Article

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CARTOGRAPHIC PROCESSING OF THE MULTI-SOURCE GEOSPATIAL DATASETS BY GMT FOR MAPPING VARIABILITY IN GEOLOGIC SETTING AND BATHYMETRY OF THE PACIFIC OCEAN

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Abstract

The paper presents spatial analysis of the geological settings and topographic structure of the Pacific Ocean by Generic Mapping Tools (GMT). Its tectonic and geomorphic features have complex character and include, among others, trenches, ridges, East Pacific Rise, basins, fracture zones, rifts, rises, fault systems. Such topographic complexity results in the variability of the seafloor fabric and sedimentation reflecting correlations between the tectonic geomorphic markers and bathymetry. The methodology of this paper is based on the advanced cartographic toolset GMT which utilizes a shell scripting approach using a variety of modules. The tectonics showed strong correlation with the seafloor topography, and weaker correlation with sedimentation, which is influenced by geomorphology, gravity anomalies and bathymetry. The paper contributes to the oceanographic and geologic studies of the Pacific Ocean and methodology of GMT.

Keywords: GMT, Pacific Ocean, Tectonics, Mapping, Cartography, GIS, Data.

Resumo / Resumen

PROCESSAMENTO CARTOGRÁFICO DOS CONJUNTOS DE DADOS GEOESPACIAIS DE MÚLTIPLAS FONTES POR GMT PARA MAPEAMENTO DA VARIABILIDADE NO CENÁRIO GEOLÓGICO E BATIMETRIA DO OCEANO PACÍFICO

O artigo apresenta uma análise espacial das configurações geológicas e da estrutura topográfica do Oceano Pacífico por Generic Mapping Tools (GMT). As características tectônicas e geomórficas do Oceano Pacífico têm um caráter complexo e incluem trincheiras, cristas, elevação do Pacífico Leste, bacias, zonas de fratura, fendas, elevações, sistemas de falha. Como resultado, o tecido do fundo do mar tem uma variabilidade na sedimentação refletindo correlações entre os marcadores geomórficos tectônicos e a batimetria. A metodologia é baseada no conjunto de ferramentas cartográficas avançadas GMT, que utiliza uma abordagem de script de shell usando uma variedade de módulos. A tectônica mostrou forte correlação com a topografia do fundo do mar, e uma correlação mais fraca com a sedimentação, influenciada pela geomorfologia, localização, anomalias gravitacionais e batimetria. O artigo contribui para os estudos oceanográficos e geológicos do Oceano Pacífico e metodologia de GMT.

Palavras-chave: GMT, Oceano Pacífico, Tectônica, Mapeamento, Cartografia, GIS, Data.

PROCESAMIENTO CARTOGRÁFICO DE LOS CONJUNTOS DE DATOS GEOESPACIALES DE MÚLTIPLES FUENTES POR GMT PARA CARTOGRAFIAR LA VARIABILIDAD EN EL ENTORNO GEOLÓGICO Y LA BATIMETRÍA DEL OCÉANO PACÍFICO

El artículo presenta un análisis espacial de la configuración geológica y la estructura topográfica del Océano Pacífico mediante Generic Mapping Tools (GMT). Las características tectónicas y geomórficas del Océano Pacífico tienen un carácter complejo e incluyen trincheras, cordilleras, ascenso del Pacífico oriental, cuencas, zonas de fractura, fisuras, elevaciones, sistemas de fallas. Como resultado, el tejido del fondo marino tiene una variabilidad en la sedimentación que refleja las correlaciones entre los marcadores geomórficos tectónicos y la batimetría. La metodología se basa en el conjunto de herramientas cartográficas avanzadas GMT que utiliza un enfoque de scripting shell utilizando una variedad de módulos. La tectónica mostró una fuerte correlación con la topografía del fondo marino y una correlación más débil con la sedimentación, influenciada por la geomorfología, la ubicación, las anomalías gravitatorias y la batimetría. El artículo contribuye a los estudios oceanográficos y geológicos del Océano Pacífico y a la metodología del GMT.

Palabras-clave: GMT, Océano Pacífico, Tectónica, Cartografía, Cartografía, GIS, Fecha.

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INTRODUCTION

Understanding the structure of the seafloor landforms in the Pacific Ocean, the deepest region on the Earth, helps to improve the investigations of its regional marine geology and submarine geomorphology. Analysis of the tectonic, geological and geophysical processes in the deep-sea regions is largely based on the correct visualization of the seafloor patterns. At the same time, mapping seafloor has always been constrained by its remote location and impossible direct observations. Converging Earth observation advances (e.g. GEBCO, ETOPO datasets) and IT technologies enables accurate mapping and modelling of the least reachable areas of the Earth over the wider areas (GAUGER et al. 2007; LEMENKOVA, 2020a–c; GOHL et al. 2006a, 2006b).

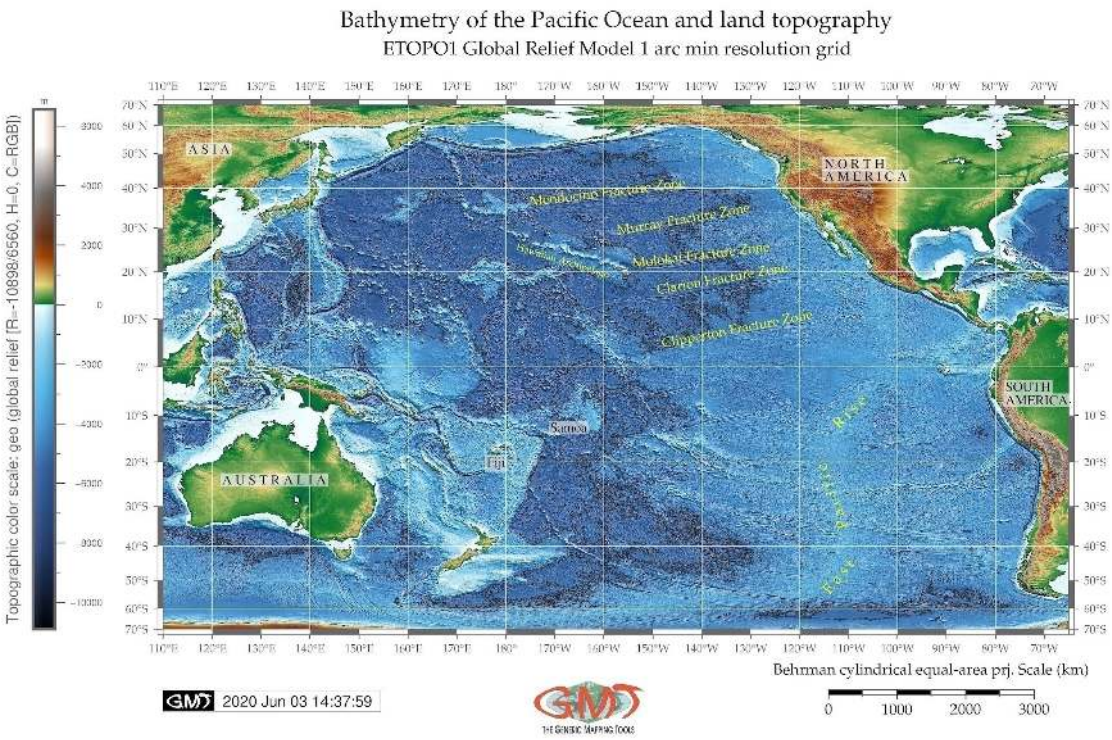

Figure 1 - General bathymetric map of the Pacific Ocean. Source: author.

