



# Bulletin of the Mineral Research and Exploration

<http://bulletin.mta.gov.tr>



## Sedimentological properties and depositional environments of the Holocene sequence in Yenikapı, İstanbul

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Research Article

### Keywords:

Holocene, Sedimentology, Grain size distribution, Theodosian harbor, İstanbul.

### ABSTRACT

During the salvage excavations in the area of the former Theodosian harbor in Yenikapı-İstanbul several ship wrecks from the Byzantine period, archaeological objects from different periods and a Holocene aged sedimentary sequence have been uncovered. In this study the lithological, lithostratigraphical and facies properties of the Holocene sequence are investigated in detail and its depositional environment is determined. For this purpose along four profiles (S1, S2, S3, S4) 14 different sections of a total thickness of 17.75 m are studied and 100 samples are collected. The grain size distribution and mineralogical composition of the samples are defined by sieve and sedigraph analysis and by XRD method, respectively. Results of these analyses and facies characteristics of this poorly known Holocene sequence are used for the definition of the depositional environment. Accordingly, the marine sediments are deposited in a near-shore environment, with a natural embayment or estuary transgressively. Terrigenous and anthropogenic material carried by the Lycos River, at the mouth of this natural embayment, resulted in first a regression and then a high-energy fluvial system in the study area.

Received Date: 26.06.2018

Accepted Date: 25.09.2018

## 1. Introduction

In the excavations carried out under the management of the Istanbul Archaeological Museum in Yenikapı (Figure 1) for the Marmaray Project, which connects both sides of the Bosphorus with the rail-tube, 36 shipwrecks belonging to the Byzantine Theodosian Harbor and various remains were found (Kızıltan, 2007; 2010; 2014; Asal, 2010; Çelik, 2007; Kocabaş, 2015; Pulak et al., 2015). In addition to numerous wrecks and various archaeological findings, a Quaternary sedimentary sequence, which was encountered in some of the drillings for engineering geology in İstanbul and its vicinity were also uncovered. In the excavation site, there are also Paleozoic and Cenozoic units together with the Quaternary sequence. Here, the sequence from bottom

to top consists of the Trakya formation (Paleozoic), Miocene deposits, marsh clay (Holocene), marine deposits (Holocene), fluvial deposits of the Bayrampaşa (Lycos) River (Holocene), agricultural soil and artificial filling deposits.

The lithological, stratigraphic and geoarchaeological features of these units have been investigated by various researchers (Algan, et al., 2007; 2009; 2010; 2011; 2014; Perinçek, 2010a; 2010b; Yalçın et al., 2015, 2019). The sequence uncovered in the ancient Theodosian Harbor excavation contains important evidences of the Holocene sedimentary environments and their changes. However, the studies on the analysis of sedimentological conditions and depositional environment of the Holocene units were limited in number and scope.

Citation info: Bulut Sezerer, M., Yalçın, M. N., Algan, O. 2019. Sedimentological properties and depositional environments of the Holocene Sequence in Yenikapı, İstanbul. Bulletin of the Mineral Research and Exploration 160, 21-43.

<http://dx.doi.org/10.19111/bulletinofmre.502415>

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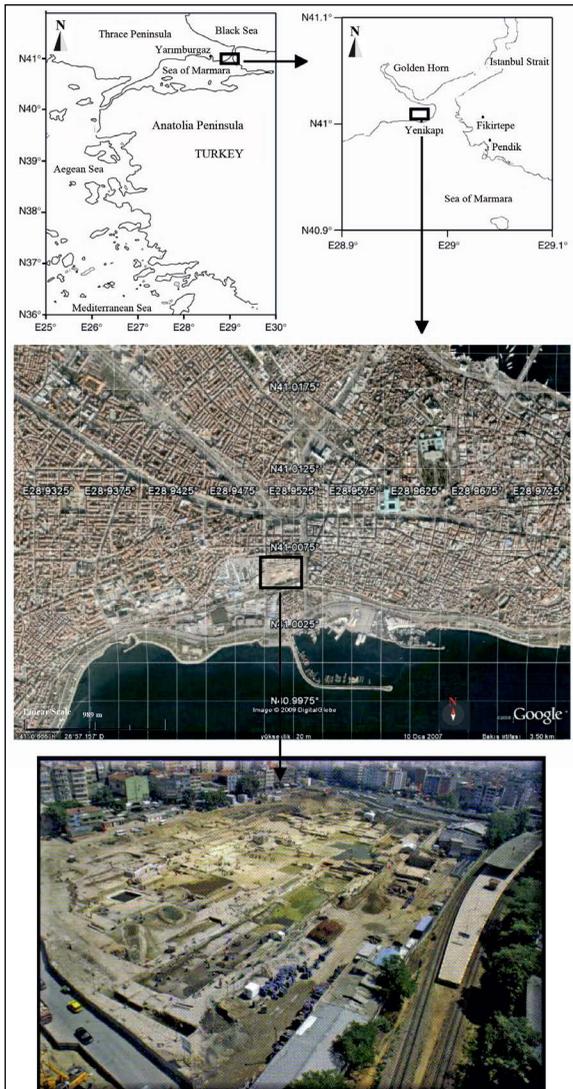


Figure 1- Location map of the study area.

In this study, it is aimed to investigate Holocene marine and fluvial deposits uncovered during the archaeological excavations in detail, to reveal their sedimentological properties and to determine depositional environments.

## 2. Material and Methods

In order to determine geological, stratigraphic and sedimentological features of the Holocene succession, a total of 17.75 m in 4 profiles (S1, S2, S3, S4) were measured in the excavation site, and 100 samples were collected for different analyzes along the sections. The location of profiles in which the section measurements are made and the samples collected are shown in figure 2.

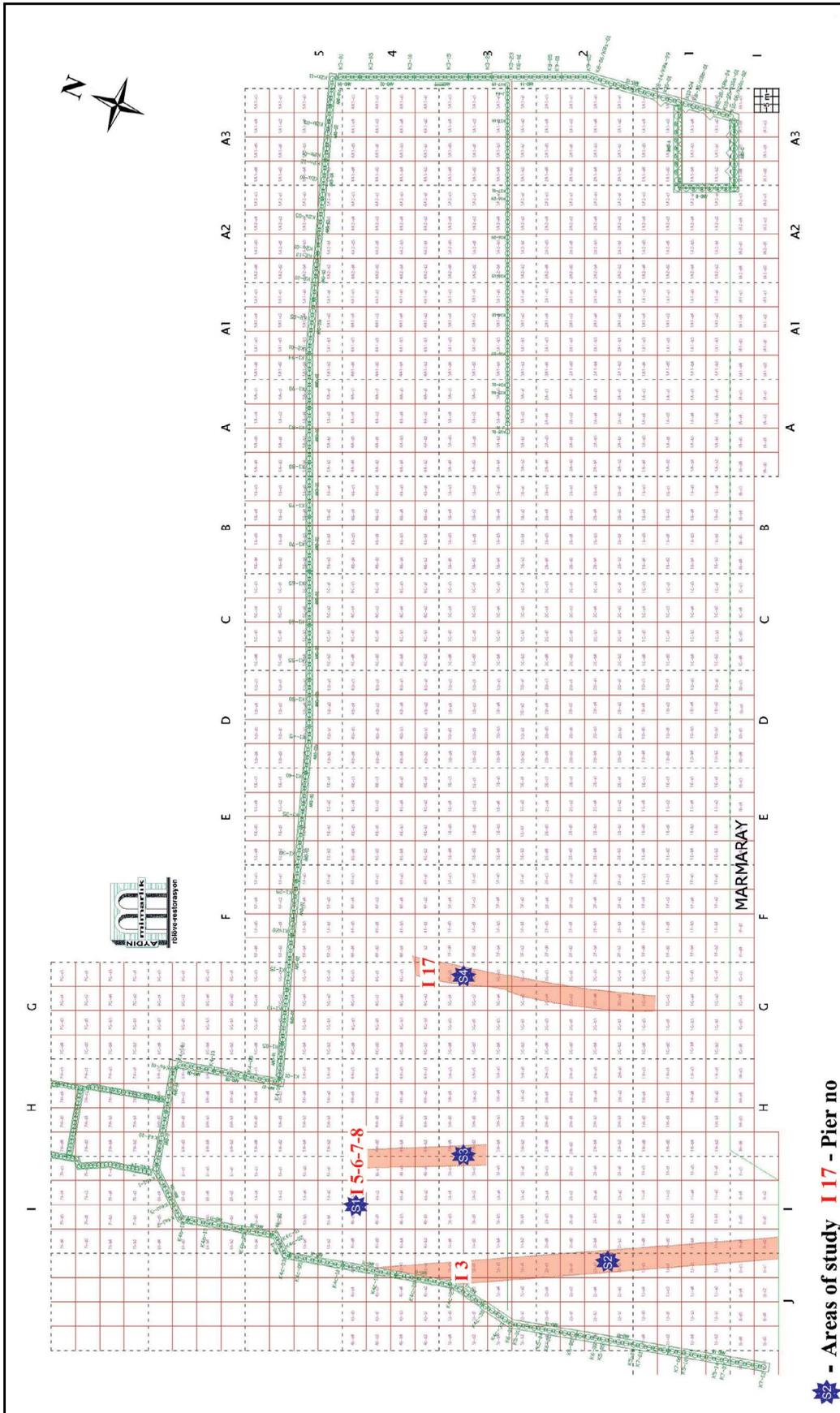
In order to determine the grain size distribution of samples, the sieve analysis for the grain size between (-8) and (4)  $\phi$  and Micromeritics Sedigraph analysis for the grain sizes between (4) - (10)  $\phi$  were performed. For this purpose, the coarse fraction (-8 to 4  $\phi$ ) was divided into different sizes by the sieve analysis, then their percentage amounts were estimated by weighing them. Fine grain size (4 to 10  $\phi$ ) group was analyzed on the Micromeritics Sedigraph device and the grain size distribution was obtained. As a result of these two analyses, the grain size distribution in the range of 256-0.001 mm was determined.

In order to determine mineralogical composition of the rocks, representative samples of each unit were milled and analyzed by X-ray diffractometer (XRD) Philips PW-1430 in the Mineralogy and Petrography Laboratory of the Geological Engineering Department of Istanbul University. In this device, the Cu K $\alpha$  radiation was performed using Ni filter, 36 kV voltage, 20 mA current,  $2\theta = 1^\circ/d$  goniometer speed and at certain C.P.S. sensitivities. For each sample, the measurement was made between  $2\theta$  values in 5-65 ranges.

