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ORIGINAL PAPER

Field evidence of Quaternary seismites in the Mostaganem-Relizane (western Algeria) region: seismotectonic implication

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Abstract

Northwestern Algeria, Tell Atlas chain, belongs to the converging Africa-Eurasia plate boundary. Several active faults have been previously identified and several earthquakes occurred in the past. In the present study, seismites are observed in the Quaternary deposits. The identified seismites include injection sand dykes, pillar structures, pillow structures, load-cast structures, water escape structures, sismoslumps, thixotropic wedges, and thixotropic bowls. The following arguments support their seismic origin: (i) presence of active faults able of producing strong earthquakes, (ii) the granulometric characteristics of the deposits are favorable to liquefaction, (iii) the observed features, mainly those related to water escape structures, are comparable to those observed in modern earthquakes. Therefore, such features are evidence of the occurrence of earthquakes of $M > 5.5$ magnitude in this study area, which may occur in the future.

Keywords Seismites · Quaternary deposits · Liquefaction · Active faults · Earthquake · Algeria

Introduction

Seismites are soft-sediment deformation structures (SSDS) induced by seismic shocks (Seilacher 1969), in recent, not yet compacted deposits (Plaziat and Ahmamou 1998; Montenat et al. 2007; Owen and Moretti 2008; Ezquerro et al. 2015). In some cases, these deformations may also affect the hardened rocks by means of hydro-fracturing (Montenat et al. 2007). Seismites can be found in different geological ages; nevertheless, Quaternary seismites are interesting to study because they can be used in seismic hazard studies (Sims 1975; Obermeier et al. 1985; Obermeier 1996; Marcos et al. 1996; Mc Calpin and Nelson 1996; Hibsch et al. 1997; Bowman et al. 2001; Ken-Tor et al. 2001; Jewell and Ettensohn 2004; Owen and Moretti 2011; Owen et al. 2011). In Algeria, liquefaction features were reported for the historical Djidjeli earthquake of 1856 (Mokrane et al. 1994; Harbi et al. 2011) and were observed during the El Asnam 1980 earthquake (surface wave magnitude, Ms = 7.3) and the Zemmouri 2003 earthquake (moment magnitude, Mw = 6.8) (Philip and Meghraoui 1983; Bouhadad et al. 2004; Bouhadad 2007). Study of seismites in Algeria is relatively recent. In the Algiers region, Djediat et al. (1995, 2011) described seismites in the Tyrrhenian marine terrace deposits. Bouhadad et al. (2009) observed Holocene liquefaction-induced features in the epicentral area of the Zemmouri earthquake (Mw = 6.8) occurred on 21 May 2003. In western Algeria, seismites were described in several works (Bouhadad 2006, 2007, 2013a; Boukhedimi et al. 2016) while in Eastern Algeria, seismites and paleoliquefaction features were described in the Jijel region by Benhamouche et al. (2013) and Benhamouche (2016). Sand escape and intrusion structures, related to liquefaction, are the most known forms of seismites throughout the world (Estevez et al. 1994; Munson et al. 1995; Obermeier 1996; Alfaro et al. 2001; Bezerra et al. 2005). The seismites can also be found in nodules and concretion form (Bachmann and Aref 2005; Merriam and Neuhauser 2009) as well as in

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Table 1 List of earthquakes occurred in northwestern Algeria (Benouar 1994; Mokrane et al. 1994; Ayadi and Bezzeghoud 2015)

Location	Date (dd/mm/yyyy)	Lat (° N)	Long (° E)	*I* (intensity)	*M*/Mw
Mitidja	03/02/1716	36.70	3.10	X	–
Oran	09/10/1790	35.70	− 0.70	X	6.5–7.5
Mascara	--/03/1819	35.4	− 0.1	X	–
Blida	02/03/1825	36.40	2.80	X–XI	–
Mascara	22/11/1851	35.4	− 0.1	VIII	–
Blida	15/05/1854	36.4	2.7	VII	7
Mouzaia ville	02/01/1867	36.42	2.68	X–XI	–
El Affroun	23/03/1876	36.5	2.6	VII	7
El Kalaa (Relizane)	29/11/1887	35.6	0.3	IX–X	–
Gouraya	15/01/1891	36.50	1.80	X	7.5
Moudjebeur	23/09/1903	36.00	2.8	VIII	5.6
Blida	04/03/1931	36.4	2.7	VIII	–
Orleansville	09/09/1954	36.29	1.52	X	6.7
Chiffa	09/01/1957	36.4	2.7	VI	–
Oued Djer	07/11/1959	36.40	2.5	VIII–IX	5.6
Sig (Mascara)	13/07/1967	35.5	− 0.1	VIII	5.1
El asnam	10/10/1980	36.16	1.41	X	7.3
Tipaza	29/10/1989	36.61	2.33	VIII	6.0
Mascara	18/08/1994	35.40	− 0.03	VIII	5.7
Ain Temouchent	22/12/1999	36.93	3.58	VII	5.8
Tadjena (Chlef)	16/12/2006	36.28	1.22	VI	5.2
Oran	06/06/2008	36.06	− 0.64	–	5.5
Chlef	18/06/2008	36.21	1.16	–	4.5
Mostaganem	22/05/2014	35.725	0.259	–	4.9

