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The grain-size characterisation of coastal sand from the Somme estuary to Belgium: Sediment sorting processes and mixing in a tide- and storm-dominated setting

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Abstract

Sand-rich Holocene to modern clastic deposits in the eastern English Channel and the southern North Sea coasts of France and Belgium occur extensively as nearshore-sand bank, estuarine-tidal flat, aeolian dune and beach sub-environments. Sand samples (n=665) collected from these deposits suggest the presence of three different populations: a largely dominant (83%) medium to fine quartz sand population ("b"), and finer- (14%) and coarser-grained (4%) populations (respectively "c" and "a"). The distribution of these populations among the four sub-environments reflects tide- and storm-dominated sorting and transport processes and a variable degree of mixing. These populations are derived from a mixture of very fine- to very coarse-grained fluvial, outwash and paraglacial sediments deposited on the beds of the eastern English Channel and southern North Sea during the late Pleistocene lowstand. The nearshore-sand bank environment, which also corresponds to the main offshore source area of the coastal deposits, exhibits population heterogeneity reflecting the variability of hydrodynamic conditions and sediment sorting in this zone. The nearshore topography of tidal ridges, banks and troughs in these tidal seas leads to variable bed and tide- and storm-induced shear stress conditions. These conditions only allow for the mobilisation and onshore transport of some of the finer fractions (populations "b" and "c"), leaving an offshore mixture of these finer populations with coarser, less mobilisable sediments (population "a"). Once in the coastal zone, these two finer populations undergo further hydrodynamic sorting and segregation. Variably sorted very fine sands to silts (population "c") are trapped in the low-energy estuarine-tidal flat sub-environment, while the highly homogeneous population "b" is further sorted in aeolian dune and beach sub-environments. This sorting occurs via a coastal sand transport pathway linking the Somme estuary mouth to the southern North Sea bight where tidal range and wave energy decrease relative to the English Channel. Since this sand transport pathway enables longshore transport of hydrodynamically sorted medium to fine sand derived directly from the immediate nearshore zone, it has further contributed to a net flux of this sand population from the eastern English Channel sea bed to the southern North Sea.

Keywords: Grain size; Sediment mixing; Sediment segregation; Tidal seas; English Channel; Southern North Sea

1. Introduction

It is axiomatic to state that the sedimentary characteristics of recent to modern coasts reflect the types of sediment available and the specific sediment

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transport processes operating on regional or local scales. Tide-dominated seas are associated with mean spring tidal ranges exceeding 4 m (Walker, 1984). The seabed in such tide-dominated settings may exhibit discrete zones of scouring and erosion variously called bedload parting or divergence zones that reflect areas of maximum tidal bed stress (Harris et al., 1995; Porter-Smith et al., 2004). As a result of local to regional-scale

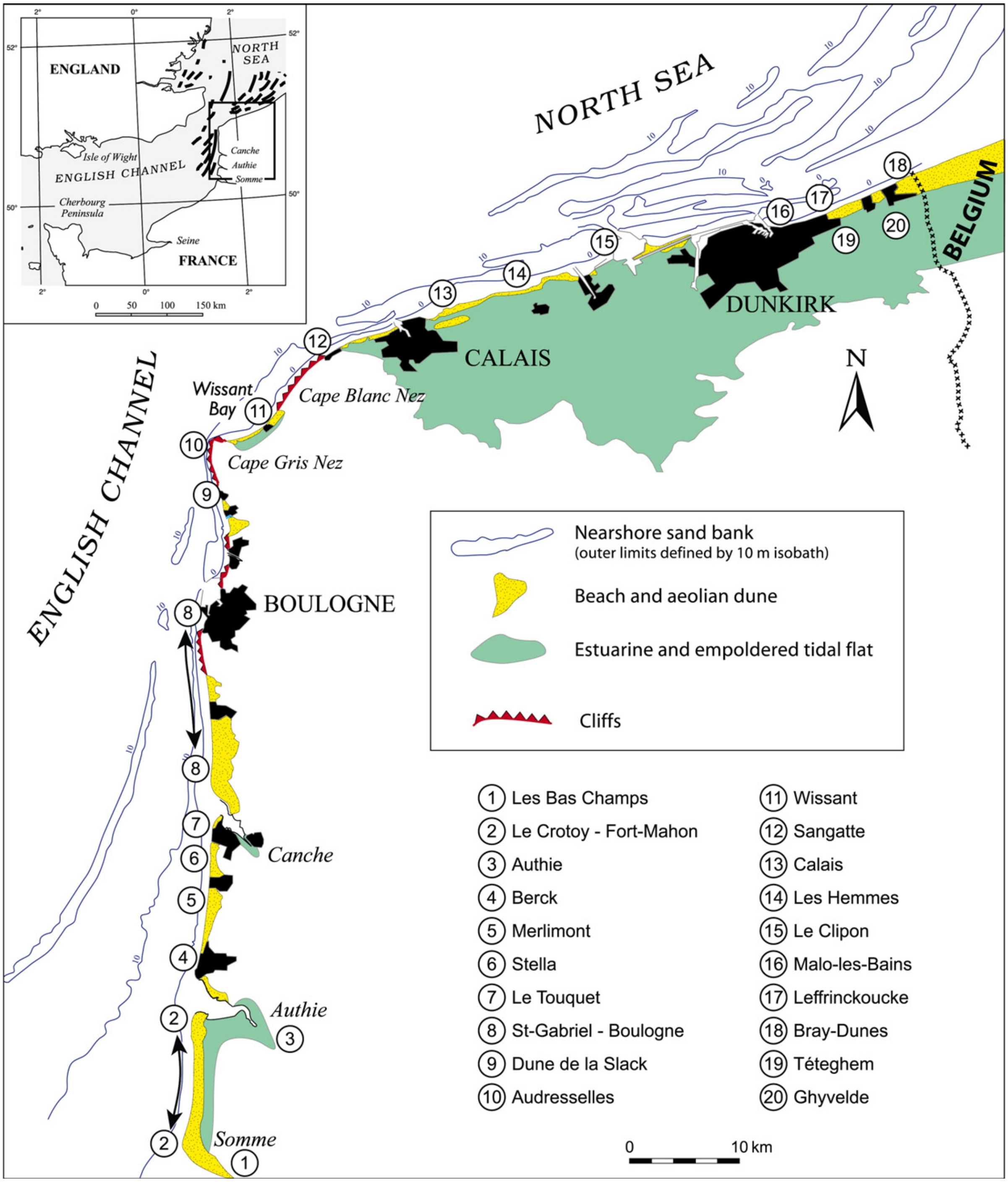

Fig. 1. The eastern English Channel and southern North Sea coast and nearshore zone from the Somme estuary to Belgium. Circled numbers refer to sampling sites or zones. Inset shows a schematic representation of sand banks.