The results of XRD analyses can be evaluated in two ways as qualitative and semi-quantitative. The quantitative/semi-quantitative method is not very reliable as different crystal systems have different diffraction properties. In addition, the errors due to overlapping of instrumental conditions and some pixels are also effective in the evaluation (Hooton and Giorgetta, 1977). Therefore, it is tried to eliminate these errors with various factor calculations (Hooton and Giorgetta, 1977). In this study, though it is not very detailed, an assessment was made in order to make an approach to the mineralogical composition of the samples without making a factor estimation according to the abundance of samples. In this evaluation, the peak intensities of all minerals in the sample were determined based on peak heights obtained as a result of XRD analysis. Then, using the direct proportions between the peak heights of the minerals in each sample, the mineral percentages from the highest to lowest peaks were determined. Thus, a ranking was made according to the abundance of minerals in the composition of each sample.

## 3. General Geology

The rock assemblages outcropping in Yenikapi, located on the southern margin of the Historic Peninsula



**★ - Areas of study I 17 - Pier no**

Figure 2- The locations of the piers (I3, I5-6-7-8, I17) studied in the excavation area and the sections examined in these areas (S1, S2, S3, S4) (used under the permission of the Directorate of Archaeological Museums).

in Istanbul, are composed of Paleozoic and Cenozoic units (Figure 3). The Paleozoic Trakya formation is represented by sandstone, siltstone, claystone alternation and forms the basement in the study area. After a long gap, the Çukurçeşme, Güngören and Bakırköy formations were distinguished (Gedik and Aksay, 2002) in Miocene deposits unconformably overlying the basement. The Çukurçeşme formation is composed of greenish gray, silty sandy clays consisting of yellow to beige sand and clayey sand bands. The Güngören formation is composed of greenish gray, clay laminated in places and contains sandy silty levels. These two formations are overlain by the Bakırköy formation which is composed of Mactra limestones with clay interlayers. The Belgrad formation, which is composed of red to brown and yellow pebbles and sands, and the Kuşdili formation consisting of blackish gray pebble, sand, clay and muds overlie the older units with an angular unconformity. At the top, the fluvial deposits and artificial fillings are confined to stream or river valleys exist.

Paleozoic and Cenozoic rock units are only partly represented in the study area and its vicinity. Therefore, only the units in Yenikapı and its vicinity were introduced in this study. The unit called as the basement rock in the Yenikapı excavation site is the Early Carboniferous Trakya formation forming the uppermost part of the Istanbul Paleozoic sequence. Although this unit did not naturally outcrop in the study area, it was encountered during excavations. The Trakya formation is generally composed of grayish, lead-green and brown greywacke and shales and is thin-medium-thick bedded. The lower boundary of the unit was not encountered in shallow drillings excavated for foundation and engineering geology purposes. There is an unconformable relationship with the overlying Güngören formation.

Among Miocene units, the unit outcropping in the Yenikapı excavation site is the Late Miocene Güngören formation. The unit has also large exposures in the study area. The Güngören formation consists of light green and yellowish green claystone, siltstone,

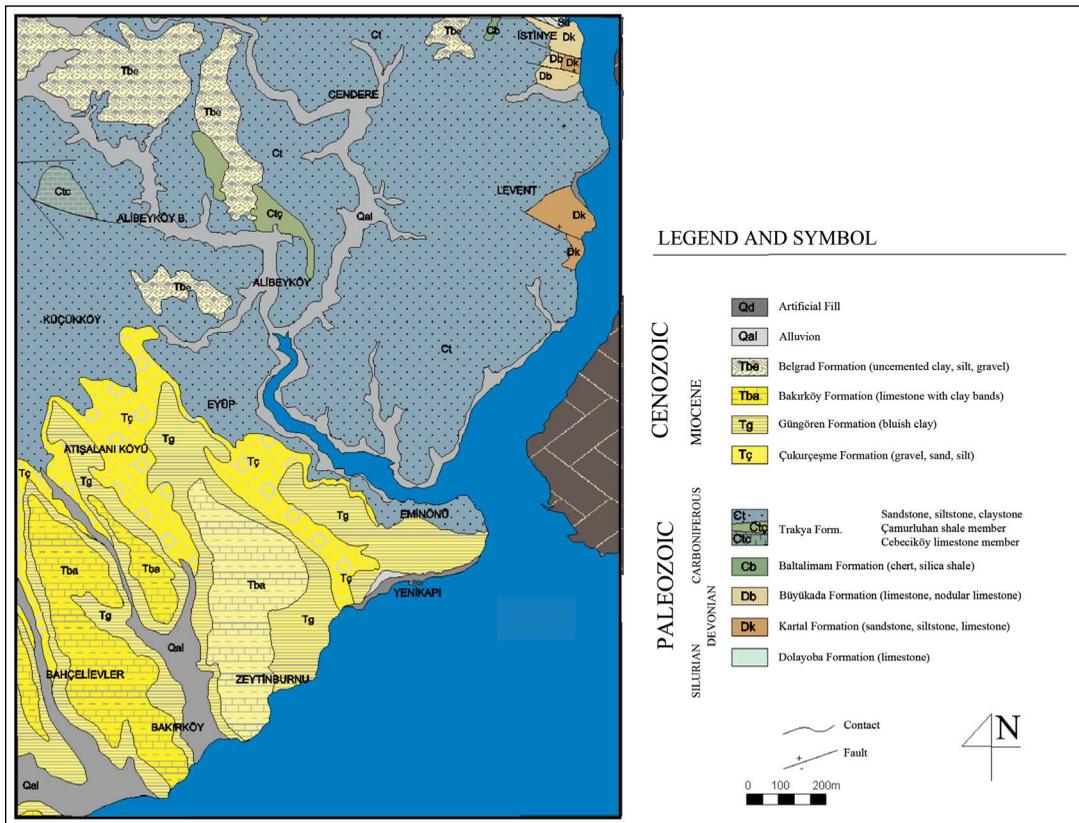


Figure 3- General geology map of the Yenikapı area and its vicinity (Sayar, 1977; Gedik and Aksay, 2002; Gedik et al., 2005; Algan et al., 2011) (The geology map for the Anatolian side was not shown, instead this region was shown with symbol).

sandstone and limestone layers. There are also observed plant stems, leaf traces, silt and sand lenses in clays. In the study area, the upper and lower contacts of the Güngören formation are unconformable. The unit is overlain by the Holocene marine unit (Kuşdili formation) and/or dark colored clay unit.

The clay unit consisting of dark gray, black and rarely brown homogeneous fine clastic sediments overlying the Güngören formation is observed in a limited area in the study area. The black clay unit has a maximum thickness of up to 9 m in the area and thins out towards the edges. The dominant lithology of the unit is clay, and lamination or layering was not distinctively encountered. In the uppermost part of the unit at the contact with the marine unit, sand fillings in cracks are observed as a result of activities of marine organisms living on the sea floor and/or due to the drying. In the lower parts of the sequence, sandy levels and sand mats are observed developed as local and small-scale channel fills (Yalçın et al., 2015).

The Holocene sedimentary sequence overlying the Miocene Güngören formation and the black clay in occasions can be divided into two units as marine and fluvial. The Holocene marine unit begins with gray, white coarse gravels, and continues with light yellow to beige sand with shells and sand, sandy silty clayey sand and consist of occasionally scattered fragments of amphora, ceramic, bone, glass and coins belonging to 5<sup>th</sup>-7<sup>th</sup> centuries (Kızıltan, 2010; 2014; Algan et al., 2011). The overlying unit is a typical fluvial deposit composed of badly to medium rounded cobbles, pebbles and coarse sands. Several ceramic pieces and anthropogenic materials belonging to 8<sup>th</sup>-11<sup>th</sup> centuries were found in it (Kızıltan, 2010; 2014; Algan et al., 2011). The artificial infill located on top of the succession contains the fillings of the Byzantine and Ottoman Periods, the agriculture soil, and the residues of concrete-rubble in the near term (20<sup>th</sup> century) (Figure 4).

#### 4. Holocene Sedimentary Sequence and its Properties

Holocene sedimentary deposits will be studied under titles of lithostratigraphy, lithological features, mineralogical composition, grain size distribution, fossil content and sedimentary structures. The sequence begins with different sizes of gravels and passes in upward direction to yellow to beige, fine grained sand and fluvial coarse sand and pebble at

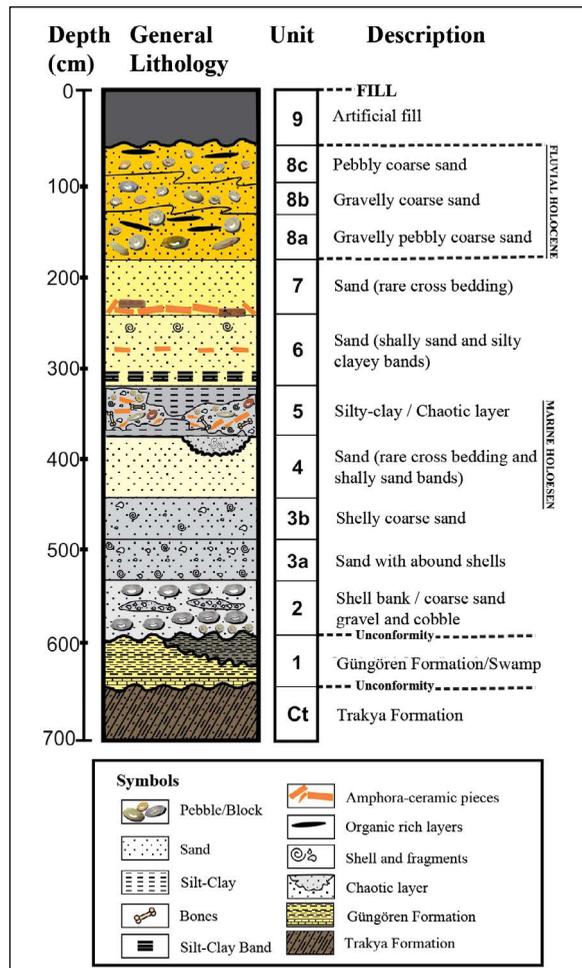


Figure 4- Generalized stratigraphical section of the Yenikapı sedimentary sequence.

the top. The Holocene sedimentary sequence was investigated separating them into 7 sub units from bottom to top as a result of detailed studies (Units 2-8).

#### 4.1. Lithostratigraphy

The stratigraphy and lithological features of the Holocene sequence are presented below from old to young. The bottom of the sequence consists of the Miocene Güngören formation and Holocene marshy clay called the Unit 1 (Figure 4).

