Late Holocene palaeoenvironmental records from the Anzali and Amirkola Lagoons (south Caspian Sea): vegetation and sea level changes

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Abstract

Two internationally important Ramsar lagoons on the south coast of the Caspian Sea (CS) have been studied by palynology on short sediment cores for palaeoenvironmental and palaeoclimatic investigations. The sites lie within a small area of very high precipitation in a region that is otherwise dry. Vegetation surveys and geomorphological investigations have been used to provide a background to multidisciplinary interpretation of the two sequences covering the last four centuries. In the small lagoon of Amirkola, the dense alder forested wetland has been briefly disturbed by fire, followed by the expansion of rice paddies from AD1720 to 1800. On the contrary, the terrestrial vegetation reflecting the diversity of the Hyrcanian vegetation around the lagoon of Anzali remained fairly complacent over time. The dinocyst and non-pollen palynomorph assemblages, revealing changes that have occurred in water salinity and water levels, indicate a high stand during the late Little Ice Age (LIA), from AD <1620 to 1800-1830. In Amirkola, the lagoon spit remained intact over time, whereas in Anzali it broke into barrier islands during the late LIA, which merged into a spit during the subsequent sea level drop. A high population density and infrastructure prevented renewed breaking up of the spit when sea level reached its maximum (AD 1995). Similar to other sites in the region around the southern CS, these two lagoonal investigations indicate that the LIA had a higher sea level as a result of more rainfall in the drainage basin of the CS.

Key words (max 6 key words)

Little Ice Age; pollen; dinocysts; sea level; vegetation; Caspian Sea

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1. Introduction

Over the period of instrumental measurements, the Caspian Sea has experienced a full sea-level cycle, i. e. a rise and a fall, of around 3 m (Rodionov, 1994; Kroonenberg et al., 2000), whilst global sea level rose by approximately 2 mm per year (Warrick, 1993). Rapid changes in the Caspian Sea (CS) level offer a unique opportunity to study global environmental changes, considering the CS as a small-scale model of the world ocean (Kroonenberg et al., 2000). The increasing demands for development of human activities in the coastal areas reinforce the necessity for unravelling the history of sea-level fluctuations (Leroy et al., 2010). Records of the CS-level changes have been discovered both offshore and in coastal sediments (Rychagov, 1997; Leroy et al., 2007). On the basis of these studies, some CS-level curves have been reconstructed. These proposed curves are very different and, to some extent, contradictory, even for a period as recent as the Little Ice Age (Kroonenberg et al., 2007; Lahijani et al., 2009).

The Iranian coast of the CS is located on the southern part of the South Caspian sub-basin (Fig. 1). Due to sea level rise, strong littoral drifts and a large influx of sediment transported by rivers, coastal lagoons have developed in the Central Guilan (Gilan) and East Mazanderan (Mazandaran) provinces (Lahijani et al., 2009). These accumulative coastal regions were selected on the basis of previous investigations indicating the need to obtain reliable sea-level signatures (Zenkovich, 1957; Lahijani, 1997). In general, coastal lagoons are infilled with sediment during sea level fall and submerged when sea level rises (Lahijani et al., 2009). The present investigation focuses on two lagoons in the province of Guilan: Amirkola and Anzali. These two lagoons are enclosed by split enlargements. As they are transitional environments, these coastal lagoons currently receive inflow from small rivers and irrigation water prior to entering the sea. Previous work has highlighted some aspects of the development of these two lagoons (Kazancı et al., 2004; Lahijani et al., 2009). Palynological analyses, pollen, spores, non-pollen palynomorphs (NPPs) and dinocysts, are provided here for the first time.

The main objective of the present study is to determine the local and regional vegetation history, climatic and sea-level fluctuations, while taking local coastal geomorphology into consideration.

2. Settings

2.1 Geographical setting

2.1.1 The Iranian coast of the Caspian Sea

Instrumental measurements of sea level, available since 1830, show fluctuations up to 3 m resulting from a seawater imbalance, mainly the difference between river influx and evaporation (Terziev, 1992). In this regard, instrumental measurements (Malinin, 1994; Rodionov, 1994) and late Holocene hydrological data (Varushenko et al., 1987) indicate that the Volga River, in the NW of the CS, is the main contributor to sea-level fluctuations (Arpe et al., 2000; Arpe and Leroy, 2007). During the past half century, several studies attempted to predict sea-level fluctuations in the Caspian basin. However, these studies failed to predict the sea-level rise of AD 1979 and the fall in AD 1995, demonstrating that the controlling factors governing the water balance are not yet fully understood. Arpe et al. (2000) found that one factor controlling the water balance in the CS is the precipitation over the Volga River of which the variability is forced by ENSO. During periods of El-Niño events, more precipitation occurs leading to an increase of the CS level.

Although it is the Volga River that provides most freshwater to the CS and sediment input for the northern part of the CS, the sediment influx for the southern basin is clearly mainly from Sefidrud and Kura Rivers (Klige and Selivanov, 1995; Mikhailov, 1997; Lahijani et al., 2008). The southern Caspian coast in the north of Iran is indeed characterized by high terrigenous sediment flux. About 61 rivers from the Iranian Caspian coast flow to the CS along the 820 km of Iranian coast (Afshin, 1994). Most originate in the northern flank of the Alborz, the Sefidrud (i.e. the Sefid River) having the largest catchment area. At present, under intense human activities, the rivers annually supply about 33 million tons of sediments and 11 km^3 of water (i. e. one volume of sediment in 300 volumes of water) to the shoreline in total, of which the Sefidrud accounts for 80% of the sediment and 40% of the water (Krasnozhon et al., 1999). Great rivers with significant sediment loads (Sefidrud in central Guilan and Gorganrud in Golestan) have developed large deltas into the CS. Their old deltas, along with fluvio-deltaic deposits of medium-size rivers, have developed a wide coastal area in the central Guilan, east Mazanderan and Golestan regions (Kousari, 1986; Lahijani, 1997). In particular, the coastal plain of the Sefidrud is characterized by abundant distributary channels and extensive flood plains, on which local swamps are common (Kousari, 1986). Here, sediments with some marine characteristics are locally observed on the coastal plain, which reflect temporal sea-level influence. The main channel of the river flows into the CS near Kiashahr city, forming the Sefidrud delta and shows high sinuosity within its alluvial valley, resulting in many abandoned channels (Fig. 1). During its development history, the Sefidrud repeatedly changed its course from west (Anzali) to the east (Lahijan), the last change occurred around 400 yr BP (Lahijani et al., 2009), from Amirkola to Kiashahr (Fig. 1). The old Sefidrud (30 km east of Kiashahr, named 'Kohneh Sefidrud' in Persian) was the main channel in historic times. Seemingly, it was responsible for the development of the ancient delta northeast of Lahijan (Kousari, 1986).

Generally, longshore currents have a great effect on coastal morphology (Lahijani et al., 2009). In the study area, lagoons and bays are formed behind the barrier beaches, which developed in central Guilan, east Mazanderan and Golestan coasts. From west to the east, Anzali, Zibakenar, Kiashahr, Amirkola, Miankaleh and Gomishan are the major lagoons that are separated from the CS by spits and bars (Kousari, 1986, 1988; Lahijani, 1997). Coastal forces, mainly sea level change, wave and wave-induced currents, combined with catchments' geological setting, and climate have determined the sediment distribution pattern along the southern Caspian coast. The modern shoreline in central Guilan is covered by sediments with a sand fraction of > 95 %.

In brief, the Amirkola and Anzali Lagoons were probably formed during the Holocene. While the Anzali Lagoon formed by littoral drift, the role of the Sefidrud delta plain was to provide an eastern limit to this lagoon. The

Amirkola Lagoon formed by littoral drift of sediments supplied by the old Sefidrud, around AD 1600. Then, the course of Sefidrud changed, passed through a wide shallow lagoon and incised the shoreline near Kiashahr (30 km west of the old mouth).

2.1.2 The lagoons of Amirkola and Anzali

Amirkola Lagoon (also known as Amirkelayeh, Shal-e Kool and Sheikh Ali Kool) is a shallow coastal lagoon (maximum water depth of 3 m and with an average depth of 1.85 m), north of Lahijan, separated to the north by the Amirkola sandy spit from the CS (Fig. 1 and 2). It is situated at 37º 19′ - 37º 22′ N and 50º 10′ - 50º 12′ E. The average altitude of this wetland is 23 m bsl relative to global sea level. The lagoon covers an area of 12.3 km^2. Since 1970, it has been protected as a “Wildlife Refuge” by the Iranian Department of the Environment. It was also registered in the Ramsar List of Wetlands of International Importance in June 1975. A small outlet (3 m wide) permits partial unidirectional flow of the lagoonal waters to the CS. The lagoon has no river inflow and receives its freshwater by surface water passing through rice fields that surround the lagoon. The barrier is about 8 km long with an average width of 1 km. Satellite images show different steps of the prograding Amirkola beach into the CS (Lahijani et al., 2009).

The Amirkola Lagoon was once a part of the CS, but due to an enlargement of the Amirkola spit it has been isolated from the sea. The old Sefidrud barrier-lagoon in the Amirkola area was developed under high sediment supply of the Sefidrud and longshore currents with east-south eastward directions. Owing to a south-eastward growth of the Amirkola spit, its lagoon became entirely separated from the CS. Nevertheless, sea-level fall of the late 16th century has accelerated Amirkola Lagoon closure (Terziev, 1992; Lahijani et al., 2009).

Since the sea-level rise in 1979, the same processes have been active in the Sefidrud delta and have formed two lagoons, i.e. Zibakenar and Kiashahr, in the west and the east of the Sefidrud, respectively (Lahijani et al., 2009).

The Anzali (Bandar–e Anzali, Bandar Pahlevi, Enseli and Enzelli) Lagoon, also called, Anzali Mordab and Anzali Talab (37° 26’ - 37° 35’ N and 49° 15’ - 49° 27’ E) in the Guilan province (Fig. 1 and 3) is not only the largest freshwater reservoir of the southern Caspian depression, but also a famous wetland as it is one of the first certificated Ramsar sites in the world (June 1975). The lagoon’s maximum water depth is 5.5 m. The surface of the Anzali Lagoon and its outlet are at around 24 m bsl. It has a surface area of approximately 160 km^2, which fluctuates widely with sea level change. The Anzali wetland consists of three main parts: the central part near Bandar-e Anzali town, the western part and the southern part. The latter part, called Siah-Keshim, is preserved by the Department of Environment as a “protected area” and thus possesses well-protected vegetation and biodiversity. Fifteen small rivers with a catchment of 3700 km^2 discharge freshwater into the lagoon. The outlet is 300 m wide and allows bilateral exchange of brackish sea water and fresh lagoon water. Moreover, during storms, CS water affects the water in the outlet by mixing or causing a gradient of salinity. Moreover, when the salinity of the CS of 12.5–13.5 is taken into consideration, the water of Anzali Lagoon, excluding its central sub-basin and outlet, is typically limnetic or fresh (< 0.5). More details are available in Kazancı et al. (2004). The phytoplankton of the Anzali Lagoon was studied in 1992, a time close to the maximal levels of 1995, alongside measurements of salinity and sulphates (Ramezanpoor, 2004). The highest salinities (10) were found in the bottom waters close to the harbour in the navigation channel, and in the east the waters were fresh but eutrophic. The influence of the CS is felt everywhere, with the harbour showing both freshwater and marine species.

Kazancı et al. (2004) have suggested that the lagoon should actually be called a lake. The lake has an evolutional development based on coastal dynamics. The water level of the CS and coastal sands are clearly the primary factors for its development. The sands transported from the Sefidrud delta by a local westward drift probably accelerated the formation of the coastal sand ridges. The progradation of the coastal zone by the development of beach ridges was sufficiently rapid (because of sediment availability from the Sefidrud delta) that the coastal sands formed a dammed lake in a limited time. However, this mechanism is questioned by the present authors. Indeed the dominant littoral drift is from west to east and the old morphological features show the same direction. Therefore the Sefidrud simply closed the eastern part of the lagoon by fluvial and deltaic deposits and cannot have affected the beach ridges on the Anzali spit.

The general shape and orientation of the central Guilan coast (Anzali to Amirkola area) depend on the geographical setting. Fluvial supply from Sefidrud and other rivers in this area have been redistributed by wave and wave-induced currents. Prevailing eastward longshore currents caused the enlargement of the Anzali and Amirkola spits, which have separated these water bodies from the CS. They differ in origin from shore-parallel small lagoons that have formed due to rapid sea – level rise since 1979 (Lahijani et al., 2009).

2.2 Climate

Both Amirkola and Anzali Lagoons are located in an area with a warm temperate climate displaying a sub-Mediterranean character but still with some precipitation in summer. The southern Azerbaijan and the north-western Iran coasts along the CS benefit from an exceptionally wet and mild climate. Because of the general westerly flow in the middle troposphere, one might assume that the major sources of the humidity for the area are the North Atlantic, the Mediterranean and the Black Sea. However, it will be shown below that this general view must be revised. In autumn, the Siberian High becomes stronger and intensifies the north-easterly winds which sweep the surface of CS bringing considerable moisture to the southwest Caspian area. This humid air comes into contact with warm dry air masses descending from the Iranian plateau through Sefidrud gorge and a front is created at the contact zone causing an exceptionally high rainfall (Khalili, 1973). This author also found that, on the northern slopes of the Alborz, the annual precipitation decreases with altitude, and maximum rainfall occurs in the coastal plain. However the gradient of the decreasing rainfall varies between 22 and 68 mm of rain per 100 meters, which is contrary to most other places in the world. This suggests the existence of two air masses, a dry one from the Iranian plateau and a humid one from the CS, which come into contact between the mountains and the CS.

