NATURAL MARINE HAZARDS IN THE BLACK SEA AND THE SYSTEM OF THEIR MONITORING AND REAL-TIME WARNING

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Abstract. This paper presents results obtained in two projects of GeoEcoMar, which led from the study of extreme marine events and the inventory of marine geohazards to the creation of a real-time warning system for marine hazards in the Black Sea. Project Profet resulted in establishment of the main marine hazards that could trigger a tsunami-type event in the Black Sea, like earthquakes, active faults, landslides, gas hydrates, gas seeps and mud-volcanoes. Also, major tsunami-type events in the Black Sea were listed and described from various sources. Through project MARINEGEOHAZARD, the EUXINUS and GeoPontica networks have been established, which produce data for the National Data Centres in Constanța and Varna. The EUXINUS network is a complex automatic marine measurement system, consisting of 5 measuring instruments installed in key points of the Western Black Sea shelf. The main task of one of its main components, the Black Sea Security System, is to elaborate risk assessments and to send early-warning notifications to authorities.

Key words: seismic source, active fault, landslide, tsunami, early warning system, gauge, 2D marine seismics

1. INTRODUCTION

The internationally agreed "Glossary of Basic Terms Related to Disaster Management" (DHA, 1992) defines "the hazard" as "a probable event, with effects upon the environment and with possible potential to produce social-economic damage, including human life loss, in a certain time span and on a certain area". The hazard is a phenomenon with behaviour and consequences difficult to predict.

The Indian Ocean tsunami from December 2004, or the 2011 Tōhoku earthquake and tsunami from the Pacific Ocean, accompanied by great losses and damage, remind us of or own tsunami risks.

The characteristic features of the Romanian seashore (large shelf area, low water depths, low topography) make it vulnerable to the tsunami phenomenon.

In Europe there are various organisations, initiatives and projects that focus especially on tsunami phenomena and its triggers (e.g. ESPON, IOC, EMSO, FP 7 projects). The monitoring of marine hazards is possible using early warning systems. There are three centres in Europe dedicated to marine hazards, mainly for tsunami events, in France, Greece and Turkey. Starting with the year 2013, a new one is operating in Romania and Bulgaria. The latter was accomplished using structural funds within a cross border cooperation programme between Romania and Bulgaria. Today, this centre is active and has a real contribution to the monitoring of the western Black Sea area. The Black Sea Security System EUXINUS contributes to enrich marine sciences data base.

This paper presents the results obtained within two projects, one dedicated to tsunami-type events in the Black Sea, the other to the establishment of a new center in the north-western part of the Black Sea, receiving data from the EUXINUS network, parts of a real-time early warning system for marine geohazards.

2. GEOTECTONIC FRAMEWORK OF THE WESTERN BLACK SEA

Located between the Eurasian plate in the north and the African-Arabian plates in the south, the Black Sea is a Cretaceous-Tertiary basin surrounded by orogenic belts derived through the closure of the Tethys ocean: the Caucasus to the east, the Pontides to the south, the Srednogorie and Balkans to the west and the North Dobrogea Orogen and South Crimea Fold belt to the north (Fig. 1). Although it is largely agreed that the Black Sea formed in extensional, backarc setting, in connection with closure of the Tethys by northward subduction (Spadini *et al*., 1997; Nikishin *et al*., 2003 and references therein), there are several issues that remain controversial: the timing of opening, mechanisms of basin formation and crustal affinities (Stephenson and Schellart 2010; Yegorova and Gobarenko, 2010). The continental crust, supposed to consist of a collage of microplates and terranes of different affinities accreted to the SW margin of the East European Craton, is concealed by the thick sediment succession of the two Black Sea basins. Recent results from integration of 3D gravity backstripping analysis and seismic tomography data show that the Black Sea is underlain by a rheologically strong and cold continental lithosphere, quite similar to the Precambrian lithosphere of the East European Craton (Yegorova *et al*., 2013).

The Black Sea is composed of two basins, which are separated by the Mid Black Sea Ridge consisting, in turn, of Andrusov and Arhangelskiy ridges (Tugolesov *et al*., 1985). Different origins of the WBS and EBS basins were suggested by Robinson *et al*. (1996), Banks and Robinson (1997) and Robinson and Kerusov (1997). Geological and geophysical data suggest an Eurasian setting for the West Black Sea basin (Săndulescu, 1995; Banks and Robinson, 1997; Hippolyte *et al*., 1996; Hippolyte, 2002; Yegorova and Gobarenko, 2010), on the crust of the Moesian platform due to rifting and strike-slip tectonics along the fault zone between the Moesian and Scythian Platforms.

According to Görür (1988, 1997), the Western Black Sea basin opened in the Aptian-Albian, through the separation of the Istanbul zone (Western Pontides) from the Odessa shelf, translated southward along the West Black Sea and West Crimea Faults (Okay *et al*., 1994). Rifting was followed by post-rift subsidence and oceanic crust emplacement during the Cenomanian (Finetti *et al*., 1988; Görür, 1988). The Eastern Black Sea Basin opened in the Late Palaeocene, with rotation of the Mid-Black Sea High (Andrusov and Archangelskiy ridges) away from the Shatsky Ridge, or by rifting along an Early Cretaceous volcanic arc (Nikishin *et al*., 2015). The West Black Sea began also to close in the Eocene-Oligocene time, while the eastern Black Sea continued to close from Miocene up to present (Robinson *et al*., 1996). Interpretation of recent seismic reflection data suggest that both basins of the Black Sea show not only highly extended continental crust, but also oceanic crust (Nikishin *et al*., 2015).

The current kinematic framework, derived from space geodetic measurements, features the northward moving African and Arabian plates, colliding with the Eurasian plate and the westward escape of the Anatolian plate as result of this movement, with a rotation pole located approximately in the north of the Sinai peninsula (Dewey *et al*., 1973; Reilinger *et al*., 1997). A large part of this escape is accommodated along the North Anatolian Fault system, which shows a progressive westward rupture migration since 1939, with velocities of 10–20 mm/year (Tari *et al*., 2000). Geological and geophysical evidence from various studies support a compressional regime active in the E Black Sea region and an extensional regime in the NW part of the West Black Sea basin (Barka and Reillinger, 1997; Tari *et al*., 2000). The more complicated neotectonics of central and western Black Sea is influenced by the escape of the Anatolian block, northward motion of the African Plate and the Aegean extension, while blocks forming the NW Black Sea margin show differential displacements on a NW-SE direction (Biter *et al*., 1998).

3. STRUCTURE OF THE WESTERN MARGIN OF THE BLACK SEA

South of the East European Craton, the north western margin of the Black Sea is formed of three main geotectonic units, separated by major faults (Fig. 1). The Scythian and Moesian platforms are small-sized crustal fragments in the Carpathian foreland, located south of the East European Platform as part of the Eurasian plate (Oxburgh, 1974; Burchfiel, 1980). In between these platforms, the North Dobrogea Orogen represents an Early Alpine (Cimmerian) fold and thrust belt, correlated with the South Crimea Fold Belt (Murgoci, 1915; Dumitrescu and Săndulescu, 1968; Săndulescu, 1984, 2009) and included in the Anatolian Cimmerides (Istanbul Nappe, Şengör *et al*., 1984), or correlated to the Küre basin from the Central Pontides (Ustaömer and Robertson, 1994).

Geophysical and borehole data show that the current structure of the NW Black Sea margin in Romania resulted through displacements along major faults, striking WNW-ESE and extending NW to the East Carpathians bend zone (Fig. 2).

The Sfântu Gheorghe Fault (SGF) follows the southern margin of the Danube Delta and the Lower Danube East of Prut River (Gavăt *et al*., 1967; Airinei, 1973) (Fig. 2). Most authors agree that it represents the limit between the North Dobrogea Orogen and the Scythian Platform, although the trace of this fault is variously interpreted (Săndulescu, 1984; Săndulescu and Visarion, 1988; Seghedi, 2001). Onshore gravity studies and magnetotelluric soundings emphasize that SGF is a deep fault, with an active seismic behaviour suggested by normal earthquakes (Constantinescu *et al*., 1976; Stănică and Stănică, 1988; Cristea *et al*., 1994). Although north of the Lower Danube, the SGF is burried beneath Holocene deposits, detailed studies of borehole cores enabled to trace the fault quite precisely along strike, as both the Paleozoic and Triassic-Jurassic successions of the Scythian Platform are distinct in facies from those of North Dobrogea (Baltres, 1993; Seghedi, in Ioane *et al*., 1996). Based on geological information from boreholes, the SGF continues onshore on the Odessa shelf to the south of the Snake Island (Seghedi *et al*., 2003). However, on seismic sections in the offshore area, the Sfântu Gheorghe