Unit 2 (bottom clastics) begins to deposit with light yellow to beige, coarse sand and/or blocks-coarse cobbles-pebbles and consists of medium to coarse grained sand, sand lenses with many shells and shell fragments that have no lateral continuity and coarse pebbles and blocks forming a second level (Figure 5). Angular, flat, large pebbles and blocks consisting

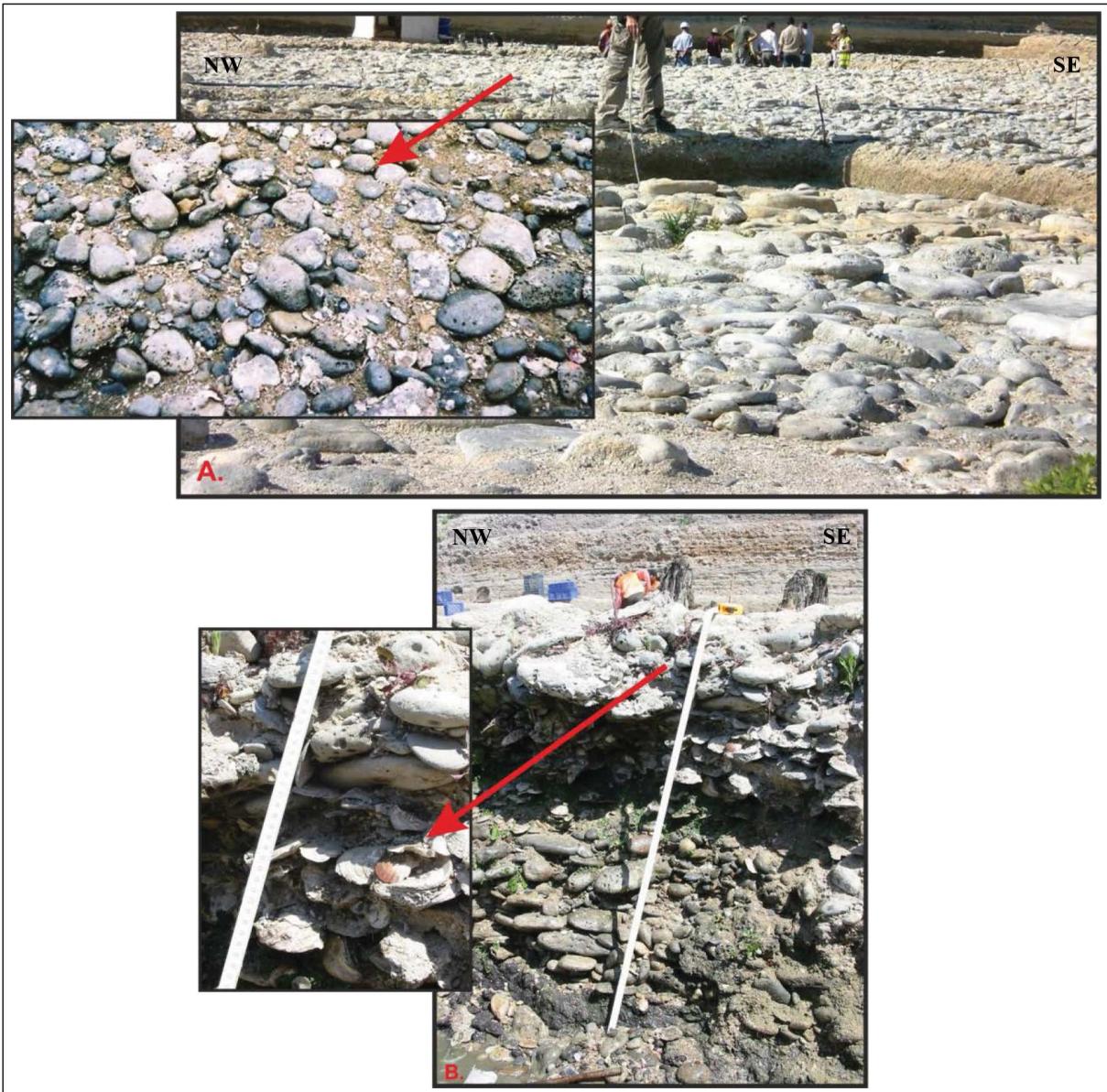


Figure 5- Flat block and coarse pebbles (A) observed in two levels, and rounded pebbles with coarse shells presenting imbricated structures (B) in Unit 2.

of bioperforation holes appear at the bottom of Unit 2. The presence of bioperforation holes of a marine benthic fauna on these blocks and pebbles, arranged in two levels, indicates that they have remained in the marine environment for a long time. These pebbles are derived from the Paleozoic-Cenozoic rocks in Istanbul (Algan et al., 2010). Yalçın et al. (2015) stated that the functional purposes of these very large and angular blocks could be recognized despite the sea and/or wave effect, that they could have been carried by human hands and used in the Neolithic period buildings. In addition, there are smaller (nearly 10 cm), rounded basal pebbles, which could present

imbricated structures and were transported by the sea transgressing landward due to the rising sea level on the black clay here (Yalçın et al., 2015). The unit overlies both the Miocene Güngören formation and the black clay in the study area. The total thickness of this coarse pebble and blocks, the sand in between and the lenticular sand layer that have not any lateral continuity is about 25-50 cm. The pebble ratio decreases to the south towards the sea and the first level pebble and sand layer intertongue with each other and the second level smaller pebbles directly overlie the basement.

Unit 3 (sands with shells); begins with 30-70 cm thick coarse sand (3a) with many shells and shell fragments then grades into coarse sand unit (3b) of which its sand amount reaches nearly 30-60 cm and consist of disseminated shells. In studied profiles (S1-S2-S3-S4) oxidized layers as thin bands were observed on the upper section of the unit 3 (Figure 6). These levels, which are especially oxidized in profiles S3 and S4, are very prominent. This is due to paint of sands of the unit 3 at the bottom as a result of the oxidation of materials such as amphora etc. in unit 4 located on top of the Unit 3.

Unit 4 (Sandy level) is a light yellow, coarse sandy unit and contains locally silty, clayey layers, small scale cross beddings and occasionally clay-mud pellets. Particularly, at the lower parts of the unit there are abundant shell lenses, few amphora pieces, bone and rotten wood fragments and rare pebbles (Figures 6 and 7). Although the thickness of Unit 4 shows variations laterally in short distances within the study area, it generally varies between 50-100 cm.

Unit 5 (Chaotic level) is composed of silty-clayey sands with an erosional bottom and a chaotic association of a complex depositional process. Unit 5 is formed by chaotic levels in S1, S2 and S4 profiles, however this level is observed within a fine grained matrix in the S3 profile. This chaotic unit contains plenty of amphorae-ceramic pieces, animal bones, coins, broken or fully preserved glassware, marble pebble and blocks. These ceramics and amphorae belong to the 5<sup>th</sup> and 7<sup>th</sup> centuries (Algan et al., 2011). The thickness of Unit 5 generally varies in 20-50 cm's in the studied S 2-3-4 profiles, whereas the thickness of the S1 profile (north of the S2-3-4 profiles) does not exceed 20 cm (Figure 7).

This unit, which is formed by a complex depositional process is a tsunami deposit of the earthquake in 557 AD according to Perinçek (2010a) and Bony et al. (2011). Algan et al. (2011), though not ignoring the possibility of flood or tsunami, stated that this material was subsided as a result of daily activities within the Byzantine Theodosian harbor. Yalçın, et al. (2015) indicated that there was needed more data to understand the depositional mechanism, and it was unlikely that there would be a usual port fill when the unit's characteristics and chaotic structure had been considered. They also suggested that a flood that would drag all sorts of materials into the sea would create a

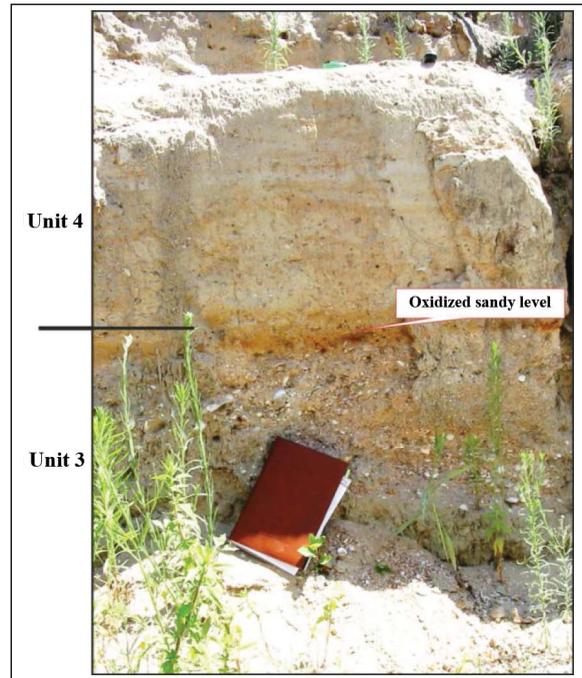


Figure 6- View of Units 3 and 4 in the field.



Figure 7- View of the level containing chaotic-anthropogenic additives in Unit 5 in S1 profile located in the northern part of the study area.

similar set of sediments. Göktürk et al. (2011) showed that rainfall was effective in the mentioned period. Pearson et al. (2012) and Kuniholm et al. (2014; 2015) stated in the light of dendrochronological data that chaotic unit was younger than 557 earthquake which was thought to cause tsunami. It is concluded that there is a need for new data to clarify the process leading to the deposition of Unit 5.

Unit 6 (silt and clay interlayered sands with shells) consists of light yellow to beige, fine grained sands. There are lenticular layers composed of shells and silty-clayey bands in places (Figure 8). The transition between the Units 5 and 6 is gradational. Because the

Unit 6 has been removed earlier than this study during the archeological investigations carried out in the study area in S2 and S4 profiles, it was observed only in S1 and S3 profiles. The thickness of the unit in the study area reaches up to 100 cm.

Unit 7 (sparsely cross-layered sands) begins with amphorae-ceramic fragments, pebble and blocks at the bottom and passes into homogeneous light yellow, medium to fine grained sands with similar characteristics to the Unit 6 in the upper parts (Figure 8). In sandy layers of the Unit 7, the cross stratifications and silty-clayey bands can be seen as well . The amphorae and ceramics at the bottom of this unit belong to the 10<sup>th</sup> and 11<sup>th</sup> centuries (Algan et al., 2007). According to Perinçek (2008), the shores of Istanbul were subjected to the influence of two big storms in the 10<sup>th</sup> and 11<sup>th</sup> centuries, and these pottery levels were formed as a result of storm waves. The unit was observed only in S1 and S3 profiles due to the previous archaeological excavations and has a thickness of 40-70 cm.

