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Visualization of the geophysical settings in the Philippine Sea margins by means of GMT and ISC data

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Abstract: The presented research aimed to perform geophysical modelling (gravity and geoid) and to evaluate the spatio-temporal variation of the marine geological data (distribution and depth of earthquakes) using combination of the Generic Mapping Tools (GMT) and available sources from the International Seismological Centre (ISC-EHB) that produce data on earthquakes as part of seismic survey and regional research projects. The target study area is a Philippine Sea basin (PSB) with two focused marginal areas: Philippine Trench and Mariana Trench, two hadal trenches located in the places of the tectonic plates subduction. Marine free-air gravity anomaly in the PSP shows higher values (>80 mGal) of the gravity fields structure at the volcanic areas and Philippine archipelago. Current study presented comparative geophysical analysis, and mapping free-air gravity and geoid in the Philippine Sea basin area. As a result of this study, the average level of earthquakes located in the Philippine Trench and Mariana Trench areas were compared, and those located in the Philippine archipelago are determined to be in the souther-western part (area of west Mindanao, south-west Visayas islands), while Luzon Islands shown shallower located earthquakes. The results on the Mariana Trench segment shown shallower located earthquakes compared of the other marginal regions of the Philippine Sea Basin. Current paper contributes to the studies on natural hazards through visualization and analysis of the earthquakes activities (occurrence and magnitude intensity), due to increasing interest to the problems of seismicity in the Pacific Ocean, which may have environmental effects causing harmful consequences and possible risks for coastal population of the Philippine islands through aftershocks and tsunami.

Key words: GMT, cartography, shell scripting, geoid, free-air gravity, geophysics, visualization, earthquake

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1. INTRODUCTION

The study is focused on the Philippine Sea region, a large and tectonically complex area located in the west Pacific Ocean (Figure 1). The Philippine Sea is marked by complex interaction of three tectonic plates: Eurasian, Australian and the Philippine Sea. Subduction of the lithosphere plates is a complex geological process that involves collision, subduction and accretion. Old, heavy and large Pacific Plate is situated eastwards from the Philippine Sea. The Philippine Sea Plate, located beneath the Philippine Sea, between the Pacific, Eurasian, Caroline and Australian plates, is the worlds largest marginal basin plate [1]. It has two back-arc basins formed in Oligocene to Miocene period: Parece Vela and Shikoku Basins.

The region of the Philippines is notable for the Philippine Mobile Belt, a complex part of the tectonic boundary between the Eurasian and the Philippine Sea plates, including subduction zones, deep-sea trenches and Philippine Fault System. The Philippine Sea Plate is bordered by convergent boundaries where tectonic plates collide with cold and dense Philippine Sea plate is sliding beneath the warmer, and less dense Eurasian Plate as a result of subduction process, due to lithospheric density differences.

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Necessarily, it causes active and repetitive volcanism, earthquakes, orogenesis, regional destruction of the lithosphere and local geological deformations.

As Philippine Sea Plate subducts into the mantle, it releases water from minerals dehydration in the oceanic crust. It causes partial melting of rocks in the asthenosphere, which rise up reaching the surface, and forming volcanic island arcs. These volcanic island arcs are notable along the margins of the Philippine Sea, parallel to the chain of the oceanic trenches. For example, prominent volcanic island arcs are in this region include Izu-Bonin-Mariana Arc (including Izu Islands, Bonin Islands, Mariana Islands), Luzon Volcanic Arc stretching from Taiwan to Luzon, and the Philippines. Isotopes and trace elements show unique geochemical characteristics of the volcanic chains (strong niobium anomalies and calc-alkaline characteristics, strontium isotopic ratios) studied previously [2-5].

