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Map of Plio-Quaternary sediment depths in the Mediterranean Sea

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ABSTRACT The Mediterranean Sea is an extremely interesting region, still under investigation, owing to its complex evolution related to plate tectonics. Research has focused particularly on the first layer, namely the Plio-Quaternary sediments, a geological unit directly related to the tectonics dynamic, with very different thickness (varying from 0 to more than 4500 m) depending on its location. In recent decades, many institutions have carried out seismic campaigns which have led to compiling a first map of thickness of the Plio-Quaternary layer. This map, being a product derived from seismic data, is expressed in seconds, which represent the time taken by a seismic wave to to travel from the source on surface to a given reflector and back. Our objective was to convert times to depths by combining the map profiles available in literature. An analysis of the gravitational signal generated by these sediments was, then, undertaken, showing the importance of this layer in terms of the gravity field. The final map of Plio-Quaternary sediment depths, together with its predicted accuracy, can be downloaded at the BGTA website.

Key words: Plio-Quaternary sediments, map of depths, Mediterranean Sea, gravity field analysis, gravity field interpretation.

1. Introduction

The evolution of the Mediterranean Sea is complex but also highly interesting because it is closely related to plate tectonics. Over the past millions of years, the displacements of the Eurasian and African plates have caused many morphological changes within the basins of the area. As a result, the Mediterranean basins are considerably different from the geophysical and geodynamical point of view. The eastern Mediterranean basin, for example, contains traces of the slow continental subduction process of the African plate below the Eurasian one (Le Pichon and Angelier, 1979); the separation of the Corsica-Sardinia block from Europe has instead contributed to the creation of the western Mediterranean deep basin (Gueguen *et al.*, 1998). Moreover, the migration of the Calabro-Sicilian arc to the SE led to the formation of the Tyrrhenian Sea, likewise characterised by the presence of crust (Savelli and Ligi, 2017). In the late Miocene, another consequence of the collision between African and European plates was the reduction of water inflows into the Mediterranean. An important effect of the reduced inflows was a process of evaporation, also due to the dry climate (generally called the Messinian salinity crisis), during which salt deposits of various thickness precipitated (Sonnenfeld and Finetti, 1985). These peculiar salt structures in some areas of the western basin can reach a thickness of 3 km. It is, therefore, undeniable that the Mediterranean Sea region is made up of a variety of morphological units of different age, i.e. the north Libyan margin of the Jurassic, the margins of the western basin of the early Miocene or the margins of the Tyrrhenian Sea of the Plio-Quaternary and the salt deposits of the Messinian crisis. Due to the ongoing movements of the plates, some of these morphological units are still active today, for example the Hellenic or Calabrian arcs (Gennesseaux *et al.*, 1998).

All the basins in the Mediterranean area, due to the very different boundary conditions at the time of their creation, are made up of different layers of sediments which can be studied to understand the evolution phases of the basins. The history of the basins and their morphological evolution, which in some cases may be very recent (e.g. the Tyrrhenian basin), can provide interesting study regions to model the early stages of sea floor creation (Stanley, 1977).

The shallowest layer of sediments, namely the Plio-Quaternary sediments, found throughout the Mediterranean area, is among the most important ones, especially for gravimetric studies. It can be useful to reconstruct the evolution processes and the geological history of the Mediterranean Sea. For these reasons, over the last 20 years numerous seismic profiles have been shot in the Mediterranean area. The resolution and penetration depths vary depending on the scope of the surveys: oil companies for example concentrate on shallower structures, while research institutes are usually more interested in the deep crust and lithosphere.

In 1998, a first map of the thickness of Plio-Quaternary sediments (IBCM-PQ) was published by a multidisciplinary working group created after the Intergovernmental Oceanographic Commission (IOC) of UNESCO published the first edition of the International Bathymetric Chart of the Mediterranean in 1980 (IOC, 1981). This group was chiefly formed to continue the study over the Mediterranean region by publishing geophysical and geological chart series. Various charts have been compiled over the years (i.e. the gravity and magnetic anomalies maps, the seismicity map, etc.) and among them, the maps of the thickness of the Plio-Quaternary was started in 1981 by M.E. Winnock and completed by the Equipe de Recherche Associée au CNRS 718 at the Departement de Géologie Dynamique of the Université Pierre et Marie Curie in collaboration with various international institutions (Gennesseaux *et al.*, 1998). A great variety of seismic surveys was used to create the map. In particular, data from some of the campaigns conducted by CFP-Total, ELF Aquitaine, and AGIP were used, as well as data acquired by research institutions such as IFP, Institute of Oceanography and Experimental Geophysics of Trieste, Universities of Villefranche-sur-Mer, Paris VI and Bologna. The map of the thickness of Plio-Quaternary sediments published in 1998 is expressed in two-way travel time which represents the time taken for a seismic wave to travel from the source to a given reflector and back to the surface. For an immediate estimation of the real depth of the Plio-Quaternary sediments, the authors proposed an average velocity of about 2 km/s. It was known that this assumption was not so accurate, due to the fact that the characteristics (i.e. composition, compaction, etc.) vary considerably within the Mediterranean area and with depth, from 1.65 km/s to more than 3 km/s. However, the average velocity had the advantage of allowing an immediate conversion from two-way travel time to depths in km.