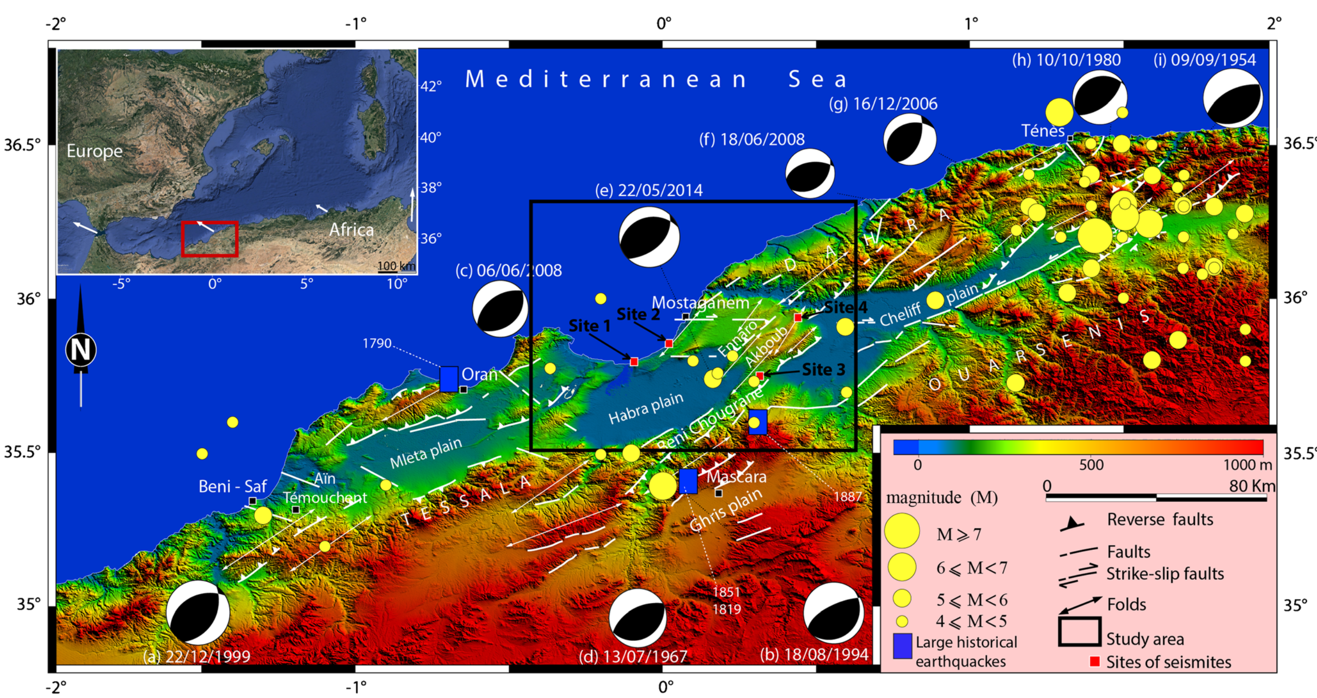

Fig. 1 Seismotectonic setting of the studied area. Seismicity is from Ayadi and Bezzeghoud (2015) and active faults are from Meghraoui et al. (1988), Bouhadad (2001), and Belabbès et al. (2009). Focal mechanisms (a), (b), and (h) are from Global CMT (centroid-moment tensors) catalog (c) from Mednet; (d) from McKenzie 1972 (in Maouche 2010); (e) from Abbouda et al. 2018; (f) and (g) Beldjoudi 2011; (i) from Espinoza and Lopez-Arroyo 1984 (in Maouche 2010). The transparence rectangle indicates the studied area

dish structure form (Plaziat and Ahmamou 1998). Empirical relationship of liquefaction occurrence versus fault distance has been proposed by several authors (Kuribayashi and Tatsuoka 1975; Youd 1977; Youd and Perkins 1978; Ambraseys 1988; Papadopoulos and Lefkopoulos 1993).

Seismic effects on sediments may be subdivided into several classes: (i) sedimentary perturbations which result from gravitational phenomena (Seed 1968; Cita and Ricci Lucchi 1984; Keefer 1984; Mutti et al. 1984; Sauret and Bousquet 1984; Kleverlaan 1987; Montenat et al. 1987; Montenat et al. 2007; Bouhadad et al. 2010), (ii) fracturing and filled cracks in hardened rocks such as broken stalactite and stalagmites, (iii) soft-sediment deformation in loose sediments due to seismic shocks known as senso stricto seismites. On the other hand, seismites are modeled by shaking table tests to understand the triggering mechanism (Moretti et al. 1999).

The seismites can be useful to assess seismic potential of active geological structures because they correspond to indirect induced effects of historical earthquakes. The aim of this work is to describe and place the seismites observed in Mostaganem and Relizane regions, located in northwestern Algeria, in their seismotectonic context.

Seismotectonic and geological setting

Northwestern Algeria is a part of the Tell Atlas chain of Algeria that belongs to the Africa-Eurasia tectonic plate boundary that forms a deformed band of about 100 km width. The amount of NW-SE shortening amount is estimated at 6–8 mm/year (De Mets et al. 1990; Nocquet and Calais 2004). The strongest earthquakes known in this region are the October 9, 1790, Oran earthquake ($I_0 = X$); the 1819 ($I_0 = X$) and 1851 ($I_0 = VIII$) Masacra earthquakes; and the 1887 El Kalaa earthquake ($I_0 = IX–X$) (Table 1 Philip and Meghraoui 1983; Vogt and Ambraseys 1991; Meghraoui et al. 1988;

