RECENT SEDIMENTS AS ENVIROMAGNETIC ARCHIVES. A BRIEF OVERVIEW

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Abstract. A vast enviromagnetic archive has been recovered from the recent sediments of the Danube Delta (DD), Razim (Razelm) – Sinoie Lagoonal Complex (RSLC), Black Sea Littoral Zone (BSLZ) and Northwestern Black Sea (NWBS), which have been sampled over ca 35 years. The identified magnetic signatures can be used to characterize and differentiate the depositional environments inside an extended, diversified, and, at the same time, unitary complex of fluvial, lacustrine, littoral and marine ecosystems. The presence of the anthropogenic influence on some zones from these aquatic areas is clearly demonstrated by the modified magnetic fingerprints recovered from the bottom sediments and cores, at different time intervals. The most extended enviromagnetic archive belongs to the DD and RSLC. This is based on thousands of (sub)samples collected during numerous cruises carried out during the 1976 – 2011 period. To calibrate the modern sediments of the various aquatic environments and compare the different magnetic fingerprints, a Magnetic Susceptibility Scale (Rădan & Rădan, 2006a, 2007) is successfuly used.

Key words: environmental magnetism, aquatic ecosystem, sedimentary environment, bottom sediment, anthropogenic impact, magnetic susceptibility, lithological components, geoecology, magneto-sedimentology, Danube Delta, Razim – Sinoie Lagoonal Complex, Black Sea Littoral Zone, Northwestern Black Sea.

1. INTRODUCTION. SHORT ENVIROMAGNETIC BACKGROUND AND STUDY AREAS

The lake sediments have played an important role in the start of the environmental applications of the magnetic measurements (Thompson *et al.*, 1975; 1980; Oldfield *et al.*, 1978).

The fact that the magnetic properties are susceptible to the grain-size variations was among the main factors which recommended their use in the environmental magnetism. The lacustrine and also the marine sediments, utilized as environmental geomaterials, have contributed to the development of this new discipline and to the diversification of its applications (*e.g.*, Thouveny, 1991; Dearing, 1994, 1999; Verosub & Roberts, 1995; Opdyke & Channel, 1996; Dekkers, 1997; Petrovsky & Ellwood, 1999; Shouyun *et al.*, 2002; Jenkins *et al.*, 2002; Evans & Heller, 2003; Rădan & Rădan, 2006a,b, 2007, 2009, 2010a,b; Rădan *et al.*, 1998a,b, 2008c, 2011a,b).

The low-field or initial magnetic susceptibility measurements may enable to create "environmental fingerprints" (Dearing, 1994, 1999), which are then deciphered and interpreted, giving us information of use for the mineralogical and geochemical characterization of the environmental materials, in various geoscientific contexts. Particularly, the initial magnetic susceptibility is a proxy parameter for the anthropogenic pollution, the studies showing connections with different contaminants of organic or inorganic chemical origin (Dekkers, 2007). The magnetic susceptibility variations recorded on sediment cores are also a very useful tool of correlation in lakes (*e.g.*, Rădan *et al.*, 2011a).

Other magnetic properties can be used as proxy parameters, as well: *e.g.*, the anhysteretic remanent magnetisation (**ARM**), isothermal remanent magnetisation (**IRM**), saturation isothermal remanent magnetisation (**SIRM**), frequency-dependent susceptibility ($\mathbf{k}_{fd}$), magnetic hysteresis loops *etc*. (Verosub & Roberts, 1995; Opdyke and Channel, 1996; Evans & Heller, 2003; Dekkers, 1997, 2007).

The initial magnetic susceptibility ($\mathbf{k}_{in}$), which measures the "magnetisability" of a material, is a very attractive proxy parameter. The measurements can be made on all the materials and require no specific preparation (in some cases, the samples must be cut into cubic specimens or must be crushed). They enable us to classify various types of (geo) materials, and help us to identify the minerals with different kinds of magnetic behaviour (*i.e.*, ferromagnetic, ferrimagnetic, canted antiferromagnetic, paramagnetic, diamagnetic), which are present in a sample. The magnetic susceptibility measurements can be made in the laboratory or field, they are safe, fast and non-destructive, features which recommend them as a low cost and efficient investigation tool to be applied. In fact, the magnetic susceptibility complements many other types of environmental analyses; it is used in conjunction with the analyses of chemistry, radioisotopes, microfossils, as well as with a series of other magnetic properties (Dearing, 1994, 1999). The $\mathbf{k}_{in}$ of a geologic sample is a composite of the diamagnetic, paramagnetic, and ferromagnetic (*sensu lato*) contributions, a very important fact which should be taken into consideration when interpreting susceptibillity profiles (Dekkers, 2007), and generally, when this proxy parameter is used for different applications. Numerous examples support this overview. Actually, in Chapter 3.3, in a comment on the interpretation of the magnetic susceptibility results obtained for the *Siutghiol Lake* sediments, elements from this general background are explicitly used.

The present paper is focused on the capabilities of the initial magnetic susceptibility measured on recent sediments from deltaic, lagoonal and littoral lakes from the main Southeastern Romania aquatic areas, as well as on marine sediments sampled from the Northwestern Black Sea.

The *Danube Delta* and the *Razelm (Razim) – Sinoie Lagoonal Complex* (Fig.1) are two special units of the Danube – Black Sea hydrosedimentary geosystem, acting as a buffer interface between the *Danube River* water and sediment supplies collected from a large catchment area, and the *Black Sea* semi-enclosed marine basin. As regards the littoral lakes (Fig.1), these were formed by retaining of some valleys – which have been discharging into the sea – by the sand bars deposited due to the littoral currents system. The composite enviromagnetic archive under attention in the paper is completed with magnetic susceptibility data from the terminal sector of the *River Danube – Danube Delta – Black Sea* macrosystem, *i.e.* from the sedimentary environments located in

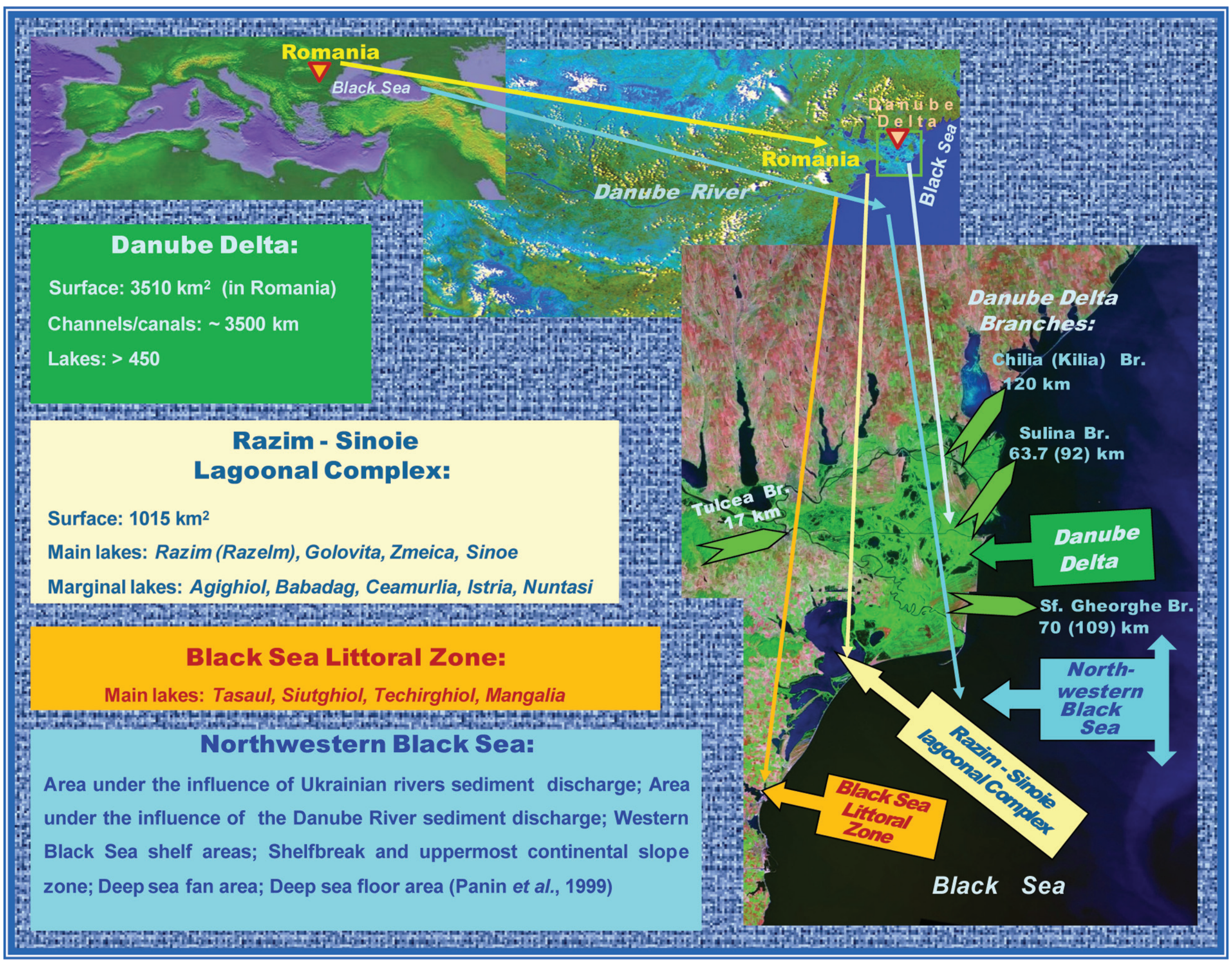


Fig. 1 Location of the aquatic areas wherefrom the enviromagnetic archives were recovered.

the fluvial-marine interaction zone from the Northwestern *Black Sea* (Fig.1).

The study – based on a representative enviromagnetic archive of modern sediments, sampled from this vast and various aquatic system, within a long time interval (1976 – 2011) – is mostly focused on the sediments of the standing water bodies – the delta lakes, located within the *Danube Delta* interdistributary depressions (Fig. 1). With regard to the running waters (*i.e.*, channels, canals and Danube branches), only the main *DD* distributaries (two cut-off meanders included) are taken here into consideration (Fig. 1). The intensity of the magnetic signatures characterizing the fluvial-deltaic environments of the *Danube Branches* is compared with the magnetic fingerprints recovered from the *DD* lake sediments.

Magnetic susceptibility (**MS**) models for the four main lakes of the *Razim – Sinoie Lagoonal Complex* (Fig.1) are presented, and the connections between the (higher intensity) **MS** regime and the structure of the surrounding sand ridges are relieved.

The modern sediments of four lakes from the *Black Sea Littoral Zone* (Fig. 1), namely *Taşaul*, *Siutghiol*, *Techirghiol* and *Mangalia*, have been investigated with regard to the magnetic susceptibility and the lithological composition.

The **MS** classes to which the recent sediments are calibrated, according to the Magnetic Susceptibility Scale (Rădan & Rădan, 2006a, 2007), are used to give information on the "sediment quality", which is commonly evaluated by geochemical and ecological scales.

As concerns the fluvial-marine interaction zone (Fig. 1), the **MS** maps of the sediments sampled in the Northwestern *Black Sea* are commented upon in connection with the main sedimentary environments established in the area (*e.g.*, the "Danube Delta front area" and the "Danube prodelta area"; Panin *et al.*, 1997,1999).

2. LOGISTICS, GEOMATERIALS AND METHODS

In the first stage of the study, the campaigns were carried out on board of the fluvial vessel "*Stuful*", and, in the last period, on board of the fluvial research vessel "*Istros*" (Fig. 2). To locate the sampling stations, the ("Garmin") GPS and the ("Simrad") echosounder equipment were used (Fig. 2). Relatively undisturbed "sediment packets" (Figs. 2 and 3) were taken by using "van Veen"-type grab samplers (Fig. 2). A gravitational corer and a box corer (Fig. 2) were also on board of the fluvial vessels at the disposal of the team carrying out the sampling works.

The magnetic susceptibility measurements on unconsolidated sediment samples were performed with a KLY-1 Kappabridge (in the first stage of the study) and a KLY-2 Kappabridge (during the last time period). To calibrate the modern sediments and to compare different magnetic fingerprints recovered from the various aquatic environments, a Magnetic Susceptibility Scale was used (Fig. 3).

Fig. 2 Research vessels and sampling equipment.

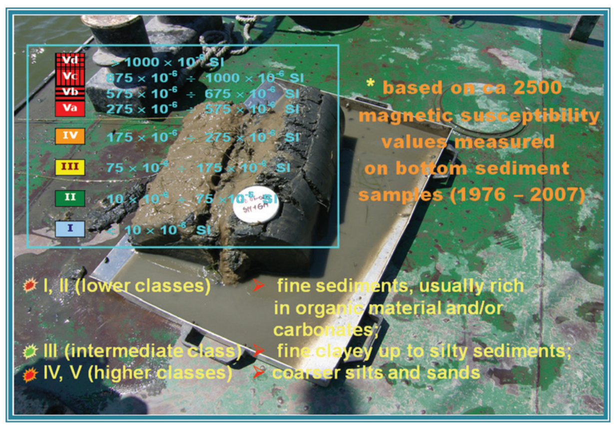


Fig. 3 Magnetic susceptibility (**MS**; **k**) scale used for calibration of bottom sediments (Rădan and Rădan, 2007; see also Plate 1).