The results by Khalili (1973), which covered the period 1960 to 1969, can now be extended due to the availability of more complete data sets (www.irimo.ir/english). The climate of the southwest corner of the CS stands out in a generally dry area with contrasting seasons (Fig. 4a). The Iranian coast shows a strong gradient of annual precipitation from west to east, 2106 mm in Pilimbra-Nehalestan, 1860 mm in Anzali, 1379 mm in Astara and 472 mm in Torkaman on the SE coast; while a little further inland to the east, on the slopes of the mountains, it is 620 mm in Gorgan. A very strong gradient also occurs from the coast to the south, 1860 mm in Anzali, 1354 mm in Rasht, 203 mm in Manjil, only 170 km south of Rasht in the valley of the Sefidrud at a level of 330 m, and 313 mm in Zanjan, at a level of 1663 m asl which is on the plateau of the Iranian highland. Anzali and Pilimbra-Nehalestan have the highest amounts of precipitation in the region. The temperatures there are mild with a coldest monthly mean temperature of 6.8 °C in February which can be as low as 1.2 °C in a specific year (e.g. 1972). Seven days below 0 °C occur on average per year. The maximum temperature is observed in July with a mean value of 26.0 °C but which reached 28.2 °C in 1975.

The mean wind in the region is from the west (data obtained when investigating the upper air circulation), especially during seasons with higher precipitation. The wind for the 700 hPa level (about 3200 m above ground), averaged for the period 1979 to 1999, as obtained from the ECMWF reanalysis (ERA40, Uppala et al., 2005), has been investigated. The 700 hPa level has been chosen here because it is low enough to carry a substantial amount of moisture and high enough to show the general circulation and lies above the main mountain ranges. The air descends from the Iranian plateau through the Sefidrud gorge, leading to dry conditions due to the Foehn effect, with the lowest precipitation, of only 203 mm per year in the area around Manjil.

The above description applies for a large-scale view; the north Iranian coast is, however, strongly influenced by local orography; this is especially obvious for surface winds. The prevailing surface winds at the station Anzali are from west to north in summer and north to east in winter according to www.irimo.ir. In the ERA40 data, which uses a different averaging method, i.e. wind components have been averaged, the wind comes more or less from the north east throughout the year. This would suggest that most of the precipitation around Anzali comes from the CS. Some information about the origin of precipitable water can be gained by investigating time series of the Anzali precipitation and the wind components at different levels. One might expect that with increased westerlies at higher levels the air would descend the mountain slopes towards the CS, leading to a Foehn effect, i.e. a warming of the air and less precipitation. In fact one finds a significant negative correlation between westerlies at 700 hPa and the precipitation at Anzali with an anomaly correlation factor of -0.34. Conversely, it is expected with enhanced north easterlies at lower levels that the air would rise along the slopes of the mountains or when meeting the down-slope winds from the Iranian plateau leading to enhanced precipitation. The anomaly correlation between the two components of the winds at the surface and the precipitation at Anzali are significant: -0.46 and -0.64 for the zonal and meridional component respectively; so the northerly winds have the highest impact on the precipitation for Anzali, probably also because these winds stay longest over the CS and can take up more moisture from the sea. This suggests that the source of moisture for the precipitation over Anzali is the CS. Knowing that the evaporation over the CS is sufficient to compensate for the inflow into the CS by all rivers, including the Volga, makes this assumption acceptable. The assumption that the precipitation around Anzali has its source over the CS is further supported by the annual cycle of evaporation over the southern CS. Like the precipitation over Anzali and neighbouring stations, shown in Fig. 4b, the maximum evaporation occurs during autumn, extending into winter, however the evaporation is leading the precipitation by perhaps 2 months.

The precipitation at Anzali has been investigated in this study because of the good availability of data at this locality. No station is present at Amirkola, for which the nearest station is Lahijan (further inland and therefore probably with lower precipitation amounts than Amirkola). The wind data are on a much coarser grid and can be assumed to be identical for both sites. The importance of the low-level north-easterly winds for the precipitation explains why the maximal precipitation occurs around Anzali. To the west the wind is blocked by a mountain range that runs in a north-south direction and to the south by the Alborz Mountains with an east-west direction; where the two mountain ranges converge, the air is trapped in a corner and uplifted which is where Anzali is located. According to Khalili (1973) the wind is not uplifted at the mountains themselves but where the dry down-slope winds from the Iranian highland plateau meet the low-level winds from the CS. This is supported by the very low precipitation rates in Manjil, half way up the mountains. It is illustrated in Fig. 4c, where south-westerlies on the highland plateau bounce against the north-easterlies from the CS on the slope of the mountains in the area SW of Anzali.

2.3 Vegetation

The Hyrcanian forests occur along an altitudinal and climatic gradient ranging from below sea level (vegetation ‘sensitive to cold’) up to 2700 m (vegetation ‘resistant to cold’) (Bobeck, 1951; Frey and Probst, 1986; Zohary, 1973). The Hyrcanian vegetation extends over an area benefiting from the wet and mild climate detailed in section 2.2 (Zohary, 1973). It is characterised by a rich biodiversity and many endemics. It contains many elements of the forest that were widespread in Europe, but have disappeared during the Quaternary glaciations (Leroy and Roiron, 1996). The most striking is *Parrotia persica*, but *Pterocarya* and *Zelkova* are also genera that have seen their distribution shrinking over time (Bobeck, 1951; Meusel et al., 1965). Moreover *Gleditsia* is another survival from the Tertiary.

Three main forest zones occur in the Hyrcanian area: lowland, submountain and mountain forest zones. Historically, the lowland Hyrcanian forest zone was characterized by a large and relatively homogenous community of Querco-Buxetum (with *Quercus castaneifolia* and *Buxus hyrcana* as dominant species) that occurred across all the Caspian lowland area. Other important plant species of this community are: *Diospyros lotus, Gleditsia caspica, Albizzia julibrissin* and *Acer velutinum*. Moreover, some azonal hygrophytic vegetations including *Alnus glutinosa* subsp. *barbata* and *Pterocarya fraxinifolia* stands are also observed in this vegetation zone (Djazirei, 1965; Tregubov and Mobayen, 1970) where they represent more or less distinct hygrophyte communities in some remnant forests (Hamzeh'ee et al., 2008; Naqinezhad et al., 2008). Additionally, anthropogenic deforestation of Querco-Buxetum resulted in the clearing of many important trees such as *Quercus castaneifolia* and *Buxus hyrcana* due to economic uses of their woods. Many original remnants of this community were naturally invaded by *Parrotia persica, Gleditsia caspica* and other invasive species (Zohary, 1973; Hamzeh'ee et al., 2008). Historically, the lowland zones are much affected by decline due to agricultural intensification and urban development. The introduction of rice possibly occurred more than 2500 years ago. In some deforested places in the Hyrcanian area, some woody species form scrub vegetation with plants such as *Paliurus spina-christi, Punica granatum*, *Crataegus* spp., *Berberis* spp.

From the middle of the 20th century, attention was given to the restoration of some of these forests (particularly lowland and submountain forests). Therefore, in many places, large-scale cultivation of *Alnus subcordata, Populus caspica, Acer* spp., *Populus* spp. and *Salix* spp. was conducted by many national organisations in Iran. Plantations of many non-native species, such as *Pinus, Cedrus* and other needle-leave trees (e.g. *Cupressus* and *Juniperus* species), were also created by these governmental departments. The latter trees were cultivated in some parts of Hyrcanian forests even in the natural forest communities. Many new or old introduced plant species have also been recorded in recent years in Iran especially in the north (e.g. Mozaffarian, 1994; Kukkonen et al., 2001; Amini-Rad and Naqinezhad, 2003; Naqinezhad and Saeidi Mehrvarz, 2007; Naqinezhad et al., 2007; Naqinezhad and Sharafi, 2007; Hamzeh'ee and Naqinezhad, 2009). Most of these species have their origins far away from Iran mainly South America or Africa. It is not exactly known when and how these species arrived in the north of Iran, but one possibility would be by migratory birds that visit for wintering in the northern wetlands of Iran. Although *Salvinia* is a native fern species, *Azolla*, another fern, has been introduced to contained pools from the Philippines. The fishery officers in Anzali observed no *Azolla* in 1990, but by 1992 it had escaped and was dispersed in the wetland. The massive invasion by the latter fern has had catastrophic effects on natural plant and animal life of the Anzali wetland. It causes a similar situation in some parts of the Amirkola wetland. In hot years, with increasing water levels, the negative effect of *Azolla* is especially obvious.

Due to falling levels of the CS in the late 1960s, a rapid expansion of the *Phragmites* reed beds began and by the early 1980s large parts of the main wetland were covered. The recent rapid rise in water level in the wetland from early-80s to mid-90s stopped this expansion of *Phragmites* and even replaced many reed beds by open water areas (Kazancı et al., 2004; Ramezanpoor, 2004; Anonymous, 2006).

2.4 Past investigations

Kazancı et al. (2004) have studied the geomorphology of the lagoon of Anzali and surroundings in order to identify a series of natural cycles in the changes of the CS levels. These authors presented a series of maps of the extensive changes in the area of the lagoon since AD 1972 based on historical documents. The main results showed that, during sea level rise, the lagoon area extends overall, but especially to the east, through flooding by the sea. Five surface samples were studied for their pollen and dinocyst content.

Lahijani et al. (2009) have focused on the central Guilan and east Mazandaran coasts, which are two accumulative areas, for disentangling records of Late Holocene CS level change. The internal structure of the old beaches in the Amirkola and Kiashahr areas was retrieved through ground penetrating radar and showed prograding beaches. Their specifications are similar of those in modern beaches in the area. In the Anzali spit, steep slope seaward dipping layers with coarse-grained materials represent a high-energy coast formed during early and the middle parts of last millennium.

The vegetation history of the area is poorly known from previous pollen diagrams, although three records cover the last millennia. Recently, a pollen diagram from the mire of Muzidarbon near Nowshahr at 550 m altitude (Ramezani et al., 2008) has been published, covering the last 1000 years (Fig. 1). It suggests a possible record of the Medieval Climatic Optimum and the Little Ice Age (LIA). A clear increase of human activity is seen since the beginning of the 19th century. The LIA is also definitely recorded by higher lake levels most probably due to both lower summer temperatures leading to reduced evaporation and higher annual precipitations in the Lake Almalou sequence, on the eastern flanks of the Sahand Volcanic Complex in NW Iran (Djamali et al., 2009b) (Fig. 1). The relatively long period of stability under the Safavids (AD 1491–1736) resulted in prosperity, construction and the development of much of Iran, but in the Almalou sequence it is not translated by agriculture expansion but by nomadism, perhaps due to conflicts with Ottoman Turks. In contrast, the modern period (AD 1850 onwards) is characterized by expansion of agricultural activities to upland areas and intensified pastoralism. A palynological study of the last 200 years was obtained from a core in the NW of the Kara-Bogaz Gol, where human activities were by far the strongest signal in the proxies (Leroy et al., 2006). Leroy et al. (2007) published the results of a joint pollen and dinocyst study of marine cores, one of them from the south basin of the CS, which covers the period ca 5.5–0.8 cal. ka BP (core CP14, Fig. 1). Two phases with a stronger river influence were identified: one from the core base to 3.9 cal. ka BP and one from 2.1 to 1.7 cal. ka BP.

The study in the Turali barrier (Dagestan, Russia), although without palynological investigations, is relevant as it has recorded two Caspian level high stands, one 2600 years ago and one during the LIA (Kroonenberg et al., 2007) (Fig. 1). High sea levels were also reconstructed from AD1300 to the middle of the 19th century, i.e. the LIA, derived from radiocarbon dating of several bays and lagoons on east coast of the CS (Karpychev, 1993, 2001).

The instrumental record going back to AD1837 shows a very stable CS level until AD1935 followed by a drop of 2.7 m until AD1977 and a sudden increase with a maximum high-stand in AD1995. These large variations have been studied by several researchers, e.g. Arpe et al. (2000). Before the instrumental records, scattered observations by travellers in the area are available. Brückner (1890) collated some of them, such as islands emerging from the sea in paintings or descriptions and markings left on walls along the coast. Both can be used to extend the time span of CS level records though with higher uncertainty because of the gaps in this document-based record.

A synthesis of various proxy records over the last 1000 years from the CS to southern Mongolian Plateau indicates that the LIA in the arid central Asia was not only relatively wet (high P/E) but also had high precipitation (Chen et al., 2010). They suggest that cold temperatures during LIA would cause a southward shift of the westerly jet stream as the meridional temperature gradient increased, resulting in increased occurrences of mid-latitude cyclone activity and extreme events of precipitation.

3. Methods

3.1 Vegetation maps

For Amirkola, a detailed vegetation map at the plant community level has already been published in a local Persian journal by Asri and Moradi (2006). For the vegetation map used here in figures 2 and 3, many additional sources were however combined (Aghustin Sandar, 1969; Ghahreman et al., 2004). Many plant communities and their locations especially for the vegetation zones between the wetland and the sea are from Aghustin Sandar (1969). From 1969 up to now a clear alteration in these vegetation zones occurred and many of them do not exist anymore. One of the main reasons for this is the fluctuation of sea level. For the whole of Anzali wetland, no comprehensive vegetation map is available. The present map has been prepared by using personal assessments (satellite and aerial photos) and also data from Eftekhari (1995), Asri and Eftekhari (2002), Ghahreman and Attar (2003), Riazi (1996) and many unpublished data.

