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Caspian Sea level changes during the last millennium: historical and geological evidences from the south Caspian Sea

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Abstract

Historical literature may constitute a valuable source of information to reconstruct sea level changes. Here, historical documents and geological records have been combined to reconstruct Caspian sea-level (CSL) changes during the last millennium. In addition to a literature survey, new data from two short sediment cores were obtained from the south-eastern Caspian coast to identify coastal change driven by water-level changes. Two articulated bivalve shells from the marine facies were radiocarbon dated and calibrated to establish a chronology and to compare them with historical findings. The overall results indicate a high-stand during the Little Ice Age, up to −19 m, with a −28 m low-stand during the Medieval Climate Anomaly, while presently the CSL stands at −26.5 m. A comparison of the CSL curve with other lake systems and proxy records suggests that the main sea-level oscillations are essentially paced by solar irradiance. Although the major controller of the long-term CSL changes is driven by climatological factors, the seismicity of the basin could create locally changes in base level. These local base-level changes should be considered in any CSL reconstruction.

1 Introduction

The Caspian Sea (CS) is characterized by substantial fluctuations during its geological life time (Varushchenko et al., 1987; Rychagov, 1997; Dolukhanov et al., 2010). It is believed that climate-induced changes are the main reason for the Caspian Sea Level (CSL) fluctuations by influencing the hydrological budget of the sea (Arpe and Leroy, 2007; Arpe et al., 2012). According to the latitudinal extension of the CS and its watershed from dry low-latitude to temperate high-latitude climates (Fig. 1) and in view of the ongoing global warming, it provides a good opportunity to investigate the impacts of global climate variations on sea level and their socio-economic consequences (Gümilev, 1980; Dolukhanov et al., 2010). Historical and archaeological documents show that the CS has experienced frequent sea-level oscillations during the historical period. The CSL changes followed by huge socio-economic impacts on the surrounding societies such as coastal property destruction, major tribal migrations and rising/falling of civilizations (Gümilev, 1964, 1980; Létolle, 2000; Rekavandi et al., 2007).

Historical documents may provide valuable information on Late Holocene geological events such as tsunamis (Dotsenko et al., 2002; Shah-hosseini et al., 2011), earthquakes (Ambraseys and Melville, 1982; Berberian, 1994; Berberian and Yeats, 1999), climatic variability (Brown, 2001; Okhravi and Djamali, 2003), and sea-level changes (Brückner, 1890; Varushchenko et al., 1987; Karpychev, 2001). The cultural evolution of human societies has mainly occurred during the Holocene that has, in turn, undergone significant environmental changes (Mayewski et al., 2004). From this view, historical and archaeological evidences are particularly pertinent in understanding human-environment interactions (Berberian et al., 2012).

So far, the Holocene Caspian sea-level (CSL) change has been a key focus of geological research (Mamedov, 1997; Rychagov, 1997; Kroonenberg et al., 2000; Karpychev, 2001; Kazancı et al., 2004; Hoogendoorn et al., 2005; Lahijani et al., 2009; Dolukhanov et al., 2010; Leroy et al., 2011; Kakroodi et al., 2012; Naderi Beni et al., 2013), mostly based on the indirect interpretation of a variety of proxy data.

Direct instrumental measurements of the CSL fluctuations only began in the mid-nineteenth century (Leroy et al., 2006). Leroy et al. (2006) showed a good correlation between proxy-based interpretations and instrumental observations since 1871 in the Kārā-Bogāz Gol in the eastern coast of the Caspian Sea (CS) (Fig. 1). Due to the relatively short timeframe of instrumental observations, palaeoenvironmental data contribute to extend the length of the sea-level records, which, in turn, may be accompanied with some uncertainties. One of the ways to decrease the uncertainties relating to the pre-instrumental geological data is to correlate the results with historical evidence recorded in ancient literature.

Although the history of civilization in the Caspian region dates back to more than 6000 yr (Gilbert, 1978), little literature pre-dating the last millennium is available to compare and contrast with geological interpretations. In light of this, we here focus on the last millennium (the tenth to twentieth centuries AD) to compare the historical events with related geological findings and to independently test the accuracy of palaeo-environmental data.

2 Geographical setting

2.1 General view

The CS has a surface area of 360 000 km^2 and 3.5 million km^2 of catchment area and is surrounded by five countries, i.e. Iran, Azerbaijan, Russia, Kazakhstan and Turkmenistan (Fig. 1). Due to its vast area, the lake is referred to as a sea in the literature. The land-locked nature of the sea has been known since ancient times. Ibn Hawqal (1988, page 129) stated that: *“the Sea is not linked to any other sea and the Atil River* (the Volga) *discharges into the sea and only this river is connected to the Constantine Sea* (Black Sea) *through one of its branches and if someone goes round the sea, one will return to the starting point.”*

The sea is saline and tide free (ibn Hawqal, 1988). The salinity of the sea is one third of that of the open sea and reaches up to 13 psu in the south-east. The CS separated from the open sea in the Pliocene (Varushchenko et al., 1987). Today the CSL is around −26.5 m below mean sea level. Owing to its land-locked nature, the CS has fluctuated repeatedly during its geological lifetime.

2.2 The Caspian sea-level changes

The CS is known for its pronounced sea-level changes at various time scales (Kazancı et al., 2004). During the latest Pleistocene, sea level rose up to ∼50 m (Khvalynian Transgression) (Mamedov, 1997) and then dropped to at least −50 m at the beginning of the Holocene (Mangyshlak Regression) (Dolukhanov et al., 2010). CSL oscillations during the Holocene have been estimated by Rychagov (1997; Fig. 2). Apart from these two extensive changes in sea level, at least eight minor oscillations have been recognized for the last 4000 yr (Mamedov, 1997). During the past ~ 1000 yr, the CS has experienced two major sea-level changes associated with the Medieval Climate Anomaly (MCA: 950–1250) and the Little Ice Age (LIA: 1350–1850) (Ruddiman, 2008). According to Kroonenberg et al. (2007) and Leroy et al. (2011), during the MCA the CSL dropped and then during the LIA sea level rose. CSL changes continued to fluctuate during the nineteenth and the twentieth centuries. The sea level fell ~ 3 m from 1929 to 1978, and was followed by a rise of ~ 2.7 m from 1978 to 1995, at a rate one hundred times faster than present global sea-level rise (Kroonenberg et al., 2000).

In addition to long-term CSL changes, on several occasions, abnormal, alternate rising and lowering of the sea level have been reported in old manuscripts and the recent instrumental record. Some unexpected sudden sea-level fluctuations were possibly related to large-magnitude inland or sea-based earthquakes (Shilo and Krivoshey, 1989; Rodkin, 1992a,b; Ozyavas et al., 2010).

2.3 Geological and seismotectonic setting

The CS intercontinental basin is located on old platforms to the north and the young orogens to the south. The northern part of the depression is located on the Turān in the NE and the Scythian aseismic platforms in the NW. The southern part of the sea, the South Caspian deep basin is surrounded by the Late Miocene-Pliocene uplifted and overthrust active orogens of the Caucasus and Tālesh (SW), the Alborz (S), and the Kopeh Dāgh (also known as Kopet Dag) (SE) (Fig. 1). The South Caspian deep basin is a relatively rigid aseismic stable block floored by a trapped, modified oceanic crust surrounded by overthrust continental crust (Gegelyantz et al., 1958; Berberian, 1983; Priestley et al., 1994; Mangino and Priestley, 1998). It is being subducted beneath the North Caspian (Fig. 1) along the Āpshehron-Bālkhān Sill (Knapp et al., 2004).

Seismological analysis of the central and southern parts of the CS has shown that the most probable area of seismic seiche generation is between the Āpsheron-Bālkhān Sill and Derbent in the central Caspian basin (Dotsenko et al., 2002) (Fig. 1). Berberian and Walker (2010) showed that the inland earthquakes on the southern and western coasts could provide some irregularities in the CSL (see below).

According to Kazancı et al. (2004), the late Quaternary deposits of the south CS show an uplift of ca. 4–6 m that is negligible for the Late Holocene.

2.4 Hydrology of the Caspian Sea

The hydrological balance between input and output of the sea controls the sea level (Kroonenberg et al., 2000; Arpe et al., 2012). The sea's inputs are mainly governed by rivers, discharging from the north, west and south as well as precipitation over the sea. The output is mainly controlled by evaporation over the sea and the watershed (Arpe and Leroy, 2007; Arpe et al., 2012). This means that the sea-level oscillations are strongly dependent on climatic variations (Kroonenberg et al., 2000), at least as long as no major changes are taking place in the size of the hydrographical basin. The surface area of the Caspian catchment basin is around ten times greater than the CS surface itself (Fig. 1 inset). The latitudinal extension of the sea results in climate variations over the basin from sub-tropical in the southwest to desertic in the east and northeast (Leroy et al., 2011).

The Volga River is the greatest river of the CS discharging from the north (Fig. 1) and providing ~ 80 % of all river influx of the sea.

al-Maqdisī (1982) in 985 AD described the southern coast of the CS with frequent rivers flowing from the Tus (southern Kopeh Dāgh), Tabarestān and Daylam (the Alborz) Mountains (Fig. 1). Although most of the Iranian rivers originate from the northern flank of the Alborz Mountains, the Sefidrud originates further, in the Zāgros and the Alborz Mountains. The Gorgān and Atrak Rivers in the east have headwaters in the Kopeh Dāgh (Lahijani et al., 2009) (Fig. 1). The Sefidrud and the Gorgān River have developed large deltas along the Caspian coast due to considerable sediment supply, and have repeatedly changed their courses (Kousari, 1986; Voropaev et al., 1998). The largest input of sediments in the whole of the CS comes, however, from the Sefidrud (Lahijani et al., 2008). According to Leroy et al. (2007), the Aral Sea and

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CS were connected episodically during the last millennia through Uzboy pass (Fig. 1) due to sea level fluctuations, tectonic events or human intervention. The Uzboy River received water from low latitudes via Amu-daryā and discharged into the Caspian Sea in Turkmenbāshi Bay (Leroy et al., 2007) (Fig. 1).

The winds over the CS produce prevailing southward longshore currents on the west and east coasts, and eastward currents along the Iranian shoreline (Lahijani et al., 2009).

