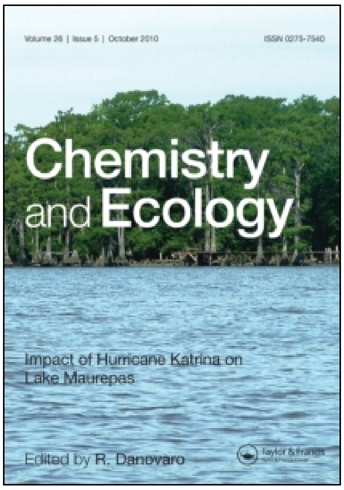

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SEDIMENT PARAMETERS OF NORTHWEST BLACK SEA SHELF AND SLOPE: IMPLICATIONS FOR TRANSPORT OF HEAVY METALS AND RADIONUCLIDES

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In June 1990, sediment cores were obtained from several locations in the Northwest Black Sea shelf and slope by a joint US/USSR scientific team aboard the survey vessel R/V VODYANITSKY. The goal of this investigation was to determine the distribution and levels of radioactivity resulting from the Chernobyl 1986 nuclear accident. The sediment was characterized for texture, mineral composition, redox state, heavy metals, and radionuclides. Correlations emerging from these data reveal paths of dispersal and transport of materials from river sources to deposition sites on the shelf and slope. Kaolinite in the clay mineral suite clearly reflects a dispersal pattern originating in the Danube River and progressing in an easterly direction across the shelf. Sand-size gypsum and the elemental heavy metals Zn, Cu, Cr, and Pb (probable industrial source) as well as the elements Al and Mg (probable terrigenous source) also show a dispersal pattern from the Danube station location in an easterly direction across the shelf. The dispersal direction indicated by these materials is not in conflict with recent existing notions concerning the hydrology of the Northwest Black Sea. Barium anomalies at a midshelf location may be related to operations in the Lebada oil fields situated updrift. Heavy mineral dispersal reflect the Danube and Crimean Provinces established for the shelf and relate to terrestrial source areas. In addition, the heavy mineral monazite correlates with the radioactive Th 232 found most abundantly in the Crimean Province. Local anomalies of Mn, Fe and U in the sediment at station locations are related to redox (Eh) conditions and other factors. $Cs^{134/137}$ data, reported by Curtis and Broadway (1991), correspond to transport and dispersal patterns implicit in the mineralogic, anthropogenic indicators, and sediment characteristics of the study area.

KEY WORDS: Black Sea, sediments, redox state, Chernobyl, heavy metals, radionuclides

INTRODUCTION

The United States and the Soviet Union, under a US/USSR bilateral agreement for cooperation in environmental protection, in June 1990 conducted a survey of 14 stations in the Northwest Black Sea shelf and slope area to seek evidence of Chernobyl radioactivity in the biota, water column, and bottom sediment. This Black Sea survey was part of a larger three-year cooperative US/USSR study entitled "Transport, Partitioning, and Effects of Radioactivity Released into a Marine Ecosystem." The survey was conducted aboard the USSR Institute of Biology of the Southern Seas survey vessel, the R/V VODYANITSKY which has its home port in Sevastopol. Samples of water, biota, and sediment were obtained for analysis by United States and Soviet laboratories to determine the ratios of caesium 134 and caesium 137 in these materials. An estimated 50 million Curie release of radioactivity occurred in April 1986 at Chernobyl, which is located approximately 550 kilometers from the Black Sea, the largest body of salt water near the site (Figure 1). Buesseler (1987) discusses the nature of the release and the types of radionuclides released as well as the airborne distribution during the incident. Winds from the northwest directed some of the radioactivity directly to the Black Sea area on the fifth and sixth day of the accident. The main source of Chernobyl radioactivity to the Black sea, however, is from terrigenous runoff and discharge of rivers that drain the region. According to Hay (1987), the Dnepr River drains the Chernobyl site and annually discharges 2.5 million tons of terrigenous matter to the Black Sea. Shimkus and Trimonis (1974) indicate a generally similar discharge for the nearby Dnestr River but they estimate that 83 million tons of suspended matter are annually contributed by the Danube River. These rivers and the proximity of the Chernobyl site to the Black Sea study area are depicted in Figure 1.

The station locations within the Northwest Black Sea study area visited by the R/V VODYANITSKY and the type of study that was conducted at each station are shown in Figure 1. Sediment was obtained from stations 4, 5, 6, 7, 8, 10, 11, and 12. Other stations were limited to water samples or biota trawls because of predominance of shell hash in the sediment (1, 2, and 3) or excessive water depth (9) beyond the capability of sediment recovery.

