

# Analysis of morphodynamic beach states along the South Brittany coast

## *Analyse des comportements morphodynamiques des plages de Bretagne Sud*

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### Abstract

This study presents a classification of morphodynamic beach states monitored along the South Brittany coast, on the western part of France. The investigated area faces the Atlantic Ocean and it is exposed to prevailing wind and waves mainly coming from the NW to SW and experience similar waves and wind climates as most beaches located on the French Atlantic coast. However, morphological settings of Brittany coast display more specific characteristics which contribute to make the morphodynamic beach behaviours more complex. To characterise the morphodynamic beach states, a beach survey programme was carried out from February 2008 to June 2009. Twenty five beaches were surveyed. Beach profiles were levelled from the toe of the dune to the water level line using a TRIMBLE electronic theodolite. Wave data were obtained from two offshore buoys, named l'Ile d'Yeu Nord (8503) and Le plateau du Four (04403), and owned by CETMEF (*Centre d'Etudes Techniques Maritimes Et Fluviales*). Wave characteristics used include significant wave height (Hs) and its associated period (Ts). Morphodynamic beach states were determined by the surf scaling and the surf similarity parameters using breaker wave's height values derived from offshore wave height. Temporal changes of morphodynamic beach states were assessed in relation with beaches profiles and hydrodynamic factors variations. Six different morphodynamic beach behaviours were identified, mainly varying between reflective and intermediate states. Multivariate statistical analyses were then carried out to assess the main factors driving morphologic and morphodynamic beach disparities. Obtained results are related to both coastline orientation and nearshore bedrocks distribution, enhancing the role of these specific morphologic constraints in the complex behaviour of South Brittany coast.

**Key words:** South Brittany coast, morphodynamic, multivariate statistical analyses.

### Résumé

*Cette étude présente une classification des plages des côtes morbihannaises (Bretagne) basée sur l'identification de leurs comportements morphodynamiques à court terme. Ces côtes sont exposées à des houles et vents dominants provenant d'un quart NW-SW, caractéristiques de la façade Ouest Atlantique de la France. Toutefois, à une échelle régionale, la complexité morphologique et bathymétrique des littoraux morbihannais confère à la zone d'étude une forte originalité d'un point de vue géomorphologique. Afin de caractériser le comportement morphodynamique de ces plages, plusieurs campagnes de levés topographiques ont été mises en place entre Février 2008 et Juin 2009. Trente-cinq plages ont été étudiées. Les profils de plage ont été levés lors des basses mers à l'aide d'un théodolite électronique TRIMBLE, à partir du pied de dune et jusqu'à la limite des eaux de mer au moment du levé. Les données de houle proviennent de deux bouées, gérées par le CETMEF (Centre d'Etudes Techniques Maritimes Et Fluviales), situées au large de la zone d'étude. Les caractéristiques des vagues retenues pour l'analyse sont la hauteur significative des vagues (Hs) et sa période associée (Ts). Les états morphodynamiques associés à chaque profil de plage ont été estimés à partir du calcul des paramètres de répliation et d'échelonnement de barres. Afin d'obtenir ces indicateurs, la hauteur des brisants a été estimée à partir de la houle au large à l'aide de la formule de P.D. Komar et M.K. Gaughan (1972). L'évolution des états morphodynamiques a été mise en relation avec les variations des profils de plage et l'évolution des contraintes hydrodynamiques. Au total, l'analyse a permis d'identifier 6 types de comportements morphodynamiques, évoluant principalement entre des états réfléchissants et intermédiaires. Des analyses multivariées ont été réalisées à partir de l'ensemble de ces données de façon à identifier les principaux facteurs associés à la disparité des comportements morphologiques et morphodynamiques observés. Les principaux résultats mettent en avant le rôle majeur joué par l'orientation du trait de côte et la distribution des zones de roches en bas de plage et dans les petits fonds, soulignant ainsi l'importance de ces contraintes morphologiques dans le fonctionnement des plages morbihannaises.*

**Mots clés :** Côtes de Bretagne sud, morphodynamique, analyses multivariées.

## Version française abrégée

Cette étude propose une classification des plages de Bretagne Sud, basée sur l'identification de leur comportement morphodynamique à court terme, entre Février 2008 et Juin 2009. Les côtes de Bretagne Sud sont exposées à des houles et des vents provenant d'un large quart NW-SW, caractéristiques des côtes de la façade Ouest Atlantique en France. Toutefois, à une échelle régionale, la complexité morphologique et bathymétrique des littoraux morbihannais confère à la zone d'étude une forte originalité d'un point de vue géomorphologique. Le trait de côte est marqué par une forte rugosité : les littoraux sud bretons sont principalement constitués d'une succession de plages de poche, encastrées entre des pointes rocheuses et adossées à des falaises altérées dont la hauteur est en moyenne inférieure à 10 m ou à des dunes bordières dont la hauteur moyenne est comprise entre 1 m et 2 m. Dans les petits fonds, la couverture sédimentaire est principalement composée de dépôts fins et, à l'ouest, de sables plus grossiers. De nombreuses zones de roches affleurent dans les petits fonds. Au large, les îles de Belle-Ile, Houat, Hoedic et Groix contribuent à réduire l'impact des houles océaniques à la côte (Pian, 2010 ; Pian et Menier, 2011). Peu d'études ont cherché à comprendre l'évolution de ces plages sur le court terme. Dans ce contexte, cette étude a été réalisée de manière à proposer une classification morphodynamique de ces plages, basée sur l'utilisation du paramètre de réplification et d'échelonnement de barre, en tenant compte des spécificités morphologiques de la zone d'étude. L'analyse permet d'une part, de discuter l'utilisation de ces paramètres dans ces types d'environnements côtiers, et d'autre part, d'examiner l'impact des contraintes morphologiques propres à la zone d'étude sur le comportement des plages à court terme. Au total, l'étude s'est intéressée à 25 plages (fig. 1), réparties dans trois systèmes côtiers différents : le massif dunaire Gávres Penhièvre, la baie de Quiberon et la presqu'île de Rhuys, tous trois caractérisés par une exposition aux houles et vents dominants différents. Chacune de ces plages a fait l'objet d'une étude détaillée afin de définir la forme du profil, la taille des sédiments, l'orientation de plage et la morphologie de l'arrière-plage. Entre février 2008 et juin 2009, ces plages ont fait l'objet d'un suivi topographique, mis en relation avec les variations des données de houle et de vent au large, permettant de définir les différentes conditions d'agitation prévalant entre deux levées topographiques. À partir des données de houle au large, la hauteur des brisants a été estimée à l'aide de la formule de P.D. Komar et M.K. Gaughan (1972). À la suite des travaux d'Anfuso et al. (2007) ou de O.E. Frihy et al. (2008), les paramètres de réplification de barres (Battjes, 1974) et d'échelonnement de barres (Guza et Inman, 1975) ont été calculés pour caractériser les états morphodynamiques associés à chaque profil levé. L'évolution des états morphodynamiques d'une plage dans le temps s'inscrit dans des séquences d'érosion ou d'accrétion (Short, 1999). De façon à interpréter les variations dans le temps des valeurs obtenues par les paramètres de réplification et d'échelonnement de barres pour chaque profil et à examiner la pertinence de l'utilisation de ces indicateurs, ces variations ont été comparées aux

