Long term evolution of sandwaves in estuaries illustrated by active, intermediate and moribund sandwaves of the French Atlantic coast (Charente-maritime)

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Abstract
Combination of accurate bathymetric, seismic data and vibracores gives new insights about long-term sandwaves evolution. Three sandwave fields located along the Charente coast (Bay of Biscay, France) represent interesting cases that record both the spatial and temporal evolution of the sedimentary dynamics in estuaries. They are indicators of estuary sand infill driven by tidal current and they record the progressive seaward migration of estuarine supply in suspended matter.

1. Introduction:
Sandwaves are good indicators of residual bedload sand transport and are therefore key features to characterize short time scale sand transport in estuaries where they are widespread (Dalrymple et al., 1990; Dyer and Huntley 1999; Harris et al., 1992; Zeiler et al., 2000). Nevertheless, few studies have been conducted to evidence sandwaves long-term evolution and how their become moribund features (Berné, 2000). One of the clues of this contribution is to examine the long-term evolution of sandwaves in estuaries. To achieve this end we present three sandwave fields, located in two estuaries of the French Atlantic coast, which show a gradient from sandwaves made of clean sands, to sandwaves showing sand and mud alternations, to sandwaves buried under a thick mud drape.

2. General setting :
2.1 Morphology and sedimentology
The studied area is located within the western Atlantic coast of France (fig. 1). The morphology of the coastline is dominated by two embayments (the "Pertuis Breton" northward and the "Pertuis d'Antioche" southward, fig. 1). They are approximately 10 km wide and 40 km long. The bathymetry of these embayments is characterized by relatively deep troughs (- 40 m for the Pertuis d'Antioche and –58 m for the Pertuis Breton, fig. 1), isolated from the shelf by crescent-like shoals, culminating at about - 20 m (Fig. 1). Recent seismic studies (Weber et al., 2003b) have evidenced that theses embayments belong to drowned incised valleys segments.
The three sandwave fields presented here include: (1) the West-Chevarache sandwave field, located in the western part of the Pertuis Breton, (2) the East-Chevarache sandwave field, located in the central part of the Pertuis Breton, (3) the Antioche sandwave field, located in the eastern part of the Pertuis d'Antioche.
Present-day sea-floor of the Charente estuaries consists of two major sediment sheets (1) a sand sheet located seaward and along the wave-dominated coastlines; (2) a mud sheet located shoreward which prolongates in the deepest parts of the estuaries. Shoreline and seabed evolution, at centuries time scale, evidence a seaward mud infill migration in the inner parts of the estuaries.

2.2 Hydrodynamic setting
Those estuaries are characterized by small fluvial input due to small rivers and small drainage basin areas. The tide that affects the study area is semi-diurnal and varies from 2 m to 6 m, thus this area is classified as being macrotidal. Tide-induced currents, in the three studied sandwave fields, range from 0.55 to 1 m/s (Table 1), they exhibit flood-dominated tidal currents. Large swells (wave height: 2 to more than 6 m and wave period: 8 to 20 s) predominantly coming from West and North-west directions (more than 56%), propagate inside those estuaries (LHF, 1994). Taking into account those hydrodynamic parameters, we consider those embayment constitute mixed tide -and -wave dominated estuaries (Dalrymple et al., 1992).