3.2 Coring and surface sampling

During field campaigns organised by the Iranian National Centre of Oceanography (INCO) in 2004, a series of cores were taken in the two lagoons. In Amirkola, four c. 1 m-long cores were collected with a Russian-type peat-coring device from the lagoon for sedimentological and palynological studies, of which three have been studied (Table 1). In Anzali, three cores (up to 2 m long) have been taken using a small heavy Kayak corer (Table 1). The core samples were preserved in wrapped PVC pipe with a 5.5 cm inner diameter. The cores were then transferred to the central laboratories of INCO for further studies. Subsampling took place immediately as no cooling facilities were available.

Moss pollsters and in some cases forest litters were taken in spring 2006 from seven localities in the surroundings of Amirkola Lagoon in order to establish the modern pollen rain. Samples R1 to R4 correspond to four phytosociological surveys made by one of the authors in the *Alnus glutinosa* subsp. *barbata* forest to the south-west of the wetland (Table 2). The relevés were allocated according to Braun-Blanquet approach (Braun-Blanquet, 1964). Samples a1 to a3 are as follows: a1: between alderwood and Amirkola Lagoon on an old tree bark of *Alnus glutinosa* subsp. *barbata* (Titiprizad Village), 30/03/2006; a2: Hassanbakande Village, 2 km to the CS, on the bark of an old *Salix alba* tree beside the lagoon, 03/04/2006; and a3: Hassanbakande Village, beside the lagoon under a *Phragmites* stand, 03/04/2006.

3.3 Sedimentology

For both sites, dried samples were homogenized and a representative subsample was taken for grain size analysis. The distribution for the fraction coarser than 1 mm was determined using the standard wet sieving procedure. Grain-size analysis for particles less than 1 mm was undertaken using a "Fritsch Analysette Comfort 22" Laser Particle Sizer. Organic matter was determined by wet digestion through oxidation in hydrogen peroxide on bulk samples (Schumacher, 2002). The calcium carbonate was determined by using a Bernard calcimetre. The Laser particle size analysis of core HCGL02 from Amirkola was done in France on a LS 13 320 Multi-Wavelength Particle Size Analyzer, ASTM standard calibrated.

The magnetic susceptibility was measured on core HCGL02 using a Bartington Multisusceptibility MS2E1 sensor in Laboratory of Palaeomagnetism of CEREGE, Aix-en-Provence, France. For Anzali core HCGA05, the same device was used at Brunel University to measure the magnetic susceptibility of the sediments. The measurements were made on dry sediment samples with the MS2B Dual Frequency Sensor. Three measurements were taken for each sample and then corrected for their sample volume as susceptibility values assume a sample volume of 10 cm^3. A mean reading of the three calibrated measurements of magnetic susceptibility was then determined (Hamilton et al., 1986).

3.4 Chronology

For the Amirkola cores, two radiocarbon dates can be taken in consideration. The wood samples and shells were calibrated using respectively intcal04.14C and marine04.14C softwares (Hughen et al., 2004; Reimer et al., 2004).

An age-depth model for an Anzali core, core HCGA05, was obtained through ^{210}Pb dating on the top 50 cm (Vahabi-Asil, 2006; Lahijani et al., 2009). ^{210}Pb activities were measured by partial digestion of sediment samples using HNO_3 and HCl acids to extract grand-daughter ^{210}Po, which was then analysed by alpha spectrometry system using surface barrier detectors. The supported ^{210}Pb were estimated by assaying ^{226}Ra through gamma spectrometry using HPGe detectors.

3.5 Palynology

For the Amirkola core HCGL02, seventeen samples of 1 cm^3 were treated using the classical method of Moore et al. (1991): HCl at 10 %, HF, concentrated HCl, acetolysis and sieving at 160 µm. The seven surface samples were also treated with the same technique as described above. In a further study of the core residues, the thecamoebians and the foraminifera were counted on twenty-two samples that were additionally sieved at 10 µm. For the Anzali core HCGA05, twenty-seven samples taken every 6 cm were used for all the pollen, spores and dinocyst analyses. Initial processing of samples (1 ml in volume) involved the addition of sodium pyrophosphate to deflocculate the sediment. Samples were then treated with cold hydrochloric acid (10%) and cold hydrofluoric acid (32%), followed by a repeat HCl. The residual organic fraction was then screened through 120 and 10 µm mesh sieves and mounted on slides in glycerol. For both studies, the number of pollen and spores counted was usually around 350. *Lycopodium* tablets were added at the beginning of the process for concentration estimates in the core samples only.

Incertae sedis 5b and some other palynomorphs typical of the Caspian Sea and the Kara-Bogaz Gol are illustrated in Leroy (in press). The taxonomy of many dinocyst taxa of the CS has been established by Marret et al. (2004).

Pollen percentages were calculated on the terrestrial sum (excluding aquatic, spores and unknown or unidentifiable pollen). The diagrams were plotted with psimpoll4 (Bennett, 2007). A zonation by cluster analysis (CONISS) after square root transformation was applied; that method is also available in psimpoll. The zonation, based only on terrestrial taxa, was calculated for the percentage diagrams.

The dinocysts were counted at the same time as pollen and other microfossils in Anzali. The foraminifera, the thecamoebians and the dinocysts were counted separately from the initial pollen count in Amirkola. The zones built on percentages of dinocysts are called dinozones. The total sum for percentage calculations (between 59 and 437) is made of all dinocysts except *Brigantedinium* spp. (including all round-brown specimens), because of its ubiquitous character and frequent dominance of the spectra. *Brigantedinium* is expressed as a percentage of the same sum as the other dinocysts. *Brigantedinium* is however included in the concentration diagram (in number of cysts per ml of wet sediment). In Amirkola, the zonation is visually defined based on the concentration curves of the thecamoebians, foraminifera and dinocysts whereas it is done on percentages by CONISS in Anzali. A ratio pollen concentration on dinocyst concentration (P:D) has been calculated according to McCarthy and Mudie (1998) to establish the terrestrial influence versus the marine one.

4. Results

4.1 Vegetation maps

4.1.1 Amirkola vegetation

In an investigation on this wetland and surrounding areas, 320 vascular plant species were found. About 105 species grow within or just beside the wetland. Twenty-seven species are submerged and floating and others are linked to wet places around the wetland (Ghahreman et al., 2004). Moreover, fifteen plant communities from three phytosociological classes were recognized within the lagoon and its surrounding (Asri and Moradi, 2006). These communities are:

Chara vulgaris-Chara canescentis comm., *Nitella* sp. comm., *Potamogeton pectinatus* comm., *Ceratophyllum demersum* comm., *Ceratophyllum demersum-Azolla filiculoides* comm., *Nymphaea alba* comm., *Nelumbium nuciferum* comm.. *Phragmites australis* comm., *Hydrocotyle ranunculoides* comm., *Typha latifolia* comm., *Cladium mariscus* comm., *Sparganium neglectum* comm., *Cyperus odoratus* subsp. *transcaucasus* comm., *Paspalum distichum* comm., and *Carex distans* comm..

Floristically, all these plant communities can be grouped into three main groups of vegetation: a peripheral large group including hygrophytic communities (vegetation zone 1) and helophytic communities (vegetation zone 2) and a central group including the real aquatic (hydrophytic) communities (vegetation zone 3) (Fig. 2) (Table 3).

Marginal (emergent) plants: The marginal parts of Amirkola wetland possess a high biodiversity of plant species which can be classified into two groups of vegetation: hygrophytic group (vegetation zone 1) which is less adapted to water-logged conditions and prefers drier habitats and the helophytic group (vegetation zone 2) with a higher adaptation to water. Some of the most important emergent plants of the marginal parts of the wetland are presented in Table 3.

Woody vegetation around the lagoon: Two main species, i.e. *Alnus glutinosa* subsp. *barbata* and *Salix alba,* dominate the closed forest around the lagoon. *Alnus glutinosa* subsp. *barbata* forms very dense stands in the western and south-western parts of the wetland with a surface area exceeding 100 ha. *Alnus glutinosa* subsp. *barbata*, an Euxino-Hyrcanian species, grows in the Hyrcanian lowland forests. *A. glutinosa* is a hygrophytic species, which forms some communities with other hygrophytic plants in lowland areas (Hamzeh'ee et al., 2008; Naqinezhad et al., 2008). The *Alnus* stands in the Amirkola wetland were considered as a plant association, *Galio elongatae–Alnetum barbatae* (Hamzeh' ee et al., 2008). Some characteristic herbal species of this community include *Thelypteris limbosperma*, *Galium elongatum*, *Phytolacca americana* and *Polygonum barbatum*. Other important species in this community are as following: *Smilax excelsa, Ficus carica, Berula angustifolia, Ranunculus lingua, Solanum persicum, Sambucus ebulus, Rubus sanctus, Lycopus europaeus, Carex riparia, Hydrocotyle vulgaris, Sparganium neglectum, Iris pseudacorus, Phragmites australis, Prunus divaricata, Mentha aquatica, Lythrum salicaria* and *Calystegia sylvestris. Alnus glutinosa* stands of Amirkola wetland constitute an intermediate and transitional vegetation community between the lagoonal system and the Hyrcanian closed lowland forests (e.g. Naqinezhad et al., 2008).

Central part, i.e. the open water area (vegetation zone 3): The flora of this part of the lagoon can be divided into submerged and floating plants (Table 3)..

4.1.2 Anzali wetland vegetation

The wetland is bordered to the north by sand dunes with grassland and scrubby vegetation and to the south by cultivated land (mainly ricefields) and patches of woodland (Fig. 3). The dominant vegetation throughout much of the Anzali wetland consists of vast beds of *Phragmites australis*.

In total, 291 plant taxa and 32 plant communities were recognized in the Anzali wetland (Asri and Eftekhari, 2002; Ghahreman and Attar, 2003). Details of the extent of 32 plant communities are given in Table 4. These plant communities are from the Siah-Keshim part of Anzali wetland (Fig. 3). Aquatic communities in Anzali wetland, like other wetland ecosystems, are homogenous, species-poor, mostly dominated by one or two species. Some plant communities like *Hydrocotyle ranunculoides* comm., *Nelumbium nuciferum* comm., *Paspalum distichum* comm. and *Phragmites australis* comm. possessing large masses, are observed in many parts of the wetland.

The pattern of vegetation zonation in the Anzali wetland is almost similar to that of Amirkola. Three main vegetation groups occur across all parts of the Anzali wetland (Fig. 3). These vegetation groups are ecologically adapted to different levels of groundwater.

Wet places surrounding the Anzali Lagoon (vegetation zone 1): Some plant species are adapted to relatively low humidity and grow on wet places near the wetland, rivers and on vast alluvial plains related to the wetland. This habitat is affected by flooding in heavy rain situations. Most parts of wetland margin are converted to cultivated lands now, but our evidence shows that many natural forest communities such as *Alnus glutinosa* subsp. *barbata* community, *Populus caspica* community, and *Alnus–Populus* community occurred as large pure patches in the area. Now only some sporadical and small stands of *Alnus glutinosa* subsp. *barbata*, *Populus caspica*, *Punica granatum*, *Gleditsia caspica*, *Salix alba*, *Celtis australis* and *Ulmus minor* occur in the area. No community is related to a dominant arboreal species. Some parts of this habitat (vegetation zone 1) have been covered with more or less large patches of *Juncus acutus* populations. The most important wetland plant growing in this zone are shown in table 3.

Marginal parts (vegetation zone 2): The next vegetation zone of the wetland occurs close to open water areas and is characterized by emergent helophytic flora and plant communities. This part constitutes the main vegetation cover in the wetland (Table 3). Central part, i.e. the open water area (vegetation zone 3): Although most parts of this zone particularly in the deepest places are occupied by open water areas without any vegetation cover, submerged and floating plant communities characterize the vegetation zone of this part (Table 3).

4.2 Lithology/sedimentology

Amirkola

The Amirkola cores generally consist of dark grey to yellowish silt and clay with horizons of sands and organic materials. The sandy layers contain articulated bivalves mostly of *Cerastoderma lamarcki, Didacna, Dreissena s. str.* and *Theodoxus pallassi*. Also frequently interspersed are plant remains, *Phragmites* and gastropods (Fig. 5 and 6). The content of organic matter increases from the base to the core tops. The calcium carbonate content shows an overall ascending trend along the cores with however a maximum reached earlier than the maxima of organic matter.

More especially, the lithology of core HCGL02 is from bottom to top:
98-81 cm: dark grey fine sands with fine dispersed plant remains.
81-70 cm: grey clay
70-55 cm: brown clay with very scattered *Phragmites* remains
55-44 cm: grey clay with gastropod fragments and *Phragmites* remains
44-29 cm: gastropod-rich silty mud with scattered fragments of *Phragmites*
29-25 cm: dark grey silty peat with *Phragmites* remains
25-0 cm: *Phragmites* peat.
This core is distinctively different from the two other cores with its very high content of organic matter in the top third of the core, probably due to its closer proximity to the shores. The magnetic susceptibility of core HCGL02 shows two peaks, the second one clearly in line with the brown clay.

Anzali

The visual characteristics and the sedimentology of the Anzali cores demonstrate the presence of a fine-grained dark grey sediment (Fig. 5 and 6). The amount of organic material varies along the cores without significant trend. Carbonate content has a background of 5% and a maximum of 25%. Silt and clay are the dominating fractions of the Anzali sediment. Sand-bearing layers appear in disconnected horizon along the cores.

