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Sedimentological, geochemical and morphoscopic characterization of sediments from Nador Harbor (Morocco)

Caractérisations granulométrique, morphoscopique, minéralogique et géochimique des sédiments du port de Nador (Maroc)

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Abstract. The phenomenon of siltation constitutes a major problem in Nador Harbor, limiting navigation and requiring very costly dredging operations. In order to determine the origin (marine or continental) of the sediments that cause this phenomenon, 25 surface sediment samples were collected in the bottom of Nador Harbor with a Van Veen grab sampler. Then the grain size, mineralogy and geochemical evolution of the sediments were studied in order to identify the mode of transportation and the sedimentation processes in that harbor. The spatial characteristics of surface sediments at the bottom of Nador Harbor indicate two types of deposits: The first, less significant, is of marine origin, and the second, more dominant, is of continental origin. The identification of the continental origin of the deposit suggests the need to develop solutions in the upper watershed to reduce the siltation rate of Nador Harbor.

Keywords : Grain size, geochemistry, morphoscopy, sediment transport, siltation, Nador Harbor.

Résumé. Le phénomène dôenvasement constitue une problématique majeure dans le Port de Nador, limitant la navigation et nécessitant des opérations de dragage très coûteuses. Dans le but de déterminer lôorigine (marine ou continentale) des sédiments qui causent ce phénomène, 25 échantillons de sédiments de surface ont été prélevés dans le fond du port de Nador avec une benne Van Veen. Ensuite, la taille des grains, la minéralogie, et l'évolution géochimique des dépôts du fond ont été étudiés en vue d'identifier le mode de transport et les processus de sédimentation dans ledit port. Les caractéristiques spatiales des sédiments de surface au fond du Port de Nador indiquent deux types de dépôts : le premier, d'origine marine, qui est moins important, et le second, d'origine continentale, qui est le plus dominant. Lôidentification de lôorigine continentale de ce dépôt implique la nécessité de développer des solutions dans lôamont du bassin versant pour réduire le taux dôenvasement du port de Nador.

Mots clés : Granulométrie, géochimie, morphoscopie, transport sédimentaire, envasement, port de Nador.

INTRODUCTION

The Mediterranean coast of Morocco is characterized by a wide variety of landforms and significant variations in slope. The basins are separated by narrow, moderately sized, steep ranges of up to 1000 m in height and have a unique torrential river system due to the steep slopes, concentrated rainfall, and limited infiltration capacity of the soils, which promotes runoff.

The Mediterranean coast of Morocco has many harbors, including those of Tangier, Tetouan, Al Hoceima, Nador, and Saidia, in addition to Ceuta and Melilla Harbors, which are Spanish enclaves in Morocco. A substantial amount of dredging is conducted annually in these harbors, e.g., 92,060 m^3/yr in Nador Harbor (Draport 2007) and more than 420,169 m^3/yr in Melilla Harbor (INFORMS CEDEX 2013). Dredging is necessary because sediment deposits, which may be of marine (sandy) or continental (muddy) origin, interfere with navigation and create environmental problems.

Determining the source of deposition is economically important, because it would be the first step in designing engineering solutions to minimize siltation in the harbors. In addition, it would reduce the frequency and expense of dredging operations. According to Tabet (2002) and Niazi (2007), the coastline equilibrium is affected by the following sedimentary processes: (1) fluvial and wind sediment transport, erosion of beaches and adjacent shoreline cliffs, and transport of sediments from the sea to the shoreline (cross- and longshore); (2) drainages that trap sediments in estuaries and lagoons, wind erosion of sand beaches, formation of coastal dunes, coastal drainage of sediments toward submarine canyons, slides along underwater slopes, and transfer of sediments from the shoreline to the sea; (3) coastal transport affecting only the coastal sediment system, whose intensity may vary between two transverse boundaries of the subject area.

The aim of this study was to determine the source of sediments in Nador Harbor (also known as Beni Ansar Harbor) (Fig. 1). The source of these sediments is unknown, because there have been no previous studies of the nature of the harbor catchment area. According to Irzi (2002), the cliffs of Cape Three Forks, located 20 km west of Nador Harbor, are impacted by storms and swells and produce sand that replenishes the beach of Melilla and produces siltation in Nador Harbor (Fig. 2). Moreover, field studies and a map of the area show that the water system (channeled, due to urbanization of Beni Ansar) (Fig. 3) flows directly into Nador Harbor during floods, carrying a substantial sediment budget of silt and mud. This observation suggests that the origin of the sediments is likely continental.