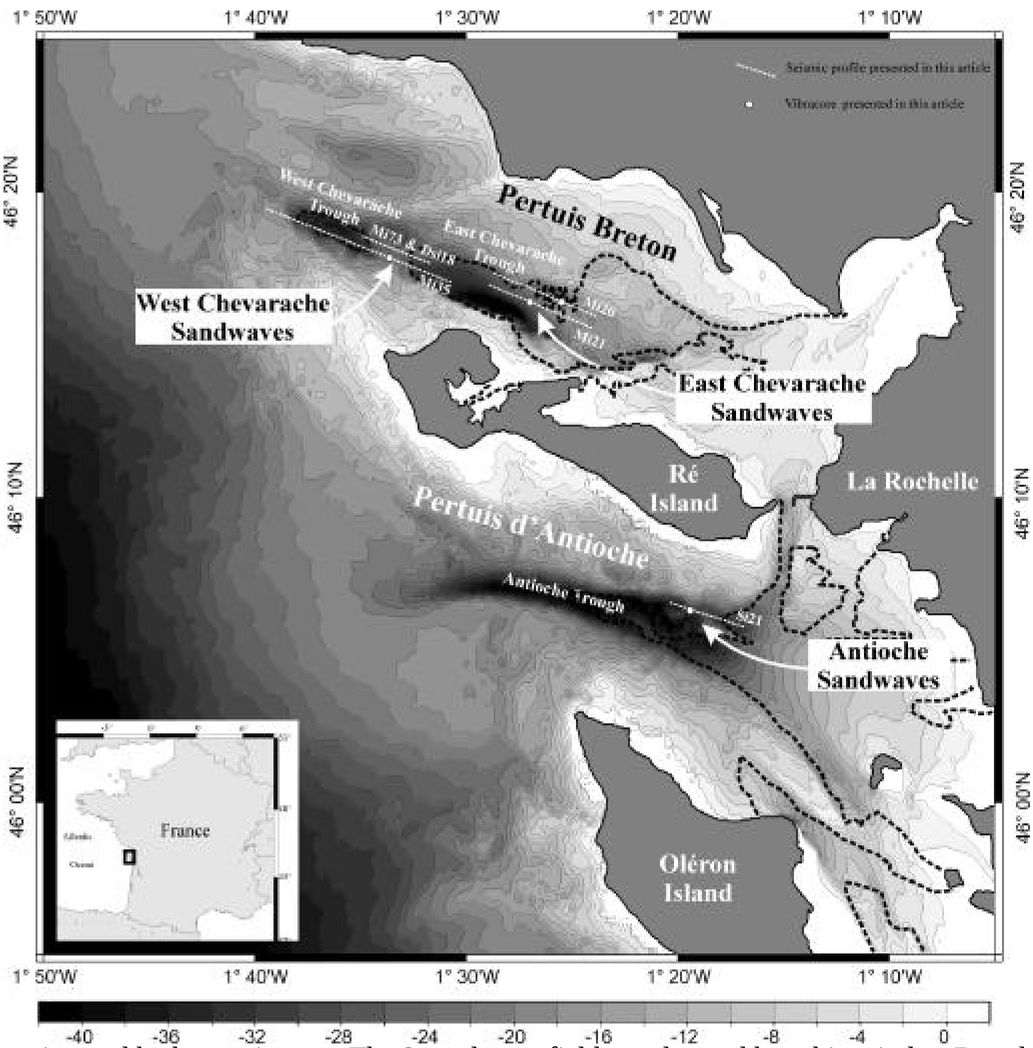

Fig. 1 : Location and bathymetric map. The 3 sandwave fields are located by white circles. Doted black line corresponds to the sand / mud limit.

Sandwave field	Flood-induced current	Ebb-induced current
West-Chevarache	0.85 $m.s^{-1}$	0.7 $m.s^{-1}$
East-Chevarache	0.75 $m.s^{-1}$	0.55 $m.s^{-1}$
Antioche	1 $m.s^{-1}$	0.85 $m.s^{-1}$

Table 1: Maximum depth-average velocities in the area of the three sandwave fields of the Charente coast estuaries (SHOM calculation, TELEMAC).

3. Data and methods:

Our analysis is mainly based on VHR seismic data analysis. For those studies, we have used two different seismic packages, which provide complementary informations:

- a Sparker source (50 J, band pass frequency: 200 –1200 Hz), associated with a traditional single-channel streamer, dedicated to extensive seismic exploration (seismic cruises: SIFADO 1999, MOBIDYC1 2000; MOBIDYC2 2001). Sparker profiles are used for the three sandwave fields.
- a Boomer source (band pass frequency: 1-10 kHz) associated with a line-in-cone receiver (Simpkin and Davis, 1993), dedicated to very shallow water seismic profiling (seismic cruise DSIRé 2001). This profiler is used to evidence thin layers.

