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ORIGINAL PAPER

Distribution of heavy and clay minerals in coastal sediment of Jijel, East of Algeria: indicators of sediment sources and transport and deposition environments

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Abstract The identification of bulk, clay (<2 μm), and heavy (63–200 μm) minerals has been investigated on 42 coastal samples along the Jijel bay (Eastern Algeria). The mineralogical assemblages are used to identify the mineral sources and to interpret the mineral distribution. The samples were subjected to grain-size analysis by sieving and by X-ray diffraction on powder (bulk mineralogy) and on oriented aggregates (clay fraction). The bulk fraction is composed by muscovite, plagioclase, calcite, anhydrite, clay fraction, and a predominance of quartz (11 to 45 %). Clay fraction is composed of kaolinite, chlorite, smectite, interstratified minerals, and a predominance of illite (43–65 %). In addition, the heavy minerals assemblages of sediments have been identified by binocular observation, X-ray diffraction, and optical microscope. The heavy minerals are dominated by opaque minerals (16–65 %) associated with variable proportions of muscovite, chlorite, kyanite, sillimanite, biotite, pyroxene, amphibole, garnet, epidote, zircon, tourmaline, and rutile. Both fluvial hydrodynamic and marine agents control the sediment distribution along the coast. Indeed, the passage from areas in accretion toward those in erosion has caused a concentration in heavy minerals on coastal sections in recession; however, the light minerals were moved selectively toward accretional areas. The heavy mineral assemblages present in rivers sediment indicate that they were delivered to the coast in a highly selective manner. This assemblage of heavy mineral is also present with high concentration in a variety of fluvio-marine environments such as river mouths, coastal dunes, and beaches. These sediments are derived from the various geological formations (metamorphic formations of the basement, magmatic rocks, and other sedimentary rocks) observed in the watershed.

Keywords Heavy minerals · Clay minerals · Grain size · Sediment sources · Sediment distribution · Jijel coast

Introduction

The sediment dynamic along coastal environment is mainly related to marine and fluvial hydrodynamic processes (Rao 1957; Komar 1989; Frihy and Dewidar 2003; Anfuso et al. 1999; Ergin et al. 2007). It is also influenced by sediment sorting, which is controlled by grain size and density of source sediment (Sahu 1964; Folk 1966; Parefenoff et al. 1970; Nordstrom 1977; Pino and Jaramillo 1992; Frihy and Dewidar 1993; Pujos et al. 2001). Heavy minerals are excellent tracers for identifying the origins of sedimentary deposits in beaches and barrier dunes (Imbrie and Van Andel 1964; Pomerol 1968; Jones and Davies 1979; Hounslow and Morton 2004; Okay and Ergün 2005; Ergin et al. 2007). Therefore, the study of heavy minerals allows us to give an identity to the detrital formations; several studies have been undertaken worldwide to identify the origin and mechanisms of their formation (Emmanuel et al. 2010; Beiner et al. 2009; Pujos et al. 2001; Frihy and Dewidar 1993; Abuodha 2003).

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The grain size and mineralogical characterization of sedimentary stocks has been debated around the world: Achab et al. (2005). on the Bay of Tangier (NW-Morocco) and Cadix (SW-Spain); Frihy and Dewidar (1993, 2003). on the beach sands of the Burullus coast, north-central Nile delta (Egypt); Richard and Davis (1989). in the coast of Victoria (Australia); Gandhi and Raja (2014). in the coastal sediments of Tamil Nadu (India); Pons et al. (1991). in the bay of Fort-France; Hein et al. (2013) and Wong et al. (2013). in the San Francisco Bay Coastal System (USA); and Bouhamadouche and Boutiba (2012). in the coastal area of Boumerdes (Algeria). Here, we focus on the Jijelian East Coast where no previous study has been undertaken.

The choice of the Jijelian East coast is motivated by the strong coastal dynamics evidenced by several characters: (1) the succession of multiple geomorphological forms (sandy beaches, sand dunes, coastal plains, and many wadis) falling into bay subdividing the study area into different sectors. (2) A geologically diverse hinterland characterized by the predominance of metamorphic formations of the basement of the small Kabylia, magmatic rocks (Beni Touffout, El Milia), and other sedimentary rocks (Durand Delga 1955; Bouillin et al. 1977; Raoult 1974; Djellit 1987). (3) A dense wadis system leading into the bay (Mencha, Nil, Djen djen, and El Kebir). Sedimentary exchanges take place between the different morphological units from the coast.

The objectives of this work are:

- To define the mineralogical composition (bulk, clay, and heavy mineral) and grain-size distribution of coastal sediments.
- To define the transport processes through grain-size analysis and distribution of heavy minerals (percentage of opaque minerals and ZTR index).
- To identify the origin of sedimentary sources by comparing the mineral assemblages in sedimentary stocks on the coast such as beaches, cords current, and old dunes, and in the fluvial sand carried by the major wadis.

Regional physical setting

Location of study area

The study area corresponds to the Eastern part of Jijel's bay; it is situated at approximately 350 km East of the capital Algiers. It is located between latitude 36.6° and 37° North and longitude 6° and 6.6° East, and represents the maritime part of a topographic depression situated between two Capes, that of the meridian of Jijel city, to the West, and the promontory of Ras Mouadène to the East (Fig. 1).

Geological and geomorphological context

The geology of the Jijelian region (Fig. 2) is composed of crystalline basement, outcropping in almost the entire study area; this socle is formed of metamorphic rocks (mainly schists, micaschists, marbles, and gneiss), a discordant sedimentary cover greso-mecaceous dating from Oligo-Miocene age, in which are inserted the olistostromes debris coming from the flyschs, and secondly, the granites and microgranites from (Beni-Teffout, El Milia), and outcrops of allochtonous sedimentary rocks of Tellian domaine and an neogene coastal sedimentary basin of Taher-Jijel (Durand Delga 1955; Bouillin et al. 1977; Raoult 1974; Djellit 1987).

The morphology of the Jijelian sandy coast is formed of diverse landscapes showing the influence of neotectonic and eustatic factors during the Holocene (Boutiba 2006). The study of the global context of this area shows the presence of a remarkable morphological entity formed essentially of a long and beautiful sandy coast (54 km), and which is interrupted eastward by the spur of Ras Mouadène which isolates the beach of oued Z'Hor from the rest of the sandy coast. The width of the beach varies from a few meters to the West to a few tens of meters to the East. The actual dune cord is relatively narrow; it forms a sand accumulation that marches along the immense beach and orientate according to the dominant direction of coastal hydrodynamic mechanisms, generally NE–SW between the Ras Oum Chiche and the mouth of El Kebir wadi and East–West up to the mouth of Mencha wadi. It is constituted of quite low dunes between Jijel and the mouth of Djen djen wadi, then gradually higher 15–20 m up to Ras Mouadène. The continuity of these dunes is interrupted, in its turn, by the rocky coast of Ras Mouadène, then they resume up to the mouth of Wadi Z'Hor over a distance of 6.5 km. These dunes are developed at the mouths of major wadis which debouch into the bay and particularly at the mouth of El Kebir wadi where they culminate at about 30 m. The analysis of sedimentary stock shows uniform grained sands, a good sorting, and a good ranking testifying constant energy conditions during deposition. This actual dune cord is relayed toward inland by the old dune cord of reddish color and well consolidated. This narrow strip of sand forming the essential of the Jijelian coast connects to SW to a large plain which stretches from the city of Jijel to the city of El Kennar, and to the alluvial plain formed by the valley of El Kebir wadi in the central part of the coast.

Coastal hydrodynamic

The distribution and the mobility of sedimentary stocks along the Jijelian coast is the result of interactions between sediment and coastal hydrodynamics. The general configuration of Jijel bay makes her a very open bay to marine agitations coming mainly from sectors NW, N, and NE.

