GEOPHYSICAL CONSIDERATIONS ON THE BLACK SEA OPENING AND ITS SEISMO-TECTONIC CONSEQUENCES[1]

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Considérations géophysiques sur l'ouverture de la Mer Noire et ses conséquences sismo-tectoniques. L'article traite principalement des problèmes liés à l'ouverture de la Mer Noire et, spécialement, ses échos sismiques dans la croûte continentale de nord-ouest. À partir des données acquises antérieurement dans la zone de la Mer Noire et du territoire qui l'entoure, et en utilisant les ressources des mathématiques supérieures et de l'interprétation des champs géopotentiels, on a fait des progrès dans la connaissance de la naissance et de l'évolution de la Mer Noire. Les zones géomagnétiques et gravitationnelles du fond de la mer, qui sont orientées vers le nord-est dans le bassin de l'ouest et vers le nord-ouest dans le bassin de l'est, indiquent une ouverture des bassins de l'est et de l'ouest de la Mer Noire en deux directions plutôt perpendiculaires. Ce fait n'est pas conforme au modèle actuel qui considère l'ouverture du bassin de la Mer Noire comme un résultat d'un événement géodynamique unique. Ainsi, il paraît plus raisonnable de considérer une ouverture séparée des bassins de la Mer Noire pendant deux événements géodynamiques différents. Il paraît que l'existence des deux rifts indépendants, ayant des directions presque perpendiculaires l'un sur l'autre, a été responsable de l'ouverture des bassins de l'ouest et de l'est de la Mer Noire. Des recherches sismiques sur la mer ont montré une légère poussée des Pontides de l'est sur les Pontides de l'ouest, ce qui indique clairement une ouverture antérieure du bassin d'ouest de la Mer Noire.
La naissance de la croûte et son déplacement vers le nord-ouest a provoqué la cassure de l'avant-pays des Carpates du Sud-Est. Les failles qui cassent la croûte ont partagé la MoP en plusieurs blocs croûteux. Sur l'action combinée des rifts actifs de la Mer Rouge et du Golfe d'Aden, les compartiments de la croûte bougent relativement l'un vers l'autre, ceci générant des tremblements de terre croûteux le long de leurs bords.

Key words: gravity, geomagnetism, seismicity, earthquake, fault, regional tectonics, geodynamics, Black Sea, Mœsian Plate.

1. GENERAL CONSIDERATIONS

Despite many years of research effort, the strange intra-continental position of the ocean-type crust of the Black Sea still stands as a challenge for geoscientists. The assumption concerning the absence of the granite layer within the full

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continental environment is based on the values of the seismic wave's velocity only. Drilling attempts to confirm seismic data have failed due to the extremely thick sediments (more than 15 km) that cover the central Black Sea basins.

The present work represents an attempt to improve the knowledge on the geodynamic processes related to the Black Sea opening and its echoes on the adjacent NW inland. The considerations are mainly based on the interpretation of gravity and geomagnetic data previously acquired within the Black Sea offshore and the NW neighbouring inland. To diminish the inherent ambiguity in the potential field interpretation, additional data (offshore seismics, earthquake focal mechanism, stress tensor state, and so on) were also used.

2. GEOLOGICAL SETTING OF THE BLACK SEA

The Black Sea basin is located within the full continental environment (Fig. 1). It is surrounded by relatively high mountain chains (Crimea, Caucasus, Pontides and Balkans) except for the north-western inland, consisting of the North Dobrogea belt, and the Moesian and Scythian platforms. Based on a large amount of information collected by scientific institutions from various countries some basic ideas concerning its regional geological setting will be presented in the following.

The Black Sea is formed of two deep basins separated by the Mid-Black Sea ridge (Belousov *et al.*, 1988; Finetti *et al.*, 1988). Even if generated simultaneously, by the same geodynamic event, they exhibit distinct crustal peculiarities. The central part of the two basins seems to show an **ocean-type crust,** with the granite layer missing. The hypothesis is based on the high value of the seismic wave velocity, usually observed on the basalt floor of the oceans.