Utilization of the cartographic approaches for comparative analysis of the geomorphology, tectonics and geological setting of the Pacific Ocean seafloor enables to highlight variations between the seafloor bathymetry and correlations between the environmental factors with response to geologic processes and topography of the submarine landforms (KUHN et al. 2006; LEMENKOVA, 2020d, 2020e). Rapidly developing IT methods revolutionized bathymetry and seafloor mapping of the deepest landforms, enabling to collect the contextual information for the seafloor visualization and thereby established the knowledge base for the marine geo-science. For many years, oceanic seafloor has been treated as the least accessible geographic object, and scientific interests have primarily focused on the terrains accessible through visual observations and direct measurements. Application of the remote sensing survey for seafloor investigations changed the possibilities of the marine geology. Current study is based on using high-resolution datasets visualized through advanced cartographic approach of the Generic Mapping Tools (GMT) scripting toolset (WESSEL & SMITH, 2018).

OBJECTIVES

Remote location and a complex bathymetry of the Pacific Ocean necessarily arises a need for the machine-learning GIS approaches to visualize, model and map seafloor, both to visualize and compare various settings: topography, geology, tectonics, sediment thickness. At the same time, it aims to assist in the development of the effective cartographic methods, technical tools and accurate datasets for

submarine mapping contributing to analysis of the seafloor topography.

Machine learning techniques in cartography takes an advantage of the scripting approaches along with rapid development of the programming algorithms of data processing. Generally speaking, the stronger the mathematical foundation in a geographic data modelling the more accurate is the resulting geospatial grid. The GMT presents the example of such a cartographic toolset with scripting approach that results in fine cartographic products and solutions.

Therefore, one of the objectives of the undertaken study is to enable the analysis of the geological settings and topographic structure of the Pacific Ocean seafloor. A series of the thematic maps aimed to determine the relationship between its various settings: bathymetry, geology, tectonics, marine free-air gravity anomalies (Faye's) and seafloor sedimentation.

THEORETICAL FRAMEWORK

In this framework, following questions were addressed: how depths distribution and closeness to the coasts affect the sediment distribution along the seafloor, and how can knowledge on geological and tectonic settings be used to explain variations in the geomorphology of the regional areas of the Pacific Ocean.

Large study area and limited datasets available to perform the study determined that these questions had to be answered through mapping and interpretation of the results performed via the GMT. The mapping was based on a sequence of the GMT modules using existing methodology (LEMENKOVA 2019a, 2019b). Using advanced methods of automatization in cartography is well established in the literature.

The GMT has been developed in 1980s by the American cartographers P. Wessel and W.H.F. Smith and is being constantly developing since then (WESSEL & SMITH, 1991; WESSEL et al. 2013). Due to its effectiveness, the toolset is being largely used in geophysics and mapping (LEMENKOVA, 2019e, 2019f). Along with recent development of robotics and machine learning for processing of the big data and rapid computations, an interest in scripting cartographic methods and the use of programming languages and automatization in geosciences had significantly increased (SCHENKE & LEMENKOVA, 2008; DOBSON, 1983; LEMENKOV & LEMENKOVA, 2021; OPENSHAW, 1995; HORN, 1995; LEMENKOVA 2019g, 2019h; JOHNSTON & SEMPLE, 1983).

Some works report the development of the new approaches to mapping based on a GMT using raster and vector datas and shell scripting techniques (LEMENKOVA, 2021a–c). International scientific organizations establish relation between modern mapping approaches and precise high-resolution datasets available publicly: NOAA, Scripps Institution of Oceanography (SIO). These datasets were used in this research.

NOVELTY AND ACTUALITY

The present paper proposes a strategy of the geospatial data analysis that combines the visualization of the topographic grids with geological, tectonics, sedimentation and gravimetric raster data using scripting approach of GMT. Previous studies on the geology of the Pacific Ocean demonstrated that its geology has unique features, such as grandiose fault system, the deepest trenches of the Earth located along its margins, repetitive earthquakes and seismicity together with volcanism and tsunami in the zones of plate subduction, strongly dissected its submarine relief.

This study proposes an integration of the data for an analysis of the identification of the correlation between geological and topographic variables. Comparative studies of various settings of the Pacific Ocean seafloor exist and have been analysed in this study as sources of literature (DELANEY et al. 1981; LISITSYN, 1976; MAMMERICKS et al. 1975; KAWABE & TAIRA, 1998; HAIN, 1971; JOHNSON & TOOLE, 1993; MORTIMER et al. 1998; AGHAEI et al. 2014; CARBOTTE & MACDONALD, 1992; CARBOTTE & MACDONALD, 1994; FORNARI et al. 2012; DUNN & TOOMEY, 1997). The presented maps were plotted using GMT which has the procedure of the semi-automatic mapping workflow.

All maps were plotted from a command line with layers controlled by a GMT syntax in a code.

DATA AND METHODS

Mapping Pacific Ocean seafloor was based on using the data from the ETOPO1 1 minute resolution raster grid, since bathymetric maps should be based on the high resolution data with isolines highlighting steepness and gradient through cartographic interpretation. Therefore, the ETOPO1 dataset was chosen for mapping Figure 1. Techniques of mapping included a number of GMT modules (e.g. pscoast, pshistogram, pstext, gmtset, gmtdefaults, grdcut, makecpt, grdimage, psscale, grdcontour, psbasemap, gmtlogo, psconvert, img2grd, grd2cpt), described in previous research (LEMENKOVA, 2020d). These methodology was applied and used to visualize, model and map the seafloor of the Pacific Ocean, its geomorphology, tectonic and geological setting. The maps were plotted using various cartographic projections: 1) Behrman cylindrical equal-area (Figures 1, 4 and 5); 2) Mollweide pseudocylindrical homolographic equal-area (Figure 2); 3) Eckert IV equal-area pseudocylindrical (Figure 3).