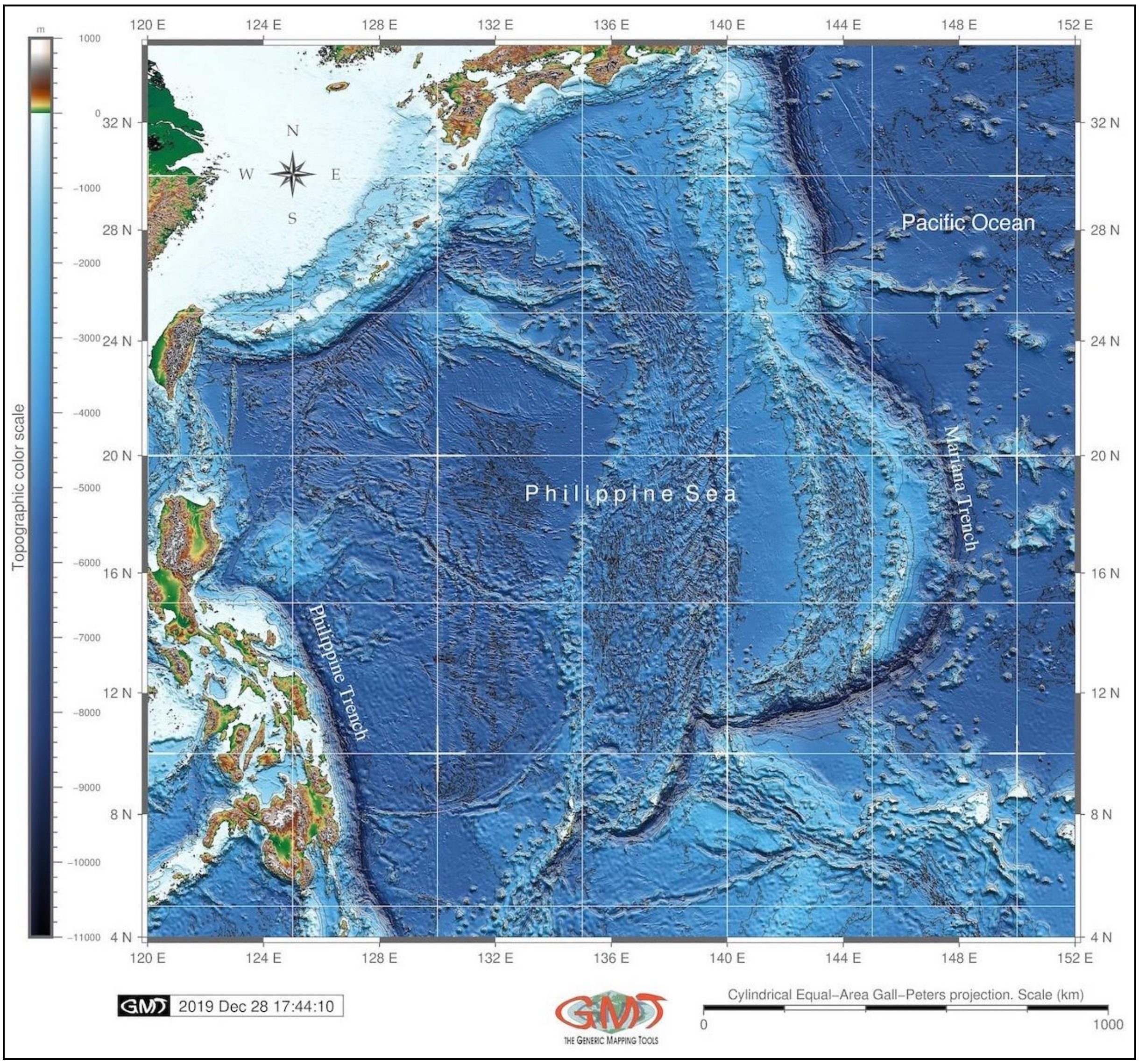


Figure 1. Bathymetric map of the Philippine Sea Basin. Bathymetry: GEBCO Global Relief Model 15 arc sec resolution grid, mapping: GMT
(Source: author)

Several deep-sea trenches are located along the margins of the Philippine Sea (clockwise): Mariana, Yap, Palau, Manila, Philippine, Ryukyu and Izu-Bonin Trench. Current work combines geophysical modelling with visualization of the earthquakes location and depths to visualize seismicity of the area. Hence, Philippine Sea belongs to the seismically active region of 'Ring of Fire' along the margins of the Pacific Ocean, where numerous earthquakes and volcanic eruptions take place. Two specific foci within the study area are two deep-sea trenches, the Mariana Trench (a prominent crescent arc on Figure 1) and the Philippine Trench, located on the east and western margins of the Philippine Sea, respectively. Geodetic modelling and seismic mapping are important parts of the geophysical analysis of the region, because visualizing data observation enables to indicate a coupled or planar tectonic plate interface and give deeper insights to the plate subduction structure and mechanisms of the interfaces in the colliding tectonic plates. Marine free-air gravity modelling defines details of the crust, upper mantle and slab structure in the subduction zone, based on the available terrestrial and satellite gravity data.

Understanding such complex relationships between tectonic plate subduction, as well as fore-arc and back-arc structures requires precise and accurate modelling and detailed spatial analysis of the seismicity in the region which reflects variations in the crust and upper mantle structure. Geoid, bathymetric and gravity modelling demonstrated in this paper is made using GMT with presented codes, while schematic maps and cross-sections of the earthquake events were derived from the International Seismological Centre.

2. LITERATURE REVIEW

Mariana Trench is a strongly elongated, narrow and lesser rectilinear topographic depression of the seafloor, crescent-like in its geometric plain shape. It is located in the west Pacific Ocean, 200 km to the east of the Mariana volcanic island arc. Stretching for hundreds kilometers, it is formed as a result of the subduction of the Pacific plate beneath the PSP as a result of the subducted cooled plate into the mantle, which leads to the formation of the trench, and originates earthquakes and tsunamis. The subduction boundaries have classified 'Mariana type' where the coupling between the two tectonic plates is either weak or non existent [6]. Westward slope of the Mariana Trench presents a barren trench wall with no uplift, while eastern part is the border along which western edge of the Pacific Plate is subducting beneath the smaller Mariana Plate. As a result, the geomorphic feature of the Mariana Trench is its very steep slopes and depths of 3-5 km width of the bottoms [7].