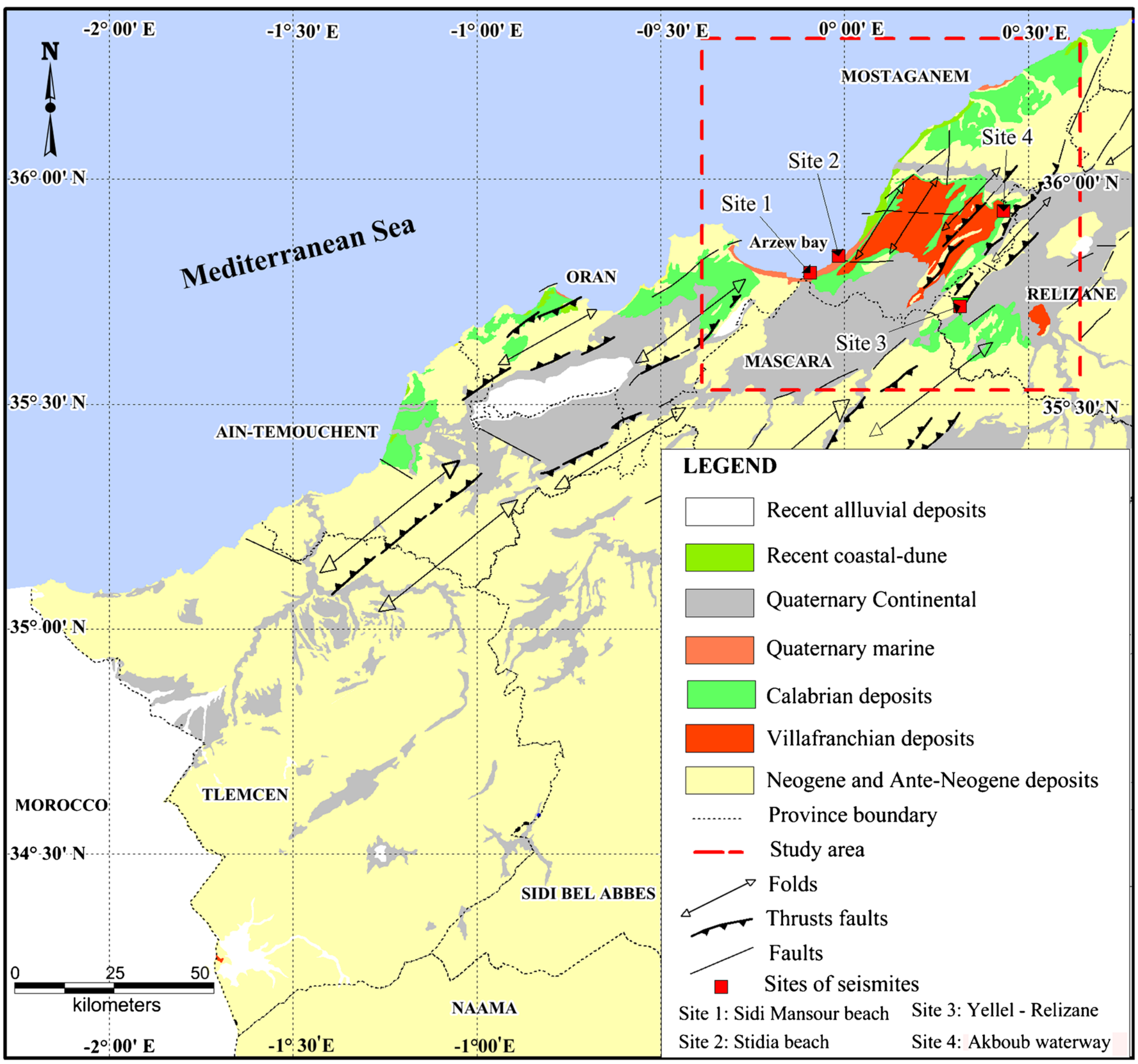

Fig. 2 Extract geological map of Algeria (2nd ed. 1952) sheet Oran—North at 1:50,0000 and the active faults are from Meghraoui et al. (1988)

Mokrane et al. 1994; Bouhadad 2013b; Ayadi and Bezzeghoud 2015). Recently, this area was hit by moderate earthquakes of Oran (1959, Ms = 5.6); Mascara (1994, Mw = 5.6), and Ain Temouchent (1999, Mw = 5.6) (Benouar 1994; Bezzeghoud and Buforn 1999; Yelles-Chaouche 2001; Belabbès et al. 2009) (Fig. 1). Several active reverse faults related to the folds were identified in this region (Bouhadad 2001; Belabbès et al. 2009).

Quaternary deposit distribution in the studied area

The study area deposits are from Villafranchian (Upper Pliocene–Lower Pleistocene) to the present. They may be distinguished (Figs. 2 and 3) (Thomas 1985): (i) recent alluvial deposits observed along rivers and lakes beds. They are represented by limons and gypsum crusts, (ii) recent coastal-dune,

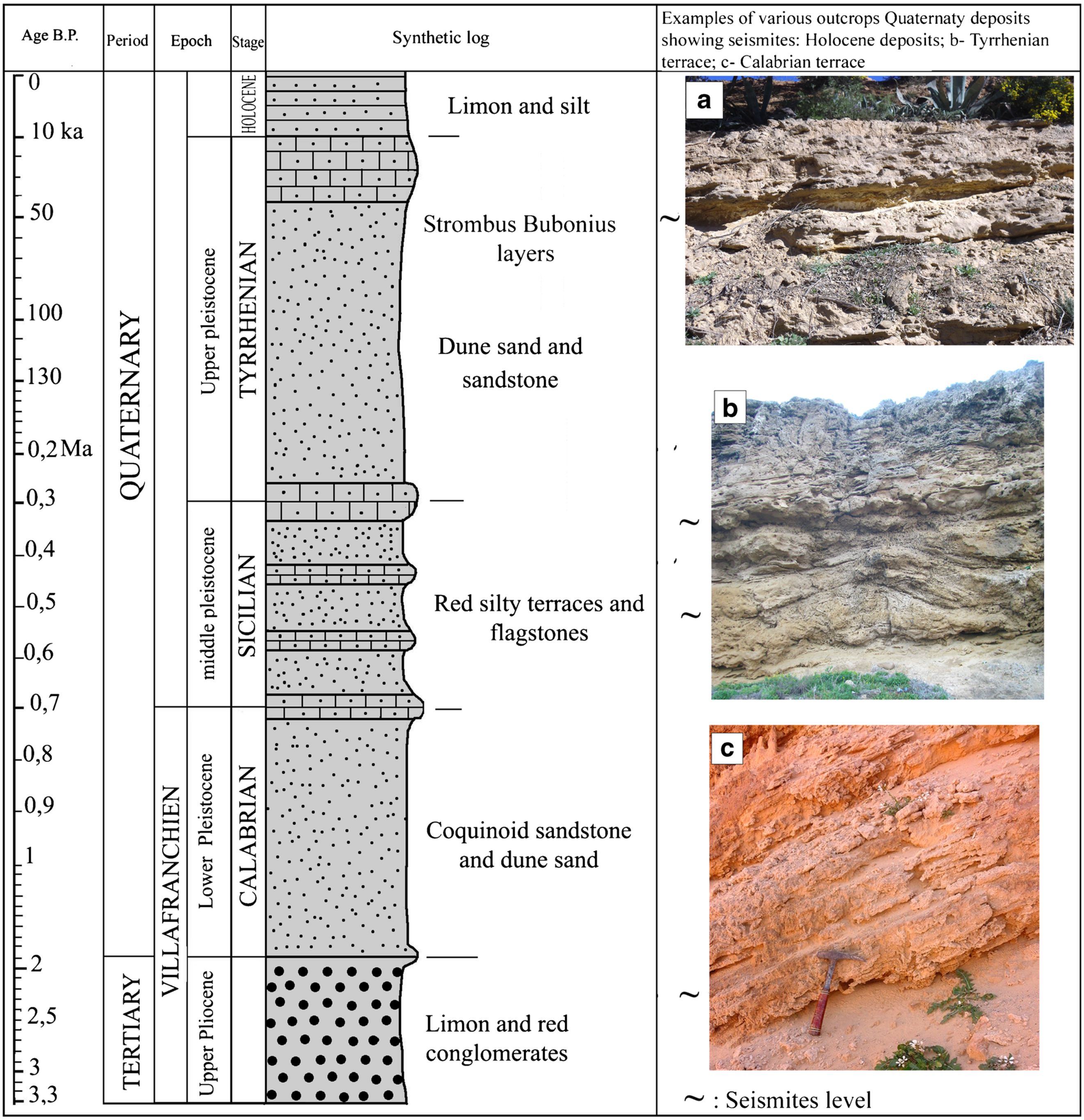

Fig. 3 Lithostratigraphic log of the Quaternary deposits of the Mostaganem-Relizane region (in Hassani 1987) and Quaternary chronology by Texier et al. (1985)

