Methods

Current research included various aspects of the manipulating with data: data search from the web resources, data storage in the Quantum GIS platform, geospatial processing, digitizing and geospatial processing using various GIS plugins, data capture and export to the csv tables, transfer data sets to R and Python libraries, statistical processing, and finally, modeling and visualizing graphical plots.
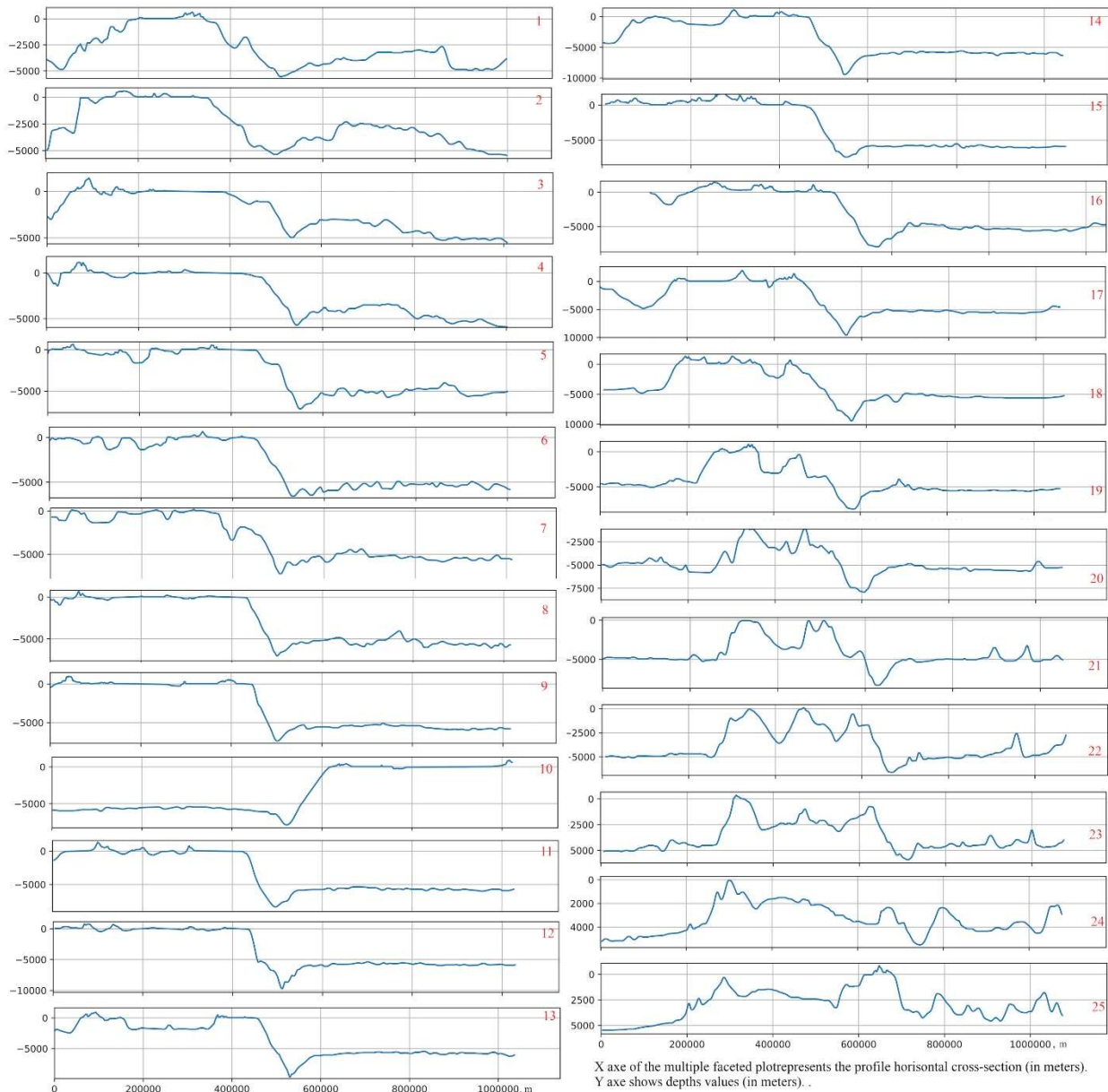

Fig. 2. Faceted plot of the 25 profiles crossing the Philippine Trench area. Plotting: QGIS.

 The GIS part of this project was performed using Quantum GIS, version 3.6.1 Noosa. The study area overview and a GIS digitizing workflow are illustrated on the Fig. 1. The stepwise GIS part of this research consists of the following steps:

   1. The 1.000 km long profiles were drawn along the trench using 'Add Line Feature' tool from the Digitizing Toolbar.

   2. The intersections between the lines and the bathymetry was done using 'Vector / Analysis Tools / Lines Intersection' command. This resulted in the array of the points along each profile. Each point has now a bathymetry depth value and a point reference number.

3. The latitude and longitude coordinates were then added to the attribute table of each corresponding intersection line using 'Lat Lon Tools' plugin of QGIS. This plugin was selected since is provided external map support, point digitizing tools, and enables to capture and zoom to coordinates of the profiles.

4. The coordinates were added to each corresponding profile using plugin function 'Lat Lon Tools / Conversion / Point layer to fields'. This operation added the initial 25 layer's latitude, longitude (Y, X) to be copied into the text fields in the new layers. Thus, the coordinates were added to the attribute tables.

5. The csv files of the attribute tables were exported from the QGIS shape files ('Export / Save Features As') to csv format for each of the 25 profiles, respectively.

The topography of the 25 profiles (Fig. 2) was plotted using 'ProfileFromPoints' plugin of QGIS that enables to plot cross section profile of observation points. Using this plugin the topography data were plotted along a centerline of the cross section profiles using elevation Z (depth values). The resulting profiles are shown on Fig. 2.
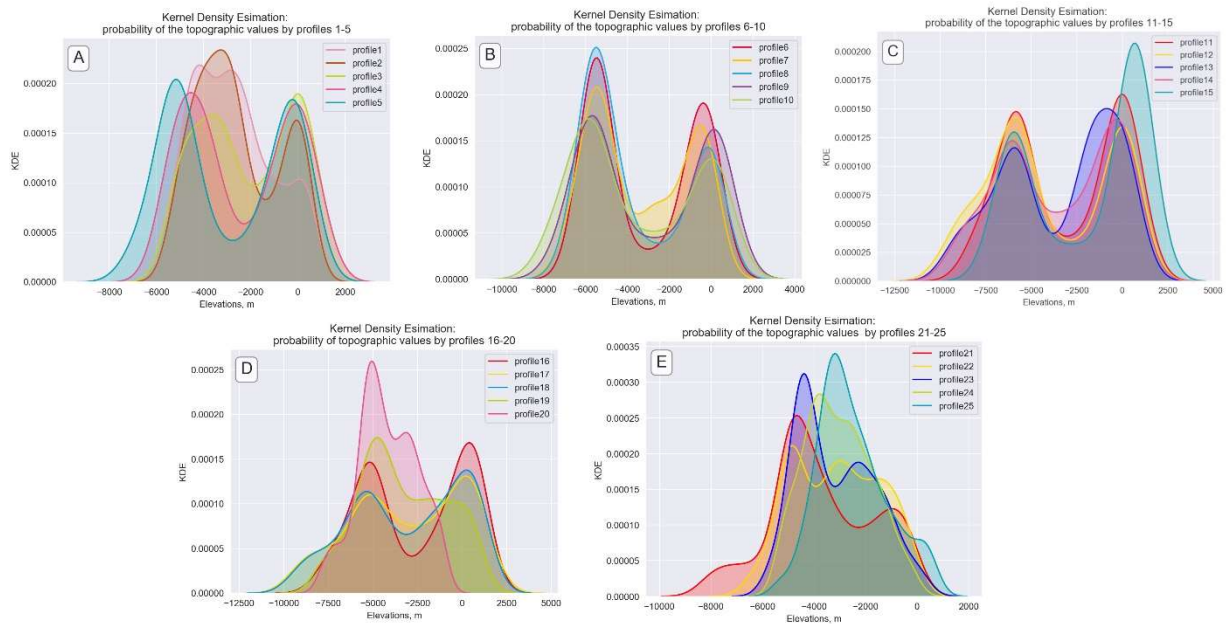

Fig. 3. KDE plots for the 25 profiles crossing the Philippine Trench area. Plotting: Python.