The last version of the scale (Fig. 3) extends between **k** values lower than 10×10^{-6} SI (negative values included) and **k** values higher than 1000×10^{-6} SI. The Magnetic Susceptibility Scale has practically originated in the sediments of the *Danube Delta* and the *Razim (Razelm) – Sinoie Lagoonal Complex*. Consequently, the **MS** scale has a "genuine" lithological support and it is based on ca 2500 **k** values measured on thousands of sub-samples collected from the lakes located in five depressions of the *Danube Delta*, from its main branches, as well as from the four main lakes of the lagoonal complex (Fig. 1).

A very large number of **MS** patterns resulted from the huge data bank, the most part of the models using the **k** classes to which the sediments were calibrated. The long time period (about 35 years) covered by magnetic susceptibility measurements made feasible a number of composite patterns to be performed for the same aquatic zone, and equally for different "moments" of the investigation works. These models were further used to compare the **MS** data obtained on bottom sediments collected in successive phases, from the same zones, within a long time interval. Therefore, a "back-monitoring process" was carried out, resulting in the detection of some changes within the submerged sedimentary environments, caused by the anthropogenic activities which adversely affect the various lacustrine and fluvial-deltaic ecosystems. Based on the **k** scale, the intensity of the enviromagnetic fingerprints of the natural and anthropogenic pressure on the different ecosystems was evaluated.

The two synoptic models which are given in Plates 1 and 2 show a series of applications of the **MS** scale regarding the characterization of the recent sediments which constitute the enviromagnetic archives recovered from the Southeastern Romania aquatic areas.

The results can be correlated to the data obtained by using the "geochemical scale" and the "scale with the normative definitions of the ecological status classification" (NDESC scale). The **k** classes **I** and **II** correlate to the "high" and "good" quality categories of the NDESC scale (fig. 3, in Plate 1), the class **III** to the "moderate" quality, and the classes **IV** and **V** (*i.e.*, **Va**, **Vb**, **Vc**, **Vd**; see Fig. 3), to the "poor" and "bad" qualities.

3. RESULTS AND DISCUSSION

Lacustrine/deltaic, fluvial-deltaic, lagoonal, littoral and marine ecosystems were investigated. The results are further presented within four subchapters: *Danube Delta*, *Razim (Razelm) – Sinoie Lagoonal Complex*, *Black Sea Littoral Zone* and *Northwestern Black Sea*.

3.1. Danube Delta

In relation to their position to the Danubian inputs, some of the delta lakes are, to a certain extent, protected from the direct *Danube* influence (*confined deltaic environments*), others are more or less directly influenced by the riverine supplies (*dynamic deltaic environments*). The **MS** measurements performed on recent sediments show the clear differentiation of the magnetic signatures recovered from these two types of deltaic environments (some examples, in Fig. 4).

The sediments of the lakes that are successively located along a main water flow way modify their lithological, mineralogical and chemical characteristics, as a consequence of differential transport and sedimentation, and by passing from a dynamic towards a more or less stagnant aquatic envi-

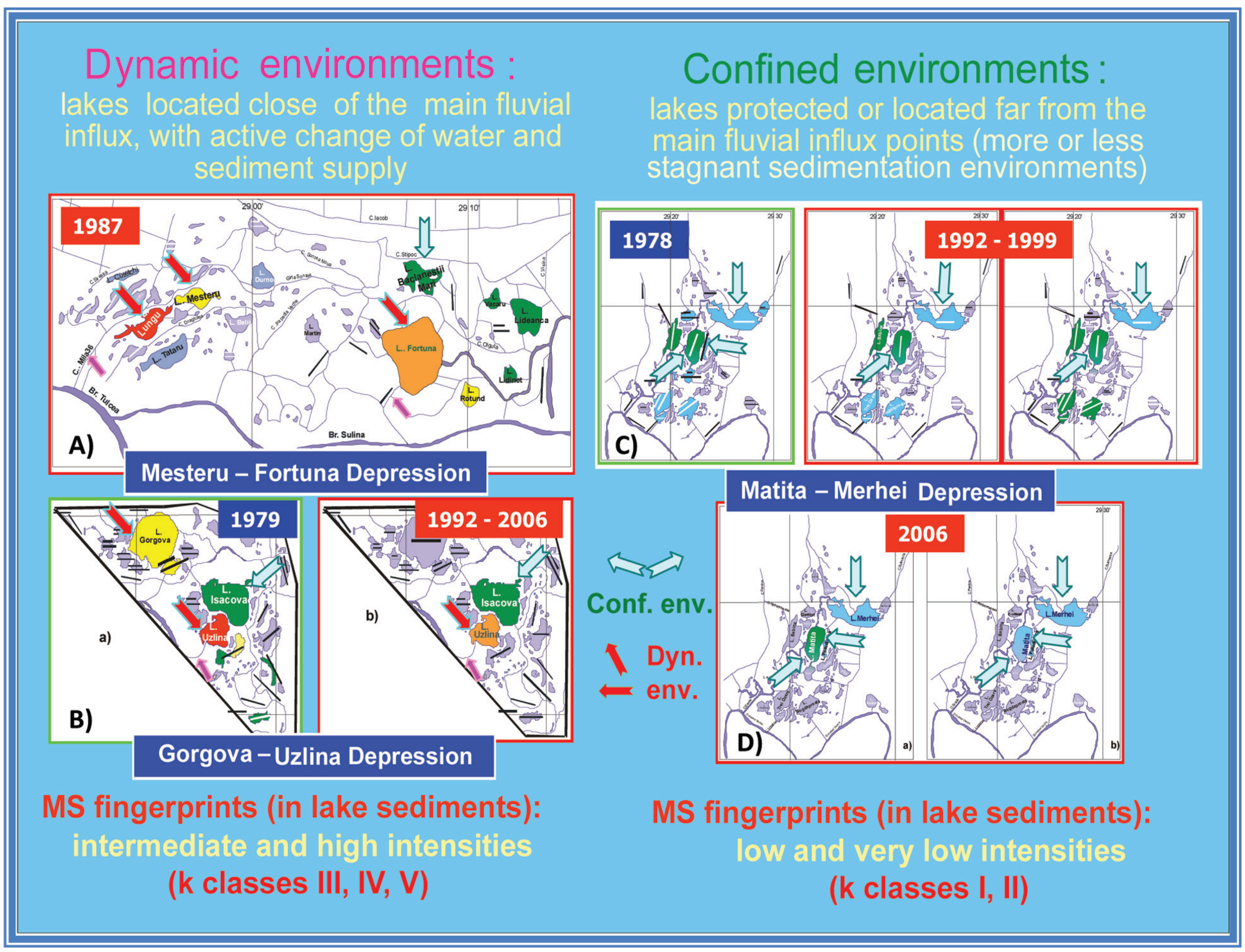


Fig. 4 Magnetic susceptibility characterization of the lake sediments sampled from dynamic *(dyn. env.)* and confined *(conf. env.)* deltaic environments. *Note:* The **MS** fingerprint intensities are shown by the average **k** values (based on all the samples which were measured for each lake). The assigned colours are according to **k** scale from Fig. 3.

ronment. This situation is well reflected by the magnetic signatures, and it is firstly presented at a regional scale, for two lacustrine areas situated close to the main fluvial influx points (Fig. 4A,B), and one located at the end of a long water way (Fig. 4C,D). At a local scale, a similar differentiation is identified, this time, along a short distance; it is the case of several "couples of lakes" (*e.g.*, *Uzlina – Isacova*; Fig. 4B).

The presence of the anthropogenic impact on the deltaic ecosystems was proved by the modified **MS** signatures identified within the modern sediments sampled in the western *Meşteru – Fortuna Depression* during 1980-1997 (an example in Fig. 4A). According to the environmental changes induced by cutting the *"Mila 36" Canal* between two *Danube branches* (in 1982-1983), the **MS** fingerprint intensities detected in the bottom sediments of two main lakes were modified, showing "dynamic sedimentary environments", directly controlled by the riverine supplies (Fig. 4A). When the lakes are protected from the direct fluvial influx, and they are located at the end of a long way of access of the *Danube* waters – as it is the case of the *Matiţa – Merhei Depression* (Fig. 4C,D) –, they are characterized by a more or less "confined sedimentary environment", which is developing in a relatively stagnant aquatic area. The natural conditions did not change too much from the point of view of the chemical pollution. Consequently, the magnetic susceptibility fingerprints recovered from the sediments sampled in these lakes, in 11 cruises, are expressed by low and very low **k** values, mainly calibrated to class **I** (**k** scale, in Fig. 3), with many susceptibilities defined by negative values, and to the class **II** (Fig. 4C,D).

The synoptic model from Plate 1 extends the presentation of the different lacustrine, fluvial-deltaic and lagoonal enviromagnetic archives. So, the simplest cases identified are related to the more or less stagnant sedimentation environments, protected or located away from the main fluvial influx points, where only insignificant changes have occurred for a long period of time. This is the situation of the *Lakes Băclăneşti* (eastern *Meşteru – Fortuna Depression*; fig. 1 and fig. 4, in Plate 1), *Matiţa*, *Poludionca*, *Merhei*, *Babina*, *Trei Ozere*, *Bogdaproste* (*Matiţa – Merhei Depression*; fig. 1 and fig. 5, in Plate 1), *Isacova* (*Gorgova – Uzlina Depression*; fig. 1 and fig. 6, in Plate 1), *Răducu* (*Răducu – Răduculeţ Depression*; fig. 1 and fig. 7, in Plate 1), *Roşu* and *Roşulet* (*Lumina – Roşu Depression*; fig. 1 and fig. 8, in Plate 1). The intensity of the magnetic susceptibility fingerprints is calibrated to the **k** classes **I** and **II**, excepting the samples collected from the supply channels' mouths (*e.g.*, in the *Matiţa*, *Isacova*, *Roşu lakes*). The sedimentary environments remained totally or nearly undisturbed, or underwent slight alterations only (see the NDESC Scale – fig. 3, in Plate 1).

The second case is represented by "dynamic environments", with active change of water and sediment supply. This is the situation of the *lakes Fortuna* (fig. 4a,b2,c2, in Plate 1) and *Uzlina* (fig. 6b1-b4, in Plate 1). There is also the case of the *lakes Lungu* (fig. 9a2,a3, in Plate 1) and *Meşteru* (fig. 9b2, b3, in Plate 1), but after digging of the *Canal* "*Mila 36*" (marked by an arrow, in fig. 10b, Plate 1). The intensity of the **MS** fingerprints is calibrated to the intermediate class, and mainly to the higher **k** classes **IV** and **V** (related to the *Fortuna*, *Lungu* and *Meşteru lakes*, see Fig. 4A). Instead, the magnetic signature identified in the sediments sampled in the *Lungu* and *Meşteru lakes* in 1980 was mainly characterized by **MS** values assigned to **k** classes **II** and **III** (fig. 9a1, and 9b1, respectively, in Plate 1); therefore, the initial environments could be classified into an intermediate category (like in the *Puiu Lake* case from the *Lumina – Roşu Depression*; see fig. 8a1,a3,a4, in Plate 1). After digging up the *Canal* "*Mila 36*" in the area, in 1982-1983, the **MS** characterization of the lake sediments points out **k** values mainly assigned to the higher **k** classes (**IV**, **Va**, **Vb**), for the *Lungu L.* (closer to the *C. "M.36"* influx point), and to the intermediate (**III**) and high classes (**IV** and **Va**), for the *Meşteru L.* (fig. 9a2,a3, and 9b2,b3, respectively, in Plate 1). According to the environmental changes produced by the above-mentioned *canal*, the **MS** fingerprints detected in the bottom sediments were modified (fig. 10a,b, in Plate 1), showing "dynamic sedimentary environments", directly controlled by the riverine supplies. It is worth seeing the good correlation to the NDESC Scale from fig. 3 (Plate 1).

The analyses carried out on the sediment samples collected in different campaigns emphasized important variations of the principal components of the lacustrine sediments (organic substance, carbonates, siliciclastic fraction). For example, regarding the campaign 2006 (see Rădan & Rădan, 2009), the average contents of the organic matter reached the highest values in the *Poludionca Lake*, followed by *Merhei*, *Matiţa*, *Roşuleţ*, *Isacova*, *Puiu*, *Tătaru* and *Roşu*, while the lowest values were obtained for the sediments from the *Lungu* and *Uzlina lakes*. The carbonates recorded maximum values in the *Roşu Lake* (18.1%), followed by the *Isacova*, *Puiu*, *Merhei*, *Roşuleţ*, *Tătaru*, *Matiţa*, *Uzlina* and *Poludionca lakes*; the lowest content was found in the *Lungu Lake*. Consequently, the difference is assigned to the siliciclastic component, so that the highest values characterize the sediments of the *Uzlina* and *Lungu lakes*, while the lowest values were recorded for the *Merhei* and *Poludionca lakes*.

The ternary diagrams from Fig. 5, showing the lithological classification of the lake sediments, clearly illustrate the above presented situation: the samples from the *Tătaru L.* are assigned to the organic-mineral muds category (Fig. 5a); the *Lungu L.* contains, dominantly, mineral-organic, and subordinately, organic-mineral sediments (Fig. 5a); the *Uzlina L.* sediments show a preferential cover of the distributions relating to the mineral and mineral-organic fields (Fig. 5b); the muds from the *Puiu L.* (Fig. 5c) are distributed within the organic-mineral field, and subordinately, to the organic one; the *Isacova* (Fig. 5b) and *Roşuleţ* (Fig. 5c) *lakes* are almost entirely placed in the organic-mineral field, the same for the *Roşu L.*, but with a well-pronounced tendency towards the carbonatic field (Fig. 5c); the *Matiţa L.* sediments are defined in the more organic side of the organic-mineral field and within the organic muds field (Fig. 5d); the *Merhei L.* is entirely placed within the organic muds field, and the *Poludionca L.* is situated in the closest position related to the organic pole (Fig. 5d). These data evidence similar lithological characteristics for the couple of lakes *Uzlina – Isacova* (Fig.5b) and the pair of lakes *Lungu – Tătaru* (Fig. 5a).