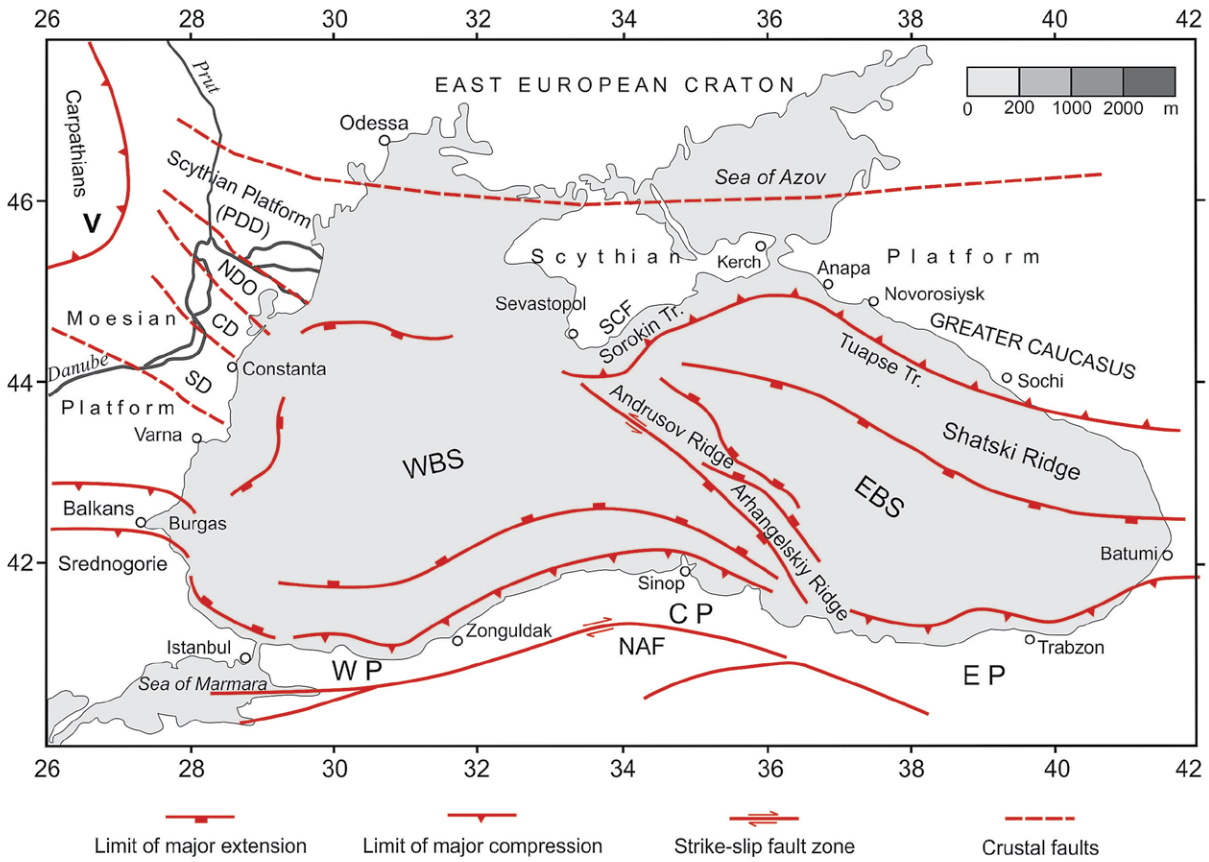

Fig. 1. Schematic map showing the major tectonic units and morphological structures of the Black Sea (modified after Robinson *et al*., 1996). Abbreviations: PDD, Pre-Dobrogea Depression; NDO, North Dobrogea Orogen; CD, Central Dobrogea, SD, South Dobrogea; SCF, South Crimea Fold Belt; V, Vrancea zone; WP, West Pontides; CP, Central Pontides; EP, East Pontides; NAF, North Anatolian Fault; EBS, East Black Sea basin; WBS, West Black Sea basin.

Fault is interpreted as a second-order fault splay, affecting the post-Paleozoic successions as a minor offset reverse fault, accompanied by drag folding displayed in Late Cretaceous sediments (Dinu *et al*., 2005).

The Peceneaga-Camena Fault (PCF) separates the northern margin of the East Moesian Platform from the North Dobrogea Orogen. Seismic studies revealed that PCF is a transcrustal fault, depressing the Moho with about 10 km (from 35 to 45km), with the North Dobrogea block in its footwall (Constantinescu *et al*., 1976; Rădulescu *et al*., 1976). Considering that alkaline volcanism along the northern margin of the PCF shows SE younging, it was supposed that the activity along this fault commenced already at the end of the Permian (Seghedi, 2001). Sedimentation and volcanism along its north-western segment in Dobrogea suggest that the PCF was active in transtensional and transpressional regime since the Lower Jurassic (Grădinaru, 1988) and was reactivated during the opening of the West Black Sea Basin (Beşuţiu and Zugrăvescu, 2004; Beşuţiu, 2009). An alternative interpretation is that the PCF was an active transform fault during extensional events connected to the Black Sea opening, extending within the continental margins (Săndulescu, 1984). During the Pliocene, activity along the PCF continued along its concealed prolongation towards the Carpathian foredeep (Cornea and Polonic, 1979). Currently, certain segments of the fault are considered active (Beşuţiu, 2009; Beşuţiu et al., 2014). In Dobrogea, the PCF shows a straight WNW-ESE segment, with a horse-tail splay at its north-western end, close to the Danube (Seghedi and Oaie, 1994).

On the continental shelf, the PCF is sealed by Late Cretaceous deposits, as shown by interpretation of seismic sections (Dinu *et al*., 2005). This is consistent with the situation visible in outcrops, as the eastern segment of the PCF in the north-eastern part of Central Dobrogea is sealed by the Late Cretaceous cover of the North Dobrogea orogen, the Babadag "basin" (Săndulescu *et al*., 1978). The PCF was mapped about 100 km eastward on the Romanian shelf, where its submarine trace on the continental slope is marked by the Viteaz canyon of the Danube (Popescu *et al*., 2004).

The Ostrov-Sinoe Fault parallels to the south the PCF, bordering a basement uplift which exposes in the core of an antiformal fold the metamorphic basement of Central Dobrogea. This fault is better visible in the offshore than the PCF, burried beneat by the Cenozoic sediments of the Euxinic cover (Dinu *et al.,* 2005).

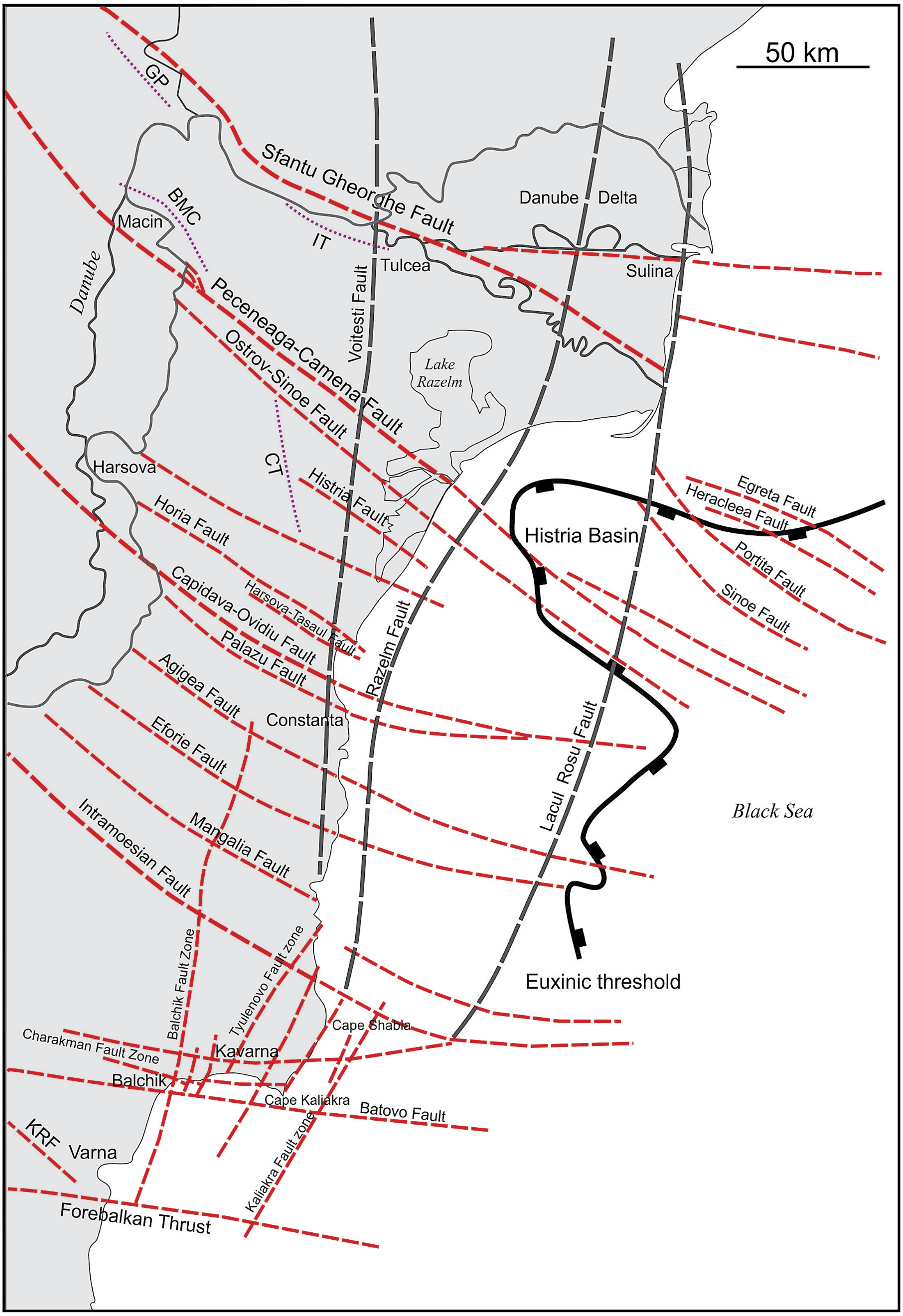

Fig. 2. Major faults on the north-western Black Sea margin. Purple dotted lines are lineaments of seismic instability. Abbreviations: KRF, Kemanlar-Ruslar Fault; GP, Galați-Pechea line; IT, Issacea-Tulcea line; CT, Cogealac-Topolog line; BMC, Brăila-Măcin-Cerna line.

The Capidava-Ovidiu Fault – COF, separating between the Central and South Dobrogea blocks of East Moesia, is recognized on seismic sections, offseting the Conrad discontinuity with 5 km (Rădulescu *et al*., 1976; Constantinescu *et al*., 1976; Stănică and Stănică, 1988; Visarion *et al*., 1988; Cristea *et al*., 1994). In the footwall of this fault, the base of the Late Jurassic limestones overlying the Precambrian basement of Central Dobrogea is downthrown about 600 m. Onshore, artificial exposures in the walls of the Poarta Alba-Ovidiu canal show the COF juxtaposing the Aptian continental deposits and Turonian sandstones of South Dobrogea to the Late Jurassic carbonate platform limestones of Central Dobrogea (Avram *et al*., 1998). The fault shows a subvertical fan shaped fault-zone, clearly visible in the southern wall of the canal. The Lower Cretaceous–Tertiary cover in the offshore area shows no offsets along the COF, suggesting that activity along this fault ceased after the opening of the West Black Sea basin (Dinu *et al*., 2005).

Horst and graben structures develop in Central and South Dobrogea, due to the system of secondary faults parallel to PCF and COF (Fig. 2): Histria, Horia (Horia-Pantelimonu de Sus) and Hârşova-Taşaul in Central Dobrogea and Palazu, Agigea, Eforie and Mangalia in South Dobrogea (Visarion *et al*., 1988).

The Intramoesian Fault – IMF. Referred to as Shabla Fault by Bulgarian authors, the Intramoesian Fault is a trans-lithospheric fracture separating the Moesian Platform into two main regions with distinct basement and geophysical properties (Dumitrescu and Săndulescu, 1968; Săndulescu, 1984; Enescu and Enescu, 1992; Săndulescu and Visarion, 2000), crustal thickness (Rădulescu *et al*., 1976) distinct seismicity (Cornea and Polonic, 1979; Stanciu and Ioane, 2016), as well as distinct paleocontinental affinity (Seghedi *et al*., 2005; Oczlon *et al*., 2007). The trace of the IMF is underlined by seismic epicenters (Rădulescu *et al*., 1976; Cornea and Polonic, 1979). The IMF prolongates NW from the eastern shore of the Black Sea to underneath the Cretaceous nappe system of the South Carpathians, showing features of composite faults. Fault plane solutions indicate strike-slip displacement, with a normal component, suggesting an extensional model of the stress field; the dominant rupture plane is NW-SE (Constantinescu *et al*., 1976; Enescu *et al*., 1996). On the southern Romanian shelf, near the Bulgarian border, the IMF diverges into the Black Sea with a horsetail splay (Dinu *et al*., 2005). Onshore, South Dobrogea zone is crossed by a system of NW– SE oriented normal faults; their offshore extensions were reactivated during the Albian - Senonian interval (Fig. 2) (Dinu *et* al., 2005). The IMF is an active transcrustal fault, as demonstrated by the earthquake at Călăraşi on March 3rd 1994, at depth of 40 km below the Moho (Moho depth is at 30 km in this area) (Biter et al., 1998).