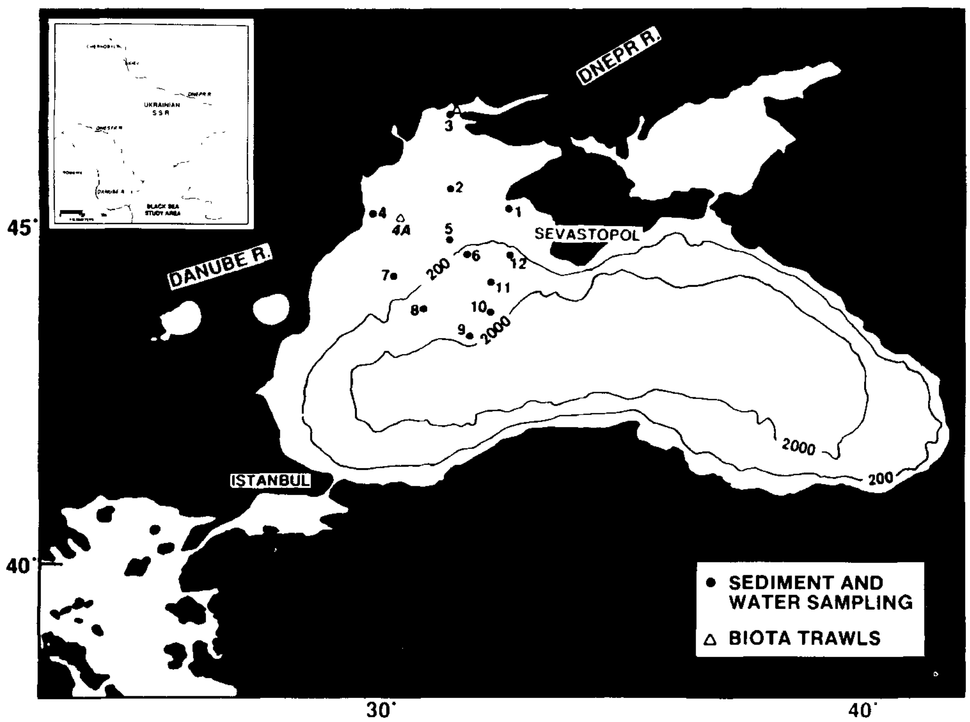

Figure 1 Location and depth of sampling stations surveyed by R/V Vodyanitsky during June 1990. Inset shows location of Chernobyl and major rivers that discharge into the Black Sea.

The characterization of the sediment and the sediment transport direction and dispersal from source areas are the primary objectives of this portion of the investigation. The sediment parameters that will be considered include texture, mineral identification (including heavy minerals and clay material suite), pH, Eh (oxidation-reduction potential), heavy metals and other anthropogenic materials. Differences in parameters resulting from varying lithology of different source areas in the watersheds provides indicators of transport direction and dispersal of materials. These indicators are compared with preliminary data on $Cs^{134 \text{ and } 137}$ (Curtis and Broadway, 1991) to evaluate the sources and dispersion of the Chernobyl radioactivity.

PHYSICAL SETTING OF THE NORTHWEST BLACK SEA STUDY AREA

The Black Sea is an oval shaped basin with an area of 423,000 square kilometres, a volume of 534,000 cubic kilometres and a maximum depth of 2206 metres. The surface waters to about 150 metres depth have a salinity of 16 to 18 parts per thousand while the deeper waters are 21 to 23 parts per thousand salinity. Anaerobic conditions prevail below 200 metres in these marine waters. The physiographic units of the Northwest Black Sea study area include the shelf and slope areas and a deep central basin. The broadest expanse of shelf area occurs in the Northwest Black Sea where the width ranges up to 190 km and the depth on the seaward edge is 130 metres. The basin slope is also more gentle in the northwest part of the Sea. According to Shimkus and Trimonis (1974), the rivers tributary to the Northwest Black Sea contribute 59% of the annual discharge of terrigenous matter to the basin.

The uppermost sediment unit in the Black Sea averages 30 cm in thickness across the basin with greatest thickness on the shelf area in proximity to major discharge areas. The base of this unit has been dated at 3000 years by radiocarbon dating. Ross and Degens (1974) have described this sediment unit as carbonate rich with alternating dark and light coloured microlaminated bands in which the light bands have been characterized as mainly coccoliths and dark bands as terrigenous silts and clays plus organic carbon. Coarser carbonate shell material is also characteristic of the shelf area. All the sediment tested in this investigation was obtained from the uppermost unit.

METHODS

An O'Hare Box Corer was used to obtain relatively undisturbed sediment samples at the eight Black Sea stations (4, 5, 6, 7, 8, 10, 11, and 12) shown in Figure 1. After the box core was received aboard ship, subcores were obtained by pressing a 1 inch diameter polyethylene tube for each set of sediment parameters to be measured. One of the polyethylene tubes had ports drilled at 1, 5, 10, and 15 cm intervals for shipboard measurement of temperature, pH and Eh. These measurements were made with a digital 230 Model, Orion pH meter as soon as the subcore was recovered from the box corer. Subcores for heavy metal analysis by US/USSR laboratories were extruded and sectioned for test samples at 0–1, 1–5, 5–10, and 10–15 cm intervals. The subcores for texture and mineral testing were sealed as taken from the box corer for analysis in the United States.

Sediment texture, mineral analysis, chemical and radio-chemical measurements were conducted at the EPA Montgomery, Alabama and Athens, Georgia, laboratories and the Army Corps of Engineers, Marietta, Georgia laboratory. Sediment texture was obtained by the pipette method in accordance with the procedure of Galehouse (1971). The petrography of sand and clay-size sediment fractions were in accordance with the methods of Muller and Stoffers (1974). The silt-size sediment fraction was identified in accordance with the method described by Buck (1972), whereby known mineral assemblages mixed in various proportions are used to estimate percentages of the minerals from x-ray diffraction analysis. Scanning electron micrographs (SEM) for coccolith identification were obtained from the Microbiology Laboratory of the University of Rhode Island. Chemical analysis of major and minor elements in the sediment was made at the USEPA, Athens Laboratory with the 31 channel Thermo Jarrell Ash ICP after digestion of the sample in accordance with Method 3050 of the USEPA Manual (1986). In addition, the lead values were confirmed by graphite furnace atomic absorption (Zeeman STPF) spectroscopy. At least one sample from each station was also analyzed by methods of additions to monitor for any unusual effects associated with that core.

