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Recent geological activity along the northeastern Bulgarian Black Sea coast

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The densely populated northeastern Bulgarian Black Sea coast is a territory of intensive contemporary development. It is, though, marked by considerable recent geological activity along the coastal zone comprising: faulting, earthquakes, landslides, earthflows, rockfalls, ground subsidence, marine erosion and variations of sea level. These are locally exacerbated by the ongoing development, resulting in increased instability. Notably, a part of the coastline has been lost as a result of gravity sliding. Analysis of this recent geological coastal activity, including the landslides, earthflows and rockfalls of 1996–1997, needs be taken into account for the protection of the population and the cultural heritage.

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INTRODUCTION

The northeastern Bulgarian Black Sea coast has a long history of settlement by ancient Thracians, Greeks, Romans and Slavs prior to the creation of the Bulgarian State. Thus, much historical information is available for the coastal region in Bulgaria and abroad, and this includes accounts of geological phenomena.

Current scientific coastal investigations are numerous and diverse. Some recent geological studies have focussed on impressive landslides, earthflows and rockfalls which took place along the coast, mainly between the city of Varna and the town of Balchik, in 1996–1997.

NATURE OF THE RECENT GEOLOGICAL ACTIVITY

Recent geological activity along the northeastern Bulgarian Black Sea coast may be interpreted generally within the context of location of the region at the southern margin of the Eurasian Plate. Moreover, the northeastern Bulgarian Black Sea coastal zone includes the boundary of two tectonic units with contrasting development during the Neogene — the Moesian Platform and the Black Sea Depression. Tectonism continues to the present day.

Current geological activity along the northeastern Bulgarian Black Sea coast takes the form of active faulting, seismic activity, frequent small- and large-scale landslides, earthflows and rockfalls, ground subsidence and so on. This study was provoked by the latest remarkable series of landslides, earthflows and rockfalls in the northeastern Bulgarian Black Sea coastal zone in 1996–1997.

ACTIVE FAULTS AND PHOTOLINEAMENTS

Active faults are present between the Moesian Platform and the Black Sea Depression. These have been traced by field research, remote sensing (Gocev *et al.*, 1984), tectonic interpretation of seismic data (Matova, 1970; Shebalin *et al.*, 1974; Ranguelov and Gospodinov, 1994; Matova *et al.*, 1996) and integrated geological-geophysical research (Kuprin *et al.*, 1980). The main fault zones (Gocev *et al.*, 1984; Matova *et al.*, 1996) are oriented NNE–SSW or NE–SW (Kaliakra, Tyulenovo and Balchik faults), and E–W or ESE–WNW (Forebalkan and Charakman faults) (Fig. 1).

Segments of the Charakman fault zone (E–W) were traced during field research to the west and south-west of Balchik and on the Kaliakra Cape. The geophysically established component of the zone, the Batovo fault (E–W), was traced on the