évolutions décrites par les variations des profils de plage. D'une manière générale, l'analyse des données de vents et de houles met en évidence la forte occurrence d'épisodes violents et de conditions d'agitation fortes sur toute la période février 2008 – juin 2009. Il en résulte une forte variabilité des profils de plage pouvant être mise en relation avec des transports sédimentaires transversaux, orientés alternativement vers le large et la côte, et la mise en place de courants de dérive littorale entre les plages, dépendant de l'orientation des houles, des mers levées par le vent et du trait de côte (Pian et al., 2011). Par ailleurs, l'analyse des variations des paramètres de réplification et d'échelonnement de barres a permis d'identifier 6 types de comportements morphodynamiques, principalement caractérisés par des états réfléchissants ou intermédiaires, en haut de plage, et dissipatifs en bas de plage. En fonction des plages, les comportements intermédiaires sont moins efficacement définis par les indicateurs utilisés, conformément aux observations de B.O. Bauer et B. Greenwood (1988). À partir d'une analyse de données multivariée, ces six types de comportements morphodynamiques ont été mis en relation avec les caractéristiques morphologiques des plages. Les trois premiers axes factoriels définis par l'Analyse Multiple des Correspondances (AMC) expliquent environ 68 % de la variance totale et permettent d'identifier les variables spécifiquement associées à des comportements réfléchissants en haut de plage (présence d'un mur de défense en haut de plage, de platiers rocheux en bas de plage, pente raide et présence d'une rupture de pente en haut de plage). Par ailleurs, les deux comportements intermédiaires définis par les différentes réponses des paramètres de réplification et d'échelonnement de barres sont associés à des orientations différentes du trait de côte. La Classification Ascendante Hiérarchique (CAH) apporte une information plus détaillée en classant les plages en 6 groupes tenant compte de leur spécificités morphologiques et de leurs comportements morphodynamiques entre février 2008 et juin 2009. Elle permet d'identifier trois groupes composés de plages marquées par un haut de plage réfléchissant, puis un bas de plage dissipatif ou intermédiaire, et deux groupes de plages marqués par des comportements intermédiaires. Le sixième groupe est plus hétérogène et comprend uniquement deux plages. Au sein des 5 premiers groupes, les plages partagent les mêmes caractéristiques morphologiques (forme du profil, orientation, présence de platiers rocheux...), détaillant ainsi les relations entre les variables décrites par l'ACM. D'une manière générale, les comportements réfléchissants sont favorisés sur les plages où les processus de dépôts sédimentaires sont contraints vers le large et la côte par des contraintes extérieures, type platiers rocheux ou mur de défense contre la mer. Ces observations sont cohérentes avec celles réalisées par D.W.T. Jackson et al. (2005) sur les côtes irlandaises où les contraintes géologiques favorisent la mise en place de profils réfléchissants sur la partie supérieure des plages. Par ailleurs les différentes plages intermédiaires observées sont caractérisées par une orientation différente et une morphologie contrastée marquée par l'absence ou la présence de platiers rocheux en bas de plage. Les plages localisées en situation plus exposée sont caracté-

sées par une pente moins forte, évoluant vers des états dissipatifs alors que les changements morphologiques observés entre février 2008 et juin 2009 sont concentrés sur le haut de plage. À l'inverse, les plages plus abritées sont caractérisées par une pente plus raide, notamment lorsque les platiers rocheux sont abondants. La combinaison entre les variations locales de l'orientation du trait de côte et les variations bathymétriques associées à la présence de zones de roches dans les petits fonds et en bas de plage contribue à contrôler la distribution de l'énergie des vagues à la côte et explique ces différences de comportement morphodynamiques. Conformément aux observations de G. Anfuso et al. (2003), les plages les plus dissipatives sont situées sur les portions de côte les moins abritées. De manière plus synthétique, deux facteurs semblent essentiels pour expliquer les disparités morphologiques et morphodynamiques des plages en Bretagne Sud : la présence de zones de roches dans les petits fonds et les variations de l'orientation du trait de côte, toutes deux liés à la forte rugosité du trait de côte à une échelle régionale. Ces résultats sont cohérents avec les études actuelles (Loureiro et al., 2009 ; Short, 1999) qui soulignent l'importance de l'héritage géologique dans les systèmes de plages de baie. De plus, sur de nombreuses plages, le caractère réfléchissant du haut de plage peut également être mis en relation avec la présence de mur de défense contre la mer. Pour conclure, cette étude propose une classification permettant de définir les principales caractéristiques des plages de Bretagne Sud, en mettant en évidence les contraintes morphologiques qui influencent leurs évolutions sur le court terme. La présence de zones de roches dans les petits fonds et en bas de plage ainsi que la forte rugosité du trait de côte jouent un rôle essentiel. La présence de mur de défense en haut de plage est également systématiquement associée à des plages plus réfléchissantes. Toutefois, cette première étude pourrait être développée par des analyses ultérieures de manière à examiner plus en détail les effets d'abri associés aux variations du trait de côte et à prendre en compte les processus de transports sédimentaires dans l'évolution des plages et de leur comportement morphodynamique à court terme.

## Introduction

In order to describe the main constraints associated with beaches behaviours over a regional scale, numerous regional beach morphodynamic classifications based on widespread models have been established in various coastal environments (Anfuso et al., 2003; Jackson et al., 2005; Gomez et al., 2007). First beach classification models have been developed from previous works carried out on Australian beaches by L.D. Wright and B.G. Thom (1977) or L.D. Wright and A.D. Short (1984). Using the Dean's number (1) developed by M.R. Gourlay (1968) and then R. Dean (1973), L.D. Wright and A.D. Short (1984) propose a beach classification taking into account relationships between grain size parameters and waves characteristics.

$$\Omega = H_b / W_s T \quad (1)$$

with  $H_b$  the breaking wave height,  $T$  the period and  $W_s$  the sediment fall velocity.

Because this model does not take into account the effect of tides, G. Masselink and A.D. Short (1993) introduce a new parameter, the Relative Tidal Range parameter (2) to assess the relative influence of tides and wave regime with  $H_b$  referring to the breaking wave height and TR to the tidal range.

$$\text{RTR} = \text{MTR} / H_b \quad (2)$$

with  $H_b$  the breaking wave height and MTR the mean tidal range.

These models permit to classify beaches in different categories ranging from dissipative to reflective states. In the same time, J.A. Battjes (1974) and R. Guza and D.L. Inman (1975) have respectively contributed to develop the surf similarity (3) and the surf scaling (4) parameters also used to characterise beach state according to wave processes in surf zone.

$$\xi = \tan \beta (H_b / \Lambda_o)^{0.5} \quad (3)$$

$$\varepsilon = (0.5 H_b \sigma^2) / (\gamma \tan^2 \beta) \quad (4)$$

$H_b$  is the breaking wave height in m,  $\sigma = 2\pi T$  with  $T$  the wave period in s and represents wave radial frequency,  $\tan \beta$  the beach slope in degrees,  $g$  the acceleration due to gravity and  $\Lambda_o$  the offshore wavelength.

Because these models have been set up from a limited range of coastal environments, their use to assess beach morphodynamic behaviour has been put into question. The use of the Dean number in particular has been criticized especially in macro tidal environment (Anthony, 1998), in low energetic environments (Gomez et al., 2007) or in geological constrained coasts where beach behaviour is strongly influenced by the presence of nearshore reef (Masselink and Pattiarchi, 2001) or by geologic settings over a regional scale (Jackson et al., 2005). On macro to meso tidal environments characterised by embayed beaches, better beach state predictions are obtained when using the surf scaling and the surf similarity parameters (Dehouck, 2006). Based on a measure of beach slope rather than grain size, these indicators appear more appropriate to describe beaches affected by high tidal range and moderate wave energy (Levoy et al., 2000).

The southern coast of Brittany (fig. 1) is a mesotidal environment (4 to 5 meters), open to moderate oceanic swell. Due to coastline roughness and nearshore bathymetric variability, it encompasses various sandy beach systems characterised by a wide range of grain size, slope gradient, beach exposure and wave energy (Pian, 2010; Pian and Menier, 2011). Because few studies have been carried out to assess the morphodynamic behaviour of the investigated coast, this study attempts to: i) provide a broad description of beach morphodynamic states using the surf scaling and similarity parameters; ii) propose a beach morphodynamic classification taking into account the specific morphological features of the South Brittany coast. A comparison between these different analyses is then undertaken in order to discuss the relevance of the use of the surf scaling and similarity parameters to predict South Brittany beach states and to assess the main constraints associated with beach disparities.