Vector layers of Pacific Ocean coasts, continents and shorelines embedded in the GMT were used for visualization: coastal borders on all the maps were based on the GSHHG to visualize and map thematic maps of topography, geology and seafloor fabric (Figures 1, 2 and 3). The map of the Pacific Ocean (Figure 1) was done using ETOPO1 1 Arc-Minute Global Relief Model grid originally developed by NOAA (AMANTE, EAKINS, 2009). The free-air gravity and gravimetric geoid data grids are based on the EGM96 with n=m=360 and WGS84 reference system (MALYS 1996). The EGM96 has reference ellipsoid the same as WGS 84, but higher spatial resolution and more accurate geoid. The data are made public by NIMA, NASA GSFC, and the Ohio State University.

The free-air gravity and geoid models present a complex function that depends on various geophysical phenomena, such as postglacial land uplift, sea level changes, polar drift and other parameters (EKMAN 1995; BURSA 1995; HEISKANEN, MORITZ, 1967). Therefore, various existing gravity and geoid concepts originate from differing numerical applications and approaches in processing of the permanent Earth's tide (EKMAN 1989). In this study, the gravity model was based on available data on grav_27.1.img and EGM96, a geopotential model is a spherical harmonic model of the Earth's gravitational potential complete to degree and order 360 (LEMOINE et al., 1998). The data for global free-air marine gravity grids from CryoSat-2, Jason-1 were retrieved from the SIO (SANDWELL et al. 2014). The EGM96 contains fully-normalized, unitless spherical harmonic coefficients and their standard deviations for a gravitational model from 2°, to 360°, the grav_27.1.img contains free-air gravity of the Earth's surface, available at SIO. These coefficients are consistent with scaling values of gravitational models and 'a' appearing in the equation (RAPP 1994). The data are based on the surface gravity data covering various regions of the globe.

GMT SCRIPTS

GMT SCRIPT 1 FOR FIGURE 1 (TOPOGRAPHY)

In this script, used for mapping topography of the Pacific Ocean in Figure 1, several GMT modules are presented. First of all, the 'grdcut' module was used for clipping the area of the Pacific Ocean from the global grid ETOPO1. Then, the colour palette was adjusted to the topographic extent using 'makecpt' module. One of the most used GMT modules is 'grdimage' which visualizes raster data using coordinate positions and elevation values in each points of the grid and visualizes the topography based on previously made colour palette using values in raster cells. The 'grdcontour' was used for plotting the isolines. The full script is below:

```
# Extract a subset of ETOPO1m . format: -R0/360/-90/90
grdcut ETOPO1_Ice_g_gmt4.grd -R110/295/-70/70 -Gpo_relief.nc
#gdalinfo po_relief.nc -stats
# z#actual_range={-10898,6560}
# Make color palette
gmt makecpt -Cgeo.cpt -V -T-10898/6560 > poocean.cpt
```

```
# Generate a file
ps=BathymetryPO.ps
# Make raster image
gmt grdimage po_relief.nc -Cpoocean.cpt -R -JY180/0/6.5i -I+a15+ne0.75 -Xc -K > $ps
# Add color legend
gmt psscale -Dg80/-70+w9.5c/0.4c+v+o0.3/0i+ml \
-Rpo_relief.nc -J -Cpoocean.cpt \
--FONT_LABEL=8p,Helvetica,dimgray \
--FONT_ANNOT_PRIMARY=5p,Helvetica,dimgray \
-Baf+l"Topographic color scale: geo (global relief [R=-10898/6560, H=0, C=RGB])" \
-I0.2 -By+lm -O -K >> $ps
# Add shorelines
gmt grdcontour po_relief.nc -R -J -C5000 -W0.05p,black -O -K >> $ps
# Add grid with major and minor lines
gmt psbasemap -R -J \
-Bxg20f10a10 -Byg20f10a10 \
--MAP_GRID_PEN_PRIMARY=thinnest,white \
--MAP_GRID_PEN_SECONDARY=thinnest,white \
--MAP_TITLE_OFFSET=1.0c \
-B+t"Bathymetry of the Pacific Ocean and land topography" -O -K >> $ps
# Add scale bar
gmt psbasemap -R -J \
--FONT=8p,Palatino-Roman,black \
--MAP_TITLE_OFFSET=0.3c \
-Lx14c/-1.2c+c50+w3000k+l"Behrman cylindrical equal-area prj. Scale (km)"+f \
-UBL/0.0c/-1.5c -O -K >> $ps
# Texts
gmt pstext -R -J -N -O -K \
-F+jTL+f7p,Times−Bold,yellow+jLB+a-353 >> $ps
185.0 35.4 Mendocino Fracture Zone
EOF
# in similar way all other texts
# Add GMT logo
gmt logo -Dx6.5/-2.2+o0.1i/0.1i+w2c -O -K >> $ps
# Add subtitle
gmt pstext -R0/10/0/15 -JX10/10 -X1.0c -Y4.5c -N -O \
-F+f10p,Palatino-Roman,black+jLB >> $ps
3.0 9.0 ETOPO1 Global Relief Model 1 arc min resolution grid
EOF
# Convert to image file using GhostScript
gmt psconvert BathymetryPO.ps -A0.5c -E720 -Tj -Z
```

GMT SCRIPT 2 FOR FIGURE 2 (GEOLOGY)

The next script has been made for plotting geological map in Figure 2. Here the 'psxy' module of GMT presents the method which is used for adding vector symbols on a map to depict geological lines,