2.5 Morphology of the Iranian Caspian coast

The Iranian Caspian coastline stretches over 800 km along the three Iranian provinces of Gilān in the west, Māzandarān in the middle and Golestān in the east (Fig. 3). According to Voropaev et al. (1998), the Iranian Caspian coast can be classified into four morphological zones based on beach and nearshore gradient (Fig. 3). This classification clearly shows that the southeast corner of the CS has a gentler slope offshore and on land, and will, therefore, be more sensitive to small changes in sea level.

The Iranian coast of the CS consists of different landforms and geomorphological features including bays, spits, lagoons and deltas, mainly developed during the Quaternary (Kazancı et al., 2004). Amongst the landforms, the Anzali Lagoon and the Sefidrud Delta in the west and the Gorgān Bay, the Gorgān Delta, as well as the Gomishān Lagoon and the Hassanqoli Bay in the east are the most prominent ones (Fig. 3), whose formation and evolution are largely driven by the CSL changes coupled with the hydrodynamic regime (Kroonenberg et al., 2007; Kakroodi et al., 2012; Naderi Beni et al., 2013).

3 Material and methods

Two short cores (two meters in length and five cm in diameter) were obtained from the southeast of the CS, in front of the Hassanqoli Bay using a vibracorer (Fig. 3). They

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were taken from the morphological zone 1 of Voropaev et al. (1998), which is the most sensitive area to sea level changes. The cores were analysed sedimentologically to correlate with historical documents as well as other geological findings.

The elevation of the coring sites was measured using an Ashtech Mobile Mapper 100. The magnetic susceptibility (MS) of the core samples was measured using a MS2C core-logging scanner from Bartington. The diameter of the susceptibility meter loop was 10 cm and the progression step was 2 cm. The sensitivity of the meter was about 2×10^{-6} SI.

Both of core samples were split and sub-sampled at the laboratory of the Iranian National Institute for Oceanography (INIO) for sedimentological analysis. A Nabertherm P330 furnace was used for loss-on-ignition to measure organic matter and carbonate content based on the methods outlined in Heiri et al. (2001). Grain-size measurements were made using a Horiba Laser Scattering Particle Size Distribution Analyzer LA-950.

Fossil content was identified to aid in characterizing the past depositional environments based on the atlas of the invertebrates of the CS (Birstein et al., 1968).

Two articulated bivalve shells of *Cerastoderma lamarcki*, an indicator of marine environment, were selected and sent to Poznan Radiocarbon laboratory for ^{14}C dating. Calendar ages were obtained from the CALIB Rev 6.0.1 software (Reimer et al., 2009) based on three different databases of IntCal09, Marine09 and Mixed Marine NoHem to compare the results and correlate them with historical findings.

Several historical documents were studied mainly in the library of the Ferdowsi University of Mashhad and related geographical names and positions were extracted based on the "Historical Geography of Cities" (Nahchiri, 1999). We have used the most reliable literature sources covering the last millennium. Historical observations of the CS environments were gathered to compare and contrast with geological records for the same period.

Note that in this study the dates are given in AD, unless otherwise stated. The Persian geographic names and other Persian words are written as they are pronounced and were originally written, with direct and simplified transliteration from Persian to English.

Diacritical marks and special characters are used to differentiate vowel the “A” [short; e.g. ant] from “Ā” [long; e.g. Rāmsar], and Arabic “ain” (also used in Persian) as “‘A” [e.g. ‘Abbās]. Elevations are above or below the present mean sea level. Rud and Daryā mean river and Dāgh means mountains.

4 Results and interpretation

4.1 Geological findings

The CSL changes and their impact on coastal evolution have been investigated by several researchers e.g. Kroonenberg et al. (2000, 2007), Lahijani et al. (2009), Kazancı et al. (2004), Leroy et al. (2011), Kakroodi et al. (2012) and Naderi Beni et al. (2013). The results of the geological investigations on the CSL are summarized in Table 1.

In this study we focused on two short cores from the south-eastern flank of the CS to compare the results with other geological findings as well as historical evidence.

The lithology of the cores shows a succession of terrestrial (fluviodeltaic in Kakroodi et al., 2012) and marine environments during the last millennium (Fig. 4). Generally, the marine facies comprise finer-grained materials compared to terrestrial deposits based on the modal grain size and contain marine bivalve fossils of *Cerastoderma lamarcki*. The terrestrial deposits constitute alternations of thin layers of fine sand, silt and clay, without any fossil content but containing gypsum minerals that are concentrated in some horizons. The presence of gypsum minerals in terrestrial sediments could be related to the flat topography of the region and warm climatic conditions that lead to water evaporation during dry seasons. Sea level rise is indicated by a change from the terrestrial facies to marine facies. In the marine facies, organic matter and carbonate contents tend to increase due to higher organic activity in shallow marine environment and presence of calcareous shell bearing organisms (Fig. 4).

The magnetic susceptibility results show lower values in terrestrial deposits, which could be related to the provenance of the grains or the increase in evaporative minerals.

The feeding watercourses have their headwaters in the Kopeh Dāgh that is mantled in calcareous deposits. The higher values of the magnetic susceptibility in the marine facies could be linked to the presence of paramagnetic minerals, e.g. muscovite, flogopite and biotite, which are transported by longshore currents from the southern coast of the CS. The paramagnetic components of the southern coast deposits are provided by igneous and metamorphic rock outcrops of Alborz Mountains (Lahijani and Tavakoli, 2012). According to the presence of some brackish water gastropods such as *Theodoxus palassii*, as well as Charophytes that coexist with marine gastropods *Horatia marina* and *Pyrgohydrobia* sp. and marine bivalve of *Cerastoderma lamarcki* (Birstein et al., 1968), it seems that the marine facies could represent a shallow marine environment and/or an open lagoon that was influenced by fresh-water input. The formation of barrier-lagoon complexes during rapid sea-level rise has been reported by Kroonenberg et al. (2007), Lahijani et al. (2009) and Naderi Beni et al. (2013) in different parts of the Caspian coast and, therefore, it is more probable to link the marine facies to an open lagoon environment which was influenced by fresh water input.

4.2 Radiocarbon dating

The age of the oldest marine facies of cores A and B (Fig. 4) is dependent on the database used to calibrate the radiocarbon data (Table 2). Although almost all of the chronological data are coincident with the LIA in the North Atlantic Ocean and already recorded in the CS by a high-stand (Leroy et al., 2011 in Gilān, and Kakroodi et al., 2012 in Golestān), they could be linked to different sea-level rise episodes between the thirteenth to the seventeenth centuries depending on the databases used for calibration (Table 2).

According to the elevation of the coring site (Table 2), it seems that sea level in dating horizons reached −26.75 m and −25.8 m for core A and B, respectively, as the subsidence of the region is negligible for the last millennium.

4.3 Historical evidence

The CSL variability before the instrumental observations (prior to 1850) was investigated by Brückner (1890) on along the CS coast. He used a wide range of observational evidence, e.g. travel descriptions, navigation maps, and paintings to garner data on CSL changes. Typical examples were walls along the shore with markings of sea levels, reports about buildings that disappeared under the water, and islands that emerged or disappeared. The results of Brückner (1890) are summarized in Table 3.

Fedchina (1980) used the Russian cartographic data from 1556 to 1925 to reconstruct a CSL curve. The same method was followed by Komarova (1980) for 1700 to 1850 time period. The results of Fedchina (1980) and Komarova (1980) are summarized for the 1700 to 1850 time period in Fig. 5. In spite of some differences between their analyses, the results generally show a good agreement in the CSL changes during the time period with high-stands up to −22 m (Fig. 5).

Varushchenko et al. (1987) used a wide range of historical, archaeological and geological evidences to reconstruct CSL changes for the last 2400 yr. Many historical and archaeological documents used by Varushchenko et al. (1987) for the last millennium are the same that Brückner (1890) and Komarova (1980) considered in their works (Table 4). However, their results have many differences especially in the early centuries of the last millennium.

Lithological evidence from coring along the Caspian coastline was investigated by Karpychev (1998) and combined with historical information (Karpychev, 2001) for layers of pebbles, for instance, which are an indication for shores at that level and for which the age was determined by radiocarbon-dating. The results of Karpychev (1998, 2001) are summarized in Table 5.

According to the results of Tables 3, 4 and 5, the CSL curve could be plotted from the tenth to the twentieth centuries (Fig. 6).

The Iranian literary texts are especially rich in statements pertinent to understanding the historical geography and geological events of the Iranian Plateau and its neighbouring regions (e.g. Berberian, 1994; Okhravi and Djamali, 2003). Here, we present historical literature related mainly to the south CS to elucidate evidence of CSL changes during the last millennium split into three periods: the ninth–fourteenth centuries, the sixteenth and seventeenth centuries, and the eighteenth–twentieth centuries.

4.3.1 The Caspian sea level during the ninth to fourteenth centuries

One of the most important cities of the Caspian coasts in ancient times was Ābeskun/Ābaskun (Figs. 7 and 8) which, apparently, disappeared in the early fourteenth century due to sea level rise (Mostowfi, 1999). Nedjati (in Gümilev, 1980) described how the port of Ābeskun was flooded and swallowed up by sea in 1304 in agreement with other reports of a CSL high-stand (Tables 3 and 4). al-Istakhri (1961) in the tenth century described Ābeskun as the best port in the CS. The tenth century historians and geographers such as al-Mas'ūdī (2012), al-Istakhri (1961) and ibn Hawqal (1988) reported Ābeskun as a port; while the later geographers like Jovayni (1911) in the thirteenth century and Banāketi (1969) and Mostowfi (1999; possibly compiled older treatises) in the fourteenth century described it as an island. According to the dates of the descriptions, it seems that an important change in the CSL occurred during this time period. When sea level was relatively lower during the ninth and tenth centuries, Ābeskun lay on the shoreline, whereas when the sea level rose in the thirteenth and fourteenth centuries it was surrounded by the sea.

Barthold (1984) speculated that the location of Ābeskun is consistent with the present Gomishān, which lies at about −23.5 m elevation, in line with the level by Karpychev (1998, 2001) in 1304 (Table 5). Gümilev (1964) assumed that the CSL was at −33 m in the tenth century and rose to −28.5 m in the eleventh century based on al-Istakhri's observation in Derbent, in present-day Dagestan, Russia (Fig. 1). Also, Varushchenko et al. (1987) reported about such a rise but from −35 to −33 m. The eleventh century sea-level rise reduced the area of the Volga Delta and endangered the Kingdom of Khazaria due to the reduction of its farmlands (Gümilev, 1964).

