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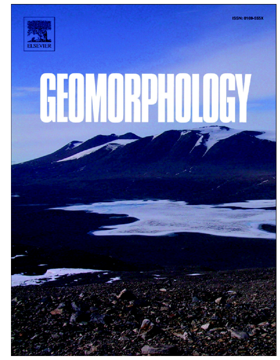

150 years of foredune initiation and evolution driven by human and natural processes

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150 years of foredune initiation and evolution driven by human and natural processes

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Abstract: Foredunes are efficient natural coastal defenses acting as protective barriers during storm events. They also have the capacity to be an ecosystem hosting significant biodiversity. The economic development and/or recreational use of the foredune commonly results in a modification of natural functioning and the concomitant mixing of natural and anthropogenic processes. While the impact of human interventions on the short term evolution of coastal dunes is reasonably well understood, relatively less is known on their imprint at a scale of several decades. The Truc Vert beach-dune system (SW France), which has been exposed to various dune management strategies for more than a century, provides a relevant site to explore the respective contributions of natural and anthropogenic processes on coastal foredune evolution and the current coastal dune landscape. For this purpose, the coastal dune system was investigated using several approaches that combine ground penetrating radar (GPR), topographic data, aerial photographs and historical maps.

A 20-m thick GPR sequence provides a stratigraphic record from which we detail ~150-year period of coastal dune change, including the initiation of the foredune. Results show a mixture of radar facies typical of natural aeolian erosion or deposition and radar facies that are the signature of human actions. These anthropogenic works include a large fence emplaced in 1860 to build and fix the foredune, and intense mechanical reshaping of the dune profile by bulldozers in 1972 followed by an intensive planting of vegetation. These various management strategies had a profound influence on coastal dune changes and, in turn, on the current coastal dune landscape. Historic archives documenting coastal dune works were critical to discriminate some of the radar facies, which could be wrongfully interpreted as natural erosion or deposition facies. Therefore, these results demonstrate the importance of coupling GPR and historical documentation wherever possible to determine, in part or fully, the contributions of human interventions and actions in modern dune evolution and morphological development.

Key words: Foredune, Coastal dune history, GPR, Foredune stratification, Anthropogenic influence, Sand fences, Truc Vert

1. Introduction

Foredunes are shore-parallel aeolian landforms formed on the backshore zone of beaches by aeolian sand deposition trapped by vegetation (Hesp, 1988). They occur worldwide on coastlines, range from nebkha fields to continuous alongshore ridges, and are especially well developed on wave-dominated temperate coasts with moderate to high sediment supply. A broad literature describes conditions favoring coastal foredune growth. Several key processes are identified including the influence of surfzone-beach type (Short and Hesp, 1982), vegetation species type and density (Hesp et al., 2019), regional and local wind characteristics (Miot da Silva and Hesp, 2010), topographic influences, fetch (Bauer and Davidson-Arnott, 2003, Delgado-Fernandez and Davidson-Arnott, 2009), and the effects of surface conditions especially moisture content (Hesp and Walker, 2013, Anderson and Walker, 2006, Edwards and Namikas, 2009 for reviews). Recently, some studies have also stressed the role of marine controls on coastal foredune evolution, such as sediment supply, wave energy or intertidal sandbar welding during certain seasons (Houser and Mathew, 2011; Hesp and Smyth, 2016; Cohn et al., 2018, 2019; Pellon et al., 2020). So, foredunes respond to process forcing over a broad spectrum of spatial and temporal scales (Walker et al., 2017). These complex process interactions take place between the beach-dune system or on the dune itself, inducing a spatial development variability in coastal dunes at the global, regional and local scale (Hesp 2002; Crapoulet et al., 2017; Garcia-Romero et al., 2019; Pickart and Hesp, 2019; Bossard and Nicolae Lerma, 2020). Research on surfzone-beach-dune interactions has also driven the development of conceptual and predictive models to explain patterns of coastal dune development and preservation (Short and Hesp, 1982; Hesp, 1988, 2002, Psuty, 1988, 1992; Sherman and Bauer, 1993; Dougherty, 2014; Nicolae Lerma et al., 2019; Costas et al., 2020; Pellon et al., 2020).

Coastal areas are one of the most heavily used environments with tourism and residential uses leading to ecosystem loss and beach-dune degradation (Martinez et al., 2013; Delgado-Fernandez et al., 2019). Thus, the development of various management plans promoting dune stabilization are common. Indeed, foredunes are of great importance due to their role as frontline protection from wave attack and risk of flooding during storms (Arens et al., 2013). They also have the capacity to be a significant sediment reservoir available to the system, or to be an ecosystem hosting significant biodiversity. The economic and/or recreational development of this environment induces a modification of its natural behavior with often, the concomitant mixing of natural and anthropogenic processes (Nordstrom, 1994; Jackson and Nordstrom, 2011, 2013; Arens et al., 2013; Jackson et al., 2013). Past management of coastal dunes in Western Europe was primarily concerned with a vulnerability to sand invasion and the burial of settlements and agricultural land (Paskoff, 2001; Clemmensen and Murray, 2006; Clarke and Rendell, 2009). Therefore, since the 14th century, many European coastal dunes have been artificially stabilized by the planting of marram grass or by afforestation and the installation of fences to trap sediment drift. In the last decades, coastal dune management was primarily concerned with erosion control. The traditional strategy to counteract erosion was to stabilize foredunes as much as possible, and to suppress natural dynamic processes that would mobilize dunes and cause sand “loss” from the foredune system (Arens et al., 2013). To achieve this goal, several management activities were used, including beach nourishment (Bakker et al., 2012; de Schipper et al., 2016), vegetation planting (Arens et al., 2001; Hacker et al., 2019), sand fencing (Ruz and Anthony, 2008; Itzkin et al., 2020), removal of beach-dune wrack by raking (Jackson and Nordstrom, 2011; Nordstrom et al., 2012), and reshaping of the dune profile (Nordstrom and Arens, 1998; Matias et al., 2005). Recently, many managers of coastal environments advocate greater dynamism to retain diversity and restoration of dune mobility (Nordstrom et al., 2000;

Jackson and Nordstrom, 2011; Jackson et al., 2013; Arens et al., 2013; Delgado-Fernandez et al., 2019; Castelle et al., 2019). The impact of these methods on the short term evolution of the coastal dunes are relatively well perceived in terms of influence on the sediment transport or on the sediment budget of the system. Relatively less is known on their imprints at a scale of several decades. The dunes are archive locations ("black boxes") where their internal structure can potentially provide elements of understanding of the impact of these activities at a larger time scale.