SEDIMENT TEXTURE

Sediment textural data for the 8 stations was obtained on bulk core samples to 15 cm depth by the pipette method (Galehouse, 1971). The percentage of sand, silt, and clay sizes obtained from the grain size distribution curves is listed in Table 1. These parameters are used to classify the sediment in accordance with the Shepard (1954) sediment size classification. The sediment from stations 6, 7, 10, 11, and 12 are silty clays. Sediment from station 4 (near the Danube River) is a clayey silt. The finest sediment in the sandy clay of station 5.

Only the sediment samples from the mid-shelf station locations contain more than a few percent sand-size material. Sediments from stations 5 and 7 contain respectively 23% and 16% sand-size materials which are predominantly comprised of shell and shell fragments. In general, clay-size particles (less than 2 microns), are the predominant material at the rest of the stations. However, sediment from station 4 is predominantly silt-size and contains appreciable amounts of terrigenous materials as well as anthropogenic contaminants discharged to the Black Sea by the Danube River.

Table 1 Average sand, silt, and clay size sediment in cores from station locations in Northwest Black Sea

Station Number	*Depth (m)*	*Latitude (N)*	*Longitude (E)*	*% Size Fractions of Sediment*		
				Sand	*Silt*	*Clay*
4	27	45° 14.0′	29° 48.7′	3	60	37
5	105	44° 42.5′	31° 20.8′	23	20	57
6	510	44° 38.9′	31° 29.2′	1	46	53
7	114	44° 10.8′	30° 28.2′	16	20	64
8	564	43° 57.9′	30° 49.0′	T	28	77
10	1715	43° 58.9′	31° 22.8′	1	25	74
11	1109	44° 32.4′	31′ 56.0′	3	32	65
12	335	44° 54.1	32° 13.2′	2	34	64

MINERAL COMPOSITION OF SEDIMENT CORES

The average mineral composition for each station location is listed in Table 2. This average was computed as a weighted mean of the sand, silt, and clay-size fractions. Biogenous carbonate materials (calcite) comprise the predominant component of the sediment reaching a maximum at station 7 located in the mid-shelf area. The major terrigenous fractions are quartz (5–17%), feldspar (7–18%), and clay mineral species (15–32%). Detrital heavy minerals and diagenetic pyrite range from trace amounts to 2% of the sediment. Organic carbon was not measured in these sediments, but according to Rozanov, *et al.* (1974), organic carbon ranges between 0.91 and 4.62 % in the Northwest Black Sea sediment.

Biogenous Materials

As noted, the biogenous calcareous materials comprise the most abundant constituents of the sediment. Shell and shell fragments comprise between 30 and 50% of the sand-size and upper silt-size fractions. Abundant shell and shell fragments of molluscs and minor benthic foramanifera and other materials occur in this particle size range. The silt and clay-size fractions contain proportionally greater quantity of biogenous carbonate with material of less than 40 micron size comprised almost exclusively of the coccolithophore species *Emiliania huxleyi.* Shimkus and Trimonis (1974) point out that the major introduction of biogenous carbonate coincides with maximum productivity in the spring. However, they also credit some of the carbonate to chemogenic carbonate which may form in the summer when Black Sea waters become supersaturated with calcium carbonate.

Dolomite content, measured by X-ray diffraction methods after Tennant and Berger (1957), ranges from trace amounts to 5% (average 2%) for the sediment cores. The largest occurrence of dolomite is in the sediment at station 4 near the Danube River. Aragonite occurs in some shell materials but seldom exceeds a few percent of the carbonate fraction.

Table 2 Mineral composition of sediment from station locations in the Northwest Black Sea study area

Mineral	*Station Location*							
	4	5	6	7	8	10	11	12
				Average Percent				
Calcite	31	38	53	59	50	52	55	54
Dolomite	5	2	3	2	1	2	T	3
Quartz	14	17	10	12	16	9	5	9
Feldspar	18	11	12	11	9	14	12	7
Illite/Mica	19	15	10	6	11	10	14	15
Kaolinite	7	7	6	4	6	5	5	5
Chlorite	4	4	3	3	3	3	4	3
Montmorillonite	2	3	2	2	2	3	4	2
Other[1]	1	3	1	1	2	2	1	2
				Percent Clay-Mineral Fraction				
Illite	60	55	48	62	65	56	62	63
Kaolinite	23	25	24	18	16	18	17	20
Chlorite	11	15	16	14	8	12	13	10
Montmorillonite	6	5	12	6	11	14	8	7

1. Other minerals include aragonite (T–1%), pyrite (1–2%), and heavy minerals (0.5–1%).

Terrigenous Materials

Terrigenous materials in the sediment include quartz, feldspars, mica, clay minerals, and heavy minerals. The composition of these materials in sand size materials is based on statistical point counts of grains with both binocular and petrographic microscopes. The silt-size fraction is based on X-ray diffraction techniques and comparison of the silt fraction at 5 cm intervals was conducted at all station locations. Semi-quantitative methods were used to determine the materials of clay-size (less than 2 microns) sediment. The carbonate fraction for silt and clay sizes was determined by 1:4 HCl leaching technique and the major clay mineral components by X-ray diffraction techniques. The percentages of major clay mineral components of the clay mineral suite was calculated based upon their weighted basal peak areas. Illite is the most abundant clay mineral of the clay mineral suite (Table 2) at all station locations. The separation of kaolinite and chlorite, which are common to the 7 Angstrom peak, was made in accordance with the method of Biscay (1964).