More especially, for Anzali core HCGA05, the visual description is the following. The basal 20 cm contains a series of dark and grey muddy sediment: it has the highest contents of organic matter, carbonates and sand. Besides this, the physical properties of the sediment vary little. At around 100 and 40 cm depth, two layers of organic-rich material occur. Discrete occurrences of sand occur only up to 64 cm depth. The top 25 cm consists of grey and light brown fine-grained material. The magnetic susceptibility is relatively stable, with slightly higher values at 138-130 cm depth.

4.3 Chronology

For the Amirkola cores, two ^{14}C dates provide us with a reasonably good estimation of the sedimentation rates in the eastern part of the western lobe of the lagoon despite the plateaux due to the young ages. For HCGL02, the calibrated age of a wood fragment gave an age of AD1750 at 63-62 cm depth (Table 5). Therefore the base of the core could be extrapolated at AD 1620 with a sedimentation rate of 0.25 cm per year. For core HCGL04 (Table 5), a calibration could not been obtained using marine04.14C due to the too young age of the shells. In such young sequences, dating shells is more problematic than wood due to the existence of a reservoir effect and the uncertainty regarding which one to use, that of marine04.14C (Hughen et al., 2004) or another one. Indeed in the literature, various reservoir effects for the CS may be found to correct radiocarbon dates. They range from 290 to 440 yr with: 383 yr in Leroy et al. (2007), 290 yr in Kroonenberg et al. (2007), 390-440 yr in Kuzmin et al. (2007), and 345 to 384 yr in Karpychev (1993).

In the Anzali core HCGA05, the sedimentation rate is estimated as 0.5 cm yr^{-1} by using the CIC model based on experimental results. The total error in estimating unsupported ^{210}Pb is in the range of 8-19%. This sedimentation rate result is within the range of 0.1-0.6 cm yr^{-1} determined by independent studies on sedimentation rate in Anzali Lagoon also using radionuclids (JICA, 2004; Ardebili, 2005). Therefore the base of core HCGA05 is estimated at AD 1670.

4.4 Palynology

Amirkola

Overall the pollen diagram from Amirkola is largely dominated by *Alnus*, with a significant abundance of *Carpinus* and Poaceae (Fig. 7). Four pollen zones were identified. In pollen zone Am2-1, *Alnus* percentages reach a maximum of 72%, while *Carpinus, Fagus, Quercus, Parrotia persica, Pterocarya* and *Ulmus-Zelkova* display continuous curves. In the non-arboreal pollen, *Artemisia* and Poaceae are relatively abundant. Pollen zone Am2-2 and 3 (70 to 53 cm) are characterised by very sharp fluctuations of *Alnus* with a decrease to 12%. The Amaranthaceae-Chenopodiaceae, Asteraceae, *Artemisia*, Caryophyllaceae, and Cyperaceae largely benefit from this. A range of anthropogenic indicators including *Cerealia*-t., *Centaurea* (*C. solstitialis*-type), *Juglans*, *Morus*, and probably *Polygonum aviculare*-type pollen and the undeterminable grains are showing a brief abundance. The concentration in pollen and spores is minimal. The microcharcoals, already present in the zone below, display extremely high values in line with the brownish colour of the sediment. Then in pollen zone Am2-4, the spectra are roughly similar to pollen zone Am2-1, although the Poaceae are slightly more abundant. Towards the top of this zone, *Cerealia*-t. is again frequent. In this zone the aquatic taxa are abundant, with at first *Zannichellia palustris* and *Potamogeton* and then *Nymphaea* and *Typha-Sparganium*. *Pediastrum* is frequent at first; it is then followed by *Botryococcus* and various spores. Charcoal values are very low.

Three zones were identified in the dinocyst record. In the first part of dinozone Am2-1 up to 83 cm depth, some dinocysts and foraminifera are present in low numbers and become very scarce in the second part of this zone (Fig. 7). The dinocysts reflect the modern assemblages of the CS (Marret et al., 2004). In dinozone Am2-2 from 50 cm depth upwards, the assemblages change with the foraminifera and dinocysts being replaced by thecamoebians.

The four modern samples taken in the alder forest of Amirkola (R1 to R4) are completely dominated by pollen of *Alnus* (Fig. 8) and provide an extremely local signal whereas the three others samples taken in surrounding landscapes with lower density of alder trees better reflect the regional vegetation. The alder forest samples are the closest to the assemblages of pollen zone Am2-1. Sample a2 taken on the bark of a willow tree shows high values of *Salix*, while sample a3 taken in the *Phragmites* belt contains a good range of aquatic taxa and NPPs. The recently introduced *Azolla* fern is illustrated both by microspores and by massulae with the typical glochidiae (Leroy, 1992) in these modern spectra but not visible in the sedimentary sequences.

Anzali

Overall, the AP part of this diagram is dominated by *Carpinus betulus*-t., with a good abundance of *Alnus, Fagus, Quercus, Parrotia persica, Pterocarya* and *Ulmus-Zelkova* (Fig. 9). Within the non-arboreal pollen, Poaceae and Cyperaceae are the most abundant. The anthropogenic influence can be observed with the presence of *Vitis, Juglans* and *Cerealia*-t. and with the occurrence of isolated pollen rains of *Olea, Diospyros, Cucumis* and *Secale*-t. This situation changes little throughout the diagram, if not with slightly higher Cyperaceae in An5-1 and more *Alnus* in An5-2. A relatively large diversity of aquatic taxa and spores is present. A few grains of *Ruppia* occur in An5-2. Regarding the NPPs, green algae, such as *Botryococcus*, *Pediastrum boryanum* and *Tetraedron* are very abundant in the first samples of zone An5-1. Their values then drop and remain low throughout An5-2. These algal remains are frequent to abundant in zone An5-3. Incertae sedis 5b, *Pterosperma* and foraminifera indicate the influence of the CS and these microfossils are frequent in the middle and top part of zone An5-1, and in most of An5-2.

Dinozone An5-1 is a short zone characterised by a clear dominance of *Spiniferites cruciformis*, typical of slightly brackish waters (Leroy et al., 2007). In Dinozone An5-2, the cysts of *Impagidinium caspienense* and of *Lingulodinium machaerophorum* form B are dominant, showing assemblages closer to those of the open CS (Leroy et al., 2007; Marret et al., 2004). Dinozone An5-3 sees the return of *S. cruciformis*, this time with moderate values alongside *I. caspienense*.

5. Interpretation and discussion

5.1 Sediment sources and lagoon history under various sea levels

In general the present study, confirming previous studies, indicates that the spits formed during Holocene high stands (Kroonenberg et al., 2000; Lahijani et al., 2009) have their source of sediment in the river supply and littoral drift.

The Amirkola Lagoon without river inflow is mainly infilled by eroded rice fields and vegetation. However, in the past, the Amirkola Lagoon had free water exchange with the CS (Fig. 10). The presence of articulated brackish bivalves in the sediment cores proves this connection. The latter closed later due to fluvial supply of the old Sefidrud redistributed through littoral drift. A likely evolution of the present lagoon, with no change in sea level, would be the closing up of its surface with vegetation and sediment containing increased organic matter content. However, if the sea level continues to rise, a renewed invasion by the sea can easily happen. For comparison, the Turali barrier formed during sea level rise after AD 1977.

The regional geological setting has determined a change in shoreline direction from N – S in west Guilan to W – E in the central Guilan (Fig. 10). The southward longshore current strength declines in the Anzali region, which causes a reduction in water energy and the settlement of sediment. This led to the formation of the Anzali spit (Lahijani et al., 2009). Sediment for littoral drift is supplied from western Guilan rivers (Lahijani et al., 2008). During historical highstands, the Anzali spit broke into barriers with inlets. Therefore the Anzali Lagoon could receive more brackish seawater. It provided condition for bivalves that are frequent in marine water such as *Cerastoderma lamarcki* (Lahijani et al., 2009). Moreover, rivers crossing the Anzali Lagoon and barriers could nourish the Anzali spit (Fig. 10). Nowadays, the low energy environment in Anzali Lagoon allows deposition of fine-grained materials. The supply of nutrients from natural and anthropogenic sources and the dominantly limnic situation provide better environment for lagoonal vegetation. The high amount of organic material in the core sediments reflects the eutrophic environment of the Anzali Lagoon. In the future under rising sea level, the spit would again break up into barrier islands.

5.2 Vegetation and vegetation history

Both the Amirkola and Anzali wetlands are characterized as "aquatic wetlands" contrary to "telmatic wetlands" according to classification of Wheeler and Proctor (2000). A more or less similar zonation pattern occurs in both wetlands which is also consistent with many freshwater wetlands vegetation zonation elsewhere (e.g. Mitsch and Gosselink, 2000). In both wetlands, three main vegetation zones with specific floristic composition and plant communities for each zone have been recognised from land to water. All these vegetation zones are ecologically adapted to different levels of ground water.

The water depth is higher in the Anzali wetland and thus open water area in this wetland is larger than in Amirkola. Many parts of the open water area in Anzali Lagoon have no vegetation, except the Siah-Keshim part that has accumulated large amounts of aquatic submerged and floating plants.

Floristically, most of the plant species are the same in the two wetlands, except a few plants such as *Trapa natans, Nymphoides peltatum, Vallisneria spiralis* (all from vegetation zone 3)*, Centella asiatica* (vegetation zone 1) which occur only in the Anzali wetland, and *Ranunculus lingua* which only occurs in Amirkola. The most prominent distinguishing feature between the two wetlands is the occurrence of large patches of *Alnus glutinosa* around Amirkola (especially in its SW parts), which constitutes some plant communities together with other aquatic herbs (Hamzeh'ee et al., 2008; Asri and Moradi, 2006). Some parts of the Amirkola wetland are under desiccation because of high accumulation of aquatic herbs (especially penetration of plants from zone 2 to the centre of the wetland). One of these places is in SW of Amirkola, Mordab-e Hassan–Alideh, which is near to *Alnus glutinosa* patches.

Different hydrological regimes characterise these two wetlands, Amirkola is a closed wetland well separated from the sea; but Anzali has some river connection with the sea. From the point of view of vegetation and floristic aspects, no clear evidence of salty water intrusion appears in Anzali. This is however not the case in the palynomorph assemblages, which show clear brackish waters both in surface samples and in sediment cores (Kazancı et., 2004).

Overall, the Hyrcanian lowland and plain vegetation is rather well represented by its pollen rain in the two lagoons with taxa such as *Pterocarya, Zelkova* and *Parrotia*. In addition, the Amirkola sequence records spectra typical of a forested wetland of alder.

The pollen diagram of Amirkola starting at AD 1620 (Fig. 11) shows a dense alder forest (most certainly *Alnus glutinosa*), but less dense than those present nowadays along the lagoon (Fig. 2 and 8). This environment was regularly flooded by the sea, as indicated by the presence of dinocysts typical of the CS, until 83 cm depth, or AD 1670. The marine influence decreases until it stops at 50 cm depth, or c. AD 1800. It is followed by a brief period of slightly brackish waters as illustrated by *Z. palustris*. As soon as the water body became isolated from the sea, the anthropogenic activities locally intensified and impacted the lagoon area. People further increased the disturbance of the natural environment from 70 cm depth, or c. AD 1720, by deliberate fires most likely related to the subsequent development of rice paddies. Therefore both the ruderal species of *Artemisia annua*, and some of the long-distance transport species of steppic *Artemisia*, are possible. In the Golestan National Park (GNP on Fig. 1), the high percentages of *Artemisia annua* in some floristic relevés is due to the rapid colonization in destroyed habitats after several successive flood events; these translate into 20-40% of *Artemisia* pollen in the surface spectra (Djamali et al., 2009a). The sudden fall of *Alnus* pollen during the Am2-3 pollen zone most probably indicates a large-scale deforestation of the alder forest by humans. Many possible causes for fire are, in order of likelihood: exceptionally intense Foehn effect, competition between large landowners to get agricultural land from the forest, and the intensified boat construction and marine trade during the rule of Nadir Shah of Afsharid Dynasty AD 1722 – 1750. Abandonment of this human activity occurred at 50 cm, or c. AD 1800. In the immediate vicinity of the lagoon, the alder forest returned quickly. As the lagoon became shallower and more isolated from the sea, a range of freshwater aquatic plants developed. The recent human influence can be seen more discreetly than earlier in the form of progressively increasing Poaceae and re-occurrence of *Cerealia*-t, reflecting the rice paddies now present in the region.

The pollen diagram of Anzali starting at c. AD 1670 illustrates a stable vegetation surrounding a wetland with a good representation from vegetation zones beyond the wetland, such as along the lower slopes of the Alborz Mountains (Fig. 11). Human influence is rather weak but continuous. NPPs, dinocysts and to a lesser extent aquatic vegetation (*Ruppia*) illustrate a slightly brackish lagoon continually influenced by the CS. The salinity of the water has, however, fluctuated throughout time, with the highest values, closer to those of the CS, from 152 to 86 cm depth, i.e. from c. AD 1700 to c. 1830. Although there is no record of the occurrence of *Ruppia* in the wetland now (Asri and Eftekhari, 2002; Ghahreman and Attar, 2003), some evidence indicates that *Ruppia* grows in coastal lagoons where they are affected by the tidal cycles of the CS. For example the situation in Boujagh National Park, Guilan Province, where water flows from the CS to an inland wet depression in parts of the coast cause the formation of temporary wetlands with brackish water with *Ruppia* growth (Naqinezhad et al., 2006). Although the vegetation surveys do not show the influence of the CS, the presence of dinoflagellates in the phytoplankton survey and the sulphate concentration confirm the influence of the CS respectively in the entrance channel and far into the lagoon (Ramezanpoor, 2004).

