SEISMICITY AND TSUNAMIGENIC POTENTIAL OF THE BLACK SEA AND SURROUNDING AREAS*

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The main purpose of the paper is to highlight the crustal seismicity of the Black Sea, taking into account and the tsunamigenic potential. According to the distribution map of earthquakes epicenters and as well as to the map of the areas with active faults, were established nine seismic sources such as Central Dobrogea (S1), Shabla (S2), Istanbul (S3), North Anatolian Fault (S4), Georgia (S5), Novorossjsk (S6), Crimea (S7), West Black Sea (S8) and Mid Black Sea (S9). The maximum possible magnitude of the seismic source was made on seismotectonic and geological database, concerning international practice and IAEA recommendation or applying empirical formulas of Wells and Coopersmith. From the seismological point of view, the types of faults (earthquakes types) which are responsible for a tsunami are the thrust fault (associated with subduction zones), normal/inverse faults, and less strike-slip fault, if the oblique-slip and deep slip components are a predominant, magnitude higher than 6.5 and depth, a crustal one, less than 4^{0} km depth. The major contribution to the total seismic hazard in the western part of the Black Sea is given by the Shabla crustal source with a maximum epicentral intensity equal to VIII ½.

Key words: active faults, earthquake types, earthquakes distribution, earthquake magnitude.

1. INTRODUCTION

After Italy and Greece, Romania is the next country that has high seismicity of over 300 earthquakes of magnitudes M>2.5 are recorded annually. In the complex tectonic environment of the Romanian territory, several individual seismogenic zones have been identified: Bârlad Depression (BD), Predodrogean Depression (PD), Moesian Platform (MP), and Crișana-Maramureș (CM) in the North and Făgăraș-Câmpulung zone (FC) in central Romania, Banat (BA) and Danubian (DA) zones in the western part of the country. The most active seismogenic zone is Vrancea, lying at the eastern corner of the Carpathian Belt. Besides these zones, the western part of the Black Sea is an area with high seismicity. Even though it has only one area that produced an earthquake with a magnitude over 7 (Shabla), the western part of the Black Sea is recorded as having overtime several tsunami-like phenomena in western Crimea, Bulgaria, and Turkey (Table 1). Of the nine areas with tsunami potential, we will specifically analyze those that may affect the west coast of the Black Sea, as follows: Central Dobrogea (S1), Shabla (S2), Istanbul (S3), North Anatolian Fault Zone (S4), the western part of the Crimea (S7), and West Black Sea (S8).

2. GEOTECTONIC SETTINGS

The Black Sea is the largest European back-arc basin, situated at the transition zone between a group of orogenic belts and a tectonic mosaic of units at the southern margin of the East-European craton (Okay *et al.*, 1996; Robinson *et al.*, 1996; Stephenson *et al.*, 2004; Saintot *et al.*, 2006).

Black Sea Basin consists of two sub-basins, eastern (EBSB) and western (WBSB) separated by the Mid-Black Sea Ridge (High), (Fig. 1, Munteanu *et al.*, 2011).

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Table 1

The most relevant tsunami at the Black Sea
(after Papadopulos *et al.*, 2011, and National Geophysical Data Center / World Data Service)

	Year	**Mo**	**Day**	**Hr**	**Mn**	M_W	**Country**	**Name**	**Latitude**	**Longitude**
1	-50					–	BULGARIA	BLACK SEA	43.500	28.500
2	103					**7.0**	UKRAINA,	CRIMEA, BLACK SEA	44.420	33.180
3	544					**7.5**	BULGARIA	BLACK SEA	43.120	28.180
4	1427					**7.0**	UKRAINA	SOUTH CRIMEA, BLACK SEA	44.240	34.180
5	1598	5				**7.0**	TURKISH	BLACK SEA COAST	40.240	35.240
6	1615	6	5			**5.7**	UKRAINE	SW CRIMEA, BLACK SEA	44.900	35.500
7	1650					**7.0**	UKRAINA	BLACK SEA	44.420	33.180
8	1802	10	12			**7.7**	UKRAINA	WEST CRIMEA, BLACK SEA	45.420	26.360
9	1838	1	23			**6.7**	UKRAINA	BLACK SEA	45.420	26.360
10	1869	10	11	13		**5.6**	UKRAINE	BLACK SEA	44.750	35.000
11	1875	7	25			**5.5**	UKRAINA	WEST CRIMEA, BLACK SEA	44.300	33.180
12	1901	3	31	7	12	**7.2**	BULGARIA	BLACK SEA	43.400	28.500
13	1927	6	26	11	20	**6.0**	UKRAINE	CRIMEA, BLACK SEA	44.400	34.400
14	1927	9	11	22	15	**6.8**	UKRAINE	CRIMEA, BLACK SEA	44.400	34.500
15	1968	9	3	8	19	**6.6**	TURKEY	BLACK SEA	41.800	32.300
16	2007	5	7			–	BULGARIA	BLACK SEA	43.000	29.000
17	2014	6	27	10	37	–	UKRAINE	ODESSA	46.320	30.670

