INTEGRATED MAGNETIC SUSCEPTIBILITY AND LITHOLOGICAL STUDIES ON LACUSTRINE RECENT SEDIMENTS FROM THE DANUBE DELTA

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Abstract. The present paper is the first of a series of three, focused on the results of the integrated magnetic susceptibility and lithological studies carried out in several lacustrine areas of the Danube Delta, the Razim (Razelm) - Sinoie lagoonal Complex and the Black Sea Littoral Zone. Enviromagnetic fingerprints are recovered from the bottom sediments sampled in dynamic and confined aquatic environments and their intensities are evaluated and compared. Distinguishing features identified between different lakes are clearly reflected by the investigated enviromagnetic parameter (**MS**). The connection between the **MS** regime recorded within the lake sediments and the ternary diagrams showing their lithological classification (*i.e. mineral-siliciclastic fraction, carbonate fraction* and *organic matter*) is discussed, as well. Besides, several composite models illustrate the correlations between the **k** values and the main lithological components (*i.e*. organic/**TOC**, carbonate/**CAR** and mineral-siliciclastic/**SIL**, respectively). On the basis of the magneto-lithological data base obtained for the lake sediments sampled in the 2006 cruises, several correlation coefficients (**r**) were calculated, *e.g.* related to **k** *vs* **TOC**, **k** *vs* **CAR**, **k** *vs* **(TOC+CAR)** and **k** *vs* **SIL**. The graphical correlation is also taken into consideration to show and interpret the connection between the enviromagnetic parameter and the lithological characters. Generally, positive (direct) correlations characterise the magnetic susceptibility (**MS**) *vs* mineral component (**SIL**), whereas negative (reverse) correlations define **MS** *vs* **TOC**, as well as **MS** *vs* (**TOC+CAR**). The modern sediments sampled in various deltaic environments stand for high fidelity enviromagnetic archives, which are deciphered within the presented case studies.

Key words: environmental magnetism, magnetic susceptibility, lithology, total organic matter content, carbonate component, mineral-siliciclastic component, lacustrine recent sediments, Danube Delta.

1. INTRODUCTION

Within the system of techniques concerning the environmental magnetism and the magnetic mineralogy, the magnetic susceptibility (**MS**; **k**) measurements are considered a basic investigation tool.

The magnetic parameters are useful for describing and classifying all types of environmental materials, their "magnetisability" being characterised and measured by the magnetic susceptibility (Dearing, 1999). Among the main information provided by the **MS** measurements, there are mentioned the abilities to identify the *Fe*-bearing minerals that are present in a rock sample, to classify different types of materials, to identify the processes of their formation or transport, to define/detect "environmental fingerprints" that can be used to differentiate and characterise the (geo)materials, in our case – the lacustrine recent sediments.

In this context, our results demonstrate the capability of the magnetic susceptibility as sedimentogenetic index and the strong connections with the lithological components of the sediments. At the same time, our extended study carried out on recent sediments from deltaic, lagoonal and littoral lakes provides clear examples supporting this relatively new discipline, *i.e.* the **environmental magnetism** (Verosub & Roberts, 1995; Dekkers, 1997, 2007; Evans & Heller, 2003), as well as the abilities of the investigation tool to decipher geological, environmental and geoecological contexts inside of the aquatic systems.

2. STUDY AREAS

The bottom sediments were sampled from four important interdistributary depressions located in both the *Fluvial Delta Plain* (*i.e., Meşteru – Fortuna*, *Matiţa – Merhei* and *Gorgova – Uzlina*; **1**, **2**, and **4**, in Fig. 1) and *Fluvio-Marine Delta Plain* (*i.e.*, *Lumina – Roşu*; **3**, in Fig. 1).

Fig. 1 Location of the studied area: Danube Delta and the sectors under attention: **1**. Lungu – Tătaru; **2**. Uzlina – Isacova; **3**. Puiu – Roşu – Roşuleţ; **4**. Merhei – Matiţa – Poludionca.
Note: The lagoonal lakes (**5** – Razim/Razelm; **6** – Goloviţa; **7** – Sinoie; **8** – Zmeica; bottom-left picture) and the littoral lakes (**9** – Taşaul; **10** – Siutghiol; **11** – Techirghiol; **12** – Mangalia; right-hand pictures), which are the subject of the next papers, are also shown in this figure.

3. LOGISTICS, (GEO)MATERIALS AND METHODS

There is a huge magnetic susceptibility data bank resulted from more than 2500 **MS** measurements on bottom sediments sampled from the Danube Delta along three decades (Rădan & Rădan, 2006; Rădan & Rădan, 2007a,b, Rădan, 2008). The data that are here analysed are mainly based on the collections taken during the 2006 cruises. The field campaigns have been performed on board of the fluvial research vessel "*Istros*" (Fig. 2a) and the motor-boat "*Măriuca*" (Fig. 2b). Sediment sampling station networks have been conceived, so that the lacustrine areas were uniformly covered. To locate the sampling points, a high precision was ensured by the GPS ("Garmin") and the echosounder ("*Simrad*") equipments. Relatively undisturbed "sediment packets" (Fig. 2e) were taken by using "*van Veen*" type grab samplers. The main lithological components (organic matter, carbonates and detrital siliciclastic material) have been determined by Dr. Consuela Milu – University of Bucharest (in Rădan *et al*., 2006, *Geological Institute of Romania/GIR Archive*, Bucharest, Romania). Ternary diagrams were drawn up to show the lithological classification of the bottom sediments. The **MS** measurements on unconsolidated sediment samples were done with KLY Kappabridges. To calibrate the lake sediments, a "Magnetic Susceptibility (**k**) Scale" (Rădan & Rădan, 2007c; Fig. 2c) was used.

Numerous **MS** models were performed to analyse the characteristic magnetic signatures of the various sedimentary environments. Based on the magnetic susceptibility values (**k**) and the contents of the lithological components (*i.e.*, **TOC** – *Total Organic matter Content*; **CAR** – *carbonate fraction*; **SIL** – *mineral/siliciclastic fraction*) obtained for the investigated lake sediments, a series of integrated magneto-lithological models were carried out, as well. To show and interpret the connection between the enviromagnetic parameter (Fig. 2f) and the lithological components (Fig. 2g), some correlation coefficients (**r**) were calculated and graphically presented [**k** *vs* **TOC**, **k** *vs* **CAR**, **k** *vs* (**TOC**+**CAR**) and **k** *vs* **SIL**] (Fig. 2h). Moreover, a scale to evaluate the size of the correlation has been used (Fig. 2d).

4. RESULTS AND DISCUSSION

The capability of the investigated magnetic property (*i.e.*, **k** or **MS**) as a proxy parameter to differentiating dynamic and confined aquatic environments inside the *Danube Delta* (*DD*) interdistributary area is presented.

Enviromagnetic fingerprints were recovered from the bottom sediments sampled in various aquatic ecosystems and their intensities were evaluated and compared.

The recent sediments of the *Danube Delta* lakes show variations from clayey to sandy muds (predominantly constituted of detrital allogenic silica minerals, with high contents of Al_2O_3 and Fe_2O_3), up to organic and/or calcareous muds (rich in authigenic components, characterised by notable levels of *TOC* and $CaCO_3$ contents). The main sediment source of the *Danube Delta* is represented by the Danubian supplies, which are entering into the delta through three main branches. Instead, the largest part of the organic matter included in the recent sediments shows an autochthonous origin. In relation to their position to the Danubian inputs, the *Danube Delta* water-system is defined by two categories of lakes: a) strongly (more or less directly) influenced by the riverine supplies, *e.g. Lungu L*. and *Uzlina L*. (1 and 2, in Fig. 1; see also Figs. 3g and 5d); b) not significantly affected (relatively stagnant conditions), *e.g*., *Isacova L*., *Roşu L*., *Merhei L*., *Poludionca L*. (2, 3 and 4, in Fig. 1; see also Figs. 5d, 10a and 11a). There is also a third category, namely the lakes with intermediate conditions, *e.g*., *Tătaru L*. and *Puiu L*. (1 and 3, in Fig. 1; see also Figs. 3g and 10a). These three different sedimentary environments are characterised by specific magnetic fingerprints, which are further presented and discussed.

4.1. Lungu – Tătaru zone (Meşteru -Fortuna Depression)

The analysed case in the *Meşteru – Fortuna Depression* (1, in Fig.1) is concerning with the magnetic susceptibility and lithological data obtained for a dynamic (*i.e*., *Lungu Lake*) and, respectively, an intermediate sedimentary environment (*i.e*., *Tătaru Lake*) (Fig. 3g). Before digging the "*Mila 36*" *Canal* (in 1982-1983), the *Lungu L*. was a lake protected by the direct danubian supplies; the sediments were similar to those found in the lakes with intermediary conditions, *e.g*., *Tătaru L*. or *Cuteţchi L*. (placed in the north-western part of the depression). The **MS** fingerprints confirm this situation; their intensities are correlated to **k** values assigned to the classes **II** and **III**, only (Rădan & Rădan, 2007a, Rădan, 2008). After the human intervention in the western part (see the "*Mila 36" Canal* in Fig. 3g), the northern half o the lake is permanently washed by the waters coming from the *Canal*, the silting up process being very strong in this sector. The sediments are clayey, siltic or fine sandy muds; their grain size decreases towards the southern part of the lake, where the muds are also of mineral type, but richer in organic matter and strongly bioturbated. As the sediment samples were collected in the 2006 cruise from the eastern – north-eastern area of the *Lungu Lake* (Fig. 3g), the measured **k** values are not correlated to the highest **MS** class (*i.e*., **V**), as it was the case of the sediments sampled in 1987 (Fig.3j), but to **k** classes **III** and **IV** (Fig. 3g). Anyway, the samples taken in 2006 show that they are mainly placed within the mineral-organic sediment field (Fig. 3i), and, subordinately, within the organic-mineral field. Passing to the *Tătaru L*. – a lake with a double protection against the direct Danubian supplies –, the magnetic signatures were recovered from the sediments sampled during around a quarter of century (1980 – 2006) (Rădan & Rădan, 2007a, Rădan, 2008). They have pointed out that after the brutal modification of the hydrological conditions in the *Meşteru – Fortuna Depression* there have not occurred very important changes within the lacustrine ecosystem from this sector, although the *Tătaru L*. location is between the "*Mila 36*" *Canal*, *Tulcea* and *Sulina*

Magnetic susceptibility (MS; k) scale		
Vd	> 1000	Coarse silts and sands
Vc	675 ÷ 1000	
Vb	575 ÷ 675	
Va	275 ÷ 575	
IV	175 ÷ 275	
III	75 ÷ 175	Clayey fine up to siltic sediments
II	10 ÷ 75	Fine sediments, usually rich in organic matter and / or carbonates
I	< 10	

c)

Correlation coefficients (r)		
	0.65 ÷ 1.00	Strong positive correlation
	0.32 ÷ 0.64	Moderate positive correlation
	0.00 ÷ 0.31	No correlation – Weak positive correlation
	0.00 ÷ (- 0.31)	No correlation – Weak negative correlation
	(- 0.32) ÷ (- 0.64)	Moderate negative correlation
	(- 0.65) ÷ (- 1.00)	Strong negative correlation

d)

Fig. 2 Logistics, (geo) materials and methods. **a)** Fluvial research vessel "Istros"; **b)** Motor-boat "Măriuca"; **c)** Magnetic susceptibility (**k**) scale (Rădan & Rădan, 2007c); **d)** Scale used to evaluate the size of the correlation (**r**) between the enviromagnetic parameter (**k**) and the lithological components (**TOC** – Total Organic matter Content; **CAR** – Carbonate fraction; **SIL** – mineral/siliciclastic fraction); **e)** "Sediment packet" collected with the „van Veen" type grab sampler; **f)** Model showing the magnetic susceptibility calibration of lake sediments (**k** classes, in %); **g)** Model showing the lithological components of the sediments and their contents (in %); **h)** Diagrams used to illustrate and calculate the correlation coefficients (**r**).