It is interesting to note that the grab samples, collected in AD 1995 at the time of highest lake level (Kazancı et al., 2004), have *Alnus* percentages of 43 to 60 % and to compare these high values with those of the top sample of core HCGA05 at 11 cm depth or AD 1982, which is therefore older than the grab samples, and which has much lower percentages. The whole core never reaches values higher than 38 %. It is generally known that *Alnus glutinosa* penetrates as an invasive community in wetlands that are desiccating. According to ecological succession, the alderwood community is the next seral community after the open water community toward drier inland forest. Some investigations have been carried out both on the succession from open water to alderwoods of Alnion glutinosae, which is generally considered as a final successional stage, and also on the further succession towards more drier Alno–Ulmion communities (e.g. McVean, 1956; Fremstad, 1983; Prieditis, 1997; Kollar, 2001). The result of Kazancı et al. (2004) could indicate that in the recent years a natural afforestation occurs due to the accumulation of aquatic plant litter (large mats of *Phragmites* and other marginal plants) and subsequent mineralization in the open water parts of Anzali wetland with penetration of *Alnus* in these parts (e.g. Prieditis, 1997; Naqinezhad et al., 2008).

Overall, the diagram of Muzidarbon, south of Nowshahr, has less *Fagus, Quercus, Parrotia, Ulmus-Zelkova*, Amaranthaceae-Chenopodiaceae, *Artemisia* and Poaceae than the two lagoonal diagrams, but more *Carpinus*, reflecting the vegetation directly around the mire (Ramezani et al., 2008). The modern spectra of Amirkola fall in the same category of a record dominated by local vegetation. Anzali being a relatively large and open lagoon is able to record both local and regional vegetation, whereas Amirkola, despite the obvious dominance of *Alnus*, a local tree species, is able nevertheless to record a range of vegetation communities. This reflects the capacity of larger water bodies, i.e. Anzali 160 km^2, versus much smaller ones, i.e. Muzidarbon, 0.003 km^2, to capture pollen rain from a larger area. At 12.3 km^2, Amirkola is of intermediate size and behaviour. An additional factor for the higher diversity of community represented is the river input to Anzali, virtually absent from Amirkola and Muzidarbon. These two factors, size of the open water body and size of catchment, have long been recognised in the literature to increase the record of the regional vegetation rather than local one (e.g. Pennington, 1979; Jackson, 1990).

5.3 Climate and sea levels

The more marine phase of the Amirkola core, from core base to 50 cm depth and the more marine phase of the Anzali core between 152 and 86 cm depth, seem to be largely synchronous, dating to before AD 1800 in one case and AD1700-1830 in the other (Fig. 11).

This corresponds to the high water levels of the LIA and agrees with data from Brückner (1890). It was found that the CS level was 3 m higher around AD1800 than 1835 according to markings on a coastal wall in Baku; also the Derwisch and Naphtha Islands (off Cheleken in Turkmenistan) were separated from AD1809 to 1814 and united by AD1819. Further evidence for a brief low CS level was found around AD1719 to 1730, which was followed by a high level in the 1740s obvious from several islands that could be seen before and later submerged. The Derwisch and Naphtha Islands were separated by a 3.0 to 3.7 m deep channel that could be crossed by foot around AD1720. Roughly one can say that the CS had a low level, similar to the present one, with an increase around AD1730 by 3 m and stayed high until 1809, i.e. considerably higher than now. After that, the CS level dropped sharply by 3.5 m to a level similar to the present and remained nearly stable for more than 100 years.

During the LIA, Kroonenberg et al. (2007) reconstructed high water levels from the barrier of Turali (Dagestan), which agree with the findings by Brückner (1890). They explained these higher sea levels by a decreased evaporation over the CS and/or enhanced precipitation over the very large CS basin, which they hypothesised correlated with a lower solar activity.

The recent high levels over the last 30 years are not visible in Amirkola as the lagoon is now closed and too remote from the sea, whereas in Anzali the last sample at 11 cm depth, or AD 1982, with a re-increase of *I. caspienense,* could be a sign of the recent high levels.

In the high altitude peat of Lake Almalou, the LIA has also been recorded by high water table caused by lower evaporation, lower summer temperatures and/or higher annual precipitation (Djamali et al., 2009b). All these records agree in reconstructing more rainfall and higher water levels during the LIA. Similar to the CS, Lake Almalou also had a high stand during the LIA. This suggests that the cause for the high level of the CS does not stem from the Volga alone but caused by regional climatic factors.

6. Conclusions

The southern part of CS, particularly the SW corner, with its subtropical and humid Mediterranean climate hosts very specific Hyrcanian vegetation. This climate is an island of high precipitation in an otherwise belt of continental dryland. The moisture is clearly brought to the area by winds mainly from the CS.

Combined analysis of pollen grains for terrestrial and aquatic vegetation reconstruction, NPPs for parameters linked to water, dinocysts for past salinities and sedimentological analyses appear to be suitable to reconstruct past climatic and hydrological (sea level) changes in these environments. In this case of minor climatic fluctuations over the last few centuries, the investigation of terrestrial vegetation alone would not suffice, as the signal is subtle and susceptible to anthropogenic modification. Fortunately, the study of the full range of palynomorphs offers a comprehensive multiproxy approach.

The site of Amirkola shows a recent (*ca* 18th century) and temporary destruction of the alder coastal forests especially by fire. Our data indicate that the wetland forest can potentially recover quickly, although not completely. After a high stand, the lagoon becomes increasingly isolated from the sea.

In Anzali, the regional terrestrial vegetation is rather stable, except that the water body becomes more or less open to the sea. Specifically, during the period from c. AD 1700 to 1830, a stronger marine influence is detected in agreement with observations reported by Brückner (1890).

In both lagoons, the period of the late LIA corresponds to high water levels and contacts with the CS. However the two lagoons reacted differently to sea level rise. The high sediment supply of the Sefidrud nourished the beaches east of the Sefidrud mouth on a long distance. This easily compensated for the coastal erosion of the Amirkola spit due to sea level rise. In the case of the Anzali spit that broke into barrier islands during the late LIA, the sediment supplied through littoral drift and medium-size rivers was possibly insufficient to exceed the rate of erosional processes. The last sea level rise of the end of 20th century also opened new inlets in the lagoons of the southeast CS such as the Miankaleh and Gomishan Lagoons, whereas the Anzali spit with its high-density population was partially protected by engineering measures.

Moreover, in Amirkola, changes in the river delta geomorphology could also have had a strong influence on the lagoon evolution since the position of the main branch of the Sefidrud changes over time. The Amirkola Lagoon being in precarious equilibrium, it is not impossible to predict that under continued sea level rise, the lagoon will be once again in contact with the CS.

A comparison of these two lagoons of the south of the CS to other sites, Lake Almalou and the Turali barrier, indicates that the LIA climate was regionally cooler and wetter, possibly also with less evaporation leading to higher levels in the CS and other water bodies of the NW continental Middle East.

Overall our observations fit with the idea, proposed earlier by some authors for the Caspian Sea to explain the wide Quaternary sea level variations of more than 160 m amplitude (Karpychev, 1993; Chalié et al., 1997): higher sea levels during cooler periods and lower sea levels during warmer periods.

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Tables

Table 1: List of core names, locations, lengths and depths. In bold, cores studied for palynology.

Site	Core name	Latitude N	Longitude E	Water depth in cm	Length in cm
Amirkola	**HCGL02**	37 21 25.6	50 11 42.2	100	95
	HCGL03	37 21 7.2	50 11 42.3	200	33
	HCGL04	37 20 33.1	50 11 33.4	200	80
Anzali	**HCGA05**	37 26 56.6	49 22 49.8	300	170
	HCGA04	37 27 06.7	49 23 35.7	300	164
	HCGA08 (= PLS08)	37 26 56	49 22 49	300	92

Table 2: Phytosociological surveys 25 by 25 m around the moss pollsters and forest litter taken for modern pollen rain in the Amirkola wetland. The number opposite to each plant indicates its cover-abundance according to the Braun-Blanquet scale. DBH = diameter at breast height.

Relevé number	R1	R2	R3	R4
Average DBH (in cm)	27	24	21	23
Number of trees	4	11	15	18
Associated species				
Alnus glutinosa subsp. *barbata*	3	4	5	5
Berula angustifolia			1	
Calystegia sylvestris		1	1	
Carex riparia	4	4	1	1
Ficus carica	2	2	1	1
Galium elongatum	1	1	1	1
Hydrocotyle vulgaris		2	1	1
Iris pseudacorus	1	1	2	1
Lycopus europaeus	1		1	
Nasturtium officinale				1
Polygonum sp.	1		1	1
Prunus divaricata				1
Ranunculus lingua				1
Ranunculus scleratus	2			
Rubus caesius	1		1	
Rubus sanctus	1	1	1	1
Rumex sanguineus			1	
Sambucus ebulus	1	1	1	
Smilax excelsa	2	1	1	1
Solanum dulcamara		1		1
Thelypteris limbosperma	1	2	2	2
Urtica dioica			1	

Species collected around the relevés

Sparganium neglectum, Cladium mariscus subsp. *mariscus, Rumex conglomeratus, Ulmus minor, Polygonum hydropiper* subsp. *hydropiper, Solanum nigrum, Sonchus oleraceus, Periploca graeca, Phragmites australis, Phytolacca americana, Cardamine hirsuta, Carex remota* subsp. *remota, Lythrum salicaria, Mentha aquatica, Geum urbanum, Humulus lupulus, Cornus australis*

Table 3: List of the most important plants found in each vegetation zone in Amirkola and Anzali wetlands. Underlined species are found exclusively in Anzali. The species with asterisk are only found in Amirkola.

Vegetation zone 3	
Floating plants	Submerged plants
*Azolla filiculoides, Hydrocharis morsus-ranae, Lemna gibba, L. minor, Nymphaea alba, Nymphoides peltatum, Potamogeton natans, P. nodosus, Ricciaocarpus natans** (aquatic liverwort), *Salvinia natans, Spirodella polyrhiza, Wolfia arhyza*.	*Batrachium trichophyllum, Callitriche palustris, Ceratophyllum demersum, Chara fragilis* (green algae), *Hydrilla verticillata, Lemna trisulca, Myriophyllum spicatum, Najas* spp., *Nitella spp.* (green algae), *Potamogeton crispus, P. lucense, P. pectinatus, P. pusilus, Riccia fluitans** (aquatic liverwort), *Utricularia neglecta, Vallisneria spiralis, Zannichellia palustris*.
Vegetation zone 1	**Vegetation zone 2**
Abutilon theophrasti, Alnus glutinosa subsp. *barbata, Alisma plantago–aquatica, Bidens tripartita, Butomus umbellatus, Centella asiatica, Coix lacryma-jobi, Gleditsia caspica, Kosteletzkya pentacarpa, Inula britanica, Ludwigia palustris, Lythrum salicaria, Mentha aquatic, Ranunculus dolosus, R. scleratus, Sagittaria trifolia, Smilax excels, Rubus* spp., *Pterocarya fraxinifolia, Populus caspica, Polygonum* spp., *Salix* spp.	*Berula angustifolia, Cladium mariscus, Galium elongatum, Hydrocotyle ranunculoides, Iris pseudacorus, Nasturtium officinale, Nelumbium nuciferum, Phragmites australis, Pteridium aquilinum, R. lingua*, Schoenoplectus lacustris, Solanum dulcamara, Solanum persicum, Sparganium neglectum* , *Typha* spp.

Table 4: Plant communities within three main vegetation zones in the Anzali wetland. The cover percentage for each community is estimated only in Siah-Keshim wetland (the southern lobe of the Anzali wetland).

Plant community	**Some other characteristic or companion species**	**Approx. %**
Vegetation zone #1		**8.9**
Bidens tripartita-Polygonum hydropiper	*Cyperus fuscus, Fimbristylis bisumbellata, Cyperus difformis*	5.5
Paspalum distichum		0.8
Rorippa islandica		0.4
Cyperus serotina		0.4
Alisma plantago-aquatica-Sagittaria sagittifolia		0.4
Carex riparia	*Berula angustifolia*	0.4
Juncus effuses	*Polygonum hydropiper*	0.4

Cyperus longus		0.4
Bidens cernua		0.2
Vegetation zone #2		**51.1**
Phragmites australis	*Solanum persicum, Azolla filiculoides, Sparganium erectum subsp. neglectus*	35.2
Sparganium erectum var. neglectum	*Berula angustifolia, Nasturtium officinalis*	13.2
Typha latifolia	*Phragmites australis, Paspalus distichum*	1
Nelumbium nuciferum		0.4
Schoenoplectus lacustris		0.4
Hydrocotyle ranunculoides		0.4
Iris pseudacorus		0.4
Nasturtium officinalis	*Alisma plantago-aquatica, Berula angustifolia*	0.1
Vegetation zone #3		**15.8**
Trapa natans-Potamogeton crispus	*Wolffia arrhiza, Zannichellia palustris, Azolla filiculoides*	11.1
Lemna minor-Azolla filiculoides	*Wolffia arrhiza, Lemna trisulca*	1.2
Lemna minor-Spirodella polyrrhiza	*Azolla filiculoides*	0.1
Lemna minor-Lemna trisulca	*Utricularia neglecta, Wolffia arrhiza*	0.1
Salvinia natans	*Azolla filiculoides, Spirodella polyrrhiza*	0.1
Hydrocharis morsus-ranae	*Utricularia neglecta*	0.1
Utricularia neglecta	*Lemna trisulca, Zannichellia palustris*	0.1
Trapa natans-Potamogeton pectinatus		2
Potamogeton pectinatus		0.4
Ceratophyllum demersusm		0.1
Hydrilla verticillata		0.1
Myriophyllum verticillatum		0.1
Batrachium trichophyllum		0.1
Marsilium quadrifolia-Callitriche brutia		0.1
Potamogeton nodusus		0.1

Table 5: Radiocarbon dates of Amirkola Lagoon

core	depth in cm	dated material	lab n°	^{14}C yr BP	calibrated age (1 σ)	δ^{13}C ‰
HCGL02	63-62	*Alnus* wood	Poz23314	150 ± 25	AD1779-1727 or AD 1750 (1)	n/a
HCGL04	60-58	shells	UB15740	379 ± 25	too young (2)	-2.3

(1) intcal04.14C, Reimer et al., 2004
(2) marine04.14C, Hughen et al., 2004

Captions

Fig. 1: Location maps

1a: Location of the lagoons of Anzali and Amirkola and the main inflows to the Caspian Sea.

