MAIN RESULTS OF MARINE GRAVITY AND MAGNETIC RESEARCHES CARRIED OUT AT THE NATIONAL RESEARCH & DEVELOPMENT INSTITUTE FOR MARINE GEOLOGY AND GEOECOLOGY

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Abstract. Since the resume in 2005 of the systematic geophysical and geo-ecological investigation of the Romanian offshore, over 13,400 km of gravity lines and over 48,000 km of magnetic lines have been acquired on the entire surface of the Romanian maritime space and over most of the Bulgarian one. Based on this data numerous maps of the gravity and magnetic anomalies, at scales ranging from regional to the highest detail, have been compiled. If prior to 1990, marine gravity and magnetic researches were exclusively used for the study of the Romanian continental shelf deep geological structure and for the assessment of its hydrocarbon potential, the latter researches has expanded the range of topics addressed: deciphering of also near surface structures, marine site characterization, geo-archaeology, environmental geophysics, detection of submerged objects, maritime space security. Mainly during the last years, an increasing involvement of marine magnetometry in projects dedicated to the study of the submarine cultural heritage and to enhancement of maritime space safety is noticed. The present results and findings due to marine magnetometry go far beyond all initial expectations.

Key words: Black Sea, gravity, magnetics, mapping, interpretation, modelling

1. INTRODUCTION: A HISTORICAL REVIEW OF THE GRAVITY AND MAGNETIC INVESTIGATIONS ON THE ROMANIAN OFFSHORE

Carried out in the early '70s, the first gravity and magnetic mappings of the Black Sea led to the first geophysical maps which depict the regional morphology of the gravity (Goncharov *et al.*, 1972) and magnetic (Ross *et al.*, 1974) fields over the maritime basin, but lack of information regarding the Romanian maritime space. The gravity and magnetic survey of the Romanian offshore have been carried out during three main phases: the first one during 1969-1970, the later one between 1980 and 1990, both prior to the establishment in 1993 of GeoEcoMar institute and the last one starting from 2003 until present.

The first magnetic mapping of the Romanian offshore was carried out in 1969-1970 (Romanescu *et al.*, 1972) and has allowed to obtain the first map of the total magnetic field anomaly (Fig. 1) and later to elaborate the first structural model of the offshore crystalline basement (Romanescu *et al.*, 1975).

Starting from 1980 the second phase of the survey, consisting this time of both marine gravity and magnetic mappings, begun. The first marine gravity researches have been carried out with GD-K sea-bottom gravity meters made in former USSR. These measurements continued until 1985 (Sava, 2000) and covered with around 140 sea-bottom gravity stations a marine sector with water depths ranging from 10 to 40 m (Fig. 2), bordered northwardly and southwardly respectively by the latitudes of Periboina[1] and Cape Tuzla.

[1] Discharging mouth of Sinoie lake in the Black Sea.

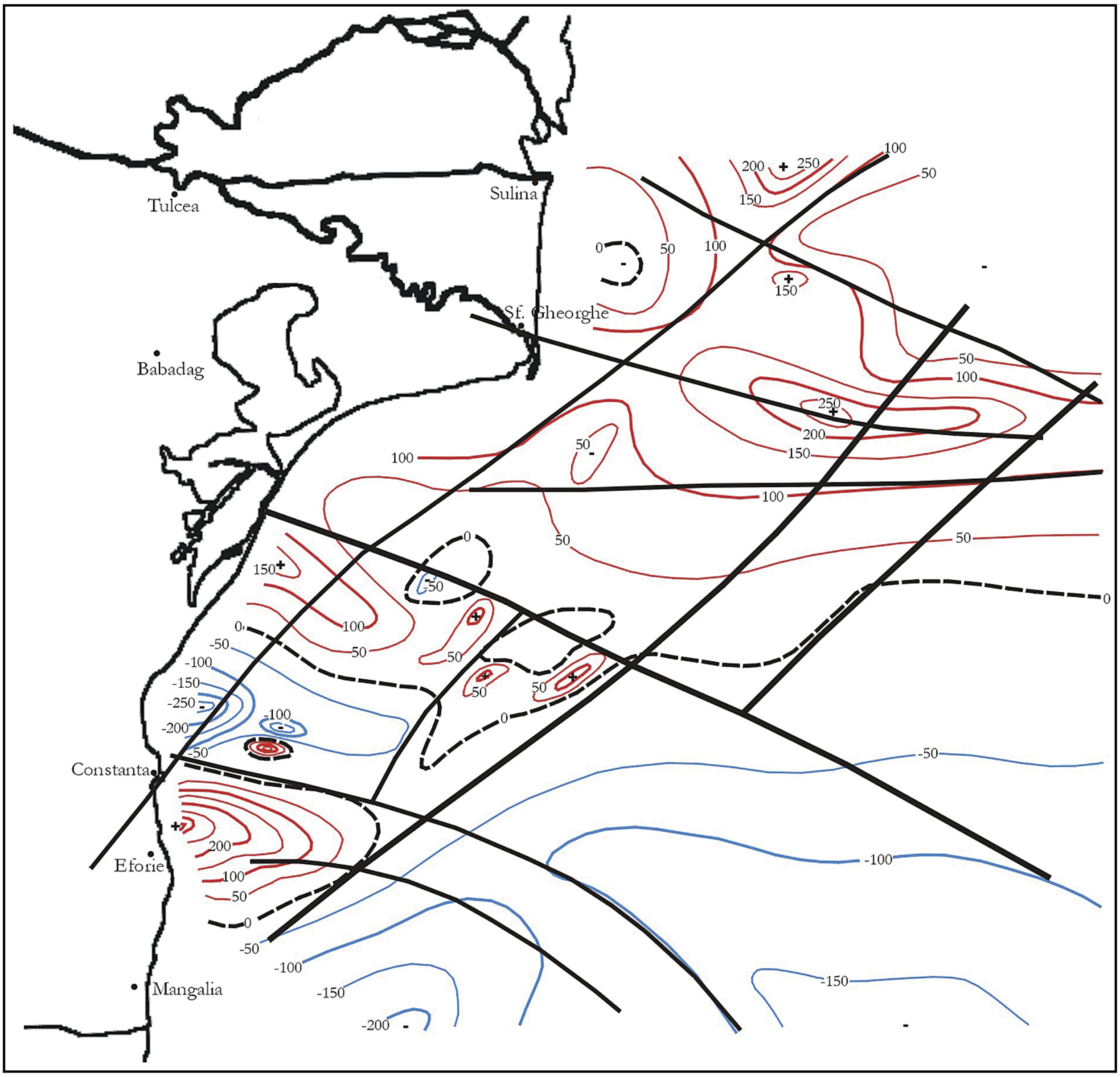


Fig. 1. Map of the total magnetic field and the structural sketch of the Romanian continental shelf. Positive and negative magnetic anomalies are depicted respectively in red and blue (compiled from Romanescu *et al.*, 1972, 1975)

In 1980 also begun the systematic magnetic mapping of the continental shelf based until 1983 on an original methodology, according to which terrestrial proton magnetometers, whose sensors were mounted on the mast of a fiberglass towed boat, have been used (Sava, 2000) to acquire around 3,850 km of magnetic lines within a sector covered by sea with water depth up to 50 m (Fig. 2).

Starting from 1984 marine onboard gravity meter systems, model GMN-K, also made in former USSR, were used (e.g. Sava *et al.*, 1994, Sava, 2000) to map most of the Romanian continental shelf (Fig. 3). Until 1990, over 24,200 km of marine gravity lines have been acquired. Also, between 1985 and 1990 a marine proton magnetometer, with towed sensor, made in the former Institute of Geology and Geophysics was used (Sava *et al.*, 1994, Sava, 2000) to cover almost the entire Romanian continental shelf (Fig. 3). Over 10,000 km of marine magnetic lines were acquired during those years. Unfortunately, very few[2] of this most valuable raw geophysical data, although still exist on paper was transferred until present on digital format and included in the modern DPA[3] databases which are operational today at GeoEcoMar institute.

[2] All near shore, sea-bottom gravity stations and around 2100 km of magnetic lines acquired with the methodology based on the use of the towed, fiberglass boat were transferred on digital support. All remaining raw geophysical data is still on paper records.

[3] DPA – Data Processing and Analysis.

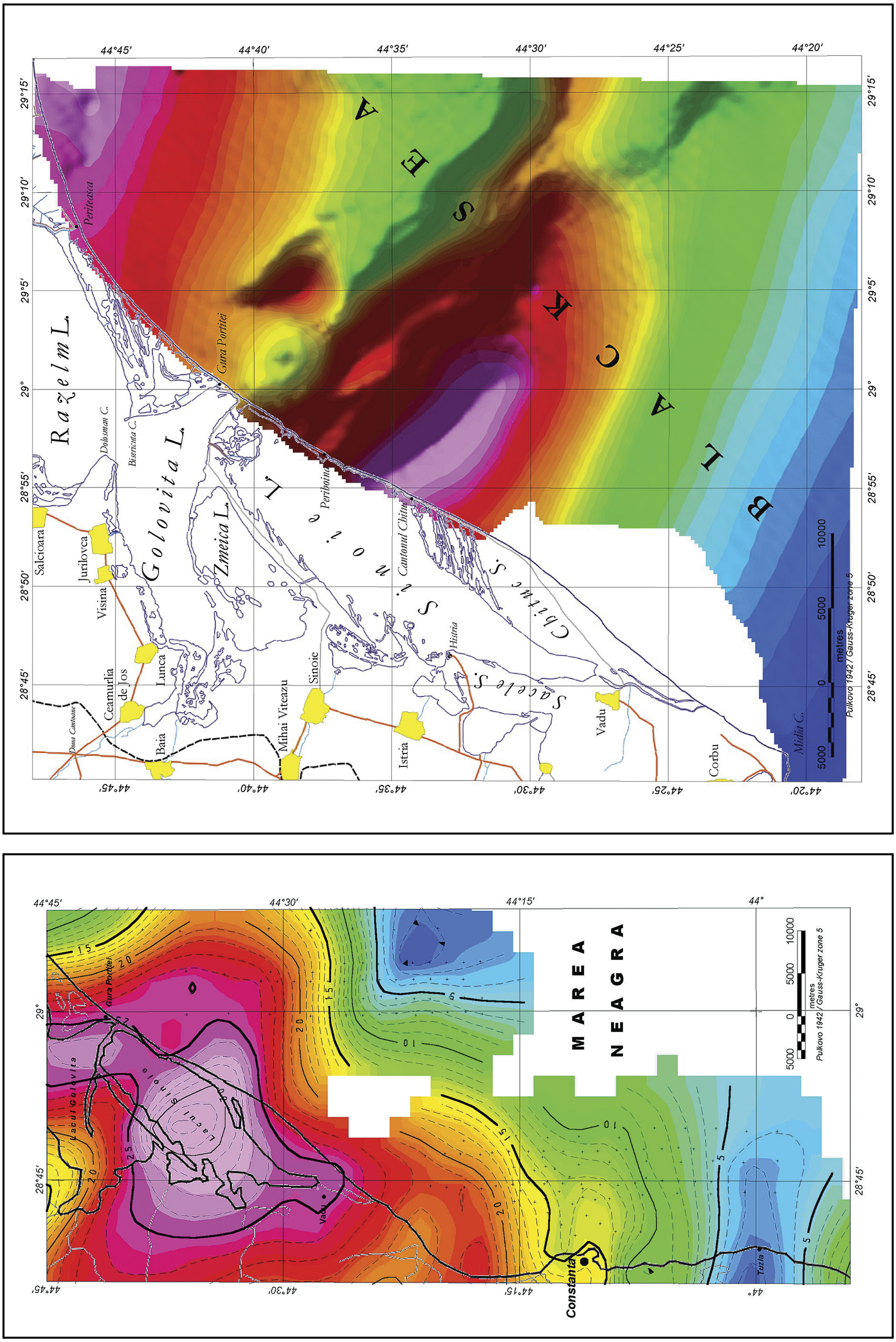
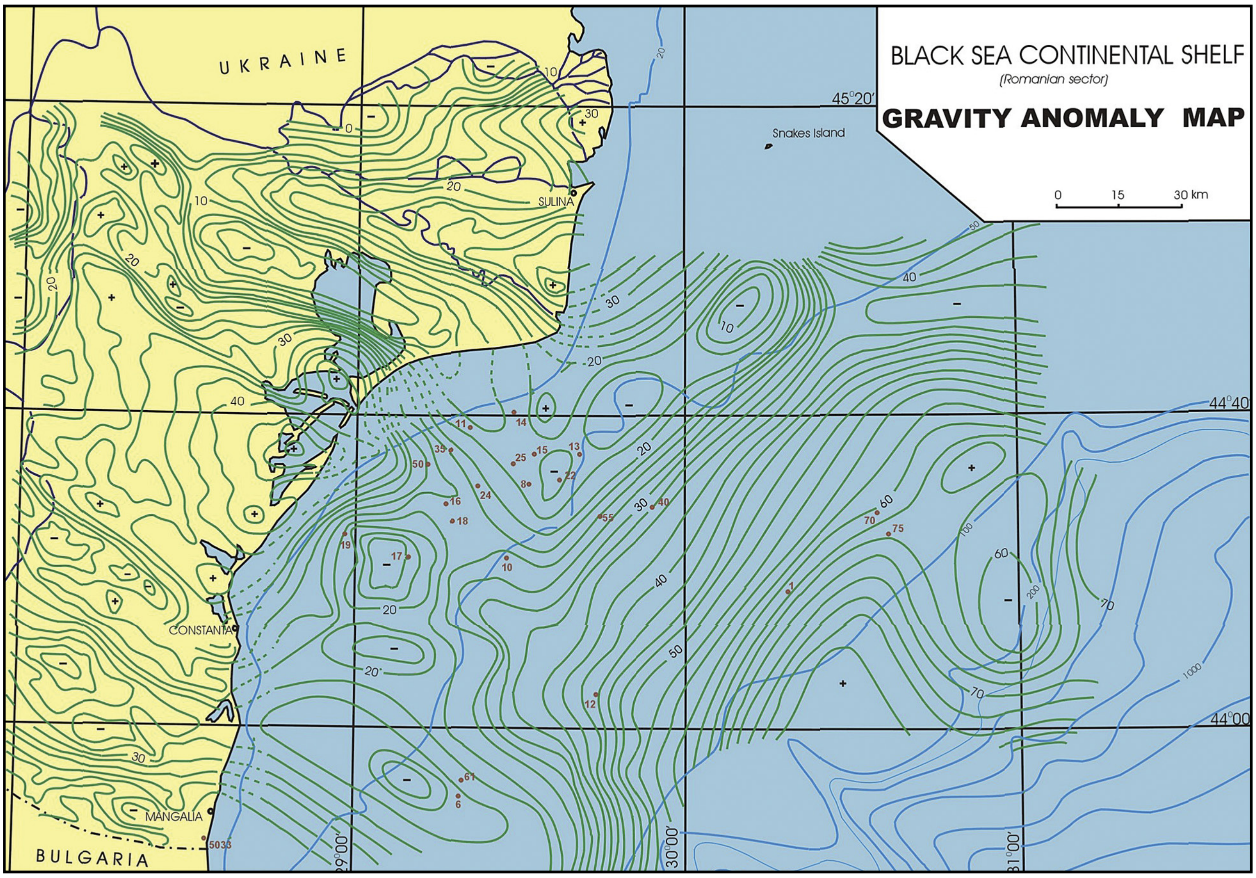