ophiolites, ridges, transform lines, large igneous provinces etc (see Figure 2). The algorithm of plotting legend is presented by module 'pslegend'. The 'psbasemap' module was used for adding cartographic elements, such as grid and scale bar on the map.

```
# Step-1. Generate file
ps=GMT_geology_World_JW.ps
# Step-2. GMT set up
gmt set FORMAT_GEO_MAP=dddF \
# Step-3. Overwrite defaults of GMT
gmtdefaults -D > .gmtdefaults
# Step-4. Plot coastmap
gmt pscoast -Rg -JW180/9i -Gwheat1 -Slightsteelblue1 -W0.25p -Dc \
-B+t"Pacific Ocean: geological setting. Central meridian at 180\232" \
-Vv -K > $ps
# Step-5. Add geology
gmt psxy -R -J hotspots.gmt -Sc0.2c -Gred -O -K >> $ps
gmt psxy -R -J ridge.gmt -Sf0.5c/0.15c+l+t -Wthin,purple -Gpurple -O -K >> $ps
gmt psxy -R -J transform.gmt -Sf0.5c/0.15c+l+t -Wthin,orange -Gorange -O -K >> $ps
gmt psxy -R -J LIPS.2001.points.gmt -Sc0.1c -Gmediumpurple3 -O -K >> $ps
gmt psxy -R -J LIPS.2011.gmt -L -Gplum1@50 -Wthinnest,red -O -K >> $ps
gmt psxy -R -J ophiolites.gmt -Sc0.1c -Gtan2 -O -K >> $ps
gmt psxy -R -J volcanoes.gmt -Sc0.1c -Gmaroon4 -O -K >> $ps
gmt psxy -R -J trench.gmt -Sf1.5c/0.15c+l+t -Wthickest,yellow -Gyellow -O -K >> $ps
# Step-6. Add grid, scale bar
gmt psbasemap -R -J \
-Bpx30g30 -Bpy10g10 \
-Lx11.4c/-1.3c+c50+w10000k+l"Mollweide pseudocylindrical/homolographic equal-area projection. Scale (km)"+f \
-UBL/45p/-40p -O -K >> $ps
# Step-7. Add legend
gmt pslegend -R -J -Dx19.0/-2.0+w5.2c+o0.0/0.2c -F+pthin+ithinner+gwhite \
--FONT_ANNOT_PRIMARY=8p -O -K > $ps
S 0.3c c 0.2c red 0.15p 1.0c Hotspots
S 0.3c f+l+t 0.7c yellow 0.15p 1.0c Trench/Fault
S 0.3c f+l+t 0.7c purple 0.15p 1.0c Ridge
S 0.3c f+l+t 0.7c orange 0.15p 1.0c Transform lines
S 0.3c c 0.1c tan2 0.15p 1.0c Ophiolites
S 0.3c r 0.7c plum1@50 0.01c 1.0c Large igneous provinces
S 0.3c c 0.1c mediumpurple3 0.15p 1.0c Spots of LIPs
S 0.3c c 0.1c maroon4 0.15p 1.0c Volcanoes
EOF
# Step-8. Add logo
gmt logo -R -J -Dx10.5/-2.7+o0.1i/0.1i+w2c -O >> $ps
# Step-9. Convert to image file using GhostScript (landscape orientation, 720 dpi)
gmt psconvert GMT_geology_World_JW.ps -A0.5c -E720 -Tj -Z
```

GMT SCRIPT 3 FOR FIGURE 3 (TECTONICS)

The next script show the stepwise workflow of codes used for plotting tectonic map in Figure 3. The first step, the 'ps=GMT_tect_seafloor.ps' generates a file which creates a sort of 'basket' where all other lines are put stepwise. Accordingly, every line of the script is 'responsible' for adding special cartographic element on the map (grid, annotating text, visualized raster, modified and adjusted colour palette, converted graphical format, etc). The 'gmt set FORMAT_GEO_MAP dddF' defines general appearance of the map (annotated degrees, in geographic coordinates). The script finished with a final step which converts the created graphics into the necessary format by the 'psconvert' module. Finally, a particular part of this script is the use of the 'echo' Linux utility for annotating part of the textual information.

```
# Step-1. Generate a file
ps=GMT_tect_seafloor.ps
# Step-2. GMT set up
gmt set FORMAT_GEO_MAP dddF
# Step-3. Overwrite defaults of GMT
gmtdefaults -D > .gmtdefaults
# Step-4. Add grid, scale bar, time stamp
gmt psbasemap -Rg -JKf180/9i \
-Lx11.8c/-1.3c+c50+w10000k+l"Eckert IV equal-area
pseudocylindrical projection. Scale (km)"+f \
-UBL/45p/-40p -K > $ps
# Step-4. Add coastline, title
gmt pscoast -R -J -Gpapayawhip -Sazure -W0.25p -Dl \
-Bpxg30f15a30 -Bpyg10f5a10 \
-B+t"Tectonic plates boundaries, rotation poles, steps, slab contours,
global seafloor fabric and magnetic lineation picks" \
-Vv -O -K >> $ps
# Step-5. Add tectonic plates
gmt psxy -R -J TP_Pacific.txt -L -Wthick,red -O -K >> $ps
# other plates were added in a similar way
# add poles of plates rotation: lon/lat coords and Rotation rate (deg./Ma)
#gmt psxy -R -J PB2002_poles.dat.txt -i2,1,3 -Sc0.1c -Crain.cpt -Wthinner -O -K >> $ps
gmt psxy -R -J PB2002_poles.dat.txt -i2,1,3 -Sc0.1c -Wthinner,red -O -K >> $ps
gmt makecpt -Crainbow -T0/100/1 -Z > steps.cpt
#gmt psxy -R -J PB2002_steps.dat.txt -i3,2,6 -Sc0.1c -Wthickest,red -O -K >> $ps
gmt psxy -R -J PB2002_steps.dat.txt -i3,2,6 -Sc0.1c -Csteps.cpt -Wthinnest -O -K >> $ps
# Step-6. Add fracture zones and magnetic anomalies
gmt psxy -R -J GSFML_SF_DZ_KM.gmt -Wthin,green -O -K >> $ps
# other fracture zones and magnetic anomalies were added in a similar way
# Step-7. Add magnetic lineation picks (gray-colored)
gmt psxy -R -J GSFML.global.picks.gmt -Sp -Gdimgray -O -K >> $ps
# Step-8. Add text labels
echo "-160 7 PA" | gmt pstext -R -J -F+jTL+f10p,Times-Roman,black -O -K >> $ps
# other annotations were added in a similar way
# Step-9. Add slab contours
gmt makecpt -Crainbow -T0/700/50 -Z > rain.cpt
gmt psxy -R -J SC_aleutians.txt -Sp -Crain.cpt -O -K >> $ps
```

```
# other slab contours were added in a similar way
# Step-10. Add logo
gmt logo -R -J -Dx10.2/-2.7+o0.1i/0.1i+w2c -O >> $ps
# Step-11. Convert to image file using GhostScript (landscape orientation, 720 dpi)
gmt psconvert GMT_tect_seafloor.ps -A0.2c -E720 -Tj -Z
```

GMT SCRIPT 4 FOR FIGURE 4 (SEDIMENT THICKNESS)