Previous studies obtained stratigraphic information on aeolian landforms by reconstructing evolutionary characteristics of the near surface by observing exposures in natural profiles or by artificial trenching (Bigarella et al., 1969; Hesp 1988; Fryberger, 1990; Byrne and McCann, 1993; Ruz and Allard, 1995). This approach can evaluate shallow structures to typical depths of only 2-3 m and provide limited information. Due to these obvious problems, the studies of coastal aeolian landform sedimentary structures were limited. However, the development in recent decades of geophysical methods such as the ground penetrating radar (GPR) make it possible to substantially fill these gaps (Jol et al., 1996; Bristow et al., 2000a; Neal 2004; Robin et al., 2020). The GPR is a non-destructive method that offers fast and high quality stratigraphic data acquisition, making it an efficient tool for imaging of sedimentary structures up to 15-20 m depth. The analysis of GPR data results in the interpretation of radar facies indicating the architectural elements related to depositional environments. It makes it possible to reconstitute aeolian landform development, thereby identifying different phases of progradation, deposition and erosion that can possibly further reveal changes in climatic or environmental conditions (Jol et al., 1996, Pedersen and Clemmensen, 2005, Buynevich et al., 2007; Clemmensen et al., 2007; Hein et al., 2012; Ludwig et al., 2017; Fruergaard et al., 2020). Abundant studies have demonstrated the effectiveness of applying GPR to examine the internal structures of aeolian sedimentary deposits, including, for example, desert dunes

(Bristow et al., 1996; Bristow et al., 2000b), Holocene coastal dunes (Costas et al., 2006; Billy et al., 2015), coastal parabolic/barchan dunes (Gomez-Ortiz et al., 2009; Girardi and Davis, 2010; Fu et al., 2019; Dillenburg et al., 2020), and blowout evolution (Neal and Roberts, 2001; Gonzalez-Villanueva et al., 2011). GPR investigations on modern coastal dunes, particularly foredunes are scarce, although they have the potential to provide new insights into coastal change and key processes (natural or anthropogenic) involved in their construction (Bristow et al., 2000a; Neal and Roberts, 2001; Van Dam et al., 2003; Costas et al., 2006; Ramos et al., 2011; Bakker et al., 2012; Gonzalez-Villanueva et al., 2011; Moulton et al., 2013; Dougherty, 2014; Weymer et al., 2015; De Oliveira et al., 2019; Oliver et al., 2019; Billy et al., 2020; Robin et al., 2020).

The purpose of this paper is to assess the impact of natural and anthropogenic processes on coastal foredune evolution at multi-decadal to century scale. In this case 'anthropogenic processes' refer to action by humans to deliberately modify the landscape by actions such as re-shaping dunescapes or landforms, planting native and/or exotic vegetation, establishing sand trapping fences and structures. More precisely, the study seeks to understand how these processes are recorded in the stratigraphy of the dune at Truc Vert beach (southwest, France) using GPR and historical data. Truc Vert beach presents well-developed aeolian dunes (up to 20-25-m high and 250-m wide) which are situated far from beach resorts (Figure 1). Observation of the dune landscape might suggest a natural evolutionary process. However, since the 19th century, coastal dune stakeholders undertook major actions of coastal management. So, the coastal dune system at Truc Vert is an ideal candidate to address the impact of natural and anthropogenic processes on coastal dune evolution.

2. Study area

2.1. Gironde coastal region

Truc Vert beach is located on the Gironde coast in southwest France (Figure 1a), which covers approximately 135 km of sandy surf beaches from the Medoc peninsula in the north to the Biscarrosse border in the south. It is a wave-dominated, meso- macro-tidal environment (mean spring tide range of 3.7 m) (Castelle et al., 2018). The offshore wave climate is characterized by a dominant WNW incidence, generated in the North Atlantic Ocean, with an annual mean significant wave height (Hs) of 1.8 m. Winds on the Gironde Coast principally flow from west to north (Nicolae-Lerma et al., 2019). Previous studies have reported a significant contribution of aeolian sediment transport with an estimated flux of about 15-30 m^3/m/yr (Froidefond and Prud'homme, 1991).

The Gironde coast is made of a 0.2- to 10-km wide dune complex (Figure 1b, c) composed of quartz sand that formed as several distinct and successive transgressive dunefields (Tastet and Pontee, 1998). Since the last glaciation, the combination of high sediment supply, sea level-variation, and sustained wind dynamics has led to the development of several dune phases or generations (Tastet and Pontee, 1998). Three different dune generations spreading across 10 km inland (Figure 1) have been identified (Froidefond and Prud'homme, 1991). The older and more remote inland structures are parabolic dunes. They naturally developed and migrated from 500 to 1200AD (Tastet and Pontee, 1998). A second generation is composed of barchanoid dunes. They developed from 1500 to the beginning of the 19th century. In the middle of the 19th century, these mobile dunes were stabilised by intensive maritime pine (*Pinus maritima*) planting. This forest, which became the primary economic resource in the area, was threatened by the windblown sand and corrosive effects of salt spray particularly along the western coastal margin. The two dune generations represent approximately 25,000 and 85,000 ha, respectively on the Aquitaine coast, (BRGM and ONF, 2018). The last generation comprises an established foredune partially formed by natural processes and principally shaped by human management actions to safeguard the marine pine forest (Figure 2), which is detailed below.