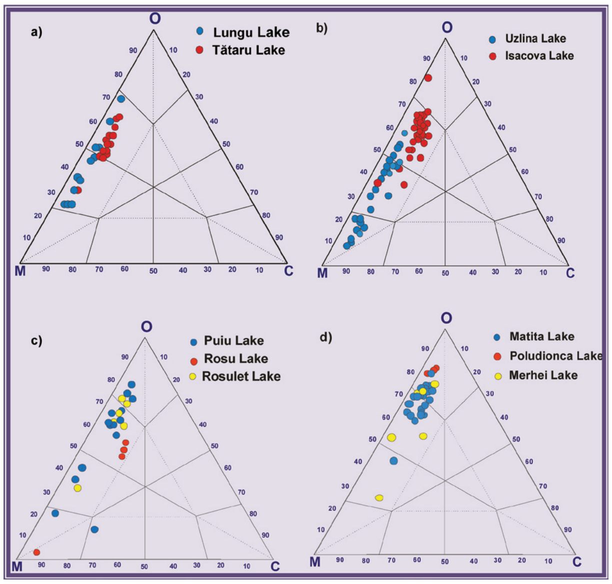


Fig. 5 The lithology of the recent sediments sampled in 10 lakes from four main depressions of the Danube Delta. *Legend* (ternary diagrams): **M** – Detrital mineral fraction (quartz, silicates); **C** – Carbonates (authigenic); **O** – Organic matter.

A detailed data analysis, in connection with the magnetic susceptibility characterization of the recent sediments sampled in these 10 lakes, was presented in a previously published paper (Rădan & Rădan, 2009). The conclusion was the magnetic susceptibility fingerprint that is recovered from the deltaic lakes which are, to a certain extent, protected from the direct Danube influence (*e.g.*, *Poludionca*, *Merhei*, *Matița*, *Roşuleț*, *Isacova*) is of low intensity and it is assigned to the lower **k** classes **I** and **II**. It is the case of the "confined environments", characterized by relatively stagnant conditions and a reduced water circulation. We can notice that the lakes previously nominated are mentioned among the first 5 lakes with high values of the organic matter average contents, and also among the lakes with higher values of the carbonates contents; on the other side, in the *Merhei* and *Poludionca lakes*, the sediments are characterized by the lowest values of the siliciclastic component contents.

In the fore-cited paper, another concluding remark was that in the sediments from the lakes which are more or less directly influenced by the riverine supplies are recorded intermediate, high and very high intensities of the magnetic susceptibility fingerprints (assigned to the **k** classes **III**, **IV** and **V**). Usually, these lakes are placed close to the influx points of the master canals or are connected by relatively short canals to the main *Danube Delta Branches*. This is the case of the *Lungu*, *Uzlina* and *Fortuna lakes*, characterized by "dynamic environments", usually with an active change of water and sediments.

A third category – intermediate – represented by the *Tătaru* and *Puiu lakes* was also mentioned (Rădan & Rădan, 2009); the sedimentary environments which belong to this type are characterized by **k** values assigned to the classes **II** and **III**.

All these data shortly here presented are in agreement with the good correlation between the magnetic susceptibility characterization of the bottom sediments and the lithological composition: a negative correlation for **MS** *versus* **organic matter** and **carbonates**, but a positive correlation for **MS** *versus* **siliciclastic fraction** (examples, in Rădan & Rădan, 2009, 2010a,b).

Some thicker enviromagnetic archives were recovered from a series of short sediment cores taken from different *Danube Delta* aquatic ecosystems, during 2006 – 2011 period (Rădan *et al.*, 2011a). By using a transparent Hydro-Bios corer, recent sediments up to ca 56 cm depth under the water/sediment interface were sampled. The variations in the magnetic susceptibility regime along the cores have indicated, in certain cases, the increasing of the magnetic parameter "intensity" (**k**) from the upper part towards the bottom.

Here, is presented an example related to the *Matița – Merhei Depression*; 5 short cores were collected from the *Babina* and *Matița lakes*, in 2010 and 2011 (Fig. 6a).

The 3-D bar charts drawn for the Core DD 10-106 (*Babina Lake*; Fig. 6a,c), and the Core DD 11-01 (*Matița Lake*; Fig. 6a,d), respectively, show in the first 35 cm, and 40 cm, respectively, a low **k** "intensity" level of the magnetic regime (defined by **MS** classes **I** and **II**). It is interesting to compare these magnetic fingerprints, recovered from sediments sampled in 2010 – 2011, with the magnetic signatures shown by the maps with **k** contours, performed for the two lakes on the basis of the sediments sampled with "van Veen-type grabs", 33 years ago (Fig. 6b; Rădan *et al.*, 1979, in Mihăilescu *et al.*, 1979). The average **MS** values calculated for the sliced sediments along a depth interval (related to the cores) which is comparable with the usual thickness of a "sediment packet" taken with the grab sampler (ca 30 cm) are 10.08×10^{-6} SI (Core DD 10-106; Fig. 6c), and 17.66×10^{-6} SI (Core DD 11-01; Fig. 6d), respectively. As regards the sediments sampled in the lower part of the cores, *i.e.* at the depth intervals 35 – 45.5 cm (Fig. 6c), and 40 – 53 cm (Fig. 6d), respectively, the **k** values are assigned to the **MS** classes **III**, and **III** and **IV** (in the longer core case), respectively. The lower **k** values measured on the sediment sub-samples sliced from the upper part of the cores are connected to the muds rich in organic matter. The magnetic susceptibility profiles clearly suggest – by the increasing **k** values from top to the bottom – the increasing tendency of the detrital component towards the core base. Such data demonstrate the availability of the investigated magnetic parameter as sedimentogenetic indicator; the higher **k** values could be correlated with the interception of a underwater sandy bar. On the other hand, it is confirmed the capability of the recent sediments as enviromagnetic archives, in this case the mag-

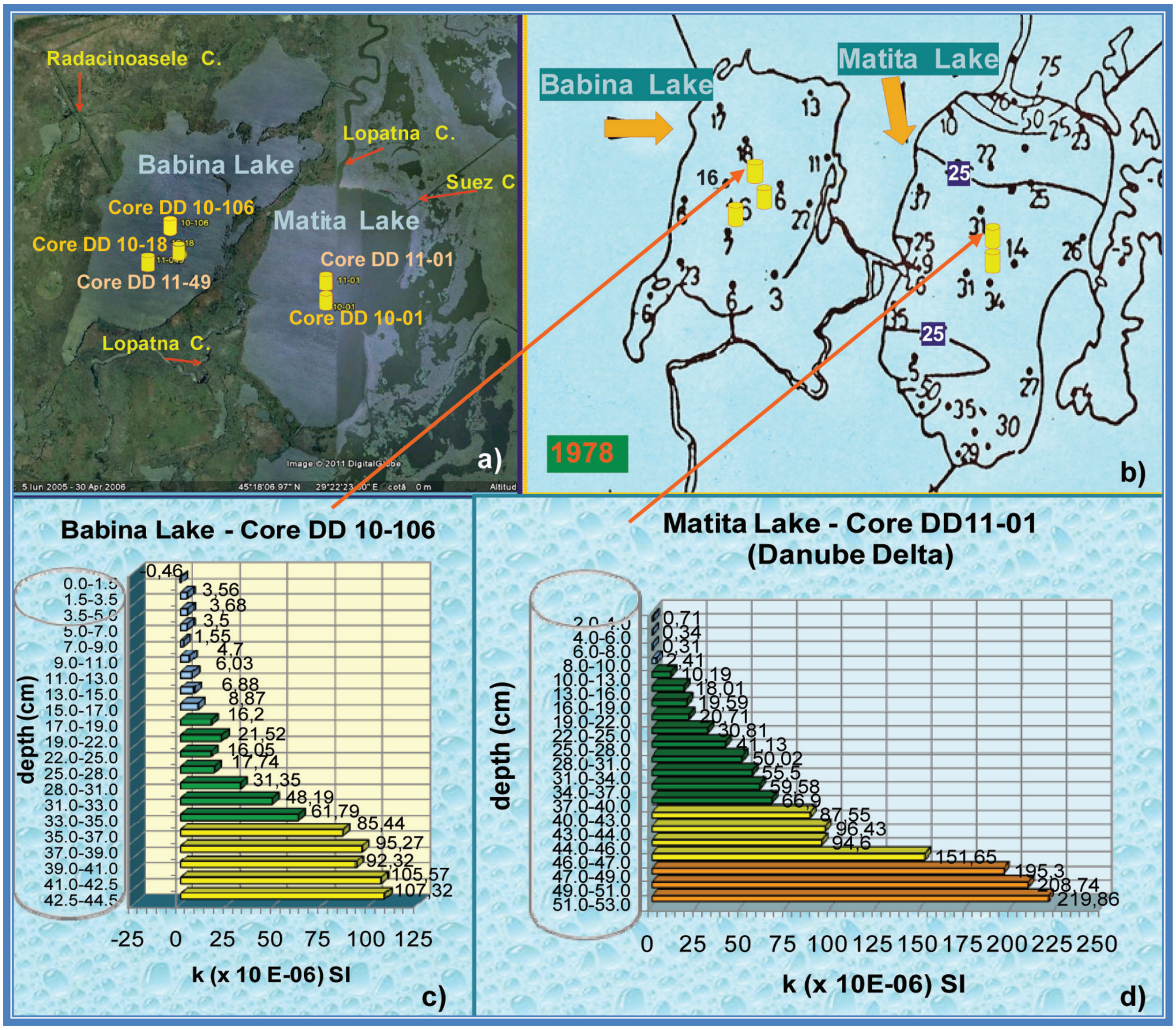


Fig. 6 Magnetic susceptibility of recent sediments from two lakes of the Matita - Merhei Depression (Danube Delta). **a)** Location of five cores taken from the Babina and Matita lakes, during the 2010 and 2011 GeoEcoMar cruises; **b)** Magnetic susceptibility (**k**) map drawn up for the bottom sediments sampled with "van Veen-type" grabs in the fore-mentioned lakes, during the 1978 cruise, carried out by the Institute of Geology and Geophysics. *Note*: The locations of the cores are marked on the **k** maps; **c)** Vertical distribution of the magnetic susceptibility along the sediment core DD 10-106, taken from the Babina Lake, in 2010; **d)** Vertical distribution of the magnetic susceptibility along the sediment core DD 11-01, collected from the Matita Lake, in 2011. *Note 1*: The 3-D bars (in the charts from **c** and **d**) are coloured according to **k** scale from Fig. 3. *Note 2*: The orange arrows mark the location of the two cores under attention in the present paper

netic signatures being recovered from them at both ends of the time interval 1978 – (2010-2011). The comparable intensities of the **MS** fingerprints could be used as a proof for the absence of an anthropogenic pressure on the ecosystems from the two lakes of the *Matița – Merhei Depression*, characterized by "confined environments".

As regards the *Danube Delta Branches*, much higher intensities were determined for the magnetic fingerprints recovered from the "fluvial-deltaic environments" (Fig. 7), as compared to those detected in the lakes.

The sediments are mainly constituted of sands, with a variable grain size. The **MS** signatures are significantly different from those identified for the *Danube Delta* lakes (fig. 11f, as compared with fig. 11 a,b,c,d,e, in Plate 1). Most **k** values (77%) are assigned to **k** classes **Va**, **Vb**, **Vc** and **Vd**. The pie charts from Fig. 7 show the magnetic susceptibility characterization of the bottom sediments sampled in each branch of the Danube Delta, in the 1992 - 2004 interval.