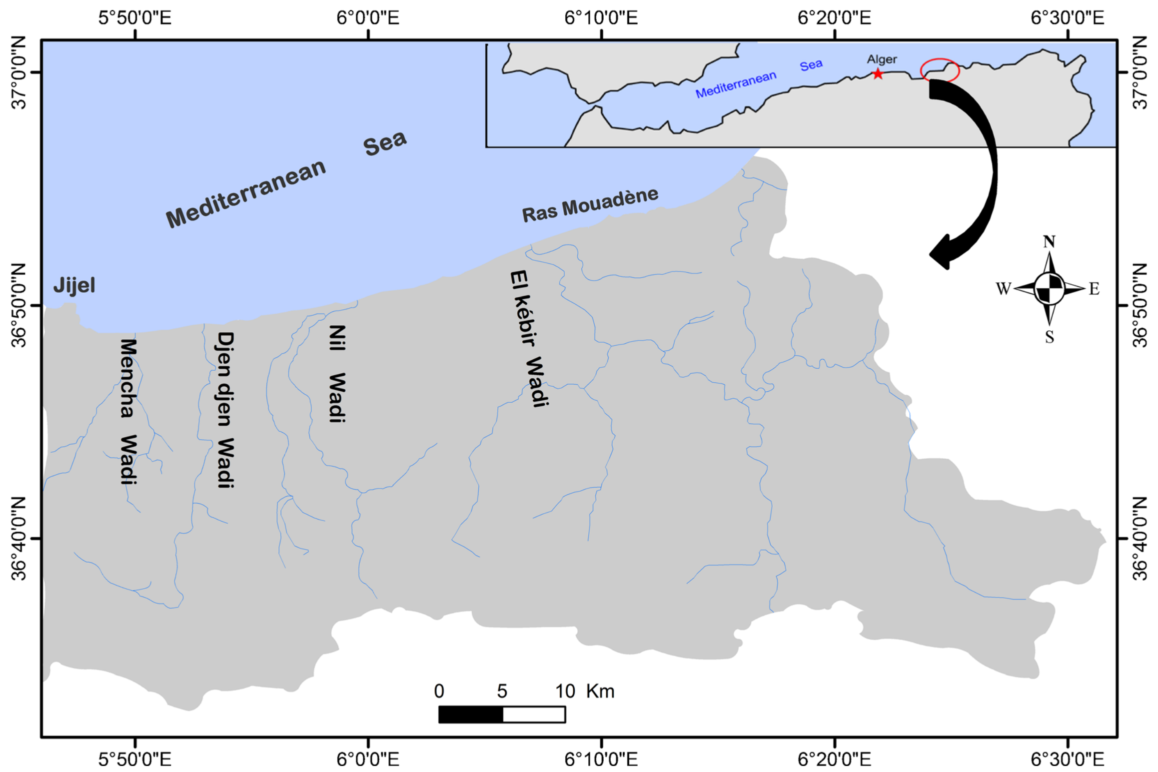

Fig. 1 Location of the study area

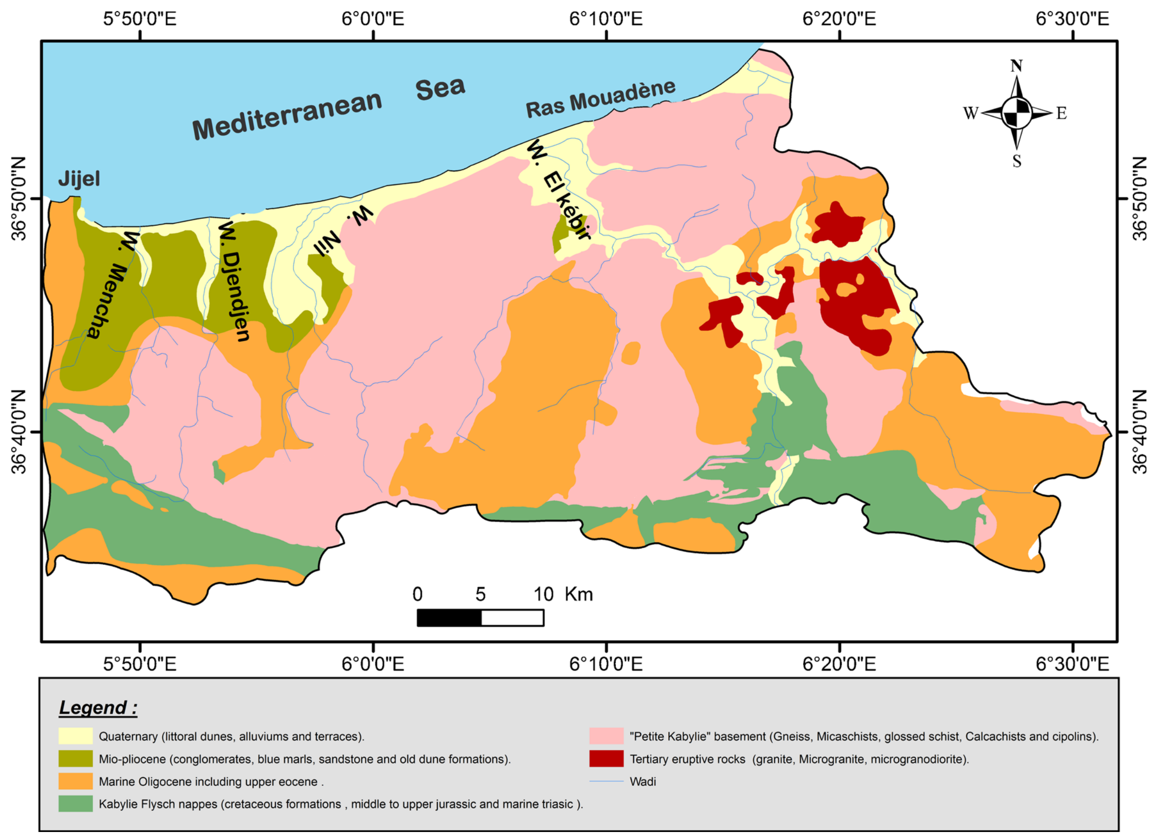

Fig. 2 Geology of the studied area (source: Geological map of Northern Constantine 1/500.0000e, edit. Geological Map Service of Algeria, 1951)

The dominant waves are from the East and West sectors with respective frequencies of 31 % et17%. The strong marine agitations with heights exceeding 2.75 m are observed during the first and fourth quarter. From October to March, during 15 to 30 % of the time, the swell heights vary between 2.75 and 3.75 m. The low heights of swells come from the Northeast sector with a rate of 17 % and a height that ranges between 0.75 and 1.75 m. Between April and September, Western, Eastern, and Northeastern swells are mainly dominating with respective frequencies of 23, 18, and 12.2 %, and heights that vary from 0.75 to 1.75 m. Between April and September, the swells coming from the West, East, and Northeast are mainly dominant with respective frequencies of 23, 18, and 12 %, and heights that vary from 0.75 to 1.75 m. The recorded wave's heights vary between 0.25 and 6 m. The periods of dominant swells vary between 5.03 and 8.1 s (Boutiba 2006).

The solids apports transported to the sea by wadis during flood periods are very important (National Agency of Water Resources) (Table 1). The main wadis which are draining and carrying along a significant quantity of sediment from the watershed of the hinterland of Jijel Bay, from West to East: Mencha wadi with an quantity equal to 0.5×10^6 m^3/year, Djen djen wadi with 1.45×10^6 m^3/year, Nil wadi with 1.15×10^6 m^3/year, and El Kebir wadi which carries the largest quantity of sediment with discharge 11.70×10^6 m^3/year.

Materials and methods

In this study, the collection of surface samples was carried out during the various missions realized during the years 2012 and 2013. A total of 42 superficial sediment samples were taken on different morphological systems (Fig. 3). Twenty-four samples were collected from beaches, current and older dunes, and 18 samples taken at the mouths and beds of wadis. The positioning of the sampling points was operated using a GPS with a precision of 4 to 5 m (Table 2). The weight of the sample is as a function of the grain size and the content of heavy minerals (Parefenoff et al. 1970).

Table 1 Hydrological characteristics of the principal wadis which emerge in the Jijel bay. (Source: National Agency of Water Resources "ANRH")

Wadis	Wadi length (km)	Watersheds area (km^2)	Annual average of precipitations (mm)	Liquid apports (10^6 m^3/an)	Solid apports (10^6 m^3/an)
Mencha wadi	26	135	1500	100	0.5
Djen djen wadi	63	391	1470	290	1.45
Nil wadi	40	315	1500	230	1.15
El Kébir wadi	200	3000	630	2520	11.70

Grain-size analysis

Sediment samples from oueds and aerial part of the coast were collected at 42 stations during Jun 2013. Sampling at near shore was carried of aboard IBTACIM ship, using a Van-Veen grab (Boutiba 2006). A total of 40 samples were collected along the coast. Sediment particle size analysis was conducted on each 200-g sub-sample according to standard protocols described by Boyd (2002). After separating underwater, through a sieve of 40 μm, the coarser fraction of sediment (∅>40 μm) was dried, weighed, and sieved through a series of sieves 2000 to 40 μm mesh, installment following the AFNOR standard. The results from sieving where then used to calculate the percentage weight per Wentworth (phi) scale ($\Phi=-log_2$D (mm)) and to calculate, three grain-size indices; the mean grain size (μ_z), standard deviation (Φi), and index of asymmetry (Ski) according to Falk and Ward (1957) for each sample.

Mineralogical analysis

The mineralogical analyses are to determine the qualitative and semi-quantitative mineralogical distribution of sediment arriving on the coast sedimentary stocks. Studied among these analyses was an analysis of the bulk, clay, and heavy mineral fractions. In total, 16 representative samples have been selected for the bulk and clay minerals analyses by X-ray diffraction.

For the bulk mineralogy, 1 g of the crude sample sieved to 250 μm, installed on a sample holder compacted carefully and regularly in order to limit any preferential orientation of minerals (method of Moore and Reynolds 1989). Semi-quantitative assessment was obtained by applying correction factors to the measured intensities of reflections of diagnostic mineral.

Clay minerals analyses were recorded from oriented aggregates on the glass slide (Moore and Reynolds 1989) and were prepared from the fraction <2 μm, obtained by suspension in distilled water of 1 to 2 g of dried bulk sediment sieved at 63 μm and then at 30 μm. Pretreatments requirements are based on analysis of bulk sediment. The fraction <2 μm is taken from the suspension after a settling time calculated according to Stoke's law. The suspension is placed on a glass slide and dried overnight at room temperature. We recorded for the same sample, three x-ray patterns in different experimental conditions, the first in the natural condition or under air-dried (N runs), solvated with ethylene glycol during 24 h (EG runs) and the third after heating at 500 °C for 4 h (H runs). Qualitative identification of the clay species is based on the relative position and intensity of specific reflections between the three X-ray patterns. Semi-quantitative estimation is based on the height of specific reflections measured in general in

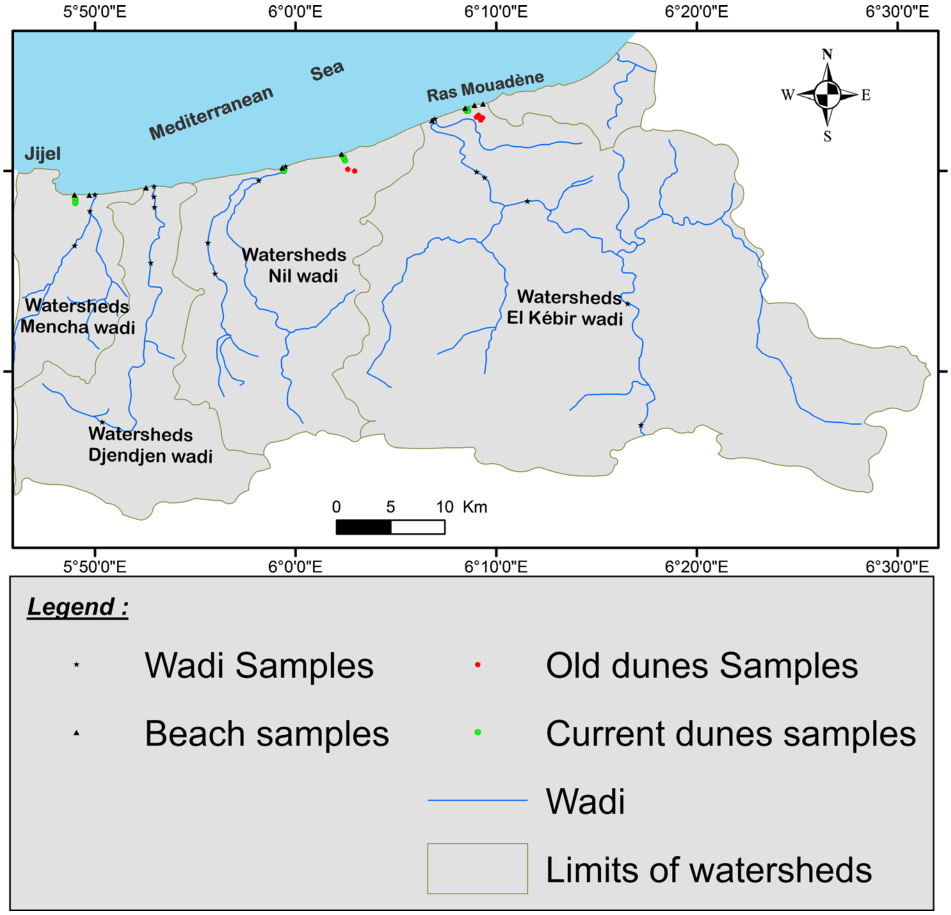

Fig. 3 Samples positioning and watersheds limits of the study area

the EG runs (Fagel and Boës 2008; Fagel et al. 2007). Corrective factors for clay minerals were determined by long-term empirical experiments at the University of Liege, for illite (×1), kaolinite (×0.7), chlorite (×0.34), smectite (×0.25), and interstratified 10–14 (×0.40) (see Fagel et al. 2007 for more explanation).