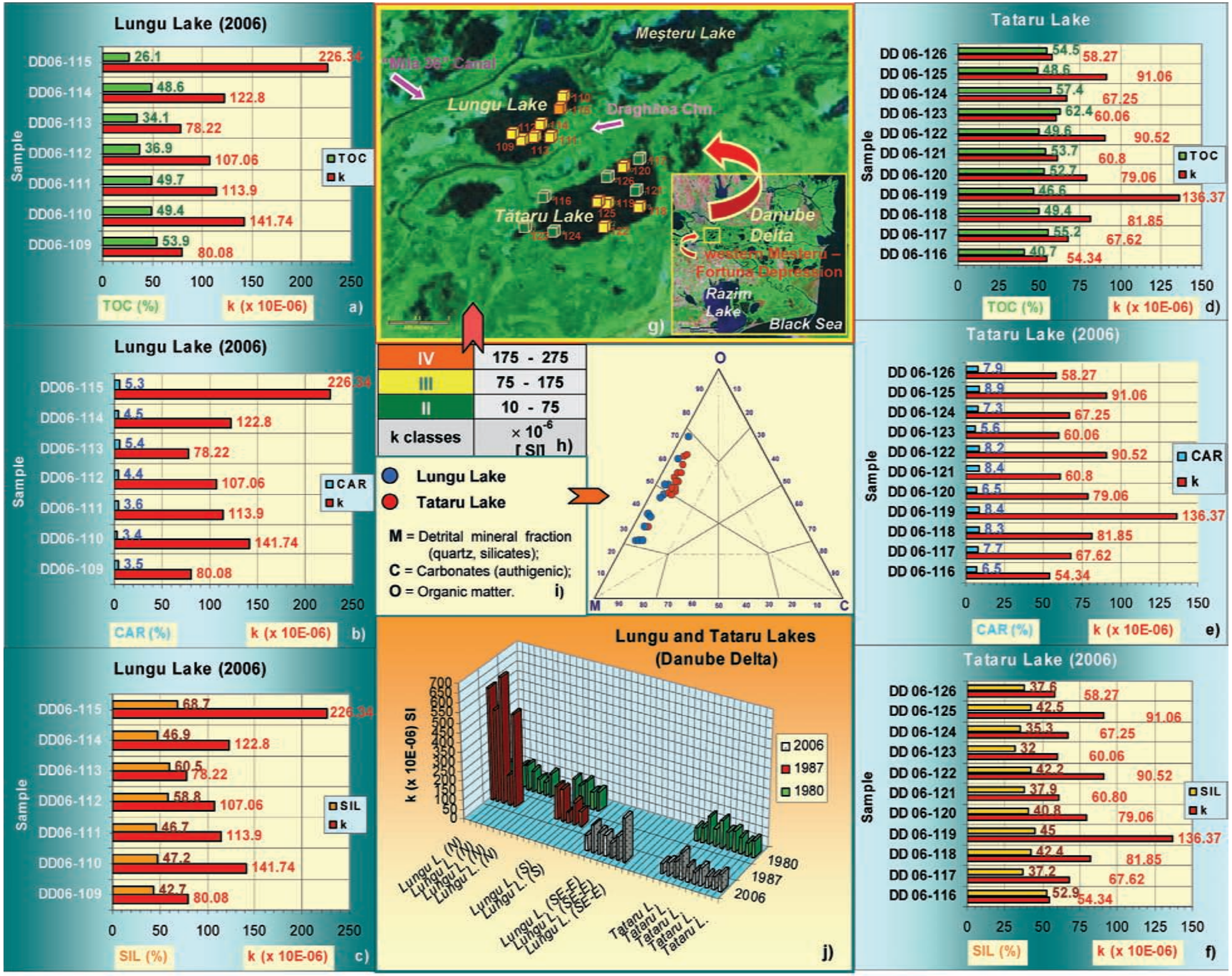


Fig. 3 Magneto-lithological model for recent sediments sampled from dynamic and intermediate aquatic environments (Lungu Lake and, respectively, Tătaru Lake) in the Fluvial Delta Plain (Danube Delta; **1**, in Fig. 1). For further explanations, see Legend in Fig. 2 and the text. **Note**: The magnetic susceptibility (**k**) is expressed in **SI** (*Système International*) **units**

Branches. The lake sediments consist in clayey or siltic muds, relatively coarser in the supply area, and finer in the central and eastern zones, where they are richer in organic matter and carbonates. The sediment samples taken in 2006 show an organic-mineral constitution and generally have higher carbonate contents (Fig. 3e), as compared, for example, with the sediments collected from the *Lungu Lake* (Fig. 3b) (see also the ternary diagram in Fig. 3i).

Concerning the bottom sediments of the *Lungu* and *Tătaru Lakes* (2006 sampling cruise; Fig. 3g, Fig. 4a), some examples of the correlation of the magnetic susceptibility (**k**) with each of the three principal lithological components (**TOC**, **CAR** and **SIL**) are illustrated in Fig. 3a,b,c and Fig. 3d,e,f, respectively. In addition, in the magneto-lithological model from Fig. 4b,c,d,e, the explicit graphical connection between the environmental parameter (**k**) and the litholological components are shown; moreover, in Fig. 4f, are specified the calculated correlation coefficients (**r**) for **k** *vs* **TOC**, **k** *vs* **CAR**, **k** *vs* **(TOC+CAR)**, and, respectively, **k** *vs* **SIL**. It can be noticed that moderate negative correlations were obtained for **k** *vs* **TOC** and **k** *vs* **CAR**, and strong negative and positive correlations for **k** *vs* **(TOC+CAR)**, and, respectively, **k** *vs* **SIL** (Fig. 4f; see also the scale in Fig. 2d). Parallel diagrams illustrating the magnetic susceptibility characterisation and the lithological composition of the modern sediments sampled from the *Lungu* and *Tataru Lakes* in the 2006 cruise are presented in Figs. 4g and 4h.

4.2. Uzlina – Isacova zone (Gorgova – Uzlina Depression)

Another interesting case is related to a "couple of lakes" (*i.e. Uzlina* and *Isacova*; Figs. 5d,6a), located in the *Gorgova – Uzlina Depression* (2, in Fig.1). First, it worths mentioning some peculiarities of the sedimentary environments associated with the lakes that are successively placed along a main water flow way. Their lithological, mineralogical and chemical characteristics are modified as a consequence of differential transport and sedimentation, and by passing from a dynamic towards a more or less stagnant aquatic environment. This behaviour occurs both at regional and local scales. The changes are clearly reflected by the magnetic susceptibility regime recorded in the lake sediments. As proofs of these remarks, sets of several magneto-cartographic images covering the period 1979 – 2006 can be found in previous papers (*e.g.*, Rădan & Rădan, 2007b, Rădan, 2008; Rădan & Rădan, 2007c) and unpublished scientific reports (*e.g.*, Rădan & Rădan, 2004; Rădan *et al*., 2008, *GIR Archive*, Bucharest, Romania). In the present article, more details are given in connection with the results obtained on the sediment samples collected in 2006 from the *Uzlina – Isacova* «couple of lakes». In this case, the change from a **MS** regime to the other is made abruptly, simulating the natural threshold existing between the two connected lakes, and respectively, the sudden water transit. As concerns the *Uzlina Lake*, defined by a "dynamic environment", the magnetic susceptibility ranges between 98.18×10E-06 SI – 332.15×10E-06 SI; **k** values are assigned to the classes **III**, **IV** and **Va** (according to **MS** scale; Fig. 5f,g). The maximum **k** value was measured on a coarse siltic-fine sandy mud sampled in the DD 06-236 station (Fig. 5d), placed in the "delta" zone created in the southwestern part of the lake, due to the detrital material supply carried by the *Uzlina Canal* from the *Danube River* (particularly from the *Sf. Gheorghe Branch*). This sediment sample revealed the highest **SIL** content (80.2%), and respectively, the lowest **TOC**+**CAR** content (19.8%) that were determined for the 2006 collection. On the other hand, the coarse mud with vegetal fragments and fauna, with the highest (**TOC**+**CAR**) content (*i.e.*, 63.0%), and the lowest **SIL** content (*i.e.*, 37.0%), which was sampled in the north – north-eastern part of the *Uzlina Lake* (station DD 06-232; Fig. 5d) provided the lowest **k** value, indicating the minimum limit of the above specified **MS** range. It can be noticed the reverse correlation of the magnetic susceptibility (**k**) with the *Total Organic matter Content* (**TOC**) and *Carbonate content* (**CAR**), and the direct correlation of the **MS** with the *mineral/detrital fraction* (**SIL**). This remark is suggested by the values illustrated in Fig. 5a,b,c and is clearly demonstrated by means of the diagrams from Fig. 6b,c,d,e,f (related to both the Uzlina and Isacova Lakes). The **MS** characteristics that define the sediments sampled in the *Uzlina L.* are specific to the aquatic ecosystems disturbed by important amounts of water and material in suspension, characterising the "dynamic environments". Passing to the *Isacova Lake*, which is coupled with the *Uzlina L.*, and is placed after this lake along the flowing water way (Figs. 1 and 5d), it must be pointed out that all the sediment samples collected in October 2006 were calibrated to the lower **k** class **II**. The *Uzlina Lake* works as a buffer interface between the *Danube* supplies and the *Isacova Lake* (Rădan & Rădan, 2007b, Rădan, 2008). In the latter lake case, a leveling and diminishing role has the organic substance, mainly present as fine triturated vegetal material, and the carbonates, which occur in a greater quantity, as well as the very porous character of the sediments (Rădan & Rădan, 2004, *GIR Archive*, Bucharest, Romania, unpublished report). The samples taken in 2006 confirm these characteristics, the (**TOC**+**CAR**) content ranging between 53.7% - 82.8% (May 2006 cruise), and, respectively, 68.0% - 72.8% (October 2006 cruise). The connections between these lithological parameters and the magnetic susceptibility are evident. The diagram from Fig. 5e, based on all the samples collected from the *Isacova Lake* in 2006, shows that 94% of them are calibrated to lower classes **I** and **II**, as compared with the *Uzlina Lake*, in which case 92% of the measured samples (Fig. 5f) are correlated to the intermediary class **III** and to the higher ones, **IV** and **V**. Several **MS** models carried out for the sediments sampled in 17 cruises in the two coupled lakes, in the period 1979 – 2006 (*e.g.*, Rădan & Rădan, 2006; Rădan & Rădan, 2007b, Rădan, 2008), confirm the net difference between the measured magnetic susceptibility values: low and very low for the *Isacova L.*, characterised as a "confined environment", and much higher for the *Uzlina L.*, connected by a short canal

