ORIGIN OF SOME OFFSHORE SAND BODIES AROUND FRANCE

Serge BERNÉ[1], Tania MARSSET[1], Gilles LERICOLAIS[1], Jean François BOURILLET[1], Marc de BATIST[2], Jean Yves REYNAUD[3] & Bernadette TESSIER[3]

[1] IFREMER, Centre de Brest, BP 70; 29280 Plouzané, France;
Tel.: +33-298.22.42.49, Fax: +33-298.22.45.70; E-mail: sberne@ifremer.fr
[2] University of Gent, Belgium
[3] Université de Lille 1, Laboratoire de Sédimentologie et Géodynamique, 59655 Villeneuve d'Ascq, France;
Tel: +33-320.43.43.96; Fax: +33-320.43.49.10; E-mail: bernadette.tessier@univ-lille1.fr

Abstract. Offshore sand bodies are described in many continental shelves in the world, as well as in the stratigraphic record where they represent interesting reservoirs. Many of the latest, initially interpreted as sand ridges built by physical processes, are now re-interpreted as lowstand shorefacies. In contrast, relatively few attention has been paid to the origin of *recent* offshore sand ridges, mainly because of the lack of data about their internal structure. Improved techniques in acquisition and processing of very high resolution seismic and some shallow cores allow to reconstruct the architecture of "offshore sand bodies" from the Celtic Sea (tide dominated) and the Gulf of Lions (wave dominated) shelves around France. In both cases, our investigation demonstrates that the sand bodies mainly consist of lowstand deposits (estuarine/deltaic systems, sharp-based shorefaces), instead of transgressive deposits as proposed by several workers. However, the shape and position of the "ridges" mainly results from control by physical processes. In the Celtic Sea, intense erosion resulted in the shaping of shore-normal ridges "cannibalizing" lowstand deposits, while the shore-parallel orientation of the lowstand shorefaces has been preserved in the Gulf of Lions. The understanding of the architecture and distribution of offshore sand bodies requires to take into account not only the classical sequence stratigraphic concepts (relative sea-level changes, sediment supply...) but also hydrodynamic processes. The erosional sand bodies we describe represent a new category of outer shelf sand bodies, in between the purely hydrodynamic examples described by Houbolt (1968) in the Southern North Sea and the purely "allocyclic" lowstand shorefaces mainly described in the stratigraphic record of the Western Interior Seaway. This finding may have interesting applications for predicting the geometry, orientation and position of fossil sand bodies with respect to paleo-shorelines. The magnitude of erosional processes evidenced by our investigations also implies that a large amount of shelf sediments (mainly sand) has been transferred to the adjacent deep sea fans.

Résumé. Des corps sableux de plate-forme sont décrits en diverses régions du monde, ainsi que dans de nombreuses roches sédimentaires où ils constituent des réservoirs intéressants. En Mer Celtique et dans le Golfe du lion, on observe ainsi, à des profondeurs comprises entre 100 et 160 m mètres, des accumulations sableuses d'épaisseur importante (>30m). L'analyse sismique à haute résolution et quelques carottages suggèrent que ces accumulations correspondent à des dépôts régressifs ou de bas niveau, remaniés et fortement érodés par la transgression post-glaciaire. Une nouvelle catégorie de corps sableux, résultant à la fois de processus autocycliques (remaniement par des courants) et allocycliques (glacio-eustatisme) est ainsi mise en évidence. Cette découverte à des implications quant à la géométrie et à l'orientation de ces corps sédimentaires ; elle implique aussi qu'un volume sédimentaire important a été érodé et transferré au domaine profond.

Key-words: sand body, outer shelf, lowstand shoreface

INTRODUCTION

Shallow marine sandstone, generally encased in shales, are common in the stratigraphic record, where they represent interesting reservoirs, especially in the Western Interior Basins of North America. Comparison with Quaternary shelves led several authors to interpret these sand bodies as transgressive (tide- or wave-dominated) sand ridges similar to that described around NW Europe (Stride et al., 1982) and the Atlantic coast of the US (Swift, 1975; Swift and Field, 1981). Most of these sand bodies are now re-interpreted as lowstand and transgressive shorefaces, whose isolated position on the shelf can be related to (forced) regressions (Plint, 1988; Posamentier et al., 1992; Walker and Bergman, 1993; Walker and Plint, 1992; Walker and Wiseman, 1995). Surprisingly, few attention has been paid to the structure and origin of modern (Quaternary) outer shelf sand bodies, in order to examine whether such a re-interpretation also could be applied. This paper documents two outer shelf case studies around France, with distinct sedimentary and hydrodynamical regimes. High resolution seismic data and some shallow cores suggest that erosional processes may have had a very important role in remodelling lowstand deposits, resulting in the formation of a new "hybrid" type of shelf sedimentary body in-between classical ridges and classical lowstand shorelines.

BACKGROUND

It has long been observed that sediments covering most of the outer part of continental shelves around the world do not match the present day hydrodynamical regimes (Bourcart, 1945; Dangeard, 1928; Shepard, 1932). In particular, these authors observed the presence of coarse grained sediments (mainly sands) in area where current velocities near the bed were (or were supposed to be) lower than the velocity threshold for sediment transport (the present source of sand being along the coastline). This contradiction led

Emery (1968) to propose that the sands covering a large part of the continental shelves were relict deposits inherited from periods of low sea levels. However, Swift et al., (1971) suggested that the energy available during subsequent sea level rise and highstand was sufficient for re-distributing sediments, these reworked sediments being named "palimpsests". More recently, Swift and Thorne (1991) developed the concept of equilibrium shelf, where the shelf surface is viewed as a surface of dynamic equilibrium *over geological time-scales.* From a wide range of seismic data, Field and Trincardi (1991) demonstrated that Quaternary regressive coastal deposits were more likely to be preserved offshore of the lowstand shoreline, whereas those deposited inshore were generally truncated and reworked by the transgressive erosion.

One particular type of "offshore sands" is represented by sand ridges (or sand banks of several authors), which have been extensively studied on modern continental shelves (Stride et al., 1982, for instance; Swift and Field, 1981). They are elongated sand bodies (several km or tenths of km long, several hundred of meters or km wide and one to several tenth of meters thick). They are generally subdivided into storm-dominated sand ridges and tide-dominated sand ridges. Both types are generally referred to as "offshore bars" by geologists studying the stratigraphic record, but this term does not refer to any process nor any given sedimentary environment and should be disregarded.

The *tidal* sand ridges have generally been interpreted as the result of "autocyclic" processes (formation of residual eddies generated by the Coriolis force and bottom friction (Hulscher et al., 1993; Huthnance, 1982a; Huthnance, 1982b). This interpretation was supported by the seismic data of Houbolt (1968) were the sand ridges of the Southern North Sea appeared as sand bodies resting on a flat surface (the post-glacial transgressive surface). In contrast, on the other side of the Atlantic Ocean, sand ridges of the *storm-dominated* middle Atlantic Bight were interpreted as the result of the evolution of sand bodies formed on the shoreface, eventually resting in an offshore position at the "leading edge of the transgression" (Field, 1980; Swift et al., 1991). Thus, these "sand" bodies could incorporate back barrier sands and lagoonal muds, and should be the result of a partly "allocyclic" process. It is worth noting that most of the attention was paid to inner shelf sand ridges, and that few studies describe outer shelf offshore ridges at water depth more than 90 m (Bouysse et al., 1976; Moslow et al., 1989; Yang and Sun, 1988). In this paper, we examine data recently collected from two contrasted outer shelves around France: The tide-dominated Southern Celtic Sea (A in Fig.1) and the wave-dominated Gulf of Lions in the Western Mediterranean Sea (B in Fig.1). The seismic data were acquired with a SIG sparker seismic device, using an ELICS DELPH 2 digital recorder. All the records presented in this article were posprocessed using the "SITHERE" programme (Lericolais et al., 1990).

"Moribund" sand ridges in the Southern Celtic Sea

General setting

One of the largest and best studied sand ridge field in the world is in the Southern Celtic Sea. It was firstly mapped by Berthois (1974) and Bouysse et al., (1976). Up to 60 m in height, 200 km in length, 7 km in width, without clear asymmetry in cross-section, these ridges, trending Northeast-Southwest, lie at water depths comprised between 120 m and 170 m (Fig.2). Their superficial lithology consists of medium to coarse grained sand whose carbonate content (mainly shell hash) is about 60%, the remaining fraction consisting of terrigenous grains. Current measurements over a 2 month period in the vicinity of the Kaiser I Hind at a point where water depth is 165 m (point C in Fig.2), indicate that, during spring tides, surface velocities are higher than 100 cm/s, whereas those measured 50 m above the bed reach 80 cm/s (Chapelier, 1986). Even if one take into account the attenuation of current velocity near the bed, there is no doubt that the tidal current is able to maintain the mobility of the sand fraction on the floor, as demonstrated by side scan sonar imaging over the Kaiser I Hind, showing large dunes circulating clockwise around the ridge (Reynaud, 1996).

In addition to the tidal current, storm waves may also have some effect on sediment transport. Side scan imaging reveals, at the top of the ridges (depth about 120 m), the occurrence of symmetrical small dunes, about 2 m in length, whose crest is oriented N20°. These bed forms are similar to the "wave ripples" formed in many coarse-grained sediments of modern shelves (see the review by Leckie (1988). The fact that trawling marks are reworked by these bed forms confirms their recent origin.

Few shallow cores, mainly sampled by the British Geological Survey, are available. They reveal that the sandy mobile layer previously mentioned is underlained by a lag pavement consisting of coarse sand and gravel, dating from the Flandrian (post-glacial) sea level rise (Evans, 1990). As to the inner part of the ridges, named the Melville Formation by the British oceanographers, it consists of clean, sporadically gravely, sand. It is dated late Devansian / Weichseilian (Pantin and Evans, 1984). It must be emphasised

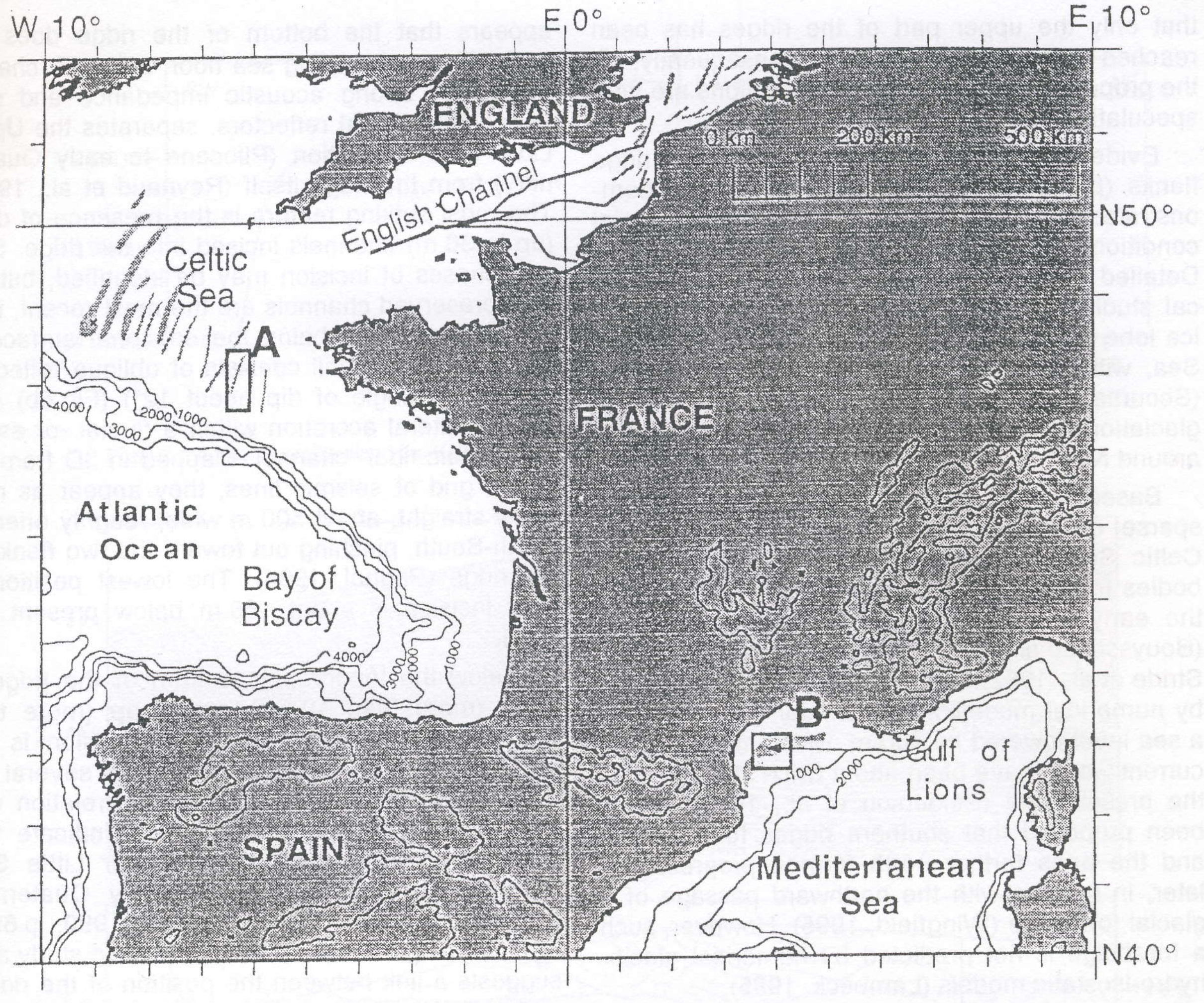

Fig.1 Position of the studied areas on the outer shelves of the tide-dominated Celtic Sea (A) and the wave-dominated Gulf of Lions (B). The dotted areas correspond to the major sand accumulations mapped on the shelves. The dark lines in the English Channel correspond to the major incisions by rivers during low stands of the sea.