(iii) river plain deposits (Habra and Mleta plains), formed by brown or gray clays with calcareous intercalation, (iv) marine Quaternary deposits represented by ancient beaches and Tyrrhenian marine dunes that outcrop in Arzew and Mostaganem. In Algeria, the Tyrrhenian age of marine quaternary deposits has been advanced by various authors (De Lamothe 1911; Dalloni 1953; Aymé 1948, 1952 Thomas 1985). This age is attested by a fauna characteristic of the Tyrrhenian including the Strombus (*Strombus bubonius*) (Maouche 2010). Strata marine at *Strombus bubonius* and *Conus testutlinarius* is observed in western part of the Arzew Gulf by De Lamothe (1911), (v) marine Calabrian deposits tilted and affected by recent folding that well developed in the Mostaganem Plateau. They are formed by sandstone and associated dune, (vi) outcrops of Villafranchian deposits in the Mostaganem Plateau composed by red limon, lacustrine calcareous, and clay. Most seismites observed in the field have been found in Pleistocene marine terrace deposits.

Seismites in the studied area

Field geological work allowed us to identify various types of seismites found in Quaternary deposits, including Holocene alluvial and Pleistocene marine terraces deposits in the Mostaganem and Relizane regions (Fig. 4). In favorable geological, hydrogeological, and geotechnical site conditions, soils may liquefy during seismic shaking (Youd and Perkins 1978; AFPS 1995; Youd 1998; CDMG 1999; Seed et al. 2003). The soil liquefaction susceptibility depends on the nature and the geological age of the deposits, geotechnical characteristics of the deposits and the depth of the static groundwater table (Youd and Perkins 1978; AFPS 1995; Bourenane et al. 2017). Occurrence of liquefaction needs moderate magnitude ($M > 5.0$) earthquakes (Ambraseys 2008). The characteristic structures of the liquefaction phenomenon such as dykes, sills, sand volcanoes, and disharmonic

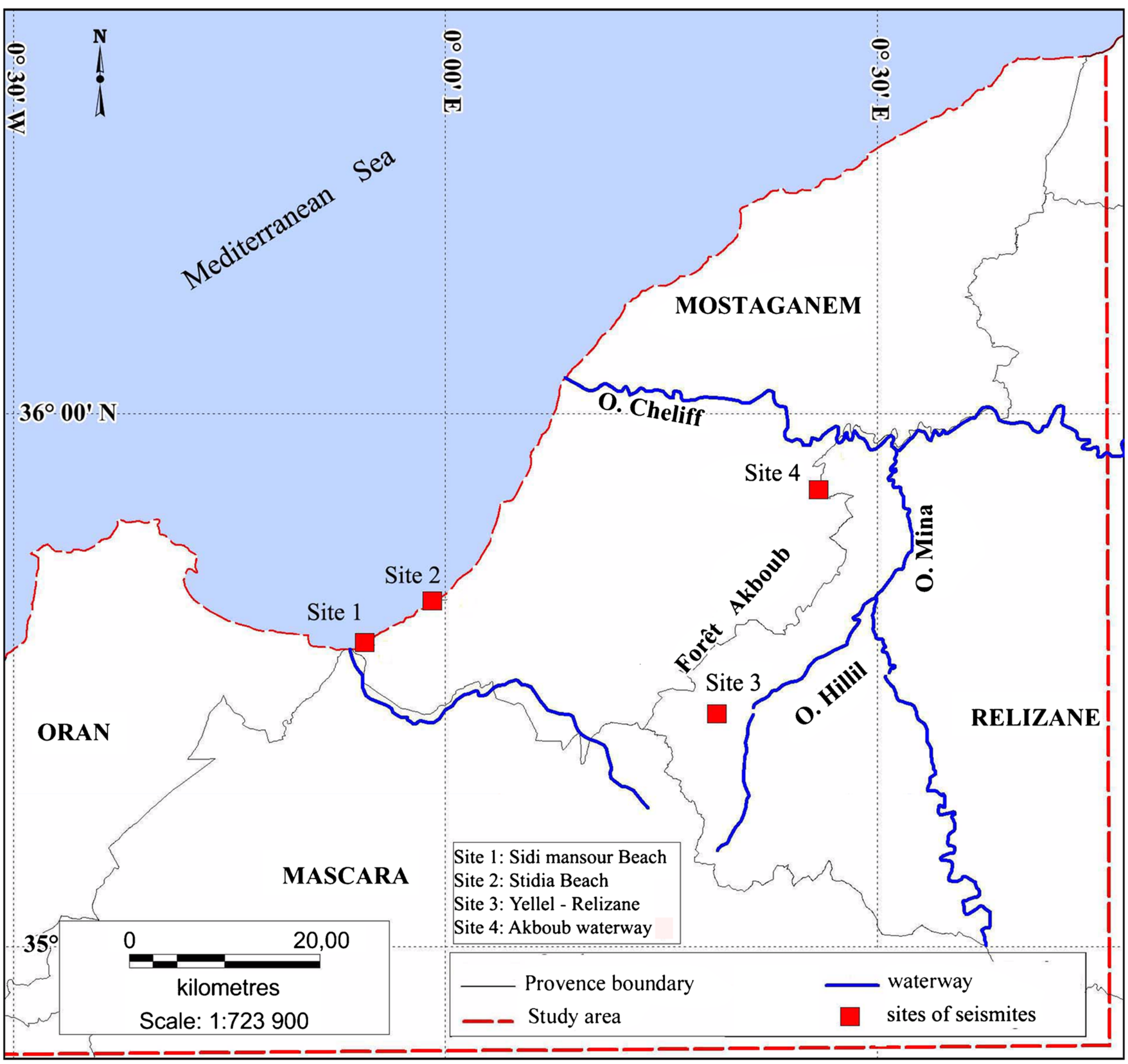

Fig. 4 Geographical location of the identified seismites (province boundary from INCT: National Institute of Cartography and Remote Sensing (Algeria) and waterway from geological map of Algeria (2nd ed., 1952) Oran—North at 1:50,0000)

folds result from stratification destruction by fluidization and related settlement at the surface that causes faults and fractures.