The Script 4 presents the workflow for plotting map of sediment thickness in the Pacific Ocean, shown in Figure 4. One of the most important used modules, used here as in previous scripts is the 'psbasemap' which enables to add all the important cartographic elements on the map. For instance, the option 'Bxg20f10a10 -Byg20f10a10' depicts the frequency of the major and minor ticks on the map in longitudes (x axis) and latitude (y axis): every 20 and 10 degrees, respectively. The 'psscale' module places the colour scale with defined position and aesthetics. The 'logo' module places the GMT logo in the bottom of the map. The script is shown below.

```
# Generate a file
ps=PO_Sediments.ps
# Make raster image
grdcut GlobSed-v2.nc -R110/295/-70/70 -Gpo_sed.nc
gmt grdimage po_sed.nc -Csediments.cpt -R -JY180/0/6.5i -P -I+a15+ne0.75 -Xc -K > $ps
# Add grid
gmt psbasemap -R -J \
-Bxg20f10a10 -Byg20f10a10 \
--MAP_TITLE_OFFSET=0.8c \
-B+t"Sediment thickness on the Pacific Ocean seafloor" -O -K >> $ps
# Add legend
gmt psscale -Dg85/-70+w9.5c/0.4c+v+o0.3/0i+ml \
-Rpo_relief.nc -J -Csediments.cpt \
--FONT_LABEL=8p,Helvetica,dimgray \
--FONT_ANNOT_PRIMARY=5p,Helvetica,dimgray \
-Baf+l"Color scale: turbo (Google's Improved Rainbow Colormap for Visualization [C=RGB])" \
-I0.2 -By+lm -O -K >> $ps
# Add scale, directional rose
gmt psbasemap -R -J \
--FONT=8p,Palatino-Roman,black \
--MAP_TITLE_OFFSET=0.3c \
-Lx14c/-1.2c+c50+w3000k+l"Behrman cylindrical equal-area prj. Scale: km"+f \
-UBL/0.0c/-1.5c -O -K >> $ps
# Add GMT logo
gmt logo -Dx6.5/-2.2+o0.1i/0.1i+w2c -O -K >> $ps
# Add subtitle
gmt pstext -R0/10/0/15 -JX10/10 -X1.0c -Y4.5c -N -O \
-F+f10p,Palatino-Roman,black+jLB >> $ps
3.7 9.0 GlobSed five arc minute grid version three
EOF
# Convert to image file using GhostScript
gmt psconvert PO_Sediments.ps -A1.0c -E720 -Tj -Z
```

GMT SCRIPT 5 FOR FIGURE 5 (GRAVITY)

The script 5 has been used for plotting Figure The 'img2grd; module of GMT was the other method applied for conversion of formats in mapping. This method has been used to convert the IMG format into GRD. The 'haxby' color palette was applied for visualization, which was developed by W. F. Haxby in 1985 for geoid and gravity fields of the World's oceans. The Behrman cylindrical projection was defined in the flag '-JY180/0/6.5i' where the 180/0 denote the standard coordinates, while the '6.5i' defines the physical extensions of the map layout (6.5 inches). The annotations on the maps were plotted using the 'pstext' module, as demonstrated in the script below:

```
# Extract subset of img file in Mercator or Geographic format
img2grd grav_27.1.img -R110/295/-70/70 -Ggrav.grd -T1 -I1 -E -S0.1 -V
# Generate a color palette table from grid
gdalinfo geoid.egm96.grd -stats
#Minimum=-106.505, Maximum=86.417, Mean=-0.808, StdDev=29.198
# gmt grd2cpt grav.grd -Crainbow > grav.cpt
gmt makecpt -Chaxby -T-106.505/86.417/1 > colors.cpt
# Generate a file
ps=Grav_PO.ps
# Generate gravity image with shading
gmt grdimage grav.grd -I+a45+nt1 -R110/295/-70/70 -JY180/0/6.5i -Ccolors.cpt -P -K > $ps
# Add basemap: grid, title, coastline
gmt psbasemap -R -J \
-Bxg20f10a10 -Byg20f10a10 \
--MAP_TITLE_OFFSET=0.8c \
-B+t"Marine free-air gravity anomaly: Pacific Ocean" -O -K >> $ps
# Add scale, directional rose
gmt psbasemap -R -J \
--FONT=8p,Palatino-Roman,black \
--MAP_TITLE_OFFSET=0.3c \
-Lx14c/-1.2c+c50+w3000k+l"Behrman cylindrical equal-area prj. Scale: km"+f \
-UBL/0.0c/-1.5c -O -K >> $ps
# Add legend
gmt psscale -Dg85/-70+w9.5c/0.4c+v+o0.3/0i+ml \
-Rpo_relief.nc -J -Ccolors.cpt \
--FONT_LABEL=8p,Helvetica,dimgray \
--FONT_ANNOT_PRIMARY=5p,Helvetica,dimgray \
-Baf+l"Color scale: Haxby: Bill Haxby's color scheme for geoid & gravity [C=RGB]" \
-I0.2 -By+lmGal -O -K >> $ps
# Add logo
gmt logo -Dx6.5/-2.2+o0.1i/0.1i+w2c -O -K >> $ps
# Add subtitle
gmt pstext -R0/10/0/15 -JX10/10 -X1.0c -Y4.5c -N -O \
-F+f10p,Palatino-Roman,black+jLB >> $ps
2.2 8.8 Global gravity grid from CryoSat-2 and Jason-1, 1 min resolution
EOF
# Convert to image file using GhostScript (portrait orientation, 720 dpi)
```

```
gmt psconvert Grav_PO.ps -A0.2c -E720 -Tj -P -Z
```

RESULTS AND DISCUSSION

Data models presented in this study have incorporated GMT data models with high-resolution datasets that are useful for the mapping and geospatial analysis of the Pacific Ocean. A series of the thematic maps produced and demonstrated in this study are useful for seafloor analysis and geomorphological modelling at regional local scales of the Pacific Ocean, e.g., focused on selected coastal areas, basins, depressions, or others submarine landforms, e.g. ridges or deep-sea trenches. As a result of the mapping based on high-resolution datasets and raster grids, this work presented a series of the thematic geological maps detailing information on the bathymetry, geology, tectonics and topography of the Pacific Ocean. Therefore, using multi-source data as layers for complex analysis of the geographically extended regions, such as Pacific Ocean as a basis for spatial analysis is strongly recommended in future similar works.

BATHYMETRY

As can be seen on the topographic map (Figure 1), the basement seafloor surface in the rift zone of the South Pacific Rise and East Pacific Rise almost coincides with the modern submarine bathymetric isolines (plotted every 5,000 m on the map on Figure 1), which typically has a block ridge fragmentation. Southward from the region of Easter Island (Polynesian Triangle in Oceania) in the rift zone it is dominated by depths of 2.5 to 3 km, and in the north direction – about 3 km and more (dark blue colour, Figure 1).