gradients in tidal bed stress, bedload parting zones may supply sand that accumulates in convergence zones or in low-energy sinks. Between zones of divergence and convergence occur transport pathways where hydrodynamic forces are sufficiently high as to maintain transport. Since these features are associated with tidal energy gradients, they may involve grain-size gradients, depending on regional variations in the strength of tides. A fine example is provided by the English Channel, where large-scale tidal energy gradients are reflected in grain-size variations over the sea bed (Kenyon and Stride, 1970; Johnson et al., 1980). However, grain-size trends in all types of environments affected by fluid forces may also reflect the mixing, in different proportions, of two or more hydraulic populations (Folk and Ward, 1957; Flemming, 1988; Bartholomä and Flemming, 2004). These populations may be inherited from a single or multiple sources, and mixing may be due to sediment injection along transport pathways, and variations in tidal energy and flow direction. The more complicated the morphology, sediment supply and hydrodynamic conditions, the more complex the grain-size and sorting patterns.

The aim of this study is to analyse simple grain-size patterns, notably mean and sorting values, of coastal sub-environments bordering the tide-dominated seas of the eastern English Channel and the adjacent southern North Sea (Fig. 1), characterised by a complex sediment source, nearshore bathymetry and hydrodynamic circulation. More specifically, the study explores the potential roles of hydrodynamic processes and population mixing in accounting for these grain-size characteristics. The results are pertinent not only in terms of further understanding the relationship between sand sorting and a regional to local tide-dominated hydrodynamic context, but may also contribute to the understanding of observed patterns of shoreline development on this coast.

2. Study area

2.1. Hydrodynamics, nearshore bedforms and sea-bed sediments

The dominant winds affecting the eastern English Channel and southern North Sea coasts are from south to west-southwest (38–40%), north to northeast (19–22%), and southeast (12–14%). Offshore and longshore winds represented by the south to west-southwest and the southeast windows are thus largely dominant. This wind regime is associated with a storm-wave environment characterised by short period waves (<6 s) from both a wide window embracing west-southwest to north-east on the north-facing (North Sea) coast, and from southwest to west-southwest on the west-facing (English Channel) coast. Offshore modal significant wave heights are less than 1.5 m, but may attain up to 3 m during short spates of storms that may last 2 to 3 days, with a recurrence of days to 1–3 weeks in autumn and winter, and weeks to 1–2 months in spring and summer. Considerable refraction and dissipation of waves occur, especially over the shallow tidal sand ridges in the southern North Sea, resulting in modal inshore wave heights less than 0.5 m high. Inshore wave heights are higher (0.5 to 0.7 m) on the less dissipative west-facing coast.

The tidal regime is semi-diurnal, with large tidal ranges that diminish from the Somme estuary to Belgium (Fig. 2A). Globally, the tidal regime in the English Channel is characterised by a decrease in current velocity towards the eastern corner of this sea and the southern North Sea (Fig. 2B). The coastal zone from the Somme to Belgium is associated with a flood-dominated residual flow corridor towards the North Sea (Prandle, 1978; Salomon et al., 1993). Current velocity measurements carried out at various sites on this coast between 0.5 and 1 km offshore highlight not only this flood-dominated asymmetry but also significant forcing due to winds (Anthony, 2002). Currents are stronger along the west-facing coast than on the north-facing coast. Peak spring tide velocities without wind forcing generally range from 0.6 to 0.8 m s^{-1}. Forcing by the dominant westerly winds may add up to a 50% increase in current velocities. Velocities are about 20% lower along the North Sea coast. Velocities are generally higher in the nearshore zone but peak near-surface spring tide values of 1.5 m s^{-1}, reflecting topographically-forced flows, are only attained in narrow troughs between ridges.

The dominant aspect of the sea bed sediments is the remarkable development of tidal sand bodies collectively referred to as sand banks (Fig. 1). South of Cape Gris Nez, these form large relict features overlain by modern sand waves and ribbons that migrate actively under the present current regime (Beck et al., 1991; De Batist et al., 1993). This longshore sand transport is manifested in the intertidal zone by the northward migration of beach bars and of mesoscale trough bedforms (Anthony et al., 2004, 2005). East of Cape Gris Nez, the nearshore zone of the southern North Sea comprises numerous linear sub-shore-parallel sand ridges that are a hallmark of this tidal sea. The North Sea sand ridges are relatively mobile in places (Aernouts, 2005), especially near Calais (Fig. 1). Overall, the nearshore zone and the sand banks are