South of the Intramoesian Fault, several E-W trending faults occur between Shabla and Varna, more or less paralell to the Forebalkan Thrust (Ranguelov and Gospodinov, 1994; Matova, 2000).

The Kaliakra Fault Zone in Western Black Sea is the most active structure of the Shabla Seismic Zone (Ranguelov and Gospodinov, 1995; Matova, 2000). This zone is characterised by very strong earthquakes with a relatively well-known frequency of occurrence. According to historical data, every 400-600 years a strong earthquake with magnitude of the range of 7.0 affected the coastal territories. The last earthquake, with an estimated magnitude of 7.2, produced considerable damage in 1901. Recently published data on active faults in this area, based on onshore drilling and offshore acoustic and seismic profiles, have identified a number of activated fault segments. The Kaliakra Fault Zone is related to significant faulting and deformation of Mesozoic and Palaeozoic sediments along N-S to NNE-SSW and E-W faults. The width of the deformation zone varies between 1-3 km to 6-8 km, depending on the author. Some of the peripheral associated faults are mapped onshore, along the coastal area. The offshore investigations indicate about 100 m amplitude of displacement in Palaeogene sediments and tens of meters in the Neogene sediments (Matova, 2000).

Voiteşti fault. An important fault, usually overlooked by most researchers, was described by Popescu Voiteşti (1933) and interpreted as as a flexure-induced fracture – the Voiteşti flexure (1938) (fig. 2). Going N-S from Tulcea through Mangalia to Kaliakra, this fault was active in historical times, as indicated by negative movements of the Dobrogea sea-shore, enabling the sea to advance inland to form numerous embayments and drowning various parts of archaeological sites at Histria and Callatis (Alexandrescu and Baltres, 2008). The Voiteşti Fault more or less parallels the Razelm and Lacul Roşu faults in the offshore area (Fig. 2).

The entire area of Dobrogea is also affected by systems of secondary faults, producing horst and graben structures. The Scythian Platform (Pre-Dobrogea Depression) in the basement of the Danube Delta is strongly deformed by a system of latitudinal faults; their interference with a N-S trending fault system resulted in a graben along the Sulina distributary (Neaga and Moroz, 1987; Seghedi *et al*., 2003).

Seismic studies in the Black Sea identified not only the prolongation of major crustal faults on the continental shelf, but also secondary NW-SE faults of the same fault systems, both in Histria depression and south of it (Ţambrea, 2007). This system is affected by three major faults, oriented N, NE or SE: Razelm, Lacul Roşu and west Midia Faults, generating a block structure with vertical displacement. Detailed seismic studies showed that most faults in the southern part of Histria depression show en echelon pattern, forming NNW-SSE oriented horst and graben structures (Ţambrea, 2007).

Geological, geophysical and tectonic studies reveal a complex structure of the coastal area of Dobrogea and the Black Sea continental shelf of Romania. The faults are partly active, demonstrating the existence in the West Black Sea basin of processes (earthquakes, displacements on active faults) that might generate natural hazards with risk for the coastal area.

4. NATURAL HAZARDS IN THE BLACK SEA AREA

Using geological and geophysical information and other scientific data, several main natural hazard categories can be described for the western part of the Black Sea basin. These hazards include submarine earthquakes, or earthquakes produced in the immediate vecinity of the sea, submarine landslides, tsunami waves, tectonic activity along active faults, potential gas eruptions from sea bottom sediments and extreme meteorological events.

4.1. Historical data

The existence of hazards producing tsunami-type waves in the Black Sea is based on numerical, historical and instrumental data. The most known natural hazards-generating events produced in the Black Sea and documented from various sources are shown in Table 1. These events have been recently analyzed and interpreted in terms of tsunami intensity or reliability (Papadopoulos *et al*., 2011).

Table 1. Major natural hazardous events trigerred by seismic sources in the Black Sea basin. Reliability according to Papadopoulos *et al*. (2011)

2	3	4

Date	Location	Magnitude/ cause	Tsunami intensity	Observations	Source of information
I-st century Presumably 50 BC	Cities of Bizone (modern Kavarna)	Earthquake-landslide 7		The cities have been destroyed by the earthquake, as well as by waves (the land was flooded)	Strabo, 64 B.C.–19 A.D. Ranguelov, 2008; GITEC Database/Maps
72 – 71 BC	Histria Fortress, Central Dobrogea			Earthquake that resulted in destruction of the temple of Aphrodites (in Histria fortress), according to archaeological observations sometime before 72-71 BC (similarity with the earthquake that destroyed the city of Bizone); tension gushes and shears occur on temple ruins, on pedestal and rows	Alexandrescu, Baltres, 2007
I-st century	The city of Dyoskuria (modern Sukhumi, Georgia)	6.5 Earthquake marine slide		Tsunami waves of over 2.5 m. The city of Dyoskuriada was completely destroyed and covered by waters.	Nikonov, 1997a, b; GITEC/Maps
II-nd century	Sevastopol Bay (Crimea peninsula, Ukraine)	7 Earthquake-associated		The sea retreated 500 m and wave height was over 2 m	Nikonov, 1997a, b
AD 543$\pm$1 (544/545)	Varna Bay (Bulgaria) Coastal zone of Thrace	7.5/ (7.3-7.6) Submarine earthquake	Tsunami intensity VII (scale P and I). 4-5 8-9	*In this year* [544/545] *the sea advanced on Thrace by four miles* [ca. 6 km] *and covered it in the territories of Odessus (Varna) and Dionysopolis (Balchik) and also Aphrodisium. Many were drowned in the waters. By God's command the sea then retreated to its own place.*	Theophanes (in Guidoboni *et al*., 1994) Nikonov, 1997a; NIEP; HTDB/WLD/NTL; Ranguelov, 2008.
557	Burgas (Bulgaria)	7.5		The 2 m high wave penetrated 4.5 km on land	Nikonov, 1997a
1427	Southern coast of Crimea	6 Submarine earthquake	4-5/ 7-8	Entire villages close to Yalta have been flooded	Nikonov, 1997a; NIEP
1444, XI	Shabla-Kaliakra Epicentre on shelf, close to Varna – activation of E-W and WNW-ESE Forebalkan and NE-SW Tyulenovo Faults and of their intersection offshore	7.5		Changes of river course; settlements surrounding Varna completely destroyed	Shebalin *et al*., 1974; Matova, 2000; Diaconescu and Ranguelov, in Oaie *et al*., 2013

Table 1 (continued)

Date	Location	Magnitude/ cause	Tsunami intensity	Observations	Source of information
07.05.1598	Central and northern part of Anatolia, in Amasya and Çorum areas	Earthquake-marine slide	4–5/ 8–9	*„...the sea was driven back drowning a few thousand people in towns and villages*"; and "*. . . in Amasya* [the ground] *was cleaved engulfing many villages* The sea penetrated in the land interior on a distance of over 1,5 km.	Ambraseys and Finkel, 1995; Nikonov, 1997b; Altinok and Ersoy, 2000.
1650	Sivash, Azov Sea	Submarine earthquake	2-3 4-5	Sea flooded in Sivash, then receded near Genichesk and Arabat. Geological traces of tsunami in Sevastopol Bay.	
06.04.1790	Constanța, South Dobrogea			*"The cliff of Constanta city collapsed"*	Popescu, 1938
12.10.1802 (26.10 new style dating)	Western Crimea (associated to earthquake at Vrancea seismic source, 150 km depth)	7.9	2-3 3-4	Big waves observed close to the beach of Evpatoria (Crimea) while the sea was calm. Possibly a submarine slump caused by the earth shaking	Nikonov, 1997a; NIEP Yalciner *et al*., 2004; Constantinescu and Mârza, 1989
17.11.1821	Ukrainian coast	Earthquake-associated Submarine slump or seiche	2-3 3-4	Sea rose above the ordinary level near Odessa	Nikonov, 1997a
23.01.1838	Odessa, Ukraine	7.5 Vrancea earthquake-associated	7-8 5-6	Ships moored in Odessa bay (Ukraine) damaged by strong sea swell	Nikonov, 1997a
11.11.1869	Crimea	Submarine earthquake	2-3 3-4	*Town of Sudak: a violent horizontal recession of the sea by 2m and a slow return to the ordinary level in 10 min. A strong tidal wave as high as 1m near the town of Evpatoria."* Strong sea level changes in Sudak and Evpatoria	Nikonov, 1997a; Pelinovsky, 1999
14.10.1892, 06.38 hours a.m.	Sulina, Issacea, Tulcea, Ostrov, Constanța, Kavarna	6.9 9 in epicenter		*"The cliff of Constanta city collapsed 10 m on 500m length"* * No observations related to the state of the sea. Very violent earthquake, duration 14 (25) seconds.	Popescu, 1938; NIMH; NIEP
31.03.1901	Shelf zone near Shabla Balchik, activity on Charakman (E-W), Kaliakra WW) and a local un-named fault (NW-SE)	7.2 degrees on Richter scale Submarine earthquake off-shore Kaliakra (VIII in Bazargic, VII – VIII in Constanta, Mangalia)	2-3 3-4	The sea waves were 5 m high. In Balchik waves would have been up to 3 m high. V-VI tsunami intensity (on the Papadopoulos-Imamura scale). In Balchik "*house walls were cracked, large part of a hill was displaced*"; in Shabla "*several houses and a church collapsed*" coastal villages were destroyed and numerous cases of landslides, rockfalls and land subsidence were documented in the annual bulletin of 1901	Popescu, 1938; Panin, 2005; NIEP; Grigorova and Grigorov, 1964; Ranguelov, 1996; Matova, 2000

Table 1 (continued)

