

Age and Thickness of the Lithosphere within the Western and Eastern Basins of the Black Sea according to Geophysical Data

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Abstract: The ages of the western and eastern basins of the Black Sea have been estimated on the basis of heat-flow data. The obtained ages (70–60 Ma) are in good accord with the time of basins' origin as determined from seismic and magnetic data. During this time, the Black Sea opened as a back-arc basin to the north of the Pontide magmatic arc. The arc prehistory of the Pontides is confirmed by the existence of relict mantle seismicity, which is most active in the eastern Pontides. Nearly synchronous times of origin for the western and eastern basins supports the concept of their simultaneous genesis as a result of clockwise rotation of the Andrusov Rise. The lithosphere thickness of both basins (60–65 km) was also determined using geothermal data. The calculated thickness of the lithosphere corresponds to this one for oceanic lithosphere of Early Cenozoic age; this is confirmed by study of velocity dispersion for surface waves which propagate from Mediterranean earthquakes to seismic stations of the Crimea and western Caucasus. Analysis of heat-flow data strongly suggests that the sea floor of the western basin is underlain by oceanic crust, while the sea floor of the eastern basin is characterized by a thinned continental crust. According to geothermal modelling, the thickness of the granite layer in the eastern basin is about 4 km and that of the basaltic layer is approximately 6 km. The estimated thickness of crustal layers within this basin is confirmed by seismic data.

Key Words: Black Sea, heat flow, sea floor age, surface waves, lithosphere thickness

Jeofizik Verilerine Göre Batı ve Doğu Karadeniz Havzalarının Litosfer Yaşı ve Kalınlığı

Özet: Bu çalışmada batı ve doğu Karadeniz havzalarının yaşı ısı-akış verilerine göre belirlenmiştir. Elde edilen yaşlar (70–60 My) sismik ve manyetik verilerden elde edilen sonuçlar ile uyumludur. Bu zaman diliminde Karadeniz, Pontid magmatik yayının kuzeyinde yer alan bir yayardı havza olarak açılmaya başlamıştır. Pontidlerin ark tarihçesi, doğu Pontidler'de aktif olarak gözlenen kalıtsal manto kökenli sismisite ile de desteklenmektedir. Batı ve doğu Karadeniz havzalarının eş zamanlı gelişimleri, bu havzaların Andrusov yükseliminin saat yönündeki rotasyonuna bağlı olarak birlikte geliştiklerini ileri süren teoriyi de desteklemektedir. Her iki havzanın litosfer kalınlığı jeotermal verilere göre 60–65 km'dir ve bu değerler Erken Cenozoyik yaşlı okyanusal litosfer kalınlığına takabül etmektedir. Bu hesaplamalar Kırım ve Batı Kafkaslardaki sismik istasyonlarda kayıt edilen Akdeniz depremlerinin yüzey dalgalarının hız dağılımlarının incelenmesi ile de desteklenmiştir. Isı-akış verilerinin detay incelenmesi, batı Karadeniz havza tabanının okyanusal kabuktan, doğu Karadeniz havza tabanının ise ince kıta kabuğundan oluştuğunu ortaya koymuştur. Jeotermal modellemeye göre, doğudaki havza tabanındaki granit tabakasının kalınlığı yaklaşık 4 km, bazaltik tabaka kalınlığı ise yaklaşık 6 km dir. Ayrıca, havzada hesaplanan kıtasal tabaka kalınlıkları sismik veriler ile de desteklenmiştir.

Anahtar Sözcükler: Karadeniz, ısı akışı, deniz tabanı yalı, yüzey dalgaları, litosfer kalınlığı

Introduction

There are a great number of hypotheses about the mechanism which caused the origin of the Black Sea. The time of formation of this basin occurred from Palaeozoic to Mesozoic and Cenozoic, including Neogene and Anthropogene (Zonenshain & Le Pichon 1987; Belousov & Volvovsky 1989). The following three hypotheses based on different ideas – oceanization, relict basin, back-arc rifting and spreading – are the most widely known.

The first hypothesis concerns a mechanism of oceanization for the continental basement owing to eclogitization of the rocks of granite composition, and the age of the depression origin is considered to be the end of Miocene to Pliocene (Muratov 1972; Shlezinger 1981; Yanshin *et al.* 1980).

According to the second hypothesis, underlying the Black Sea floor is a relic of the Early Mesozoic Tethys ocean (Sorokhtin 1974).

Finally, the most acceptable hypothesis, suggests that the Black Sea is a back-arc basin which opened behind the Pontide magmatic arc and formed in the process of continental crust taphrogeny and spreading (Adamia *et al.* 1974).

The Pontide magmatic arc formed as a result of taking up in the subduction zone of the Tethys Ocean lithosphere (Dercourt *et al.* 1986); this extends from Georgia through the eastern Pontides, and offshore from the western Pontides to the Srednogorie zone in Bulgaria (Robinson *et al.* 1996).

It is supposed that western basin of the Black Sea is more ancient in comparison with the eastern basin (Okay *et al.* 1994; Robinson *et al.* 1995, 1996). According to these publications the time of western-basin formation is Early Cretaceous–Cenomanian. This estimation is based on the syn-rifting age (Barremian–Albian) and postrifting (Cenomanian) age of sediment complexes within the western Pontides. Discordance at the base of Cenomanian deposits corresponds to transition from a rifting regime to spreading. The age of the eastern basin is Palaeocene. It has been proposed that western and eastern basins formed simultaneously in the Late Cretaceous (Nikishin & Korotaev 2000). The other major idea is a two-stage formation for these basins. The first stage corresponds to Aptian–Albian time and the second to Palaeocene–Eocene (Kazmin 2000).