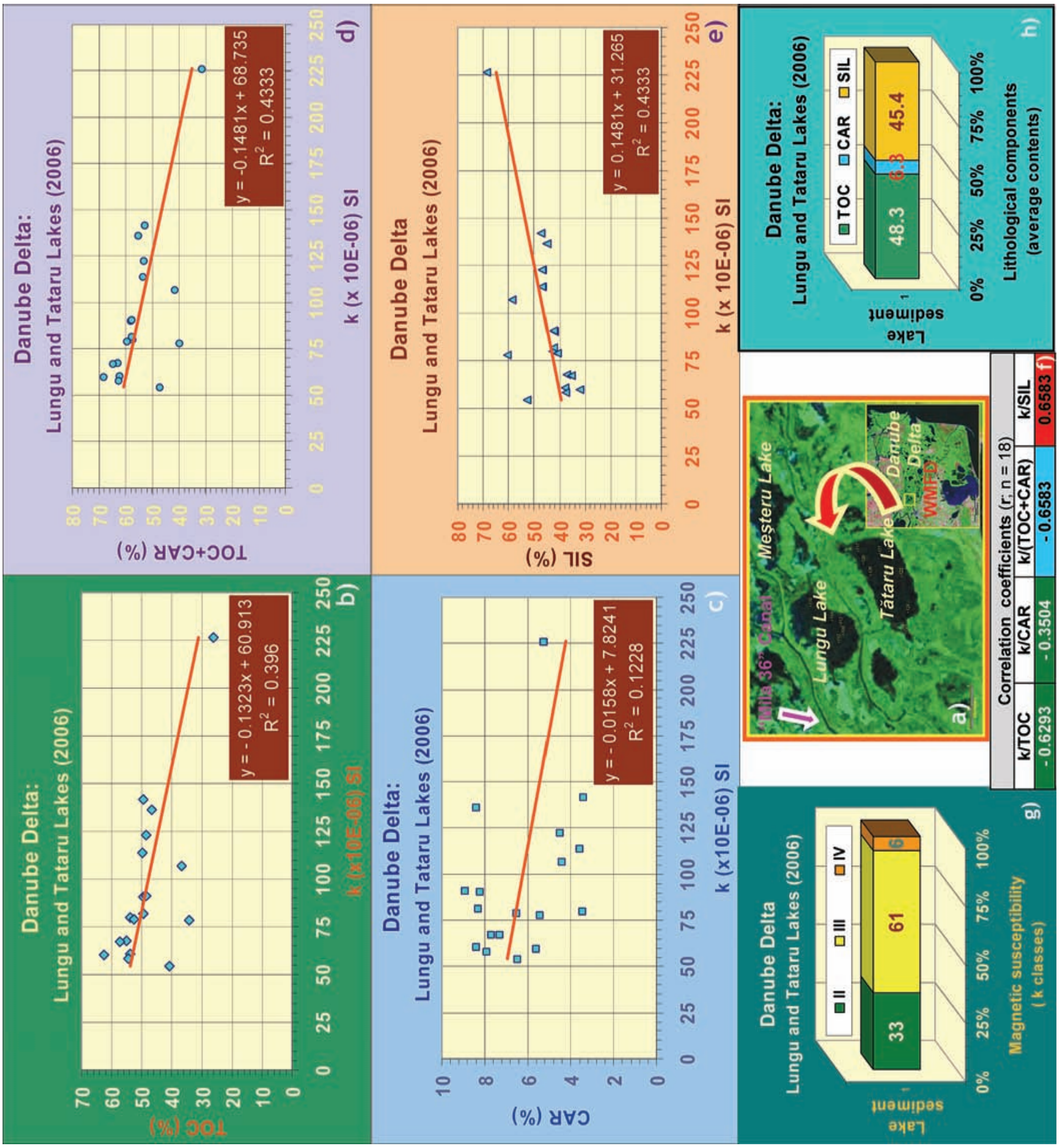
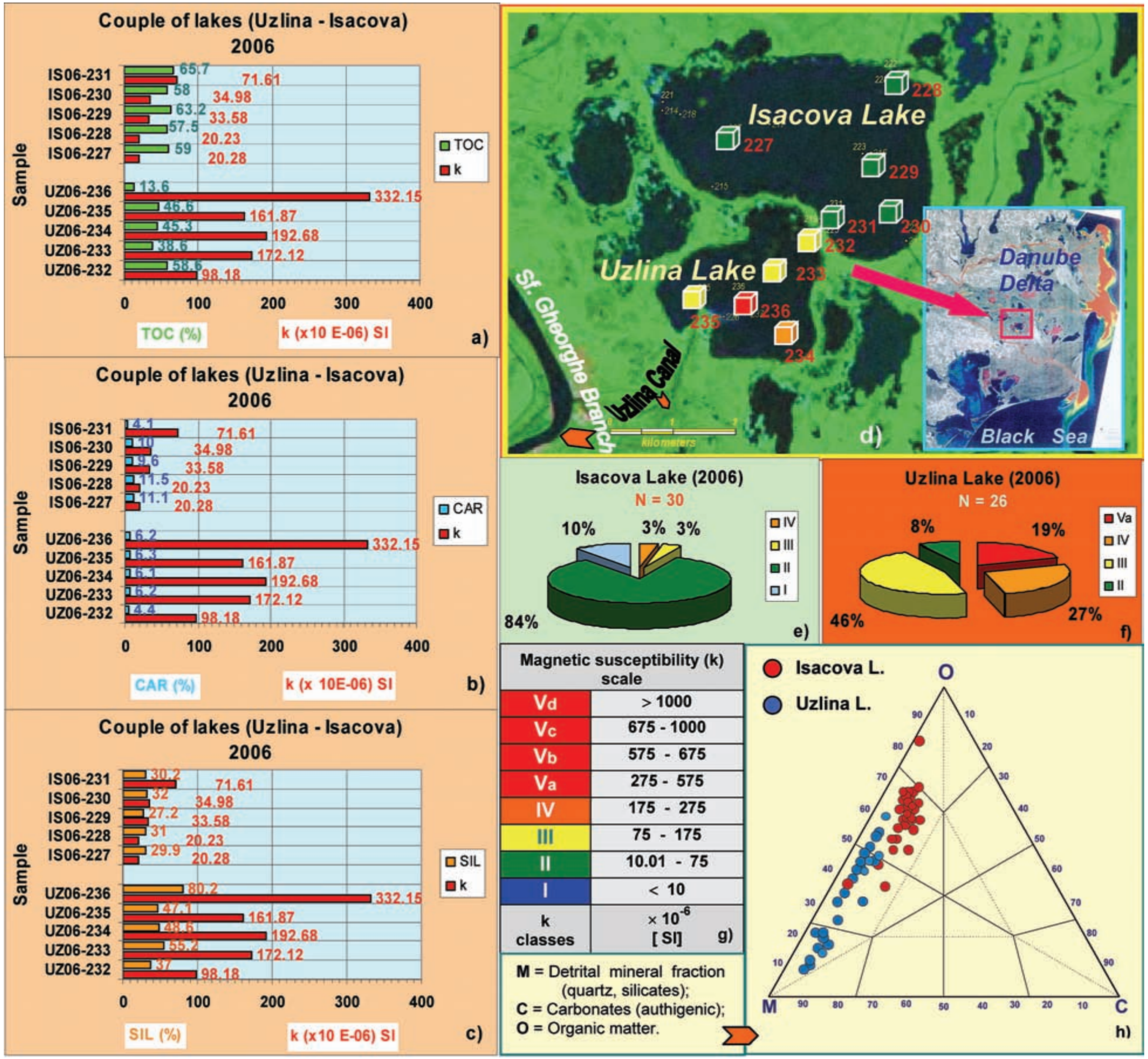


Fig. 4 Magneto-lithological model for bottom sediments sampled from two lakes in the Meşteru – Fortuna Depression (Danube Delta; **1** in Fig. 1), showing the correlation between the enviromagnetic parameter (**k**) and the lithological components (**TOC, CAR, SIL**). For further explanations, see Legend in Fig. 2 and the text.



Magnetic susceptibility (k) scale	
Vd	> 1000
Vc	675 - 1000
Vb	575 - 675
Va	275 - 575
IV	175 - 275
III	75 - 175
II	10.01 - 75
I	< 10
k classes	$\times 10^{-6}$ [SI]

Fig. 5 Magneto-lithological model for recent sediments sampled from a "couple of lakes" in the Fluvial Delta Plain (Danube Delta; **2** in Fig. 1). **Legend**: **UZ** – Uzlina L. (dynamic aquatic environment); **IS** – Isacova L. (intermediate aquatic environment). **Note**: The diagrams **a), b), c)** refer to the samples collected in the October 2006 cruise. The pie-diagrams **e)** and **f)** and the ternary diagram **h**) are based on two sample collections (taken in May and October, 2006). For further explanations, see Legend in Fig. 2 and the text.

to the Danube River, and characterised by a "dynamc environment". The **MS**-lithological diagrams from Fig. 5a,b,c can also be taken as proofs for this assertion. The ternary diagram illustrated in Fig. 5h shows the clear differentiation between the positions of the two fields characterising the lithology of the recent sediments from the couple of lakes under our attention. The samples from the *Uzlina Lake* are mostly projected in the *mineral-organic field*, a high weight having the dominantly detrital mineral sediments, whereas the samples from the *Isacova Lake* show a relatively reverse situation: the most samples are situated in the *organic-mineral field*, a few only in the *mineral-organic field* (two of them taken from the influence area of the *Isac I Channel*), and one in the *domain of the organic muds* (Fig. 5h).

In addition, like in the previous case, a composite magneto-lithological model showing the explicit graphical correlation between the magnetic susceptibility **k** and the lithological components **TOC**, **CAR** and **SIL** (Fig. 6b,c,d,e), as well as the corresponding calculated correlation coefficients (**r**), was performed (Fig. 6f). Parallel patterns illustrating the percentages of the **k** classes (Fig. 6g) and, respectively, of the lithological components contents (**TOC**, **CAR**, **SIL**) (Fig. 6h), which characterise the modern sediments sampled in the *Uzlina* and *Isacova Lakes* in the 2006 cruise, are also presented in the same composite model. Strong negative correlations (according to the scale from Fig. 2d) were shown by **k** *vs* **TOC** and **k** *vs* (**TOC+CAR**), and moderate correlations for **k** *vs* **CAR**; the relation **k** *vs* **SIL** is defined by **r** = 0,820, revealing a strong positive correlation (Fig. 6f). Actually, the very good correlation between the **k** values measured for the enviromagnetic parameter **MS** and the contents of the lithological components is suggested also by the two diagrams from Fig. 6g,h. These show very close percentages of the lower **k** classes **(I+II)** (53%) and of the (**TOC+CAR**) contents (54.6%), and on the other hand, very close percentages of the intermediate and higher classes (**III+IV+Va**) (47%) and of the **SIL** content (45.4%). These data can be considered as new proofs for the lithological support (Rădan & Rădan, 2007c) of the **k** scale from Fig. 2c.