The study of the procession of heavy mineral with a density >2.89 was performed according to the experimental protocol proposed by Parefenoff et al. (1970). This technique has several steps for the separation of sediment: (1) the gross weight of sediments is of 2 kg, a quartering was done 200 g (initial weight in our study). (2) A sieving with a mesh size of 250 μm to remove the coarse fraction. (3) The sieved sediment has undergone a densimetric separation using bromoform (density 2.89) in special bulbs then rinsed with methyl alcohol. (4) The heavy minerals recovered underwent an electromagnetic separation by Frantz isodynamic, according to magnetic susceptibility. (5) The identification and counting of heavy minerals were carried on 20 representative samples under a binocular microscope, identification by X-ray diffraction, and an examination through optical microscope, after assembly with a synthetic resin.

Results and discussion

Grain-size distribution

The sediments collected along the Jijelian coast were subject of a grain-size analysis that allowed us to systematically calculate the three size indices (mean grain, sorting index, Skewness) necessary to determine the sediment distribution pattern along the Jijelian coast. The results of this analysis are consigned in Table 2.

The median, or medium grain diameter, corresponds to 50 % of the sample distribution. The remoteness of the inputs sources results in a decrease in the medium grain; this last one is, according to H. Chamley (1987). the expression of the strength of a current (wind, water) capable to have put in motion the essential of sediment. Along the coast of Jijel, According to Boutiba (2006). the coarse sand Ø>1.73 φ is located at the coast at a distance less than 150 m from the shoreline. In this area, sediment transfer direction can be determined from the gradient of the average grain size: oversized >1.73 φ at the mouth of the wadi Mencha and East from the mouth of Djen djen opposes the lowest values in the East of the port of Jijel. If we feel that the sediment transfer is carried

Table 2 Sediment particle size parameters of Jijelian coast sedimentary environments

Sectors	Sample codes	Longitude (ρ)	Latitude (λ)	Mean « UZ »	Skewness « Ski »	Storing « Φi »
Nil wadi	O.N.1	36.827921	5.937990	1.20	−0.11	0.71
	O.N.2	36.821808	5.936321	1.94	0.08	0.91
	O.N.3	36.773967	5.929101	2.61	0.22	1.08
	O.N.4	36.747500	5.941300	2.21	−0.11	0.74
Djen djen wadi	O.D.1	36.813144	5.855452	1.92	0.16	0.95
	O.D.2	36.811029	5.864201	2.17	−0.03	0.73
	O.D.3	36.805044	5.863136	0.94	0.09	0.63
	O.D.4	36.755655	5.863136	2.96	0.32	0.98
	O.D.5	36.628500	5.797300	2.31	−0.25	0.55
El Kebir wadi	O.E.K.1	36.870700	6.086700	2.74	0.22	0.67
	O.E.K.2	36.832300	6.133700	2.49	0.02	0.84
	O.E.K.3	36.806314	6.169399	2.27	0.01	0.85
	O.E.K.4	36.725599	6.260924	0.78	−0.17	1.46
	O.E.K.5	36.636468	6.276812	0.30	−0.03	1.46
	O.E.K.6	36.602465	6.281557	1.02	−0.21	0.74
Mencha wadi	O.M.1	36.807900	5.821500	1.59	0.00	0.87
	O.M.2	36.803319	5.811636	2.65	0.07	0.93
	O.M.3	36.771302	5.799381	1.80	0.24	0.61
The eastern sector (region of Beni Belaid)	E.P.1	36.892105	6.144518	0.91	0.12	0.63
	E.P.2	36.885684	6.124858	1.42	−0.17	0.45
	E.P.3	36.871082	6.083319	1.46	0.15	0.71
	C.D.Ac1	36.884700	6.125300	1.20	−0.22	0.60
	C.D.Ac2	36.884800	6.126600	1.15	−0.12	0.66
	C.D.Ac3	36.884790	6.126589	1.15	−0.18	0.62
	C.D.Ac4	36.885100	6.127300	1.13	−0.17	0.64
	C.D.A.1	36.878100	6.140000	1.06	0.01	0.85
	C.D.A.2	36.880400	6.139400	1.49	0.05	0.64
	C.D.A.3	36.880300	6.137800	1.77	0.29	1.04
	C.D.A.4	36.880275	6.137753	1.67	0.09	0.73
The sector between El Kebir and Nil wadis.	E.P.4	36.848167	6.025001	1.43	0.01	0.92
	C.D.Ac5	36.847655	6.025205	1.48	−0.03	0.51
	C.D.Ac6	36.846561	6.025713	1.19	−0.21	0.62
	C.D.A.5	36.845100	6.043600	1.51	0.19	0.57
	C.D.A.6	36.844059	6.023762	0.90	0.08	0.70
Sector West, between Nil wadi and Jijel city	E.P.5	36.827391	5.935234	1.20	−0.23	0.61
	C.D.Ac7	36.824700	5.935600	1.49	−0.01	0.54
	C.D.Ac8	36.825600	5.935300	1.64	0.23	0.52
	E.P.6	36.808221	5.819247	1.31	−0.09	0.93
	E.P.7	36.806900	5.805500	2.04	−0.11	0.63
	E.P.8	36.812727	5.848360	1.66	0.21	0.54
	C.D.Ac9	36.806548	5.805562	1.50	0.05	0.35
	C.D.Ac10	36.806336	5.805603	1.05	−0.09	0.62

The mentioned samples codes in the table of Jijelian coast sediment size parameters show that samples of wadis (O.N, O.M, O.D, and O.E.K) marked from 1 to 6, of which the mouth is toward upstream of wadi. For beach samples (E.P), current dunes (C.D.Ac) and old dune cord (C.D.A), they are marked by 1 to 10, so these samples are charged from the West to the East coast out from the high-energy zones to areas of low energy, this transfer will therefore be conducted from East to West. Between the mouth of Nil wadi and Sidi Abdelaziz, the value of mean grain, if we set aside the station at the East of the mouth of the El Kebir wadi, is homogeneous; it ranges from 2.95 φ to 2 φ. The station located at the East of oued Nil is characterized by relatively coarse sands Ø>−0.189 φ. This makes us think that littoral drift starts from this station. The presence of coarse sediments in this location leaves us to also suppose that this station can be considered as a source area. Between Sidi Abdelaziz and the mouth of the El Kebir wadi, the mean grain is relatively coarse (2 φ) and tends refine from either sides of this area. This fineness of particle size of the samples of the neighboring stations at this coastal area could come from the reduction in the competence of long shore current or from dissipation of wave energy. From El Kebir wadi to Z'Hor wadi, the values of the mean grain vary from 2.06 φ to 1.29 φ, even if the high values are located at the mouth of Z'Hor wadi. The medium sands (2.06 to 0.73 φ) are located along the coast to a depth of −9 m, while the fine sediments (0.16 mm<Tm< 0.24 mm) are positioned at depths −9 m above. This classic sediment distribution pattern can be explained by the importance of the coastal hydrodynamics prevailing in this area.

For the sediments collected from beds of wadis that debouch into the bay, the mean grain size (μ_z) of almost all samples varied between 1.20 φ and 2.94 φ, indicating the dominance of fine to medium sand at over 50 % except, those collected at the upstream of wadi El Kébir that show a mean value of $\mu_z<1$ φ, denoting the dominance of coarser sand. These results show that the diameter of the sediment decreases from upstream, where medium to coarse sands dominate, with a percentage that varies between 43 and 55 %, to downstream where the percentages of fine sands oscillate between 66 and 90 %. In samples collected from different beaches, the beaches sands show a value of the mean grain size (μ_z) which varies between 2 φ and 1φ, indicating a high proportion of fine to medium sands (66 and 95 % of fine sand), except for samples collected at the beach of Beni Belaid, located in the Eastern part of the coast, where the values of the mean grain size is around 0.91 φ, indicating the predominance of coarse sands with a percentage of 58 %. At the Westerly coast beaches, the encountered sediments show that values of the mean grain size oscillate between 1.66 φ and 2.04 φ reflecting the dominance of fine sand (90–95 %).

The standard deviation values, from the city of Jijel to the mouth of oued Nil, on the seabed of this coastal portion, and the encountered sorting index values do not exceed 0.7 φ; they vary between 0.4 φ and 0.7 φ. Globally, all stations present a good sorting even if from West to East the classification index evolves in "saw tooth." Stations, which present a moderate sorting, could characterize starting areas; they meet throughout this coastal portion and are spaced a few hundred meters. These stations are characterized by relatively coarse sand compared to those of neighboring stations and denote either starting zones or accumulation zones. Between oued Nil and oued El Kébir globally, sediments of all stations are poorly sorted to very poorly sorted. On the coast, poor sorting of the collected sediments could be related, if one refers to the model of Gao and Collins, either to the starting areas or to the areas of accumulation of very fine sand, which greatly affect the dispersion index. From the mouth of oued El Kébir to Ras Oum Chiche, the geographic distribution of the sorting index is homogeneous. The recorded values oscillate between 0.35 φ and 0.71 φ and denote of a good sorting of sediments (Boutiba 2006). The majority of samples taken in the wadis beds show standard deviation values ranging from 0.55 φ to 0.98 φ (Table 2). They are therefore moderately graded except for samples from upstream of oued El Kebir (O.K5 and O.K6) and those of Nil wadi (ON3) that show the values of the standard deviation of 1.46 φ and 1.08φ, respectively, and are therefore poorly graded. These results are evidence of a strong energy used to carry sediment upstream of the wadis. This energy decreases toward the mouths and so the sediment settles in low agitated areas. In the East of the study area, beach sediments show standard deviation values ranging from 0.45 φ to 0.71 φ. They are therefore moderately graded to well grade and are deposited in low turbulent environments, at average energy of the action of waves and currents.