According to stratigraphic dates, which are available for the Pontides sedimentary basin, it is determined that the break-up of continental crust and onset of oceanic spreading was during the Cenomanian–Santonian (Görür 1988; Görür *et al.* 1993; Tüysüz 1999).

Thus, as a whole, the cause of the origin and evolution of the Black Sea basins is a debatable one. The age of the western and eastern basins is also open to debate because of the absence of representative data on the structure of the lower part of the sedimentary fill of the basins.

In previous publications (Golmshtok *et al.* 1992; Golmshtok & Hahalev 1987) there were attempts at determination of the age of lithosphere under western and eastern basins on the basis of heat-flow data. Those authors supposed that both basins were formed as result of oceanic spreading within Black Sea.

According to that estimation, the age of the western basin is 135–95 Ma, whereas the age of the eastern one is 110 Ma. The lithosphere thickness in these basins is 80–90 km. According to Zolotarev (1986), the age of the western and eastern basins is approximately the same (55 Ma). Age estimation based on sea-floor subsidence in accordance with a geothermal model of lithosphere formation gave an age 80 Ma for the opening of the whole Black Sea basin (Zonenshain and Le Pichon 1987).

Taking into account the paramount importance of the definition of the age of the Black Sea sedimentary basin to understand its evolution, and a great variety of assessments, we have carried out analysis of the recent geological-geophysical data. First of all, representative seismic data from the Black Sea floor, obtained by Italian researchers, (Finetti *et al.* 1988), were used. New geological-geophysical interpretation of seismic material by Russian-Italian research groups were also used (Belousov & Volvovsky 1989). In light of these data, a conclusion was permitted in a recent paper (Kazmin *et al.* 2000), that the main stage of opening of the eastern and eastern basins took place either at the end of the Cretaceous or at the beginning of the Palaeocene. Such a conclusion does not agree with the above-mentioned estimation of basins' age, and consequently with the assessment of lithosphere thickness obtained from geothermal data. To obtain additional information about the thickness of the Black Sea lithosphere and its genesis, seismological data using the distribution of the mantle earthquakes (mainly within the eastern Pontides) were

used. In addition, the data on surface-wave dispersion from Mediterranean earthquakes at stations of the Crimea and Caucasus have been taken into account (Sikharulidze *et al.* 1983). Finally, a comparison of estimations of lithosphere thickness has been done based on geothermal data for the Black Sea and for its continental framework from the north and north-west according to deep seismic sounding (DSS) data and data of geothermics, magnetotelluric sounding and seismology (Chekunov *et al.* 1993).

This paper is devoted to discussion of uniqueness of approach, which is based on more precise estimation of the influence of sedimentary sequence upon heat flow. In addition, the depth component of heat flow is determined. This guarantees a more reliable approach both with respect to age estimation and lithosphere thickness of the Black Sea basin. Data from a magnetic survey presented by Shreider *et al.* (1997) were also used to frame the age determination.

Geothermal Regime and Time of Origin of the Western and Eastern Black Sea Basins

Figure 1 shows major structures, heat flow and mantle seismicity of the Black Sea area, which are taken from previous papers (Finetti *et al.* 1988; Golmshtok & Zolotarev 1980; Artemenko *et al.* 1988; Erickson *et al.* 1974, 1978; World Earthquake Catalogue 1990).

For the western basin there are 18 heat-flow measurements, and 17 for the eastern basin. The average measured (background) values are 32 ± 14 mW/m² and 34 ± 12 mW/m², respectively; that is, roughly two times lower than average global geothermal background (60 mW/m²) and 1.5 times less than background heat flow for the deep depressions of the world's oceans (40 mW/m²). Taking into consideration the great thickness of sediments in the western and eastern basins (12 km as an average, Finetti *et al.* 1988), a correction for the velocity of sediment accumulation and contrast of thermal conductivity and diffusivity of sediments must be introduced into the background heat flow.

A value for the correction can be determined by equation (1), which takes into account the thickness of sedimentary layer in the basin without compaction of sediments under the influence of lithostatic pressure (Golmshtok & Hahalev 1987).

$$Z_1 = \tilde{Z}_1 - \frac{n_m}{K} \left[\exp - \tilde{K} (\tilde{Z}_n - \tilde{Z}_1) - \exp - \tilde{K} \tilde{Z}_n \right] + \frac{n_m}{K} (1 - \exp - \tilde{K} Z_1) \quad (1)$$

where Z_1 is the thickness of the lower sedimentary layer without the effect of pressure of overlying layers; \tilde{Z}_1 is the observed thickness of the lower sedimentary layer; \tilde{Z}_n is the thickness of the whole sedimentary sequence; n_m is the sediment porosity at the bottom; K is a parameter of sediment compaction. Equation (1) is solved by the iteration method.

A chronological scale of thickness for sedimentary layers of the western and eastern basins was used in calculation. This scale is based on data of deep Seismic Sounding (DSS) (Finetti *et al.* 1988). According to these data $Z_1 = 8$ km (for Palaeocene-Oligocene sedimentary sequence) and $\tilde{Z}_n = 12$ km (for the whole sedimentary cover), with $n_m = 0.6$ and $\tilde{K} = 0.45$ km (Golmshtok & Hahalev 1987), we find $Z_1 = 11$ km.

To introduce a correction for sediment accumulation into the background heat flow, a technique from Golmshtok (1979) was used. The following parameters were determined for this purpose:

$$P = \frac{H}{2\sqrt{a_2 t}} \quad S = \frac{\lambda_2}{\lambda_1} \sqrt{\frac{a_1}{a_2}} \quad (2)$$

where H is the thickness of the sedimentary layer; λ_1 and a_1 are coefficients of thermal conductivity and diffusivity of rocks in the lower sedimentary layer; λ_2 and a_2 - the same values for upper sedimentary layer, t is the age of the sediments.