Unit 8 (coarse clastics), named as the fluvial Holocene, conformably and gradually overlies the sequence representing the Holocene marine units ranging from Unit 2 to Unit 7 (Figure 4). The fluvial Holocene unit is generally represented by yellow to brown, coarse grained deposits of natural clastic and anthropogenic material transported by the Lycos River. The Unit 8 is divided into three sub units as; 8a, 8b, 8c (Figure 9). Unit 8a is composed of coarse grained sand with well to medium rounded coarse pebbles that does and/or does not offer gradation based on the location. The overlying Unit 8b consists of well-rounded pebbles and granules at a certain level

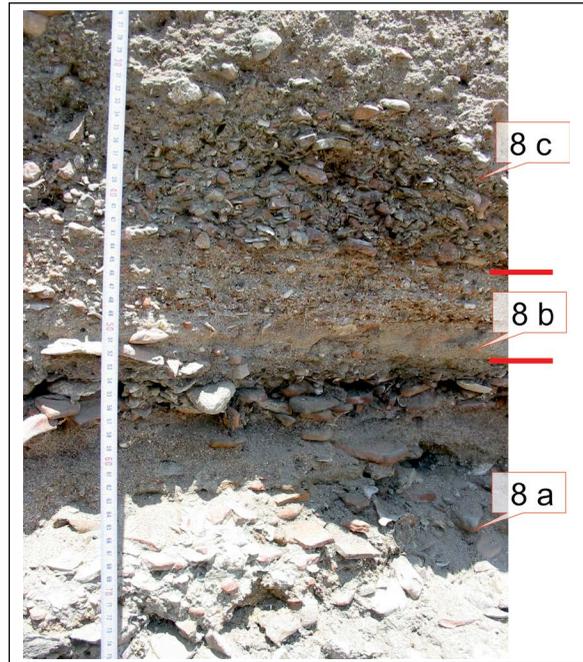


Figure 9- The view of lithological properties of three sub Units (8a, 8b, 8c) of the Unit 8 in S1 profile.

and well sorted sands better than the Unit 8a. At the topmost level 8c the grain size increases. The unit is represented by well-poorly rounded pebbly coarse sands. Unit 8 is usually red, black and beige in color. It also includes fine, well-rounded ceramics, pottery, bones and shells, and thin levels rich in black organic matter. The unit is then overlain by an artificial fill (Unit 9, soil cover). The average thickness of the fluvial unit in the study area is 1 m. It was determined that the thickness increases towards the west of the study area.

#### 4.2. Lithological Properties

The results of sieve analyses of the samples collected from the studied S1, S2, S3 and S4 profiles were used in order to redefine the lithological definitions based on macro observations given above as numerical data. In this context, the results of sieve analysis of the samples collected from each unit were evaluated with the help of Folk and Ward (1957) diagrams. In these ternary diagrams, gravel (G) -sand (S) - mud (M) percentages are used to determine coarse grain content and the sand (S) - silt (Z) - clay (C) percentages are considered for fine grained content. Figures 10a and 10b illustrate the ternary diagrams for each profile and lithologies of the units.



Figure 8- The views of Unit 6 and its silty layers, and the bottom layers of Unit7.

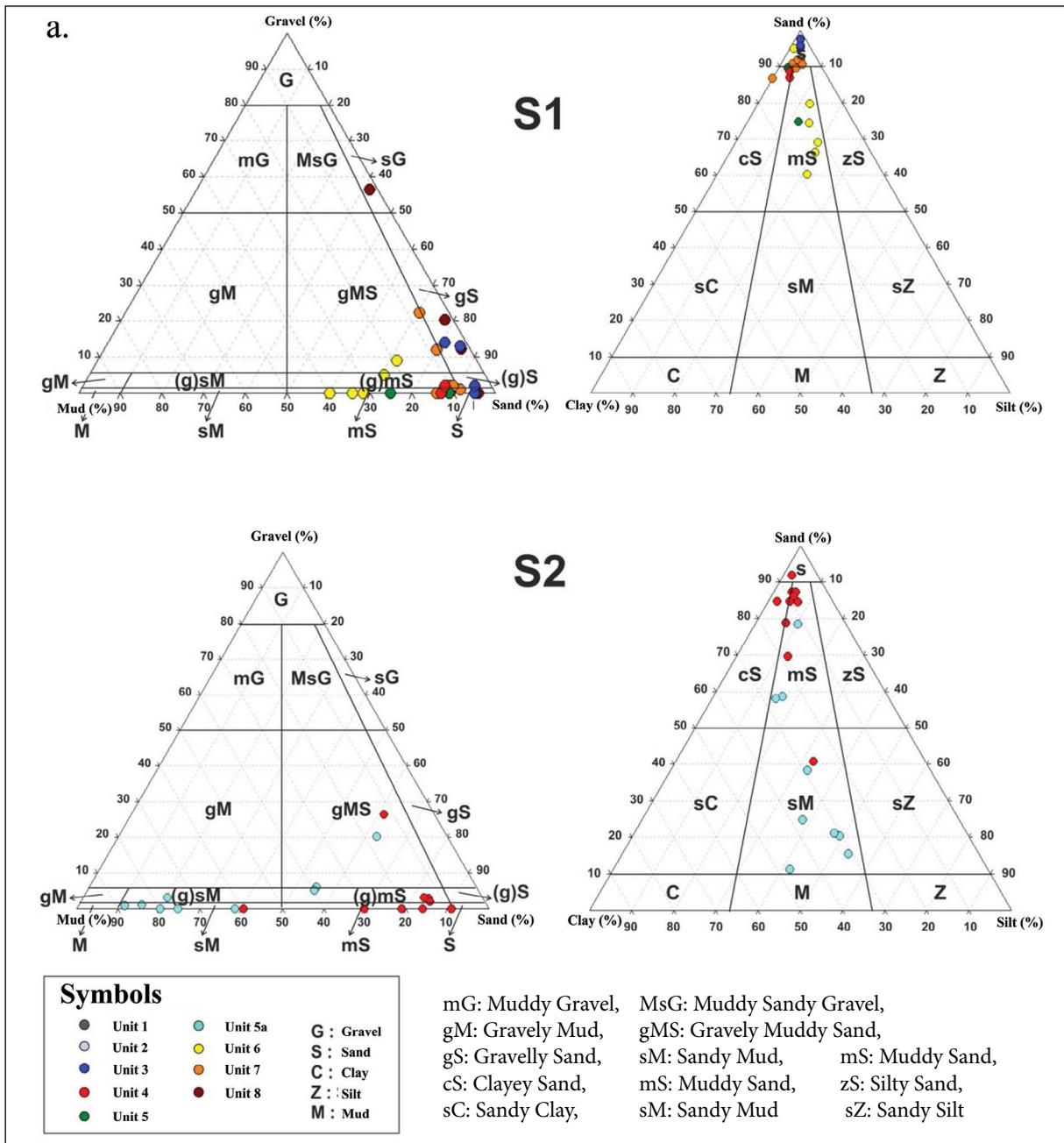


Figure 10- a) Descriptions of marine and fluvial Holocene sediments for each unit in S1 and S2 profiles in ternary diagrams of Folk and Ward (1957).

According to figures 10a and 10b, the Unit 2 is represented by blocks and coarse pebbles due to the grain size greater than 8mm. The dominant lithology in Unit 3 is pebbly sand and sand. Depending on the decrease in the grain size starting from Unit 4, the lithologies such as sand, clayey-silty sand, silty-clayey sand, sandy-silty clay and sandy mud come to the fore in later units. The marine phase ends with the dominant lithology of sand, clayey sand of Unit 7. Starting with the pebbly sand, the grain size,

which first thins out then becomes thick towards the end, indicates that the deposition, which began with shallow and high energy environment then turned into a lower energy environment and then again became a high energy environment. In the continuation of this process, the dominant lithologies defined as the fluvial Holocene in Unit 8 indicate that the energy of the environment further increased and the deposition period was completed.

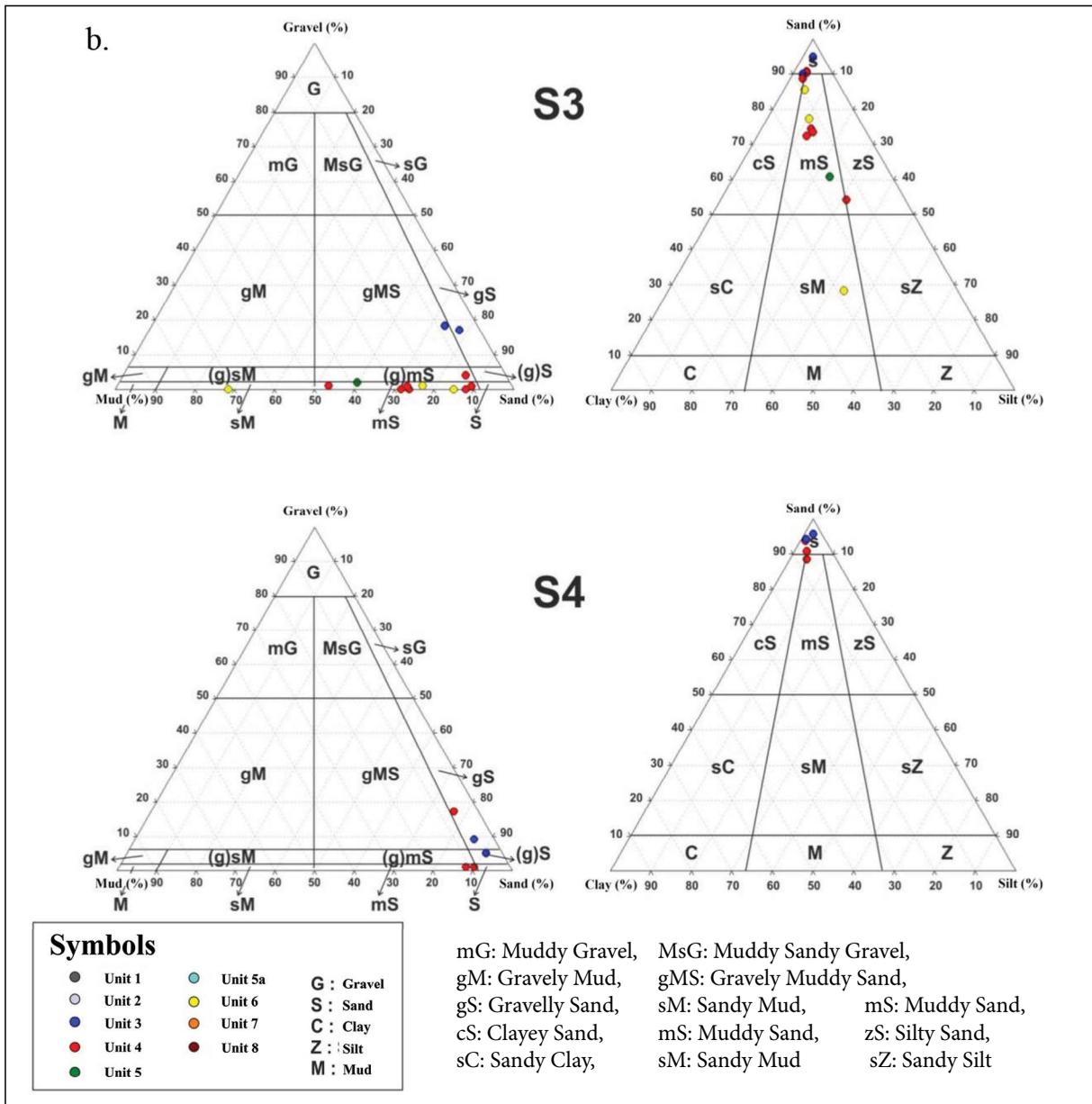


Figure 10- b- Descriptions of marine and fluvial Holocene sediments for each unit in S3 and S4 profiles in ternary diagrams of Folk and Ward (1957).

