Provenance analyses of the heavy-mineral beach sands of the Annaba coast, northeast Algeria, and their consequences for the evaluation of fossil placer deposit

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The paper presents the first study of heavy-mineral sand beaches from the Mediterranean coast of Annaba/Algeria. The studied beaches run along the basement outcrops of the Edough massif, which are mainly composed by micaschists, tourmaline-rich quartzo-feldspathic veins, gneisses, skarns and marbles. Sand samples were taken from three localities (Ain Achir, Plage-Militaire and El Nasr). The heavy-mineral fraction comprises between 74 and 91 vol%. The garnets of the beaches are almandine rich and tourmalines vary with respect to their location from schorl to dravite. Tourmaline at Ain Achir and the Plage-Militaire is schorlites, while at El Nasr beach dravite is ubiquitous. The World Shale Average normalised REE of the sands and the basement outcrops reveal: (i) *Ain Achir beach*: REE pattern of sand and the coastal rocks from the studied beaches reflects a multiple sources; (ii) *Plage-Militaire*: the sand and the coastal outcrops show similar LREE and a strong enrichment in HREE, suggesting the presence HREE-rich phases found as inclusions in staurolite; (iii) *El Nasr*: two types of sand patterns are found: one with flat REE pattern similar to the proximal rocks and other one enriched in HREE suggesting a mixed source.

Keywords. Provenance; heavy minerals; beach sediments; fossil placer; geochemistry; Annaba/Algeria.

1. Introduction

The mineralogy of modern beaches depends on the nature of a source rock from which the detrital material is derived, and comprises minerals that are resistant to weathering. Heavy-sand components are mainly derived through erosive processes on rock outcrops. The studied area consists of three flat sandy coast beaches in front of the

Edough massif (Annaba/Algeria). Out of dozen, only three beaches show high concentrations of toned heavy-mineral sands: the Ain Achir beach characterised by light- and dark-toned sands and the Plage-Militaire and El Nasr beaches comprising consistently dark-toned sands. The outcrops surrounding these three beaches are garnet–staurolite (and/or andalusite), and kyanite micaschists, marbles, epidotic skarns, migmatites and numerous

tourmaline-bearing quartzo-feldspathic veins. This paper presents the first study of the provenance of dark-toned heavy-mineral sands from coastlines of Annaba/Algeria and of Algeria.

2. Study area

2.1 Actual geographic setting

The studied areas are located at the northeastern coast of Annaba city (figure 1a). They are composed of two fields: the Cap de Garde field and the Harbor field. The Cap de Garde field (figure 1b)

is composed of two small beaches: Ain Achir (275×30 m) and Plage-Militaire (236×20 m), their shoreline lay between 36°57'52"–36°57'51"N latitude and 7°46'89"–7°46'94"E longitude, respectively. The Harbor field (figure 1c) includes the El Nasr beach, its shoreline is between 36°54'36"–36°54'31"N and 7°46'17"–7°46'24"E.

2.1.1 Temperature and rainfall

Annaba is characterised by a warm-temperature climate. The climate map of Köppen-Geiger (Hufty 2001) classifies the climate as Csa (warm temperature to dry climate). Annaba displays an

Figure 1. Aerial photographs: (a) the Annaba town coast, (b) the Cap de Garde field with the two studied beaches (Ain Achir and the Plage-Militaire beaches), and (c) the Harbor field (El Nasr beach). • = sand samples, □ = proximal rock outcrops samples locations. Google Earth 2016.

average temperature of 18.4°C throughout the year. Rainfall averages 712 mm (650 and 1000 mm/yr; [ANDI 2013](#)) per year. The probability of rainfall is very high during the period January–March and during October–December (temperatureweather.com 2016).

2.1.2 Hydrography

The hydrographic network of the Annaba region is rather dense ([Hilly 1962](#); figure 2a). It consists mainly of Lake Fetzara (freshwater) covering 18,670 ha and the Oued Seybouse with a length of 127.5 km ([ANDI 2013](#)).

2.1.3 Topography

The relief of the Annaba region is dominated by the Edough massif (52%), and shaped by the hogbacks (28%) and the plains (18%) as well. The Edough massif extends over a length of 50 km in the direction SW–NE. The central part of the massif culminates at 1008 m (Bouazizi). The altitudes of the southwestern (Bou-Maiza) and northeastern (Cap de Garde) slopes are low, on average 200–300 m ([Oularbi and Zeghiche 2009](#)). Depending on the intensity of erosion, [Oularbi and Zeghiche \(2009\)](#) distinguish four principal erosional zones in the Edough massif (figure 2b), i.e., zones with: (i) intense erosion, (ii) medium erosion, (iii) low

Figure 2. Maps of (a) the hydrographic network of the Annaba region ([Hilly 1962](#)), modified, and (b) erosion susceptibility of the Edough massif ([Oularbi and Zeghiche 2009](#)).

erosion and (iv) zero erosion. The erosional sensitivity map (Oularbi and Zeghiche 2009) shows that the study areas (Ain Achir, the Plage-Militaire and El Nasr beaches) lay in the 'zero erosion' zone.

2.1.4 Swell and sea wave

The coasts of Annaba are characterised by a north–northwestern swell. In winters, the height of the waves is high and can exceed 3 m. In summer, the height of the waves is low and does not exceed 1 m.

2.1.5 Morphology

The geomorphology of the study area is characterised by a flat topography and the lack of an active hydrographic system, the Cap de Garde (Ain Achir and the Plage-Militaire beach) and the Harbor (El Nasr beach) fields are characterised by low continental erosion.

2.2 Geological background

Geologically, the studied areas are a part of the crystalline Edough Massif. The latter experienced a regional and polycyclic metamorphism characterised by high-pressure (12–14 kbar) and medium-temperature metamorphic conditions (500–600°C) (Brunnel *et al.* 1988; Caby and Hammor 1992; Ahmed-Said *et al.* 1993; Caby *et al.* 2001). The different metamorphic units underwent a first oblique deformation characterised by syn-metamorphic folds followed by flexural shear generating upright folds of 140°N direction, anticlines with direction 50–60°N and shear senses of 120–160°N. In the studied areas, the coastal rock outcrops are mainly composed by garnet, staurolite (and/or andalusite), kyanite micaschists, marble, epidotic skarns, migmatites and numerous quartzofeldspathic veins (figure 3).

2.2.1 Cap de Garde field

The two beaches at this field are underlain by metamorphic rocks. The northern part of the Cap de Garde is composed by kyanite-bearing micaschists (figure 3a), migmatised gneisses (figure 3b) followed by tourmaline-bearing quartzofeldspathic veins occurring in garnet–staurolite micaschists and/or in garnet micaschists (figure 3c) and small garnetite outcrops (figure 3d). In these beaches, most of the outcrops are staurolite–garnet

micaschists with some quartz veins (figure 3e) or staurolite–garnet micaschist alternating with marble layers. The contact between the staurolite–garnet micaschists and the marble layers is marked by epidote-rich skarns (figure 3f). The northern part of the Plage-Militaire beach is composed by garnet micaschists with some tourmaline-rich quartzofeldspathic veins (figure 3g) and the same garnet–staurolite micaschist alternating with marble layers as at the Ain Achir beach. The other parts show mainly staurolite–garnet micaschists (figure 3h).

2.2.2 The Harbor field

This field encloses the El Nasr beach. Concrete slabs cover the back of the shoreline. Only a 20-m garnet–staurolite micaschist outcrop with tourmaline-rich veins is visible in the southern part of the beach (figure 3i and j).

3. Analytical methods and sampling

Sands from the studied beaches and the proximal rock outcrops have been sampled. A set of 23 hand-specimen rock samples (8 at Ain Achir, 12 at the Plage-Militaire and 3 at El Nasr beach) and 44 (18 at Ain Achir, 17 at the Plage-Militaire and 9 at El Nasr beach) surface sand samples with a single weight of 3 kg were taken. The sand sampling was done along with a 10×15 m surface grid and a depth of 25–30 cm. The bulk sample was reduced by coning and quartering and a 100 g portion of the sample was selected for the analysis (following Darnley *et al.* 1995). Powders of the selected unaltered samples were dried overnight at 105°C prior to the analyses. The compositions of the whole-rock samples, including major, minor and trace elements, were determined by wavelength dispersive X-ray fluorescence spectrometry, inductively coupled plasma-mass spectrometry and inductively coupled plasma-atomic emission spectrometry at laboratories of the GeoForschungsZentrum Potsdam and the Institute of Earth and Environmental Science, Potsdam University, Germany. International and internal reference samples were used for calibration. Analyses for major and minor elements and for trace elements were conducted on fused glass and pressed powder disks, respectively. Both of the disks were prepared at the Institute of Earth and Environmental Science, Potsdam.

Figure 3. Simplified geological maps of the Cap de Garde (AA-PM) and the Harbor (EN) fields with the studied beach locations and field photography of the basement outcrops: (a) kyanite-bearing micaschist, (b) migmatized gneisses, (c) tourmaline-bearing quartzo-feldspathic veins, (d) small garnetite outcrops, (e) staurolite-garnet micaschist with quartz veins, (f) skarns, (g) garnet micaschist with tourmaline-rich quartzo-feldspathic layers, (h) staurolite-garnet micaschists, (i) garnet-staurolite micaschist, and (j) micaschist with tourmaline-rich quartzo-feldspathic veins.

Whole heavy-mineral grains were identified under incident light using a binocular microscope. Random grain samples were also mounted in thin section for identification using a petrographic microscope, thus providing a means of verifying the bulk identifications achieved under incident light. The minerals identified by microscopic investigations were further checked by X-ray.

The mineral chemical analyses were conducted using a fully automated JEOL JXA-8200 electron microprobe at the Institute of Earth and Environmental Science laboratory/Potsdam.