In this work, the authors sought to investigate a refined way to convert the IBCM-PQ map into depths, by exploiting the available information found in literature, with the objective of producing a quantitative map of depths of the bottom of Plio-Quaternary sediments to be used for geophysical investigations, in absence of better data. Moreover, an analysis of the gravity field produced by this sediment layer is also proposed.

2. Methodology

The first objective was to convert the IBCM-PQ map of the thickness of Plio-Quaternary sediments, freely available for users as a geotiff image (www.ngdc.noaa.gov/mgg/ibcm/ibcmsedt.html), from two-way travel time to depths. To do so, at first we collected as many as possible publicly available interpreted seismic profiles. The interpreted profiles, that report the sequence of layers in terms of depths, can be used as observations in a least squares procedure to estimate the map conversion parameters. At the same time, the downloadable geotiff map was imported in Matlab to perform some necessary cleaning and filtering operations before applying the least squares principle to estimate the thickness (in metres). The imported map is shown in Fig. 1.

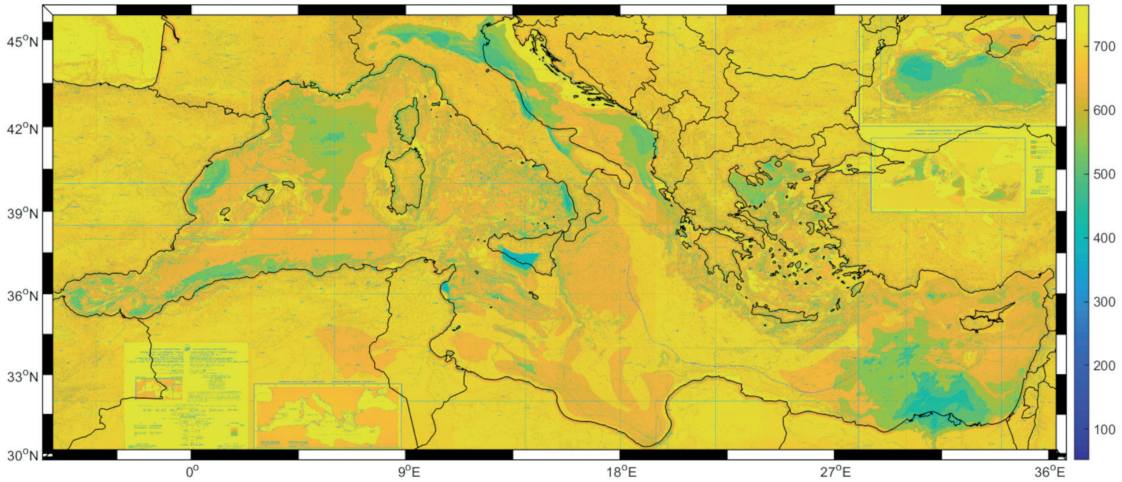

Fig. 1 - Digitalised IBCM-PQ map of thickness of Plio-Quaternary sediments. The original Geotiff image is freely available at www.ngdc.noaa.gov/mgg/ibcm/ibcmsedt.html. Unit is RGB.

The colourbar reports the sum of the RGB values of the current colourmap without any physical meaning. It can be seen that by directly importing the map in Matlab some graphical artefacts, like the vertical and horizontal blue lines or the tables in the upper right and lower left corners, remain in the map. They need to be removed to avoid affecting the subsequent least squares estimate of the conversion parameters from RGB values to thicknesses. So, a proper filter to smooth the colour variations was applied (see for example the Tyrrhenian Sea zoom in Fig. 2): i.e. a bidimensional moving median with size 3 arc-minutes. The size of the moving median window has been empirically set in such a way to remove possible high frequency noise in the original image (due for instance to the photo-reduction process), but in any case to keep a resolution comparable to that of global gravity field models. Another artefact we found in the map was due to the fact that the downloadable map is actually a scan of multiple sheets and this has led to areas with a slightly different colourmap (see Fig. 3). This last artefact required an operation of equalisation. The resulting complete map, after the cleaning and filtering operations, is shown in Fig. 4, in which only the Mediterranean Sea region is visible and the remaining parts over the continents are masked and set to zero.

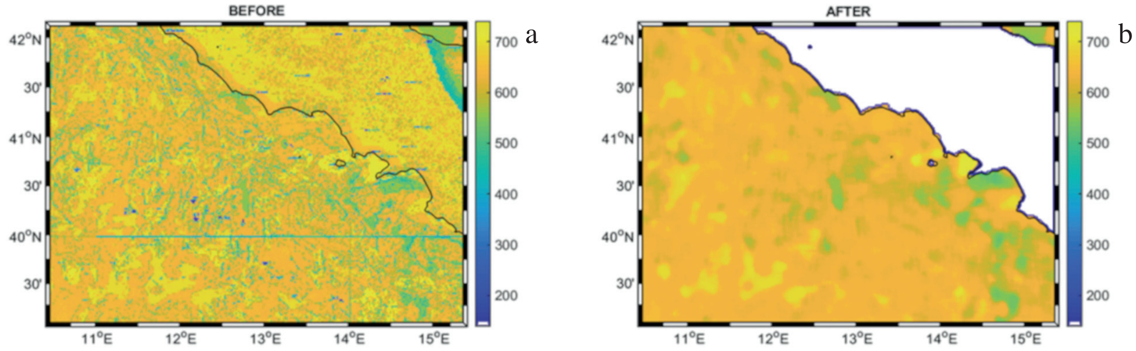

Fig. 2 - Digitalised IBCM-PQ map of thickness of Plio-Quaternary sediments. Zoom on the Tyrrhenian Sea area before (a) and after (b) cleaning and filtering operations. Unit is RGB.