Skewness « Ski » reflects sorting in the "tails" of a grain-size population. Along the coast of Jijel, longitudinal evolution of asymmetry index is not uniform; it varies from one place to another. From the city of Jijel to the mouth of El Kébir wadi, the evolution of skewness indicates enrichment in fine sediments of the areas located at the mouth of Djen djen and El Kébir wadis. The distribution of skewness in this part of the coast testifies therefore of an accumulation zone. In this zone, the encountered sands are fine and well-sorted and enriched in fine particles in the direction of the longshore sediment transport. Between oued El Kébir and Ras Oum Chiche, on the seabed of this zone, the values of skewness found show a general tendency to granulometric symmetry +0.1<Ski< −0.1. In conclusion, we say simply that we must remain very cautious about the interpretation of this index in our study area because the recorded values are not very fluctuating and close to the limit of the particle size symmetry (Boutiba 2006). In wadi sediments samples, the "Ski" values vary from negatively skewed to very positively skewed (−0.25 to 0.24). It implies the presence of conditions of high and low energy of fluvial environments, favoring a mixed distribution of coarse and fine sediments. At the beaches, actual and old dunes, recorded values of Skewness vary from negatively skewed to positively skewed (−0.22 to 0.10) except for samples from Tassoust beach (E.P.8) and the beach sample from the right bank of oued El Kebir (E.P.3) which present skewness values ranging from 0.15 to 0.21 (Table 2) indicating a low-energy environment (low energy of currents and waves).

Bulk minerals content

Quartz, muscovite, plagioclase, calcite, and anhydrite form the principal components of the superficial sediments. However, clay minerals are present with contents that vary from a sample to the other (Table 3, Fig. 4).

Quartz is the most dominant mineral in coastal sediment of the study area. It is generally present in irregular fragments more or less angular or in rounded grains. High quartz contents (45 to 50 %) are detected in all beach sediments (Table 3 and Fig. 4). These contents diminish while going toward inland. In coastal dunes (actual and old dunes), the recorded contents vary between 36 and 45 %. In the river sands, contents increase from upstream (16 and 24 %) to downstream (34 %), except in those from oued El Kebir, which have average contents between 29 and 38 % over its entire length but, in sediments of oued Nil, contents are smaller (11 to 15 %).

Muscovite is very abundant in all oueds sediments with maximum contents that vary between 50 to 64 %, in oued Nil (Table 3). This mineral is less abundant in sediments of Djen djen and Mancha wadis, where recorded contents fluctuate between 12 and 37 %. It is also present in samples collected from oued El Kébir with smaller average contents (3 and 16 %). Muscovite is totally absent in the beach sediments and dunes except in the old dunes of Beni Belaid where it is detected with smaller contents (4 %). The relative high muscovite content of oueds sediments, indicating derivation from metamorphic basement rocks rich in muscovite and the entire upper and lower of gneissic substratum (Djellit. 1987). It is also present in samples of oued El Kebir, with smaller content (3 and 16 %), indicating probable derivation from the formations of the Oligo-Miocene Kabyle, metapelites formations, and granites of Beni Belaid. Muscovite is absent in beaches and dunes sediments. This absence is probably due to its alteration during fluvial transport. The presence of this mineral

Table 3 Bulk and clay mineralogy percentages of the Jijelian coast sediments and the principal wadis

No. of sample	Bulk mineralogy (powder) %								Clay mineralogy (fraction <02 μm) %				
	Muscovite	Quartz	Clay fraction	Microcline	Plagioclase	Calcite	Anhydrite	Dolomite	Chlorite	Kaolinite	Illite	Smectite	Intestratified 10–14
	Corrective factors of each mineral												
	(6.00) Cook et al. (1975)	(1.00) Cook et al. (1975)	(20.00) Boski et al. (1998)	(4.3) Cook et al. (1975)	(2.80) Cook et al. (1975)	(1.65) Cook et al. (1975)	(0.9) Cook et al. (1975)	(1.53) Cook et al. (1975)	(0.34) Fagel et al. 2007	(0.70) Fagel et al. 2007	(1.00) Fagel et al. 2007	(0.25) Fagel et al. 2007	(0.40) Fagel et al. 2007
O.K.1	3	34	20	18	0	15	4	6	7	48	43	2	0
O.K.2	12	38	24	12	0	13	1	0	6	50	42	2	0
O.K.6	16	29	25	7	0	21	2	0	9	35	45	0	11
O.N.1	65	11	9	0	7	0	8	0	6	29	65	0	0
O.N.2	50	15	14	10	6	0	5	0	6	38	56	0	0
O.D.2	12	34	22	0	8	22	2	0	10	50	40	0	0
O.D.4	37	16	15	0	6	22	2	2	9	43	43	5	0
O.M.1	24	34	21	0	11	8	2	0	7	36	57	0	0
O.M.3	36	27	15	4	9	6	3	0	8	36	61	1	0
P3	0	46	15	10	8	16	5	0	8	46	42	4	0
P7	0	50	19	0	12	11	8	0	9	30	61	0	0
CDAc1	0	36	21	0	5	35	3	0	5	31	64	0	0
CDA.1	4	39	28	23	5	0	1	0	12	31	52	4	0
CDA.3	0	45	28	0	21	3	3	0	7	28	61	4	0
CDA.5	0	42	28	15	12	0	3	0	9	34	41	4	12
CDA.6	0	40	38	0	17	0	5	0	13	33	51	3	0

The code samples selected for bulk fraction and clays mineralogy analysis which are mentioned in the table are (OK1, OK2, and OK3): El Kebir wadi samples from the mouth to the upstream. (O.N.1et O.N.2): Nil wadi samples. (OD2 and OD4) Djen djen wadi samples. (OM1et OM3) oued Mencha samples. (P3 and P7): beaches samples. CDAc1: current dune sample. (CDA.1, CDA.3, CDA.5, and CDA.6): old dune samples. The numbers between brackets present correction factors of each mineral it used for semi-quantitative estimation. For bulk mineral fraction, the corrective factors were mentioned by Cook et al. (1975) and Boski et al. (1998). For the clay minerals, the corrective factors were determined by Fagel et al. (2007) for more explanation

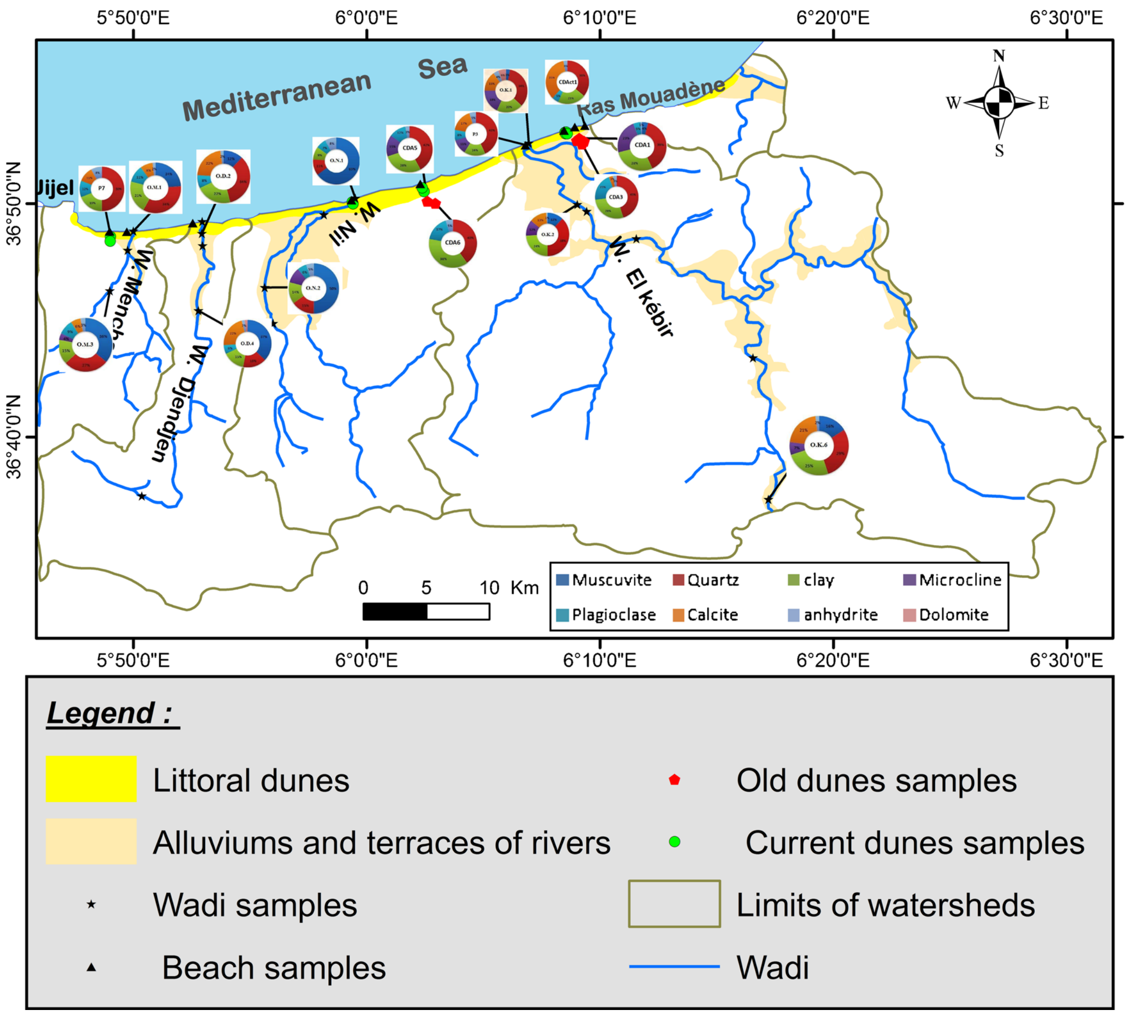

Fig. 4 Bulk mineralogy in percent of the Jijelian coast sediments and their river beds

in old dunes sediments of Beni Belaid with low content (4 %) can be explained by derivation from local outcrops of micaschists of the Kabylian basement.