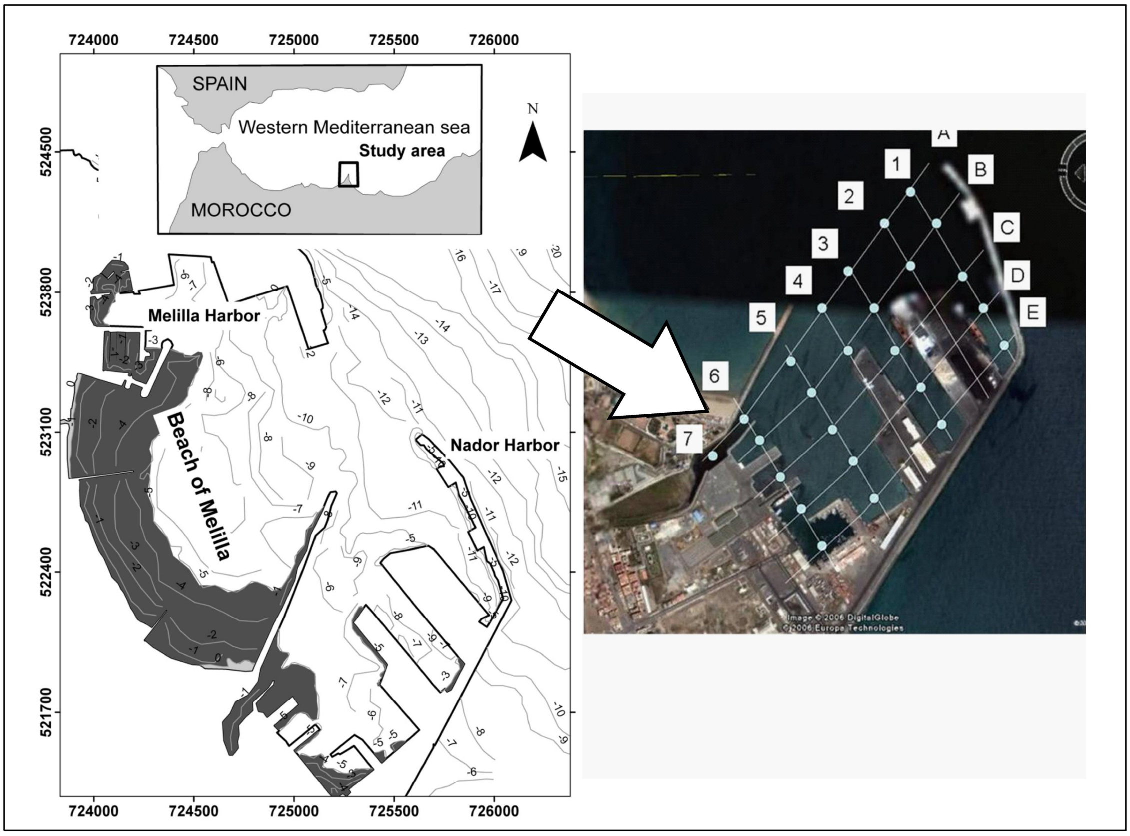

Figure 1. Overview of the study site and the grid of samples (image obtained from Google Earth 2006).

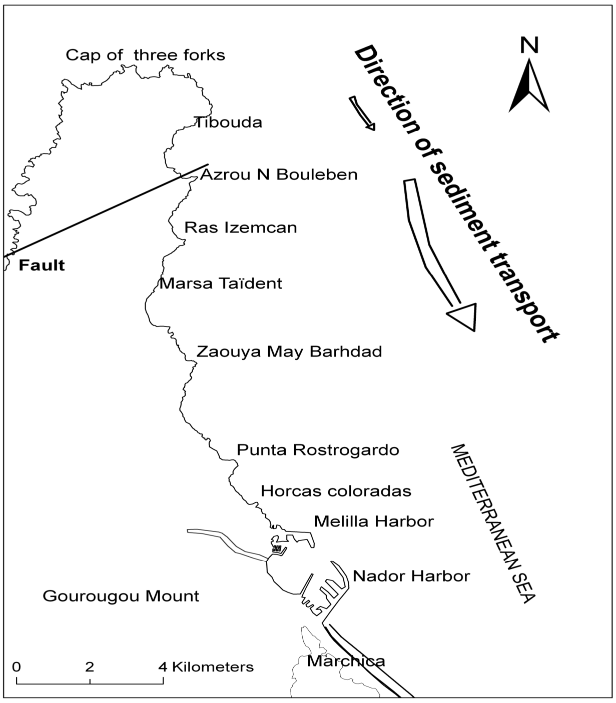

Figure 2. Direction of sediment transport (Irzi 2002).

The present analyses were carried out on samples collected during an oceanographic campaign in May 2007. This study was conducted as part of a global research project entitled ñUsing the bio-indicators (Benthic foraminifera) to evaluate the quality of the environment in Nador Harbor and nearby beaches.ò

Study area

Nador Harbor is located in Beni Ansar. It is influenced by runoff from massifs that rise to about 790 m to the southwest (Figs. 3, 4). These massifs are drained by five major creeks known as wadis that cross the urban area of the harbor. Two of the main wadis flow into the Marchica Lagoon. The third is located further to the north (Oued Ouchen, also known as Barranco del Infierno) and flows into Nador Harbor without reaching the sea. This wadi can cause severe flooding, particularly during heavy rains. In addition, the wadi drains the watershed known as Wadi Ouchen, which has been heavily altered due to urbanization that blocks runoff, causing flooding in the urban areas of Beni Ansar (Fig. 3).

Nador Harbor is also the outlet of another wadi that is deviated from Melilla, whose origin is Gourougou Mount. This wadi flows to the entrance of the thalweg Arroyo La Mesquita near Melilla Airport and from there into Nador Harbor. Arroyo La Mesquita forms the border between Melilla and Nador. Wadi Ouchen has a flow of 20 m^3/s with a velocity of 40 m/s and a return period T of 100 yr (Municipality report of Beni Ansar 2005). As erosion is proportional to the flow, this wadi discharges a large amount of sludge into Beni Ansar, causing significant barriers to traffic and movement in residential areas.

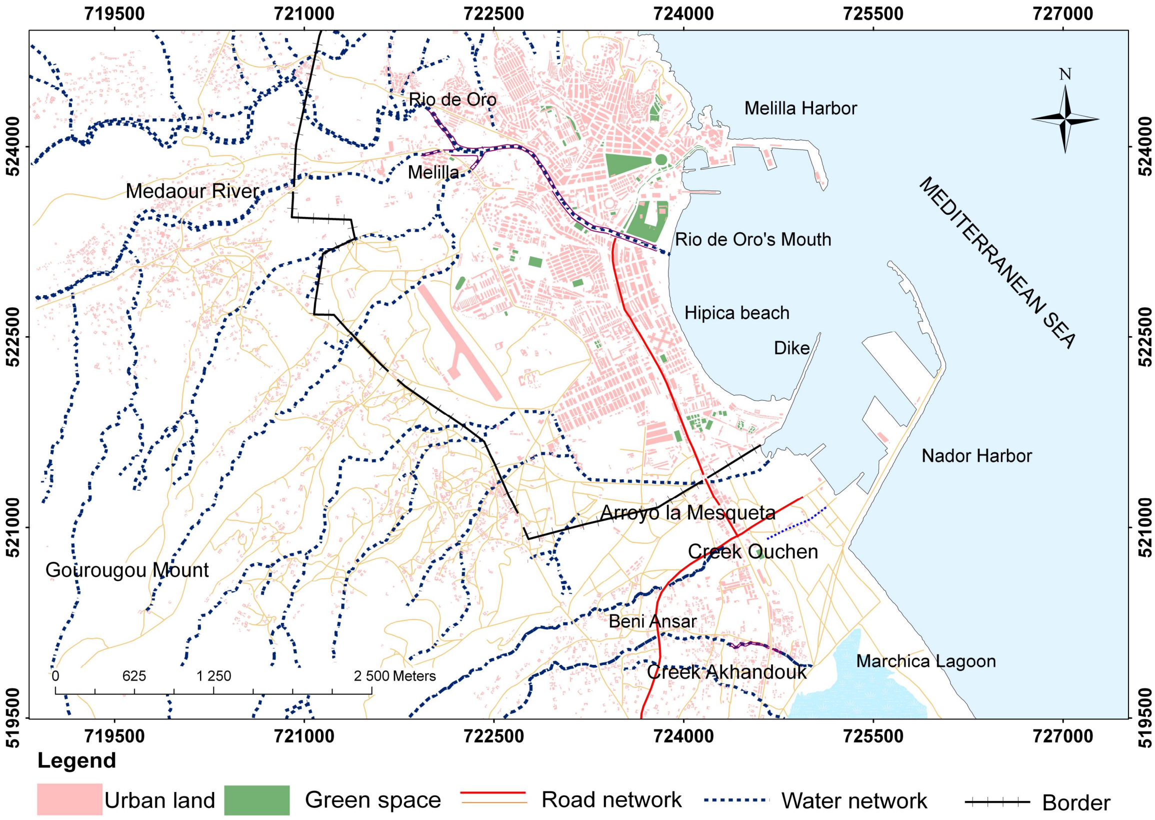

Figure 3. Drainages near the study site (Melilla map 1/10.000).