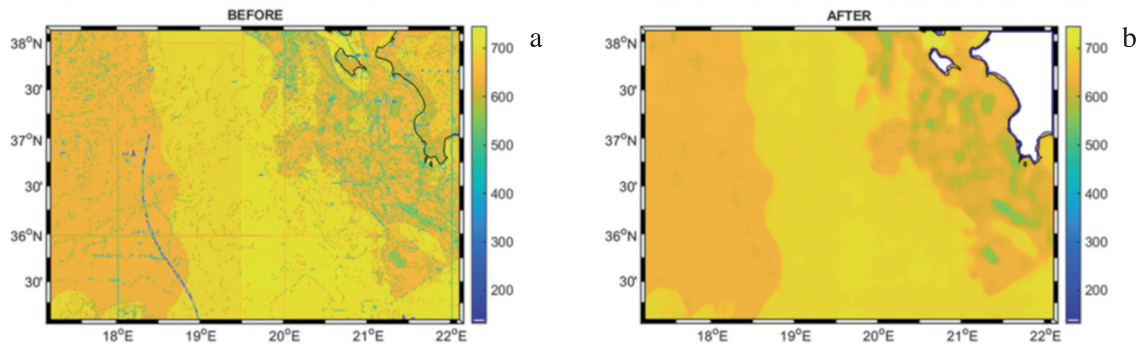

Fig. 3 - Digitalised IBCM-PQ map of thickness of Plio-Quaternary sediments. Zoom on the Ionian Sea area before (a) and after (b) the equalisation and cleaning operations. Unit is RGB.

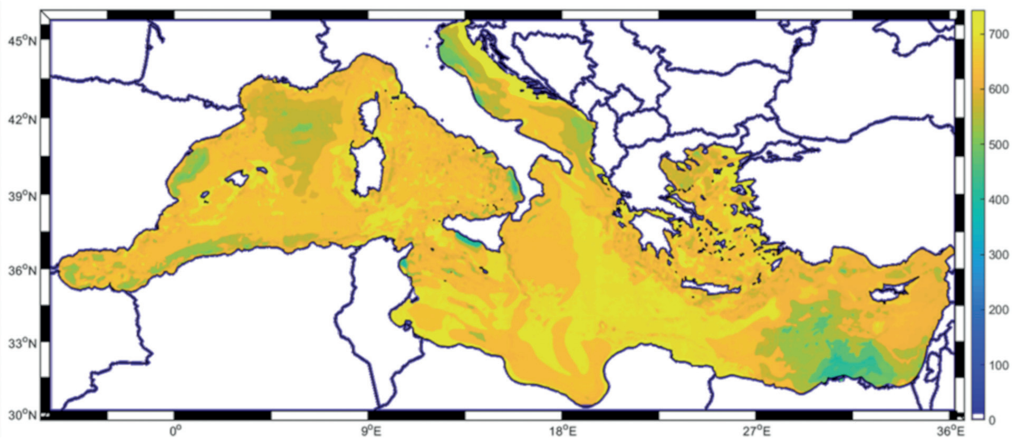

Fig. 4 - Pre-processed map of thickness of Plio-Quaternary sediments after the application of a bidimensional moving median filter and colour equalisation. Unit is RGB.

After the pre-processing of the Plio-Quaternary sediments RGB map, the seismic profiles and freely available data set found in literature were digitalised, georeferenced with QGIS (QGIS Development Team, 2015) and finally imported in Matlab. Fig. 5 reports the thickness in metres of the Plio-Quaternary sediments as found in the interpreted seismic profiles and public data from (de Voogd *et al*., 1992; Maillard and Mauffret, 1999; Le Pichon *et al*., 2002; Zecchin *et al*., 2017; Andronikidis *et al*., 2018; Micallef *et al*., 2018).