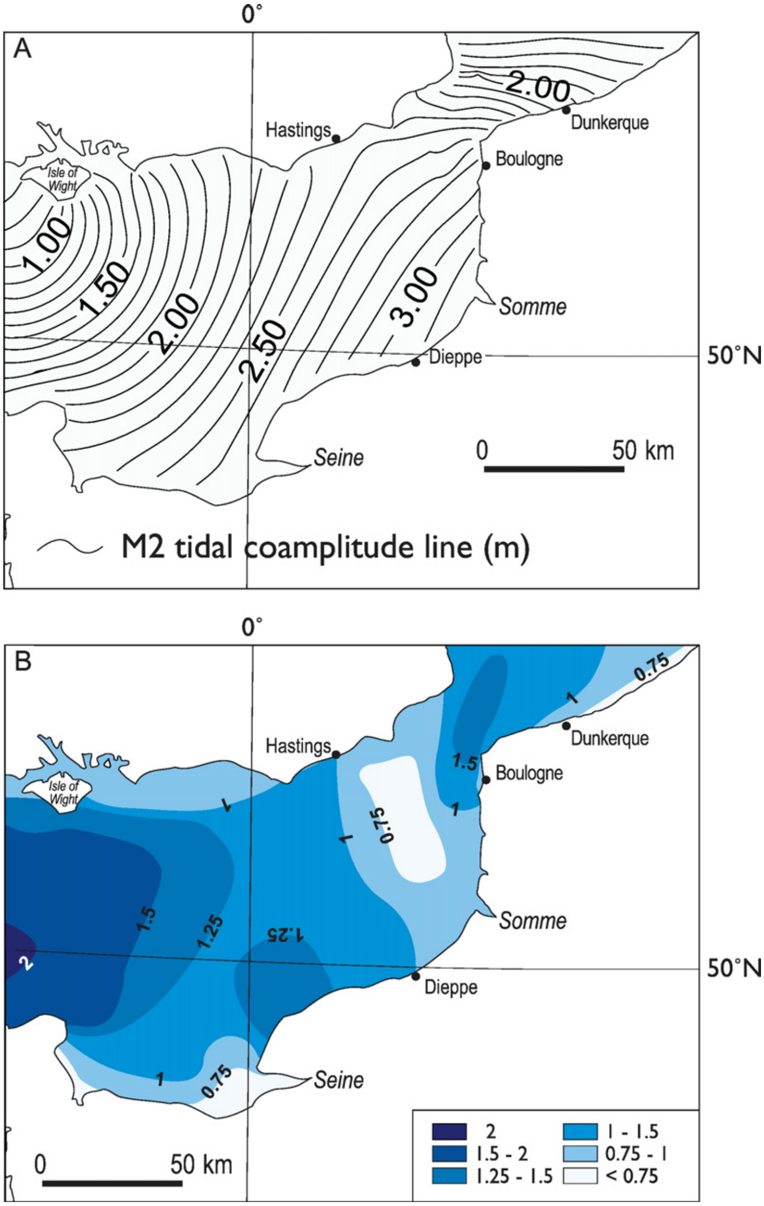

Fig. 2. (A) Isoamplitude lines of the M2 tidal harmonic in the eastern English Channel and southern North Sea (from Chabert D'Hières and Le Provost, 1978), and (B) tidal current velocities in the same area (from Service Hydrographique et Océanographique de la Marine, 1968).

dominantly characterised by medium to fine, clean and poorly to very well sorted siliciclastic grains, especially at depths of 5–10 m, and by medium to coarse grains at greater depths (Augris et al., 1995; Van Lancker, 1999).

The sediment that originally accumulated on the beds of the Channel and southern North Sea was derived from heterogeneous paraglacial, outwash and terrestrial runoff deposits, notably supplied by the Thames, Rhine and Meuse rivers from adjacent lands during the Pleistocene, and from sea-bed and cliff erosion during both the Holocene transgression and under present conditions (Larsonneur et al., 1982; Hamblin et al., 1992; Bellamy, 1995). Holocene and contemporary fluvial sediment inputs to the coasts under consideration are limited because the rivers debouching in the study area are small and have estuaries that actively trap both incoming fluvial sediments and marine sands (De Moor, 1988; Anthony and Dobroniak, 2000).

The clear spatial relationship with tidal energy exhibited by the grain-size distribution of the superficial sediment cover in the English Channel (Kenyon and Stride, 1970; Johnson et al., 1980) suggests long-term

(Holocene) hydrodynamic reorganisation of the initial heterogeneous sediments by tides that underwent considerable amplification following the opening of the Dover Strait 8000 years ago (Austin, 1991). The net result of this reorganisation has been long-term nearshore sand depletion or concentration patterns, leading respectively, to gravel-rich banks and nearshore deposits or to burial of gravel deposits under sand (Anthony, 2002). This tidal reorganisation of the loose sediment cover involves zones of sand divergence or parting, and convergence, defined from geomorphic and sedimentologic data and from numerical modelling (Kenyon and Stride, 1970; Johnson et al., 1980; Dewez et al., 1989; Beck et al., 1991; Grochowski et al., 1993a,b). The bedload parting zone in the English Channel lies in the area of the strongest tidal currents, between the Isle of Wight and the Cherbourg Peninsula (Fig. 3), offshore of a degraded amphidromic point located in southern England. Geomorphic and sedimentological data (Kenyon and Stride, 1970; Johnson et al., 1980), and more recently, numerical modelling of bed shear stresses (Austin, 1991; Grochowski et al., 1993a,b), suggest that sand has moved both east and west of this parting zone, leaving a lag of very coarse bedload (Fig. 3). A major product of these large-scale bedload segregation processes during the Holocene has been the transport and accumulation of sand in the eastern corner of the English Channel, and the southern North Sea, leading to the significant development of infilled tidal embayments, aeolian dunes and nearshore sand banks on the west-facing French coast of the eastern Channel and on the southern North Sea coasts of France and Belgium (Anthony, 2002).

2.2. Coastal morphology

The significant development of nearshore sand bank deposits is matched on the coast by abundant Holocene deposits incorporated in three sub-environments: beaches, aeolian dunes, and estuarine/tidal flats (Fig. 4). Beaches from the Somme estuary to Belgium fall into the bar-trough (‘ridge-and-runnel’) category (Masselink and Anthony, 2001; Reichmüth, 2003; Anthony et al., 2004, 2005). They are backed either by cliffs or by aeolian dunes. In the western half of Wissant Bay (Fig. 1), where the beach and the adjacent dunes are presently undergoing erosion, the upper beach comprises a local concentration of gravel derived from nearby cliff sources and possibly from the nearshore zone (Anthony and Dolique, 2001). This is the only area where a significant concentration of beach gravel is encountered between the Somme estuary and Belgium. Dunes between Calais and the Belgian border bound a large, former tidal embayment, the Flemish coastal plain, which stretches across to the Netherlands. The tidal deposits in this embayment comprise facies belonging to mudflat, sandy tidal flat and infilled channel environments as well as peat interbeds representing former freshwater to