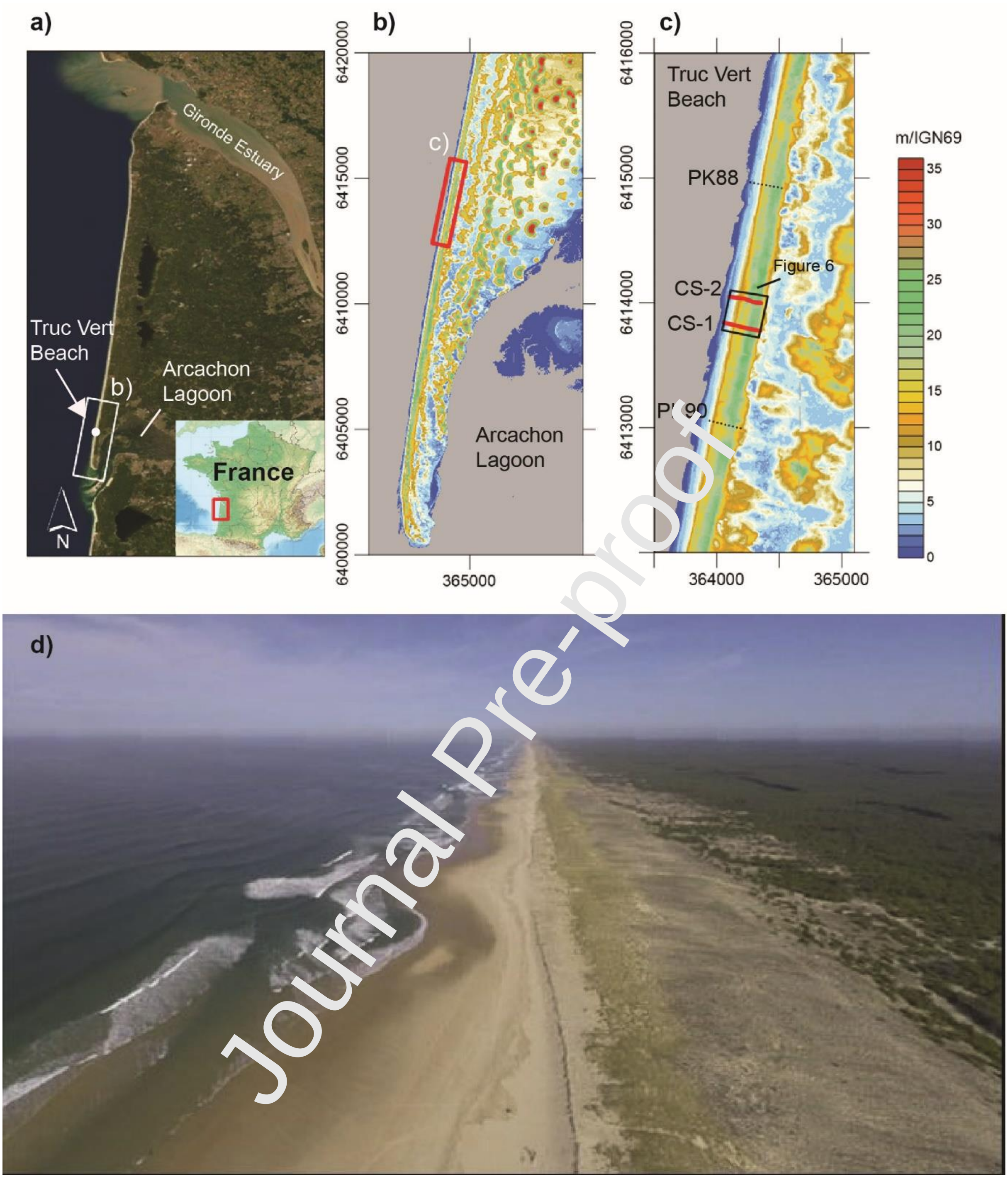

Fig.1: (a) Location map. (b) Location of the study area on Cap Ferret spit (2005 LiDAR Data, source SIBA), (c) Truc Vert beach with ground-penetrating radar (GPR) (CS) and topographic (PK) profiles (PK as "Point Kilometrique" in French is the location of historical beach profiles of the French National Forestry Office (ONF)), (d) Oblique aerial photograph (03/07/2018) of the Truc Vert beach (photograph by V.Marieu).

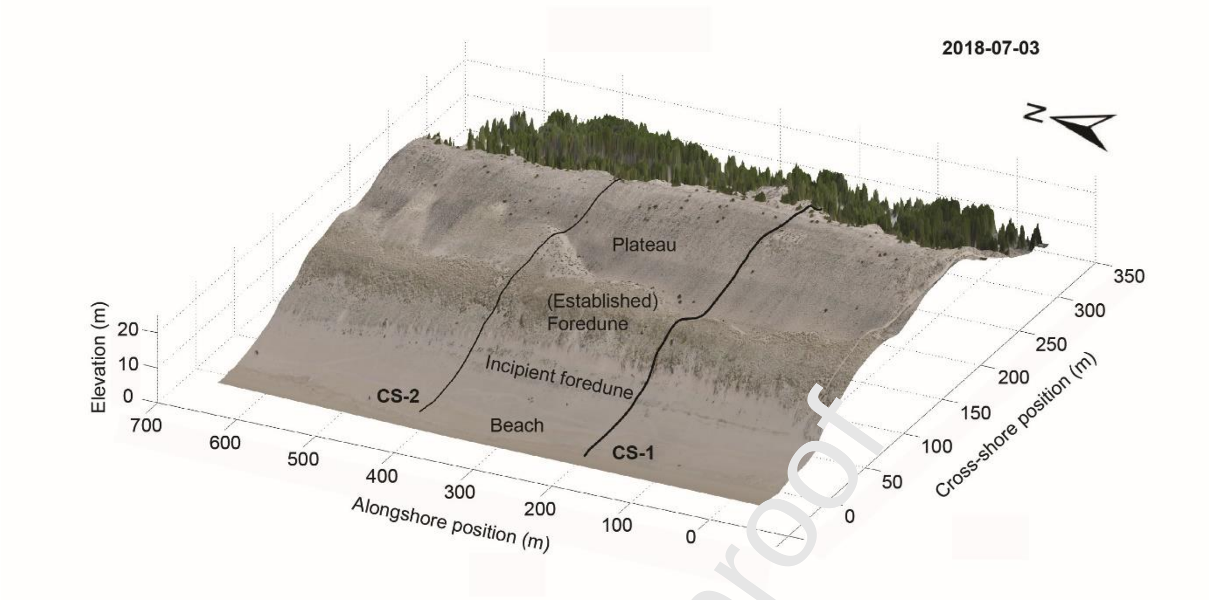

Fig.2: The studied beach dune system (03/07/2018) with location of the two GPR profiles. The terminology used in this paper is indicated on the diagram.

2.2. Truc Vert region

In order to protect the forest, an artificial "contemporary" dune, hereafter referred to as the foredune as opposed to the fixed and forested dune complex, was created along the entire coast in the 19th century (Buffault, 1942). The windblown sand from the beach was progressively trapped by fences which were systematically raised as they were buried, with subsequent intense marram (*Ammophila arenaria*) planting (Figure 3a), in order to obtain an "ideal" engineered profile designed by Engineer J.S. Goury (Figure 3b). This idealized profile is not based on an understanding of the aeolian sediment transport processes and deposition on this coast but on basic empirical knowledge of coastal dune profiles along the coast and the objective to shape an alongshore-uniform feature. The artificial profile was characterized by a gently sloping (approximately 2/10) seaward slope, a sub-horizontal plateau, both being planted, and a steep lee slope of approximately 6/10 corresponding to the sediment angle of repose. The artificial dune was typically 150-200 m wide and 12-15 m high (Paskoff, 2001). The coastal dune subsequently suffered large-scale erosion from some severe winter storms in the 1910s and 1920s, and was impaired during the Second World War when the coastal dunes were restricted areas used as a source of aggregate for the German war machine (Bossard and Nicolae Lerma, 2020). Until the early 1960s, the coastal dunes were largely dissected by blowouts and hollowed out by gullies. In order to restore the coastal dune system (Barrère, 1992; Prat and Auly, 2010), the engineered profile was further imposed all along the coast in the 1970's-80's using large-scale mechanical machinery and intensive marram planting (Figure 4).

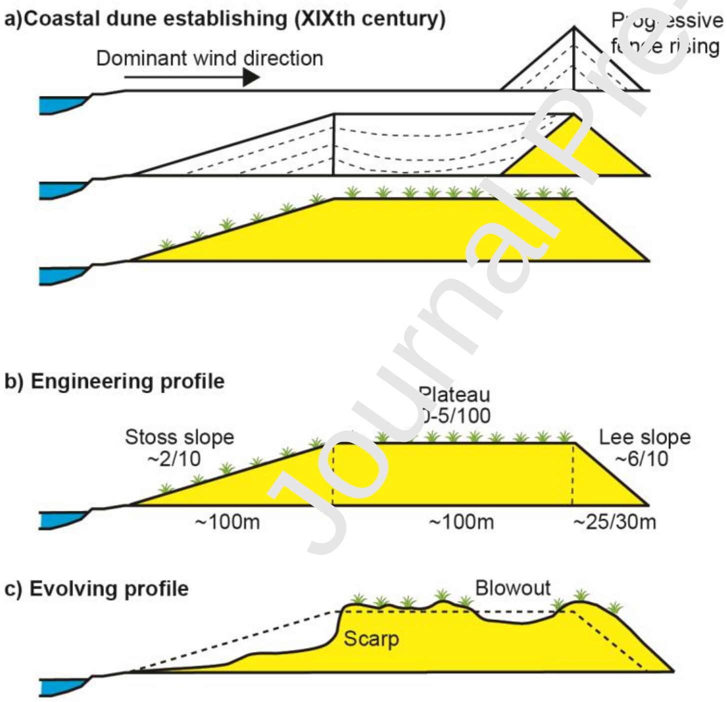

Fig.3: Steps of the progressive implementation of the engineered profile and dune evolution, (a) Raising of the dune (dimensions and shape) following Engineer J.S. Goury's recommendations during the XIXth century by progressively raising fences trapping the windblown sand and subsequent planting (note the presence of two fences was not systematic

on the Aquitaine coast) ; (b) engineered profile, that was further imposed by large-scale mechanical works in the 1970s-80s (Figure 4), and (c) subsequent natural evolution qualitatively observed by Paskoff (2001). (adapted from Paskoff, 2001, Prat and Auly, 2010).