Accurate positioning of each profile was provided by using a differential GPS navigational system. Seismic signals have been digitised in real time using Delph seismic V.2.01. Processing of both Sparker and Boomer seismic data includes: (1) Frequency band pass filtering, (2) Amplitude correction by applying an automatic gain correction, (3) Stacking of adjacent traces. Seismic data interpretation has been done following the general concepts of seismic stratigraphy (Payton, 1977).

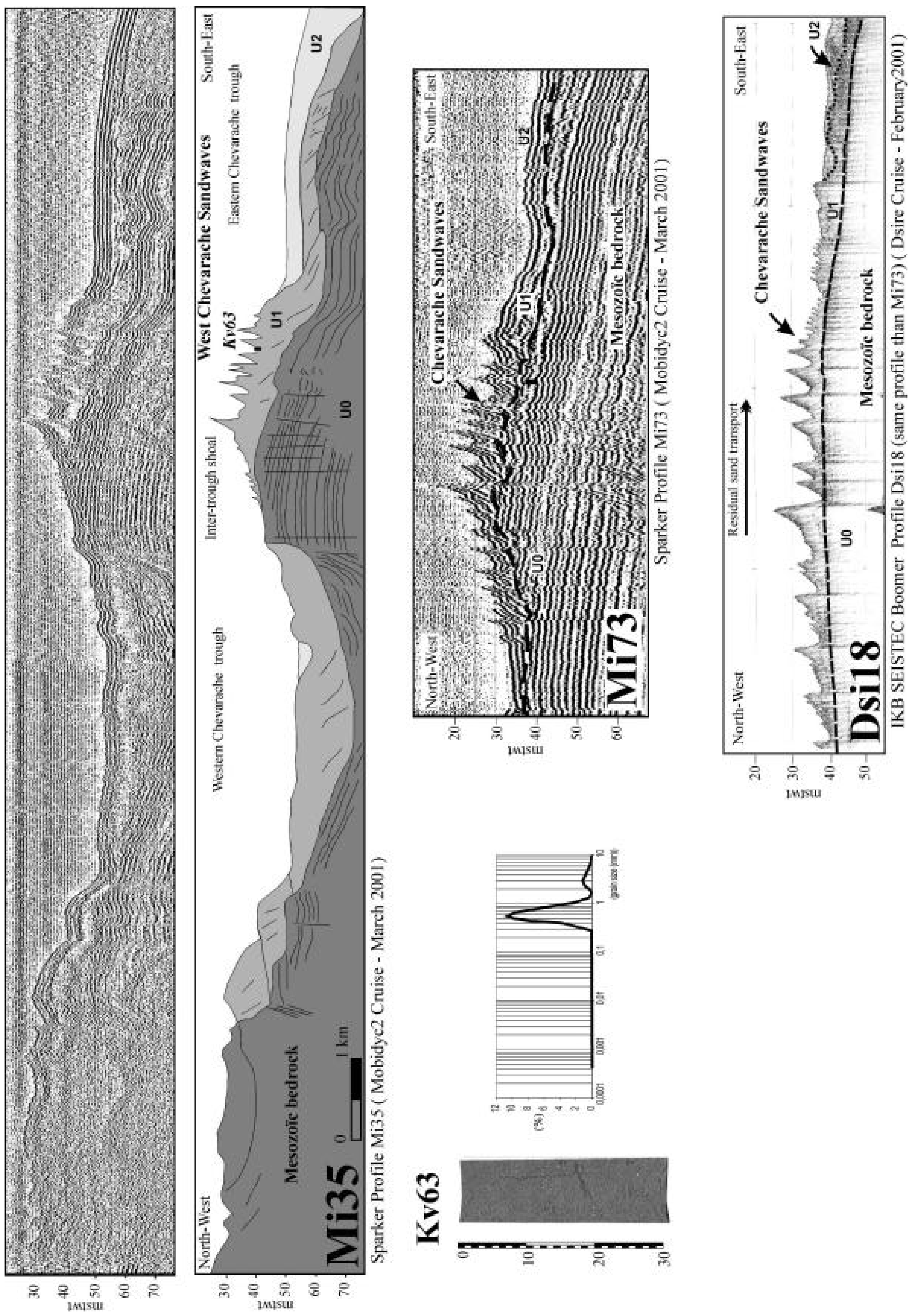

Fig. 2 : Mi35, Mi73 sparker seismic profiles; Dsi22 Ikb Seistec boomer profile and Kv63 vibracore obtained in the Chevarache sandwave field