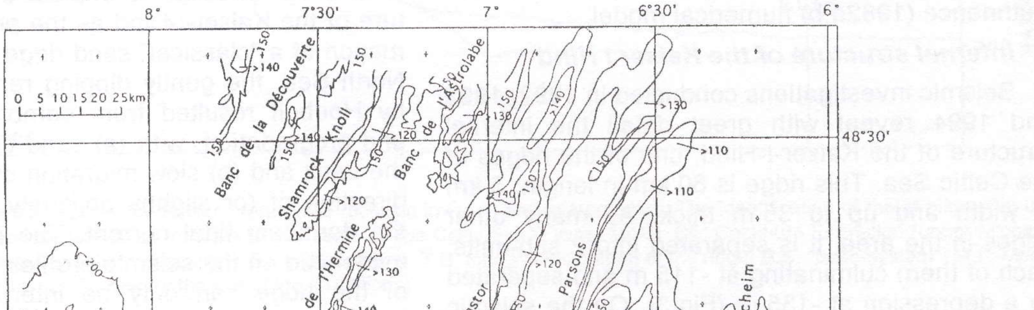

Fig.2 Bathymetric map of the Southern termination of the Celtic Sea. (the contour lines for the sand ridges are from Bouysse et al., 1976, those for the La Chapelle area and the continental margin are from Bourillet and Loubrieu (1995). C is the position of current measurements by Chapelier (1986). Thick lines give the position of seismic profiles in Figs 4 and 5a.

that only the upper part of the ridges has been reached by vibrocores to date; consequently, all the proposed stratigraphic reconstructions are very speculative.

Evidence of glacial sediments on the ridge flanks (probably transported by ice-rafting) demonstrates that the ridges existed before glacial conditions retreated from the surrounding region. Detailed sedimentological and micropaleontological studies suggest that, during Weichseilian, an ice lobe advanced in the Celtic Sea from the Irish Sea, with grounded ice as far south as N49°30' (Scourse et al., 1990), but there is no evidence of glaciation in the study area, which is located around N48°.

Based on the present tidal regime and the sparse dated samples, the sand ridges in the Celtic Sea have been interpreted as tidal sand bodies formed between the last low sea level and the early stage of the Flandrian sea level rise, (Bouysse et al., 1976; Pantin and Evans, 1984; Stride et al., 1982). This interpretation is supported by numerical modelling of M2 tidal constituent for a sea level lowered by 100 m, which indicates that current would have been about twice stronger than the present one (Belderson et al., 1986). It has been proposed that southern ridges formed first, and the ones farther north formed progressively later, in relation with the northward passage of a glacial forebulge (Wingfield, 1995). However, such a forebulge is not predicted by numerical glacio-hydro-isostatic models (Lambeck, 1995).

In any of these interpretations, the inferred mechanism for ridge formation is an up-building process controlled by tidal currents, as in the Huthnance (1982a,b) numerical model.

Internal structure of the Kaiser I Hind

Seismic investigations conducted in 1992, 1993 and 1994 reveal with great detail the internal structure of the Kaiser-I-Hind, one of the ridges of the Celtic Sea. This ridge is 60 km in length, 5 km in width and up to 35 m thick. As many other ridges in the area, it is separated into 2 sub-units, each of them culminating at -115 m and separated by a depression at -135 m (Fig.3). On the seismic profiles, the ridge does not exhibit the low angle clinoforms commonly described within tidal sand ridges, as the Well Bank and the Smith Knoll in the Southern North Sea (Houbolt, 1968), but a very complex pattern of cut and fill structures (Figs 4 and 5). Major bounding surfaces are gently dipping toward the East. As a result, the major seismic units they delimit are shifted in that direction from the bottom to the top of the bank. Most of these units exhibit clinoforms whose true angle of dip (determined from measurements along 2 perpendicular directions) reaches up to 10°. Most of these clinoforms dip toward the *South West*. It also appears that the bottom of the ridge does not match the surrounding sea floor: a "core", characterised by strong acoustic impedance and sub-horizontal internal reflectors, separates the Upper Little Sole Formation (Pliocene to early Quaternary) from the ridge itself (Reynaud et al., 1995). The most striking feature is the presence of deep (up to 30 m) channels incised into the ridge. Several phases of incision may be identified, but the best preserved channels are the most recent, their upper termination being the erosional surface of the ridge. Their infill consists of oblique reflectors (maximum angle of dip about 12°) (Fig.5b) suggesting lateral accretion within a fluvial -or estuarine/deltaic tidal- channel. Mapped in 3D from the dense grid of seismic lines, they appear as relatively straight, about 500 m wide, roughly oriented North-South, pinching out toward the two flanks of the ridge (Pagnol, 1995). The lowest position of their incision is about 150 m below present sea level.

Below the topographic bottom of the ridge, a large (more than 10 km) and deep (more than 200 m below present sea level) incision is observed. The infill is characterised by several cut and fill phases (Figs 4 and 5a). Correlation with investigations in the British sector indicate that these deposits belong to the Upper Little Sole Formation, dated Pliocene to Early Quaternary (Pantin and Evans, 1984, Evans, 1990, p.659). The mapping of this unit over the whole study area suggests a link between the position of the ridges and that of the infills (Vanhauwaert, 1993, Fig.6).

Origin and evolution of the Kaiser-I-Hind

It is not possible to explain the internal structure of the Kaiser-I-Hind as the product of the formation of a "classical" sand ridge. In the Southern North Sea, the gently dipping reflectors observed by Houbolt resulted from combined aggradation and progradation, with (a) sand circulating around the bank and (b) slow migration of the ridge in the direction of (or slightly obliquely with respect to) the dominant tidal current. The incised channels evidenced on the seismic profiles in the upper part of the ridge can only be interpreted as fluvial and/or estuarine or deltaic tidal channels which must have formed during Quaternary lowstands. As the upper channels almost outcrop (at the resolution of the seismic device), it is most likely that they would correspond to the last lowstand (stage 2). If we interpret these features as *fluvial channels*, this implies a sea level lower than, or equal to, 150 m. It can be noted that a geometric model of sea-level during the end-Pleistocene to Holocene transition locates a peak forebulge in the southern Celtic Sea, at 12 ka BP, at a present water depth 160 m below present mean sea level (Wingfield, 1995). In contrast, numerical models of

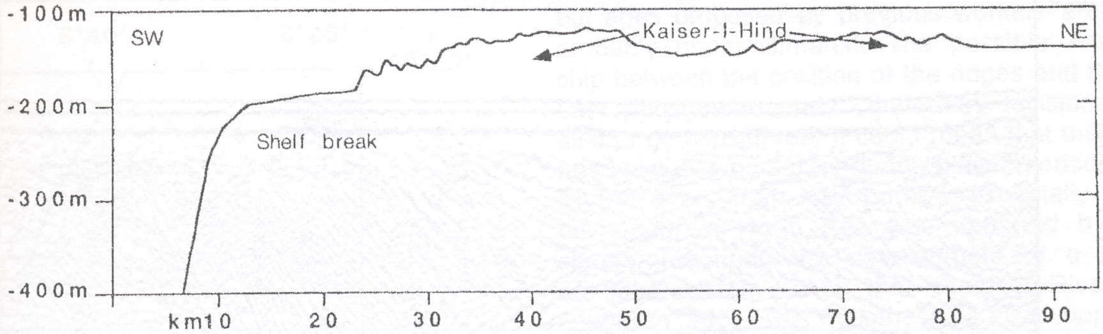

Fig.3 Topographic profile along the Kaiser-I-Hind and the adjacent continental slope (Sedimanche 1 cruise).

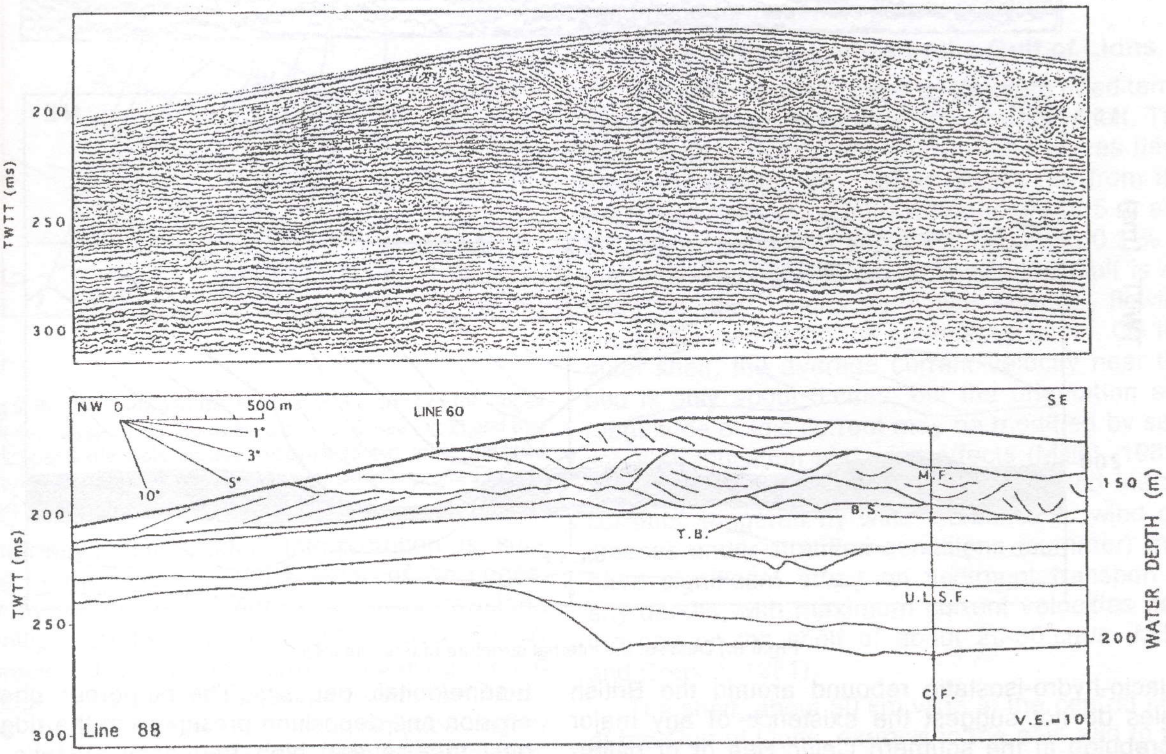

Fig.4 Seismic section across the Kaiser-I-Hind ridge (position in Fig.1) and interpretation. The identification of the stratigraphic units is based on correlation with boreholes from the British sector of the Celtic Sea (Evans, 1990). **CF**: Cockburn Formation (upper Miocene); **ULSF**: Upper Little Sole Formation (Pliocene to Early Quaternary); **T.B**: topographic bottom of the ridge; **B.S**: "base-system"; M.F: Melville formation (see discussion in the text for the age of the formations).

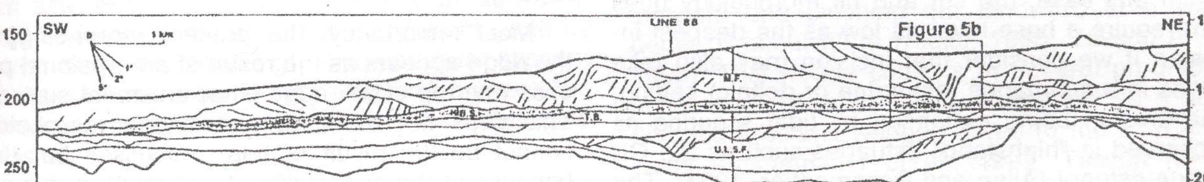

Fig.5 Internal structure of the Kaiser I Hind ridge in an along crest (**correct ?**) direction. The abbreviations are the same as in Fig.4. (a) Line drawing for a profile along the Kaiser-I-Hind ridge (position in Fig.2). The rectangle gives the position of Fig.5b.

