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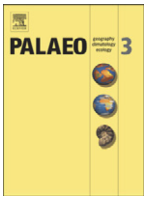

Intense storm activity during the Little Ice Age on the French Mediterranean coast

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ABSTRACT

Understanding long-term variability in the frequency of intense storm activity is important for assessing whether changes are controlled by climate evolution. Understanding this variability is also important for predicting present and future community vulnerability and economic loss. Our ability to make these assessments has been limited by the short (less than 50 years) instrument record of storm activity. Storm-induced deposits preserved in the sediments of coastal lagoons offer the opportunity to study the links between climatic conditions and storm activity on longer timescales. In this study, we present a record of these extreme climatic events that have occurred in the French Mediterrannean coast over the past 1500 years. The identification of these extreme events is based on the analysis of sediment cores from Gulf of Aigues-Mortes lagoons that contain a specific sedimentary and geochemical signature associated with intense storms.

Overwash deposits do not show any evidence of intense storm landfalls in the region for several hundred years prior to the late 17th century A.D. The apparent increase in intense storms around 250 years ago occurs during the latter half of the Little Ice Age, a time of lower continental surface temperatures. Comparison of the sediment record with palaeoclimate records indicates that this variability was probably modulated by atmospheric dynamics. The apparent increase of the superstorm activity during the latter half of the Little Ice Age was probably due to the thermal gradient increase leading to enhanced lower tropospheric baroclinicity over a large Central Atlantic/European domain and leading to a modification of the occurrence of extreme wind events along the French Mediterranean coast. A complete understanding of the relationship between climate fluctuations, storm activity, and the coastal response will be crucial to predicting the impacts of future climate change.

1. Introduction

It has been clearly established that our planet has been warming since pre-industrial times (Solomon et al., 2007). The effects of climate change on extreme events are difficult to assess because of many forms of nonlinearity and long-term memory. Several storms have hit France and Europe in recent years but the link between these events and climate change is not yet proven. The effect of people on their environment, the development of our societies and our greater wealth are at increasing risk and are more likely to be destroyed because of the destructive impact of climate intense episodes. However, the issue of extreme events remains: are they linked to global warming or are they part of natural climate variability? To answer this question, it is essential to place such events in a broader context of time, and trace the history of climate changes over several centuries or several millennia, because these extreme events are inherently rare and therefore difficult to observe in the period of a human life.

In this study, we focus mainly on the Languedoc–Roussillon (Fig. 1), a region of the French Mediterranean coast. This area is particularly sensitive in terms of societal issues for the risks of floods and coastal erosion/submersion during storm events. In this area, the primary forcing of sea-level variations mostly related to atmospheric variability (Tsimplis and Josey, 2001), including extra-tropical storms (Moron and Ullmann, 2005; Pirazzoli, 2000; Ullmann and Moron, 2008; Ullmann et al., 2007). Travelling mid-latitude low-pressure systems act to raise the sea level directly below them, but this effect alone is quite weak in semi-enclosed basins such as the

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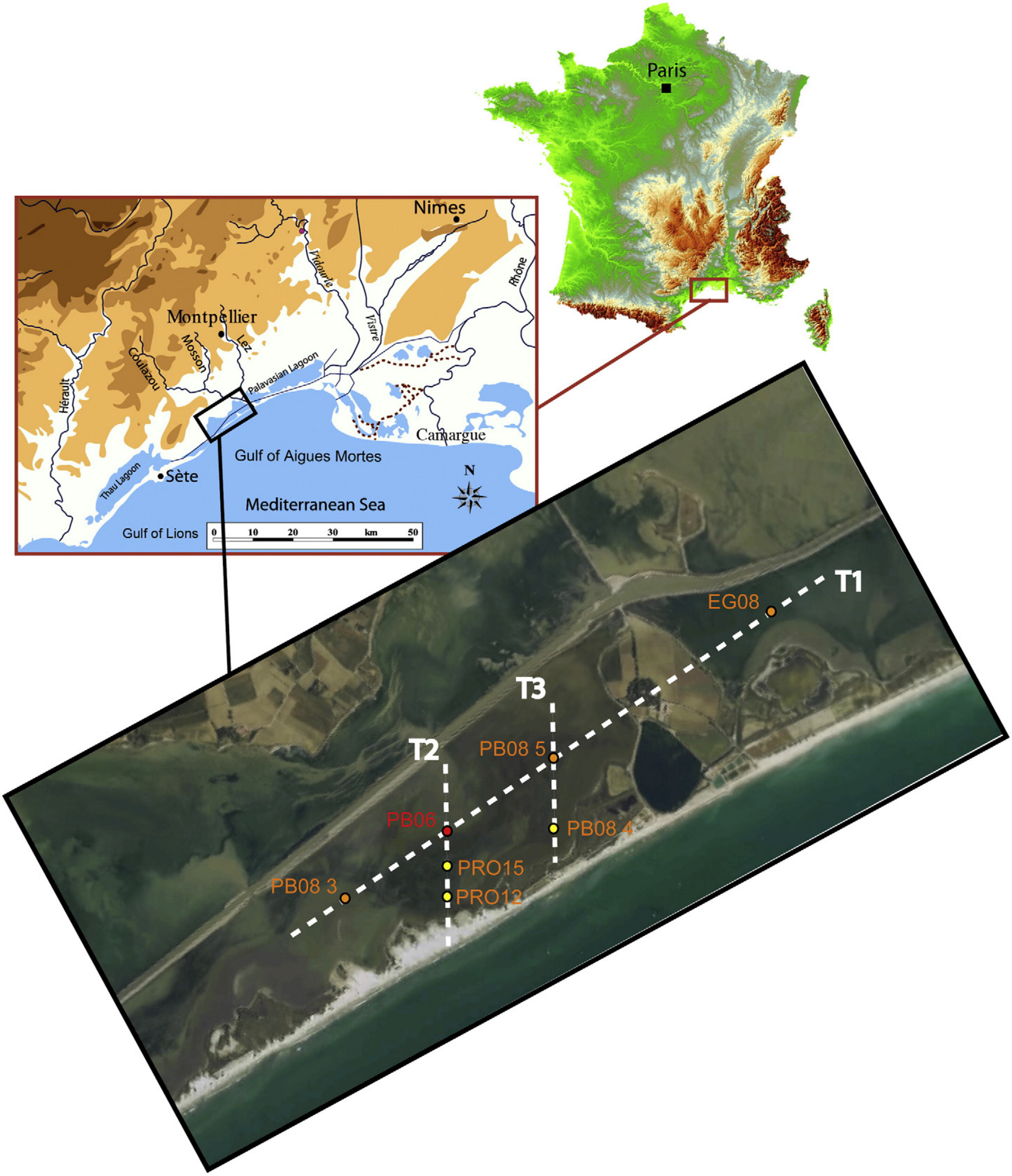