Qualitative observations by Paskoff (2001) indicate that during the subsequent decades, marine erosion, breaches developing into blowouts and migration of windblown sand tended to (i) modify the overall shape of the artificial dune and (2) drive inland dune migration (Figure 3c). Instead of fighting against marine and aeolian erosion, the landward migration of the dune is accommodated rather than opposed. Soft ecodynamic methods are typically used by the "Office National des Forets" (ONF) coastal dune stakeholders, *e.g.*, through fencing in developing blowouts and planting, and natural degradation and deterioration from trampling pressures are minimized. The evolution shown in Figure 3c is, however, extremely variable along the coast depending on, but not only, the proactiveness of each coastal manager in charge of each stretch of coast, and the magnitude of the erosion rate which ranges from 0-5m/year along the Gironde coast (Castelle et al., 2018). As a result, the current morphological characteristics of the coastal dune are highly variable along the coast with a prominent north-south gradient. Dune width ranges from tens to several hundred meters (mean width = 187m), and the dune height ranges from 10-21m (mean height = 16.6m) (Bossard and Nicolae Lerma, 2020).

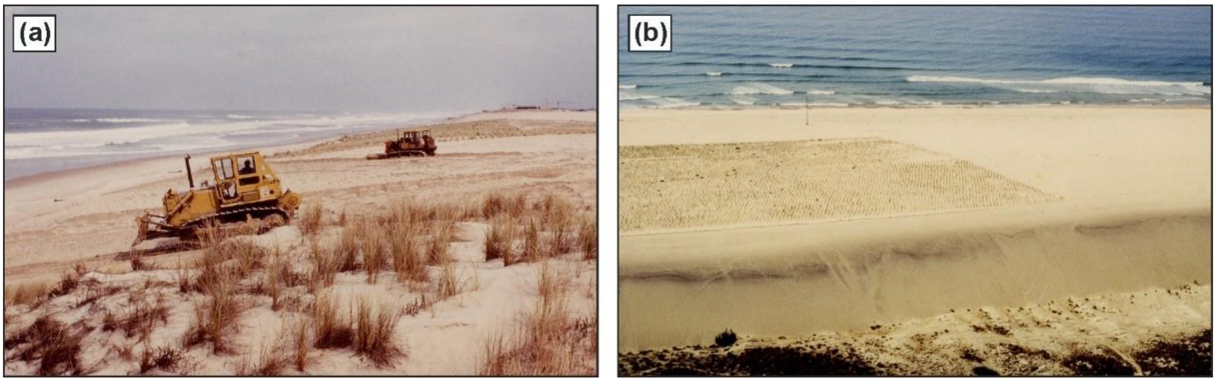

Fig.4: Photographs showing (a) mechanical shaping of the foredune, (b) subsequent marram planting of the engineered coastal dune plateau in the early 1970s-80s at Lacanau, (Gironde coast), 24km northward of the study site (Photos © ONF).

Contrary to most of the Gironde coast, Truc Vert beach lies in an approximately 20-km stretch of coast that has been relatively stable since, at least, the 1950s (Castelle et al., 2018). The general dune shape approximate the engineered dune shape and dimension desired by J.S Goury (Figure 2). However, aeolian sediments transported during the last decades have been, and are accumulating on the lower stoss slope, and directly beyond the seaward dune crest because of a steep seaward stoss slope. In addition, and despite the stormy winter of 2013/2014 that caused severe erosion at Truc Vert (Castelle et al., 2015; Nicolae Lerma et al., 2019; Robin et al., 2020) and along most of the Atlantic coast of Europe (Masselink et al., 2016), the sediment budget of the beach-dune system over the last 10 years is positive (Nicolae Lerma et al., 2019), although with substantial seasonal and interannual variability (Laporte-Fauret et al., 2020). Therefore, it is hypothesized that the internal structure of the current coastal dune has preserved some of the past natural and anthropogenic coastal dune evolution landform units. The anthropogenic signature through the coastal dune has never been explored. GPR therefore has the potential to provide new insight into the internal structure of the coastal dune at Truc Vert and elucidate its history (Robin et al., 2020).

3. Methods

The Truc Vert coastal dune system was investigated using several approaches that combined aerial photographs, historical maps, topographic data and GPR profiles.

3.1. Historical documents

Historical documents from the ONF archives were used, including:

1) an abundant literature illustrating the environmental context of the region since the 19th century;

2) an old map from 1940 showing fence position in 1860, which was digitized at a high resolution and georeferenced with the same method as for the aerial photographs;

3) a historical map and two mechanically shaped topographic profiles (historical beach profiles PK 88 and PK 90 of ONF; PK is a French acronym for Point Kilometrique ONF) between 1972 and 1977, which were also georeferenced. The field site of this study is located between PK 88 and PK 90;

4) three LiDAR (Light Detection And Ranging) surveys (2005, 2011, 2018) to provide a quantitative analysis of the current morphology and the recent evolution. The generated datasets have been acquired within the framework of the Observatoire de la Côte Aquitaine (OCA); see Bossard and Nicolae Lerma, 2020, for technical details).

3.2. Aerial photographs from 1947 to 2018

Coastal dune landscape changes were studied using historic aerial photographs and old maps. The present study is based on the analysis of 12 vertical photographs taken by the French National Geographic Institute (IGN, data available on line: https://remonterletemps.ign.fr/) from 1947 to 2004 (1947, 1950, 1955, 1965, 1972, 1977, 1982, 1985, 1991, 1998, 2004) using Geographic Information System software (ArcGis). Raster data were georeferenced (French planar projection: Lambert 93) to the orthophotograph of 2018. Once the calibration points were set, a transformation model computed the georeferenced image coordinates and associated mean quadratic error. This error was systematically less than 10 m.

A new aerial photograph from 2018 was obtained by a UAV survey using a camera-equipped quadcopter. 36 permanent ground control points set up in 250-m spaced pairs along 4 km of dune together with photogrammetric techniques allow the generation of <0.1 m accuracy orthophotograph data (see Laporte-Fauret et al., 2019 for more detail).

Indications of anthropogenic activities, dune management, and salient dune evolution have been identified on each photograph and then mapped into the GIS.

3.3.Ground-Penetrating Radar (GPR) data

Ground Penetrating Radar (GPR) data were acquired using a Mala ProEx system coupled with survey wheel and a Magellan-Ashtech RTK-GPS (Billy *et al.*, 2014). GPR technology is based on the propagation and reflection of transmitted electromagnetic pulses (Neal, 2004). The detailed internal architecture of the Truc Vert coastal dune system was imaged on July 3, 2018 using three GPR antennae, with center frequencies of 100, 250 and 500 MHz (Figure 5). These antennae have different depths of penetration and resolution (30 cm, 12 cm and 6 cm resolutions for the 100, 250 and 500 MHz antennae, respectively). GPR sections were collected along two cross-shore transects (named CS-1 and CS-2) and each transect was investigated with the three antennae (Figure 2). Data were processed (time-zero drift, background removal, band-pass filtering, amplitude correction and topographic correction) using ReflexW Software and a constant radar velocity of 0.12 m/ns was used for the time-depth conversion. After processing, the GPR images were interpreted on the basis of radar facies identified on the profiles following the concepts of Neal (2004). Radar facies are defined as units with particular reflection properties (including geometry, magnitude and continuity) that differ from those of adjacent units. The Truc Vert dune system showed an excellent radar penetration nearly down to ~20m deep before encountering salty groundwater.