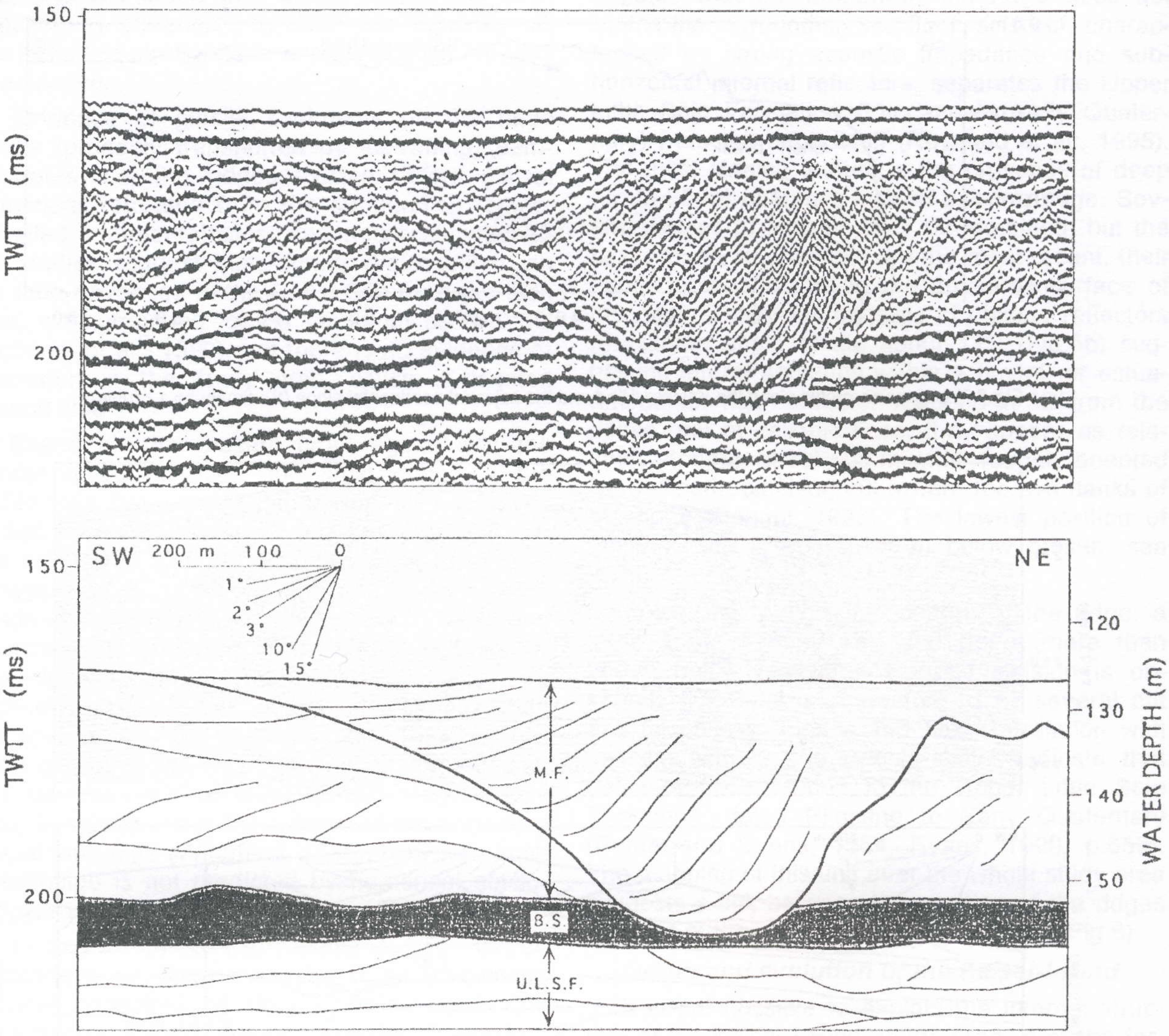

Fig.5 (b) Detail of the internal structure of a recent infill

glacio-hydro-isostatic rebound around the British Isles do not suggest the existence of any major forebulge in the southern Celtic Sea or of paleo-shorelines at positions to the west of 5°30' W (Lambeck ; Lambeck, 1995). This means that, *in this area*, sea level since -20,000 B.P. was never deeper than about -120 m, not -160 m as suggested by Wingfield (1995).

In any case, the cut and fill morphology does not require a base level as low as the deepest incision if we consider that incision may also take place in a *submarine* (estuarine or deltaic) setting, the erosion being enhanced by tidal scouring as observed in "highstand" estuaries such as the Gironde estuary (Allen and Posamentier, 1993). The presence of incised channels within the ridges implies an origin different from the "classical" upbuilding process, as well as different lithologic constituents and sedimentary structures. It means that a large amount of the ridge constituents are not shelf-tidal sands but fluvial, or more likely estuarine/deltaic deposits. The numerous phases of erosion and deposition preserved in the ridge suggest that several high frequency eustatic cycles have been preserved. However, the lack of correlation of bounding surfaces at a regional scale and the absence of ground truthing prevent from distinguishing possible autocyclic processes (lobe or channel migrations) from global, glacio-eustatic forcing.

Most importantly, the present morphology of the ridge appears as the result of an erosional process (the top of the ridge is an erosional surface). This does not mean that the ridge morphology cannot be the result of tidal processes but that, because of the availability of sediment in this particular area, the tidal currents "shaped" deltaic or estuarine deposits into sand ridges. At a smaller scale, large dunes migrating with a negative angle of climb and incorporating underlying deposits have already been mentioned in aeolian (Rubin, 1987, p. 25) or subtidal (Berné et al., 1991, Fig.7)

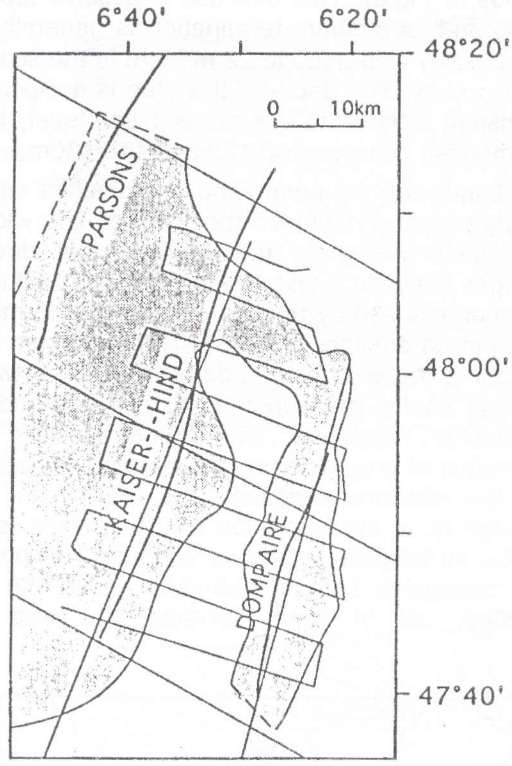

Fig.6 Relation between the position of the crest of the ridges (thick lines, mapped from Bouysse et al., 1976, see Fig.2) and that of the Upper Little Sole incised valley-fill (doted area) modified from Vanhauwaert (1993). The position of seismic profiles is represented by thin lines.

environments. This "tidal" interpretation is supported by the shape and orientation of the ridges, which match the orientation of modelled lowstand tidal ellipse (Belderson et al., 1986), and also by the present day tidal bed forms circulating around the ridge. It is also in agreement with the Huthnance model (1982a, b), which implies higher bottom friction (and consequently possible substrate erosion) in between the ridges. Considering that the ridge morphology mainly results from an erosional process also provide an explanation for the depression observed along most of the ridge profiles, at a water depth about 135 m below present sea level. This could be the result of a still-stand favouring the action of ravinement (both by wave and tidal scouring), this particular type of wave-cut terrace being only observable where the sediments were not removed by subsequent tidal erosion.

Finally, the Kaiser-I-Hind sand ridge appears as a sedimentary body resulting from remodelling by tidal (or combined tidal/wave) processes of pre-existing estuarine or deltaic lowstand deposits. Seismic facies suggest that sand is the dominant constituent of this sedimentary body. The timing of depositional events is not possible at this stage, but ages proposed by previous workers are very probably underestimated. The possible relationship between the position of the ridges and that of Late Pliocene to early Quaternary incisions has also to be considered. It could mean that the zone has been a depo-center during glacial periods, fed by the rivers from NW Europe, especially when the Southern North Sea was dammed by ice-sheets, favouring the development of a major drainage system called the "Channel River" by Gibbard (1988). This hypothesis is also supported by the sedimentological and micro-paleontological observations of Scourse et al., (1990), who proposed that the sands in the Central and Southwestern Celtic Sea were deposited previous to sand ridge formation as glacial outwash.

Offshore sand bodies in the Gulf of Lions

The Gulf of Lions, in the Western Mediterranean Sea, is regarded as a "low energy" shelf. The tidal range is only a few cm, and the waves have moderate energy. The largest swells are from the Southeast, with maximum wave height of 5 m and associated periods of about 8 s, occurring 0.1 % of the time. The general circulation in the Gulf is related to the Liguro-provencal current, flowing southwestward along the continental slope. On the outer shelf, the average current velocity near the bed is only about 5 cm/s, but the orientation and magnitude of this current may be modified by seasonal stratification and wind effects (Millot, 1981). In addition, internal waves and associated inertial currents, triggered by wind increases or wind decreases under stratified conditions (summer) may have significant effect on sediment transport at any depths, with maximum current velocities near the bed on the shelf of about 20-30 cm/s (Millot and Crépon, 1981).

The shelf, about 50 km wide in the central area of the Gulf of Lions, narrows to the east and to the west (Fig.7). The shelf break is located at water depths ranging between 120 and 150 m, depending on the occurrence or not of recent slope failures within the canyons. Seismic investigations show that, on the outer and median shelf, Late Quaternary sediments form a wedge thickening seaward and pinching out landward at a water depth of about 80 m (Aloïsi, 1986; Tesson et al., 1990). This wedge consists of several prograding units, each of them being interpreted as a shelf perched lowstand wedge related to forced regressions (Posamentier et al., 1992; Tesson et al., 1993). Between 80 and 100 m water depth, large sand accumulations, named *"sables du large"* ("offshore sands") by Bourcart (1945) occur (Fig.7). They cover a large part of the outer shelf (Aloïsi, 1986, Gensous, 1993, p.780; Monaco, 1971). Shallow cores indicate that their upper part is fine grained (mean grain size about 200 mm) to the West, coarser (mean grain size between 400 and 500 mm) and less well sorted to the East (Aloïsi, 1986; Monaco, 1971). The carbonate content of these sands, mainly of biogenic origin, is comprised between 25 and 50 % (Aloïsi, 1986). Faunal analysis and carbon dating of the upper part of these sands led Monaco (1971) to interpret them as littoral sands deposited during the last glacial maximum and during a short stillstand (at -85 or -90 m) within the overall post glacial sea level rise.

NEW RESULTS

Compilation of previous hydrographic surveys and swath bathymetry over selected areas, as well as a dense grid of seismic profiling, over a zone of about 1200 km^2 and some shallow cores allow us to reconstruct the architecture of the most recent sand units.

Seismic profiles across the "offshore sands" of Bourcart (1945) indicate that they consist of a large prograding unit, up to 32 m thick (assuming an acoustic velocity of 1800 m/s within sands) (150s in Fig.8). This unit has a *positive topography*, and its offshore termination is generally well marked by a step (up to 22 m high) in the sea floor topography. The depth of this step is not perfectly constant relative to the present sea-level, but is comprised between 100/120 and 110/130m.