To date, geological research on Mariana Trench and Izu-Bonin-Mariana (IBM) volcanic arc has focused on various aspects of the tectonic processes and mechanisms of plate movement including subduction system dynamics [8], faulting and consequent deformation in the subducting plates [9], [10], geometry of the lithospheric gradient dips [11], dependance between the plate motion, geologic structure and penetration depths of slabs. [12] in their petrogenetic studies on geochemic traces of volcanic rocks from the Mariana Trench pointed at its tectono-magmatic evolution. Recent bathymetric and topographic analyses [13] indicate that thin lithosphere in the IBM region (20 km) might have been intensely deformed during tectonic evolution of the region. It may explain notable variation in microstructure of samples taken from the ground on the Mariana Trench, which range from coarse granular and intensely elongated texture to fine porphyroclastic and fine-grained equigranular textures.

Philippine Trench is located eastwards from the Philippine archipelago (Figure 1), where the Philippine Sea Plate (PSP) subducts under the Philippine archipelago (4°–15°N), which is a part of a convergence zone between the Eurasian plate (Sunda block) and the PSP [14]. Subducting PSP causes a high-velocity anomaly in the Kyushu-Palau Ridge (KPR) area. The PSP tears and forms a 'slab window' corresponding to the KPR subduction. Tearing of the tectonic plate in the northwestern corner of the subducting PSP is further discussed by [15]. The Philippine Sea Basin is a complicated region, notable for complex bathymetry and tectonic plate shape [16-18], consisting of many different patchworks of the seafloor ages [19].

3. METHODS AND DATA

Gravity and bathymetric data were examined to obtain a visualization and better understanding of the seafloor fabric and structures within the PSB. The EGM96 gravity grid was visualized based on the with the satellite altimetry data [20] using existing examples [21-23] producing gravity map of the PSB (Figure 2). The subset of the img file was extracted through the following code snippet:

```
img2grd grav_27.1.img -R120/152/4/35 -Ggrav.grd -T1 -I1 -E -S0.1 -V
```

A cpt from grid was generated (H=0, C=RGB):

```
gmt grd2cpt grav.grd -Cno_green > grav.cpt.
```

The geoid model (Figure 2) was visualized by the following GMT codes sequence:

Generated geoid image with shading:

```
gmt grdimage geoid.egm96.grd -I+a45+nt1
-R120/152/4/35 -JY140/15/6.5i -Cgeoid.cpt -P -K >ps
```

Adding basemap: grid, title, costline:

```
gmt pscoast -R -J -P -V -W0.25p -Df -B+t"Geoid gravitational regional model: Philippine Sea Basin" -
Bxa4g3f2 -Bya4g3f2 -O -K >>ps
```

Adding geoid contour:

```
gmt grdcontour geoid.egm96.grd -R -J -C2 -A5
```

```
-Wthinnest,dimgray -O -K >>ps
```

The gravity model (Figure 3) was visualized through the following GMT code sequence:

```
gmt grdimage grav.grd -I+a45+nt1 -R120/152/4/35 -JM6i -Cgrav.cpt -P -K >ps.
```