Ibn Hawqal (1988) described Ābeskun's air as malodorous and full of mosquitoes, which could be linked to the presence of marshlands and/or lagoons. The town was populous and repeatedly invaded between 880 and 913 by Russian tribes (al-Istakhri, 1961). al-Bakri (1999) described Ābeskun as a small village on the Caspian shoreline in 1208. In 1219 it was disturbed due to an increase of the CSL which Mostowfi (1999) and Létolle (2000) assigned to the man-made avulsion of the Āmu-daryā towards the CS by the Mongols (sons of Genghis Khan). The suggestion of Mostowfi (1999) in linking the Ābeskun flooding to the river avulsion could not be correct as the position of Uzboy pass (Fig. 1) is too far from Ābeskun. Moreover, even the largest observed amount of the Amu-darya discharge in the 20th century (around 98 $\mathrm{km^3\,yr^{-1}}$) to flow into the CS, it would raise the CSL only by 2 $\mathrm{cm\,yr^{-1}}$. The Ābeskun flooding is certainly related to Caspian sea level rise as the Italian traveller Marin Sanudo (1320, in Gümilev, 1980) mentioned that the sea-level rise in the early fourteenth century was catastrophic and destroyed many important cities around the CS. The 1304 rapid sea level rise accentuated the demise of the Khazars dominion on the northern coast of the CS (Gümilev, 1980). Berg (1949, in Gümilev, 1980) reported that the CSL rise in the fourteenth century could not have reached more than −24 m; while Gümilev (1980) believed that the sea level rose up to −19 m based on articulated bivalve shells, dated to the fourteenth century, on a historical wall near the Terek River, Russia.

Jayhāni (1989) noted that at the end of ninth century, in an area between Māzandarān and Gilān (near the present city of Rāmsar, Fig. 3) the sea and the mountains were in contact and the only way to cross the area was through the mountains. This observation is supported by ibn Hawqal (1988, page 120) who noted that *"Chālus is the entrance of Daylam* (Gilān) *and the city opens to the sea and only one guardsman is enough to close the way"* (Fig. 8). Today, the foothills of the Alborz Mountains extend to the sea at −23 m in Rāmsar, just at the border of Māzandarān and Gilān. According to the above-mentioned reports, it seems that the CSL in the tenth century rose up to ≤ −23 m and the sea level was more or less around the same level until the thirteenth century. This is corroborated by the position of Ābeskun that remained a port from the ninth to the thirteenth centuries. After this time, the sea level started to rise around 1208 and finally in the fourteenth century reached −19 m (Gümilev, 1980).

About 250 km north of Ābeskun a populated region was known as the Dahestān District (Barthold, 1984). According to the approximate position of Ābeskun in Gomishān (Barthold, 1984; Rabino, 1917), the Dahestān District could be somewhere around the present Turkmenbāshi Bay (Fig. 1), where Barthold (1984) claimed that he found ancient ruins of the city in Qezel Ārvāt, tens of kilometres from the shoreline (the exact position is not yet known).

al-Maqdisī (1982) mentioned that the Dahestān District comprised 24 villages and the capital of the District was Ākhor on the Caspian shoreline. Ibn Hawqal (1988) remarked that the sea level started to fall when he met Ākhor as the sea became shallow and let the ship and boats use it as a shelter during stormy conditions. Barthold (1984) reported that people in the tenth century constructed a 50-km long channel from the Atrak River to Dahestān to provide fresh water to its people.

The anonymous writer of the Hudud al-'Alam (1973) highlighted that in 982 the CS did not have any bays but it had two islands; one of them was known as Siāh Kuh. The other island was on the western side of the CS in front of Bāb (Fig. 7) and was called the Jazirat al Bāb (Bāb Island). It is reported in Hudud al-'Alam (1973) that a peninsula existed in front of Dahestān, named Dahestānān-Sar (the Dahestān Cape) and it was a place for hunting. This report may support the approximate position of the Dahestān District around Turkmenbāshi Bay as the Cheleken peninsula (Fig. 1), at c. 50 m in elevation, could be considered as the Dahestān Cape. The report of the Hudud al-'Alam (1973) is supported by Ibn Hawqal (1988), who referred to Siāh Kuh Island as Siah Kubeh (Fig. 7). He also located the Bāb Island in front of the Kur River (Kura River, in modern Azerbaijan). Ibn Hawqal (1988) wrote that the Bāb Island was a grazing land and locals brought their cattle to the island to fatten them. If this is true, then the water between the island and main land was possibly shallow. According to the position of Bāb Island (Fig. 7), this island could be consistent with Chechen Island with −23.8 m elevation (Varushchenko et al., 1987), which was reported by some other historians such as Genuetzev (in Varushchenko et al., 1987).

Although Ibn Hawqal (1988) and the Hudud al-‘Alam (1973) described only two unoccupied islands in the tenth century, al-‘Umarī (2010) in 1349 remarked that several islands existed in front of the city of Rasht and people used them as a haven when they were attacked by the pirates.

Mostowfi (1999) mentioned that a bay existed on the south-eastern flank of the CS, near Ābeskun and called it the Nim-mardān Bay (the Half-men Bay). According to his remarks, the Gorgān River discharged close to Ābeskun into the bay. Attributing the name of Nim-mardān to the bay could be interpreted as a shallow-water bay in which fishermen could stand in order to fish (Nahchiri, 1999), the same way as fishermen do today in Gomishān. Nahchiri (1999) also believed that Nim-mardān Bay is the present Gorgān Bay. However based on other historical evidence, the proposed position of Ābeskun by some geographers (Barthold, 1984; Rabino, 1980) and new geological findings from the Gorgān Bay (Kakroodi, 2012) Nahchiri's suggestion seems unlikely. It is, therefore, more likely to link Nim-mardān Bay to the present Hassanqoli Bay (Fig. 3).

4.3.2 The Caspian sea-level during the sixteenth to seventeenth centuries

In 1628 Ashraf al-Belād (the Ashraf port) was constructed on the southern flank of the Gorgān Bay (present-day Behshahr; Fig. 3) (Parodi, 1997). The remains of an old port of the Safavid era (1501–1722) were found at an altitude of −23.5 m in the plain of Behshahr, south of Shāhkileh (Asgari, 1971) (Fig. 3), which could be linked to this information. The seventeenth century sea-level rise was mentioned by Kotov, a Russian entrepreneur who described the inundation of a castle in Derbent in 1623 (Gümilev, 1980). This castle was built on the site of the Sasanian fortified town in 1587, and the remains of the structure were found at −28 m by the Russian archaeologists (Gümilev, 1980).

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According to the above-mentioned reports, it seems that sea level rose to −23 m in the seventeenth century after a sea-level fall during the sixteenth century (see also Brückner, 1890; Table 3).

4.3.3 Caspian sea-level during the eighteenth to twentieth centuries

Changes in the position of the Caspian's shoreline have been mentioned in more recent literature such as Farhād Mirzā (1987) who stated that a royal tower, built in 1868 in Anzali (Fig. 2), was subsequently threatened by sea water in 1875. According to Rabino (1917), the building was demolished in 1913. The modern watchtower of the Anzali port has been built near the same position at about −25 m elevation on a concrete foundation (www.anzali.ir).

Due to its vast area, the Anzali Lagoon was described as a bay by Gimelin in 1771 (Rabino, 1917). This suggests a higher CSL in 1771 than today, previously reported by Brückner (1890) at −23 m elevation. Abbott (1858) indicated that Anzali water was influenced by sea waves during his stay in Gilān from 1847 to 1848. Eastwick (1864 in Rabino, 1917) explained that the coastal plain of Anzali was flat because during storm conditions the lagoon water surged onto the land without any obstacle, destroying boats in Anzali as well as more inland in Pirbāzār near Rasht (Fig. 3).

Rabino (1980) wrote that the Gorgān Bay was the safest place in the CS for ships, and followed that from 1860 to 1906 the area of the Gorgān Bay had reduced dramatically. According to his report, the Galugāh farmlands on the southern coast of the Gorgān Bay (Fig. 8) were completely inundated in 1815. This information supports Moraviev's observation (in Rabino, 1980), reporting that Gomishān was an island in 1815, while the city was 3 km from the shoreline when Rabino visited the city in 1906. A high-stand at and before 1805 with values of −22.7 m and −22.0 m was also reported by Brückner (1890) and Karpychev (2001), respectively (Fig. 6).

It seems that the CSL underwent fluctuations from 1771 to 1900 and that the area of the Anzali Lagoon and Gorgān Bay changed in accordance with these fluctuations, as their surface area reduced during low stands and increased during high stands.

4.3.4 Unexpected Caspian sea-level fluctuations

Tusi (1966; p. 82), in 1160 mentioned that: *“Earthquakes can cause disturbances along the shorelines, and the properties close to sea shake and impacted by the water and waves. I have heard from people of Gilān that the Kabudān* (Blue) *Sea was agitated by high tides, the city of Ardébil was shaken; and the distance of Ardébil to the Kabudān Sea is 12 farsangs* (∼ 72 km)”.

The “Kabudān Sea” (the Blue Lake) is the ancient name of the Lake Urumiyeh (Fig. 1), but it is located about 240 km to the west of Ardébil, while the CS is located 55 km to the east of Ardébil, and the author seems to be confused with the correct names of the seas. It is probable that the people of Gilān were referring to the 958 $M_s \sim 7.7$ Ruyān (central Alborz) earthquake (Ambraseys and Melville, 1982; Berberian, 1994), which might have caused some changes in the CSL. It seems unlikely that the reference is made to the 957 $M \sim 5.5$ Derbent earthquake (Kondorskaya and Shebalin, 1977, 1982), because of the much lower magnitude and farther distance of the latter to the south Caspian shore.

Based on the publication by Kazin (1974) who gave the year 915 and Nikitin (1974) citing the period 915–921, Kondorskaya and Shebalin (1977) reported that during the 918 $M_s \sim 5.5$ earthquake in Derbent (Fig. 1), the Caspian shore with the fortress walls sank. This event definitely caused abnormal waves in the Derbent area of the CS. On the authority of Nikitin (1963) who dates the event to 968, Kondorskaya and Shebalin (1977) reported an earthquake in 957 with $M_s \sim 5.5$ in the west Caspian where the sea experienced horizontal displacement of the shoreline towards the sea by around 150 m from its normal position.