Fig. 1. Study area and core location in Pierre Blanche and Prevost lagoons. Seven short cores and one long core were extracted from the two lagoons along three transects (One longitudinal transect T1 and two transverse transects T2 and T3).

Mediterranean Sea (Pirazzoli, 2000). The most important meteorological factors are the associated winds (Ullmann et al., 2007). For example, sea surges >40 cm in the Camargue recorded between 1974 and 2001 are usually associated with storms moving southeastward across the North Atlantic to the south of 55°N, and strengthening as they approach the Bay of Biscay (Moron and Ullmann, 2005). During such storms, strong onshore winds cause water to pile up against the north coast of the Gulf of Lions (Moron and Ullmann, 2005).

These storm events can have dramatic actions attacking coastal sand dunes, sometimes breaking the sandy barrier (Pierre Blanche lagoon in 1999), and weakening certain human infrastructure (ports, defense barriers, housing). For the last few decades, the most important storms are those of 1982, 1997 and 1999. From the fifteenth-century to present-day, the analysis of historical documents reveals many periods of hydrological irregularities particularly during the Little Ice Age (Blanchemanche, 2010). Over longer periods of time, we have no information on the existence of extreme storm events. The frequency of these events is difficult to estimate from the instrumental and documentary records due to their relative rarity and the short historical period of instrumental observation. Therefore, geological data offer the only hope of reconstructing a long historic record of intense events and deciphering any long-term changes in storm activities.

In this study, we propose to use bio- and geo-indicators (proxies) from sedimentary archives to reconstruct past storm activities in the Languedoc–Roussillon region. Pioneer studies from this area demonstrated that overwash sand layers preserved in the sediments of coastal lagoons can provide a record of catastrophic storms during the last 250 years (Dezileau et al., 2005; Sabatier et al., 2008). Here a multi transect approach is used to assess the frequency and intensity of these events during the last 1500 years and to study the possible links between past climatic conditions and storm activities. To date, the study of historic and prehistoric storms, named Paleotempestology by Liu and Fearn (2000), has been confined to the study of tropical cyclones in tropical Australia (Chappell et al., 1983; Chivas et al., 1986; Hayne and Chappell, 2001; Nott, 2004) and southern and eastern United States (Collins et al., 1999; Donnelly and Webb, 2004; Donnelly et al., 2001a,b; Donnelly and Woodruff, 2007; Liu and Fearn, 1993, 2000; Scileppi and Donnelly, 2007). Up to now, this relatively new branch of science was not applied to mid- and high-latitude events (Nott, 2004). The identification of storm events in the Mediterranean region is a new area of investigation.

2. Study site

Pierre Blanche and Prevost lagoons are located in the northwestern part of the occidental Mediterranean Sea (Fig. 1). These hypersaline backbarrier lagoons are separated from the Mediterranean Sea by a wave-produced, sandy barrier 150 m wide and 2–3 m above the mean sea level. These lagoons have a flat bottom with a maximum water depth of approximately 1 m. Modern sediments accumulating at the bottom of this lagoon are made of clay/silt but no sand. Tidal variability is modest (with a mean range of 0.30 m), which minimizes the influence of dynamic tidal currents. The study site is located along the southeastern-facing shoreline, and is extremely vulnerable to intense storms coming from south and southeast.

3. Materials and methods

3.1. Core material

Six short cores and one long core were extracted from the two lagoons (Pierre Blanche, and Prevost) along three transects (transverse and longitudinal transects, Fig. 1). The long core was extracted using the Uwitec platform (University of Chambery and Laboratoire des Sciences du Climat et de l'Environnement). All cores were collected at water depths between 0.5 and 1.5 m. The locations for all coring sites were determined using a handheld GPS unit which provided a horizontal accuracy of 3 to 6 m.

3.2. Physical measures

Back at the laboratory, cores were X-radiographed (imagery department in “Clinique du Millénaire” and University of Bordeaux), sliced open, photographed and logged. Cores were refrigerated at 5 °C to prevent dessication. Core PB06 was run through a non-destructive Itrax core scanner to obtain subcentimeter-resolution X-ray fluorescence measurements of the sediment's elemental composition (Laboratory EPOC, University of Boreaux 1). Grain-size analysis was conducted on contiguous 2-cm samples using a Beckman-Coulter LS13320 laser diffraction particle-size analyser. Grain-size distribution measurements were made on the less than 0.3 mm sediment fraction without decarbonatation.