A special case was investigated with regard to the *Sf. Gheorghe Branch* (fig. 4.1.5, in Plate 2). The meander cutting intervention resulted in a decreasing water and sediment circulation on the loops, leading to some silting-up processes, which occur at the upstream and downstream meander ends. The cut-off meanders are going to become "oxbow"-type lakes, similar to the *Erenciuc* and *Belciug lakes* from the

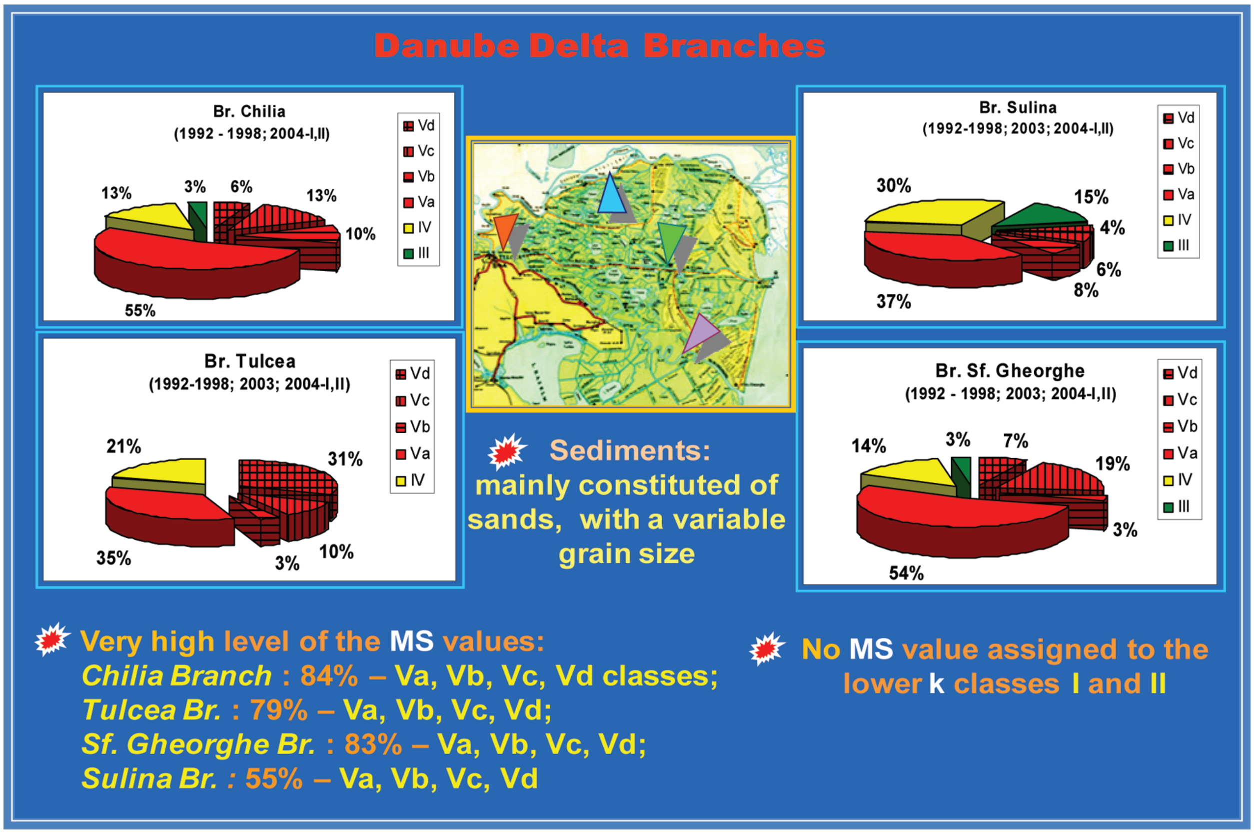


Fig. 7 Magnetic susceptibility characterization of the modern sediments from the Danube Branches (for additional data, see fig. 4.1.5, in Plate 2).

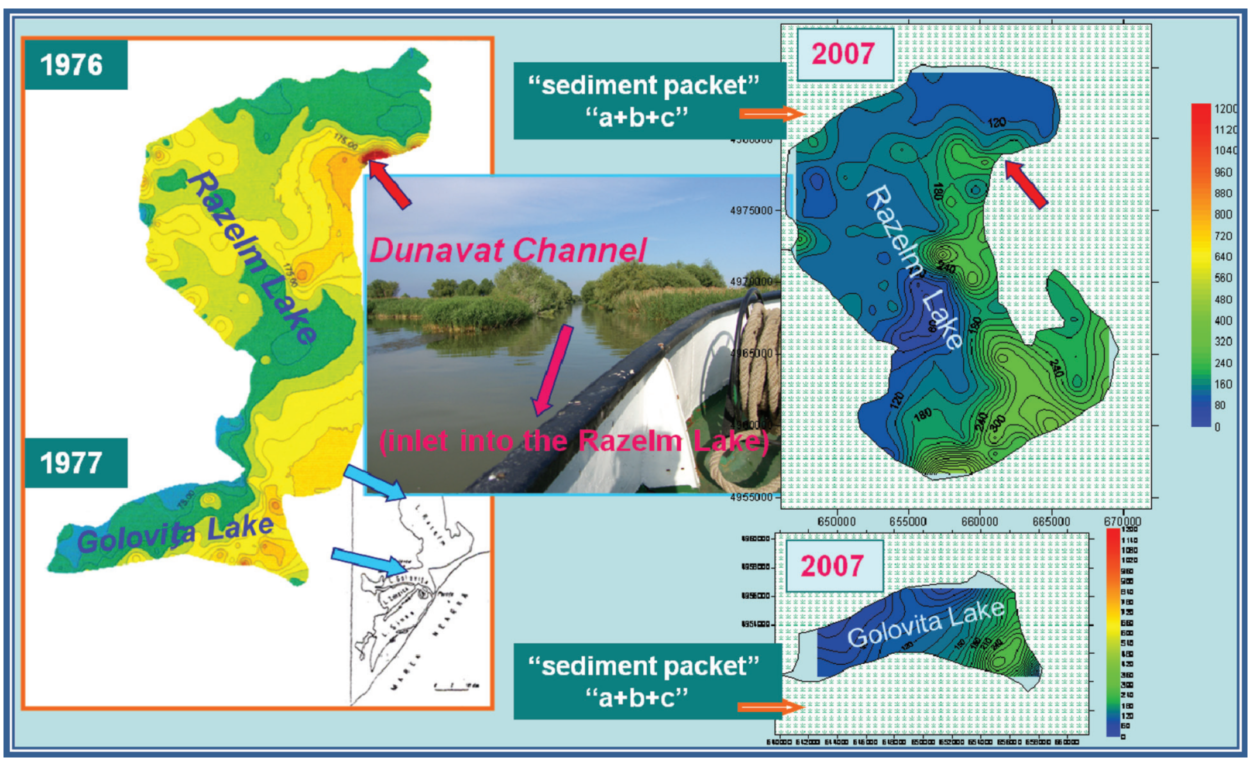


Fig. 8 Magnetic susceptibility maps for two lakes from the lagoonal complex, sampled at both ends of a 30-year period. *Note*: The scales are not similarly calibrated by coloured intervals.

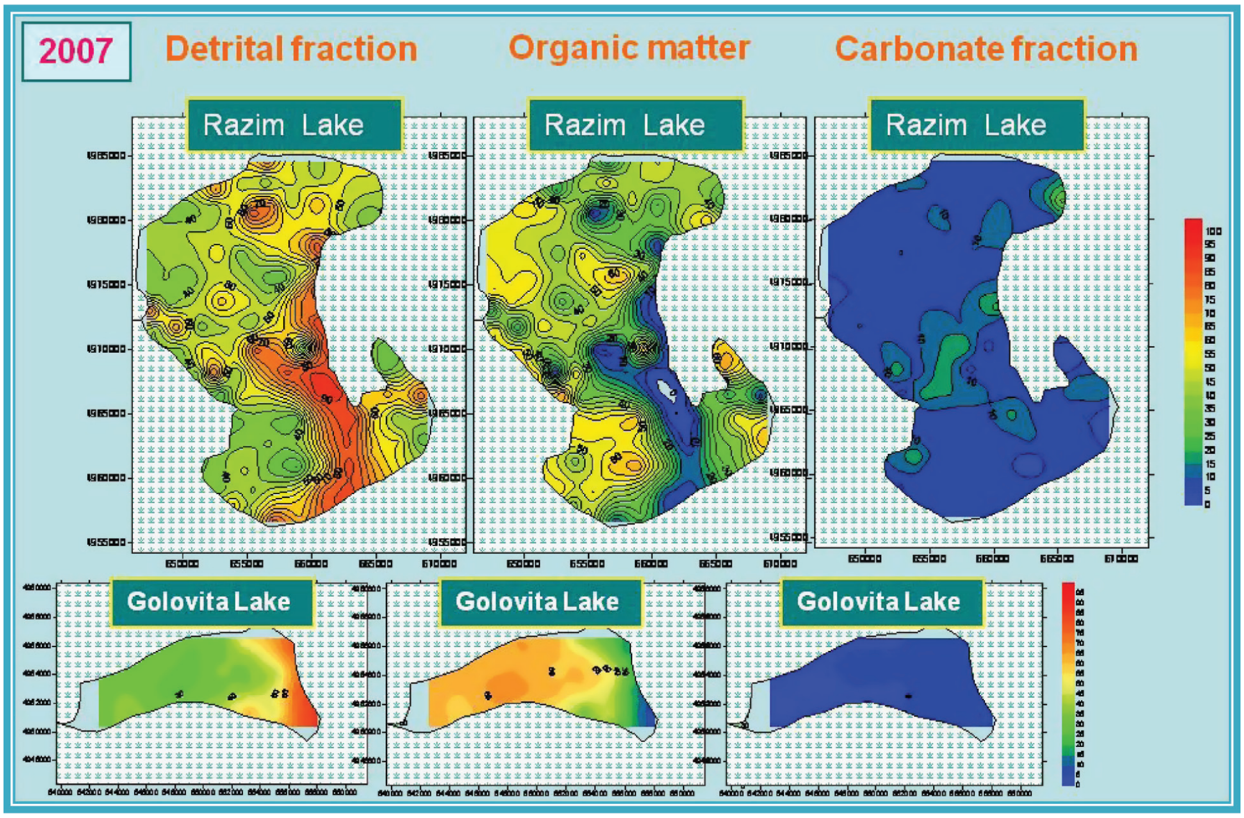


Fig. 9 Lithological components of the sediments sampled in two lakes from the Razim (Razelm) – Sinoie Lagoonal Complex.

Danube Delta (Rădan & Rădan, 2010a). The modifications of the hydrological regime induce changes of the sedimentary environments, and consequently, different magnetic susceptibility signatures are recovered from the enviromagnetic archives. Moreover, some hydrobiological consequences are observed when comparing the fauna identified in the upstream sectors of the cut-off meanders of the *Sf. Gheorghe Danube distributary* with the fauna detected in the downstream zones, which get lacustrine trends (Rădan *et al.*, 2008b).

For more data regarding the capabilities of the *Danube Delta* recent sediments as enviromagnetic archives, the reader is referred to Rădan & Rădan (2009, 2010a,b).

3.2. Razim (Razelm) – Sinoie Lagoonal Complex

The examples presented in this chapter concern the magnetic signatures recovered from the bottom sediments (a sampling station network, in fig. 3.1c, Plate 2) of a particular unit, a lagoon system (*i.e.*, the *Razelm - Sinoie Lagoonal Complex*/RSLC), isolated from the *Black Sea*, but linked with the *Danube Delta* (Fig. 1; also, fig. 2.1, in Plate 2). The variations of the enviromagnetic parameter are controlled especially by the sediment grain size, generally coarser than in the *Danube Delta* lakes, and are influenced by the less significant organic and carbonate contents (except for the *Zmeica Lake*) (Fig. 8; see also fig. 11g,h,i,j, in Plate 1). The sediments sampled in the main RSLC lakes (Fig. 1) are calibrated to **k** classes **II – V**, predominantly, to **k** class **III** (again, excepting the *Zmeica L.*, but also the *Sinoie L.* – data from 2008).

The areas that are characterized by higher **k** values in the **MS** maps (Fig. 8) coincide with the zones pointed out by the detrital/siliciclastic component distribution map (Fig. 9). High **MS** values are recorded for the main channel inlets into the *Razim Lake* (an example, in Fig. 8). The **MS** maps are slightly similar for the 3 layers (separated as "a", "b" and "c") and for the whole "sediment packet" ("a+b+c") (Fig. 8; fig. 4.2.2, in Plate 2). The **k** maps show good connections between the higher intensity magnetic signatures and the prolongation of the surrounding sand ridges (see also, Mihăilescu *et al.*, 1983).

Based on the magnetic susceptibility data banks achieved for three time intervals (1976 – 1978; 2002 – 2004; 2007 – 2008), covering a 32-year period (Fig. 10), some interesting remarks have been done.

The increasing trend in the occurrence of finer sediments southwards, associated with the general water flow direction from North southwards, is accompanied by a simultaneous increasing trend of the lower **k** class **II** and a decreasing trend of the higher **k** classes (**IV**+**V**), in the direction Razelm ➲ Golovita ➲ Sinoie ➲ Zmeica (Fig. 11). The *Zmeica Lake* is placed after the *Sinoie Lake* due to its more isolated character, which is favourable to the finer sediment deposition.