## Study area

The South Brittany coast is mainly composed of a succession of pocket beaches spread along low and soft rocks cliffs

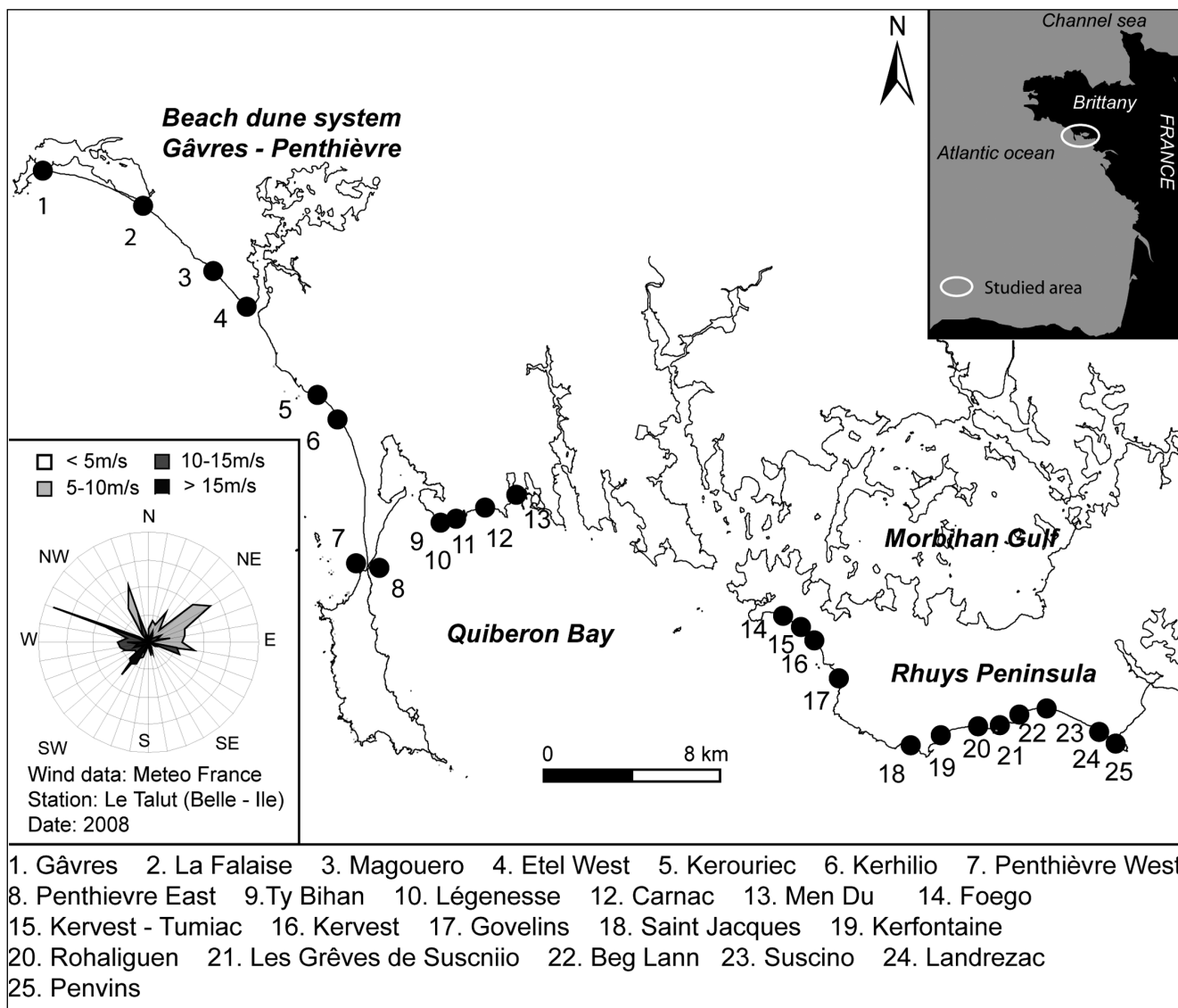


Fig. 1 – Location map.

Fig. 1 – Carte de localisation.

or of embayed beaches backed by sand dune and nested in between rocky headlands. Headlands are composed of weathered material derived from granite rocks. Except on a very local scale, they provide few sediment inputs in the coastal system. Continental shelf is covered by mud sediments, except in the Western part where sand deposits prevail (Menier *et al.*, 2010). Numerous bedrocks extend nearshore and offshore, and contribute to obstruct sediment transports. Large islands act as shelters and protect the main land from the open ocean swell (Pian, 2010). This study focuses on twenty five beaches, located in three different beach-dune coastal systems along the South Brittany coast (fig. 1). Each one of these coastal system is characterised by different wave energy conditions (Pian, 2010): the Gâvres-Penthièvre sand dune system is exposed to prevailing incident waves, the Bay of Quiberon is a very sheltered environment where coastal currents are dominated by the refraction of wind waves and the beaches of the Rhuys Peninsula are both

exposed to moderate oblique swell and sea waves driven by local winds. Most beaches are characterised by heterogeneous sediment sizes ranging from fine sands to coarse sands or pebbles. Coarser deposits are located on the upper part of beaches and finer sand deposits cover the lower parts. Grain size distributions are consistent with profile shapes since upper beach slopes are steeper. Where beaches are not backed by a sea wall, foredunes display gentle slopes and their height varies according to the beach-dune coastal system. Between Gâvres and Penthièvre, the front dune height can exceed 2 m. Along the Bay of Quiberon and the Rhuys Peninsula coastlines, dunes height rarely reaches 2 m, it usually showing values lower than 1 m.

## Methods

To determine beach morphology, a beach survey programme was carried out from February 2008 to June 2009. Twenty five beaches were surveyed three to six times each in order to take into account both winter and summer conditions. Shore normal beach profiles were levelled from the toe of the dune to the water level line using a TRIMBLE

electronic theodolite. For each site, the theodolite was placed on a fixed feature whose location was carefully recorded using GPS data, marked with visual indicators, and referenced to a benchmark of the French National Geodetic Service (I.G.N. 69). Location of beach profiles was defined according to coastline orientation and nearshore morphology. Beach slope ( $\tan \beta$ ) was then calculated for the foreshore portion of the beach.

Sediments were sampled along each beach profile on the upper and lower beachface. Samples were washed, dried, sieved and weighted in laboratory. Grain size parameters were calculated using the gradistat program developed by S. Blott (2001) which allows assessing grain size data with the Method of Moment in Microsoft Visual Basic programming language. In the scope of this paper, samples statistical parameters calculated with the R.L. Folk and W.C. Ward (1957) graphical methods and their derived physical descriptions were used.

Wave data were obtained from two offshore buoys, named l’Ile d’Yeu Nord (8503) and Le plateau du Four (04403), and owned by CETMEF (*Centre d’Etudes Techniques Maritimes Et Fluviales*). Wave characteristics used include significant wave height ( $H_s$ ) and its associated period ( $T_s$ ). Following F. Sabatier (2001), A. Stepanian (2002) and D.W.T. Jackson *et al.* (2005) breaking wave height ( $H_b$ ) was estimated from offshore waves characteristics by means of the relation (5) developed by P.D. Komar and M.K. Gaughan (1972) where  $H_b$  is the breaking wave height,  $H_o$  the offshore wave height and  $L_o$  the wavelength, all expressed in m. Values obtained have been compared to visual estimates of breaker heights (Dail *et al.*, 2000). The use of this method is justified by the large width of the continental shelf and has been validated by a comparison between estimates derived from this method and estimated derived from a nearshore wave refraction model (Pian, 2010).

$$H_b/H_o = 0.56 (L_o/H_o)^{1/5} \tag{5}$$

Following G. Anfuso *et al.* (2007), O.E. Frihy *et al.* (2008), the surf similarity index (Battjes, 1974) and the surf scaling parameter (Guza and Inman, 1975) have been calculated from equation (3) and (4) to characterise the morphodynamic state of the beaches during each survey. They were also successfully tested by A. Dehouck (2006) on the beaches of the Mer d’Iroise (West Brittany) characterised by similar morphological characteristics. To compute these parameters, we used the tidal cycle wave record prevailing before each beach survey (Levoy *et al.*, 2000). The interpretation of the values obtained for the surf scaling and similarity parameters is synthesized on table 1.

Beaches morphological states evolve over different time scales in relation to waves and sediments characteristics (Short, 1999). These evolutions reflect

either erosional or accretional sequences. A decrease of  $\varepsilon$  values indicates a shift from a dissipative state to a reflective one and inversely an increase of  $\zeta$  values indicates a shift towards a reflective state. Such an evolution reflects the occurrence of accretion processes. In order to interpret the relevance and temporal variations of the surf scaling and similarity parameters, obtained values were compared with beach profiles and hydrodynamic factors. For each beach, erosion and accretion sequences were identified between each survey. Profiles variations were computed between each survey. Then, results were compared to the variations of both the surf scaling and the surf similarity parameters during the same period. Results were then used to form a first and broad classification of the investigated beaches.