Landward, the prograding unit pinches out at a fairly constant depth of about 95 m. The width of the sand wedge in the shore-normal direction ranges between 7 and 18 km. This prograding unit is characterised by relatively steep clinoforms dipping in an offshore direction. The maximum angle of dip of these reflectors, determined from two apparent angles measured along two perpendicular directions, reaches 9°, with an average of 4°. The direction of progradation is systematically oriented in the offshore direction. The top of the sand wedge is, at the resolution of the sparker seismic data, an irregular erosional surface. It is possible to distinguish several sub-units within the sand wedge, all of them forming a "sand belt"

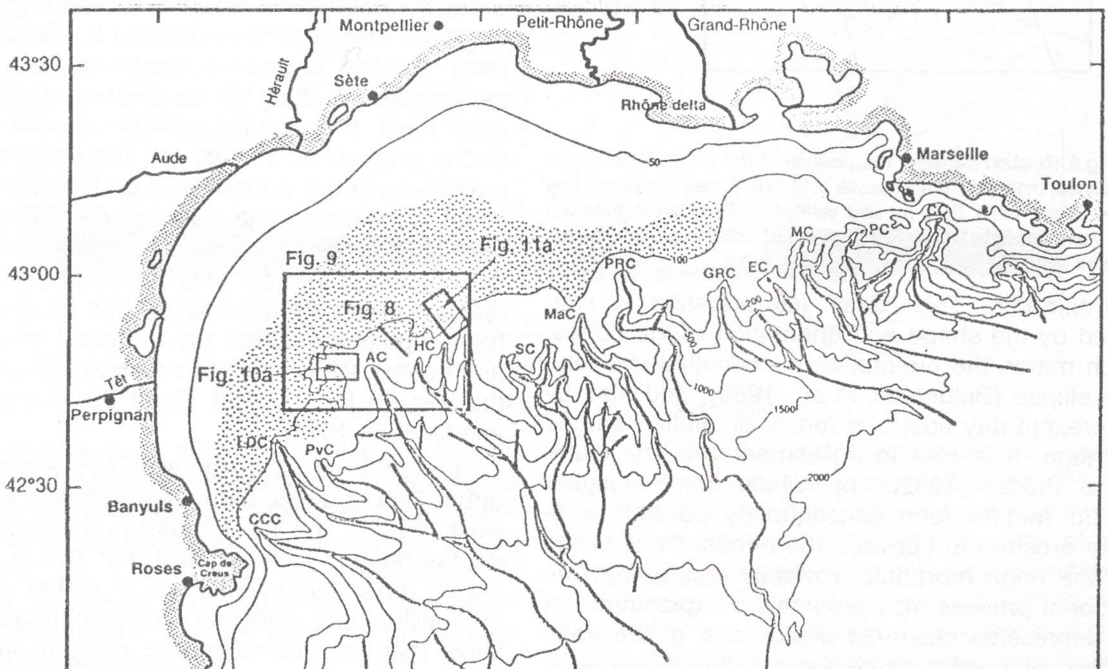

Fig.7 Morphology of the Gulf of Lions (Western Mediterranean Sea). The dotted area corresponds to the extension of the "offshore sands". FC: Fonera Canyon; CCC: Cap de Creus Canyon; LDC: Lacaze-Duthiers Canyon; PvC: Pruvot Canyon; AC: Aude Canyon; HC: Herault Canyon; SC: Sète Canyon; MaC: Marti Canyon; PRC: Petit-Rhône Canyon; GRC: Grand-Rhône Canyon; EC: Estocade Canyon; MC: Marseille Canyon; PC: Planier Canyon; CC: Cassidaigne Canyon. PCDSB: Pyrenean canyons deep sedimentary body. The position of offshore sands is from Aloïsi (1986) and Gensous et al., (1993).

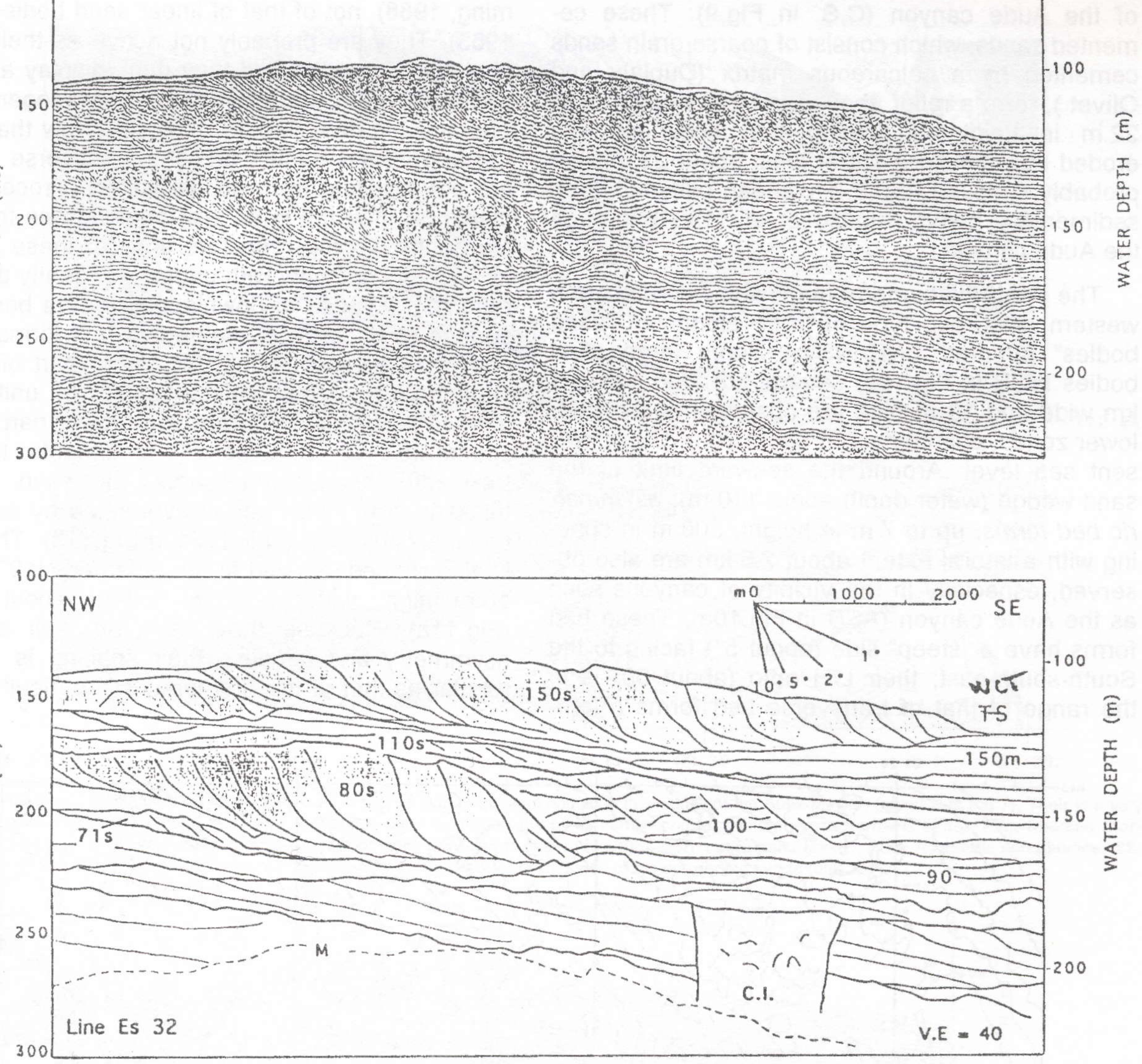

Fig.8 Seismic (dip) section across the "offshore sands" of Bourcart (1945). The upper sand unit (unit 15s) forms a positive topography. Note similar underlying sand wedges (especially unit 80s), which will be described elsewhere. Vertical exaggeration is 40. Position in Fig.8.

whose lateral extent is more than 40 km. The seismic profiles also indicate that several very similar sand wedges can be detected underneath (the characteristics of these older units will be detailed elsewhere). Shallow (3 m) cores indicate that the upper part of this sand wedge consists of medium to coarse olive-grey sand (mean grain size between 150 and 350 mm). Within some of the cores, a coarse lag, with large shell debris and pebbles, is observed. This coarse unit overlies sands similar to the upper deposits. The dating of one well preserved (not transported) shell yield an AMS 14C age of 12,710 ± 80 y. B.P., -1.80 m below the surface (water depth -93 m). At the bottom of the sand wedge, the clinoforms downlap over a generally erosional surface, cutting across another seismic unit consisting of parallel, sub-horizontal continuous reflectors (150m in Fig.8). In some other situations, they pass progressively to the sub-horizontal reflectors. Seaward of the sand wedge, the upper part of these sub-horizontal reflectors outcrops and it has been sampled by shallow (5m) cores. It consists mainly of dark grey clayey silts (mean grain size about 30 mm), with numerous thin interstratified fine sand layers. One dating at -4.50 m within this core (water depth -126 m) gave an AMS 14C age of 20,040 ± 400 y.BP.

Beside this general organisation, differences may be observed from the west to the east of the study area. To the West, the top of the upper sand wedge becomes more and more erosional (the preserved thickness of unit 150s decreases along this direction and the erosional surface becomes more undulated). The importance of erosional processes is confirmed by the presence of cemented sands at the top of the sand wedge, in the vicinity of the Aude canyon (C.S. in Fig.9). These cemented sands, which consist of coarse grain sands cemented by a calcareous matrix (Duplaix and Olivet), form a relief above the sand wedge up to 22 m in height, indicating that sediment was eroded by a thickness of at least about 22 m, and probably supplied to the "Pyrenean canyons deep sedimentary body" (Alonso et al., 1991) through the Aude canyon.

The swath bathymetry maps show, in the same western area, two type of large elongated "sand bodies" oriented ENE-WSW. Some large sand bodies (LSB in Fig.10a) several km long, up to 1 km wide and 10 m high are observed in the shallower zones, culminating at about 90 m below present sea level. Around the seaward limit of the sand wedge (water depth about 110 m), *asymmetric bed forms*, up to 7 m in height, 500 m in spacing with a lateral extent about 2.5 km are also observed, especially in the vicinity of canyons such as the Aude canyon (ASB in Fig.10a). These bed forms have a "steep" side (about 5°) facing to the South-south-east; their L/H ratio (about 60) is in the range of that of transverse bed forms (Flemming, 1988), not of that of linear sand bodies (Off, 1963). They are probably not active as their morphology is rounded and they don't display any superimposed bed form (small dune or megaripple). The seismic data (Fig.10b) clearly show that both the large sand bodies and the transverse dunes are not resulting from an up-building process because (a) their top is an erosional surface truncating gently dipping reflectors and (b) these reflectors are in continuity with underlying gently dipping reflectors (instead of downlapping overa bounding surface as in classical prograding bed forms). Lateral correlation show that the upper part of these sand bodies corresponds to sands of unit 150s defined previously, whereas their lower part corresponds to unit 150m, i.e. silty sediments. In contrast with this erosional area, the sand wedge thickens to the East and is overlained by an additional seismic unit (unit 155s in Fig.11b). This unit is also shaped into bed forms, oriented N10°, up to 10 m high, with a lateral extent about 1 km (Fig.11a). Because they have no well defined asymmetry and because their spacing is not as regular as that of the first type, it is difficult to de-

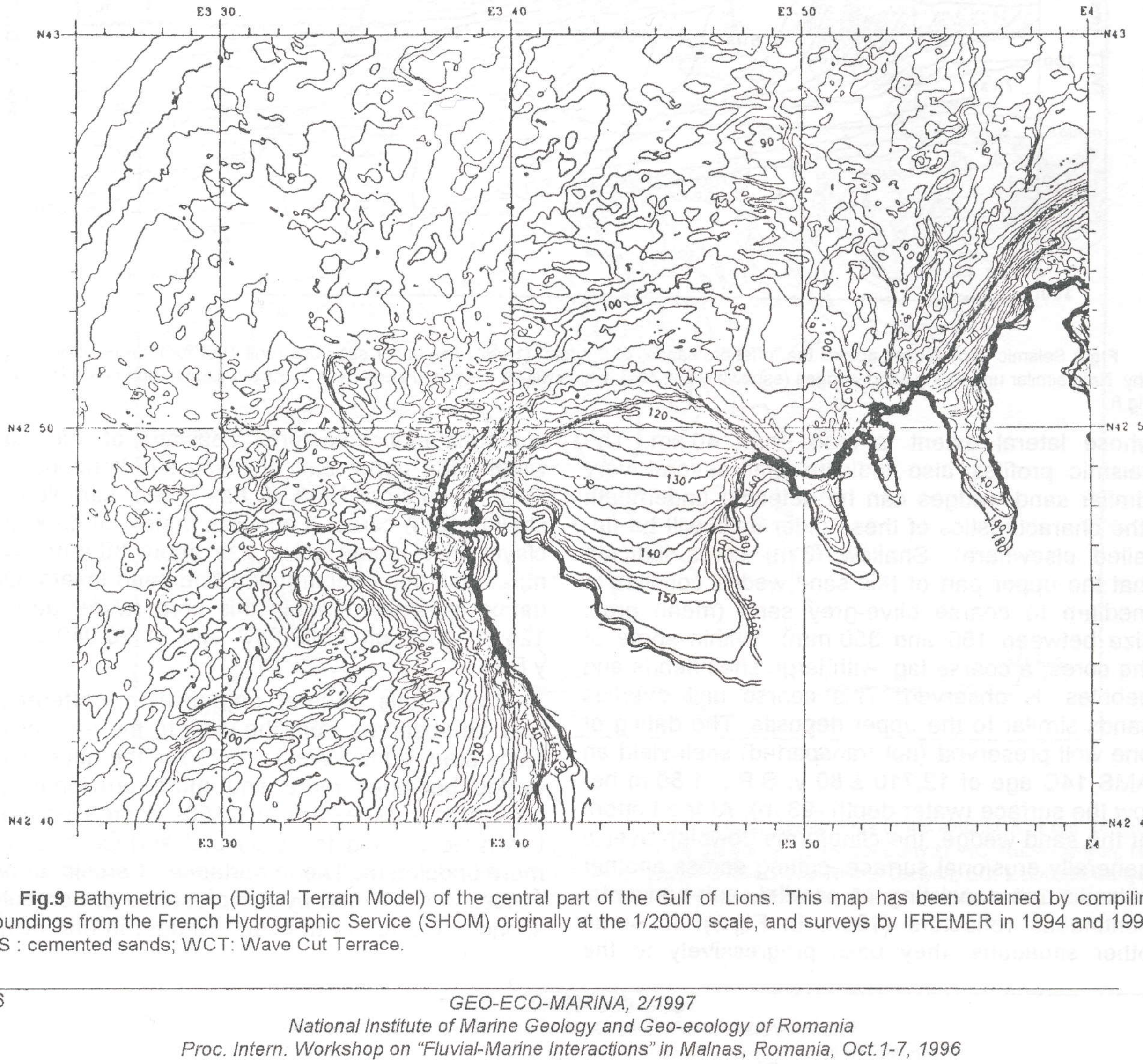

Fig.9 Bathymetric map (Digital Terrain Model) of the central part of the Gulf of Lions. This map has been obtained by compiling soundings from the French Hydrographic Service (SHOM) originally at the 1/20000 scale, and surveys by IFREMER in 1994 and 1995. CS : cemented sands; WCT: Wave Cut Terrace.