The statistical analysis was done using table containing attribute values of the oceanological and geospatial parameters of the Philippine area. The topographic values of the profiles were derived from the table with depth values of all the observation points. The code snippet for the mean statistics: df = pd.read_csv("Tab-PhilBathy.csv") df df['profile4'].mean() Likewise, the minimal, maximal and quartile values on bathymetry were read into the table.

Table 1. Abbreviations used for the geology and lithology

Lithology Code	Lithology / Rock type	Geology (classes from the Geological World Map (Dottin et al. 1990)
Vb	Basic volcanic rocks	Cenozoic volcanic formations
P	Precambrian (shield) rocks	Precambrian (Archean + Proterozoic)
C	Complex lithology	Mesozoic Jurassic and Cretaceous
M	Metamorphic rocks	Metamorphic formations
Smi	Mixed sedimentary consolidated rocks	Cenozoic
A	Alluvial deposits	Quaternary
Pb	Basic-ultrabasic Plutonic rocks	Plutonic rocks of all ages

The cross-sectional profiles give the insight to the variations in the geomorphological shape of the Philippine Trench and archipelago (Fig. 2). The bathymetric transects were digitized in QGIS and their coordinates and attribute values collected as a csv table. Using queries of the QGIS, the information on geology of the underlying surface was

retrieved (Table 1) to study local geomorphic conditions, variation in the lithology and sedimentation transport processes. The 25 bathymetric transects collected cross-sections of the Philippine Trench and adjacent territories of the Philippine archipelago. Geology and tectonics as attributes were used to analyze their effects on variations in the geomorphology of the trench.
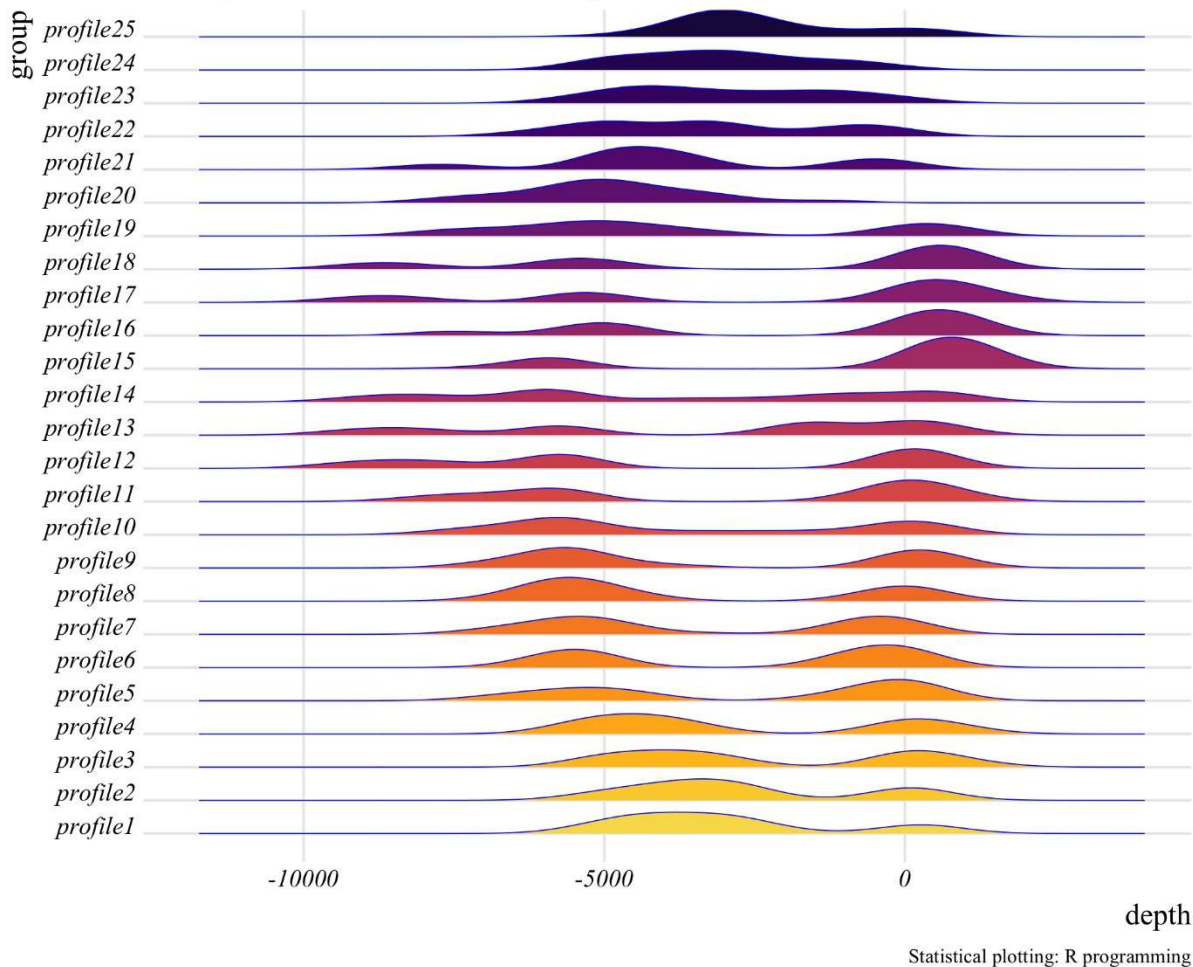

Fig. 4. Ridgeline plot on the topography of the cross-section profiles, Philippine Trench area and Philippine archipelago. Plotting: R.