At least 100 dark-toned minerals were counted for mode composition, using the ribbon counting method (Mange and Maurer 1991; Morton and Hallsworth 1994). Counts of minerals were made using microphotographs taken along regular grid spacing on the thin section and using the free software Mesurim.

4. Results

4.1 Petrography and mineralogy

4.1.1 Proximal belts outcrops

Cap de Garde field (Ain Achir beach): Three samples representing the major proximal outcrops of the Ain Achir beach have been studied under a petrographic microscope. The samples (E60, E62 and E74) are micaschists. Kyanite-bearing micaschists at northern part of the Cap de Garde (Vivier zone) have also been sampled (five samples Viv1–5 and Dviv). Samples of the micaschists are mainly composed by elongated and sometimes cracked staurolite with zircon inclusions, altered biotite, quartz with wavy extinction and euhedral garnet with inclusions (figure 4a and b). The mineralogical composition of the skarn sample is calcite, amphibole, epidote and rare scapolite (figure 4c and d). Kyanite from the Vivier micaschists is elongated with minor quartz inclusions.

Plage-Militaire beach: The outcrop is composed of a garnet–staurolite with rare kyanite micaschists. The staurolite grains are smaller than those of the Ain Achir field. Kyanite grains elongated with minor garnet inclusions (figure 4e). Garnets are euhedral and show sometimes quartz inclusions (figure 4f).

Harbor field (El Nasr beach): The basement outcrop is very small (5 m), and composed of a garnet–staurolite micaschists. Feldspars are highly altered (figure 4g). Small garnets are common (figure 4h).

4.1.2 Sand description

The Ain Achir and the Plage-Militaire sand show significant differences in their mode (table 1). The Ain Achir sand shows two kinds of colours: light coloured sands, containing an average of 39% heavy minerals, and dark sands, showing an average of 74% heavy minerals. The black sand typically consists of staurolite (43%) as the main mineral, followed by garnet (19%), tourmaline (9%), kyanite and epidote (2%). The Plage-Militaire is characterised by a higher average in heavy-mineral content (91%). As in the Ain Achir sand, staurolite is the main mineral (45%) followed by garnet (29%). The tourmaline content is higher (13%) than in Ain Achir sand, whereas kyanite and epidote are low (2 and 1%, respectively).

The binocular analysis of the Ain Achir and Plage-Militaire dark sand yielded a variegated spectrum of minerals (figure 5) with dominantly metastable minerals: (i) epidote occurs in both the beach sand samples in relatively low abundance ranging from 1 to 2%. Under the stereo-microscope, epidote is pale green with short prism and sometimes rounded shape (figure 5a), (ii) staurolite is well represented and is the most common mineral in the two beaches. The crystals have dark yellowish brown colour. They occur as irregular, elongated or fractured grains. Some crystals show zircon inclusions (figure 5b and c), (iii) garnets occur as euhedral, subrounded to rounded crystals (figure 5a and b). Some grains are sharp irregular fragments. All crystals are pale pink to red. Some are pinkish brown, ilmenite and quartz inclusions are common, but some garnets from the Plage-Militaire sand show also zircon inclusions (not shown), (iv) kyanite is present in prismatic fragments. All crystals are sharp edged. Some crystals show small typical kyanite cleavage and exhibit characteristic step-like fractures, ilmenite inclusions are common (figure 5b and c).

There are no major differences between the mineralogical composition of the El Nasr sand and those from the Cap de Garde. The El Nasr sand is characterised by an average of 84% of heavy mineral (staurolite 60%, garnet 14%, kyanite 5%, tourmaline 4%) and an average of light minerals (16%) composed of quartz and calcite (table 2). The heavy-mineral assemblage is restricted to few selective minerals such as: pink garnet with quartz and/or ilmenite inclusions, yellow-brown staurolite with inclusions (figure 5d and e) and kyanite in

Figure 4. Microphotograph of proximal outcrops of the studied fields: Ain Achir: (a and b) micaschist, (c and d) epidote-rich skarn; Plage-Militaire: (e) garnet–staurolite–kyanite micaschist, and (f) garnet micaschist; El Nasr: (g) garnet–staurolite micaschist with some feldspars, and (h) garnet micaschist.

Table 1. Heavy-mineral composition of the sands from Ain Achir, Plage-Militaire and El Nasr beaches.

Samples		Grt	St	Ky	Tur	Ep	Qz	Cal	ΣHM%	ΣLM%
Ain Achir beach (AA)										
Light sand (LS)	AA1a	4	10	4	8	9	7	57	36	64
	AA1b	7	36	5	4	0	10	38	52	48
	AA2b	5	10	4	4	3	14	59	27	73
	AA4a	10	31	4	5	1	10	37	52	48
	AA4b	6	26	3	1	2	18	43	39	61
	AA5a	11	25	6	7	0	11	41	48	52
	AA5b	7	10	10	7	0	11	54	35	65
	AA5c	11	9	2	4	0	20	54	26	74
Dark sand (DS)	AAGa	13	24	2	8	2	16	35	49	51
	AACa	25	43	0	16	5	2	9	89	11
	AA2a	17	48	1	6	3	2	23	75	25
	AA2c	15	33	5	15	3	8	21	70	30
	AAMa	15	44	1	6	0	10	24	66	34
	AAMb	23	67	0	3	2	1	3	96	4
	AA3a	11	43	0	8	3	8	28	64	36
	AA3b	18	40	1	6	0	9	26	65	35
	AA3c	13	44	6	9	0	6	22	72	28
	AAGb	39	40	0	15	1	0	5	95	5
Average %HM LS		7.8	19.8	4.7	5.1	2.0	12.7	48.0	39.3	60.7
Average %HM DS		18.9	42.6	1.6	9.2	1.8	6.3	19.6	74.2	25.8
Plage-Militaire beach (PM)										
Dark sand (DS)	Pms6a	9	25	5	15	5	6	34	60	40
	Pms1a	28	38	3	19	4	3	5	92	8
	Pms2a	32	46	1	11	2	1	8	91	9
	Pms3a	38	50	2	2	1	1	5	94	6
	Pms4a	39	45	2	6	1	2	4	94	6
	Pms5a	36	41	2	16	0	2	3	95	5
	Pms1b	9	44	1	24	4	1	15	83	17
	Pms2b	37	41	2	15	1	0	3	96	4
	Pms3b	29	50	1	15	1	2	3	95	5
	Pms4b	14	53	2	16	1	1	13	86	14
	Pms5b	35	48	0	10	0	4	4	92	8
	Pms6b	19	46	0	21	2	1	12	88	13
	Pms1C	32	55	1	7	1	0	3	97	3
	Pms2c	35	41	1	17	0	1	5	94	6
	Pms3c	33	52	4	6	0	1	3	95	5
	Pms5c	29	52	2	11	0	1	5	93	7
	Pms6c	46	39	1	10	2	0	2	98	2
Average %HM DS		29.4	45.0	1.8	13.1	1.5	1.6	7.6	90.8	9.2
El Nasr beach (NS)										
Dark sand (DS)	EN S 1a	19	66	0	8	0	1	6	92	8
	EN S 2a	6	32	19	0	0	21	21	57	43
	EN S 3a	4	58	2	0	0	7	29	64	36
	EN S 1b	9	66	7	7	0	3	9	88	12
	EN S 2b	18	72	5	0	0	0	5	95	5
	EN S 3b	16	63	2	7	0	2	9	89	11
	EN S 1c	15	63	0	7	0	2	13	85	15
	EN S 2c	24	61	7	2	0	2	5	93	7
	EN S 3c	17	59	4	10	0	3	7	90	10
Average %HM		14.4	59.9	5.1	4.5	0.0	4.5	11.6	83.8	16.2

The values are given as percentages of the number of grains recorded.

Figure 5. Microphotograph of heavy-mineral assemblage: (a, b and c) from Ain Achir and Plage-Militaire beaches; (d, e, and f) from El Nasr beach.

prismatic fragments with typical step-like fractures (figure 5e) and rounded and elongated tourmaline grains (figure 5d and f). Epidote is not present in the El Nasr sand samples.

4.1.3 Heavy-mineral inclusions

Most of the heavy minerals of the three beaches have solid inclusions. Hand-picked single garnet, staurolite and kyanite grains with solid inclusions from the beaches have been analysed by X-ray diffraction (XRD). The detrital garnets from the Ain Achir, Plage-Militaire and El Nasr sands show different types of inclusions such as quartz

(figure 6a). At the Ain Achir, most of the staurolite grains have garnet inclusions (figure 6b) and those from the Plage-Militaire and El Nasr sands have tourmaline, garnet and zircon inclusions (figure 6c). Kyanite grains from the three beaches show no differences. Their inclusions are mostly garnet or quartz (figure 6d).

4.2 Sand mineral chemistry

4.2.1 Garnet

The structural formula of the analysed garnets was calculated according to Locock (2008) on the

Table 2. Chemical composition and end-member compositions of the garnets from the three beaches.