4. Results

4.1. Core descriptions

Cores collected from the two lagoons contain organic-rich clay and silt interbedded with coarse-grained layers comprised of a mixture of siliciclastic sand and shell fragments. X-ray images, X-ray fluorescence and high-resolution grain-size analysis for PB06, PB08-3, PB08-4, PB08-5, PRO 12, PRO 15 and EG08 indicate several thin, coarse-grained layers preserved within mud sediments which were not detected by visual inspection. The more prominent sand layers are typically composed of sand and have often sharp contacts with the organic-rich clay and silt sediments below (Fig. 2). These sand layers preserved in the cores seems to be overwash layers, i.e., coming from marine incursions during intense storm events. However, these coarse-grained event layers can have another source such as rivers for example. Consequently, we investigated the origin of the detrital material.

4.2. Detrital input and transport mechanisms

In the two lagoons, terrigenous particles may originate from any of the surrounding land masses, i.e., old Mesozoïc/Cenozoïc calcareous watershed sediment and/or that of the sandy barrier. These potential source areas are characterized by different major and trace-element compositions. Thus, by connecting the major and trace-element compositions of source areas to the terrigenous particles in the sediment, the origin of the particles can be identified. In order to characterize temporal changes in detrital fluxes during the last 1500 years, we chose to focus on core PB06 extracted in the centre of the Pierre Blanche lagoon.

In order to obtain the best resolution in this identification, we chose to use the ratio Zr/Al, which discriminates between the two potential source areas. The high Zr/Al ratio value is explained by a high concentration of heavy minerals (like zircon) from Camargue sand. The Zr/Al ratios of coarse-grained event layers are well above 3 (Fig. 2), indicating a higher relative contribution of terrigenous particle from the sandy barrier. These sand layers preserved in the cores are interpreted as overwash layers given their geochemical and sedimentary characteristics, i.e. all these coarse layers are the result of marine flooding events overtopping or breaching the barrier and transporting these barrier and nearshore sediments into the lagoon. The marine origin of these sand layers was also ascertained through identification of molluscs (*Bittium recticulatum* and *Rissoa ventricosa*), unique to the marine environment (Dezileau et al., 2005; Sabatier et al., 2008).

In conclusion, storm surge associated with an intense storm strike, is the only mechanism that can generate these high-energy events with seawater influx. There is no evidence of earthquakes or tsunamis affecting the Languedoc coast in the historical record. The data cannot be explained by any other fluvial or lacustrine processes.

4.3. Stratigraphic framework and age model

To allow for a more detailed discussion of the markers and their comparison with other records, a chronostratigraphic scale was constructed. Time scales for cores PB06, PRO 12 and PRO 15 are based on ^{137}Cs, ^{210}Pb and AMS ^{14}C dates (Sabatier et al., 2008, 2010).