Fig. 2. Maps of Bouguer gravity anomaly of Gura Portița – Cape Tuzla littoral sector (left) and of the magnetic anomaly of Perișor – Cape Midia littoral sector (right) (from Dimitriu, 2001)



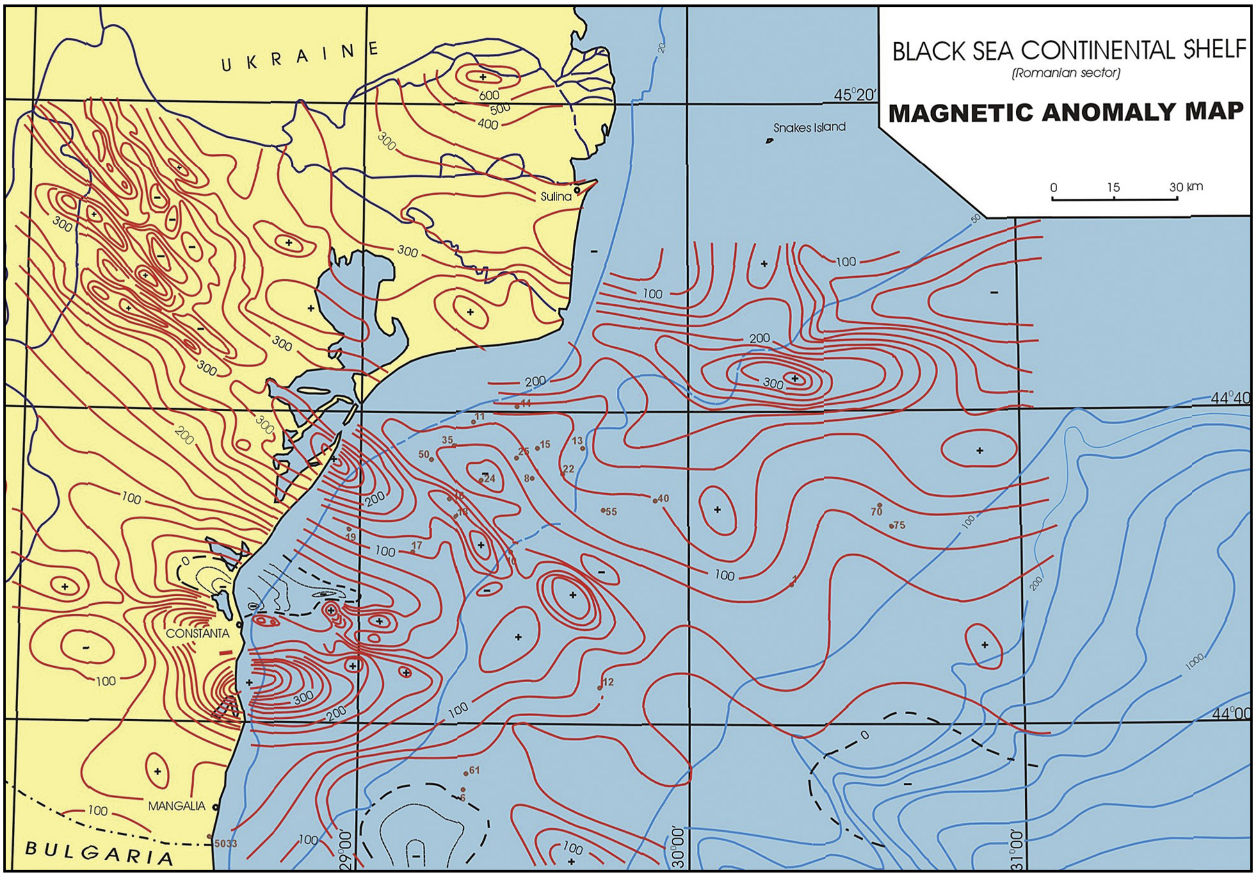


Fig. 3. Maps of Bouguer gravity anomaly (top) and total magnetic field (bottom) anomalies (after Sava *et al.*, 1994)

A feature that characterizes the first two phases of the geophysical investigation of the marine domain was the lack of coverage with raw data within the land-to-sea transition zone, which is drowned by lagoon and sea shallow waters. During the decade of the '90s, when Romania was subject of a gloomy and painful transition, most of the geophysical researches were only possible within the southern Danube delta and Razelm-Sinoie lagoon complex. Fortunately, during those years most of the hybrid research methodologies, namely meant to grant access and good coverage of the land-to-sea transition zone, were developed and will be extensively used in the next years.

The third phase of the complex, geophysical investigation of the entire Romanian maritime space started approximately in 2005 and continue now-a-days. It also consists of both marine gravity and magnetic researches, carried out until recently with the old marine GMN-K and GMN-KM[4] onboard gravity meters and respectively with state-of-the-art marine proton precession, G-877 model and from 2015 with Cesium vapor, G-882 model magnetometers, produced in USA by Geometrics company.

Since 2003 have been acquired over 13,400 km of marine gravity lines, all during 2011-2012, within the CBC project MARINEGEOHAZARD[5] and over 48,000 km of marine magnetic lines, within the multiple research projects and services contracts of GeoEcoMar institute (Fig. 4).

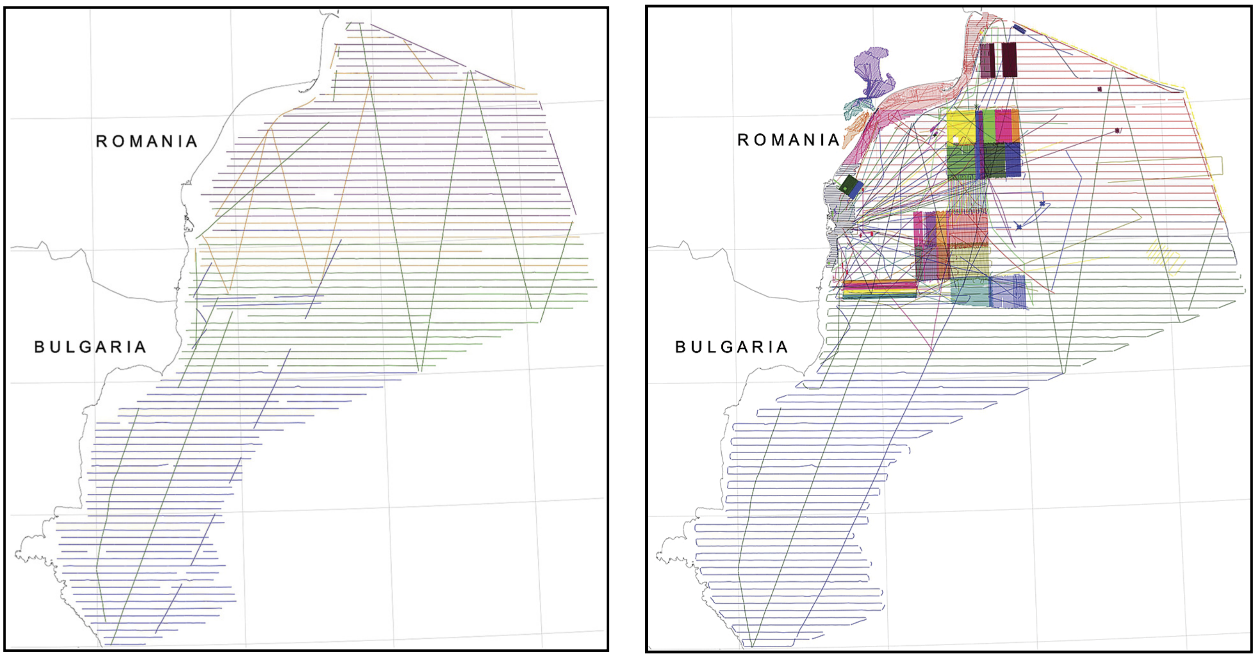


Fig. 4. Maps of marine gravity lines network (left) acquired during 2011-2012 and of marine magnetic lines network (right) acquired since 2003 on the Romanian & Bulgarian offshore

The network of geophysical lines acquired since 2003 is covering the entire Romanian offshore, most of the Bulgarian one and, for the first time, extended sectors of the Romanian littoral shallow waters (magnetometry only) and of lagoons.

2. MAIN TASKS OF THE MARINE GRAVITY AND MAGNETIC INVESTIGATIONS

Before 1990 the marine gravity and magnetic surveys were almost exclusively focused on the deciphering of the Romanian continental shelf's deep geological structure and the assessment of its hydrocarbon potential. After the establishment in 1993 of GeoEcoMar institute and after the resuming in 2003 of the systematic research activities within the land-to-sea and maritime domains, the marine gravimetry and especially the marine magnetometry have been successfully involved in a wide variety of new research fields: the deciphering of near surface structures, site characterization, geo-archaeology, environmental geophysics, detection of submerged objects (pipes, anchors, chains, shipwrecks, UXO[6], USO[7], etc.).

The main tasks for which the marine gravity and magnetics had to involve have been: (a) – the systematic mapping of the Romanian offshore, (b) – the research and service contracts

[4] GMN-KM represent the GMN-K onboard gravity meter system modernized in 1990 by the Russian meters manufacturer.

[5] MARINEGEOHAZARD project: Set-up and implementation of key core components of a regional early-warning system for marine geohazards of risk to the Romanian-Bulgarian Black Sea coastal area (http://www.geohazard-blacksea.eu)

[6] UXO: **U**n-e**X**ploded **O**rdnance.

[7] USO – **U**nidentified **S**ubmerged **O**bjects.

with offshore operators, (c) – the study of submarine cultural heritage and (d) - the maritime space security enhancement.

2.1. Systematic mapping of the Romanian offshore

This long-term process, which began decades ago, took place until 1990 at the recognition (1:500,000) and regional (1:200,000) scales. Starting from 1990 it was carried out on the detail scale (1:50,000). Following the implementation of the cross-border-cooperation project MARINEGEOHAZARD, the geoscientists of GeoEcoMar institute were able to cover in 2011-2012 the entire maritime space of Romania and most of the Bulgarian one with a network of complex geophysical lines, 4 km apart one from the other. In Fig. 5 and 6 there are presented (Dimitriu *et al.*, 2016-a) respectively the composite maps of gravity anomaly (Bouguer gravity onshore, free air gravity offshore) and of the magnetic anomaly (total geomagnetic field) of the western Black Sea continental margin (Romanian and Bulgarian sector).

Multiple studies at scales ranging from regional to high detail have covered distinct sectors of the offshore and nearshore, depending on the specific interests and goals aimed. In Fig. 7 are presented for instance maps of the gravity and magnetic anomalies for an offshore area comprising

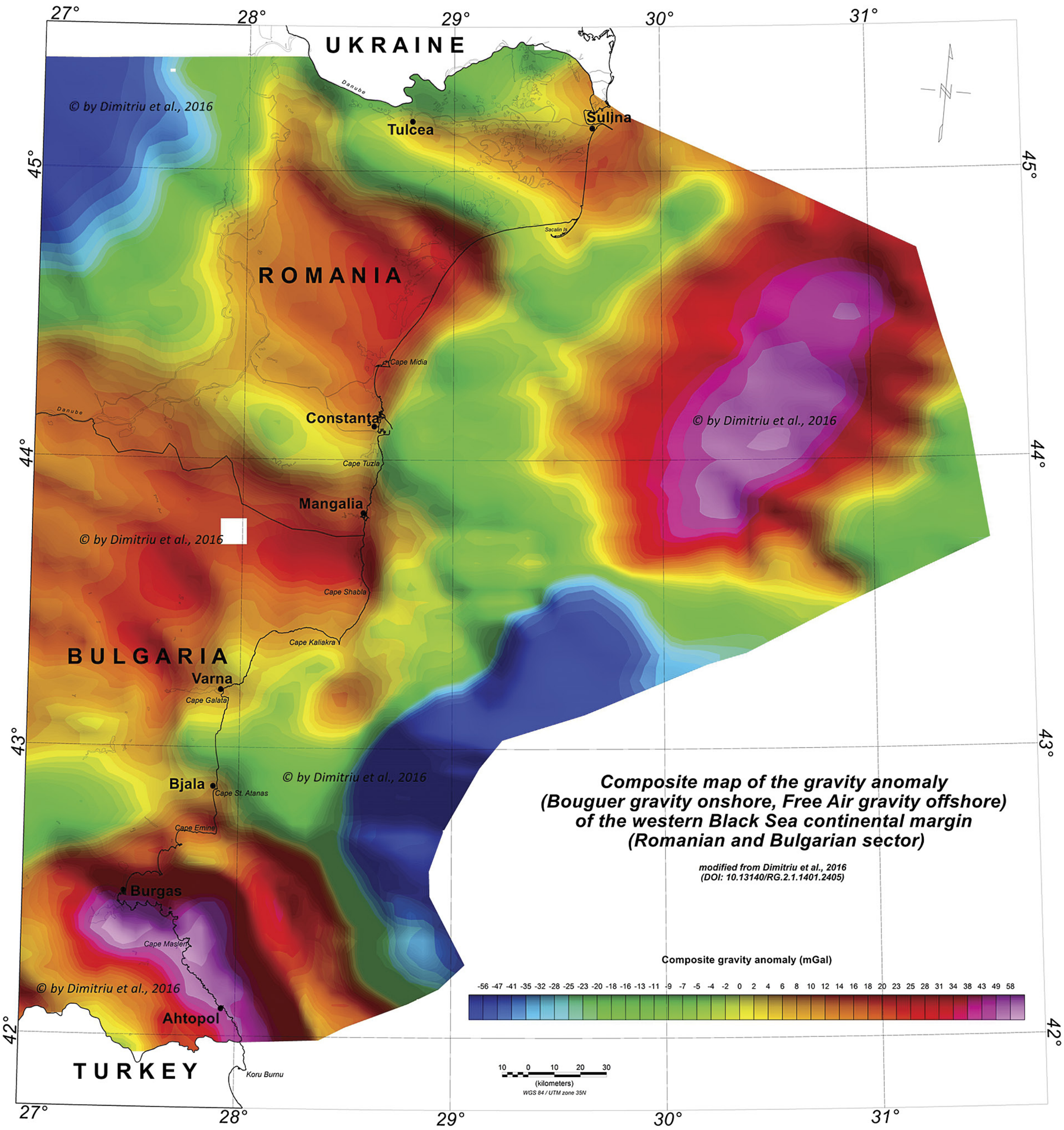


Fig. 5. Composite map of the regional gravity anomaly (modified from Dimitriu *et al.*, 2016-a)