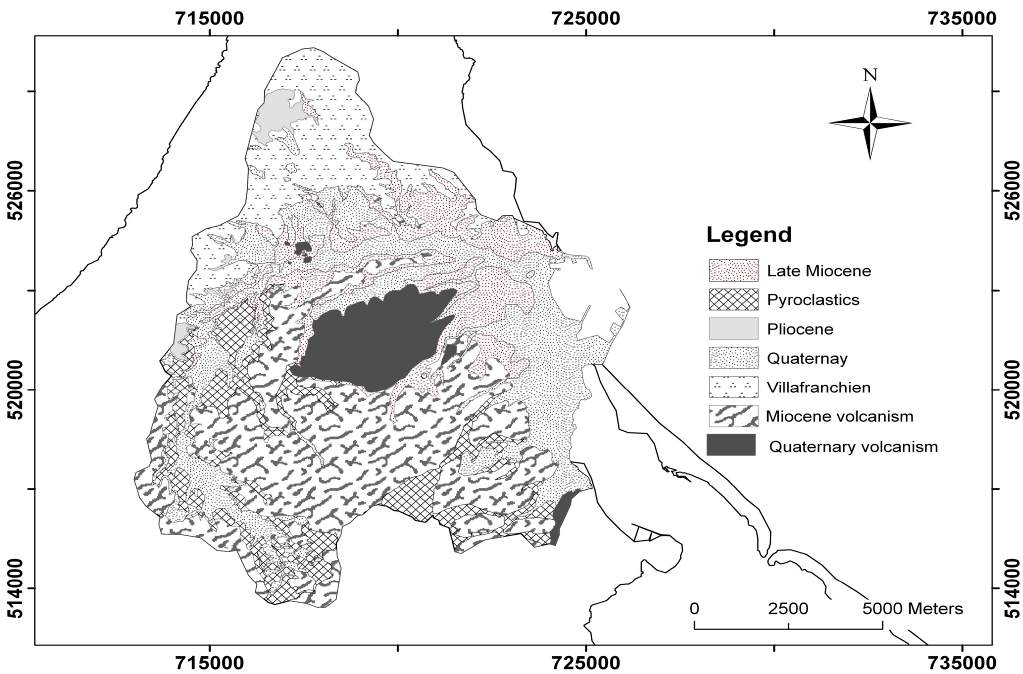

Figure 4. Geologic map of the watershed of Nador Harbor.

The study area is characterized by a semi-arid Mediterranean climate, with often irregular and insufficient annual average rainfall of 350 mm (Sauvage 1963, Carlier 1971, Barathon 1987, Ramas & Hernandez 1986, Sbai 1992). Winds in the area are characterized by dual flow directions from the eastïnortheast and westïsouthwest. Wind directions vary seasonally, with east-northeasterly winds dominating from April to September (Barathon 1987, Barathon 1989, Irzi 2002, Sbai 1992). The typical wind speed is 4.3 m/s, but may increase in winter to 11 m/s, particularly for northwesterly winds. The speed of the littoral drift is normally below 1 m/s (Marsa Morocco 2008). Swells in this area have periods of 7ï11 s and amplitudes of 5ï7.5 m (Tesson & Gensous 1979), with the northeasterly and the east-northeasterly swells being the largest. However, the northerly swells have a short fetch as

Nador Harbor is sheltered by a dike. In the Mediterranean Sea, the tides are relatively weak and thus, H = 0.4 m is typical of slack water in the harbor (Marsa Morocco 2008).

MATERIAL AND METHODS

To determine the sources of sediments to the harbor, comprehensive sedimentological studies were conducted to determine the particle size distribution, morphoscopy, mineralogy, and geochemistry of the sediments. The results were entered into a Geographic Information System (GIS) and mapped to visualize the influence of marine hydrodynamic parameters on the spatial distributions of the deposits.

Sediment sampling

To identify the sources of sediments responsible for siltation in Nador Harbor, an oceanographic campaign was conducted in May 2007 from a fishing boat. Bottom sediment samples were collected from Nador Harbor using a Van Veen grab sampler. The sample locations were selected using a Google Earth map (2006) and Global Positioning System (GPS) on a regular grid of about 200 m (Fig. 1).

Five longitudinal transects oriented northeastï southwest identified as Aï E and seven northwestï southeast transverse transects identified as 1ï 7 were selected to evaluate particle size evolution along these transects. The station locations were closely spaced at 150ï 360 m to ensure an accurate grid.

Laboratory analyses

Twenty-five surface samples were dry-sieved in the laboratory to determine the particle size distribution, as previously described (Krumbein 1936, Folk & Ward 1957, Friedman 1967, Vatan 1967, Rivere 1977, Chamley 1988, 2000, Farhat *et al.* 2010). After washing and separating the sand fraction, the samples were treated with HCl and H_2O_2 and then dried in an oven at 80 °C. The samples were dry-sieved in a column of twelve vibrating screens (AFNOR) with sieve sizes varying from 0.04 to 5 mm. The material remaining on each sieve was weighed. Frequency histograms and cumulative curves were calculated using Excel and expressed in phi (Ø), and grain size fractions were calculated as previously described (Sahu 1964, Wentworth, 1972, Amani 2010).

Morphoscopic analyses were conducted using a binocular microscope (Petit-John 1957, Egbérongbé 1979) at a magnification of 5ï 80× to determine the mode of particle transport. Geochemical analysis was also conducted by X-ray fluorescence (XRF). The sedimentological data were analyzed using Arc-Gis 9.3, Statistica, and Excel software.

RESULTS

Lithology of surface sediments

Macroscopic analysis of the surface sediments at the bottom of Nador Harbor identified three lithological facies: sand, mud, and mixed sediments.

.Å Mud was more abundant than sand in the surface sediment of the harbor and was smooth. Its color varied from black to brown to green. It was bioturbated and contained lamellibranchs (Samples B6, C3, D1, E1, E3).