The thickness of the sedimentary layers H within the western and eastern basins is nearly the same, (Finetti *et al.* 1988; Legend to the Album of Structural Maps and Maps of Thickness of the Black Sea Cenozoic Sediments 1993). Coefficients of thermal conductivity λ , thermal diffusivity a and of radioactive heat generation σ were taken from previous works (Initial Reports Deep Sea Drilling Projects 1978; Belousov & Volvovsky 1989). Heat flow q_0 was corrected for sediment accumulation, which was determined by defined parameters P and S from (2). The corrected heat flow for the western and eastern basins is nearly the same because of the close

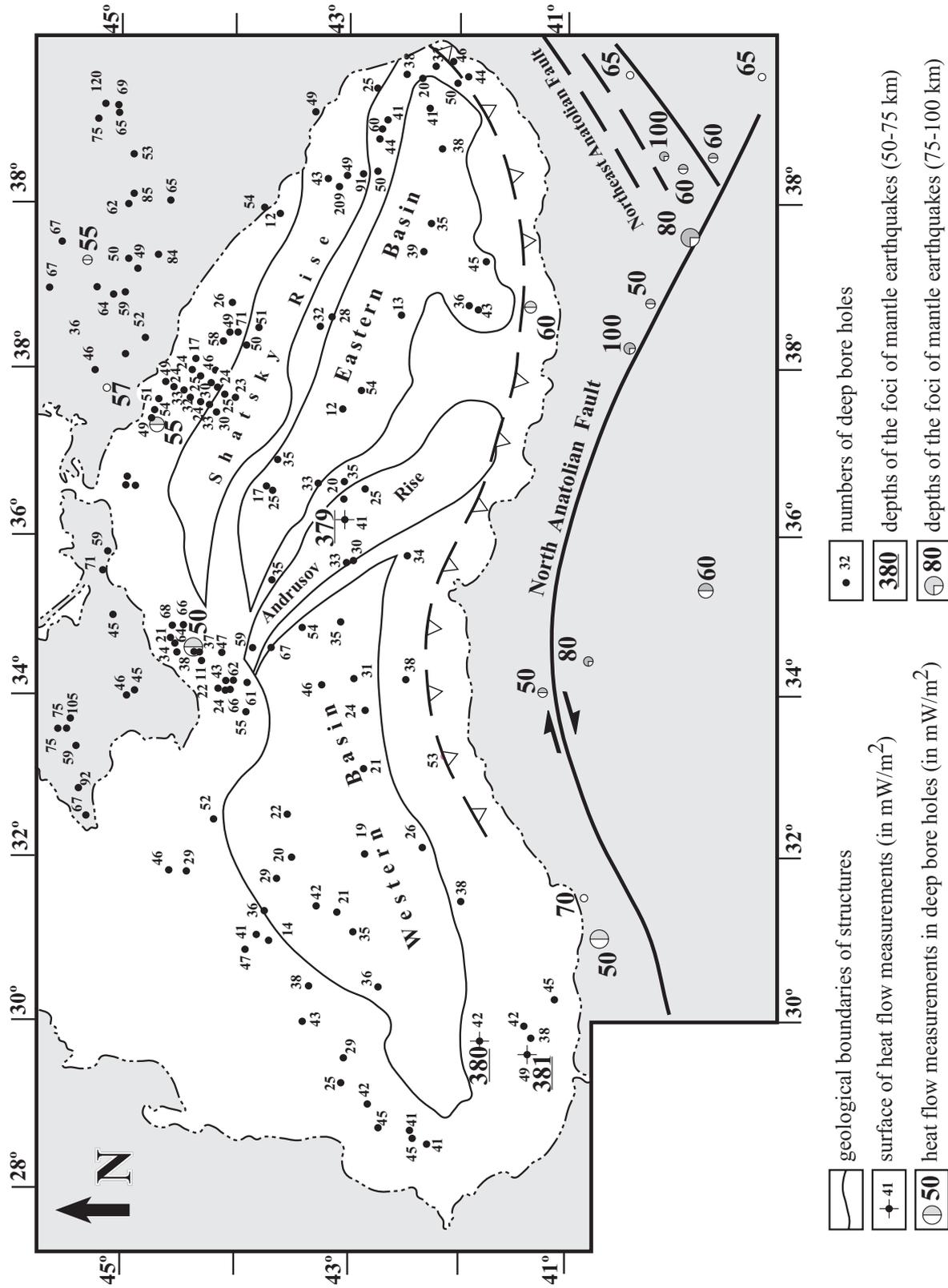


Figure 1. Map of main structures, heat flow and mantle seismicity within the Black Sea region. North Anatolian and East Anatolian faults according to Barka (1992) and to Trifonov et al. (1994).

thickness of sedimentary layers within both basins (see Tables 1 & 2).

Calculated heat flow for the western basin is 60 mW/m², and is close to a deep heat flow (from the mantle and basement). Based on the analysis of results of seismic research, it has been proposed that the lithosphere of the western basin was formed as a result of the oceanic spreading (Neprochnov 1960). Thus using the aforementioned value for heat flow, an estimate of the age of the basin's lithosphere can be obtained by applying the following expression, which is the solution of the equation for geothermal model of oceanic floor of spreading origin (Davies & Lister 1974; Parsons & Sclater 1977; Carlson & Johnson 1994),

$$t = \frac{\lambda \cdot T_a}{\pi a q^2} = 23,2 \cdot 10^4 / q^2, \quad (3)$$

where t is the age of the lithosphere, (Ma); $\lambda = 3.2$ W/m·K is a coefficient of thermal conductivity of the lithosphere material; $T_a = 1350^\circ\text{C}$ is the temperature of the asthenosphere; $a = 7.8 \cdot 10^{-7}$ m²/s is a coefficient of thermal diffusivity of the mantle substance; q - mW/m² is heat flow.