### 4.3. Grain Size Distribution

In order to evaluate the energy level in a depositional environment and interpret the mechanisms effective in deposition, the grain size distribution of the units is utilized (Spencer, 1963; Blott and Pye, 2001). In this study, the grain size analysis was performed for representatively selected 62 samples from 100 specimens collected from the Holocene units. The samples were collected along the profiles S1, S2, S3 and S4 to represent differentiated units. The grain size distributions determined according to the results of

the sieve and sedigraph analysis will be presented by means of histogram and total cumulative grain size curves on the basis of units. Although such diagrams were prepared for all of the 62 samples, only one or two representative diagrams for each unit will be mentioned.

Since the Unit 2 at the bottom of Holocene sequence is composed of block and coarse pebbles, this unit was not evaluated in terms of grain size characteristics.

Unit 3 was evaluated using 8 samples collected from S1-S3-S4 profiles. The grain size distribution in these 8 samples does not differ significantly and the fine grained sand ( $\phi=3$ ) with a share of approximately 45% constitutes the dominant grain size. In the light

of histograms, it was found that the samples of Unit 3 exhibited a unimodal distribution (Figure 11). This shows that there is a single mechanism controlling the grain size in the depositional environment. In this context, it should be noted that the material in the neck

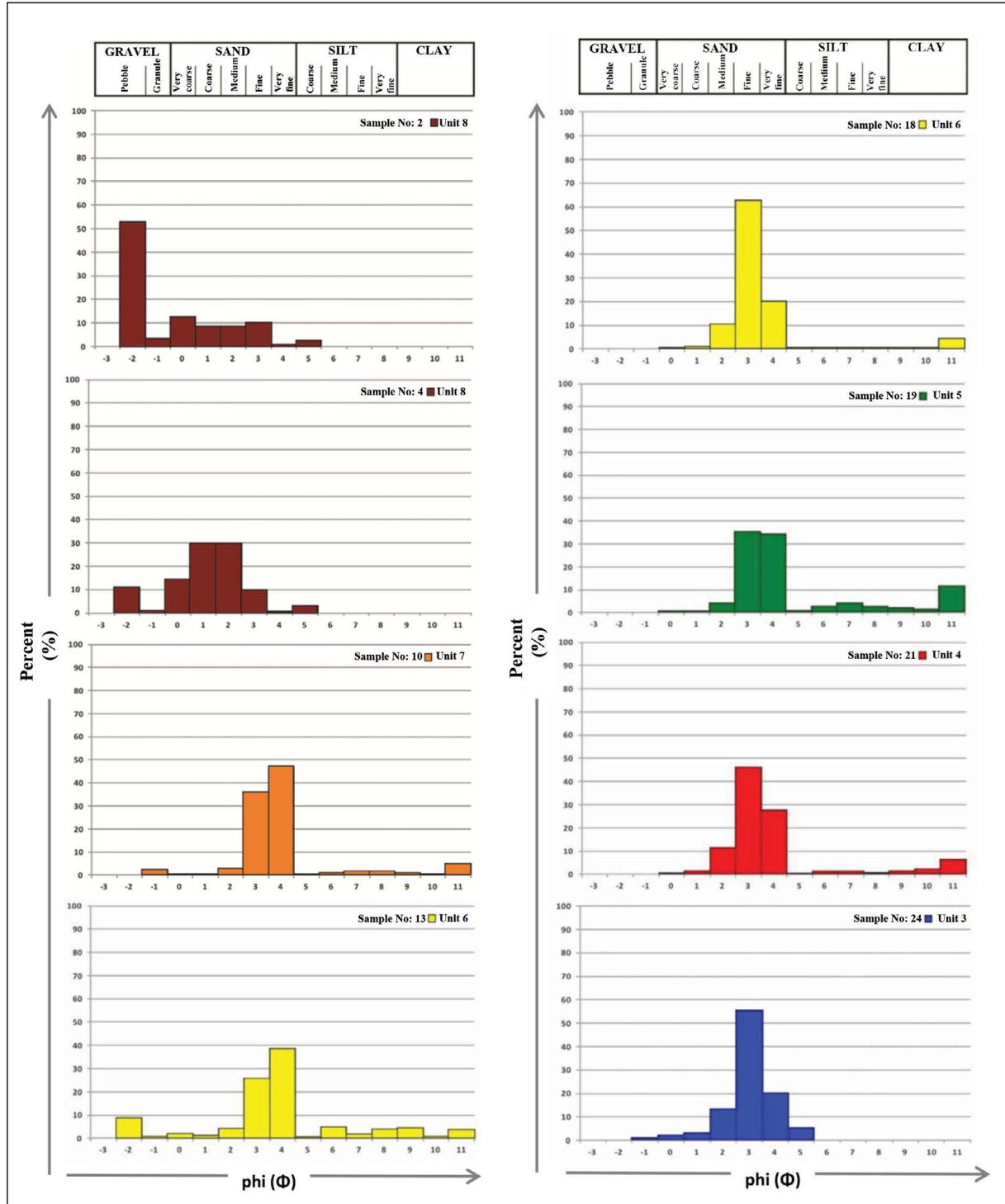


Figure 11- Grain size distributions of the samples selected to represent different units.

of fine grained pebble-granule ( $\phi = -1$ ) with less than 10% in profiles represents shells and shell fragments in the unit.

The analysis of grain size distribution of the Unit 4 was performed for 22 samples collected from S1, S2, S3 and S4 profiles. As a result, the dominant grain size of Unit 4 was determined as fine to very fine grained sand ( $\phi = 3$ ,  $\phi = 4$ ) with a share of approximately 50% to 40% (Figure 11).

Unit 4 contains about 10% of clay and lesser amounts of silt grain size fractions in places, reflecting the silt and clay bands in the unit. For this reason, a bimodal distribution can be recognized in histograms, though not very clear and this can be interpreted as an indication that material has come from two different sources. Especially the increasing pebble ratio (5-10%) in the samples taken from the lower levels of the Unit 4 in S2, S3 and S4 profiles belong to the level containing pebble, marble piece and shell fragments at a level at the bottom of Unit 4. It should be noted that this level is the result of anthropogenic activities at the harbor and therefore does not reflect a change in the energy level of the environment.

Unit 5, which contains the chaotic community in a matrix of silty-clayey sand, was investigated in the study area with three samples collected from S1 and S3 profiles. These samples were collected from the matrix of Unit 5. The histograms showing the particle size distribution showed that the matrix of Unit 5 displayed a bimodal distribution. Approximately 45% of the dominant grain size is fine to very fine sand ( $\phi = 3$ ,  $\phi = 4$ ) and approximately 10% of silt-clay size material is seen as well (Figure 11). Thus, it was understood that the matrix of Unit 5 was composed of clayey-silty fine grained sand. However, it has not been possible to make an assessment on the formation mechanism of the chaotic community characterizing the Unit 5.

Unit 6 was evaluated using 9 samples collected from S1 and S3 profiles. In figure 11, two samples taken from different sections of Unit 6 show that the dominant grain size is fine to very fine grained sand ( $\phi = 3$ ,  $\phi = 4$ ). However, all the other grain size fractions are also represented even they are at very low percentages (Figure 11). This distribution indicates that different elements have started to be effective in the depositional environment.

The histograms of Unit 7 generated by using 6 samples from S1 profile exhibit a unimodal distribution (Figure 11). The mod value of this distribution consists of fine to very fine sand size material with percentage of 30-55%. In some examples, the fine grained pebble material reaching up to 20% represents a level in which the amphora, coin, glass fragments and animal bones are present within the unit and do not show a rising energy level in the environment.

The grain size distribution of Unit 8 evaluated by means of 4 samples from S1 profile begins with well sorted fine grained sand at 80% and extends badly sorted, coarse to medium grained sand and pebble size material in the upper layers (Figure 11). This distribution indicates that there have been a high energy environment.

The grain size distribution of units was evaluated also by forming the cumulative grain size curves along with histograms (Figure 12). The cumulative curves show that Unit 3 is medium grained sand, Unit 4 is fine grained sand, Unit 5 (matrix) and Unit 6 are fine to very fine grained sand, silt and clay, Unit 7 is fine grained sand and Unit 8 is coarse grained sand-pebble and created different clusters from each other. In this sense, the cumulative grain size curves correspond to the histogram results as expected.

