

Sedimentological and mineralogical study of the distribution of heavy minerals (black sands) in Ierissos Gulf, Chalkidiki, Greece.

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Abstract

In the present work, the coastal sediments of the Gulf of Ierissos from the coast to a depth of 10m are studied. Aim of this study is to determine the positions that are rich in heavy minerals, their identification and study their impact in the sediments of the area. For the purposes of work performed sampling and grain size analysis of the samples. The identified of magnetic separator and method of settling for the separation of heavy minerals from the mineral aggregates were used. The positions deposition of heavy minerals and their concentrations within the coastal sediments of the Gulf of Ierissos were identified. The minerals contained in the sediments were identified. Finally, experiments were conducted to determine the fractions of aggregates sand hydrodynamic equivalent with fractions rich in heavy minerals.

Keywords: Ierissos Gulf, Stratoni, Greece, environment, sedimentology, mineralogy, black sand, heavy minerals.

Introduction

The Gulf of Ierissos is located in the central part of the North Aegean Sea and is one of the largest semi closed water surfaces in the North Aegean area of 166 km² and volume 8.3×10⁹ m³. The Gulf of Ierissos has elliptical shape and NW-SE orientation with a 10km opening in length A towards the Strymon Gulf. The bottom is steep near the coast, with the contour of 50m very close to the latter, the midpoint of the bottom depth is 80 m, but outside near the entrance of the bay shows a sill. The seabed closes slightly in the SE part presenting an inclined depth of 65-70 m (Fig. 1) (Perissoratis and Mitropoulos 1988).

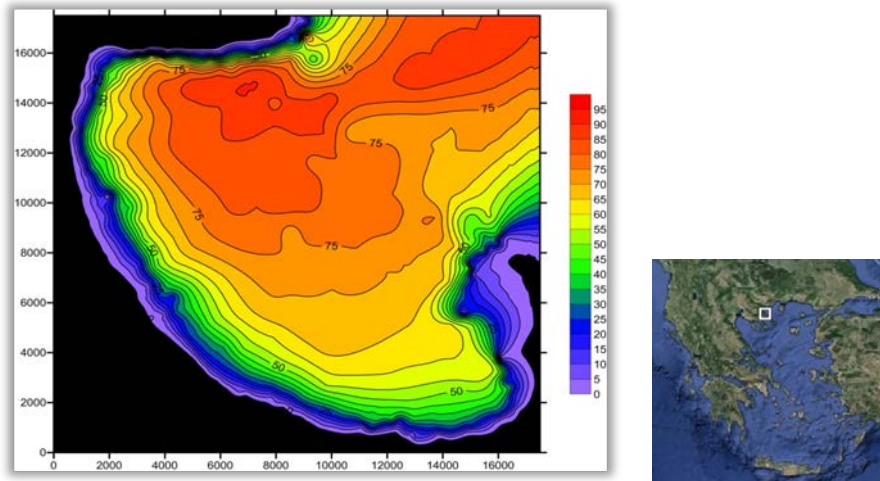


Figure 1: Bathymetric map of the Gulf of Ierissos 100m x 100m, based on the maps of GMS (Geographical Military Service) 1:50.000 (sheets of Ierissos, Karies and Stratoni) (Xatzi 2012).

In restricted basin of the Gulf of Ierissos different types of mineralization viewed as porphyritic Cu, Cu-skarn, Pb-Zn-Au-Ag carbonate-replacement were located (Gilg 1993). The source rock on which grows mineralization belongs to Serbo-Macedonian Massif. A significant amount is also held by the igneous rocks developed on either side of the Stratoni fault (Fig. 2). The mining activity is active and the inception dates back to prehistoric times (Vavelidis et al. 1983; Wagner et al. 1986; Vavelidis 1989). The processing and loading of ore are being made from as early as the 7th century BC. The transportation of ore is taking place, to date, by sea, at port facilities owned by the mining company located in the NW end of the bay, in the area of Stratoni.

Both the naturally enriched in minerals catchment area and the long mining activities have created intense pollution of the coastal and marine space and it seems that the Gulf of Ierissos shows higher concentrations of heavy minerals in sediments from the Strymonikos bay (Ioannidou 1999; Stamatis et al. 2001).

According to Xatzi (2012) the direction of flow in the coastal zone of the Gulf of Ierissos for Northern, Eastern and Northeastern winds, of 3 and 5 Buford scale intensity, in each case is directed from the northern part of the bay to its south-west, meaning from Stratoni to Ierissos. The movement of sea mass in the bay, decisively affects the transportation and deposition of sediments in the coastal zone (Xatzi 2012).

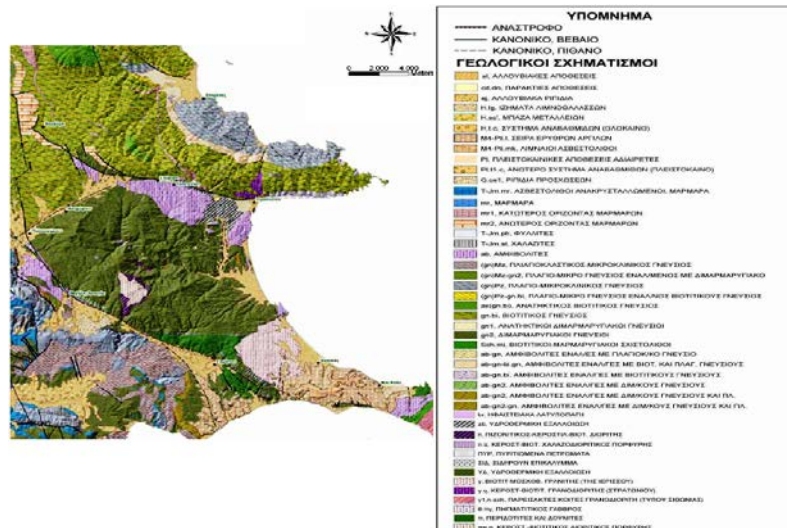


Figure 2: Geological Map of the region of Ierissos (Bulletin of Hellenic Gold company in Halkidiki) (Xatzi 2012).

Methods

In the Gulf of Ierissos a total of four visits were made regarding the recognition of geomorphologic structures of the area and 19 samples were taken both from the shore (C) and in the Gulf within a 300m range of the coast (St). The reception of the coordinates was conducted via portable satellite «GPS» tracking system formula Garmin 60 CSx.