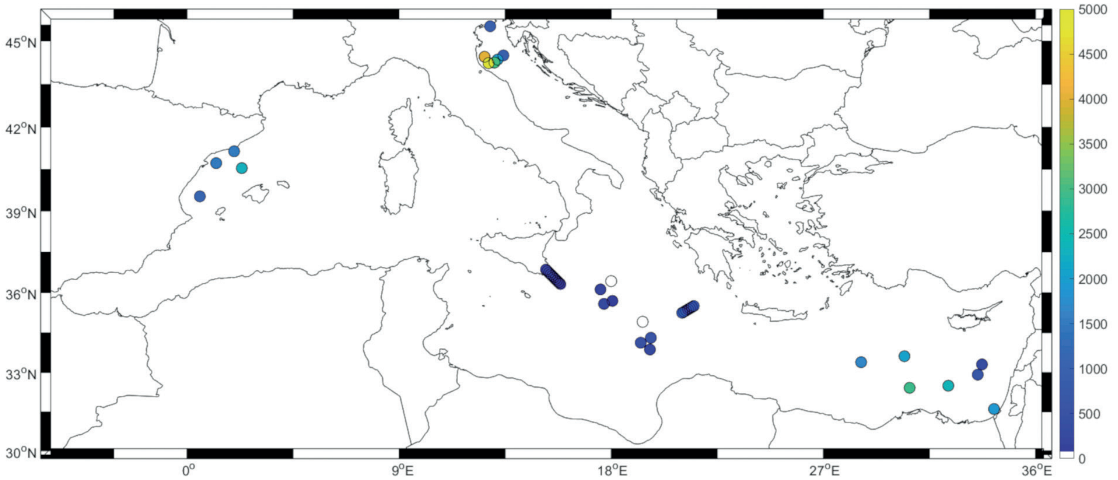

Fig. 5 - Plio-Quaternary sediments thickness derived from interpreted seismic profiles and freely available data set found in literature. Unit is m.

To convert the RGB map into thickness in metres, the next step is the setting of the least squares system, using as observations the thicknesses from the retrieved profiles and data. The assumptions we made to apply the least squares adjustment are:

- the velocity of seismic waves propagation is linearly proportional to the two-way travel time, which can also be considered linearly proportional to the RGB scale values:

$$v \propto 2way\ tt \propto RGB \qquad (1)$$

- the thickness is proportional to the velocity of waves propagation by means of a quadratic relation under the assumption that sediments also follow a quadratic compaction law (Jackson *et al*., 2010):

$$\Delta z = a + b \cdot v + c \cdot v^2 \qquad (2)$$

With such assumptions, the least squares system has:

$$A = \begin{bmatrix} 1 & RGB_1 & RGB_1^2 \\ 1 & RGB_2 & RGB_2^2 \\ \vdots & \vdots & \vdots \\ 1 & RGB_n & RGB_n^2 \end{bmatrix}; \; y = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}; \quad x = \begin{bmatrix} a \\ b \\ c \end{bmatrix}; \qquad (3)$$

where d_i are the thickness values of the observations (Fig. 5), RGB_i are the corresponding values interpolated from the processed RGB thickness map (Fig. 4) and x the map conversion parameters we want to estimate. The solution is given by:

$$\hat{x} = (A^T A)^{-1} A^T y \tag{4}$$

and the final thicknesses are obtained as $\hat{y} = A\hat{x}$.

3. Results

The map of Plio-Quaternary sediments thickness, obtained by solving the least squares system, is presented here together with some considerations on its predicted accuracy.

Once the least squares adjustment is applied, the derived map conversion parameters $\hat{x}$ have been used to estimate the thickness of the Plio-Quaternary sediments on a regular grid all over the Mediterranean Sea area. The thickness map and its relative accuracy (expressed in terms of standard deviation) are presented in Figs. 6 and 7 (see the data in the electronic supplement ES1). To derive the map of the accuracy, we evaluated $\hat{\sigma}^2 = \frac{\left(y - \hat{y}\right)^T \left(y - \hat{y}\right)}{(n - m)}$ from the residuals between the seismic observed thickness and the estimated ones, finding an error with a standard deviation of about 300 m. After that, we computed the covariance matrix of the map conversion parameters (C_{xx}) and applied the covariance propagation law to obtain the error covariance of the final estimated thicknesses ($C_{yy} = A^T C_{xx} A$). The diagonal of C_{yy}, shown in Fig. 7, being derived from the combination with seismic information, represents the expected uncertainty of the Plio-Quaternary sediments thickness.

From Fig. 6, it can be seen that in some areas there are quite large deposits of sediments. In the eastern Mediterranean area, which proves to be one of the most complex and investigated

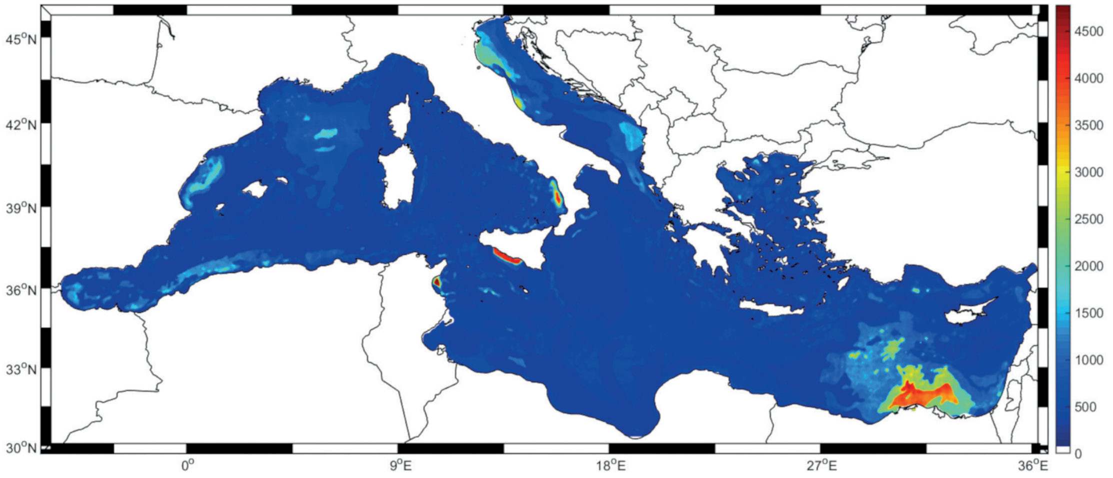

Fig. 6 - Resulting map of thickness of Plio-Quaternary sediments over the Mediterranean Sea region. Unit is m.