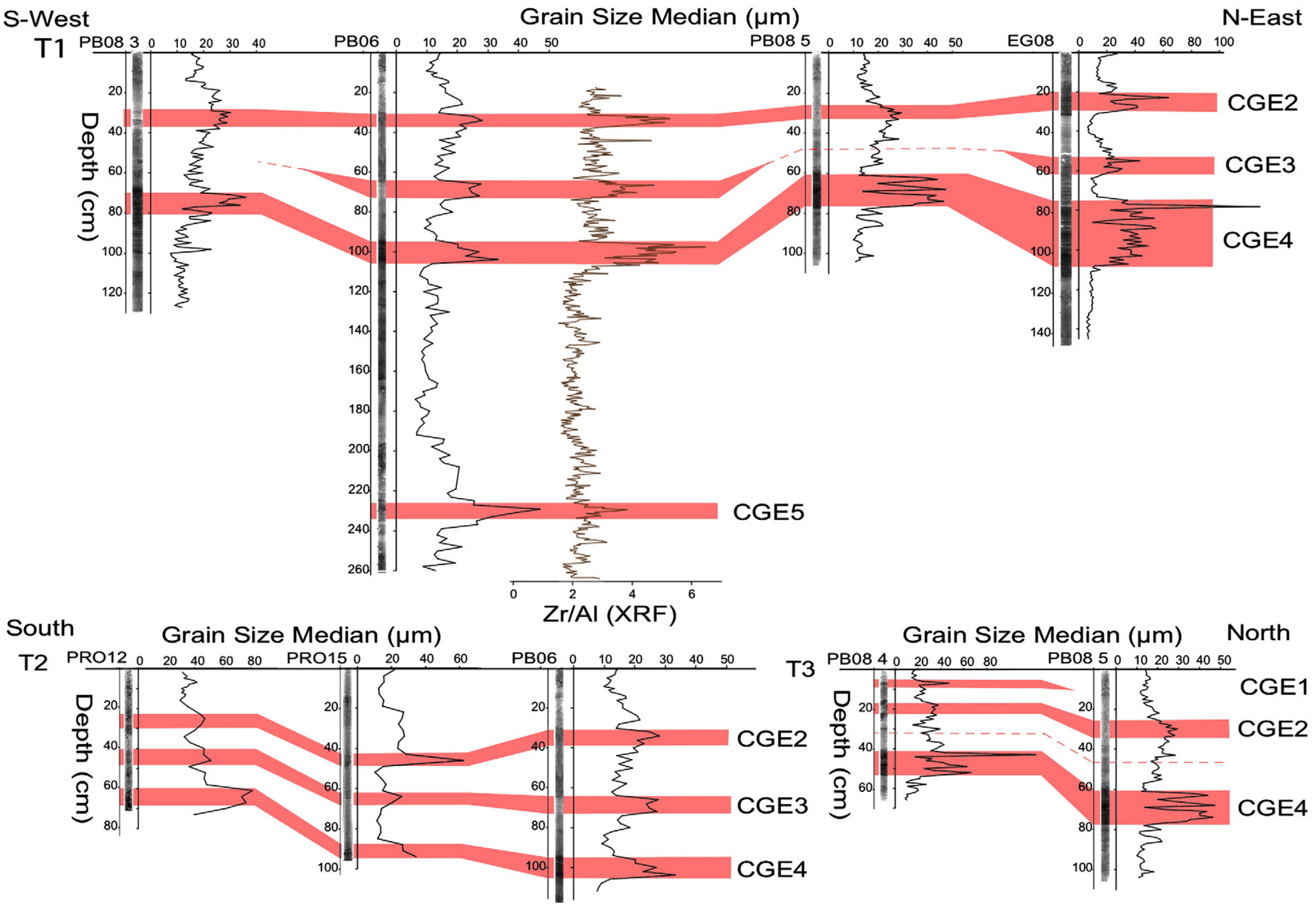


Fig. 2. Grain-size distribution of the seven short cores (PB08-3, PB08-4, PB08-5, PRO 12, PRO 15 and EG08) and one long core (PB06) following three transects (one longitutinal T1 and two transverses T2 and T3). The Zr/Al ratios of core PB06 are well above 3 indicating a higher contribution of terrigenous particle from the sandy barrier. Five different coarse-grained event layers have been identified in the different cores (CGE 1 to 5).

Samples shells were radiocarbon-dated at the Laboratoire de Mesure ^{14}C on ARTEMIS in CEA institute at Saclay (ECLICA, INTEMPERIES, PALEOSTORMS projects, coordinator L. Dezileau 2004; 2006; 2008). These measurements were obtained from monospecific samples *Cerastoderma Glaucum* at each level. ^{14}C ages were corrected for reservoir age (see Sabatier et al., 2010 for method) and converted to calendar years using the Calib 5.0.2 calibration program (Hughen et al., 2004) at two standard deviations. For the four cores, PB08-3, PB08-4, PB08-5 and EG08, we have no absolute age constraints. The proposed age scale for these cores was developed by graphic correlation to core PB 06.

4.4. Overwash deposits chronology

In communal archives, intense storm events were mentioned because they caused damage in the vicinity of the studied city (Sabatier et al., 2008). For the last 400 years, eighteen intense storms occurred in the Languedoc. Among all of these, some seem to be more intense. The storm of December 4th, 1742, recorded in many city archives around the Aigues-Mortes gulf, is considered as the most catastrophic event in the study area. This storm, probably due to S to SE winds, submerged some local cultivated lands which had been gained at the expense of the older parts of the lagoon. The lagoon was covered with a sand layer over “300 toises”, i.e. 500 m. One of the main consequences was the creation of a large inlet, near Maguelone, which remained open until 1761. The storm of November 23, 1848 associated with strong SSE winds induced the wreckage of a few ships in the Sète Harbour, the biggest port in the region. The sea has completely submerged defense barriers in the harbour. This storm caused the death of numerous people. Certified by many engraved illustrations, the storm of September 21, 1893 also resulted in the devastation of the Sète harbour and the wreckage of a few ships. The winter storm of 1982, with 46 m/s wind (category 2 in the Saffir-Simpson scale) caused the death of 15 people and economic losses estimated at 400 million Euros. This storm caused a partial devastation of the new Palavas and Carnon harbours.

To determine which historical events left coarse-grained layers, we used our detailed age model previously defined. Five different coarse-grained event layers (CGE) have been identified in the different cores. The coarse-grained event deposits (CGE-2 and 4) are consistent between all cores (Fig. 2). Historic overwash (CGE-1 and 3) layers are not consistent across the two lagoons, suggesting that these storms may have been nearly absent or less-intense storms that overtopped the barrier in localized areas, producing overwash lobes as opposed to sheet overwash. Nothing may be deduced from CGE-5, the deeper coarse-grained event in the long core PB 06. CGE-1 is observed only in the core PB 04 which was retrieved near the lagoon shore suggesting the existence of a less-intense storm. This layer is consistent with the storm of 1982 (category 2). The three subjacent layers CGE-2, CGE-3 and CGE-4 are consistent with the storm events which occurred in 1893, 1848 and 1742, respectively. These dates were obtained by comparison between ^{210}Pb, ^{14}C data and historical archives (Sabatier et al., 2008). The storm of 1848 was chosen instead of the less-intense storm of 1839 (Sabatier et al., 2008). For the oldest layer CGE-5, dated at 455 +/− 145 cal AD, we have no communal archives.

On the basis of our age model, a quiescent interval is evident between 455 and 1742. After this time, there is a period of intense storms between 1742 and 1900. The interval from 1900 to today was relatively quiet.

5. Discussion

5.1. Site sensitivity through time

Barrier coasts are dynamic systems and differences in backbarrier sensitivities can result from several factors including changes in sea level, sediment supply, inlet, and barrier-elevation (Donnelly and Webb, 2004; Hennessy and Zarillo, 1987; Rampino and Sanders, 1981; Scileppi and Donnelly, 2007).