Date	Location	Magnitude/ cause	Tsunami intensity	Observations	Source of information
04.10.1905, 22:29 hours (GMT)	North-east coast of the Black Sea	7.0 In Romania – 5.1 degrees Earthquake-associated	3-4	Waves off Anapa, Russia, shook up a ship; Georgian coast affected (Poti, Batumi, Sukhumi)	Nikonov, 1997a; KOERI database; HTDB/WLD/NTL; GITEC/ Maps
1908	Crimea			Vessels affected – according to the Russian fleet reports	GITEC/Maps
26.07.1927	Yalta, Crimea	6.0 Submarine earthquake slide	2-3 3-4	In Alupka, the sea receded and then returned onto the shore and overwhelmed the beach.	Nikonov, 1997a
11.09.1927, 22:15 hours (GTM)	South Crimea	6.5 Submarine earthquake	3-4 5-6	Waves produced had heights over 2 m; in Balaklava the sea advanced inland 15 m; two houses were destroyed	Pelinovsky, 1999 KOERI database; NIMH; NIEP; HTDB/WLD/NTL; GITEC/Maps
26.12.1939 23:57 hours (GMT)	Fatsa, Turkish coast and East Black Sea	8 degrees on Richter scale. Earthquake marine slide Earthquake refered to as the *Great Erzincan*	2-3 3-4	Sea receded 100m in Ünye; tide-gauge records of max. height of 53 cm in Novorossiysk . Epicenter on land at a distance of 60 km from the southern Black Sea coast. Tsunami waves originated either through translation on the major crustal fault, or reactivation of a secondary fault or submarine landslide. The tsunami has crossed the Black Sea being registered by tide gaurge from Russian ports, showing wave heights of 50 cm in Sevastopol and Novorosiysk and 40 cm in Tuapse.	Nikonov, 1997b; Kuran, Yalciner, 1993; Altinok and Ersoy, 2000; KOERI database; NIMH; NIEP; HTDB/WLD/NTL
12.07.1966	Crimea, Anapa	5.8 Earthquake marine slide	2-3 3-4	Tide-gauge records of max. height of 50 cm in Gelendzhik	
03.09.1968	Amasra, Turkish Black Sea coast	6.6 Submarine earthquake	3-4 4-5	In the Big Port of Amasra, the water rose 3 m and moved boats onshore; the sea inundated 100 m in Amasra; after 14 min., the second wave inundated the shore about 50–60 m, dragging many objects and causing many boats to be stranded. Coastal uplift between Amasra and Çakraz.	Altinok and Ersoy, 2000
26.08.1993	Sulina Canal	5.0		Flooding of the canal jetties – recordings with sea level measurement equipment	Sulina hydro-meteorological station; Oaie *et al*., 2006a; NIEP

Table 1 (continued)

Date	Location	Magnitude/ cause	Tsunami intensity	Observations	Source of information
05.07.2007	Bulgarian Black Sea coast	Gravitative marine slide?	3-4 4-5	Tsunami-like sea disturbance of non-seismic origin lasting for several hours; small fishing boats were cast onto the beach in Kavarna and Balchik; debris was deposited on the shore	Ranguelov *et al.*, 2008 Vilibić *et al.*, 2010

* Earthquakes produced along the Romanian coastal zone and in the basin have been registered (data from the National Institute of Meteorology and Hydrology – NIMH and from the data base of the National Institute of Earth Physics - NIEP), even if special hydrodynamic marine events, like tsunami-type waves, have not been registered (data need additional checking). S-A – Sieberg-Ambraseys 6-grade scale; P-I – Papadopoulos, Imamura, 12-grade scale. Abbreviations: GITEC – Government Information Technology Executive Council; HTDB/WLD/NTL – Historical Tsunami Database for the World Ocean/Novosibirsk Tsunami Laboratory.

Table 1 shows that the majority of the Black Sea tsunamis were observed in the NE part of the basin, especially in the coastal zones of Crimea, while frequent tsunamis were produced offshore of the Bulgarian and of the northern Anatolian coast (Papadopoulos *et al*., 2011). It is possible that the cause of tsunami-like disturbances in Odessa, Ukraine, are due to distant, large intermediate-depth earthquakes occurring in the Vrancea seismic source in Romania. Considering tsunami frequency, the cited authors estimate a low to moderate tsunami hazard in the Black Sea, however not negligible.

It is worth mentioning that field observations in the Temple of the Phrygian Godess Cybele in Balchik, uncovered by accident in 2007, indicate that the sea wave in year 544/545 was a tsunami, triggered by a strong, shallow earthquake (Ranguelov, 2008), occurring offshore at Varna. Run-up heights exceeding 2–4m were estimated. The temple was affected first by fire and roof collapse, very possibly due to a strong earthquake, and very soon after the fire the floor was flooded by sea water, leaving behind a layer of sand and shells. The possible mechanism for the tsunami initiation may involve a submarine land-slide or slump in Saros Bay, triggered by the earthquake (Papadopoulos *et al*., 2011).

Other documented events were produced in 557, 1341, 1598 (Altinok and Ersoy, 2000) and 1615, 1821, 1875 (Nikonov, 1997a). In the last century, other main events were mentioned by different sources.

One of the largest earthquakes recorded instrumentally in the Black Sea area was the Great Erzincan earthquake (26 September 1939), with a magnitude of 8 degrees on Richter scale. The sea has receded about 100 m. When the sea returned, the edge of the coast rose by 20 m (Altinok and Ersoy, 2000). The tsunami crossed mainly the Eastern part of Black Sea and was recorded on the Northern Black Sea shore, with heights of 50 cm in Sevastopol and 53 cm in Novorossiysk (Grigorash and Korneva, 1969, 1972; Dotsenko, 1995; Nikonov, 1997a; Pelinovsky, 1999).

On the 3-rd of September 1968, the Bartin earthquake generated waves in the southern part of the Black Sea, close to the city of Amasra. The coastline between Amasra and Çakraz uplifted by 35–40 cm. The sea receded 12 to 15 m in Çakraz and flooded 100 m in Amasra. 14 minutes after the first wave, the second wave inundated the shore on about 50-60 m (Lander, 1969).

On July 5, 2007, along the Bulgarian Black Sea coast, a tsunami-like wave of non-seismic origin (meteotsunami, Vilibrić *et al*., 2010), was observed on a distance of about 150 km. The sea level rose and the lowering varied between +1.2 m and -2.0 m (Ranguelov *et al*., 2008).

Romanian researchers inferred that an increase in earthquakes frequency might result in apparition of tsunami waves in the Black Sea. According to Panin *et al*. (2005), a tsunami is possible in the Black Sea due to the sliding of sediments accumulated on the outer shelf, close the continental slope. This phenomenon appears when an earthquake is produced, or when the sediment load is too high. The same author considers that in the past such phenomena have had a quite high intensity.

Recently documented informations indicate that anomalous hydrodynamic events occurred along the Romanian-Bulgarian coast, usually described by eye-witnesses. Starting with the XXth century, such events were measured by instruments, or mentioned in written documents; however, their causes are difficult to interpret.

Anomalous flooding events on the Romanian Black Sea coastal zone were mentioned by various specialists, mainly for the coastal area in front of the Danube Delta. The most important of them include: May, 1958 – flooding of the eastern part of the Sulina city and of the Sulina canal jetties; December, 1960 – flooding of the Sulina canal jetties and of the meteo station, removal of jetties and boulders, violent movement of the ships; August, 1993 – flooding of the Sulina canal jetties (instrumental measurements of the sea level variations); May, 1995 – flooding of the Sulina beach and canal jetties; March, 1995 – complete flooding of the Sahalin Island summer, 2003 – the sea first retreated about 100 m, then flooded the Sulina jetty (Oaie *et al*., 2008, 2013).

Geological and biological observations on sediment cores sampled along the northern Romanian Black Sea coastal area, in front of the Danube Delta, onshore and on the internal shelf, showed coarse sand beds rich in vegetal debris, with whole or fragmented shells. These beds, underlain and overlain by fine lacustrine sediments (muds, silts), might probably represent significant marine events (tsunami, storms?). Geological investigations revealed the presence of several types of anomalous (tsunami-type?) layers in geological formations along the Romanian – Bulgarian Black Sea coast (Ranguelov, 2003; Oaie *et al*., 2008, 2013).

4.2. Seismic sources in the Black Sea area

Although the seismic hazard of the Romanian territory is controlled largely by intermediate-depth seismicity of the Vrancea zone, in the area of Dobrogea the seismic hazard corresponds to shallow earthquakes (0-10 km) (Radulian *et al*., 2010). There are three areas concentrating the foci of shallow earthquakes (western part of North Dobrogea, east of Tulcea and the SE of Central and NW of South Dobrogea). However, the seismic hazard derived from shallow earthquakes is higher in South Dobrogea, controlled by the events in the Shabla region.

4.2.1. Crustal seismicity in the area of Dobrogea

Seismological data indicate that three types of earthquakes occur in the area of Dobrogea, as mentioned in historical documents (Atanasiu, 1961; Radulian *et al*., 2000; Bălă *et al*., 2015).

Pontic earthquakes have their foci along the Black Sea coast, in Constanța-Mangalia-Kavarna-Balchik-Shabla area (Atanasiu, 1961). This very active lineament produced 23 earthquakes during 1905-1914 (around 2-3 quakes per year). These earthquakes were described as polykinetic, as an initial, very strong quake, is followed for several years by lower intensity quakes. They are tectonic in origin, produced at moderate depths (30 km) and at large time interval. Intensities of Pontic earthquakes are up to IV; large earthquakes, with intensities > VIII, are rare. Historical events from 1869, 1870 and 1892, as well as the catastrophic 1901 earthquake from Shabla, with Mw = 7.2, are all related to Pontic earthquakes. Excepting the two earthquakes from antiquity (Table 1), separated by a time interval of about 600 years, there are no other records of a catastrophal earthquake until that in 1901.

Prebalcanic earthquakes, with foci situated in the Dulovo region of the Bulgarian part of South Dobrogea (along Kemanlar-Ruslar tectonic line). Unlike the Pontic earthquakes, they are not followed by a long series of aftershocks.

Cimmerian earthquakes have their foci along the Topolog - Cogealac seismic line in Central Dobrogea (Fig. 2). They are located along the eastern segment of the Peceneaga-Camena fault and its satellites from Dobrogea, with seismic events up to magnitudes Mw = 4.9. Moderate seismic activity is recorded in Central Dobrogea on two directions parallel to the Capidava-Ovidiu fault (Bălă *et al*., 2015).