1b: Location of the Caspian Sea in relation to neighbouring countries with main sites cited in the text (asterisk), GNP = Golestan National Park; KBG = Kara-Bogaz Gol.

Fig. 2: Vegetation map of Amirkola Lagoon and its surrounding with location of cored sequences and surface samples.

Fig. 3: Vegetation map of Anzali Lagoon with core locations.

Fig. 4: The climate along the north Iranian coast.

4a: Annual mean precipitation (in shades of grey) calculated from monthly means by GPCC (Rudolf et al., 2003) on a half degree grid (units: mm month^{-1}) overlaid by the orography in contours. The dashed line shows the 2000 m topographic height contour. The position of the meteorological stations is indicated by markers. Circles: ANZ = Anzali, RAS = Rasht, LAH = Lahijan, RAM = Ramsar, AST = Astara, BAB = Babolsar, TOR = Torkaman, ZAN = Zanjan; plusses: PIL = Pilimbra-Nehalestan, MAN = Manjil, GOR = Gorgan.

4b: Annual cycle of precipitation (pre) and temperature (T2m), or Koeppen diagrams, for the meteorological stations shown in fig. 4a by circle markers. Data are provided by the Iran Meteorological Organization (www.irimo.ir/english); the averages are taken for the longest time available, at least 10 years. Ordinate on the left: precipitation in mm month^{-1}, on the right: temperature in °C.

4c: Surface wind during autumn (SON) from ERAinterim (ERAin), a more modern and higher resolution than the ERA40 reanalysis by the ECMWF but with a shorter time span, overlaid by orographic height contours. The arrow lengths are proportional to the wind speed. The maximum speeds are 3 m s^{-1} and typical values in the highlands SW of Anzali are 1 m s^{-1}. Contours of orographic height at 500, 1000, 1500 and 2000 m.

Fig. 5: Lithological logs of the six cores from Amirkola and Anzali Lagoons and dating elements.

Fig. 6: Amirkola and Anzali sedimentology and magnetic susceptibility. OM = organic matter, MS = magnetic susceptibility. * = radiocarbon dates, thick vertical bar = radionuclide profile.

Fig. 7: Palynological diagrams of Amirkola, core HCGL02. 10 x exaggeration curve, dot for values lower than 5 %.

Fig. 8: Palynological diagrams of the surface samples of Amirkola, dot for values lower than 5 %.

Fig. 9: Palynological diagrams of Anzali, core HCGA05. 10 x exaggeration curve, dot for values lower than 5 %.

Fig. 10: Block diagram of the modern coast of central Guilan (top) and the blow-up of the two investigated lagoons as reconstructed for the high stand of the late Little Ice Age (bottom).

Fig. 11: Summary of the main results for the Amirkola and the Anzali palynological diagrams. Thin waves on white background: weaker marine influence, dark waves on grey background stronger marine influence.

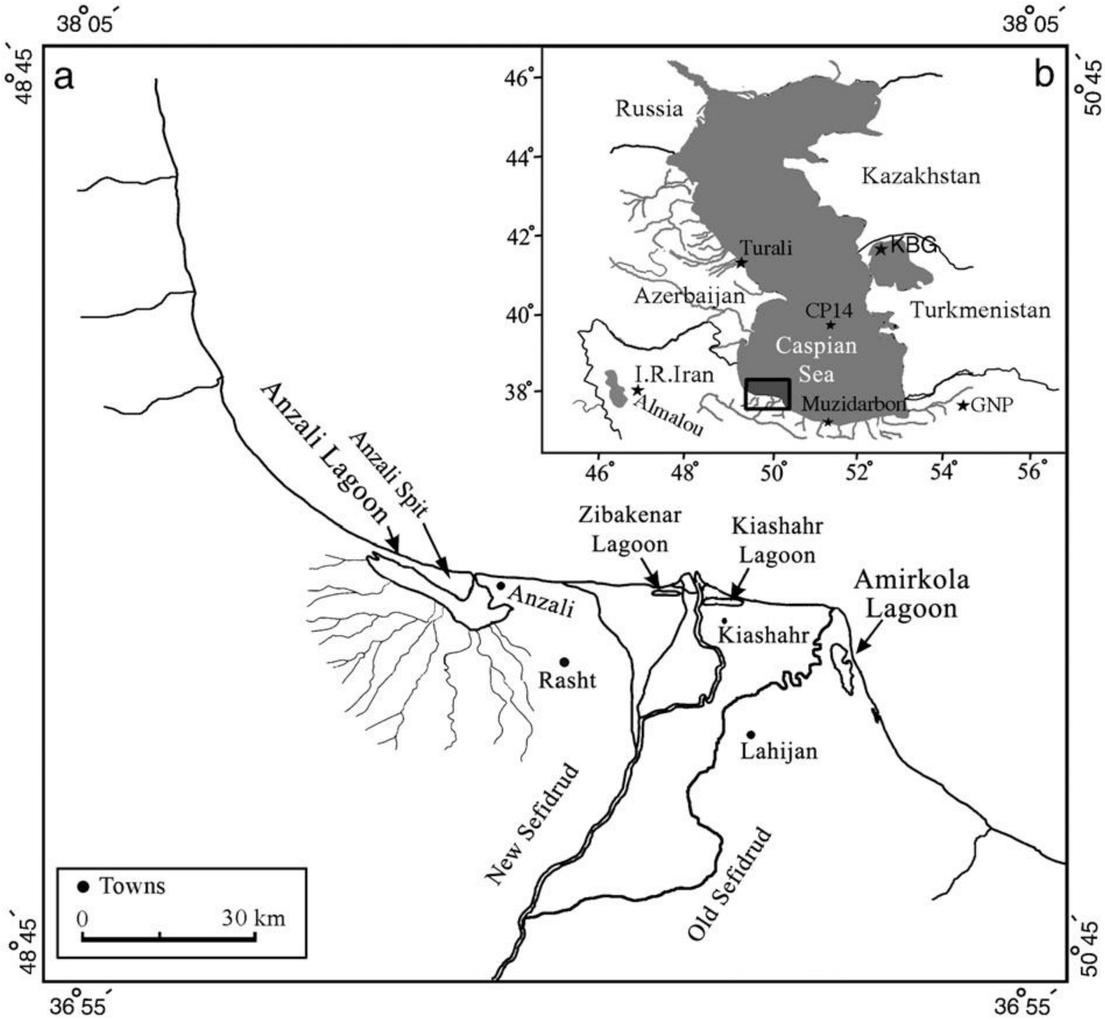
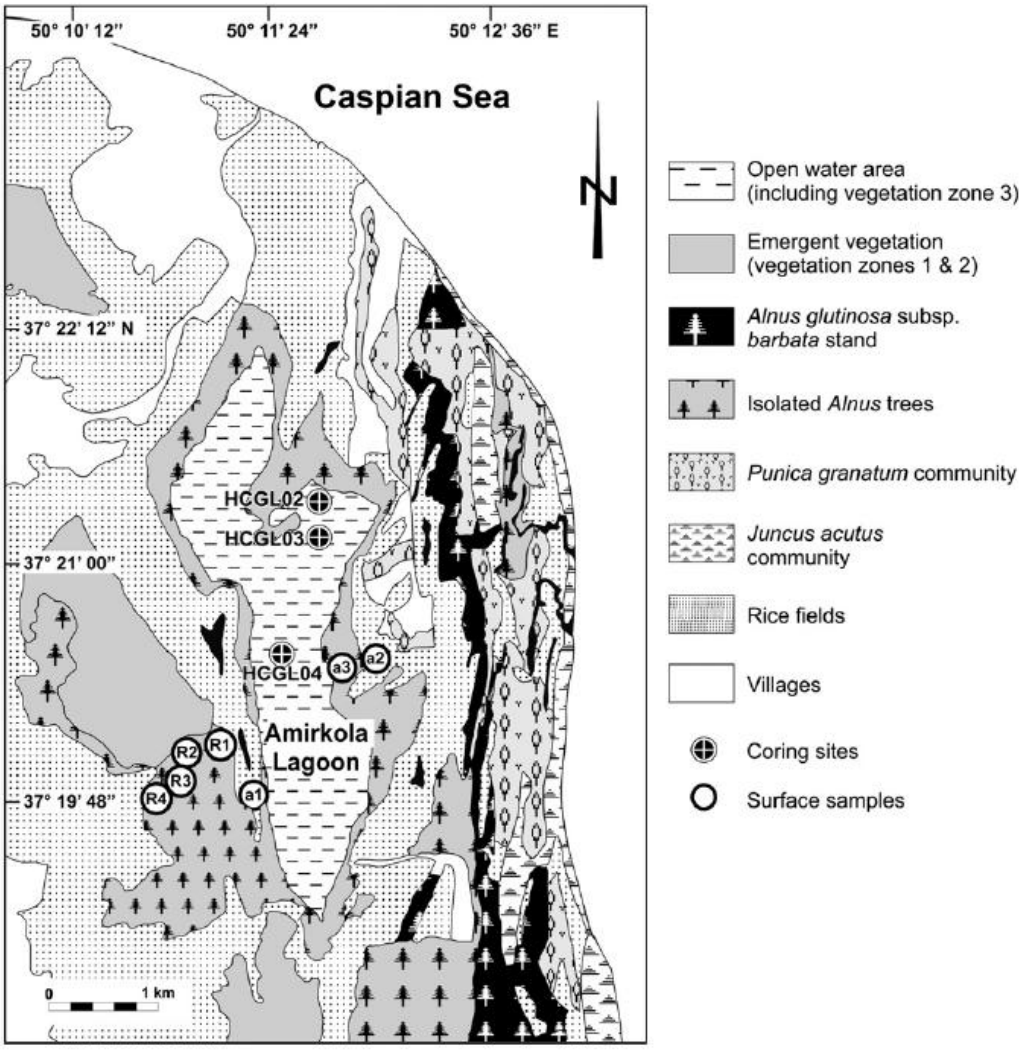


Figure 1



50° 10' 12"
50° 11' 24"
50° 12' 36" E
Caspian Sea
N
37° 22' 12" N
37° 21' 00"
37° 19' 48"
HCGL02
HCGL03
HCGL04
a1
a2
a3
R1
R2
R3
R4
Amirkola Lagoon
0
1 km
Open water area (including vegetation zone 3)
Emergent vegetation (vegetation zones 1 & 2)
Alnus glutinosa subsp. *barbata* stand
Isolated *Alnus* trees
Punica granatum community
Juncus acutus community
Rice fields
Villages
Coring sites
Surface samples

Figure 2.

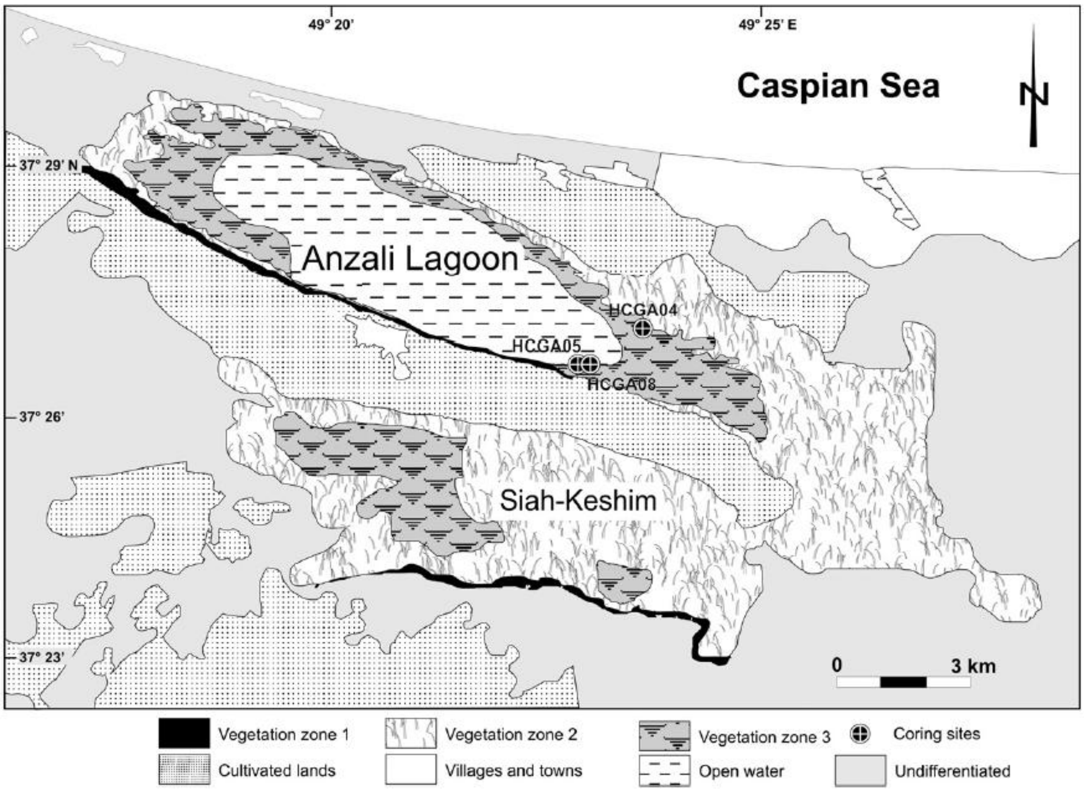


Figure 3.