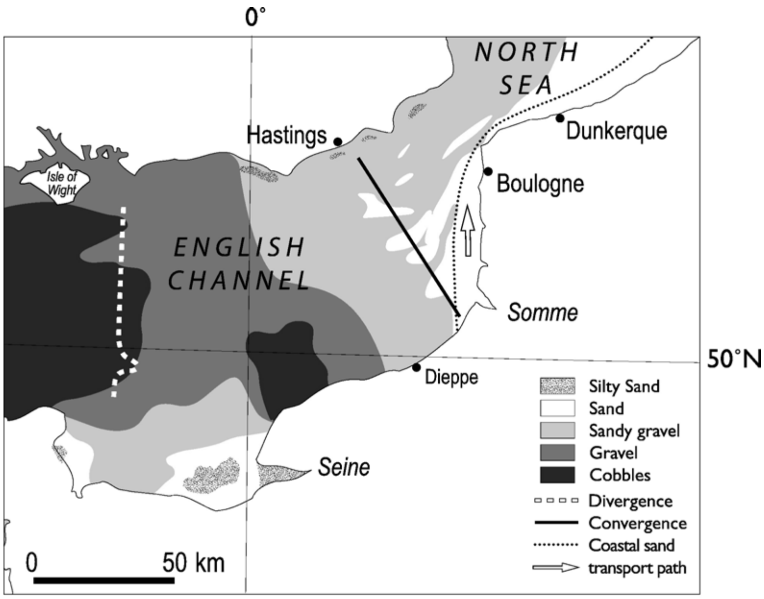

Fig. 3. The surficial sea-bed sediments in the English Channel, showing eastward fining and features of the large-scale, tide-dominated dynamics involved in the coastal transport of fine sand from the Somme estuary to Belgium (adapted from various workers, see text).

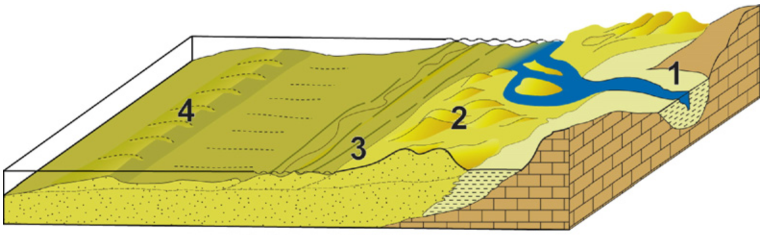

Fig. 4. The four coastal and nearshore sub-environments discussed in the text (from Anthony, 2000). See text for description.

brackish swamps (Baeteman et al., 2002; Mrani-Allaoui and Anthony, 2004; Mrani-Allaoui, 2006). Estuaries indenting the coast are shallow, largely filled with fine to very fine sand, and are all subject to present rapid accretion (Anthony, 2000; Anthony and Dobroniak, 2000). Aeolian dunes along this coastline abruptly end in the vicinity of the Somme estuary, giving way southwards to Jurassic–Cretaceous chalk cliffs comprising flint beds and having modern fringing gravel beaches dominantly composed of flint (Anthony and Dolique, 2001).

3. Methods

In order to determine the grain sizes of the sandy sediments that have accumulated in coastal embayments and in the nearshore zone, data were collated from published and unpublished sources and from a sampling campaign specifically carried out for the purpose of this study. A total of 665 samples was collected from the various sub-environments (Fig. 4) – beaches, aeolian dunes, estuarine/tidal flats, and nearshore sand banks – between 1996 and 2004. Tidal flat samples were collected from a 10-m core in Téteghem (Fig. 1). The number of samples, and sampling densities and procedures for the four sub-environments differed during the various campaigns, depending on the objective of each study. There is a certain bias towards beach samples which account for 51% of the samples available for this study. However, problems of sampling density and bias are largely offset by the grain-size homogeneity of the sand, and by the random sample collection during each campaign. Analytical methods also differed. Samples collected between 1996 and 2000 were analysed using nested sieves and the grain-size parameters determined using the Folk and Ward (1957) method. Since 2001, sample analysis has been carried out using a laser grain sizer and the statistical moments method (McBride, 1971) for determining grain-size parameters. In both methods, analysis was carried out on the siliciclastic fraction which varied from 80% to 100% in each sample, the rest being shelly debris. The data on the samples used in this study all included the two main grain-size descriptors, mean grain size and sorting. The Folk and Ward and moments methods may yield different values of these two descriptors when applied to the same samples, although differences are rather insignificant when only the mean grain size is considered, and moderate when sorting values are compared (e.g., Leeder, 1982). Indeed, the mean grain-size results presented here using the two methods are very close, on the strength of experience gained during calibration of the laser grain sizer. Skewness values were missing for over 30% of the

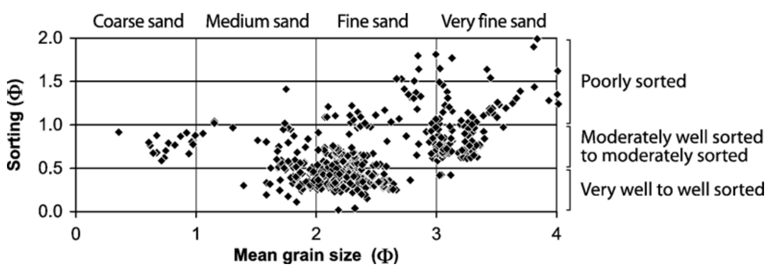

Fig. 5. Mean grain size and sorting for the entire sample database ($n=665$).