The grain size distribution data were statistically evaluated in the next step. These statistical parameters help to determine the depositional environment (Blott and Pye, 2001). The average grain size (median) (value that divides the curve into two equal areas), sorting (whether the distribution curve is spread or narrow), skewness (which direction the curve is tilted, + or - skewness) and kurtosis (whether the curve is (+) leptokurtic or (-) platykurtic) values for the samples collected from S1-S2-S3-S4 profiles were determined. The change in depth for the samples belonging to S1 profile in which all the units are represented is given in figure 13. Unit 3, which is medium to badly sorted, (-) skewed, leptokurtic and platykurtic, coarse to medium grained sand, at the bottom of S1 profile underlies the Unit 4, which is badly sorted, symmetrical to (+) skewed, leptokurtic fine grained sand. Unit 5 is very badly sorted, (+) skewed, leptokurtic, coarse grained silt-clay. This is followed by Unit 6 which is very badly sorted, (+) skewed, leptokurtic very fine sand. On top of that, the Unit 7, which is badly-very badly sorted, (+) - (-) skewed, leptokurtic fine grained sand

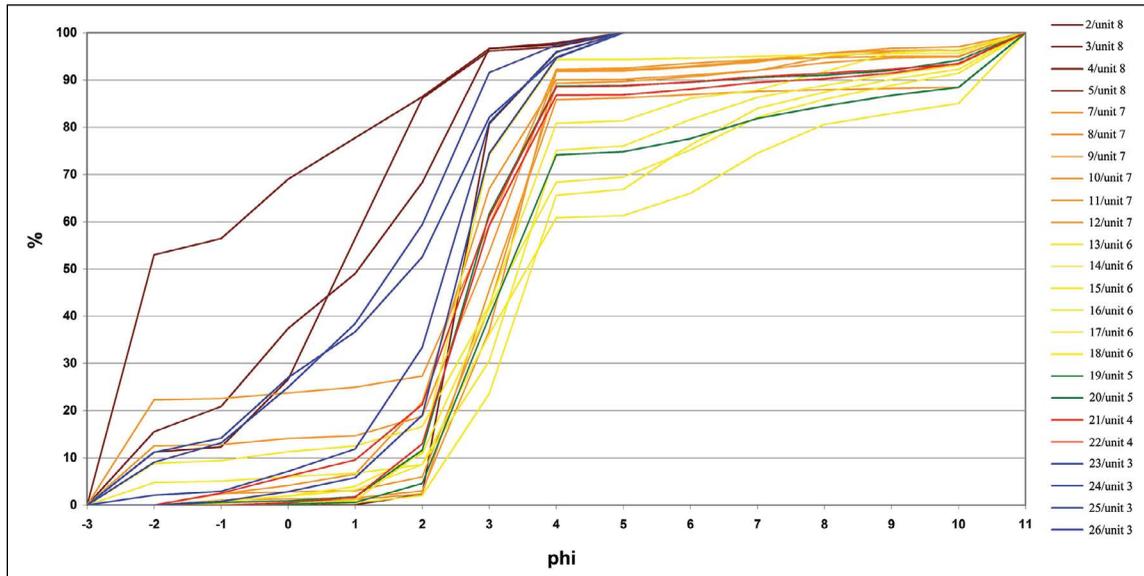


Figure 12- The grain size distribution of the units along the S1 profile by means of cumulative grain size curves.

is observed. Unit 8 at the top of this sequence is poorly sorted, (+) - (-) skewed, leptocurtic pebble-granule.

When the statistical parameters of the average grain size for all profiles are evaluated together, it is noticed that all the units are generally badly to medium sorted, and that the dominant type of sediment, generally represented by sand is also accompanied by

the coarse and/or clay-silt size material. The Units 8, 7 and 6 have all types of skewness values, however the Units 5 and 4 have only (+)/very (+) skewness. The Unit 3 is separated from the other units only with (-) skewness values. It is observed that a more complicated sedimentation mechanism develops after Unit 3, which has (-) skewness, and the (+) skewness occurs in Units 4 and 5 (Figure 13). This situation has

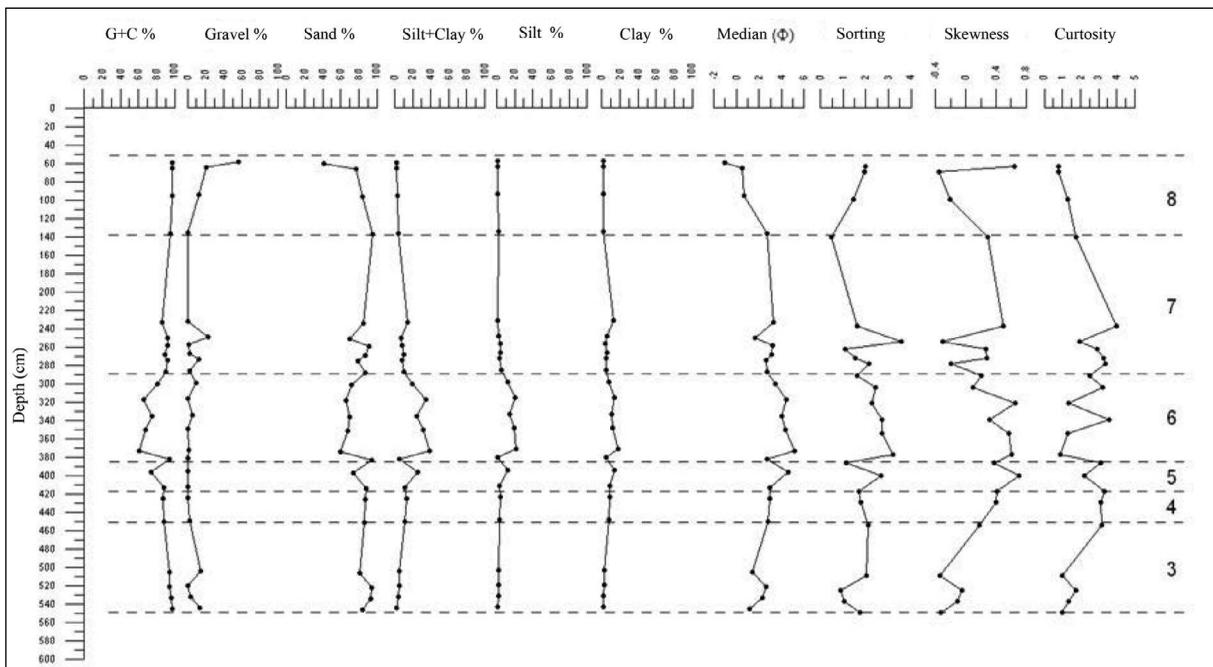


Figure 13- The change of grain size and statistical parameters of samples collected from S1 section based on units and depth.

continued during the deposition of the upper parts of the sequence.

As a result, it can be said that the sand, which shows unimodal distribution, was generally deposited in the marine Holocene sequence in Yenikapı. From time to time the energy level of the environment decreased and thin silt and clay bands were formed in the succession. In addition, a complex deposition also occurred as well due to the harbor activities and tsunami/flood events in the marine Holocene sequence in Yenikapı. It is concluded that Unit 8, which was located in the upper part of the sequence, was formed by the deposition of the material transported by the Lycos stream in a high-energy fluvial environment.

#### 4.4. Fossil Content

In this study, the fossil assemblage in the sequence was not studied in detail and the fossil content of the Yenikapı sedimentary sequence was compiled from Algan et al. (2011), Bony et al. (2011), Meriç et al. (2009) and Perinçek et al. (2007). The Yenikapı sedimentary sequence generally consists of foraminifera, ostracod, pelecypod and gastropod shells.

Among benthic foraminifers; *Ammonia* sp., *Elphidium* sp. and *Quinqueloculina* sp. are dominant and *Adelosina carinata striata*, *Cycloforina contorta*, *Massilina secans*, *Miliolinella subrotunda*, *Pseudotriloculina* spp., *Rosalina* spp., *Porosonion subgranosum* and *Haynesina depressula* are encountered in few amounts. The foraminifer assemblage has poor genus diversity and a low population, and the dominant genera are *Ammonia* sp., then *Elphidium* sp. Although the diversity starts to increase starting from Unit 7, the total benthic foraminifer amount reaches the maximum in Unit 5.

The ostracod fauna with general features consist of marine (*Aurila convexa*, *Paracytheridea depressa*, *Urocythereis oblonga*, *Pontocythere elongate*, *Semicytherura inverse*, *Semicytherura sulcata*, *Callistocythere intricatoides*, *Carinocythereis carinata*, *Hiltermannicythere turbida*, *Pseudocytherura calcarata*, *Loxococoncha elliptica*, *L. rhomboidea*, *L. stellifera*, *Xestoleberis comunis*, *X. dispar*, *Henryhowella asperrima*, *Leptocythere* sp.), oligohaline (*Candona neglecta*, *Heterocypris salina*,

*Euxinocythere* sp., *Ilyocypris gibba*) and eurihalina (*Cyprideis torosa*) species. The most spread of them are *Aurila* sp., *Semicytherura* sp., *Urocythereis* sp., *Callistocythere* sp., *Pseudocytherura* sp. and *Pontocythere* sp. which prefers sandy floors. The genera diversity and population are high in Units 5, 4 and 3, and reaches the maximum in Unit 6. The diversity and population decrease over these values. At the topmost Unit 8, a couple of marine species and genera such as; *Candona* sp., *Heterocypris* sp. and *Ilyocypris* sp. indicating the fresh water input are observed (Algan et al. , 2011).

Benthic foraminifer assemblage shows that there is a transition from marine to fluvial environment from bottom to top. Species such as; *Ammonia* and *Elphidium* can adopt itself to salinity conditions in a large interval ranging from hyposaline to hypersaline and they are largely observed in inner shelf, lagoon and tidal flats (Murray, 1973). *Massilina*, *Quinqueloculina*, *Miliolinella* and *Rosalina* prefers salinity conditions less than 32‰ (Murray, 1973). *Elphidium*, *Ammonia* and *Quinqueloculina*, which are seen in Units 3 and 4 below the succession, are dominant and the assemblage that possess rich species diversity characterizes shallow marine environment. *A. parasovica* and *A. tepida* are known as eurihaline species and can tolerate low salinities (1-26‰) (Yanko, 1990). The fossil assemblage that has low population and species diversity of which these species are dominant are located at the top part of the succession (Units 8 and 7) and reflect the decreasing salinity conditions. The ostracod fauna shows that marine forms are dominant in the lower parts of the succession. However, the oligohaline species become dominant towards the upper layers and support a change from marine to fluvial conditions (Algan et al., 2011).

#### 4.5. Sedimentary Structures

The sand lenses with abundant shells and shell fragments, which have no lateral continuity are the first conspicuous sedimentary structure in Unit 2 forming the bottom of the marine Holocene unit. In addition, there are rounded pebbles with diameters of nearly 5-10 cm that present imbricated structures in the lowermost parts of the unit. These levels represent basal conglomerates of the transgressing sea. The typical sedimentary structure identified in Unit 3 is the

lenticular shell aggregations, which do not have lateral continuity, and represent the sedimentation in a shore (beach) environment. In the upper parts of Unit 4, the silt-clay bands are noticed. Besides, the mud pellets were determined (Figure 14) and these pellets were possibly associated with bioturbation. The chaotic level within Unit 5, which is erosional at the bottom, offers extremely complex structure. For this reason, as mentioned earlier, it has been thought that this structure had occurred as a result of a very high energy, sudden and effective event. Unit 6 as well, includes silt-clay bands with occasionally disseminated or arranged shells like Unit 4. Within Unit 7, where marine sand is dominant, the micro-scale cross-bedding associated with decayed and charred plant material and macro-scale, cross-bedded sand levels were observed. In addition, there are sedimentary structures called the “seismite” in lower parts of the unit 7. The seismites are structures formed as a result of the segregation of water from unconsolidated sediments and deterioration of stratification as a result of earthquakes (Figure 15).