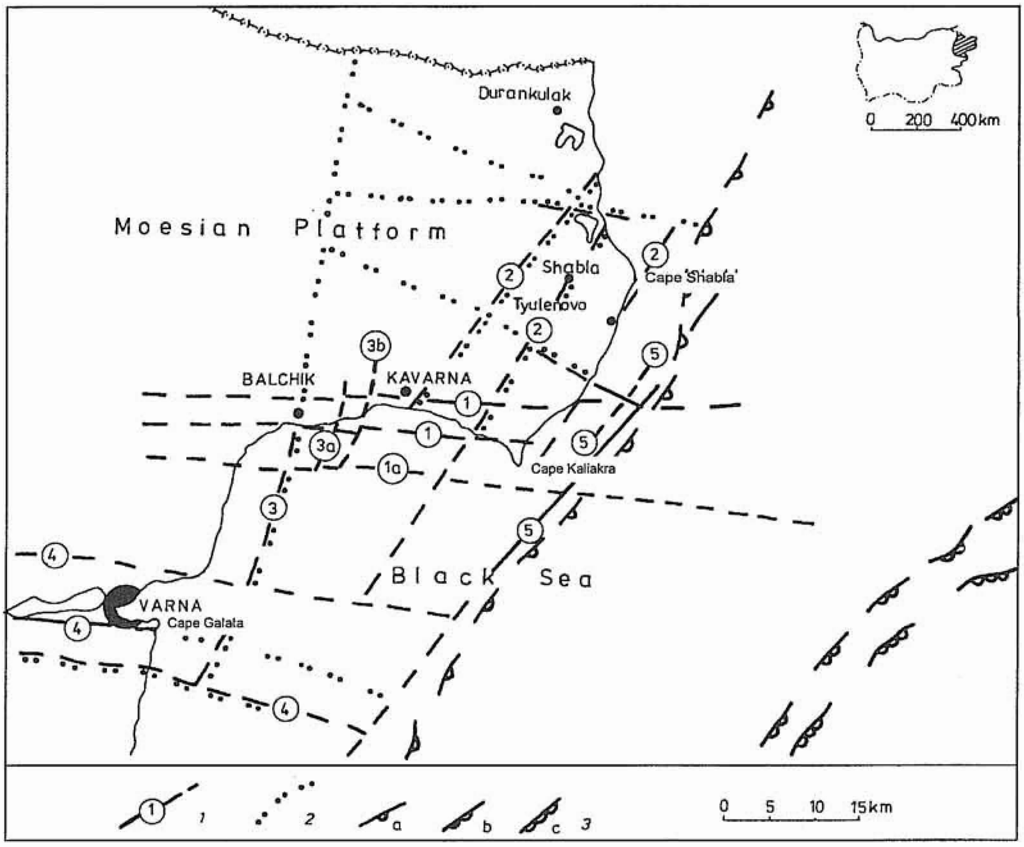

Fig. 1. Faults and photolineaments along the northeastern Bulgarian Black Sea coast (Matova, 1970; Kuprin *et al.*, 1980; Gocev *et al.*, 1984; Matova *et al.*, 1996)

1 — main fault zones (1) — Charakman zone, (1a) — Batovo fault, (2) — Tyulenovo zone, (3) — Balchik zone, (3a) — Eastern Balchik fault, (3b) — Touzlata fault, (4) — Forebalkan zone, (5) — Kaliakra zone); 2 — photolineaments; 3a–c — geologically and geophysically established boundaries on the shelf

Black Sea shelf (Kuprin *et al.*, 1980). The geophysically investigated Balchik, Touzlata and the Eastern Balchik faults (NNE–SSW) (Kuprin *et al.*, 1980) are included in the Balchik fault zone. In the east' the Moesian Platform and shelf are cut by the geologically and geophysically established Tyulenovo fault zone (NE–SW) and by the Kaliakra fault (NE–SW). The latter is situated close to the boundary between the internal and the middle zone of the shelf. The Forebalkan fault zone (E–W and WNW–ESE) is geologically and geophysically traceable in the vicinity of Varna and the adjacent shelf.

The Charakman, Tyulenovo, Balchik, Forebalkan and the Kaliakra fault zones define the approximately N–S and E–W orientation of the coastlines in the territory. For example, the Charakman faults define the coastline between Balchik and the Kaliakra Cape, as do the Tyulenovo faults between the Kaliakra and the Shabla Capes. The Balchik and Forebalkan faults determine the block segmentation in the region of Varna and the adjacent shelf. A boundary on the shelf coincides generally with the most representative fault of the Kaliakra fault zone (Fig. 1).

Many approximately N–S and E–W photolineaments (Gocev *et al.*, 1984) are marked also on the Moesian Platform and the Black Sea Depression (Fig. 1). The photolineaments are situated longitudinally, transversally and obliquely to the coastline. Two photolineaments with a NW–SE direction are present on the coast, respectively to the north of the Kaliakra Cape and to the north of Shabla. Most of these photolineaments coincide with the fault zones, which have resulted in considerable block fragmentation especially around Varna and Balchik (Fig. 1).

ACTIVE FAULT INTERSECTIONS

Intersections of longitudinal, transversal and oblique faults and photolineaments have been plotted along the coast (Matova, 1970; Gocev *et al.*, 1984), many being concentrated between Balchik and the Kaliakra Cape (Fig. 1). Other intersections occur around Varna and Shabla.