K-Feldspar is present in sediments of oued El Kebir, ancient dunes, and beaches of Beni Belaid, with average content of 7 to 23 %. This mineral may be derived from granite and microgranite of Beni-Touffout and pegmatite of Beni-Belaid. In the Western and central oueds surface sediments, K-feldspar shows lower contents between 4 and 10 % at the upstream of the Nil and Mencha wadis which carryout these minerals derived from the alteration of gneissic basement. However, it is fairly presents in ancient dune sediments of Sidi Abdelaziz with an average content of 15 % (Table 3), indicating that their origin is related to the alteration of micaschist of the underlying metamorphic basement.

Plagioclases are present in sediments, of the beaches and recent dunes, of the oriental part of the coast, with very low contents (5 to 8 %). However, it is more frequent in sediments of ancient dunes of Beni Belaid with an average content of 8 to 12 %. This mineral is absent in the loads of El Kebir wadi. So, the origin of this mineral is probably linked to the in situ alteration of the metamorphic basement rocks. In the Western part of the coast, the plagioclases are present in sediments of different oueds and different sedimentary stocks (beaches, ancient, and actual dunes) with contents that vary from 6 to 26 %. These minerals come from alteration of gneissic rocks exposed in the catchments of different oueds that debouch into the bay.

Carbonates are represented by calcite and dolomite. The calcite is present in all sediments of the studied coast, except those of oued Nil and ancient dunes, with average contents of 6 to 35 %. The dolomite is more present in the samples from the mouth of El Kebir wadi, whose sediments have average content of 6 %, than in samples from the upstream of Nil wadi with average proportion of 2 % (Table 3). This small content is due to its high solubility in the runoff waters rich in CO_2 (Parefenoff et al. 1970).

Anhydrite is present only in sediments collected at the upstream of different oueds, with an average content of 1 to 8 %. This mineral, which derived mainly from soles of allochtonous flyschs, is quickly dissolved during fluvial transport.

Clay fraction is present in all samples with contents that vary between 9 and 25 % in the wadi and beach samples. It is higher in the samples from the old dune cords with an average content of 28 to 38 %. Kaolinite, chlorite, illite, and smectite are the major components of the clay minerals spectrum (Table 3). For a better identification of this clay fraction, we realized a study both qualitative and semi-quantitative.

Augite, monazite, hematite, magnetite, and garnet are present in the semi-quantitative analysis of bulk fraction but in negligible quantities (<0.5 %).

Clay minerals distribution

The qualitative identification of clay minerals was made on the X-ray diffraction diagrams. It is based on the relative position and specific reflection of peak intensity: illite has been identified by the intensity of 10 Å in natural condition (N runs); it does not change in EG runs, and after heating (H runs). Kaolinite shows a reflection peak at 7.1 Å in natural conditions, the same peak value remaining after solvation in ethylene glycol and shows the disappearance of the peak after the heating at 500 °C (H runs). Chlorites were identified by the intensity of 14 Å in N runs without changes on EG and H runs. Smectites were identified by the intensity of 15.4 Å in natural conditions, the intensity of 17 Å after solvation in ethylene glycol (EG runs), and 10 Å intensity after heating to 500 °C (Fagel et al. 2007; Thorez 1976). The percentages of clay phases identified in studied sediments were evaluated by applying corrective factors (Table 3).

Kaolinite, illite, chlorite, smectite, and random 10–14 Å mixed-layers with variable proportions are the main components of clay minerals spectrum obtained in detrital fraction of the Jijelian coast (Table 3, Fig. 5). This distribution is controlled by clay deposit and Miocene outcrops in catchments of the hinterland. The results of mineralogical analysis of samples from the upstream part of the bed of oued El Kebir show the presence of illite and interstratified with a percentage of 45 and 12 %, respectively. At the mouth, the mineralogical

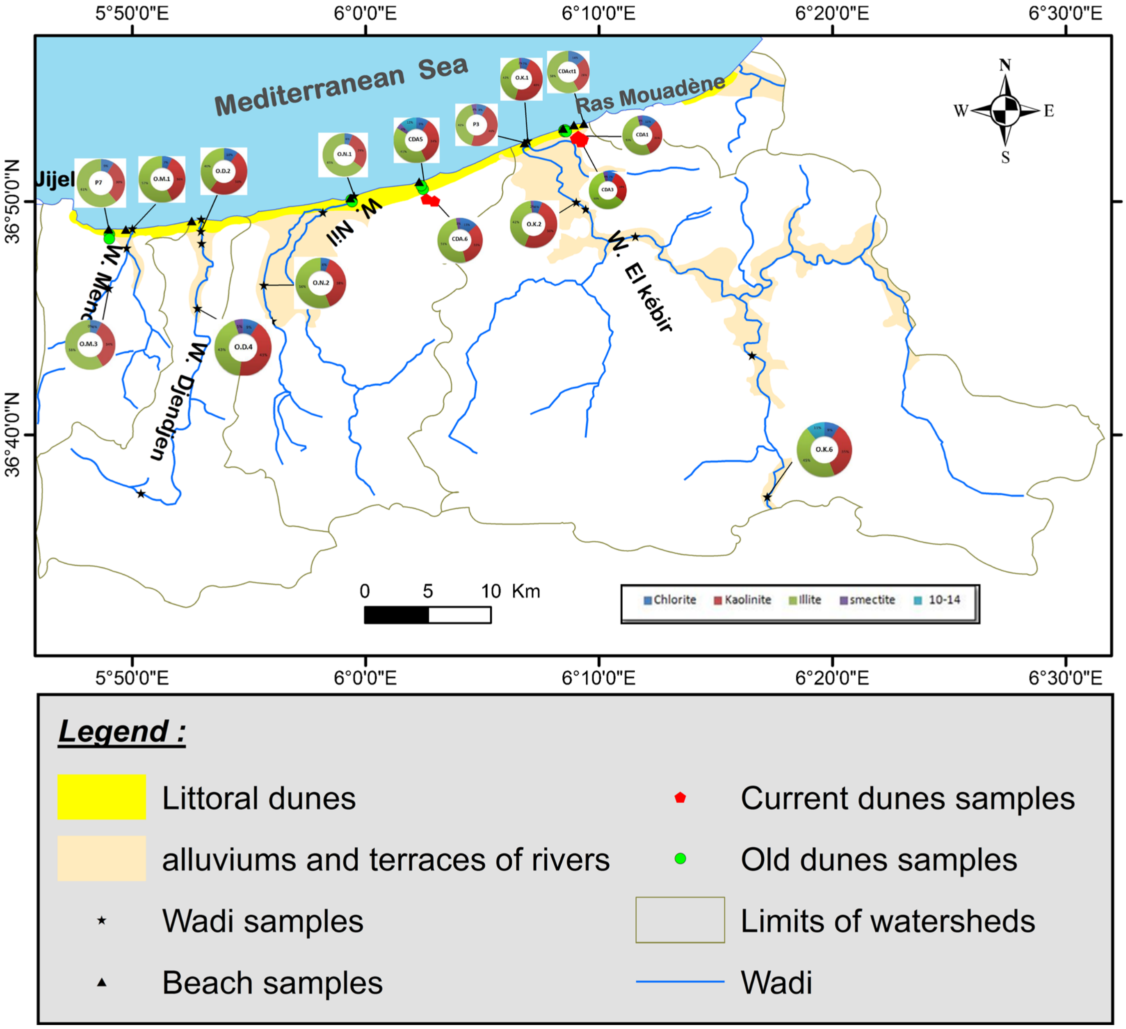

Fig. 5 Clay minerals distribution of Jijelian coast sediments and their river beds

cortege is mainly composed of illite (42–43 %), kaolinite (45–50 %), chlorite, vermiculite, and interstratified are present with low contents, 6 to 9 % and 2 to 12%, respectively. High kaolinite contents (42 %) are detected in beach samples of Beni Belaid. Illite is observed in sediments from actual and ancient dunes of this region with maximum proportions that range between 52 and 64 %. Kaolinite and chlorite are also present with percentages ranging from 28 to 31 % and 52 to 64 %, respectively. In central and Western parts of the coast, sediments collected upstream from beds of three main wadis (Nil, Djen djen, and Mencha) show the presence of high proportion of illite (41–65 %), except sediments of oued Djen djen where kaolinite dominates with a percentage of 50 % compared to illite 40 %. In sediment samples, from beaches and dunes of these areas, kaolinite is more presented (29–38 %) than illite (6–13 %). Vermiculite is absent in sediments from these beaches and beds wadis but it is present in low quantities (<4 %) in samples from ancient dunes of Sidi Abdelaziz (Table 3).

Kaolinite transported in suspension by various wadis that debouch into the bay is derived from the alteration (hydrolysis) of feldspars of leuco-granites, veins of pegmatite and aplite, which cross the cristallophyllian rocks of the Kabylian basement and the alteration of ortho-gneiss basement of Tamazert located at the northern El Milia. Illite is present in abundance in sediments of Djen djen and Mencha wadis in the Western part of Jijelian coast. Illite and chlorite could come from alteration of sub-littoral Neogene basins (Constantine and Jijel). These clay minerals can be derived, also, from the weathering of the basement crystalline schist. Clay minerals from sediments samples of the continental shelf of the bay of Jijel are illite (21 %), chlorite (18 %), and Kaolinite (15 %). The distribution (Fig. 5) of these minerals in shallow zones are low; they increase toward off the mouths of the main wadis, which debouch into the bay (Boutiba 2006). This marine distribution of clay minerals is controlled by dominant clay minerals found in the wadis discharges and coastal processes such as waves, longshore current, undertows, coastal erosion, sediment transport, and deposition. Indeed, illite, kaolinite, and chlorite are dominant clay minerals in sediment discharges of oueds. These sediments are deposited off the mouths by rip currents and longshore current (Fig. 6).