ÅThe sand was very fine and found mainly at the bottom of the harbor. The sand was greenish-brown and contained plant and shellfish debris (Samples A3, B2 and E5).

ÅThe mixed sediments consisted of muddy sands and sandy muds. The mixed sediments varied from black to green and contained plant and shell debris (Samples A5, A6, A7, B1, B3 and E3).

Particle size analysis of the sand fractions

The particle size data were graphed as cumulative percentages to determine the characteristic parameters of the sand samples collected in the harbor (mean, standard deviation, skewness, etc.). Figure 5 illustrates particle size results for two analyzed sand samples with different origins.

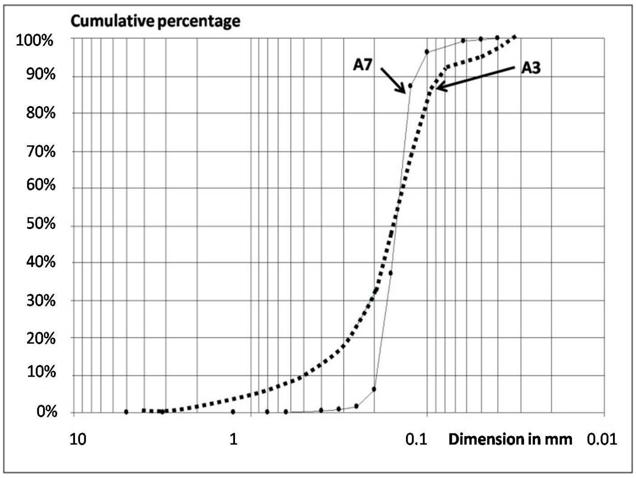

Figure 5. Particle size curves for samples A3 and A7.

Particle size indices

Standard deviation (STDV) or sorting class marks

Mz indices (Perriaux 1961) and standard deviations (STDV) (Folk & Ward 1957) show important differences between the sediment samples; sample A3 is very well sorted and A5 is moderately sorted, while A6, B1, and B2 are well sorted and A7, B3, B6, C3, D1, E1, E3 and E5 are poorly sorted (Fig. 6).

Skewness indices

According to the skewness indices S-Trask (Trask 1932) with S > 1 and Asq (Pomerol 1963) with Asq < 0, the fine fraction was very finely skewed for samples A3, A7, B1, B2, B3 and C3, the coarse fraction was coarsely skewed for samples A5, A6, B6, D1, E1, E3 and E5 (Fig. 7).

Sediment transport mode

The Visher curves (Visher 1969) for samples A3 and A6 show two different sedimentary environments (Fig. 8). There are three transport modes of particles in rivers: saltation, which occurs in many environments, suspension, which is more prevalent in marine environments, and traction, which is often dominant in fluvial environments.

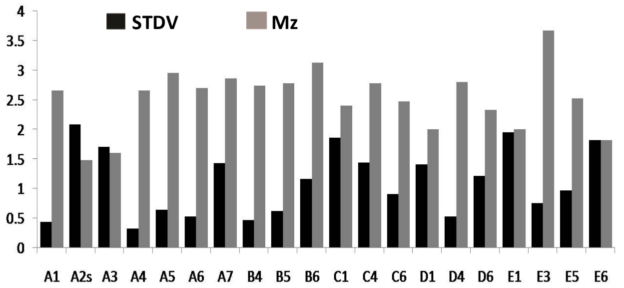

Figure 6. Mz indices (Perriaux 1961) and standard deviations (STDV) (Folk & Ward 1957) for the sediment samples.

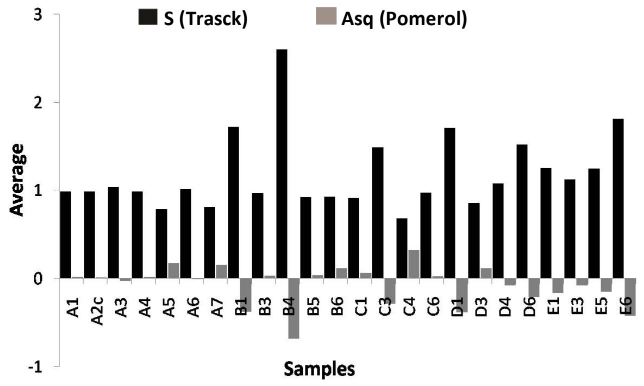

Figure 7. S and Asq skewness indices for the sediment samples.

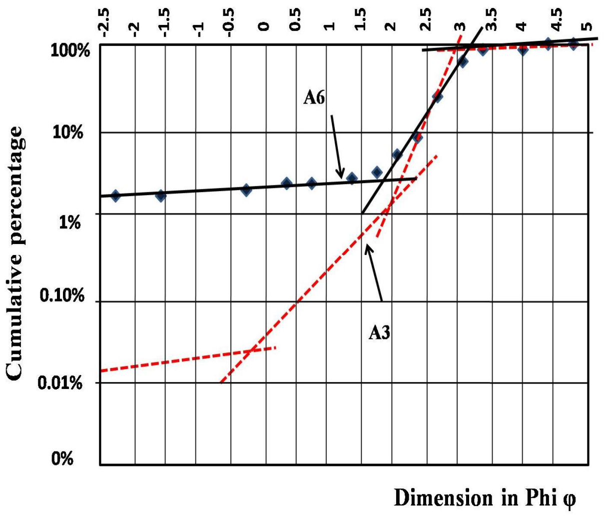

Figure 8. Visher curve showing cumulative percentages of sediment, representing the intertidal zone for samples A3 and the fluvial environment for sample A6.

Friedman diagrams

Figure 9 presents the results for the sieved samples in a Friedman diagram (1967). Using this diagram, sediments deposited in a fluvial environment and those deposited on a beach can be distinguished. In the present study, all of the samples were deposited in fluvial environment except A3, which was more open to the marine environment (Fig. 1).

Sediment classes

A ternary diagram after Shepard (1954) was used to differentiate among the sedimentôs class: rudites, arenites and lutites for the analyzed samples (Fig. 10). The dominant class was arenite, whose mode of transport is saltation, followed by lutites. However, the coarser class of rudites was represented by samples A6 and A7, which were closest to the Arroyo La Mesquita area (Fig. 3). This class can be transported only by the high hydrodynamic energy generated by wadi drainage.