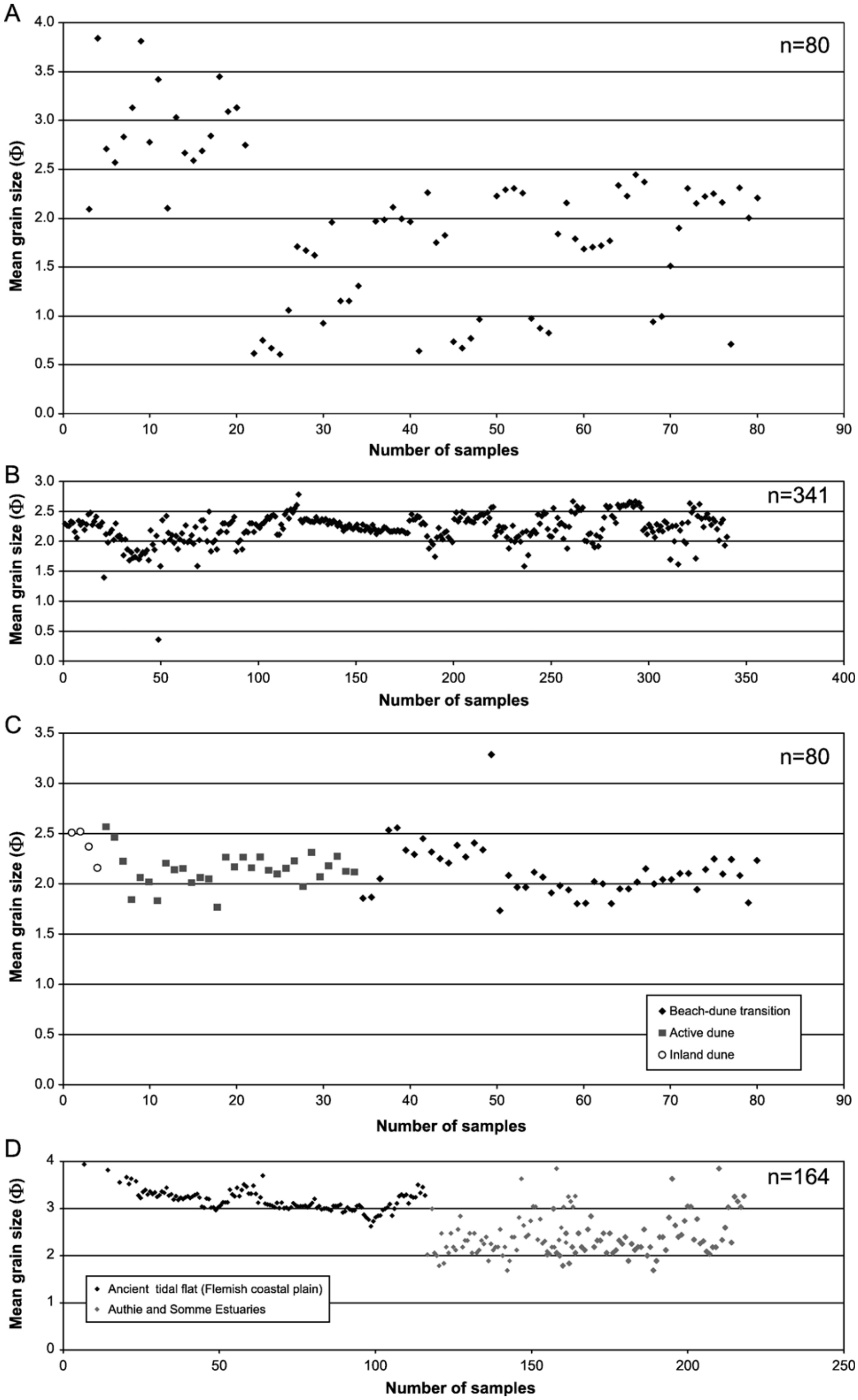

Fig. 6. Mean grain-size data for the four sub-environments: (A) nearshore-sand bank; (B) beach; (C) aeolian dune; (D) estuary–tidal flat. Note that *x*-axis is sample number, and that vertical and horizontal scales differ.