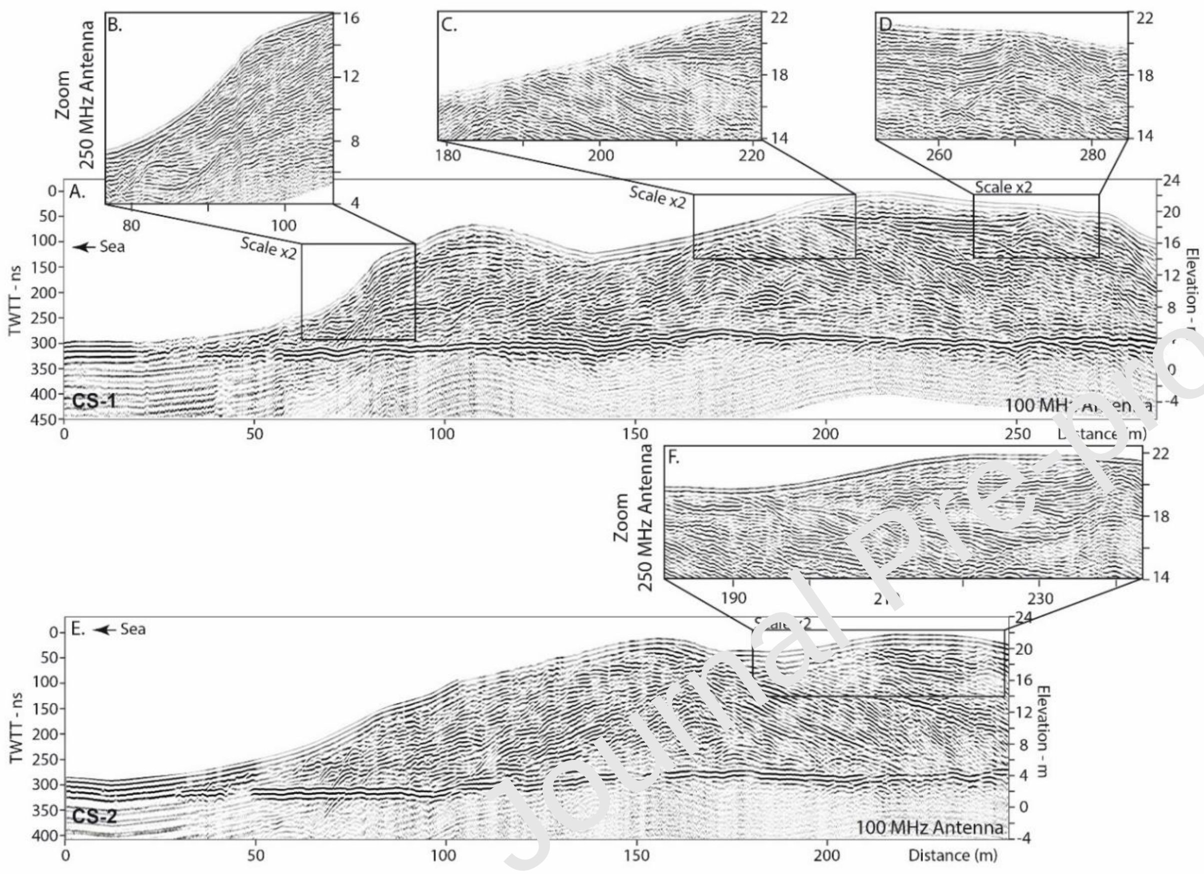

Fig.5: Processed versions of the profiles CS-1 (a) and CS-2 (e) acquired with 100 MHz frequency antennae. High resolution image acquired with 250 MHz frequency antennae showing oblique to sigmoidal reflectors of U_{3B} (b); truncated oblique reflectors at the top of U_2 (c, f) and influence of a fence on U_4 (d, f). GPR data are given in nanosecond (ns) two-way travel time (TWTT) and elevations are with reference to mea sea-level (amsl). Units are detailed on figure 9.

4 Results

4.1 Historical management of the dune

The ONF's archives (literature, maps and state archives) coupled with a large database of aerial photographs enables the authors to trace back the historical management of the Truc Vert foredune since the mid-19th century. These archives largely describe the different human interventions, their characteristics and their impacts on the dune that have taken place since the initiation of the dune.

Following large sand invasions that threatened various activities and villages located leeward of the dunes, state archives mentioned a significant management plan in the mid- 19th century to fight against this hazard. This lead to the construction of two large fences along a large part of the Aquitaine coast (Figure 3). One of these fences is drawn on the 1916 and 1940s historic maps and its position corresponds, after placement in a GIS, to the distance X = 168 m and X = 162 m on the axis of the profiles CS-1 and CS-2 respectively (Figure 5). The archival data indicates that this fence was built approximately in 1860. However, the second fence as initially planned in the state plan is not mentioned in any historical document dealing with the Truc Vert area.

In 1947 (first aerial photographs), the former fence is no longer visible in the landscape. At this period, it is instead possible to observe a wide plateau largely cut by blowouts and gullies (Figure 6a). The dune foot is located 40 m seawards of the 1860s fence position (Figure 7a). Due to the increase in blowout density and erosion of the top of the dune, a second important human intervention took place in 1972 with an intense mechanical reshaping of the dune profile by bulldozers. This artificial topographic profile (theoretical profile Figure 3 and real reshaping at PK.88 and PK.90 at the study area; Figure 8) allows for a better evaluation of this huge re-shaping effort, with a gently seaward slope, a subhorizontal plateau, and a lee slipface slope. This profile is classically derived as the "ideal" engineered profile (Paskoff, 2001).

Comparing the post-reshaping profile to the 1968 dune morphology, it appears that the dune foot has greatly prograded seaward (+29 m and +20 m on the profiles CS-1 and CS-2 respectively) due to reshaping (Figure 7a). During this period of important human intervention, the reshaping is accompanied by a large planting of vegetation on the dune plateau (marram grass and mulch) and placement of a small fence at its eastward limit (X = 255 m on CS-1; Figure 5, and Figure 6e). Following the beginning of persistent erosion and development of blowouts on the top of the dune, a new intervention with mulching was carried out in 1979 in order to limit this erosion (Figure 6f and g). Finally, the existence of small fences on the top of the dune identified on the 1977, 1998 and 2004 historical photographs is observed on the eastward limit of the plateau (X = 267 m on CS1; Figure 5 and Figure 6j and k). These fences are covered by sand and no longer visible today in the landscape.