4.2.2. Seismogenic zones

Seismogenic zones are areas with grouped seismicity, where the seismic activity and the stress field orientation are considered relatively uniform. Seismic hazard assessment requires identification of the long term characteristics of the earthquake generation process within each seismogenic zone. Several seismic sources were compiled from studies of active tectonics in the Black Sea area (Diaconescu, in Oaie *et al*., 2006b; Diaconescu and Malița, 2008): Dobrogea, Shabla, Istanbul, North Anatolian Fault Zone, Georgia, Novorossysk, Crimea, West Black Sea and Mid Black Sea. Their main features are summarized in Table 2. The most important seismic areas (measured by magnitudes on the Richter scale) are Shab-

Table 2. Main features of seismic sources in the Black Sea area, compiled using eathquakes with magnitudes Mw>2 (after Diaconescu, in Oaie *et al*., 2011)

Seismic source	Maximum magnitude	Minimum magnitude	Focal depth	Length of active segments	No. of eathquakes/ period	Fault plane solutions
North Dobrogea	5.1	3				reverse and strike-slip faults
Central Dobrogea	4.2	3	10-34 km		28/1980-2010	
Shabla	7.2	3	14 km	25 km		normal faults
Istanbul	6.1	3	14 km	100 km	874/984-2010	strike-slip faults
North Anatolian Fault Zone					256/1954-2010	
Georgia	5.8	3	10 km		346/1958-2010	
Novorossysk	5.5	3	4-39 km		39/1966-2010	reverse faults
Crimea	6.5	3	17 km		36/2007-2010	strike-slip (marine) reverse (onshore)
West Black Sea	4.9	3	14 km		8/1967-2010	strike-slip
Mid Black Sea	5.3	3	4-34 km		12/1970-2006	

la (Bulgaria), with magnitude of earthquakes up to 7.2 (e.g. 1901), the North Anatolian Fault, with seismic events up to 8 (e.g. 1939), or the Crimeea area, with earthquakes of maximum 6.5 magnitude.

The main features of seismogenic zones on the NW margin of the Black Sea are presented below.

The Predobrogea depression shows moderate seismic activity (M_W ~5.3) occuring along the Sfântu Gheorghe Fault, in extensional deformational regime. Earthquakes cluster around Tulcea and scatter to the NW along the trace of the SGF, indicating that this fault is active in connection with the seismic activity in the Vrancea zone. Seismicity is grouped at a depth range of 15–20 km (Bălă *et al*., 2015).

The North Dobrogea seismic source includes two lineaments of seismic instability, active mostly during earthquakes of Vrancea zone: Tulcea-Isaccea (representing the eastward prolongation of Galați-Pechea line) and Brăila-Măcin-Cerna (corresponding to fault zones in the Paleozoic basement of the North Dobrogea) (Fig. 2). Other lineaments, like Babadag and Cernavodă-Medgidia lines, are sensitive to Prebalkanic earthquakes. However, except for the Brăila-Măcin-Cerna line, the others do not continue in the Black Sea offshore.

The Central Dobrogea Seismic Source includes earthquakes associated to the Capidava – Ovidiu and Horia – Pantelimonul de Sus faults (Fig. 2), as well as with the NE-SW fault around the city of Medgidia. Epicenters of weak earthquakes (Mw ≤ 3.0) are grouped along the NW-SE faults (the COF fault and a fault oriented towards Palazu Mic-Hârşova). Some events with Mw ≥ 3.0 are located on the NW-SE lineament of secondary faults. Rare earthquakes with magnitude 3.2 ≤ Mw ≤ 4.9 concentrate along the Camena-Peceneaga fault (Bălă *et al*., 2015).

Popescu (1938) mentioned several earthquakes occuring in Dobrogea, the most important being on 6 April 1790 and 14 October 1892 (*collapse of the Constanța cliff on a length of 500m*), and on 31March 1901 (in Balchic – earthquake of XI degree – "*houses cracked, chimneys and roofs were knocked down…even large pieces of a hill moved from place*"; Shabla – "*... several houses and a church were knocked down*"; the earthquake had various magnitudes in the northern part of South Dobrogea: Bazargic – VIII, Constanța and Mangalia – VII – VIII). Statistically speaking, 76% of the earthquakes from Dobrogea (including its Bulgarian part) took place in Shabla – Cape Kaliakra region. The author states that "*epicenters seem to be in the offshore area, where the isobath of –100 m occurs in the prolongation of the Peceneaga – Camena Fault*".

The Shabla Seismic Source. Located on Bulgarian territory, the Shabla seismic area develops in the tectonic framework of the Moesian Platform, which is plunging here eastward, beneath its euxinic cover. In the Shabla – Cape Kaliakra area, epicenters of pontic crustal earthquakes are distributed along a series of NE-SW normal faults (Figs 2, 3). This active tectonic area represents the north-eastern limit of major NE-SW trending crustal faults which develop parallel to the Black Sea shore and enter the mainland in the Burgas area. The foci of Shabla seismic source have a limited development, with their active sector about 20-25 km long (49 earthquakes with M_w≥2). According to Atanasiu (1961), over 82 earthquakes were produced in Shabla – Cavarna – Ghiaur Suiugiuc – Balcic from 1901 to 1920. Analysis of existing record suggests that a strong pontic earthquake (8 degree) is produced once about every 600 years. Atanasiu (1961) also mentions important earthquakes produced in the I-st century and the years 543, 1869 and 1901.

The seismic activity along the IMF is weak and scattered, with only two events showing magnitude greater than 5. However, in the Shabla area, the Mw=7.2 earthquake from 1901 had a focal depth of about 35 km, suggesting an active process in the lower crust or in the upper lithosphere (Moldovan *et al*., 2005).

On the map of seismicity of the Black Sea region, based on corrected parameters of the earthquakes that were used for their seismic tomography study, Yegorova *et al*. (2013) distinguished two significant seismogenic zones in the Black Sea basin (Fig. 3): the Crimea-Caucasus zone in the northern part of the EBS, located along the Crimea-Caucasus coast, and the North Anatolian zone, in the southern part of the WBS. The distinct types of seismicity of these two zones is explained by differences in rheological properties of the two lithospheric blocks under the two Black Sea basins, as well as by different type of unloading the accumulated stress. The Crimea-Caucasus zone is characterized by earthquakes with epicenters at depth between 15-33 km or > 33 km and magnitudes Mw=3-6. The strengths accumulated in the EBS is unloaded along the northern seismic zone, where active underthrusting of the EBS is taking place beneath the Scythian Platform, confirming the accretionary origin of Sorokin and Kerch-Taman troughs (Yegorova, Gobarenko, 2010). The North Anatolian zone shows shallow earthquakes (0-15 km) with magnitudes of 3-6, but several quakes > 6 also occured. Only one quake with a deeper epicenter and magnitude > 6 occured in this zone. Both the north-eastern and the southern margin of the Black Sea are under compressional regimes, which is also supported by GPS measurements (Barka and Reillinger, 1997), as in the WBS underthrusting is taking place southwards beneath the Pontides.

The tsunami catalogue for the Black Sea basin (Papadopoulos *et al*., 2011) shows that 9 out of 21 tsunamis documented in the Black Sea were triggered in the Crimea seismogenic zone. Tsunami modelling scenarios for the Crimea region, performed using TAT software (Partheniu and Ioane, 2015) show that an earthquake with magnitude Mw=7 can generate minimum waves of 0.1 m, while maximum waves of 2.2 m can be the consequence of an earthquake of magnitude Mw=8.

As shown in table 2, the areas with tsunamigenic potential from the Black Sea can be classified according to their

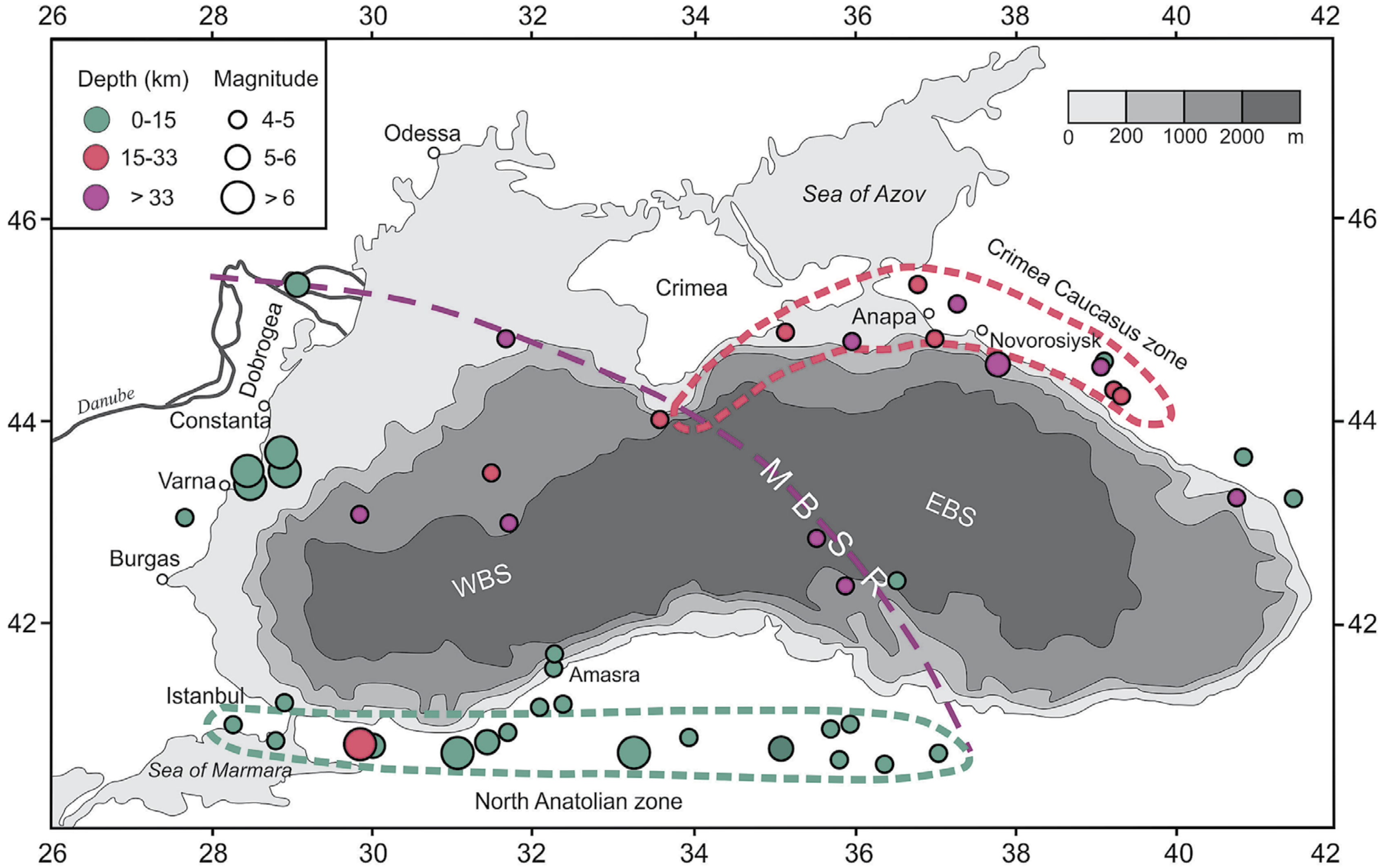

Fig. 3. Distribution of the main seismic areas in the Black Sea region (modified after Yegorova *et al*., 2013). Earthquakes with magnitudes Mw < 4 are ommited. The North Anatolian seismic zone includes shallow and strong (*M*>6) earthquakes. Crimea-Caucasus zone includes earthquakes that occurred in the lower crust-upper mantle. Shabla zone, between Varna and Constanța, includes shallow and strong earthquakes. Abbreviations: EBS, East Black Sea basin; WBS, West Black Sea basin; MBSR, Mid Black Sea Ridge.

fault plane solution, magnitude and focal depth. Three seismic sources are distinguished considering fault plane solutions: Shabla seismic source, North Anatolian seismic source (western part) and Crimea seismic source. According to earthquake magnitude, most tsunami type waves are generated by earthquakes with magnitudes > 7.5 (Richter scale), and/or magnitudes 6.9 - 7.5. The latter can produce small scale tsunamis, with local effects. Two seismic sources are important in the Black Sea from this point of view (Diaconescu and Malița, 2008): Shabla seismic source, with maximum recorded magnitude of 7.2 and a possible maximum magnitude of 7.3 (however, the length of the fault zone of only 25 km suggests limited tsunamigenic potential of the Shabla source); Crimea seismic source, with significantly longer faults and magnitudes of 6.5, indicating a tsunamigenic potential with local effects.