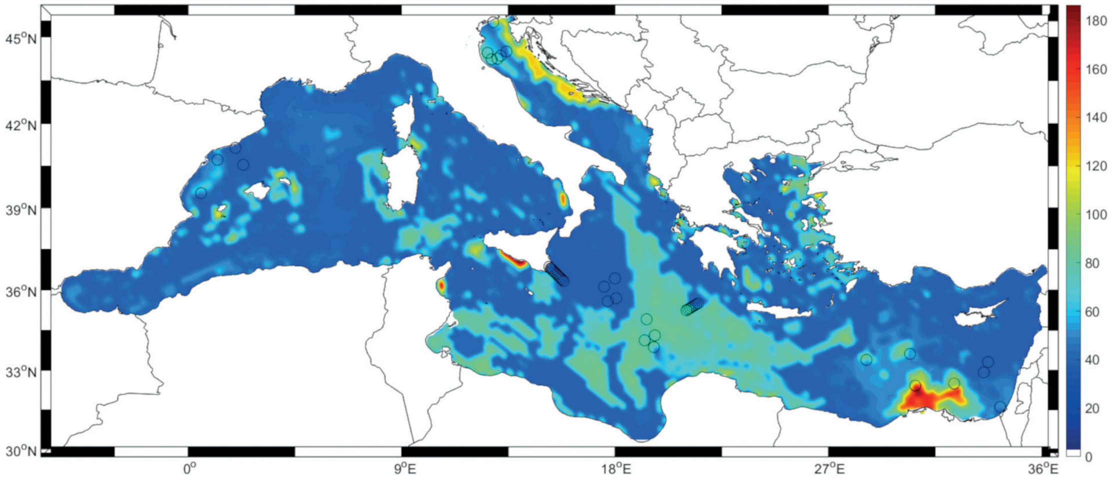

Fig. 7 - Map of accuracy (standard deviation) of Plio-Quaternary sediments thickness over the Mediterranean Sea region derived by the least squares adjustments. Black circles identify the observations. Unit is m; data available in ES1.

regions (Sampietro *et al*., 2018), the thickness reaches maximum values of about 4200 m. This large amount of sediments is due to the presence of the Nile River that has brought them into the Mediterranean Sea over the years. Another important and localised deposit of Plio-Quaternary sediments is located at the foot of the southern coast of Sicily, where its thickness reaches values of about 5000 m, coherently with the geological history of the region (Catalano *et al*., 1996). Note also that in the Adriatic Sea region, and in particular in proximity of the Po River delta, a fairly large slab of sediments is present with thicknesses of about 2500 m. The accuracies of Fig. 7 show a standard deviation ranging from less than 100 m up to about 200 m. This predicted accuracy, as expected, mainly depends from the actual thickness of the Plio-Quaternary sediment pack.

Comparing the estimated thickness with the data from literature, we obtained the residuals shown in Fig. 8. They demonstrate that there is a good agreement between the estimates and the

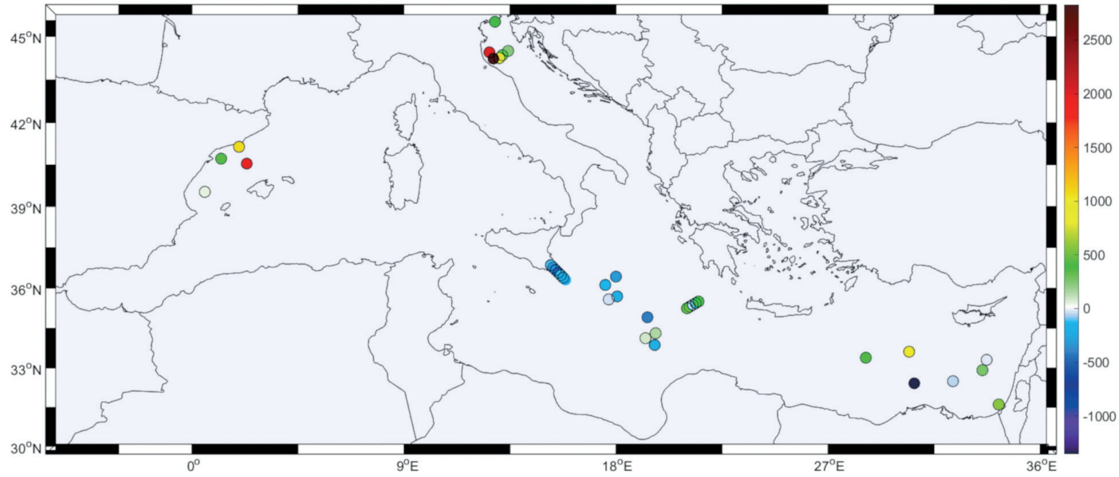

Fig. 8 - Residuals between observed (Fig. 5) and estimated (Fig. 6) thickness of Plio-Quaternary sediments. Unit is m.

observations with 83% of points with values ranging from -500 to 500 m and only 3% of them with absolute differences above 1500 m.