The 1608 $M_s \sim 7.6$ Alamutrud (West Alborz) earthquake, about 55 km to the SW of the CS shore (Berberian and Walker, 2010), caused large waves in the CS which crashed up the coast and resulted in great alarm among men and animals (Ambraseys and Melville, 1982).

Abnormal fluctuations were also observed at Baku, Lankarān and the southern Caspian shore, where sea level oscillated within the space of an hour by fifty to more than a hundred centimetres in 1868 and 1960 (Hedin, 1892; Musketov and Orlov, 1893; Ambraseys and Melville, 1982).

Large sea-waves were also observed at Āstārā associated with the 1910, M_s 5.4, Moghān earthquake (Kondorskaya and Shebalin, 1977). Large sea-waves were noticed all along the southern Caspian coast from Miānkāleh in the east to Anzali in the west (Ambraseys and Melville, 1982) during the 1890, $M_s \sim 7.2$ Tāsh earthquake in the east Alborz, about 60 km to the SE of the Caspian shore.

Sea waves flooded the coast of the Cheleken Island during the 1895 M_s 7.4 Krasnovodsk (Qezel Suyu, Turkmenbāshi) earthquake on the eastern Caspian shore (Kondorskaya and Shebalin, 1977; Ambraseys, 1997). The water in the harbour quickly swelled and reached the railroad tracks. A ship 30 km from Krasnovodsk reported that the sea swelled with the shock and ejected a column of water and smoke (possible submarine mud-volcano eruption).

During the 1962 M_w 7.0 Bu’in earthquake, which took place 142 km to the SW of the Caspian shore, some irregularities in the behaviour of the water level of the CS were noticed at the Anzali, Naushahr and Bābolsar ports, where waves followed the earthquake. The tide gauge records at the Anzali port showed abnormal variations in sea level before and after the earthquake; waves with amplitudes of nearly two feet and periods between 15 and 50 min were recorded. At the Naushahr port, a series of swells had been reported but made no noticeable damage. In addition, the morning after the earthquake, the CS was muddy for more than a nautical mile (Ambraseys, 1962, 1963).

The 1990 M_w 7.3 Rudbār earthquake (Berberian et al., 1992; Berberian and Walker, 2010), which was much larger than the 1962 M_w 7.0 Bu’in earthquake, and its epicentre was closer to the CS (about 68 km to the SW of the Caspian shore vs. 142 km), should have caused unusual fluctuations in the CS, much greater than the 1962 event. Unfortunately, our efforts in obtaining the hourly/daily records at the south CS failed because the gauge station was broken down during the earthquake.

4.3.5 Other historical findings

Ibn Hawqal (1988, page 141) in tenth century described the Aral Sea (Fig. 1) as a salt lake that had not been freshened even by the Āmu-daryā water: *"Although considerable water from the Jayhun River* (Āmu-daryā) *discharges into the lake, the area of the lake has not been increased and the water is not freshened and people believe that the lake is connected to the CS via an underground channel"*. Although this is corroborated by the Hudud al-'Alam (1973), Mostowfi (1999) mentioned that the Jayhun River (Āmu-daryā) was diverted from the Aral Sea towards the CS by the sons of Genghis Khan when they surged towards Iran in 1219 (Létolle, 2000).

Mar'ashi (1982) quoted that during the invasion of Māzandarān by Uzbeks in 1392, the army invaded Āmol (Fig. 8), then arrested people and after that transferred them to Khārazm by ship from the CS and the Jayhun River. This story indicates that Āmu-daryā was discharging into the CS at that time via the Uzboy waterway. According to Barthold (1984), this waterway was open until the late sixteenth century.

In addition to the above-mentioned river avulsion, some reports on other Caspian rivers provide useful information on the south Caspian river courses.

The Sefidrud was reported as the largest river on the south Caspian coast in the Hudud al-'Alam (1973). According to this report, the people of Gilān could be categorized into two groups, the first group settled between the river and the sea, i.e. Rasht; while the other group was situated between the river and the mountains, i.e. Lahijan (Fig. 1). Regarding the East-West direction of the Alborz Mountains (Fig. 1), this categorization is true when the river direction is parallel to the mountains and flow eastward in the plain. Rabino (1917) stated that in 1740 a large tributary separated from the Sefidrud, 6 km south of the river mouth, and discharged into the Anzali Lagoon, and that this tributary was large enough to enable ships to carry passengers from Anzali to Pirbāzār near Rasht. This tributary could be navigated in 1875 because Farhād Mirzā (1987) used it in his journey to Europe. Barthold (1984) mentioned that the tributary was called Shāhrud and discharged into the Anzali Lagoon at the beginning of the twentieth century. At present, this tributary is abandoned.

The Gorgān River, on the south-eastern flank of the CS (Fig. 8), according to Rabino (1980), discharged into the Gorgān Bay before 1854 near Bāsh Youzki (the present Bandar Turkman, Fig. 1). Then the river avulsed northward and split into two tributaries. In 1886 the southern branch of the river was completely abandoned and the river discharged into the CS at Khājeh Nafas where it still meets the sea to this day. According to this account, the present delta of the Gorgān River has been in formation since 1854 only.

5 Discussion

5.1 Caspian sea-level during the last millennium

The CSL during the tenth century is the most controversial time period for the last millennium as it has been reported less than −35 m by Varushchenko et al. (1987), −33 m by Gümilev (1980) and (Karpychev, 1998; 2001) to more than −17 m by Brückner (1890) during the early tenth century (Fig. 6). Because the shoreline accommodating the fort walls in Derbent sank due to the 918 earthquake (Kazin, 1974; Nikitin, 1974) (discussed earlier), the sea-level position mentioned by Brückner (1890) for 915 to 921 (Table 3) could partially be related to the shore subsidence instead of sea-level rise. As Brückner (1890) compared paintings of that period with those in 1638 and estimated the CSL difference between both periods from how many projections in the wall were reached by water (6 in 915–921 and 3 in 1638), it is also possible that the wall might have been altered meanwhile. According to the existence of Ābeskun as a port from the beginning of the ninth century (al-Istakhri, 1961; ibn Hawqal, 1988) to the beginning of the fourteenth century (Mostowfi, 1999), and the historical observations in Chālus and Rāmsar (Hudud al-‘Alam, 1973; ibn Hawqal, 1988), it is probable that sea level during this period did not change as dramatically as mentioned. This suggestion is supported by the reports on the CSL during the next catastrophic sea-level rise in the fourteenth century with a maximum level at −19 m (Gümilev, 1980) that drowned Ābeskun and was much greater than the high-stand of the first half of the tenth century. As the approximate position of the Ābeskun possibly lies at about −24 m elevation, the sea-level position in the early tenth century was at least −24 m as the CSL must have been lower than the height of the town, which could be supported by the geological findings of Lahijani et al. (2009) who described a sea-level rise for the first centuries of the last millennium to around −24 m in central Gilān.

According to ibn Hawqal's (1988) observations in 977 in the Dahestān District, it seems that the sea level started to fall at the second half of the tenth century, which has been reported elsewhere in the scientific literature (Leroy et al., 2011; Kakroodi et al., 2012) as the Medieval Climate Anomaly (MCA) lowstand. Horizontal displacement of the shoreline in 957 in Derbent (Dotsenko et al., 2002) could also be related to this sea-level fall rather than the seismic event. Although the MCA in the North Atlantic region extended to the middle of the thirteenth century (Ruddiman, 2008), the observations of (al-Bakri, 1999) and (Jovayni, 1911) in the early thirteenth century suggest that the regression did not stretch beyond 1208. At this time sea level started to rise and reached the highest level at the beginning of the fourteenth century (Banāketi, 1969; Mostowfi, 1999). This observation could be correlated with the dating results of this study using IntCal09 and Mixed Marine NoHem databases. This sea level rise was reported previously by Kakroodi et al. (2012) in Gomishān and Naderi Beni et al. (2013) in Anzali. The rapid catastrophic sea level rise in 1304 (Brückner, 1890; Gümilev, 1980; Karpychev, 2001) inundated Ābeskun completely and engendered spit-lagoon development in different stretches of the Caspian coastal areas (Kroonenberg et al., 2007; Storms and Kroonenberg, 2007; Naderi Beni et al., 2013). The formation of Nim-mardān Bay (Mostowfi, 1999) could possibly be linked to this rapid sea-level rise that is reflected in the study of Kakroodi et al. (2012) as shell-bearing layer. The successive transgressions of the thirteenth and fourteenth centuries are also recorded in the Anzali Spit as two different horizons of shell-bearing sands (Naderi Beni et al., 2013), as well as in

Dagestan (Kroonenberg et al., 2007), the Gorgān Wall (Rekavandi et al., 2007) and Gomishān (Kakroodi et al., 2012).

According to the historical documents presented in this study, the geological findings in the south CS (Table 7), and other evidences reported by Brückner (1890), Varushchenko et al. (1987) and Karpychev (1998, 2001), in addition to other findings by Komarova (1980) and Gümilev (1980) from other parts of the CS, the sea-level curve could be reconstructed as illustrated in Fig. 9.

5.2 Dating the last millennium Caspian sea-level changes

The water age effect, or reservoir effect (RE), in a close environment such as the CS is more variable in time and space than in the open ocean. It means that the present-day age of seawater may not necessarily be applicable for correction of a fossil material from a particular locality (Walker, 2005). Various RE have been reported for the CS: from 290 to 400 yr by different researchers (Leroy et al., 2011). If a marine RE (Marine09) is applied to the dating results of this study, then the ages could be linked to the younger high-stands of the seventeenth century (Fig. 9). According to the elevation of the dated horizons of Core A and B at −26.75 m and −25.8 m, respectively (Table 2) and the reconstructed sea level curve (Fig. 9), the sea level rise in the seventeenth century is more appropriate for the dated horizons. During the tenth to seventeenth centuries the sea level was always higher than −26 m and hence the terrestrial facies below the dated horizons in Core A and B (Fig. 4) could only be formed during the sixteenth century low-stand.