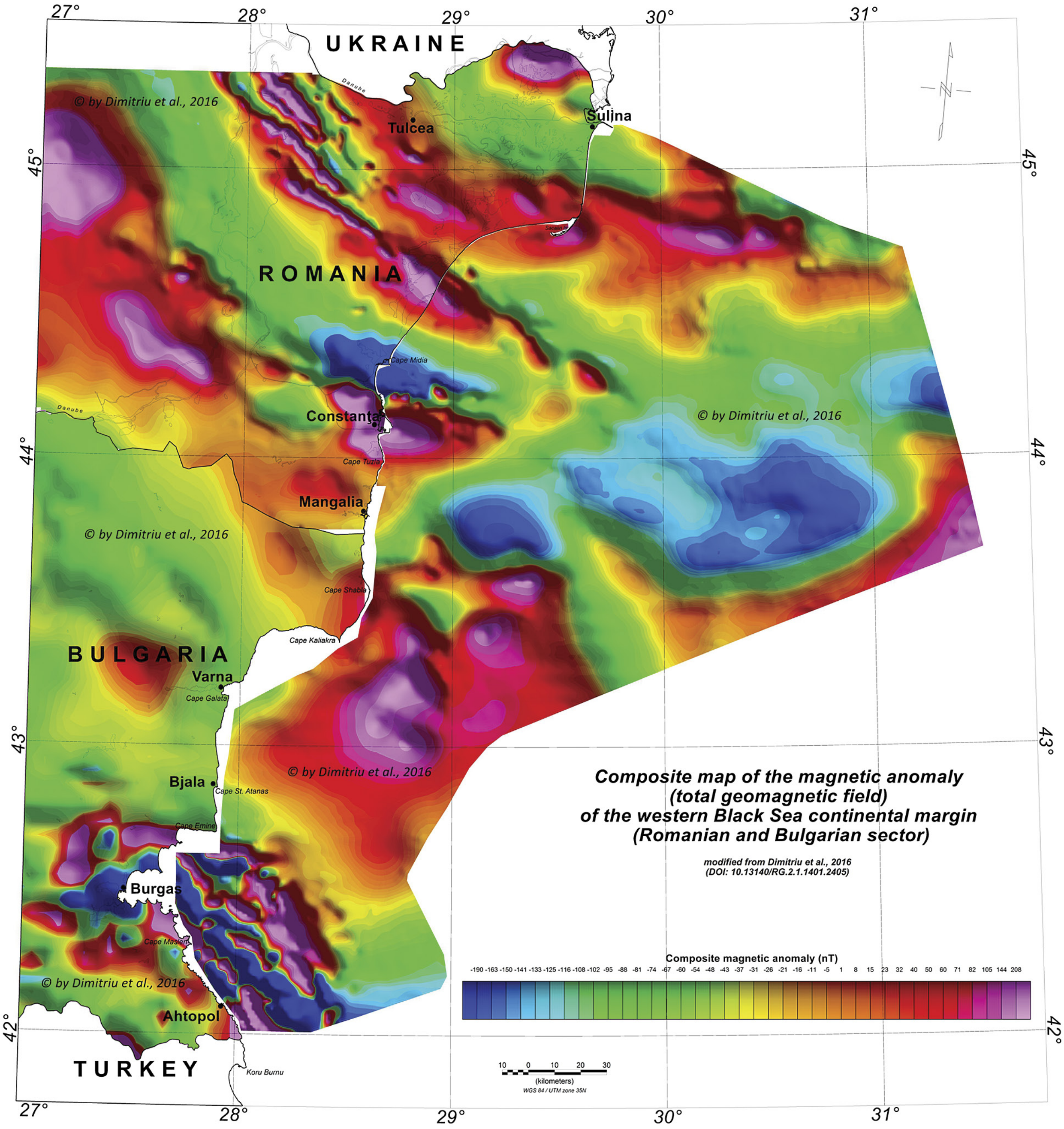
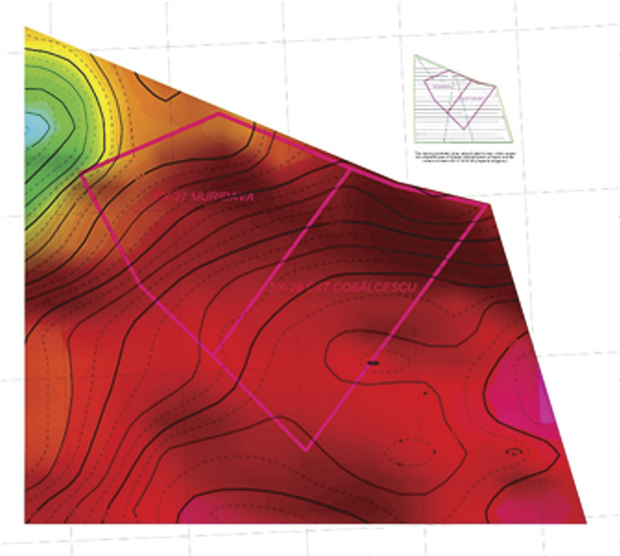


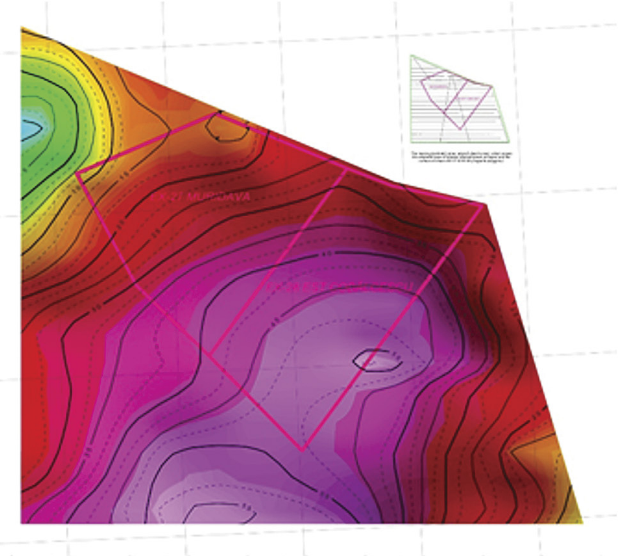
Fig. 6. Composite map of the regional magnetic anomaly (modified from Dimitriu *et al.*, 2016-a)

Muridava and East Cobălcescu blocks, namely elaborated (Dimitriu *et al.*, 2016-b) for the oil company interested in assessing the hydrocarbon perspective of an elevated structure of interest discovered by 3D seismics in the deep.

During 2005-2006 most of the marine shallow waters, located off Danube delta, have been covered by a dense network of geophysical lines. Fig. 8 depicts the map of the total magnetic field anomaly corresponding to that elongated littoral sector totally lacked of geophysical information until that time.

The systematic geophysical mapping of the Romanian offshore resumed in 2005, with the start of R/V *Mare Nigrum*'s activity, produced numerous thematic maps, at scale of 1:50,000. In Fig. 9 is presented the magnetic anomaly map corresponding to map sheets L-35-132-A & C, which perfectly illustrates the presence on the investigated surface and the combination of magnetic effects, with very different wavelengths, due to sources located at deep depths in the crust, as well as within the shallow sedimentary cover.





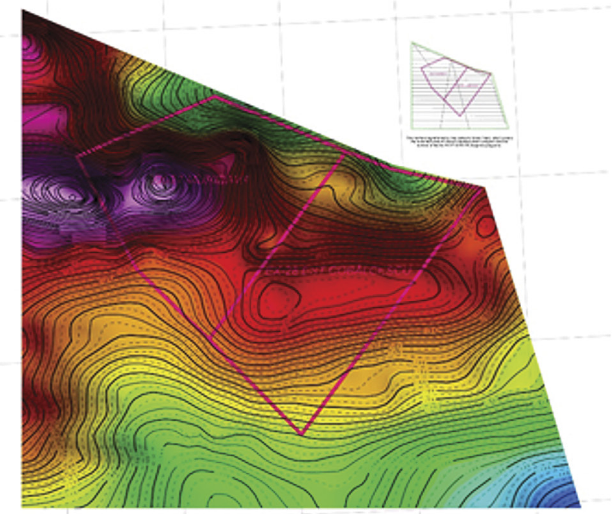


Fig. 7. Maps of Bouguer gravity anomaly (top, left), of free air gravity anomaly (top, right) and of total magnetic field (right) for the offshore area comprising Muridava and East Cobălcescu blocks (modified after Dimitriu *et al.*, 2016-b)

Based on the integrated interpretation of gravity and magnetic information resulted from these researches and mappings, the geotectonic frame of the western Black Sea continental margin was inferred (Fig. 10), as well as its deep geological structure (Dimitriu *et al.*, 2004, 2009). The presence on the offshore of three main fault systems is well depicted.

The **Primary Fault System**, of pre-Albian age, generally trends NW-SE and gathers all major faults that existed prior to the opening of western Black Sea basin. It includes major strike-slip faults, normal faults and reverse faults which divide the crust into a series of horst and grabens: *Sulina-Tarkhankut Fault, a* reverse fault which represents the contact between the Scythian Platform (Pre-Dobrogea Depression) and the North Dobrogea Folded Belt; *Sfântu Gheorghe (=Văcăreni-Agighiol) Fault*, a strike-slip fault which separates within North Dobrogea Folded Belt two types of pre-Triassic (Hercynian) basement, corresponding to Măcin and Tulcea Units; *Peceneaga-Camena Fault*, a strike-slip crustal fault that separates the North Dobrogea Folded Belt from the Moesian Platform; *Ostrov-Sinoie Fault* represents the southern border of an uplifted block of the Moesian crystalline basement; *Capidava-Ovidiu Fault* separates within the Moesian Platform, the Central Dobrogea horst from the Southern Dobrogea and the *Intramoesian Fault* which separates the Wallachian and Dobrogean Sectors of the Moesian Platform.

The **Secondary Faults System** of Albian-Oligocene age, generally trends NE-SW and gathers extensional faults directly related to the opening of the Black Sea basin. The extensional tectonics also lead to the formation of a half-graben structure on the northern flank of *Peceneaga-Camena crustal Fault*, well-known as *Histria Depression* which is prolonging onshore with the *Babadag Syncline*. Histria Depression is bordered towards mainland by a major structural feature, the *"Euxinian Threshold"*, which represents a continental paleo-slope developed during the Upper Eocene, bordering an area in which the Paleogene deposits are intensively subsiding (Ionescu, 2000).

The **Tertiary Fault System**, of Miocene-Pleistocene age, generally trends NE-SW and gathers extensional faults of different types: gravity slide, shale diapir, reversed due to gravitational expansion, etc., some of them being pre-Oligocene, reactivated faults.