INCIDENCE OF EARTHQUAKES AND TSUNAMI

Information on 19th and 20th century earthquakes has been systematically accumulated but there is only sporadic information on historical earthquakes. The seismic data are based on the Balkan Seismological Catalogue (Shebalin *et al.*, 1974), annual and regional investigations (Watzof, 1903; Ranguelov and

Gospodinov, 1994), tsunami research (Ranguelov, 1998). Archaeological (Toncheva, 1963) studies of strong and moderate earthquakes in the investigated territory have also been used.

The epicentres of the local historical and contemporary strong earthquakes with $M \geq 7$ are sited mainly in the shelf of the Moesian Platform close to the Black Sea Depression (Fig. 2). The most prominent of these were:

— 1st century B.C. (presumably 50 B.C.) Bizone earthquake with $M = 7.0$,

— 543 A.D. Black Sea earthquake with $M = 7.5$,

— 1444 A.D. Varna earthquake with $M = 7.5$,

— 1901 A.D. Shabla earthquake with $M = 7.2$.

The epicentre of the 1st century B.C. Bizone earthquake was situated midway along the coast investigated (Fig. 2). Its name came from the ancient Thracian town-fortress and part of Bizone that was built on the coastal hill known as Charakman, south-west of the present town of Kavarna. The Bizone fortress was used during the Thracian, the Hellenic and the Roman periods of the history of the Balkan territories. Its seismic destruction during the Roman period was commented on by Strabo (58 B.C.–21/25 A.D.) and Plinium (23–79 A.D.).

Part of the town of Bizone fell in the sea mainly as a result of earthquake shocks, landslides, earthflows and ground subsidence in the southern periphery of Charakman hill (Fig. 2). Archaeological research on the northern and central parts of Charakman hill, as well as on the Black Sea bottom around Kavarna (Toncheva, 1963), found evidence of this co-seismic destruction. It is likely that there were considerable human losses.

Direct (field) and indirect (documentary) information was used to assess the extent of the destructive seismic effects . During the 1st century B.C. the effects of seismic deformation and destruction could be traced along 25 km of the coast between the town of Balchik and Cape Kaliakra. The Bizone earthquake produced several changes in coastal topography. Historical documents indicate reconstruction of the town of Dionisopolis (the present town of Balchik), in the village of Touzlata and in the town-fortress of Acre Castelianum (the present Kaliakra Cape). This indicates a total destruction of Bizone and partial destruction of Dionisopolis and Acre Castelianum. The seismic effects were related to the movement along the Charakman fault zone. The location of the earthquake's epicentre may have lain at the intersection of the Charakman (E–W), the Balchik (NNE–SSW) and the Tyulenovo (NE–SW) fault zones (Fig. 2).

The epicentres of the second (543 A.D. Black Sea) and of the third (1444 A.D. Varna) strong earthquakes were situated in the shelf zone, around Varna. The 543 A.D. Black Sea earthquake is not well localized or described. Its epicentre around Varna (Fig. 2) suggests activation of the Forebalkan (E–W and WNW–ESE) and the Tyulenovo (NE–SW) faults, and of their intersection on the Black Sea shelf (Fig. 2).

The epicentre of the 1444 A.D. Varna earthquake was located on the shelf, close to Varna (Fig. 2). The earthquake caused changes to river courses (Shebalin *et al.*, 1974). Completely destroyed settlements in the surrounding of Varna were also noted in historical sources. The epicentre of the earthquake was close to the intersection of the recently active Forebalkan (E–W and WNW–ESE) and Balchik (NNE–SSW) faults (Fig. 2).

The epicentre of the fourth (1901 A.D. Shabla) earthquake was also in the shelf zone near Shabla. The earthquake provoked human and material losses in the lightly populated coastal zone between the capes of Kaliakra and Shabla. Many coastal villages were destroyed and numerous instances of landslides, rockfalls and land subsidence were documented in the annual bulletin of 1901 (Watzof, 1903). The earthquake was related to activity along the Charakman (E–W), Kaliakra (NE–SW) and a local un-named fault (NW–SE) (Fig. 2).

The northeastern Bulgarian Black Sea coast was also affected by more distant earthquakes the Balkan Peninsula in particular those with epicentres around. The intermediate Vrancea and in the Aegean Sea.