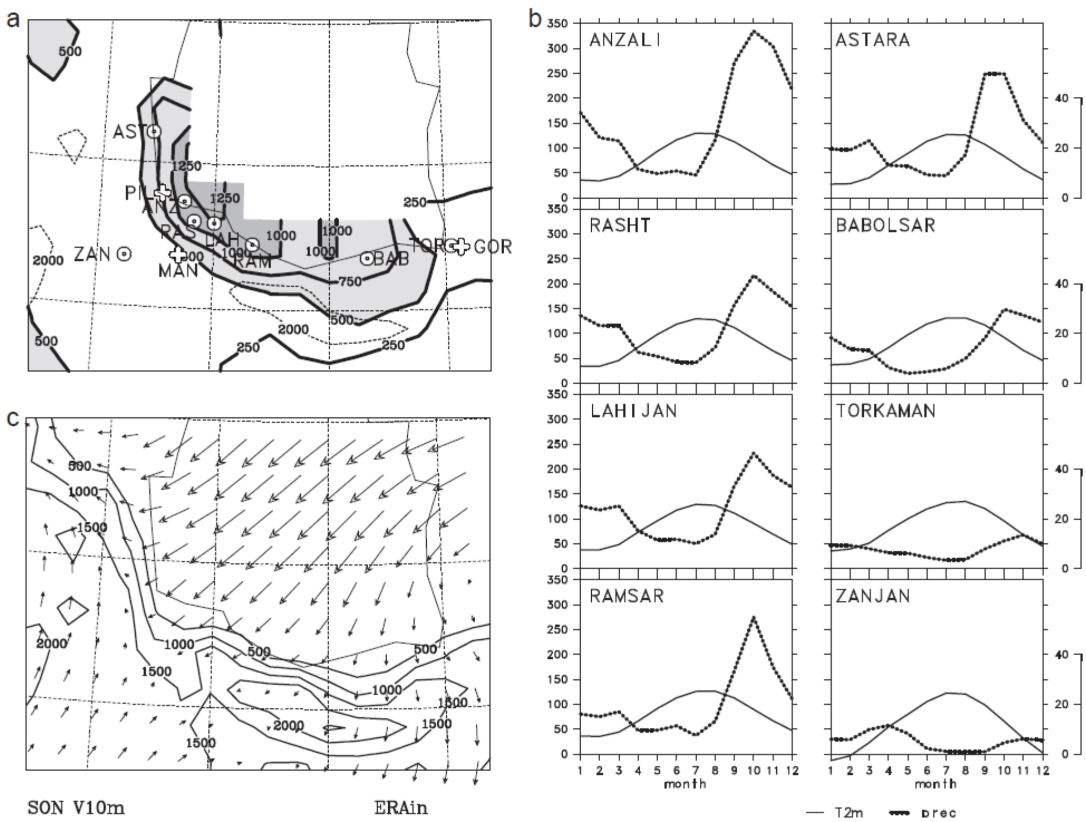
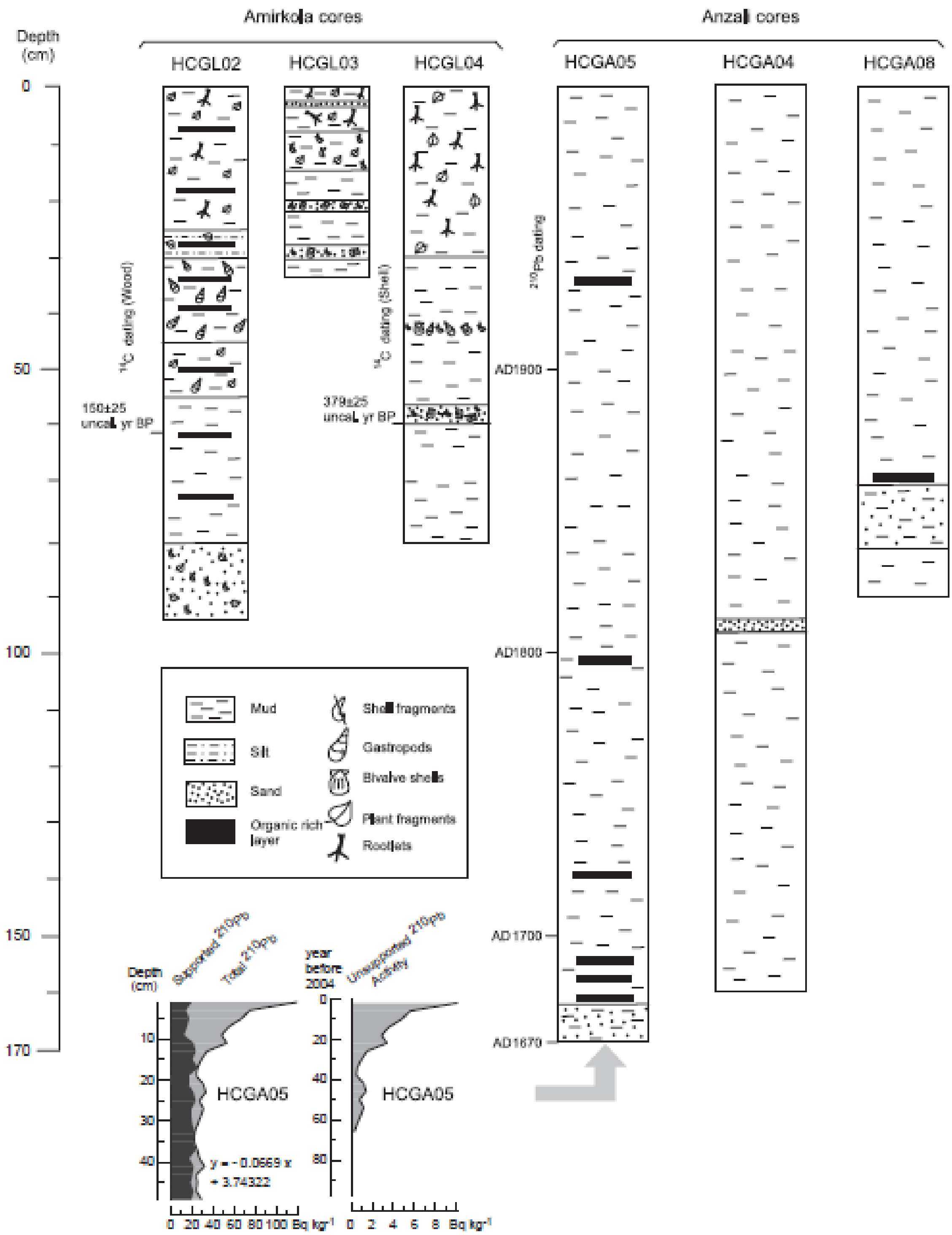


Figure 4.



1420
1421 Figure 5.
1422
1423

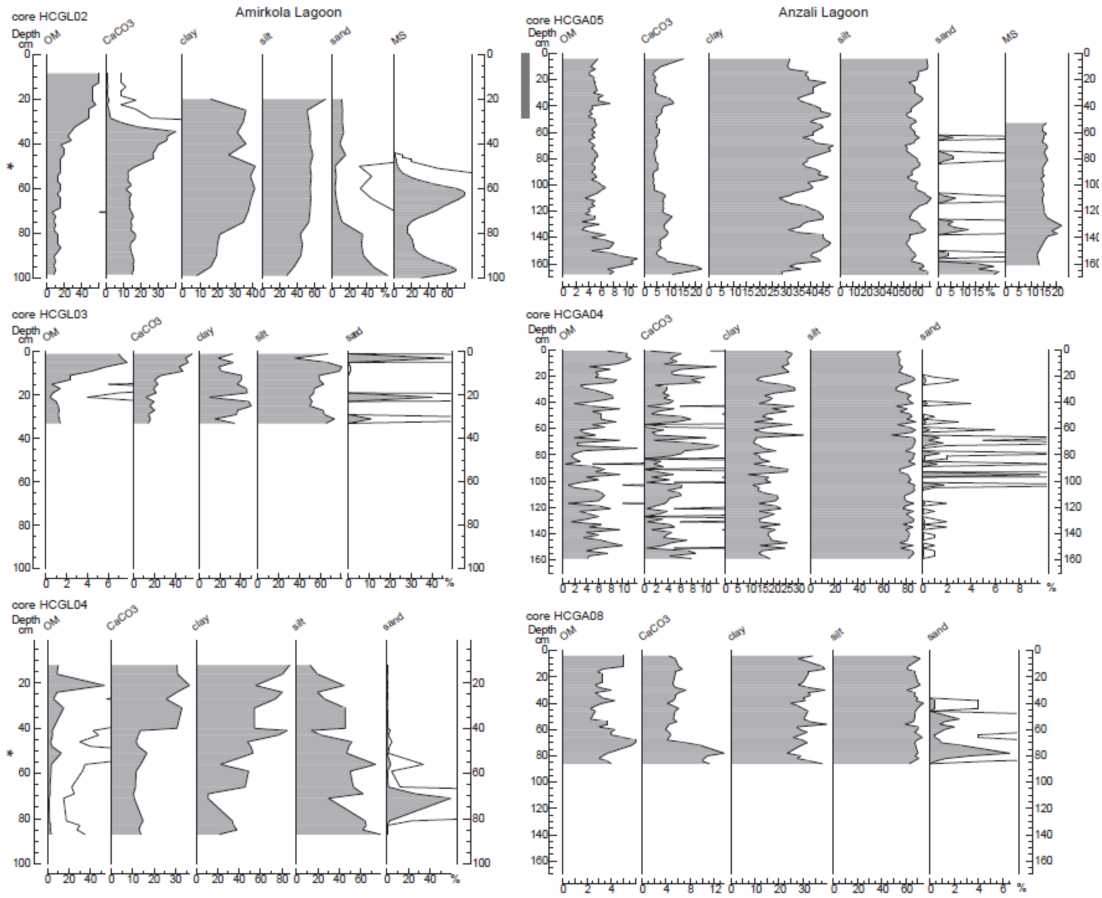

Amirkola Lagoon
Anzali Lagoon
core HCGL02
core HCGL03
core HCGL04
core HCGA05
core HCGA04
core HCGA08
Depth cm
OM
CaCO3
clay
silt
sand
MS
%

Figure 6.

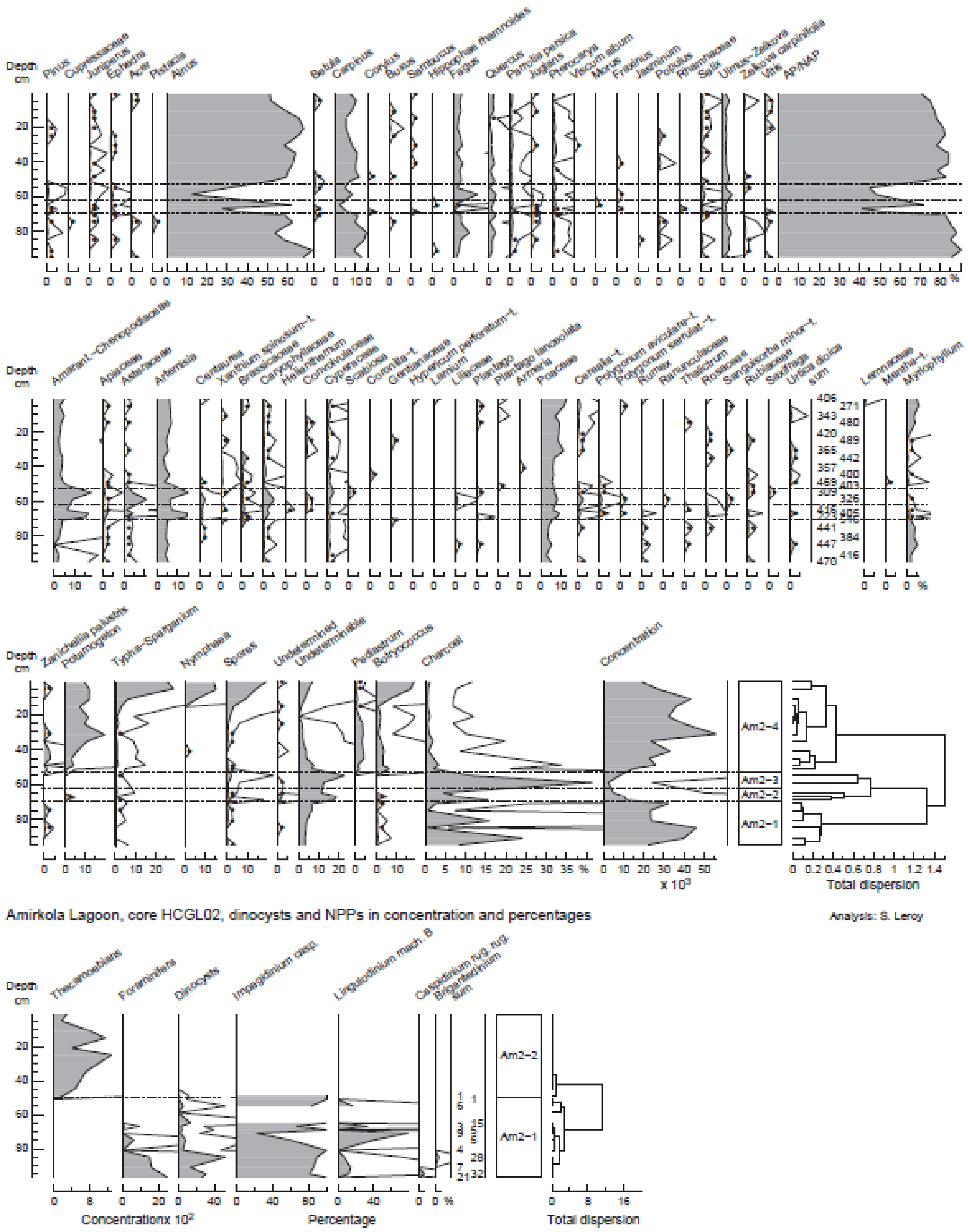

Depth cm
Am2-4
Am2-3
Am2-2
Am2-1
Total dispersion
Amirkola Lagoon, core HCGL02, dinocysts and NPPs in concentration and percentages
Analysis: S. Leroy
Concentrationx 10²
Percentage
Total dispersion