Owing to frequent CSL changes during the Holocene (Kroonenberg et al., 2000) and owing to the poorly known RE of the CS, many researchers prefer to conduct their interpretations based on uncalibrated ages (e.g. Rychagov, 1997), or on calibrated age data without considering the marine RE of 400 yr (IntCal09 database). It seems that this approach as well as using the Mixed Marine NoHem database has less reliable results comparing to Marine09 database in this particular region.

5.3 Caspian sea-level changes and the hydroseismicity

Following Shilo and Krivoshey (1989), Rodkin (1992a,b) reported some correlation between the seismic and hydrodynamic regimes in the CS area and the observed delay times between the CS water imbalances (oscillations in water level due to river inflow, precipitation over the Sea, evaporation and outflow from the sea) and regional seismicity. The hydroseismic research avenue was later followed by Ulomov (2003) who found some correlation between seismicity and hydrological variations in the central and south CS by utilizing regional $M > 6.0$ magnitude earthquakes. Since reliable instrumental measurements on CSL fluctuations before the mid-nineteenth century are not available, the first large-magnitude earthquake selected by Ulomov (2003) was the 1895 M_s 7.4 Krasnovodsk (Cheleken) earthquake along the eastern Caspian shore (though he assigned a M 8.0). Most of the earthquakes were apparently preceded by a short rise in the CSL followed by noticeable sea-level drops.

Nonetheless, some of the selected large-magnitude events by Ulomov (2003) such as the 1930 Salmās, 1948 Ashkābād, 1968 Dasht-e Bayāz, 1978 Tabas-e Golshan, 1979 Koli, and 1990 Rudbār earthquakes, macro-seismic epicentres are far from the Caspian shoreline (360, 400, 520, 450, 430, 570, and 68 km, respectively). Hence, some of his data points may not be closely linked to the hydroseismicity of the CS. Despite deleting most of his $M > 7.0$ earthquakes, if his correlation is still valid, then one can state that the factors controlling the fluctuations of the CSL may also partially contribute to the seismicity of the basin and lead to destruction of coastal settlements. These kinds of destruction, although short in time, should be considered in any historical and archaeological reconstructions of CSL changes.

5.4 Validation of the last millennium sea-level curve

Comparison of the CSL changes with the climate history of the last millennium shows that during the MCA (c. 977 to 1208) the CSL experienced a lowstand; while during the LIA some significant sea-level fluctuations occurred (Fig. 9). The CSL rose up to

−19 m at the beginning of the fourteenth century (i.e. nearly 4 m higher than at present) and then dropped to −28 m in the sixteenth century. Generally the CSL was high during the late LIA from the seventeenth to the nineteenth centuries, although with some fluctuations (Fig. 9).

The CSL changes during the last millennium manifest similarities with changes in Alpine lake levels (Magny et al., 2011) and the Aral Sea (Boomer et al., 2009) (Fig. 10). Furthermore, there seems to be synchronicity between lake-level changes and solar activity during the last millennium (Bard et al., 2000) (Fig. 10). Decreases in solar irradiance are generally coincident with increasing CSL, Alpine lake levels (Magny et al., 2011) and the Aral Sea (Boomer et al., 2009), which could be related to increases in precipitation, decreasing temperatures and consequently a reduction in evaporation over the sea and its catchment basin (Arpe and Leroy, 2007; Leroy et al., 2011).

5.5 Other findings

Leroy et al. (2011) reconstructed environmental changes in the Anzali Lagoon and Spit during the LIA high-stand and concluded that barrier islands with inlets could be found during this period in place of the Anzali Spit. This suggestion is in good agreement with the observations of al-‘Umarī (2010) in the fifteenth century that described the presence of islands in front of Rasht. Generally, during the CS high-stands, spits could be split into barriers and inlets as Kakroodi (2012) have described for the Miyānkāleh Spit, in the southeast CS.

Kazancı et al. (2004) suggested that the Sefidrud flowed in an area between Amirkolā and the Anzali lagoons during its lifetime (Fig. 1). For the last millennium, this suggestion could be supported by the observations of Hudud al-‘Alam (1973), Farhād Mirzā (1987), Barthold (1984) and Rabino (1917) who mention different directions for the Sefidrud and its tributaries.

The Sefidrud avulsion was investigated by Leroy et al. (2011) and Naderi Beni et al. (2013). They showed that an avulsion occurred around the beginning of the seventeenth century and the river and/or one of its major tributaries avulsed from W–E to S–N direction. The W–E course of the river was observed by anonymous writer of Hudud al-‘Alam (1973).

River avulsion is one of the consequences of rapid sea-level change in the CS (Naderi Beni et al., 2013). During the late LIA, some rivers such as the Kura River (Hoogendoorn et al., 2005), the Gorgān River (Barthold, 1984) and the Sefidrud (Leroy et al., 2011; Naderi Beni et al., 2013) experienced changes in their main courses and/or tributaries. The thirteenth century Āmu-daryā avulsion (Mar’ashi, 1982; Mostowfi, 1999) from the Aral Sea to the CS could also be linked to changes in the level of the Aral Sea. According to Boomer et al. (2009), the Aral Sea experienced a severe regression in 1220, which could be correlated with the thirteenth century avulsion of the Āmu-daryā. Boomer et al. (2009) also found a gypsum horizon in their Aral Sea cores with a date of 1200 and much higher water salinity in 1220. Moreover, Sorrel et al. (2006) reported that the salinity of the Aral Sea changed from more saline to less saline around 1380. These findings could be correlated with the Āmu-daryā avulsion and the consequent decrease of fresh water input into the Aral Sea. Scientifically, this scenario is more acceptable than Mostowfi’s report (1999) that evoked damage to Jayhun Dam by Mongols that directed the water towards Ābeskun.

Palynological studies showed that from 2200 to 1700 yr BP (calibrated age using Marine09), the salinity of the CS was lowered due to increasing freshwater inputs by the Volga River and the Āmu-daryā, which discharged into the sea at that time (Leroy et al., 2007). The suggestion of the Āmu-daryā avulsion in 2200 to 1700 cal. yr BP (Leroy et al., 2007) and the historical records of the avulsion in the thirteenth century (Mostowfi, 1999) show the possibility and frequency of river avulsion between the two basins (see also Létolle, 2000).

6 Conclusions

This study shows that historical evidence is a valuable source for reconstructing the last millennium sea-level changes of the CS. They could provide us with a better understanding of the impacts of CSL changes on the environment as well as human societies.

Owing to descriptive nature of many historical sources, some uncertainties in quantifying sea-level variations exist. These uncertainties may be related to observational errors, different standards in describing the events used by different historians and geographers and seismic events. Considering negligible rate of uplifting/subsidence of the region during the last millennium and due to seismicity of the CS region, earthquakes could cause considerable vertical displacement of the shoreline in some places. These local vertical movements should be taken into account when attempting to reconstruct CSL changes based on historical and archaeological evidence.

One of the ways to decrease the uncertainties associated with historical data is the correlation with geological findings as well as the comparison of individual observations with other contemporaneous reports. The multidisciplinary approach leads to a better understanding of past environments and, moreover, to corroborate the accuracy of geological findings.

Some contradictions, however, occur between historical evidence and proxy-based interpretation when determining the relative sea-level position (e.g. historical sea level low-stand from 950 to 1250 a period in which a high-stand was dated by some geoscientists such as Lahijani et al., 2009). It seems that this problem partially comes from uncertainties in dating methods as well as our geological interpretations. Precisely constraining the RE for the CS is a high priority for future studies. Nonetheless, our study on the southeast CS shows that using the Marine09 database for calibration of ^{14}C ages yields more reliable results for this particular region.

As the CS and its watershed area spans the sub-tropics in the southwest to desertic climate in east-northeast, and the humid mid-latitudes in the northwest of the watershed, this could provide a good opportunity for geoscientists to investigate climate change in the Northern Hemisphere. Comparison of the CSL reconstruction for the last millennium with solar irradiance and with the fluctuation of lakes in Middle Asia and Europe, show relatively good agreement between different curves. Based on the antiphase relationship between the CSL changes and the solar irradiance during the last millennium, it could be concluded that the main historical CSL fluctuations have been modulated by solar activity. However, in some periods no good agreement occurs between the curves, which could be linked to the absence of data from the CSL for certain periods as well as regional irregularities, such as earthquakes.

Despite these problems, this study is able to construct a curve of the CSL variability for the last millennium, which fits to a multitude of observational evidences and can be used for validating simulations with climate models. In the early part of the millennium the absolute values have a wider range of uncertainty but most data agree in the events of increases and decreases of the CSL.

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Table 1. Geological findings on the Caspian sea-level (CSL) changes in the Late Holocene. The sea level position is inserted where the data are available.

Location	Event	Age (AD)	CSL	Reference
South CS	Sea-level rise and spit development	1042	−24	Lahijani et al. (2009)
South CS	Sea level rises to −24 m	1289–1403	−24	Kakroodi et al. (2012)
South CS	Relative sea level rise	1311–1445	–	Naderi Beni et al. (2013)
South CS	Sea level rises to −24 m	1335–1446	−24	Kakroodi et al. (2012)
South CS	Inundation of Gorgān Wall	1344–1460	−22	Rekavandi et al. (2007)
West CS	Sea-level rise and barrier formation	1350–1640	−24	Kroonenberg et al. (2007)
South CS	Relative sea-level rise	1408–1514	–	Naderi Beni et al. (2013)
South CS	Sea-level rise	1460	−25	Lahijani et al. (2009)
West CS	Sea-level rise and barrier formation	1590–1710	−24	Kroonenberg et al. (2007)
South CS	Sefidrud avulsion	1600	–	Lahijani et al. (2009)
West CS	Kura River diverted to Qezel Agac Bay	1600–1800	–	Hoogendoorn et al. (2005)
South CS	Age of the core base in Amirkolā	1620	–	Leroy et al. (2011b)
South CS	Relative sea-level rise	1696–1726	–	Naderi Beni et al. (2013)
South CS	Anzali Spit broken into barrier islands	1700–1830	–	Leroy et al. (2011b)
West CS	Development of new Kura Delta	1800	–	Hoogendoorn et al. (2005)
East CS	Sea-level rise	1830	−25.5	Leroy et al. (2006)

Table 2. AMS radiocarbon dating of the sediment cores. The calibrated ages are reported based on three databases for 2σ range with the highest probabilities shown in parentheses. For core location, see Fig. 3.