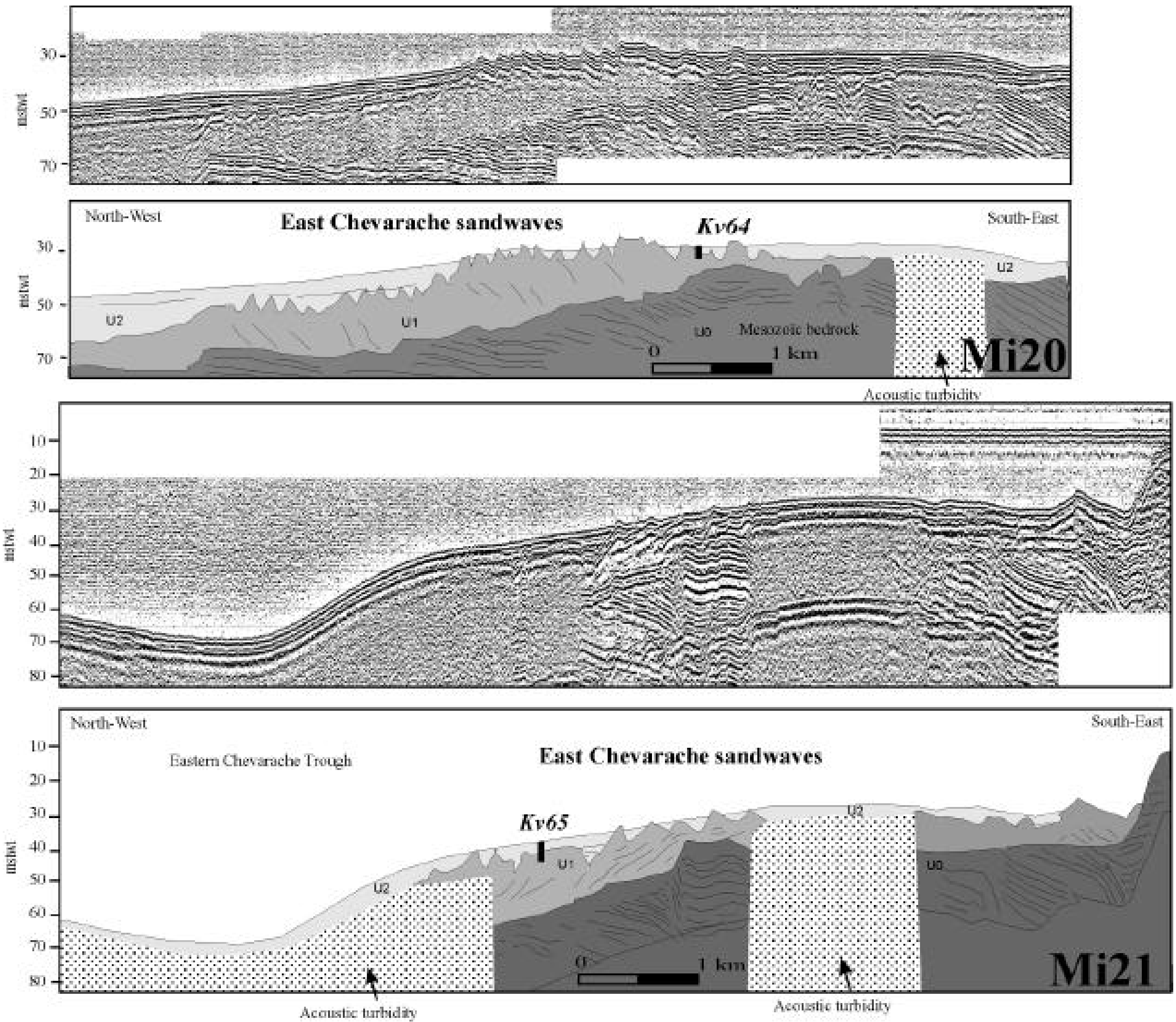

Fig. 3 : Mi20 and Mi21 sparker seismic profiles; showing the Eastern Chevarache sandwaves

We also used bathymetric data from SHOM (1960 and 1998) database and from bathymetric cruise (SPAT 2001) to elaborate Digital Elevation Model of the seafloor morphology.