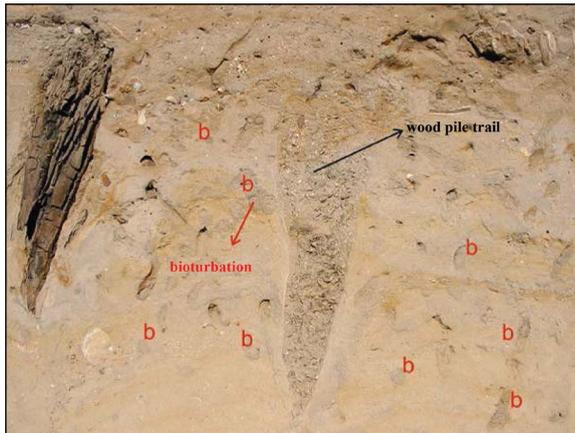


Figure 14- Mud pellets resulting from the bioturbation in Unit 4 (b).



Figure 15- Seismite structure seen in Unit 7 (Algan et al., 2009)

The most striking sediment structure in Unit 8 is the channel structures in different sizes which are typical indicators for a fluvial environment. Since the majority of channel fillings consist of anthropogenic material transported by the Lycos River, these structures were clearly visible in the exposed sections (Figure 16).



Figure 16- Channel filled with organic rich material in Unit 8.

#### 4.6. Mineralogical Composition

The mineralogical composition of the representative samples selected from Bakırköy, Çukurçeşme and Trakya formations, which form the basis of this sequence with the Holocene succession in the Yenikapı excavation area, and have outcrops in the immediate vicinity were determined and a correlation was made between the Holocene sequence and the source area.

The XRD analyzes showed that quartz, calcite, albite and aragonite minerals were most commonly found in the composition of all samples taken from the Holocene sequence. The amount of quartz ( $\text{SiO}_2$ ) and calcite ( $\text{CaCO}_3$ ) in the samples ranges from 10% to 90%, while the amount of albite ( $\text{NaAlSi}_3\text{O}_8$ ) and aragonite ( $\text{CaCO}_3$ ) reaches a maximum of 30%. In three representative samples selected from Bakırköy, Çukurçeşme and Trakya formations mainly the calcite, quartz and albite minerals were detected. In the light of these findings, it was concluded that the grains of Holocene sequence originated mainly from the Trakya formation and from Miocene units. The source of aragonite mineral should be the shells which are abundant in Holocene units. In addition, the hematite ( $\text{Fe}_2\text{O}_3$ ), dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ), rutile ( $\text{TiO}_2$ ), pyrite ( $\text{FeS}_2$ ) and orthoclase ( $\text{KAlSi}_3\text{O}_8$ ) minerals in nearly 10% were determined in Yenikapı samples.

It was possible to conclude that the mineralogical composition of the Holocene units may vary depending on the activities of the harbor and the city as well as the natural resource area. While there is orthoclase mineral in Units 3 and 4, it was not found in the upper part of the sequence (Figure 17). This situation shows

that the participation of the orthoclase mineral into the environment discontinued after the construction of the port. When it is considered that the harbor is protected with one or two breakwaters, it can be said that the orthoclase was transported to the environment by sea and its source is the Pliocene-Pleistocene units at the

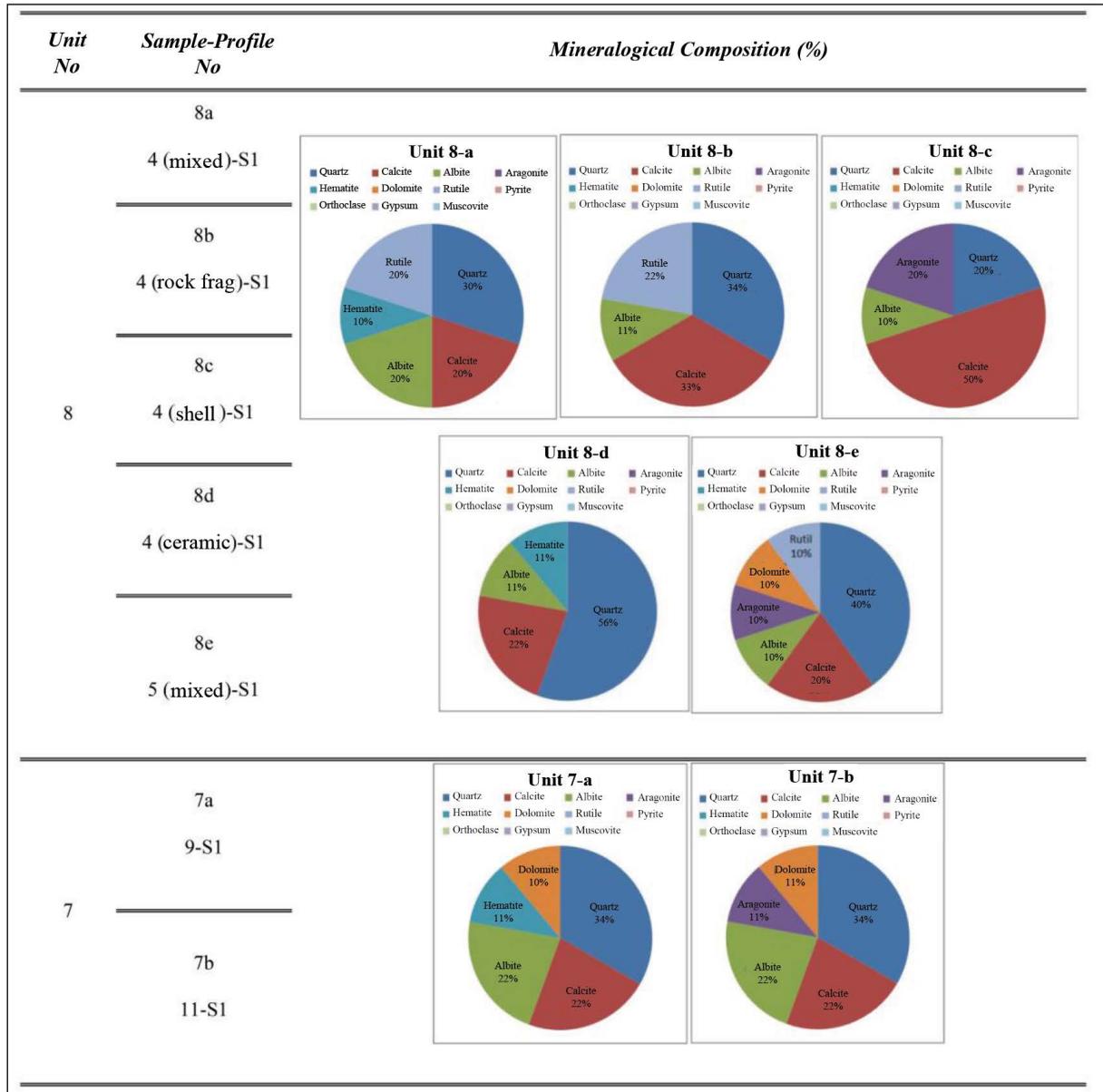


Figure 17- The mineralogical composition of the samples collected from the Holocene sequence and from Bakırköy, Çukurçeşme and Trakya formations, which have outcrops in the vicinity of Yenikapı.

base of the Sea of Marmara. The dolomite, hematite and pyrite minerals occurring in Units 6, 7 and 8 are very likely to originate from harbor and urban activities (Figure 17) because these minerals are not present in units (units 2-4) where there was no harbor or city and/or when they were very small. The reveal of these minerals as well are among the first indicators

that the material transported by the Lycos stream began to fill the harbor gradually. The rutile should be derived from two sources, both natural (Trakya formation) and anthropogenic because of its presence in Unit 4. The increase in the amount of rutile in young units supports this (Figure 17).

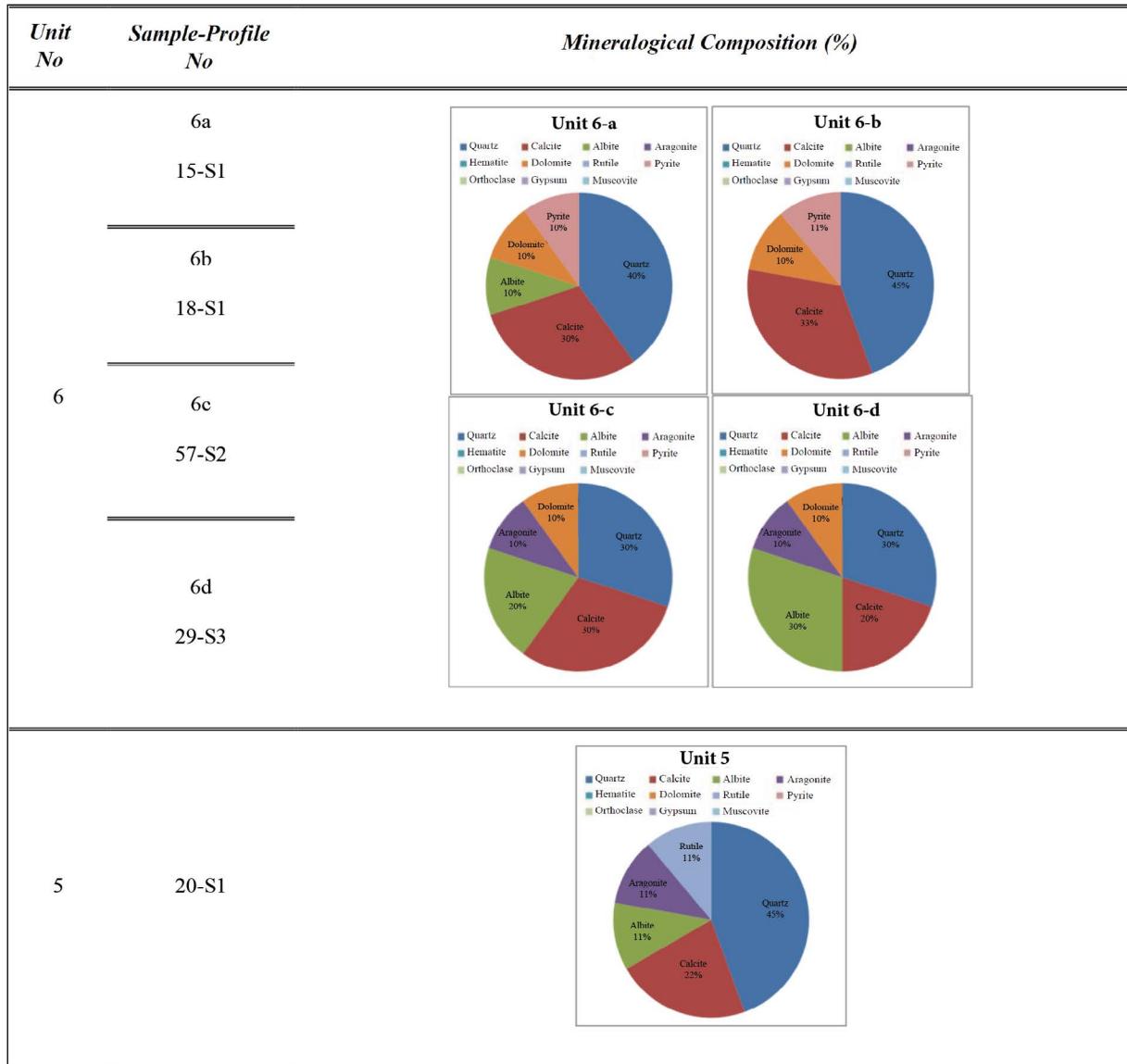


Figure 17- Continue.