Better results in offshore seismics interpretation were obtained for the W Black Sea basin due to the possibilities for an accurate calibration. Within the central area, on a substantially flat acoustic basement attributable to the basaltic layer, lies an over 14 km strong reflective sedimentary sequence, which started in the upper part of the *Lower Cretaceous*. It is worth mentioning that the western Black Sea floor is progressively younger from north (*about 110 m.y.*) to south (*55 m.y.*). Several zones striking NE, with distinct seismic behaviour, have been outlined in the area, underlying the sea floor geology (Fig. 2).

In the E Black Sea basin, the acoustic basement **is not flat,** but affected by tectonization and fault displacements, and is covered by a sedimentary succession with a total thickness of about 13.5 km. It should be mentioned that some authors consider that in the central E Black Sea basin the granite layer is not absent, but strongly thinned only and, accordingly, the sea floor would remain continental in nature.

To conclude, several results of the previous research should be kept in mind for a better understanding of future statements in this paper related to the sea basin opening:

– the missing granite layer in the central part of the basin;
– distinct crust peculiarities for western and eastern Black Sea;
– the progressively younger basement of the W Black Sea from north to south.

3. MAIN IDEAS CONCERNING THE BLACK SEA GENESIS

The first ideas on the nature of the Black Sea basin were based on studies on the surrounding land and fragmentary bathometry (Andrusov, 1893; Dobrynin, 1922). They imagined the Black Sea basin as an intra-continental **graben-like structure** of *Neogene to Quaternary* age, within the frame of a vast continent (*Pontida*) including Crimea and Asia Minor.

Obruchev (1926), Nalivkin (1928), Lichkov (1933), Arhangelskii, Strahov (1933) and Muratov (1949) considered the Black Sea as a **modern dynamic geosynclinal** area, with continuous subsidence.

Later on, Muratov (1955) reconsidered his former idea by interpreting the basaltic basement of the Black Sea bottom as a **relict ocean floor**. Milanovskii (1963, 1965), Sorskii (1965), Goncharov *et al.* (1972) developed the Muratov idea. By taking into account the thickness of the sedimentary cover, a *Palaeozoic* or even *Precambrian* age of basin occurrence was considered by the authors.

Gegelyantz *et al.* (1958) and Neprochonov (1966) brought the first evidence for the absence of the granite layer in the central basin of the Black Sea, advocating for the presence of an ocean-type crust in the area. Kropotkin (1967) and Adamia *et al.* (1974) firstly considered that the Black Sea floor is a **rifting structure**, located in the extent of the Adjaro-Triatlet depression. Later on, Beliavskii and Mikhailov (1980) stated out that the rifting started in the *Jurassic*.

Dewey *et al.* (1973) and Sorokhtin (1979) joined the previous idea of Muratov (1955) and considered the crust without the granite layer as simple **remnants of the Tethys ocean floor** of *Early Mesozoic* age.

Apolskii (1974) considered the Black Sea and the Caspian Sea as **pull-apart basins** generated by *en-échelon* sinistral strike-slip faults acting from the SE Carpathians to the Caspian Sea area.

Adamia *et al.* (1974), Bocaletti, Guazone (1974) brought into account the modern hypothesis presenting the Black Sea floor as **a remnant of a back-arc basin** provoked by an extension from *Late Cretaceous to Palaeogene*. The idea was developed by Letouzey *et al.* (1977) who used the plate tectonics concept to explain the Black Sea formation. In the authors' opinion, the Black Sea occurred as a **back-arc basin** behind the Pontides due to the Mesozoic Tethys Ocean northward subduction. It evolved from *Late Cretaceous to Eocene-Oligocene*.

A rather different model, which fully denies the rifting hypothesis, was proposed by Janshin *et al.* (1980) and Shlezinger *et al.* (1981). These authors considered that the ocean-type crust within the central Black Sea and the Caspian Sea occurred as a result of the **basification of the continental crust by eclogitization of granite rocks.**

Zonenshain and LePichon (1986) came back to the idea of *Mesozoic* **back-arc basins related to the Neo-Tethys subduction**.

