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ANALYSIS OF VEGETATION-ENVIRONMENT RELATIONSHIPS IN THE BAY OF SOZOPOL, BULGARIAN BLACK SEA COAST BY THE CCA METHOD

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ABSTRACT. A 2.20 m long sediment core, belonging to profile of square "D" in the Bay of Sozopol, Bulgarian Black Sea coast, was analysed for diatoms, chrysophycean stomatocystae, dinocysts and pollen. The main objective of this study is to present a mathematical model, based on Canonical Correspondence Analysis (CCA), of the palaeoenvironmental changes in salinity and tidal exposure and to test our hypothesis about the successive phases in the development of the bay during the Eneolithic and Early Bronze age.

KEY WORDS: diatoms, pollen, canonical correspondence analysis, Black Sea coastal deposits, the Late Holocene, palaeoecology

INTRODUCTION

Mathematical models can be used as a perfect combination of ecological, cultural, geological and climatic variables, recalculated to a certain archaeological period in a certain local area. The main objective of this study is to present a mathematical model of the palaeoenvironmental changes in salinity and tidal exposure, based on different microfossil groups (diatoms, chrysophycean stomatocystae, pollen and dinocysts). This model is impossible without the use of an experimental database, containing all the information, archaeological, geological and palaeoecological, collected during the underwater excavation of settlements in the harbour of Sozopol, Bulgarian Black Sea coast, carried out between 1990 and 1993. The history of these settlements gives more information about the genesis of the Thracian tribal community from the end of the Eneolithic to the end of the Early Bronze Age (Draganov 1995).

STUDY AREA

The study area included two zones of investigation: Sozopol 1 and Sozopol 2. Eight more or less connected squares, 5 by 5 meters in size, were excaveted in these zones. Three of the squares contained only Early Bronze age material (A, C, E); two contained Early Bronze age material and, under a hiatus, Eneolithic material (B and F), and three contained only Eneolithic material (D, G, H). A complete synthesis of the results of diatom and pollen analysis of the profile of square "D" have been previously published (Ognjanova-Rumenova 1995, Ognjanova-Rumenova & Popova 1996, Ognjanova-Rumenova & Zaprjanova in press, Filipova-Marinova in press).

MATERIAL AND METHODS

The profile of square "D" was studied to a depth of 4.30–4.60 m below the sea level in the Eneolithic part of the settlement. 22 samples were analysed, the material was collected at 10 cm intervals. Sampling, slide preparation, identification and counting are described in more detail by Ognjanova-Rumenova (1995) and Filipova-Marinova (in press). A spectra of physico-chemical tolerances, based on the studies of recent diatoms, were used to interpret the palaeoecological data (Proshkina-Lavrenko 1963, Schrader 1978, Vos & Wolf 1993). The ecological spectra covering the habitat, salinity, pH, nutrient content, temperature, geographic distribution and saprobity were determined. A percentage ratio diatom frustules/chrysophycean stomatocystae was used as a trophic status index (Smol 1985). Canonical correspondence analysis (CCA) was applied to reveal the principal patterns of diatom species distribution and their relationships with "external" explanatory variables, connected with environment (Ter Braak 1986).

RESULTS AND DISCUSSION

A total of 119 diatom taxa have been identified (Appendix 1). The diatom flora consists of recent species.