However, on the Galapagos Rift (86°W and 89°W) and on the Gorda Ridge and Juan de Fuca Ridge (mid-ocean spreading centres near Vancouver Island at 46°N and 130°W, northward of Mendocino Fracture Zone), the depths of the seafloor surface again increase to 2-3 km (light blue colour, Figure 1). In the transverse troughs of transform faults, the depths of the seafloor basement increase to 4 km, in some places more than 5 km (for example, in the region of Eltanin Fault System near Antarctic). On both sides of the rift zone, the seafloor depths gradually decrease, reaching ca. 5 km at the outer borders of the South Pacific Rise depths, about 4.5 km at the East Pacific Rise, and

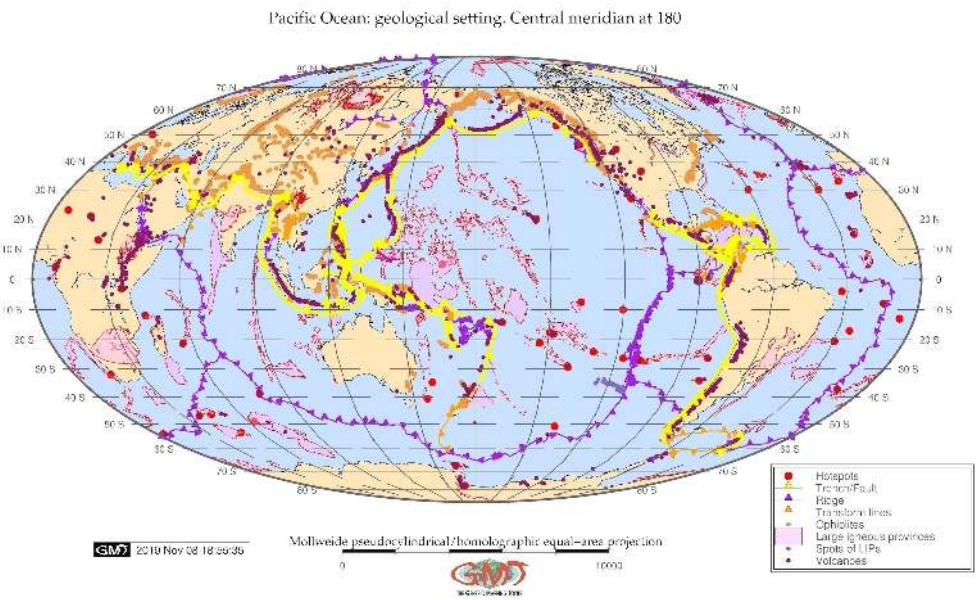

Figure 2 - Geologic map of the Pacific Ocean region. Source: author.

The bathymetry of the Pacific Ocean is notable for its dissymmetry observed in the location of its basins. More than 75% of its area is located northwest of the East Pacific Rise (Figure 1). According to

the features of the underwater relief, this part of the Pacific Ocean seafloor can be divided into two more areas: eastern and western.

Regional variations can be seen on Figure 1. Eastern region adjacent to the East Pacific Rise includes southern and northeastern basins. The last one is characterized by distribution of the abyssal hills and presence of great sub-latitudinal fracture zones stretching for thousands km: Mendocino, Murray, Molokai, Clarion, Clipperton (yellow texts on Figure 1, purple lines on Figure 3). Western region, including among other the basins of Northwest, Central and Melanesian Basin is characterized by a large number of submarine block and volcanic uplifts and ridges, volcanic islands and seamounts. Basins located southeast from the East Pacific Rise divided by the Galapagos Rise and Chilean Rise can be divided into three sectors: Central American, South American and Antarctic according to their bathymetric settings.

GEOLOGY

The East Pacific Rise is dissected by numerous faults, along which its middle part is directed mainly westward, and the southern and northern parts — eastward displacements (Figure 2). The values of the faults reach from 90 up to 180 km, for the Easter fault – up to 750 km. Most of the faults are located within the rises, but the largest ones extend farther into the ocean basins. These include Menard Transform Fault (50°S), Agassiz Fracture Zone (42°S), Challenger (Chile) Fracture Zone (35°S), Easter Fracture Zone (25–27°S).

The depths in the transverse minor trenches in the rift zone reach up to 3500–3800 m, while on the flanks – until 5000–5500 m. The western extension of the Challenger Fracture Zone reaches 6500 m (Zhivago, 1979). South Pacific Rise is also dissected in a northwestern direction by numerous transverse faults (Figure 3). Most of the faults extend beyond the ridge into the ocean basins. These include Balleny Fracture Zone (155°E), Scott Fracture Zone (178°E), Udintsev Fracture Zone (144-145°W). These fracture zones are expressed in the rift zone, deep minor trenches associated with bordering ridges, along which there is a right-side displacement of the rift structures at distances from 90 to 280 km. Depths in the transverse minor trenches reach up to 4000–4500 m or more. The East Pacific Rise is stretching up to 1900 km (Figure 1) northward from the Eltanin Fault System and then gradually narrowing to 550 km. The relief structure is almost identical throughout the extension of the rise.

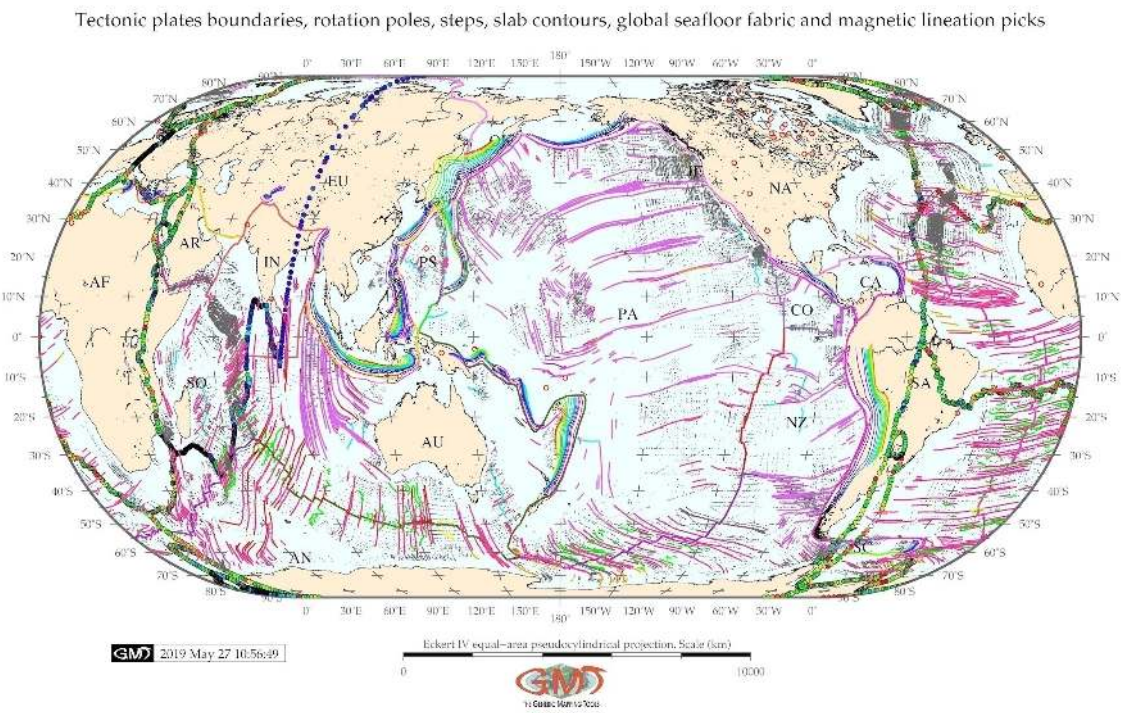

Figure 3 - Tectonic map of the Pacific Ocean: tectonic lineaments, ridges, trenches. Source: author.