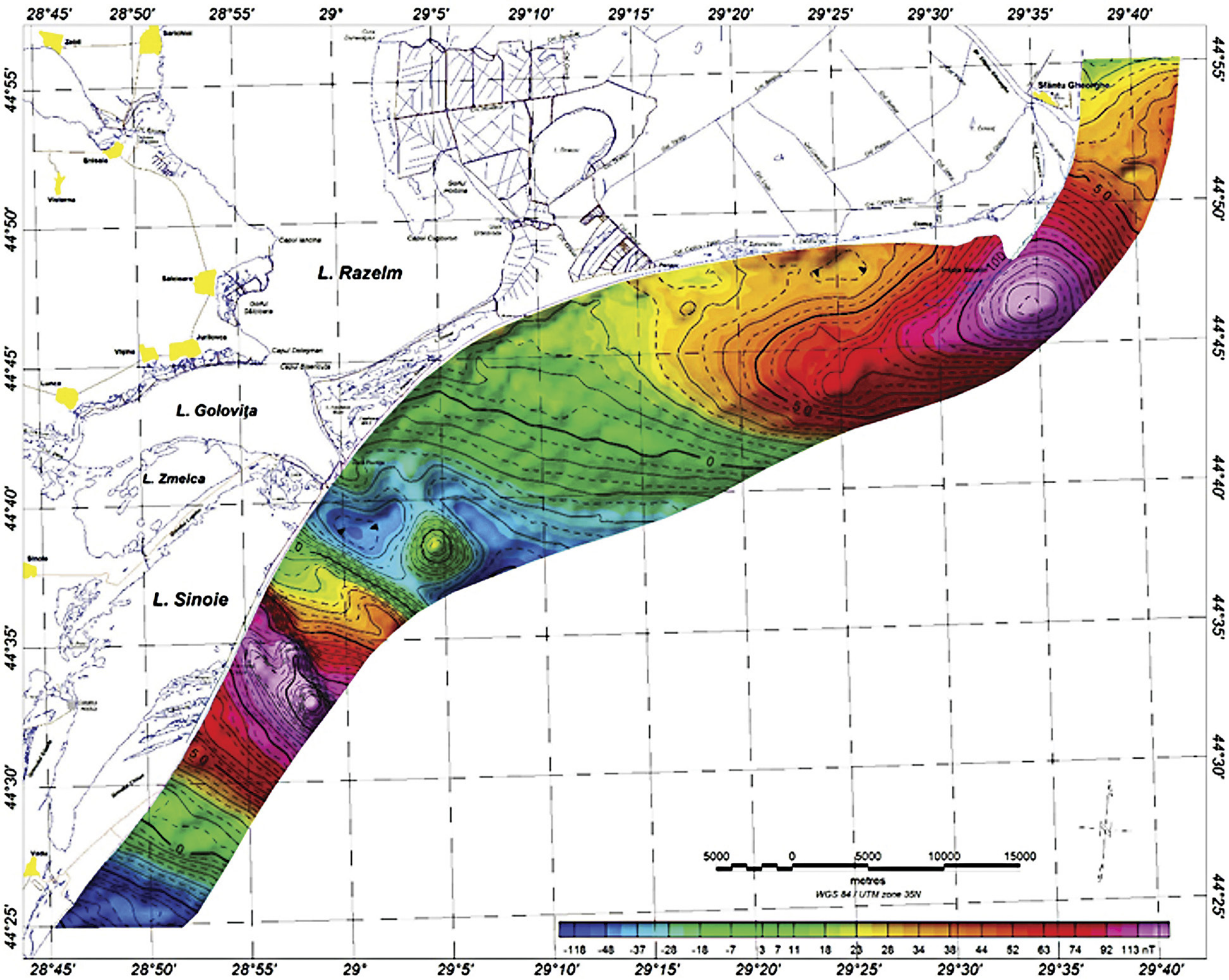


Fig. 8. The map of the magnetic anomaly of Sfântu Gheorghe-Vadu littoral sector

The 2¾D models of the deep geological structure built up at regional scale (Fig. 11), based on gravity and magnetic data, but integrating seismic and well drilling data, clearly illustrates the lithological composition of the Earth crust bellow the maritime space, as well as the gradual transition from the continental-type crust, 30-35 km thick on the dryland, to oceanic-type crust, 10-12 km thick on the inner sector of the basin (Dimitriu *et al.*, 2009). Such models of the deep geological structure, based on the gravity and magnetic data, have also been elaborated for oil companies operating on the Romanian offshore. Fig. 12 depicts two 2¾D models, built up (Dimitriu *et al.*, 2016-b) at regional and detail scales, of an uplifted structure found by 3D marine seismics in the deep of Muridava and East Cobălcescu blocks. The potential data interpretation and modelling was requested to determine whether the investigated structure corresponds to an intrusion, a reef or is only a tilted tectonic block. At the end of the study, it was concluded that the uplifted structure corresponds to a fault-delineated tectonic block, strongly rotated, consisting of less dense Palaeozoic sedimentary deposits, approximately 5.5 km thick, bellow which, within the crystalline basement, Hercynian intrusive bodies are placed.

2.2. Research contracts with offshore operators

Marine magnetometry was also requested during the last 10-15 years by the most important companies that operate on the Romanian offshore (e.g. Petromar SA, OMV-Petrom, Prospecțiuni SA, Sterling Energy plc, Paladin Resources plc, Melrose Resources plc, Petroceltic International plc, etc.) for the accurate identification of pipelines paths, for finding lost objects and tools (anchors, chains, corers, penetrometers, etc.), for the complex site characterization of locations where drilling rigs, pipelines, oil terminals were to be deployed, etc. Magnetometry is in particular extremely effective in tracking the real route of submarine pipelines and cables, even when these are buried in sediments, which makes their detection by most acoustic methods (e.g. side-scan sonar, scanning sonar, multibeam bathymetry, etc.) difficult or uncertain. In Fig. 13 we notice that the real routes of the oil and gas pipelines pinpointed by magnetics may differ quite substantially from those depicted on the official navigation charts or on hydrocarbon exploitation maps.

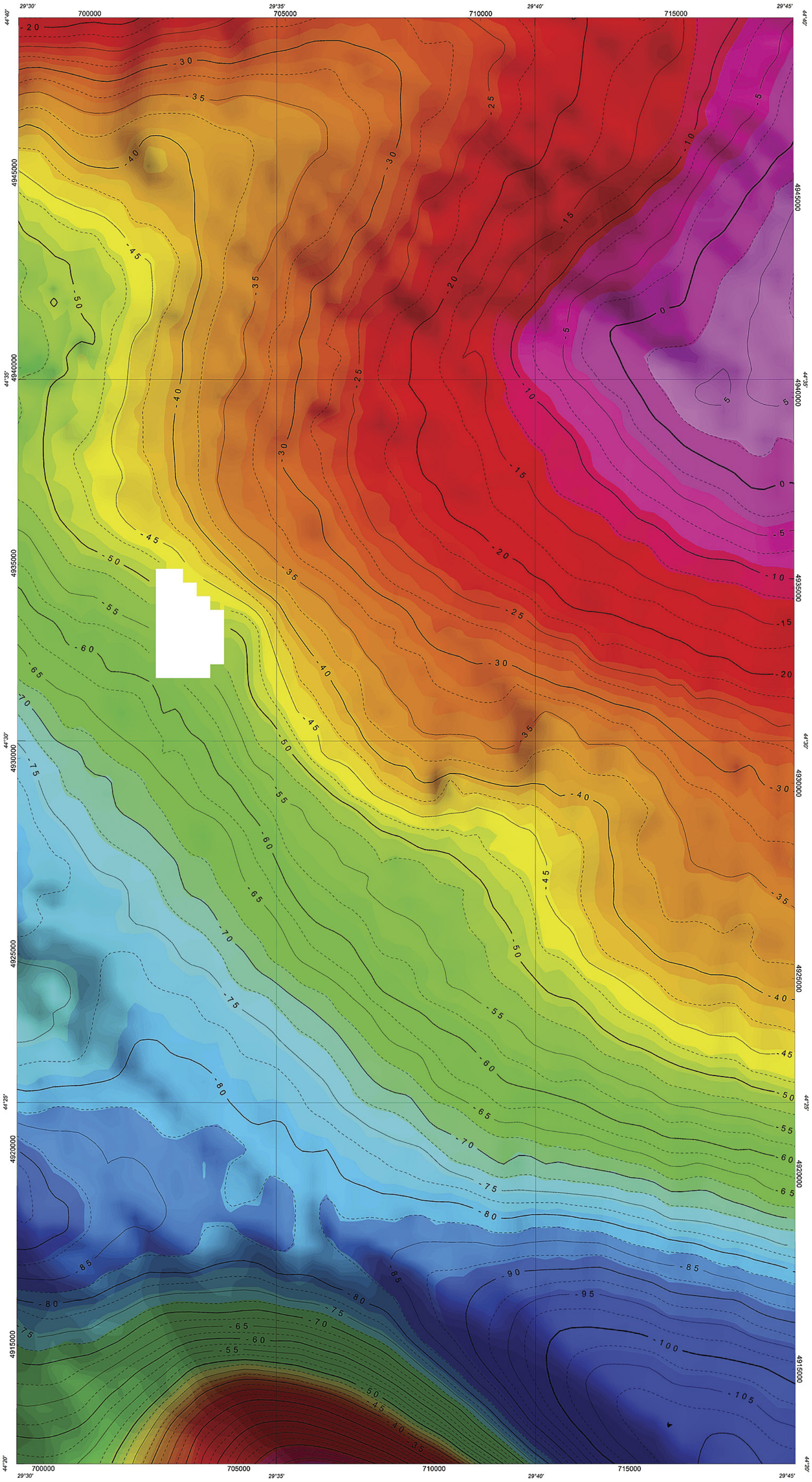


Fig. 9. Map of the total magnetic field anomaly of 1:50,000 scale map sheets L-35-142-A & C, on which many of the offshore hydrocarbon infrastructure elements are located and in operation

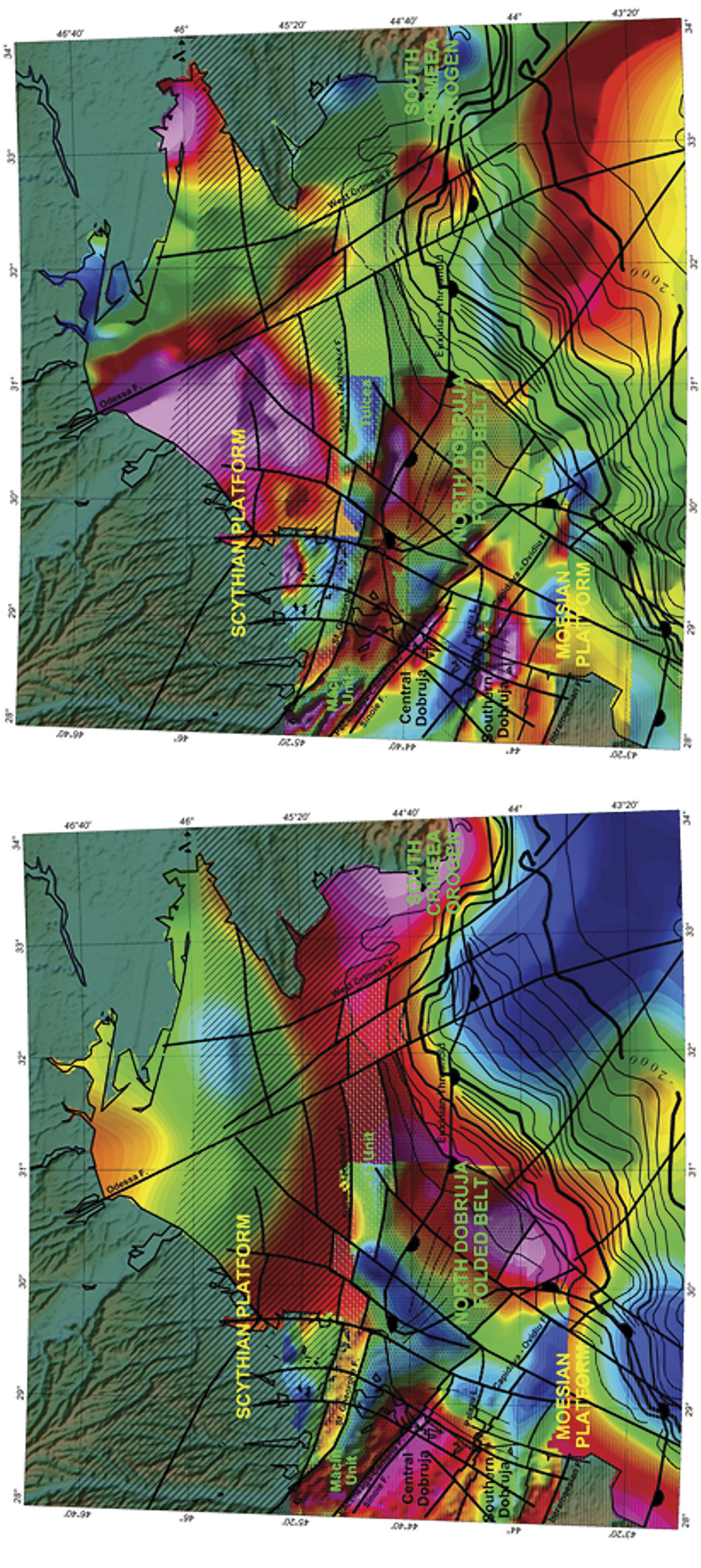
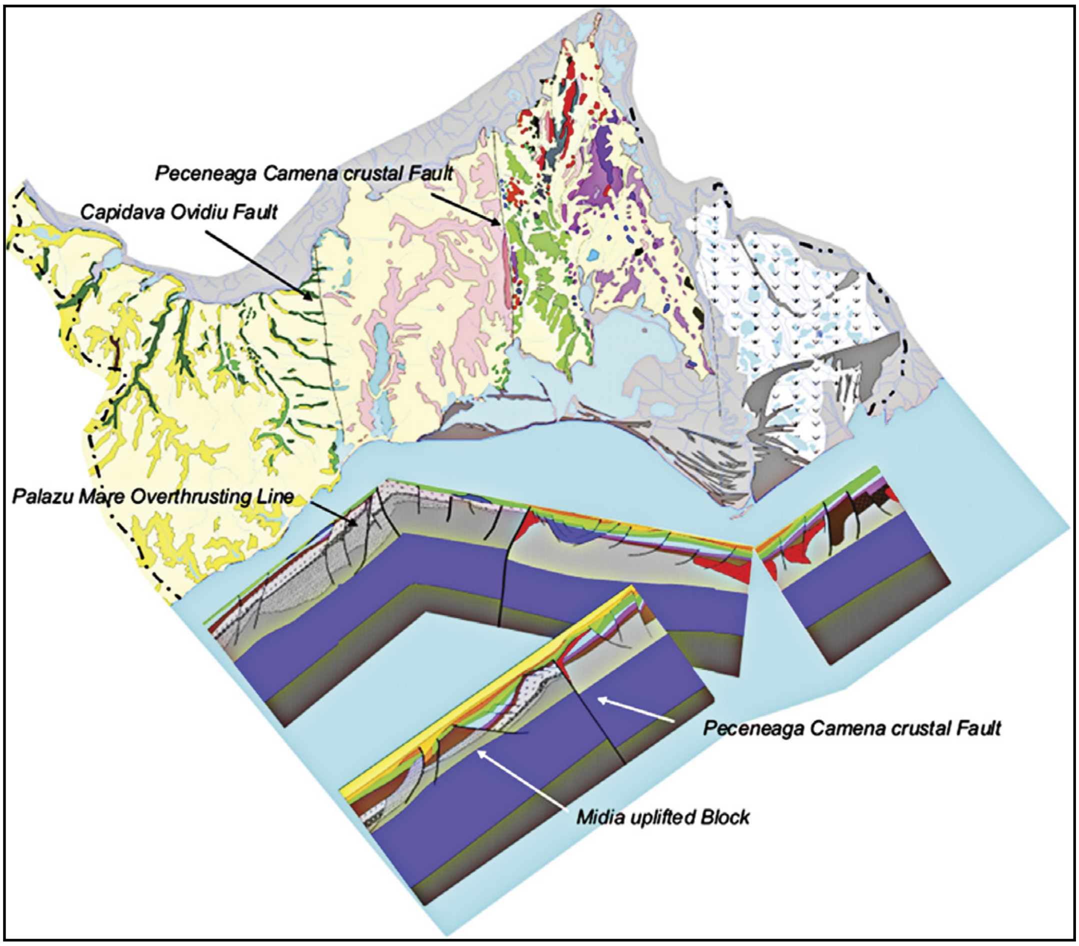