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Alm	Sps	Prp	Grs	Adr	Uv
Ain Achir beach														
AAS1	37.0	0.1	21.4	38.7	0.2	2.0	0.5	100.0	90	0	8	2	0	0
AAS2	36.9	0.1	21.3	39.0	0.1	1.9	0.5	99.9	90	0	8	2	0	0
AAS3	36.9	0.1	21.3	39.0	0.2	2.0	0.6	100.0	90	0	8	2	0	0
AAS4	37.0	0.1	21.3	39.0	0.1	2.0	0.6	100.1	90	0	8	2	0	0
AAS5	37.8	0.1	21.4	35.0	1.2	2.4	2.1	99.9	82	3	10	6	0	0
AAS6	37.7	0.1	21.3	35.1	1.2	2.4	2.3	100.0	81	3	9	7	0	0
AAS7	37.7	0.1	21.4	34.9	1.2	2.3	2.2	99.9	82	3	9	7	0	0
AAS8	37.6	0.1	21.4	35.1	1.3	2.2	2.2	99.9	82	3	9	7	0	0
AAS9	37.6	0.1	21.5	34.9	1.3	2.2	2.1	99.8	82	3	9	6	0	0
AAS10	37.9	0.1	21.1	36.5	0.2	3.2	1.0	100.0	84	0	12	3	0	0
AAS11	37.7	0.0	21.3	36.7	0.2	3.1	1.0	99.9	85	0	12	3	0	0
AAS12	37.7	0.1	21.3	36.5	0.2	2.9	1.2	99.9	85	0	12	3	0	0
AAS13	37.7	0.1	21.2	36.7	0.2	2.9	1.2	99.9	85	0	11	4	0	0
AAS14	37.7	0.1	21.2	36.6	0.1	2.9	1.2	99.8	85	0	11	3	0	0
AAS15	37.7	0.1	21.2	36.8	0.2	2.7	1.1	99.9	86	0	11	3	0	0
AAS16	37.5	0.1	21.2	37.3	0.2	2.6	1.1	100.1	86	0	10	3	0	0
AAS17	37.8	0.1	21.2	37.2	0.2	2.5	1.1	100.0	87	0	10	3	0	0
AAS18	37.6	0.1	21.1	35.4	1.3	1.1	3.5	100.1	83	3	4	10	0	0
AAS19	37.4	0.1	21.1	34.7	1.3	1.1	4.1	99.9	81	3	4	12	0	0
AAS20	37.4	0.1	21.3	34.3	1.5	1.0	4.6	100.1	80	3	4	13	0	0
Plage-Militaire beach														
PMS1	37.6	0.0	22.5	34.3	0.0	5.1	0.5	100.1	78	0	20	2	0	0
PMS2	37.3	0.0	22.1	36.1	0.0	4.0	0.4	100.0	83	0	16	1	0	0
PMS3	37.3	0.0	21.9	36.7	0.0	3.7	0.4	100.0	84	0	15	1	0	0
PMS4	37.1	0.1	21.9	36.8	0.1	3.7	0.4	100.0	84	0	15	1	0	0
PMS5	37.7	0.0	22.1	36.2	0.0	3.7	0.4	100.0	84	0	15	1	0	0
PMS6	37.5	0.0	22.0	36.4	0.0	3.9	0.4	100.1	84	0	15	1	0	0
PMS7	37.5	0.0	22.2	35.4	0.0	4.5	0.4	100.0	81	0	18	1	0	0
PMS8	37.8	0.1	22.0	35.0	0.0	4.5	0.5	99.9	81	0	18	1	0	0
PMS9	36.7	0.1	21.7	36.3	2.1	1.6	1.3	99.9	85	5	7	4	0	0
PMS10	36.5	0.1	21.7	36.6	1.6	2.1	1.4	100.0	84	4	9	4	0	0
PMS11	36.6	0.1	21.7	36.1	1.6	2.2	1.6	100.0	83	4	9	5	0	0
PMS12	36.6	0.1	21.8	35.9	1.7	2.1	1.6	99.9	83	4	8	5	0	0
PMS13	36.9	0.1	21.7	35.8	1.7	2.0	1.7	99.9	83	4	8	5	0	0
PMS14	37.1	0.1	21.8	35.2	1.7	2.0	2.1	100.1	82	4	8	6	0	0
PMS15	37.0	0.1	21.8	35.7	1.7	2.0	1.8	100.1	83	4	8	5	0	0
PMS16	36.6	0.2	21.8	36.4	1.6	2.0	1.4	100.0	84	4	8	4	0	0
PMS17	36.4	0.2	22.0	36.3	2.0	1.8	1.3	99.9	84	5	7	4	0	0
PMS18	37.5	0.1	21.3	28.1	2.7	1.2	8.7	99.7	64	6	5	25	0	0
PMS19	37.4	0.1	21.3	28.2	3.1	1.0	8.8	99.9	64	7	4	25	0	0
PMS20	37.5	0.1	21.2	28.4	3.1	1.0	8.8	100.1	64	7	4	25	0	0
PMS21	37.5	0.1	21.4	28.6	3.2	0.9	8.4	100.0	65	7	4	24	0	0
PMS22	37.2	0.1	21.3	29.0	3.1	0.9	8.4	100.1	65	7	4	24	0	0
PMS23	37.3	0.1	21.3	29.3	2.8	1.0	8.0	99.9	67	6	4	23	0	0
PMS24	37.7	0.1	21.4	29.4	2.3	1.1	8.1	100.0	68	5	4	24	0	0
PMS25	36.6	0.0	21.5	34.8	0.5	0.8	5.5	99.8	80	1	3	16	0	0
PMS26	36.5	0.1	21.4	35.0	0.5	0.7	5.9	100.1	79	1	3	17	0	0
PMS27	36.7	0.1	21.5	34.6	0.5	0.7	5.8	100.0	79	1	3	17	0	0
PMS28	36.7	0.1	21.5	35.1	0.3	0.7	5.4	100.0	80	1	3	16	0	0
PMS29	37.0	0.1	21.5	34.8	0.4	0.7	5.6	100.1	80	1	3	16	0	0
PMS30	36.9	0.1	21.3	35.5	0.3	0.8	5.0	100.0	81	1	3	15	0	0
PMS31	36.7	0.1	21.3	35.7	0.3	0.8	4.9	99.9	82	1	3	14	0	0

Table 2. (Continued.)

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Alm	Sps	Prp	Grs	Adr	Uv
PMS32	37.0	0.1	21.3	34.5	0.6	1.2	5.1	99.9	79	1	5	15	0	0
PMS33	37.1	0.1	21.4	34.3	0.6	1.2	5.2	100.0	79	1	5	15	0	0
PMS34	37.0	0.1	21.7	34.0	0.6	1.2	5.2	99.9	79	1	5	15	0	0
PMS35	37.0	0.1	21.5	34.6	0.5	1.3	5.0	100.0	79	1	5	15	0	0
PMS36	37.3	0.1	21.2	34.3	0.6	1.2	5.3	100.0	79	1	5	16	0	0
PMS37	36.8	0.1	21.5	35.8	0.5	1.3	4.2	100.1	82	1	5	12	0	0
PMS38	37.1	0.1	21.4	35.4	0.3	1.5	4.1	100.0	82	1	6	12	0	0
El Nasr beach														
EN1	37.7	0.0	21.7	34.9	0.2	4.8	0.8	100.1	79	0	19	2	0	0
EN2	37.8	0.0	21.6	33.8	0.5	3.8	2.4	99.9	77	1	15	7	0	0
EN3	38.2	0.1	21.9	33.1	0.3	4.3	2.3	100.1	75	1	18	6	0	0
EN4	38.3	0.0	21.5	33.1	0.7	4.0	2.5	100.1	76	2	16	7	0	0

Alm: Almandine, Sps: Spessartine, Prp: Pyrope, Adr: Andradite, Uv: Uvarovite, Grs: Grossular (Whitney and Evans 2010).

basis of 12 oxygen atoms (table 2). Although all analysed garnet grains represent a chemical mixture of the different components, they are extremely rich in almandine component. Their chemical compositions are plotted in the Alm–Prp–Grs diagram (figure 7).

Garnets at the Ain Achir beach have a relatively homogeneous end-member composition: (Prp 4–12 mol%, Alm 81–90 mol%, Grs 2–13 mol%) (figure 7a). The Plage-Militaire sand is characterised by four kinds of garnet composition (figure 7b): (i) (Prp 15–20 mol%, Alm 78–84 mol%, Grs 1–2 mol%), (ii) (Prp 7–9 mol%, Alm 82–85 mol%, Grs 4–6 mol%), (iii) (Prp 4–5 mol%, Alm 64–68 mol%, Grs 23–25 mol%) and (iv) (Prp 3–6 mol%, Alm 79–82 mol%, Grs 12–17 mol%). In contrast to those from the Plage-Militaire, the compositions of garnet of El Nasr sands show a higher pyrope end-member content (Prp 16–19 mol%, Alm 75–79 mol%, Grs 2–7 mol%) (figure 7c).

4.2.2 Tourmaline

The program WinTcac (Yavuz *et al.* 2006) has been used for mineral recalculation and classification of tourmaline. The normalisation approach based on the Si=15 (apfu) is useful for tourmaline analyses with unanalysed elements such as Li and B and is appropriate for tourmalines from metamorphic rocks (Henry *et al.* 2011). The composition of tourmalines from each beach type is presented in table 3.

All tourmaline samples plot in the alkali-tourmaline group field on the Ca–X_{vac}–(Na+K) ternary diagram (figure 8a–c) of Jiang *et al.* (1995, 1996). Detrital tourmaline of the Ain Achir and Plage-Militaire beaches is Fe rich with X_{Fe} = (Fe/Fe+Mg) varying between 0.76 and 0.94, respectively; therefore, they are schorlitic in their composition (figure 8d and e). Tourmalines from the El Nasr beach are Fe-poor with a mean value of X_{Fe} = 0.26 and plot in the dravite field (figure 8f).

4.3 Geochemistry of whole sand and basement

At the Ain Achir beach, the light and dark sands show some differences in their chemical compositions (table 4a). The average total REE content at the Ain Achir beach is 69 and 128 ppm for the light and dark sands, respectively. The Ain Achir light sands are mainly high in LREE (Σ LREE = 56 ppm) rather than HREE (Σ HREE = 12 ppm). Whereas the dark sand shows higher LREE and HREE concentrations (Σ LREE = 100 ppm and Σ HREE = 28 ppm). Compared to the REE data from the Ain Achir, the Plage-Militaire sands show somewhat higher values of Σ REE, Σ LREE and Σ HREE: Σ REE = 130–274 ppm, average 230 ppm; Σ LREE = 141–198 ppm, average 168 ppm and Σ HREE = 41–75 ppm, average 61 ppm (table 4a). At the El Nasr (table 4a), the averages are: Σ REE = 196 ppm, Σ LREE = 149 ppm and Σ HREE = 47 ppm.