Table 1: Sampling sites in September 2011-March 2012

Sampling sites	Coordinates		Depth (m)	Location
	X	Y		
<i>C1₀</i>	23° 49' 44.3"	40°30'53.32"	0	Stratoni beach
<i>C2₀</i>	23° 49' 43.69"	40°30'51.22"	0	Stratoni beach
<i>C3₀</i>	23° 49' 41.59"	40°30'46.45"	0	Stratoni beach
<i>C4₀</i>	23° 49' 40.1"	40° 30' 42.5"	0	Stratoni beach
<i>C5₀</i>	23° 49' 24"	40° 30' 16.2"	0	Stratoni beach
<i>C6₀</i>	23° 49' 14.8"	40°28'59.2"	0	Kruoneri beach-Estuaries of Kokkinolakka
<i>C7₀</i>	23° 51' 4"	40° 25' 41.2"	0	Beach south of Gavrada area
<i>St1_{5,7}</i>	23° 49' 50.6"	40° 30' 49.6"	5.7	Stratoni – Estuaries of Arguro (5,7m depth)
<i>St2_{0,4}</i>	23° 49' 40.1"	40° 30' 42.5"	4	Stratoni
<i>St3_{5,9}</i>	23° 49' 47.3"	40°30'43.5"	5.9	Stratoni
<i>St4_{9,5}</i>	23° 49' 49.4"	40° 30' 43.3"	9.5	Stratoni
<i>St5_{5,5}</i>	23° 49' 43.8"	40° 30' 36.2"	5.5	Stratoni
<i>St6_{2,5}</i>	23° 49' 35.99"	40° 30'31.46"	2.5	Stratoni
<i>St7_{2,9}</i>	23° 49' 31.6"	40° 30' 26"	2.9	Stratoni Estuaries of Karvounoskala
<i>St8₅</i>	23° 49' 32.4"	40° 30' 19.8"	0.5	Stratoni
<i>St9_{2,7}</i>	23° 49' 18.2"	40° 28' 58.5"	2.7	Kruoneri beach - Estuaries of Kokkinolakka
<i>St10_{1,9}</i>	23° 52' 18"	40° 24' 30.7"	1.9	Ierissos
<i>St11₃</i>	23° 52' 53.8"	40° 24' 4.3"	3	Ierissos
<i>St12_{1,5}</i>	23° 52' 53.1"	40° 24' 1.8"	1.5	Ierissos

For the particle size analysis of the samples a-2 Φ series of sieves (4mm) to + 4 Φ (0.062mm) were employed (method Folk & Walk, 1975). The processing of particle size analysis results was made by the Gradistat V 6.0 program (Blott 2008).

The separation of the magnetic from non-magnetic minerals of the samples was carried out in a magnetic Frantz type separator (Isodynamic Model-1). The identification of minerals was made by an optical observer at a Jena-type stereoscope under specific optical and physical properties of the minerals (Sapountzis 1985) and in metallographic microscope, type Leitz (Laborlux 11 Pol S). To complete the mineralogical study an identification and photography of specimens in electron microscopy (SEM-EDS) JEOL (840A) analytical system with EDS Link AN10000 was conducted.

For the study of hydrodynamics of sedimentary grains in the aquatic environment the method of settling in a vertical cylindrical tube (constructed in the Laboratory of Physical Geography, AUTH) was used, with the provision for selective removal of sediment from its base. Particles' settling velocities were calculated by Heywoods' tables according to Holdich (2002) and URL1: www.filtration-and-separation.com/settling/settling.htm. The sedimentation tube was used in two ways. In one way, a sedimentation of sand fractions of the same diameter was made after their separation in sieves and as for the other way the caving of sand which was derived from the same hydrodynamic environment but consists of grains of different diameter and very different specific weight.

To determine the fractions of mineral aggregates hydrodynamic equivalent to the fractions rich in heavy mineral, an experiment of reclaiming the precipitation grains in controlled laboratory conditions was conducted. The experiment was based on the principle that in nature all grain sizes coexist and in the coastal zone of the study area grains with different grain size, mineralogical composition and specific gravity are located in zones of similar hydrodynamic regime. Due to the fact that the determining factor for the hydrodynamic grain behavior of the waves is the specific weight (Folk 1975; Psilovikos and Psilovikos 2010) a sample precipitation consisted of both granules of different diameter and different specific gravity was held. This sample was artificially produced by the following methodology. Two samples (C1₀ and C4₀) from the beach of the Stratoni that lied very close to one another, with similar hydrodynamic character and completely different sedimentological and mineralogical characteristics were selected. The C1₀ sample consists of what is characterized as medium sand, moderately sorted, symmetrically skewed and leptokurtic, while the C4₀ sample consists of sand characterized as very coarse skewed, well sorted, symmetrically skewed and mesokurtic. From each sample, the two fractions involving the largest percentage in particle size % were selected and from each of these an amount of 2 grams was extracted. From the C1₀ sample -1 Φ (2mm) and -1.5 Φ (3mm) fractions were selected, while from the C4₀ sample 0 Φ (1mm) and 0.5 Φ (0.707mm) were chosen fractions. Afterwards the four new selected samples were mixed. Consequently an 8 gram sample of sedimentary grains of different size, composition and specific gravity was produced. The mixed sample was subjected to a precipitation process within a 1 meter settling tube which was filled with purified water. After completion of the sedimentation the crude sample was separated into three parts that were identified visually. Each of the three parts that arose included both heavy mineral small size grain compact and large specific gravity as well as aggregate minerals with a larger grain size, of low specific gravity. The aggregate minerals and heavy minerals that are involved in the same part of the sample are considered of equivalent hydrodynamic value because they precipitated at the same time. The hydrodynamic equivalent fractions of aggregate minerals

can be used to replace the coastal sediment concentrations of heavy minerals, where it's deemed necessary.

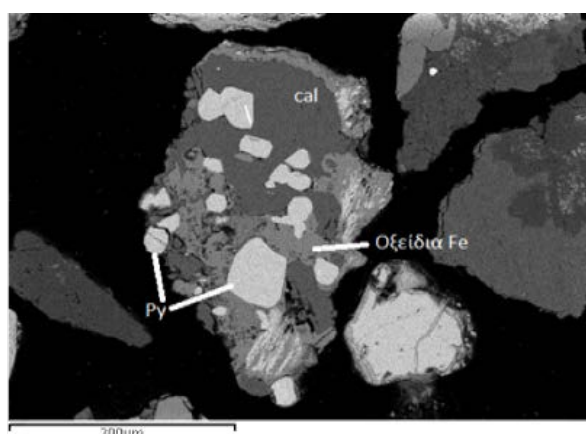
Results and Discussion

The results of particle size analysis of samples from the Gulf of Ierissos showed that they consist mainly of sand (Tab. 2). The size of clastic grains according their classification make up an indirect measure of the capacity of the means of transport, as well as the distance of their transport (Pettijohn 1957).