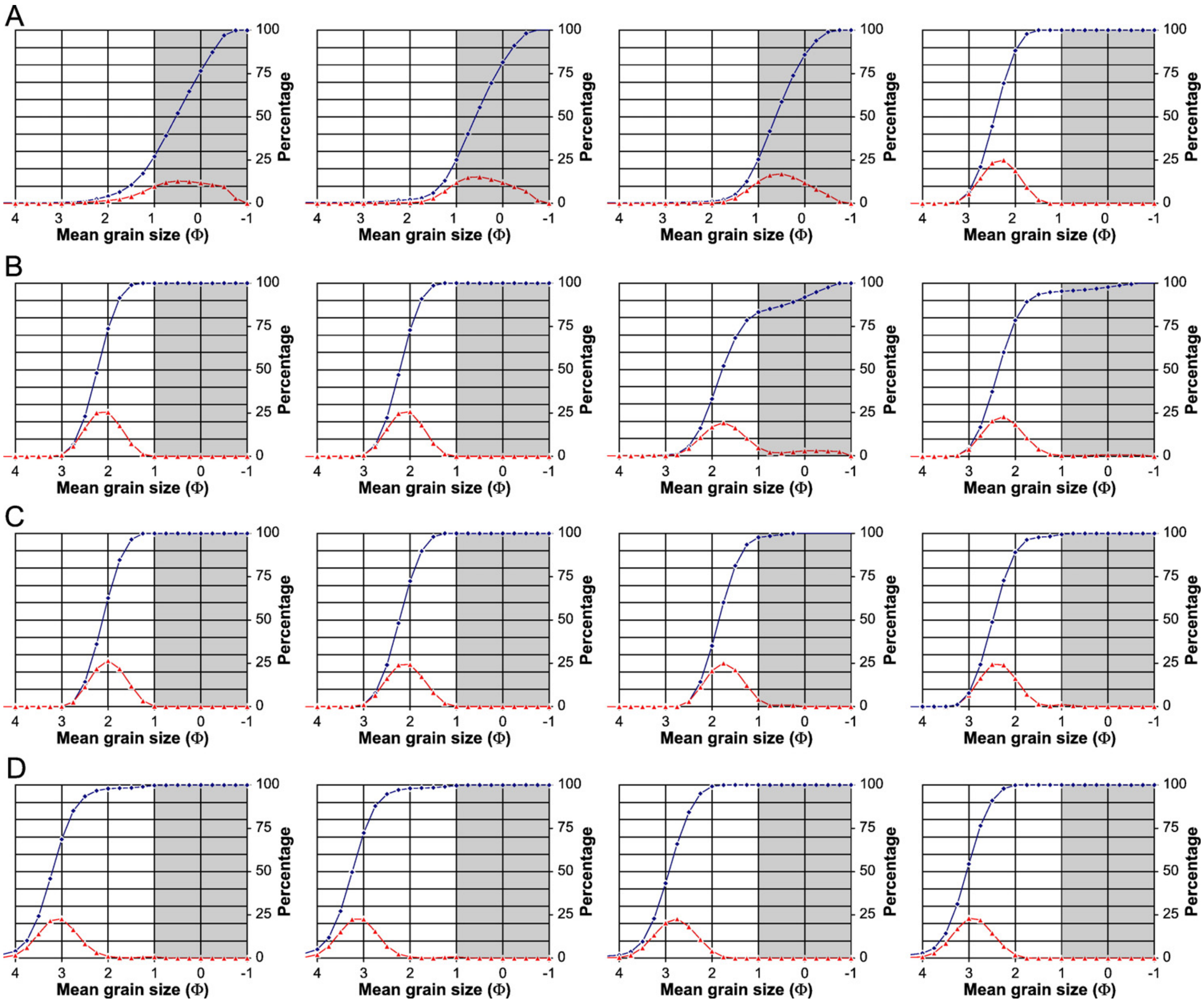

Fig. 7. Representative cumulative frequency and size-range frequency curves of sand samples from the four sub-environments: (A) nearshore-sand bank; (B) beach; (C) aeolian dune; (D) estuary–tidal flat. Grey shading corresponds to the coarse (<1ø) sand fraction.

available samples and may diverge much more using the two methods (Leeder, 1982). Skewness values are therefore not considered in this study.

4. Results

The mean grain sizes of all samples are plotted against their sorting values in Fig. 5. Over 97% of the samples have mean grain sizes ranging from medium to very fine sand. Mean grain sizes in the very fine, fine and medium ranges are respectively 14%, 68% and 15%, highlighting the importance of the finer sand fractions in these deposits. The bulk of the samples are very well to well sorted (54%), especially in the fine and medium size ranges. Sorting diminishes both in the coarse and very fine sand ranges. Mean grain sizes for each sub-environment are shown in Fig. 6, and representative grain-size curves in Fig. 7. The nearshore-sand bank samples exhibit the largest grain-size range from very fine to coarse sand (Fig. 6A). The coarse sand fraction varies from almost 0 to 80% in individual samples. The very fine sand samples associated with this sub-environment were probably collected from the troughs between tidal ridges where the sand generally forms a veneer associated with silt and clay (Van Lancker, 1999). Overall, however, the bulk (82%) of the sand bank samples are characterised by medium to fine sands, in agreement with previous work on these deposits (Augris et al., 1995; Van Lancker, 1999). The rather poor sorting of samples from this sub-environment may be due to the grab sampling method which collects a mixture of sand and silt.

Beach and aeolian dune mean grain sizes are remarkably clustered in the fine sand range (Fig. 6B,C). There is hardly any variation between inland, active dune and beach–dune transition samples, thus highlighting the common background population of sand in these two sub-environments and the sand interchanges characterising beach–dune morphodynamics (Anthony et al., 2006). Of the 341 randomly collected beach samples, only one falls within the coarse mean grain-size range (Fig. 6B), derived from an eroding cliff sector. Tidal flat samples exhibit the finest mean grain sizes, while estuarine samples show a wider spread (Fig. 6D).

The grain-size curves (Fig. 7) represent randomly selected samples from each sub-environment. They clearly show the relatively high sorting values of the samples shown in Fig. 5, the low percentage of the coarse sand fraction in beach, dune, tidal flat–estuarine samples, and the grain-size heterogeneity of samples from the nearshore-sand bank sub-environment.

5. Discussion and conclusions

It has been argued from source considerations as well as regional grain-size patterns in the English Channel (Fig. 3) that the sand deposits on the French coast between the Somme mouth and Belgium are essentially derived from the bed of this sea (Anthony, 2002). Potentially, therefore, the background grain-size range exhibits inherited heterogeneity reflecting the original mixing of several populations. A scrutiny of the data depicted in Figs. 5 and 6 suggests that this background heterogeneity is still imprinted on the grain-size distribution of the sandy deposits in the four sub-environments in the study area. Interpretation of the data in Fig. 5 suggests, as has been shown by Folk and Ward (1957) and Flemming (1988), the mixing, in different proportions, of at least three sediment populations (Fig. 8). Population “a” is a very coarse sand population whose source is most likely the heterogeneous sediment stock of the nearshore zone. This population is most representative of the nearshore sub-environment (Fig. 6), which also corresponds to the immediate source area. The low percentage of clastic deposits coarser than medium sand (i.e., <1.0 ø) in the other sub-environments reflects the operation of grain-size sorting processes in the nearby offshore source zone. A prime consideration in these processes is the way in which sand from the sea bed reaches the coast to build up aeolian dunes and infill estuaries. Various studies

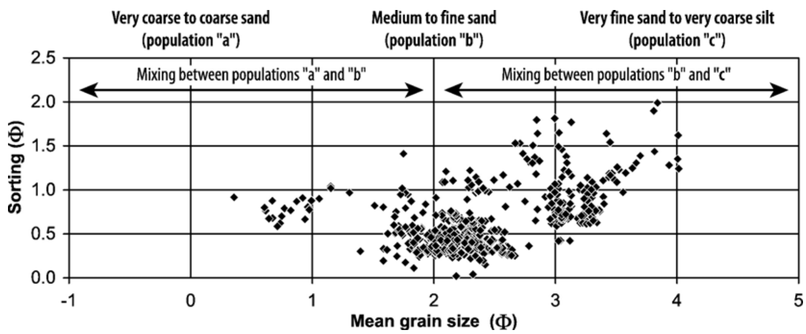

Fig. 8. The mixing of the three populations (“a”, “b”, “c”) composing the entire mean grain-size versus sorting database ($n = 665$).

concerning the southern North Sea have shown that sediment transport is driven jointly by tidal currents, waves, and compensatory flows in response to storm wind forcing in both the topographically-confined shallow nearshore zone where sub-parallel sand ridges alternate with troughs (Soulsby, 1997; Van Lancker, 1999; Héquette et al., in press) and over the intertidal beach bars and troughs (Reichmüth, 2003; Anthony et al., 2004). Waves, notably during storms, provide a mechanism for sand bed-stirring while strong tide- and wind-driven currents transport the sand. Storm waves tend to drive sand ridges onshore while strong rotating tidal currents tend to stretch them alongshore (Tessier et al., 1999). Using diverse empirical bed stress formulations, Van Lancker (1999) and Héquette et al. (in press) obtained similar results that show that present bed stress levels due to modal currents and waves are not sufficient to mobilise coarse sand, which is concentrated in depths greater than 8–10 m. It has been shown that over large areas of the nearshore zone off Belgium, mobility of even the finest sands may be limited to short bursts of peak tidal currents under non-storm conditions (Van Lancker, 1999).