Finally, with the aim of compiling the map of the Plio-Quaternary layer depths (i.e. the depths of the bottom of the layer), we extracted the bathymetry from ETOPO1 model (Amante and Eakins, 2009) on a regular grid with spatial resolution of 1 arc-minute and, after interpolating the Plio-Quaternary thicknesses on the same grid, we derived the depths of the sediments. The resulting map of depths is reported in Fig. 9 (see the data in the electronic supplement ES2).

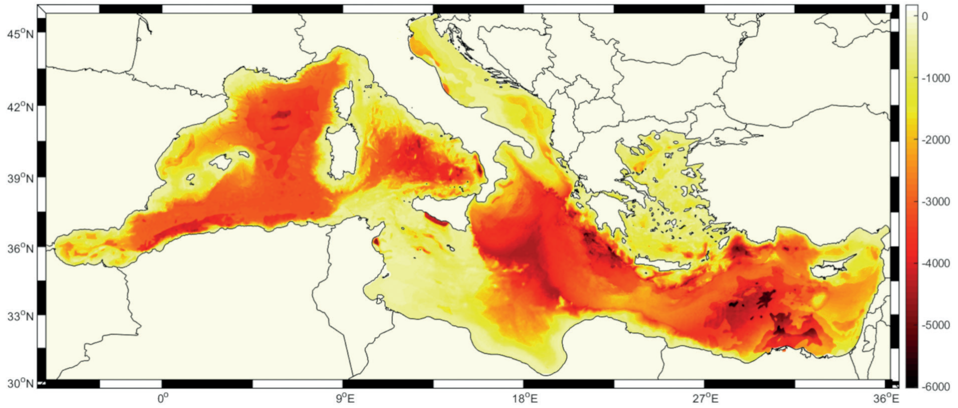

Fig. 9 - Map of depths of Plio-Quaternary sediments over the Mediterranean Sea region obtained from the ETOPO1 bathymetry model and the estimated Plio-Quaternary thickness (Fig. 6). Unit is m; data available in ES2.

4. Gravity field analysis

The last part of this work focused on the analysis of the gravity field due to the Plio-Quaternary sediments layer. First of all, once the top and bottom surfaces delimiting this layer (i.e. the bathymetry from ETOPO1 and the estimated depths map of Fig. 9) were derived, we applied the forward operator to evaluate the effect, in terms of gravity anomalies, of these sediments. We computed the gravity anomalies on a regular grid with spatial resolution of 3 arc-minutes at 5000 m of height. The choice of the grid spatial resolution was mainly prompted by the computational burden time required to apply the forward operator by means of the GTE software. GTE is a tool to compute the gravitational terrain effect based on a hybrid algorithm which combines classical prisms and FFT methods [for more details the interested reader can refer to Sampietro *et al.* (2016)]. Fig. 10 shows the resulting gravity anomalies which are a clear demonstration that this shallow layer, that can reach thickness values of a few kilometres, produces a rather large effect, with values of about -90 mGal at the thickest deposits. This means that for studies related to the interpretation of gravity field data over the Mediterranean area, neglecting this layer can lead to misleading results. Moreover, a proper knowledge of the gravitational effect of the Plio-Quaternary sediments, would allow to enhance other gravity effects due to deeper mass density anomalies. For instance, comparing the result in Fig. 10 with the residual Bouguer anomaly in the Adriatic Sea shown in Braitenberg *et al.* (2013), it is possible to confirm some of the hypotheses made in the paper on the source of the residual Bouguer anomalies, but also to separate the sediments effect from the effects of the lighter crustal material of the overthrusting sequences of the upper Apennine.

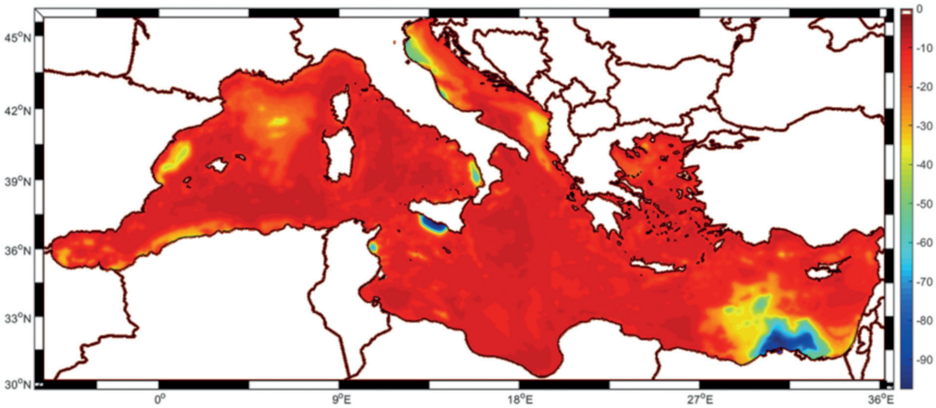

Fig. 10 - Forward modelling of gravity anomalies of the Plio-Quaternary sediments layer on a grid at 5000 m height. Unit is mGal.