The Western Black Sea Basin, an area of interest, interpreted as a remnant or extensional back-arc basin related to the Northward subduction of the Neotethys behind the Serbomacedonian – Rhodope – Pontide, was open in **late Early Cretaceous** times (Aptian-Albian), (Finetti *et al.*, 1988; Görür, 1988).

Concerning the tectonic units from the Romanian Black Sea coast, we highlight:

A) the Scythian Platform, by Precambrian age; its study was made only through indirect methods: magnetometry, gravimetry, seismic, and drilling, was separated a system of major overthrusts, with regional character and northern vergences, such as Chilia, Șerpilor Island, Sulina–Tarhankut and Golitin overthrusts. This unit is bounded to the south by Sulina–Tarhankut fault and to the North by the Trotus Fault.

B) Northern Dobrogea, also known as North Dobrogea Orogen, represents a relatively narrow area situated between the Scythian Platform at North and Moesian Platform to the South, bounded Sulina–Tarhankut fault to the North and Peceneaga–Camena fault to the south. The Northern Dobrogea has a complex structure, being formed by several tectonic units between which there is an over thrusting relation, the vergence being northeastern.

C) Moesian Platform border westwards the Black Sea, spread from north, from Peceneaga–Camena fault until south, in front of Balkans, formed from a Baikalian basement and a phanerozoic sedimentary cover.

The faults from the Western Black Sea Basin consist almost of three fault systems. The first one contains the prolongations of the terrestrial faults such as the Sulina–Tarhankut fault, Luncavița Fault, Peceneaga–Camena fault, Sinoe Fault, Horia–Pantelimonul de Sus fault, Ovidiu Fault, Mangalia fault, Intramoesian Fault. The second one is composed of the faults parallel to the Black Sea coast, such as Razelm Fault, Lacul Roșu fault, West Midia fault. The last system is represented by the group of faults with an NW to SE orientation, such as Nistru Fault, Odesa Fault, and West Crimea Fault (Figs. 1, 2).