Over time, however, storms and tidal currents have engendered large-scale sorting by segregating some of the fine to very fine sand from the coarser original sand stock and organising this fraction into the numerous sand ridges characterising the southern North Sea. Sand sourcing of the coast then depends on the capacity of the hydrodynamic regime (notably storms) in driving these sorted deposits (sand ridges) onshore. The nearshore ridge and trough topography and the shore-parallel tidal flows considerably dissipate and refract waves, thus limiting the capacity for shoreward storm wave reworking of the inner nearshore sand ridges. The only presently-known example where large-scale sand ridge migration with onshore welding has occurred is the Calais area (Fig. 1), where hydrodynamic and aeolian size-sorting processes result in a minor medium to coarse upper beach lag deposit of shelly debris and the winnowing out of abundant fine quartz sand to build embryo dunes. The processes operating in the nearshore zone thus entail selective winnowing and onshore transport of medium to very fine sand (populations “b” and “c”) from a heterogeneous sea-bed source.

Although both these populations are initially derived from the nearshore zone, essentially through cross-shore transport and onshore ridge welding, the significant concentration of medium to very fine sand in the three coastal sub-environments also reflects strong longshore transport processes during the Holocene. Globally, the dynamics of the coast and nearshore area of the eastern English Channel and southern North Sea include all the ingredients for tidal sand transport and accumulation of population “b” in the study area (Fig. 3): a convergence zone of medium to fine sand off the Somme estuary, a coastal transport pathway, and a major sand sink corresponding to the southern North Sea. The sand convergence zone between Hastings and the Somme estuary has been identified by radioactive tracer studies (Dewez et al., 1989; Beck et al., 1991) and by numerical modelling (Grochowski et al., 1993a,b). This convergence zone is bypassed by a pathway of sand transport towards the North Sea along the French coast (Dewez et al., 1989; Beck et al., 1991; Grochowski et al., 1993a,b; Anthony et al., 2005). This 1–10 km wide transport pathway is driven by the strong flood-dominated longshore currents affecting this coast and lies on the substrate of relict sand banks. There are very limited data on short-term sand transport volumes in this pathway other than those of Beck et al. (1991), who identified a northward sand transport of about 0.2 m^3 per linear m of coast per day.

Sand mobilisation, transport and deposition between the Somme mouth and Belgium was probably modulated by low-energy coastal embayments and estuaries in which were trapped abundant quantities of silt and very fine to fine sand (populations “b” and “c”) in tidal and aeolian environments. As these embayments and estuaries were filled and the shoreline regularised, the north–south wall of the French coast from the Somme to Cape Gris Nez developed into a major transport pathway, the finest sand ending up essentially in the southern North Sea sink, where this fraction has been progressively organised by the prevailing storm and tidal processes into the numerous shallow-water sand ridges evoked earlier. The Somme limit of the transport pathway coincides remarkably with the sharply defined southern limit of the massive aeolian dunes (Fig. 1) that have developed against the north–south wall formed by this coast (Anthony, 2002).

Hydrodynamic processes operating on the coast further lead to segregation of the very fine sand fraction (population “c”) which is rapidly evacuated from the beach system and trapped in tidal embayments and estuaries. Mixing of this fraction with coarse silt in these low-energy settings explains the rather poor sorting of this population (Figs. 5, 8). These processes leave a well sorted medium to fine sand population “b” in the beach and aeolian dune sub-environments. Sea-bed scouring during severe storms and resuspension and transport of fractions ranging from silt to coarse sand, as well resuspension of the finest fractions during flow peaks in each tidal cycle, may explain the rather poor sorting of