We also analysed how the gravity signal, synthesised from a global model [for our study we chose the GECO model (Gilardoni *et al*., 2016)], changes if we reduce it only for the effect of the topography/bathymetry and for the effects of both topography/bathymetry and Plio-Quaternary sediments. The densities assumed for the computation are 2670 kg/m^3 for the topography/bathymetry and 2200 kg/m^3 for the Plio-Quaternary sediments. The two reduced signals on the same grid as before (at 5000 m of height) are presented in Figs. 11 and 12, respectively. In terms of standard deviation of the signals, we find for the former (Fig. 11) a standard deviation of about 67 mGal, while for the latter (Fig. 12) a standard deviation of about 65 mGal. The statistics, even showing a small improvement, are not so different in both cases indicating that to obtain a reduced signal more homogeneous than this one we need to model all the other principal geological units/layers. This is a reasonable result taking into account the complexity, from the geological history point of view, of the Mediterranean Sea region.

Looking at the differences between the two signals and focusing on the eastern Mediterranean area, where the Plio-Quaternary sediments are thicker (zoomed in Fig. 13), we can observe how the signal reduced for both topography/bathymetry and sediments highlights the features of the

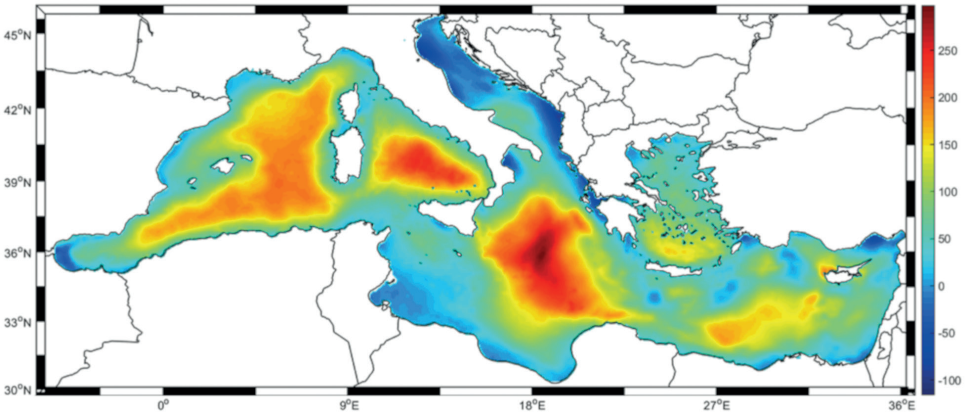

Fig. 11 - Gravity anomalies synthesised from GECO model on a grid at 5000 m height reduced for the effect of topography/bathymetry. Unit is mGal.

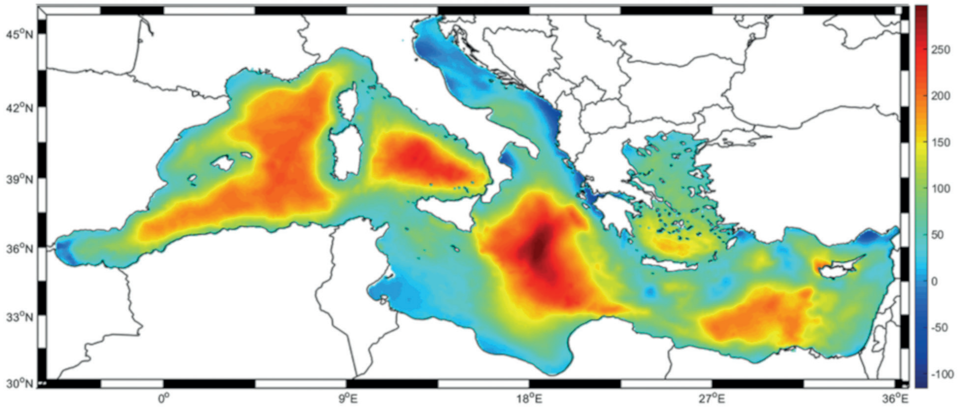

Fig. 12 - Gravity anomalies synthesised from GECO model on a grid at 5000 m height reduced for the effect of topography/bathymetry, and Plio-Quaternary sediments. Unit is mGal.

deeper geological units better. In particular, the positive regions, reflecting the effects of the superposition of the thin and dense oceanic crust and the light sedimentary layers, are locally highlighted such that the Herodotus basin can now be clearly recognised and distinguished from the Levant basin (Sampietro *et al.*, 2018). Note that in Fig. 13 the black lines delimit only the Herodotus and Levant basins in a qualitative way.

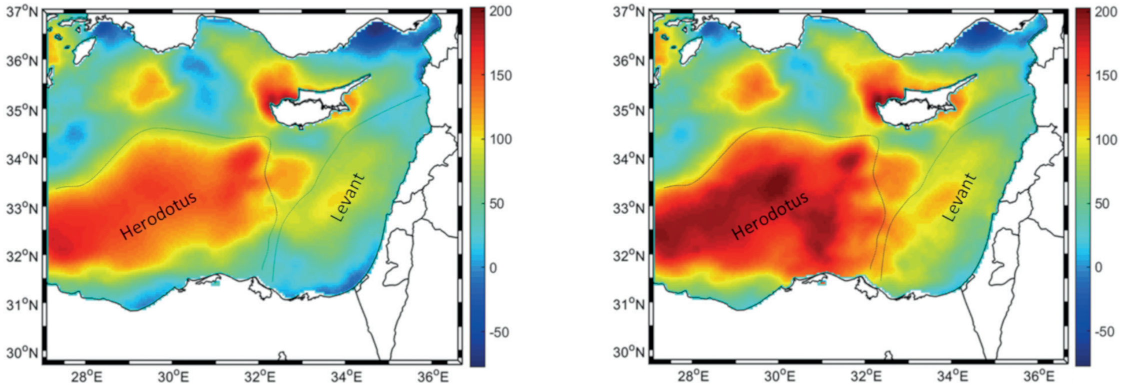

Fig. 13 - Gravity anomalies synthesised from GECO model on a grid at 5000 m height in the eastern Mediterranean region reduced for the effect of topography/bathymetry only (on the left) and for topography/bathymetry and Plio-Quaternary sediments (on the right). Black lines delimit in a qualitative way the Herodotus and Levant basins. Unit is mGal.