From equation (3) it follows that for heat flow 60 mW/m² the age of the floor of the Black Sea western basin is about 64 Ma (Early Palaeocene). Taking into account an error of the bottom-age estimation based on geothermal data ($\pm 10\%$), the time of formation of this basin should be taken as 70–60 Ma.

Present maps of surfaces of seismostratigraphic units of the Black Sea use data from Italian (Finetti *et al.* 1988) and Russian researchers (Legend to the Album of Structural Maps and Maps of Thickness of the Black Sea Cenozoic Sediments 1993). Analysis of these maps indicate that two palaeorifts in the western basin are filled with Upper Cretaceous and Palaeocene–Eocene sediments. Their opening took place on the rear side of the Pontide magmatic arc. Rift depressions were the depocenters for accumulation of post-rift sediments. On the whole, the Palaeocene–Eocene sediments in the central part of western basin were deposited on a basaltic substratum. The Cretaceous deposition is revealed at margins of this basin only (Neprochnov *et al.* 1974; Finetti *et al.* 1988). Consequently the age of the lithosphere of this basin as determined by heat-flow data

(64 Ma), is in accordance with its rift origin and indicates a spreading nature for bottom formation.

This enables assessment of the thickness of the western basin lithosphere according to a ratio based on a connection between the thickness of oceanic lithosphere and the time of its cooling (Parker & Oldenburg 1973).

$$H_1 = (T_s/T_a) \sqrt{\pi a t} = 1,6 \cdot 10^{-3} \sqrt{a t} = 7,8 \sqrt{t}, \quad (4)$$

where H_1 , km is the thickness of the lithosphere; $T_s/T_a = 1200/1350^\circ\text{C}$ is a ratio of the temperature of the solidus and liquidus for the mantle basalts; $a = 7.8 \cdot 10^{-7}$ m²/s is a coefficient of thermal diffusivity for mantle substance; t Ma is the age of the lithosphere.

If we substitute in equation (4) the basin's age as determined from heat-flow data (64Ma), we shall obtain a lithosphere thickness of 62 km and, with regard to the time interval of the bottom formation, it is 60–65 km. This value agrees with the thickness of oceanic lithosphere of Early Cenozoic age (Yoshii 1975).

The eastern basin is narrows to the northwest, and then western one – toward the southeast (see Figure 1). This configuration resembles the so-called “Afar” kinematic scheme (see papers in Tectonophysics, Volume 123, 1986). Related to the opening of the eastern basin was the clockwise rotation of a narrow block of continental crust – the Andrusov Rise (Kazmin 1987; Okay *et al.* 1994; Shreider *et al.* 1997). Such a motion was possible only when the Pontian island arc drifted southward, with the simultaneous opening of the western basin (Figure 2) (Kazmin 1997; Kazmin *et al.* 2000).

Seismic research has revealed an equal thickness of Palaeocene–Eocene deposits (2–3 km) in the eastern and western basins, consequently indicating the same regime of subsidence and sedimentation (Finetti *et al.* 1988; Kazmin 2000). The western basin also rifted but attained oceanic spreading, while the eastern did not reached oceanic stage.

Similar values of the deep heat flow (67 and 60 mW/m², respectively) in the eastern and western basins are indicated at by the closeness of age of their origin (Tables 1 & 2), attributable to their simultaneous opening.

According to seismic investigation, the eastern basin is underlain by thinned ($\beta \cong 3$) continental crust (Finetti *et al.* 1988; Belousov & Volvovsky 1989). Taking into