4.3. Puiu – Roşu – Roşuleţ zone (Lumina – Roşu Depression)

The sedimentary environments from the principal lakes located in the *Lumina – Roşu Depression* (3, in Fig. 1) are of various types, in connection with their positions related to the water transfer system in the area. The lakes from this zone are placed in a distal position related to the direct fluviatile supplies and are situated in the fluvio-marine delta plain. *Puiu*, *Roşu* and *Roşuleţ* are mentioned among the deltaic lakes with the highest average organic substance contents: 55.5%, 50.4% and, respectively, 61.0%. There is a representative magnetic susceptibility data base, especially for these 3 lakes, resulted from the investigation of the recent sediments sampled in 15 cruises carried out during 25 years (1981-2006). New results concerning the integrated petromagnetic and lithological study of the sedimentary environments associated with the *Puiu Lake* are here presented. The magnetic susceptibility measured on the sediments sampled in this lake in May 2006 emphasize that 70% of **k** values are placed within the **MS** class **II** (Fig. 7e,f); a similar situation is revealed in the previous investigation phases, *e.g*. 55% in the 1993 – 1997 period, and 64%, in the first stage (1981). The class **III** and the class **I** share, equally, the remaining procents (30%) (Fig. 7e,f). The highest **k** value (115.88×10E-06 SI) was recorded for the sediment sampled in the discharge zone of the *Crişan – Caraorman Canal*, the sandy material supply explaining the **MS** regime intensity. The mineral fraction content is 72.2%, while the organic material content is 22.7%. In an opposite situation are the sediment samples taken from the northern zone of the *Puiu L*., which is to a greater distance of the emerged littoral ridges; the sediments are generally finer and rich in vegetal detritus. Consequently, high **TOC** values (69.7 – 70.2%) and low mineral fraction contents (21.0 – 21.5%) were determined. The ternary diagram from Fig. 7g shows the lithological composition of the sediments sampled in the *Puiu L*., in May 2006. The muds of the *Puiu Lake* are distributed within the *organic-mineral field*, and, subordinately, within the *organic one*. Some details regarding the correlation between the **k** values and the **TOC**, **CAR**, **SIL** or (**TOC+CAR**) components are illustrated in Fig. 7a,b,c,d (for 13 sediment samples collected from *Puiu Lake* during the mentioned cruise). It can be concluded that the integrated magnetic susceptibility and lithological data obtained for this lake argue its assignment to an *intermediate sedimentary environment* and it has not recorded important changes during a quarter of century.

Similar magneto-lithological models were performed for the *Roşu* and *Roşuleţ Lakes* (Figs. 8 and 9, respectively). Four samples were collected in May 2006 from the central part of the first mentioned lake and six from the latter. The highest **k** value (155.67×10E-06 SI) measured on a medium-fine sand, sampled from the mouth of the *Puiu – Roşu Channel*, is well correlated with the lithological composition of the sediment: **TOC** – 2.4%, **CAR** – 6.0% and **SIL** – 91.6% (Fig. 8a,b,c). The other samples show slight variations of the lithological component contents (**TOC**: 46.0 – 54.0%; **CAR**: 16.2 – 19.8%; **SIL**: 29.8 – 34.2%), and, correspondingly, very low susceptibilities (a negative **MS** value included), also placed within a narrow interval: (-1.24)×10E-06 SI – 7.67×10E-06 SI (Fig. 8a,b,c,d). The ternary diagram (Fig. 8g) emphasizes the high level of the *carbonate fraction* (18.1%), which recommends the *Roşu Lake* as the aquatic environment with the most carbonatic sediments of the Danube Delta; these data confirm the previous results (Rădan *et al*., 1997, 2000). It must be remarked that the **MS** pie-diagram from Fig. 8e is based on 6 samples collected along the 2006 year, not only in May.

As regards the *Rosuleţ Lake*, the magneto-ltihological model shows very low **k** values measured on the botom sediments sampled in 2006: 60% – class **I**, 40% – class **II** (Fig. 9a). This lake is characterised by sediments rich in organic substance (**TOC**: 32.4 – 72.1%; Fig. 9b), the average being 61.0%;

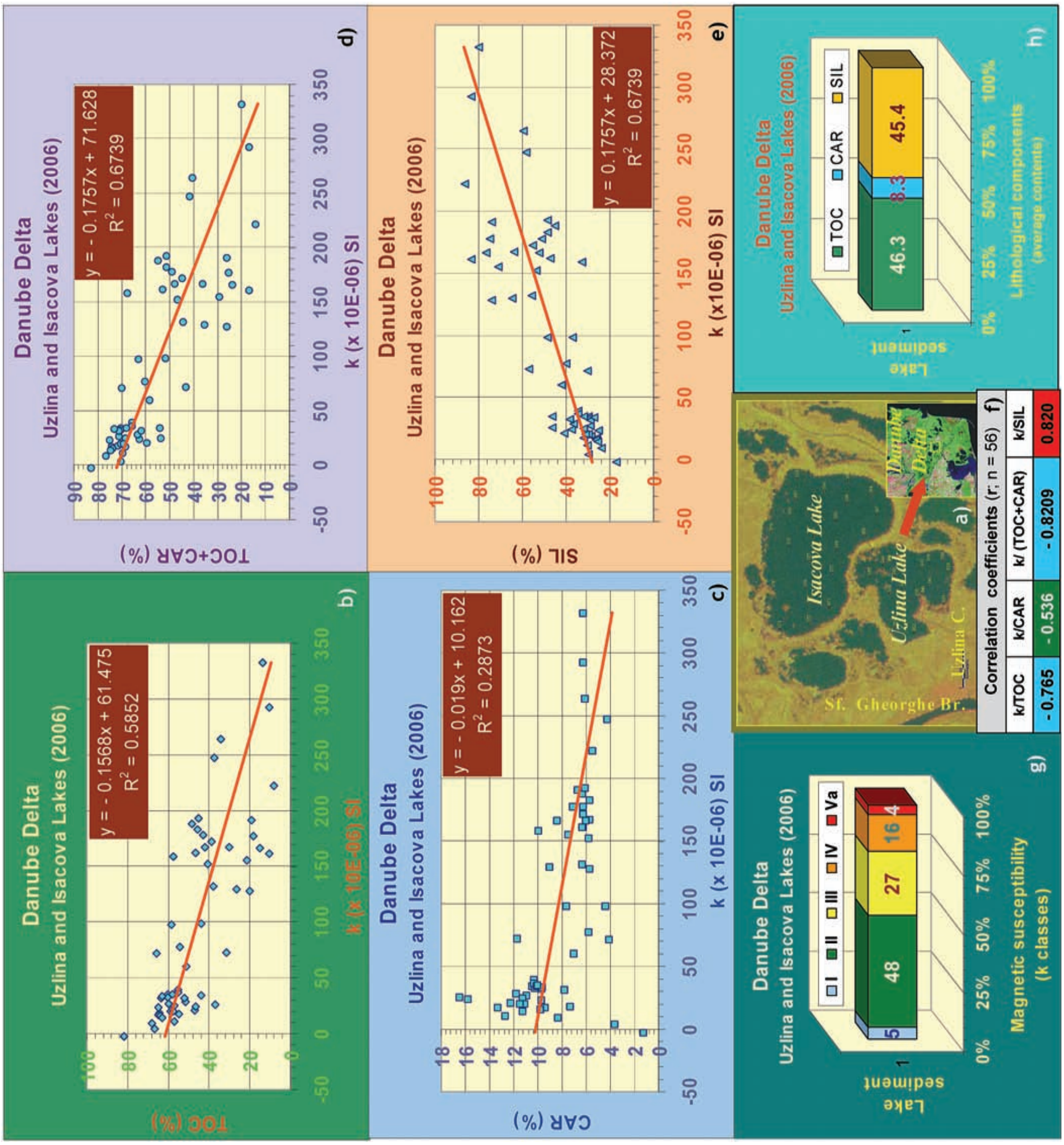


Fig. 6 Magneto-lithological model for bottom sediments sampled from two lakes in the Gorgova – Uzlina Depression (Danube Delta; **2**, in Fig. 1), showing the correlation between the enviromagnetic parameter (**k**) and the lithological components (**TOC, CAR, SIL**). For further explanations, see Legend in Fig. 2 and the text.

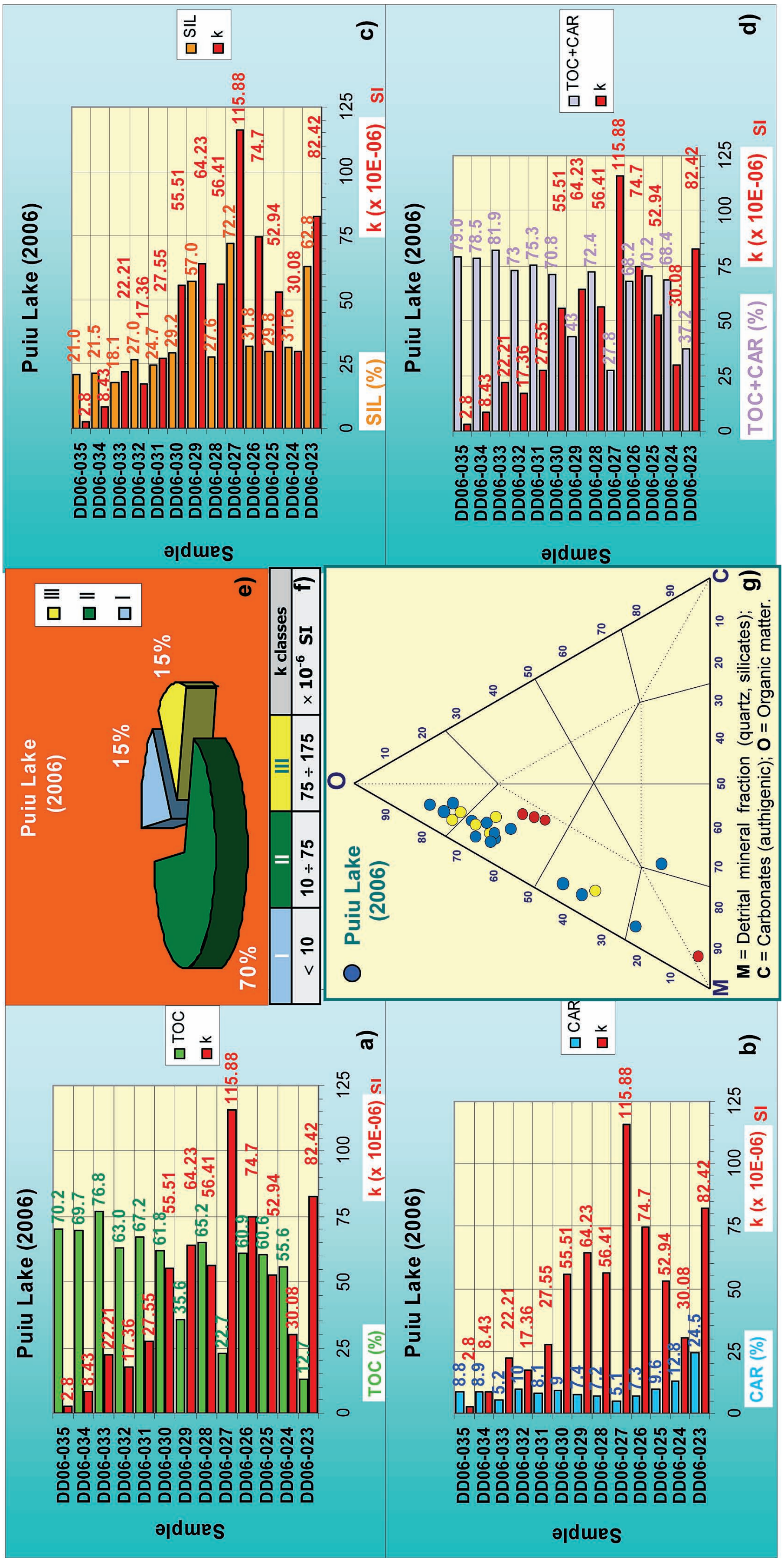


Fig. 7 Magneto-lithological model for recent sediments sampled from an intermediate aquatic environment (Puiu Lake) in the Marine Delta Plain (Lumina – Roşu Depression, Danube Delta; **3**, in Fig. 1). For further explanations, see Legend in Fig. 2 and the text.