Table 2: Results of particle size analysis of samples from the Gulf of Ierissos.

Samples	Mean (\bar{x})	Sorting (σ)	Skewness (sK)	Kurtosis (Ku)
C1 ₀	1.261	0.762	0.087	1.205
	Medium Sand	Moderately Sorted	Symmetrical Skewed	Leptokurtic
C2 ₀	0.146	1.268	-0.33	0.908
	Coarse Sand	Poorly Sorted	Very Coarse Skewed	Mesokurtic
C3 ₀	0.6	2.068	-0.247	0.975
	Coarse Sand	Very Poorly Sorted	Coarse Skewed	Mesokurtic
C4 ₀	-0.546	0.432	0.177	1.055
	Very Coarse Sand	Well Sorted	Fine Skewed	Mesokurtic
C5 ₀	1.998	0.486	0.161	1.224
	Medium Sand	Well Sorted	Fine Skewed	Leptokurtic
C6 ₀	0.721	1.205	0	1.182
	Coarse Sand	Poorly Sorted	Symmetrical Skewed	Leptokurtic
C7 ₀	0.233	1.702	-0.199	0.924
	Coarse Sand	Poorly Sorted	Coarse Skewed	Mesokurtic
St1 _{5,7}	2.417	0.758	-0.002	1.061
	Fine Sand	Moderately Sorted	Symmetrical Skewed	Mesokurtic
St2 _{0,4}	-0.443	1.54	0.139	0.655
	Very Coarse Sand	Poorly Sorted	Fine Skewed	Very Platykurtic
St3 _{5,9}	2.555	0.735	-0.147	1.176
	Fine Sand	Moderately Sorted	Coarse Skewed	Leptokurtic
St4 _{9,5}	2.553	0.774	-0.103	1.127
	Fine Sand	Moderately Sorted	Coarse Skewed	Leptokurtic
St5 _{5,5}	1.639	0.811	0.019	1.165
	Medium Sand	Moderately Sorted	Symmetrical Skewed	Leptokurtic
St6 _{2,5}	2.445	0.863	-0.114	1.504
	Fine Sand	Moderately Sorted	Coarse Skewed	Very Leptokurtic
St7 _{2,9}	2.195	0.743	0.114	0.988
	Fine Sand	Moderately Sorted	Fine Skewed	Mesokurtic
St8 ₅	2.913	0.577	0.091	1.213
	Fine Sand	Moderately Well Sorted	Symmetrical Skewed	Leptokurtic
St9 _{2,7}	1.74	0.667	0.159	1.18
	Medium Sand	Moderately Well Sorted	Fine Skewed	Leptokurtic
St10 _{1,9}	-0.578	1.116	0.159	0.811
	Very Coarse Sand	Poorly Sorted	Fine Skewed	Platykurtic
St11 ₃	1.007	1.349	-0.31	0.769
	Medium Sand	Poorly Sorted	Very Coarse Skewed	Platykurtic
St12 _{1,5}	-1.718	0.276	0.059	1.297
	Very Fine Gravel	Very Well Sorted	Symmetrical Skewed	Leptokurtic

During the mineralogical analysis 17 samples were studied, of 2 Φ (0.25mm) and 2.5 Φ (0.177mm) grain diameter, at the Jena type stereoscope (C1₀, C2₀, C3₀, C5₀, C6₀, C7₀, St1_{5,7}, St2₄, St3_{5, 9}, St4_{9,5}, St5_{5,5}, St6_{2,5}, St7_{2,9}, St8_{0,5}, St9_{2,7}, St10_{1,9}, St11₃) to visually identify the existing minerals (Tables 4 & 5). It was determined, to a large extent, existence of metallic mineral inclusions inside silicate minerals (Fig. 3; Fig. 4). Based on this finding, the magnetic and non-magnetic minerals in the magnetic separator method was selected and followed in order to find the percentage of magnetic/metallic and non-magnetic/non-metallic mineral involved in the sediment composition. It was observed that large percentages of each sample were classified in the category of magnetic minerals although this did not appear macroscopically. Then, fraction samples that passed through the magnetic separator and classified as magnetic (C1₀, C2₀, C3₀, St5_{5,5}, St2₄, St7_{2,9}) suffered a special kind of processing and metallographic sections were created, which were studied in the metallographic



microscope. From the same samples confections were made for the electron microscopy (SEM-EDS), as to determine the chemical composition of metallic and non-metallic minerals, to study the morphology as well as the minerals contained in the inclusions. In table 6, the heavy metal minerals and the percentage (%) of concentration in the samples in the area of Stratoni that have been taken at a depth of 0 to 5.5 m, are presented. The results that were obtained after studying

the samples in the metallographic microscope, mainly concern the recording of heavy minerals that are not listed in inclusions.

In particular it showed that the content of magnetite in the sediments is ranging from 2.85% (St7_{2,9}) to 6.17% (C2₀). The pyrite content ranges from 3.69% (C2₀) to 64.62% (C1₀). The content of chalcopyrite ranges from 0.18% (St7_{2,9}) to 0.74% (C2₀). The concentrations of the minerals of manganese in the containing samples range from 3.86% (C3₀) to 49.14% (C2₀) while in the St5_{5,5} sample it's not detected at all (0% content). The content of sphalerite fluctuates from 0% (C3₀), 0.89% (St7_{2,9}) to 2.83% (C2₀). The content of arsenopyrite ranges from 0% (C3₀, St5_{5,5} and St7_{2,9}), 0.49% (C2₀) to 2.49% (C1₀). The galena ranges from 0% (C2₀, St5_{5,5} and St7_{2,9}), 0.15% (C3₀) to 1.66% (C1₀). Tetraedritis and voulazeritis present 0% concentrations in all the sampling areas other than C1₀ and C2₀, respectively.