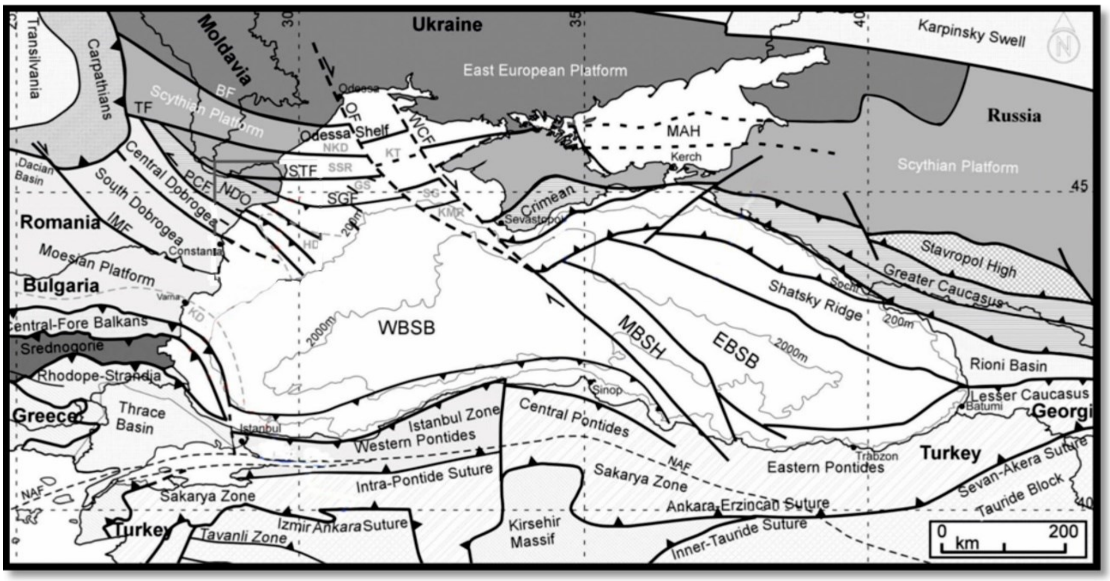

Fig. 1 – Tectonic map of the Black Sea and adjacent areas (after Munteanu *et al.*, 2011). BF, Bistriţa Fault; IMF, Intramoesian Fault; NAF, North Anatolian Fault; OF, Odesa Fault; PCF, Peceneaga-Camena Fault; SGF, Sfântu Gheorghe Fault; STF, Sulina-Tarhankut Fault; TF, Trotuş Fault; WCF, West Crimea Fault; EBSB, East Black Sea Basin; WBSB, West Black Sea Basin; GS, Gubkin Swell; HD, Histria Depression; KD, Kamchya Depression; KT, Karkinit Trough; KMR, Kalamit Ridge; MAH, Mid Azov High; MBSH, Mid Black Sea High; NDO, North Dobrogea Orogen; NKD, North Kilia Depression; SG, Shtormovaya Graben; SSR, Surov-Snake Island Ridge.

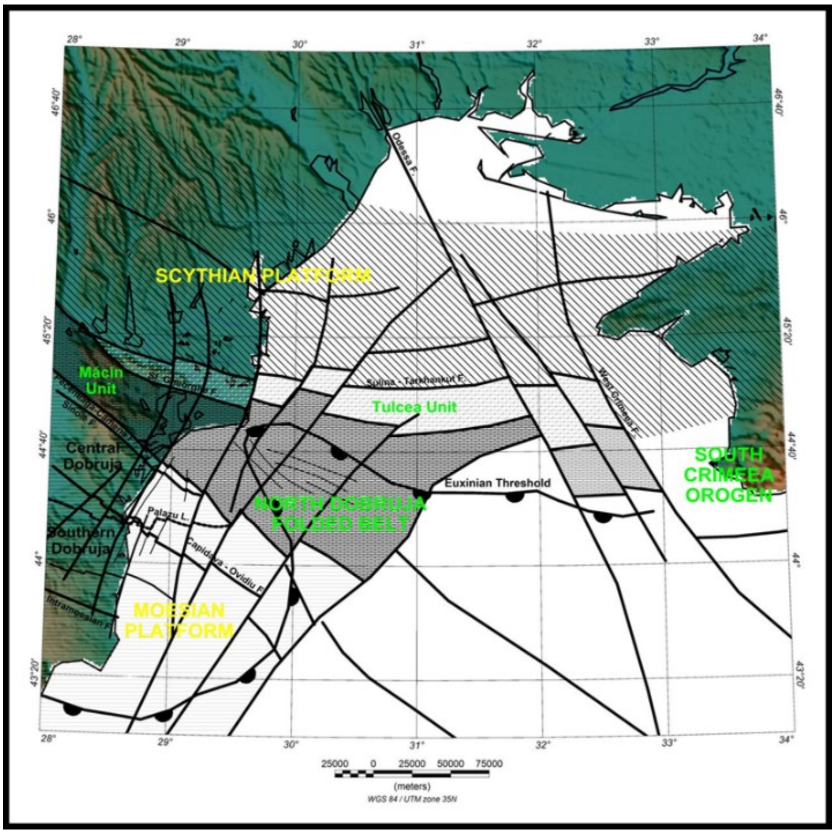

Fig. 2 – Tectonic map of the Western Black Sea, after Dimitriu *et al.* (2009).

3. SEISMICITY

The earthquake catalog consists of 11,500 earthquakes with a magnitude higher than 2.5 (M_L). Of which 276 have a magnitude greater than 5. The maximum depth is 220 km. More than 90% of earthquakes are situated at crustal depth, taken into account the map with isobaths at Moho level published by V. Starostenko (2004).