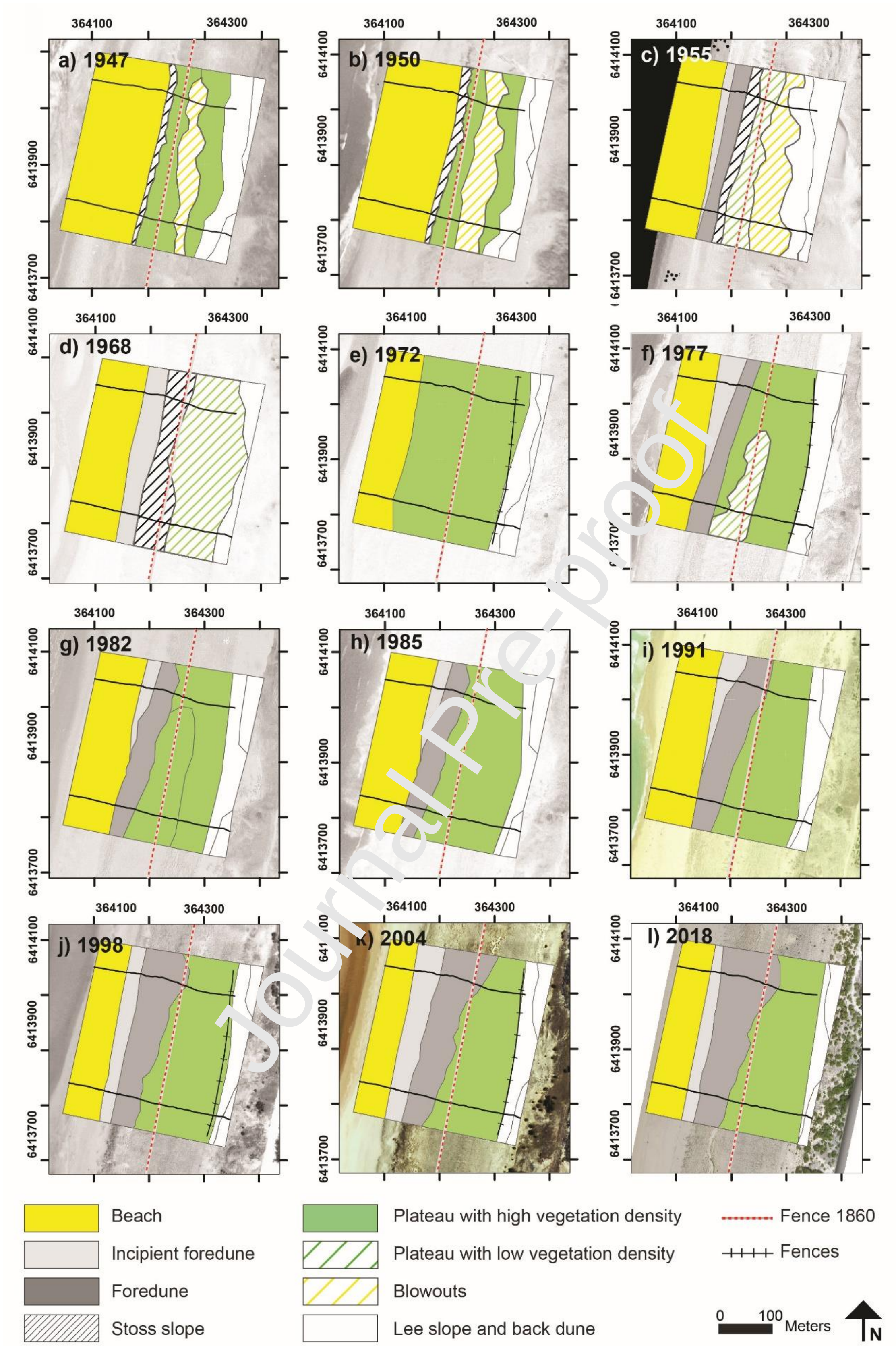

Fig.6: Foredune evolution between 1947 and 2018 (aerial photographs, IGN). Fences, geomorphology and interpretation of the dune morphology are indicated.

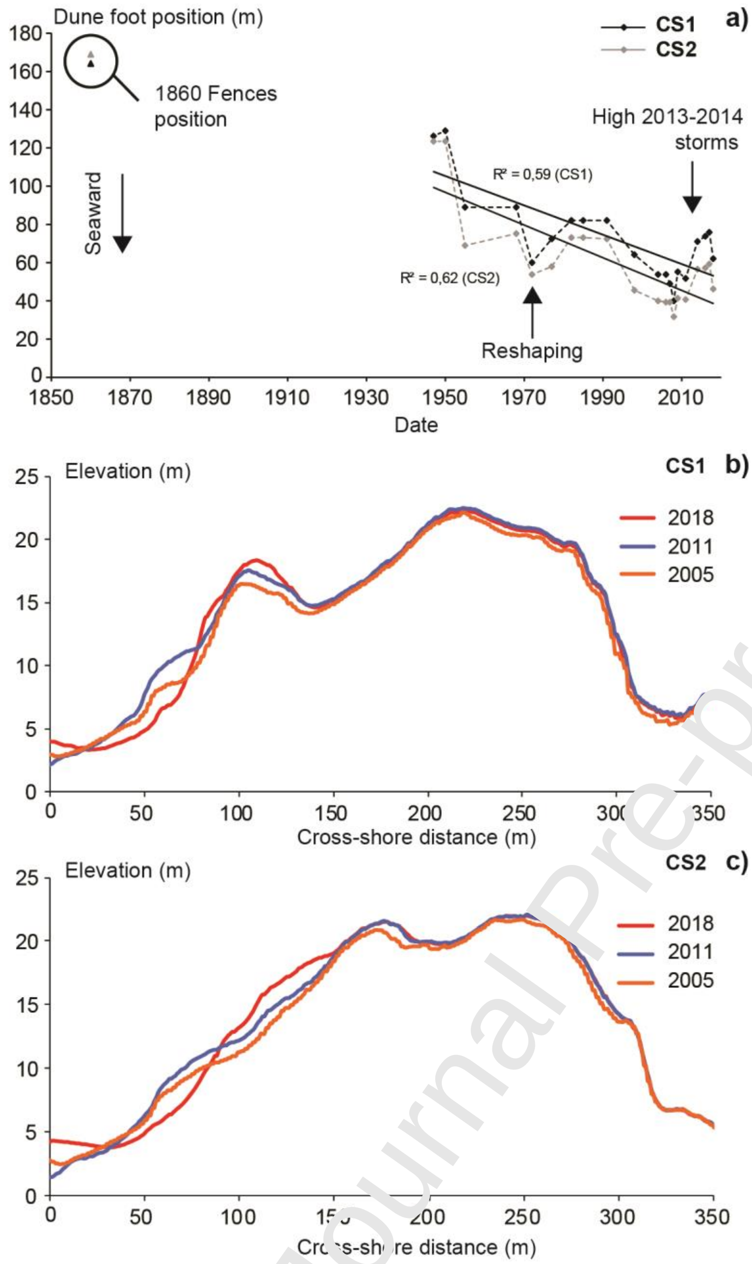

Fig.7: (a) Dune foot evolution on CS-1 and CS-2 profiles (distance is in relation to the GPR axis), (b) Topographic evolution on CS-1 and (c) CS-2 between 2005 and 2018. Elevation in meters above mean sea-level (amsl).