The rift valley is not distinguished clearly being replaced by an axial ridge, bordered by the lateral shallow trough-like depressions such as hollows, and a series of the parallel rift ridges. Further analysis of the bathymetry shows (Figure 1) that depths in the rift zone southward from Easter Island (Rapa Nui, 27°S 109°W) are generally at 2500 to 2800 m (intense blue colour, Figure 1), with some peaks with minimal depths at 1400-1600 m (light blue colours, Figure 1). Depths in the rift zone decrease to the north of Easter Island reaching up to 3000–3300 m, however individual peaks rise in depths up to 1600–1800 m. On the flanks of the East Pacific Rise, the depths gradually decrease in both directions, reaching 4000–4300 m, and

Correlation between the geologic basement surface and modern seafloor relief is much less direct on the continental margins due to the variety of factors. These include deep submergence of the basement surface, active denudation under the subaerial conditions in the past geologic history, fluctuations in the ocean level, change of active wave zone, sediment accumulation in course of geological development. The analysis of the raster grids and overlay of the topographic, sediment and geology maps, enabled to identify general correlations in the structure of the sediment cover on the continental margins of the Pacific Ocean.

SEDIMENT THICKNESS

The sediment thickness in the rift zone of the East Pacific Rise is either absent or insignificant having 100-200 m (Figure 4). A sedimentary cover increases only in the deep transverse troughs of the transform faults (200-800 m, blue colours on Figure 4). Previous publications also indicate the absence of precipitation on the top of the East Pacific Rise. The outcrops of the basaltic lava are almost not covered by sediments (BALLARD et al. 1981; VAN ANDEL & BALLARD 1979). Sedimentation of the Pacific Ocean seafloor has a typical nesting distribution on the flanks of the East Pacific Rise.

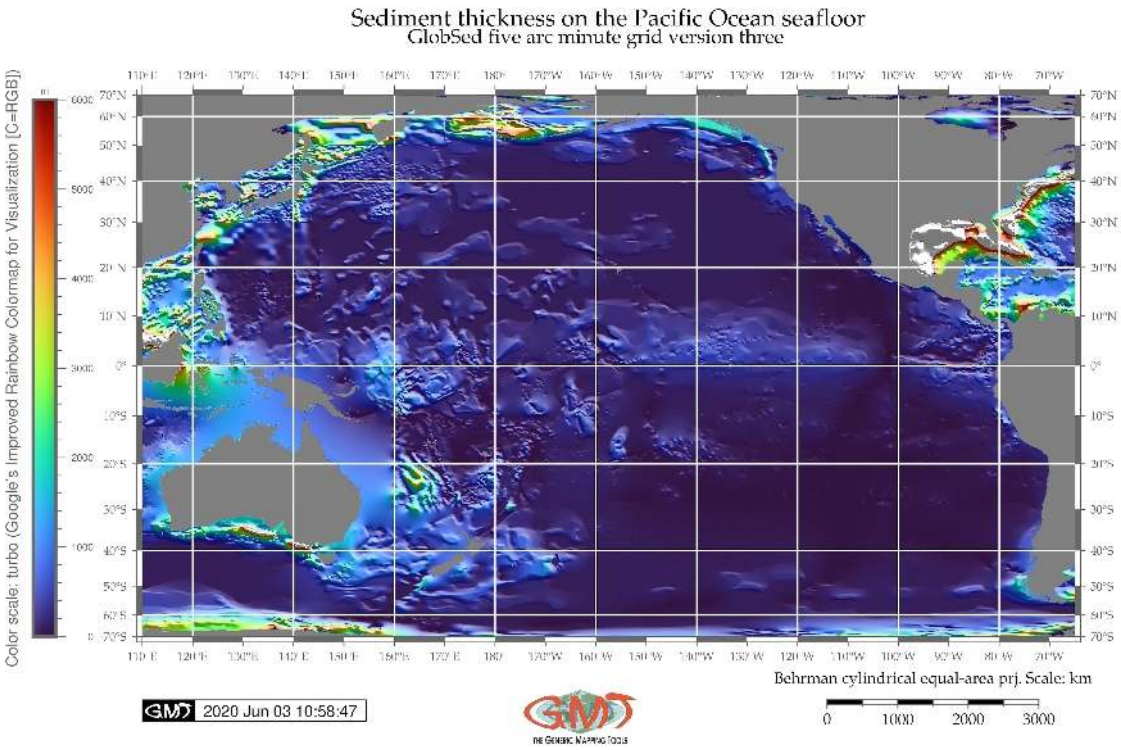

Figure 4 - Sediment thickness of the Pacific Ocean seafloor. Source: author.

Sediment thickness in such local depressions gradually increases toward its outer borders, but almost everywhere does not exceed 100 m, with the exception of the area in the north of the Eltanin Fracture Zone and the equatorial zone, where it reaches 200–300 m. Along with an increase in sediment thickness, the age of basal sediments dating also increases from Pliocene-Quaternary to Paleogene on

the ridge flanks. Visualised seafloor topography of the oceanic basement and sediment thickness are of great importance for understanding of the origin and history of the development of the modern bathymetry of the ocean seafloor, as well as for assessing the role of the sedimentation in relief formation. This is especially important for the ocean seafloor and mid-ocean ridges where the unevenness of the of the seafloor basement is almost directly reflected in the modern relief, due to the low thickness of the sediment cover and low impact of the denudation. In general, in the vast areas of the Pacific Ocean basin, sediment thickness is rather low comparing to Atlantic of Arctic Ocean. Thus, in the basins of the Pacific Ocean it does not exceed 0.1-0.5 km, only in the marginal northern and northwestern parts of the ocean it does exceed 1 km (all colours except blue, Figure 4).