Figure 6. XRD diagrams of (a) detrital garnets with quartz inclusions, (b) staurolite grains with garnet inclusions, (c) staurolite grains with tourmaline, zircon and garnet inclusions, and (d) kyanite grains with garnet inclusion.

Figure 7. Ternary garnet composition diagrams showing abundances of almandine, grossular and pyrope end-members from the heavy-mineral sand beaches. AA S: Ain Achir sand, PM S: Plage-Militaire sand, EN S: El Nasr sand.

The average REE values of the kyanite-bearing micaschists from the Vivier zone at the Cap de Garde (R Av. REE VIV) are clearly higher: $\Sigma\text{REE} = 249$ ppm, $\Sigma\text{LREE} = 218$ ppm and $\Sigma\text{HREE} = 30$ ppm than those of the Ain Achir garnet-staurolite micaschist outcrops (R Av. REE AA): $\Sigma\text{REE} = 207$ ppm, $\Sigma\text{LREE} = 182$ ppm and $\Sigma\text{HREE} = 24$ ppm (table 4b). At the Plage-Militaire, the REE concentrations are nearly similar and their $\Sigma\text{REE} = 148$ ppm, $\Sigma\text{LREE} = 129$ ppm and $\Sigma\text{HREE} = 18$ ppm. The El Nasr rock outcrops have high average REE values: $\Sigma\text{REE} = 218$ ppm, $\Sigma\text{LREE} = 193$ ppm and $\Sigma\text{HREE} = 25$ ppm (table 4b).

5. Discussion of the provenance

Heavy-mineral (specific gravity 2.85 or greater) assemblages reflect the mineralogy of the source rocks. Mineral chemistry of heavy minerals such as garnet (Mange and Wright 2007) and tourmaline (Henry and Guidotti 1985) is applicable to provenance studies and they are useful indicators of the nature of the source area.

5.1 Garnet

Garnet is resistant to weathering, and has compositions that may reflect the composition of the source rocks. Garnet shows significant differences in the composition between different types of garnet-bearing lithologies. In general, detrital garnet is considered to mostly originate from metamorphic rocks (Blatt *et al.* 2006).

The Ain Achir sand garnet (Prp-Alm-Grs) compositions are relatively homogeneous. In figure 9(a), all samples are grouped in the field Bi for intermediate to felsic igneous rocks suggesting

a single-source type. The single source of garnet at Ain Achir can be explained by the presence of only one variety of garnet (almandine rich) in the micaschist outcrop (e.g., garnet-staurolite micaschist). The garnets from the Plage-Militaire sand split into two groups with a noticeable difference in garnet end-member composition (figure 9b). The first group is dominated by almandine-pyrope with low grossular content and the second by higher grossular and lower pyrope concentration. The presence of two garnet compositions might result from mixed sources (probably the proximal garnet-staurolite micaschists and the garnet micaschist) or multiple garnet varieties in a single source). The garnet samples plot both in the field Bi for intermediate to felsic igneous rocks and in the field B for amphibolite-facies metasedimentary rocks. The difference in abundance of garnet varieties in the Plage-Militaire garnet sand samples may also reflect mixed sources (e.g., proximal garnet-staurolite micaschists and garnet micaschists). The El Nasr garnets are homogeneous and show a relatively high pyrope component. All samples plot in the field Bi for intermediate to felsic igneous rocks. Their high abundance in pyrope reflects a single magnesian-rich source (figure 9c).

5.2 Tourmaline

The source-rock types of detrital tourmaline can be identified with the triangular Ca-Fe-Mg diagrams of Henry and Guidotti (1985). Comparison of the tourmaline data from the studied sands with compositional fields of tourmaline of known origins (figure 10) indicates a strong diversity of the source rock. According to the $\text{Fe}/(\text{Fe}+\text{Mg})$, $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio and Ca^{2+} content, tourmaline

Table 3. Composition of tourmalines from each beach.

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	B ₂ O ₃	Total
Ain Achir beach											
AAS1	34.93	0.44	36.30	11.54	0.07	2.50	0.21	1.89	0.03	9.99	97.89
AAS2	35.14	0.46	36.41	11.76	0.10	2.53	0.23	1.87	0.04	10.05	98.58
AAS3	35.06	0.50	35.99	11.75	0.09	2.58	0.24	1.87	0.03	10.03	98.13
AAS4	35.01	0.51	36.01	11.68	0.08	2.61	0.23	1.95	0.03	10.02	98.13
AAS5	34.99	0.51	35.87	11.77	0.09	2.64	0.21	1.98	0.04	10.01	98.12
AAS6	34.84	0.49	35.90	11.88	0.08	2.59	0.23	1.92	0.04	9.97	97.95
AAS7	35.15	0.50	35.73	11.66	0.09	2.67	0.22	1.96	0.04	10.06	98.10
AAS8	35.15	0.48	35.63	11.88	0.04	2.69	0.23	1.93	0.04	10.06	98.15
AAS9	35.00	0.51	35.80	11.79	0.08	2.64	0.22	2.02	0.04	10.01	98.13
AAS10	34.83	0.55	36.14	11.90	0.06	2.60	0.23	2.20	0.04	9.97	98.53
AAS11	34.46	0.52	36.15	11.66	0.04	2.49	0.25	2.31	0.04	9.86	97.78
AAS12	34.62	0.45	36.31	11.68	0.09	2.46	0.27	1.90	0.04	9.90	97.72
AAS13	34.64	0.49	36.17	11.81	0.04	2.52	0.25	2.36	0.05	9.91	98.25
AAS14	34.85	0.50	36.18	11.73	0.07	2.52	0.25	2.25	0.05	9.97	98.36
AAS15	34.80	0.50	36.26	11.76	0.07	2.53	0.24	2.40	0.04	9.96	98.56
AAS16	34.62	0.53	36.11	11.66	0.06	2.56	0.25	2.44	0.05	9.91	98.18
AAS17	34.54	0.45	36.15	11.96	0.08	2.57	0.25	2.33	0.04	9.88	98.28
AAS18	34.62	0.49	36.23	11.99	0.05	2.36	0.25	2.32	0.04	9.91	98.28
AAS19	34.84	0.48	36.24	12.05	0.10	2.45	0.26	2.34	0.05	9.97	98.79
AAS20	36.01	0.70	34.56	8.31	0.00	4.61	1.05	2.28	0.06	10.30	97.91
AAS21	36.00	0.74	34.74	8.44	0.04	4.60	1.06	2.38	0.05	10.30	98.37
AAS22	35.77	0.73	34.78	8.27	0.02	4.66	0.99	2.37	0.06	10.24	97.88
AAS23	36.00	0.70	34.95	8.31	0.03	4.68	1.03	2.42	0.06	10.30	98.52
AAS24	35.57	0.77	34.75	8.39	0.00	4.60	1.01	2.36	0.07	10.18	97.73
AAS25	35.97	0.71	34.80	8.34	0.03	4.61	0.96	2.10	0.05	10.30	97.88
AAS26	36.00	0.67	34.78	8.44	0.02	4.62	0.95	2.15	0.06	10.30	98.04
AAS27	35.70	0.45	36.20	10.52	0.09	2.33	0.38	1.76	0.03	10.22	97.68
AAS28	35.72	0.52	34.85	10.70	0.01	2.67	0.33	1.84	0.03	10.22	96.91
AAS29	36.11	0.44	35.52	10.50	0.05	2.68	0.31	1.82	0.04	10.33	97.85
AAS30	35.96	0.49	35.07	10.67	0.07	2.74	0.33	1.91	0.05	10.29	97.63
AAS31	35.87	0.71	34.50	11.11	0.03	2.85	0.36	1.99	0.05	10.26	97.74
AAS32	35.87	0.65	33.90	10.89	0.05	3.17	0.46	1.98	0.04	10.26	97.27
AAS33	35.73	0.51	34.51	10.99	0.08	2.94	0.42	1.93	0.05	10.22	97.43
Plage-Militaire beach											
PMS1	34.00	1.00	33.00	9.00	0.00	4.66	0.38	2.01	0.05	10.10	94.19
PMS2	34.00	0.00	34.00	11.00	0.00	3.26	0.35	2.12	0.07	10.17	94.96
PMS3	33.00	0.00	34.00	13.00	0.00	1.63	0.31	2.08	0.04	9.90	93.96
PMS4	33.00	0.00	33.00	13.00	0.00	2.16	0.34	2.14	0.04	9.94	93.62
PMS5	33.00	0.00	34.00	13.00	0.00	1.65	0.33	2.03	0.06	9.90	93.96
PMS6	33.00	0.00	34.00	12.00	0.00	2.18	0.33	2.14	0.05	9.98	93.68
El Nasr beach											
EN S1	36.00	0.00	33.00	5.00	0.00	7.65	0.89	2.14	0.02	10.57	84.57
EN S2	36.00	0.00	33.00	5.00	0.00	7.31	1.16	2.09	0.02	10.43	84.43
EN S3	36.00	0.00	32.00	5.00	0.00	7.66	0.85	2.07	0.03	10.35	83.35
EN S4	36.00	0.00	30.00	6.00	0.00	8.94	0.98	2.31	0.06	10.39	82.39
EN S5	36.00	0.00	31.00	5.00	0.00	9.32	0.72	2.31	0.01	10.50	82.50
EN S6	35.00	0.00	31.00	6.00	0.00	8.68	1.62	1.78	0.07	10.37	82.37

Table 3. (Continued.)