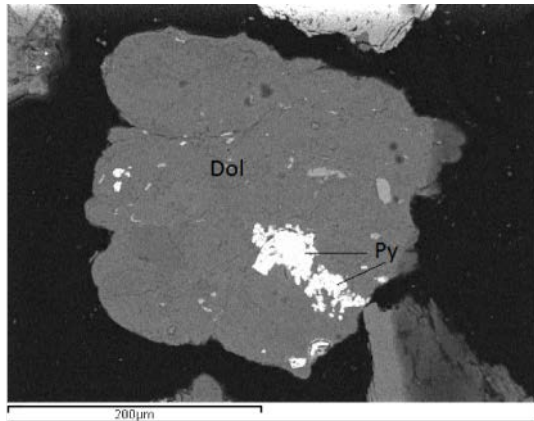


Figure 3: Dolomite (Dol) with inclusions of pyrite (Py), sample St5 (5.5m), picture by scanning electron microscopy (SEM-EDS)

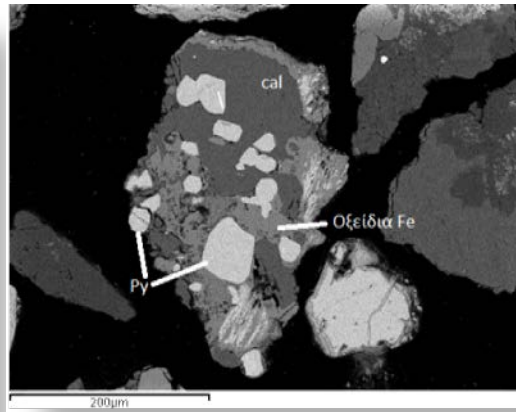


Figure 4: Symphysis Pyrite (Py), Calcite (cal) and iron oxides, sample St5 (5.5m), picture by scanning electron microscopy (SEM-EDS)

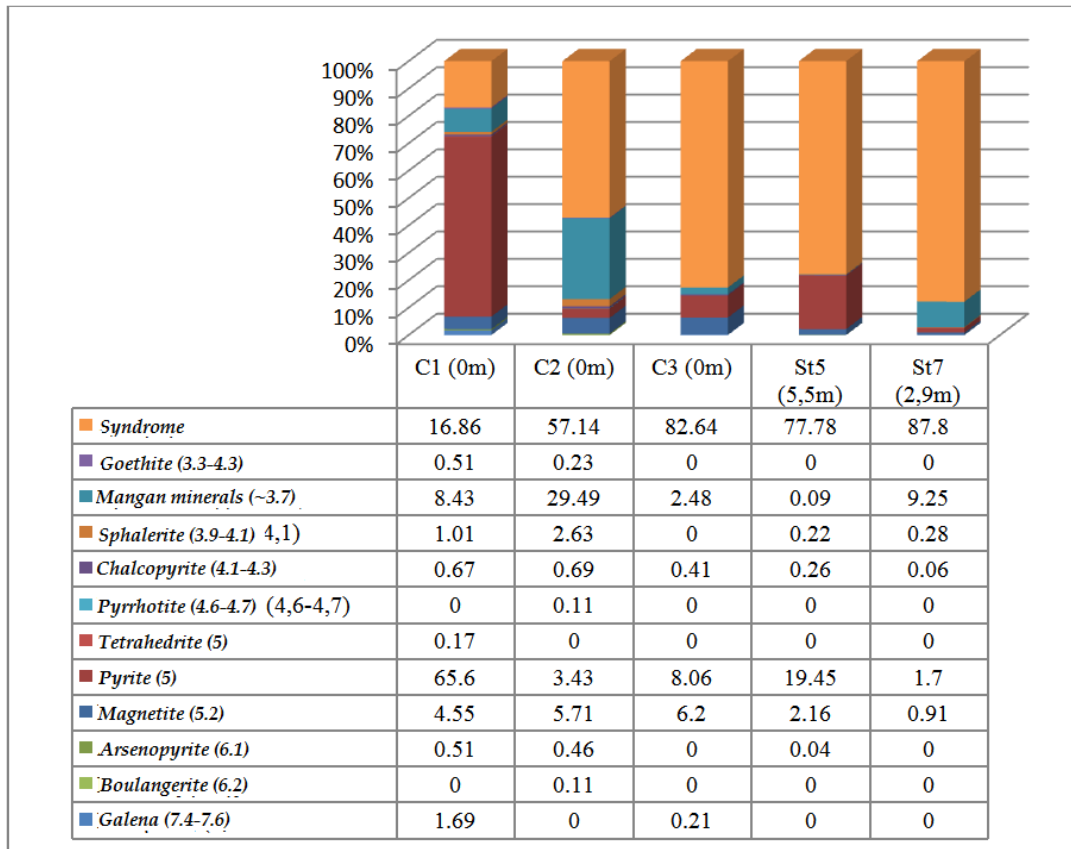
Table 4: Metallic minerals identified in the samples of Gulf Ierissos.

Samples	C1o	C2o	C3o	C5o	C6o	C7o	St15,7	St2a	St35,9	St49,5	St55,5	St62,5	St72,9	St80,5	St92,7	St101,9	St113
Sphalerite	•	•	•					•									
Pyrite	•	•	•					•	•	•	•		•				
Chalcopyrite	•	•	•						•	•	•	•	•	•			
Galena	•	•	•	•						•	•						
Arsenopyrite	•	•	•								•		•				
Galenobismutite	•																
Kesterite		•															
Pyrrhotite		•															
Tetrahedrite	•	•	•														
Boulangerite		•	•														
Ilmenite										•			•				
Goethite	•	•	•														
Magnetite	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Haematite		•	•														•
Mangan minerals	•	•	•				•	•				•	•			•	

Table 5: Non-metallic minerals identified in the samples of Gulf Ierissos.

Samples	C1o	C2o	C3o	C5o	C6o	C7o	St15,7	St2a	St49,5	St55,5	St62,5	St72,9	St80,5	St92,7	St101,9	St113
Barite			•													
Gypsum			•													
Jarosite												•				
Rutile	•		•							•		•				
Titanite	•	•	•		•		•	•			•	•	•	•	•	•
Pyroxene	•	•	•							•		•				
Kaolinite		•						•								
Hornblende		•		•	•	•	•	•	•		•	•	•	•	•	•
Biotite	•				•	•	•	•	•		•	•	•	•	•	•
Chlorite		•			•	•	•	•	•		•	•	•	•	•	•
Muscovite					•	•	•				•	•	•	•	•	•
Allanite/Orthite												•				
Epidote		•		•	•		•		•		•	•		•	•	
Feldspars	•	•	•					•				•				
Tourmaline							•									•
Garnet	•	•	•				•	•	•		•	•				
Zircon												•				
Quartz	•	•	•	•	•	•	•	•	•		•	•	•	•	•	•
Dolomite												•				
Calcite								•								
Rhodochrosite		•								•	•				•	

Table 6: Heavy metal minerals and the percent (%) concentration in the samples area of Stratoni.