The fluidized sand can escape either vertically or laterally as seen during the Zemmouri 2003 earthquake (Mw, 6.8). The identified seismites in study area are essentially injection dykes, pillar structures, pillow structures, load-cast structures, water escape structures, sismoslumps, thixotropic wedges, and thixotropic bowls.

Injection dykes

They are typical example of structures generated by overpressure water (Montenat et al. 2007). The dynamics of injection dykes result from a combination of fluidization phenomena and hydro-fracturing (or hydraulic jacking) (Lowe and LoPiccolo 1974; Lowe 1975, 1976; Cosgrove 1995). Figure 5a shows an injection dykes of fine sand along the fractures and cracks crossing the stratification in Tyrrhenian deposits and Fig. 5b shows an injection of the liquefied fine material through cracks and laterally spreading between the stratification to form a sill in Holocene deposits. Pillar structures are a category of limited extension injection dykes, which usually affect single strata. They are formed when soft sediments likely to be liquefied are covered with consolidated and resistant layers. Figure 6 shows cylindrical pillar structures of a few centimeters in diameter in Holocene deposits.

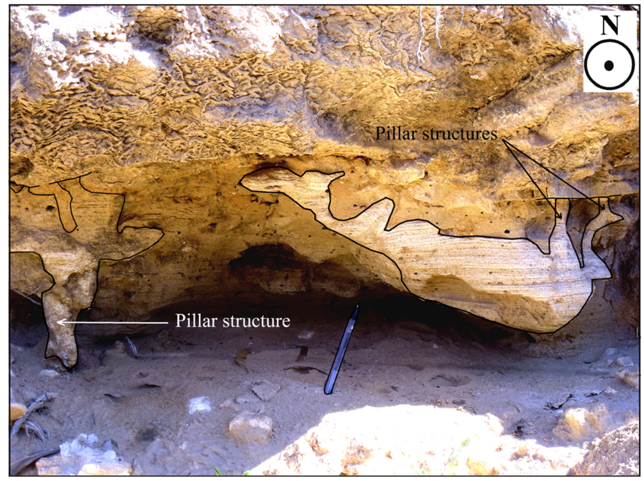

Fig. 6 Pillar structures observed in Holocene deposits (site 4) (dot inside the circle indicates the North is back)

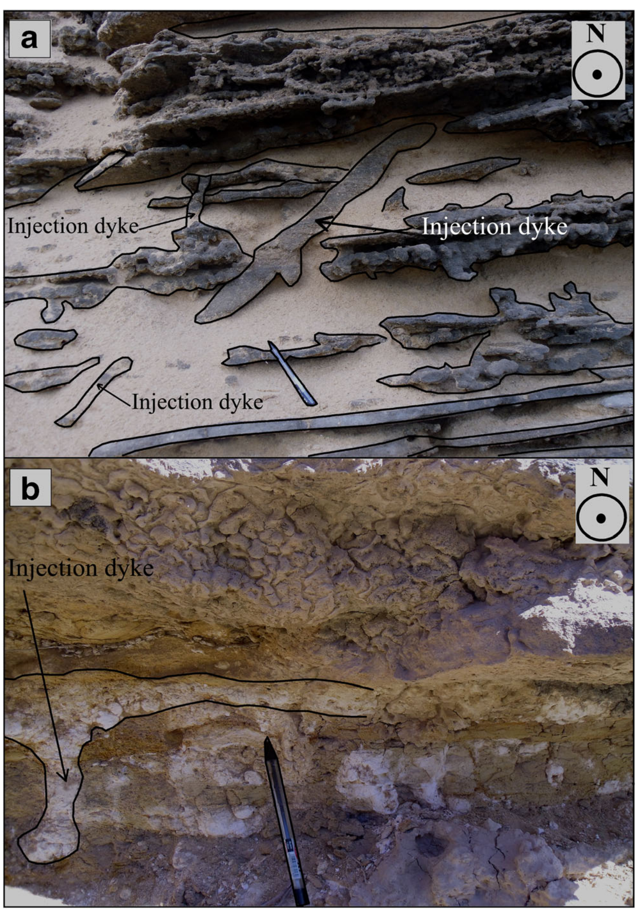

Fig. 5 Injection dyke. **a** In the Tyrrhenian marine terrace (site 2). **b** In the Holocene deposits (site 4) (dot inside the circle indicates the North is back)

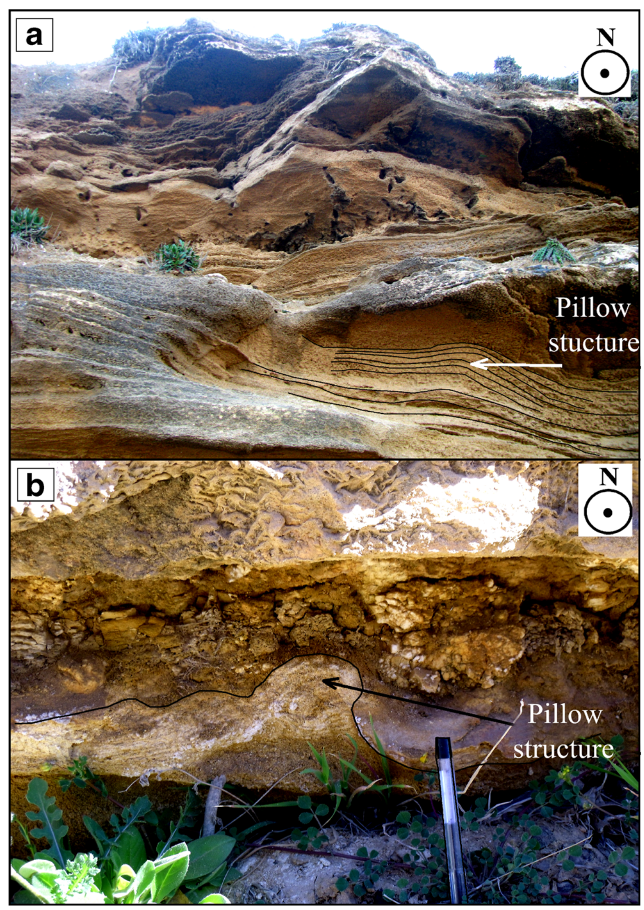

Fig. 7 Pillow structures. **a** In the Tyrrhenian terrace marine (site 1). **b** In the Holocene deposits (site 4) (dot inside the circle indicates the North is back)

Pillow structures

These structures also known as diapir-like structures have been extensively discussed in the literature (Pettijohn and Potter 1964; Reineck and Singh 1980; Hempton and Dewey 1983; Allen 1986; Moretti et al. 1995; Montenat et al. 2007). They consist of regular portions of beds, locally sheared and deformed by sills injected upward from an underlying liquefied level. Each part the bed looks like small pillows which are made up of a succession of alternating sand and silt. In the study area, pillow structures are observed in different sites. Figure 7a shows a pillow structure in laminated sandy horizon of the Tyrrhenian marine terrace while Fig. 7b shows a pillow structure in Holocene deposits formed by stratified sandstone.