Fig. 10. Geotectonic sketch of the northwestern Black Sea continental margin as inferred from the interpretation of gravity (left) and magnetic (right) information (from Dimitriu *et al.*, 2009)



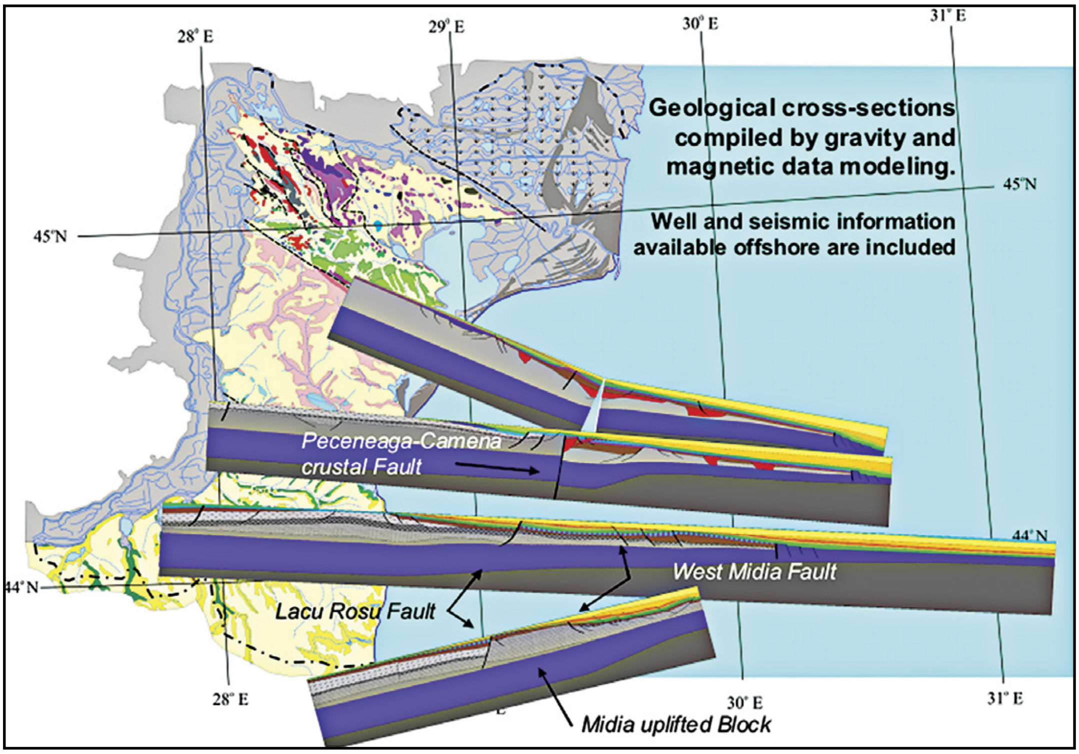
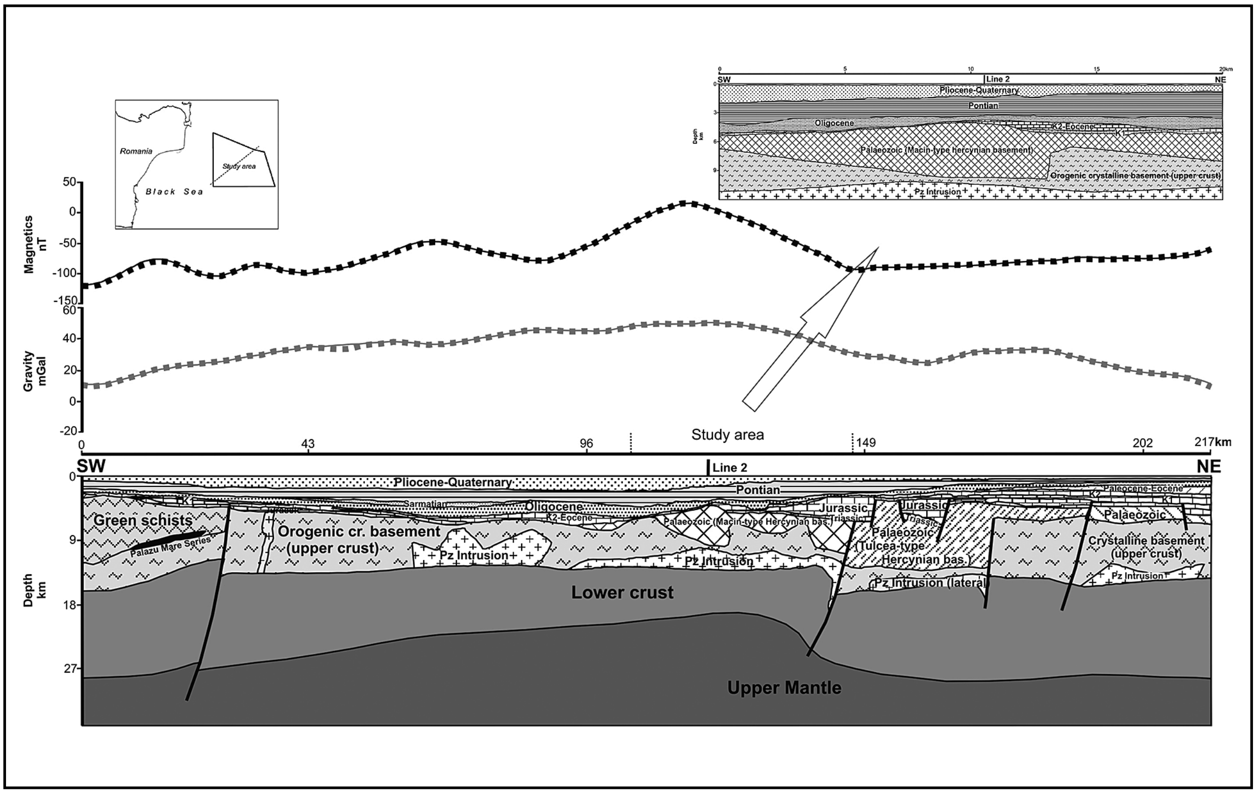


Fig. 11. 2¾D models, built up based on gravity and magnetic data, which integrate seismic, well and petrophysical data available and reveal the deep geotectonic structure of the crust and its transition from the continental-type to the oceanic-type (from Dimitriu *et al.*, 2009)



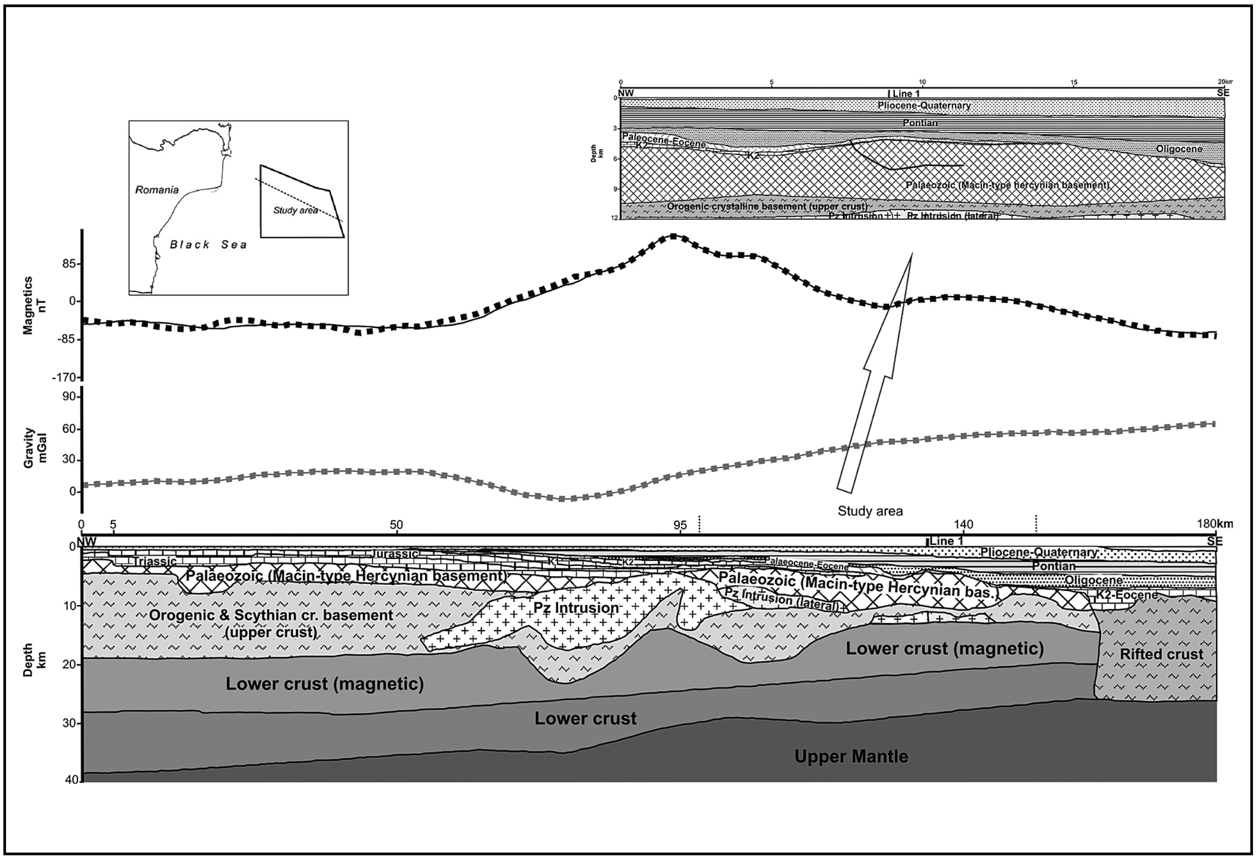
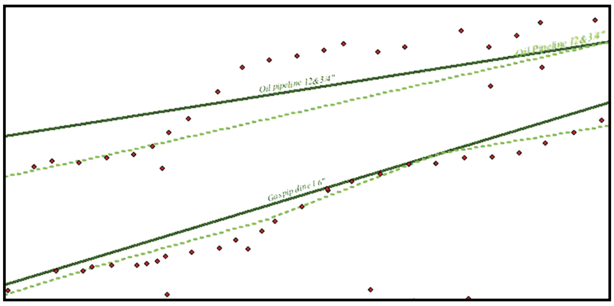


Fig. 12. 2¾D models, trending SW-NE and NW-SE, of the elevated structure of interest found within Muridava and East Cobălcescu maritime blocks (modified from Dimitriu *et al.*, 2016-b)



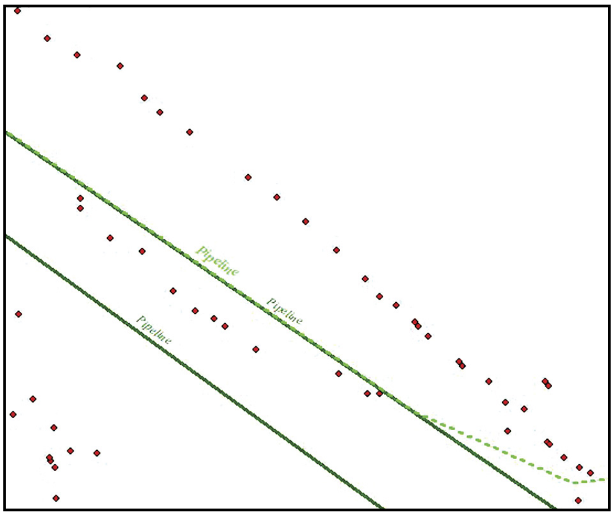


Fig. 13. Two examples of submarine pipelines routes as they are depicted on the navigation charts (dark green lines), on the oil industry maps (light green dashed lines) and resulted from the interpretation of magnetic data (red dots)

Given that unknown objects located on the seabed, at surface or buried in sediments, may sometimes elude detection by acoustic methods, magnetometry become a must for any site characterization survey carried out for any future marine drilling location, pipeline and cable deployment and others. In Fig. 14 are presented high detail maps of two marine locations, one lacking local sources of magnetic anomalies, the second showing an intense local magnetic anomaly due to the presence on the sea bottom of a previous drilling.

A high resolution magnetic mapping carried out in May 2007 off Midia harbor, as part of an UXO clearance survey, on the planned location of the fully functional today Midia Maritime Terminal (MMT) and along the route of the pipeline that links it to Midia refinary, led to the discovery of only several small magnetic targets, most of them near the shore (Fig. 15). The MMT site was found to be safe, the only relevant magnetic anomaly mapped on the eastern border of the surveyed area being of geological origin.