5.1.1. Sea-level changes

Sea-level rise can increase the sensitivity of backbarrier study sites by moving the shoreline further inland and narrowing the barrier beach through time. In this context, an increase or decrease in sand layers through time can solely be caused by a sea-level change. Major discrepancies exist about the chronology and shape of postglacial sea-level curves reconstructed for the Mediterranean Sea (Lanbeck and Bard, 2000; Pirazzoli, 1991). However, for the last 1500 years, no significant relative sea-level fluctuation (<1 m) has been documented for the Mediterranean Sea (Morhange et al., 2001; Pirazzoli, 1991; Vella and Provansal, 2000). The abrupt increase in sand layer frequency after ca. 1740 A.D cannot be explained by differences in relative sea levels. Moreover, as suggested by ancient maps (Service maritime maps of 1819, 1938 and the Cassini map, 1774, Fig. 3) the position of the sandy barrier, has not shifted significantly during the last 300 years (between 30 and 80 m landward approximately). Therefore, while it is likely that there were minor relative sea-level fluctuations and shoreline changes during the last 1500 years, these changes were probably inadequate to alter drastically the depositional environment of the lagoon and hence the sensitivity of the site in recording intense paleostorms.

5.1.2. Sediment supply changes

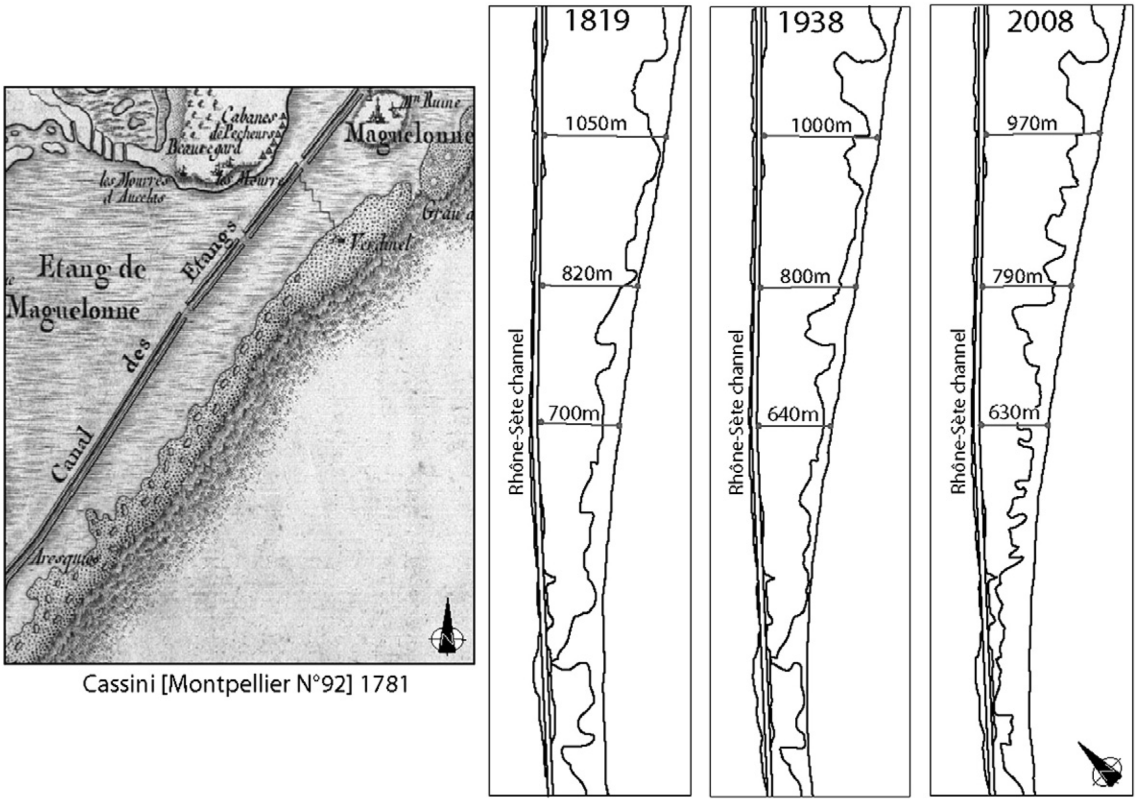
A change in sand layers through time can be caused by the availability of sand oceanside. The seismic campaign CALAMAR IV (Raynal et al., 2009) demonstrated the various morphologies and the pattern of sediment layers related to the Quaternary history of this coastal system. Different seismic profiles, across the shore show different seismic units. These units present a seismic facies typical of a high-energy environment which corresponds to large sand deposits (Certain et al., 2004). The present huge sand deposits observed with the seismic campaign cannot explain the decrease of sand layers between 1740 and today. It is difficult to estimate sand availability through longer timescale, however, the large sand deposits present problems in explaining the changes at the site over last 1500 years.

5.1.3. Inlet changes

The presence of a nearby inlet may increase the sensitivity of a particular area to storm-induced deposition. It allows for storm energy to more easily penetrate into the backbarrier area, letting a lesser storm with lower wave surge transport coarse sediment into the backbarrier. Texts and maps from the 18th and 19th centuries clearly show that ephemeral small inlets have been created by storm activity along the Pierre Blanche Lagoon and often have not induced longlasting coastal features. If a large inlet had existed over a long period and had provided a ready conduit for sand from the Gulf of Aigues-Mortes to the Pierre Blanche lagoon, this would have been reflected in the cores. However, no evidence of such active tidal connection lasting a long time is found in sedimentological and geochemical data for the past 1500 years. Our cores contain overwash sand layers embedded by organic lagoon mud with sharp stratigraphic contacts, again indicating that no active Gulf inlet existed during the past 1500 years. The small inlets along the Pierre Blanche lagoon during the 18 and 19th centuries have been the result of increased storm activity.