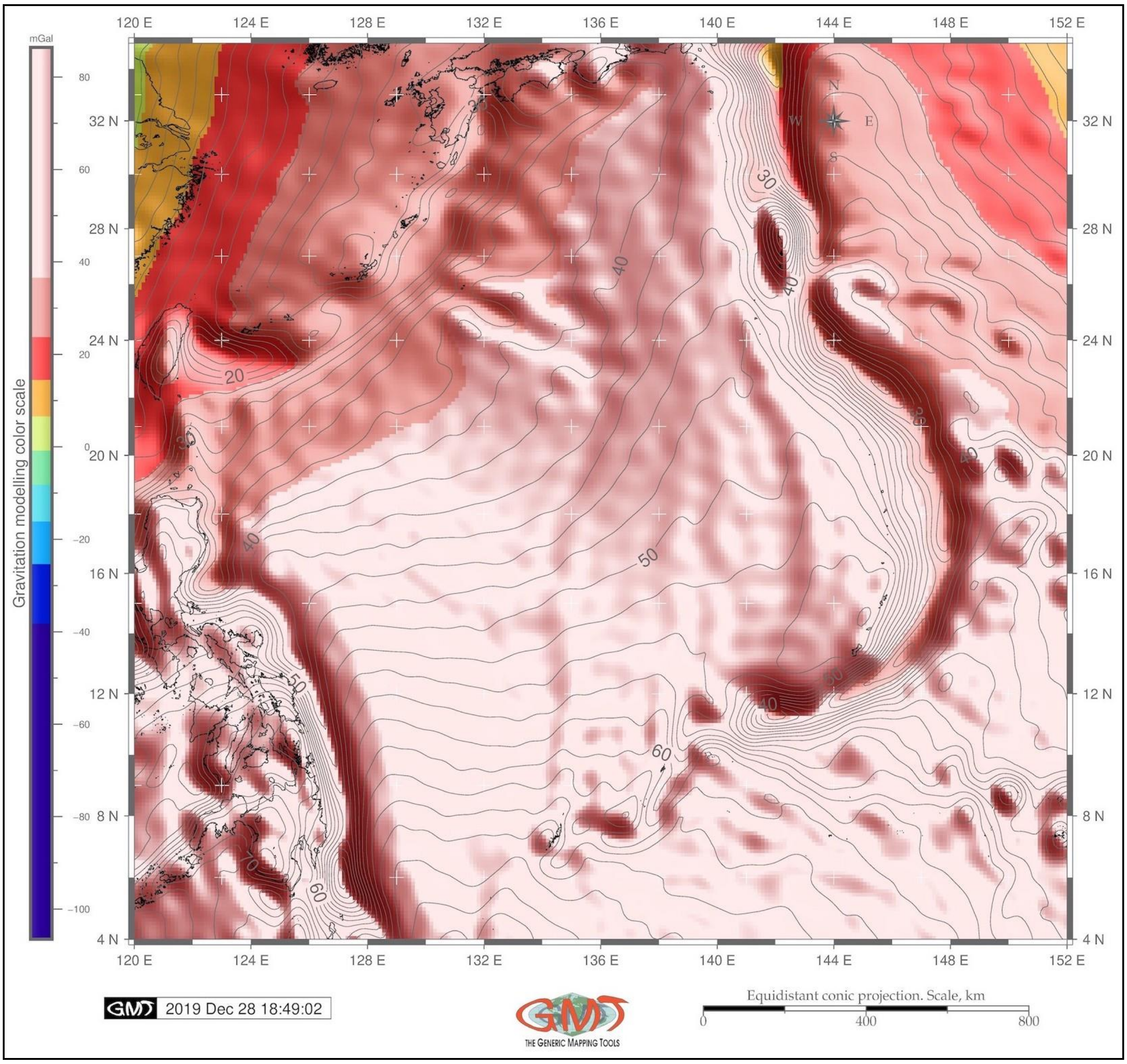


Figure 2. Geoid regional model: Philippine Sea Basin. World Geoid Image EGM96, version 9.2 2-min resolution, mapping: GMT
(Source: author)

Presented cross-section transecting profiles are derived from the existing data source of International Seismological Centre (ISC-EHB). The ISC-EHB is an abbreviation which stands for the "Engdahl-van der Hilst-Buland (EHB) Bulletin" of hypocentres and associated traveltime residuals of the seismic events. It was originally developed and technically described by Engdahl et al. [24] and finished in 2008. It is a widely used seismological data set, which is now expanded and reconstructed.

The cross-section profiles and map visualization location of the earthquake events are presented on Figure 4 and 5. Transecting cross-sections is a common cartographic technique that are descried in detail in many existing works [25-30], the main approach consists in deriving information as a table reflecting coordinates of the sample points (X, Y) and a Z-value in each of the sampling points. Variations of attributes values can be analyzed along the transecting line and spatial analysis of the observed trends.

4. RESULTS

Marine free-air gravity anomaly in the PSB is visualized on Figure 3. Anomalies >60 mGal are evident in the trench areas (Figure 3), which are consistent with previous results [31-33]. The results were compared with existing 2D and 3D geophysical and geological maps, visualization of the slab gaps or tears in the Philippine Sea Plate region [34-42] to highlight the geology, geophysical settings and geomorphic features of the submarine trenches in PSB area. Higher values (>80 mGal) of the gravity fields structure are apparent at volcanic areas and Philippine archipelago, as seen in orange to red colored areas, Figure 3.