4. Results

4.1 Bathymetric results:

- West Chevarache Sandwaves (Fig. 2):

Chevarache sandwaves are located between the eastern and the western Chevarache troughs at about 20 m of water depth. This sandwave field exhibits two sandwaves groups (bathymetric data of 1960): (1) large amplitude (10 m) and large wavelength (200 m) sandwaves located in the central part of the field and (2) small amplitude (2 m) and small wavelengths (60 m) sandwaves, located on the gentle slope of the largest sandwaves. Both large and small sandwaves show lee sides dipping eastward (toward the inner part of the estuary) indicating that they are flood-dominated.

- East Chevarache sandwaves (Fig. 3):

East Chevarache sandwaves are located on the Eastern wall of the eastern Chevarache trough at about 20 m of water depth. Between some sandwaves crest, bathymetric data (1960) show a surprisingly flat area instead of the classical trough characterised by a concave upward shape. Their amplitudes range between 2 and 8 m and wavelengths between 150 and 400 m (very large dune (Ashley, 1990)). In the northern part of the sandwave field, lee sides are dipping eastward shoreward (toward the inner part of the estuary) indicating that they are flood-dominated. In the southern part of the sandwave field, lee sides are dipping westward (seaward) indicating that they are ebb-dominated.

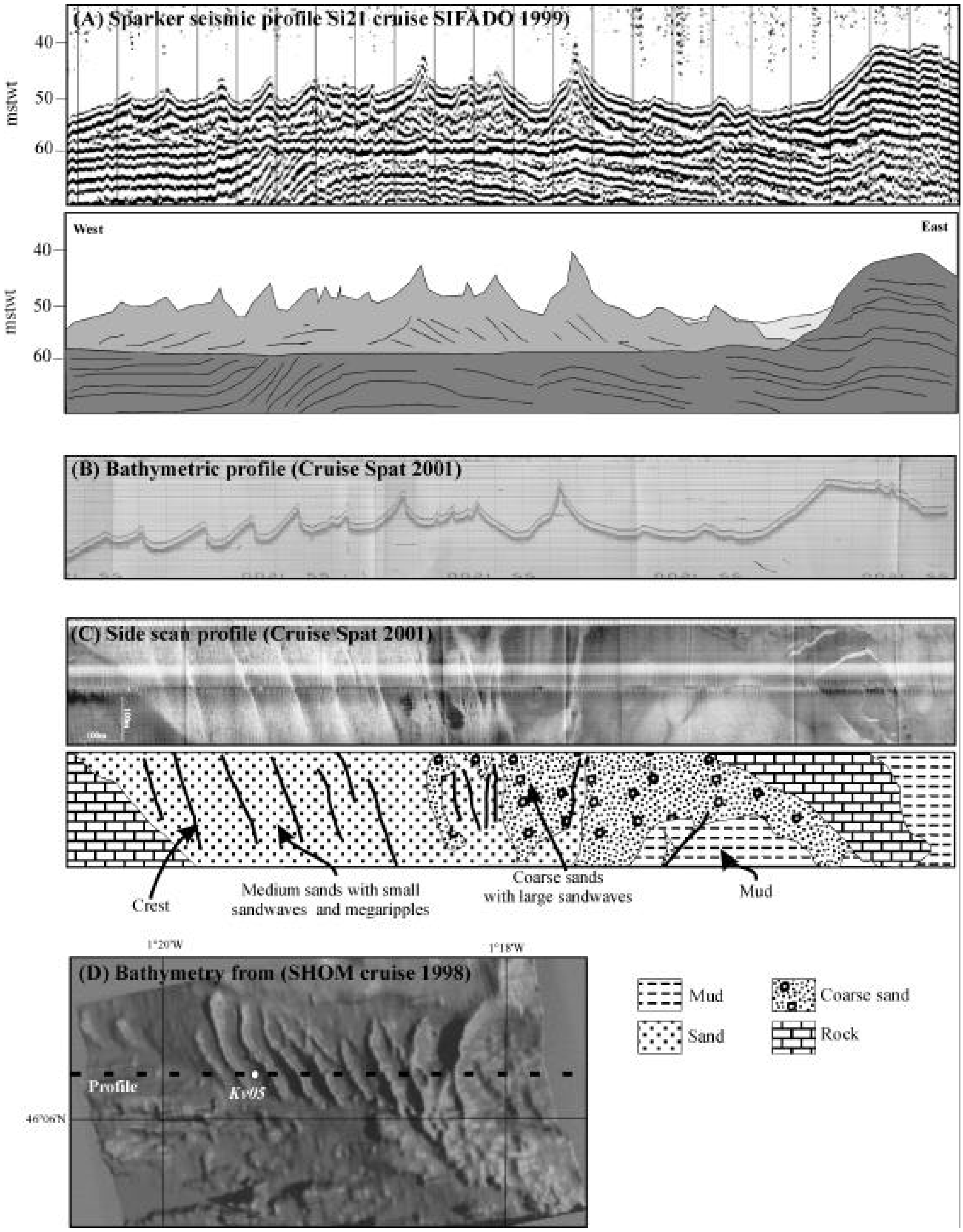