Heavy mineral content and provenance

The heavy minerals at Jijelian coast present a small portion of sediment. They have a density which is greater than 2.81. They are most often used as natural tracers to identify the sediment source in different geological environments (Parefenoff et al. 1970; Joshua and Oyebanjo 2009; Pujos et al. 2001; Mange and Wright 2007; Wong et al. 2013). Since heavy minerals are denser than quartz and feldspar grains, they behave differently during transport and deposition. The proportions of heavy minerals, along the Jijelian coast, differ from one morphological sector to the other. They depend on the density of the mineral, its hardness, transport agents, and alteration. The results of qualitative and quantitative analysis of heavy minerals in the sediments of the Jijelian coast are shown in Table 4. This table shows the predominance of opaque mineral associations and muscovite, chlorite, kyanites, sillimanites, biotite, pyroxene, hornblende, garnet, epidote, and association of ubiquitous minerals. The association of ubiquitous minerals is characterized by ZTR index (Zircon, Toumaline, Rutile). This index is the sum of the percentage of zircon, tourmaline, and rutile, which are minerals resistant to

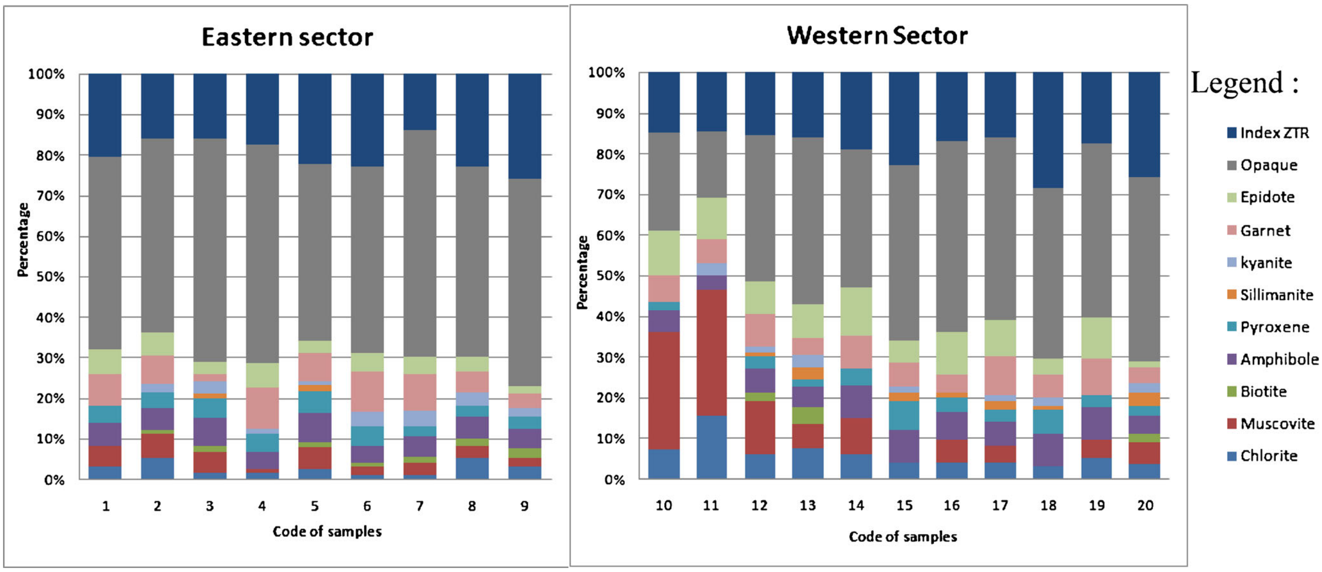

Fig. 6 Histograms of heavy minerals distribution of Jijelian coast surface sediments

Table 4 Heavy minerals percentages of the Jijel bay samples

Sectors	Samples	Code	Chlorite	Muscovite	Biotite	Amphibole (hornblende)	Pyroxene (augite)	Sillimanite	Kyanite	Garnet	Epidote	Opaque	Zircon	Tourmaline	Rutile	Index ZTR
East sector of the study area	OK1	01	03	05	–	06	04	–	–	08	06	47.5	12.5	05	03	20.5 %
	OK3	02	05	06	01	05.5	04	–	02	07	05.5	48	07	05	04	16 %
	OK6	03	1.5	05	01.5	07	05	01	03	02	03	55	09	05	02	16 %
	P1	04	1.5	01	–	04	04.5	–	01.5	10	06	54	09	05	03.5	17.5 %
	P3	05	2.5	06	01.5	08	06	1.5	01	07.5	03.5	48	6.5	06	02	24.5 %
	CDAc2	06	01	02	01	04	05	–	03.5	10	04.5	46	10	08	05	23 %
	CDAc4	06	01	03	01.5	05	02.5	–	04	9	04	56	07	04.5	02.5	14 %
	CDA1	07	05	03	02	05.5	02.5	–	3.5	05	03.5	47	17	03.5	02.5	23 %
	CDA3	08	03	02	02.5	05	03	–	02	03.5	02	51	17.5	05.5	03	26 %
Western sector of the study area	ON1	09	07	29	–	05.5	02	–	–	06.5	11	24	07	04.5	03.5	15 %
	ON4	10	15.5	31	–	03.5	–	–	03	06	10	16.5	8.5	04	02	14.5 %
	OD1	11	06	13	02	06	03	01	1.5	08	08	36	08	05	2.5	15.5 %
	OD3	12	07.5	06	04	05	02	03	03	04	08.5	41	05.5	07.5	03	16 %
	OM1	13	06	09	–	08	04	–	–	08	12	34	09.5	05.5	04	19 %
	P04	15	04	–	–	08	07	02	01.5	06	05.5	43	13.5	05.5	06	23 %
	P06	14	04	05.5	–	07	03.5	01	–	04.5	10.5	47	09	05	03	17 %
	P07	15	04	04	–	06	03	02	01.5	09.5	09	45	7.5	06	02.5	16 %
	CDAc6	16	03	–	–	08	06	01	02	05.5	04	42	17.5	04	07	28.5 %
	CDAc9	17	05	04.5	–	08	03	–	–	09	10	43	09	06	02.5	17.5 %
	CDA5	18	3.5	05.5	02	4.5	02.5	03	02.5	04	01.5	45	15	07	04	26 %

Index ZTR% = % Zircon + % Tourmaline + % Rutile

The codes samples selected for the studies of heavy minerals are mentioned: (OK1, OK3 and OK6): El Kebir wadi samples from the mouth to upstream. (ON1 and ON4): Nil wadi samples from the mouth to upstream. (OD1 and OD3): Djen djen samples from the mouth to upstream. (OM1): sample from the mouth of Mencha wadi. (P1, P3, P4, P6 and P7): beaches samples from East to West. (CDAc1, CDAc1, CDAc6, and CDAc9): current dune samples from East to West. (CDA.1, CDA.3 and CDA.5): old dune samples. The index ZTR shows the sum of the percentages of zircon, tourmaline, and rutile weathering agents and constitute effective natural tracers for the tracing of the sediment dynamics along the coast (Parefenoff et al. 1970; Joshua and Oyebanjo 2009; Emmanuel et al. 2010). Table 5 shows the main characteristics of heavy minerals identified under the binocular (Fig. 7a, b), optical microscope (Fig. 7c), and X-ray diffractometry. The density and hardness of each mineral found on the coast facilitates the interpretation of transport mechanisms (Parefenoff et al. 1970).

The heavy fraction in sediments comes from erosion and physical and chemical weathering of surface rocks in catchments of Jijelian hinterland (Fig. 9). In the Eastern area, these formations have been studied by Amri (1996) and Ouabadi (1994). In the Western part of the study area, the mineralogical composition of geological formations in this region was defined by Bouillin et al. (1977) and Djellit (1987). who reported the predominance of metamorphic formations of Kabilian basement (Table 6). This fraction is transported (Fig. 9) in fluvial environments (El kebir, Nil, Djen djen, and Mencha), controlled (1) by fluvial hydrodynamics (low-energy flow), (2) encounters obstacles, (3) the morphology of the wadis, and (4) by the size and density of the mineral grains (Morton and Hallsworth 1999; Tsikouras et al. 2011; Okay and Ergün 2005). This dense mineralogy is deposited in the beds and terraces of wadis, forming heavy mineral placers. The heavy minerals cortege transported toward downstream shows predominance of the opaque minerals association in all sediments oueds, with proportions that decrease from upstream to downstream of the wadi. In sediment “black sands” from El Kebir wadi, opaque minerals are present with percentages that vary between 47 and 56 %. This proportion of heavy minerals decreases in sediments wadis of West sector, where lower percentages (16 to 24 %) are recorded in Nil wadi. The heavy minerals cortege transported toward downstream shows predominance of the opaque minerals association in all sediments oueds (Table 4), with proportions that decrease from upstream to downstream of the wadi. But, there are significant differences in the heavy mineral proportions in going from East to West. The easternmost oued El Kébir has a percentage of black minerals varying between 47 and 56 %. This proportion of heavy minerals decreases in sediments oueds of West sector, where lower percentages (16 to 24 %) are recorded in oued Nil. Another important aspect is the presence of relatively high assemblage muscovite chlorite percentage (6 to 31 %) in sediments oueds of West sector indicating derivation from the metamorphic basement. This assemblage is present in lower percentage <6 % in sediments from El Kebir wadi. The ZTR index is present with percentages ranging between 14

Table 5 Main characteristics of heavy minerals observed in Jijelian coast sediments

Heavy minerals	Data-gathering	Density	Hardness
Opaque minerals	They are identified by reflected light, presented primarily by hematite, magnetite, ilmenite, limonite, sulphides (pyrite and marcassite), and others composed of oxides and hydroxides iron.	4.2 to 5.3	3.5 to 6.5
Muscovite	It is presented essentially in the flakes form, with more or less rounded contours, slightly greenish color or colorless by natural light.	2.77 to 2.88	2.5 to 3
Chlorite	They are often associated with muscovite, show small plates at the irregular, angular, sometimes oval storytellers or rounded form, yellow greenish or blue greenish colors by optical microscope.	2.6 to 3.3	2 to 3
Kyanite	It show generally flattened tablets, low thickness, and also lengthened form, usually colorless, sometimes greenish or bluish by natural light.	3.6 to 3.7	4 to 5
Sillimanite	They show long flattened or needle sticks form, striated or fibrous, white colorless or colored slightly in green, blue or gray.	3.23 to 3.27	6.5 to 7.5
Biotite	They present as yellow brown laminated to more or less rounded contours.	2.7 to 3.3	2.5 to 3
Augite (pyroxene)	They show a brown to green color by natural light, with irregular breaks, sometimes running stairs and cleavage at an angle near 90°.	3.2 to 3.6	5 to 6
Hornblende (Amphibole)	They feature a cleavage at an angle nearly 120 °, green to brown color or colorless by natural light and elongated grains or angular roughly rolled form.	3 to 3.5	5 to 6
Garnet (almandin)	They feature rounded grains aggrieved surface or corroded form, sometimes sub-spherical crystals because of its high hardness; they show a pale pink, purple pink color, or even colorless by natural light.	4.1 to 4.3	7
Epidote	They present a general light yellowish green color or rarely by light natural, and irregular grains, more or less elongated or somewhat rounded form.	3.38 to 3.49	6
Zircon	They present as colorless grains and more rarely rosé prismatic more or less elongated fragments, with bright edges or slightly dull.	4.6 to 4.7	7
Tourmaline	They are present with color varieties, from very light to dark brown, green-brown.	3 to 3.25	7 to 7.5
Rutile	It present with a yellow to dark red, prismatic crystals more or less elongated or twinned with very rarely worn or rounded form contours, because of its high resistance to weathering agents.	4.32 to 5.5	6 to 6.5