Load-cast structures

They are a variety of deformation structures in soft sediments of seismic origin (Sims 1975). Load cast is the expression that refers to a load sinking into its underlying cast (mold).

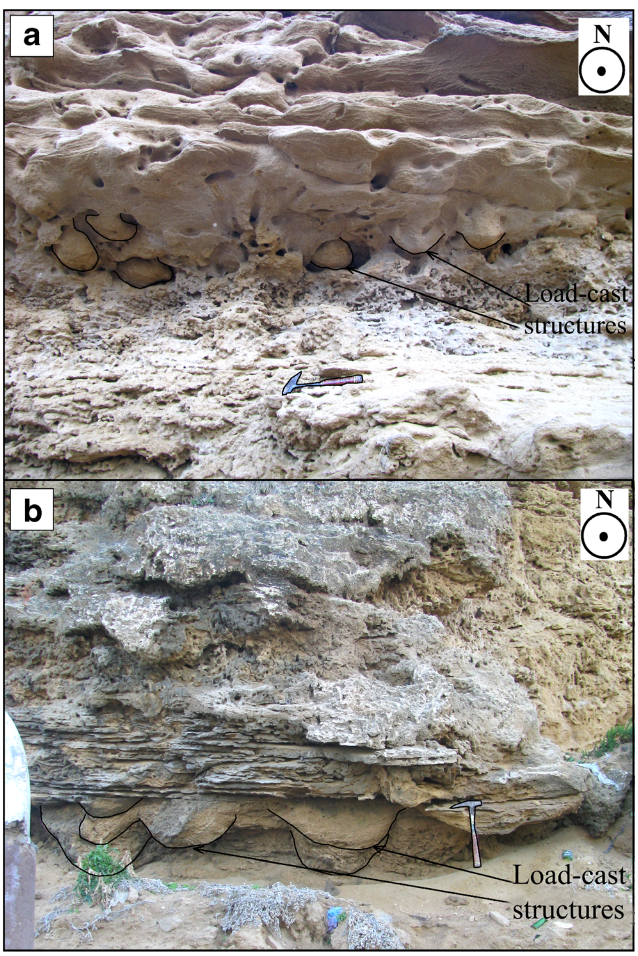

Fig. 8 Load-cast structures in Tyrrhenian terrace marine (**a**, **b** site 1) (dot inside the circle indicates the North is back)

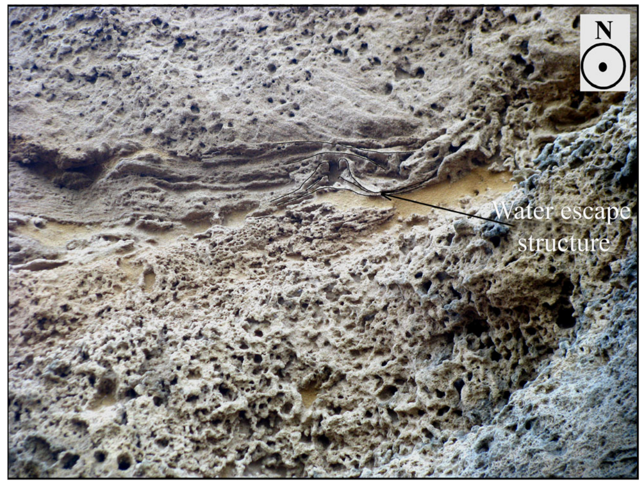

Fig. 9 Water escape structures in the Tyrrhenian marine terrace (site 1) (dot inside the circle indicates the North is back)

The load casts can develop the pseudo-nodules, ball, and pillow structures and they do not have regular morphology. The size of the structures ranges between 5 and 50 cm. They develop in sand beds overlying very clayey silt (Alfaro et al. 1997). These structures are observed in the

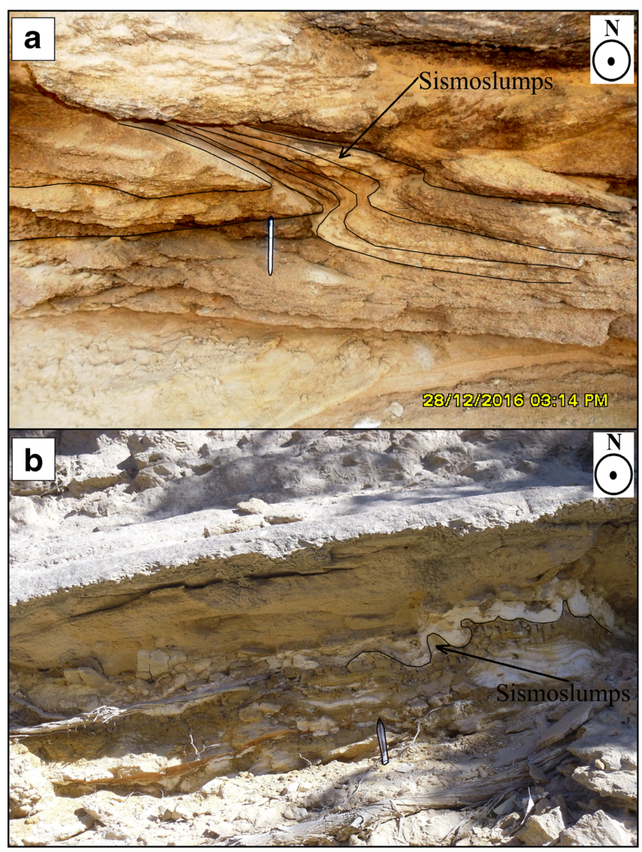

Fig. 10 Sismoslumps. **a** In the Tyrrhenian terrace marine (site 1). **b** In the Holocene deposits (site 4) (dot inside the circle indicates the North is back)

Tyrrhenian marine terraces formed by fine sand forming a succession of balls which was previously a sandy layer interposed between two clayey beds before the seismic shock. These structures can be between the load-cast structures and the pseudo-nodules structures (Fig. 8a, b).