Fig. 4 : (A) Sparker seismic profiles; (B) Bathymetric profile, (C) side scan profile and (D) Bathymetric chart.

- Antioche sandwaves (Fig. 4):

Antioche sandwaves are located in the eastern part of the Antioche through at about 25 to 30 m of water depth (Chaumillon et al., 2000). Bathymetric survey obtained in 1998, evidence sandwave crests with a sinuous and dichotomic morphology. Sandwave amplitudes range between 2 and 9 m and sandwave wavelengths range between 50 and 200 m. Sandwaves asymmetry show that the northern part of the sandwave field is flood dominated as its southern part is ebb dominated (Fig. 4).. Bathymetric surveys realised in 1998 and 2001, evidence sandwave crests migration of 30 to 40 m (10 to 13 m/year) and asymmetry reversal of some sandwaves.

4.2 Seismic results (Fig. 2,3 & 4) :

Seismic profiles evidence three main seismic units. From bottom to top we observe:

(Unit U0) : This basal seismic unit can be correlated with bedrock submarine outcrops and corresponds to the Mesozoic bedrock. Its upper erosional unconformity is sharp and evidences a complex incised channels network (Weber et al., 2003a; Weber et al., 2003b).

(Unit U1) : This intermediate seismic unit exhibit transparent or oblique parallel internal configuration. U1 corresponds to sandwave fields and underlying sandbody.

(Unit U2) : This uppermost unit consists of a sheet drape characterised by sub-parallel internal reflectors.