Prior to further statistical analyses, we visually inspected the bathymetry cross sections per 25 profiles as shown on the joint facetted plot (Fig. 2). The attribute data were obtained by digitizing cross-sectioning profiles overlaying vector layers on geology, lithology and tectonics. Despite the variations in the density of the observation data points caused by the geomorphic shapes (ranging from extremely steep slope to strong slope), it was possible to merge and integrate the results of the vector overlay. The statistical part of this research was based on using Python and R statistical libraries that include existing mathematical algorithms and common approaches for the data processing and analysis [43], [44], [45], [46]. The Kernel Density Estimation (KDE) analysis (Fig. 3) was carried out using Seaborn library of Python using mathematical algorithms described by [47]. The visualized results of combining five KDE plots for the bathymetric cross-section profiles are shown on Fig. 3. It can be seen that combining five profiles enables to compare the geomorphology of the Philippine Trench and significantly increases the recognition of variations and depth and heights from plotting single profiles separately. Thus, the range of the density distribution in the elevations across the Philippine archipelago and Philippine Trench can be seen (Fig. 3).
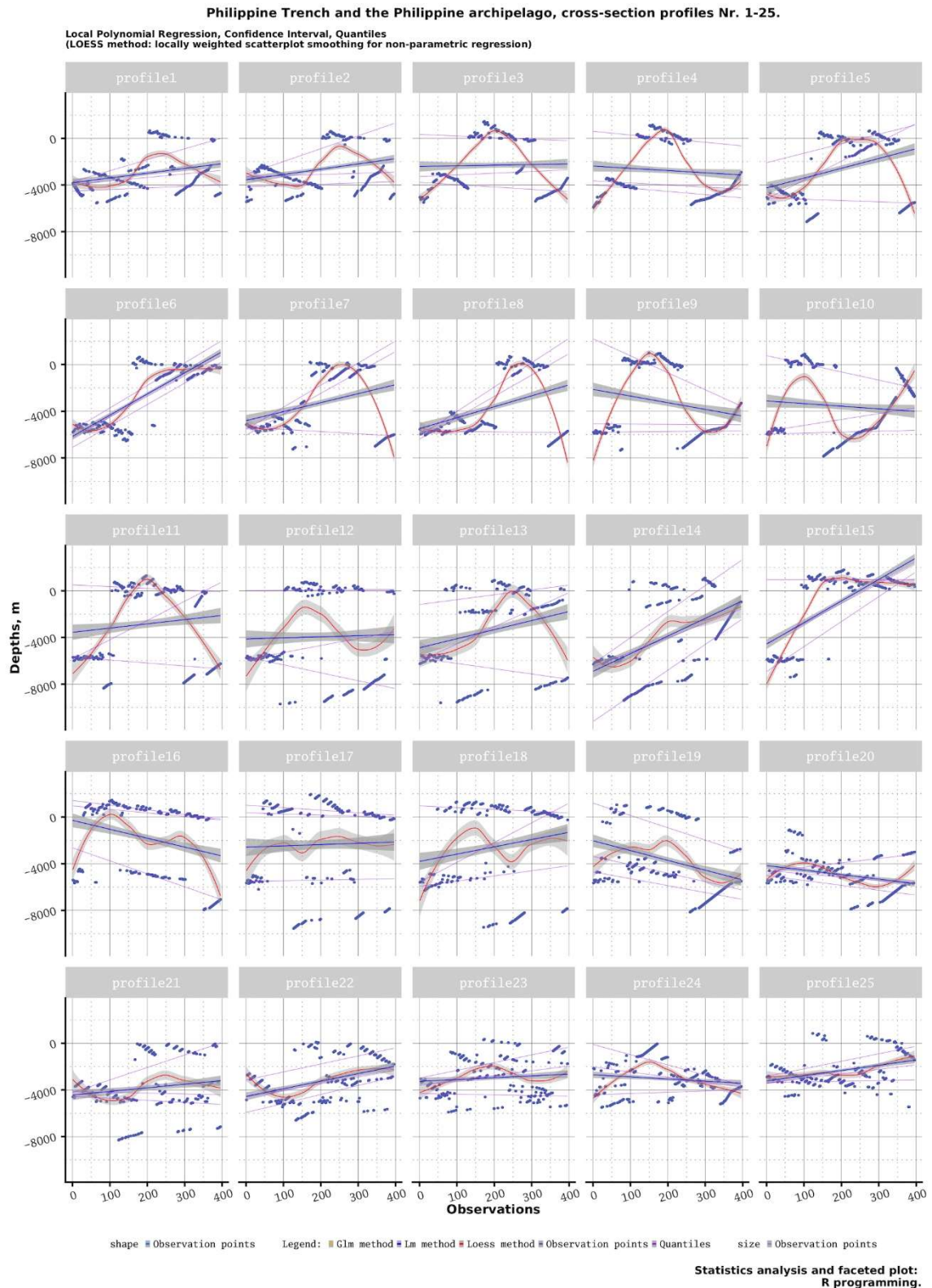
Fig. 5. Regression analysis plot showing statistical modeling of the cross-section profiles: topography of the Philippine Trench area and Philippine archipelago. Plotting: R.

To better understand the behavior of the spatial distribution in elevations as a stream view, we applied a ridge line technics of the landforms data visualization using functionality of R [48]. From the graph showing ridge lines (Fig. 4) one can see the comparative visualization of the density distribution of depths by profiles. Ridgeline profiling provides insight into the statistical distribution of the depth and elevation ranges of the Philippine Trench and

archipelago regions. From these profiles (Fig. 4), it is possible to comparatively analyze and observe distribution of the elevation values varied for 25 cross-section profiles.
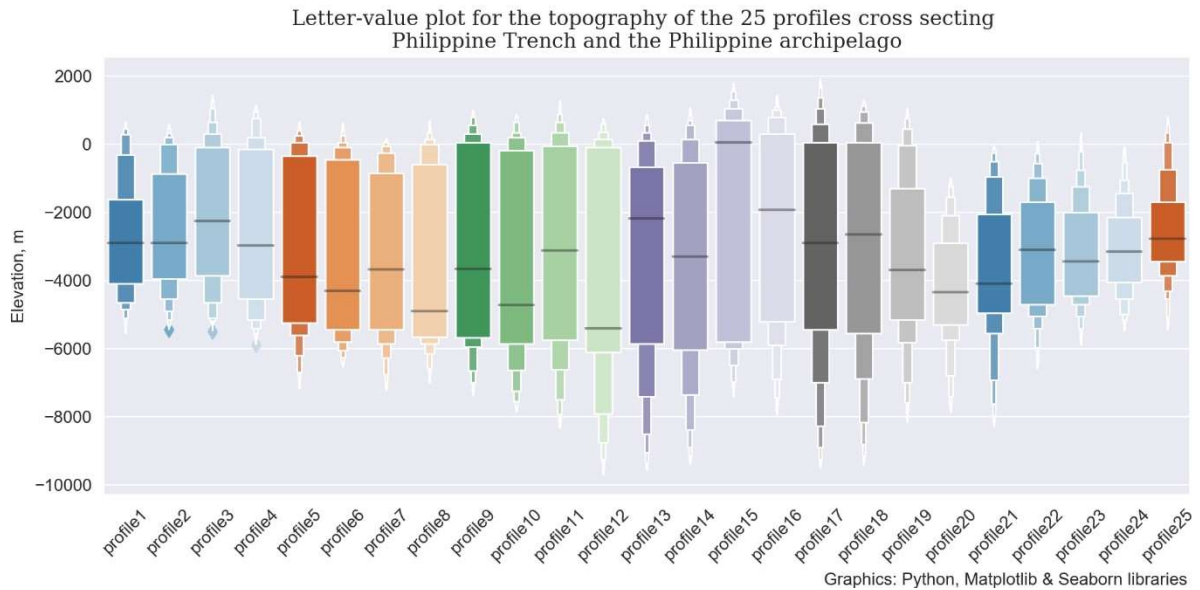

Fig. 6. Letter-value plot (statistically modified box plot) visualizing descriptive statistics of the topography of the cross-section profiles: mean, median, upper and lower quartiles of the data distribution. Plotting: Python.