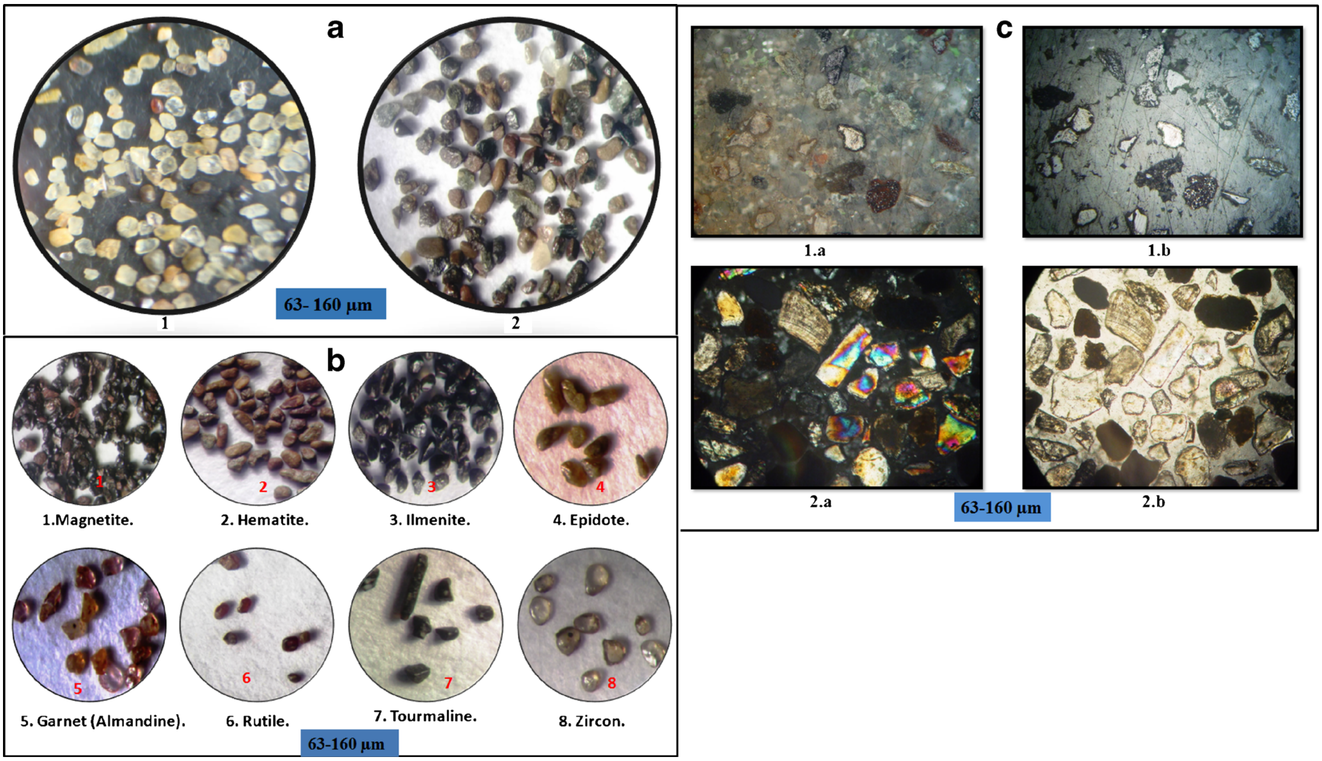

Fig. 7 Study of heavy minerals. **a** Microphotographs showing the heavy mineral under the binocular (×4), (*1*) transparent minerals, (*2*) opaque minerals. **b** Microphotographs showing the principal heavy minerals under the binocular (×4). **c** Microphotographs showing the optical microscopic study of heavy minerals. (*1.a*) Opaque minerals study by natural light. (*1.b*) Opaque minerals study by transmitted light. (*2.a*) Transparent minerals study by natural light. (*2.b*) Transparent minerals study by transmitted light

Table 6 Principal source rocks of the main heavy mineral species, in Jijelian oueds watershed

Source	Location	Mineral component
Metapelites and granite	Outcrops in Cape Mouadene Beni Belaid, El Milia, Beni Teffout, and oued El Kébir basin	Quartz, muscovite, garnet, kyanite, tourmaline, plagioclase, biotite, cordierite, ilmenite, feldspars, zircon, apatite, and tourmaline
Micaschists and schist	Outcrops in Marbouha unit, metamorphic basement	Quartz, muscovite, biotite, plagioclase, and garnet
Microgranites	Outcrops in Beni Touffout	Cordierite, biotite, quartz, plagioclase, feldspars, zircon, apatite, ilmenite, and tourmaline
Formations of the "Oligo-Miocene-Kabyle"	Cover of metamorphic basement	Quartz, muscovite, chlorite, monazite, rutile, and ironoxide
Formation of Numidian flysch	El kebir watershed	Quartz, tourmaline, zircon, rutile, muscovite, and biotite
Khondalite	An overall lower gneissic Kabylian basement	Sphene, rutile, graphite, spinel, sillimanite, zircon, opaque minerals, quartz, garnet, feldspar, kyanite, muscovite (white mica), and biotite
The Khondalite retromorphosed	An overall lower gneissic Kabylian basement	Opaque minerals (ilminite), sphene, rutile, epidote, biotite and sillimanite, quartz, and garnet
The metatexites	An overall lower gneissic Kabylian basement	Rutile, biotite, sillimanite, chlorite, spinel, graphite, zircon, epidote, sphene, mafic minerals, and garnets
Para-gneiss (the kinzigites)	A higher overall of gneissic basement	Garnet and poor in quartz, sillimanite, spinel, plagioclase, feldspar, rutile, epidote, apatite, zircon, chlorite, kyanite, and opaques
Marbles	A higher overall of gneissic basement	Calcite, opaque, highly crystalline pyrite, muscovite, quartz, and feldspar

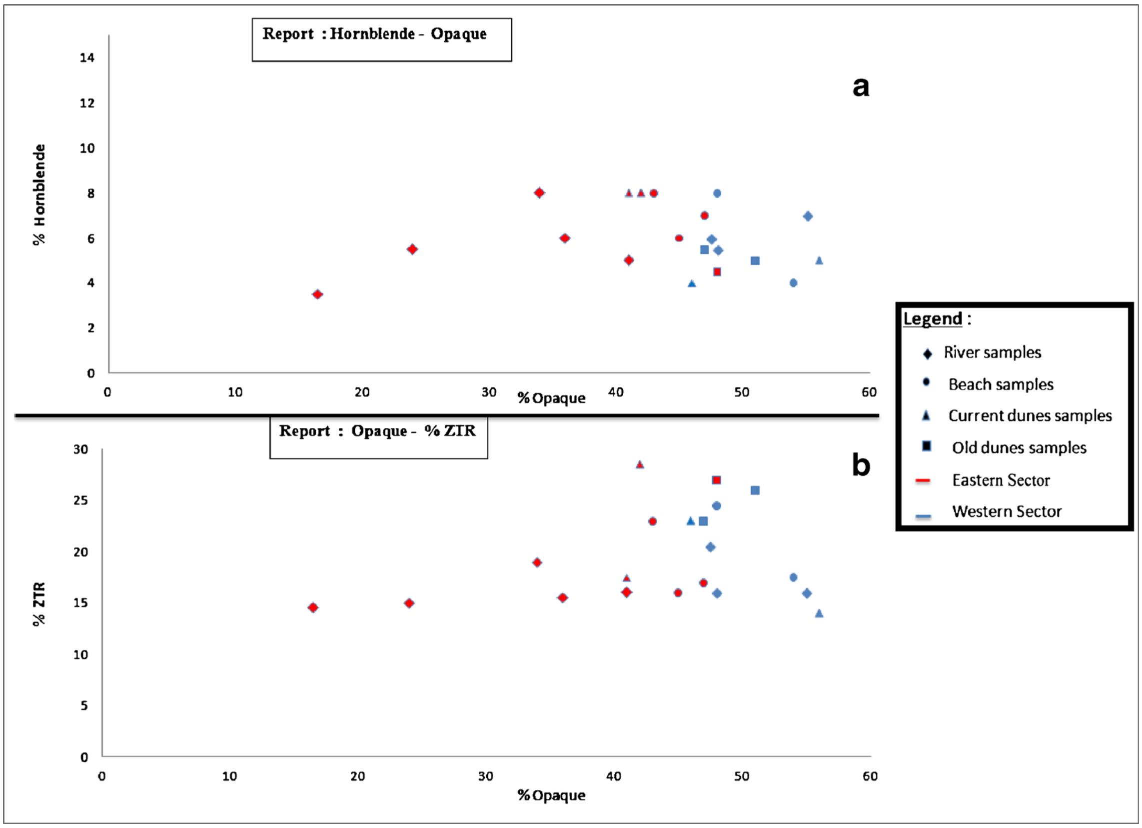

Fig. 8 Diagrams showing the relationship between heavy minerals percentages resistant to weathering agents versus abundant heavy minerals on the coast. **a** Relationship between hornblendes and opaque minerals. **b** Relationship between the percentage of ZTR index (zircon + tourmaline + rutile) and opaque minerals

and 21 %, with the dominance of zircon in all wadis. Garnet, epidote, pyroxene, and hornblende assemblage exhibit low contents less than 10 %, except epidote which presents percentages between 10 and 12 % in both oueds Nil and Mencha. The very low contents of some minerals such as garnet and epidote in El Kebir wadi, garnet in Djen djen wadi, and hornblende and epidote encountered upstream of Nil wadi inform about the proximal source of these minerals. Indeed, the presence of olivine at the mouth of oued Djen djen would come from the alteration of the volcano-sedimentary complex of Texanna (Rekada Metlatine). Garnet, present at the mouths, comes from the weathering of metamorphic rocks exposed in different catchments (Boutiba 2006). Biotites, sillimanites, and kyanites are present in the mineralogical cortege of wadis with very low proportions (0–4 %).