To assess the main factors leading to the occurrence of beach morphology and morphodynamic disparities along the coastline, their spatial and statistical distribution was assessed through the use of multivariate data analyses (Souza Pereira *et al.*, 2010). Statistical analyses were carried out using the Xlstat2011 software. A Multiple Component Analysis (MCA) was carried out taking into account specific morphological characteristics, such as beach orientation, beach slope gradient, position of break slope, presence of nearshore bedrocks and back beach morphology, which were recorded as qualitative binary data (tab. 2). These variables were identified from both field data and air photographs analysis. Beach orientation, nearshore bedrocks and back beach morphology were identified from visual air photographs analysis taken at low tide. When bedrocks cover more than a half of the lower beach and nearshore

	Reflective beaches	Intermediate beaches	Dissipative beaches
Surf scaling parameter	$\varepsilon < 2.5$	$2.5 < \varepsilon < 20$	$\varepsilon > 20$
Surf similarity parameter	$\zeta > 1$	$1 > \zeta > 0.23$	$\zeta < 0.23$

Tab. 1 – Limits of the morphodynamic domains according to the surf scaling and surf similarity parameters from J.A. Battjes (1974) and R. Guza and D.L. Inman (1975).

Tab. 1 – Limites des domaines morphodynamiques en fonction des valeurs d’échelonnement et de répliation de barres, d’après J.A. Battjes (1974) et R. Guza et D.L. Inman (1975).

Variables	Modalities
Beach orientation	N, NE, E, SE, S, SW, W, NW
Nearshore bedrocks	Numerous, Few, Absent
Break slope position	Landward (< 10m), Intermediate (10-50 m), Seaward (> 50 m), no break slope
Beach slope gradient	Steep, steeply concave, gentle
Back beach morphology	Sea wall, Foredune
Morphodynamic state	Type 1, Type 2, Type 3, Type 4, Type 5 and Type 6

Tab. 2 – Variables and modalities used in multivariate analyses.

Tab. 2 – Variables et modalités utilisées pour les analyses multivariées.

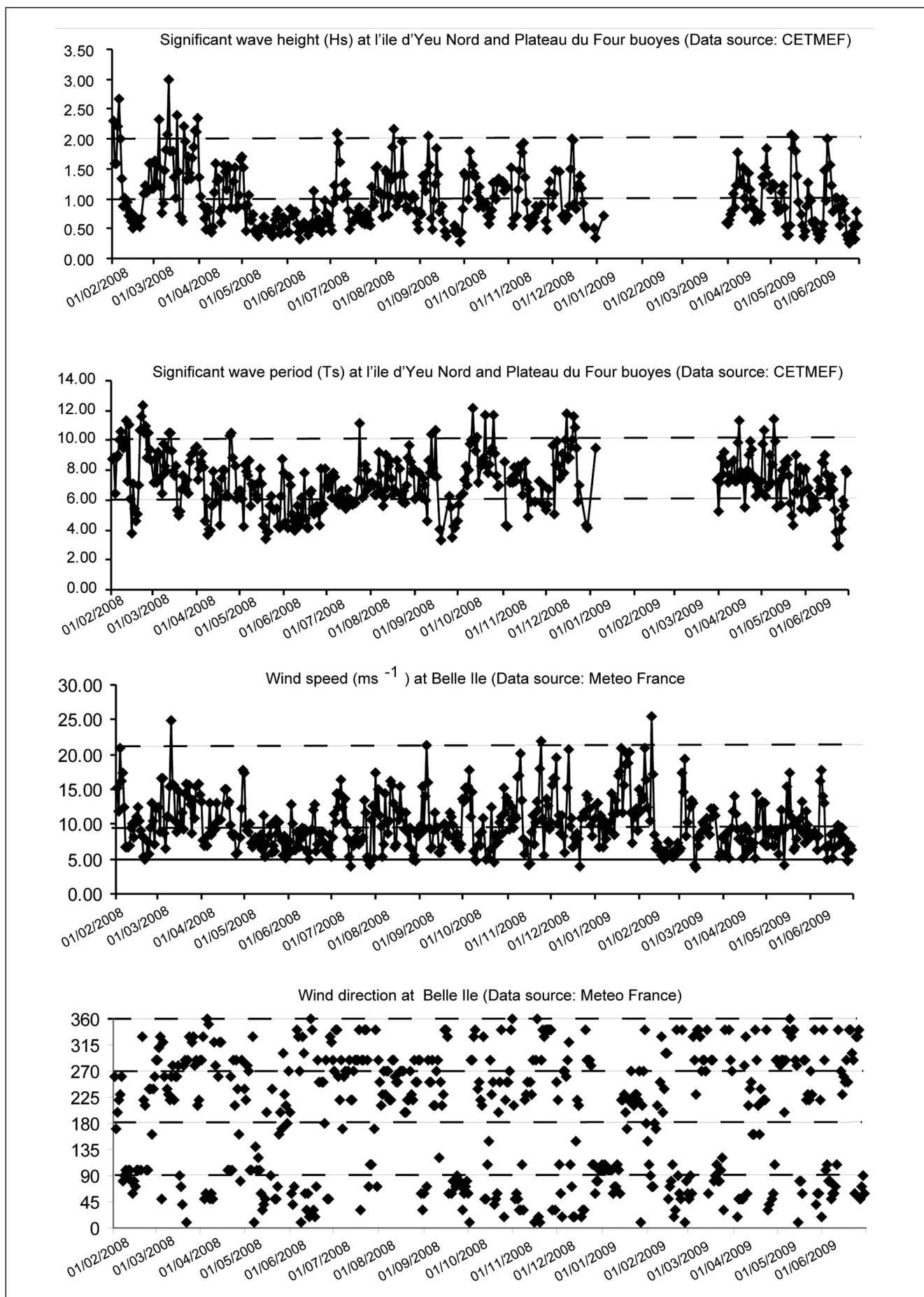


Fig. 2 – Wind and offshore wave data variations between February 2008 and June 2009.

Fig. 2 – Variations des données de vent et de houle au large entre février 2008 et juin 2009.

areas, they were classified as “numerous” (tab. 2). When they cover only very partially these areas, they were classified as “few” (tab. 2). When no bedrocks were identified, the “absent” value was assigned to this variable (tab. 2). Break slope position, break slope gradient and morphodynamic state variables were identified through an assessment of field data. The position of the break slope along each beach profile was measured from the upper beach along standardised profiles. Values obtained range from 5 m to 63 m. They were grouped in three classes: landward (less than 10 m from the upper beach), intermediate (10-50 m from the upper beach) and seaward (more than 50 m from the upper beach) (tab. 2). When no break slope was identified along the profile the “no break slope” modality was assigned to the beach. Beach slope gradient were identified taking into account both mean beach slope values derived from each surveys and the general shape of beach profiles. Mean beach slope values range from  $1^{\circ}50$  to  $6^{\circ}15$ . “Gentle” beaches refers to low slope gradient beaches (less than  $2^{\circ}$ ), “steeply concave” beaches refers to high slope gradient (more than  $2^{\circ}$ ) with concave beach profile shape, and “steep” beaches refers to high slope gradient (more than  $2^{\circ}$ ) with a slightly convex beach profile (tab. 2). Morphodynamic states were identified from an assessment of the surf scaling and surf similarity values obtained for each survey. They are detailed in the following section. Due to the high range of grain size variations along beach profiles, sediment parameters were not taken into account in the analysis. Then, a Hierarchical Clustering Analysis (HCA) was undertaken from the coordinates of each modality on factorial axis. This last analysis aims at grouping the beaches on the basis of their resemblance, defined as close location on factorial axes.

## Results

Between February 2008 and June 2009 offshore wave climate was characterised by relatively rough wave conditions (fig. 2), except between May and July 2008 when significant waves presented low height (less than 1 m or 0.5 m) and short wave periods. In March 2008, July 2008, August 2008, September 2008, November 2008, December 2008, May 2009 and June 2009, significant wave heights exceeded 2 m with long wave periods observed during several days. Over the whole period, modal and mean wave heights were both nearly 1 m. In most cases, storm conditions were associated with strong winds coming from the North-West to the South-West. Fair weather conditions and low wave heights were associated with east winds.