Two elevation curves (Fig. 4) illustrate the ranges across profiles transversal to the main channel of the Philippine Trench and transecting Philippine archipelago, respectively (Fig. 5). For assessment of the variation in the trench geomorphology, it is of significant advantage to visualize the data set using regression analysis (Fig. 5).
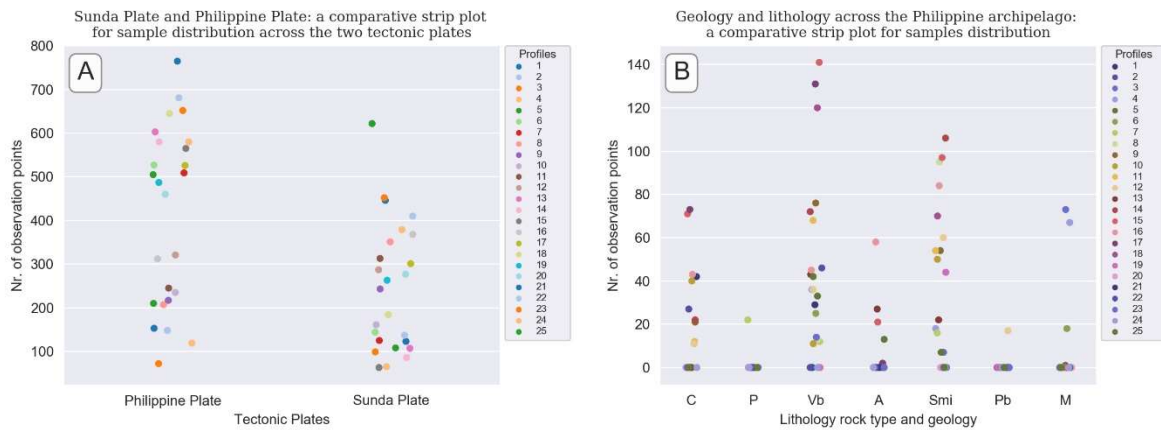

Fig. 7. Strip plots showing data distribution across tectonic plates (A) and geology (B). Plotting: Python.

Regression analysis determines the range, general trend in data distribution and scale of the changes in the observed bathymetry by analyzing changes in the values of the elevation and (Fig. 5). Advantages of plotting a facetted graph consists in visualizing a stream of the data at one look. The algorithms and approaches for the performed regression analysis use existing methods [49], [50], [51] and embedded in {ggplot} library of R. The technical implementation of the letter values plots was based on the existing methods [52], [53] embedded in modern Python Seaborn library. More sophisticated theoretical explanation on the box plots was given by [54]. Comparing the box plots, the letter value plots are better suited to the oceanographic data sets, since they represent more detailed information in the tails using letter values (Fig. 6) showing statistical data distribution: the samples shown on the letter-value plot illustrate actual range of the bathymetric observations (Y axe) by 25 profiles (X axe). The median, mean and quantiles are shown as horizontal lines on each 'box' representing the set of the samples across each of the profile.

The plots for the 25 profiles include reliable estimates of their corresponding quantiles as Tukey's boxplot showing outliers (profiles 2 and 3) labeled as observations beyond the most extreme letter values.
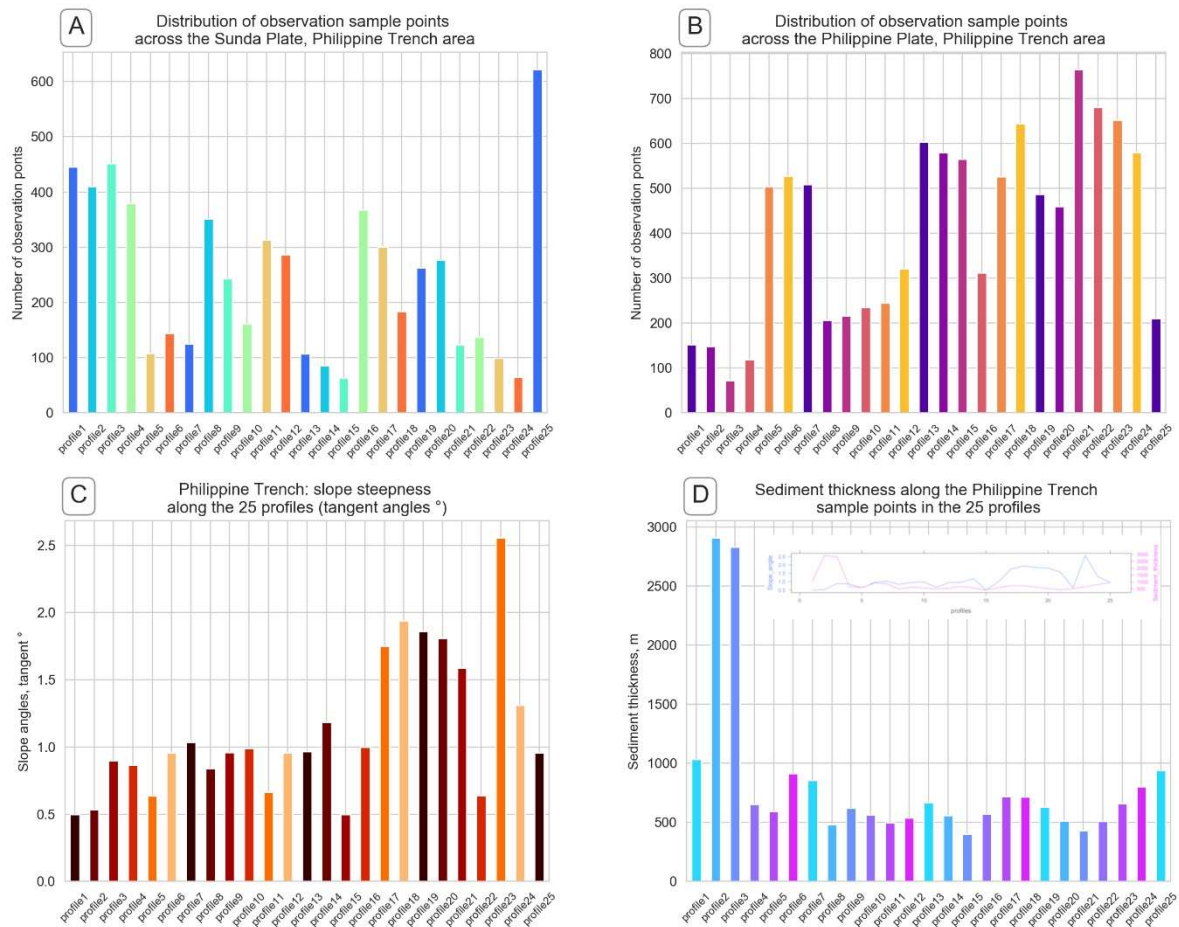

Fig. 8. Distribution of the sampling points from the cross-section profiles across the tectonic plates. Plotting: Python, Matplotlib library and R (Small subplot in 'D' showing correlation between sediment thickness and slope angles across the 25 cross-section profiles).

The next part of the research included calculation of the pairwise Pearson correlations and plotting correlation matrix between the geological, geomorphic and bathymetric factors of the Philippine Trench. Methods to plot correlation matrix (Fig. 9) include R based data analysis that embed computing correlograms for the data arrays [55]. The methods and approaches of the Matplotlib and Seaborn libraries used for plotting figures by Python language were derived from the existing literature describing statistical algorithms [56]. Finally, the geomorphic steepness of the slopes was tested (Fig. 10) using ranking plotting algorithm available in R libraries {ggsignif} and {tidyverse}.