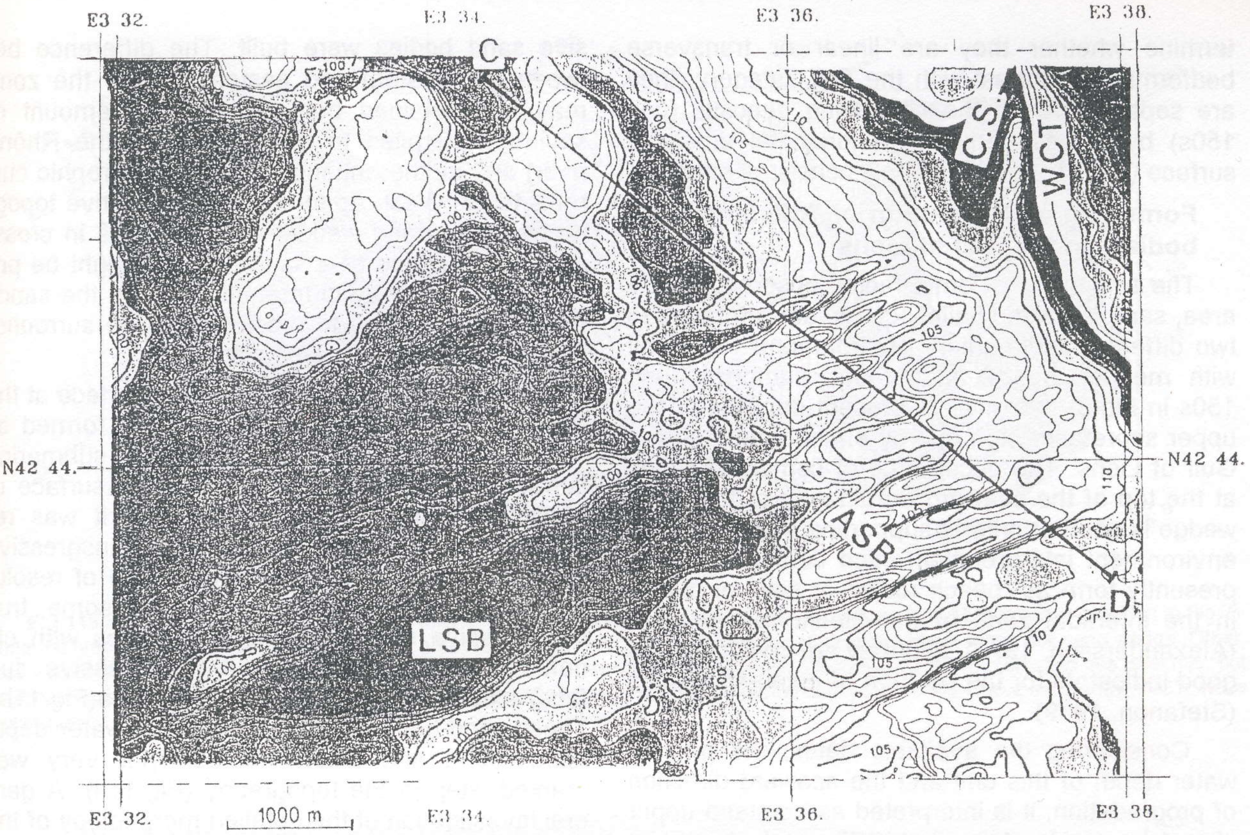

Fig.10a Swath bathymetry (SIMRAD 950) map of a zone with large sand bodies in the vicinity of the Aude canyon (position in Fig.7). Their is a very good correlation between surficial sediment distribution and topography: the highs correspond to medium sands (remains of unit 15s), whereas (**correct ?**) the surrounding lows consist of silty sands. Compare withseismic data in Fig.10b). LSB: Large sand bodies; ASB: Asymetric sand bodies; CS: Cemented sands; WCT: Wave cut terrace, corresponding to the seaward termination of the prograding sands (unit 15s).

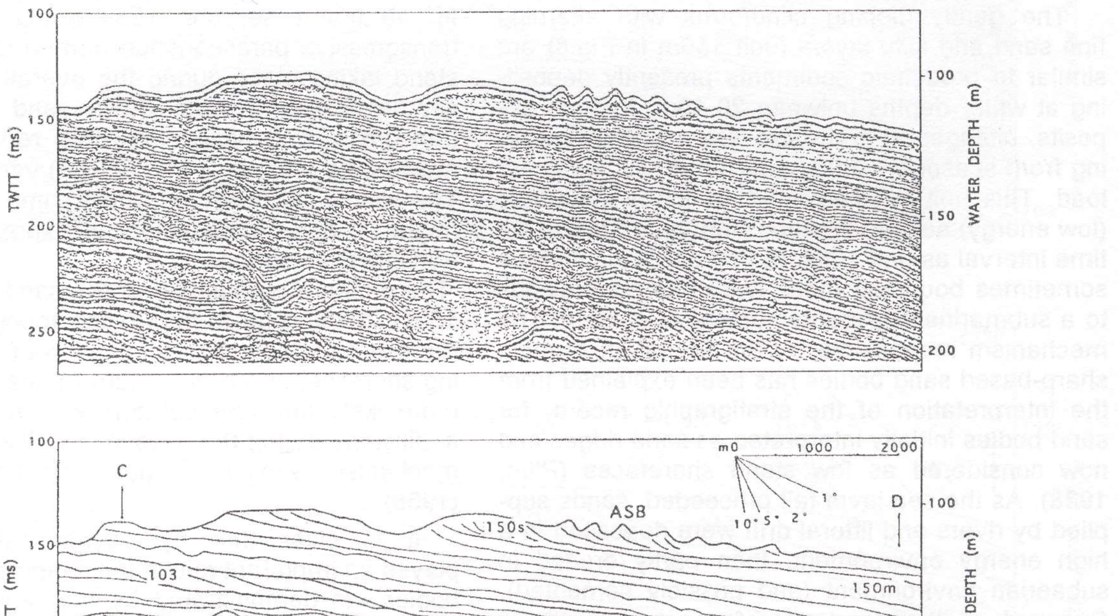

Fig.10b Seismic (dip) section in the vicinity of the Aude canyon (position in Fig.10a). Note that the gently dipping clinoforms are truncated by the (erosional) sea floor.

termine whether they are linear or transverse bedforms. In contrast with the first category, they are separated from the underlying deposits (unit 150s) by a well-marked sub-horizontal erosional surface (Fig.11b) and they only consist of sand.

Formation and evolution of "offshore sand bodies" in the Gulf of Lions

The two major seismic facies observed in the area, sampled with shallow cores, are attributed to two different sedimentary environments. The unit with medium sands and steep clinoforms (unit 150s in Fig.8) is similar to present deposits of the upper shoreface, high energy environments of the Gulf of Lions. The occurrence of cemented sands at the top of the seaward termination of this sand wedge is another criteria supporting a very shallow environment interpretation: such cemented sands presently form as "beach rocks" in several places in the intertidal zone of the Mediterranean area (Alexandersson, 1972), and they are considered as good indicators for the position of paleo-shorelines (Stefanon, 1969).

Considering the available dates, the present water depth of this unit and the seaward direction of progradation, it is interpreted as lowstand upper shoreface sands, deposited at the end of the last sea level fall and during subsequent lowstand (Last Glacial Maximum) in response to a forced regression (Posamentier et al., 1992).

The gently dipping clinoforms with alterning fine sand and silty layers (unit 150m in Fig.8) are similar to prodeltaic sediments presently depositing at water depths between 20-40m. In such deposits, changes in grain size are generally resulting from seasonal variation of the fluvial sediment load. This unit is interpreted as lower shoreface (low energy) sediments deposited during the same time interval as unit 150s. In that case, the surface sometimes bounding these two units corresponds to a submarine regressive surface of erosion. The mechanism responsible for the formation of such sharp-based sand bodies has been explained from the interpretation of the stratigraphic record, for sand bodies initially interpreted as sand ridges and now considered as low stand shorefaces (Plint, 1988). As the sea level fall proceeded, sands supplied by rivers and littoral drift were deposited in a high energy environment, then partly eroded in subaerian environment (and possibly cemented). Seaward of the sand shorefaces, a regressive surface of erosion developed above the fair weather wave base, cutting across distal silts deposited previously when sea level was slightly higher. The subsequent (post glacial) sea level rise was marked by submarine reworking, especially in zones where the energy was concentrated by the topography (such as in the vicinity of the Aude and Lacaze-Duthiers canyons), and some transgressive sand bodies were built. The difference between the western and eastern part of the zone may be explained both by a larger amount of sediment supplied to the East (from the Rhône river) and by the enhancement of geostrophic currents to the West. As to the overall positive topography of the sand wedge, which mimics in cross-section the shape of a sand ridge, it might be primarily explained by differential erosion, the sands being less sensitive to erosion than the surrounding fine grained sediments.

It must me noted that the erosion surface at the top of the sand wedge is polygenic. It formed as sea level fell, both as a regressive submarine surface of erosion and as a subaerian surface of erosion. During the subsequent rise, it was remoulded by, and merged with, the transgressive surface of erosion, at least at the scale of resolution of the seismic data. However, some true transgressive sand bodies (sand bodies with clinoforms downlapping over a transgressive surface) exist to the east of the study area(Fig.11b). These sand bodies mainly develop at water depth about 90 m and follow another, not very well marked, step in the topography (Fig.11a). A general investigation of the detailed morphology of the entire area could permit to determine whether this second step represents a second, shallower wave cut terrace, or simply the seaward termination of a sand body formed by hydrodynamical processes. In the first case, unit 155s would represent a transgressive parasequence formed during a still-stand taking place during the overall post glacial sea level rise. Except these sand bodies, the transgressive deposits are only represented, in most of the area, by a thin (0-2 m) veneer of sand. The coarse lag observed within some of the cores might be the sedimentological expression of the transgressive surface.

The offshore termination of the sand wedge (unit 150s), marked by a step in the topography, may represent the seaward termination of the prograding shoreline, at the maximum of sea level fall or, more likely, the wave-cut terrace developed during a stillstand during the subsequent rise, following a mechanism similar to that described by Swift (1968).