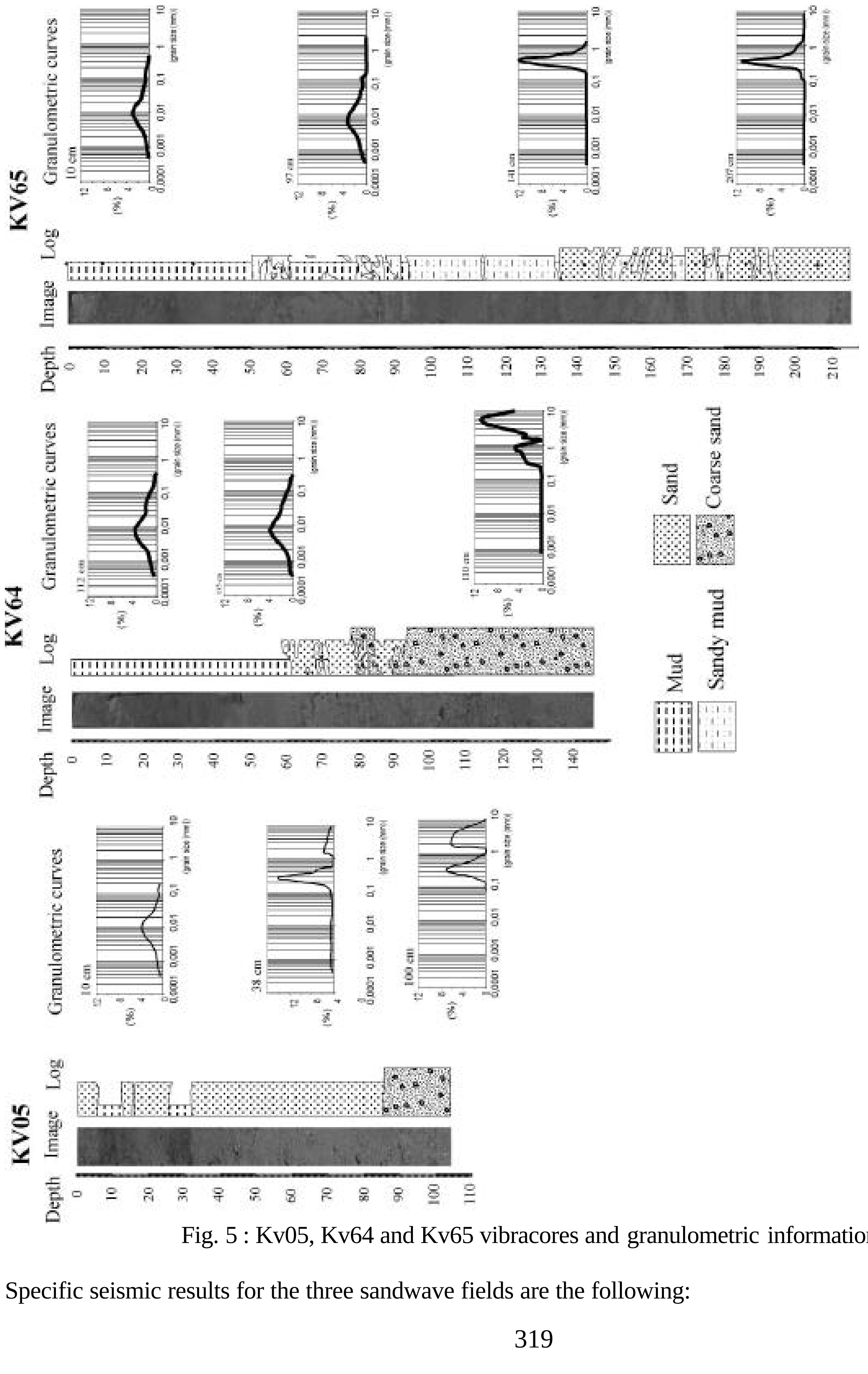

Fig. 5 : Kv05, Kv64 and Kv65 vibracores and granulometric informations

Specific seismic results for the three sandwave fields are the following:

- West Chevarache Sandwaves : This sandwave field is located on a rocky high, which isolate the eastern and the western Chevarache through. Boomer profile shows that thickness of U1 is very reduced (1 to 11 m) and exhibits high angle and eastward dipping reflectors. U2 is located just eastward of the West-Chevarache sandwave field, in the eastern Chevarache trough.
- East Chevarache sandwaves : East Chevarache sandwave field is located upon a thick (10 to 15 m) U1 unit which show southward dipping internal reflectors. This thick unit is emplaced in a bedrock incision. In the eastern and western part of the sandwave field, U1 is capped by U2.
- Antioche sandwaves : Antioche Sandwave field is located in an incised valley segment. U1 thickness range between 2 and 10 m. Internal configuration show both eastward and westward dipping reflectors. U2 rests upon the eastern edge of U1.

4.3 Coring results (fig. 2 & 5)

Cores carried out in the three sandwave fields show three main sedimentological facies:

- Coarse sands (Mode : 600 µm)
- Medium sands (Mode : 400 µm) with some marine broken shells .
- Brown mud (Mode : 6-8 µm) with some broken shells which are indicators of an estuarine environment.