Water escape structures

Water seepage, liquefaction, and fluidization are three processes of water escape which characterize the consolidation of silt-, sand-, and gravel-sized sediments (Lowe 1975). The rising liquefied sand through interconnected or isolated ground cracks is stopped by indurate layers (Lowe 1975). Figure 9 shows water escape structure in stratified sandy horizon of Tyrrhenian marine terraces.

Sismoslumps

They represent the recumbent of folds resulting from liquefaction, which generally correspond to small structures of millimeter to decimeter size in environments devoid of any evidence of slopes (Montenat et al. 2007). These structures are common in both the Tyrrhenian marine terraces (Fig. 10a) and Holocene deposits (Fig. 10b).

Thixotropic wedges

These structures are developed in fine sandy to pebbly deposits, often including shells or shell debris, and are formed within the sediments that are relatively close to the surface (Montenat et al. 2007). In the Tyrrhenian marine terraces (Fig. 11a) and in the Calabrian deposits (Fig. 11b), these

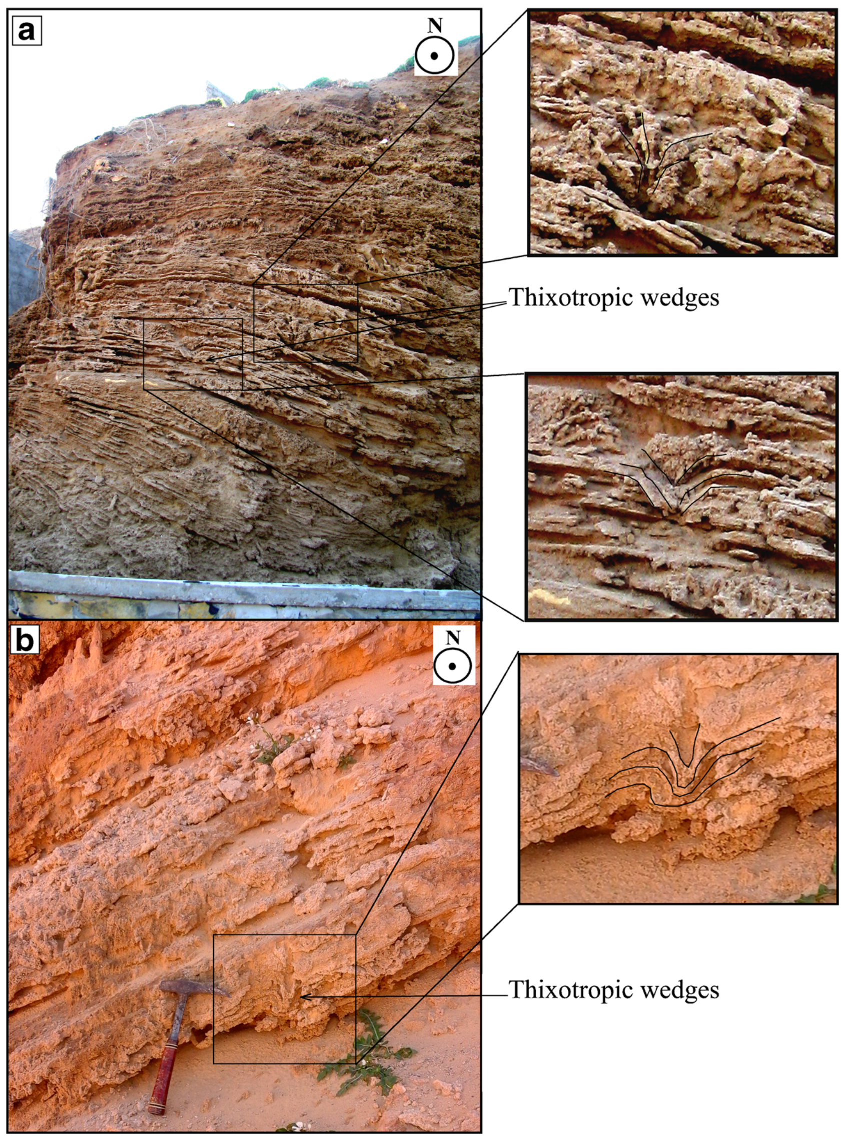

Fig. 11 Thixotropic bowls developed in the Tyrrhenian marine terrace (**a**, **b** site 1; **c** site 2) (circle with a dot in indicates the North is back)

structures correspond to a mass collapse with stepped edges that intersect the underlying stratification deformed V-shaped, initially horizontal.

Thixotropic bowls

These features correspond to hollows with asymmetric dipping related to the tilting of sediments contemporaneous with formations of the "bowls" (Montenat et al. 2007). These structures are observed in Tyrrhenian marine terraces (Fig. 12a–c).