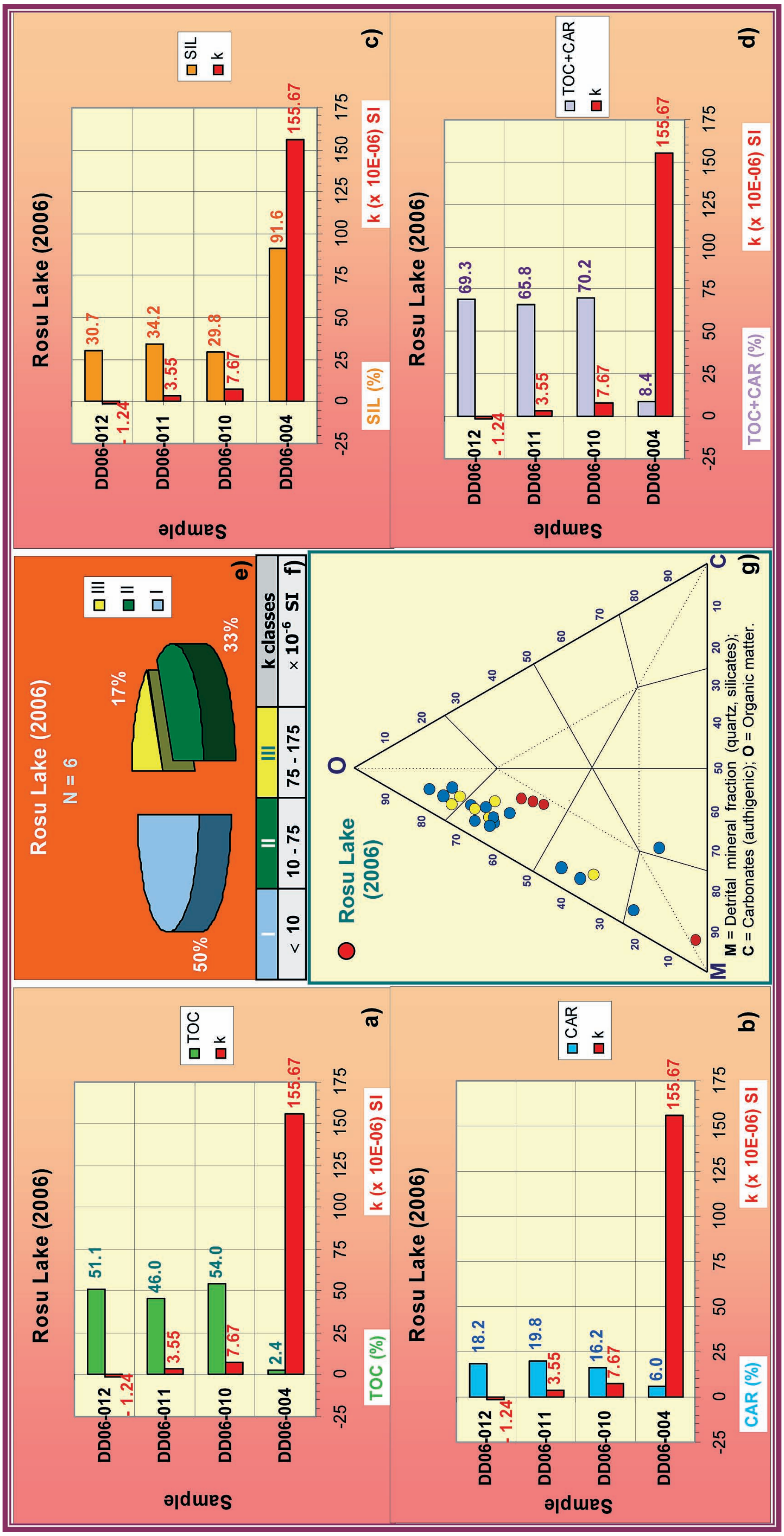


Fig. 8 Magneto-lithological model for recent sediments sampled from the Roşu Lake, in the Marine Delta Plain (Lumina – Roşu Depression, Danube Delta; **3**, in Fig. 1). For further explanations, see Legend in Fig. 2 and the text.

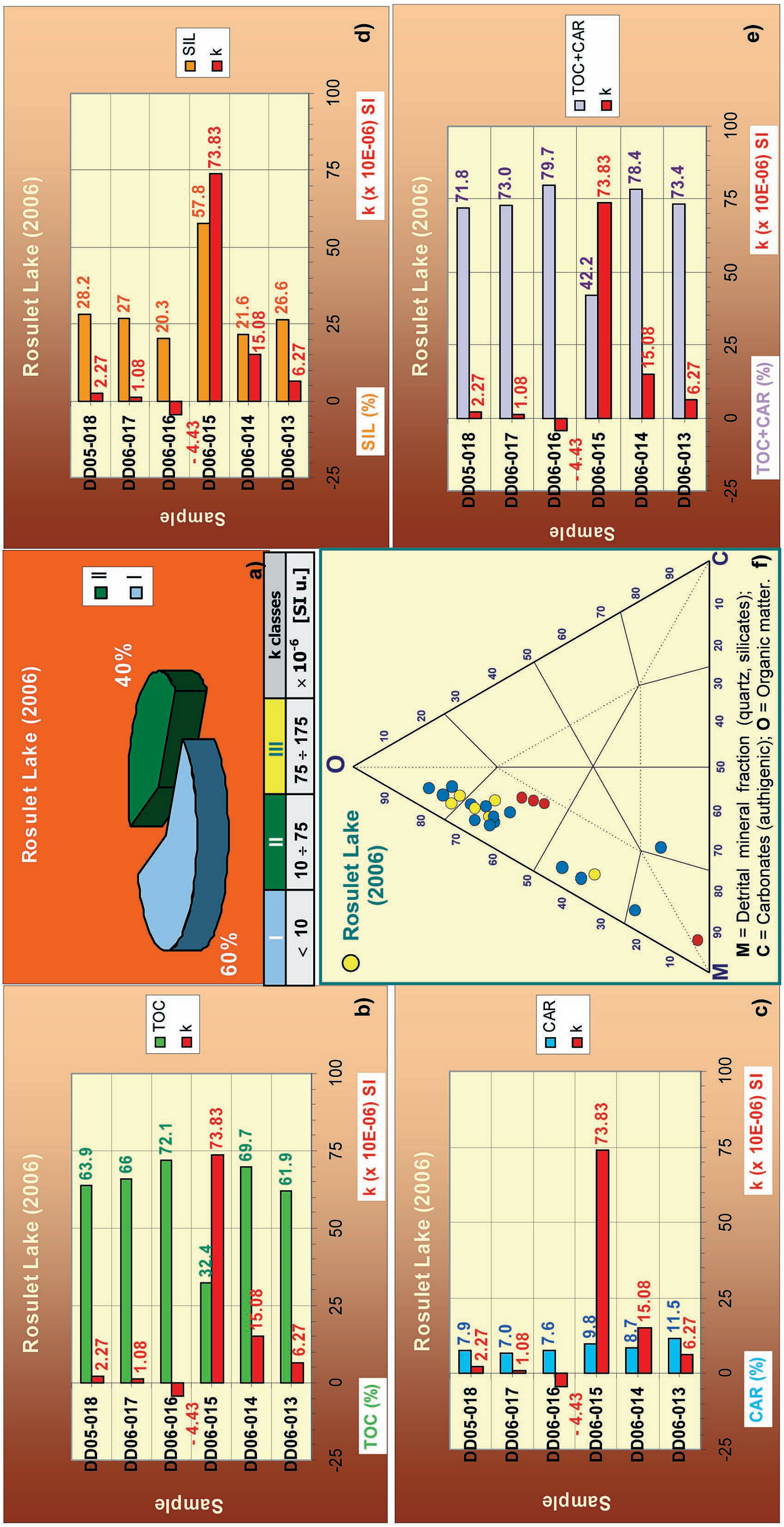


Fig. 9 Magneto-lithological model for recent sediments sampled from the Roşuleţ Lake, in the Marine Delta Plain (Lumina – Roşu Depression, Danube Delta; **3**, in Fig. 1). For further explanations, see Legend in Fig. 2 and the text.

the carbonates (**CAR**) range between 7.0 – 11.5% (Fig. 9c), with the average of 8.8%. The mineral fraction content (**SIL**; Fig. 9d) is, correspondingly, low (20.3 - 57.8%), with the average of 30.2%. The lowest values for **TOC** (32.4%) and **CAR** (9.8%), and, respectively, the highest **SIL** content (57.8%) are not representative for the *Rosuleţ Lake* sediments; they were determined on a sample (*DD 06-015*; Fig. 9b,c,d), which is probably contaminated from the nearby sand ridge. Anyway, on the respective sample (DD 06-015), the magnetic susceptibility correspondingly records the highest **k** value, *i.e*. 73.83×10E-06 SI (Fig. 9b,c,d), the other **MS** values ranging between (-4.43)×10E-06 – 15.08×10E-06 SI. The ternary diagram (Fig. 9f) confirms this magneto-lithological characterisation of the investigated sediments of the *Rosuleţ Lake*, which are mainly organic muds.

A synoptic magneto-lithological model for these three main lakes from the *Lumina – Roşu Depression*, which were under attention in the cruise 2006, is illustrated in Fig. 10. The magnetic susceptibility and the lithological models (Fig.10b,c) point out the predominance of the lower **k** classes **I**+**II** (44% + 39%), and, respectively, of the **TOC**+**CAR** contents (54.0% + 10.3%); the remaining procents are assigned to the **k** class **III** (17%), and, respectively, to the **SIL** content (35.7%). Strong negative correlations (according to the scale from Fig. 2d) were shown by **k** *vs* **TOC** and **k** *vs* (**TOC+CAR**) (Fig. 10d,g,h) and, respectively, weak for **k** *vs* **CAR** (Fig. 10e,h), whereas a strong positive correlation (**r** = 0.85) was determined for **k** *vs* **SIL** (Fig. 10f,h).

4.4. Matiţa – Poludionca – Merhei zone (Matiţa – Merhei Depression)

Although the water and sediment supplies are originated in the "*Mila 36" Canal*, the very long route of the main access way (from the *Tulcea Branch*) to the lakes from the *Matiţa – Merhei Depression* has as result that the most of them are protected against the direct Danubian influxes. In addition, in some channels, *e.g*. *Rădăcinoasele* and *Bahrova*, is possible that the water circulation sense to be changed at "low waters", they becoming discharging channels; their new state can influence the sedimentation processes in the associated sectors. The sediments are represented by mineral-organic muds and mineral-carbonatic muds. The sedimentation rates are very low and the system pollution, *e.g*. with heavy metals, is reduced.