2.3. Study of submarine cultural heritage

Starting with 2014, the attention of Romanian geoscientists has increasingly focused on the study of submarine cultural heritage. Several scientific projects (e.g. Caraivan *et al.*, 2015, 2018) and research contracts namely dedicated to this objective have been carried out in recent years, and marine magnetometry has been one of the main geophysical investigation methods involved. Thus, two of the main discoveries made in mid-January 2015 by the scientific team onboard R/V Mare Nigrum, during the first sea cruise organized within HERAS project[8], are exclusively

8 HERAS project: Submarine archaeological heritage of the western Black Sea (http://www.herasprojectcbc.eu).

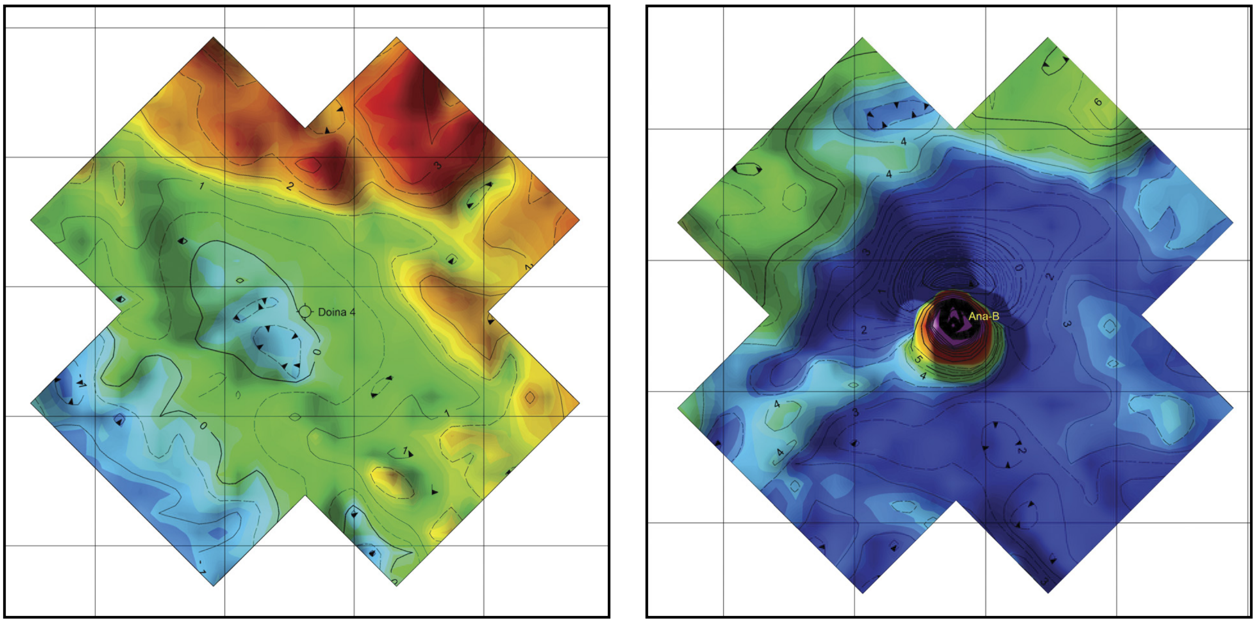


Fig. 14. High detail maps of magnetic anomalies of Doina 4 (left) and Ana-B (right) planned marine drilling sites, the first lacking any local anomalous source, the second in the close vicinity of a previous drilling

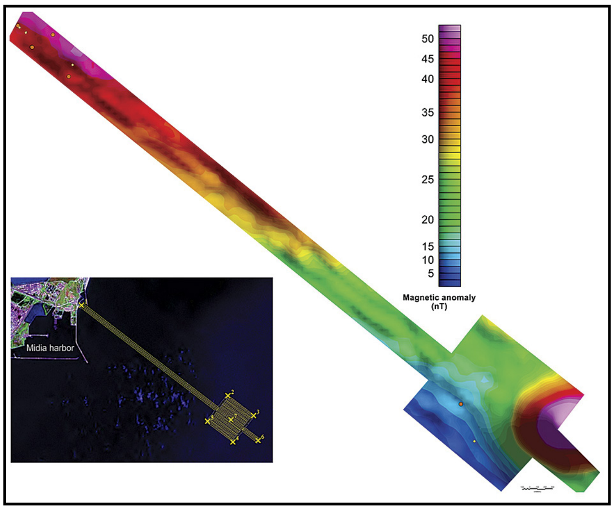


Fig. 15. Map of the magnetic anomaly off Midia harbor, covering the site of now-a-days Midia Maritime Terminal and the pipeline which links it to the dryland. The yellow and orange dots are the magnetic targets found, with amplitudes up to 10 and respectively 30 nT

due to magnetometry (Fig. 16). An unknown shipwreck, 40 m long and 6 m breadth, possibly a German naval landing craft (marinefährprahm) lost in storm in 1942, was discovered 6 miles off Cape Midia at 26 m sea water depth, as well as the wreck of a Russian, Malyutka-class submarine, most probably M-34 or maybe M-58, both lost on mines in 1941, which was localized 5 miles off Costinești village, at the depth of 40 m.

Other important discoveries were made by marine magnetometry in early August 2018 off Sulina-Sfântu Gheorghe littoral sector, during the systematic geophysical mapping of the map sheet L-35-120-B. The certain presence of a massive shipwreck (amplitude of the magnetic effect exceeds 17,700 nT) and the possible presence of a second one, less massive (magnetic anomaly of less than 400 nT), have been noticed. The swift side-scan sonar measurements carried out a few days later led to the identification of the first magnetic signal as the shipwreck of the Romanian cargo "Carpați"[9] and the certification of the presence of an unknown wreck for the second magnetic signal (Fig. 17). The extensive documentation and database created within the MAR-S project[10] give us clues about the possible identity of this unknown wreck. Taking into account the size of the wreck and the magnitude of the magnetic effect measured at the surface, this could be the German mine-layer submarine UC-15[11], lost in 1916 while being in mission off Danube delta.

9 S/S Carpați [+1942]: Romanian cargoship built in 1913, length 114.5 m, bredth 15.7 m, gross tonnage 4350 grt, torpedoed and sank by the Russian SC-216 submarine on October, 10th, 1942, at sea water depth of 33 m, 12 miles southeast of Sulina (https://gis.geoecomar.ro/marss).

10 MAR-S Project: Implementation of a geophysical investigation and monitoring tool of the Romanian maritime space security (http://intranet.geoecomar.ro/mars)

11 UC-15 [+1916]: German mine-layer submarine, built in 1915, length 34 m, bredth 3.15 m, height 6.3 m, total displacement 225 t, sank after November, 7th, 1916 off Danube's mouths, after it completed the deployment of a mine barrage. It's possible that it hit one of its own mines as it was under attack from the Romanian torpedo boat „Smeul" (https://gis.geoecomar.ro/marss).

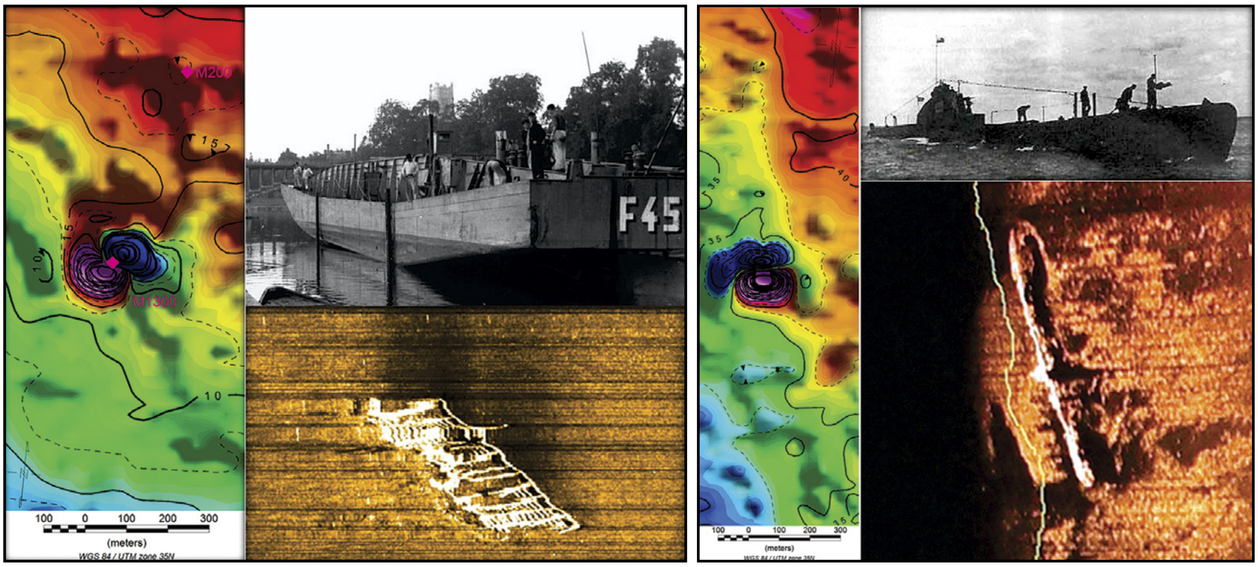


Fig. 16. Discoveries made by marine magnetometry during HERAS Project. Maps of the magnetic anomaly, acoustic images provided by the side-scan sonar and pictures of the shipwrecks found on the seabed: possibly a German landing craft on the left montage and a M-class Russian submarine on the right montage

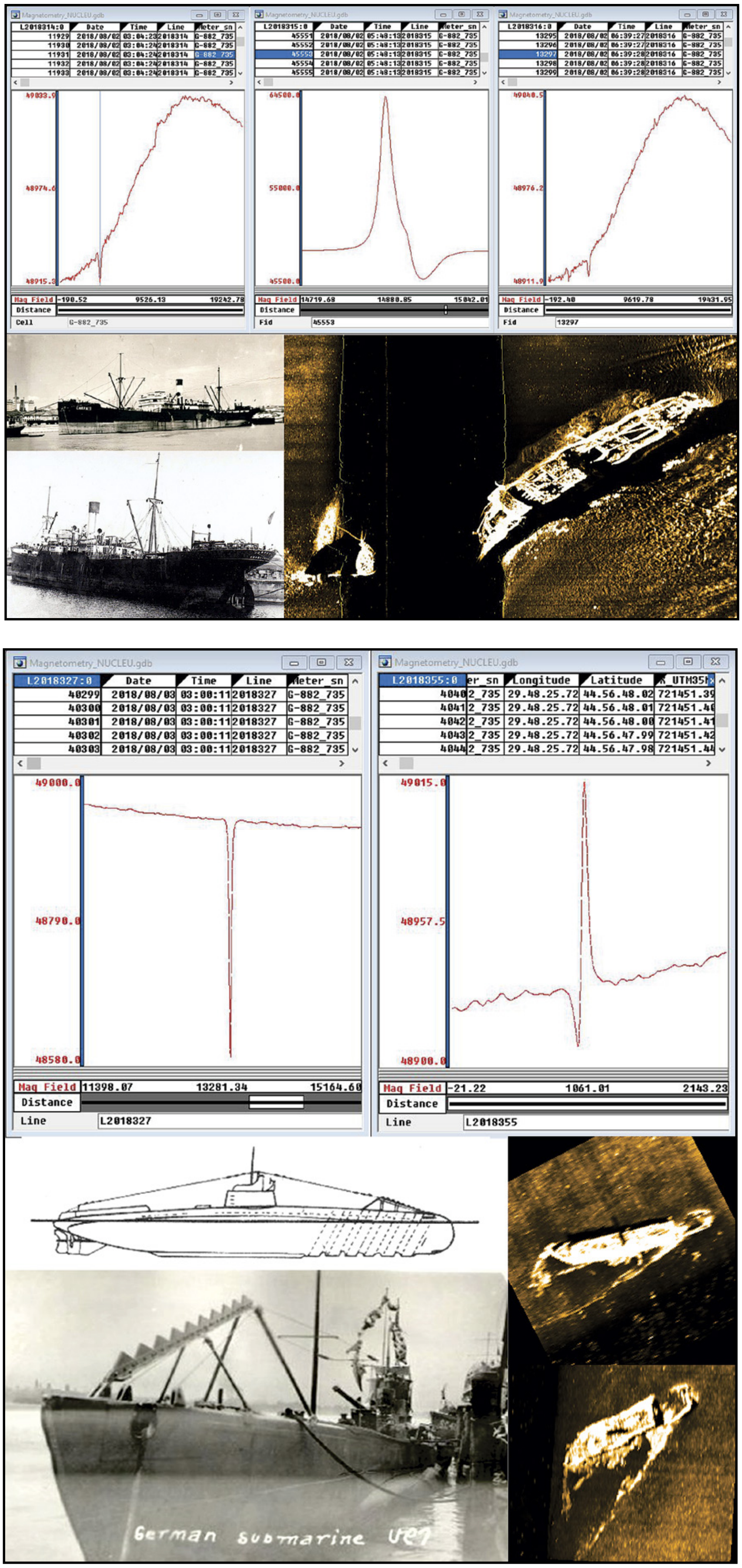


Fig. 17. Magnetic signals which led to the localization of the shipwrecks, pictures and acoustic images of the Romanian cargoship "Carpați" (top montage) and probably of the German mine-layer submarine UC-15 (bottom montage)

The effectiveness of marine magnetometry is not limited only to wrecks whose hull is made of iron or steel. If the load and/or ballast of wooden shipwrecks have distinct magnetic properties relative to those of the surrounding geological environment, they become detectable by magnetometry, even when the wrecks are dismantled and scattered on the sea bottom, or even covered by recent sediments, situations when most acoustic investigation methods become ineffective.

An example which demonstrates the effectiveness of marine magnetometry also for the localization of non-ferrous shipwrecks is the high-resolution magnetic survey carried out in May 2017 (Dimitriu *et al.*, 2017-a, 2018) within a marine sector of the Romanian northern littoral, which includes the wreckage site of an early Roman (mid-2nd Century AD), wooden shipwreck, previously discovered nearshore Gura Portița (Pflederer *et al.*, 2016, Nuțu *et al.*, 2017). The geophysical survey provided very detailed images of the total geomagnetic field anomaly, of the magnetic analytic signal (Fig. 18), on which an impressive number of local anomalies, with amplitudes ranging between a few nT and tens, even a few hundred nT, was observed. While most of these local anomalies are of geological origin (e.g. lateral variations of heavy mineral content in surface sandy sediments), many other are definitely of anthropic origin (e.g. ferrous debris accumulated on the sea bottom following the long-lasting fishing activity, from coastal navigation and last but not least, artefacts belonging to submerged cultural heritage).

The location of the ancient shipwreck on the seabed is clearly highlighted not by one, but by two local magnetic anomalies (Fig. 19) having relatively weak amplitudes, up to 10 nT, generated by the magnetically detectable cargo, represented by over 1,000 amphorae still gathered onboard the wreck and also slightly scattered around. The interpretation of magnetic data and information gathered through MAR-S project made also possible the location of the wreckage site of ”Lucia”, a wooden, fishing motorboat lost in storm and totally destroyed in December 1940, around half a mile off Gura Portița.

2.4. Maritime space security enhancement

Like many other European countries, Romania is taking today important steps towards achieving an enhanced characterization of its maritime space security. Scene of human activities since ancient times, the Romanian maritime space in a place where, over the centuries, even the millennia, an extensive variety of items, whose origin and risk to the health and security of the maritime space are unknown, have been accumulated. These items originate from traditional activities, like trading and fishing, from relatively modern ones, such as the exploration and exploitation of marine natural resources, the deployment of pipelines and cables, but also from many military operations (shipwrecks, minefields, bombardments, etc.) and the dumping of chemical and warfare waste.