As a consequence of rough wave conditions over the whole period, most beaches recorded high beach profiles variability (fig. 3). Beach changes in response to storm conditions varied according to wind, wave and beach

orientation. As an example, on the beaches of the Gâvres-Penthièvre sand dune system, storm conditions associated with strong South-West winds (25 m/s) lead to significant sand deposits at Gâvres in the upper beach whereas shorefaces was eroded on the other beaches (Pian *et al.*, 2011). Most of the time, fair weather conditions favour upper beach accretion and rough conditions favour beach erosion. This suggests the occurrence of crossshore sediment transports related to wave climate variations. Beach changes can also be related to alongshore sediment transport (Pian, 2010) leading to a temporal and spatial succession of erosion/accretion processes. Alongshore sediment transport depended on wind and shallow water wave approaching direction, beach and nearshore bathymetric characteristics.

For each beach, grain size variations are important along beach profile (Pian, 2010). Along the Gâvres-Penthièvre beach system, mean grain sizes are coarser around the Etel ria and finer South of the beach dune system. On the Quiberon bay beaches, finer sand are located on the medium part of the beach, except on Carnac beach where they are located on the upper beach. Elsewhere, upper beach are composed of medium or coarse sands and lower beaches of medium sands. The Rhuys peninsula beaches are also characterised by heterogeneous grain size along beach profiles. Coarser materials are located on the lower beaches, except on Kervest beach. Upper beaches are mostly composed of medium sands.

Table 3 summarises values given by the surf similarity and the surf scaling parameters to describe beach morphodynamic states. Most of the time, they indicate the occurrence of intermediate or reflective beach states. Their temporal variations have been compared to profiles shapes and profile variations. This comparison leads to the identification of six different morphodynamic states. The first beach morphodynamic state concerns four beaches located within the different coastal systems under study. They are Gâvres, Kerhillio, Le Men Du and Penvins (fig. 4) and are characterised by a beach profile shape displaying an important slope break between the upper and lower beach. The upper beach is characterised by a slope value ranging from around  $3^{\circ}$  to more than  $10^{\circ}$  according to the beach. It displays a reflective morphodynamic beach state correctly described by the surf scaling parameter. The lower beach is characterised by a gentle slope with a mean value ranging from less to  $1^{\circ}$  to less to  $2^{\circ}$ . It displays a dissipative morphodynamic beach state correctly described by the surf scaling parameter. Type 2 groups together beaches located within both the Gâvres - Penthièvre beach dune system and the Quiberon bay (fig. 4). Morphological changes recorded between each survey are correctly described by the temporal variations of the surf scaling parameter values which display a reflective behaviour. Average beach slope values ranged from around  $3^{\circ}$  to  $6^{\circ}$ . Type 3 and type 4 concern intermediate beaches where variations of the surf similarity and the surf scaling parameters did not match beach profile variations. Type 3 concerns beaches located within the Gâvres – Penthièvre beach dune system and along the Rhuys Peninsula (fig. 4). Morphological changes recorded

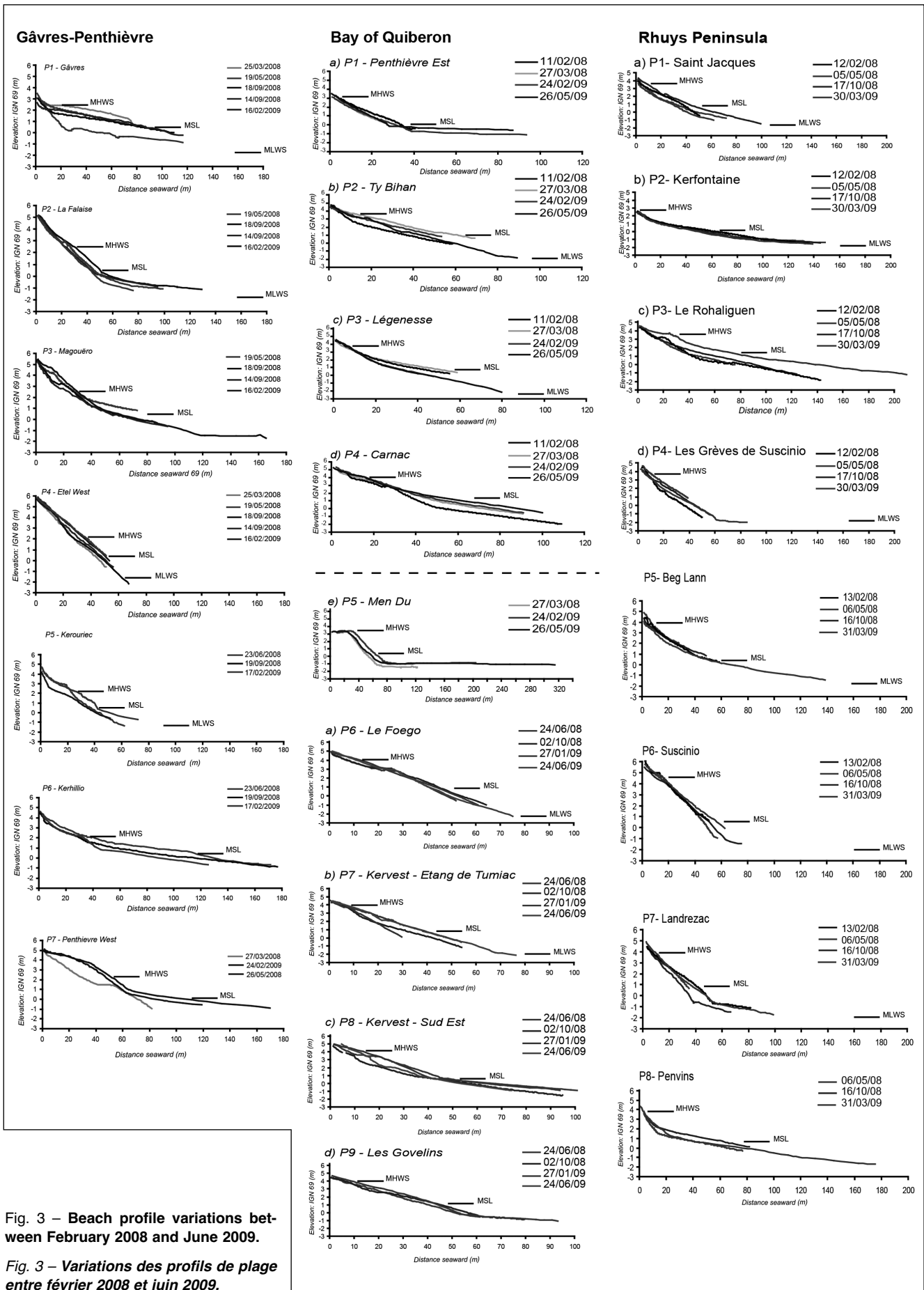


Fig. 3 – Beach profile variations between February 2008 and June 2009.

Fig. 3 – Variations des profils de plage entre février 2008 et juin 2009.

<b>Gâvres Penthièvre beaches</b>					
<b>Surf scaling parameter (e)</b>					
	March 2008	May/June 2008	Sept 2008	Nov 2008	February 2009
Gâvres	0.40	0.16	0.11	0.02	-
La falaise		0.66	0.35	1.60	-
Magouëro		0.75	0.26	1.59	-
Etel Ouest	7.21	0.72	2.07	5.24	-
Kerouriec		1.66	1.25		-
Kerhillio		0.16	0.10		-
	March 2008	February 2009	May 2009		
Penthièvre Ouest	3.94	-	0.53		
<b>Surf similarity parameter (z)</b>					
	Mars 2008	May/June 2008	Sept 2008	Nov 2008	February 2009
Gâvres	0.27	0.34	0.20	0.13	-
La falaise		0.69	0.42	0.31	-
Magouëro		0.74	0.37	0.31	-
Etel Ouest	1.14	0.72	1.03	0.57	-
Kerouriec		0.51	0.80		-
Kerhillio		0.15	0.22		-
	March 2008	February 2009	May 2009		
Penthièvre Ouest	0.57	-	0.33		