	Fe ₂ + (Y)	Mg(Y)	Ca(X)	Na(X)	K(X)	X-vacancy	Y(Fe/(Fe+Mg))	Mg/(Mg+Fe)	X(Ca/Ca+Na)	Na+K
Ain Achir beach										
AAS1	1.66	0.64	0.04	0.63	0.01	0.33	0.94	0.28	0.06	0.64
AAS2	1.68	0.64	0.04	0.62	0.01	0.33	0.94	0.28	0.06	0.63
AAS3	1.68	0.66	0.04	0.62	0.01	0.33	0.93	0.28	0.07	0.63
AAS4	1.67	0.67	0.04	0.65	0.01	0.31	0.94	0.28	0.06	0.65
AAS5	1.69	0.68	0.04	0.66	0.01	0.30	0.95	0.29	0.05	0.67
AAS6	1.71	0.67	0.04	0.64	0.01	0.31	0.94	0.28	0.06	0.65
AAS7	1.67	0.68	0.04	0.65	0.01	0.30	0.94	0.29	0.06	0.66
AAS8	1.70	0.69	0.04	0.64	0.01	0.31	0.94	0.29	0.06	0.65
AAS9	1.69	0.68	0.04	0.67	0.01	0.28	0.94	0.29	0.06	0.68
AAS10	1.71	0.67	0.04	0.73	0.01	0.22	0.95	0.28	0.05	0.74
AAS11	1.70	0.65	0.05	0.78	0.01	0.17	0.95	0.28	0.06	0.79
AAS12	1.69	0.64	0.05	0.64	0.01	0.31	0.93	0.27	0.07	0.65
AAS13	1.71	0.65	0.05	0.79	0.01	0.15	0.95	0.28	0.05	0.80
AAS14	1.69	0.65	0.05	0.75	0.01	0.19	0.94	0.28	0.06	0.76
AAS15	1.70	0.65	0.05	0.80	0.01	0.15	0.95	0.28	0.05	0.81
AAS16	1.69	0.66	0.05	0.82	0.01	0.12	0.95	0.28	0.05	0.83
AAS17	1.74	0.66	0.05	0.79	0.01	0.16	0.95	0.28	0.06	0.80
AAS18	1.74	0.61	0.05	0.78	0.01	0.17	0.94	0.26	0.06	0.79
AAS19	1.74	0.63	0.05	0.78	0.01	0.16	0.94	0.27	0.06	0.79
AAS20	1.16	1.15	0.19	0.74	0.01	0.06	0.80	0.50	0.20	0.75
AAS21	1.18	1.14	0.19	0.77	0.01	0.03	0.80	0.49	0.20	0.78
AAS22	1.16	1.17	0.18	0.77	0.01	0.04	0.81	0.50	0.19	0.78
AAS23	1.16	1.16	0.18	0.78	0.01	0.02	0.81	0.50	0.19	0.80
AAS24	1.18	1.16	0.18	0.77	0.02	0.03	0.81	0.49	0.19	0.79
AAS25	1.16	1.15	0.17	0.68	0.01	0.14	0.80	0.50	0.20	0.69
AAS26	1.18	1.15	0.17	0.70	0.01	0.12	0.80	0.49	0.20	0.71
AAS27	1.48	0.59	0.07	0.57	0.01	0.35	0.89	0.28	0.11	0.58
AAS28	1.50	0.67	0.06	0.60	0.01	0.33	0.91	0.31	0.09	0.61
AAS29	1.46	0.67	0.06	0.59	0.01	0.35	0.91	0.31	0.09	0.60
AAS30	1.49	0.68	0.06	0.62	0.01	0.31	0.91	0.31	0.09	0.63
AAS31	1.55	0.71	0.07	0.65	0.01	0.28	0.91	0.31	0.09	0.66
AAS32	1.52	0.79	0.08	0.64	0.01	0.27	0.89	0.34	0.11	0.65
AAS33	1.54	0.74	0.08	0.63	0.01	0.29	0.89	0.32	0.11	0.64
Plage-Militaire beach										
PMS1	1.30	1.03	0.07	0.67	0.01	0.33	0.56	0.44	0.09	0.68
PMS2	1.57	0.77	0.06	0.66	0.01	0.34	0.67	0.33	0.09	0.68
PMS3	1.91	0.26	0.06	0.68	0.01	0.32	0.88	0.12	0.08	0.69
PMS4	1.90	0.52	0.06	0.68	0.01	0.32	0.78	0.22	0.08	0.69
PMS5	1.91	0.26	0.06	0.68	0.01	0.32	0.88	0.12	0.08	0.69
PMS6	1.75	0.52	0.06	0.68	0.01	0.32	0.77	0.23	0.08	0.69
El Nasr beach										
EN S1	0.69	1.88	0.16	0.68	0.00	0.16	0.56	0.73	0.19	0.69
EN S2	0.70	1.82	0.21	0.68	0.00	0.11	0.28	0.72	0.23	0.68
EN S3	0.70	1.92	0.15	0.68	0.01	0.17	0.27	0.73	0.18	0.68
EN S4	0.84	2.14	0.18	0.75	0.01	0.06	0.28	0.72	0.19	0.76
EN S5	0.69	2.30	0.13	0.74	0.00	0.13	0.23	0.77	0.15	0.74
EN S6	0.84	2.16	0.29	0.58	0.01	0.12	0.28	0.72	0.33	0.59

Xv=X-vacancy, Fe*(Y)=Y(Fe/(Fe+Mg)), Mg*(Y)=Mg/(Mg+Fe), Ca*(X)=X(Ca/Ca+Na), Na*=Na+K.

Figure 8. (a–c) Classification of the tourmaline from: (a) Ain Achir beach, (b) Plage-Militaire beach and (c) El Nasr beach in the ternary Ca^{2+} –X-site vacancy–(Na+K) system based on the dominant occupancy at the X-site; (d–f) Plot of tourmaline composition from: (d) Ain Achir beach, (e) Plage-Militaire beach, and (f) El Nasr beach in a X_{Fe}^Y vs. X_{Ca}^X plot (Jiang *et al.* 1995, 1996). AA S: Ain Achir sand, PM S: Plage-Militaire sand, EN S: El Nasr sand.

from the three studied beaches can be divided into three groups with different sources. Tourmalines from the Ain Achir beach are compositionally within field 2 of Li-poor granitoids and their associated pegmatites and partly in field 4 of Ca-poor metapelites, metapsammites and quartz-tourmaline rocks (figure 10a) suggesting a mixed source rock for these tourmalines

(e.g., tourmaline-rich quartzo-feldspathic veins in the garnet–staurolite micaschists and in the garnet micaschists or a single source with two tourmaline types being more or less Fe-rich). All the tourmaline samples from the Plage-Militaire beach plot in the Li-poor granitoids and their associated pegmatites field 2 (figure 10b) indicating a single source (tourmaline-rich

Table 4. Rare earth composition of (a) the sand samples from Ain Achir, Plage-Militaire and El Nasr beaches, (b) the proximal rock outcrops from each studied beach, LS: light sand, DS: dark sand, LS Av. AA: light sand average Ain Achir, DS Av. AA: dark sand average Ain Achir, S Av. REE PM: sand average REE Plage-Militaire, S Av. REE EN: sand average REE El Nasr, (c) WSA: World Shale Average (Piper 1974; Piper and Bau 2013), zircon 91500 (Sano et al. 2002).

(a)	Sand samples	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	ΣLREE	ΣHREE
Ain Achir beach (AA)	LS AA1a	10.2	20.4	1.9	9.6	1.9	0.4	2.1	0.4	2.5	0.5	1.6	0.3	1.6	0.2	53.7	44.0	9.6
	AA1b	12.4	27.2	2.6	12.3	2.4	0.5	2.7	0.5	3.6	0.8	2.4	0.4	2.4	0.3	70.5	56.9	13.7
	AA2b	8.8	17.0	1.6	8.3	1.7	0.4	1.7	0.3	1.6	0.3	0.9	0.2	0.9	0.1	43.8	37.4	6.5
	AA4a	21.9	31.2	3.0	14.2	2.9	0.6	3.1	0.6	4.0	0.8	2.6	0.4	2.5	0.4	88.1	73.1	15.0
	AA4b	13.2	26.7	2.7	12.5	2.5	0.5	2.9	0.5	3.9	0.9	2.5	0.5	2.5	0.4	72.1	57.6	14.5
	AA5a	15.2	29.5	2.7	14.3	2.9	0.6	3.0	0.6	3.4	0.7	2.2	0.3	2.1	0.3	78.0	64.6	13.3
	AA5b	12.9	24.6	2.6	11.9	2.5	0.5	2.6	0.5	3.0	0.6	1.9	0.3	1.8	0.3	65.9	54.4	11.5
	AA5c	15.1	29.1	2.8	13.7	3.0	0.6	3.1	0.9	3.8	0.8	2.4	0.3	2.4	0.3	78.2	63.7	14.5
	LS Av. AA	13.7	25.7	2.5	12.1	2.5	0.5	2.6	0.6	3.2	0.7	2.1	0.3	2.0	0.3	68.8	56.5	12.3
	DS	41.1	83.9	9.1	36.4	7.6	1.1	9.2	2.1	15.1	3.4	10.6	1.6	10.3	1.5	232.9	178.0	54.9
DS	AAGa	21.2	40.0	4.1	17.9	3.7	0.6	4.1	0.9	5.6	1.2	3.9	0.6	3.9	0.6	108.3	86.9	21.4
	AA2a	8.5	16.2	1.6	8.1	1.6	0.4	1.7	0.3	1.7	0.4	1.0	0.2	1.0	0.2	42.8	36.0	6.8
	AA2c	10.7	21.2	1.9	9.9	2.0	0.4	2.1	0.4	2.4	0.5	1.5	0.3	1.5	0.2	55.2	45.8	9.4
	AAMa	17.0	33.5	3.3	15.3	3.2	0.6	3.4	0.8	4.3	0.9	2.9	0.5	2.8	0.5	89.1	72.4	16.7
	AAMb	44.0	89.5	9.8	38.6	8.1	1.2	10.1	2.3	17.3	4.0	12.5	2.0	12.1	1.7	253.0	189.9	63.1
	AA3a	27.2	45.8	4.6	20.1	4.1	0.7	4.8	1.0	7.6	1.7	5.3	0.9	5.2	0.7	129.9	101.8	28.1
	AA3b	23.1	48.6	5.2	21.6	4.4	0.7	5.1	1.1	7.6	1.7	5.2	0.8	5.1	0.7	131.0	102.9	28.1
	AA3c	23.8	55.4	5.3	23.4	4.8	0.8	5.5	1.2	8.4	1.9	5.9	1.0	5.8	0.8	143.8	112.6	31.2
	AAGb	18.1	34.5	3.1	15.5	3.3	0.6	3.6	0.8	4.7	1.0	3.3	0.5	3.1	0.5	92.7	74.5	18.2
	DS Av. REE AA	23.5	46.9	4.8	20.7	4.3	0.7	5.0	1.1	7.5	1.7	5.2	0.8	5.1	0.7	127.9	100.1	27.8

Table 4. (Continued.)