Figure 7

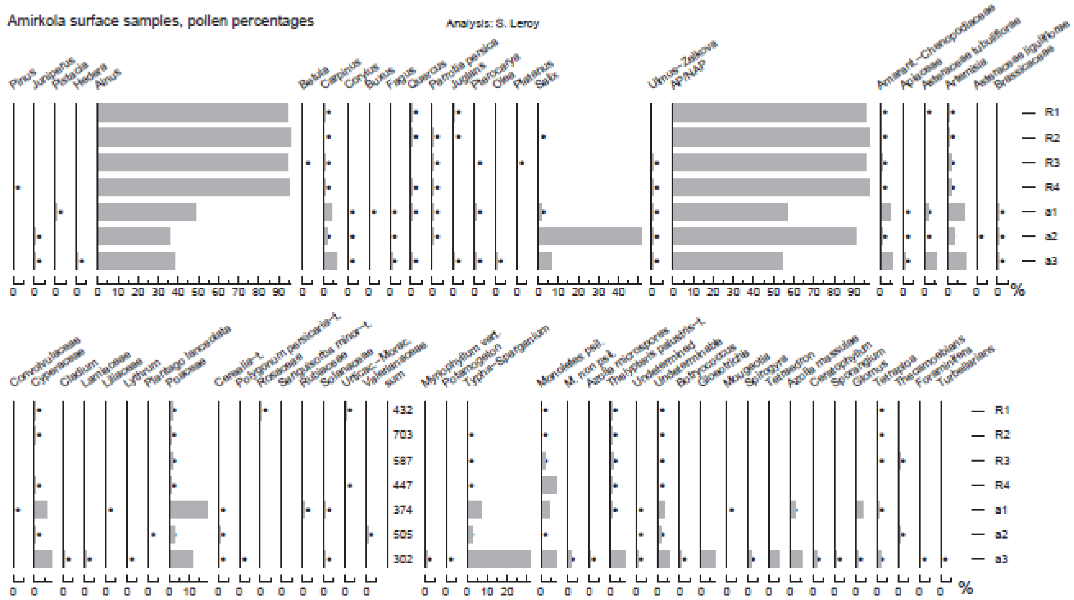

Amirkola surface samples, pollen percentages
Analysis: S. Leroy
R1
R2
R3
R4
a1
a2
a3
sum
432
703
587
447
374
505
302
%

Figure 8.

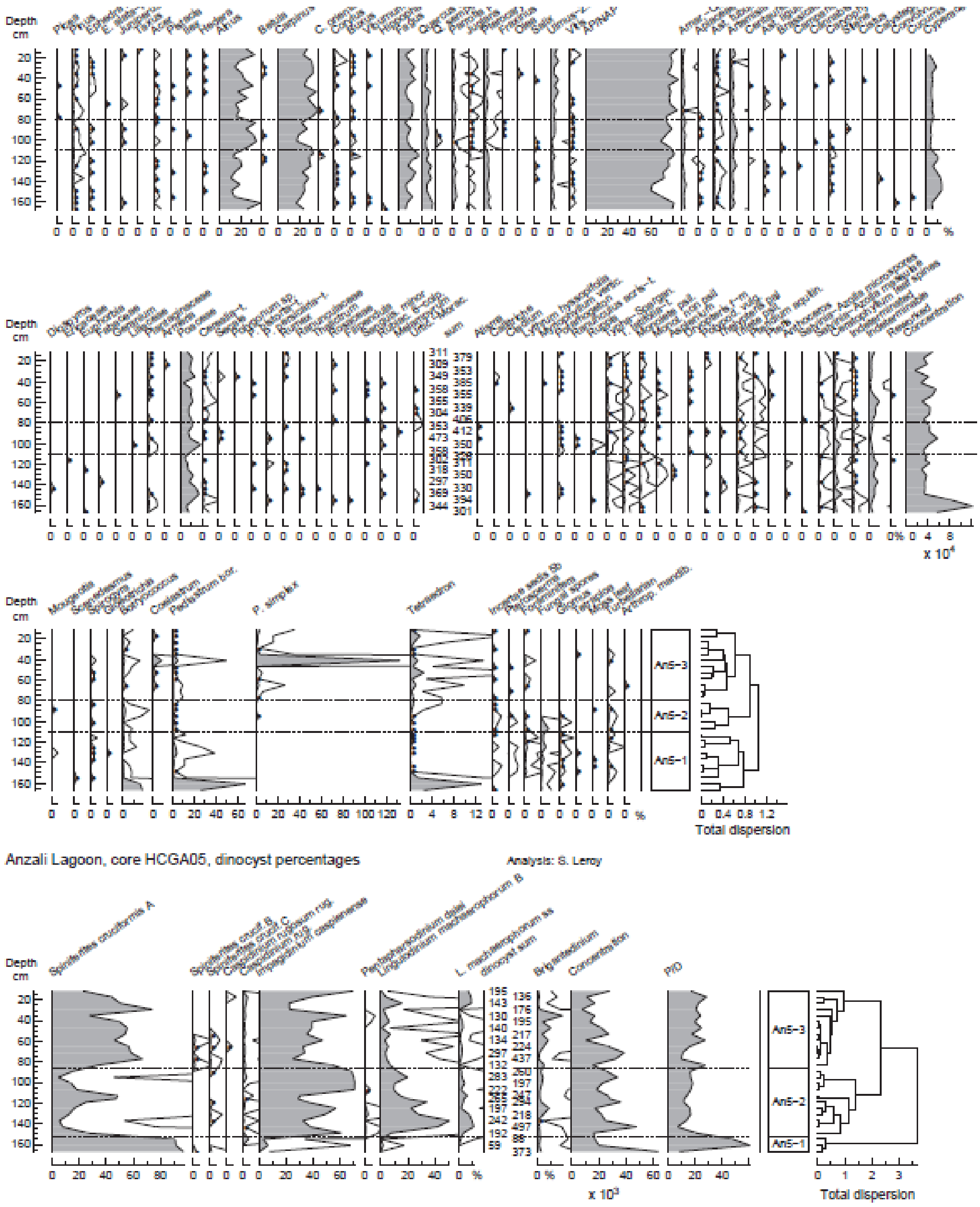

Depth cm
An5-3
An5-2
An5-1
Total dispersion
Anzali Lagoon, core HCGA05, dinocyst percentages
Analysis: S. Leroy
Spiniferites cruciformis A
Concentration
P/D
x 10³

Figure 9.

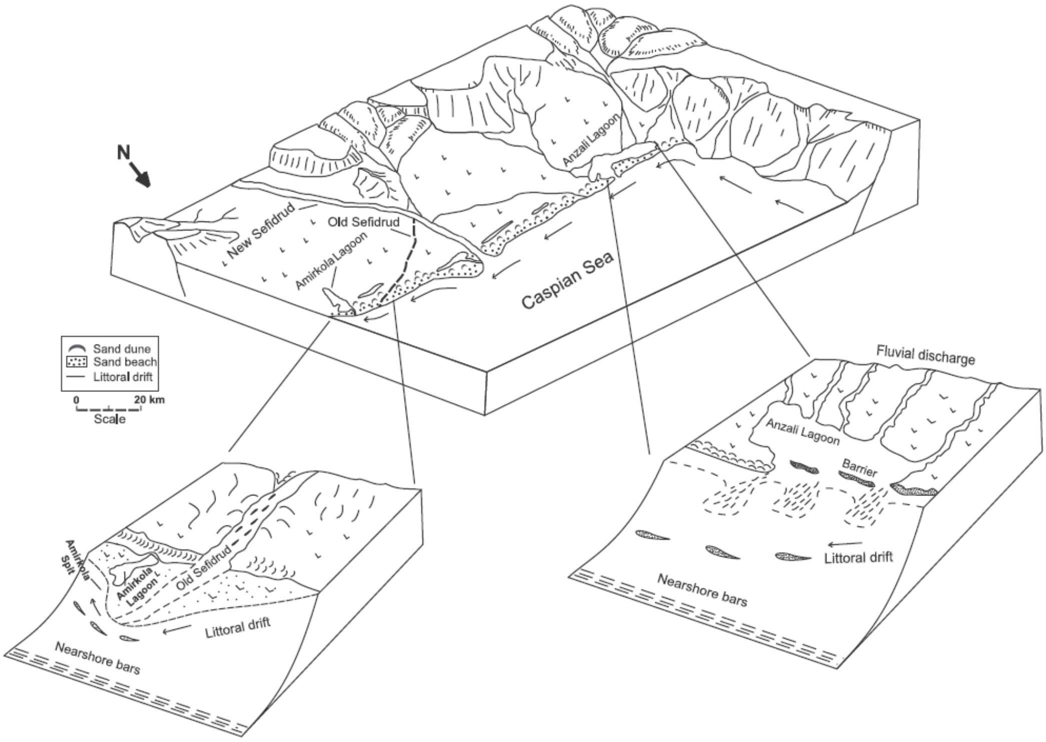


Figure 10.

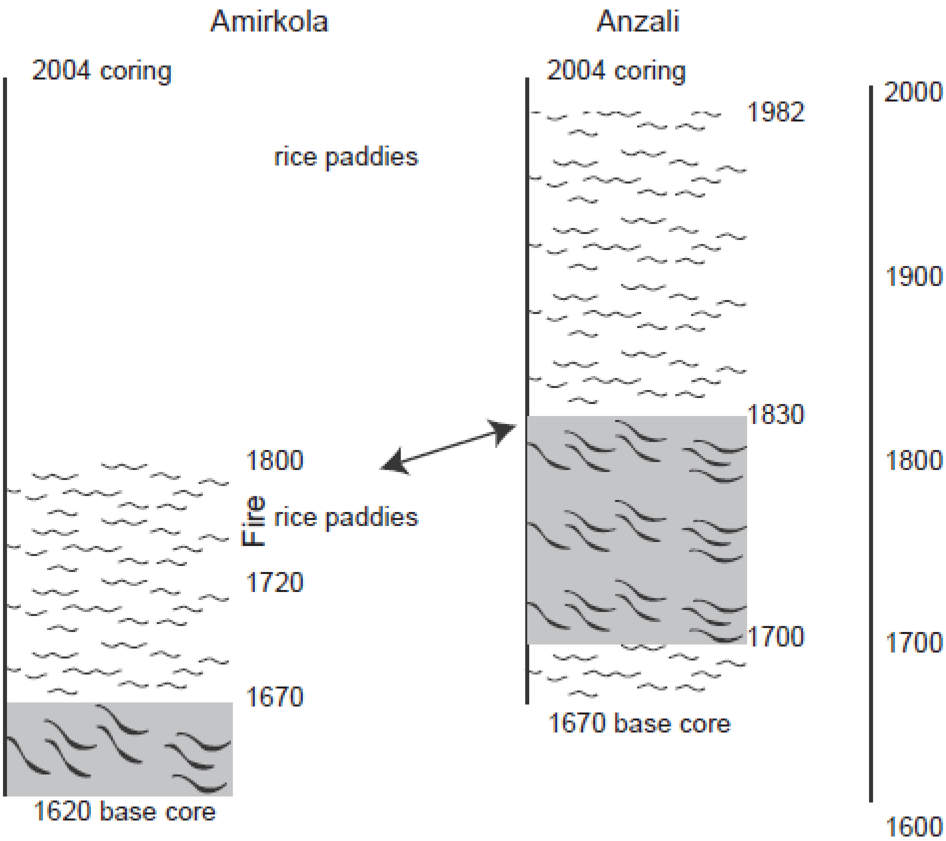


Figure 11.