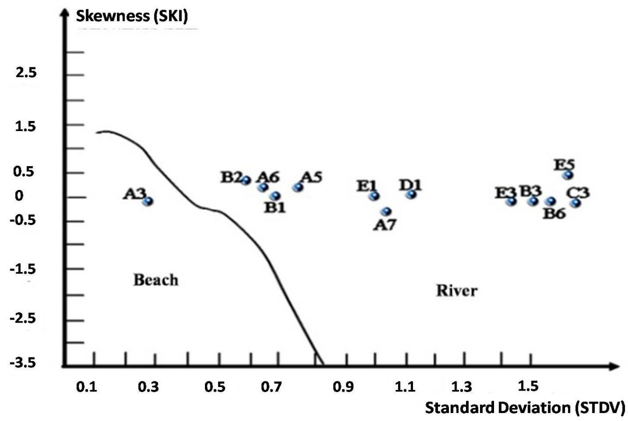

Figure 9. Friedman diagram showing the standard deviation index (STDV) vs. the skewness index (SKI).

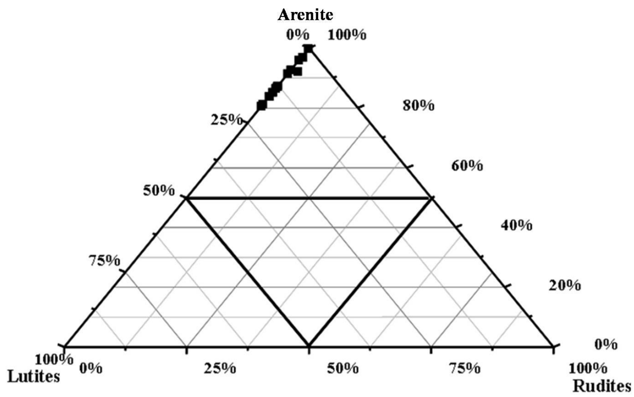

Figure 10. Ternary diagram after Shepard (1954) showing particle size classes of sediments from Nador Harbor.

Qdphi Krumbein and Cailleux diagrams

The Qdphi Krumbein (1936) and Cailleux & Tricart (1959) diagrams (Martins 1965, Folk 1966, Greenwood 1969) show that most of the samples were associated with a fluvial sedimentary environment, except for samples A1, A2, A3 and A4, which were associated with a marine environment influenced by northeastïsouthwest winds (Figs. 11, 12).

Mineralogical and morphoscopic analyses

Analysis of the sandy sediments of the harbor revealed an abundance of quartz, mica, rock fragments, greenish black pyroxene, and biotite phenocrysts.

These minerals are characteristic of volcanic facies such as the trachyte and trachyandesite of Gourougou Mount and the massive rhyolite of the Cape of Three Forks. Moreover, the mineralogy of the reworked materials from the export/import quay indicated the presence of barite, gypsum and petroleum coke debris from shipping that had accumulated in quiescent areas (Fig. 13).

Morphoscopic analysis of the quartz particles in sediments from the harbor identified several forms, including blunted glow (BG), round mat (RM), and not worn (NW) quartz grains (Table 1).

The results indicated that:

ÅBG particles were very abundant with a range of 40ï 70% and an average of 60%.

ÅRM particles were less abundant with a range of 7ï 28% and an average of 15%.

ÅNW particles were also very abundant with a range of 14ï 49% and an average of 30%.

The NW grains result from sediment transport in an aqueous environment over a moderate or short distance (Petit-John 1957). According to Cailleux (1959), BG grains are the result of long-distance transport in continental aquatic environments such as a rivers or streams. The characteristics of the quartz grains in this study also indicate transport through an aqueous environment; all of these sediments were transported by rivers.

Geochemical analysis

The samples were analyzed by XRF using an X-ray spectrometer (ARL 8460S). The major elements analyzed were CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, K_2O, and SO_3, as well as those lost upon ignition. Their contents are expressed as percentages of the total. The analyzed samples contained mud at <50 εm. In addition to XRF, the chemical composition was determined using principal component analysis (PCA), which provided additional information on the sediment distribution.

Clays, including SiO_2, Al_2O_3, and K_2, were present in samples A1 and A6. Gypsum and dolomites with SO_3 and CaO were abundant in sample A4. Ferruginous elements such as Fe_2O_3 were highest in samples A6 and A4, indicating a continental source. Organic matter was abundant in samples D6 and A1, indicating confined areas. Sample A1, situated in the open area of the harbor basin, contained clays of continental origin. The compositions of the sediments transported by the wadis are shown in figure14.

Spatial mapping

The obtained data were visualized with ArcGis 9.3. Samples A3, B1, and B3, collected from the harbor, had the finest grain size distributions. The grain size increased with distance from the shoreline, particularly for samples located between the quays. The presence of raw materials such as $BaSO_4$ dust, carbonaceous rocks, and clays such as kaolinite and bentonite were noted in loading areas (Fig. 15). These materials are transported by the wind and passing vehicles and deposited in the harbor basins. A6 and A7 were the only samples with larger grain size fractions (2 mm) due to sedimentary supply from the wadi flowing into the harbor (Fig. 15). Generally, sedimentary deposits vary with changes in the hydrodynamic energy of the environment. In this case, as the currents weakened, gravelly then sandy and muddy deposits were observed. Therefore, the sedimentary sequences had decreasing grain sizes with reduced energy in the environment.

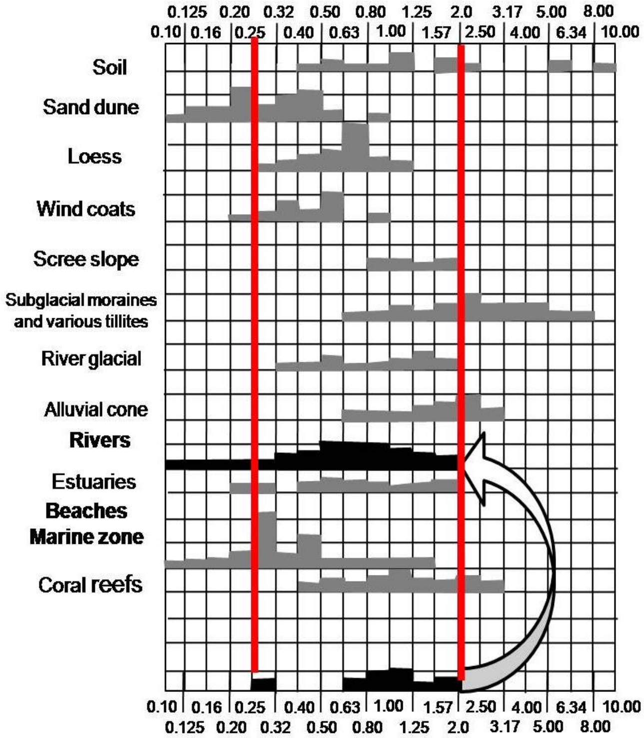

Figure 11. Qdphi Krumbein diagram. Qdphi = | Q25 ï Q75 |/2 (Krumbein 1936).