(a)	Sand samples		La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	ΣLREE	ΣHREE
Plage-Militaire beach (PM)	DS	Pms6a	42.0	84.0	9.2	36.5	7.6	1.2	9.5	2.0	16.4	3.7	11.8	1.9	11.6	1.6	239.0	179.4	59.7
		Pms1a	41.1	84.1	9.1	36.5	7.7	1.2	9.8	2.2	17.9	4.1	13.2	2.0	12.8	1.8	243.6	178.4	65.2
		Pms2a	42.9	87.2	9.6	37.8	8.1	1.3	10.9	2.6	21.0	4.9	15.4	2.4	15.0	2.1	260.9	185.6	75.4
		Pms3a	46.0	93.3	10.2	40.3	8.5	1.3	11.1	2.6	21.1	4.9	15.4	2.3	14.6	2.0	273.7	198.4	75.3
		Pms4a	40.9	82.6	8.9	36.0	7.6	1.2	9.7	2.3	18.2	4.2	13.4	2.0	13.0	1.8	241.8	176.0	65.8
		Pms4b	34.6	69.7	7.5	30.6	6.4	1.0	7.8	1.8	13.9	3.2	10.3	1.6	9.9	1.4	199.8	148.9	50.9
		Pms5b	36.3	72.1	8.0	31.6	6.6	1.0	8.2	1.8	14.2	3.3	10.3	1.6	10.0	1.4	206.2	154.5	51.7
		Pms6b	36.8	74.4	8.0	32.8	6.8	1.1	8.6	2.0	15.5	3.6	11.3	1.7	10.9	1.5	215.0	158.9	56.1
		Pms2b	40.3	80.9	8.8	35.3	7.4	1.2	9.5	2.1	16.9	3.9	12.2	1.9	12.0	1.7	234.2	172.7	61.4
		Pms3b	44.3	90.1	9.9	39.4	8.4	1.3	11.0	2.6	21.0	4.9	15.5	2.4	14.9	2.1	267.8	192.1	75.8
		Pms1c	41.7	84.4	9.2	36.5	7.7	1.2	9.9	2.2	17.7	4.1	13.0	2.0	12.7	1.8	244.0	179.5	64.5
		Pms2c	42.4	85.5	9.4	37.4	7.9	1.2	9.8	2.3	17.8	4.1	12.9	2.0	12.4	1.7	246.8	182.6	64.2
		Pms3c	42.2	85.1	9.4	37.0	7.8	1.3	10.4	2.4	19.5	4.5	14.2	2.2	13.9	2.0	251.9	181.5	70.4
		Pms5c	41.0	83.4	9.1	36.1	7.7	1.2	9.9	2.3	18.4	4.3	13.5	2.1	12.9	1.8	243.4	177.2	66.2
		Pms1b	33.0	65.8	7.2	29.1	6.0	0.9	6.9	1.5	11.2	2.6	8.0	1.2	7.8	1.1	182.2	141.0	41.2
		Pms6c	41.1	82.3	9.1	36.1	7.6	1.2	9.8	2.2	17.7	4.0	12.7	2.0	12.3	1.7	239.8	176.2	63.6
El Nasr beach (EN)	DS	Pms5a	24.1	47.4	5.1	21.2	4.3	0.7	4.9	1.0	7.5	1.7	5.4	0.8	5.3	0.7	130.0	102.0	28.1
		S Av. REE PM	39.4	79.6	8.7	34.7	7.3	1.1	9.3	2.1	16.8	3.9	12.2	1.9	11.9	1.7	230.6	169.7	60.9
		EN S 1A	48.8	97.8	11.2	43.1	8.3	1.5	6.9	1.2	6.0	1.2	3.4	0.5	3.4	0.5	233.7	209.2	24.5
		EN S 2A	9.2	16.4	1.6	8.1	1.5	0.5	1.5	0.5	1.4	0.5	0.9	0.5	0.9	0.1	43.6	36.8	6.8
		EN S 3A	10.4	18.5	2.0	9.3	1.8	0.4	1.8	0.3	2.0	0.4	1.3	0.2	1.3	0.2	49.8	42.0	7.8
		EN S 1B	50.7	98.8	11.5	43.6	8.4	1.4	7.2	1.3	7.2	1.5	4.5	0.7	4.5	0.7	241.9	213.0	28.9
		EN S 1C	36.7	72.9	8.5	32.8	6.3	1.1	5.5	1.0	5.0	1.0	2.9	0.5	2.9	0.4	177.6	157.2	20.4
		EN S 2B	31.2	60.4	7.0	28.3	6.0	1.1	8.5	2.1	15.9	3.7	11.8	1.8	11.9	1.7	191.5	132.9	58.5
		EN S 2C	57.9	117.7	13.4	51.8	10.7	1.5	15.2	3.8	29.1	6.7	20.8	3.2	20.4	2.9	355.2	251.6	103.5
		EN S 3C	35.0	68.3	7.9	31.7	7.1	1.4	12.0	3.2	25.6	5.9	19.0	2.9	18.8	2.7	241.6	150.0	91.5
		EN S 3B	34.7	67.5	7.8	31.3	6.9	1.3	11.2	2.9	22.8	5.3	17.0	2.6	16.7	2.4	230.4	148.2	82.2
		S Av. REE EN	35.0	68.7	7.9	31.1	6.3	1.1	7.8	1.8	12.8	2.9	9.1	1.4	9.0	1.3	196.1	149.0	47.1

Table 4. (Continued.)

(b)	Rock Samples	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Σ REE	Σ LREE	Σ HREE
Ain Achir beach (AA)	VIV1	52.2	103.0	12.1	45.9	9.0	1.9	8.9	1.5	9.4	1.9	5.5	0.8	5.1	0.8	257.9	222.3	35.7
	VIV2	63.8	130.1	14.9	55.2	10.3	1.8	8.0	1.2	7.0	1.4	3.9	0.6	3.7	0.5	302.3	274.3	28.0
	VIV3	44.9	84.9	11.1	42.8	8.6	1.9	8.6	1.4	9.0	1.9	5.6	0.8	5.2	0.8	227.4	192.3	35.1
	VIV4	47.2	95.8	11.2	42.3	8.2	1.6	6.9	1.1	7.0	1.4	4.0	0.6	3.7	0.6	231.8	204.8	27.0
	DvIV	46.0	93.6	10.6	41.5	8.1	1.4	7.1	1.3	6.2	1.2	3.4	0.5	3.4	0.5	224.8	199.8	25.1
	R Av. REE VIV	50.8	101.5	12.0	45.6	8.9	1.7	7.9	1.3	7.7	1.6	4.5	0.6	4.2	0.6	248.9	218.7	30.2
	E60	46.1	82.5	10.7	41.7	8.0	1.2	7.2	1.3	7.1	1.5	4.3	0.7	4.5	0.6	217.3	189.0	28.3
	E62	53.6	95.1	12.1	47.8	9.1	1.5	7.8	0.9	7.0	1.4	3.9	0.6	3.8	0.4	244.8	217.7	27.1
	E74	34.8	61.8	8.1	31.4	6.0	0.6	5.3	0.9	4.5	0.9	2.4	0.4	2.3	0.6	159.9	142.1	17.8
	R Av. REE AA	44.8	79.8	10.3	40.3	7.7	1.1	6.7	1.0	6.2	1.3	3.5	0.6	3.5	0.5	207.3	182.9	24.4
	Av. LS+DS	48.6	93.3	11.4	43.6	8.4	1.5	7.5	1.2	7.1	1.5	4.1	0.6	4.0	0.6	233.3	205.3	28.0
	PMR 3N3	40.7	68.4	9.2	35.2	6.5	1.2	5.6	1.1	5.2	1.0	3.0	0.5	3.0	0.5	181.3	160.0	21.2
	PMR 1A	41.0	75.5	9.3	35.6	6.9	1.3	6.3	1.1	6.4	1.3	3.9	0.6	4.2	0.7	194.2	168.3	25.8
	PMR 3C AA3	35.4	67.8	8.1	30.9	6.0	0.9	5.4	1.0	5.0	0.9	2.9	0.5	2.9	0.5	168.1	148.1	20.0
	PMR 3C AA1	24.2	44.5	5.4	20.5	3.9	0.5	3.5	0.7	3.3	0.7	1.9	0.5	2.1	0.3	112.1	98.4	13.6
Plage-Militaire beach (PM)	PM 3C AA2	12.4	30.8	3.3	13.3	2.8	0.5	2.7	0.5	2.0	0.5	1.2	0.5	1.6	0.3	72.4	62.6	9.8
	PMR 3C AA4	40.3	78.9	9.4	37.3	7.0	0.5	6.0	1.0	5.6	1.2	3.5	0.6	3.5	0.5	195.3	172.9	22.4
	PMR 2N1	44.9	88.2	10.4	40.3	7.9	1.3	7.2	1.4	6.6	1.3	3.8	0.6	3.8	0.6	148.4	130.1	18.3
	PMR 1A	53.1	102.8	12.1	47.1	9.1	1.5	7.7	1.3	6.9	1.4	3.9	0.6	3.9	0.6	139.3	122.4	16.8
	PMR 2N2	48.8	98.5	11.2	43.0	8.4	1.5	7.7	1.4	7.5	1.4	4.1	0.6	3.9	0.6	133.5	117.3	16.2
	PMR 1A SC1	49.1	83.2	10.7	41.7	8.0	1.8	7.0	1.2	6.3	1.2	3.6	0.6	3.5	0.5	137.8	121.0	16.7
	PMR 1A SC2	50.0	86.6	11.0	43.2	8.3	1.9	7.1	1.2	6.4	1.3	3.7	0.6	3.7	0.6	150.8	132.7	18.1
	PM 1A SC3	48.2	94.1	10.8	41.8	7.9	1.4	6.8	1.2	5.9	1.1	3.4	0.6	3.6	0.5	141.9	124.7	17.2
	R Av. REE PM	40.7	76.6	9.2	35.8	6.9	1.2	6.1	1.1	5.6	1.1	3.2	0.6	3.3	0.5	147.9	129.9	18.0
	EN R 1A	48.8	97.8	11.2	43.1	8.3	1.5	6.9	1.2	6.0	1.2	3.4	0.5	3.4	0.5	233.7	209.2	24.5
	EN R 1B	50.7	98.8	11.5	43.6	8.4	1.4	7.2	1.3	7.2	1.5	4.5	0.7	4.5	0.7	241.9	213.0	28.9
	SN R 1C	36.7	72.9	8.5	32.8	6.3	1.1	5.5	1.0	5.0	1.0	2.9	0.5	2.9	0.4	177.6	157.2	20.4
	R Av. REE EN	45.4	89.8	10.4	39.9	7.7	1.3	6.5	1.1	6.1	1.2	3.6	0.6	3.6	0.5	217.7	193.1	24.6
	El Nasr beach (EN)																	
(c) WSA	Zircon 91500	41.0	83.0	10.0	38.0	7.5	1.6	6.4	1.2	5.5	1.3	3.8	0.6	3.5	0.6	204.1	179.5	24.6
		0.0	2.6	0.0	0.3	0.3	0.2	1.6	0.8	12.0	5.0	29.0	8.0	77.0	17.0	153.8	3.2	150.6