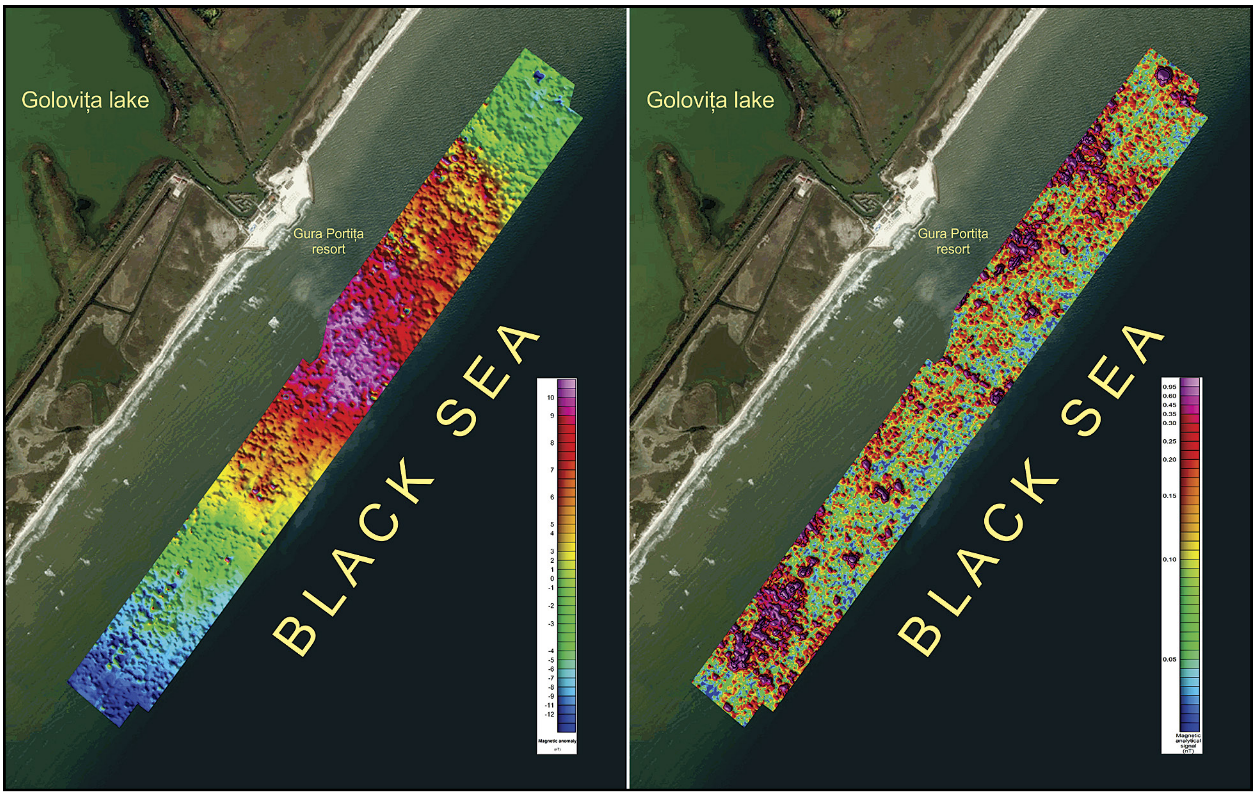


Fig. 18. Maps of the magnetic anomaly (left) and of the magnetic analytical signal (right) of Gura Portița littoral sector (modified from Dimitriu *et al.*, 2018)

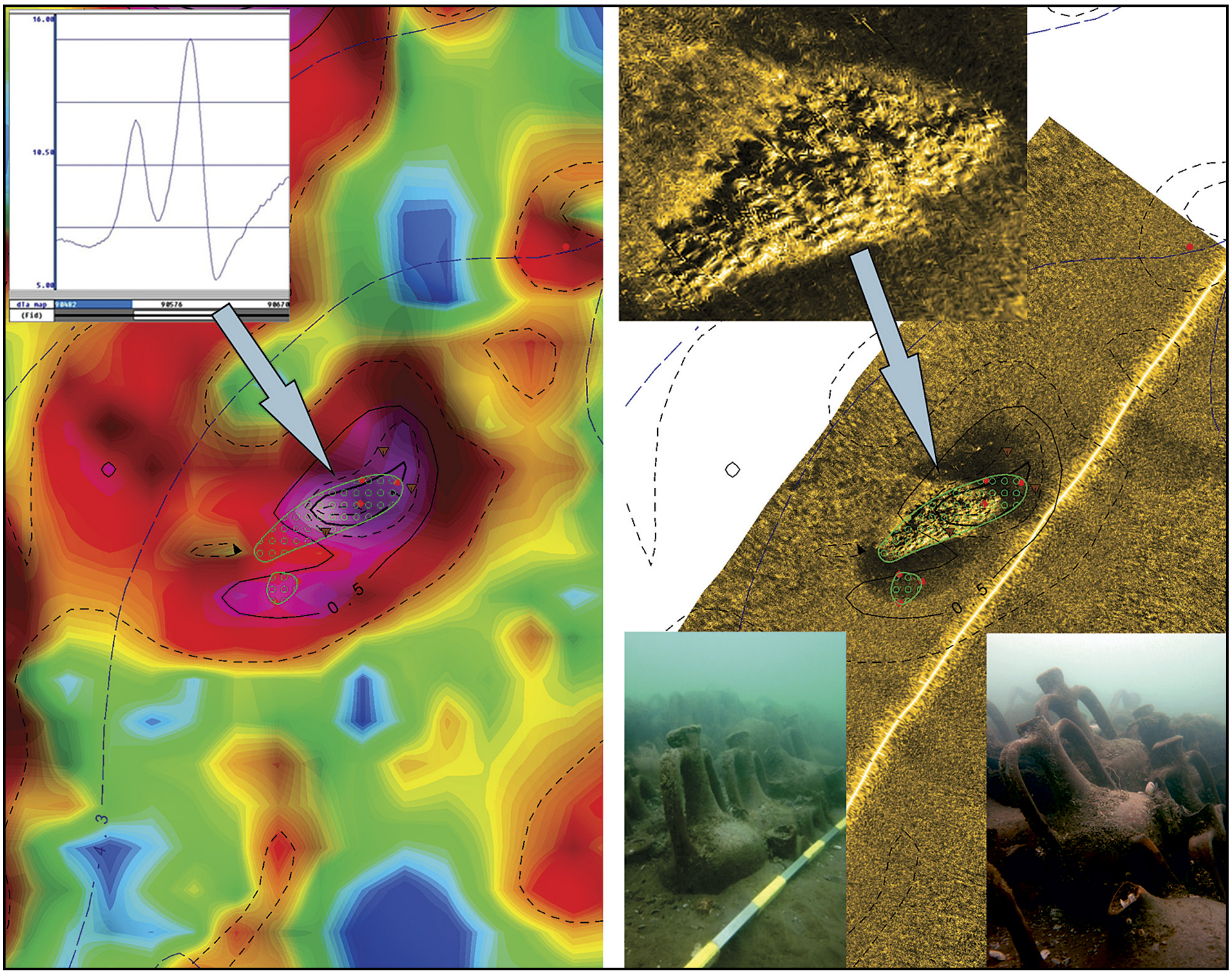


Fig. 19. Maps of the magnetic analytical signal (left side montage) and the acoustic image of the wreckage site (right side montage), with the integrated interpretation of the geophysical data: Black short-dashed lines are the intensity of the magnetic analytical signal; Blue long-dashed lines are the water depth isobaths. In green is represented the presumed extension of the ship wreck and of a secondary anomalous source (modified from Dimitriu *et al.*, 2018; underwater pictures are from Nuțu *et al.*, 2017)

One of the most effective geophysical methods for the investigation of the maritime space' safety and security has proven, over the last years, to be magnetometry. Thus, a high resolution, high detail magnetic survey was undertaken in August 2016 off the Bulgarian harbor Burgas (Dimitriu *et al.*, 2017-b), aiming to identify possible locations of dumped UXO, as well as other types of ferrous objects lying on the seabed and/or shallowly buried in sediments, prior to dredging operation planned for the harbor extension to be performed.

The study was carried out in one of the most unfriendly magnetic environments dominated by huge and very rapid (over 1000 nT only within the study area) variations of the magnetic field (Fig. 20) due to outcropping or shallow intrusions of Paleozoic and Late Cretaceous age, to lens of "black sands" with high contents of titanomagnetite minerals, located on the seabed, and not least to the large pile of steel pipelines sections stored on the neighboring quay. Still, the careful analysis of the magnetic analytic signal as well as the individual analysis of each marine magnetic line were able to highlight the presence of over 75 potential target sites (Fig. 20) where the presence of UXO items and possibly of dumped or lost ferrous objects was highly likely. During the scuba diving inspection, that subsequently followed the geophysical job, over 2,000 pieces of artillery shells and other ferrous objects have been recovered from the sea bottom and many others, buried in sediments, were expected to be recovered during the dredging.

Another important contribution for the study and enhancement of maritime space security was brought by magnetometry within MAR-S project, implemented by GeoEcoMar Institute during 2017-2018. The main tasks of the project were to experiment and prove the effectiveness of a set of geophysical methods (e.g. magnetometry, bathymetry, side-scan sonar and other) of investigation and monitoring of the maritime space, for the accurate location and identification of submerged objects and also to gather, structure and hierarchize all available and new acquired information in a dedicated GIS database.

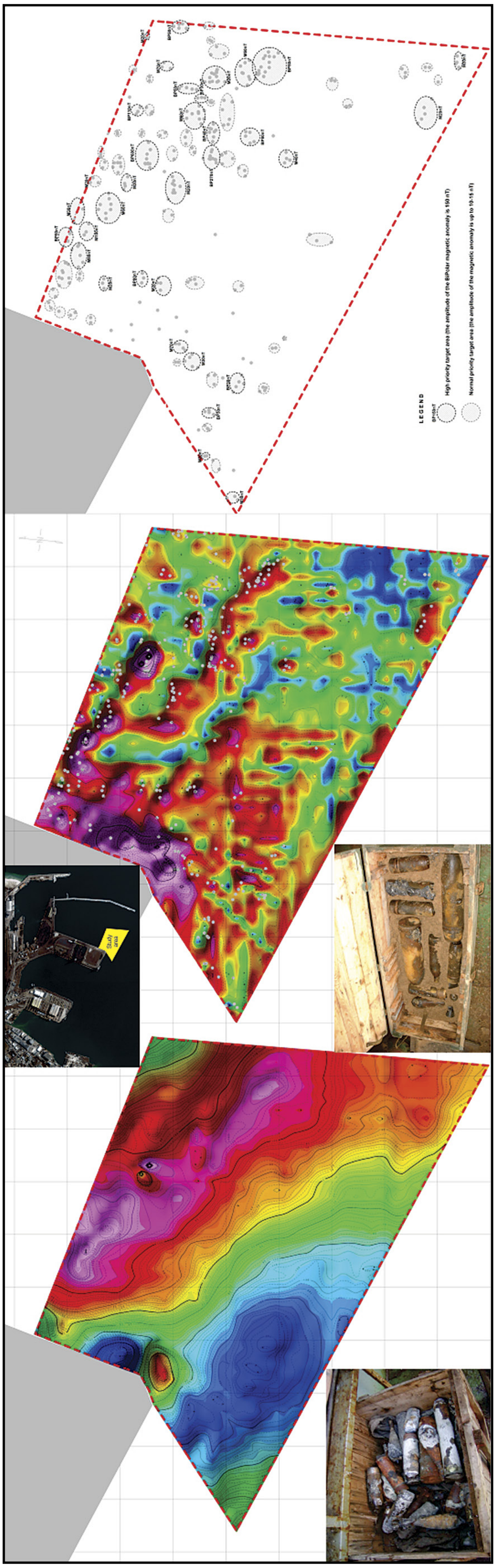


Fig. 20. Maps of the local magnetic anomaly (left side montage) of the magnetic analytic signal (center montage) and of the target areas (right side montage) identified within Burgas harbor. Grey dots are magnetic targets resulting from the individual analysis of all magnetic lines measured on the study area

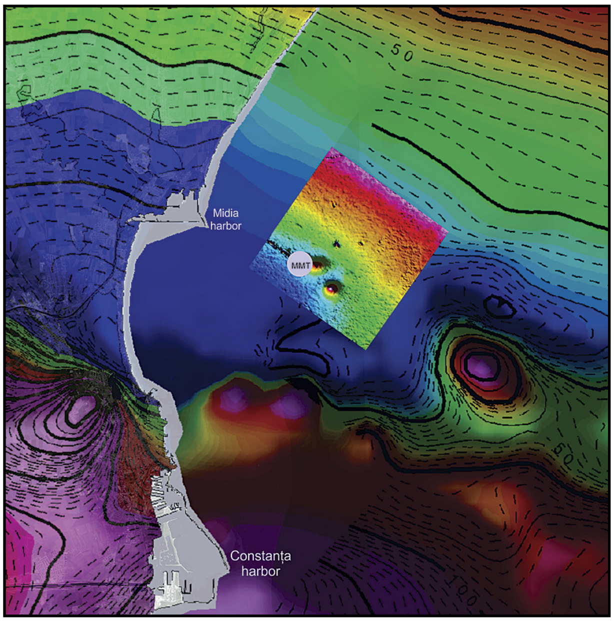


Fig. 21. High detail map of the magnetic anomaly of MAR-S project main testing maritime area off Midia harbor (central square), superimposed on a map that illustrates at regional scale the morphology of the magnetic field anomaly both on- and offshore