Some integrated magnetic susceptibility and lithological results obtained for the most extended lake of the depression (*Merhei L.*) and for one of the smallest ones (*Poludionca L.*), located to the east of *Matiţa L.* (Fig. 11a), are further presented. The *Merhei Lake*, which is situated at the end of the principal supply route (*Mila 36 – Şontea – Eracle – Lopatna*), is characterised by a slow water circulation. The sample *DD 06-127* (Fig. 11a), a coarse mud, rich in vegetal/organic material, was sampled from the *Suez Channel* mouth, in the south-western zone of the lake, where the *Merhei L.* is receiving the water from the *Matiţa L.* This explains the measured **MS** value (34.35×10E-06I), assigned to class **II** (see Fig. 11b,c,d,e,f); the other 4 samples collected in 2006 from the *Merhei L.* (not from the mouth channel) have provided very low magnetic susceptibilities (calibrated to class **I**) (see Fig. 11b,f), three of them showing negative **k** values (Fig. 11c,d,e,f). The enviromagnetic results are coherent, the sedimentation in the *Merhei Lake* having a very important autochthonous organic component, associated with a carbonatic component. The correlation of the magnetic susceptibility values with the lithological parameters is high. While for the 4 samples with **k** values placed within the class **I** the average organic matter and carbonate content (**TOC**+**CAR**) is 78.6%, and the mineral/siliciclastic fraction content (**SIL**) is 21.4%, the *DD 06-127* sample (taken from the channel mouth; Fig. 11a) is characterised by relatively balanced contents: 50.7% - **SIL** and 49.3% - **TOC+CAR**. Related to the ternary diagram (Fig. 11g), the samples collected from the *Merhei Lake* in 2006 are distributed between the fields of the *organic* and *organic-mineral* sediments, excepting the above remarked sample (*DD 06*-127), which is projected in the *mineral-organic* field (Fig. 11g). The **MS** results obtained on a large collection of sediment samples taken during the first cruise (1978) – which can be accepted as a reference level – have revealed the very large proportion of the **k** values assigned to class **I** (96%), the remaining 4% being placed within the class **II** (Fig. 11k). The **MS** characterisation of the sediments sampled in the 1992 - 1997 period confirms these results, namely, the clear predominance of the class **I** related to class **II**: 70% *versus* 30% (Rădan & Rădan, 2004-2005). Of course, a detailed comparative analysis must take into consideration the available number of **k** values, the locations of the sampling stations, the hydrological conditions *etc*.

As regards the *Poludionca L.* (Fig. 11a), the sediments provided negative magnetic susceptibilities only (Fig. 11c,d,e,.f), which, certainly, were calibrated to class **I** (Fig. 11h). Actually, the same result was obtained for the first collection sampled in the *Poludionca L.*, in 1978 (Fig.11i). The average content for **TOC** determined for the sediments sampled in 2006 was very high (81.3%), and for the *carbonate fraction* (**CAR**) was 5.0%; the remaining 13.7% belong to the mineral/siliciclastic component (**SIL**). These data prove the very good correlation between the enviromagnetic parameter **MS** (**k**) and the lithological components of the bottom sediments sampled in the *Poludionca Lake*. This satellite lake of the *Matiţa L.* shows the highest values obtained in this sector for the organic matter and, accordingly, reduced values for the carbonate and detrital mineral contents. The ternary diagram from Fig. 11g shows that the sediments from the *Poludionca Lake* are placed in the closest position to the *organic pole* (**O**).

As regards the third lake of the *Matiţa – Merhei Depression* taken into consideration in the present paper, *i.e*. the *Matiţa L.*, the results obtained on the sediment samples collected in two cruises in 2006 (May and September) are presented in Fig. 12. The *organic component* content (**TOC**) ranges between 40.6% – 79.9% (Fig. 12a), but the lowest value belongs to the sample *DD 06-082*, collected from the

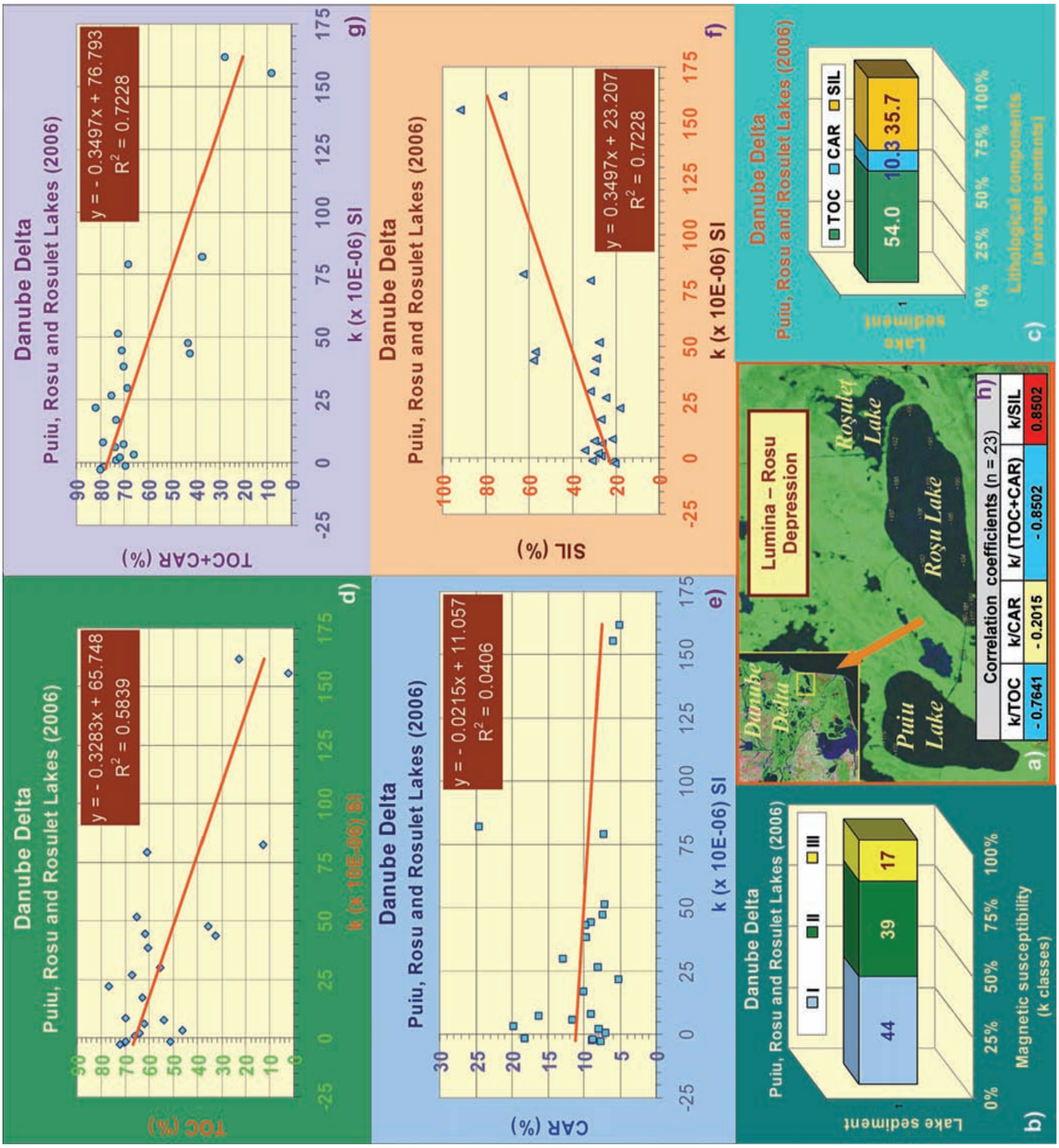


Fig. 10 Magneto-lithological model for bottom sediments sampled from three lakes in the Lumina – Roşu Depression (Marine Delta Plain; **3**, in Fig. 1), showing the correlation between the enviromagnetic parameter (**k**) and the lithological components (**TOC**, **CAR**, **SIL**). For further explanations, see Legend in Fig. 2 and the text.

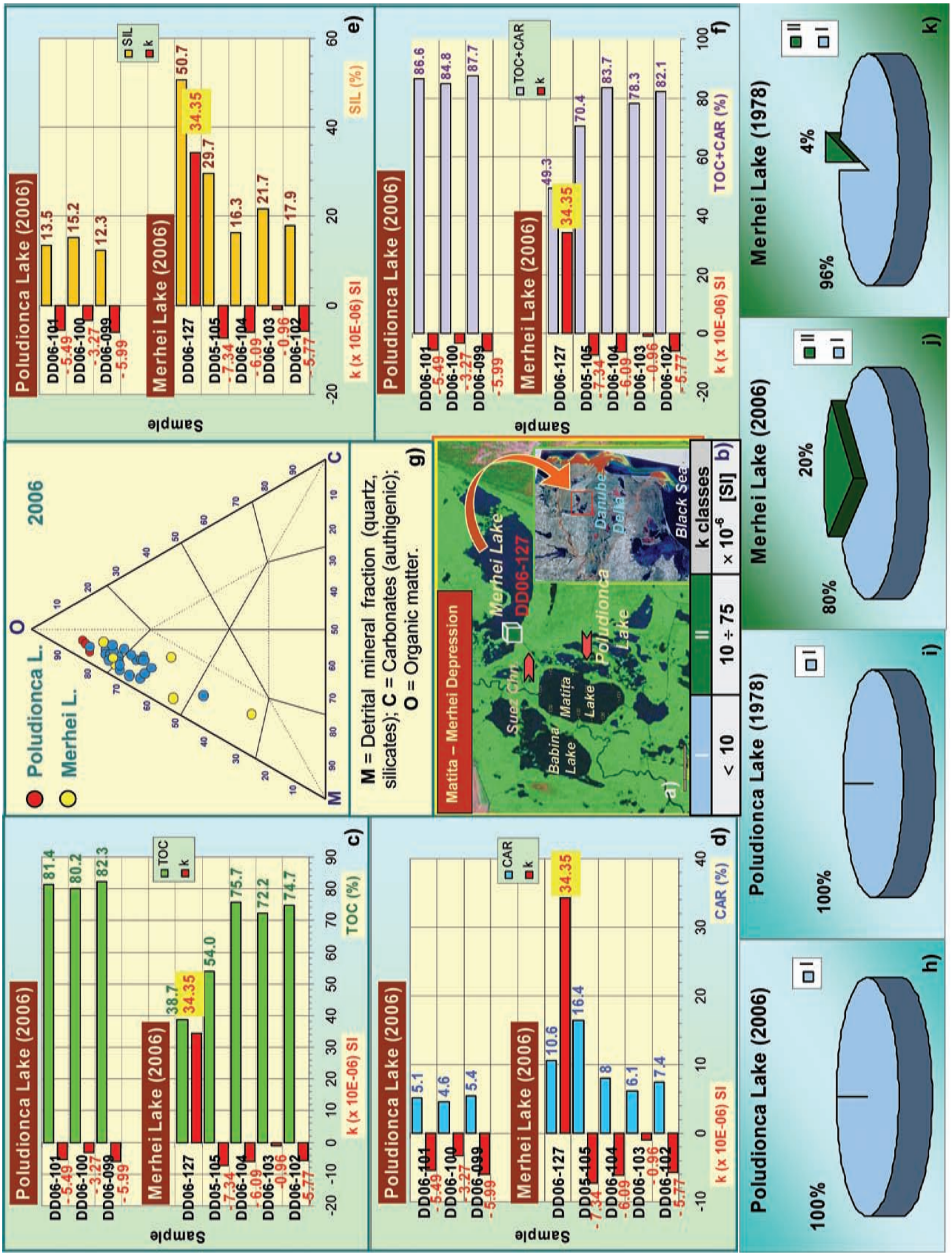


Fig. 11 Magneto-lithological model for recent sediments sampled from the Merhei and Poludionca Lakes, in the Fluvial Delta Plain (Matița – Merhei Depression, Danube Delta; **4**, in Fig. 1). For further explanations, see Legend in Fig. 2 and the text.