Based on the existing data, we can assume that significant earthquake-triggered tsunami waves in the Black Sea could be produced only by earthquakes with magnitudes higer than 6.5 on Richter scale.

4.3. Other types of geohazards in the Black Sea area

It is difficult to predict tsunamis in the Black Sea, because most events were recorded localy, on small distances from the coastal area. The magnitudes of earthquakes that produced tsunamis in the Black Sea have been quite small, and consequently their impact was mostly local. However, catalogues were produced related to the most important tsunami events for different coastal areas, as the Bulgarian (Ranguelov, 2010) or Romanian coast (Oaie, unpublished data). According to Papadopulos *et al*. (2011), sources of tsunami generation in the Black Sea are dominantly seismic sources, gravitative sliding being local, only known close to Shabla source and south of Novorossiysk. Nevertheless, several other geohazards exsting in the Black Sea could represent indirect triggers for a tsunami-type event.

4.3.1. Active faults

Geological seismic sources that are capable to produce earthquakes are active faults. Active faults on the Romanian Black Sea shelf, constrained using the study of the earthquake epicenters, are grouped into three important fault systems (Oaie *et al.*, 2006b, 2008). The NW-SE system includes some of the pre-Albian faults (crustal faults Sf. Gheorghe, Peceneaga-Camena, Ostrov-Sinoe, Capidava-Ovidiu). Displacements occurring along these faults are either strike-slip, or normal and reverse. The NE-SW system includes extensional faults directly related to the Mid Cretaceous opening of the Black Sea basin. Most of these faults are currently tectonically inverted. The NE-SW system of Miocene – Pliocene faults represent extensional faults formed through various mechanisms, like gravity sliding, diapirism, gravitational collapse, etc. Studies on active tectonics show the position of the seismic sources. Some faults may experience earthquakes, showing minimum one seismogenic segment, constrained based on the position of hypocentres. Geophysical prospecting of the most hazardous seismic area on the western Black Sea coast (Shabla-Kaliakra) suggests that complex geological, geophysical and marine seismologic investigations are necessary. Identification of surface ruptures, due to the ancient and more recent strong earthquakes, can help recognize active faults.

4.3.2. Landslides, earthflows and and rockfalls

Submarine landslides are known in the NW Black Sea basin. Studies of slope stability, especially in the area of gas hydrates accumulations (Ranguelov, 1998), revealed various unstable areas supposed to have a direct link with decomposition of gas hydrates during sea level fluctuations, when superficial sediments were often affected by sliding. Landslides, rockfalls and earthflows, showing seismic or aseismic origin, frequently occur along the Bulgarian coast (Matova, 2000). They are related to the Bizone, the 1901 Shabla, or to 1977 Vrancea earthquake. Landslides of more regional importance occur around Balchik and Varna, while those of local significance occur around Durankulak village. Significant seismic-generated landslides were maped along the coastal zone between Balchik and Kavarna. Some linear landslides are interpreted as seismic in origin (Matova, 2000). Ground subsidence, both seismically-induced or aseismic (geological or anthropogenic), has occurred around Balchik, Kavarna, Shabla and Cape Kaliakra. Following the I-st century Bizone earthquake, part of the coast between Balchik and the Cape Kaliakra subsided (Matova *et al*., 1996), while during the 1901 A.D. Shabla earthquake, an area of 200 decares (200.000 m^2) to the south-west of Balchik subsided into the Black Sea (Matova, 2000). Such subsidence varies from several meters up to 10 m in magnitude.

4.3.3. Mud vulcanoes and gas seeps

Mud volcanoes are very good markers for the presence of the gas or gas hydrates accumulations in the bottom sediments of the Black Sea (Bohrmann *et al*., 2003, 2008), their chemical composition indicating their origin (superficial or originating from a greater depth in the sea bottom). Using geophysical technics (e.g. multibeam and reflection seismics) it is possible to identify important mud volcanoe structures, most of the active mud volcanoes beeing located in the Black Sea south of the Crimeea peninsula and in the WBS, SE of the Dnepr fan (Fig. 4).

Over 200 gas seeps (95-98% methane) have been discovered in the past 15 years in the northwestern Black Sea, most often attributed to large fault zones. Many sites are associated with carbonates (Kutas *et a*l., 2002). The gas release along fault traces indicates that gas seeps are triggered by faults (Kutas *et al*., 2004). On the north-western Black Sea shelf, wider areas of deep gas are located on major paleocanyons buried in Pliocene-Quaternary deposits (Fig. 4). A narrow zone with subsurface gas and a seepage alignment developed along the modern Danube Canyon. Another indication of

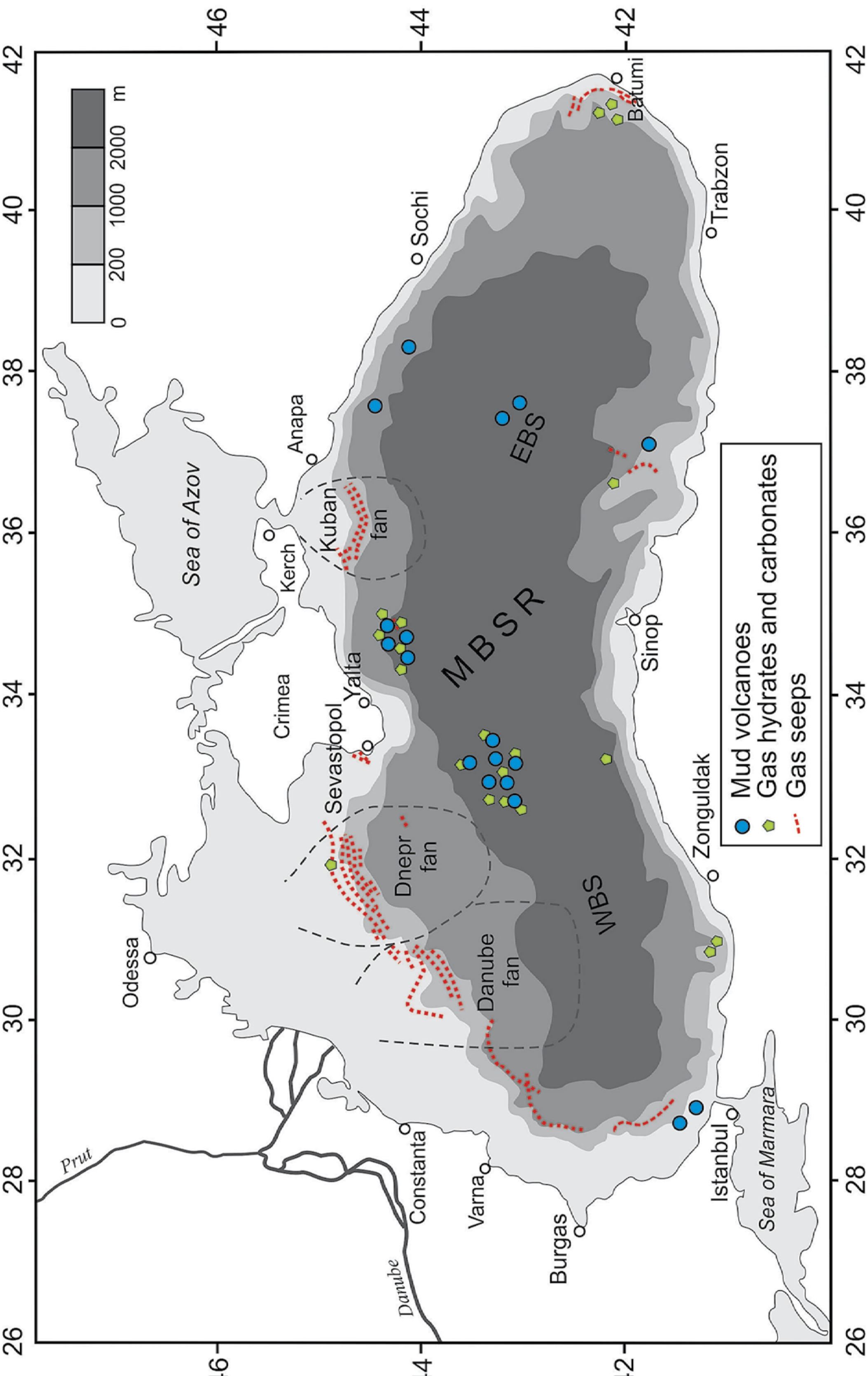

Fig. 4. Distribution of gas seeps, mud volcanoes and gas hydrates in the Black Sea (after Egorov *et al.*, 2003 and Geomar, http://www.geomar.de/forschen/fb4/fb4-gdy/projekte/doku-gas/).

deep gas is the alignment of gas seeps along major faults, such as Peceneaga-Camena (Popescu *et al*., 2004).

The Dnepr paleo-delta area (NW Black Sea) is characterized by abundant presence of methane seeps (Fig. 4). 2778 methane seeps were detected here on an area of 1540 km^2 (Naudts *et al*., 2006). They are located between the shelf and the continental slope, at water depths from 66 to 825 m. For the majority of the seeps, the water depth is the stability limit for the gas hydrates (around 725 m). On the continental shelf, the seeps are found in pockmarks above the margins of filled channels. On the continental slope, seepages occur along crests of sedimentary ridges and in the vicinity of canyons (Naudts *et al*., 2006). Such seeps are much more intense and show a wider spread on the continental slope of Ukraine (Egorov *et al.*, 2003). According to Egorov *et al*. (2001), if the water depth is less than 100 m, some massive gas seeps from the Black Sea could reach the atmosphere. Most seeps are single and only some areas are mapped so far. Data from the western Black Sea offshore indicate that gas is mainly methane with biological origin (Lein *et al*., 2002). However, both gas seeps and mud volcanoes represent triggers for possible marine hazards, mainly with local importance.