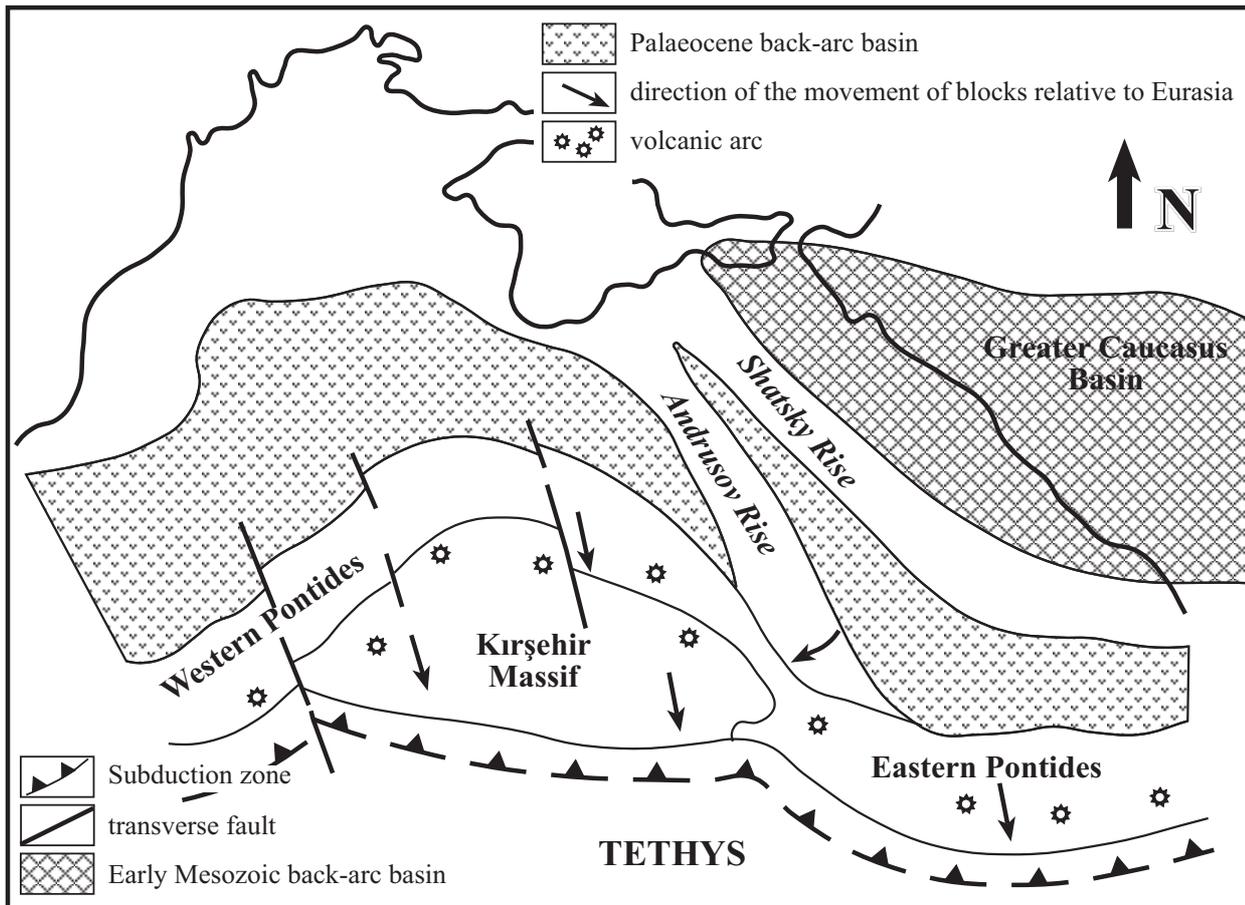


Figure 2. Palaeogeodynamic reconstruction of Palaeocene age (after Kazmin *et al.* 2000). 1– subduction zone; 2– transverse faults; 3– Early Mesozoic back-arc basin; 4– Palaeocene back-arc basin; 5– direction of the movement of blocks relative to Eurasia; 6– volcanic arc.

Table 1. Heat flow in the western Black Sea basin.

Horizon	H	q_m	λ	a	P	S	K	σ	q_0
Quaternary	1	32	1.1	2	0.14	1.12	1.27	0.85	40
Pliocene	1	40	1.2	3	0.10	1.15	1.17	1.0	46
Miocene	2	46	1.3	4.5	0.06	1.0	1.05	1.15	46
Oligocene–Palaeocene	8	46	1.6	6.5	0.19	0.67	1.57	1.55	60

Table 2. Heat flow in the eastern Black Sea basin.

Horizon	H	q_m	λ	a	P	S	K	σ	q_0
Quaternary	0.5	34	1.1	2	0.07	1.12	1.11	0.85	38
Pliocene	0.7	38	1.2	3	0.07	1.12	1.11	1.0	41
Miocene	3	41	1.3	4.5	0.09	1.0	1.19	1.15	46
Oligocene–Palaeocene	8	46	1.6	6.5	0.17	0.6	1.7	1.55	67

Notes: H is thickness of sediments (km); q_0 is surface measured heat flow (mW/m^2); λ is the coefficient of thermal conductivity ($W/m\cdot K$); a is the coefficient of thermal diffusivity ($10^{-7} m^2/s$); P, S are the parameters of heat-flow correction for sediment accumulation; K is a correction coefficient; σ is a radioactive heat generation ($10^{-6} W/m^3$); q_0 is a corrected heat flow, (mW/m^2). For calculations, we used $\lambda= 2.9 W/m\cdot K$; $a= 7\cdot 10^{-7} m^2/s$ for basaltic layer; and $\lambda= 2.5 W/m\cdot K$; $a= 5\cdot 10^{-7} m^2/s$ for granite layer.

consideration the presence of the granite layer in the crust, we carried out modelling of the basin's lithospheric structure. The following expression (5) for stationary heat field of the continental genesis was used (Polyak & Smirnov 1968; Smirnov 1980).

$$q = \lambda \cdot \Delta T / \Delta Z + A \cdot \Delta Z \quad (5)$$

where q - mW/m^2 is a deep heat flow; $\lambda = 3.2 \text{ W/m}\cdot\text{K}$ is heat conductivity of the lithosphere material; $\Delta T = 1200^\circ \text{C}$ is the temperature on the foot of lithosphere; ΔZ - is the thickness of lithosphere in meters; $A = 1.5 \cdot 10^{-6}$, $0.46 \cdot 10^{-6}$ and $0.008 \cdot 10^{-6} \text{ W/m}^3$ is the generation of radiogenic heat for granite, basaltic and mantle layers, respectively.

Model results indicate that eastern basin lithosphere is 66 km thick with a basaltic layer of 6 km and granitic layer of 4 km thickness creating a summary heat flow of 68 mW/m^2 . This is in a good accordance with deep heat

flow of 67 mW/m^2 determined from geothermal data by using the thickness of sediment layers obtained by seismic methods. This supports the proposed model of lithospheric structure. The thicknesses of the basaltic and granitic layers of the basin's crust, which were obtained as a result of modelling, are close to the average thicknesses of these layers, obtained from seismic data (Finetti *et al.* 1988; Belousov & Volvovsky 1989).

According to seismic data, the bedding of the post-rift sedimentary Palaeocene–Eocene sequence of the eastern basin is discordant with rocks of Mesozoic age (Figure 3, Finetti *et al.* 1988). This fact indicates that the main stage of the basin's formation may be dated between Late Cretaceous and the beginning of Palaeocene (Kazmin *et al.* 2000).