It is clear that hydrodynamical processes played an important role in the shaping of the sand bodies, as demonstrated by the regular spacing and asymmetric cross section of bed forms (Fig.10a). It must be noted that elongated bed forms are mainly observed in the vicinity of canyons (not only the Aude canyon presented here, but also the Lacaze Duthiers canyon further to the west), suggesting that irregularities in the topography enhanced currents near the bottom. Several processes may be invoked for explaining the focusing of the energy by canyons (Huthnance,

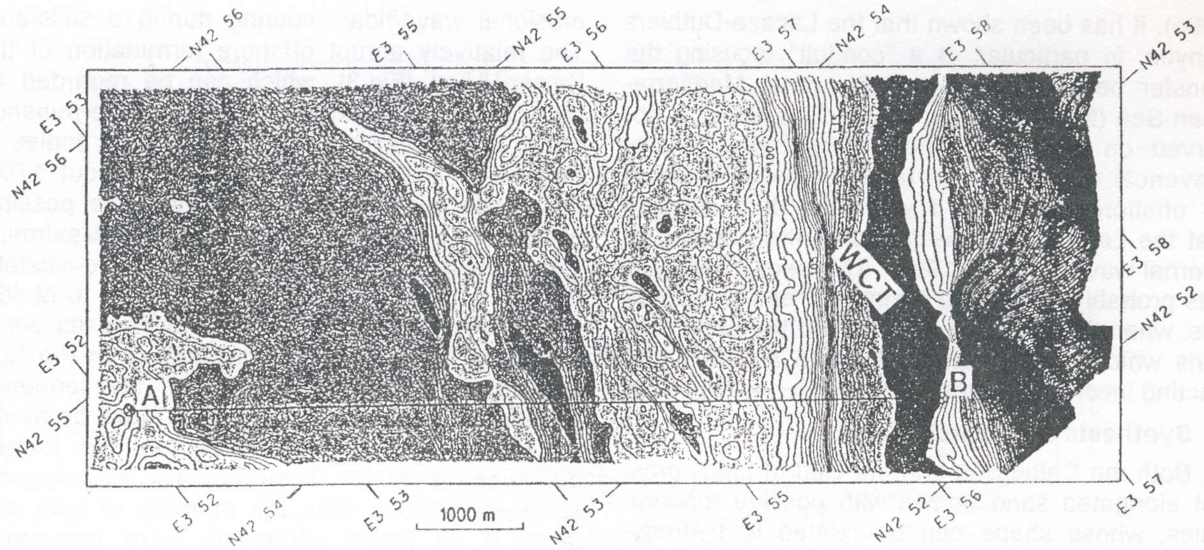

Fig.11a Swath bathymetry (SIMRAD 950) map of a zone where preservation of the sand wedge (unit 15b) is better (position in Fig.7). Note the step in the topography (between 100 and 120 meters), which corresponds to the seaward pinch out of the sand wedge. Other, less well developed steps are observed between 90 and 95 m. They could correspond to stillstands during the following sea level rise, but regional correlation would require extensive swath bathymetric surveys not already performed. TSB: transgressive sand body, WCT: wave cut terrace.

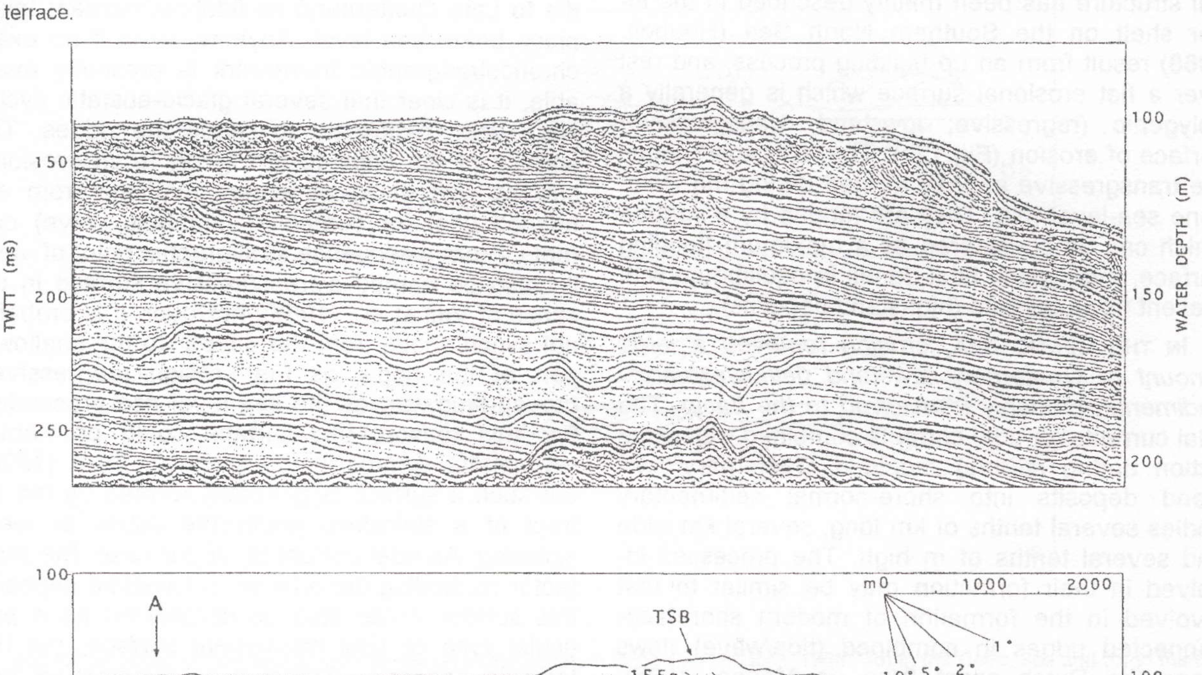

Fig.11b (position in Fig.10a) Seismic section across the sand wedge (unit 15s) a: sparker section. Note the sub-horizontal erosional surface bounding the bulk of the sand wedge and the overlying sand body.

1995). It has been shown that the Lacaze-Duthiers canyon, in particular, is a "conduit" focusing the transfer between shelf and the deep Mediterranean Sea (Monaco et al., 1990). This effect is observed on the along shore geostrophic Liguro-provencal current, which tends to be deviated in an offshore direction. It was also demonstrated that the Lacaze-Duthiers favoured the trapping of internal waves (Millot, 1990). This second process was probably intensified during low sea-level periods, when the coastline approached the deep canyons which concentrated the wave action by refracting incoming waves.

Synthesis and conclusions

Both the Celtic Sea and the Gulf of Lions present elongated sand bodies with positive topographies, whose shape can be related to hydrodynamical processes. However, these "bed forms" differ from the "classical" sand ridges in the sense that they mainly result from erosion of pre-existing deposits. The "classical" sand ridges, whose internal structure has been mainly described in the inner shelf on the Southern North Sea (Houbolt, 1968) result from an up building process, and rest over a flat erosional surface which is generally a polygenic (regressive, lowstand, transgressive) surface of erosion (Fig.12a). The "classical" ridges are transgressive as they formed during the Holocene sea-level rise. They are topped by a surface which can be considered as a maximum flooding surface, over which tidal dunes in equilibrium with present flows migrate (highstand deposits).

In the Celtic Sea, *erosion removed a large amount of Quaternary lowstand deltaic/estuarine sediments, probably transferred to the basin.* The tidal currents (or tidal currents combined with wave action during storms) moulded Quaternary lowstand deposits into shore-normal sedimentary bodies several tenths of km long, several km wide and several tenths of m high. The processes involved in their formation may be similar to that involved in the formation of modern shoreface-connected ridges in combined (tide/wave) flows along the Dutch coast (Van de Meene, 1996). Even if the shape of the ridges can be explained by purely autocyclic (hydrodynamical) processes, some other morphological features are probably due to allocyclic (glacio-eustatic) processes. The landward pinch-out of the ridges, about 120 m below present sea-level in the Southern Celtic Sea, could represent the position of the attachment of the ridges to a previous lowstand shoreline. However, despite several seismic investigations, no remnants of such paleo-shoreline has been observed so far, probably because of the high hydrodynamic conditions prevailing in the zone. As already mentioned, the depression observed across most of the ridges could mark the position of some erosional wave/tidal scouring during a stillstand. The relatively abrupt offshore termination of the Kaiser-I-Hind (Fig.3), which can be regarded as the shallowest position for the offshore termination of the prograding lowstand sedimentary bodies (if no erosion took place) is presently about 170m below sea level, much deeper than the possible position of the sea during Last Glacial Maximum. Considering the subsidence and glacio-isostatic history in the zone, this implies a Lower to Middle Quaternary age for these lowstand deposits. As to the upper incisions within the ridge (4 in Fig.12b) they may be interpreted either as sequence boundary formed during sea level drop by fluvial incision or as tidal ravinement surface formed during sea level rise. They may also be polygenic surfaces resulting from the merging of both surfaces if no fluvial sediments were preserved. These incisions being comprised between 115 and 150 m water depth, the first hypothesis implies a Lower to Middle Quaternary origin. In the second case, more recent periods may be proposed (Middle to Late Quaternary) as tidal ravinement takes place below sea level. Anyhow, even if no exact chronostratigraphic framework is presently available, it is clear that several glacio-eustatic cycles have been necessary to shape the ridges. The surface of the ridge (6 in Fig.12) is an erosional surface with a lag pavement resulting from enhanced tidal (or combined tidal and wave) currents. From a sequence stratigraphic point of view, it could be named a transgressive surface in the sense of Vail et al., (1987); however, it is probably not synchronous from the deeper to the shallower part of the ridge, as the erosion progressively moved landward as the sea level rise proceeded. For this reason, this surface could be named *ravinement surface* in the sense of Swift (1968), but such a surface is generally formed by the retreat of a shoreface under the action of *wave scouring*. As tidal current is, in our case, the main factor controlling the erosion of lowstand deposits, this surface could also be considered as a particular type of *tidal ravinement surface*, but this term is generally restricted to concave-up erosional surfaces formed within estuarine settings by tidal scouring (Allen, 1991, Dalrymple, 1992, p.883). Finally, the more appropriate term is *offshore marine erosion surface*, as defined by Nummedal and Swift (Nummedal and Swift, 1987): according to these authors, such surfaces form offshore at the beginning of sea level rise because sediment supply drops (because deltaic coasts turn into sediment trapping estuaries) and because enhanced winnowing by wave and currents. The transgressive and highstand deposits are only represented by a thin veneer of relatively fine grained sand, moulded into dunes active at least when spring tidal currents and storm wave

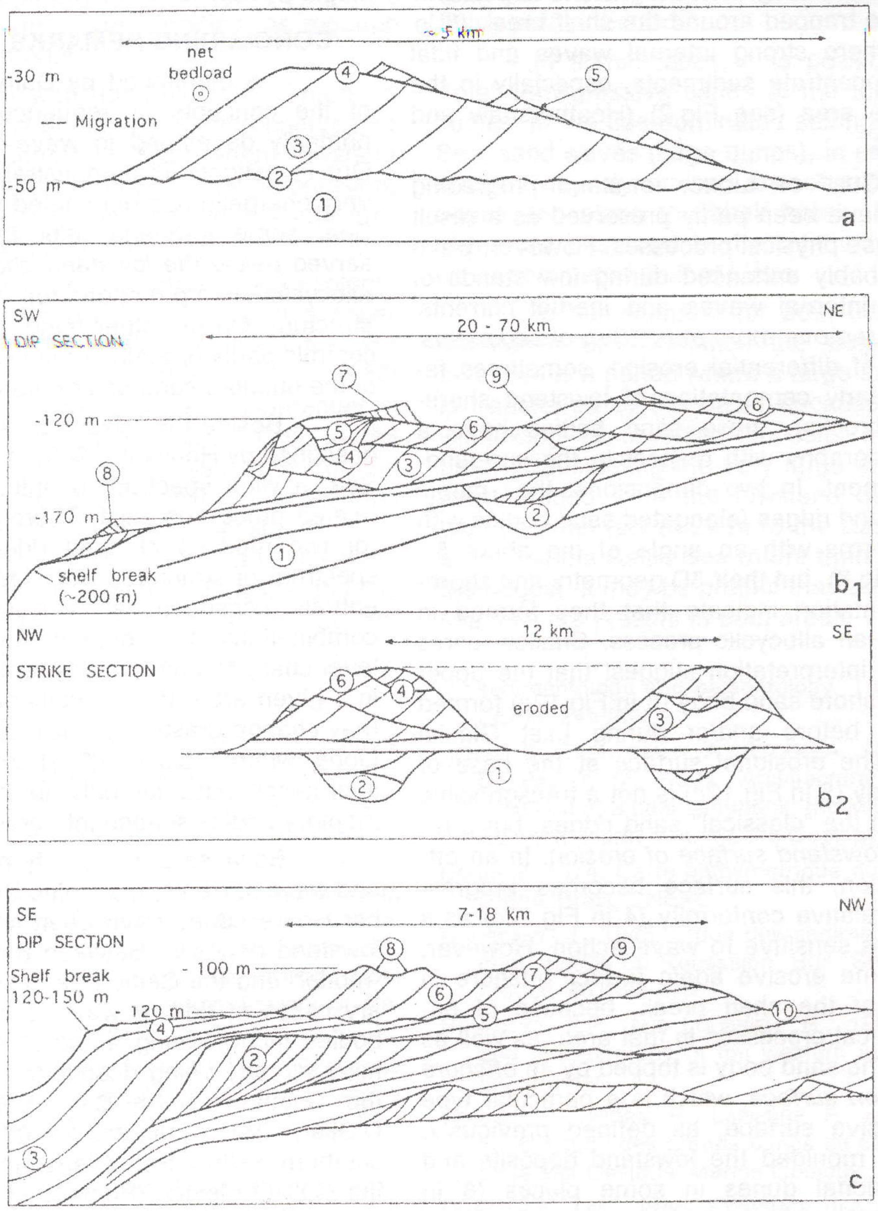

Fig.12 Simplified architecture of sand ridges (a) in the Southern North Sea (Houbolt, 1968), (b) in the Celtic Sea and (c) in the Gulf of Lions.

a; "Classical" tidal sand ridge structure from the Southern North Sea (from Houbolt, 1968). 1: coarse lag (palimpsest sediments, with mixed fluvial, estuarine, and marine reworked deposits); 2: Erosional unconformity (subaerial surface of erosion + ravinement surface); 3: transgressive sand ridge; 4: maximum flooding surface; 5: active tidal dunes

b: Celtic Sea. 1: Pliocene/early Quaternary lowstand wedges; 2: Pliocene or early Quaternary incised valley fills, 3: cut and fill structures related to Quaternary lowstand deltaic or estuarine systems; 4: incised valley (due to either or both fluvial incision during relative sea-level fall (sequence boundary) or tidal ravinement surface formed during relative sea level rise; 5: estuarine (?) mud and sand infill; 6: offshore marine erosion surface related to a subsequent glacio-eustatic cycle; 7: Transgressive dune (sand wave) active when tidal current combines with storm; 8: shelf break transgressive dunes (sand waves) in equilibrium with present day tidal/internal wave currents.