The clay minerals in the sediment from station 4 comprise 32% of the sediment as compared to 15–29% at other station locations (Table 2). The kaolinite in the clay-size fraction (less than 2 micron size), is depicted in Figure 2. The kaolinite is greater than 20% in the clay mineral suite of stations 4, 5, and 6 and less than 20% at the more seaward or southerly locations. An easterly transport direction is suggested in the kaolinite distribution. This distribution is in general accord with hydrodynamic circulation concepts discussed in a later section.

Heavy Minerals and Provinces

The heavy mineral composition of 5 of the sediment station locations is listed in Table 3. The heavy mineral data support the composition reported by Muller and Stoffers (1974) for one station located in the study area and they conform to the heavy mineral provinces they established. The Crimean and Danube heavy mineral provinces are depicted in Figure 3 with the southern Danube boundary modification resulting from a more recent study by Ruskova (1987) on the Bulgarian and Romanian shelf area. The heavy mineral suite of the Crimean and Danube Provinces as characterized by Muller and Stoffers (1974) for major, minor, and accessory non-opaque heavy minerals are as follows:

Danube Province – Major garnet, amphibole group, epidote group; minor staurolite, kyanite, and zircon; accessory andalusite and tourmaline.

Crimean Province – Major garnet, amphibole group, epidote group, and kyanite; minor staurolite, pyroxene, and zircon; accessory andalusite, rutile, and corundum.

Our current investigation discloses a similar trend of the very stable heavy minerals, rutile, monazite, and zircon, with greater abundance in the Crimean Province. Monazite (Figure 4) appears to be the only mineral not previously reported. The predominance of the more stable heavy minerals in the Crimean Province probably reflects the contribution of rivers draining the old crystalline Ukrainian Massif which is a source area for these minerals.

The significance of the heavy mineral province data for this investigation is the overpowering evidence of terrigenous sand and silt from the Danube River in this region of the Black Sea. The Dnepr and Dnestr River terrigenous sediment is also

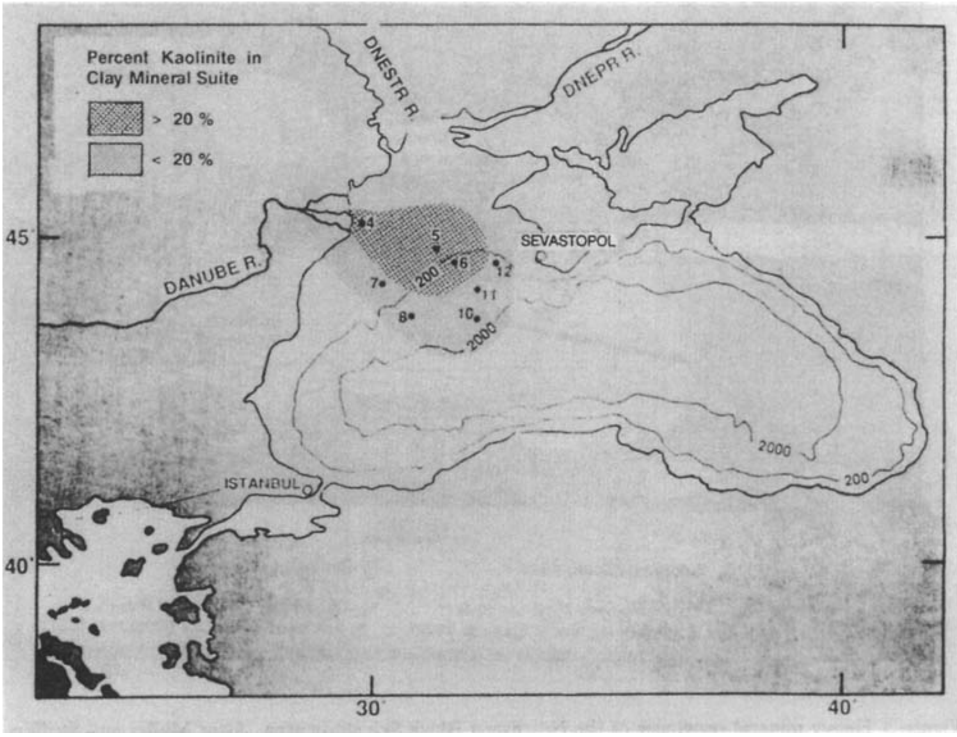

Figure 2 Kaolinite dispersal from the Danube delta area in easterly direction across the shelf and down the slope

Table 3 Heavy mineral composition of sediment samples within the Danube and Crimean Provinces

	Danube Province				*Crimean Province*	
Station	*5*	*6*	*7*	*11*	*1442*[2]	*12*
Mineral	Percent Transparent Minerals					
Garnet	33	48	53	40	36	30
Epidote Group	20	18	12	17	22	14
Amphibole Group	23	19	20	20	21	18
Kyanite	4	6	4	6	10	8
Zircon	9	4	4	6	10	12
Rutile Group	2	1	2	4	–	8
Tourmaline	3	1	1	2	–	2
Staurolite.	T	2	2	2	1	2
Monazite	T	T	T	1	–	1
Other[1]	6	1	2	2	3	5