3. Results

The data presented in this research aimed at highlighting the geomorphic variations of the Philippine Trench and multiple complex characteristics of the impact factors of geological origin. Location of the trench on to various tectonic plates along with geological factors (sediment thickness) and lithology contributes in geomorphic shaping of the actual form of the Philippine Trench. The results obtained by different statistical approaches performed using R and Python libraries are analyzed and integrated in order to provide a more detailed understanding of the character of the geomorphic structure of the Philippine Trench. The extreme depths values in the data set are notable for the following profiles: profile Nr. 12 (max depth: -9.700 meters), profile Nr. 13 (max depth: -9.600 m), profile Nr. 14 (max depth: -9.400 m), profile Nr. 18 (max depth: -9.450 m). All these profiles are cross sectioning the Philippine Trench in its central part where its geomorphic pattern can be characterized from 'steep slope' (profiles Nr. 12 and 13, see Fig. 10) to 'very steep slopes' (profiles 14 and 18). Other profiles have depths not exceeding 9.000 meters.
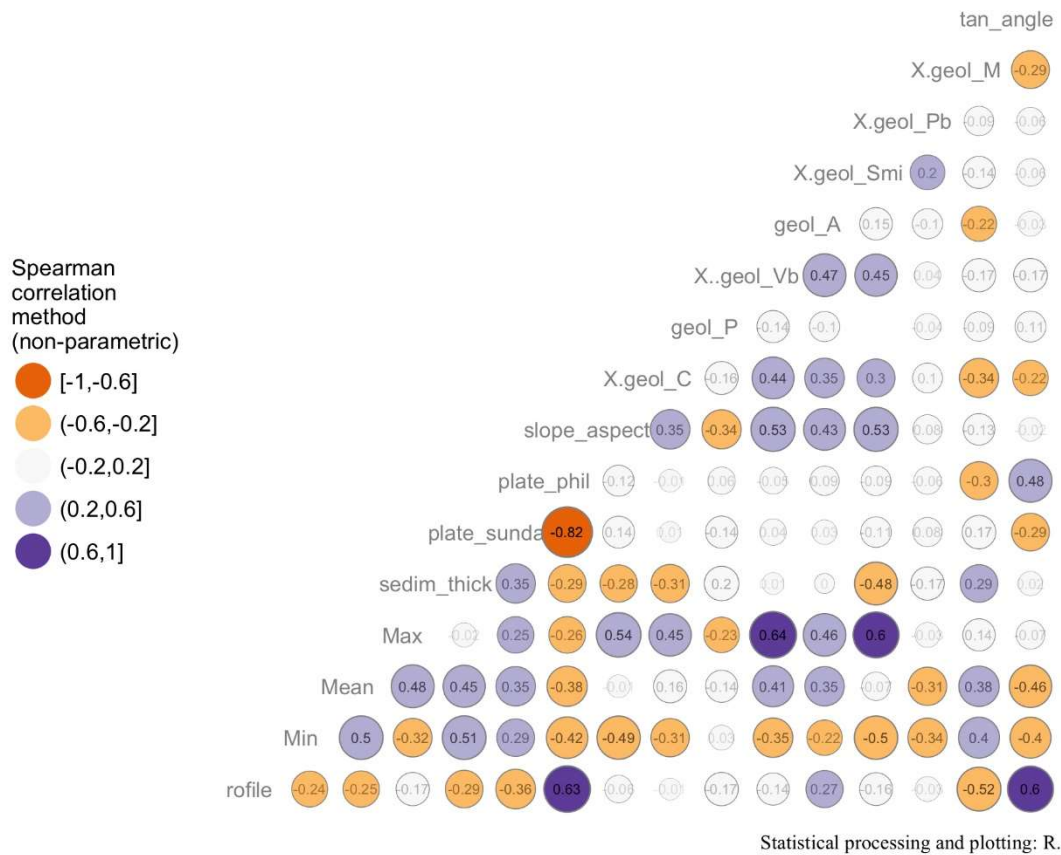
Fig. 9. Correlation matrix by Spearman method visualizing influence of the impact factors on the geomorphology of the cross-section profiles. Plotting: R.

The strip plots (Fig. 7) comprise two visualized relationship types of the data distribution, namely by seven types of the underlie geology with code given and explained in Table 1 (Fig. 7, A) and two tectonic plates: Sunda Plate and Philippine Plate (Fig. 7, B). The distribution of the samples across the two tectonic plates is uneven (Fig. 7, A). The Philippine Plate comprise more samples located in the Philippine Sea eastwards from the Philippine Trench. The maximal sampling can bee seen on the profiles 21, 22 and 23 in the southern part of the cross-sectioning (as shown on the map on Fig. 1) with 765, 651 and 652 taken samples, respectively. This is explained by the complex submarine landforms in the western part of the Philippine Sea (Fig. 2, the cross section profiles). Profiles 1-4 demonstrate (Fig. 7, A) significantly lower density of the observation samples not exceeding 200. This part of the section is located in the northern part of the Philippine Trench and is characterized gentle landforms of the submarine geomorphology. As can be seen from the Fig. 7 (B), the Precambrian (shield) rocks (P) are only present in profiles 5, 7, 24 and 19 and do not exist in the sample sets of other profiles.

South tended data distribution is characterized for lithology types basic-ultrabasic plutonic rocks (Pb) where data are recorded for the profiles Nr. 12, 18- 19, 21, 23-25, that is on the southern part of the Philippine archipelago. The metamorphic rocks (M) are noted across the profiles 23-25, 4, 6, 15-16, that is their distribution is more evenly spread across the study area. In our study, data with complex lithology of Mesozoic Jurassic and Cretaceous origin (C) and Metamorphic rocks (M) have comparable spatial heterogeneity with observation records not overcoming 80 sample observation points.
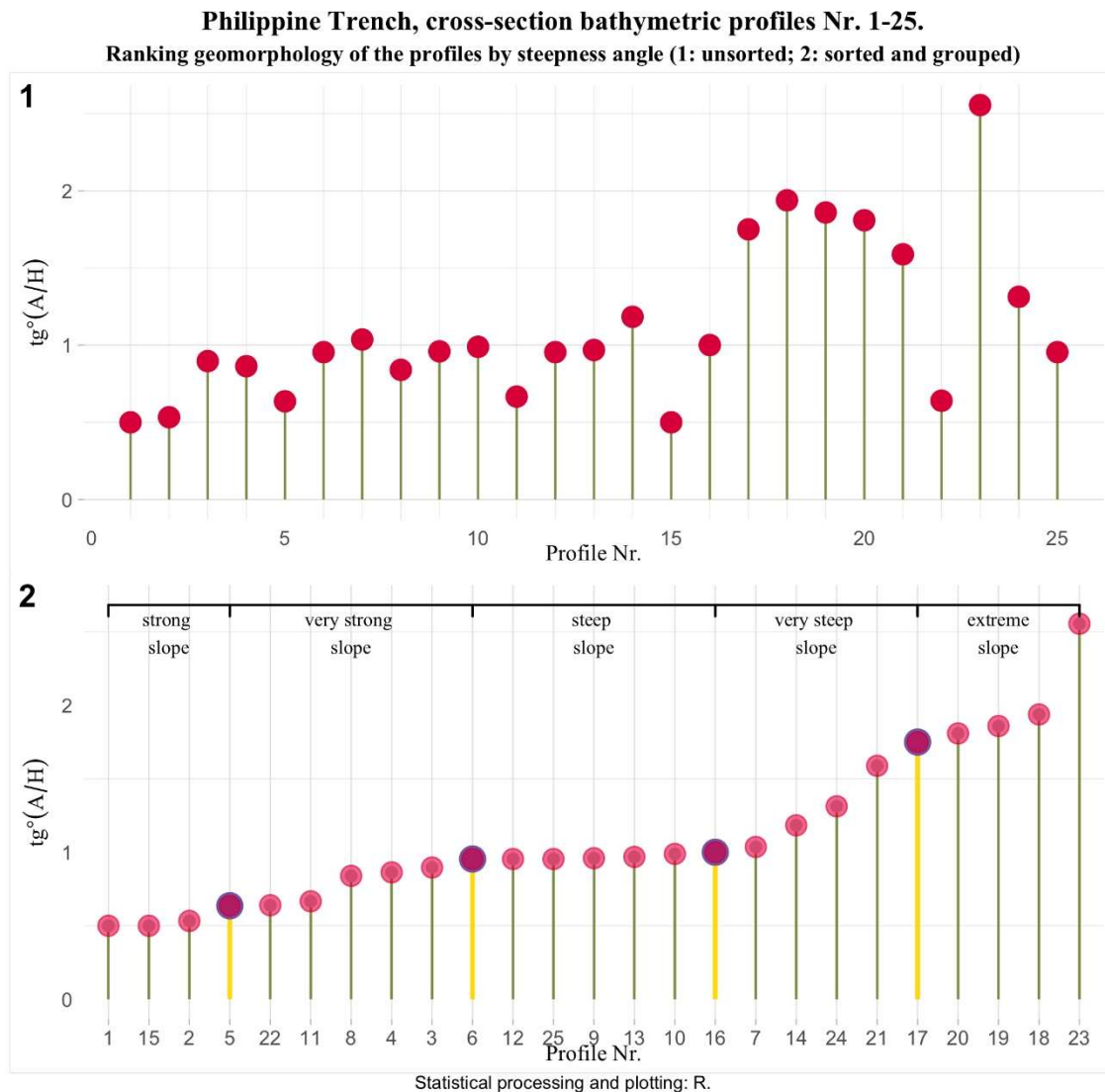
Philippine Trench, cross-section bathymetric profiles Nr. 1-25.
Ranking geomorphology of the profiles by steepness angle (1: unsorted; 2: sorted and grouped)