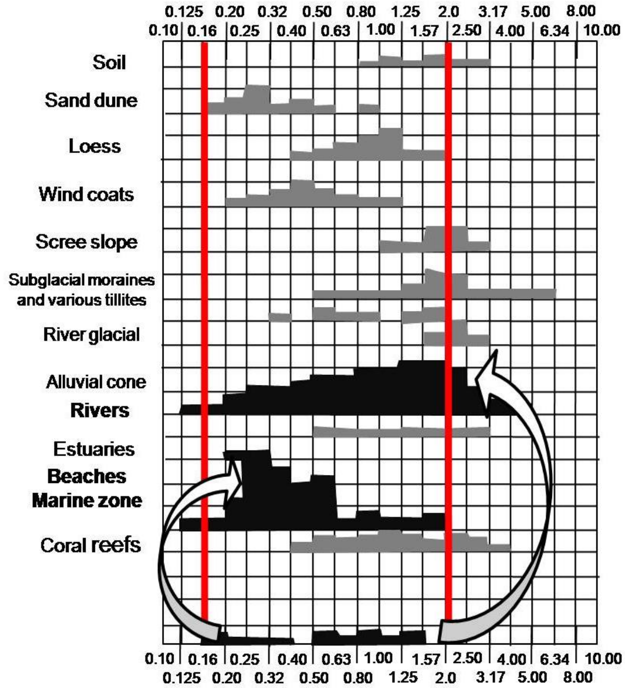

Figure 12. Cailleux & Tricart (1959) diagram.

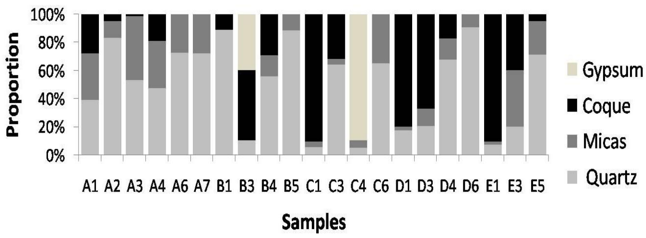

Figure13. Mineralogical composition of the sediment samples identified with a binocular microscope

Table 1. Morphoscopic analysis of quartz grains from the Nador Harbor.

Sample	Long (X)	Lat (Y)	Depth (m)	% Blunted Glow	% Round Mats	% Not worn
A1	725632.29	522716.78	13.50	47	16	37
A2	725503.28	522485.24	10.00	57	12	31
A3	725367.50	522229.80	9.00	59	16	25
A4	725305.60	522088.97	7.50	53	21	26
A6	725027.56	521573.02	2.50	53	28	19
A7	724841.05	521395.72	1.50	58	19	23
B1	725807.62	522531.01	12.50	68	18	14
B3	725527.70	522106.27	12.50	65	13	22
B4	725433.35	521948.32	8.00	58	13	29
B5	725304.01	521730.04	7.00	50	9	41
C3	725682.99	521870.70	12.50	53	21	26
C6	725177.79	521337.32	7.50	56	11	33
D1	726026.34	522158.83	13.50	40	15	45
D3	725773.86	521760.63	11.50	56	17	27
D4	725594.97	521588.27	15.00	70	7	23
D6	725285.12	521204.52	7.50	58	15	27
E5	725632.94	521224.87	6.00	58	18	24
E6	725402.19	521077.18	5.50	42	9	49

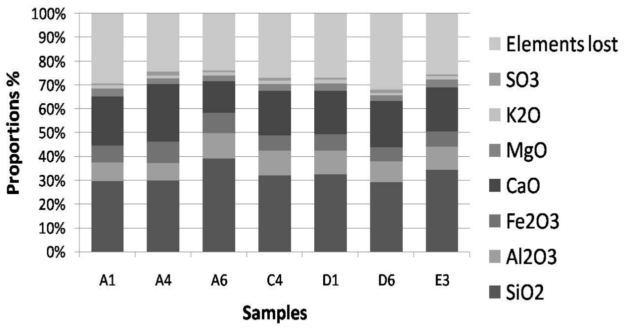

Figure14. Mineralogical compositions of selected sediments in Nador Harbor.

In this case, as the currents weakened, gravelly then sandy and muddy deposits were observed. Therefore, the sedimentary sequences had decreasing grain sizes with reduced energy in the environment. In Nador Harbor, the samples taken from the wadi mouth had a greater P5 value than those of samples obtained farther from the shoreline. The samples collected between the quays had a higher P5 value, because these samples were located in a quiescent area of the harbor and were affected by raw materials made up of fine particles (Fig. 16). A lower P5 value indicates an increase of energy. Therefore, samples with low P5 values were located in sheltered areas. In contrast, samples located in high-energy environments had high P5 values (Fig. 17).

The standard deviation index (STDV) (Folk & Ward 1957) is an environmental classification related to hydrodynamic energy and depends on the mode of sedimentation.

Well sorted values are typical of marine sediments, while very well sorted are specific to fluvial sediments (Folk & Ward 1957; Fig. 18). Sample A3 is a very well sorted, unlike other samples of the harbor bottom that are moderately to poorly sorted, indicating a fluvial deposit. Curve symmetry was evaluated using the skewness index of Folk & Ward (1957) in simple frequencies compared to the median ($Md = Q2$). According to the Asq index values of Pomerol (1963) ($Asq = (Q1 + Q3 ï 2Q2)/2$) and the S index values of Trask (1932) ($S = (Q1 \times Q3)/Q2^2$), two cases were represented in Figures 19 and 20: The black cubes ($Asq > 0$) represent coarse fractions with finely skewed values, showing positive asymmetry, whereas the circles ($Asq < 0$) represent fine fractions with coarser skewness, showing negative asymmetry (Fig. 19). The skewness index for the samples taken near the wadi mouth indicated coarse sand. Samples obtained farther from the wadi mouth had an asymmetric value, suggesting the presence of fine sand (Fig. 20). As shown in Figure 21, samples collected from the open area of the harbor indicate sediments deposited in a marine zone, whereas those obtained near the wadi mouth indicate sedimentation in a fluvial environment.