After subtraction of radiogenic heat contribution for lithosphere in the whole 8 mW/m^2 (including the granite layer of the crust from the summary heat flow 68

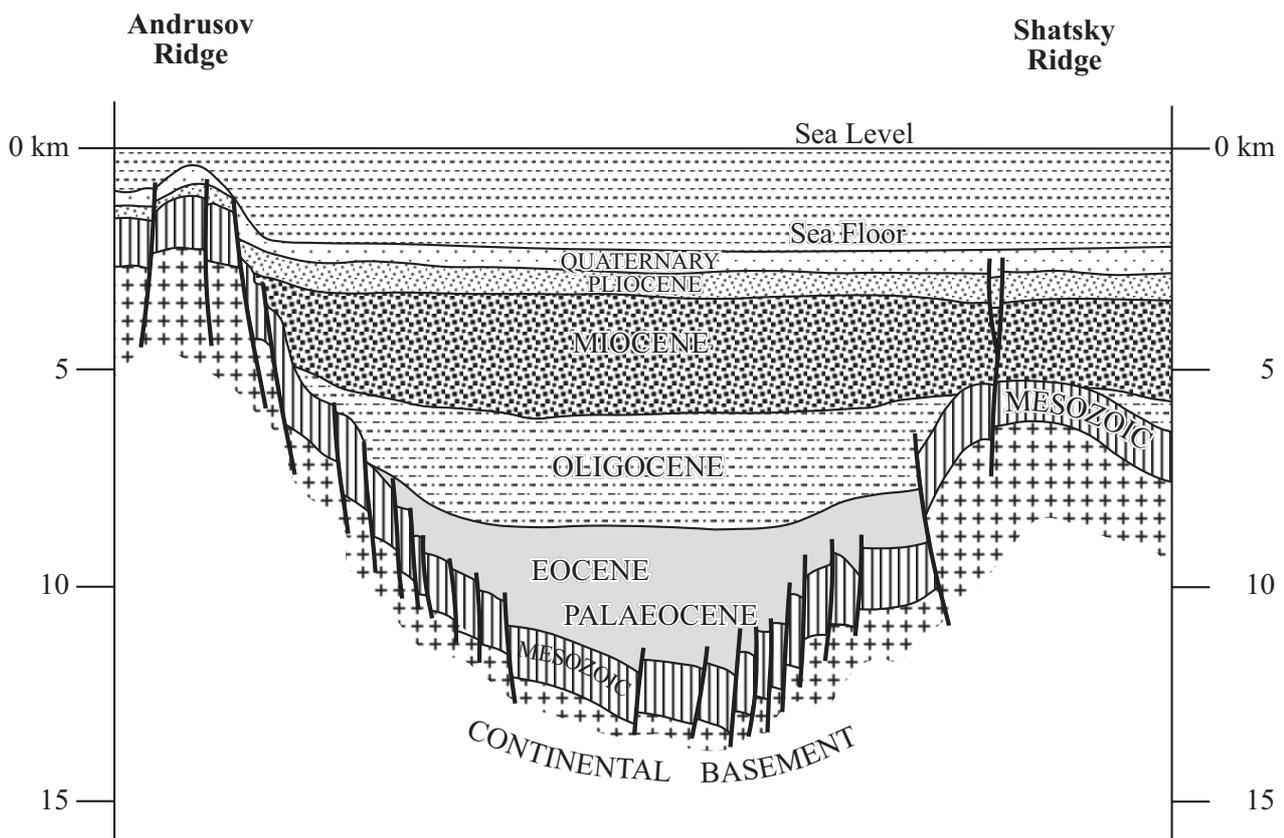


Figure 3. Seismic profile across the southern part of the Andrusov Rise, eastern basin and Shatsky Rise in a northeastern direction (after Finetti *et al.* 1988). The Palaeocene–Eocene sedimentary sequence is discordant with respect to Mesozoic rocks.

mW/m^2), we can calculate the age of the eastern basin (Verzhbitsky 1996) according to formula (2). The obtained age is practically the same as the aforementioned age of the western basin (Early Palaeocene). The calculated age is confirmed independently by magnetic data for the northeastern part of the eastern basin (at a border with the Shatsky Rise). Linear magnetic anomalies 26–23 have been observed in this region, and their age is 64–62 Ma according to scale of geomagnetic chronology (Shreider *et al.* 1997).

Thus, identical ages for the western and eastern Black Sea basins as determined from heat-flow data, is in good agreement with seismic data. This allows us to conclude that there was synchronous formation of their lithospheres in the Late Cretaceous–Early Palaeocene.

Comparison of Estimations of Lithospheric Thickness by the Geothermal Method by Assessments with Other Geophysical Data

Existing estimations of lithosphere thickness for the continental framework of the Black Sea from the north and northwest have been based on data obtained from long DSS profiles, geothermal data, magnetotelluric sounding and seismology (Chekunov *et al.* 1993). According to these data, the lithosphere beneath the Crimean peninsula and the adjacent Black Sea is 100–150 km thick (the lesser thickness corresponds to the northwestern part of Crimea). Under the southwestern flank of the eastern European Platform, the lithospheric thickness increases to 250 km, and it decreases to 70–100 or 70–120 km near the Vranich Mountains. At the same time, the thickness of the crust under the Black Sea is less, see Figure 4.

In this study, it is possible to assess the thickness of the Black Sea lithosphere using geothermal data for the points near the southern coast of the Crimea and for the coast of northwestern Caucasus. All of these points correspond to epicenters of mantle earthquakes of the northwestern Caucasus (Kuban, 1926, $M=5.4$; $H=50$ km; Anapa 1966, $M=5.8$; $H=55$ km) and of the southern Crimea (aftershock of the Crimean earthquake, 1927, with $M=5.8$ and $H=50$ km) (Kondorskaya & Shebalin 1977). Values of heat flow given in Figure 1 and published data on the Earth's crustal structure (Malovitsky & Neprochnov 1966; Sikharulidze *et al.* 1983) were taken as the basis for calculation. In

principle, the choice of calculation points for assessment of lithospheric thickness is arbitrary, but it was interesting to obtain such a thickness exactly at the points of the mantle earthquake origin in order to ascertain the location of their sources in the lithosphere. Initial data and calculated lithospheric thickness are given in Table 3.