Fig. 10. Ranking geomorphology of the cross-section profiles. Plotting: R.

On the contrary, basic volcanic rocks of the Cenozoic volcanic formations (Vb) have significantly higher values reaching maximal values at profiles 18, 17 and 15 having values of 120, 131 and 141 registered samples, respectively. Mixed sedimentary consolidated rocks of Cenozoic formation (Smi) had the highest detected values at profile 14 with 106 recorded points following by profile 8 (95 recorded samples). Finally, alluvial deposits of the Quaternary have the highest data density recorded at profiles 16 (58 samples), following below by profile 13 and 15 (27 and 21 samples, respectively), that is the central part of the Philippines crossing the archipelago in the shelf area (Fig. 7, B).

The distribution of the sample points across the Philippine Trench has four distinct groups with the increased values caused by the steep pattern in the geomorphology (Fig. 8, B): first group include profiles Nr. 5, 6, and 7 (northern part of the Philippine Trench crossing further Manila Trench. Second group comprises a group of profiles Nr. 13, 14 and 15: central transect of the Philippine Trench moving westwards towards the Negros Trench. Third part includes two profiles Nr. 17 and 18. Finally, fourth part includes profiles Nr. 21, 22, 23, 24, that is a southern part of the Philippine Trench where the transects move further crossing Sulu Trench and Cotabato Trench on the block of Sunda tectonic plate.

The opposite distribution can be seen for the Sunda Plate (Fig. 8, A): profiles 1-4 (northern Sunda) have increased values, followed by the second group of profiles (8-12), then third group (profiles 16-17 and 19-20) and finally, profile Nr. 25 with maximal value for the Sunda Plate. The sediment thickness has a relatively even distribution for all the profiles, which is previously described by [57] who pointed that the sedimentation in the Philippine Trench

is not significantly high to fill in the axis along the trench. However, the exception have profiles Nr. 2 and 3 with a distinct rise in the sedimentation volume caused by the geologic conditions (Fig. 8, D). South-eastern part of the Philippine Trench (profiles 17-21) has a distinct steeper geomorphic shape (Fig. 8, C) which is caused by the complex relationship between the tectonic slabs and geological settings in this area.

The fitted model of the matrix shows (Fig. 9) following variables representing the relationships between the elements of the Philippine Trench system: elevation values as topographic and bathymetric sampling points (maximal, minimal and mean values of the depths and heights in meters), sediment thickness (in meters), number of observation samples across two tectonic plates (Sunda Plate and Philippine Plate), geomorphic elements of slope across the trench (tangent degree and slope aspect), and seven types of the geology (rock lithology: see Table 1 for details). The absolute coordinates were excluded as a factor to remove the effect of the geodetic location. In total 15 variables were tested using following attribute classes: geology – 7, geomorphology – 2, sedimentation – 1, tectonics – 2 and bathymetry – 3. The computed matrix is shown on Fig. 9.

The effects of the variations in the slope degree were tested by computed tangent angles for each of the 25 profiles, respectively (Fig. 10 plot 1) and repeated the analysis by ranking bathymetric profiles according to the geomorphic slope steepness (Fig. 10 plot 2). Finally, the grouping of the profiles by slopes was performed by dividing the range into five classes, as follows: 'strong slope', 'very strong slope', 'steep slope', 'very steep slope', 'extreme slope'. The results demonstrate the importance of data analysis in the marine geology aimed at considering various impact factors to understand the variability of the submarine geomorphology. Usage of the advanced methods of the statistical analysis enables to visualize combined effects of multiple geological and lithological attributes and factors that affect geomorphology of the hadal trenches.

4. Discussion

The history of the studies of ocean geomorphology, origin of the formation and types of the submarine landforms have been constantly arising interest of the geoscientists throughout the 20th century until now, the chronology of the landmark research include, for instance: [58], [59], [60], [61], [62], [63], [64]. Understanding a variety of factors that impact the geomorphology of the sea floor is a very complex task that includes a variety of the multi-disciplinary approaches that is geospatial data visualization, geostatistical analysis, geological modeling, etc. Rapid recent development of the IT technologies in 21st century enables to analyze geological and oceanological stream data in large quantities which facilitates the studies of the marine geomorphology.

Mapping seafloor geomorphic features and understanding factors of its variability centers several important components of the development of the marine geology. First, support spatial marine observations and ecosystem management; second, supporting environmental monitoring of the marine areas; third, generating knowledge of the Earth's shape; fourth, economic monitoring and evaluation of the seabed natural marine resources that has a strategic aim of governmental planning. Many attempt of the seafloor mapping and monitoring exist so far [65], [66]; [67], [68], [69], [70], [71] and the advances in marine seafloor mapping are constantly developing.

The advantages of the application of modern technologies for oceanography and in marine geology include, above all, the possibility to perform a multi-disciplinary approach that is not necessarily constraint by the GIS geospatial analysis but includes algorithms of data analysis provided by high-level programming languages, such as Python and R. Combination of the advanced methods of scripting libraries of R and Python together with spatial analysis by GIS plugins enables to process oceanological data sets. Oceanography and marine geology traditionally have a specifically large volumes of the sampling observation points derived from the cruises, along with their variety and different types (e.g., lithology and rocks of the seafloor, geological structure, tectonics etc).

The velocity of the data processing by R and Python and operating with large data volumes enable to generate new data frames for reprocessing and modeling, which is indisputable actual for oceanography. Given these reasons, the advantages of using programming in the ocean research opens clear and distinct perspectives. In addition, specifically designed libraries of Python and R embedded specialized techniques to extract the insights in the complexity of the marine geological factors affecting the structure of the submarine seafloor.