High underwater gas emission and large mud-volcano eruptions could generate tsunamis. These have to be seen at most as elements in support of the submarine landslide hypothesis. These events are processes that tend to be concurrent with submarine instabilities, or that have a role in triggering the landslides that represent the direct cause of the tsunami.

4.3.4. Meteotsunami

Another potential marine hazard is related to the „meteotsunami". Meteotsunamis are caused by a substantial change in air pressure, which yields local strong seiches. It is difficult to find examples of places affected by meteotsunamis with very long return time, since such events tend to be repeated in the same places with relatively short inter-event times, mostly of the order of years (Monserrat *et al*., 2006; Ranguelov *et al*., 2008). Such an event, a traveling atmospheric disturbance, was supposed to have affected the Bulgarian coast on 7 May 2010 (Vilibrić *et al*., 2010), producing tsunami-type waves 2-3 m in height. An alternative interpretation, of landslide- triggered tsunami (Ranguelov *et al*., 2008) is not supported by data, as no earthquake was reported that time. On 27 June 2014, a meteotsunami hit several localities on the Adriatic coast and a 3 m wave washed away more than 10 people on Chernomorka beach in Odessa region. There was a sharp sea level rise of about 1.5 meters in Odessa and the neighbouring port-town Illichevsk and several boats were damaged. Numerical modeling confirm the cause of the event was a meteotsunami, caused by air pressure disturbances observed in the Black Sea (Sepic *et al*., 2016).

5. TECHNICAL SUPPORT AND METHODS TO MONITOR THE MARINE NATURAL HAZARDS

In 2010, GeoEcoMar (Romania) had the first major initiative related to a regional early-warning system for marine geohazards of risk to the western Black Sea coastal area. Functional since June 2013, the system is managed by two National Data Centres from Romania (GeoEcoMar, Constanța Branch) and Bulgaria (IO-BAS HQ, Varna). The real-time, automatic deep-sea gauge has two modules, involving sea stations and on-shore coordination centers (one center for each country).

The need to kickstart this activity came from the proven vulnerability of the Black Sea area to the natural extreme events, such as earthquakes, submarine landslides, extreme storms, some of them with a high tsunamigenic risk.

5.1. The Romanian-Bulgarian Early warning System

One of the main components of the early-warning system is the EUXINUS network, a complex automatic marine measurement system, consisting of 5 measuring instruments installed in key points of the Western Black Sea shelf, 4 being deployed in water depths around 100 m and one deployed near the shoreline (15 m water depth) (Fig. 5). The last one represents a key component of the coastal wave monitoring system, located in Mangalia (Romania), close to the Romanian – Bulgarian border.

The Black Sea Security System is an integrated multi-parameter system that provides long time series of physical and bio-chemical data, regarding the properties of the water masses (temperature, pressure, conductivity, dissolved O_2, chlorophyll, turbidity, water current direction and amplitude, etc.) and local meteorological parameters (air temperature, air pressure, humidity, wind direction and speed, precipitation) (Fig. 6).

The other important key component of the system is the Marine Seismic Acquisition System (MSAS), composed from one 2D Marine Seismic Acquisition System with 96 channels streamer and 7 Ocean Bottom Seismometers. The aim of the 2D MSAS is to deliver information regarding the submarine Earth crust structure, as the stratigraphy and geometry of sedimentary formations, the relationship between the tectonic blocks, as well as active shallow depositional/erosional processes, in order to understand and map potential threats. The Ocean Bottom Seismometers (OBS) provide critical data about regional earthquakes. When used as seafloor recorders, they acquire information from deeper crustal areas, offering information about crustal and upper astenosphere architecture and composition.

The Coordination Centers from the two countries have the important task to automatically operate the stations for tsunami detection, as well as to elaborate and transmit the tsunami alarm notifications to decision-makers. They also receive and store all the real time or near-real time data originating from all equipments.

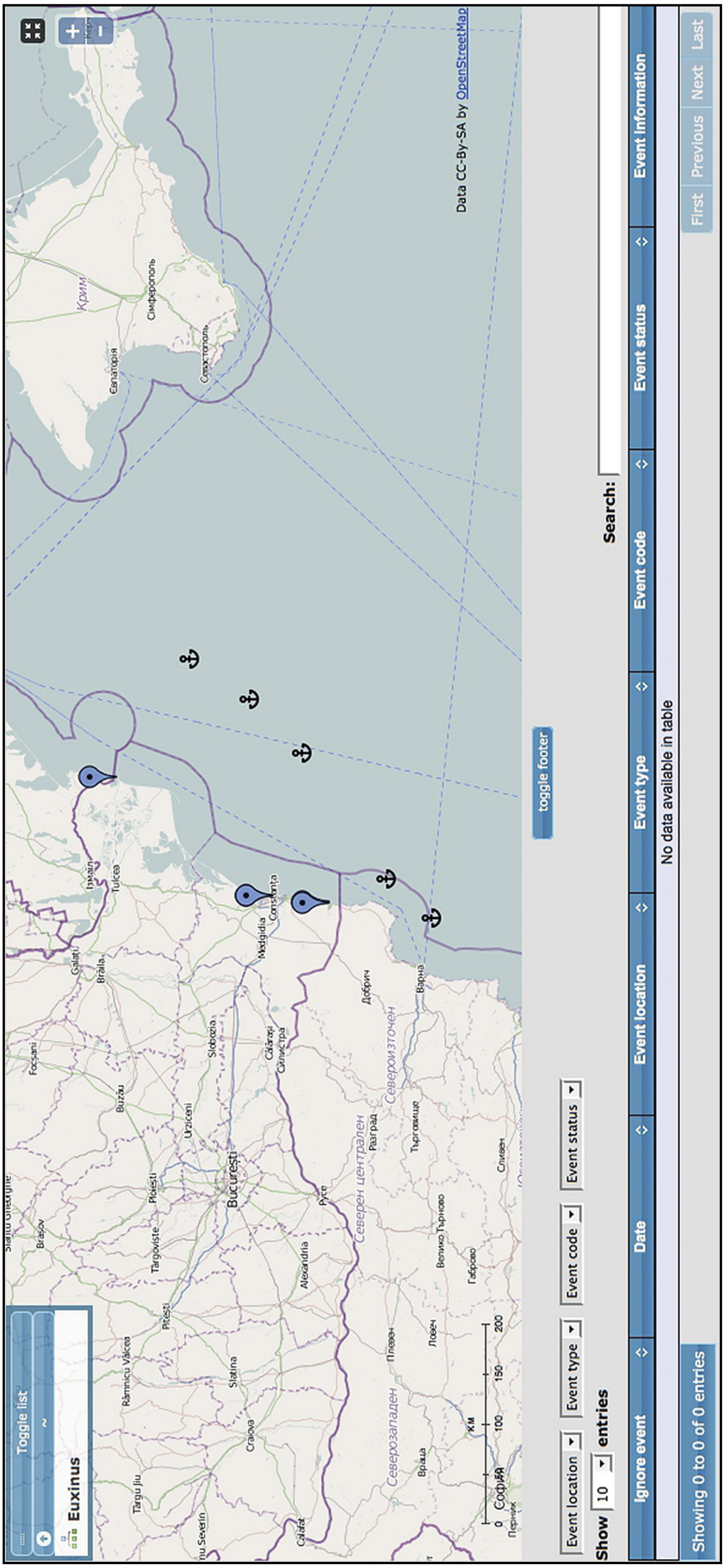

Fig. 5. The *EUXINUS* network shown in GEM 2.1. software.

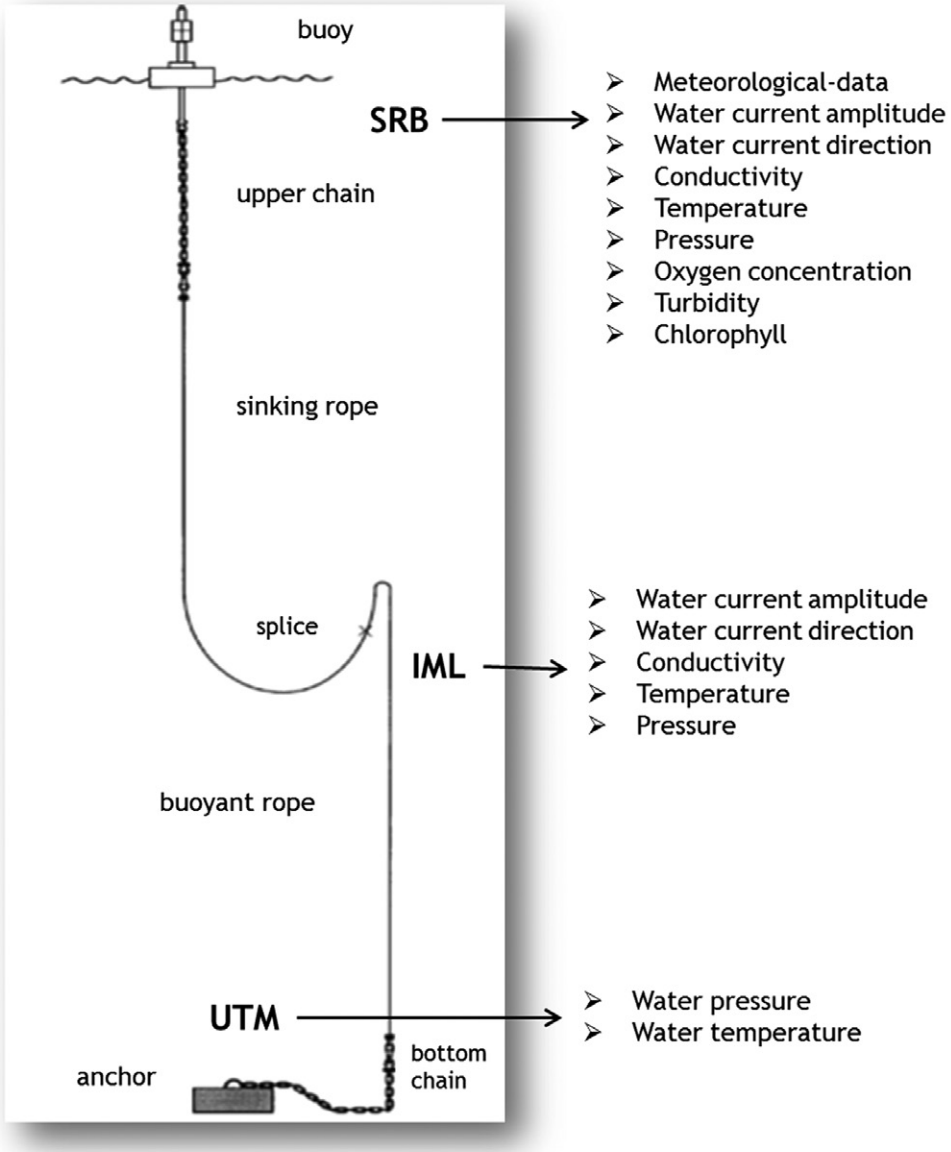

Fig. 6. Types of data collected from the EUXINUS buoys. Abbreviations: SRB, surface relay buoy; IML, intermediate module layer; UTM, underwater tsunamometer module.