There is a decrease in the seismic activity once with depth to a depth of 220–222 km depth from where seismic stations have not recorded until this time seismic activity. A closer look at the prolific horizons (Fig. 3) from the point of view of earthquakes shows that for the intervals of 10–35 km, predominant in number are earthquakes with a magnitude of 2.7, considered to be minor seismic events and can be included in the broader category of local resettlement earthquakes. However, there are also earthquakes with a magnitude of 7.2 (M_w) that are already strong earthquakes, with significant tectonic and tsunami-producing implications under certain conditions (Fig. 4).

For the other two predominant intervals, 100–110 km depth and 130–160 km depth, there are earthquakes of moderate to small magnitude, but even here, there are earthquakes with magnitudes greater than 7 (M_w).

The maximum magnitude is considered to be 7.9 on the Richter scale (7.7 M_w as by NOAA) for seismic events from 26 October 1802, 45.7°N and 26.6°E at a depth of 150 km. In the instrumental era, the maximum known magnitude of 7.8 is for the seismic event from 17 august 1999, 40.75°N and 29.68°E at a depth of 17 km (Fig. 4).

On the Black Sea and the related areas are known as seismic sources, several areas that we cite: North Dobrogea seismic source with Peceneaga–Camena fault and Sf. Gheorghe fault, South Dobrogea seismic source with Capidava–Ovidiu fault and Sabla area, and the western seismic source Dulovo.

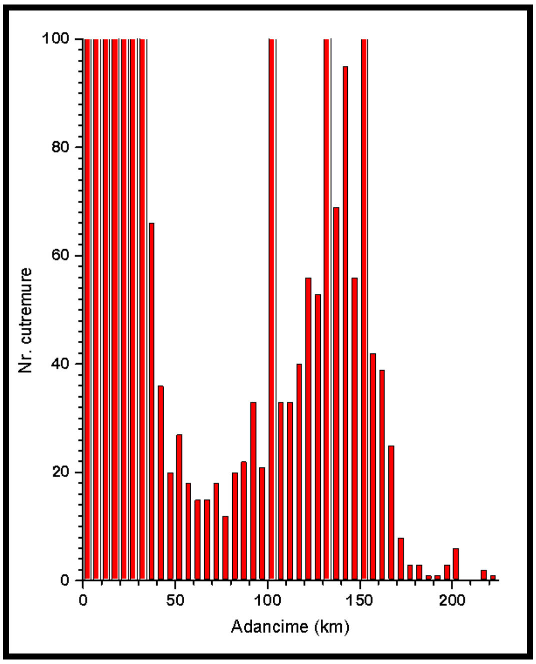

Fig. 3 – The Black Sea and surrounding areas. Detail histogram number of earthquakes vs. depth.

To the northeast of the Black Sea, the Crimea and the Sea of Azov stand out as seismic sources. More to the east is an area recognized as the seismic source of the Caucasus Mountains and, finally, the northern part of Turkey, the North Anatolian fault.

The areas recognized and treated in the literature, such as producers of the tsunami, are the Sabla area, the Crimea peninsula – south of Odesa, and the Sea of Azov, the Caucasus, and the northern coast of Turkey. In the literature are cited about 33 tsunami phenomena, which are characterized by a wavelength of 45–110 m, a speed of 120–140 km/h, and travel time from one coast to another of 10–110 minutes (Nikonov, 1997).

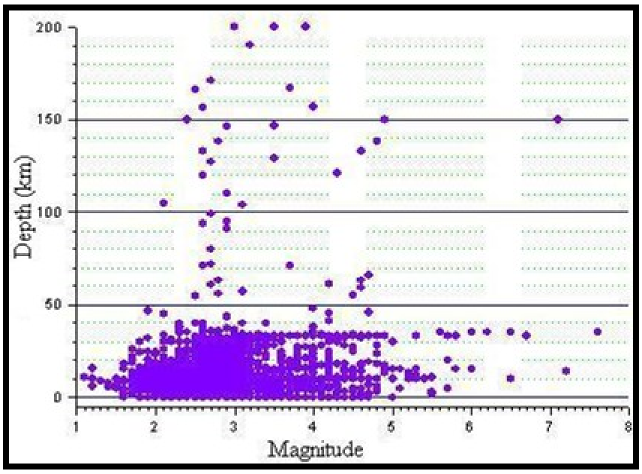

Fig. 4 – The Black Sea and surrounding areas.
Plot depth vs. magnitude.