5. Conclusions

Advanced data computing and processing by R and Python in marine geology and oceanography is a dynamically developing extension of the existing geostatistical and GIS tools. Scripting libraries of Python and R enable to deal with the massive amounts of oceanographic data produced by cruise observations applying methods from computer

science and statistics towards traditional geological analysis. The number of use cases in processing large data sets in marine geology and oceanography is increasing since they are produced in a machine-generated stream in almost every oceanographic cruise as massive of the observation series taken from the research vessels, not only as a data arrays, but also as captured streams of video and imageries.

The value of big data in geoscience is indisputable nowadays. However, the question is not about the need for the massive data processing and their storage but in *how* can we manipulate effectively with large structured data sets in oceanography, and which machine learning algorithms and advanced methods can be applied for the stream data processing. The effective answer to these questions are successively given by programming languages, such as Python and R that enable to process data arrays by complex methods.

Graph-based analysis of the geological data modeling by Python and R enables to gain insights into the seafloor geomorphology, dynamics of the tectonic slab processes, functioning of the marine ecosystems and benthos, directions of the water currents, and other parameters otherwise not feasible by the traditional methods and approaches. Effective manipulating of the geospatial data sets in marine geology by programming languages using statistical machine algorithms required multi-disciplinary knowledge approaches demonstrated in the current research.

Acknowledgement

References

[1] Journel, A., Huijbregts, C., "Mining geostatistics". Chapter 5. Academic Press, 600 pp. (1978).
[2] Swan, A. R. H., Sandilands, M., "Introduction to Geological Data Analysis". Blackwell Science (1995).
[3] Lemenkova, P., "Numerical Data Modelling and Classification in Marine Geology by the SPSS Statistics", International Journal of Engineering Technologies, 5(2) 90–99. (2019).
[4] Milliman, J. D., Syvitski, J. P. M., "Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers", The Journal of Geology 100, 525-544 (1992).
[5] Seekings, L. C., Teng, T.-L., "Lateral variations in the structure of the Philippine Sea Plate", Journal of Geophysical Research 82, 317–324 (1977).
[6] Lemenkova, P., "Plotting Ternary Diagrams by R Library ggtern for Geological Modelling", Eastern Anatolian Journal of Science 5(2), 16–25 (2019).
[7] Gorini, M. A. V., "Physiographic classification of the ocean floor: a multi-scale geomorphometric approach". Proceedings Geomorphometry 2009. Zurich, 98–105 (2009).
[8] Seno, T., Maruyama, S., "Paleogeographic reconstruction and origin of the Philippine Sea". Tectonophysics 102, 53–84 (1984).
[9] Yoshida, M., "Trench dynamics: Effects of dynamically migrating trench on subducting slab morphology and characteristics of subduction zones systems". Physics of the Earth and Planetary Interiors 268, 35–53 (2017).
[10] Yu, G.-K., Chang, W.Y., "Lateral variations in the upper mantle structure of the Philippine Sea basin". Terrestrial, Atmospheric and Oceanic 2, 281–296 (1991).
[11] Yu, G.-K., Tsai, M.-T., Hwang, R.-D., "Velocity dispersion and amplitude attenuation of Rayleigh waves across the Philippine Sea", Terrestrial, Atmospheric and Oceanic 11, 515–524 (2000).
[12] Pollnac, R. B., Crawford, B. R., Gorospe, M. L., "Discovering factors that influence the success of community-based marine protected areas in the Visayas, Philippines", Ocean & Coastal Management 44(11), 683-710 (2001).
[13] Lemenkova, P., "Factor Analysis by R Programming to Assess Variability Among Environmental Determinants of the Mariana Trench", Turkish Journal of Maritime and Marine Sciences 4, 146–155 (2018).
[14] Wright, J., Rothery, D. A., "The Ocean Basins: Their Structure and Evolution", 2nd ed. (1998).
[15] Lemenkova, P., "Testing Linear Regressions by StatsModel Library of Python for Oceanological Data Interpretation", Aquatic Sciences and Engineering 34, 51–60 (2019)
[16] Lemenkova, P., "An Empirical Study of R Applications for Data Analysis in Marine Geology", Marine Science and Technology Bulletin 8(1), 1-9 (2019).
[17] Menard, H. W., "Deep-sea channels, topography, and sedimentation". American Association of Petroleum Geologists Bulletin 39, 236-255 (1955).
[18] Macdonald, K. C., "Mid-ocean ridge tectonics, volcanism and geomorphology", Encyclopedia of Ocean Sciences, Elsevier 1798–1813 (2001).

[19] Nelson, C. H., Kulm, L. D., "Submarine fans and channels". In: Turbidites and Deep Water Sedimentation, eds. G. V. Middleton, A. H. Bouma, Tulsa, OK: Society of Economic Paleontologists and Mineralogists, 39-70 (1973).

[20] Divins, D., "Total Sediment Thickness of the World's Oceans and Marginal Seas". NOAA National Geophysical Data Center (2003).

[21] Chang, W.-Y., Yu, G.-K., Hwang, R.-D., Chiu, J.-K., "Lateral Variations of Rayleigh-wave Dispersions in the Philippine Sea region". Terrestrial, Atmospheric and Oceanic 18, 859–878 (2007).

[22] Fujioka, K., Okino, K., Kanamatsu, T., Ohara, Y., Ishizuka, O., Haraguchi, S., Ishii, T., "Enigmatic extinct spreading center in the West Philippine backarc basin unveiled". Geology 27, 1135–1138 (1999).

[23] Hall, R., Ali, J. R., Anderson, C. D., Baker, S. J., "Origin and motion history of the Philippine Sea Plate". Tectonophysics 251, 229–250 (1995).

[24] Lemenkova, P., "Processing oceanographic data by Python libraries NumPy, SciPy and Pandas", Aquatic Research 2, 73-91 (2019).

[25] Dolotov, Y. S., "Processes of Relief Formation and Sedimentation on the Tidal Coasts of the World Ocean". (2010).

[26] Gille, S. T., Metzger, E. J., Tokmakian, R., "Seafloor topography and ocean circulation", Oceanography 17, 47–54 (2004).

[27] Harris P. T., Macmillan-Lawler M., Rupp J., Baker, E. K., "Geomorphology of the oceans", Marine Geology 352, 4–24 (2014).

[28] Harris, P. T., Whiteway, T., "Global distribution of large submarine canyons: geomorphic differences between active and passive continental margins", Marine Geology 285, 69–86 (2011).

[29] Covault, J. A. "Submarine fans and canyon–channel systems: a review of processes, products, and models", Nature Education Knowledge 3 (10), 4 (2011).

[30] Lemenkova, P., "Scatterplot Matrices of the Geomorphic Structure of the Mariana Trench at Four Tectonic Plates (Pacific, Philippine, Mariana and Caroline): a Geostatistical Analysis by R", Problems of Tectonics of Continents and Oceans. 51st Tectonics Meeting 1, 347–352 (2019).

[31] Lemenkova, P., "Hierarchical Cluster Analysis by R language for Pattern Recognition in the Bathymetric Data Frame: a Case Study of the Mariana Trench, Pacific Ocean", Virtual Simulation, Prototyping and Industrial Design 2(5), 147–152 (2018).

[32] Sdrolias, M., Roset, W. R., Muller, R. D., "An expression of Philippine Sea Plate rotation: the Parece Vela and Shikoku Basins", Tectonophysics 394, 69–86 (2004).