Core No.	Lab. No.	Elevation (m)	Depth of sampling (cm)	Type of material	Radiocarbon Age (yr BP)	Calibrated Age (yr AD) 2σ range IntCal09	Mixed Marine NoHem	Marine09
A	Poz-51062	−25.3	145	Articulated bivalve	665 ± 35	1273–1394 (1)	1409–1498 (1)	1538–1697 (1)
B	Poz-51060	−24.8	100	Articulated bivalve	790 ± 30	1207–1279 (0.98)	1307–1418 (1)	1457–1600 (0.97)

Table 3. Dates, type of historical evidence and the Caspian sea-level summary from the tenth to nineteenth centuries (Brückner, 1890).

Year	Information	Caspian sea-level (m)
915–921	6 projections in the wall at the fort in Derbent reached into the sea	−17.4
1100–1150	Building of a caravanserai near Baku which was submerged later	< -30.4
1306–1320	Tomb of Sheik Zahed in Lankarān in danger of flooding	< -16.0
1400	Mosque in Baku (but some doubts)	−21.4
1556	Navigation at Volga exit to Caspian Sea (less reliable)	−24.7
1638	Markings on fort wall in Derbent	−21.3
1715–1720	Many sources 1715 lowest level	−25.9
1735–1743	Many sources 1723 to 1743 rise by 2.4 m	−22.7
1754–1766	Many sources	−22.75
1767–1780	Many sources	−22.65
1805	Many sources	−22.7
1816	Many sources	−23.8
1830	Many sources	−25.8
1843–1846	Many sources	−26.7
1847	Many sources	−26.0
1851–1855	Many sources	−26.4
1856–1860	Many sources	−26.47
1861–1865	Many sources	−26.39
1866–1870	Many sources	−26.01
1871–1875	Many sources	−26.03
1876–1878	Many sources	−25.66

Table 4. Dates, type of historical and geological evidences and the Caspian sea-level summary from the tenth to nineteenth centuries (Varushchenko et al., 1987).

Historical record (AD)	Dating (BP)	CSL (m)	Information
8th to 10th centuries	–	−28 to −30	Historical documents of al-Istakhri (951) and geomorphological data of Derbent Wall
934–945	–	−35 to −36	Derbent Wall was a mile in the sea (al-Masʿūdī, 947)
–	880 ± 94	−26 (−25?)	^{14}C dating on peat layer, Balakhan, 75 km east of Turkmenbāshi Bay
–	860 ± 40	−26 (−25?)	^{14}C dating on peat layer, Balakhan, 75 km east of Turkmenbāshi Bay
11th to 13th century		−31.7 to −34	Cultural horizon of Bayandovan city near Kura Delta has minimum level of −29.7 m
1234–1235	–	−29.2 to −27	Construction of Cārvānsarāi in Baku in level of −27.2, sea level is unknown
1303	–	−22	Poet Nedjati has written in the early 14th century that Ābeskun port submerged
1306–1307	–	−22	Safiaddin Es'haghi quoted that tomb of Sheikh Zahed in Lankarān was on the shoreline
14th century	–	−27 to −28	Position of tomb of Sheikh Zahed in Lankarān (1306–1307)
14th century	–	−22.5	Footnotes of Marin Sanudo map: every year the sea level increases about a Ladon (?)
14th century	–	−26	The Chechen Island with −24 m elevation was reported in Genuetzev map in the late 14th century
14th century	–	−26 to −25	Many fortifies submerged in the city of Baku and the sea was near the mosque
–	510 ± 40	−26	^{14}C, Balakhan, 75 km 75 km east of Turkmenbāshi Bay
1474–1478	–	−27 to −28	Barbaro reported Derbent Wall emerged
1556	–	−26.5 to −29	Astarakhan nautical charts in 1556
1558	–	−26.5 to −29	Map of Jenkinson
1590	–	−29	A mile of Derbent Wall emerged
1588	–	−26 to −29	Terek city was on the Terek river mouth
1604	–	−25.3	Terek city was about 7.4 km from the river mouth and the Chechen Island with −23.8 m elevation was 52 km from the coastline.
1606–1629	–	−23 to −24	Derbent fort was constructed by Shāh-Abbās Safavid
1623	–	–	F. A. Kotov report on Derbent fort built by Shāh-Abbās
1623	–	−25 to −24.5	Terek city was about 35 to 55 km from shoreline
1668	–	−24	Visiting the Derbent Wall by Aliyāri who did not mention the wall was in the sea
1668	–	−24	The Terek city was displaced due to flooding
1715–1717	–	−25.5	Map of A. Bekovich & Cherkasski
1720	–	−25.6	The first Russian cartographic map of V. Soymonov
1726–1731	–	−25.5 to −26.2	Based on Soymonov map
1745	–	−23	Based on Vodrov map
1764–1765	–	−24 to −24.5	Based on a map of Tolmachev–Ladyzhensky
1781–1782	–	−22	Based on Voynovich map
1796	–	−22.7 to −23	A map with anonymous cartographer
1809–1817	–	−23.7 to −24	Map of A. E. Kolodkin
1820	–	−24 to −24.2	A report from a Russian newspaper
1819–1821	–	−24.5	Information from Moraviev
1825–1826	–	−25	CSL reconstructed based on Berg (1934)

Table 5. Summary of the dates of the Caspian sea level based on historical documents and uncalibrated radiocarbon ages (Karpychev, 1998, 2001).

Year	Information	CSL (m)
600–900	Silt in Turkmenbāshi Bay	−28 to −31
800–1300	Dating	< 33
1234	Building of a caravanserai in Derbent which was submerged later	< −31
1300–1304	Dating	−28.5
1305–1306	Settlement of Bayandovan was flooded	−28
1300–1400	Dating	rise to −24
1380–1395	Dating	−29.0
1430–1450	Dating	−26.0
1480–1490	Dating	−31.0
1550–1680	Dating	−22.0
1587–1606	A tower was added to a wall near the water line in Derbent	−28.5
1710–1720	Dating	−26.0
1740–1750	Dating	−24.5
1740–1750	Many historical evidences	−23
1760	Fortification under water	< 23
1770–1790	Dating	−25.0
1795–1810	Dating	−22.0
1850–1900	Dating	−25.0

Table 6. Historical earthquakes in the Caspian Sea region and the observed consequences on the sea level (Modified after Dotsenko et al., 2002).

Year (AD)	Location	Evidence
918	Derbent	Part of the coast with fortifications was submerged in the sea.
957–972	Derbent	The fall of sea level caused horizontal displacement of the shoreline by around 150 m from its normal position.
958	Ruyān	The Caspian Sea in Gilān was agitated by high tides
1668	Terka	The sea submerged part of the beach. The rise of water level was observed in the delta of the Terek River.
1868	Bāku	Short-term rise and fall of sea level with amplitude about 0.45 m were observed.
1876	Oblivnoy (island)	Unusual sea-level oscillations occurred after strong underwater explosion in conditions of dead calm. Event was observed from the ship.
1890	Tāsh	Large sea waves were noticed along the Iranian Caspian coast
1895	Cheleken Island	Flooding of north and west areas of Uzun-Ada as a result of a rise in water level in the bay. Large waves caused flooding of buildings and the dock. A few wooden houses were washed out to sea. Pipeline was destroyed.
1902	Bāku	Unusual waves resulted in dangerous motion of ships in the port. The event was observed after a destructive earthquake near Shimaha.
1910	Moghān	Large sea waves were observed in Āstārā
1933	Kuuli-Mayak	Sudden rise of sea level up to 1.35 m for 10 min. Fishing boats and equipment were washed out to sea.
1939	Livanov Shoal	The passing of a solitary large wave was observed from two ships that were 15 miles apart.
1960	Bāku	Sea-level oscillations up to 1 m were observed for 2–3 h.
1962	Bu'in	Irregularities were noticed at Anzali, Naushahr and Babolsar ports
1986	Livanov Shoal	Unusual high-frequency sea level oscillations of 2–3 cm amplitude were observed over the earthquake for 1–1.5 min. The event was fixed from the seiner and 45 fishing ships.

Table 7. The Caspian sea level (CSL) during the last millennium based on comparison between historical observations and geological events.

No	Age (AD)	CSL (m)	Historical observation	Reference	Geological event	Reference
1	907	−23	Sea level position in Ahlam, Chālus and Rāmsar	Hudud al-‘Alam (1973), ibn Hawqal (1988), Jayhāni (1989)	Progradation of the old Kura Delta	Hoogendoorn et al. (2005)
2	977	−24	Sea level fall	Hudud al-‘Alam (1973), ibn Hawqal (1988)	Sea-level fall	Hoogendoorn et al. (2005)
3	982	≪ −23.8	Bāb Island is in the map	Hudud al-‘Alam (1973), ibn Hawqal (1988),	–	–
4	1208	−24	Ābeskun was on the shoreline	Al-Bakri (1999)	–	–
5	1260	> −24	Ābeskun was flooded	Jovayni (1911)	High-stand	Naderi Beni et al. (2013)
6	1304	−19	Rapid sea-level rise	Banāketi (1969), Mostowfi (1999), Marin Sanudo (1320 in Gümilev, 1980), Al-‘Umarī (2010)	High-stand	Kakroodi et al. (2012), Naderi Beni et al. (2013), Rekavandi et al. (2007)
7	1587	−28	Construction of Safavid castle in Derbent	Gümilev (1980)	–	–
8	1628	−23	Establishment of ports and structures along the Caspian Sea coast	Parodi (1987), Gümilev (1980)	Sea-level rise and barrier formation	Kroonenberg et al. (2007)
9	1771	−23	Sea-level rise	Abbott (1858), Brückner (1890), Rabino (1980),	Widespread evidence	Leroy et al. (2011), Naderi Beni et al. (2013)
10	1815	−23.5	Sea-level position in Galugāh and Gomishān	Rabino (1980)	Anzali Spit broken into barriers	Leroy et al. (2011)
11	1875	−25	Sea-level rise at Anzali royal tower	Farhād Mirzā (1987)	Karā Bogāz Gol	Leroy et al. (2006)