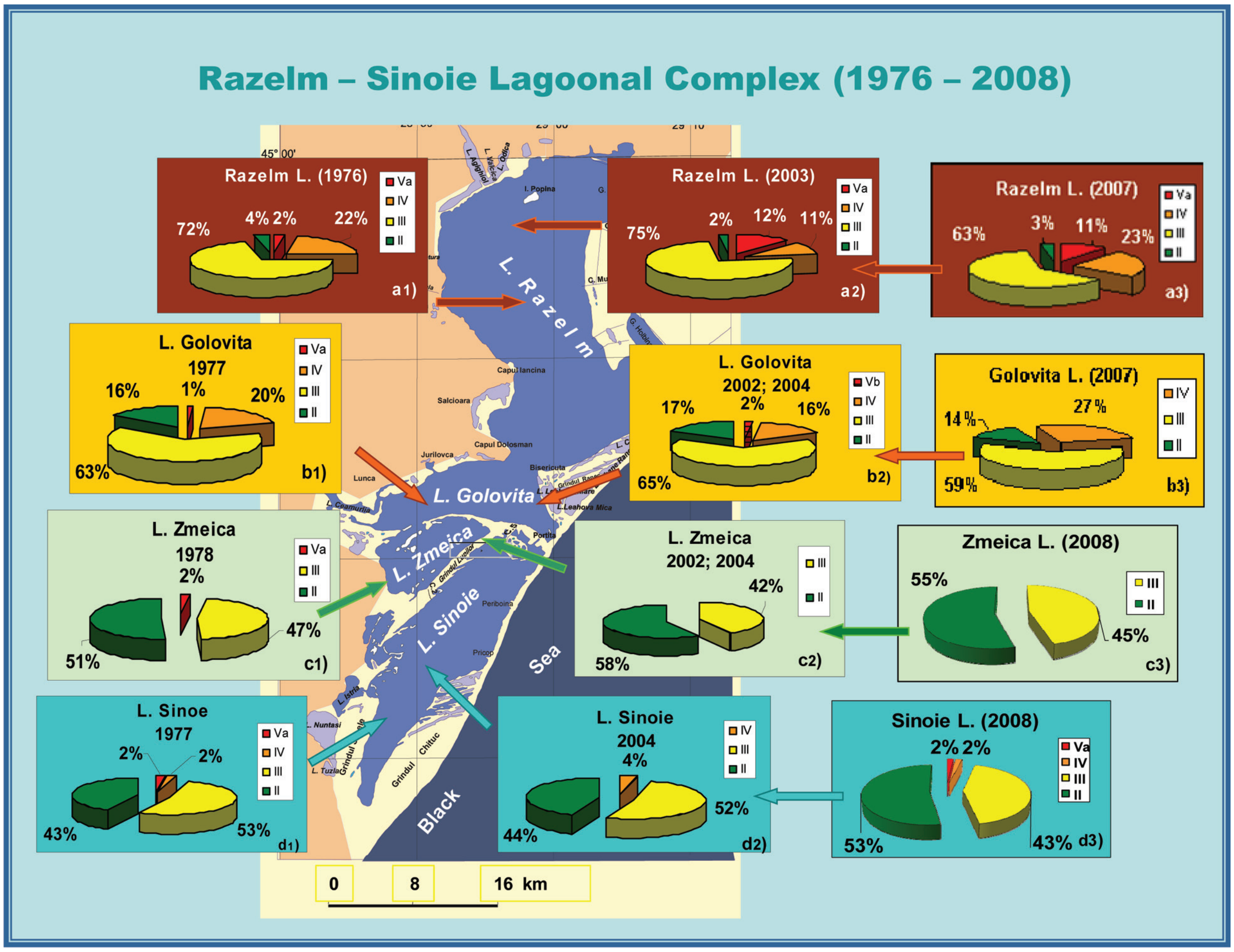


Fig. 10 Synoptic model showing the magnetic susceptibility characterization of the recent sediments of the Razim (Razelm) – Sinoie Lagoonal Complex four main lakes, related to three periods: 1976 – 1978 (left; a1, b1, c1, d1); 2002 – 2004 (middle; a2, b2, c2, d2); 2007 – 2008 (right; a3, b3, c3, d3).

The magnetic susceptibility variations are in agreement with the macroscopic description of the lithological constitution of the bottom sediments that was performed on board of the research vessels, immediately after their sampling with "van Veen"-type grabs, and are well correlated with the laboratory results concerning the three lithological components (*i.e.*, **TOM** – Total Organic Matter; **CAR** – Carbonates; **SIL** – mineral/siliciclastic fraction). High **k** values correspond to high **SIL** contents, and to low **TOM** and **CAR** contents, respectively. The magnetic susceptibility becomes low and very low when the organic and/or carbonatic components are (very) significant within the constitution of the bottom sediments, to the detriment of the mineral component content, defined by a low weight. Two composite magneto-lithological models for the bottom sediments sampled from the *Razim* and *Golovița lakes*, in 2007, were presented in a recent paper (Rădan & Rădan, 2010a).

As regards the *Sinoie* and *Zmeica lakes*, some magnetic susceptibility and lithological data obtained for the sediment samples collected by GeoEcoMar, in the August 2008 campaign, are presented in Fig. 12 and Fig. 13, respectively. A remark could be done with regard to the calibration to **k**

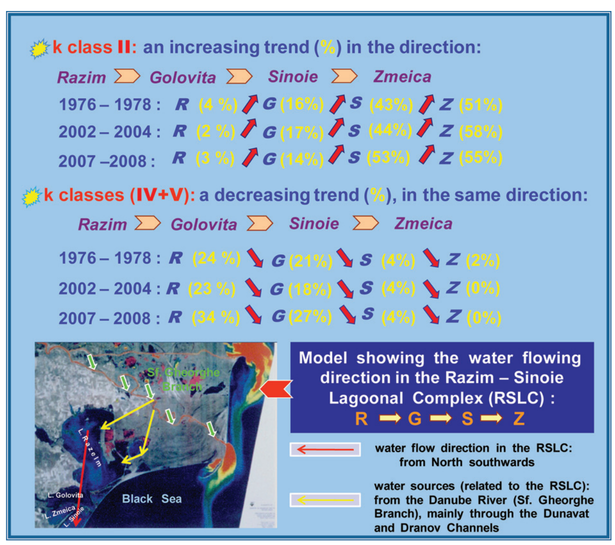


Fig. 11 Composite model showing the trends features of the magnetic susceptibility classes which characterize the bottom sediments of the Razim – Sinoie Lagoonal Complex four main lakes (based on the synoptic model presented in Fig. 10). *Note*: in the lower part of the figure, the water flow direction within the lagoonal complex is indicated, in connection with the main water sources.

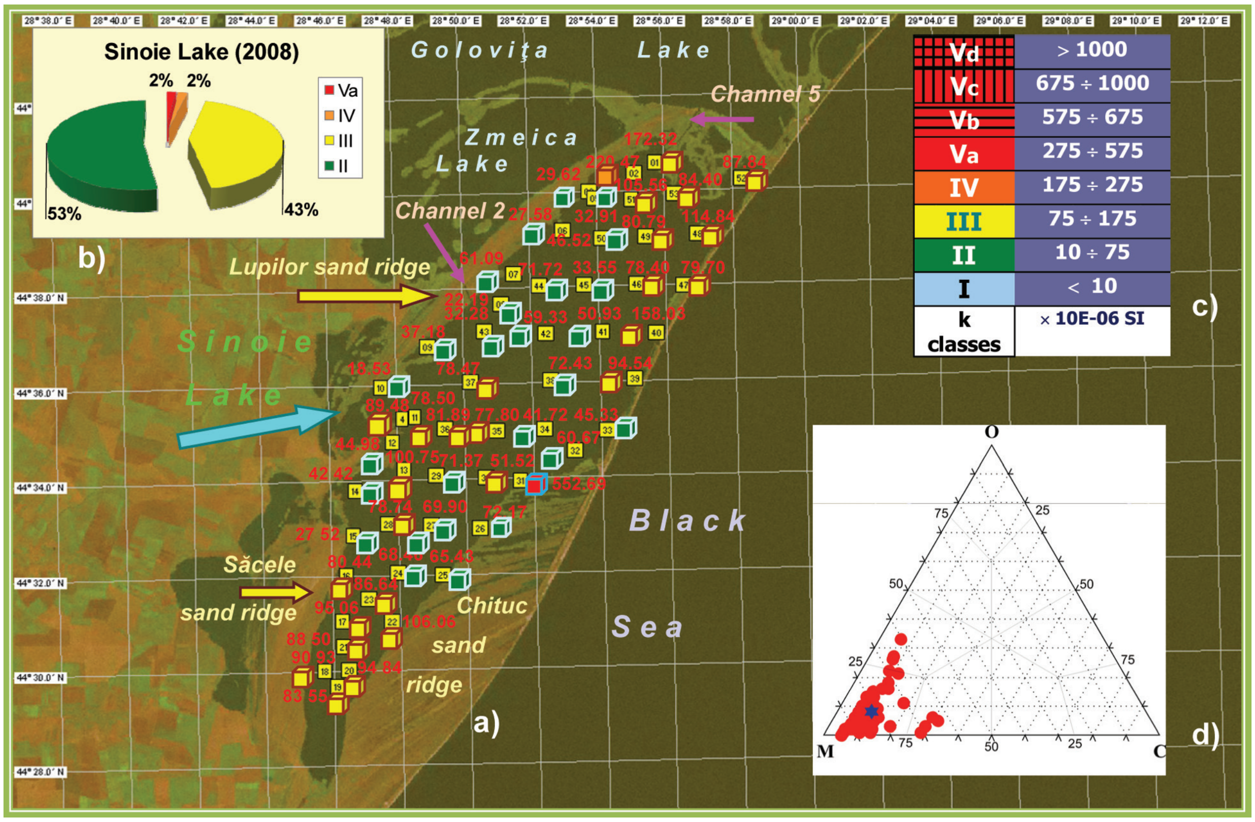


Fig. 12 Magnetic susceptibility characterization and lithological classification of the sediments collected from the Sinoie Lake (August 2008). **a)** chart with the areal distribution of the **k** values, indicating also the **MS** classes to which the lake sediments were calibrated [marked by coloured cubes, according to the **k** scale reproduced in **c)**]; **b)** 3-D pie chart with the **MS** characterization of the bottom sediments [based on the **k** classes from **c)**]; **c) MS** scale (see also Fig. 3); **d)** ternary diagram showing the lithological classification of the sampled recent sediments.

class **III** of the sediments sampled in the *Sinoie Lake* on the profile starting with the station S08-039 and ending with S08-52 (Fig. 12a), placed on the direction Periboina – Portița, along the narrow beach ridge that separates the *lagoonal complex* and the *Black Sea*.

Another two areas where the bottom sediments are characterized by **MS** values correlated to the class **III** were identified in the northern part of the *Sinoie Lake*, and in the southern sector, *i.e.* in a zone situated between the *Săcele* and *Chituc* (*Kituc*) *sand ridges*, respectively (Fig. 12a). In a paper published in 1983 (Mihăilescu *et al.*, 1983), we presented similar remarks regarding the significance of the magnetic susceptibility signatures recovered from the modern sediments of the *Sinoie Lake*. The enviromagnetic archives sampled and deciphered three decades ago indicated the prolongation of the fan-like structure of the Lupilor sand ridge southward of the Channel 5 up to Portița, and the continuity of the sand bar deposits of the *Chituc* (*Kituc*) *formation* below the immerged zone, respectively. The lithological classification of the bottom sediments (Fig. 12d), as well as the grain size maps (particularly related to the sandy fraction distribution and to the average diameter values; Rădan *et al.*, 2008b) support the magnetic susceptibility data, also suggesting the submerged prolongation of the *Lupilor sand ridge* in the north-northwestern part, and of the *Chituc (Kituc) sand ridge* and of the beach (littoral) ridge in the south - southeastern side.

With regard to the *Zmeica Lake*, which is situated in the category of the aquatic environments with a reduced water exchange, it can be observed an area of low magnetic susceptibility measured on bottom sediments, which crosses the central zone and is defined by **MS** values correlated to **k** class **II** (Fig. 13a). This result could be explained in connection with the offshore zones, characterized by a quieter sedimentation, with finer deposits or with sectors with a larger presence of the subaquatic vegetation, where the sediments can be richer in organic detritus.

The macroscopic lithological characterization of the *Zmeica Lake* sediments sampled in 2008 has indicated that they are constituted of grey-blackish muds, bioturbated, oxidized at the top, while in the marginal zones there is a transition towards the sandy muds (rarely, sands), sometimes very rich in shells. The higher **k** values (assigned to **k** class **III**) are recorded in the northern and southern-southeastern zones, suggesting a possible influence of the coarser-grained material provided by the sandy bars located between the *Golovița* and *Zmeica lakes*, respectively a possible reworking of the sandy material from the *Lupilor ridge*. Similar results, based on

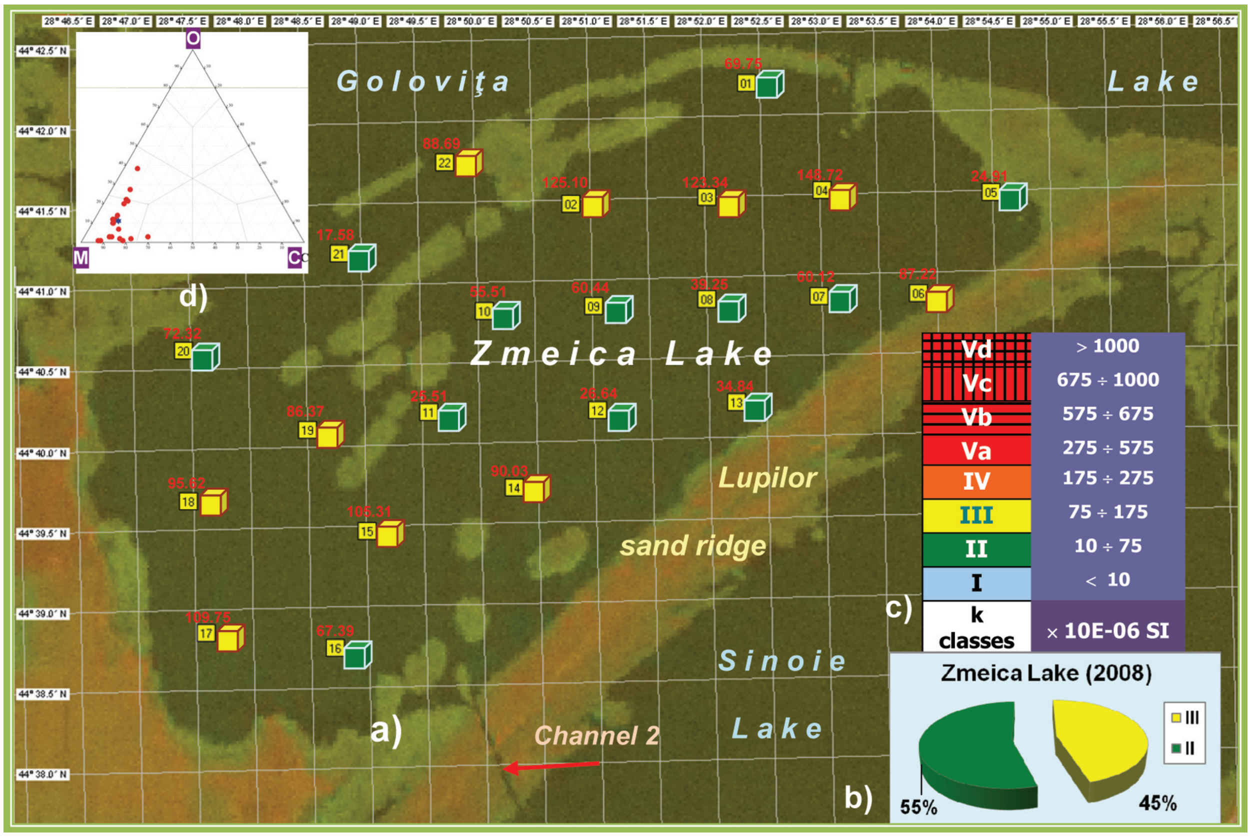


Fig. 13 Magnetic susceptibility characterization and lithological classification of the sediments collected from the Zmeica Lake (August, 2008). **a)** chart with the areal distribution of the **k** values, indicating also the **MS** classes to which the lake sediments were calibrated [marked by coloured cubes, according to the **k** scale reproduced in **c)**]; **b)** 3-D pie chart with the **MS** characterization of the bottom sediments [based on the **k** classes from **c)**]; **c) MS** scale (see also Fig. 3); **d)** ternary diagram showing the lithological classification of the sampled recent sediments.