Some of the periodically repeated Vrancea earthquakes with $M \geq 7$ may have caused destructive effects in the territory investigated, even though their epicentres were 250–300 km to NNW. The 1977 A.D. Vrancea earthquake ($M = 7.2$) caused landslides and coastal deformation, mainly around Balchik (Ranguelov, 1998).

Study of tsunami incidence and of their effects on the coast is at an initial stage (Ranguelov, 1998). Some tsunamis could be related to recognized earthquakes (1st century B.C. Bizone and 1901 A.D. Shabla earthquakes), while others have no recognized cause. Evidence of tsunamis is present in the vicinity of Kavarna and Balchik, and also at Kabakum near Varna (Ranguelov, 1998). The tsunamis came from the shelf, mainly from a section of the Kaliakra fault to the north of the Forebalkan fault zone (Broutchev, 1994) (Fig. 2).

These local and regional earthquakes caused human and material losses.

LOCATION OF LANDSLIDES, EARTHFLOWS AND ROCKFALLS

Landslides, earthflows and rockfalls commonly took place along the coast (Fig. 3).

At any locality, landslides were commonly repeated on a timescale of decades or centuries. Many of the landslides, earthflows and rockfalls are of aseismic origin, while others are of seismic origin. The latest aseismic landslides, earthflows and rockfalls were observed in 1996–1997 after heavy rainfall.

Some of the landslides, earthflows and rockfalls relate, though, to historical and contemporary earthquakes. Most are related to the local 1st century B.C. Bizone ($M = 7.0$) and to the 1901 A.D. Shabla ($M = 7.2$) earthquakes, and to the regional intermediately strong Vrancea earthquakes, including the shock in 1977 ($M = 7.2$).

Landslides. Landslides of local significance occur around Durankulak village, while those of more regional importance occur around Balchik and Varna (Fig. 3).

Impressive seismically provoked landslides occur along several sections of the coastal zone in the region of Balchik and Kavarna. Some linear landslides to the north of the Golden Sands resort (Varna) may also have a seismic origin.

Aseismic landslides are more widely distributed in the territory investigated than the seismic ones. They occur around