Taking into account the distribution of the earthquakes and magnitude (Figs. 5 and 6), we distinguished on the all of Black Sea areal, nine seismic sources: Central Dobrogea (S1)), Shabla (S2), Istanbul (S3), North Anatolian Fault (S4), Georgia (S5), Novorossjsk (S6), Crimea (S7), West Black Sea (S8) and Mid Black Sea (S9).

The present paper focuses on the seismic sources from the western part of the Black Sea, as follows: Central Dobrogea (S1), Shabla (S2), Istanbul (S3), North Anatolian Fault (S4), Crimea (S7), and West Black Sea (S8) (Fig. 5).

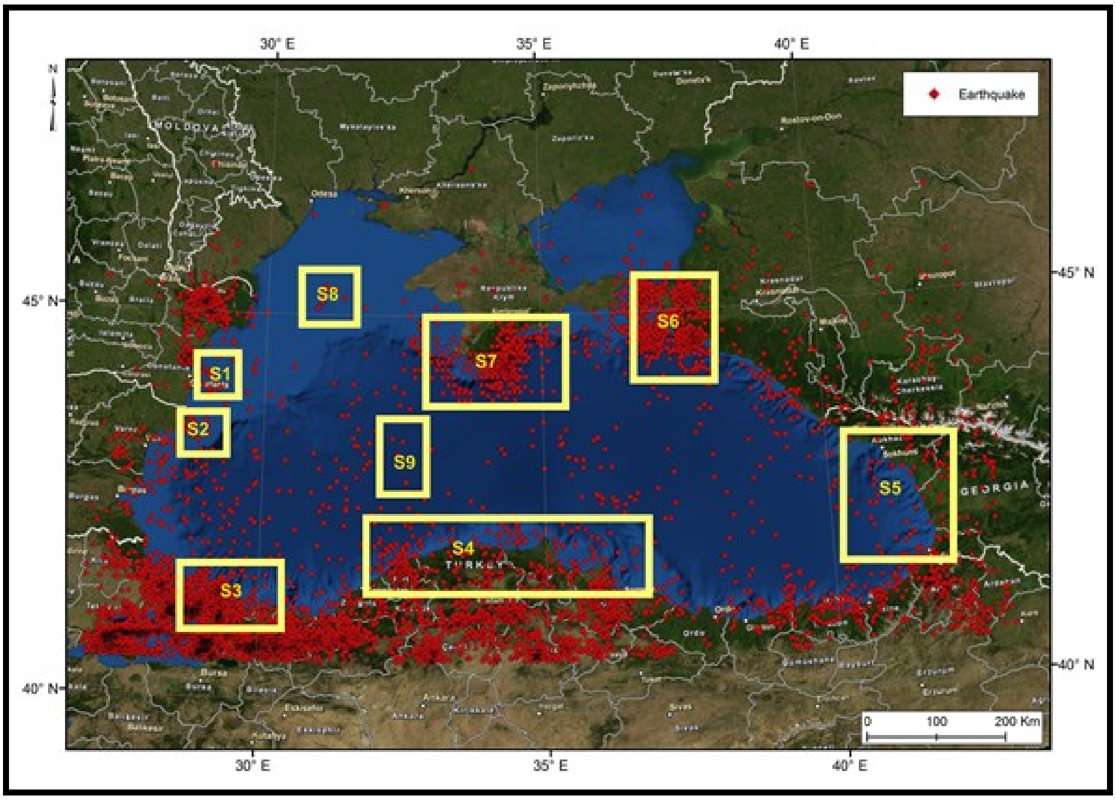

Fig. 5 – Seismic sources on Black Sea areal.