The sandy facies are located in the lower parts of vibracores obtained in the East-Chevarache (KV64 and 65, figure 5) and Antioche sandwave fields (KV05, figure 5) and correspond to the whole vibracore obtained in the West-Chevarache sandwave field (KV63, figure 2).

The muddy facies are located in the upper parts of vibracores obtained in the East-Chevarache and Antioche sandwave fields. They consists of

(1) a thick (60 to 150 cm) layer located in the upper part of KV64 and 65 (East Chevarache sandwaves, figure 5);

(2) thin (2 to 3 cm) layers intercalated with the sandy facies in the upper part of KV05 (Antioche sandwaves, figure 3) and at the transition between the lower sandy facies and the upper muddy facies in KV64 and 65(East Chevarache sandwaves, figure 5).

This muddy facies is not observed in the West-Chevarache sandwave field (KV63, figure 2).

5. Discussion

From this study, it appears that the three sandwave fields show similarities concerning the maximum velocity of tide-induced currents, their water-depth, the amplitude and wavelenght of the sandwaves. Based on their location and their seismic and sedimentological characters, we propose that the three sandwave fields shown in this paper illustrate two major sedimentary dynamic settings: (1) The West-Chevarache sandwave field is located in the outer part of the Pertuis Breton estuary and is constituted of clean sands. It is indicative of onshore sand transport that contributes to the estuary sand infill; (2) The East-Chevarache and Antioche sandwave fields are located in the inner and central parts of the estuaries. They include both flood and ebb sandwaves, indicating that they are areas of sand convergence.

Cores obtained in the East-Chevarache and Antioche sandwave fields indicate that their upper part is composed by sand and mud alternations. Cores also show that the East-Chevarache sandwave field is capped under a mud drape. This indicates that those sandwaves are moribund (Berné, 2000). To explain this sharp transition between sand and mud deposition two hypotheses can be proposed : (1) the sand to mud transition record a tidal current velocity decrease; (2) the sand to mud transition record an increasing mud supply. Taking into account the velocity current similarities between the three sandwave fields, we postulate that the sand to mud transition mostly record an increase in mud supply. This change in sediment supply can be explained by the progressive infilling of the inner parts of the estuaries leading to the seaward migration of estuarine supply in suspended matter. This increase in suspended matter can be also linked to human activity (mainly land reclamation) and / or climate changes (Lesueur et al., 2002). The Antioche sandwave field bring an interesting case because it shows both sandwave crest migration and sand and mud alternations deposited between the sandwave crests. This support the idea that muds can be deposited while sandwaves are still active. The Antioche sandwave field is located close to the boundary between the sand and the mud drapes that covers the Pertuis d'Antioche estuary, indicating that they may represent an incipient stage of sandwave buried by muds. We propose that the Chauveau sandwave field represent an intermediate case (active sandwaves with incipient mud deposition) between the two end-members corresponding to the West-Chevarache sandwaves (active sandwaves made of clean sands) and the East-Chevarache sandwaves (moribund sandwaves capped under a mud drape).

Conclusion

This study demonstrates that accurate bathymetric and seismic data combined with vibracores give new insights about long-term sandwave evolutions. The three sandwave fields of the Charente coast estuaries represent interesting cases of sandwaves that respectively record: (1) onshore transport of clean sands, driven by flood, within the estuary mouth, (2) recent mud drape deposition, that have lead to sandwave preservation, in the inner part of the estuary; (3) mud deposition between active sandwave crests. This later example is interpreted as a transitional stage between typical active sandwaves and preserved sandwaves. Moreover, similarities in current velocities, water depth and sandwaves morphology, for those three examples, may indicate that the mechanism for sandwave preservation is the progressive seaward migration of estuarine supply in suspended matter.

Acknowledgment

The authors wish to thank the officers and crews of RV Côte d'Aquitaine, RV Côte de la Manche (CNRS/INSU), BH2 Borda (SHOM). This study has been supported by the French Hydrographic and Oceanographic Service (SHOM). We thank Dr. B. Tessier from Caen University and Dr. M. Tesson, from Perpignan University for carrying out seismic profilers.

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