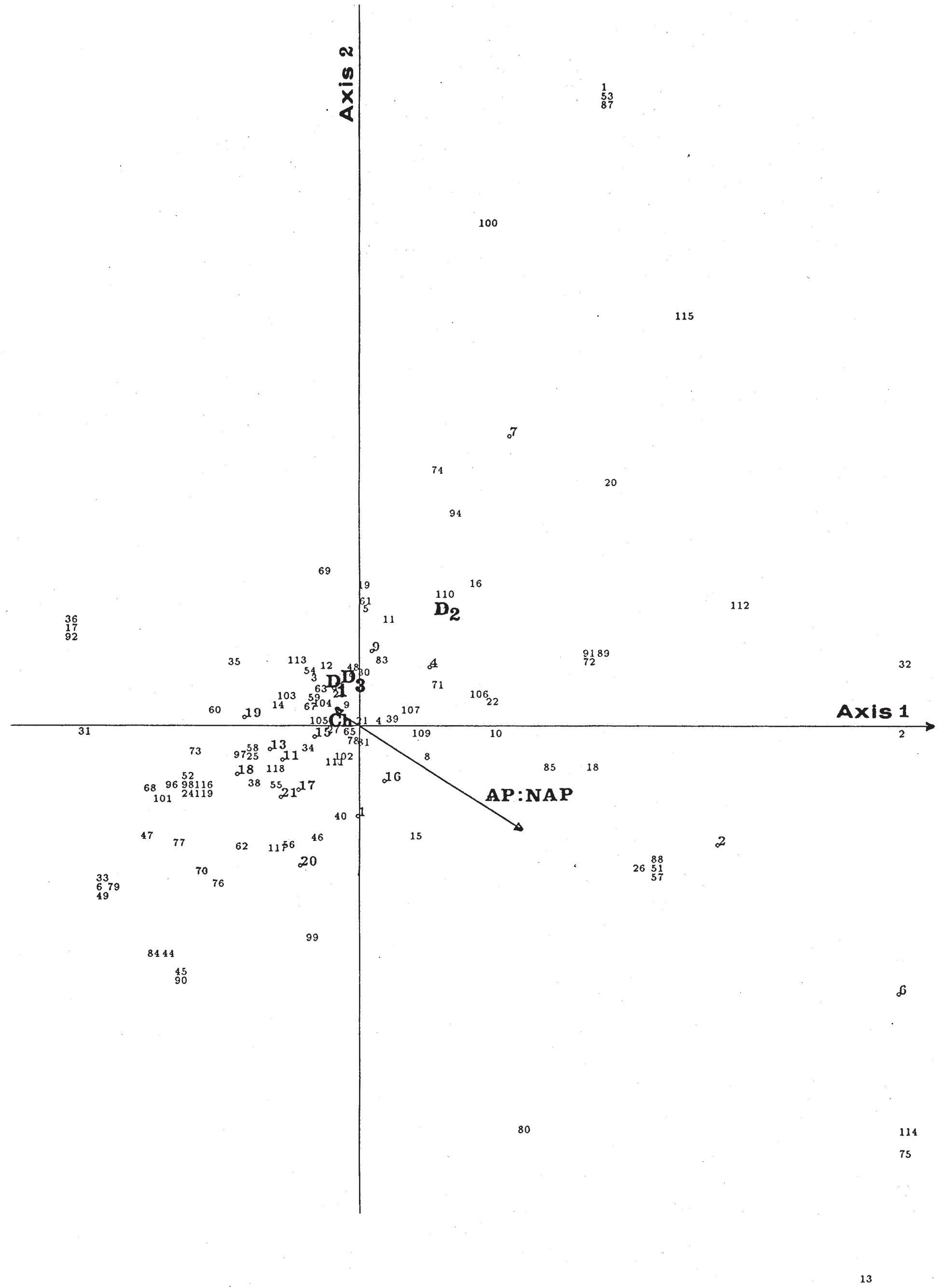

Fig. 1. CCA ordination diagram with samples (numbered o), diatom taxa (numbers) and external variables (arrows). The diatom taxa codes and the samples are explained in Appendix I, resp. Appendix II

Only 6.8% of the determined taxa are of unknown ecology. On the basis of species composition and the relationships between the ecological groups two local diatom assemblage zones have been distinguished in the diagram (Ognjanova-Rumenova 1995): Diatom zone A (2.20–0.70 m) – the diatom flora indicates fresh-brackish sedimentary conditions, the dominant taxa are epiphitic; Diatom zone B (0.70–0.10 m) – the diatom flora marks marine-brackish sedimentary environment.