<b>Quiberon bay beaches</b>								
<b>Surf scaling parameter (e)</b>								
	February 2008	March 2008	February 2009	May 2009	June 2008	Oct 2008	January 2009	June 2009
Penthièvre Est	5.38	12.39	-	0.99				
Ty bihan	3.88	2.34	-	2.47				
Légenesse	3.49	3.29	-	3.11				
Carnac	2.48	1.71	-	1.78				
Men Du	-	1.14	-	0.08				
Foego					1.85	4.15	-	1.29
Etang de Tumiac					1.52	3.65	-	1.01
Kervest					0.63	2.2	-	0.96
Govelin					1.18	2.23	-	2.22
<b>Surf similarity parameter (z)</b>								
	February 2008	March 2008	February 2009	May 2009	June 2008	Oct 2008	January 2009	June 2009
Penthièvre Est	0.47	1.01	-	0.46				
Ty bihan	0.4	0.44	-	0.72				
Légenesse	0.38	0.52	-	0.81				
Carnac	0.32	0.37	-	0.67				
Men Du	-	0.4	-	0.11				
Foego					0.54	0.87	-	0.63
Etang de Tumiac					0.82	0.96	-	0.46
Kervest					0.32	0.63	-	0.45
Govelin					0.43	0.64	-	0.69

<b>Rhuys peninsula beaches</b>				
<b>Surf scaling parameter (e)</b>				
	February 2008	May 2008	October 2008	March 2009
Saint Jacques	5.67	6.48	1.25	-
Kerfontaine	0.22	0.82	0.33	-
Rohaliguen	1.37	4.59	0.92	-
Grèves de Suscinio	11.15	14.64	4.41	-
Beg Lann	5.26	11.04	7.19	-
Suscinio	12.05	13.36	6.41	6.1
Landrezac	4.93	12.62	6.26	3.19
Penvins	0.66	2.52	1.57	0.81
<b>Surf similarity parameter (z)</b>				
	February 2008	May 2008	October 2008	March 2009
Saint Jacques	1.03	0.49	0.34	-
Kerfontaine	0.15	0.18	0.26	-
Rohaliguen	0.37	0.53	0.83	-
Grèves de Suscinio	1.07	0.77	0.96	-
Beg Lann	0.34	0.65	0.54	-
Suscinio	0.51	0.71	0.52	0.56
Landrezac	0.32	2.20	0.54	0.40
Penvins	0.26	0.31	0.27	0.20

Tab. 3 – Surf similarity and surf scaling parameters values computed for each beach during the survey periods.

Tab. 3 – Valeurs du paramètre de réplcation et d'échelonnement de barres estimées pour chaque plage des suivis topographiques.

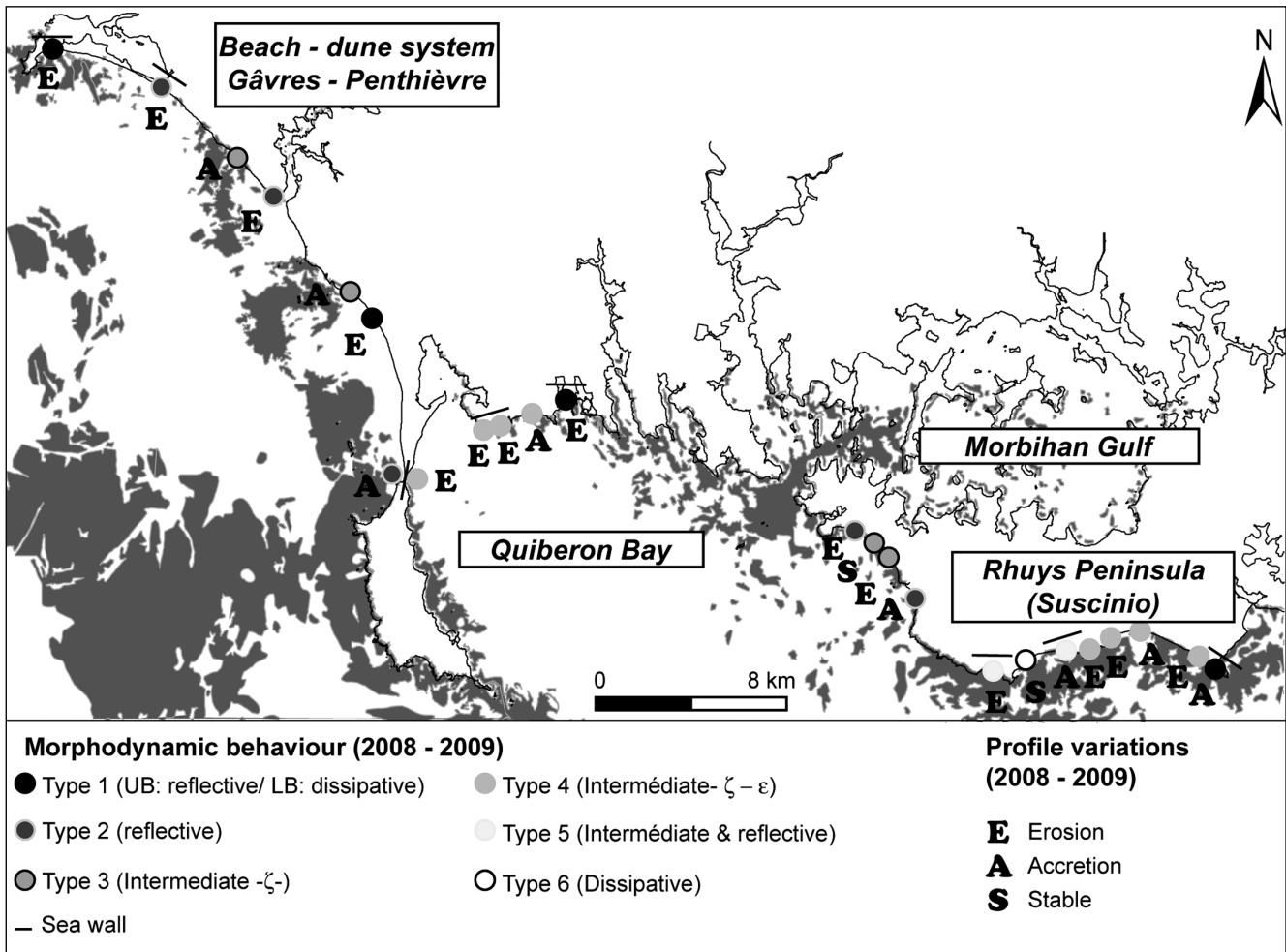


Fig. 4 – Distribution of the morphodynamic behaviour along the coastline (February 2008 – June 2009).

Fig. 4 – Distribution des comportements morphodynamiques le long du trait de côte (février 2008 – juin 2009).

between each survey are correctly described by the temporal variations of the surf similarity parameter values. These values indicate the occurrence of intermediate morphodynamic beach states. Type 4 also refers to intermediate morphodynamic beach states. It concerns beaches located either along the Bay of Quiberon or the Rhuys Peninsula coastlines (fig. 4). The morphological changes of these beaches between different surveys are well described by the temporal variations of the surf scaling parameter. During the same period, the surf similarity parameter values indicate the occurrence of either reflective or intermediate morphodynamic beach states according to the survey under consideration. Type 5 is only represented in the Rhuys Peninsula (fig. 4) and describes highly variable beach. Between each survey periods, these beaches shift from reflective to intermediate morphodynamic beach states. Such variability corresponds to an alternation of both accretion and lowering profiles between each survey. Type 6 only concerns the Kerfontaine beach located in the Rhuys Peninsula (fig. 4) and refers to a dissipative morphodynamic beach state.

Multivariate analysis permits to identify some variables related to different morphodynamic behaviours previously discussed and to classify beaches on the basis of their resem-

blance regarding criteria displayed in table 2. The first two factorial axis derived from the MCA explain around 60% of the total variance (fig. 5). This value reaches around 68% when including the third axis. Main variables associated with these axes are beach gradient, break slope and, secondarily, back beach morphology, nearshore bedrocks extent and coastline orientation. Reflective beaches are likely to be associated with specific morphological features such as a landward break slope, the presence of numerous bedrocks extending nearshore or the presence of a sea wall on the upper part of the beach. Steep foreshores with no break slope are backed by foredune and record reflective morphodynamic behaviour as well. Intermediate beaches where the ability of the surf similarity and scaling parameters to reflect topographic changes is variable are associated with specific coastline orientation. Beaches orientated South-West record morphological changes better described by the surf similarity parameter (Type 3). Morphological changes recorded by intermediate beaches orientated South and South-East are better described by the surf scaling parameter.