1. Other includes andalusite, sillimanite, titanite and apatite.
2. Station 1442 reported by Muller and Stoffers (1974).

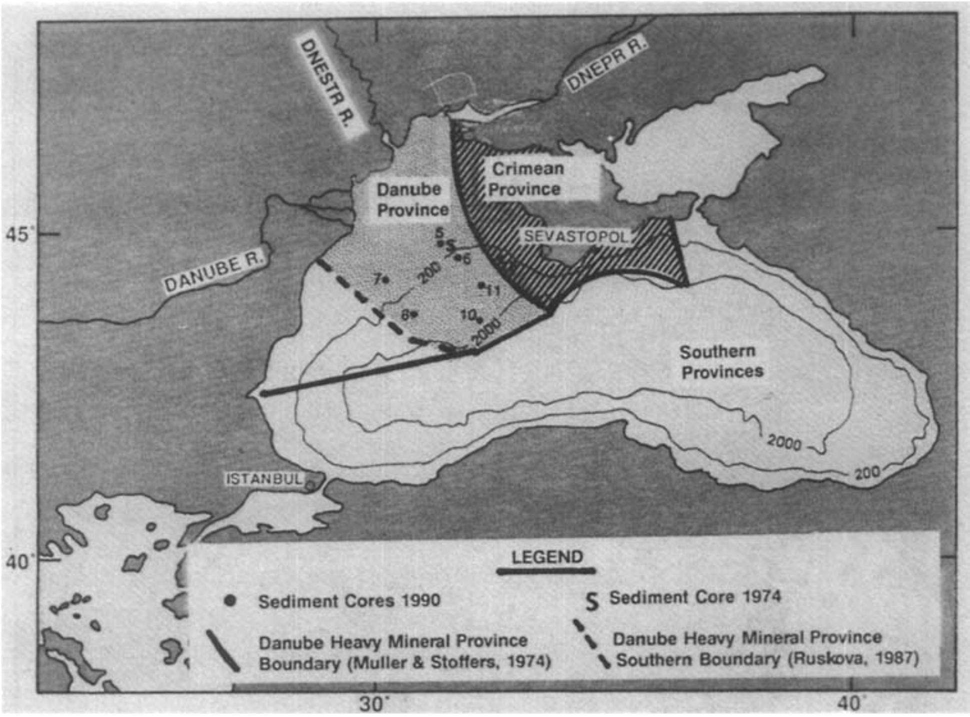

Figure 3 Heavy mineral provinces of the Northwest Black Sea study area. After Muller and Stoffers, (1974) and Ruskova (1987)

probably represented in the Danube Province; speculation on the degree of influence of these rivers is not warranted in this study.

Gypsum

White to colourless, anhedral, tabular shaped, sand-size gypsum occurs in the sediment from most stations (Figure 5). The gypsum comprises but trace amounts as regards total sediment, but its relative abundance in the larger sieve sizes is highly significant. The gypsum comprises approximately 5% of the coarser sieve fractions of the sediment from station 4. The size is smaller and the proportional representation at station 5 is estimated at approximately one-fifth that at station 4. In the finer textured (silty clay) only trace amounts are found in the upper silt size fraction. The fact that gypsum has not been reported in previous investigations, its rather easily abraded nature, and its presence in less quantity and diminishing size in a seaward direction warrants the speculation that this is probably anthropogenic material from various activities in the watersheds.