Additional data about chrysophycean stomatocystae, dinocysts and pollen, found in the material from profile of square "D", allowed us to perform cannonical correspondence analysis (CCA) with quantitative and explanatory variables in order to find direct relationships among the investigated fossil groups (Ter Braak 1986). The successions of all these plant groups with known ecology may be used as "external" explanatory variables in CCA. The primary result of CCA is an ordination diagram, i.e. a graph with a coordinate system formed by ordination axis (i.e. the synthetic gradient extracted by CCA). This biplot diagram is informative and reveals corellations between diatom succession and successions

Table 1. Canonical coefficients and intraset correlations of the external (environmental) variables with the four axes of canonical correspondence analysis

External variable	Axis variable	Canonical coefficients				Correlation coefficients			
		1	2	3	4	1	2	3	4
Chrysophycean stomatocystae		0,397	-0,24	0,34	-0,646	-0,141	0,077	0,747	-0,547
Dino 1		0,025	-0,053	0,176	0,146	-0,131	0,177	0,253	-0,049
Dino 2		0,469	0,53	-0,07	-0,116	0,425	0,803	-0,206	-0,184
Dino 3		-0,235	0,37	0,313	0,533	-0,038	0,217	0,792	0,346
AP:NAP ratio		0,849	-0,361	0,161	-0,003	0,698	-0,425	-0,024	0,455

of other fossil groups (Fig. 1). The diagram consists of the following elements: points of species, samples and arrows for quantitative "external" environmental variables. All determined diatom species are displayed on the CCA-ordination diagram, independently of their too crowded disposition. CCA has been carried out on 15 samples (Appendix 2), which were included to pollen analysis. Consequently, each species point in diagram is at the centroid (weighted average) of the sample points in which it occurs. The centroid principle then implies that the species occurring in a particular sample are scattered around the point of sample. The importance of the "external" variables is proportional to the length of the environmental vector in the biplot. The interpretation of the axes is unambiguous (Table 1): the first axis is defined by the ratio: arboreal/non-arboreal pollen type (AP:NAP) and it reflects the human influence; the second – by the acritarch – *Cymatosphaera globulosa* (Dino 2), a planktonic, eurohaline species, which distribution depends on the rise of the sea level. The diatom taxa are further differentiated on the third axis, determined by Dino 3 – *Spiniferites ramosus*, a stenohaline, cool-water species and the ratio diatom frustules/chrysophycean stomatocystae expressed changes in trophy (the eutrophication) during the bay development.

The main results of the CCA analysis is that there is a good correspondence between the diatom taxa and ratio AP:NAP from the pollen analysis. This arrow is the longest on the biplot and some samples with a high positive score on that axis are projected on it. This proportion is connected with the human influence – land use and eutrophication in the bay. All these samples determined the sediment level (0.10–0.60 m), which corresponds to the local pollen assemblage zone PAZ-S_2 (Filipova-Marinova in press). It is characterized by decrease of tree and shrub taxa in pollen diagram, due to the quantity diminution of *Quercus* (up to 18%). A great variety of anthropophytic elements is remarkable: *Plantago lanceolata*, *Centaurea cyanus*, *Polygonum aviculare*, *Cirsium*, etc. Among pollen of cereals there are: Cerealia-type and *Triticum.*

Although the chrysophycean arrow is short and the variance accounted for by the ordination diagram is small, statistical test shows a significant correlation between diatoms and chrysophycean species. This finding proves once more that the ratio diatom frustules/chrysophycean stomatocystae is an useful characteristic and can be used to study Quaternary brackish-marine history of the Black sea. The *Lingulodinium machaerophorum* centroid (Dino 1) is located positively along the Chrysophycean arrow with marine, mesohalobous and halophilous diatoms grouped around it: *Mastogloia baldjikiana* Grun., *M. pusilla* Grun., *Hyalodiscus scoticus* var. *griseolus* Pr. Lavr., *Diploneis smithii* (Breb.) Cl., etc. The centroid of *Spiniferites ramosus* (Dino 3) is situated very near to Dino 1. The diatom taxa, which are scattered around it are also marine and mesohalobous, i.e. *Lyrella abrupta* (Greg.) Mann and *Gyrosigma balticum* (Ehr.) Rab. Sample 9 (0.90 m) is projected next to these centroides, which are surrounded with diatoms, characteristic for more saline environment. Probably, this level corresponds to the stage of marine influx. The sea level rose and the littoral cleyey sediments have been replaced by more terrigenous sediments. The decrease of *Chaetoceros* spp. resting spores is explained by this influx of marine-brackish water and the decrease of nutrients. This had probably triggered the development of the second diatom assemblage (Ognjanova-Rumenova 1995). These data mark the time of the Black sea Post-Eneolithic transgression (Draganov 1995).