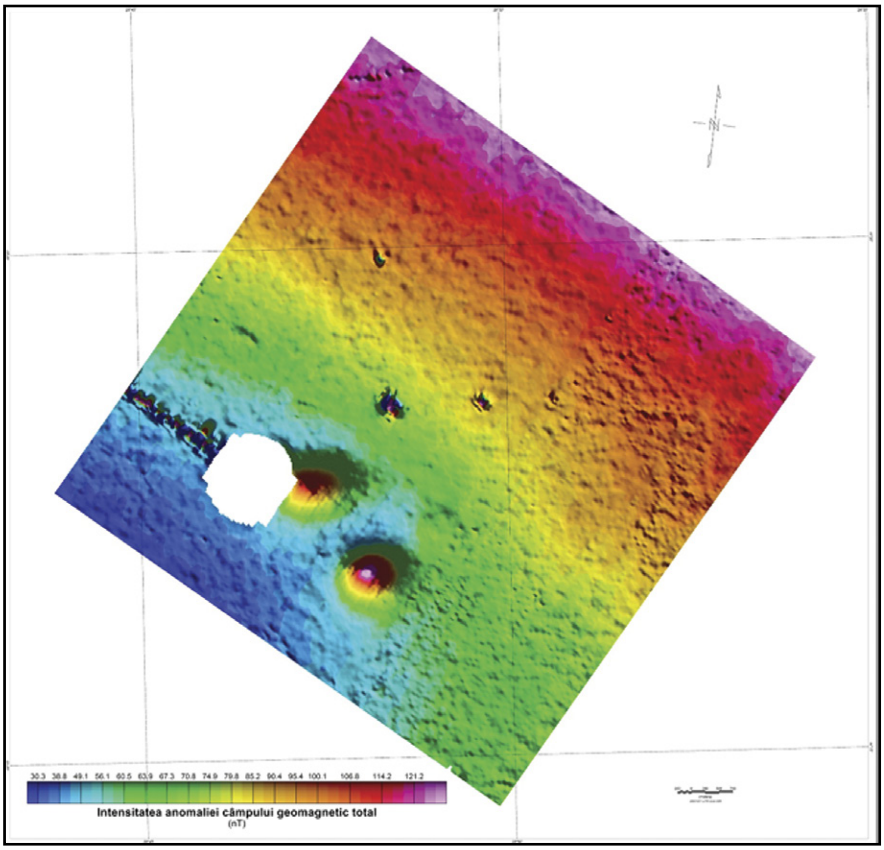
The high resolution and high detail magnetic mapping carried out in mid-2018 covered the surface of MAR-S project's main testing area, located off Midia harbor (Fig. 21, 22) and surrounding Midia maritime terminal (MMT). The two magnetic anomalies (Midia 1 and Midia 2) mapped at east and southeast of MMT, with amplitudes of 60 and 80 nT and wavelengths of 1.4-1.6 km, are due to geological sources located within the crystalline basement at depths, according to the 3D modelling carried out, of respectively 450 m and 400 m. The regional morphology of the magnetic field (Fig. 21) strongly suggests the same common origin for all intense magnetic anomalies mapped both on the dryland and the adjacent offshore, their sources being represented by variable volumes of Early Proterozoic meso-metamorphites of Palazu Mare Series, with high contents of magnetite, whose magnetic susceptibility may range up to 10,000-25,000 μuCGS (Dimitriu, 2001; Dimitriu *et al.*, 2004). Several other local, intense and very intense magnetic anomalies have also been noticed, along with a swarm of quite discreet magnetic anomalies (low and very low amplitudes, from only a few nT to 10-15 nT and wavelengths from 10-20 m up to 300-400 m) due to UXO- and USO-type submerged sources. In order to separate these local magnetic effects, of highest interest for MAR-S project's aims, an analysis of the analytic magnetic signal was performed and the map resulted is also presented in Fig. 22.

The integrated interpretation of magnetic, bathymetry, side-scan sonar as well as of all other historic and cartographic information available (Fig. 23) highlighted the following:

- 117 magnetic targets were found on the maritime surface investigated, of which 67 correlate very well with acoustic targets found by the side-scan sonar mapping;
- a very good correlation between the route of the pipeline that connects MMT and Midia refinery, shown on the navigation chart and the real one, is obvious on the investigated surface;
- the existence of shipwrecks in two locations received from unofficial sources is infirmed;
- the existence of four certain shipwrecks, of which one was completely unknown before, is confirmed;
- the possible existence of an unknown shipwreck is assumed on the location of an intense magnetic anomaly, but the lack of any conclusive acoustic image suggests that it might by dismembered and covered by sediments;
- in the central area of the investigated perimeter many magnetic and acoustic targets are grouped and overlaps very well a restriction area imposed by the Romanian Maritime Hydrographic Directorate, it corresponding to a minefield from WWII;
- the stripe alignment of magnetic targets discovered on the northern border of the study area (Fig. 23), which seems to continue towards the site where a naval mine was found by fishermen a few years ago, was interpreted as a possible former minefield, unknown by authorities. The fact that no acoustic target was found in that sector suggests that the ferrous remains are buried in sediments;
- the possible existence of another former minefield on the easternmost part of the study zone, also unknown by authorities, is suggested by the strip zone along which numerous magnetic and acoustic targets, as well as the wreck of a soviet submarine (SC-213 sunk in 1942) and the previously mentioned site where a naval mine was hung, are all aligning (Fig. 23).

3. CONCLUSION

Decades after their first use on the Romanian offshore, marine gravity and magnetics turns out to be still very effective tools for deciphering and modelling the deep geological structure and the geotectonics of the continental



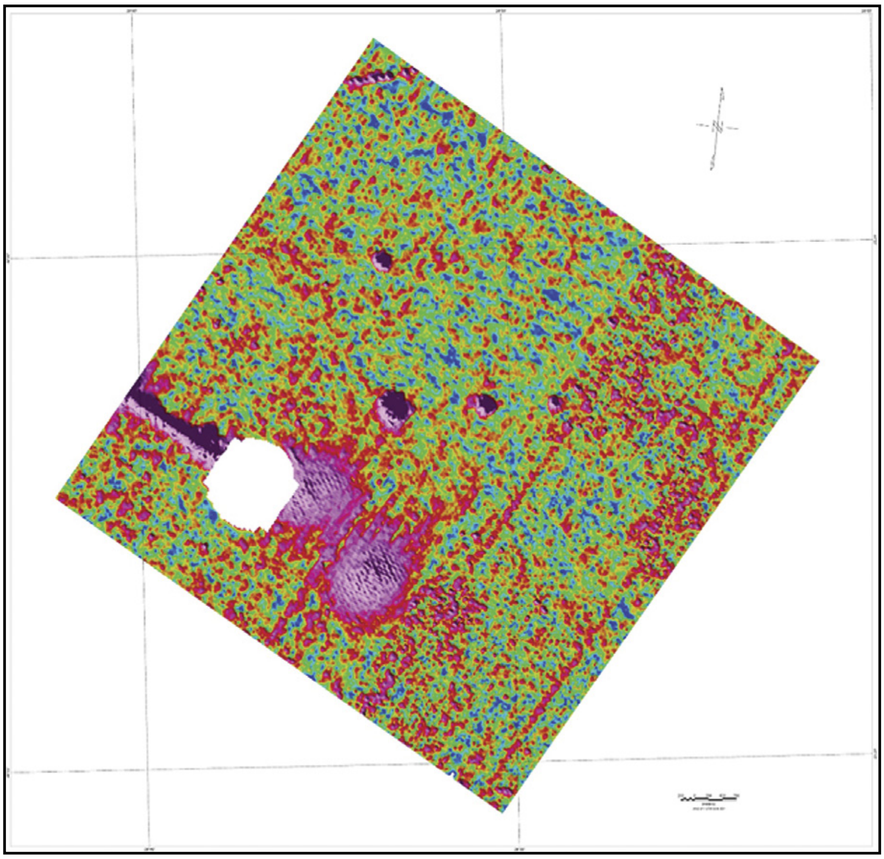


Fig. 22. Maps of the magnetic anomaly (top) and of the analytic magnetic signal (bottom) of the maritime testing area investigated in 2018 off Midia harbor, in MAR-S project

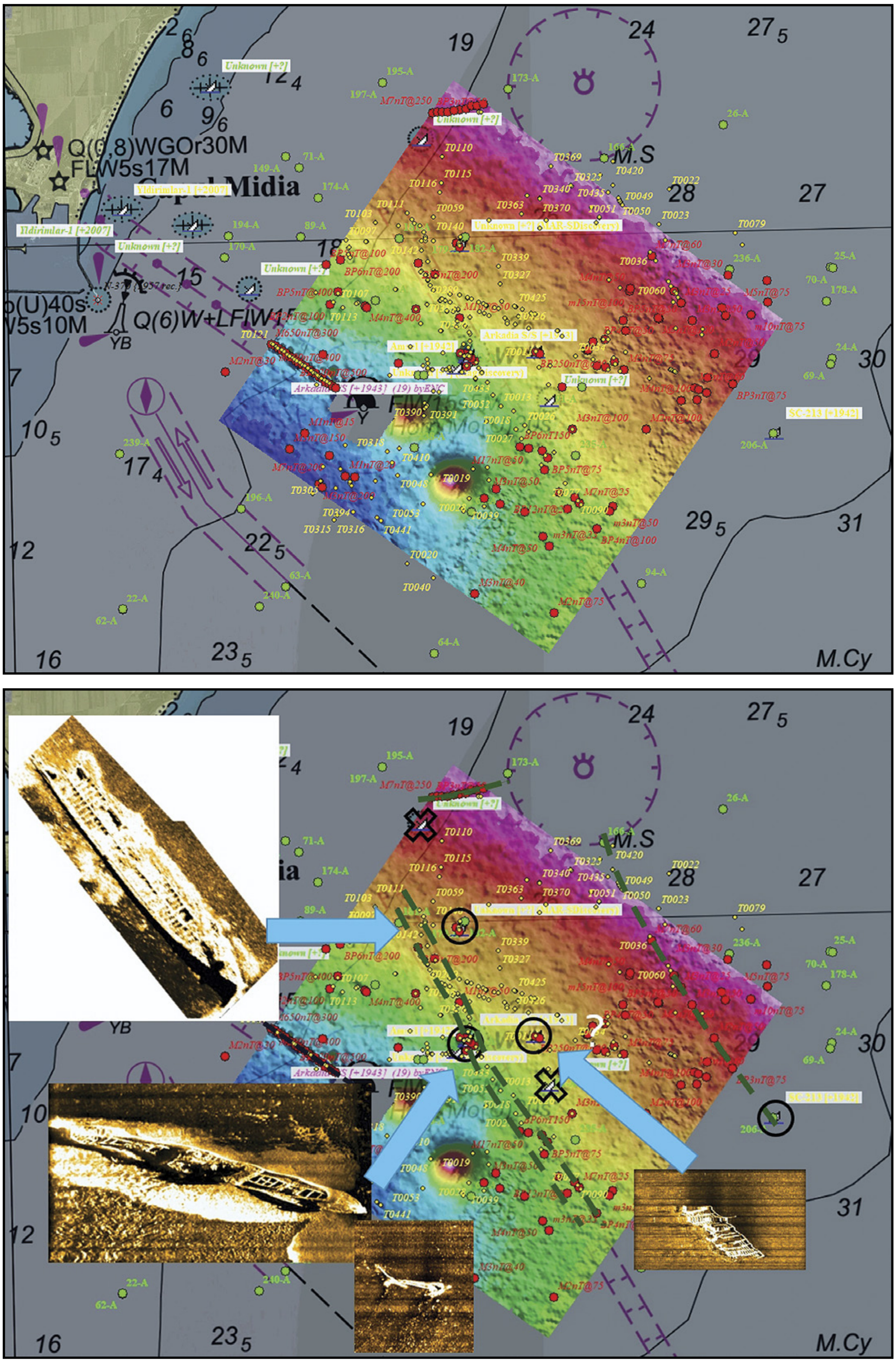


Fig. 23. Composite maps depicting the integrated interpretation of geophysical data, made for Midia offshore. The magnetic targets found are represented by red dots, the acoustic targets by small yellow dots and the snags by light-green dots. The position of previously known and assumed shipwrecks are figured. Big, black circles are locations where shipwrecks were found on the seabed. Big, black crosses are locations where the existence of shipwrecks was infirmed. The white question mark indicates the location where the existence of an unknown, dismembered and covered by sediments shipwreck is supposed. The dark-green, dashed heavy lines represents alignments which could correspond to both known (central sector) and unknown former minefields (northern and eastern sectors)

margin, as well as of the shallower structures of interest for oil industry, located within the sedimentary cover of the Black Sea basin. Both methods are getting involved more and more every day in studies dedicated to marine geohazards, the assessment of the methane hydrates resources and the development of methods for their exploration and future exploitation.

The study highlights the substantially increased efficiency of the geophysical investigation for deciphering and modelling of the deep geological structure and its geotectonics, reached mainly when both these complementary survey methods, gravity and magnetics, are involved.

Marine magnetometry demonstrates, in particular, a notable capability to integrate and prove its usefulness for the new domains of advanced offshore research: the identification and geo-ecological assess of dumping sites, the search, accurate location and recovery of various objects and tools (e.g. anchors, chains, corers, containers, boxes, barrels, pipelines, cables, etc.) lost or deployed on the seabed or covered by sediments, situation which dramatically diminish the efficiency of classic video and acoustic search methods. Besides its remarkable and unanimously recognized capability for discovery and accurate location of the ferrous wrecks, marine magnetometry proves also to be effective in the case of non-ferrous shipwrecks, but having onboard a cargo (e.g. amphoras, ceramics, weaponry, ammunition, etc.) or ballast with above average magnetic properties. Thus, marine magnetics continuously strengthens its widely accepted position as a main provider of extremely useful information for disclosing the submerse cultural heritage and also for enhancing the maritime space safety and security.

4. ACKNOWLEDGEMENTS

Far from being exhaustive, the previous presentation only shows some of the most representative results of gravity and magnetic researches conducted by GeoEcoMar Institute on maritime space after 2005. Similar studies were also carried out on the surface of the Razelm-Sinoie lagoon complex, in southern Danube delta and upstream, on different sectors of Danube river. The funding of these researches was mostly provided by the Ministry of Research (i.e. the national programmes NUCLEU I-III, CERES, MENER, CEEX, etc.), by European funds (e.g. CBC Romania-Bulgaria, EASME & EMFF and other) but also by the research contracts concluded with different offshore operators (e.g. OMV-Petrom, Petromar, Sterling Energy, Melrose Resources, Paladin Resources, Petroceltic Intenational, etc.).

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