GEOCHEMISTRY OF THE SEDIMENT

The geochemical measurements of the sediments include the determination of redox

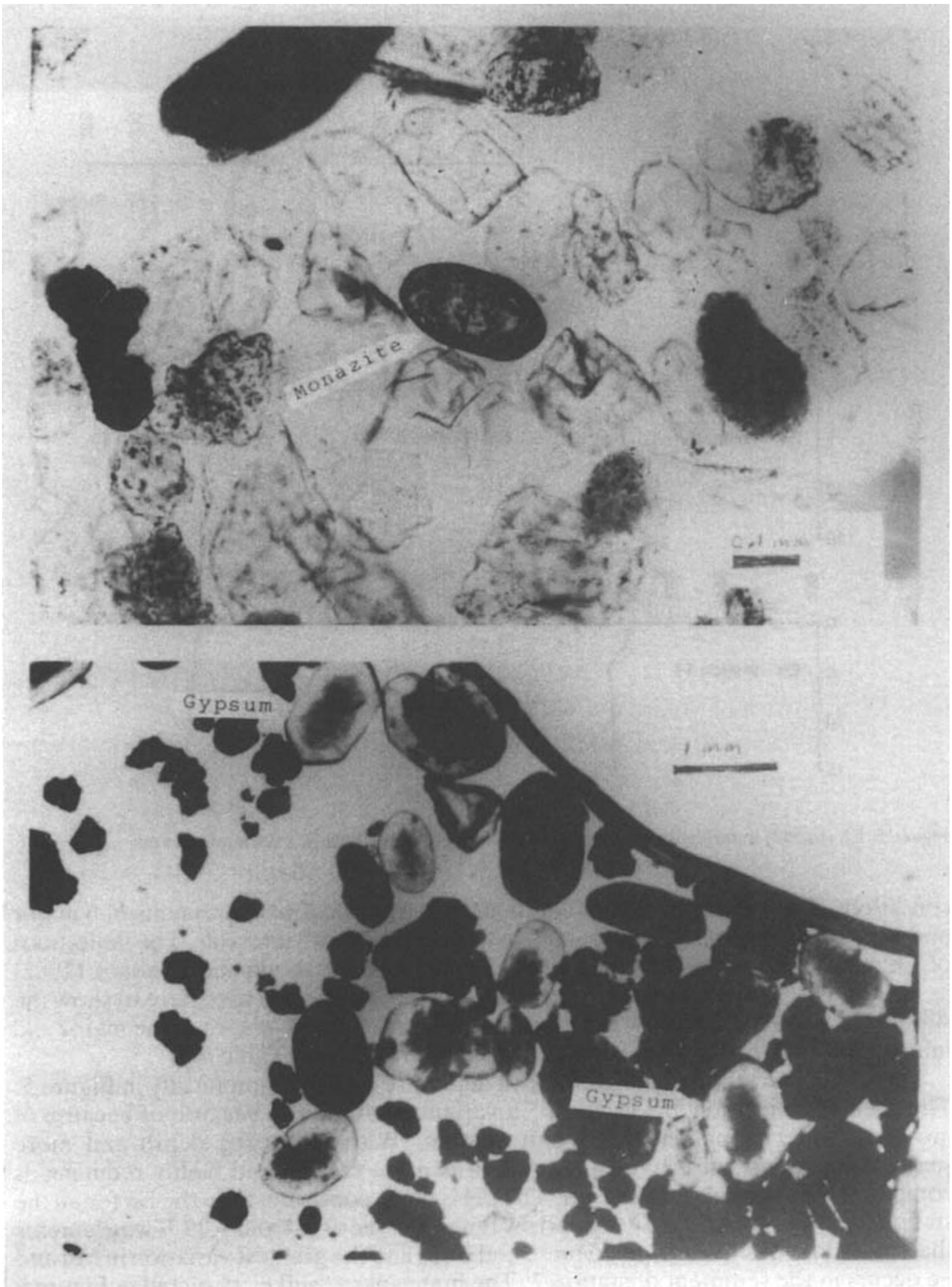

Figure 4 Photomicrographs (transmitted light) of monazite in fine-sand fraction of sediment from station 12 (top) and gypsum in medium sand-size fraction of sediment from station 5 (bottom)

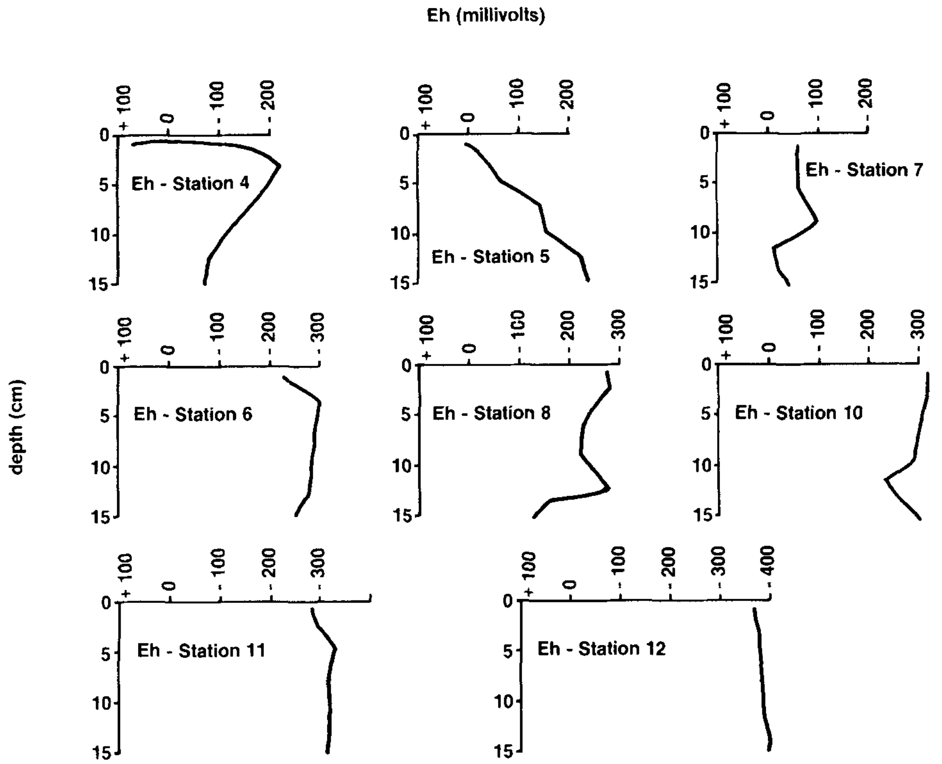

Figure 5 Eh (redox) in millivolts with depth (cm) at Northwest Black Sea station locations

conditions (Eh and pH) to 15 cm depth and the analytical measurements of 6 major and 13 minor elements (heavy metals) over the same depth intervals. The limitations of Eh measurements have been well documented by Vershinin and Rozanov (1982) as well as other investigators. Our use of Eh in the sediment is used here to show the similarity or differences between stations. The ranges and averages of the major and minor elements for the eight sediment stations are given in Table 4.

The Eh (redox) data in millivolts with depth are depicted graphically in Figure 5. The shelf stations show the greatest Eh variation with depth because of because of more dynamic factors including bioturbation. With increasing depth and more seaward locations, the Eh of the sediment is more regular and highly reducing as compared with stations on the shelf. The pH is more consistent than the Eh for all the station locations with a relatively narrow range between 6.84 and 7.25. Two elements that are redox sensitive are manganese and iron, and the greatest variation in Mn and Fe occurs in the sediment of station 7. The manganese "spike" depicted in Figure 6 stands in sharp contrast to the more regular distribution in other stations. Such manganese concretions or spikes have been described by Froelich, *et al.* (1979) and others as probably resulting from a process of manganese reduction and mobilization

Table 4 Averages and ranges of metal concentrations in Northwest Black Sea Sediment

Element	*Avg mg/kg*	*Range mg/kg*
Yttrium	11	8–17
Cobalt	15	10–23
Molybdenum	18	3–46
Lead	21	10–64
Chromium	29	15–66
Copper	45	21–92
Vanadium	49	35–71
Nickel	50	36–78
Zinc	63	37–160
Titanium	117	52–220
Barium	295	110–940
Manganese	630	210–3000
Strontium	693	110–11000
Element	*Avg %*	*Range %*
Potassium	0.34	0.18–0.6
Magnesium	0.76	0.55–1.2
Sodium	1.22	0.53–1.8
Aluminium	1.45	0.75–2.5
Iron	2.16	1.3–3.3
Calcium	13.58	2.7–21

NOTE: Values for Cd, Se, Sn, Te and Tl were below the analytical detection limit and were not included

at greater depth followed by upward diffusion and redeposition of manganese oxide in a discrete layer. Iron concretion follows a generally similar distribution at station 7.