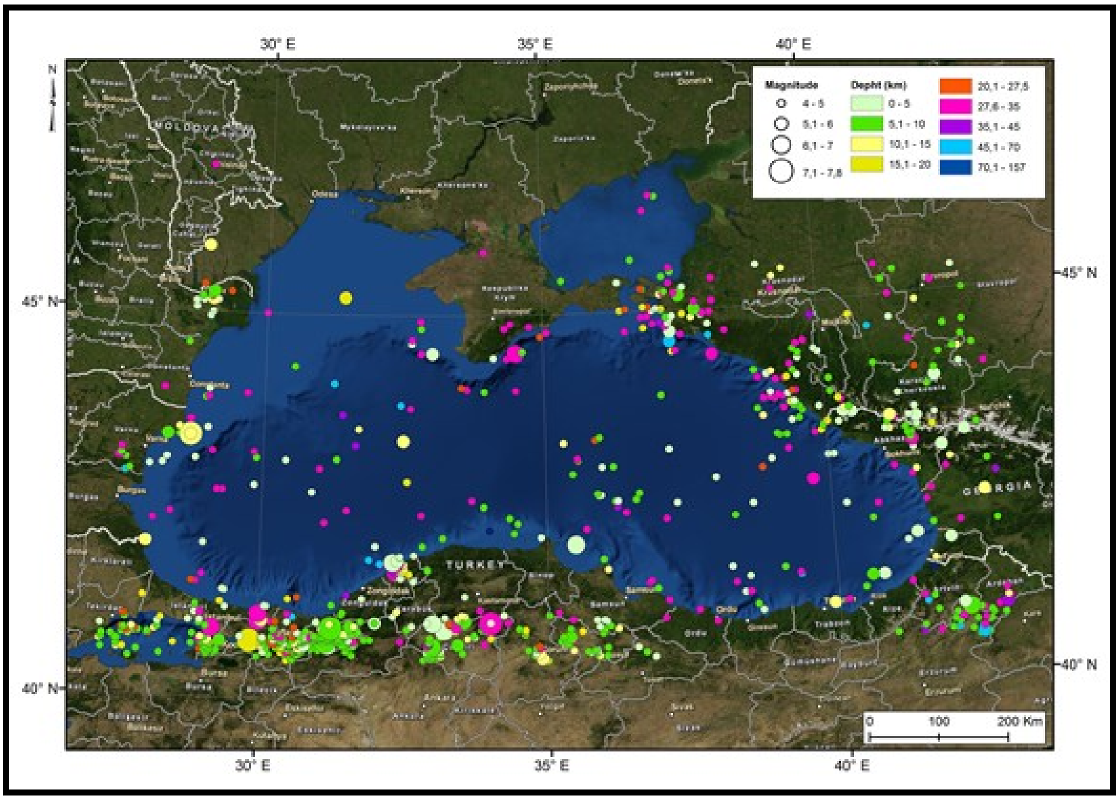

Fig. 6 – The distribution of earthquakes with magnitude more or equal to 4 (M_w).

4. ANALYSIS OF EACH IDENTIFIED SEISMIC SOURCES

S1 – CENTRAL DOBROGEA

The earthquake in this area is associate with Capidava – Ovidiu and Horia – Pantelimonul de Sus faults like transversal faults. The maximum magnitude observed during the period 1980–2010 was Mw = 5 (12.12.1986). Applying the practice of increment, the expected value of the maximum possible magnitude is considered to be $M_{w.max} = 5.2$ with an error value of ± 0.1.

Seismic activity ν_0 = 0.367 seismic events/ year with a magnitude higher than 4.

S2 – SHABLA

Shabla seismic source, even have a tsunamigenic potential (from a historical point of view), is poorly documented. From the geological and tectonic point of view, the Shabla area is superimposed on the intersection between the faults parallel to the Black Sea coast (which have a strike-slip character with a predominate oblique-slip type) and the Intramoesian fault.

In the Shabla – Cap Caliacra area was localized a normal crop of foci with development in NE–SW direction, along which are distributing the epicenters of crustal earthquakes. This active tectonic area is the north-east border of major crustal foci, which is developed collateral by the Black Sea with NE–SW direction and which sinks in the Burgas area. The foci by Shabla have a consistent development, the active sector having a 20–25 km length.

The distribution of epicenters marks the coupling between existent structural lines in the Shabla area, characterized by the 7.2 (31.03. 1901) powerful maximum. Applying the practice of the expected value of the maximum possible magnitude is considered to be $M_{w.max} = 7.4$ with an error value of ± 0.1.

Seismic activity ν_0 = 0,139 seismic events/ year with magnitude higher than 4.

S3 – ISTANBUL

The distribution of epicenters, which characterizes the Istanbul source, mark the flections of the structural lines belonging to the North Anatolian Faults Zone. The maximum observed in this area is 6.2 (Mw) in 20.06.1943 (41° Lat N and 30° Long E. depth 35 km). In the instrumental era, the maximum observed is 6.7 (M_W) 6.08.1983 (41.1° Lat N and 30° Long E. depth 33 km). The continental maximum observed is 7.6 (Mw) on 17.08.1999 (41.01° N and 29.97° E. depth 17 km).