5.1.4. Barrier-elevation changes

A change in barrier height may change the sensitivity of a particular area to storm-induced deposition. Coastal sand dunes frequently erode when they are overtopped by surges and waves (Nott, 2004). The diminution in height of a dune barrier, will allow subsequent smaller surges and waves generated by lower intensity



Cassini [Montpellier N°92] 1781

Fig. 3. Service martime maps of 1819, 1938 and the Cassini map, 1774. The position of the sandy barrier, has not shifted significantly during the last 300 years (between 30 and 80 m landward approximately).

storms to penetrate inland and deposit sandy sediments into back barrier environments. This situation may remain the case for many centuries and possibly longer. Eventually, the dunes will rebuild to their former height, and over time will show no evidence of once being eroded.

At present, our sandy barrier functions as a barrier with a current height of 2–3 m. Historical topographic information on the evolution of the height of this sandy barrier is limited. The barrier heights appear to have been constant for at least the past 50 years. For a longer period, we cannot assume that the barrier has remained the same height. It is very likely that the increase of intense storms between 1742 and 1900 caused the diminution in height of a dune barrier increasing the sensitivity of this area for the 20th century. Nevertheless, it is clear from sediment cores that this time interval (1900 to 2008) was relatively quiet. The present morphology of the coastal barrier with a succession of overwash sand fans well vegetated is probably the result of the increase of intense storms during the 18 and 19th centuries.

To conclude, the record of paleostorm occurrences can be complicated by different factors (coastal dynamics, sea-level changes, sediment supply, inlet, and barrier-elevation changes), however, the organic-rich clay/silt sediment types appearing throughout the record show that these areas were experiencing quiescent sedimentation during at least the past 1500 years, indicating that the study sites were likely protected behind the barrier system over that time. Finally, the close agreement between documented intense storms and the recent sedimentary record in our study area indicate these backbarrier lagoons have been sensitive to overwash deposition associated with the strongest storms impacting on the area. However, in order to control localized sensitivity changes, it will be necessary in the future to employ a vast multiple-site approach, as extreme storms in all the northwestern Mediterranean area would likely result in storm surges and waves of sufficient height to overtop the barrier across wide stretches of coast and not only in localized areas.

5.2. Intensity of storms through time

The relationship between storm intensity and the size of the overwash sand body deposited in a coastal backbarrier lagoon is complex. We have acknowledged some of these confounding factors, including the abundance of sand supply, emphasizing that our working hypothesis is subject to the assumption that the geomorphic setting remains roughly the same for Pierre Blanche and Prévost lagoons during the last 1500 years and that storm conditions (e.g., timing, duration, angle of approach) occur randomly over time (Liu and Fearn, 2000; see also Liu and Fearn, 1993). However, recognizing these complexities does not prevent us from generalizing that a positive relationship exists between hurricane and storm intensity, storm-surge height, and the size of the overwash sand body. Donnelly et al. (2001a, 2001b) demonstrate that recent and historic major hurricanes on the Atlantic coast caused significantly higher storm surges than minor hurricanes and winter storms, and that over the past several centuries only the major hurricanes left a stratigraphically distinct and regionally consistent record of overwash sand layers in the sediments of the coastal marshes.

During the past 50 years no catastrophic intense storm has directly struck Pierre Blanche, and Prevost lagoons, except maybe the 1982 storm of category 2 intensity that was not strong enough to directly deposit sand into the centre of the two lagoons; the coarse-grained event layers (CGE-1/1982 event) have been identified only in one core PB04, near the lagoon shore. The four thin sand/silt layers in core PB06 have interpolated ages of approximately 455, 1742, 1848 and 1893 A.D.. If the geomorphic setting of the two lagoons has not changed drastically during the last 1500 years and if a positive relationship exists between storm intensity, storm-surge height, and the size of the overwash sand body, these four thin sand/silt layers recorded in the lagoon at more than 500 m from the sandy barrier, were probably formed by a catastrophic storm of category 3 intensity or more. Taking into account text description of the 1742 storm and the large overwash sand body deposited in the core PB06, the distinct 1742 sand layers were probably formed by overwash processes that occurred during a catastrophic storm of category more than 4 in intensity. This storm is probably the most intense event ever recorded during the last 1500 years in that region. To conclude, these 4 storms of very high intensity can be called superstorms.

5.3. Paleoclimatological interpretations

5.3.1. Do we have a link between intense storm events and past climatic changes?

Geological data (Fig. 2) show a superstorm event at 455 +/− 145 cal AD. After this event, we do not have any evidence of superstorms in the region for several hundred years prior to the late 17th century A.D (i.e. between 455 and 1742 A.D.). The apparent increase in intense storms around 250 years ago lasts to about 1900 AD. This apparent intense meteorological activity seems to return to a quiescent interval after (i.e. during the 20th century AD). Interestingly, the two periods of most frequent superstorms strikes in the Aigues-Mortes Gulf (AD 455 and 1700–1900) coincide with two of the coldest periods in Europe during the late Holocene (Bond cycle 1 and the latter half of the Little ice Age). Is this link to past climatic changes real or fortuitous? We are aware that the number of these extraordinary events is low and it is difficult on this basis to undertake a statistical approach. Although additional long records are necessary to test this hypothesis, one of the most likely explanations of this apparent increase in superstorm events affecting the Languedoc region during the coldest periods (particularly during the latter half of the Little Ice Age) is a result of modifications in atmospheric circulation and variability.