Although manganese nodules are not associated with the elevated manganese found in the sediment at station 7, Belyayev and Konduforova (1987) cite areas of iron-manganese nodules on the surface in nearby Kalmit Bay off the Crimean coast. They present a mathematical model for the generation of the iron-manganese nodules. According to this model, nodules in the surface layer of a sediment are formed by deposition, dehydration and crystallization of colloidal iron and manganese hydroxide on various nuclei resting on the surface of the sediment.

According to Manheim and Chan (1974), there is a discharge of fresh to brackish ground water off the western shelf of the Crimean peninsula. To determine if this phenomenon is present in sediments at stations 5 or 7, conductance and chloride tests are being conducted on pore water extracted from three depths in these cores.

A comparison of the ranges and averages of the elements of the Northwest Black Sea sediments (Table 4) with a similar list of elements of the entire Black Sea sediments by Hirst (1974) shows a marked difference (more than double) in 5 of the elements. The average concentrations of calcium and strontium in the sediment of the Northwest Black Sea study area are twice that of the average Black Sea, probably as a result of greater biological productivity on the broader shelf that occurs in the Northwest Black Sea. The average Black Sea sediment contains elevated aluminium, chromium and vanadium: concentrations compared to the Northwest Black Sea study area, a factor we attribute to source areas drained by rivers tributary to the entire Black Sea basin. Muller and Stoffers (1974), in their description of sources of

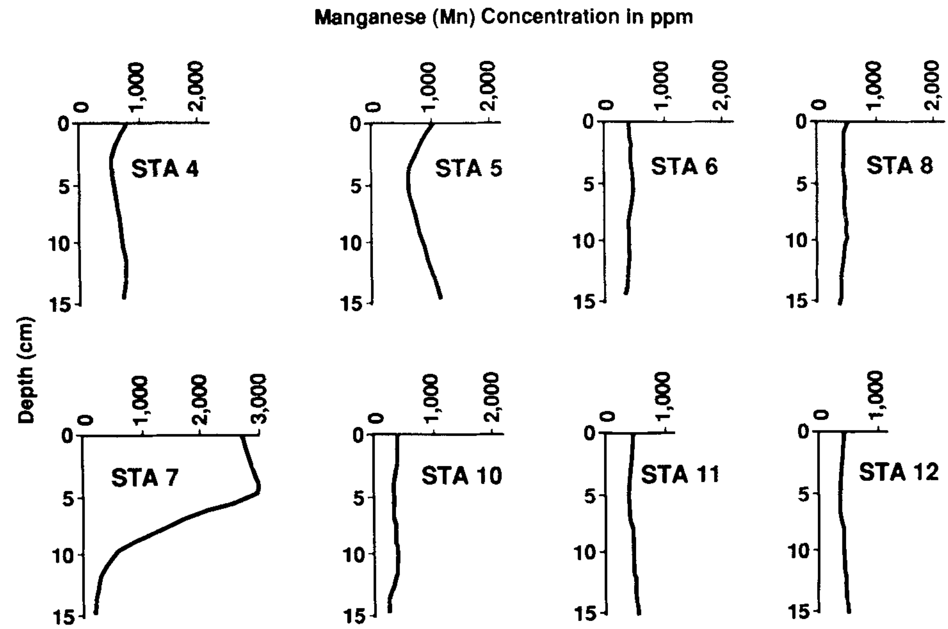

Figure 6 Manganese concentration (ppm) with depth at Northwest Black Sea station locations

materials to the Black Sea basin, describe the eastern Black Sea source materials as being rich in Eocene volcanic rocks. The mafic-rich volcanic rocks are a probable source for these elements since the older crystalline granitic rocks that occur in the Northwest Black Sea area are poorer in aluminium, chromium and vanadium.

HEAVY METAL DISPERSAL IN NORTHWEST BLACK SEA

A comparison of 4 minor and 2 major elements for sediment at the Northwest Black Sea station locations is shown graphically in Figure 7. The average and maximum concentration for zinc, copper, chromium and magnesium in sediments from 0–15 cm depth intervals is depicted for each location. The maximum concentration of each of these elements was found in the sediment of station 4 located near the Danube River. The average concentration of these elements occupies a relatively narrow range at other stations. Thus the major source of the heavy metals (Zn, Cu, Cr, and Pb) appears related to terrigenous runoff discharged into the Danube River and the major elements aluminium and magnesium to natural sediment (e.g. kaolinite and dolomite), with transport of these elements to the Black Sea coastal area for dispersal and distribution by the hydrodynamics of the coastal regimen. The Danube River contributes the major tonnage of sediment load to the Northwest Black Sea and in its route to the sea receives contributions of considerable industrial wastes from several European countries. Dispersal of the heavy metals follows a distribution similar to that shown for the kaolinite in Figure 2.