The faults from the Istanbul area have ample development, the active sectors being of hundred of km, maximum of possible magnitude exceeds the maximum of observed magnitude. Seismic activity ν_0 = 0.24 seismic events/year with magnitude higher than 4.

The maximum observed magnitude in Istanbul was M_w = 7,6 (17.08.1999). Applying the practice of increment, the expected value of the maximum possible magnitude is considered to be $M_{w.max}$ = 7.8 with an error value of ± 0.1.

S4 – NORTH ANATOLIAN FAULT ZONE SEISMIC SOURCE

We are talking here about a fault system situated to the north of the North Anatolian Fault Zone, which presents an intense tectonic activity, with more than 350 earthquakes ($M_w \geq 2$).

The distribution of epicenters marks the association of existing structural lines in the area with a maximum observed magnitude of 6.1 (19.08.1954). Seismic activity ν_0 = 0.39 seismic events/year with a magnitude higher than 4.

The maximum observed magnitude in the North Anatolian Fault was M_w = 6.1 (19.08.1954). Applying the practice of increment, the expected value of the maximum possible magnitude is considered to be $M_{w.max}$ = 6.3 with an error value of ± 0.1.

S7 – CRIMEA SOURCE

In Crimea seismic, the epicenter distribution marks the existent tectonic lines, characterized by a maximum observed of 6.5 M_w (11.09.1927).

Seismic activity ν_0 = 0.17 seismic events/year with a magnitude higher than 4.

The maximum observed magnitude in Crimea was 6.5 M_w (11.09.1927). Applying the practice of increment, the expected value of the maximum possible magnitude is considered to be $M_{w.max}$ = 6.7 with an error value of ± 0.1.

S8 – WEST BLACK SEA SOURCE

The geometry of the seismic source of the West Black Sea Fault (WBS Fault) is defined by the distribution of the crustal earthquakes at the intersection of longitudinal faults with transversal faults. The maximum magnitude observed in West Black Sea Fault was Mw = 4.9 (07.05. 2008). Applying the practice of increment, the expected value of the maximum possible magnitude is considered to be M_w = 5.1 with an error value of ± 0.1.

Seismic activity ν_0 = 0.186 seismic events/ year with magnitude higher than 4.

5. CONCLUSION

Studies of seismic hazard highlight the significant contribution to the total seismic hazard in the cross-border area given by Shabla crustal source (S2) with a maximum epicentral intensity equal with VIII ½ that is also a little bit underestimated from the value Io = IX (Moldovan *et al.*, 2017).

From the seismological theoretical point of view, the earthquakes which are responsible for a tsunami are the thrust fault (associated with subduction zones), normal and inverse faults, and less strike-slip fault (only if the oblique-slip and deep slip components are predominant).

So, as a result, the possible areas with tsunami-genetic potential are as follows:

- From the **type of fault plain** solutions perspective, there are:
  – **Shabla** seismic source,
  – faults associated with **North Anatolian Fault Zone** (in the western part where are more reverse and normal fault type) and
  – the **Crimea** seismic source.
- Another criterion to describe a tsunami genetic area is the **magnitude** of the earthquakes: major tsunamis are generated by earthquakes with a magnitude more than 7.5 on the Richter scale; also, earthquakes

with a magnitude between 6.5 and 7.5 could generate a tsunami but a small one, with local effects. Here are tsunami-genetic potential areas such as:

– **Shabla** seismic source with a magnitude observed of 7.2 on the Richter scale, and maximum possible magnitude of 7.3 on Richter scale, but the limited length of the active faults only of 25–30 km, indicated limited effects of a potential tsunami.
– The **Crimea** seismic source, where even the length of the faults are sensible greater than in the Shabla area, the maximum magnitude observed are 6.5 and indicate a potential tsunami-genetic area but with local effects.

• The third criteria to describe a tsunami-genetic area is the **depth** of the earthquakes. The seismic events with a shallow depth (less than 20 km) are mostly tsunami-genetic then crustal earthquakes with deeper depth. Here they are:

– **Shabla** seismic source where the average focal depth is around 14 km;
– **Crimea** **s**eismic source where the average focal depth is around 17 km.

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• Assessment, Strategy And Risk Reduction for Tsunamis in Europe, Astarte, 603839/2013.
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