Lithospheric thickness in Table 3 was calculated by equation (4). Regional background values of heat flow were used; they are $\sim 50 \text{ mW/m}^2$ for the Anapa and Crimean earthquakes and $\sim 60 \text{ mW/m}^2$ for the Kuban earthquake. Generation of radiogenic heat in the sediments is $1.4 \cdot 10^{-6} \text{ W/m}^3$.

It follows from Table 3 that estimations of lithospheric thickness from geothermal data for the northwestern Caucasus are close to those for the Crimea and, for the southern coast of the Crimea, they concur with independent assessments from Chekunov *et al.* (1993). Taking into consideration estimations of lithosphere thickness by the geothermal method ($\pm 10\%$), coincidence of the results can be considered good.

Another conclusion from Table 3 is that, according to its thickness, lithosphere of the northwestern Caucasus and a large part of the Crimea is nearly of continental type, and the sources of mantle earthquakes coincide with its upper layers.

Figure 1 also shows epicenters of mantle earthquakes in the Pontides according to the catalogue of the International Seismological Center (World Earthquake Catalogue 1990). It follows from Figure 1 that the majority of mantle earthquakes with focal depths 50–100 km are clustered within the eastern Pontides. Such a situation can be explained partly by the proximity of this region to regional seismic stations of Caucasus. It is known that research on the seismicity of Turkey began to develop only after a disastrous Erzincan earthquake in 1939 ($M=8$, $I_0=10\text{--}11 \text{ MM}$), and the development of the seismic network roughly from 1960. In the middle of 1960s, only there seismic stations operated at the territory of Turkey: to the northeast from Ankara, near İzmit and in the northwest of the country (Polyakova 1985). According to available data during the period after 1939 only a single mantle earthquake has occurred within the western Pontides (1957, $M=5.8$; $H=50$ km) (Polyakova 1985).

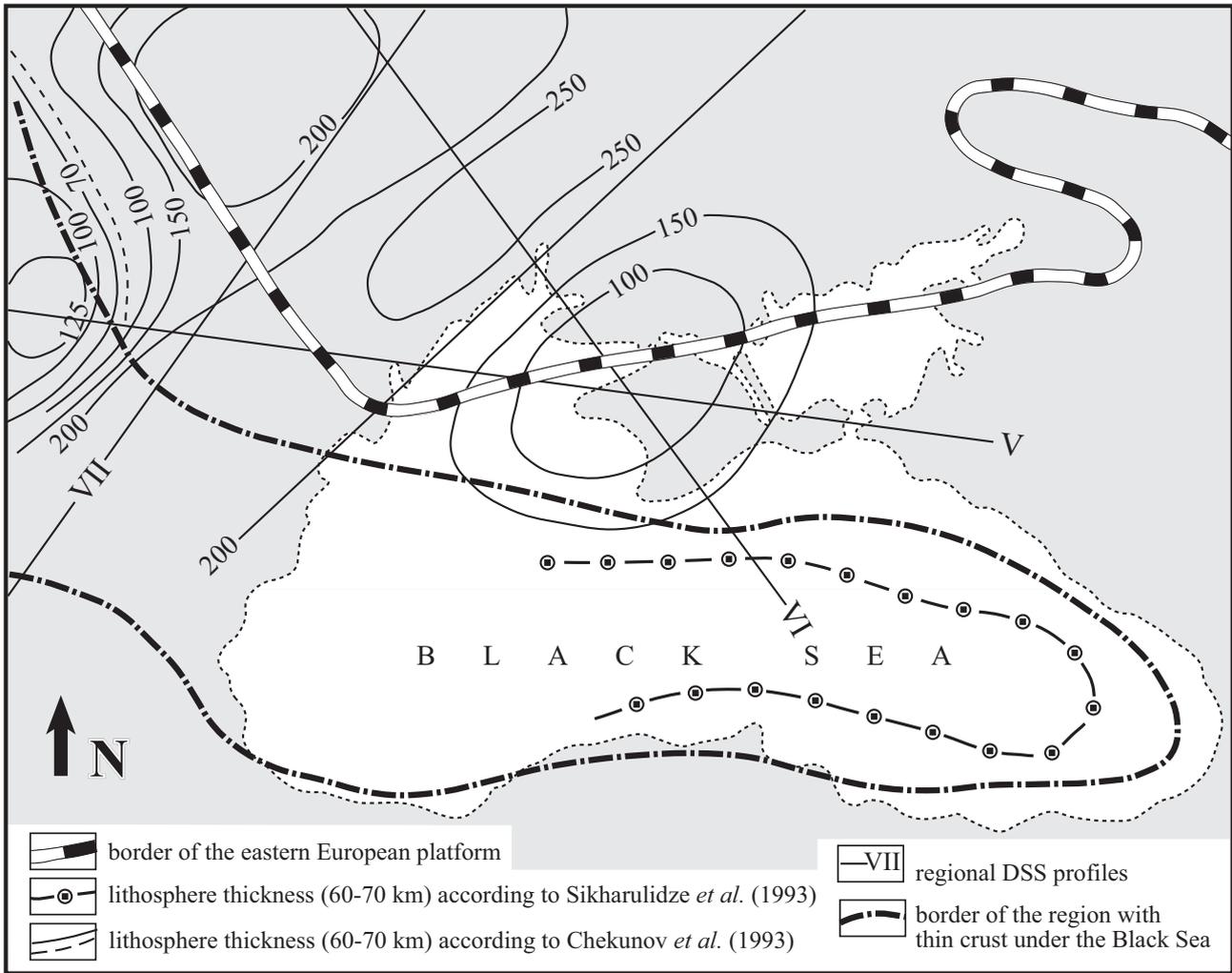


Figure 4. Map of lithosphere thickness in the Black Sea region. 1– regional DSS profiles; 2– border of the region with thin crust under the Black Sea; 3– border of the eastern European platform; 4– lithosphere thickness (60–70 km) according to (Sikharulidze *et al.* 1983); 5– the same according to (Chekunov *et al.* 1993).