Considering instead the Adriatic Sea region, shown in Fig. 14, we can readily note how the signal becomes more uniform, as a demonstration that we have improved the modelling of the shallowest layers, enhancing the effects of deeper structures. This results in a reduced standard deviation of the signal that goes from 40 mGal (in case of reduction for topography/bathymetry only) to 34 mGal (in case of reduction for both topography/bathymetry and sediments).

Both these regional cases confirm the importance in gravity field interpretation of modelling these sediments when dealing with geophysical regional/local studies.

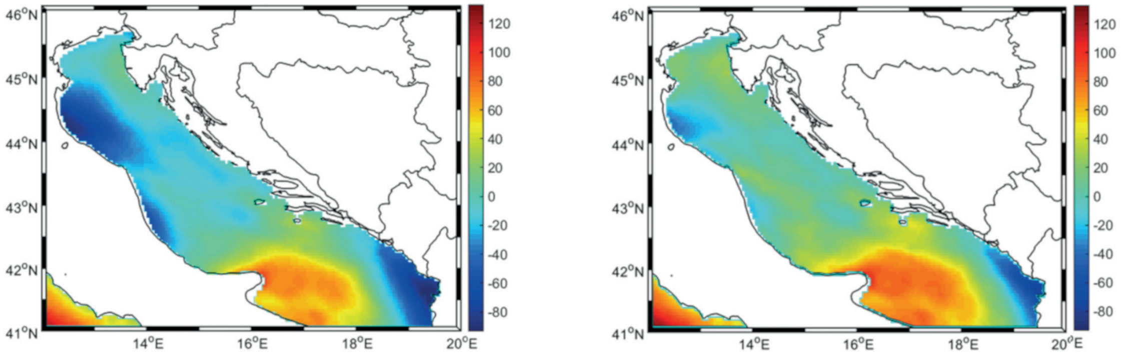

Fig. 14 - Gravity anomalies synthesised from GECO model on a grid at 5000 m height in the Adriatic Sea region reduced for the effect of topography/bathymetry only (on the left) and for topography/bathymetry and Plio-Quaternary sediments (on the right). Unit is mGal.

5. Conclusions

The importance of the Mediterranean Sea for the understanding of plate tectonics is undeniable and even today the study of this region provides valuable information about current displacements between the European and African plates. In its geological history, the Mediterranean Sea has been subjected to extremely different "stress" conditions that have led to the formations of basins made up of different geological units. The shallowest layer of sediments, which can be directly investigated by using seismic techniques, is referred to as the Plio-Quaternary sediments layer. In the late 1990s, by collecting all the data obtained from seismic surveys, a first map of thickness of this layer was produced and made freely available to the scientific community.

In this work, our starting point was the IBCM-PQ thickness map, expressed in two-way travel times, which we digitalised, cleaned, and filtered. The pre-processing operations were necessary to apply a least squares procedure aimed at converting the map into units of length (metres) and producing an equivalent map of depths. To do so, we explored from literature the freely available data (interpreted seismic profiles or wells data) and used them to estimate the map conversion parameters. The resulting converted thickness map shows that, especially near the most important river deltas (i.e. the Nile and Po rivers), the thickness can reach values of about a few kilometres; but other important deposits can also be found in the western Mediterranean area as well as close to Sicily. The estimated thickness map has an accuracy ranging from less than 100 m up to about 200 m.

Once the upper and lower limits of the Plio-Quaternary sediments layer are defined, i.e. the bathymetry and the estimated depths respectively, we performed an analysis in terms of gravity field to evaluate the importance of this geological unit. By simply applying the forward operator in terms of gravity anomalies we found, as expected, a signal over a grid at 5000 m height, of about -90 mGal near to the thicker deposits of sediments. We, therefore, decided to also analyse how the gravity signal changes if we reduce it only for the topography/bathymetry or for both topography/bathymetry and Plio-Quaternary sediments. The reduced signals show different features in particular over the regions where the sediment deposits have a thickness of 1 km or more. Analysing the standard deviations of the two reduced signals, a small improvement is found if we consider the whole Mediterranean region, since the standard deviation decreases from 67 to 65 mGal. A larger improvement (more than 10%) is obtained if we consider local regions such as the Adriatic Sea, where the standard deviation goes from 40 to 34 mGal. Both results prove the importance of a proper reduction for the Plio-Quaternary sediments for geodetic/geophysical studies in the Mediterranean area by exploiting gravity observations.

Supplementary material related to this article is available online at the BGTA website www.bgta.eu.

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