The deposits between the present sea floor and the dashed line (strike section b2) have been eroded.

c. Gulf of Lions: 1,2: Former lowstand shorefaces or deltaic lobes; 3: canyon infill; 4: regressive erosion surface, becoming a correlative conformity in an offshore direction. Note that it may become again an erosional surface in the vicinity of the shelf break because of enhanced wave action and/or mass wasting. 5: regressive surface of erosion; this surface cuts across time lines, separating sandy from muddy facies. 6: Lowstand shoreline with large scale prograding clinoforms (topsets generally not preserved); 7: offshore marine erosion surface; 8: erosional dunes; 9: transgressive dunes and/or transgressive parasequence; 10: polygenic erosion surface (subaerial erosion surface + offshore marine erosion surface). Note the positive topography of this offshore "sand body". N.B.: the erosional and "transgressive" dunes generally do not coexist; the former are observed to the west, the latest to the east of the study area.

orbital currents are combined (7 in Fig.12b). The most important transgressive/highstand deposits in that area are trapped around the shelf break (8 in Fig.12b), where strong internal waves and tidal currents concentrate sediments, especially in the *La Chapelle* area (see Fig.2) (Heathershaw and Codd, 1985).

In the Gulf of Lions, lowstand prograding shorelines have been partly preserved as a result of less intense physical processes. However, wave energy, probably enhanced during low stands of the sea by internal waves and inertial currents, was able to remove more than 20 m of sediments. As a result of differential erosion, sometimes favoured by early cementation of lowstand shorelines (beachrocks), these sand bodies have a positive topography with respect to the surrounding environment. In two dimensions, they mimic "classical" sand ridges (elongated sand bodies with large clinoforms with an angle of dip about 5°, such as in Fig.8), but their 3D geometry and shore-parallel orientation indicate that they formed in response to an allocyclic process. Shallow cores and seismic interpretation suggest that the upper and most offshore sand body (6 in Fig.12c) formed immediately before and/or during Last Glacial Maximum. The erosional surface at the base of this sand body (5 in Fig.12c) is not a transgressive surface as in the "classical" sand ridges, but a *regressive or lowstand surface of erosion*. In an offshore direction, this surface becomes progressively a correlative conformity (4 in Fig.12c) as it becomes less sensitive to wave action. However, it may become erosive again further offshore in the vicinity of the shelf break, because of enhanced physical processes in that area, as well as slumpings. The sand body is topped by an *offshore marine erosion surface*, which is a particular type of transgressive surface, as defined previously. This surface moulded the lowstand deposits and shaped erosional dunes in some places (8 in Fig.12c). In other places, true transgressive sand bodies (resulting from an up-building process and developed over a transgressive surface-the *offshore marine erosion surface*-- are observed (9 in Fig.12c). It is not clear at the moment if they only represent scattered transgressive dunes, or if they formed during a stillstand during the overall post-glacial sea-level rise. In that case, they would represent a recent analogue to the sharp-based transgressive shoreface described for instance in the Cardium and Viking Formations in Alberta and the Shannon Sandstones in Wyoming (Pattison and Walker, 1992; Walker and Bergman, 1993; Walker and Eyles, 1991; Walker and Wiseman, 1995). Because of relatively weak physical regime prevailing presently, both the dunes moulded into the lowstand deposits and those developed subsequently as true transgressive sand bodies are moribund (rounded shape, no superimposed megaripples).

CONCLUDING REMARKS

- As mentioned by Dalrymple (1992), most of the concepts of sequence stratigraphy were primarily developed in wave-dominated settings. Our investigations demonstrate that, even in the very energetic tide-dominated setting of the Celtic Sea, some lowstand deposits have been preserved *below the lowstand shoreline*, implying an allocyclic interpretation for the ridge internal structure. On the other hand, the physical regime controls partly or entirely the shape and orientation of the offshore sand bodies we have studied.

- Beside the "classical" sand ridge structure described by Houlbolt (1968) in the Southern North Sea, a wide spectrum of internal structures and related processes exist. There is not one "model" (or two models) of sand ridge formation but a spectrum of structures from entirely "erosional" to entirely "constructional", corresponding to several combinations of sediment supply, relative sea-level changes and hydrodynamical regimes. Even in a given area, the depositional/erosional pattern may change drastically, for instance in the Gulf of Lions where "classical" sharp based lowstand shorefaces pass laterally to much thinner sedimentary bodies shaped into erosional sand ridges.

- Because of extremely high combined tidal and wave currents, the Celtic Sea is an end member where ridges have been sculpted into former lowstand deposits. Between the classical Houbolt "model" and the Celtic Sea case, some intermediary cases of tide or wave dominated shelf sand bodies incorporating a "core" of former deposits have already being described on *inner* shelves in the Southern North Sea (Berné et al., 1994; D'Olier, 1981; Laban and Schüttenhelm, 1981), the southern Yellow Sea (Yang and Sun, 1988) and the Gulf of Mexico (Penland et al., 1988), as well as in shoreface-attached ridges (Snedden et al., 1994). It must also be noted that Stubblefield et al., (1984) interpreted the ridges of the wave dominated outer shelf of New Jersey as relict nearshore ridges and degraded barrier islands.

- The architecture of the erosional sand ridges in the Celtic Sea is not in contradiction with the Huthnance (1982a,b) numerical model for ridge formation. This model requires initial sea-floor irregularity, inducing differential bottom friction between the swales and the ridge. If the bed is erodible, this process may conduct to scouring of the sea-floor, instead of sand pilling-up when the floor consists of a very coarse lag.

- Many shelf sand bodies present a (genetic?) link with underlying incised valley fills. It is not clear whether this is only due to the fact that more sediment is available in the vicinity of estuaries or if the topography of these valleys provides the initial vorticity for ridge accretion, as required in the Huthnance model.

- In contrast with the Celtic Sea where no evidence of paleo-shoreline has been observed so far, the Gulf of Lions is a case where lowstand shorefaces still have a morphological expression, even though they were partly reworked into erosional or constructional dunes.

- In the sequence stratigraphic terminology, the offshore sand bodies described in this paper largely result from the erosion of "shelf perched lowstand wedges" (Posamentier et al., 1988) formed during forced regressions (Posamentier et al., 1992). They are transgressive only in the sense that their shape more or less results from an erosional process dominantly taking place during relative sea-level rise (or during stillstand occurring during the overall sea-level rise). However, they mainly consist of lowstand deposits and the transgressive surface (or more precisely the offshore marine erosion surface) is almost at their top (at the resolution of the seismic devices) instead of being at their bottom.

- In some cases, it is possible to identify "true" transgressive sands at the top of the sand bodies. In the tide-dominated settings of the Celtic Sea, sand waves (large dunes), in equilibrium with present day dynamics, are observed over the ridges and along the shelf break. Moribund bed forms are observed in the relatively low energy, wave-dominated Gulf of Lions.

- In our scenario for both tidal and wave-dominated environments, the beginning of sea level rise is a period where a large amount of sand is transferred to the basin because of enhanced winnowing of lowstand deposits near the shelf break. Considering the very large amount of sediment eroded from the lowstand deposits of the Gulf of Lions (about 20 m to the East of the study area) and the Celtic Sea (more than 25 m between the ridges), it may be predict that large *sandy* deep sea fans are present in both areas.

REFERENCES

ALEXANDERSSON, T., 1972, Mediterranean beachrock cementation: marine precipitation of Mg-calcite, In: Stanley, D.J., ed., The Mediterranean Sea: a natural sedimentation laboratory. Stroudsburg, Dowden, Hutchinson & Ross, Inc., 203-223.

ALLEN, G.P., 1991, Sedimentary processes and facies in the Gironde estuary; a Recent model for macrotidal estuarine systems, In: Smith, D.G., Reinson, D.E., Zaitlin, B.A., and Rhamani, R.A., eds., Clastic Tidal Sedimentology, Calgary, Canadian Society of Petroleum Geologists Memoir 16, 29-40.

ALLEN, G.P., AND POSAMENTIER, H.W., 1993, Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France. J. Sediment. Petrol., 63, 378-391.

ALOÏSI, J.C., 1986, Sur un modèle de sédimentation deltaïque: contribution à la connaissance des marges passives. Unpublished Doctorat Thesis, University of Perpignan, 162 p.

ALONSO, B., CANALS, M., GOT, H., AND MALDONADO, A., 1991, Sea valleys and related depositional systems in the Gulf of Lion and Ebro continental margin. American Association of Petroleum Geologists Bulletin, 75, 1195-1214.

BELDERSON, R.H., PINGREE, R.D., AND GRIFFITHS, D.K., 1986, Low sea-level tidal origin of Celtic sea sand banks- Evidence from numerical modelling of M2 tidal streams. Mar. Geol., 73, 99-108.

BERNÉ, S., DURAND, J., AND WEBER, O., 1991, Architecture of modern tidal dunes (sand waves), Bay of Bourgneuf, France, In: Miall, A.D., and Tyler, N., eds., Three dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery: Concepts in sedimentology and paleontology. Tulsa, Oklahoma, SEPM, 245-260.

BERNÉ, S., TRENTESAUX, A., STOLK, A., MISSIAEN, T., AND DE BATIST, M., 1994, Architecture and long-term evolution of a tidal sandbank: the Middelkerke Bank, Southern North Sea. Marine Geology.

Berthois, 1974, Carte bathymétrique du Golfe de Gascogne. Brest, CNEXO.

BOURCART, J., 1945, Etude des sédiments pliocènes et quaternaires du Roussillon. Bull. Serv. Carte Géol. France, 45, 395-476.

BOURILLET, J.F., AND LOUBRIEU, B., 1995, Bathymetry and physiography of the western approaches margin. Ifremer.

BOUYSSE, P., HORN, R., LAPIERRE, F., AND LE LANN, F., 1976, Etude des grands bancs de sable du Sud-Est de la Mer Celtique. Marine Geology, 20, 251-275.

CHAPELIER, J.M., 1986, Résultats des mesures d'océanographie physique (courantométrie - température) réalisées sous la responsabilité de l'UBO lors de la campagne ONDINE 85, Université Bretagne Occidentale.

D'OLIER, B., 1981, Sedimentary events during Flandrian sea-level rise in the south-west corner of the North Sea, In: Nio, E.D., Schüttenhelm, R.T.E., and Van Veering, T.C.E., eds., Holocene Marine Sedimentation in the North Sea Basin. Special pub. of the International Association of Sedimentologists. Oxford, Blackwell, 221-227.

DALRYMPLE, R.W., 1992, Tidal depositional systems, In: Walker, R.W., and James, N.P., eds., Facies models: response to sea level change. St John's, Canada, Association Géologique du Canada, 195-238.

DANGEARD, L., 1928, Observations de géologie sous-marine et d'océanographie relatives à la Manche.

Annales de l'Institut Océanographique, 6, Paris, 295 p.

DUPLAIX, S., AND OLIVET, J.L., Etude sédimentologique et morphologique de la tête du rech Bourcart (Golfe du Lion). Cahiers Océanographiques.

EMERY, K.O., 1968, Relict sediments on continental shelves of the world. Bull. Am. Assoc. Petrol. Geol., 52, 445-464.