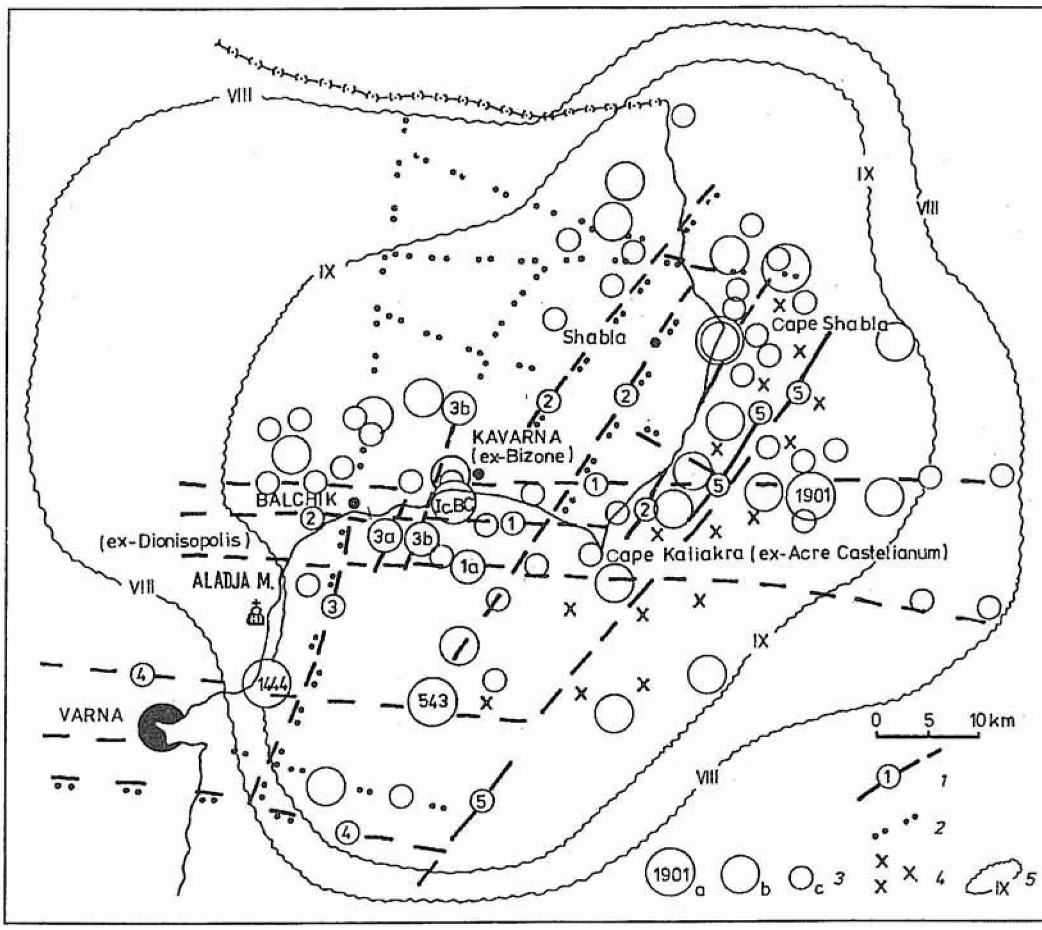

Fig. 2. Seismotectonic scheme of the coastal territory investigated (according to Shebalin *et al.*, 1974; Bonchev *et al.*, 1982; Ranguelov and Gospodinov, 1994; Ranguelov, 1998, completed by the author)

1 — main fault zones (①— Charakman zone, ①a — Batovo fault, ②— Tyulenovo zone, ③— Balchik zone, ③a — Eastern Balchik fault, ③b — Touzlata fault, ④— Forebalkan zone, ⑤— Kaliakra zone); 2 — photolineaments; 3 — epicentres of earthquakes (I c. B.C. — 1920) with magnitudes: a — M = 2.8–4.0, b — M = 4.1–6.0, c — M = 6.1–7.5; 4 — tsunamigenic locality; 5 — maximal expected intensity for a 1000 years' period

Balchik, Kranevo village, Albena, Varna (including St. Constantine and Helena) and Golden Sands.

Typical aseismic landslides occurred after heavy rainfall in 1996–1997 around Varna (between St. Constantine, Helena and Golden Sands) and Balchik. They caused severe disruption to the transport system. Damage due to coastal deformation was ameliorated by reconstruction work between Varna and Balchik. Surveys of buildings and of the geological situation in the most seriously affected regions were carried out. The rural buildings most at riste are to be removed in the next few years.

The larger coastal landslides observed are deeply based (from several tens up to hundred metres below a sea level). Such deep landslides may reflect variations of sea level during glacial and post-glacial times, as well as earthquake magnitude.

Shallow superficial landslides, widely distributed along the coast investigated, are partly related to periods of heavy rainfall, e.g. in 1996–1997.

Earthflows. These also both seismic and aseismic origins. Small seismically generated earthflows were investigated in the region of Balchik and Kavarna. These are of limited importance and are not indicated on the scheme of the landslides in the coastal zone. The earthflows due to the 1st century B.C. Bizone earthquake in the vicinity of Kavarna were a subject of engineering geological and hydrogeological studies (Koleva-Rekalova *et al.*, 1996).

Small earthflows of aseismic origin occurred to the WSW of Balchik in 1996–1997, during which lines were lost.

Rockfalls. The rockfalls are common along several sections of coast. They occurred mainly between the town of Kavarna — the Kaliakra Cape — the Kamen Bryag village and the Galata Cape (southern periphery of Varna) (Fig. 3).

Most rockfalls are of aseismic origin, associated with intense rainfall, as in 1996–1997. The "Galata" restaurant, situated at the Galata Cape, was then partly destroyed by aseismic rockfalls.

Some rockfalls in the region of Kavarna and the Kaliakra Cape probably had a seismic origin, triggered by powerful earthquakes ($M \geq 7$).