At the Eastern part of the coast, the heavy minerals contents are slightly higher at Beni Belaid beach, located on the right bank of El Kebir wadi (opaque minerals 54 %, ZTR 18 %, garnet10%, and 6 % epidote) than at the beaches situated on the left bank of El Kebir wadi (48 % opaque minerals, 24 % ZTR, 7 % garnet, and 3.5 % epidote). These results show a strong relation between the beaches of Eastern sector and the mouth of oued El Kebir that feeds them in heavy minerals. These heavy minerals are much more oriented toward the Beni Belaid beach by littoral drift current and waves where they form concentrations of heavy sand. Other minerals such as biotite, muscovite, and chlorite are present with low contents relative to those found in the mouth because of their low resistance to marine agitation (waves and currents). In Western part of the coast, the heavy mineral fraction carted by the three wadis (Nil, Djen djen, and Mencha) that debouch into the bay directly supplies the beaches of this area. Opaque minerals (about 46 %) essentially represent the mineralogical cortege from sediments of the Tassoust and Epave beaches, located on the left bank of Mencha wadi. Other minerals of high density (garnet, epidote, sillimanite, kyanite, hornblende, and pyroxene) are present with similar contents to those found at the mouths. The ZTR index is present with percentages more or less higher, 16 to 17 %. The presence of low resistance minerals (biotite, chlorite, and muscovite) carted by both oueds Nil and Djen djen testifies proximal source of sediments. These results demonstrate a stream of heavy mineral transferred from mouths toward the left bank by dominant coastal currents and form low concentrations in down-beach. In the central region, the major components of heavy mineral spectrum in sediments from Sidi Abdelaziz beaches, located

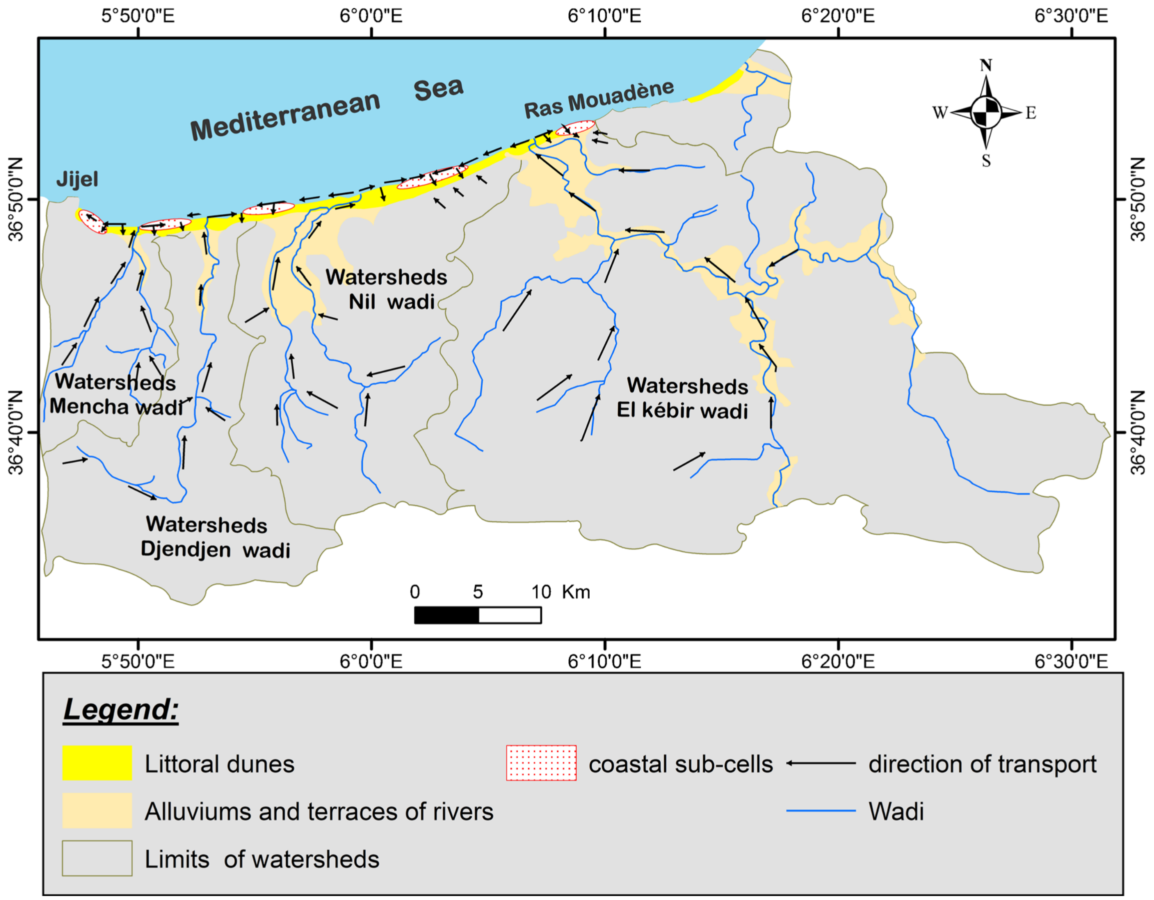

Fig. 9 Stream flowing and direction of heavy minerals from the source to sedimentary stocks of Jijelian East coast morphological units

between both mouths of oued El Kébir to the East and those of oued Nil to the West, are opaque minerals (43 %), hornblende (8 %), and pyroxene (7 %). The ZTR index is present with a high content around 20 %, indicating a long transport controlled by the action of the sea. The presence of sillimanite (2 %), only significant in the oued Nil surfacial sediments (1 to 3 %), demonstrates that these beaches are fed by solid inputs of oued Nil, transferred by the dominant long shore current oriented west–east.

In actual dune sands of Beni Belaid, the heavy mineral spectrum is essentially composed of opaque minerals (56 %) and hornblende (5 %) at the foot of dunes in concordance with the top of the dune where the contents of opaque minerals and hornblende are around 46 and 4 %, respectively. These contents remain relatively higher compared to those found in down beaches. These results indicate a preferential accumulation area of heavy minerals located at base of the actual dunes of Beni Belaid, after the transport of heavy sands of beach toward the first dune belts during large storms. Other minerals of low abundance show almost identical proportions to those encountered at the down beaches. The ZTR index shows a percentage of 14 % at the base of the actual dunes. This proportion increases to the top of the dune to reach 23 %. This index is the better tracer element of sediment dynamics (Emmanuel et al. 2010). it provides information about sediment exchange between the base and the top of the dune. In the central and Western areas, at the base of current dunes of Sidi Abd Aziz, Tassoust, and Bellouta, opaque minerals, hornblende, and the ZTR index are around 42, 8, and 28 %, respectively. The results of analysis show an exchange of heavy sands between the beach and the dune, allowing the formation of sand placers.

In ancient dunes, the heavy minerals cortege shows high contents of opaque minerals between 47 and 50 % in sand dunes of Beni Belaid and 48 % for Sidi Abdelaziz dunes. The ZTR index exhibits high contents varying between 23 and 26 % for ancient dunes of Beni Belaid and 27 % for Sidi Abdel Aziz dunes. Hornblende contents remain virtually unchanged from those recorded in the other morphological units of the coast. Garnet and epidote have relatively low percentages between 1.5 and 3.5 % for the old dune and 3.5 to 10% at beaches and current dunes. According to Parefenoff et al. (1970). the quantity of epidote decreases as age increases, since it is not stable and rarely preserved in ancient deposits. The high contents of low-density minerals, such as chlorite, biotite, and muscovite at ancient dunes (1 to 6 %), and their absence or presence with very low content at beaches and current dune (<4 %) indicating derivation from weathering and erosion of local geological basement.

The Jijelian coast is an area in which it is appropriate to distinguish the mineralogical composition of each fluvio-marine environment geographically related, such as wadis, beaches, current dunes, and old dunes. The zonation between these four current morphological units was performed using graphs combining the percentages of heavy minerals (Fig. 8). The use of these diagrams will distinguish input areas, accumulation areas, and highlight the sedimentary exchanges taking place between different morphological units of the coast (mouths, beaches, current, and old dunes). Examples for such patterns are illustrated in Fig. 8. The analysis of these diagrams with two variables, opaque minerals percentages in abscise, and the percentages of the most weathering-resistant mineral to alteration agents (hornblende and ubiquitous minerals: zircon, tourmaline, and rutile) in ordinate (Fig. 8) show that (1) the proportions of opaque minerals differ from the East to the extreme Western area especially at the wadis sediments; (2) the proportions of resistant minerals to marine and fluvial hydrodynamic agents increase in sedimentary stocks. (beaches, current, and old dunes) compared to minerals carried by the wadis that arrive to the coast; and (3) the relation between the two fractions showed the presence of areas or sedimentary sand cells (Fig. 9), where the exchange of sands is performed between the various coastal sedimentary stocks.

Conclusion

The undertaken study is a contribution to understanding of the major sediment sources, transport paths, and general patterns of sediment distributions along the Jijelian coast. The origin of associations of heavy minerals is linked to metamorphic and igneous rocks (gneiss, metapelite, micaschist, and granite) of the Kabylian basement outcropping in large areas in different catchments. Associations of clay minerals found in coastal sediments indicate provenance from geological formations exposed in different watersheds and sub-littoral basins.

The results of heavy mineral analysis of surface sediments from the coast and wadis have revealed the presence of two major heavy mineral assemblages of different densities; the first one is composed of lower density minerals and the second one, high-density minerals, both are relied to the existence of selective transport processes. Heavy minerals with lower density are often remobilized and transported toward accumulation areas (beach, actual dunes), heavy minerals with high-density, concentrate in departure sediment areas (erosion area), as a consequent of selective hydrodynamic processes.

The general pattern of sediment dynamics along the Jijelian coast was made perceptible by results of grain-size and mineralogical analyses. Thus, the existence of hydro-sedimentary sub-cells all along the coast was revealed from grain-size index and heavy minerals, they all testify, high mobility of coastal sedimentary stocks.

The mouths of various wadis, which debouch into the bay, create between them a series of hydro-sedimentary coastal sub-cells. The source of sediment for each hydro-sedimentary sub-cell comes from their watersheds. The along-shore transport of sediment by waves and long shore current generate high concentrations of heavy minerals adjacent to sub-cells limits with a dilution tendency toward the sections, in accretion (Boutiba 2006). Additional data from the geochemical analyses of the sediments would help to a better characterization of clay and heavy minerals origins.

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