EVANS, C.D.R., 1990, The geology of the western English Channel and its western approaches. London, HMSO for the British Geological Survey.

FIELD, M.E., 1980, Sand bodies on coastal plain shelves: Holocene record of the U.S. Atlantic Inner shelf off Maryland. Journal of Sediment. Petrol., 50 2, 505-528.

FIELD, M.E., AND TRINCARDI, F., 1991, Regressive coastal deposits on Quaternary continental shelves: preservation and legacy, In: Osborne, R.H., ed., From shoreline to abyss: contributions in marine geology in honor of Francis Parker Shepard. Tulsa, SEPM special publication N° 46, 107-122.

FLEMMING, B.W., 1988, Zur klassifikation subaquatischer, stromungstransversaler Transportkorper. Boch. geol. u. geotechn. Arb., 29, 44-47.

GIBBARD, P.L., 1988, The history of the great northwest European rivers during the past three million years. Phil. Trans. R. Soc. London Ser. B, 318, 559-602.

HEATHERSHAW, A.D., AND CODD, J.M., 1985, Sandwaves, internal waves and sediment mobility at the shelf-edge in the Celtic Sea. Oceanologica Acta, 8 4, 391-402.

HOUBOLT, J.J.H.C., 1968, Recent sediments in the Southern Bight of the North Sea. Geologie en Mijnbouw, 47, 245-273.

HULSCHER, S.J.M.H., DE SWART, H.E., AND DE VRIEND, H.J., 1993, The generation of offshore tidal sand banks and sand waves. Continental Shelf Research, 13, 1183-1204.

HUTHNANCE, J.M., 1982a, On one mechanism forming linear sand banks. Estuarine, Coastal and Shelf Science, 14, 279-99.

HUTHNANCE, J.M., 1982b, On the formation of sand banks of finite extent. Estuarine, Coastal and Shelf Science, 15, 277-299.

HUTHNANCE, J.M., 1995, Circulation, exchange and water masses at the ocean margin: the role of physical processes at the shelf edge. Prog. Oceanog., 35, 353-431.

LABAN, C., AND SCHÜTTENHELM, R.T.E., 1981, Some new evidence on the origin of the Zealand ridges, In: Nio, E.D., Schüttenhelm, R.T.E., and Van Veering, T.C.E., eds., Holocene Marine Sedimentation in the North Sea Basin. Special pub. no. 5, International Association of Sedimentologists. Oxford, Blackwell, 239-245.

LAMBECK, K., 1995, Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. J. Geol. Soc. London, 152, 437-448.

LECKIE, D., 1988, Wave-formed, Coarse-grained ripples and their relationship to hummocky cross-stratification. Journal of Sedimentary Petrology, 58, 607-622.

LERICOLAIS, G., ALLENOU, J.P., BERNÉ, S., AND MORVAN, P., 1990, A new system for acquisition and processing of very high-resolution seismic reflection data. Geophysics, 55, 1036-1046.

MILLOT, C., 1981, La dynamique marine du plateau continental du golfe du Lion en été. Unpublished Doctor thesis, University of Paris 6, 175 p.

MILLOT, C., 1990, The Gulf of Lions' hydrodynamics. Continental Shelf Research, 10, 885-894.

MILLOT, C., AND CRÉPON, M., 1981, Inertial oscillations on the continental shelf of the Gulf of Lions. Observations and theory. Journal of Physical Oceanography, 11, 639-657.

MONACO, A., 1971, Contribution à l'étude géologique et sédimentologique du plateau continental du Roussillon [unpublished Doctor thesis]. Perpignan, 295 p.

MONACO, A., BISCAYE, P.E., SOYER, J., POCKLINGTON, R., AND HEUSSNER, S., 1990, Particule fluxes and ecosystem response on a continental margin: the 1985-1988 Mediterranean ECOMARGE experiment. Continental Shelf Research, 10, 809-839.

MOSLOW, T.F., BARRIE, J.V., AND LUTERNAUER, J.L., 1989, Sedimentary facies of a high energy, tide-dominated continental shelf, Western canada, In: Reinson, G.E., ed., Modern and ancient examples of clastic tidal deposits - A core and peel workshop, Calgary, Canadian Society of Petroleum Geologists, 25-36.

NUMMEDAL, D., AND SWIFT, D.J.P., 1987, Transgressive stratigraphy at sequence-bounding unconformities: some principles derived from Holocene and Cretaceous examples, In: Nummedal, D., Pilkey, O.H., and Howard, J.D., eds., Sea-level fluctuation and coastal evolution. Tulsa, Society of Economic Paleontologists and Mineralogists, 242-260.

OFF, T., 1963, Rhythmic linear sand bodies caused by tidal currents. American Association of Petroleum Geologists Bulletin, 47, 324-341.

PAGNOL, C., 1995, Stratigraphie sismique à très haute résolution du banc du Kaiser-I-Hind. , IFREMER, 30.

PANTIN, H.M., AND EVANS, C.D.R., 1984, The Quaternary history of the Central and Southwestern Celtic Sea. Mar. Geol., 57, 259-293.

PATTISON, S.A.J., AND WALKER, R.G., 1992, Deposition and interpretation of long, narrow sandbodies underlain by a basinwide erosion surface: Cardium Formation, Cretaceous Western Interior Seaway, Alberta, Canada. J. Sediment. Petrol., 62, 292-309.

PENLAND, S., BOYD, R., AND SUTER, J., 1988, Transgressive depositional systems of the Mississippi delta plain: a model for barrier shoreline and shelf sand development. Journal of Sedimentary Petrology, 58, 932-949.

PLINT, A.G., 1988, Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level, In: Wilgus, C.K., Hastings, B.S., Posamentier, H., and Van Wagoner, J., eds., Sea-level changes: an integrated approach. Tulsa, SEPM Special Publication No. 42, 357-370.

POSAMENTIER, H.W., ALLEN, G.P., JAMES, D.P., AND TESSON, M., 1992, Forced regressions in a sequence stratigraphic framework: concepts, examples and exploration significance. American Association of Petroleum Geologists Bulletin, 76, 1687-1709.

POSAMENTIER, H.W., JERVEY, M.T., AND VAIL, P.R., 1988, Eustatic controls on clastic deposition II. Sequences and system tract models, In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea-Level Changes- an Integrated Approach. Tulsa, SEPM Spec. Pub. 42, 125-154.

REYNAUD, J.Y., 1996, Architecture et évolution d'un banc sableux de Mer Celtique Méridionale, 256 p.

REYNAUD, J.Y., TESSIER, B., PROUST, J.N., LERICOLAIS, G., MARSSET, T., BERNÉ, S., AND CHAMLEY, H., 1995, Apports de la sismique très haute résolution à l'interprétation génétique d'un banc sableux de la Mer Celtique. C.R. Acad. Sci. Paris, 320, 125-132.

RUBIN, D.M., 1987, Cross-bedding, bedforms, and paleocurrents. SEPM Concepts in Sedimentology and Paleontology series No. 3. Tulsa, Oklahoma, 187 p.

SCOURSE, J.D., AUSTIN, W.E.N., BATEMAN, R.M., CATT, J.A., EVANS, C.D.R., ROBINSON, J.E., AND YOUNG, J.R., 1990, Sedimentology and micropaleontology of glacimarine sediments from the Central and Southwestern Celtic Sea, In: Dowdeswell, J.A., and Scourse, J.D., eds., Glacimarine environments: Processes and sedimentation. London, Geological Society, 329-347.

SHEPARD, F.P., 1932, Sediments on the continental shelves. Geol. Assoc. Am. Bull., 43, 1017-1040.

SNEDDEN, J.W., TILLMAN, R.W., KREISA, R.D., SCHWELLER, W.J., CULVER, S.J., AND WINN, R.W., Jr, 1994, Stratigraphy and genesis of a modern shoreface-attached sand ridge, Peahala Ridge, New Jersey. Journal of Sedimentary Research, B64, 560-581.

STEFANON, A., 1969, The role of beachrocks in the study of the North Adriatic Sea. Memorie de Biogeografica Adriatica, 8, 79-87.

STRIDE, A.H., BELDERSON, R.H., KENYON, N.H., AND JOHNSON, M.A., 1982, Offshore tidal deposits: sand sheet and sand bank facies, In: Stride, A.H., ed., Offshore tidal sands: processes and deposits. New York, Chapman and Hall, 95-125.

STUBBLEFIELD, W.L., MCGRAIL, D.W., AND KERSEY, D.G., 1984, Recognition of transgressive and post-transgressive sand ridges on the New Jersey continental shelf, In: Tillman, R.W., and Siemers, C.T., eds., Siliciclastic shelf sediments. Tulsa, SEPM Special Publication N° 34, 1-23.

SWIFT, D.J.P., 1968, Coastal erosion and transgressive stratigraphy. Journal of Geology, 76, 444-456.

SWIFT, D.J.P., 1975, Tidal sand ridges and shoal-retreat massifs. Marine Geology, 18, 105-133.

SWIFT, D.J.P., AND FIELD, M.E., 1981, Evolution of a classic sand ridge field: Maryland sector, North american inner shelf. Sedimentology, 28, 461-482.

SWIFT, D.J.P., PHILLIPS, S., AND THORNE, J.A., 1991, Sedimentation on continental margins, IV: lithofacies and depositional systems, In: Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies, Geometry, Facies and Sequence Stratigraphy. Oxford, Blackwell, 89-152.

SWIFT, D.J.P., STANLEY, D.J., AND CURRAY, J.R., 1971, Relict sediments on continental shelves: a reconsideration. J. Geol., 79, 322-346.

SWIFT, D.J.P., AND THORNE, J.A., 1991, Sedimentation on continental margins, I: a general model for shelf sedimentation, In: Swift, D.J.P., Oertel, G.F., Tillman, R.W., and Thorne, J.A., eds., Shelf sand and sandstone bodies, Geometry, Facies and Sequence Stratigraphy. Oxford, Blackwell, 3-31.

TESSON, M., ALLEN, G.P., AND RAVENNE, C., 1993, Late Pleistocene shelf-perched lowstand wedges on the Rhône continental shelf, In: Posamentier, H.W., Summerhayes, C.P., Haq, B.A., and Allen, G.P., eds., Sequence stratigraphy and facies associations. Oxford, IAS Spec. Pub. 18, Blackwell Sci. Pub., 183-196.

TESSON, M., GENSOUS, B., ALLEN, G.P., AND RAVENNE, C., 1990, Late quaternary Lowstand Wedges on the Rhône Continental Shelf, France. Marine Geology, 91, 325-332.

VAIL, P.R., COLIN, J.P., DU CHENE, R.J., KUCHLY, J., MEDIAVILLA, F., AND TRIFILIEFF, V., 1987, La stratigraphie séquentielle et son application aux corrélations chronostratigraphiques dans le Jurassique du Bassin de Paris. Bull. Soc. Géol. France, 8, 1301-1321.

VAN DE MEENE, J.W.H., 1996, Sedimentary structures of combined flow deposits from the shoreface-connected ridges along the central Dutch coast. Marine Geology, 131, 151-175.

VANHAUWAERT, P., 1993, Hoge-resolutie reflectieseismische studie van Neogene en Kwartaire afzettingen in de Keltische Zee, University of Gent Internal report, 97 p.

WALKER, R.G., AND BERGMAN, K.M., 1993, Shannon sandstone in Wyoming: a shelf-ridge complex reinterpreted as lowstand shoreface deposits. J. Sediment. Petrol., 63, 839-851.

WALKER, R.G., AND EYLES, C.H., 1991, Topography and signifiance of a basinwide sequence-bounding surface in the cretaceous Cardium Formation, Canada, Alberta. J. Sediment. Petrol., 61, 473-496.

WALKER, R.G., AND PLINT, A.G., 1992, Wave- and storm-dominated shallow marine systems, In: Walker, R.G., and James, N.P., eds., Facies models - Response to sea level changes. St John, Geological Association of Canada, 219-238.

WALKER, R.G., AND WISEMAN, T.R., 1995, Lowstand shorefaces, transgressive incised shorefaces, and forced regressions: examples from the Viking Formation, Joarcam area, Alberta. Journal of Sedimentary Research, B65, 132-141.

WINGFIELD, R.T.R., 1995, A model of sea-levels in the Irish and Celtic seas during the end-Pleistocene to Holocene transition, In: Preece, R.C., ed., Island Britain: a Quaternary perspective. London, Geological Special Publication, 209-242.

YANG, C.S., AND SUN, J.S., 1988, Tidal sand ridges on the East China Sea shelf, In: de Boer, P.L., van Gelder, A., and Nio, S.D., eds., Tide-influenced sedimentary environments and facies. Sedimentology and Petroleum Geology. Dordrecht, D. Reidel, 23-38.