GROUND SUBSIDENCE

Ground subsidence has occurred around Balchik, Kavarna and Shabla, and of the Kaliakra Cape (Fig. 3). It is both of seismic and aseismic (geological or anthropogenic) origin. Part of the coast between Balchik and the Kaliakra Cape subsided during the 1st century B.C. Bizone earthquake ($M = 7.0$) (Matova, 1996). An area of 200 decares, to the south-west of Balchik, subsided into the Black Sea (Watzof, 1903) during the 1901 A.D. Shabla earthquake ($M = 7.2$). Such seismically induced subsidence varies from several to up to 10 m in magnitude.

Ground subsidence of aseismic origin includes karst collapse (to the south of the Kamen Bryag), to saturated soft rocks (in the vicinity of Shabla), and to a combination of geological and anthropogenic factors in the "Obrochishte" mine.

MARINE EROSION

The coastal deposits are of Neogene age. They are variably consolidated, the lithified rocks often being fractured and faulted. Coastal topography is steep, and much of the coast is subjected to marine erosion varying from intense to moderate (Fig. 3).

The level of marine erosion reflects sea water chemistry and rock and slope stability. High salinities (to 16%) enhance the process.

Marine erosion is particularly impressive around Balchik and to the south of Varna (Fig. 3). It is moderate along the coast between the Shabla and Kaliakra Capes, as well as between Kranevo and Varna.

KARST DEVELOPMENT AND COLLAPSE

Karst is well develop in the Neogene, particularly Sarmatian limestones, along the coast between the Shabla Cape and Golden Sands (Fig. 3). Many cavities, caves and karst collapses occur on vertical and steep slopes between the Kaliakra Cape and Kamen Bryag.

Some karst features were used historically as settlements, mostly deteriorated (around Kamen Bryag) or partially preserved. The Aladja rock monastery, for instance, is an old Pre-Bulgarian and Bulgarian cultural heritage site, protected by UNESCO since 1979. It is sited on karst on a vertical slope north-west of Golden Sands. Recent landslide activity along the coast pose a considerable threat to this historical monument.

COASTLINE MIGRATION DUE TO SEA LEVEL CHANGES

Eustatic sea level changes have led to coastline migration along the Bulgarian Black Sea coast (Mihova, 1998). Seaward coastal migration occurred during Würmien-III glacial stage (23 000 B.C.). The Black Sea was confined to a small area as a result of sea level fall of about 100 m.

The post-glacial interval (12 710±1100 B.C.) saw a rapid enlargement of the Black Sea. This time saw the first entrance of Mediterranean water and an increase in the salinity of the Black Sea.

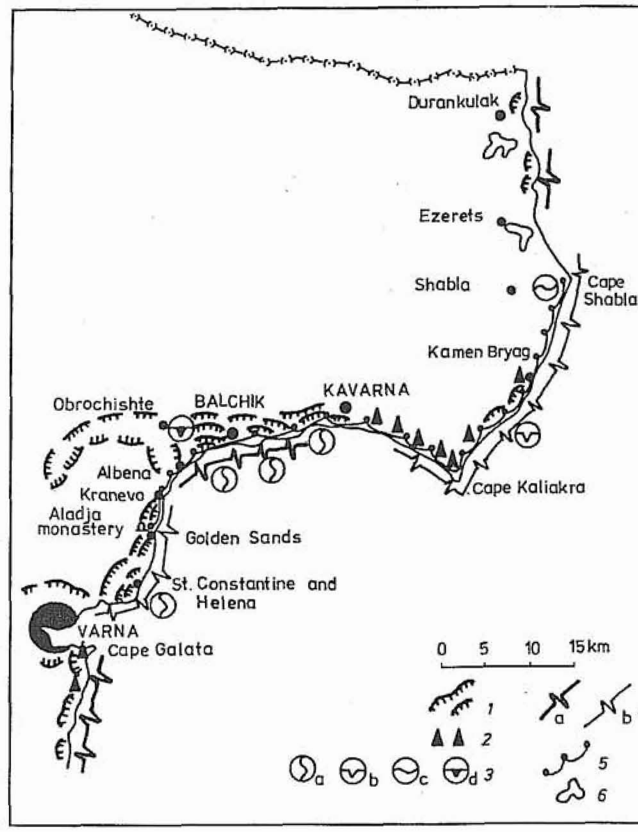

Fig. 3. The main areas of landslides, rockfalls, ground subsidence, sea erosion, karst and limans along the coast investigated (Broutchev, 1994, with the author's additions)