MARINE FREE-AIR GRAVITY

In the Pacific Ocean, Faye anomaly over the South Pacific Rise and East Pacific ranges from 20 to 40 mGal (Figure 5). Above the Gorda Ridge and Juan de Fuca Ridge (Canadian coast), the Faye anomalies decrease with mostly negative values of up to -50 mGal (blue colours, Figure 5). It can be furthermore noted that a chain of the Aleutian Islands and several deep-sea trenches (Kuril-Kamchatka, Japan, Izu-Bonin, Mariana, Vanuatu, Tonga and Kermadec) have positive Faye anomalies values increasing to +80 mGal (orange to red, Figure 5).

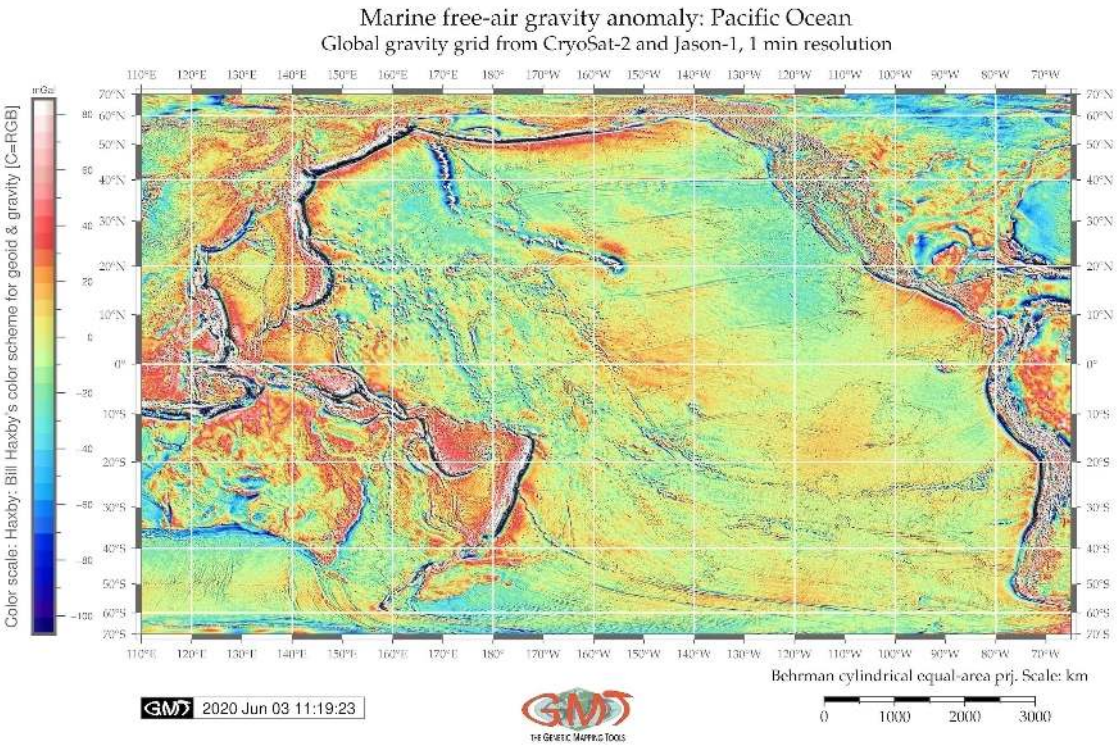

Figure 5 - Marine free-air gravity anomalies of the Pacific Ocean. Source: author.

Comparing these results with earlier studies on seismic observations (GAINANOV, 1980), a gradual decrease in density can be supposed in these areas from 3.3 g/cm3 on the seafloor of the North East Pacific Basin to 3.2g/cm3 under the ridges, and the width of the area of the decompressed mantle is ca 500 km. In general, comparing bathymetry (Figure 1) with gravity map (Figure 5), one can see that the deepest areas e.g. deep-sea trenches (yellow front line, Figure 2) correspond to the lowest Faye anomalies (

Therefore, the rocks of the lithosphere forming in the East Pacific Rise are heavier than the asthenosphere material at about 0.05-0.1g/cm3 (LITVIN, 1987). This density inversion leads to the increase in the seafloor. Thus, the seafloor level of the tectonic plates decreases along with the increase of lithosphere thickness during plate movement from the rift. As a consequence, the depth of the ocean

seafloor decreases on both sides from East Pacific Rise axis.

CONCLUSION

SUMMARY

The purpose of this study was to examine the complex geological settings of the Pacific Ocean in the context of its bathymetric and geomorphological setting and tectonic historical development. Understanding marine geology of the Pacific Ocean needs support of reliable, detailed and accurate seafloor maps visualizing regional particular settings with high resolution and accuracy, detailing seafloor landforms, modelling and visualizing geomorphic forms and shapes. This study presented a contribution towards advancing of marine geo-science studies of the Pacific Ocean through presenting a series of the thematic mapping with comparative analysis of its features: geology, bathymetry, gravity, tectonics, sedimentation. Integrating GMT based mapping with such high resolution datasets visualizing geology, sedimentation, gravimetric and bathymetric data enabled accurate series of the thematic maps of the Pacific Ocean. Machine-learning approach of GMT was used for mapping and interpretation of various settings of the Pacific Ocean (geology, tectonics, seafloor crust spreading, crustal asymmetry, sedimentation, topography).

BENEFITS

Demonstrated benefits of the GMT based seafloor mapping technology to a broad spectrum of geographers and map users visualizing ocean space, as well as convergence toward a standard suite of high quality datasets (e.g. GlobSed, ETOPO1, EGM96 gravity, geologic data on seafloor fabric), map products and interpreted visualization, were demonstrated in this research. The datasets used in this study compiled from the ETOPO1, geoid and gravity raster grids EGM96, geological vector layers, tectonics data on seafloor formation.

In contrast with traditional GIS approach with GUI, e.g. ArcGIS (SUETOVA et al. 2005; LEMENKOVA et al. 2012; KLAUČO et al. 2013, 2014, 2017), sequential use of GMT modules enabled to gain further insights into their geomorphic shape, and to compare accuracy of the data grid interpretation approaches based on the GMT scripting concept aimed to perform thematic analysis of the Pacific Ocean. Comparative map analysis presenting geophysical setting of the Pacific Ocean revealed its structural geologic and topographic characteristics. Visualized gravity, topography and geologic settings added new information to the interpretation of the data on the Pacific Ocean.

OUTLOOKS

Linking raster datasets and geologic data on tectonic spreading lineaments with seafloor processes eventually shaping present bathymetric forms, it is possible to interpolate geomorphology patters to the large scale to provide a framework within which detailed seafloor mapping can be carried out. The presented GMT-based approach provided an effective solution to the seafloor mapping. As a future recommendation for similar studies, more detailed geological and oceanological datasets can be included for complex analysis: current strength, sediment texture, water circulation at various depths. The geological interpretations can then be used to extrapolate each geomorphic type of the seafloor in various regions of the Pacific Ocean for regional comparative analysis.

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