Based on an ensemble of six simulations of the Maunder Minimum (MM, going from 1640 to 1715 with time varying forcing) using an Ocean-Atmosphere General Circulation Model (OAGCM), Raible et al. (2006) consistently find an increase in cyclone occurrence in the Mediterranean during the MM compared to present-day. They attribute this signal to a larger cooling in the high latitudes than in the low latitudes (due to polar amplification effect, Masson-Delmotte et al., 2006), leading to enhanced lower tropospheric baroclinicity over a large Central Atlantic-European domain. This result suggests that the cooling observed during the MM over Europe (Guiot et al., 2005) may be associated with upstream changes in the large scale dynamics of the atmosphere over the Mediterranean and North Atlantic sectors. It is hypothesized here that such a large-scale flow alteration may have modified the occurrence of extreme wind events along the French Mediterranean coast, thus explaining the local signal found here over the region of Languedoc.

5.3.2. Does the North Atlantic Oscillation control the frequency of superstorm events?

The North Atlantic Oscillation (NAO) is responsible for much of the climate variability observed in the Mediterranean region (Hurrell et al., 2003) at present day and possibly during the last 500 years (Luterbacher et al., 2002). During the positive phase of the NAO, the high-pressure gradient between the strong Azores anticyclone and the Iceland depression results in a northward shift and an increased strength of the westerlies (Hurrell et al., 2003). The “storm track” crosses the northern part of Europe. When the NAO is high, dry conditions develop over southern Europe and North Africa (Pittalwala and Hameed, 1991). Conversely, when the NAO is negative, the pressure gradient between the Azores high and the Iceland low decreases (Hurrell et al., 2003). The westerlies are shifted to the South providing precipitations over the Mediterranean and the North African continent. In this configuration, the “storm track” crosses southern Europe.

Ullmann et al. (2008) analysed sea surge variations around the Gulf of Lions and their relationships with local-scale winds and regional-scale atmospheric patterns (i.e. weather regimes) and clearly showed that the highest sea surges are associated with a strong negative phase of the NAO during the 20th century. Around 70% of sea surges >40 cm at all stations occurred when extra-tropical storms travelled along a southern track and are associated with onshore southerly winds that drag water toward the coast of the Gulf of Lions. Even if our superstorm records link to sea surge events probably >1–2 m in height cannot be directly compared to the analysis of Ullmann et al. (2008), it is interesting to study the potential link between NAO and our paleorecords.

Our historical archives and geological data show an apparent increase of superstorm activity in the Languedoc region during the latter half of the Little Ice Age, when tree-ring based reconstructions (Guiot et al., 2005; Luterbacher et al., 2002) indicate a negative (cooler) phase of the NAO. We could thus hypothesized that the active storm period in the Languedoc is the result of shifting storm tracks to the south related to a negative phase of the NAO. However, in our region this assumption is not completly satisfactory for several reasons: First, if the active and inactive intense storm periods are the result of shifting storm tracks between northeastern and southwestern locations, we should observe a spatial see-saw pattern of storm activity between the northern part of Europe and the Mediterranean area. However, Jelgersma et al. (1995), Aagaard et al. (2007) and Sorrel et al. (2009) clearly showed an increase of storm frequency during the Little Ice Age in the northern part of Europe. This active period in the northern locations falls within the period of an apparent increase in intense storms in the southern part of Europe. This synchroneity if true could provide evidence that a millennial-scale spatial see-saw pattern of atmospherically-driven storm tracks may not be a major climate mechanism forcing changes in the superstorm frequency in our region. Secondly, the intense storm events reconstructed from sedimentary archives do not show a correlation with the reconstructed NAO index over the last 500 years (Luterbacher et al., 2002). However, at this stage, even if the link between NAO and the superstorm frequency does not seem satisfactory, it cannot be completely discarded because of the low number of these extraordinary events. Additional long records will be necessary in the future to test this assumption.

5.4. Storm risk estimation for the last 1500 years in the Northwestern Mediterranean area

This study has implications for risk assessments. During the past 100 years no catastrophic intense storm has directly struck the Languedoc region but the sediment stratigtaphic data suggest an apparent increase of catastrophic storms of category 3 intensity or more during the latter half of the Little Ice Age. The area on average has a 0.2% probability of being struck by a catastrophic storm by years over the last 2000 years. This estimate is higher, 2% during the latter half of the Little Ice Age; the risk is increased by a factor of 10. Today, the lack of familiarity with such extreme events has led to the assumption that they are unlikely to ever occur within the lifetime of many individuals. This has led to the development of inadequate policies governing the location of buildings well within the zone of possible storm tide inundation. In the Gulf of Aigues-Mortes, the development of seaside tourism during the 20th century was marked by the construction of numerous seaside resorts (e.g. Carnon, La Grande-Motte, Port Camargue) or extension of small fishing villages (e.g. Palavas-les-Flots; Le Grau-du-Roi). These resorts were built on the sandy barrier in the 1970s. The town of Carnon is established on a wide washover fan that was probably formed during the “Little Ice Age”. The resident population on the coast has increased by a factor of 15 since 1750 with a dramatic increase since the 1970s. Today, 150 000 people live all year round on the sandy barrier and more than double that in summer (Fig. 4). The last few centuries have seen a regime shift in the occurrences of storms crossing the coast in the