An anomalous occurrence of barium and elevated vanadium and yttrium appears

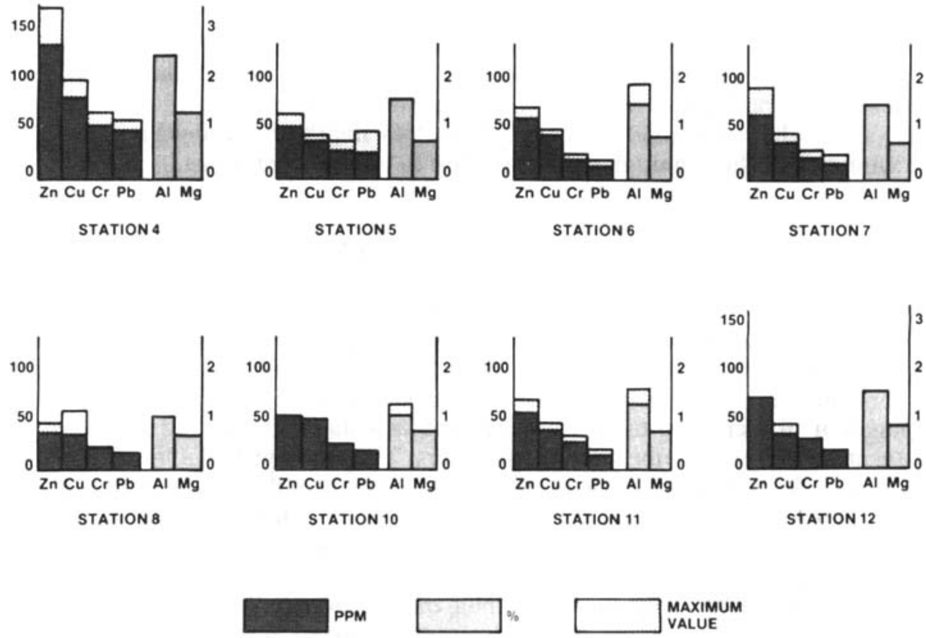

Figure 7 Distribution of Al, Mg, Zn, Pb, Cu, and Cr in sediment from station locations in the Northwest Black Sea study area

in the sediment of station 7. This is in addition to high manganese and iron relative to other stations reported earlier. Barium in the sediment of station 7 ranges between 390 and 940 ppm while the average for all stations is 295 ppm. The source of the elevated barium may be related to barium muds used in drill rig operations in the Romanian Lebada oil fields located approximately 25 km to the west.

RADIONUCLIDE DISTRIBUTION IN SEDIMENT

Buesseler (1987) has discussed the advantage of using the caesium-134 (2.07 year half-life) to caesium-137 (30.17 year half-life ratio as a positive fix to the Chernobyl fallout. Measurements were made of the caesium radioisotopes and other radionuclides in the sediment at each of the eight station locations.

Radiocaesium was measurable in the sediment of three of the station locations in the preliminary findings (Curtis and Broadway, 1991). Caesium-137 and caesium-134 occur in measurable quantities at station 4 located offshore from the Danube River and also at stations 5 and 7 located on the mid-shelf area. The highest occurrence of both Cs-134 and Cs-137 occurred at station 4 with strongest activity near the surface. The highest Cs-137 at station 4 is 8.4 pCi/g and at stations 5 and 7 respectively 0.95 pCi/g. The dispersal direction from the Danube River source is thus generally similar to that depicted for kaolinite in Figure 2.

The thorium-232 radioactivity appears related to the natural mineral distribution patterns. The highest activity level of 1.48 pCi/g occurs at 5 cm depth of sediment from station 12. This correlates with the increased monazite (rare earth, thorium orthophosphate) found in the heavy minerals (Table 3).

Preliminary measurements of uranium-238 reveal highest activity associated with the sediment from the deeper water station locations with the strongest reducing environment. The highest value (16.57 pCi/g) was measured in station 10 sediment on the slope where the water depth is 1715 metres and the Eh (redox) is in excess of −325 millivolts. The uranium appears related to natural conditions.

NORTHWEST BLACK SEA WATER CIRCULATION

The circulation of the main stream Black Sea current in a counterclockwise direction has been generally known for more than a century, but it has only been in recent time that the complex spin-off currents in the Northwest Black Sea have been identified. Kaz'min and Sklyarov (1985) have identified from Meteor satellite imagery a zone of propagation of increased turbidity water and associated fronts and eddies in the coastal areas off the Danube and Dnepr Rivers. They have provided insight into the eddy current formation and with imagery have traced the influx of Danube water into the sea along the western shore. Their interpretations indicate that easterly and southeast projected currents are vectored counterclockwise from the main river discharge systems.

Grishin, *et al.* (1989) used the LOBAN-T buoy system to investigate the velocity field of the large-scale cyclonic gyre in the western part of the sea. They interpreted from the buoys that large scale cyclonic-anticyclonic eddy pairs occur in the northwest shelf area as a result of gravitational instability of a rotating boundary current. They conclude that the gravitational instability of the main Black Sea current is an element of its seasonal circulation during the period of high river discharge.

The dispersal of sediment indicated in this investigation reflects a general net easterly projection. This is not in conflict with any of the existing interpretations concerning the rather complex hydrology of the Northwest Black Sea study area.

SUMMARY AND CONCLUSIONS

Analysis of the sediment from eight stations in the Northwest Black Sea reveals that the Danube River is probably the largest contributing source of kaolinite, dolomite, and a diagnostic heavy mineral suite. Several anthropogenic materials, including lead, zinc, copper, chromium, and gypsum are also more abundant at the sediment station located near the Danube River and reflect transport in an easterly to south easterly direction across the shelf. The Cs-134/Cs-137 activity reported here by Curtis and Broadway (1991) is also the highest for Chernobyl source materials at this station with dispersal in an easterly direction with detectable amounts in the nearest shelf stations.

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