Table 3. Estimation of lithosphere thickness obtained by geothermal data

NN	Structure of crust			Thickness of lithosphere (km)	Parameters of earthquakes				Name of earthquake and date
	sediments (h, km)	granite (h, km)	basalt (h, km)		φ° , N	λ° , E	H, km	–	
1.	6	13	20	175	45,3	39,3	50	5,4	Kuban, 19.04.1926
2.	3	9	19	148	44,3	34,3	50	5,8	Aftershock of Crimean 11.09.1927
3.	8	10	19	153	44,7	37,3	55	5,8	Anapa, 12.07.1966

Insofar as there are no data on heat flow and crustal structure, estimation of lithospheric thickness by the geothermal method is impossible. According to seismological data, one can judge only approximately about a possible lithospheric thickness. Thus, for the western Pontides, based on the maximum depth of mantle earthquake foci, the lithosphere must be thinner than 100 km. At the same time, a tendency of decreasing depth of mantle earthquake sources toward the southern Black Sea coast can be considered an indicator of decreasing lithospheric thickness beneath the Black Sea depression.

The results of analysis of direct and reflected deep-boundary surface waves, that propagate from Mediterranean earthquakes, and are recorded at the seismic stations of the Crimea, Anapa and Sochi, give more definite information about reduced lithospheric thickness beneath the Black Sea. In the paper of Sikharulidze *et al.* (1983) on the basis of determination of maximum length of direct and reflected surface waves and study of dispersion of their velocities under the eastern part of the Black Sea, it has been shown that the reflecting boundary is located at a depth of 60–70 km. Taking into account a definite lithospheric thickness determined from geothermal data (60–65 km, as shown above), the position of that boundary coincides with the base of lithosphere. According to this paper, contours of the reflecting boundary are sub-parallel to a boundary that separates regions with decreased and increased thickness of the crust (Chekunov *et al.* 1993), and they are shifted in the direction of the open sea some 30–40 to 70 km (Figure 4). Taking these data into consideration, one may expect a distinctly negative gradient of lithospheric thickness to the south of the Crimea (roughly 1.0–0.6 km/km).

In conclusion, it is necessary to emphasize that information on mantle seismicity in the Black Sea framework (as used in this paper) is of fundamental importance and plays a double role. First, taking into account a large time lag of tectonic processes, we can consider that the «arc» prehistory of the Pontides must have had an influence upon the development of recent processes (the most important aspect). Relict mantle seismicity must be one kind of manifestation of such processes. This factor is most profoundly expressed in the region of the eastern Pontides, while single mantle earthquakes in the western Pontides, southern Crimea

and in the northwestern Caucasus represent the tectonic prehistory of these regions to a lesser extent. Second, the greatest depth of the mantle earthquake sources gives an idea about probable lithospheric thickness, insofar as within asthenosphere there are no conditions for the origin of fragile deformations due to primary plastic relaxation of accumulated tectonic stress. This conclusion can, to some extent, be applied to the eastern Pontides, and less so to other regions of the Black Sea framework.

Thus, on the one hand, the use of seismological information (mantle seismicity) afforded to confirm a geological assumption about the «arc» prehistory of Pontides (to a lesser extent, for other regions active in ancient tectonic history). On the other hand, seismological data (reflection and dispersion of velocities of surface waves) provide independent confirmation of the conclusion about a decreased lithospheric thickness beneath the Black Sea (to 70 km), that was made by geothermal calculation.

Conclusions

1. Estimation of the age of the western and eastern Black Sea basins has been achieved by using heat-flow data (70–60 Ma). This assessment is in a good agreement with the age obtained by estimation of sediment-layer thicknesses according to seismic data (Late Cretaceous–Early Palaeocene) related to the basins origin as a result of the opening of back-arc basins behind the Pontide magmatic arc. The arc prehistory of the Pontides is confirmed by the existence of relict mantle seismicity which is most intensive within the eastern Pontides.
2. Similar ages for the lithosphere of the western and eastern basins obtained from geothermal data supports the idea of their simultaneous opening due to clockwise rotation of the Andrusov Rise.
3. The lithospheric thickness of the western and eastern Basins calculated from heat-flow data (60–65 km) corresponds to the thickness of the Early Cenozoic oceanic lithosphere. This conclusion is confirmed by data on the dispersion of velocities of surface waves on traces of Mediterranean earthquakes to seismic stations of the Crimea and western Caucasus (Anapa, Sochi). According to these data, under the northern and southern parts of the Black Sea, there is a

reflecting boundary at a depth of 60–70 km which has contours parallel to the shoreline. This boundary can be considered the base of the lithosphere beneath the Black Sea. Its depth agrees with the geothermal assessment of lithospheric thickness.

4. Analysis of the heat-flow data suggests an oceanic type of crust for the western basin. Geothermal modelling for eastern basin lithospheric structure reveals the presence of a basaltic layer (6 km thick)

and a granitic layer, attenuated to 4 km. These results agree with the estimates based on deep seismic sounding data.

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