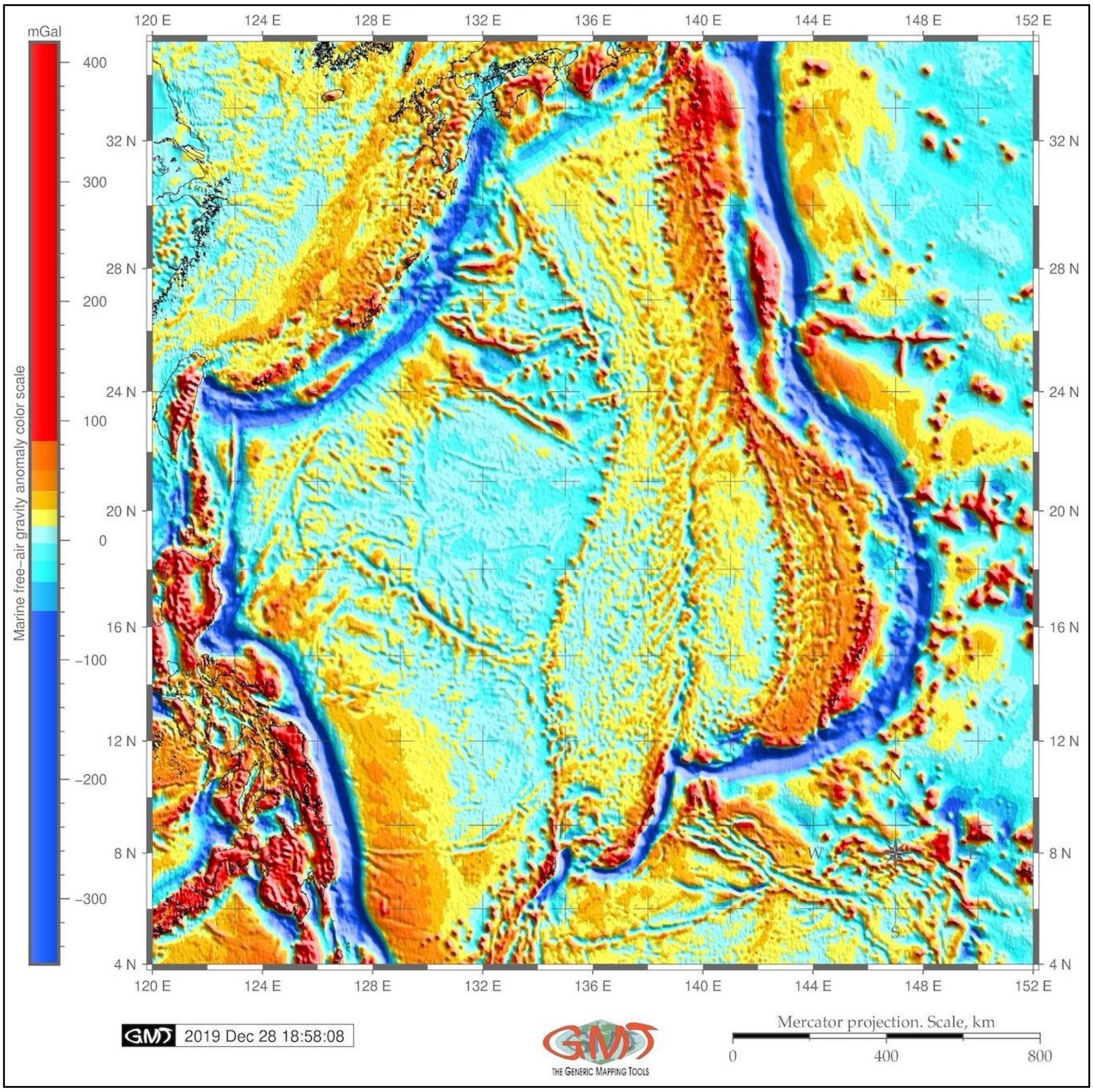
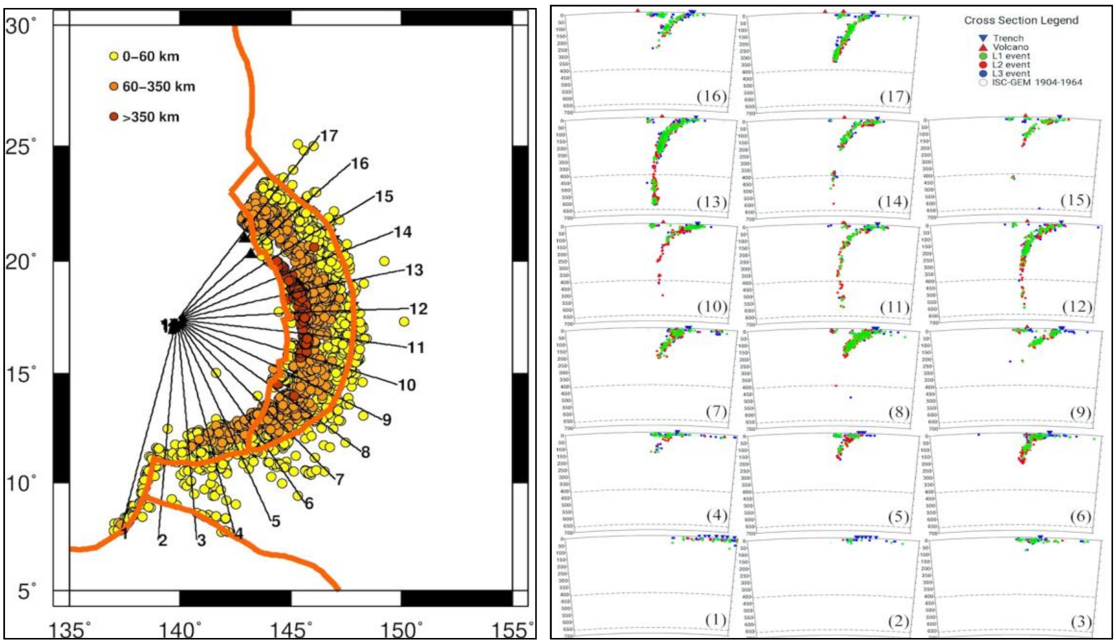


Figure 3. Marine free-air gravity anomaly model of the Philippine Sea Basin. Grids from CryoSat-2 and Jason-1, 1 min resolution, mapping: GMT
(Source: author)

The geoid model (Figure 2) represents a map showing shape that ocean surface would have with the sole influence of the gravity and rotation of the Earth under the condition that other climatical and meteorological influences (e.g. winds, tides) are absent and do not affect the model. The data as a grid raster (geoid.egm96.grd) was visualized. Afterwards, land areas were clipped as gray shaded areas to focus on the ocean region. The model implies graphical representation of the geoid data ranging from -108 to -85 mGal, where the majority of the data range (represented in pale red and rose colors) lies in the interval of 22-85 mGal.