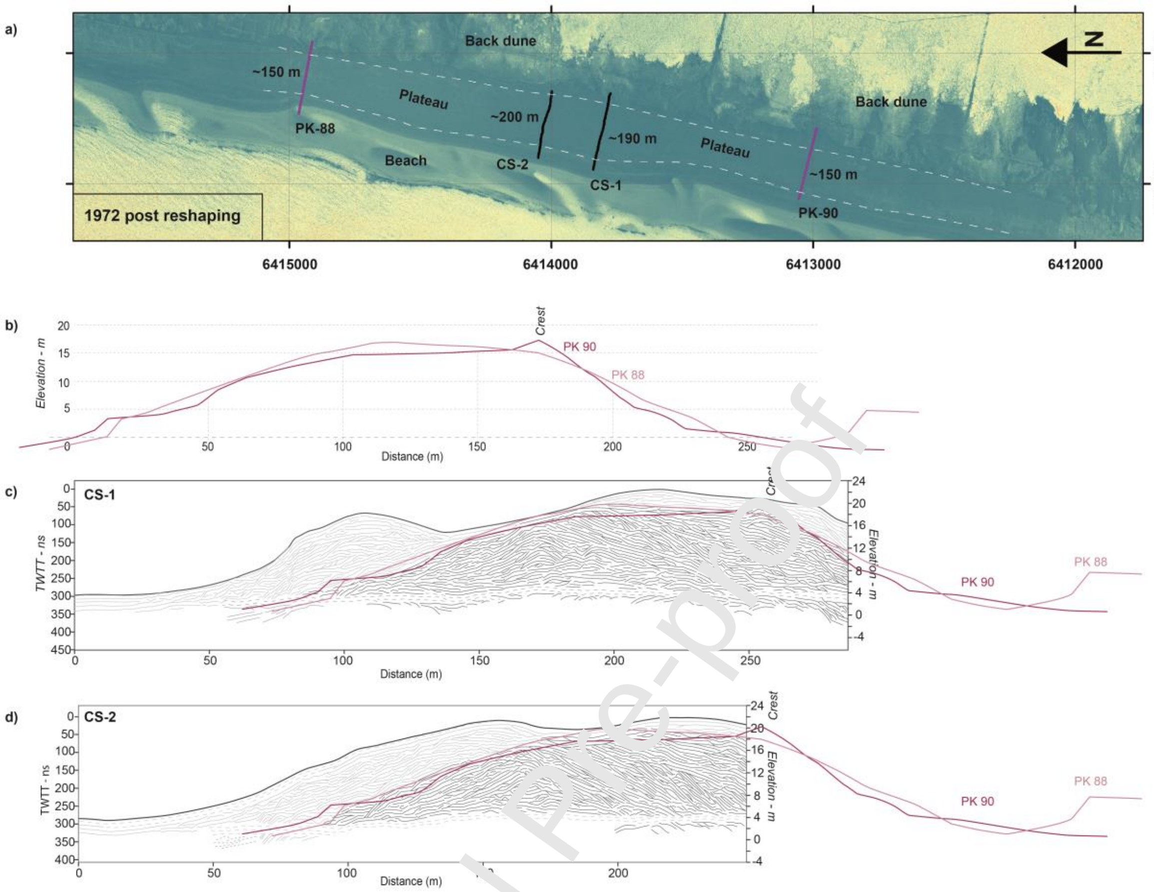

Fig.8: Reshaping of the dune in 1972, (a) 1972 aerial photograph (color filtered to contrast between beach, foredune/plateau and landward dunes) illustrating the alongshore variability of the plateau width after the mechanical reshaping; (b) topographic post reshaping profiles at PK 88 and PK 90; drawn on (c) on CS-1 and (d) on CS-2. Elevation in meters above mean sea-level (amsl).

4.2. Dune evolution from 1947 to 2018

The large database of historical aerial photographs from 1947 to 2018 makes it possible to follow the evolution of the dune (geomorphology, position of the dune foot, interpretation of the dune relief and morphoogical units) (Figure 6). Between 1947 and 1968, the dune was composed of an incipient foredune and a plateau with sparse plant cover (Figure 6a and d). The dune was also incised by blowouts the area of which increased from 8800 m^2 (1947) to 16500 m^2 (1955), with sparse vegetation colonization occurring between 1955 and 1968 (Figure 6d). During these 20 years, the position of the dune foot prograded seaward by about +37 m at CS-1 and +48 m at CS-2 (Figure 7a). High morphological change was observed in 1972 with the formation of a wide plateau (190 m on CS-1, Figure 8), associated with a seaward translation of the dune foot by 39 m and 22 m at CS1 and CS2, respectively, compared to its 1968's position. Dense vegetation was also observed on the plateau (Figure 6e). After 1972, the dune foot moved back landward by -22 m at CS-1 and -20 m at CS-2 between 1972 and 1982 (Figure 7a). From 1977, the foredune has been continuously growing with significant aggradation or deposition of aeolian sediments on the top of the plateau. Although a reduction of vegetation cover was identified on the plateau in 1977, it again became very dense in 1982 and a "grey dune" vegetation community comprising dominant species such as *Helichrysum stoechas and Artemisia campestris*, developed from 1998. Since 1991, the position of the dune foot has been slowly migrating seaward, in line with the pre-1972 period, together with the development of an incipient dune (Figure 6j). A notable modification in this trend was observed in 2018 (Figure 6i).

Lidar surveys make it possible to follow the topographic evolution of the dune between 2005 and 2018 (Figure 7b and c). The stoss slope is the part which presents the most important evolution with toe erosion and accretion on the upper stoss slope and crest. In addition, and as noted above, significant accretion of +2m on CS-1 across the plateau surface occurred.

4.3 Internal architecture of the foredune

The geophysical surveys (Cross-shore profiles CS-1 and CS-2; Figure 2) enabled the classification of 6 main radar units above the salty groundwater (Figure 9). Radar signals were attenuated at 3-4 m amsl due to the water table limit (sub-horizontal dashed line), which also crosses reflections imaging the basal unit U_0 below the dune. The global overview of the stratigraphic framework of the dunes consists of a central nucleus part (U_1) that separates two opposite systems: U_2 and U_4 form the landward system; U_3, U_5 and U_6 form the seaward system.

1) Description of radar units

Central nucleus part of the dune system: Unit 1

Central unit U_1 displays a convex-triangular-shape (120 m wide at its base and up to 16-17 m amsl height) and was sub-divided into four sub-units ($U_{1A\text{-}D}$; Figure 9). Its base U_{1A} reaches up to 4 m thick (from 6 to 10 m amsl) and is defined by small amounts of sediment (only in the central part over 30 m wide). U_{1B} overlies U_{1A}. Deposits are 4 m thick (from 10 to 14 m amsl) and form a well-defined triangular shape with a 22-24% seaward dipping slope and 22-27.5% landward dipping slope. U_{1C} overlies the nucleus of U_{1B} and images the development and the growth of unit U_1. U_{1C} and U_{1D} reach up to 16-17 m amsl. U_{1C} is defined by dipping reflectors (both landward and seaward reflectors concordant with the convex U_{1B} upper boundary), and U_{1D} displays landward dipping reflectors (28-16.5% dipping slope).

Landward system of the dune: Units 2 and 4

Radar unit U_2 adjoins the landward side of U_1 (Figure 9). This unit is 12-13 m thick (from 4 to 16-17 m amsl). U_2 was sub-divided into three sub-units ($U_{2A\text{-}c}$). $U_{2A\text{-}C}$ displays landward dipping reflectors illustrating the development of U_2. The upper part of these oblique reflectors are truncated (Figure 5c and f) and U_{2C} is draped by U_4. U_4 is defined by sub-horizontal reflectors which overlay $U_{2,}$ and form the top strata of the dunes (Figure 9). A crest than reaches 20 m amsl is visible on U_{4A}, well imaged on the CS-1 and CS-2 profiles with the 100 MHz antenna (Figure 9a and b), and in more detail with the 250 MHz antenna (Figure 5d and f).