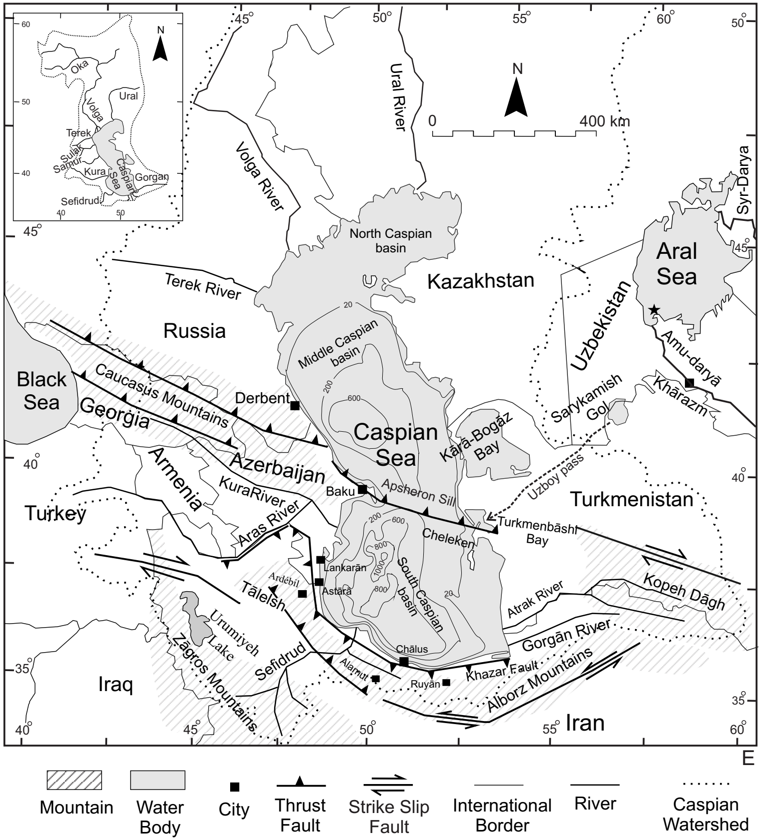

Fig. 1. Modern map of the Caspian Sea and its seaboard countries. The positions of the Aral Sea, the main rivers as well as the main faults of the region are highlighted. The inset on the top left shows the whole watershed area of the Caspian Sea.

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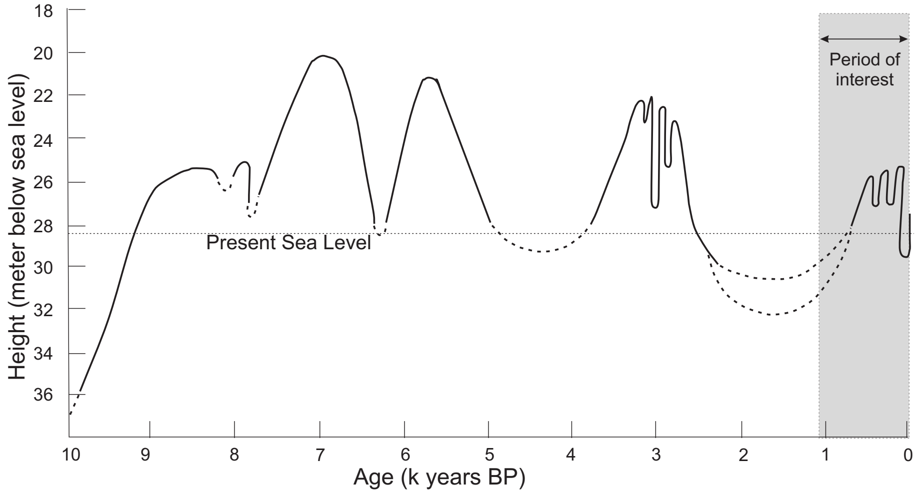

Fig. 2. Caspian Sea-level changes over the last 10 000 yr, uncalibrated radiocarbon ages (Rychagov, 1997). The study period of the present investigation is denoted by the grey shading.

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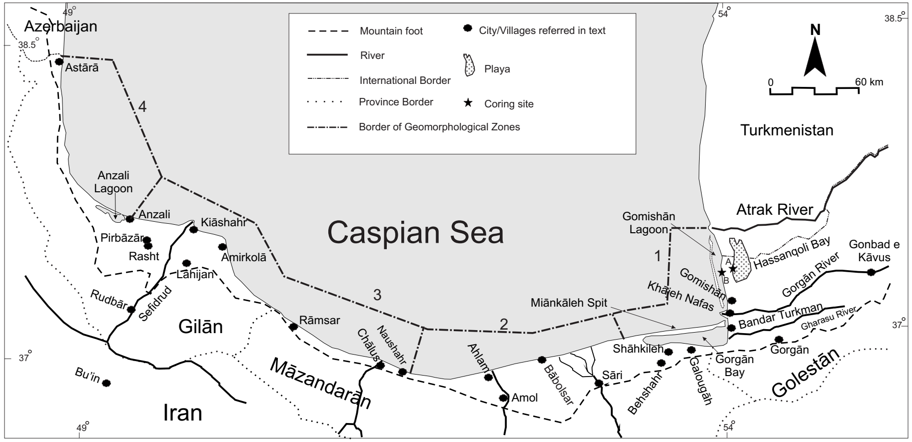

Fig. 3. The Iranian Caspian coast, its prominent coastal landforms and major rivers. The cities mentioned in this paper are marked on the map. The morphological zones of the south Caspian coast (Voropaev et al., 1998) are highlighted. 1: Coasts with gentle slopes on the beach and in the nearshore zone. 2: Coasts with gentle slopes on the beach and steep slopes in the nearshore zone. 3: Coasts with steep slopes on the beach and nearshore zone. 4: Coasts with steep slopes on the beach and gentle slopes in the nearshore zone. Core locations are indicated by the star symbol.

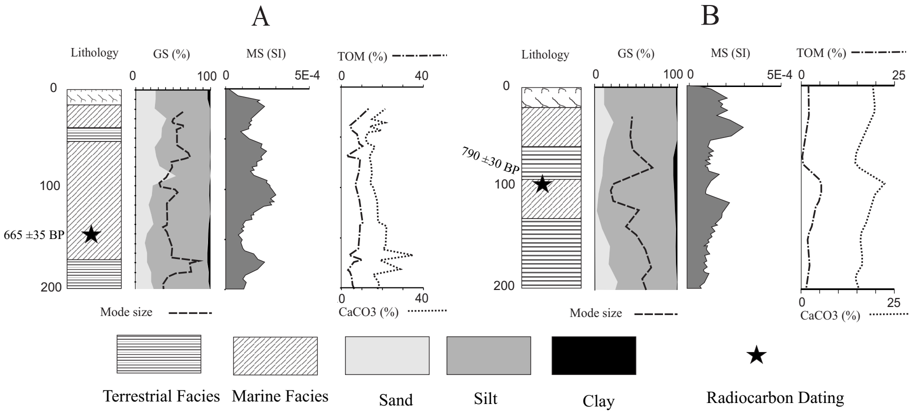

Fig. 4. Lithology of two cores taken near the Hassanqoli Bay in the southeast of the Caspian Sea. The position of the cores is presented in Fig. 3. The stars show the dated horizons and the corresponding radiocarbon ages (BP). GS: Grain Size; MS: Magnetic Susceptibility; TOM: Total Organic Matter. The vertical axis is depth in cm.

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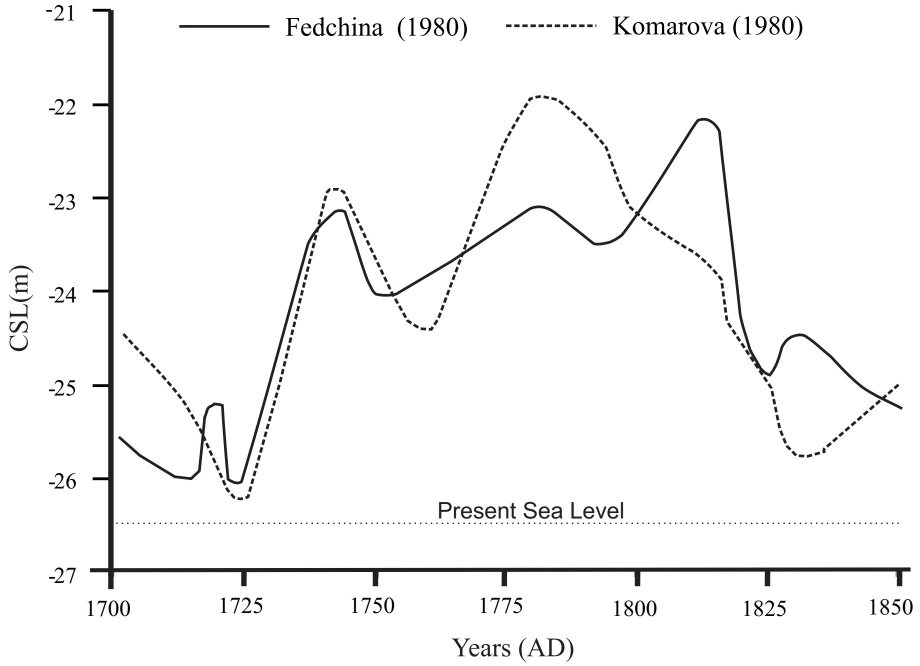

Fig. 5. The Caspian sea-level (CSL) changes during the eighteenth century and first half of the nineteenth century (Fedchina, 1980) and the sea-level curve from Komarova (1980) based on Russian cartographic maps.