Finetti *et al*. (1988) and Belousov *et al*. (1988) suggested the idea of a **two-stages rifting**. The first phase took place during the *Liass-Dogger* and seems to be responsible for the formation of the Great Caucasus basin. At that time, the Black Sea basin was a shallow sea with channels area. The deep-sea basins occurred during a secondary rifting stage (starting from the *Neocomian-Barremian*). The West and East Black Sea basins opened almost simultaneously, but had an unequal evolution. While the western Black Sea experienced a complete development, with a progressively opening from north to south, the eastern Black Sea seems to have an incomplete evolution. As previously mentioned, some authors consider that there is no ocean-type crust in its central part, but a transient crust, with a thinned granite layer. The opening phase stopped in the Palaeogene, when a compression stage started in the area.

In a more recent paper, Shreider *et al*. (1997) considered, based on magneto-stratigraphic evidence that both E and W Black Sea started almost simultaneously from *Aptian to Albian*, and evolved to the *Palaeocene–Eocene*.

As can be seen from the above presentation, the modern dominant idea is that the W and E Black Sea basins opened almost simultaneously as back-arc basins behind the West and, respectively, East Pontides, related to the northward consumption of the Neo-Tethys floor. Their development seemed to start in Late Cretaceous and lasted in the Eocene-Oligocene, when the whole area was an active depression during the cooling of the newly formed oceanic crust.

Based on geophysical evidence (mainly provided by the potential fields analysis), in the following we shall try to present some considerations on the geodynamic processes related to the Black Sea opening and, especially, their seismotectonic consequences in the neighboring NW inland.

4. DATA AND THE APPROACH

4.1. GEOMAGNETIC DATA

As a raw geomagnetic material for processing and interpretation, the data provided by the Geomagnetic Map of Europe (Simonenko, Pashkevich, 1990) was used. The map was compiled based on rather different materials, and the process of merging the previously gathered data was not always accurate. However, the advantage of using it is that it provides a homogeneous image for the Black Sea (Fig. 3), based on a consistent data set provided by a regional airborne geomagnetic survey made by teams from the former Soviet Union, using similar technologies in data acquisition and processing.

4.2. GRAVITY DATA

Due to the confidentiality of the gravity data, the relative values of the gravity variation within the Black Sea area could be taken into account only. This is the reason why the results of our investigation bear a qualitative imprint. No quantitative evaluation could be made.

The input material used within the processing was represented by a gravity diagram (Fig. 4) of the Black Sea (Makarenko, 2000), which, in fact, is a compilation of the former gravity maps published by Belousov *et al*. (1988).

4.3. THE APPROACH

Both the previously mentioned geomagnetic and gravity contour maps were digitized and coordinates brought to the same system. Data were subject to a common computer database, which was then used for further processing. From the very beginning it should be mentioned that a slight miscorrelation in the regional gravity and the geomagnetic anomaly strike for the W Black Sea basin, which had occurred in the raw maps, represented the starting point in our research. We suspected that the presence of some cumulative effects distorted the geomagnetic image.

The basic approach in the investigation of the two potential fields was the filtering technique. Various filters were applied mainly for separating local anomalies from regional trends in the area. Discriminating regional from local effects in potential fields is an old problem (Nettleton, 1949). According to Kautzleben (1963) and Le Mouël (1969) the most appropriate field should provide a zero mathematical expectation to the residual geomagnetic anomaly. Accordingly, we prepared various reference fields, to be subtracted from the observations. Good results were especially obtained using the polynomial regression technique.

5. MAIN RESULTS

5.1. THE GEOMAGNETIC REFLECTION OF THE OCEAN-TYPE CRUST

Among the numerous geomagnetic reference field models computed, an eight order polynomial trend provided the most balanced geomagnetic anomaly. Fig. 5 exhibits the pattern of the residual geomagnetic anomaly obtained by removing that trend from the observations. The image was constructed using the color shaded relief technique (which is more sensitive to the discontinuities presence) with vertical illumination. As can be seen, it succeeded to appropriately outline areas with ocean-type crust in the central part of the basin (where the anomaly exhibits a peculiar pattern) in a rather good agreement with the Black Sea geology.

Besides, the continental platform area, well reflected in a specific geomagnetic field pattern, appears as a narrow zone along the south-western shore, while the NW Black Sea basin seems to cover a wider area, in full agreement with the seismic data.