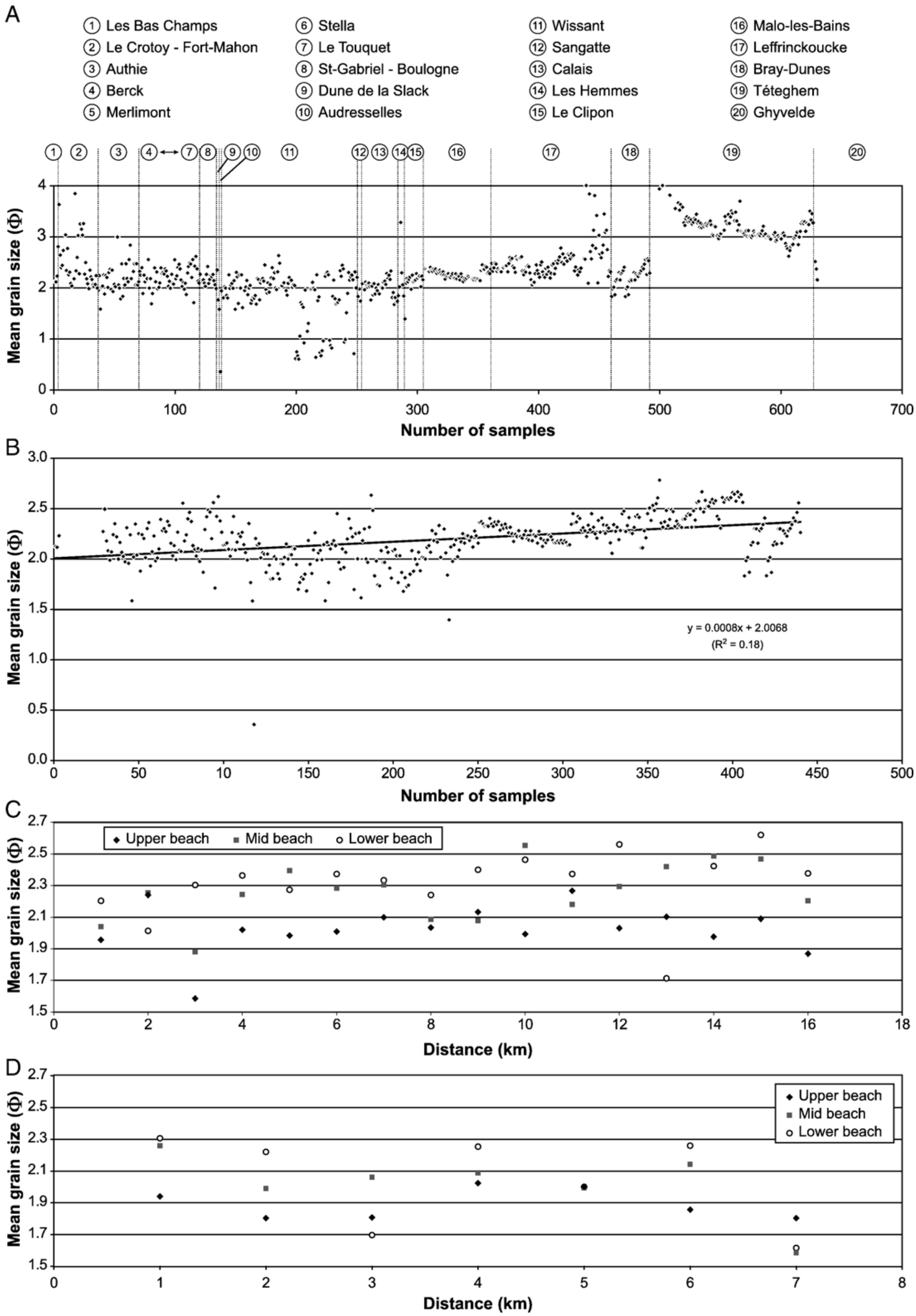

Fig. 9. Spatial patterns of mean grain-size trends: (A) mean grain-size trend of the entire grain-size database from the Somme estuary to Belgium. The outlier zone of fine to very fine sand corresponds to sampled borehole deposits from the embayed low-energy Flemish coastal plain (Fig. 1). Numbers refer to sampling sites or zones shown in Fig. 1); (B) mean grain-size trend of the entire beach sample dataset; (C), (D), mean beach grain-size trends from regular sampling at 1-km distances, respectively for zones 4 to 7 and 11.

the nearshore sand ridge samples (Figs. 5, 7A), as these processes lead to mixing.

A consideration of the hydrodynamic gradients associated with the regional-scale sediment segregation processes evoked above would suggest grain-size fining from the Somme mouth to the southern North Sea. Presentation of the whole set of mean grain sizes in terms of sampling sites between the Somme mouth and the Belgian border reveals a rather weak, and probably insignificant northward and then eastward fining trend (Fig. 9A). This very weak fining trend is confirmed by the beach dataset over this 150 km stretch of shoreline (Fig. 9B). Moreover, as would be expected from the weakness of this overall trend, no trend comes out from beach grain-size data obtained from regular distance sampling over much shorter stretches of shoreline (Fig. 9C,D). The absence of longshore gradients in mean grain size along the present beaches may be due to the fact that thresholds of sand movement are such that medium to fine sand is regularly mobilised alongshore by the strong longshore currents affecting these beaches, blurring gradients in grain size, this tendency being further reinforced by wave-induced cross-shore processes. The combination of wave, tidal and topographic flows on these beaches induces sand homogenisation, although most studies on these beaches show a slight fining trend in grain size from the upper to the lower beach (Masselink and Anthony, 2001; Anthony et al., 2004) in response to cross-shore wave energy variations. The complex beach hydrodynamic circulation patterns associated with beach 'bar-trough' topography (Anthony et al., 2004) could be one cause for the poor performance of transport vector models based on grain-size trend analysis developed over the years (e.g., Gao and Collins, 1992; Le Roux et al., 2002) and applied to these wave-tide-dominated beaches (Reichmüth, 2003). The homogeneity of population "b" in the beach and aeolian dune sub-environments is favoured by an already hydrodynamically sorted medium to fine sand fraction derived from offshore, with further sorting along the beaches by longshore currents. This leaves little scope for further sorting by aeolian processes. The dominant offshore and longshore winds on these coasts further lead to beach–dune sand interchanges without fundamentally affecting grain-size and sorting values.

Population "b" is thus a hydrodynamically homogenised population, with little grain-size mixing compared to populations "a" and "c". However, this homogeneous grain-size population comprises sand derived from the immediate nearshore zone and sand transported within the coastal transport pathway from the eastern English Channel to the southern North Sea. Although these sands form a hydrodynamically homogeneous population, they may probably be differentiated in terms of the degree of grain-size rounding. Mrani-Allaoui (2006) identified in a homogeneous medium to fine sand population ("b") in the Flemish coastal plain two quartz grain-size types under the scanning electron microscope: a dominant (>80%) sub-angular type exhibiting breakage features diagnostic of a glacial to paraglacial type source and limited transported in an aqueous medium, and a weaker fraction of sub-rounded to rounded grains associated with sustained transport. She also identified these two populations from nearshore sand ridge samples from the southern North Sea. This mixture of angular to rounded grains was also identified from nearshore deposits in the English Channel by Bellamy (1995).

Finally, the incipient development of a gravel-rich upper beach in Wissant Bay (Fig. 1) has occurred in an area of shoreline where hydrodynamic sand depletion processes leave scope for the concentration of gravel clasts reworked from nearby eroding cliffs and/or from the coarse-grained nearshore seabed. In the western part of this bay, a whittling sand supply and drop in the level of the dissipative sandy foreshore, probably related to larger-scale hydrodynamic interactions with an adjacent sand bank (Anthony and Dolique, 2001), enhance wave influence locally, leading to sorting and shoreward reworking of nearshore gravel. As the fine sand content of the beach decreases, increasing incident wave energy levels due to lessened dissipation further encourage gravel enrichment, and the formation of a reflective upper beach. The effect of this adaptative change in grain size on beach reflection further favours dune erosion and offshore bleeding of the fine sand fraction. It thus enhances a positive feedback that reinforces the reflective character of the beach (Anthony and Dolique, 2001).

The idea of grain-size sorting by regional to local tide- and storm-controlled sorting processes may be used in further studies to explain trends and patterns of stability/instability of these coasts evoked in the foregoing discussion. Despite abundant nearshore accumulations of sand, these coasts are presently stable or are even strongly erosional in places, most probably as a result, in part, of highly selective grain-size sorting processes.

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