Figure 9. The composition of garnets in the ternary classification diagram of Mange and Morton (2007) with almandine+spessartine, grossular and pyrope as poles: (a) Ain Achir, (b) Plage-Militaire, (c) El Nasr sands. A – high-grade granulite-facies metasedimentary rocks and intermediate felsic igneous rocks; B – amphibolite-facies metasedimentary rocks; Bi – intermediate to felsic igneous rocks; Ci – mainly high-grade mafic rocks; Cii – ultramafics with high Mg (pyroxenites and peridotites); D – metasomatic rocks, very low-grade metamafic rocks and ultrahigh-temperature metamorphosed calc-silicate granulites. AA S: Ain Achir sand, PM S: Plage-Militaire sand, EN S: El Nasr sand.

Figure 10. Microprobe analyses of tourmaline samples plotted on Ca-Fe^(t)-Mg diagram of Henry and Guidotti (1985): (a) Ain Achir, (b) Plage-Militaire, (c) El Nasr samples. 1. Li-rich granitoid, pegmatites and aplites; 2. Li-poor granitoids and their associated pegmatites; 3. Ca-rich metapelites and metapsammites and calc-silicate rocks; 4. Ca-poor metapelites, metapsammites and quartz-tourmaline rocks; 5. metacarbonates; 6. metaultramafics. AA S: Ain Achir sand, PM S: Plage-Militaire sand, EN S: El Nasr sand.

quartzo-feldspathic veins, e.g., in the garnet micaschists). In contrast to the two above-mentioned beaches, tourmalines from the El Nasr cluster in field 4 corresponding to Ca-poor

metapelites, metapsammites and quartz-tourmaline rocks (figure 10c). The source rock from the El Nasr tourmaline is different from those from the Ain Achir and Plage-Militaire beaches.

5.3 The rare earth element behaviour of whole sand and rock

In order to identify the provenance, the REE data from the sand samples are compared to data from the rock outcrops located relatively close to the studied sand beaches. All samples (sand and rock) from the studied areas have been normalised to the World Shale Average (WSA; Piper 1974; Piper and Bau 2013).

Many authors (e.g., Jung *et al.* 2006, 2012; Leybourne and Johannesson 2008) show that fractionation factors $LREE_N/HREE_N$ and $MREE_N/HREE_N$ ($LREE_N$: $La_N + Pr_N + Nd_N$; $MREE_N$: $Sm_N + Eu_N + Tb_N$; $HREE_N$: $Ho_N + Yb_N + Lu_N$) are helpful to discriminate among source rocks.

The fractionation factors ($LREE_N/HREE_N$ and $MREE_N/HREE_N$) of the sand samples from each beach have been plotted on the mixing diagram and compared with the rock samples (figure 11). In Ain Achir, light and the dark sand fractionation factors overlap with most of the Plage-Militaire rock outcrops (figure 11a) suggesting that the latter could be their provenance source. The Plage-Militaire sand samples plot close to/or overlap with the adjacent basement rock (Plage-Militaire) and distal (El Nasr) outcrops suggesting mixed sources of the sand (figure 11b). At the El Nasr beach the sand samples plot close to the data from the distal Cap de Garde kyanite–garnet micaschists (R Vivier) and staurolite–garnet micaschists (R Ain Achir), suggesting that these two kinds of rocks (which are probably outcropping at sea, close to the El Nasr beach) could be the source of the sand (figure 11c).

On the normalised to the WSA (Piper 1974; Piper and Bau 2013) spider-gram (figure 12a) all costal rocks display very similar flat REE patterns suggesting that these rocks have similar geological and geochemical backgrounds (figure 12a). Compared to their associated rocks and to those from the Plage-Militaire and El Nasr beaches, some Ain Achir beach sand REE patterns are more depleted. Some others, mostly dark sand samples, have similar depleted LREE and enriched HREE patterns (figure 12b–d) with respect to the rocks, point to the influence of a HEE-rich mineral (e.g., zircon). Zircon is the main mineral in the majority of igneous and metamorphic rocks. It is a host for

Figure 11. Fractionation factors diagram between $LREE_N/HREE_N$ and $MREE_N/HREE_N$ ($LREE_N$: $La_N + Pr_N + Nd_N$; $MREE_N$: $Sm_N + Eu_N + Tb_N$; $HREE_N$: $Ho_N + Yb_N + Lu_N$) for the sand and all rock samples of (a) Ain Achir beach, (b) Plage-Militaire beach and (c) El Nasr beach. R: rock, LS: light sand, DS: dark sand.

Figure 12. WSA-normalised rare earth element pattern of (a) rock samples from all three beaches, (b) sand and rocks from the Ain Achir beach, (c) Ain Achir sand and rocks from the Plage-Militaire beach, (d) Ain Achir sand and rocks from the El Nasr beach, (e) sand and rocks from the Plage-Militaire beach, (f) Plage-Militaire sand and rocks from the Ain Achir beach, (g) Plage-Militaire sand and rocks from the El Nasr beach, (h) sand and rocks from the El Nasr beach, (i) El Nasr sand and rocks from the Ain Achir beach, and (j) El Nasr sands and rocks from the Plage-Militaire beach.

Figure 13. WSA-normalised rare earth element pattern of the standard zircon 91500 (Sano *et al.* 2002) compared with (a) Ain Achir dark sand, (b) Plage-Militaire sand, and (c) El Nasr beach sand.

significant fractions of the whole-rock abundance of the REE (Bea and Montero 1999; O'Hara *et al.* 2001). All Plage-Militaire sand samples display different WSA-normalised (Piper 1974; Piper and Bau 2013) REE patterns with their proximal rock outcrops and with those from the Ain Achir (figure 12e and f) but their REE distribution is quite similar to those from the El Nasr rocks (figure 12g). Therefore, it can be concluded that the Plage-Militaire sand has a mixed source. A portion of the Plage-Militaire sand could be from the proximal rock outcrops, which are mainly staurolite–garnet micaschists and from formations similar to those of the El Nasr beach (garnet–staurolite micaschists). REEs spider graphs of El Nasr sands show differences with respect to their closeby rocks (figure 12h) and also to Ain Achir (figure 12i) and the Plage-Militaire (figure 12j) rocks. They show a flat LREE pattern and are enriched in HREE, suggesting a different metamorphic source with a HREE-rich mineral composition. All WSA-normalised sand samples show negative europium anomalies. Some studies suggest that they are due to

non-selective losses of REE during weathering and that Eu-anomalies are inherited from the sediment source (Nesbitt 1979; Condie 1991; Condie *et al.* 1995; Nesbitt and Young 1996).

Despite that, the Ain Achir, Plage-Militaire and El Nasr sand samples have nearly the same mineralogical compositions; some sand samples show a stronger HREEs enrichment than others. This is indicative of influence by a HEE-rich mineral. XRD analyses of staurolites from these sand samples show that their inclusions are mostly zircon grains. The comparison of WSA-normalised REE (Piper 1974; Piper and Bau 2013) pattern of sand samples from the Ain Achir, Plage-Militaire and El Nasr sands with selected zircon from the literature (Standard 91500, Sano *et al.* 2002) shows similar HREE pattern (figure 13). The possibility of zircon geochemistry influencing the HREEs distribution cannot be excluded.