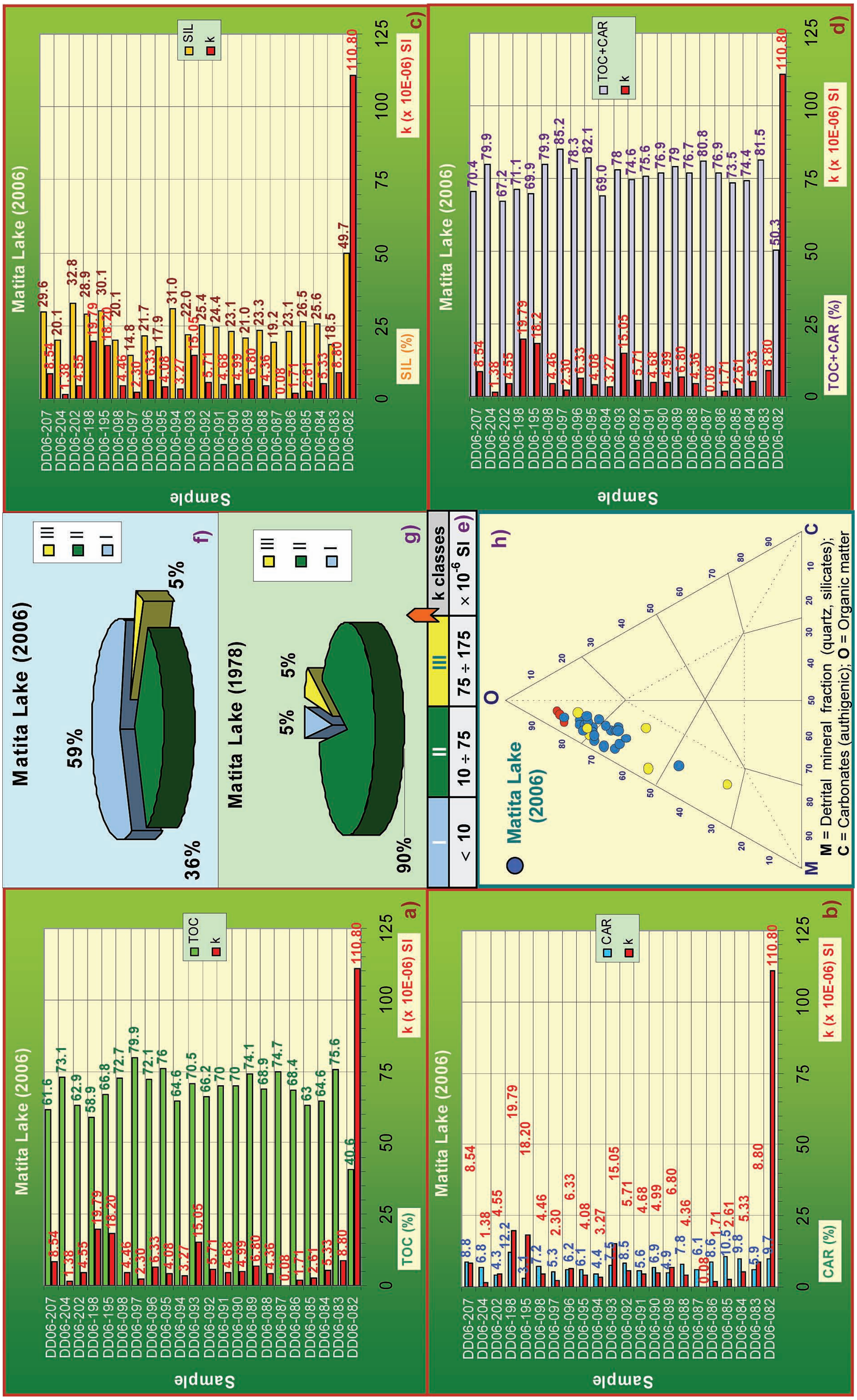


Fig. 12 Magneto-lithological model for recent sediments sampled from the Matița Lake, in the Fluvial Delta Plain (Matița – Merhei Depression, Danube Delta; **4**, in Fig. 1). For further explanations, see Legend in Fig. 2 and the text.

Lopatna Channel mouth. The *carbonates* (**CAR**) record not too high contents (3.1% – 12.2%; Fig. 12b), as well as the *detrital component* (**SIL**), which is defined in a range with low limits comparing with the sediments from other sectors, *i.e.* 14.8% – 49.7% (Fig. 12c). The highest value of the mineral component (**SIL**), *i.e*. 49.7%, also belongs to the sediment collected from the above mentioned channel mouth (sample *DD 06-082*), where the lowest value for **TOC** was determined. Correspondingly, this sample provided the highest **k** value (110.80×10E-06 SI; Fig. 12a,b,c,d) recorded in the *Matiţa Lake* sediments that were investigated during the two cruises, in May and September 2006. Actually, excepting this station located at the mouth of a channel, where the magnetic susceptibility measured on the sampled sediment is assigned to the intermediary **k** class **III** (Fig. 12e), the **MS** parameter determined for the two collections taken from the *Matiţa Lake* ranges between 0.08×10E-06 – 19.79×10E-06 SI (Fig. 12a,b,c,d), that is the **k** values are assigned to the lower classes **I** (59%) and **II** (36%) (Fig. 12f). Similar results, *i.e.* 95% of **k** values are calibrated to the lower classes **I** and **II**, and 5% to the intermediary class **III**, were obtained on the sediments sampled in the 1978 cruise (Fig. 12g; Rădan & Rădan, 2004-2005). The higher percentages (59%) recorded for the **k** class **I** on the sediments sampled in 2006 comparing with 1978, when the **k** class **II** provided a higher weight (90%), could be interpreted as an organic material increase within the recently studied sediments. The ternary diagram (Fig. 12h) shows the distribution of the sediments of the *Matiţa Lake* within a sector located between the fields of the *organic muds* and of the *organic-mineral muds*, excepting the sample *DD 06-082* (collected from the *Lopatna Channel* mouth), which is projected within the *mineral-organic field*.

Related to these three lakes of the *Matiţa – Merhei Depression*, a synoptic magneto-lithological model is presented in Fig.13, where the correlation between the enviromagnetic parameter **MS** and the lithological components (**TOC**, **CAR**, **SIL**) of the sediments is shown, as well. Thus, the magnetic susceptibility pattern (Fig. 13b) points out that 84% of **k** values are assigned to the lowest class **I**, 13% – to the lower **k** class **II**, and 3% only, to the intermediary class **III**. The parallel lithological pattern (Fig. 13c) shows that the *organic component* (**TOC**) is majoritary, *i.e.* 68.5%, the *carbonatic* one is defined by 7.3%, the remaining 24.2% belonging to the detrital component (**SIL**). The correlation between these two models (Fig. 13b,c) is strong, because of the high predominance of the lower **k** classes **I** and **II** (97%) that is supported by a high organic component content within the bottom sediments, to which the carbonatic fraction is added (**TOC** + **CAR** = 75.8%). Actually, the correlation diagrams presented in Fig. 13d,f reveal, graphically, this percentage characterisation; the calculated correlation coefficients (**r**) from Fig. 13h show that the relations **k** *vs* **TOC** and **k** *vs* **TOC+CAR** are evaluated as *strong negative correlations* (according to the scale from Fig. 2d). Also a *strong*, but *positive correlation* characterises the relation **k** *vs* **SIL** (Fig. 13h).

5. CONCLUSIONS

Various cases were approached by using the magnetic susceptibility tool as a technique of environmental magnetism. Bottom sediments from four main deltaic depressions were sampled in three cruises in 2006 and were investigated for this enviromagnetic parameter (**MS**; **k**) and for the lithological components (**TOC**, **CAR**, **SIL**).

Some of the investigated deltaic lakes are to a certain extent protected from the direct *Danube* influence (*e.g.*, *Isacova*, *Roşu*, *Roşuleţ*, *Matiţa*, *Poludionca* and *Merhei*), others are more or less directly influenced by the riverine supplies (*e.g.*, *Lungu* and *Uzlina*). The first category is characterised by relatively stagnant conditions and a reduced water circulation ("*confined environments*"), while the second one is represented by quite "*dynamic environments*", with active change of water and sediments. The third – *intermediate* – category is represented by *Tătaru* and *Puiu Lakes*.

The "*dynamic environments*", usually placed close to the influx points of the master canals or connected by relatively short canals to the main *Danube Delta Branches*, are reflected by intermediary, high and very high magnetic susceptibilities, which are assigned to the **k** classes **III**, **IV** and **V** of the **MS** scale. Regarding the "*confined environments*", situated far from the Danubian supplies and from the direct riverine inputs, the magnetic susceptibility fingerprint that is recovered from the bottom sediments is of low intensity and is assigned to the lower **k** classes **I** and **II**. As concerns the aquatic environments belonging to the "*intermediate*" category, the susceptibility regime is characterised by **k** values assigned to the classes **II** and **III**.

Concerning the interpretation of the environmental magnetism data, it has been paid attention to the spatial position of the sampling stations. This is an important aspect for the comparative analysis carried out by considering, additionally, the previous data existing in the *Danube Delta* magnetic susceptibility data base.

The magnetic susceptibility study of the bottom sediments that were sampled in 2006 clearly proved the above specified features. The **MS** variations are in agreement with the primary lithological description that was made aboard research vessel, immediately after collecting the sediments with the grab sampler. Moreover, the **k** values correlate well with the laboratory data concerning the lithological composition of the samples [organic (**TOC**), carbonatic (**CAR**) and, respectively, mineral/siliciclastic (**SIL**) components].

The synoptic magneto-lithological model presented in Fig.14 is based on the data obtained for the all ten *Danube Delta* lakes (specified at the beginning of this last chapter), which are located in four deltaic depressions (Fig. 14a) and belong to three categories of aquatic/sedimentary environments. The parallel patterns illustrated in Fig. 14b,c show a good correlation between the magnetic susceptibility characterisation of the bottom sediments and the lithological