Hadal trenches account for the deepest 45% of the oceanic depth range [43]. The majority of the seafloor (>83%) is occupied by the abyssal depths (3,000 to 6,000 m) [44-45], followed by the extreme depths of >6,000 m. Specifically for the Mariana Trench (shown as crescent arc on Figure 4a), the extreme depths are restricted mostly to the deepest part of the trench located in its south-western part (area of Challenger Deep). has following. Depressions of 6,000-7.500 m BSL occasionally occur in the central part of the Mariana Trench crescent forming unique patterns in its geomorphological structure [46]. Figure 5 shows modeled earthquake events (separated as L1, L2 and L3 by various colors) and the location of the trench is marked as a blue triangle.



(a) **(b)**

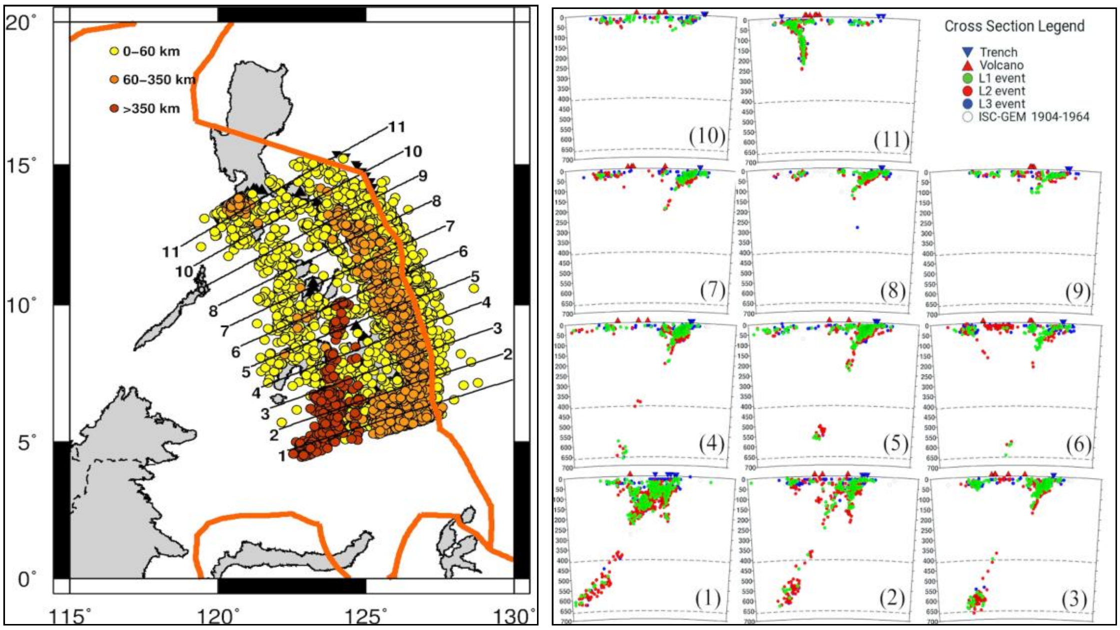
Figure 4. Example of seismic profiling through cross-sectioning:
(**a**) Map of the cross-sections of the earthquake transects: Mariana Trench;
(**b**) Cross-sections of the earthquakes (17 transects): Mariana Trench
(Source: **a.** ISC-EHB; **b.** Modified after: ISC-EHB)

The depth of the submarine volcanoes is highlighted by yellow, orange and brown colors, respectively (Figure 4a). From the analysis of the Figure 4b it can be drawn that the deepest volcanoes (located on the depths>350km) are located on the western side of the trench while shallow volcanoes (0-60 km) are situated on the eastern flank. The deepest earthquakes occur within the core of the subducting slabs of the Philippine Sea Plate (PSP) that descend into the Earth's mantle from convergent plate boundaries. Here, a dense PHP collides with a less dense continental Eurasian Plate, and sinks beneath it. As a consequence, the plate boundary contact between the PSP and Eurasian Plate generate large, shallow subduction zone earthquakes, only active at shallow depths: 0-60 km (Figure 4a and 4b).

Geomorphological structure of the Philippine Sea is notable for the chain of island arcs (Nampo, Mariana, Yap, Palau) bounding PSB from the East and the corresponding chain of the deep water trenches associated with them. According to the relief, the bottom of the Philippine Sea can be attributed to the ocean bed. The Philippine Sea is divided into the basins of the Philippine, Nampo and West Mariana by underwater ridges that differ in depths (Figure 1, various colors on the topographic map). Thus, the prevailing depths in the PSB are 5,500–5,800 m, in the Nampo and Mariana – from 4,800 to 5,200 m, although individual depressions of the bottom reach >6000 m [47].