With the sedimentation method for the same grain size fractions, the granules' separation according to their specific weight was attempted (Psilovikos and Psilovikos 2010). After the sedimentation of the hose, the samples were divided into 1, 2 or 3 parts of sand consisting of different color and specific gravity. From the base of the settling tube and according to the color separation, extraction of the parties was realized in which the specific weight was determined. The weights of the parts separated, are summarized in Table 7. By calculating the specific weights of the separated parts, an approximate determination of the contribution of heavy and non-heavy granules, based at average weight, is achieved. As indicated by the mineralogical analysis (Tables 4 and 5) two main categories of minerals excel in the samples, those with a specific weight of 3.8 to 7.6 (goethite, Pyrite, Galena) and the ones with a specific weight of 2.6 to 2.8 (Feldspar, pyroxene). It was found that the small contribution in heavy minerals within a granule consisting essentially of non-metallic mineral syndromes, gives an average specific gravity which is very close to the weight of non-metallic minerals (e.g. 2.8 or 2.9). The samples in this category, which gave a large proportion of magnetic grains in the magnetic separator, as shown by the mineralogical analysis consist of silicate grains (Inopyrititika-Soropyrititika-Tektopyrititika minerals) with small black metallic mineral inclusions.



Figure 5: Sample C3 grain size 2.5 Φ separated by sedimentation method in three parts ($\times 0.65$).

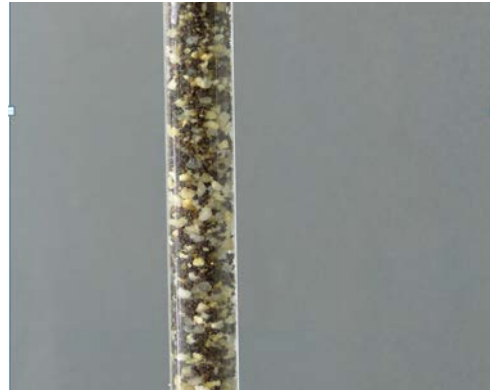


Figure 7: The result of sedimentation experiment for determining aggregate mineral fractions hydrodynamic equivalent fractions rich in heavy minerals, such as shown in Sedimentology tube (detail).

Using the sedimentation experiment it was concluded that non-metallic mineral grains sized - 1 Φ (2mm) and -1.5 Φ (3mm) precipitated along with the granules of heavy minerals, 0 Φ (1mm) and 0.5 Φ (0.707mm). These fractions are considered hydrodynamic equivalent.

From the beginning of the study two main concerns were set to be investigated.

The first concern relates to the question, if the entire quantity of heavy metal minerals found in surface sediments of the bottom, is exposed directly to the seawater of the bay or if there is an amount which is in the form of inclusions in syndromic minerals (e.g. quartz) and therefore do not come into contact with the water of the bay. The chemical analysis of heavy minerals provide pulverization of the precipitate, resulting in all heavy minerals, those that are in contact with water, and those that are enclosed in mineral syndromes, to be counted together.

The second concern which was investigated by sedimentological and mineralogical analysis, is the acceptance or rejection of the finding derived from hydrodynamic models of mathematical simulation. Xatzi (2012) proved that there is actually a mechanism that selectively transports the black sands of the deeper areas of the bay to the coastal zone. In this context the distribution of grain, with high specific weight, at the surface sediments of Ierissos Gulf was investigated.

Table 7: Table of Weight (gr) Specific Gravity (SG), velocity (U) and settling time (t) for the same grain size fractions.

		2Φ (0.25mm)			2.5Φ (0.177mm)			
Samples	Capacity range specific gravity	2.6-2.8 Silicates ***	2.9-3.8 Inclusions-Aggregates	3.8-7.6 Heavy Fractions		2.6-2.8 Silicates ***	2.9-3.8 Inclusions-Aggregates	3.8-7.6 Heavy Fractions
C1-0m	Weight (gr)	0	0.828	4.18		0	0	10.122
	S.G	*	3.345	4.59	**			4.577
	U (m/s)		0.041	0.06				0.096
	t (s)		18.293	12.5				7.813
C2-0m	Weight (gr)	3.03	0	2.151		1.101	0.25	0.637
	S.G	*	3.045	4.45	*	2.85	3.182	4.417
	U (m/s)		0.039	0.058		0.060	0.067	0.093
	t (s)		19.231	12.931		12.5	11.194	8.065
C3-0m	Weight (gr)	2.832	0.736	0.746		0.955	0.595	0.535
	S.G	*	2.793	3.254	*	3.12	3.81	4.29
	U (m/s)		0.019	0.042		0.066	0.081	0.091
	t (s)		39.474	17.857		11.363	9.259	8.242
C5-0m	Weight (gr)	10.001	0	0		0.655	1.564	0.181
	S.G	**	2.782		*	2.908	3.45	3.91
	U (m/s)		0.035			0.061	0.093	0.089
	t (s)		21.429			12.3	8.065	9.036
C6-0m	Weight (gr)	10.178	0	0		10.007	0	0
	S.G	**	2.666		**	2.688		
	U (m/s)		0.033			0.056		
	t (s)		22.727			13.393		
St1-5.7m	Weight (gr)	10.081	0	0		10.111	0	0
	S.G	**	2.78		**	2.884		
	U (m/s)		0.035			0.061		
	t (s)		21.429			12.3		
St2-0.4m	Weight (gr)	2.827	0	1.145		1.903	0.447	1.923
	S.G	*	2.889	4.19	*	2.895	3.381	4.343
	U (m/s)		0.037	0.055		0.061	0.072	0.092
	t (s)		20.27	13.636		12.3	10.417	8.152
St3-5.9m	Weight (gr)	10.014	0	0		10.212	0	0
	S.G	**	2.745		**	2.854		
	U (m/s)		0.034			0.06		
	t (s)		22.059			12.5		
* the sample is separated into 2-4 fractions								
** The sample is not separated								
*** Silicates include Inopyritika, the Soropyritika and Tektopyritika minerals								

Table 7 (continued): Table of Weight (gr) Specific Gravity (SG), velocity (U) and settling time (t) for the same grain size fractions.