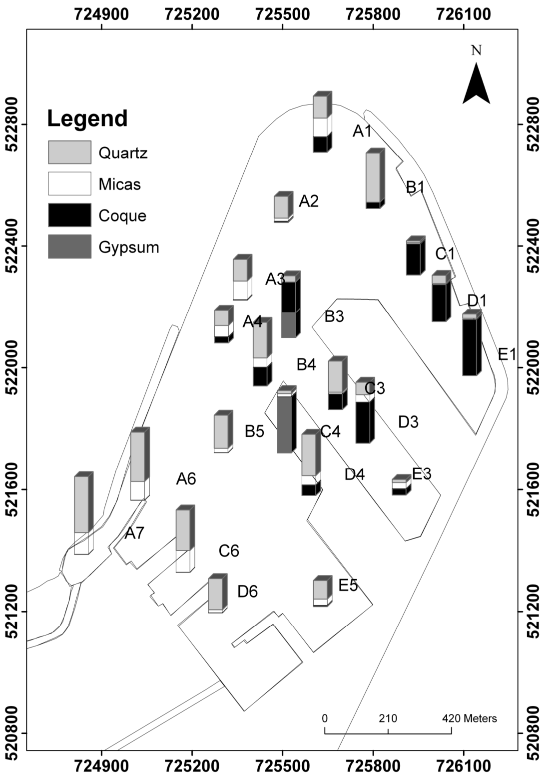

Figure 15. Spatial distributions of minerals.

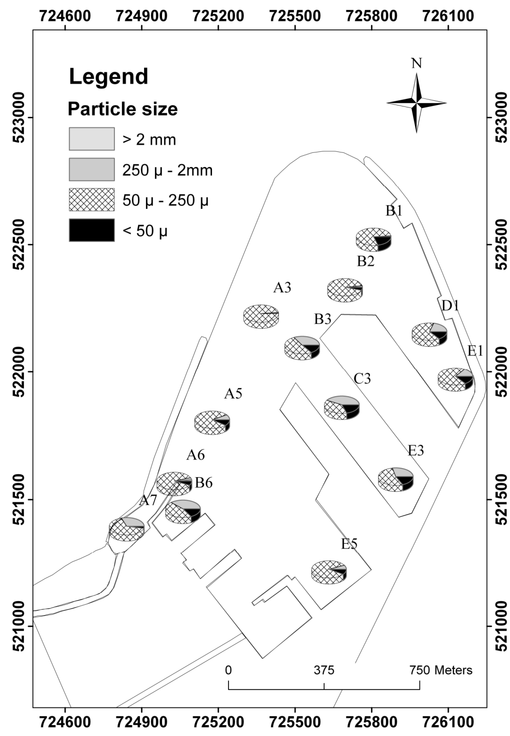

Figure 17. Spatial distribution of particle size fractions.

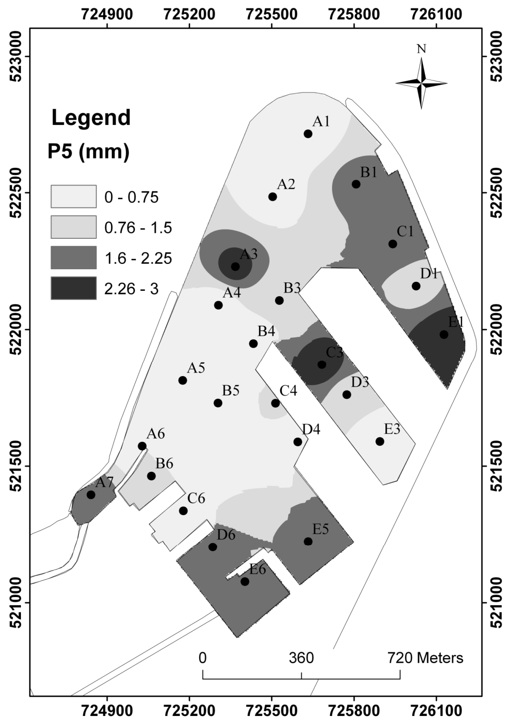

Figure 16. Spatial variations in the P5 percentile (mm).

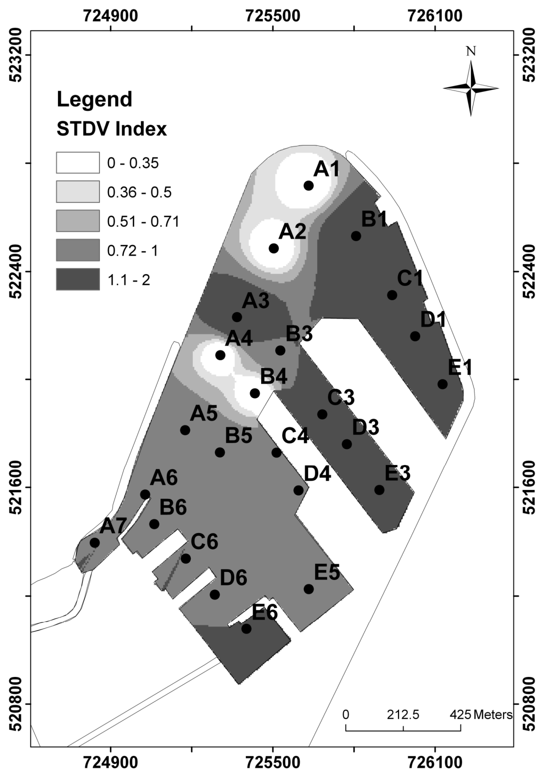

Figure 18. Standard deviation index (STDV).

DISCUSSION

The particle size analyses showed abundant mud and mixed sediments, including muddy sands and sandy mud. The classification indices showed that most of the samples were poorly sorted (A7, B3, B6, C3, D1, E1, E3 and E5); the remaining samples were very well sorted, indicating marine sediments. The skewness index showed that the fine fraction was very well sorted in samples A3, A7, B1, B2, B3 and C3, whereas the coarse fraction was poorly sorted in samples A5, A6, B6, D1, E1, E3 and E5. Therefore, these samples had fluvial characteristics, reflecting the torrential characteristics of the wadi flowing into the harbor. The Visher curves (1969) confirmed these results and also showed that most of the other samples originated from deposits in fluvial environments except sample A3, which is of marine origin. The Friedman diagrams (1967) (STDV according to skewness index) revealed that all of the samples were of fluvial origin, except sample A3, which was marine.

The ternary diagram of sedimentary classes after Shepard (1954) showed that most samples were arenites and their mode of transportation was saltation. However, samples A6 and A7, closest to the wadi mouth, were transported by high hydrodynamic energy associated with the discharge of the wadi.

The QDphi (Krumbein 1936) and Cailleux & Tricart (1959) diagrams confirmed that most of the analyzed samples had fluvial environmental characteristics, whereas the remaining samples were marine sediments transported by northeastï southwest winds.