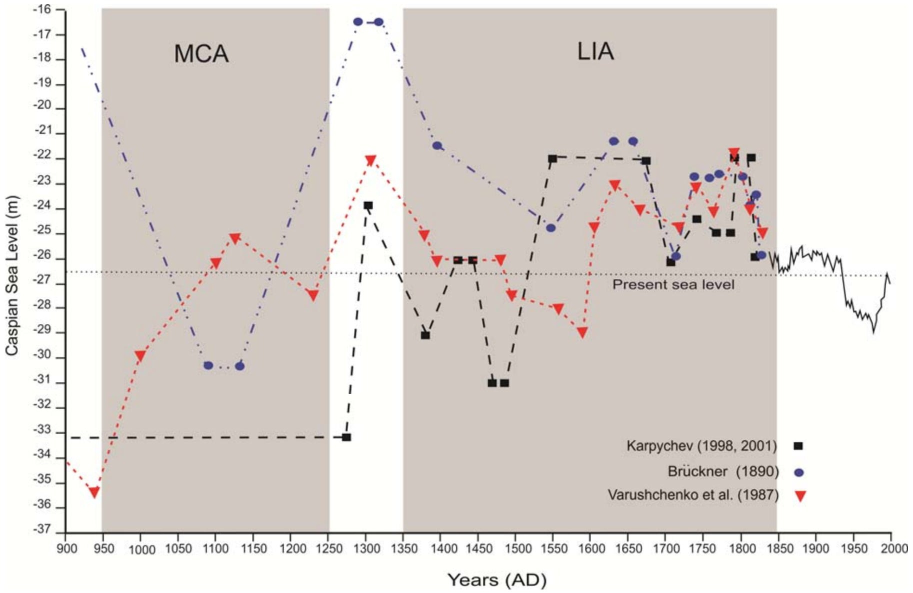

Fig. 6. The Caspian sea-level curve based on Brückner (1890), Varushchenko et al. (1987) and Karpychev (1998, 2001). The dashed lines connecting the filled symbols are interpolations. The continuous line from 1850 to 2000 shows the instrumental observations. A –26.5 line, the CSL in 1995, was added for ease of comparing the different levels during the millennium. The Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) are indicated by shaded boxes.

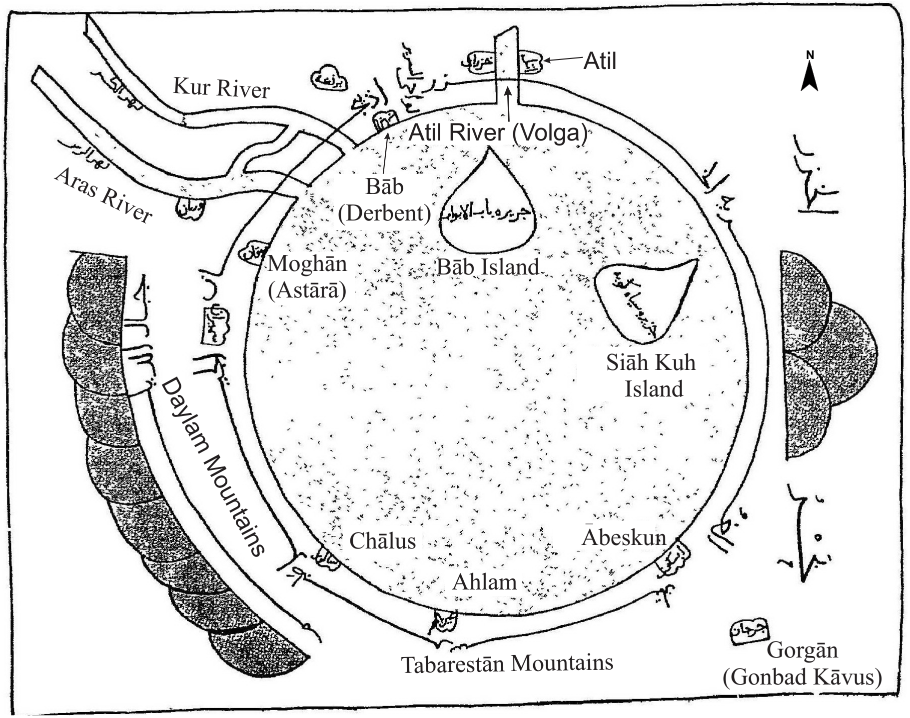

Fig. 7. The tenth century map of the Caspian Sea by Ibn Hawqal (1988). The map was rotated to show the north at the top and some of the names have been translated into English. Ābeskun, Gorgān, Ahlam and Chālus were described as the most important ports of the south Caspian Sea by the tenth century geographer.

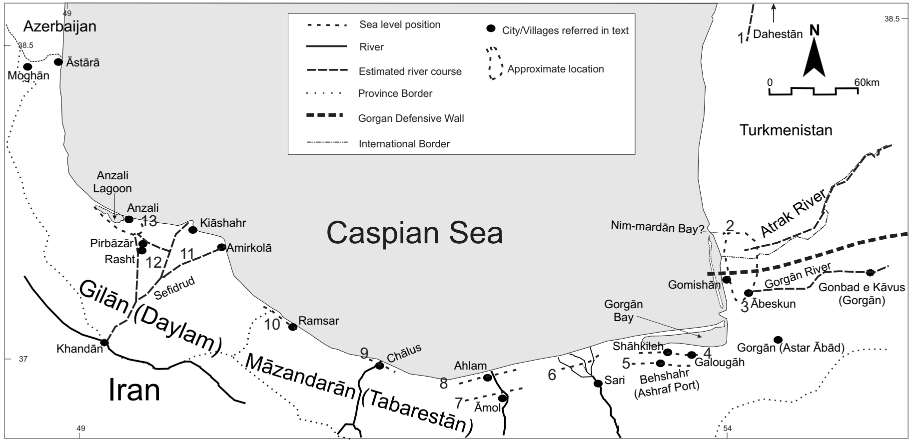

Fig. 8. The Iranian Caspian coast and reported historical observations. The ancient names are denoted in parentheses: (1) The possible position of sea level in Dahestān in second half of the tenth century (al-Istakhri, 1961, 1973; Barthold, 1984; ibn Hawqal, 1988). (2) The probable position of Nim-mardān Bay (Mostowfi, 1999; Kakroodi et al., 2012). (3) The probable position of Ābeskun along the Caspian shoreline (Jovayni, 1911; al-Istakhri, 1961; ibn Hawqal, 1988; Mostowfi, 1999; al-Mas'ūdī, 2012). (4) The sea-level position in 1906 in Galougāh (Rabino, 1980). (5) The position of Ashraf port in 1628 (Parodi, 1997). (6) Uzbeks shipped the captives of Māzandarān from Sāri (Mostowfi, 1999). (7) Sea-level position in Ahlam in the ninth century (al-Ya'qūbī, 1968). (8) Sea-level position in Ahlam reported by ibn Hawqal (1988), Mostowfi (1999) and Mar'ashi (1982). (9) Sea-level position in Chālus reported by ibn Hawqal (1988) and Jayhāni (1989) in tenth century. (10) Sea-level position in an area between Daylam and Māzandarān in the tenth century (ibn Hawqal, 1988; Jayhāni, 1989). (11) The Sefidrud or its tributary course in the tenth century (Hudud al-'Alam, 1973). (12) The main course of Sefidrud and its tributary in the eighteenth and nineteenth centuries (Rabino, 1917; Barthold, 1984; Farhād Mirzā, 1987). (13) The Anzali Spit broke into barrier islands in the fifteenth century (Mar'ashi, 1982).

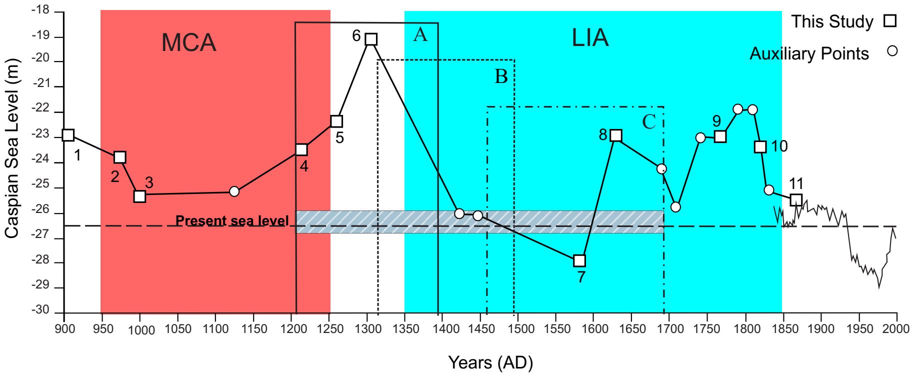

Fig. 9. The Caspian sea level curve of the last millennium based on historical evidences of this study (squares) and the most frequent reported points by different researchers (Brückner, 1890; Varushchenko et al., 1987; Karpychev, 1998, 2001) as auxiliary points (circles). Quadrangles with letters A, B and C are the ages of dated horizons in this study based on different calibration databases. A: IntCal09. B: Mixed Marine NoHem. C: Marine09. The width of boxes A, B and C correspond to age ranges (Table 2) and the height was chosen differently to distinguish the boxes. Numbers for the squares show the correspondent number of eleven historical reports in Table 7. The colored boxes show the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). The horizontal dashed box shows the thickness of the oldest marine facies in this study (Fig. 4) for the same altitude and time range.

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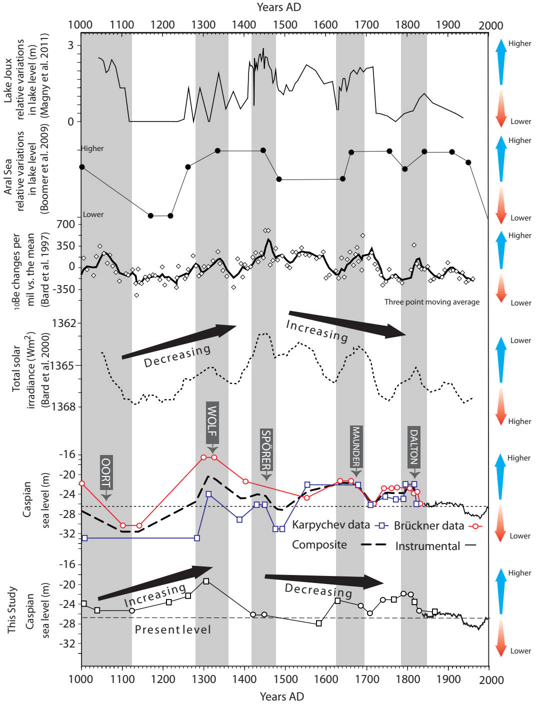

Fig. 10. Caspian sea-level reconstruction for the last millennium based on historical and geological evidence (Table 7). These data are compared with the curves of Brückner (1897) and Karpychev (1998, 2001) as well as the Aral Sea level fluctuations (Boomer et al., 2009) in Middle Asia and Lake Joux (Magny et al., 2011) in Europe. The lake-level fluctuations are compared with total solar irradiance (Bard et al., 2000) and ^{10}Be changes (Bard et al., 1997). The increasing and decreasing trends are highlighted on the right side of the graphs. The Aral Sea level fluctuations have not been precisely quantified and are depicted on a relative scale.