an analogous magnetic susceptibility regime, were obtained on the sediments sampled in the *Zmeica Lake* 30 years ago (Mihăilescu *et al.*, 1983). The ternary diagram (Fig.13d) shows the predominance of the detrital component, indicating that the sediments belong mainly to the mineral mud category. The enviromagnetic archives recovered and deciphered at both ends of a three decade interval stand for the absence of an anthropogenic impact on the lacustrine ecosystem.

3.3. Black Sea Littoral Zone

The modern sediments of four lakes from the *Black Sea Littoral Zone* (Fig. 1; also, fig. 2.1, in Plate 2), namely *Taşaul*, *Siutghiol*, *Techirghiol* and *Mangalia*, were investigated with regard to the magnetic susceptibility and the lithological composition (Rădan & Rădan, 2010b; Rădan *et al.*, 2007, 2008a,b,c, 2011b). These are located southward of the *Razim – Sinoie Lagoonal Complex*, and are characterized as fluvio-marine lymans (*i.e.*, *Taşaul*, *Techirghiol* and *Mangalia lakes*) or as littoral lagoons (*i.e.*, *Siutghiol Lake*).

The bottom sediments were sampled by using "van Veen"-type grabs, during two expeditions carried out by GeoEcoMar, in 2007 (*Taşaul L.*) and 2008 (the other 3 lakes). Based on the magnetic susceptibility measurements and on the lithological analyses (**SIL, CAR**, **TOM**), a number of maps were drawn, showing the areal distribution of each parameter in the lakes. The impact of the external sediment supplies and the sedimentary environment dynamics are well-connected with the ratio between the detrital allochthonous contribution and the predominantly autochthonous organic one.

First results achieved for the bottom sediments sampled from the *Taşaul Lake* (a fluvio-marine lyman) (Fig. 14a) have already been published (Rădan *et al.*, 2008c, Rădan & Rădan, 2010b). Some data are also included in a recent extended abstract (Rădan *et al.*, 2011b), where the first results obtained for the other three littoral lakes are shortly presented. Two composite magneto-lithological models characterizing the recent sediments of the *Techirghiol* and *Mangalia lakes* are illustrated within the fore-cited extended abstract. Some integrated magnetic susceptibility and lithological data are further discussed with regard to the enviromagnetic archives recovered from the *Taşaul* and *Siutghiol lakes*.

Related to the fluvio-marine lyman *Taşaul*, some data are presented in fig. 4.3.1 (Plate 2). The **k** values defining the maximum and minimum **MS** anomalies are compared with the lithological components determined for the sub-samples collected from the same "sediment packets" taken with the grab samplers from the stations placed in the lake. The highest **k** values (zones shown by the arrows **C** and **D** in fig. 4.3.1, Plate 2), matching the

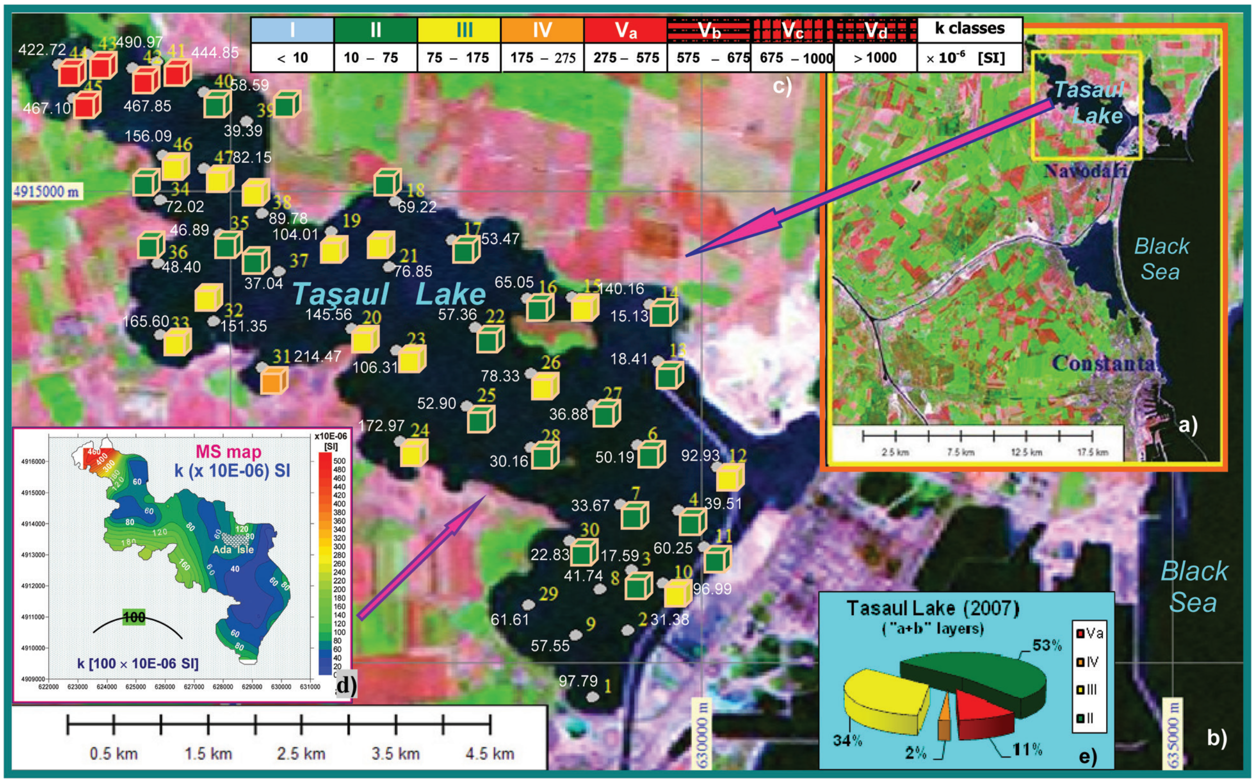
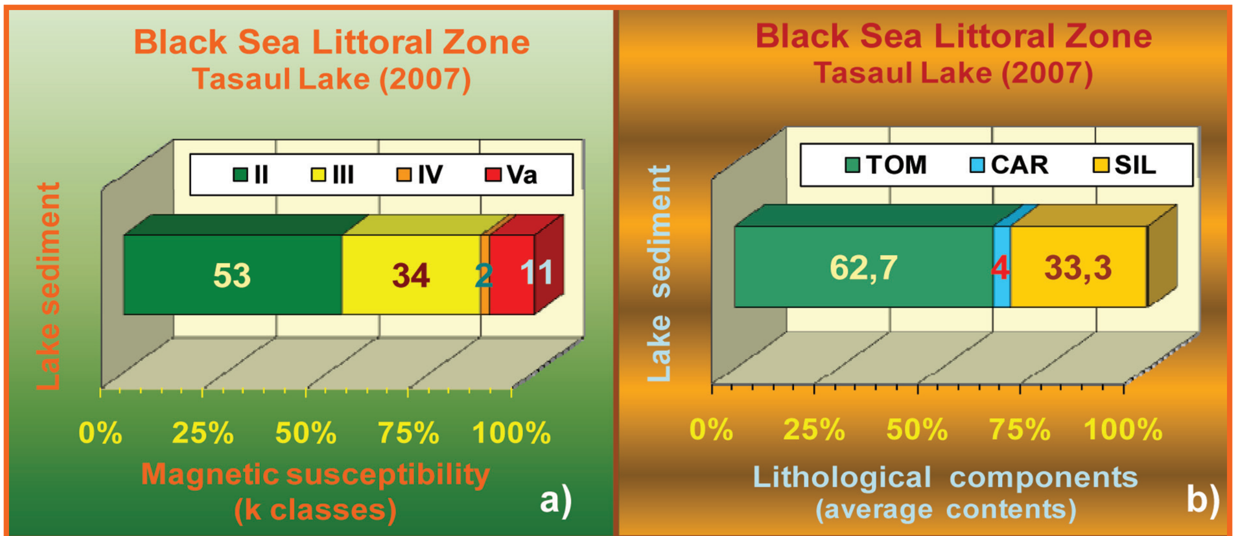


Fig. 14 Magnetic susceptibility characterization of the recent sediments of the Taşaul Lake (November, 2007). **a)** location of the Taşaul Lake in the Black Sea Littoral Zone; **b)** chart with the areal distribution of the **k** values, indicating also the **MS** classes to which the sediments were calibrated (marked by coloured cubes, according to the **k** scale); **c)** magnetic susceptibility scale (see also Fig. 3); **d) MS** map with **k** contours; **e)** 3-D pie chart showing the **MS** characterization of the bottom sediments (based on the **k** classes).

anomaly in the detrital component map (**SIL**, in fig. 4.3.1, Plate 2), were measured in the main stream inlet into the lake, while the lowest **MS** values cover its central zone, where the organic matter-rich sediments are mainly deposited.

In the composite magneto-lithological model given in Fig. 14, the areal distribution of the enviromagnetic parameter **k** is illustrated by means of two charts: one is based on the susceptibility classes to which the sediments sampled in each station from the *Taşaul Lake* were calibrated (marked by coloured cubes, in Fig. 14b), according to the **MS** scale (reproduced in Fig. 14c); the second is a **MS** map with **k** contours (Fig. 14d), carried out on the basis of the **k** values measured in the 47 sampling points placed within the lake.

Most sediment samples were calibrated to the **k** class **II** (Fig. 14e), followed by the **k** class **III** (34%), **Va** (11%) and **IV** (2%). Generally, the sectors where high contents of the detrital component (**SIL**; see the map in fig. 4.3.1h, in Plate 2) were recorded are well-shown by maximum anomalies in the **MS** maps. So, the most important **k** anomaly is located in the northern end of the *Taşaul Lake*, in the *Casimcea river* discharge area. The highest **k** values, defined between 422.72×10^{-6} SI – 490.97×10^{-6} SI, assigned to **k** class **Va** (Fig. 14b), were measured on the sediments sampled in the main stream inlet into the lake. Besides, in the western-southwestern part of the lake, there is an area defined by the **k** classes **III** and **IV** (Fig. 14b), and by higher **k** contours, respectively (Fig. 14d), suggesting a maximum **MS** anomaly. This mainly reveals the anthropogenic impact of the human activities in the Sibioara area, *i.e.* the bottom sediment contamination with the dust and the useless rocks originated in the green schists quarries. Higher **k** values (class **III**) were also measured on the sediments sampled in the (north)eastern part of the lake (between the *Ada isle* and the land), and also in the southeastern zone, along the littoral belt which dams the lyman (at present, the boundary is artificial, being represented by the canal dam). The lithological composition of the sediments sampled in these two restricted zones shows the predominance of the siliciclastic component (**SIL**; see fig. 4.3.1h, in Plate 2). On the other hand, in the greatest part of the lake are developed the sediments rich in organic matter, the principal zone of high content being located in its south-eastern half (fig. 4.3.1g in Plate 2). Consequently, most values of low susceptibility (correlated to class **II**; Fig. 14b), defining a minimum **MS** anomaly (Fig. 14d), were recorded for the bottom sediments sampled in this area. The correlation between these two lithological components (**SIL**, **TOM**; a synoptic 3-D bar chart, in Fig. 15b) and the enviromagnetic parameter **MS** (a synoptic 3-D bar chart, in Fig. 15a) is illustrated in Fig. 15c. To evaluate and interpret the degree of relationship between them, the anthropogenic impact on the sedimentary environments in the *Taşaul Lake* must not be neglected.