The seafloor relief of the PSB, unlike the basins of the marginal seas, is strongly dissected, hilly-shaped, with depth amplitudes 100-500-700 m. The orientation of the ridges is mainly sub-meridional and north-western, corresponding to the strike of large morphological structures. As a consequence of such complex geomorphological structure resulted from the geological historic development, Mariana Trench advances toward the upper plate corresponding to the subduction of very old, Mesozoic oceanic lithosphere, having typical depths of the seafloor at 4-5 km [48-49].

Now comparing the distribution of earthquakes along the cross-sections in the area of Philippine Trench (Figure 5a) to the Mariana Trench (Figure 4a), it can be seen that the deepest volcanoes (located on the depths >350 km) are mostly concentrated on the south-western part of the study area (highlighted as brown on the map), while shallow volcanoes border eastern and north-western areas. Volcanoes located along the axis of the trench mostly have depths of 60-350 km. Moreover, the depths of the volcanoes situated along the Philippine archipelago (Figure 5b) show that the deepest transects (subplots 1, 2 and 3 on Figure 5b) are mostly located at the depths crossing the marked dashed line of 400 km. These are the most southern transects directed SW-NE.



(a) **(b)**

Figure 5. Example of seismic profiling through cross-sectioning:
(**a**) Map of the cross-sections of the earthquake transects: Philippine Trench;
(**b**) Cross-sections of the earthquakes (11 transects): Philippine Trench
(Source: **a.** ISC-EHB; **b.** Modified after: ISC-EHB)

Since the strength of shaking from an earthquake naturally becomes lesser when the distance increases from the earthquake's source (that is, its depth), therefore the strength of shaking at the Earth's surface resulting from an earthquake is naturally affected: the shake is considerably less from the earthquake that occurs at >350km, and on the contrary, if the same earthquake occurred at shallow depths, e.g. 0-60 km depth, then the consequences, such as shaking, are stronger. This mostly concerns the Philippine archipelago, due to the population inhabiting the islands.

Besides environmental effects, the depths of earthquakes provides crucial information about the Earth's structure, as well as geological and tectonic setting in the area where the earthquakes are happened, because they are associated with a subduction zone. Thus, earthquakes (their depth and magnitude) indicate the subduction zones, where tectonic plates are being dipped one under another as a result of colliding caused by their complex movements.

Plotted location of earthquakes (Figures 4a and 5a) and their depths (Figures 4b and 5b), visualize details of the subduction zone's structure for Philippine and Mariana Trenches, consequently. Specifically, they indicate steepness of the dipping, and if down-going plate is planar or bending with certain degree of curvature. These correlations are important as detailing mechanics and characteristics of the deformation that takes place in the subduction zone for the Mariana and Philippine trenches, respectively.

5. DISCUSSION

Geophysical visualization and comparative assessment of the earthquake events between two trenches based on the cross-section transecting and spatial analysis of their geological, geophysical and tectonic settings based on the geospatial visualization, highlighted differences between the two marginal trenches of the PSB and visualized variations in the seismic situation between deep-sea trenches in their different segments. Presented research contributed to deeper understanding of the geophysical settings of the PSB and Mariana Trench located along its margins, as well as to test a GMT approach for geophysical mapping with example of gravity and geoid grids.

Geophysical hazards, like earthquakes, volcanic eruptions and tsunamis, belong to the category of natural hazards. A natural hazard is understood as a potentially damaging natural event that may lead to the loss of life, injury, property, destructions of buildings and roads or degradation in the neighbor areas that were affected by the events. However, it should be stressed that although earthquakes, as geophysical events, are destructive phenomena, their fundamental nature is a process of the dynamic functioning of the planet. As briefly described before, the nature of the earthquakes and origin of trench formation lie in the phenomena of the tectonic plates subduction, i.e. is a complexity of movements of the lithospheric plates. Therefore, risk of earthquake hazards in the Philippine archipelago are explained by naturally occurring processes in the earth's interior.

Earthquakes hazards in turn induce consequences such as landslides, tsunamis and volcanic eruptions that may affect sustainability of the local population. One of the most dangerous events that should be mentioned in this context is tsunami, sea waves resulting from the seafloor displacements associated with large earthquakes or exploding volcanic islands.

Specifically for the Philippine area, volcano and earthquake disasters are frequent in the top 10 among other natural disasters according to the EM-DAT: The OFDA/CRED International Disaster Database (http://www.em-dat.net/). Plotting hazards in the Philippine area through maps, particularly earthquake events, were visualized with the base map and cross-sections from the ISC-EHB, a dataset of seismic events. The base maps of the Philippine Sea region show the bathymetry and topography of the area together with geodetic modelling. Geographic Information Systems (GIS) software are traditionally used to overlay and visualize hazard maps with other layers. In contrast, this paper presents a GMT visualization which is based on the console commands from the shell scripts.

To increase sustainability of the region, a Philippine Institute on Volcanology and Seismology, PHIVOLCS (https://www.phivolcs.dost.gov.ph/) was established to record geotectonic phenomena: destructive earthquakes, volcanic eruptions, tsunami and to mitigate arising disasters providing with information since 1968, through appropriate detection, forecasting and warning system. In view of this, correct mapping of the geophysical settings and visualization of the earthquakes are useful part of such programs.