5.2. GRAVITY AND GEOMAGNETIC ZONES ON THE BLACK SEA BOTTOM

Some geomagnetic and gravity zones were visible even in the raw material used. However, the problem consisted in the presence of some miscorrelation between the geomagnetic and gravity anomalies strike. A cumulative effect was suspected from the very beginning to be the cause of the miscorrelation, as previously mentioned.

Following the Kautzleben criterion, various filters were applied in order to discriminate between local and regional trends (Fig. 6). A similar approach was applied to gravity data (Fig. 7). By appropriately filtering the input data, the obtained residuals exhibited a good correlation in the strike of the gravity and geomagnetic anomalies. It seems that the best result was obtained when removing an 8th order polynomial trend from the geomagnetic data, and, respectively, a 9th order polynomial trend from the gravity data.

As can be seen in the pictures, both gravity and geomagnetic images outline several zones striking NE in the W Black Sea basin, and NW within E Black Sea. They advocate for the presence of some crustal slivers with distinct physical properties (magnetization and density) on the sea bottom, rather similar to the situation of the oceans floor. The almost perpendicular strike in the gravity and geomagnetic trend for W and E Black Sea strongly suggests distinct rifting environments for the two basins (Fig. 8). The fact appears somehow controversial with previous models that claim for the simultaneously opening of the two basins, related to a unique geodynamic event (the consumption of the Neo-Tethys floor in a northward subduction should have generated a unique EW strike).

An examination of the earthquake focal mechanism around the Black Sea (Eva *et al.*, 1988) adds new evidence to support the idea. Different strikes for *P* axes (which are parallel to the stress tensors) in various areas clearly indicate distinct tectonic environments in the surrounding land. Therefore, several major domains could be discriminated (Fig. 9). While eastern and western Black Sea inland focal mechanisms bear the fingerprint of the distinct opening of the W and respectively, E Black Sea basin, the westward strike of the *P* axes located in westernmost area seems to reflect the tectonic escape along the North Anatolian Fault (NAF). Mention should be made to the fact that generally, within each of the above-mentioned domains, *P* axes strike almost mono-directionally, except for (i) the Vrancea region, and (ii) another area, located SW Black Sea on a confined NAF segment. Within these zones the *P*-axes exhibit almost all azimuths. The second seismic “knot”, within the westernmost West Pontides, seems to be located in an area where the NAF would join another major tectonic contact (possible the extension of TTZ beyond the Moesian Plate and the Black Sea).

5.3. CRUST EXTENSION

Looking for the inland consequences of the crust extension provided by the W Black Sea opening, the re-examination of the previously obtained geophysical data led to other interesting results. For instance, the reinterpretation of the geomagnetic and gravity information within the SE Carpathians foreland revealed a new PCF track beneath the platform sedimentary cover (Beşuţiu, Nicolescu, 1999). It seems that, due to the W Black Sea opening the fault extended northwestward, toward the Carpathians, and met TTZ in the Vrancea active seismic area.

The data provided by seismological studies (Oncescu *et al*., 1998) were used to decipher the deep crust structure peculiarities in the area (Beşuţiu, 2001). By using the polynomial regression technique, epicenters of the last millennium registered earthquakes on the Romanian territory could be lined up along the track of several major faults well known on the Romanian territory: Sfântu Gheorghe, Peceneaga–Camena, Capidava–Ovidiu, Intramoesian, Varna–Giurgiu, and so on (Fig. 10).

Scares of major crustal faults splitting the SE Carpathians foreland were also pointed out in the image of the horizontal gradient of the geomagnetic anomaly (Fig. 11). The geomagnetic map is a product of the UKROMM project, a joint venture between the Geological Institute of Romania, the Institute of Geophysics of the National Academy of Sciences, and the Institute of Geology and Geophysics of the National Academy of Sciences of the Republic of Moldova (Beşuţiu *et al.*, 2000). The project was mainly aimed to the merging of national geomagnetic maps into consistent cross-over state borders images. Research was supported by the Romanian Academy grants GAR 82/1998 and GAR 81/1999.