1 — landslide; 2 — rockfall; 3 — ground subsidence related to: a — strong seismic events, b — karst collapse, c — saturated soft rocks, d — mining activity; 4 — marine erosion: a — very intensive, b — moderate; 5 — karst; 6 — liman

Subsequent changes to the coastline were less significant, as changes in sea level were of a lesser scale. In early Holocene times (6620–5040±70 B.C.) a lowering of the Black Sea level took place. The early Holocene coast is now found at a depth of 30–34 m below sea level.

Following this, a rise of sea level occurred. The coast limans (Fig. 3) north of Shabla were formed then. The Durankulak and Ezerets limans formed at 4170 and 4800 B.C. respectively.

A subsequent drop in sea level is recorded by the appearance of peat layers between the marine sediments of the limans.

The following retreat of the coast was caused by a rise of sea level at 3500–3200 B.C. The sea level was then 4–5 m higher than the contemporary one.

Coastal advances took place at 3000–2400 B.C. due to a lowering of sea level.

The subsequent coast retreat was caused by rising sea level at 1940–1120 B.C. with coastal advance at 1600–0 B.C. The coastline then advanced some several tens or hundreds of metres on to the shelf. Greek colonisation of the Black Sea coast took place during the second half of this episode of sea level fall.

The first centuries A.D. were marked coastal retreat. The Black Sea level was relatively high then, though a brief episode of coastal advance took place during the Middle Ages.

Coastal retreat has been well expressed in the second half of the 19th century and in the early 20th century. Sea level rise, equalled 2786 mm/a in 1934–1991 according the last published data (Vesselinov and Mungov, 1998). This tendency might continue if global sea level rise is further provoked by the greenhouse effect.

ANTHROPOGENIC INFLUENCES

The geological phenomena described occur in a densely populated and industrialized region, and so today there are strong anthropogenic influences on the geology.

The combination of anthropogenic and geological activity has been interpreted in terms of a contemporary Technogene or Quinary time-span (Ter-Stepanian, 1983, 1988; Voûte, in press). The Quinary has thus succeeded the Quaternary while the Technogene follows on from the Holocene. This marks a significant change in the geological conditions since the expansion and technological development of human society.

Current anthropogenic influences include those on seismicity (Matova, 1997). These are caused by the construction of buildings and roads, industrial and mining activity, e.g. the "Obrochishte" mine, accumulations of waste *etc*. Effects are concentrated mainly in and around Varna, a city where industry and commerce is well-developed. Local failures in the drainage and sanitation networks have contributed to the development of landslides. Balchik has experienced similar problems, though fewer such effects are experienced to the north of Shabla, where settlements are smaller and the degree of development lesser.

Thus, the heavily populated northeastern Bulgarian Black Sea coast has considerable geoenvironmental problems, which threaten economic development and the cultural heritage, including the historical sites at Varna, Balchik and Kavarna, and the ancient Aladja monastery. Erosion of the coastline, meanwhile, is taking place around Balchik and Kavarna, the Kaliakra Cape and the village of Kamen Bryag.

CONCLUSIONS

This paper reviews recent geological activity along the northeastern Bulgarian Black Sea coast, in partcular faulting, landslides, rockfalls, ground subsidence and the current human impact.

The coastal zone occurs at the contact between the Moesian Platform and the Black Sea Depression, and is subject to seismic activity. The seismotectonic hazard for the coast is serious. Local powerful earthquakes ($M \geq 7$) are located along faults, photolineaments and their intersections around Varna, Shabla and Balchik, the Kaliakra Cape and to a lesser extent at Vrancea.

Climatic and sea level changes have led to landslides, earthflows, rockfalls, and coastline migration. The landslide, earthflow and rockfall events of 1996–1997 were particularly destructive.

Purely geological effects have been exacerbated by human activity, provoking considerable changes to the coastline in northeastern Bulgaria. There are now considerable geoenvironmental problems particularly as regards coastal topography and slope stability the geological hazard to the population and the cultural and historical heritage of the coastal zone is increasing.

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