The sandy sediments analyzed under a binocular microscope contained abundant quartz and mica in addition to phenocrysts of pyroxene and biotite. The high percentage of rock fragments indicates that the continental source was very close to the harbor basin; the origin was the volcanic massif of Gourougou Mount. Geochemical analysis confirmed the mineralogical results and determined the origin of most of the continental inputs as trachytic and rhyolitic rocks (El Bakkali 1995) from erosion of both Gourougou Mount and Cape Three Forks (Fig. 2). The morphoscopic study showed that fragments of rock were present mainly near the wadi mouth and these fragments were transported by the wadi, which flows directly into the harbor.

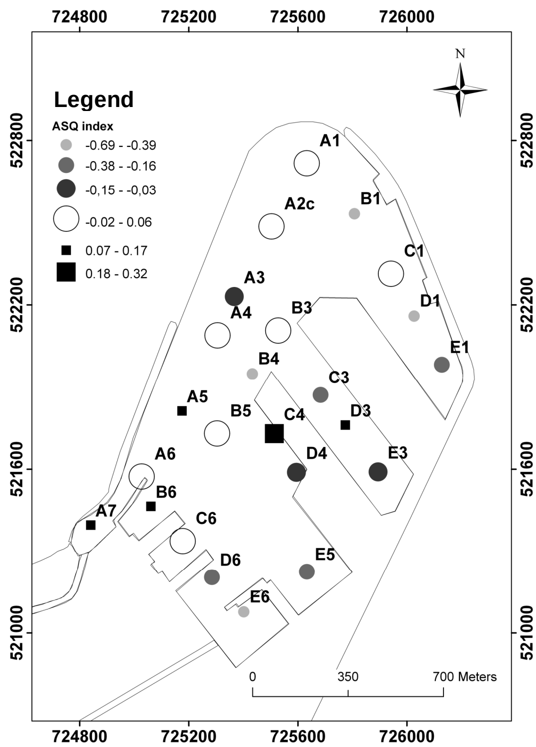

Figure 19. Asq index of Pomerol (1963).

All these results showed that the source of the majority of sediments deposited in the harbor is of continental origin. These sediments originate from erosion of Mount Gourougou (Hammadi 2008). According to Irzi (2002), the cliffs of Cape Three Forks, which are situated approximately 25 km from the harbor, are an area in which marine erosion produces large quantities of sediments. However, existing studies of marine currents and the hydrodynamic environment are not sufficient to determine the mechanisms of erosion and sedimentation along the coast. Furthermore, additional granulometric, mineralogical, and geochemical studies can be used to determine the sources of sediments in marine environments. For this reason, the present study considered particle transport modes, which offer more information about sedimentary environments.

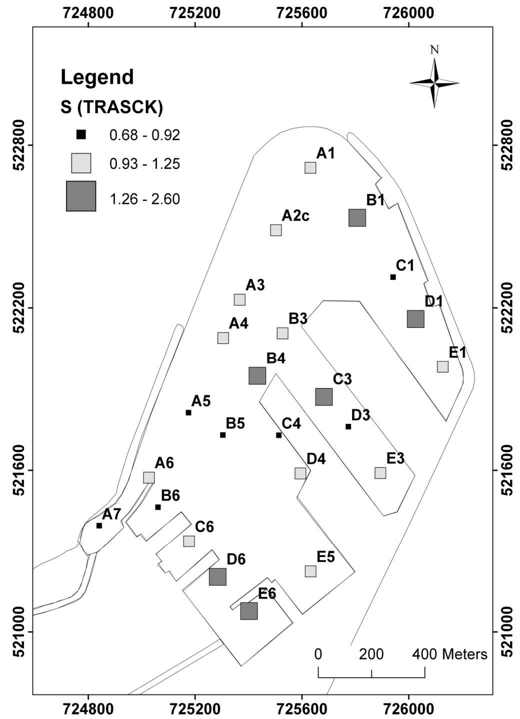

Figure 20. Skewness index S (Trask 1932).

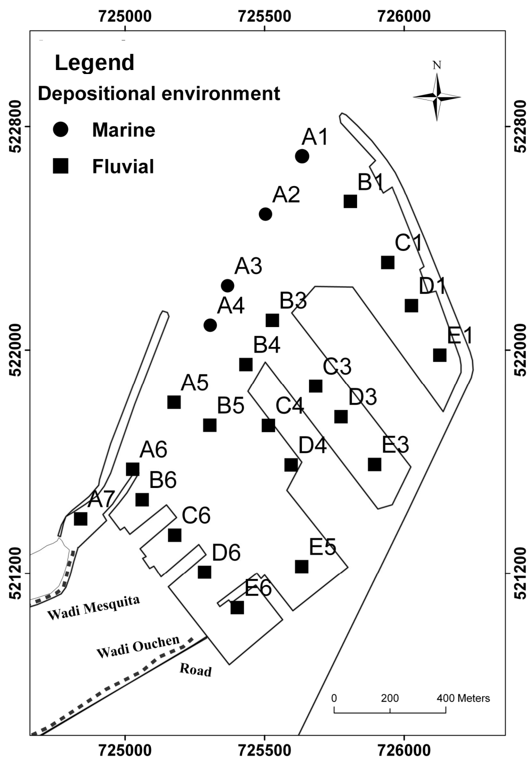

Figure 21: summarizes the result of different studies and shows the origin of sediments from Nador harbor's bottom.

CONCLUSIONS

Sedimentological and geochemical analyses confirmed that siltation in Nador Harbor originates mainly from a continental source. The origin of these continental sediments is the Wadi Ouchen and Arroyo La Mesquita, which carry eroded sediments from the watershed of Gourougou Mount during floods. Based on the sedimentary distribution in the harbor, the areas open to the sea are influenced by tidal movement, whereas those closer to the shoreline contain continental sediments. Therefore, the distribution of harbor sediments is influenced by fluvial input and waves. The results of this study contrast with those of Irzi (2002), which suggest marine origin of the sediments. The present results confirm that marine processes such as waves and swells have a minor effect on the coastline and siltation phenomena in the harbor.

Beni Ansar and Melilla are exposed to erosion in the watershed, which contains friable volcanic rocks (Hernandez 1975; Barathon 1989; Guillemin & Houzay 1982; El Kadiri 1992). Furthermore, Melilla Harbor is 3 km from Nador Harbor and both have the same issue of siltation. The bay of Melilla–Beni Ansar contains several wadi mouths that flow directly into the two harbors. Therefore, the results obtained for Nador Harbor can be extended to Melilla Harbor, where the origin of the sediments may also be continental. These results indicate that managing erosion in the watersheds of Beni Ansar and Melilla is necessary to minimize the need for dredging operations in both harbors.

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