Most of the samples are scattered very close to each other (11–21 samples; 1.10–2.10 m). This is again evidence of monotonous conditions in the palaeoenvironment at the beginning of the sediment formation.

The CCA demonstrates statistically that the palaeoenvironmental features characterizing the profile "D" are common to all the diagrams under study (diatoms, chrysophycean stomatocystae, pollen and dinocysts).

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APPENDIX 1

List of the diatom species codes in Fig. 1 and their ecological parameters.

I. "Habitat" spectrum: **pl** – planktonic species; **ep** – periphytic-epiphytic species; **be** – periphytic-deep water species.

II. Halobion spectrum: **m** – marine species; **mhb** – mesohalobous species; **hl** – oligohalobous-halophilous species; **i** – oligohalobous-indifferent species; **hb** – oligohalobous -halophobous species.

III. Geographical distribution: **c** – cosmopolitan species; **n-a** – north-alpine species; **b** – boreal species; **t** – tropical species.

IV. Saprobion spectrum: kseno – xenosaprobic species; **L-B meso** – mesosaprobic species**; oligo** – oligosaprobic species.

1. ***Thalassiosira*** *baltica* (Grun.) Ostenf. – I pl, II mshb
2. ***Cyclotella*** *caspia* Grun. – I pl, II mshb, III c
3. ***Paralia*** *sulcata* (Ehr.) Cleve – I pl, II m, III c
4. ***Melosira*** *moniliformis* (O.Mull.) Ag. – I ep, II mshb, III c
5. ***Aulacoseira*** *italica* (Ehr.) Sim. – I pl, II i, III c, IV oligo – B
6. *A. granulata* (Ehr.) Sim. – I pl, II i, III c
7. *A. islandica* (O.Mull.) Sim. – I pl, II i, III n-a
8. ***Hyalodiscus*** *scoticus* (Kutz.) Grun. – I pl, II mshb, III c
9. *H. scoticus* var. *griseolus* Pr.-Lavr. – I pl, II mshb
10. ***Coscinodiscus*** *radiatus* Ehr. – I pl, II m, III c
11. ***Actinocyclus*** *octonarius* Ehr. – I pl, II mshb, III c
12. *A. tenellus* (Breb.) Andr. – I pl, II mshb, III c
13. ***Pleurosira*** *laevis* (Ehr.) Comp. – I ep, II mshb, III c
14. ***Cerataulus*** *turgidus* (Ehr.) Ehr.– I ep, II m, III c
15. ***Chaetoceros*** sp.
16. ***Raphoneis*** sp.
17. ***Fragilaria*** *construens* f. *subsalina* (Hust.) Hust. – I ep, II hl, III c
18. *F. fasciculata* (Ag.) Lange-Bert. – II ep, II hl, III c
19. *F. leptostauron* var. *martyi* (Herib.) Lange-Bert. – I ep, II i, III b
20. *F. tabulata* var. *grandis* Mer. – I ep, II m, III t
21. ***Ardissonia*** *crystallina* (Ag.) Grun. – I ep, II mshb, III c
22. ***Toxarium*** *undulatum* (Bail.) Round – I ep, II mshb, III t
23. ***Asterionella*** *formosa* Hassall – I pl, II i, III c, IV oligo-B
24. ***Dimerogramma*** *marinum* (Greg.) Ralfs – I ep
25. *D. minor* (Greg.) Ralfs – I ep, II m
26. *D. minor* var. *nana* (Greg.) V.H. – I ep, II m
27. ***Grammatophora*** *marina* (Lyngb.) Kutz. – I ep, II m
28. *G. oceanica* Ehr. var. *macilenta* (W.Sm.) Grun. – I ep, II m
29. ***Licmophora*** sp.
30. ***Lyrella*** *abrupta* (Greg.) Mann – I ep, II m, III c
31. ***Navicula*** *arenariaeformis* Pant. – I be, II hl, III b
32. *N. capitata* var. *lueneburgensis* (Grun.) Patr. et Reim. – I be, II hl, III b, IV L-meso
33. *N. cohnii* (Hilse) Lange-Bert. – I be, II i, III c
34. *N. digitoradiata* (Greg.) Ralfs – I be, II mshb, III c
35. *N. humerosa* Breb. – I ep, II m, III c
36. *N. hyalina* Donk. – I ep, II m
37. *N. menisculus* Schum. – I be, II hl, III c
38. *N. palpebralis* Breb. – I ep, II m
39. *N. pennata* var. *pontica* Mereschk. – I ep, II mshb
40. *N. pi* Cleve – I be, II mshb
41. *N. protracta* var. *elliptica* Gallik – I be, II mshb, III b
42. *N. rhynchocephala* Kutz. – I be, II i, III c, IV L-B
43. *N. salinarum* Grun. – II mshb, III c, IV B-L
44. *Navicula* sp.
45. ***Sellaphora*** *pupula* (Kutz.) Mann – I be, II i, III c
46. ***Trachyneis*** *aspera* (Ehr.) Cleve – I ep, II m
47. ***Stauroneis*** *aspera* (Ehr.) Cleve – I ep, II mshb
48. *Gyrosigma baltícum* (Ehr.) Rab. – I ep, II mshb, III c
49. ***Pinnularia*** *braunii* var. *amphicephala* (A.Mayer) Hust. – I be, II hb, III n-a