The special software used to analyze the data series acquired in the centers has the ability to simulate tsunami waves generation due to potential sources in the area of the Black Sea basin, the propagation of tsunami waves and also to assess the inundation (without roughness of the coastal areas) of Bulgarian-Romanian coastal areas.

The main target of the Black Sea Security System is to elaborate risk assessments and to send early-warning notifications to the authorities. Moreover, the system scheme enables evolution monitoring of an ongoing marine risk situation.

The land-based components of the strong motion seismic network provide reliable information about the strong seismic motions generated by local sources, measuring displacements on all directions and planes and angular deviations.

The data series acquired from the water level sensors, pressure sensors, seismometers and accelerometers are processed and analyzed through GEM 2.1., Tsunami Analysis Tool (TAT) and Presto software at the EUXINUS centres (Fig. 7). As a result, high resolution maps and graphic scenarios are developed and risk notifications are sent to the authorities (Fig. 8).

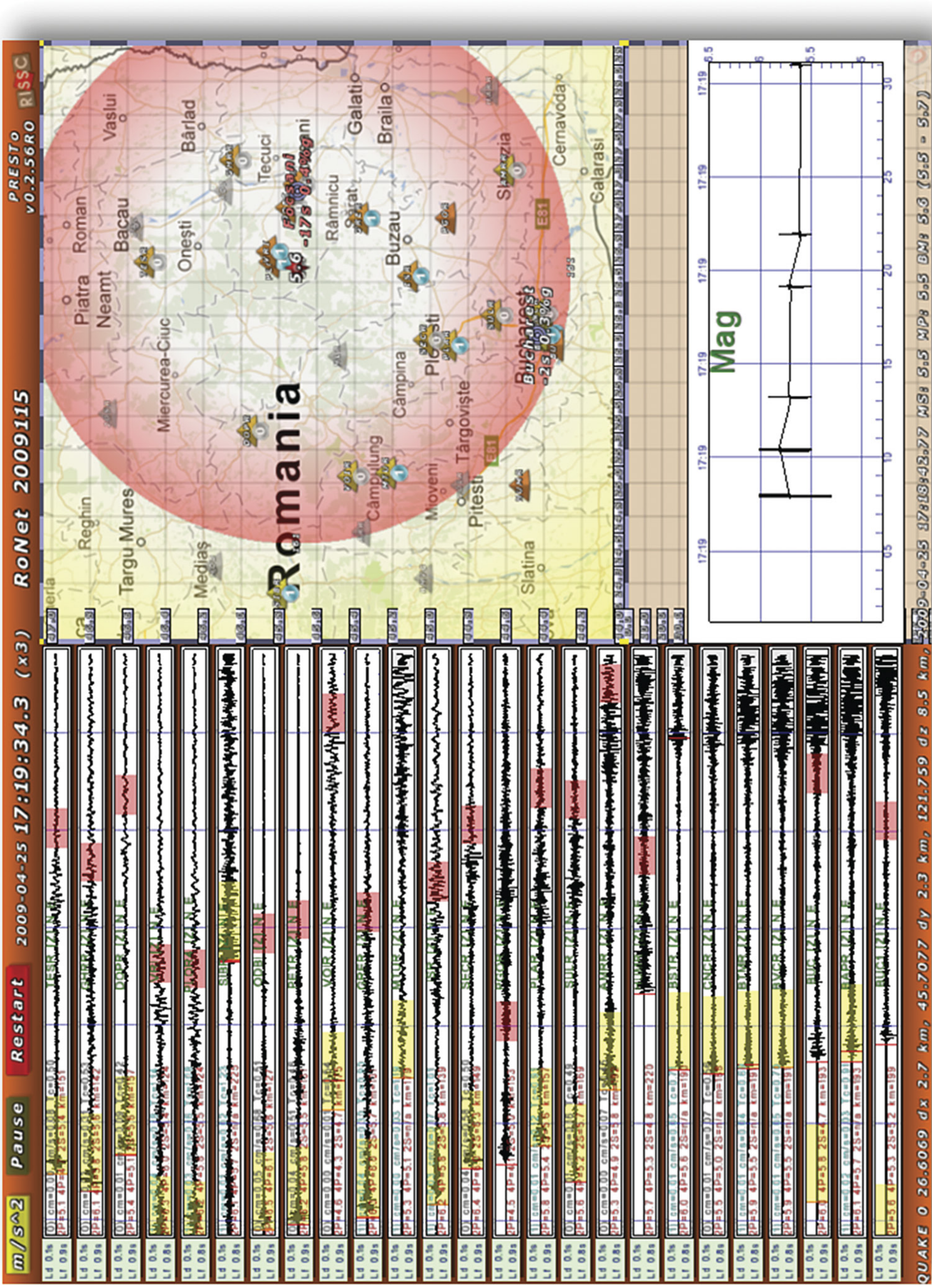

Fig. 7. Earthquake simulation in PRESTO software.

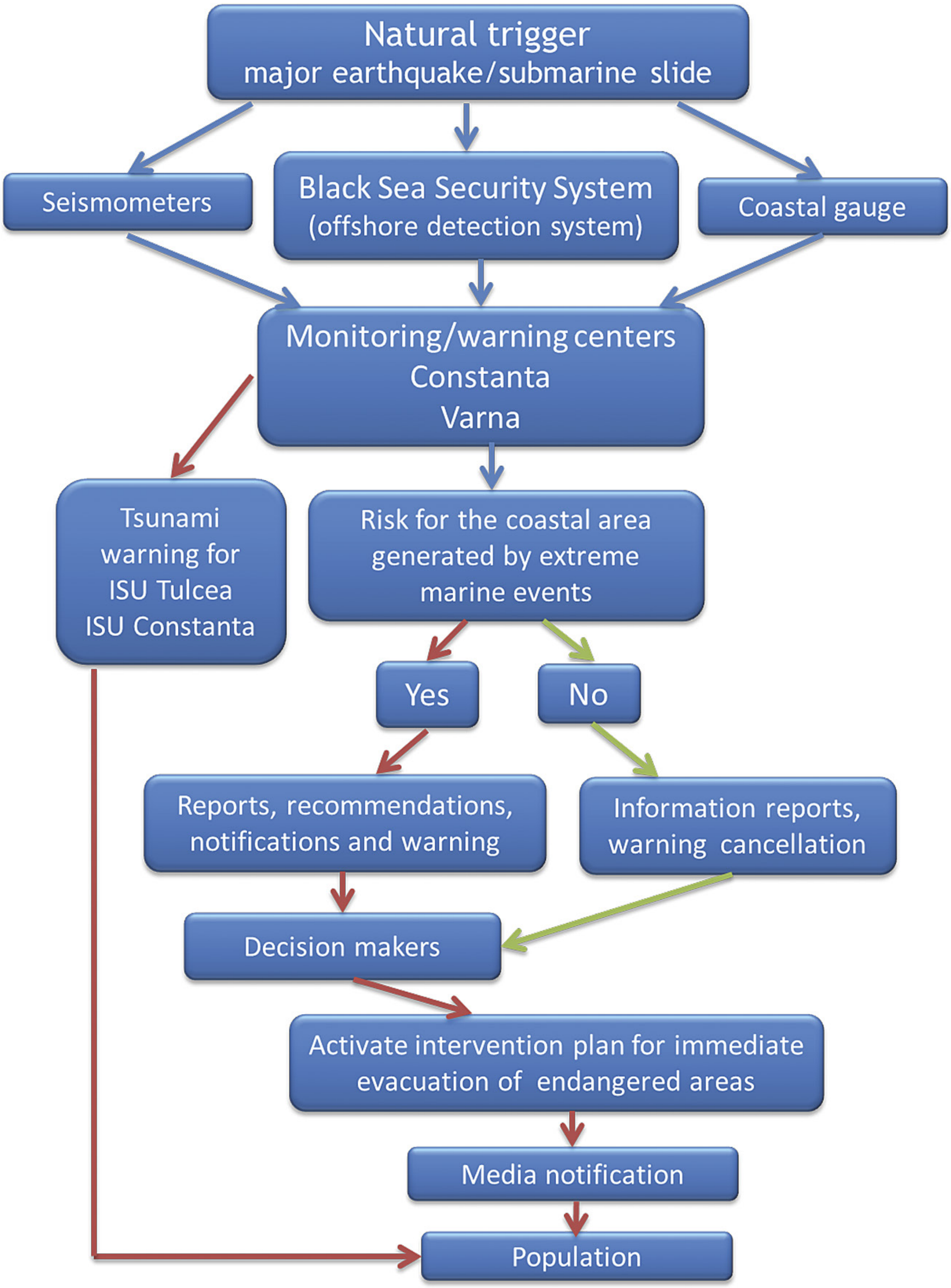

Fig. 8. Event alerts in GEM 2.1. software. Once a natural trigger is detected by the offshore detection system (the Black Sea security System), the ocean bottom seismometers and the coastal gauge, the monitoring/warning centers in Constanța and Varna are notified. These centers analyse de information and if the event represents a risk for the coastal area or Romania, a tsunami warning is sent to the Inspectorates for Emergency Situations (ISU) in Tulcea and Constanța, as well as reports, notifications and warnings to local decision makers, who are able to activate intervention plans for immediate evacuation of the population.

6. CONCLUSIONS AND PERSPECTIVES

As the main tsunami triggering mechanisms are present in the Black Sea (earthquarkes, submarine landslide, displacement along active faults or extreme meteorological events), they have imposed the necessity of acchieving an early-warning system. The Black Sea Security System, managed by GeoEcoMar (Romania), the first early-warning system from the Black Sea, envisions the prevention of natural risk and coordination of emergency responses at cross-border level.

The fully functional network has been conceived to establish a common regional system for early warning, as a joint instrument for intervention for the protection of the local communities, the environment and the goods in the cross-border area, related to the consequence of natural marine geo-hazards. The early warning system offers the necessary support in all emergency situation management stages, by continuously supplying the results of data analysis.

Therefore, a long term aspiration of this activity is to consolidate international relationships within the Black Sea basin and also to increase the connection to European and international governmental initiatives such as GEO/GMES, EMSO-ERIC, EPOS, IOC-UNESCO and other.

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