		2Φ (0.25mm)				2.5Φ (0.177mm)		
Samples	Capacity range specific gravity	2.6-2.8 Silicates ***	2.9-3.8 Inclusions-Aggregates	3.8-7.6 Heavy Fractions		2.6-2.8 Silicates ***	2.9-3.8 Inclusions-Aggregates	3.8-7.6 Heavy Fractions
St4-9.5m	Weight (gr)	10.077	0	0		10.317	0	0
	S.G	** 2.762			**	2.81		
	U (m/s)	0.034				0.057		
	t (s)	22.059				13.158		
St5-5.5m	Weight (gr)	10.471	0	0		3.182	0.786	0.267
	S.G	** 2.75			*	2.784	3.15	3.889
	U (m/s)	0.034				0.058	0.067	0.083
	t (s)	22.059				12.31	11.194	9.036
St6-2.5m	Weight (gr)	10.064	0	0		10.306	0	0
	S.G	** 2.667			**	2.614		
	U (m/s)	0.033				0.054		
	t (s)	22.727				13.889		
St7-2.9m	Weight (gr)	10.382	0	0		10.063	0	0
	S.G	** 2.706			**	2.754		
	U (m/s)	0.034				0.057		
	t (s)	22.059				13.158		
St8-5m	Weight (gr)	8.153	0	0		10.145	0	0
	S.G	** 2.709			**	2.751		
	U (m/s)	0.034				0.057		
	t (s)	22.059				13.158		
St9-2.7m	Weight (gr)	10.234	0	0		10.558	0	0
	S.G	** 2.656			**	2.684		
	U (m/s)	0.033				0.056		
	t (s)	22.727				13.393		
St11-3m	Weight (gr)	10.072	0	0		10.021	0	0
	S.G	** 2.615			**	2.622		
	U (m/s)	0.032				0.054		
	t (s)	23.438				13.889		
* the sample is separated into 2-4 fractions								
** The sample is not separated								
*** Silicates include Inopyritika, the Soropyritika and Tektopyritika minerals								

The process of separation of magnetic and non-magnetic minerals in the magnetic separator showed that large percentages of each sample were classified in the category of magnetic minerals, although this did not appear macroscopically. The stereoscopic study demonstrated, in a large percentage, the existence of metallic minerals in silicate mineral inclusions. Then sample fractions that passed through the magnetic separator and classified as magnetic (C1₀, C2₀, C3₀, St5_{5.5}, St2₄, St7_{2.9}) were studied at the metallographic microscope and the electronic microscope (SEM-EDS). The purpose of this process was for particular metallic minerals to be identified and to examine more precisely the presence of metallic mineral inclusions in silicate minerals (Tab. 6). However, the results obtained after studying the samples at the metallographic microscope mainly concern the recording of heavy minerals which are not contained in inclusions. It was noted that there are inclusions of metallic, magnetic minerals in sedimentary granules composed mainly of syndromes, non-metallic, non-magnetic, minerals (quartz, feldspar) which are attracted by the magnetic separator and are classified as magnetic mineral grains. The average weight of these grains, as found by the method of precipitation is much smaller than that of pure metallic grains, resulting in different hydrodynamic behavior in the marine environment that determines their transport and deposition.

From the results of the study three charts were produced (Fig. 8, 9, 10), representing the geographic (spatial) distribution of concentration ratios of heavy and aggregate minerals in the Ierissos Bay.

Figure 8 shows the weight ratio of magnetic / paramagnetic grain in the samples, as derived from the magnetic separator. In this figure the significant contribution of grain attracted by the magnetic separator and classified as magnetic is shown. Their distribution shows descending participation from Stratoni to Ierissos, but their presence is detected in all depths that the samples were taken from.

Figure 9 shows the weight ratio of the minerals constituting the composition of sedimentary granules, of small / large specific gravity samples. This figure gives a picture of the overall percentage of participation of all heavy minerals in the area, whether they constitute a homogeneous granule or they exist in symphysis into syndromes, in smaller proportions. The image of the spatial distribution looks very different in comparison to the previous figure. It seems that the large proportion of heavy metallic minerals is concentrated in the coastal zone of Stratoni, where they constitute the majority of the minerals, decreases towards the south of Stratoni and is very small in Ierissos beach. The distribution of heavy minerals in the deeper parts of the bay also shows a significant decrease depending on the depth and that their participation is minimal in the underwater zone Ierissos.

Finally, Figure 10 shows the weight contribution of sedimentary grains depending on their medium specific gravity. As demonstrated by the method of sedimentation an aggregate grain (quartz, feldspar, etc.) with few inclusions of heavy minerals with specific weight, e.g. 2.8, hydrodynamically is classified with the granules of pure non-metallic minerals with specific weight of 2.7. In practice these grains seem to contribute minimally to the pollution because heavy metal minerals are found in the mass of aggregate minerals. Within the coastal area of the Gulf and at depths where wave action simply transfers at low speed the granules, the possibility of their mechanical destruction is very small, consequently Figure 10 shows the areas that are actually exposed to direct contact with heavy metal minerals. Figure 10 shows a very different situation from the previous figures (Fig. 8; Fig. 9). The area of Stratoni and

especially the coastal area near the port loading facilities of the mining company shows a particularly high percentage of metallic minerals that are in direct contact with the environment. The situation is improving dramatically in the southern region of the Bay of Stratoni to the fishing port. It is also quite interesting that in the offshore area in the central part of Stratoni bay elevated concentrations of heavy metal minerals do appear. One possible explanation is that in the central region of the bay there is a very high probability of forming rip currents in periods of very large ripple (Davinson-Arnott 2010). Another striking feature is that at the bottom of the Gulf of Ierissos generally (with the exception of the northern part of Stratoni) granules of large specific gravity do not appear at all. This means that the total of heavy minerals are contained in small amounts as inclusions in non metallic minerals (quartz, feldspar, kg), with minimal exposure to the environment.