50. *P. viridis* var. *leptogongyla* (Grun.) Cl. – I be, II i, III b
51. ***Caloneis*** *amphisbaena* f. *subsalina* (Donk.) Werff. et Huls – I ep, II hl
52. *C. bacillum* (Grun.) Cleve – I be, II i, III b
53. *C. liber* (W.Sm.) Cleve – I be, II m
54. ***Diploneis*** *bombus* Ehr. – I ep, II m, III c
55. *D. didyma* (Ehr.) Ehr. – I ep, II mshb, III c
56. *D. interrupta* var. *heeri* (Pant.) – Hust. II mshb
57. *D. notabilis* var. *tenera* Pr.-Lavr. – I ep
58. *D. papula* (Schmidt) Cleve – I ep, II m
59. *D. smithii* (Breb.) Cleve – I be, II mshb, III b
60. *D. smithii* var. *pumila* (Grun.) Hust. – I be, II mshb, III b
61. *D. subadvena* Hust. – II m, III t
62. ***Mastogloia*** *angulata* Lewis – I ep, II m, III t
63. *M. baldjikiana* Grun. – I ep, II m
64. *M. braunii* Grun. – I ep, II mshb, III c
65. *M. erythraea* Grun. – I be, II m
66. *M. pumila* (Cl. et Moller) Cl. – I ep, II m, III c
67. *M. pusilla* Grun. – I ep, II mshb, III c
68. *M. smithii* Thwaites – I ep, II mshb, III c
69. ***Scoliopleura*** *tumida* (Breb. ex Kutz.) Rabenh. – II mshb
70. ***Cocconeis*** *disculus* (Schum.) Cleve – I ep, II i, III n-a
71. *C. distans* Greg. – I ep, II hl, III c, IV oligo-B
72. *C. neodiminuta* Krammer – I ep, II i, III b, IV kseno
73. *C. pediculus* Ehr. – I ep, II hl, III c, IV B
74. *C. placentula* Ehr. – I ep, II i, III c, IV L
75. *C. placentula* var. *euglypta* (Ehr.) Grun. – I ep, II i, III b, IV oligo
76. *C. placentula* var. *lineata* (Ehr.) V.H. – I ep, II i, III b, IV oligo
77. *C. quarnerensis* (Grun.) Schmidt – I ep, II m, III c
78. *C. scutellum* Ehr. – I ep, II m, III c
79. *C. scutellum* var. *minutissima* Grun. – I ep, II mshb
80. ***Achnanthes*** *brevipes* Ag. – I ep, II mshb, III c
81. *A. brevipes* var. *intermedia* (Kutz.) Cleve – I ep, II mshb
82. *A. delicatula* ssp. *hauckiana* (Grun.) Lange-Bert. – I ep, II mshb, III b
83. *A. longipes* Ag. – I ep, II m, III c, IV oligo-B
84. *A. longipes* var. *lata* Ag.
85. ***Rhoicosphenia*** *abbreviata* (C.Ag.) Lange-Bert. – I ep, II hl, II c, IV B-L