[33] Otsuki, K., "Westward migration of the Izu-Bonin Trench, northward motion of the Philippine Sea Plate, and their relationships to the Cenozoic tectonics of Japanese island arcs", Tectonophysics 180 (204), 351–367 (1990).

[34] Nakakuki, T., Hamada, C., Tagawa, M., "Generation and driving forces of plate-like motion and asymmetric subduction in dynamical models of an integrated mantle–lithosphere system", Physics of the Earth and Planetary Interiors 166 (3–4), 128–146 (2008).

[35] Hilde, T. W. C., Lee, C. S., "Origin and evolution of the West Philippine Basin: a new interpretation", Tectonophysics 102, 85–104 (1984).

[36] Karig, D. E., "Accreted terranes in the northern part of the Philippine archipelago", Tectonics 2, 211–236 (1983).

[37] Hirano, S., Nakata, T., Sangawa, A., "Fault topography and quaternary faulting along the Philippine Fault zone, Central Luzon, the Philippines", Journal of Geography 95, 1–23 (1986).

[38] Yu, G.-K., "Surface wave study of the Philippine Sea Plate." Proc. National Science Council, ROC. Part A6, 281–296 (1982).

[39] Yeh, Y. -L., Kao, H., Wen, S., Chang, W.-Y., Chen, C.-H., "Surface wave tomography and azimuthal anisotropy of the Philippine Sea Plate", Tectonophysics 592, 94–112 (2013).

[40] Salah, M. K., Seno, T., Iidaka, T., "Seismic anisotropy in the wedge above the Philippine Sea slab beneath Kanto and southwest Japan derived from shear wave splitting", Journal of Asian Sciences 34, 61–75 (2009).

[41] Kato, M., Jordan, T. H., "Seismic structure of the upper mantle beneath the western Philippine Sea", Physics of the Earth and Planetary Interiors 110, 263–283 (1999).

[42] Isse, T., Shiobara, H., Montagner, J.-P., Sugioka, H., Ito, A., Shito, A., Kanazawa, T., Yoshizawa, K., "Anisotropic structures of the upper mantle beneath the northern Philippine Sea region from Rayleigh and Love wave tomography", Physics of the Earth and Planetary Interiors 183, 33–43 (2010).

[43] Lemenkova, P., "K-means Clustering in R Libraries {cluster} and {factoextra} for Grouping Oceanographic Data", International Journal of Informatics and Applied Mathematics 2(1), 1–26 (2019).

[44] Borradaile, G. J., "Statistics of Earth Science Data". Springer (2003).

[45] Lemenkova, P., "Regression Models by Gretl and R Statistical Packages for Data Analysis in Marine Geology", International Journal of Environmental Trends 3(1), 39–59 (2019).

[46] Lemenkova, P., "R scripting libraries for comparative analysis of the correlation methods to identify factors affecting Mariana Trench formation", Journal of Marine Technology and Environment 2, 35-42 (2018).

[47] Ciaccio, A. Di, Coli, M., Angulo Ibanez, J. M. "Advanced Statistical Methods for the Anaysis of Large Data Sets". Studies in Theoretical and Applied Statistics Selected Papers of the Statistical Societies. Springer (2012).

[48] Lemenkova, P., "Statistical Analysis of the Mariana Trench Geomorphology Using R Programming Language", Geodesy and Cartography 45(2), 57–84 (2019).

[49] Cameron, A. C., Trivedi, P. K. "Regression Analysis of Count Data", Cambridge University Press.

[50] Hoaglin, D. C., "Letter values: A set of selected order statistics", Chapter 2, 33–57 (2013).

[51] Davis, J. C., "Statistics and Data Analysis in Geology", Wiley (2002).

[52] Hoffmann, H., Kafadar, K., Wickham, H., "Letter-value plots: Boxplots for large data", (2011).

[53] Hoaglin, D. C., Mosteller, F., Tukey, J. W., "Understanding Robust and Exploratory Data Analysis", New York: Wiley (1983).

[54] McGill, R., Tukey, J. W., Larson, W. "Variations of box plots", The American Statistician 32, 12–16 (1978).

[55] Lemenkova, P., "Computing and Plotting Correlograms by Python and R Libraries for Correlation Analysis of the Environmental Data in Marine Geomorphology", Jeomorfolojik Araştırmalar Dergisi / Journal of Geomorphological Researches 3, 1–16 (2019).

[56] Hunter J., Dale D., Firing, E., Droettboom, M., "Matplotlib Release 2.2.2." (2018).

[57] Hessler, R. R., Ingram, C. L., Aristides Yayanos, A., Burnett, B. R., "Scavenging amphipods from the floor of the Philippine Trench", Deep Sea Research 25, 1029–1047 (1978).

[58] Daly, R. A., "Origin of submarine "canyons"", American Journal of Science 31, 401-420 (1936).

[59] Heezen, B. C., "The floors of the oceans", I. The North Atlantic. Geological Society of America Special Paper 65, 1-122 (1959).

[60] Shepard, F. P., "Submarine Geology", Harper & Row, New York (1963).

[61] Heezen, B. C., Tharp, M., "World Ocean Floor Panorama, New York, pp. In full color, painted by H. Berann, Mercator Projection, scale 1:23,230,300, 1168×1930 mm. (1977).

[62] Suetova, I., Ushakova, L., Lemenkova, P., "Geoecological Mapping of the Barents Sea Using GIS", International Cartographic Conference ICC (2005).

[63] Suetova, I. A., Ushakova, L. A., Lemenkova, P., "Geoinformation mapping of the Barents and Pechora Seas", Geography and Natural Resources 4, 138–142 (2005).

[64] Schenke, H. W., Lemenkova, P., "Zur Frage der Meeresboden-Kartographie: Die Nutzung von AutoTrace Digitizer für die Vektorisierung der Bathymetrischen Daten in der Petschora-See", Hydrographische Nachrichten 25(81), 16–21 (2008).

[65] Gauger, S., Kuhn, G., Gohl, K., Feigl, T., Lemenkova, P. and Hillenbrand, C., "Swath-bathymetric mapping". Reports on Polar and Marine Research 557, 38–45 (2007).

[66] Lemenkova, P., "Smart Seafloor Mapping in Real Time Regime Using Deep-Sea Multibeam Echosounder Hydrosweep DS", Izvestiya MGTU 'MAMI' 5.4 (26), 23–27 (2015).

[67] Lemenkova, P., "Topographic surface modelling using raster grid datasets by GMT: example of the Kuril-Kamchatka Trench, Pacific Ocean", Reports on Geodesy and Geoinformatics 108, 9-22 (2019).

[68] Lemenkova, P., "GMT Based Comparative Analysis and Geomorphological Mapping of the Kermadec and Tonga Trenches, Southwest Pacific Ocean", Geographia Technica 14(2), 39-48 (2019).

[69] Lemenkova, P., "AWK and GNU Octave Programming Languages Integrated with Generic Mapping Tools for Geomorphological Analysis", GeoScience Engineering 65 (4), 1–22 (2019).

[70] Lemenkova, P., "Generic Mapping Tools and Matplotlib Package of Python for Geospatial Data Analysis in Marine Geology", International Journal of Environment and Geoinformatics 6(3), 225–237 (2019).

[71] Normark, W. R., Carlson, P. R., "Giant submarine canyons: Is size any clue to their importance in the rock record?", Geological Society of America Special Paper 370, 175-190 (2003).