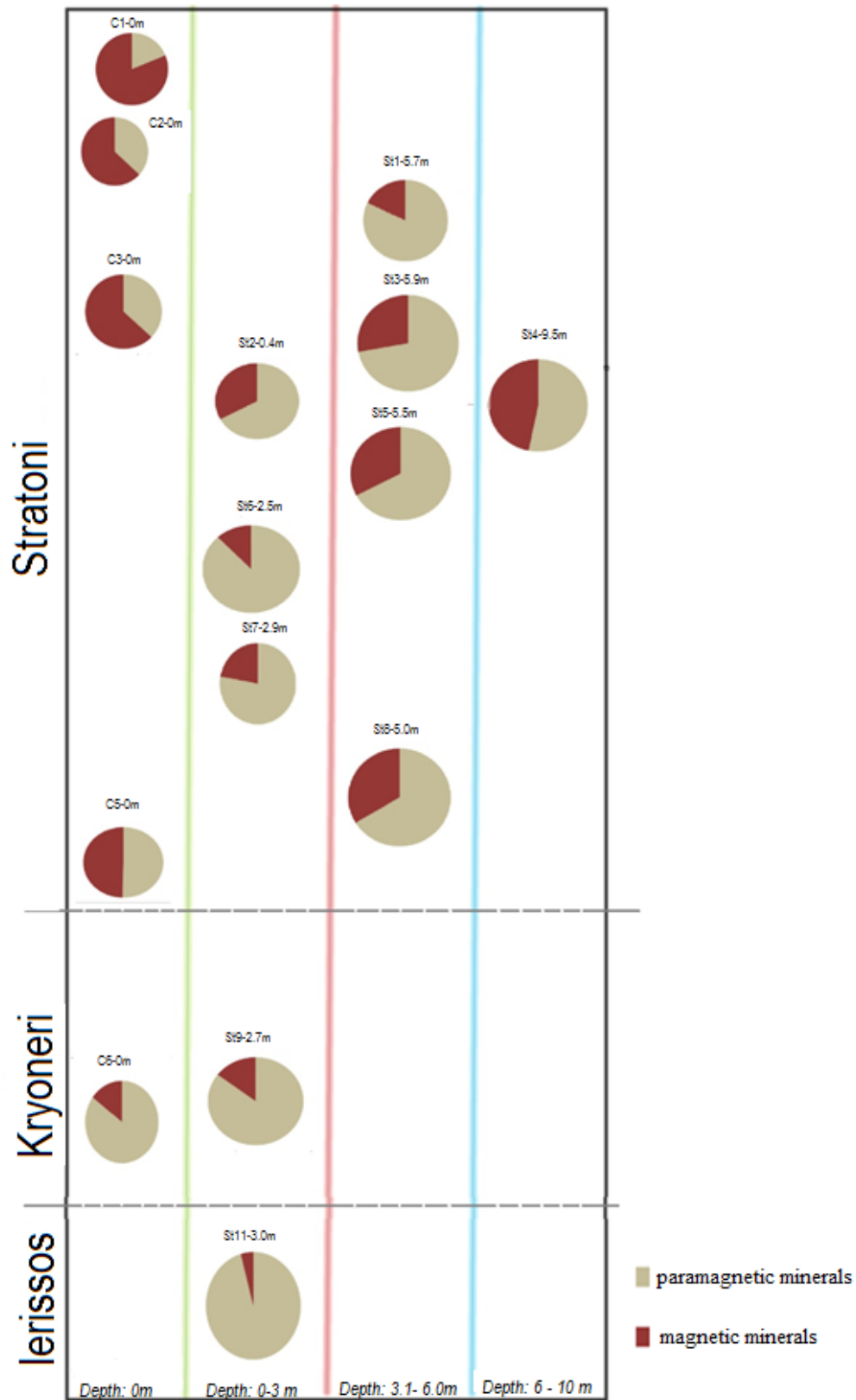


Figure 8: Weight ratio of magnetic / paramagnetic minerals in the samples as revealed by the magnetic separator (without further processing).