The cluster analysis provides more details by grouping the beaches in six different clusters according to profiles shape (beach slope gradient and break slope position), morphody-

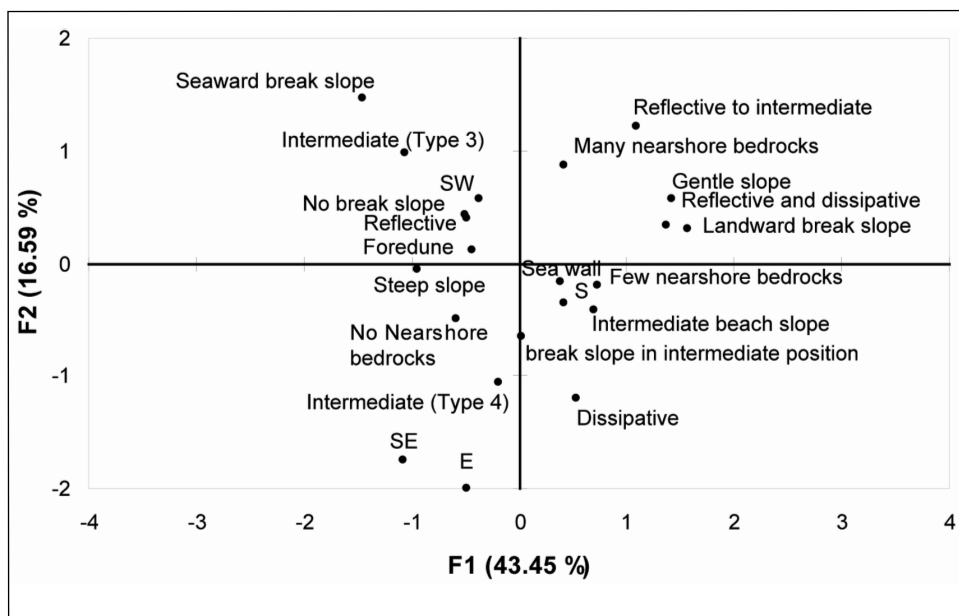


Fig. 5 – Symetrical graph of variables derived from the MCA.

Fig. 5 – Graphique symétrique des variables dérivées de l'ACM.

namic behaviour, coastline orientation and nearshore bedrocks extents (fig. 6). Clusters are mapped in figure 7. Comparisons between figure 3 and figure 7 permit to put forward main beach characteristics within each cluster. Cluster 1 groups together beaches characterised by a reflective upper beach, a dissipative lower beach (morphodynamic behaviour type 1 and type 6) and a landward position of the break slope. Most of these beaches are South orientated and backed by a sea wall. Cluster 2 encompasses beaches where the break slope between the upper and lower beaches is well marked and located around 50 m seawards. Upper beaches display a

reflective to intermediate slope. La Falaise beach apart, all these beaches are South orientated and located in a sheltered coastal system where nearshore bedrocks are important. La Falaise beach is backed by a sea wall. They have recorded both accretion and erosive profiles over the studied period. Morphologic changes are concentrated around the break slope. Cluster 3 encompasses intermediate beaches similar to cluster 2 ones, except for the break slope which is less marked and the profile slope which is more concave. These beaches are orientated South-West (fig. 7). When located in the more exposed coastal system, they are fronted by nearshore bedrocks while in the sheltered Quiberon bay coastal system, few nearshore bedrocks

extend seawards. Morphological changes mainly occur on the upper part of beaches. Steep beaches with a reflective upper beach, no break slope or a seaward break slope are grouped in cluster 4. They are South-West orientated. In spite of displaying a different profile shape, Penthièvre Est and Beg Lann belong to the same cluster. Located in a sheltered coastal system, they both recorded profile erosion during the survey period. Then, cluster 6 groups four beaches located in a sheltered coastal system, backed by sea walls, characterised by a concave profile shape, a reflective upper beach and a dissipative to intermediate lower profile slope.

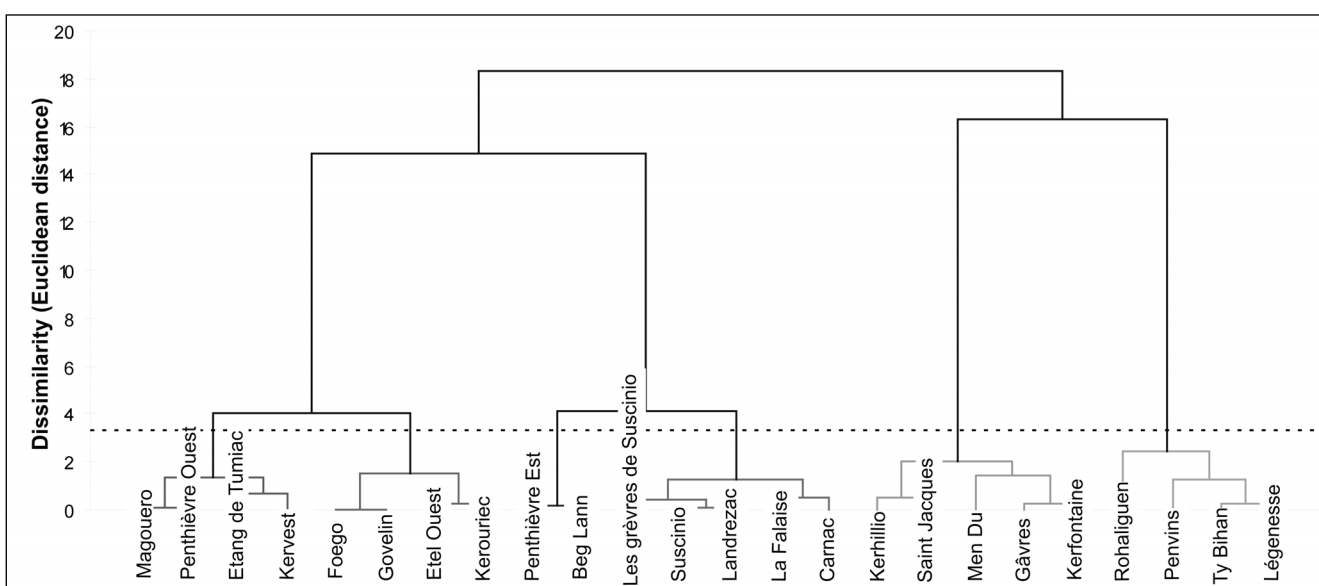


Fig. 6 – Hierarchical dendrogram produced by Cluster Analysis.

Fig. 6 – Dendrogramme produit par la classification ascendante hiérarchique.