It seems that crust extension, provided by the W Black Sea opening, reactivated some old crustal faults or created new ones, splitting the Carpathians foreland in a perpendicular direction to the rifting strike. Major crust brittle block-bounding faults shared the MoP into several sub-slabs. Within the geodynamic environment provided by the active rifting in the Red Sea and Aden Bay (Fig. 12), these crustal blocks relatively move to each other, from time to time. Their displacement generates normal earthquakes whose epicenters are lined up along their contacts. Among these crust blocks, the most active seems to be the compartment located immediately south PCF, where the main geotectonic effort was directed. It advanced hardly toward the Carpathians, taking along from time to time, by friction, the neighboring blocks and playing an important role in the Alpine chain bending.

5.4. CRUST SHORTENING

It seems that crust shortening related to the W Black Sea opening took place in various environments (Fig. 13).

In the **Eastern Carpathians**, crustal slivers met the inclined external boundary of TTZ and came into an **oblique subduction.** This way, they could be responsible for the specific peculiarities of the subduction-related South Harghita volcanism (Szakács *et al.*, 1993). It seems that the Bârlad Depression, well reflected in a gravity low striking across the direction of extension, is also a consequence of the NW pushing exerted by the crust expelled during the sea opening.

In the **Southern Carpathians**, the crustal blocks expelled by the Black Sea opening faced the vertical margin of the Intra-Alpine plate, the Trans-Getica fault (Beşuţiu, 2002a), and, consequently, did not come into a subduction process. The absence of volcanism in the area is consistent with this assumption. Instead, it is rather likely that the crust shortening took place in the area by a **lithosphere buckling** (Blundell, 1999). The presence of the lowest gravity low in front and not beneath the Southern Carpathians, the highest mountain chain on the Romanian territory, is fully consistent with this hypothesis.

Finally, **within the bending zone of the Carpathians**, the presence of a continental **unstable transform-transform-compression triple junction** has been recently assumed (Beşuţiu, 2001, 2002 b). Consequently, the lithospheric compartment located at the contact between the East European Plate, and the Moesian and Intra-Alpine microplates collapsed, and a huge mass of colder lithosphere penetrated the upper mantle. Therefore, several processes of temperature accommodation (convective cells, devolatilization, phase transform processes, and so on) could be responsible for the intermediate depth seismicity in the Vrancea zone.

6. CONCLUDING REMARKS

Based on geophysical data previously gathered within the Black Sea basin and the surrounding area, several considerations have been made on the Black Sea opening and, especially concerning its seismo-tectonic echoes on the NW neighboring inland. The paper was also aimed to demonstrate the still active potential of the gravity and geomagnetic methods for studying regional tectonics.

Following the research made, several aspects should be stressed:

– a peculiar aspect of the residual geomagnetic anomaly pattern was found within the **ocean-type sectors** of the Black Sea crust, which obviously separate it from the rest of the basin;

– an almost reciprocal perpendicular strike of the both residual gravity and geomagnetic anomalies within E and W Black Sea advocates for **distinct opening circumstances** of the two basins: **the seismo-tectonic imprint** in the Black Sea neighboring inland supports the above assumption;

– it seems that the Black Sea basins occurred along two major rifts striking almost perpendicular to each another, **in a rather similar manner to the present active rifting** within the Red Sea and the Aden Bay area (see Fig. 12);

– the off-shore seismics showing a slight thrusts of the E Pontides over the W Pontides seems to advocate for a relatively **earlier opening of the W Black Sea**;

– the crust extension provided by the W Black Sea opening **split the SE Carpathians foreland** into several compartments, by re-activating some (*Variscan*?) major faults or creating new crustal block-bounding faults striking perpendicular to the rifting direction;

– the active rifting in the Red Sea and the Aden Bay seems to determine the **present geodynamics** and crust seismicity within the SE Carpathians: the above mentioned crustal slivers are pushed toward NW and relatively move each to other thus generating normal earthquakes along their wedges;

– the crust shortening took place in **various environments**, the Eastern, and Southern Carpathians;

– according to the regional stress tensor state (Zugrăvescu, Polonic, 1997), it seems that the MoP presently experiences some **westward deriving** along the southern wedge of the IaP, somehow similar to the tectonic escape along the North Anatolian Fault.

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