6. Conclusion

Because of their flat topography and the lack of an active hydrographic system, the Cap de Garde (Ain Achir and Plage-Militaire beaches) and the Harbor (El Nasr beach) fields are characterised by insignificant low continental erosion processes. The seasonal swell and sea wave (1–3 m) are the principal erosion factors and beach sedimentation along the coast. They contribute to the beach and near-shore sand accumulation. The heavy-sand buildup is due to a hydraulic (sea water) segregation process. The mineral assemblages (staurolite, garnet, tourmaline, kyanite and rare epidote) of the three heavy-sand beaches are similar and point to the influence of metamorphic rocks as source areas and reflect the properties of these sources. The compositions of detrital garnet and tourmaline in the heavy-mineral sands vary according to the beach location. The Ain Achir sand is characterised by extreme almandine-rich garnet and schorl-tourmaline. The Plage-Militaire heavy-sand shows two kinds of garnets: Fe-rich almandine and Mg-rich almandine. Their tourmaline is schorl rich in composition. The high Mg concentration in some garnets and tourmaline-rich sand samples from the El Nasr beach reflect a magnesian-rich source.

Compared to their associated rock outcrops, the WSA-normalised REE pattern of the dark sand samples from Ain Achir, Plage-Militaire and El Nasr beaches show similar LREE patterns and enrichment of HREE suggesting the influence of

a HEE-rich mineral (e.g., zircon as inclusions in staurolite). Ain Achir sands reveal a mixed provenance: from their proximal rock outcrops garnet–staurolite micaschist (Ain Achir and Plage Militaire) and rocks similar to garnet–staurolite micaschists at the El Nasr beach outcrops. The Plage-Militaire sand samples display different normalised WSA REE patterns as compared to their proximal rock outcrops and to those from the Ain Achir. But looks quite similar to those from the El Nasr rock formations (garnet–staurolite micaschist). Sand REE distribution curves of the El Nasr show differences when compared to those from the rocks in the vicinity to Ain Achir and to the Plage-Militaire outcrops suggesting a different metamorphic source area with an HREE-rich mineral composition.

The source area of kyanite in the Ain Achir sand could be the proximal staurolite–garnet kyanite micaschists at the Plage-Militaire. The source rocks of the epidote in the sand of Ain Achir and the Plage Militaire are the epidote-bearing skarns.

The present study shows a complex mixture in the of beach sediments, although the sources seem to be very close and easily determinable. The results from the unconsolidated modern beach sand could help to evaluate the sedimentation process and provenance of solidified layers. In provenance studies of fossil beach sediment, the careful study of related outcrops can help to evaluate different sources, proximal as well as distal. A proximal situation is characterised by the similarity of mineral assemblage and proportions in different outcrops. A deviation from this points to distal sedimentation. In addition, the results add important aspects for provenance analyses of fossil heavy-mineral placer deposits, where the source evaluation is an important economic factor.

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References

- Ahmed-Said Y, Leake B E and Rogers G 1993 The petrology, geochemistry and petrogenesis of the Edough igneous rocks, Annaba, NE Algeria; *J. Afr. Earth Sci.* **17**(1) 111–123.
- ANDI 2013 (Agence Nationale de développement de l'Investissement) Invest in Algeria, Wilaya de Annaba.
- Bea F and Montero P 1999 Behaviour of accessory phases and redistribution of Zr, REE, Y, Th and U during metamorphism and partial melting of metapelites in the lower crust: An example from the Kinzigite Formation of Ivrea-Verbano, NW Italy; *Geochim. Cosmochim. Acta* **63** 1133–1153.
- Blatt H, Tracy R J and Owens E 2006 *Petrology: Igneous, sedimentary and metamorphic*, 3rd edn, W.H. Freeman and Co, New York.
- Brunnel M, Hammor D, Misseri M, Gleizes G and Bouleton J 1988 Cisaillements synmétamorphes avec transport vers le Nord-Ouest dans le massif cristallin de l'Edough (Est Algérien); *C.R. Acad. Sci.* **306** 1039–1045.
- Caby R and Hammor D 1992 Le Massif cristallin de l'Edough (Algérie): Un "Métamorphic Core Complex" d'âge miocène dans les Magrébides; *C.R. Acad. Sci.* **314** 829–835.
- Caby R, Hammor D and Delor C 2001 Metamorphic evolution, partial melting and Miocene exhumation of lower crust in the Edough metamorphic core complex, west Mediterranean orogen, eastern Algeria; *Tectonophysics* **342** 239–273.
- Condie K C 1991 Another look at rare earth elements in shales; *Geochim. Cosmochim. Acta* **55** 2527–2531.
- Condie K C, Dengate J and Cullers R L 1995 Behavior of rare elements in a paleo-weathering profile on granodiorite in the Front Range, Colorado, USA; *Geochim. Cosmochim. Acta* **59** 279–294.
- Darnley A G, Bjorklund A, Bolviken B, Gustavsson N, Koval P V, Plant J A, Steenfel A, Tauchid M and Xie X 1995 A Global geochemical database for environmental and resource management. Recommendations for international geochemical mapping; Final Report of IGCP Project 259, UNESCO Publishing.
- Henry D J and Guidotti C V 1985 Tourmaline as a petrogenetic indicator mineral: An example from the staurolite-grade metapelites of NW Maine; *Am. Miner.* **70** 1–15.
- Henry D J, Novák M, Hawthorne F C, Ertl A, Dutrow B L, Uher P and Pezozotta F 2011 Nomenclature of the tourmaline-supergroup minerals; *Am. Miner.* **96** 895–913.
- Hilly J 1962 Etude géologique du massif de l'Edough et du Cap de Fer (Est-Constantinois); *Pub. Serv. de la Carte Géol. Algérie* **19** 1–408.
- <http://www.temperatureweather.com/mediterr/meteo/fr-meteo-en-algerie-annaba.html>
- http://fr.wisuki.com/statistics/4809/annaba?a-wi=4&wi_m=0&a-wa=0&wa_m=1&temp=monthly&rain=quantity.
- Hufty A 2001 Introduction à la climatologie, Les presses de l'Université de Laval, De Böeck Université, 545.
- Jiang S Y, Palmer M R, Li Y H and Xue C J 1995 Chemical compositions of tourmaline in the Yindongzi–Tongmugou Pb–Zn deposits, Qinling, China: Implications for hydrothermal ore-forming processes; *Miner. Depos.* **30** 225–234.
- Jiang S Y, Palmer M R, McDonald A M, Slack J F and Leitch C H B 1996 Feruvite from the Sullivan Pb–Zn–Ag deposit, British Columbia; *Can. Mineral.* **34** 733–740.

- Jung H S, Lim D I, Yang S Y and Yoo H S 2006 Constraints of REE distribution patterns in core sediments and their provenance, Northern East China; *Econ. Env. Geol. Sea* **39**(1) 39–51 (in Korean with English abstract).
- Jung H S, Lim D, Choi J Y, Yoo H S, Rho K C and Lee H B 2012 Rare earth element compositions of core sediments from the shelf of the South Sea, Korea: Their controls and origins; *Cont. Shelf Res.* **48** 75–86.
- Leybourne M I and Johannesson K H 2008 Rare earth elements (REE) and yttrium in stream waters, stream sediments, and Fe–Mn oxyhydroxides: Fractionation, speciation, and controls over REE + Y patterns in the surface environment; *Geochim. Cosmochim. Acta* **72** 5962–5983.
- Locock A J 2008 An Excel spreadsheet to recast analyses of garnet into end-member components, and a synopsis of the crystal chemistry of natural silicate garnets; *Comput. Geosci.* **34** 1769–1780.
- Mange M A and Maurer H F W 1991 *Schwerminerale in Farbe*; Stuttgart, Enke, 148p.
- Mange M A and Wright D T (eds) 2007 *Heavy minerals in use*; Elsevier, Amsterdam, 1283p.
- Mesurim: <http://acces.ens-lyon.fr/acces/logiciels/applications/mesurim>
- Morton A C and Hallsworth C 1994 Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones; *Sedim. Geol.* **90** 241–256.
- Nesbitt H W 1979 Mobility and fractionation of rare earth elements during weathering of a granodiorite; *Nature* **279** 206–210.
- Nesbitt H W and Young G W 1996 Petrogenesis of sediment in the absence of chemical weathering effects of abrasion and sorting on bulk composition and mineralogy; *Sedimentology* **43** 341–358.
- O'Hara M J, Fry N and Prichard H M 2001 Minor phases as carriers of trace elements in non-modal crystal-liquid separation processes II: Illustrations and bearing on behaviour of REE, U, Th and the PGE in igneous processes; *J. Petrol.* **42** 1887–1910.
- Oularbi A and Zeghiche A 2009 Sensibilité à l'érosion du massif cristallophyllien de l'Edough (Nord-Est Algérien); *Synthèse* **20** 58–72.
- Piper D Z 1974 Rare earths in the sedimentary cycle: A summary; *Chem. Geol.* **4** 285–304.
- Piper D Z and Bau M 2013 Normalized rare earth elements in water, sediments, and wine: Identifying sources and environmental redox conditions; *Am. J. Analyt. Chem.* **4**(10A) 69–83.
- Sano Y, Terada K and Fukuoka T 2002 High mass resolution ion microprobe analysis of rare earth elements in silicate glass, apatite and zircon: Lack of matrix dependency; *Chem. Geol.* **184** 217–230.
- Whitney D L and Evans B W 2010 Abbreviations for names of rock-forming minerals; *Am. Miner.* **95**(1) 185–187.
- Yavuz F, Yavuz V and Sasmaz A 2006 WinClastour – A visual basic program for tourmaline formula recalculation and classification; *Comput. Geosci.* **32** 1156–1168.

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