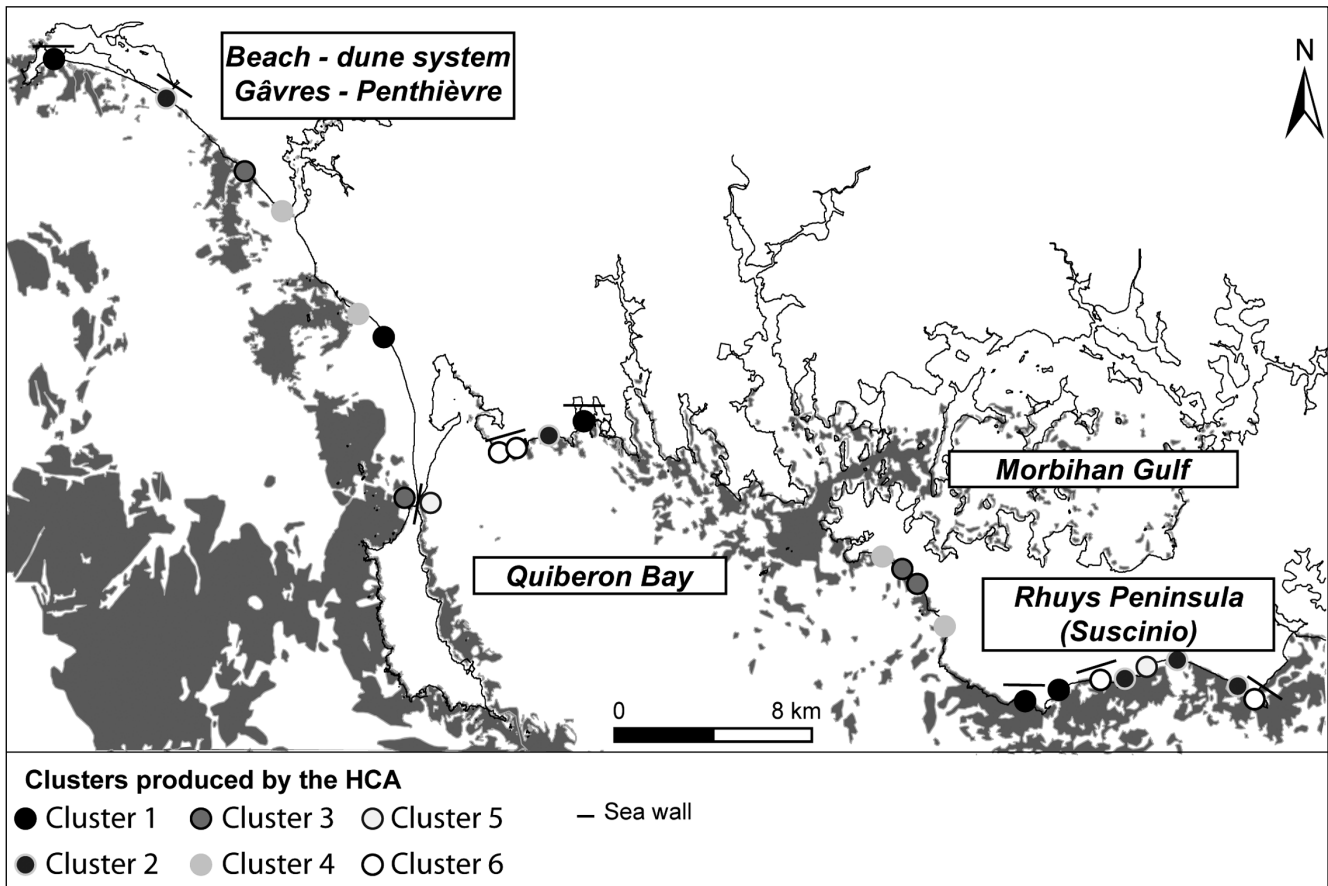


Fig. 7 – Distribution of beach clusters along the studied coastline.

Fig. 7 – Répartition spatiale des groupes de plage le long du trait de côte étudié.

## Discussion

The different analyses performed display similar results but provide different levels of details. Broadly, along the South Brittany coast, most beaches upper parts display intermediate to reflective morphodynamic beach behaviours. Kerfontaine beach, located on the Rhuys Peninsula is the only beach which displays a dissipative slope from the dune foot to the lower beach. Comparison between beach changes and variations of the surf similarity and scaling parameters values agrees with major statements expressed by previous authors. As pointed out by B.O. Bauer and B. Greenwood (1988), these parameters are likely to better describe reflective and dissipative stages than intermediate ones. Intermediate behaviour is much less accurately modelled (Wright *et al.*, 1987) and the different values obtained by the surf similarity and scaling parameters do not fit with morphological changes recorded along some beaches profiles. As underlined by Ranasinghe (2004), accuracy of beach stage models could be related to the degree of subjectivity associated with their use and, in this case, with the few amount of data available to undertake a classification of South Brittany beaches. However, the spatial distribution of morphodynamic beach states displays on figure 4 put forward some spatial trends and suggest

some relationships between for example beach morphodynamic state and coastline orientation. Synthesis of beach characteristics provided by the multivariate and the cluster analyses permits to detail such relationships by highlighting some intrinsic characteristics shared by beaches displaying same morphodynamic behaviours, especially regarding reflective and intermediate stages. On the basis of these results, it is then possible to discuss the main factors related to beach morphodynamic behaviour disparities and to partly explain spatial trends displayed in figure 4.

The cluster analysis identifies three groups of beaches dominated by a reflective behaviour of the active beach profile, at least above the mean sea level water. Cluster 4 refers to steep beaches, located in sheltered areas. These beaches are characterised either by a seaward position of the break slope or no break slope. Cluster 1 and cluster 6 group very similar beaches backed by a sea wall, fronted by bedrocks and marked by a very landward position of the break slope, but cluster 6 distinguishes beaches with a more concave profile shape. In addition, both the AMC and cluster analyses reveal that reflective upper beaches are characterised by either steep beach gradient or the presence of sea wall associated with a landward position of the break slope from where a more dissipative slope. Most of these

beaches, except Kerhillio, are South orientated (fig. 7) and located in a sheltered position behind important nearshore bedrocks. These results suggest that reflective behaviours are favoured when sediment deposition along beach profiles is limited landwards or seawards by external controls such as anthropogenic or geological features. Such a statement agrees with previous observations of D.W.T. Jackson *et al.* (2005) who point out that mesotidal beaches in Ireland are characterised by steeper upper beach profiles than expected due to geological control.

Cluster 2 and cluster 3 respectively group together intermediate beaches characterised by different profiles shapes and a more or less sheltered beach orientation. Within each of these groups, higher morphological changes are recorded on different positions along beach profiles. As previously said, they result from interactions between crossshore and alongshore sediment transports due to wave and wind variations. When upper beaches are steeper, morphological changes are concentrated around the break slope (Cluster 2). These beaches are located in a sheltered position where nearshore bedrocks are important. Inversely, South West orientated beaches display more concave profile shapes where morphological changes are concentrated on the upper part of the beach (Cluster 3). Since prevailing waves are mainly coming from the North-West and the South-West, this result could reflect different beaches behaviours related to wave incidence variations, controlling in turn the beach profile form. Thus, the combination of both coastline orientation and bedrocks location contributes to partly control the distribution of wave energy along the coast and explain the different beach morphodynamic behaviours. More exposed beaches display a gentler slope evolving towards a dissipative state with major changes occurring on the upper part of the beach. Inversely sheltered beaches tend to be steeper especially when nearshore bedrocks are numerous. This last observation reinforces statements previously discussed about relationships between geological control and beach profile form. Such results also partly the spatial distribution of morphodynamic states displayed in figure 4.

In regard to this discussion, two major factors appear as determinant in the control of morphologic beach disparities along South Brittany coast. They are nearshore bedrocks distribution and coastline orientation, both related to the roughness of the coastline over a regional scale. Such results agree with recent studies enhancing the role of geological inheritance in embayed beach systems (Loureiro *et al.*, 2009; Short, 2010). Similar results are obtained by G. Anfuso *et al.* (2003) who show alongshore morphodynamic beach state variations in the South West coast of Spain are related to local constraints such as the presence of rocky shoals affecting wave breaking processes. Moreover, in South Brittany, steepness of the upper beach could also be put into relation with the presence of a sea wall, suggesting interactions between beach morphological states and anthropogenic impacts.

However, coastline orientation variation and its associated sheltered effect are not completely discussed in this study since beaches located in each coastal system under study dis-

play similar beaches behaviour in spite of the different wave energies reaching the coast. Interactions between incident wave energy variations, nearshore distribution and alongshore sediment transports could also explain beach disparities observed along the South Brittany coast. In addition, in sheltered environments, interactions between sediment transports patterns and coastal currents induced by sea wind variations do impact beach morphology and morphodynamic behaviour (Gomez Pujol *et al.*, 2007). Such processes have been analysed in details and could also explain beach morphological disparities recorded along the coastline. Further investigations are needed to discuss these last points and enhance this first classification of South Brittany beaches.

## Conclusion

This study provides a compilation of data about the morphodynamic behaviour of 25 beaches scattered along the South Brittany coast. At least six different morphodynamic behaviours have been recorded, mainly associated with reflective or/and intermediate beach states. All beaches display heterogeneous morphological features. Taking into account the different characteristics of each beach, statistical analyses suggest that beach disparities could be related to the geological constraints of the coast and especially the roughness of the coastline as well as the presence of bedrocks nearshore. Results also point out the role of anthropogenic features. Where beaches are confined landward by a seawall and seaward by nearshore bedrocks, beach profiles tend to display more reflective behaviour. This scheme is complicated by other variables such as coastline orientation, beach slope gradient and profile shape. Because such beach characteristics are closely link to sediment availability, this last observation suggest than morphodynamic behaviour disparities could also be related to sediment inputs and sediment transport schemes occurring within South Brittany coastal system. Further investigation focusing on these last points could permit to complete this first and rough classification.

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