The actuality of the cartographic visualization of the earthquakes and geophysical settings assists in the following aspects. First, maps can be used to predict the occurrence of volcanic eruptions and earthquakes based on the geospatial comparative analysis of the repeatability and locations on the events. Second, analysis of the visualized geophysical settings may assist to determine probability of the areas affected by eruptions and earthquakes. Third, correctly visualized and sufficient datasets are useful for forecasting volcanic eruptions and earthquakes. Forth, hazards of volcanic activities can be mitigated through appropriate detection, forecast and warning system that in turn requires mapping as powerful assisting visualization tool for formulation of the appropriate disaster preparedness plans. In view of the above said, mapping geophysical situation has actuality for the Philippine Sea area.

General conceptual idea of the presented study may be extrapolated to other objects of ocean topography where disastrous events and earthquakes take place. Methodologically, the study contributes towards technical application of the GMT for gravity modelling and mapping and earthquakes visualization. Submarine earthquakes located along the two trenches, Mariana and Philippine, as well as structure of the gravity and geoid in the PSB area were examined using high-resolution GEBCO topographic and gravity data grids in NetCDF format, geologic vector layers and modeled profiles.

6. CONCLUSIONS

This paper demonstrated technical application of the GMT based methods for geophysical visualization of the raster data grids, as well as data from the International ISC-EHB, a dataset of seismically constrained events. The cross sections of seismicity in subduction zones around the world provided by the ISC-EHB, enable to get a closer insight to the repeatability and depth of the earthquakes and analyze the risks of hazardous events for the population living in the Philippine Islands.

As mentioned before, trenches of the Philippines Sea region are located on the "Ring of Fire", a Circum-Pacific belt of earthquakes and regular volcanic eruptions stretching on ca. 40,000 km along the margins of the Pacific Ocean. This explains the vulnerability of the area, and specifically, the country of Philippines, towards frequent seismicity and active volcanism. The country is at risk of the repetitive earthquakes of various magnitude that occur on a regular basis, caused by tectonic subduction of the Philippine Sea Plate, as discussed in the above chapters.

Indeed, the analysis of the Philippines Sea marginal area shown high earthquake hazard according to the information derived from the International Seismological Centre Bulletin (ISC-EHB) cross-sections and maps. Hence, there is a high possibility of the risk of potentially-damaging earthquakes shaking in coastal area of Philippines. Based on the data visualization, the impact of earthquakes and submarine volcanism should be analyzed and considered in all phases of the sustainable development of the Philippine cities during construction of buildings and infrastructure. More specifically, city planning decisions, design, and construction of roads should take into account the possibility of the earthquake hazards and risk to the population.

Besides major earthquakes, there is a risk of secondary hazards that may affect population, such as fires, landslides, tsunami in the coastal areas and aftershocks. In view of this, local building regulations should be adapted to provide earthquake protection in case of the events through engaged engineering communities together with local governments. For example, since coastal areas are the most 'in danger' places, they might be affected much during an earthquake. The illustration can be, for instance, ground failure or landslides in the zones of unstable slopes. Therefore, geotechnical soil investigations should be performed to determine physical soil properties and geomorphological stability of the slopes.

There is a broad interest to the earthquake prognosis and mapping for both the region of the Philippines, since this region is situated in the zone of tectonic plates subduction and is therefore seismically active [50-55]. Practical example of the GMT based code for visualizing free-air gravity aims to contribute to technical development of the geological mapping through cartographic assistance. Visualizing geophysical situation and mapping earthquakes events is useful for deeper understanding of the geophysical settings of the 'areas at risk', located in seismically active margins of the Pacific Ocean. The presented techniques of the gravity mapping can be utilized at similar works for geophysical visualization.

From this point of view, this work presented a spatial analysis of the earthquake activities together with geophysical settings in the study area (gravity and geodetic modelling) supported by GMT based methodology for visualization and modelling. Interpretation of the bathymetric and geological data obtained from the Mariana and Philippine trenches demonstrated GMT-based approaches to the cartographic mapping using high-resolution raster grids. In contrast to the classic cartographic approaches having traditional Graphical User Interface (GUI), e.g. ArcGIS based in geodata mapping [56-61], GMT is notable for its scripting algorithms as a core conceptual methodology.

Understanding geological and tectonic processes and associated seismicity is closely linked to effective visualization. Therefore, plotting various thematic maps visualizing geophysical settings in the Pacific oceans contributes to increase of our knowledge of the oceans in general and possible risks associated with earthquake events (aftershocks, tsunami) for people living in the coastal areas. Hence, visualized seismic and geophysical data is a significant contribution to the increase of the information pool on the marine geohazards, as well as a certain development of the ocean modelling and sustainable marine management. A spatial analysis deepen through enlarged data pools enables to respond appropriately to geohazards. This paper also demonstrated the importance of the high quality data grids for geophysical modelling, and presented snippets of the GMT codes for modelling free-air gravity and geoid with focus on compiling and processing data in command line through shell scripting.

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