Figure 17- Continue.

## 5. Discussion

The depositional environment of the Holocene sequence in Yenikapı, İstanbul were defined by means of properties such as; stratigraphy, lithology, grain size, fossil content, sedimentary structures and mineralogical compositions of this sequence defined above.

The Holocene sequence overlying the Miocene Güngören formation and the Early-Middle Holocene marsh clay was deposited in two different environments as marine (from Unit 2 to Unit 7) and fluvial (Unit 8). All the signs indicate that this differentiation is doubtless. However, it should be noted that there is not any gap between these two environments. The deposition began as marine then turned into a fluvial by gradual shoaling and completed its deposition. Hence, it can be said that the Yenikapı Holocene sequence was deposited in an environment shaped as a result of first the sea level rise then by the seaward regression of the shore due to the material transported and deposited by the river. The pebbles, which present rounded, imbricated structures consisting of the large marine pelecypod shells occasionally observed at the bottom of Unit 2, represent the beginning of transgression. This transgression should have developed due to the global sea level rise which began at the end of the last glacial age. The sea level in the last glacial age, which was 120 m (Lambeck et al., 2004) lower than today, caused the Sea of Marmara and Black Sea to turn into a lake (Çağatay et al., 2000). The sill, which is at -65 m in the entrance of the Çanakkale (Dardanelles) Strait, was exceeded nearly 12000 years ago. So, the Marmara Lake then turned into a sea and the sea level began to rise (Çağatay et al., 2000, 2003, 2009). The rising sea then began to pervade the shores of the ancient Marmara Lake. The period when the rising sea reached the study area in Yenikapı was determined as 6650-7080 cal years from the shells at the bottom of Unit 2 by Algan et al. (2011) using the  $^{14}\text{C}$  method. The age determinations carried out on shells, which are preserved in nests carved on coarse blocks again gave the age of 7330-6980 years by using the  $^{14}\text{C}$  method (Perinçek, 2010b). In the light of these data, it was understood that the sea began to invade Yenikapı approximately 7000 years ago. The age determined for the uppermost part of the clay unit observed in the area is about 7400 cal years (Yalçın, et al., 2015). Considering that some of the top sections

of the clay unit may have been eroded, it can be said that there is a few hundred years of gap between the marine deposits and marsh clays. The rising sea level must have invaded the valley of the Lycos River and flooded its mouth and turned the valley into a wide estuary or embayment. The aggregation of lenticular shells and shell fragments at the bottom of Unit 2 indicate a depositional environment very close to the shoreline in a shallow marine environment. The  $^{14}\text{C}$  ages taken from the sections in slightly upper parts of Unit 2 are clustered 3000 years ago than today (Algan et al., 2009; 2011). This situation shows the fact that the sea level, which is commonly observed in submerging coastal regions, rises and pushes the river load backward for a certain time by flooding the river mouths and the deposition rate becomes extremely low (Nichols, 1999; Coe and Church, 2003) have also been experienced in Yenikapı. For this reason, it can be said that during the following 4000 years, the working area has remained as a coastal environment where almost no deposit was recovered. Starting from 3000 years ago, since the material influx into the environment has reached the normal levels, the shell bearing sands belonging to the Unit 3 has started to be deposited in a foreshore-near shore environment in the embayment entrance. Although these conditions have continued to be effective during the deposition of the sands of the Unit 4, the transformation of this embayment into a harbor protected by breakwater towards the last stages of the unit caused the environmental conditions to change. The clay and silt bands observed in the uppermost part of the Unit 4 are the preliminary signs of a protected harbor environment (Marriner and Morhange, 2006; 2007; Marriner et al., 2008; 2010). The absence of orthoclase mineral in the deposited sequence after Unit 4 is another indication of the fact that the connection of the environment with the offshore is greatly cut off. The similar environmental conditions have continued in the period when the Unit 5 was deposited. The chaotic community observed in this unit represented by very fine sand, silt and clay size material does not reflect the essential properties of the sedimentation environment as it represents a short-term and high-energy process such as the flood or tsunami. Sand again began to deposit in this protected harbor environment with Unit 6. This situation, which seems contradictory at the first glance, can be evaluated as a meaningful process considering the existence of the Lycos River flowing into the embayment. The fact

that the well sorted, fine grained sand is relatively the dominant grain size indicates that the energy of the environment increased and the detrital source started to be more effective. Considering that the harbor is intensely being used, it was understood that the source was mainly the Lycos River which caused the propagation of delta towards the sea. In addition to both proximity and natural processes, the increase in the material transported by the stream due to anthropogenic processes is the cause of the change in the depositional regime. Another source of the sand is the sand transported to the harbor with huge waves exceeding the breakwater of an extraordinary storm (Pulak et al., 2015), which has been identified as the cause of the sinking of several wrecks in Units 6 and 7. These waves and sand caused both the sinking of ships and allowed them to be protected by rapidly covering the wrecks (Perinçek, 2010a, b; Algan, 2009; 2011; Kocabaş, 2010; Kocabaş, 2015; Pulak, et al., 2015). Another indication of the fact that the delta of the Lycos River filling the embayment became very close to the section near to the sea of the harbor is the large-scale cross-stratification due to the currents observed in the upper parts of the Unit 7. The approaching delta has reached the study area shortly after. The fluvial sequence of Unit 8, which overlies the Unit 7, was deposited as a product of typical fluvial-delta environment. Thus, the sedimentation, which began in a clastic foreshore environment, has evolved into a near shore environment where the very high sedimentation occurs as a result of the rising sea level flooding this coastal environment containing the large cove/estuary. After the construction of a harbor protected by a breakwater in the study area, a protective harbor environment emerged and the units with relatively much smaller grain sizes were deposited. Due to the fluvial activity that began to fill the cove, the sand began to be deposited again in the harbor and then the depositional period was completed with fluvio-deltaic sediments.

## 6. Results

According to sedimentological properties seven units were distinguished in the Holocene sediments in the Yenikapı district. The sequence begins with pebbles in varying sizes at the bottom then passes into yellow to beige, fine grained sand in the upward and again to coarse grained sand and pebble at the top.

In order to determine the depositional environment and environmental changes of this sequence, the grain size distribution, lithologies, fossil content, sedimentary structures and mineralogical compositions of differentiated units were investigated. The sieve analysis and grain size distribution determined by the sedigraph revealed that the Units of 3 and 4 were formed by medium-fine-very fine grained sands, the Units of 5, 6 and 7 consisted of silt and clay in addition to sand, and the Unit 8 was composed of pebble and coarse to medium grained sands at the bottom.

The pebble, coarse shells and lenticular shell aggregations presenting the clast imbrication at the bottom, the traces of bioturbation, the cross stratification and the seismites in the sandy unit in intermediate sections and the channel structures and fills in the upper sections of the Holocene sequence were observed.

In previous studies, generally the foraminifers, ostracod, pelecypod and gastropod fossils were detected in the Holocene sequence in Yenikapı. These fossils are mostly presented by benthic genera and species indicating the shallow marine and transition zones. The typical marine forms in the lower section of the sequence turn into brackish water forms towards the upper sections.

It was determined that the minerals in non-natural environment in a Holocene sequence had come out due to antropogenic activities within younger units. It was seen that the variations were controlled by the antropogenic activities in Byzantine city in addition to Paleozoic and Tertiary units in the source area.

The deposition of Holocene sequence in Yenikapı-Istanbul began in a clastic foreshore environment, but the rising sea level submerged this shore consisting of large embayment/estuary and changed it into a near shore environment where the sedimentation had become very slow. At the beginning of the 5<sup>th</sup> century, the clay-silt containing units were deposited in this sheltered environment after the installation of a harbor protected by the breakwater. The sand began to be deposited again in the harbor due to the Lycos River which began to fill the embayment and due to the increasing antropogenic activities. As a result, the shoreline began to regress towards the sea, and a fluvio-deltaic environment developed after the river plain had reached the study area.

## Acknowledgements

We would like to thank to the Division of Scientific Research Projects of the Istanbul University (Project No:10025110), the NSF (National Science Foundation (Grant Nr. BNS 1236981) and Malcolm H. Wiener Foundation, which supported the MSc Thesis of M. Sezerer; to Prof. Peter Kuniholm and Dr. Charlotte Pearson (Laboratory of Tree-Ring Research, University) of Arizona, who contributed to the study with their suggestions; to Prof. Sinan Öngen, (Department of Geological Engineering of the Istanbul University) for his helps during mineralogical studies, and to Prof. Erol Sarı, (Institute of Marine Sciences and Management of the Istanbul University), for his helps during the laboratory studies.

We also appreciate to Zeynep Kızıltan, the Director of Istanbul Archeological Museums who permitted this study in the excavation site, to all workers of the Yenikapı excavation site who helped during the study, to archeologists Mehmet Ali Polat and Sırrı Çömlekçi from the Directorate of Istanbul Archeological Museums and to Züleyha, Songül and Kadir for their helps who supported sampling stage of this study.

We also offer our special thanks to Prof. Muhittin Görmüş, Assoc. Prof. M. Akif Sarıkaya and to another referee for their contributions, which helped improve the article.

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