Correlation coefficients (n = 47)			
k *vs* TOM	k *vs* CAR	k *vs* (TOM+CAR)	k *vs* SIL
- 0.5020	- 0.1649	- 06059	0.6059

c)

Fig. 15 Magnetic susceptibility characterization and the lithological composition of the bottom sediments sampled from the Taşaul Lake (Black Sea Littoral Zone). **a)** 3-D bar chart showing the calibration of the recent sediments to the **MS** scale (illustrated in Fig. 3); **b)** 3-D bar chart indicating the contents of the lithological components (*i.e.*, **TOM**, **CAR** and **SIL)** of the bottom sediments; **TOM** – Total Organic Matter; **CAR** – Carbonates; **SIL** – mineral/siliciclastic fraction; **c)** correlation between the magnetic susceptibility and the lithological components.

Moreover, when discussing calibration to the **k** scale of the *Taşaul Lake* recent sediments, it must be taken into consideration the particular geological context of this zone, in which the green schists are remarked in the southwestern border of the lake and in the constitution of the small isle "*La Ostrov*".

It is worth pointing out that the *Danube Delta* lake sediments, with a different geological background as compared with that of the *Taşaul Lake*, were those deposits which generated the magnetic susceptibility scale (with a genuine lithological support), successfuly used in many studies as a high resolution enviromagnetic instrument (see the concluding remark from the Plate 1).

Another lake which was investigated in this area is *Siutghiol* (Fig. 16), which is separated from the *Black Sea* by the littoral bar on which the "*Mamaia*" resort has been developed. Based on a collection of 50 sediment samples taken from an almost rectangular network of stations (Fig. 16a), the areal distribution of the magnetic susceptibility values (**k**) is well defined (Fig. 16a,b).

The enviromagnetic parameter ranges between (-5.78)$\times10^{-6}$ SI (southern zone) and 949.19$\times10^{-6}$ SI (western extremity of the lake) (Fig. 16a), *i.e.* the *Siutghiol Lake* recent sediments are calibrated between the **k** class **I** and the **k** class **Vc** (**MS** scale, in Fig. 16c). As regards the magnetic susceptibility characterization of the lake sediments, the pie chart from Fig. 16d shows the clear predominance of the sediments calibrated to the lower classes **I**+**II** (*i.e.* 4% + 62%), followed by the intermediate class **III** (18%) and the higher classes **IV**+**Va**+**Vc** (4%+10%+2%). These results are in agreement with the lithological composition, the organic matter (**TOM**) and the carbonates (**CAR**) representing (51%+8%), while the mineral/siliciclastic fraction, 41% (Fig. 16e). The lithological classification of the *Siutghiol Lake* sediments (Fig. 16f) emphasizes the dominance of the organic component, followed by the siliciclastic and the carbonatic ones, the latter with a weak participation. So, most samples belong to the organic-mineral muds, as it is well indicated by the place where the average value for all the sediments is projected in the ternary diagram (Fig. 16f – the blue star). In the second position are situated – in approximately equal parts – the organic muds and the mineral muds (represented by the more sandy sediments), while the mineral-organic field is occupied by 3 samples only (Fig. 16f). The penury of the transition mineral-organic sediments shows that the general distribution is a bimodal one, that is an assemblage of dominantly organic recent sediments overlapped on some sediments resulted from the sandy beach bar remoulding. Although the "*Mamaia*" littoral bar is shown in the lithological maps by a band of sandy deposits (Rădan *et al.*, 2008b), in the magnetic susceptibility maps can not be observed a maximum **MS** zone located along the beach bar (Fig.16a,b). An explanation could be the possibility that the littoral sands which are present in the constitution of the "*Mamaia bar*" are poor in heavy minerals and/or they are more calcareous, a great part of the detrital arenaceous component being of carbonaceous origin; this has resulted from

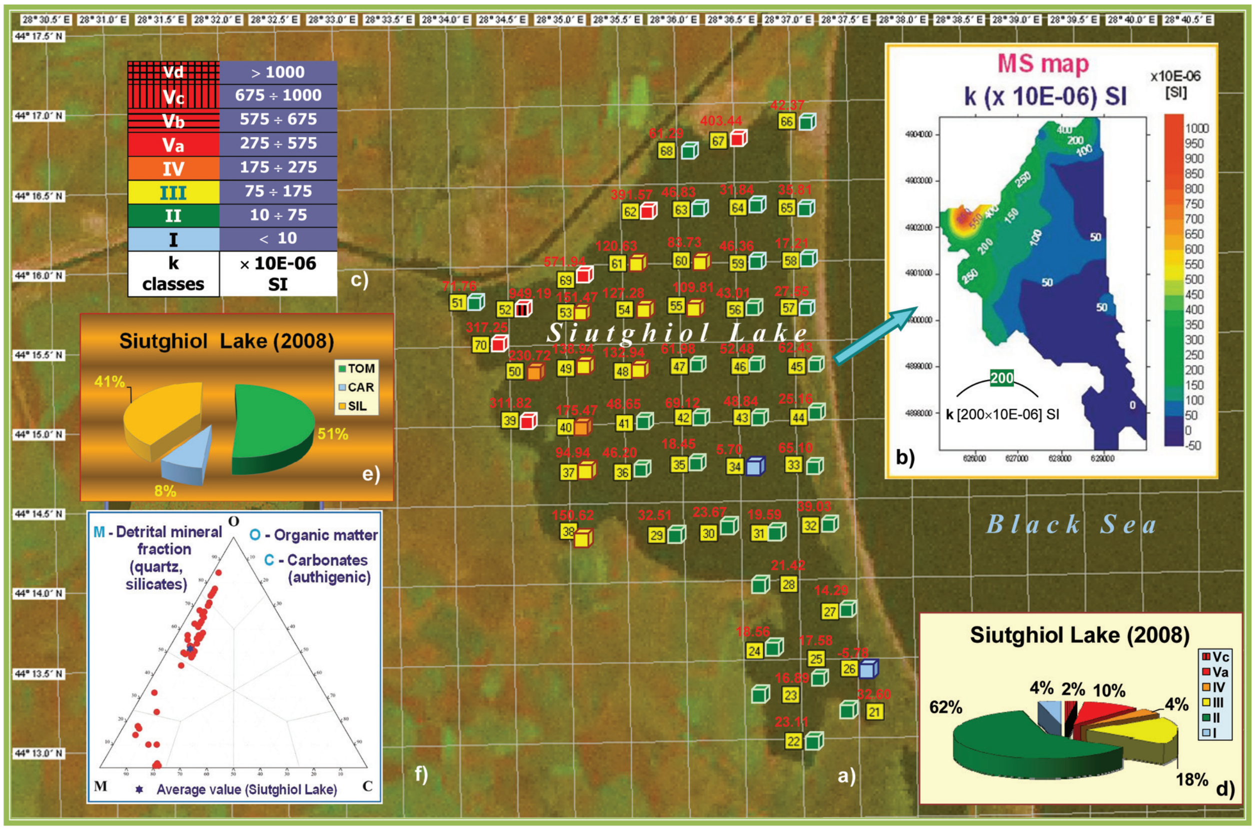


Fig. 16 Composite magneto-lithological model for the Siutghiol Lake recent sediments (sampled during the 2008 GeoEcoMar cruise). **a)** chart showing the areal distribution of the **k** values, indicating also the **MS** classes to which the sediments were calibrated (marked by coloured cubes, according to the **k** scale); **b) MS** map with **k** contours; **c)** magnetic susceptibility scale (see also Fig. 3); **d)** magnetic susceptibility characterization of the bottom sediments (based on the **k** classes); **e)** lithological composition of the recent sediments; **f)** ternary diagram showing the lithological classification of the recent sediments.

the shell fragmentation, consequently with an important diamagnetic participation to the definition of the enviromagnetic parameter (**MS**). The **k** values measured on the recent sediments sampled from the 11 stations placed along the littoral bar (Fig. 16a) range between (-5.78)×10^{-6} SI and 65.10×10^{-6} SI, *i.e.* they are calibrated to the lower classes **I** and **II** (see also the **MS** scale in Fig. 3, with the types of sediments to which these two **k** classes are assigned). The most important maximum magnetic susceptibility zones are located in the north-northwestern part of the *Siutghiol Lake*, corresponding to the high banks from the *Ovidiu* area and to the boundary with the dams of the *Poarta Albă – Năvodari Canal* (Fig. 16a,b). The recent sediments sampled in this zone are calibrated mainly to the high **k** classes **IV**, **Va** and **Vc**, the maximum **k** value (949.19×10^{-6} SI) being recorded in the sampling station Sg08-52, close to the important bend of the above mentioned canal (Fig. 16a). Moreover, in both these cases, the influences on the bottom sediment constitution could be of anthropogenic origin as well, taking into consideration that the *Ovidiu village* buildings are now located up to the lake boundary. In the western area, a contribution to increasing the **MS** values could also have the sandy deposition from the close proximity of the *Ovidiu isle*, which is going to carry out the junction with the lake border, in a more or less far future.

All these data confirm the capability of the magnetic susceptibility as a proxy environmental parameter, with application in geoecology. This integrated magnetic susceptibility and lithological study (for additional reading, see Rădan & Rădan, 2010b, Rădan *et al.*, 2007, 2008a,b,c, 2011b) represents the first enviromagnetic approach of the lacustrine ecosystems that are located in the *Black Sea Littoral Zone* (fluvio-marine lymans, closed by beach bars, and littoral lagoons).

The results demonstrated that the recent sediments of the littoral lakes can also be considered as enviromagnetic archives of high resolution, wherefrom well-defined **MS** fingerprints can be recovered and interpreted in a lithological, environmental and/or geoecological context.

3.4. Northwestern Black Sea

The first magnetic susceptibility data from the northwestern part of the *Black Sea* were obtained on two collections of samples taken by one of the authors (*S.R.*), who participated in the 1995 and 1997 cruises, legs 2 of the R/V "Prof. Vodyanitskiy", in the framework of the EROS-2000 and EROS-21, respectively, international projects.

The **MS** maps of *Northwestern Black Sea* (NWBS) recent sediments (Rădan *et al.*, 1998a,b) indicate a clear anomalous (maximum) zone (Fig. 17), which is coincident with the ″area under the influence of the Danube River sediment discharge″, particularly the ″Danube delta front″ and the ″Danube prodelta areas″ (3, 4, in Fig. 18). The area showing the ″southward drift of the Danube originated sediment flux″, as well as the ″sediment starved area″ (5, 6, in Fig. 18) – both located within the ″Western Black Sea shelf area″ – are reflected by higher, and lower, respectively, intensities of the magnetic signatures (Fig. 17).

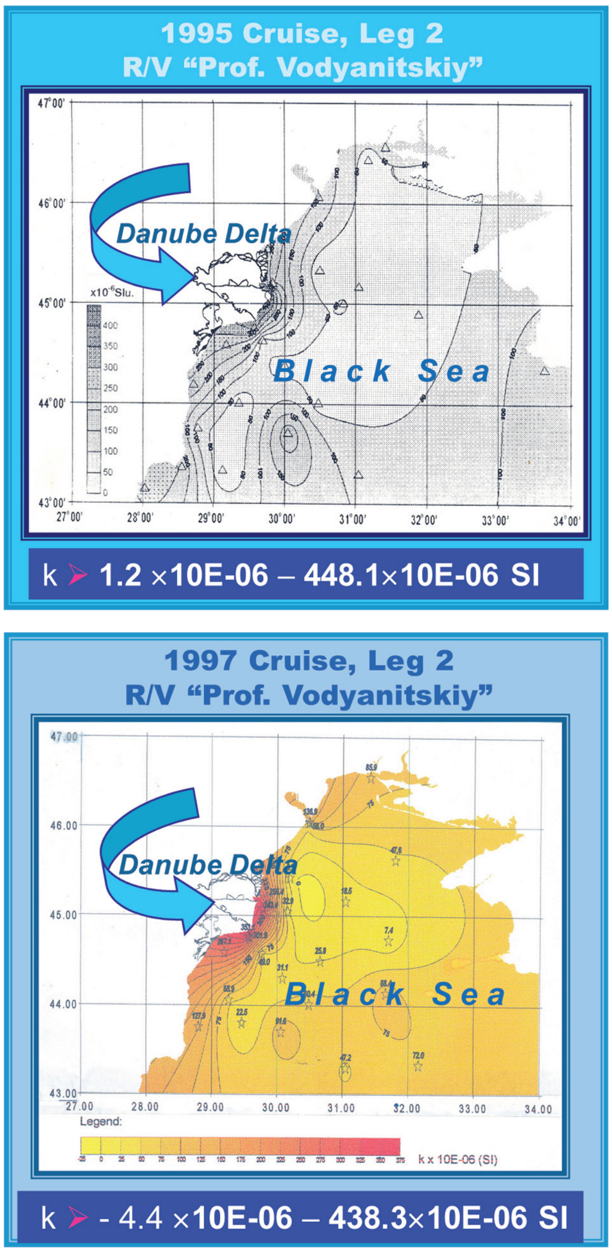


Fig. 17 Magnetic susceptibility maps for recent sediments sampled in the northwestern Black Sea.

Generally, the **MS** maps (Fig. 17) are consistent with the existence of two main areas characterized by different depositional processes, evidenced by Panin *et al.* (1999) on the Romanian *Black Sea* shelf: "the Danube sediment fed internal shelf" and "the sediment starved external shelf".

The first area consists in a shallow marine zone which receives detrital sediments supplied by the *Danube River*; the clayey and silty sediment flux comes in front of the *Danube Delta* (not reaching the external shelf) and drifts then southward towards the Bulgarian shelf, keeping closer to the shoreline (Panin *et al.*, 1999; Fig. 18). This area is suggestively reflected by the **k** contours: the lower limit is the 100×10^{-6} SI contour, in the 1995 **MS** map, where the **k** contour equidistance is 50×10^{-6} SI, and the 75×10^{-6} SI contour, respectively, in the 1997 **MS** map, in which case the **k** contour equidistance is 25×10^{-6} SI (Fig. 17).