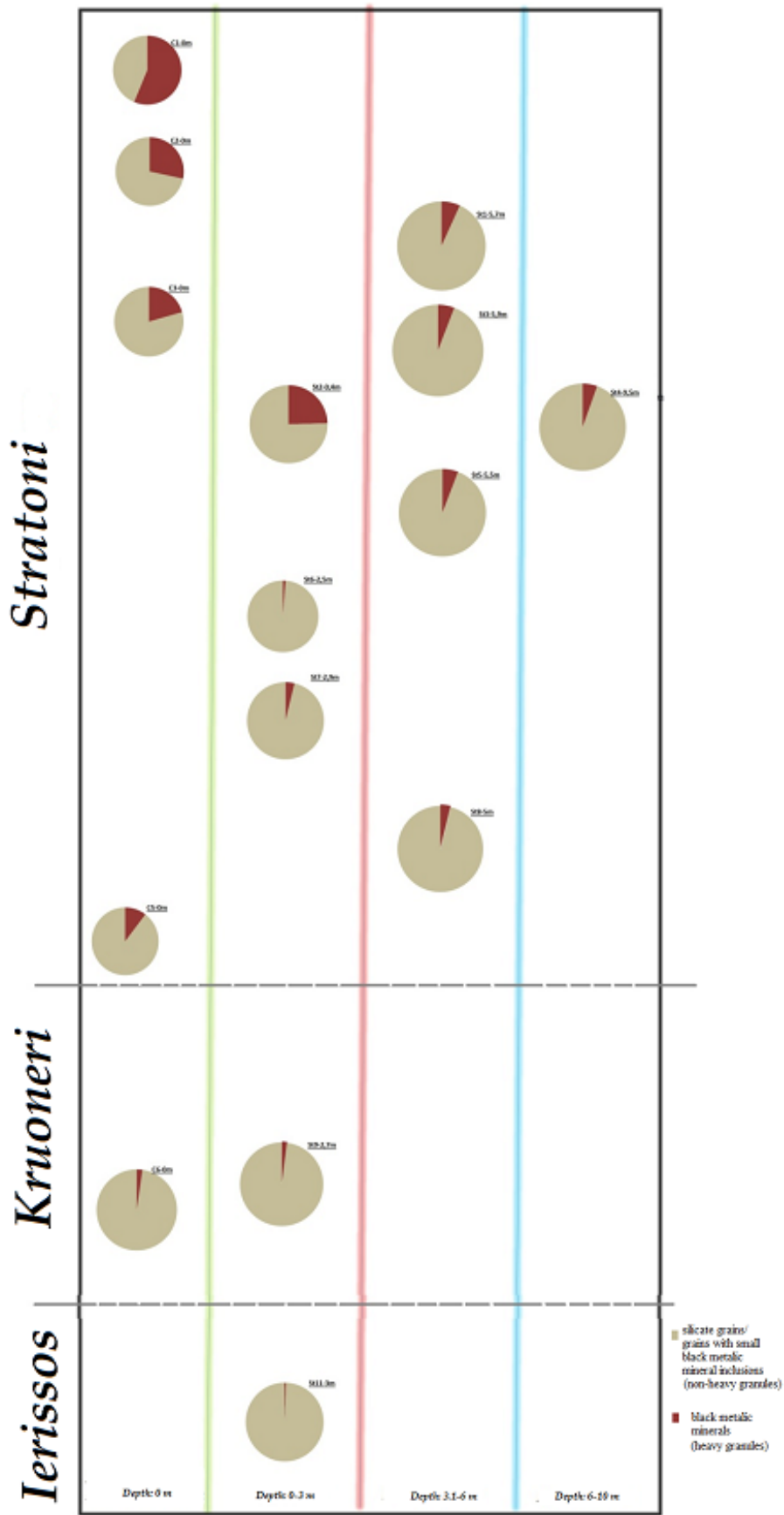


Figure 9: Weight ratio of small/big specific gravity grains (non-heavy/heavy grains respectively) as revealed by the sedimentation method.

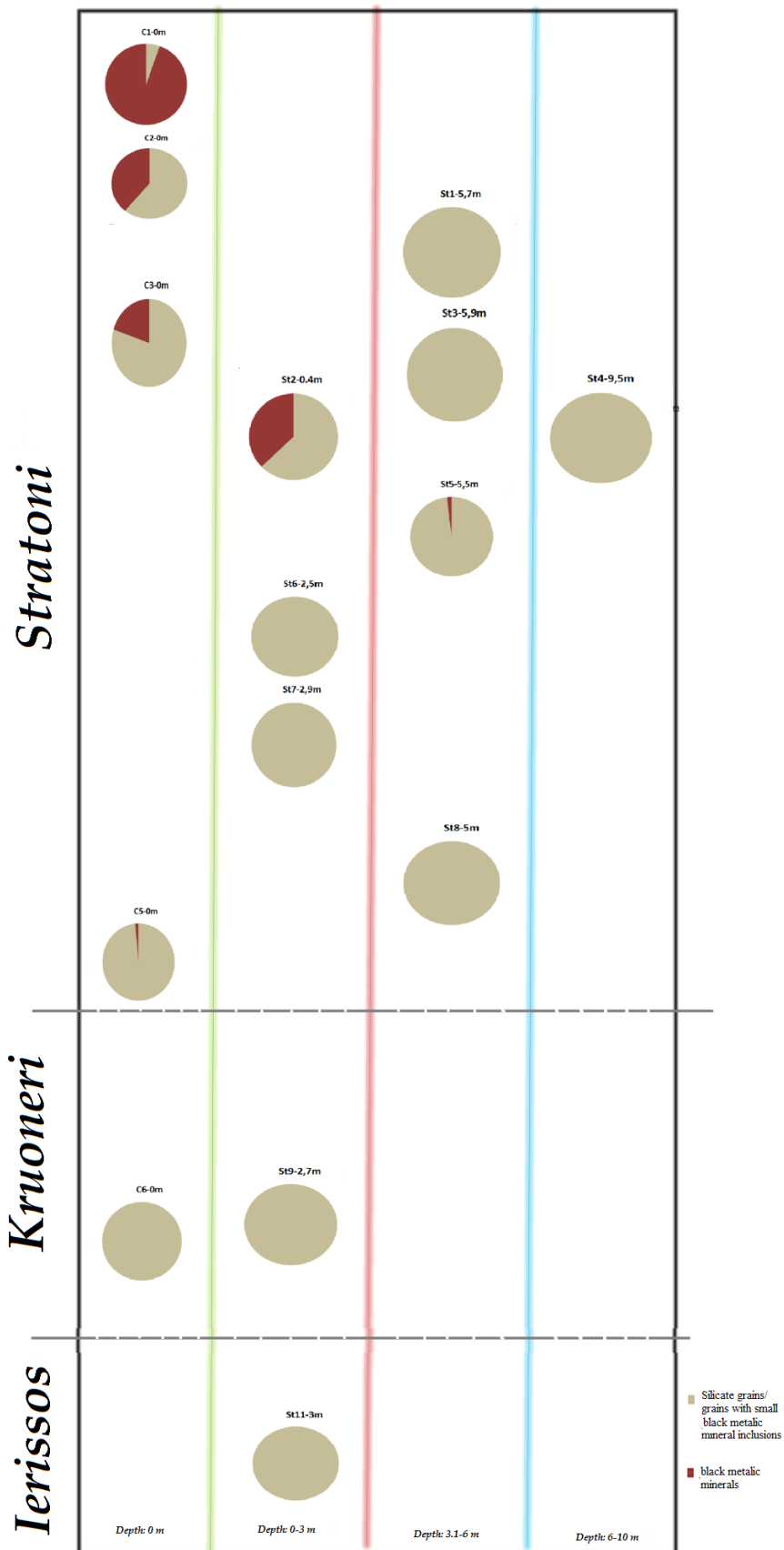


Figure 10: Weight ratio of sedimentary grains according to the average specific gravity.

Conclusions

From the results of the study the sand movement mechanism from the mathematical simulation and the fact that black sands with high specific weight in particular, are carried by the waves in the region from the deepest parts of the bottom to the land-coastal part, is confirmed.

It was proven that a large proportion of metallic minerals are found in small inclusions as content-adhesions and are enclosed by non-metallic minerals, resulting in both the weight of the samples to be small and also the other metallic minerals to not come into direct contact with the marine environment.

The concentration of black minerals decreases with both depth and lengthwise in the Gulf of Ierissos from Stratoni to Ierissos (Figure 10).

The concentration of black sands is limited to the vicinity of the port loading facilities of Stratoni, while the percentage is almost annihilated both at greater depths and with distance from the NW end of the bay of Stratoni (Figure 10).

Sands composed of quartz and feldspars sized -1Φ and -1.5Φ (2-2.6 mm) have equivalent hydrodynamic behavior with sands consisting of heavy minerals sized 0Φ as $+0.5\Phi$ (1-0.7 mm). Therefore as a first approximation, the hydrodynamic equivalent of small specific weight sand with black sands has been investigated, so in possible redevelopment scenarios of the beach, it could replace them, without risk to be removed from the waves.

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