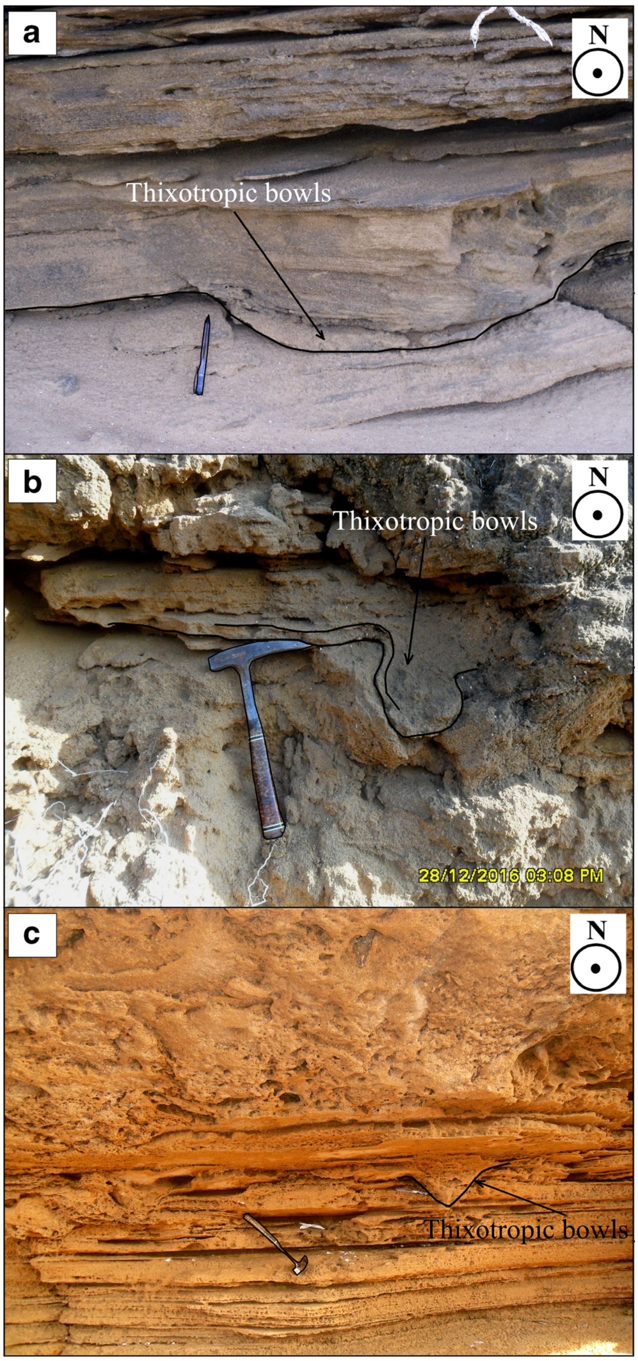

Fig. 12 Thixotropic wedges developed in the Tyrrhenian marine terrace (**a** site 2, **b** site 3) (circle with a dot in indicates the North is back)

On the other hand, we performed a granulometric analysis (Table 2) of the deposits where seismites (mainly those related to liquefaction and/or fluidization) have been observed in order to assess their susceptibility to liquefaction. Two samples were collected in Tyrrhenian marine terraces, at the beaches of Sidi Mansour (Sm) and Stidia (St) (west of the Mostaganem) and two others were taken from the Holocene deposits of Akboub (B1 and B2) (Fig. 4). The obtained granulometric curves (Fig. 13) indicate that the deposits are susceptible to liquefaction (Ishihara 1985).

Discussion and conclusion

In this work, we describe soft-sediment deformation features observed following a field work search. Indeed, several kinds of soft-sediment deformation structures were observed in Quaternary deposits of the Mostaganem-Relizane (western Algeria) regions. The observed structures include injection dyke, pillar structures, pillow structures, load-cast structures, fluid escape structures, sismoslump, thixotropic wedges, and thixotropic bowls. Such features may have several origins such as sedimentary origin, impact origin, and seismic origin (Moretti et al. 1995, 2002; Plaziat and Ahmamou 1998; Alfaro et al. 1999, 2002; Moretti 2000; Montenat et al. 2007; Moretti and Sabato 2007; Spalluto et al. 2007; Moretti and Ronchi 2011). Several arguments support the seismic origin of the various types of observed seismites including the following: (i) the presence of active faults able to produce moderate to strong ($M > 5$) earthquakes in the area, (ii) the deposits are susceptible to liquefaction as may be suggested by the granulometric characteristics, (iii) the observed features, mainly those related to fluid escape structures, are comparable to those observed in modern earthquakes (Philip and Meghraoui 1983; Bouhadad et al. 2004). On the other hand,

Table 2 Granulometric analysis of samples from the study area (*Sm*, Sidi Mansour beach; *St*, Stidia beach; *B1*, Akboub waterway; *B2*, Akboub waterway)

Sieve sizes (mm)	Cumulative percent (sample: Sm)	Cumulative percent (sample: St)	Cumulative percent (sample: B1)	Cumulative percent (sample: B2)
1	100	100	100	100
0.500	90.23	99	98.84	98.04
0.250	44.09	36.7	86.4	80.27
0.125	10.56	5.16	18.96	20.54
0.08	1.44	1.58	0.59	9.47
0.063	1.18	1.43	0.4	7.42

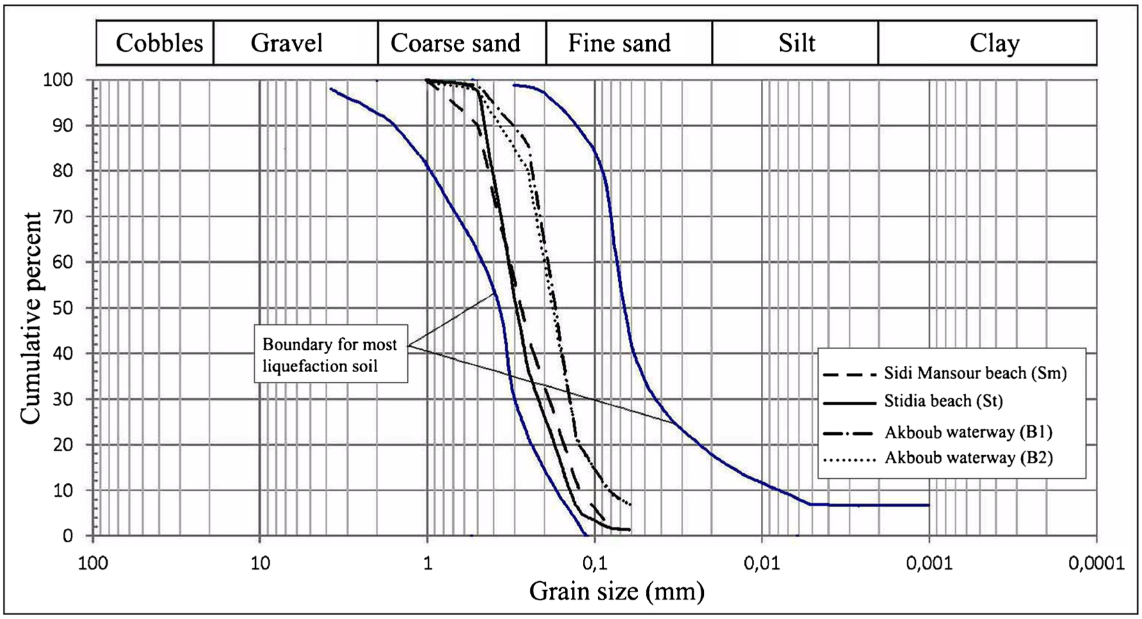

Fig. 13 Granulometric curves of the studied liquefied sand compared to the boundaries for most liquefaction soils (Ishihara 1985)

the presence of *Strombus bubonius* (Tyrrhenian indicator fossil) cited by De Lamothe (1911) and Thomas (1985), in the deposits where seismites were observed, suggests a deposit depth of 15 to 20 m, which implies a supratidal to intertidal environment which is relatively calm, protected from wave shocks and strong turbulence that ruled out the sedimentary (sea waves) origin. The observed seismites are, therefore, likely related to the activity of the surrounding active faults. Consequently, they can be used to assess their present-day seismic potential.

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