86. ***Cymbella*** *gracilis* (Ehr.) Kutz. – I ep, II hb, III n-a, IV kseno
87. ***Amphora*** *angusta* Greg. – I ep, II mshb
88. *A. crassa* Greg. – II m
89. *A.* aff. *catarinaria* Cholnoky
90. *A. exigua* Greg. – I ep, II mshb
91. *A. holsatica* Hust. – I ep, II mshb, III c
92. *A. libyca* Ehr. – I ep, II i, III c
93. *A. obtusa* Greg. – II m, III t
94. *A. ovalis* (Kutz.) Kutz. – I ep, II i, III c, IV oligo-B
95. *A. pediculus* (Kutz.) Grun. – I ep, II i, III c, IV oligo-B
96. *A. proteus* f. *ambigua* Pr.-Lavr. – I ep, II mshb
97. *A. proteus* var. *oculata* Perag. et Perag. – I ep, II mt
98. *A. spectabilis* Greg. – II m
99. *Amphora* sp. 1
100. *Amphora* sp. 2
101. ***Epithemia*** *sorex* Kutz. – I ep, II i, III c
102. *E. turgida* (Ehr.) Kutz. – I ep, II i, III c
103. *E. turgida* var. *granulata* (Ehr.) Grun. – I ep, II i, III b
104. *E. turgida* var. *westermannii* (Ehr.) Grun – I ep, II hl, III b
105. ***Rhopalodia*** *gibba* (Ehr.) O.Mull. – I ep, II i, III c, IV L
106. *R. gibberula* (Ehr.) O.Mull. – I ep, II hl, III c
107. *R. musculus* (Kutz.) O.Mull. – I ep, II mshb
108. ***Nitzschia*** *circumsuta* (Bail.) Grun. – I ep, II mshb, III c
109. *N. compressa* (Bail.) Boyer – I ep, II mshb, III n-a
110. *N. constricta* (Kutz.) Ralfs – I ep, II mshb
111. *N. granulata* Grun. – I be, II m, III c
112. *N. hungarica* Grun. – I ep, II mshb
113. *N. sigma* (Kutz.) W. Smith – I ep, II mshb, III c
114. ***Hantzschia*** *amphioxys* (Ehr.) Grun. – I be, II i, III c
115. ***Bacillaria*** *paxillifer* (O.Mull.) Hend. – I ep, II mshb, III c
116. ***Surirella*** *striatula* Turpin – I be, II mshb
117. *S. striatula* var. *minor* R.Tynni – I ep
118. ***Campylodiscus*** *daemelianus* Grun. – II mshb, III t
119. *C. fastuosus* Ehr. – I ep, II m, III c

APPENDIX 2

List of samples codes:

sa 21 (2.10 m depth); sa 20 (2.00 m); sa 19 (1.90 m); sa 18 (1.80 m); sa 17 (1.70 m); sa 16 (1.60 m); sa 15 (1.50 m); sa 13 (1.30 m); sa 11 (1.10 m); sa 9 (0.90 m); sa 7 (0.70 m); sa 6 (0.60 m); sa 4 (0.40 m); sa 2 (0.20 m); sa 1(0.10 m).