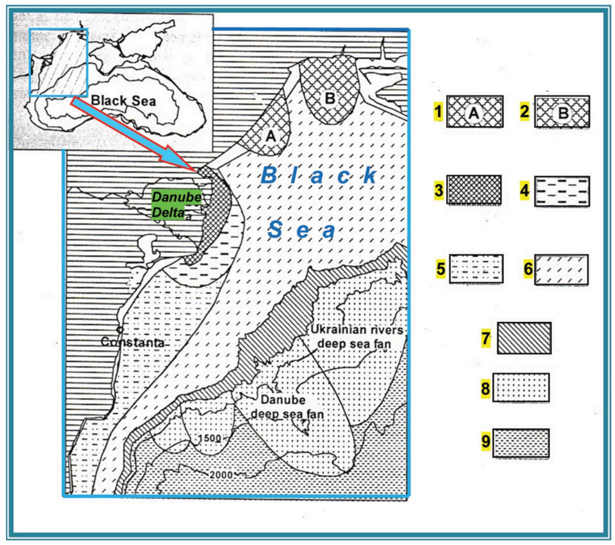


Fig. 18 Main sedimentary environments in the northwestern Black Sea area (according to Panin *et al.*, 1999). **1**, **2** – Area under the influence of the Ukrainian rivers (Dnieper and Dniester) sediment discharge. **3** – Danube delta front area; **4** – Danube prodelta area; **5 - 6** Western Black Sea shelf area (**5** – area under the influence of the Danube originated sediment flux; **6** – sediment starved area); **7** – Shelfbreak and uppermost continental slope zone; **8** – Deep sea fan area; **9** – Deep sea floor area.

In the second above-mentioned area, *i.e.* the ″sediment starved external shelf″ (6, in Fig.18), deposits of biogenic origin, corresponding to *Mytilus* and/or *Phaseolinus* mud zones, are present, the upper part of the sedimentary sequence usually consisting of coquina accumulation (Rădan *et al.*, 1998a). Therefore, in both **k** maps from Fig. 17, extended minimum zones are well defined by the **k** contour of 50×10^{-6} SI (in the 1997 **MS** map, the 25×10^{-6} SI contour is also delineated).

As regards "the area under the influence of the Ukrainian rivers sediment discharge" (1, 2, in Fig. 18), this is not reflected by clear magnetic susceptibility anomalous zones in the **k** maps from Fig. 17. In fact, Panin *et al.* (1999) mention that the *Dniester* and *Dniepr rivers* are not significant suppliers of sediments for the NWBS shelf. Moreover, the sediments supplied by the *Danube River* seldom reach the shelf area north and northwest of its mouths (Panin *et al.*, 1999). The enviromagnetic parameter **MS** confirms these data (Fig. 17); a slightly higher **k** value (136.9×10^{-6} SI) can be however noticed in the

″area under the influence of the Dniepr river sediment discharge″ (Fig. 17, Fig. 18).

The *Black Sea* recent sediments measured for magnetic susceptibility have consisted of clayey to coarse silty or sandy muds, sometimes very rich in organic matter, carbonate coccolith oozes, sapropelic muds, shelly muds, muddy coquina, and occasionally, sands.

The enviromagnetic archives recovered from the bottom sediments sampled in the *Northwestern Black Sea*, in 1995 and 1997, showed that the magnetic susceptibility values range between 1.2×10^{-6} – 448.1×10^{-6} SI (1995 cruise), and $(-4.4)\times10^{-6}$ – 438.3×10^{-6} SI (1997 cruise), respectively (Fig. 17; see also Rădan *et al.*, 1998a,b). Significant variations of the enviromagnetic parameter (**MS**; **k**), controlled by the microlayered sediment lithology of the two pierced units (*coccolithic* and *sapropelic*), were recorded along several cores (up to 55 cm) picked up from the abyssal zone, during the 1997 cruise.

New magnetic susceptibility data are available for a large collection of bottom sediments (cores included), taken by one of the authors (*S.R.*), who participated at a cruise that was carried out in the northwestern part of the *Black Sea*, in 2010, with the ″*Mare Nigrum*″ oceanographic vessel (GeoEcoMar), which is used for multidisciplinary scientific researches.

4. CONCLUSIONS

The modern sediments sampled in various aquatic environments of the *Danube Delta – Razim (Razelm) – Sinoie Lagoonal Complex – Black Sea Littoral Zone – Northwestern Black Sea* area, over 35 years (*i.e.*, 1976 – 2011), stand for high fidelity enviromagnetic archives.

The magnetic signatures identified in the sediments were able to characterize and differentiate the depositional environments inside an extended, diversified and, at the same time, unitary complex of fluvial, lacustrine/deltaic, fluvial-deltaic, lagoonal, littoral and marine ecosystems.

Based on an original magnetic susceptibility (**MS**) scale (Rădan & Rădan, 2006a, 2007) and a vast **MS** data bank for lake sediments (Rădan & Rădan, 2006b), the capability of this magnetic property as a proxy parameter to differentiate lacustrine-deltaic and fluvial-deltaic sedimentary environments was demonstrated by several examples (and some additional data presented in two plates attached to the paper).

The former is related to the aquatic ecosystems located inside the *Danube Delta* (DD) interdistributary area, while the latter is merged with the main *DD Branches*. A general feature is that the lithological characteristics and the mineralogical and chemical composition of the sediments in the *Danube Delta lakes* which are successively disposed along a main waterway have been modified in a natural manner, by transport and differentiated sedimentation, passing from a dynamic aquatic environment towards a confined one. These changes are well reflected by the enviromagnetic fingerprints recovered from the bottom sediments. At a local scale, hence related to a short transport distance, a similar differentiation was identified for several "couples of lakes".

″Confined″ *versus* ″dynamic deltaic environments″ were compared and defined by specific magnetic fingerprints. As in certain cases the bottom sediments were sampled in the same zones, in successive phases, at 5-10 years time intervals, the magnetic signatures which were recovered have clearly demonstrated the presence or the absence of the anthropogenic impact on the ecosystems. They are reliable proofs for the evaluation of the changes that were produced in the aquatic zones as a result of the pressure caused by some human activities in the area. The alterations of the hydrological regime have generated changes of the sedimentary environments, and consequently, the modifications of the magnetic fingerprints. The **k** classes used to characterize the recent sediments can give some information on the sediment quality, which is generally evaluated by means of the geochemical and ecological scales.

Besides, the particular case regarding the effects of the human intervention on the fluvial-deltaic ecosystem from one of the *Danube Delta Branches*, *i.e.* the *Sf. Gheorghe distributary* (Rădan & Rădan, 2010b), proved the capability for eco-hydrological applications of the enviromagnetic tool, which is based on magnetic susceptibility measurements on bottom sediments.

Other examples have concerned the **MS** signatures recovered from the sedimentary environments belonging to a particular unit, a lagoon system (*i.e.*, the *Razelm - Sinoie Lagoonal Complex*/RSLC), isolated from the *Black Sea*, but linked with the *Danube Delta*. The magnetic susceptibility and lithological maps carried out for the RSLC sediments show connections with the structure of the surrounding sand ridges. The data obtained from the enviromagnetic archives sampled during a 32-year period (*i.e.*, 1976–2008) were interpreted in a magneto-sedimentogenetic framework. The **k** maps drawn for some lakes of the lagoonal complex, taking into consideration each of the 3 beds (separated as ″a″, ″b″ and "c") and the whole sampled "sediment packet" ("a+b+c"), agree with the corresponding lithological maps. Moreover, generally, the magnetic susceptibility variations were in agreement with the macroscopic description of the lithological constitution of the sampled bottom sediments that was performed on board of the research vessels. The sedimentary areas that are characterized by higher **k** values in the **MS** maps coincide with the areas pointed out by the detrital/siliciclastic component distribution map. Higher **MS** values are recorded for the main channel inlets into the lake (*e.g.*, the case of the *Dunavăț Ch.* mouth zone in the *Razim. L.*). Another very interesting result, based on the enviromagnetic archives recovered from the lagoonal complex recent sediments, sampled in 3 periods, *i.e.* 1976 – 1978, 2002 – 2004, and 2007 – 2008, respectively, was that the increasing trend in the occurrence of the finer sediments southwards, associated with the general water flow direction from North southwards, is accompanied by a simultaneous increasing trend of the lower **k** class **II** and a decreasing trend of the higher **k** classes (**IV**+**V**), in the direction Razelm ➲ Golovita ➲ Sinoie ➲ Zmeica.

The magneto-lithological models performed for four main lakes from the *Black Sea Littoral Zone* (BSLZ), which were investigated in 2007 – 2008, fill up the vast data bank carried out for the aquatic ecosystems investigated in the *Danube Delta* and *Razelm – Sinoie Lagoonal Complex*, during more than three decades.

By comparing the results achieved for the littoral lakes (BSLZ) with the data obtained for a series of case studies or case histories developed for the sedimentary environments of the first two investigated aquatic areas (DD and RSLC), some new issues went out. These are particularly connected with the different processes of sedimentation taking place in deltaic lakes ("confined" or "dynamic environments"), lagoons or lymans. The latter are represented by 3 lakes from the BSLZ, *i.e. Taşaul* (discussed in this paper, Chapter 3.3), *Techirghiol* and *Mangalia* (Rădan *et al.*, 2008a,b,c, 2011b), the forth lake investigated, *i.e. Siutghiol*, being a lagoon (some data, in Chapter 3.3).

As regards the lymans, the process of filling up with sediments is complex, being controlled by the simultaneous and successive activity of several sedimentary material supplies. The special geological context of the fluvio-marine lyman *Taşaul* is a good example in this respect. In such cases, the use of the magnetic susceptibility scale, elaborated on the basis of ca 2500 sediment samples collected from the DD and RSLC lakes (Rădan & Rădan, 2007), must take into consideration the peculiar geological framework in which the lake is situated.

Anyway, the **MS** fingerprints recovered from the bottom sediments of the littoral lakes confirm the capabilities of these recent deposits as enviromagnetic archives, the features of the magnetic signatures deciphered from them giving a rapid and clear information on the environmental and geoecological status of some aquatic ecosystems from the *Black Sea Littoral Zone*. The natural and/or anthropogenic actions of some important factors, *e.g*., the *Casimcea river* discharge area, that is the main stream inlet into the *Taşaul Lake*, and respectively, the green schists quarries from the *Sibioara* zone, or the dams of the *Poarta Albă – Năvodari Canal* and the *Ovidiu village* buildings, in the *Siutghiol Lake* case, induce pressure on the sedimentary environments from these aquatic areas. The magnetic susceptibility proved to be a tracer of the environmental conditions, detecting some natural and anthropogenic influences on the ecosystems.

Besides, mineralogical and geochemical data for the sediment samples collected from the deltaic, lagoonal and littoral lakes, investigated for the magnetic susceptibility and the lithological composition, are needed. These analyses are also very useful to explain the different degree of the correlations related to the enviromagnetic parameter **MS** *versus* the lithological components (**SIL**, **TOM**, **CAR**), relationships which were investigated in various hydrosedimentary environments. The natural and the anthropogenic inferences of the integrated magneto-lithological studies carried out in these three important aquatic areas of *Southeastern Romania* (*i.e*., DD, RSLC and BSLZ) could be better emphasized, as well.

As regards the data obtained for the sediments sampled in the marine area, namely in the *Northwestern Black Sea*, in 1995 and 1997, the magnetic susceptibility maps were correlated with the main sedimentary environments from the fluvial-marine interaction zone. As we have new **MS** data from the area, based on the cruise carried out in 2010, the comparative analysis of the results obtained in 1995/1997 and 2010 could give some useful information for the evaluation of the environmental status of this very interesting region, particularly related to the area under the influence of the Danube River sediment discharge, but placed in an extended context defined by the *Danube River – Danube Delta – Western Black Sea* geosystem.

By recovering the magnetic fingerprints imprinted in the recent sediments and approaching the magnetic susceptibility distribution both in the horizontal and the vertical planes, as a result of the investigation of the grab samples and of the sediment cores, respectively, an useful and innovative contribution to the environmental and geoecological studies, as well as to the investigation of the (hydro)sedimentary environments and processes, is achievable.

The validity of the Verosub & Roberts (1995) statement, *i.e. "many types of studies that are now classified as environmental magnetism have been in existence for some time"*, is clearly proved by the enviromagnetic archives recovered from the modern sediments sampled within a long time interval (1976 –2011) in deltaic, lagoonal and littoral lakes or in the fluvial-deltaic zones of the *Danube Delta* and in the area under the influence of the *Danube River* sediment discharge (*Northwestern Black Sea*).

Finally, it is worth pointing out that the start of the investigation of the magnetic susceptibility of lake sediments in Romania was in the year 1977 (Rădan *et al*., 1978, 1979, in Mihăilescu *et al.* 1978, 1979), the results being then connected to the environmental magnetism field. Therefore, our first magnetic susceptibility data, obtained on lake sediments sampled in the *Razelm – Sinoie Lagoonal Complex* in 1976 and 1977, could be placed in the above-mentioned situation, remarked by Verosub & Roberts (1995), who consider that *"the first explicit description of environmental magnetism as a distinct field was in 1980"*, when Thompson *et al.* (1980) published in *Science* the paper entitled "*Environmental applications of the magnetic measurements*".

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