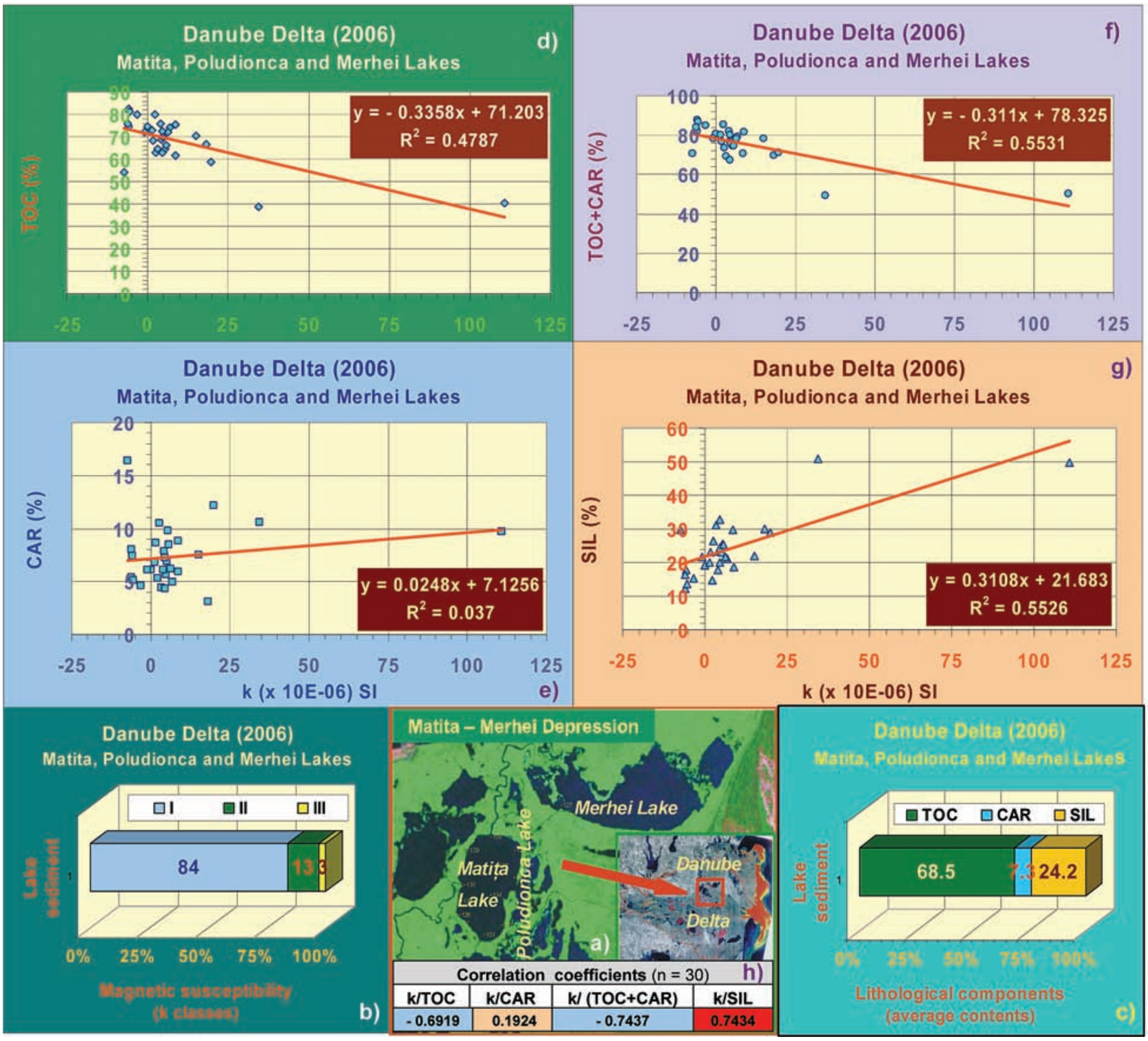


Fig. 13 Magneto-lithological model for bottom sediments sampled in three lakes from the Matița – Merhei Depression (Danube Delta; **4**, in Fig. 1), showing the correlation between the enviromagnetic parameter (**k**) and the lithological components (**TOC**, **CAR**, **SIL**). For further explanations, see Legend in Fig. 2 and the text.

composition. Thus, the measured **k** values are assigned, in a majority, to the lower **k** classes (**I**+**II**) (*i.e.*, 30% + 36% = 66%; Fig. 14b), and the **TOC**+**CAR** contents also represent the majoritary percentage weight (*i.e.*, 53.20% + 8.15% = 61.35%; Fig. 14c). Concerning **MS**, the remaining 34% belong to the intermediary **k** class **III** (24%) and to higher **k** classes **IV** (8%) and **V** (2%); as regards the lithological components, the remaining 38.65% belong to the detrital fraction content (**SIL**). The correlation graphs (Fig. 14d,e,f,g), and, particularly, the calculated correlation coefficients (**r**) for **k** *vs* **TOC** (**r** = – 0.7672), **k** *vs* **TOC**+**CAR** (**r** = – 0.8302), and **k** *vs* **SIL** (**r** = 0.8302) (Fig. 14h) show *strong negative correlations* for the first two pairs of parameters, and respectively, a *strong positive correlation* for the last one (according to the scale from Fig. 2d).

In addition, the magnetic susceptibility regimes determined for the sedimentary environments that were investigated in four representative sectors are in agreement with the data based on the lithological classification ternary diagrams performed for the recent sediments from these deltaic environments. It can be releaved a very good connection between the variation ranges of the magnetic susceptibilities values (**k**) and the "lithological fields" in which the sediment samples are projected, that define mineral-organic, organic-mineral, organic, mineral or mineral-carbonatic sediments. The integration of these results allow a quantified reasoning of the differentiation of the Danube Delta underwater sedimentary environments, and also of the sedimentation processes. These data, clearly emphasize the allochthonous

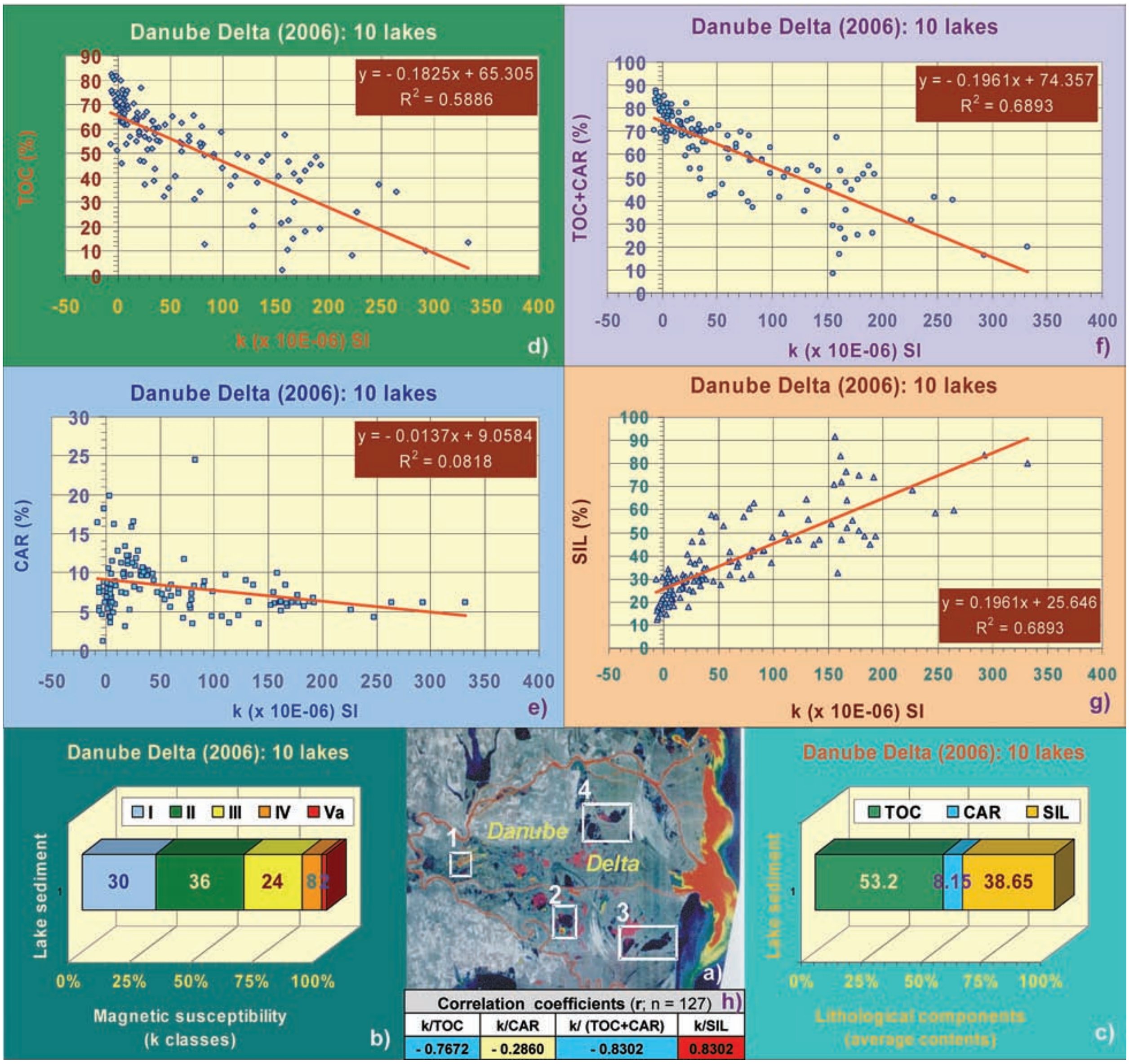


Fig. 14 Synoptic magneto-lithological model for bottom sediments sampled from ten lakes in the Danube Delta (**1**, **2**, **3** and **4**, in Fig. 1), showing the correlation between the enviromagnetic parameter (**k**) and the lithological components (**TOC**, **CAR**, **SIL**). For further explanations, see Legend in Fig. 2 and the text.

sedimentation, predominantly detrital in the lacustrine ecosystems that are directly influenced by the *Danube River*, against the dominantly autochthonous sedimentation from the distal sectors, in which the organic component is preponderant.

The organic substance average contents reach the highest values in the *Poludionca L.* (81.3%), *Merhei L.* (69.2%), *Matiţa L.* (68.9%), *Roşuleţ L.* (61.0%), *Isacova L.* (57.3%), *Puiu L.* (55.5%), *Tătaru L.* (51.1%) and *Roşu L.* (50.4%). The sediments of the *Lungu Lake* (41.5%) and *Uzlina Lake* (31.1%) are characterised by organic substance contents below 50%. The carbonates reach maximum content values in the *Roşu Lake* (18.1%), followed by *Isacova* (9.9%), *Puiu* and *Merhei* (9.5% each), *Roşuleţ* (8.1%), *Tătaru* (7.6%), *Matiţa* (7.1%), *Uzlina* (6.8%), *Poludionca* (5%) and *Lungu Lake* (4.4%). The remaining percentages belong to he mineral siliciclastic component, the highest content value being recorded for the *Uzlina L.* (62.2%) and *Lungu L.* (54.1%) sediments, and the lowest values for the *Merhei* (21.4%) and *Poludionca* (13.7%) lakes. By grouping the lakes on depressions and taking into consideration the average contents calculated for the deltaic sectors under attention in this paper, we find that the participation of the organic substance increases in the direction *Lungu – Tătaru* (46.68%) and *Uzlina – Isacova* (45.3%) ➚ *Puiu – Roşu – Roşuleţ* (60.2%) ➚ *Matiţa – Merhei – Poludionca* (71.8%). The same order of these aquatic sectors is obtained for the decrease of the participation of the mineral detrital siliciclastic component: *Lungu – Tătaru* (47.19%) and *Uzlina – Isacova* (46.2%) ➘ *Puiu – Roşu – Roşuleţ* (29.7%) ➘ *Matiţa – Poludionca – Merhei* (21.0%). As regards the carbonatic component, the maximum content value (10.1%) belongs to the *Puiu – Roşu – Roşuleţ* sector, the others being, successively, 8.5% for *Uzlina – Isacova*, 7.2% for *Matiţa – Merhei* and 6.12% for *Lungu – Tătaru* sectors. Moreover, by calculating the average magnetic susceptibilities (**k**) values for the bottom sediments sampled from the same four deltaic sectors, we find a $\mathbf{k}_{average}$ decrease, *i.e*. *Uzlina – Isacova* (102.30×10E-06 SI) and *Lungu – Tătaru* (95.41×10E-06 SI) ➘ *Puiu – Roşu – Roşuleţ* (27.92×10E-06 SI) ➘ *Matiţa – Merhei – Poludionca* (7.63×10E-06 SI), in the direction in which the organic substance contents increase, and respectively, the mineral detrital siliciclastic component contents decrease.

This distribution model points out the changes underwent by the composition of the lake sediments from the *Danube Delta*, as the distance related to the *Danubian* source increases: the greater distance to the source is, the richer in organic substance and poorer in detrital mineral material the sediments are.

The synoptic pattern (Plate 1) demonstrates that the lake sediments fingerprinting in the Danube Delta is feasible and reliable by using magnetic signatures. Based on various investigated cases and geomaterials (the sediment cores included), the model indicates the capability of the magnetic susceptibility for sediment tracing, within the framework of integrated sedimentogenetic, lithological and environmental studies being carried out in deltaic lakes.

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