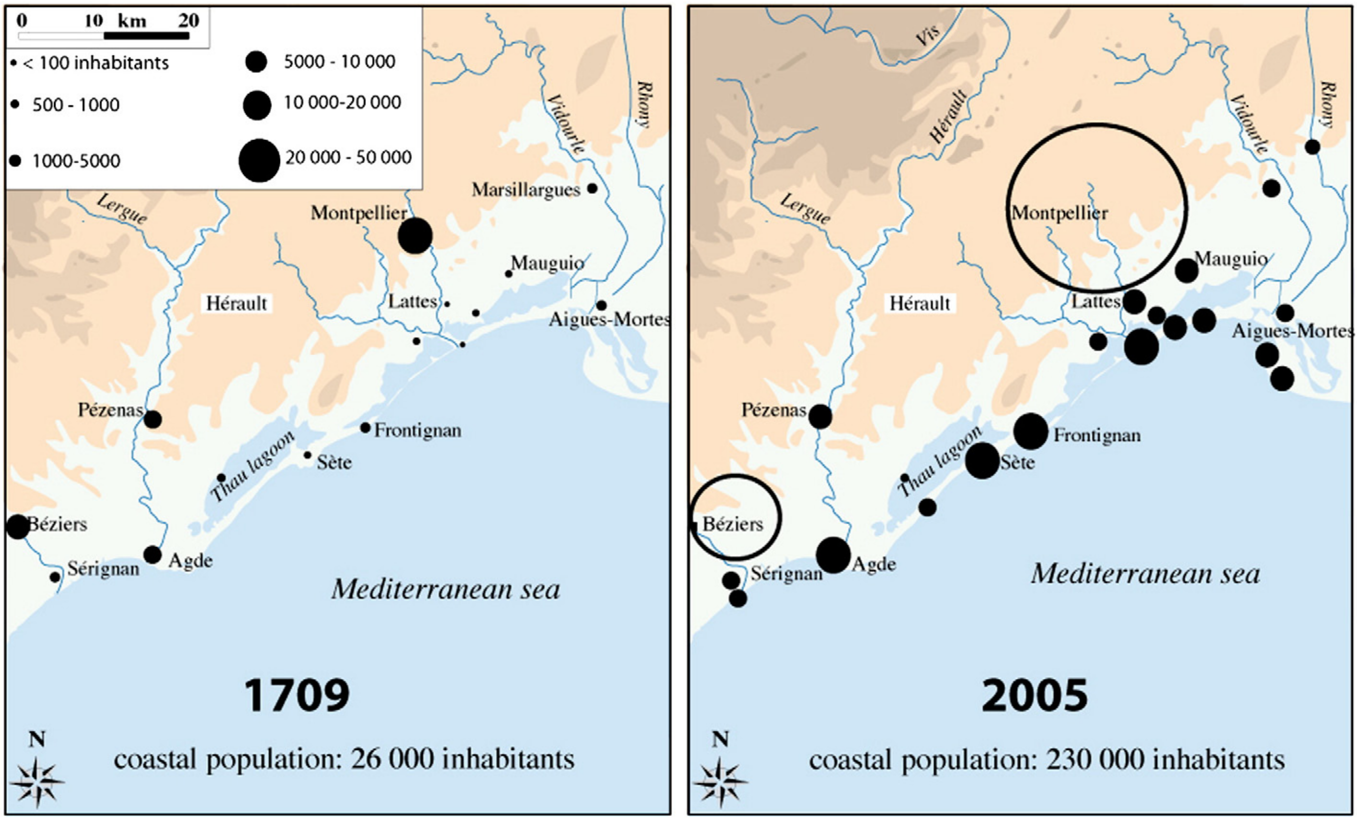


Fig. 4. The resident population on the coast has increased by a factor of 15 since 1709 with a dramatic increase since the 1970s. Today, 150 000 people live all the year on the sandy barrier.

Northwestern Mediterranean area. If the regime of the latter half of the Little Ice Age came back today, the implications would be dramatic. The percentage number of residential or business buildings and different infrastructures (dams, recent harbours) inundated will increase considerably. Moreover, this flooding risk will be particularly high if we take into account the sea-level rise predicted by recent climatic models for the 21st century (IPCC, 2007). To conclude, it is very important to better understand mechanisms causing regime shifts and sea-level change in the Northwestern Mediterranean area for making more accurate predictions of the levels of risk and exposure as human populations, urbanisation and tourism grow rapidly along this Mediterranean coast.

6. Conclusion

This study shows that reconstructing the overwash history of two backbarrier lagoons can provide a sedimentary record of intense storms. Four distinct, overwash deposits are identified in these lagoons at more than 500 m from the sandy barrier, which are much more subtantial than the deposit of sand from the storm of 1982 (category 2 intensity). Since we have demonstrated that the geomorphic setting of the two lagoons has not changed drastically during the last 1500 years, we suggest that these four overwash deposits were probably formed by catastrophic storms of category 3 intensity or more.

Comparison of sediment records with palaeoclimate records indicates that this variability was probably modulated by atmospheric dynamics. We suggest that extreme storm events are associated with a large cooling of Europe. This study has also implications for risk assessments of intense storms. During the latter half of the Little Ice Age, this risk was higher than today by a factor of 10. If this regime came back today, the implications would be dramatic.

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