Seaward system of the dune: Units 3, 5 and 6

Radar unit U_3 is connected to the seaward side of U_1. U_3 reaches up to 15-17 m amsl and can be sub-divided in two sub-units ($U_{3A\text{-}B;}$ Figure 9). The internal architecture displays progradational configurations with oblique reflectors (U_{3A}) or oblique to sigmoidal reflectors (U_{3B} ; Figure 5b), with a seaward dipping slope. A truncated seaward-dipping internal reflector due to the erosional 2013-2014 winter storms is identified and the subsequent beach-dune recovery are depicted (described in Robin et al., 2020). U_5 is defined by sub-horizontal reflectors which overlay $U_{3,}$ and form the top strata of the dunes (Figure 4). Finally, U_6, are beach deposits with sub-horizontal reflectors and data is rapidly disturbed by a salt-water signal perturbation.

2) Interpretation:

Before 1860, the foreshore is characterized by a wide and flat topography (U_0) which does not necessarily represent an early stage of foredune development. This unit is interpreted as a small sand sheet which is common when transgressive dunefields are first being formed (Hesp, 2013). The location of the first historical large fence implemented in 1860, is located at the base of the dune and corresponds to sub-unit U_{1A}. This sub-unit is interpreted as the artificial nucleus of the foredune system, created by accretion around sand fencing (and promoted by planting vegetation) during the end of 19th century, which lies at the origin of the development of the contemporaneous dune (Figure 10). While we do not have historical data for the next phase of dune development, given the thickness and triangular morphologies of sub-units U_{1B} and U_{1C}, it is hypothesized that both these units were also created by fences erected on top of the first fence. The original engineering profile of Goury (Figure 3) indicates that the position of the second fence would be located approximately 100 m seaward of the former. However, the GPR record combined with the absence of any mention of a second fence near Truc Vert in the archives suggests that the entire unit U_1 was formed by the construction and progressive further erection of this single fence. Over the years, the dune rose by approximately 12 m while extending about 60 m and 80 m seaward and landward of the fence, respectively (Figure 10b).

Most of units U_2 and U_3 were formed during the post-1880s to 1955s period as a large amount of sediment was eroded from the dune stoss face and crest and deposited on the leeward slope (Figure 11). As explained below, the fence(s) are no longer visible in 1947. Indeed, the dune foot is located 40 m seawards of the 1860's fence position which corresponds to the seaward extension of unit U_{1c} (Figure 10b). The mechanical reprofiling of the dune carried out in 1972 is characterized by a clear truncation of radar reflectors visible at the top of U_1 and the more seaward portion of U_2 (Figures 5c and f, Figure 9 and Figure 10b). Post 1972, accretion of U_3 is disturbed by an erosion scarp observed in 1982 (Figure 5b and Figure 10b) that was caused by the succession of the three high-energy winters in 1977, 1978, 1979 (Castelle et al., 2017a). Unit U_4, is related to the post 1972 dune reshaping and subsequent aeolian deposition. Its accretion has been slowed since 2005 (Figure 7) or probably 1998, corresponding to the development of an established foredune across the front and immediate crest area of the plateau on U_5 and the presence of a typical vegetation complex of a grey dune on the plateau

(*Helichrysum stoechas and Artemisia campestris*) (Figure 10). The location of a small sand fence at the top of the dune identified on the historical photographs (1972) is associated with the crest at the top of sub-unit U_{4A} (Figure 5d and f, Figure 9a, Figure 10). The U5 unit is characterized by upper stoss slope and crest accretion and post-dates the early 1972's. It is very clearly separated from U4 by its different vegetation cover (and color tones; Figure 2).

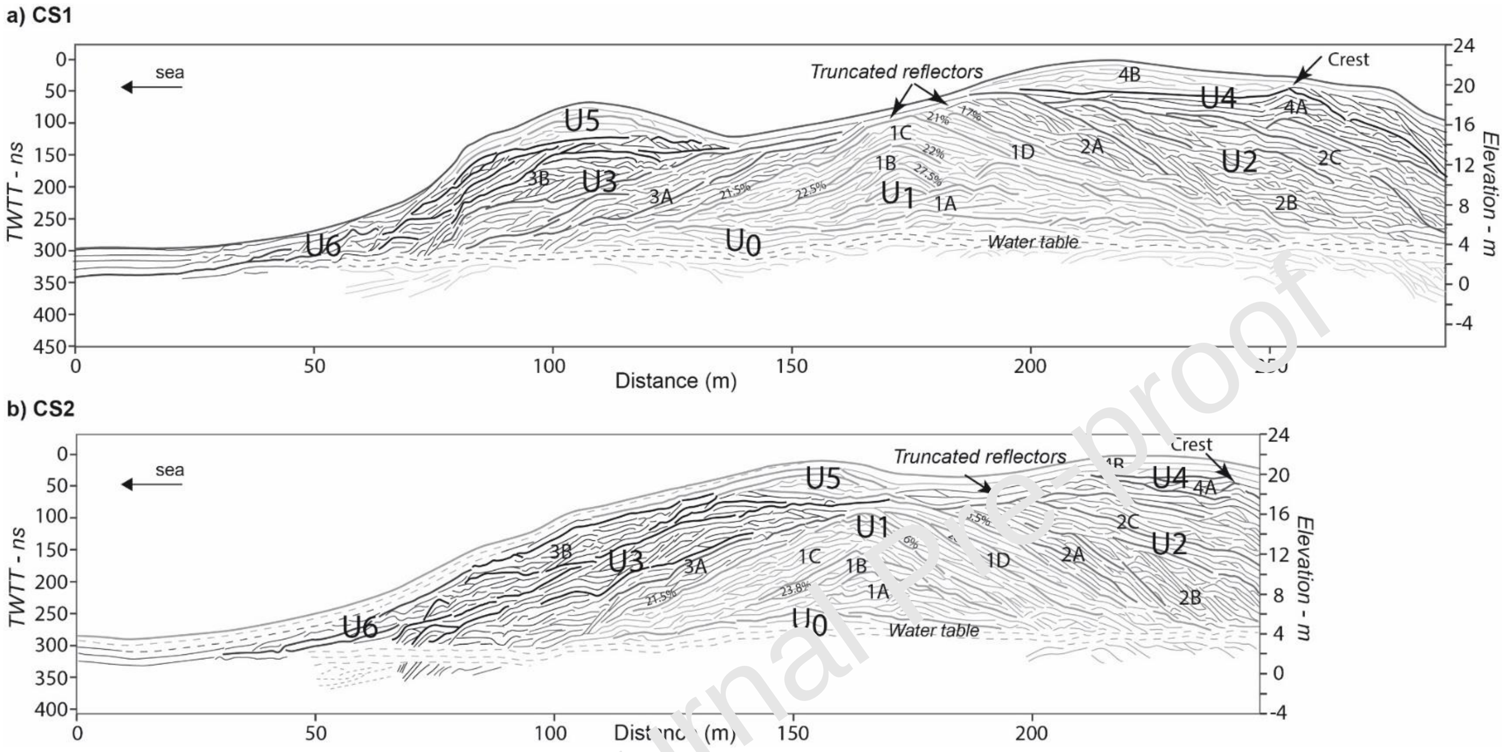

Fig.9: Reflection-traced version of radar units defining the internal architecture of the dune acquired with 100 MHz frequency antennae. (a) CS-1 profile and (b) CS-2 profile. GPR data are given in nanosecond (ns) two-way travel time (TWTT) and elevations are with reference to mea sea-level (amsl).

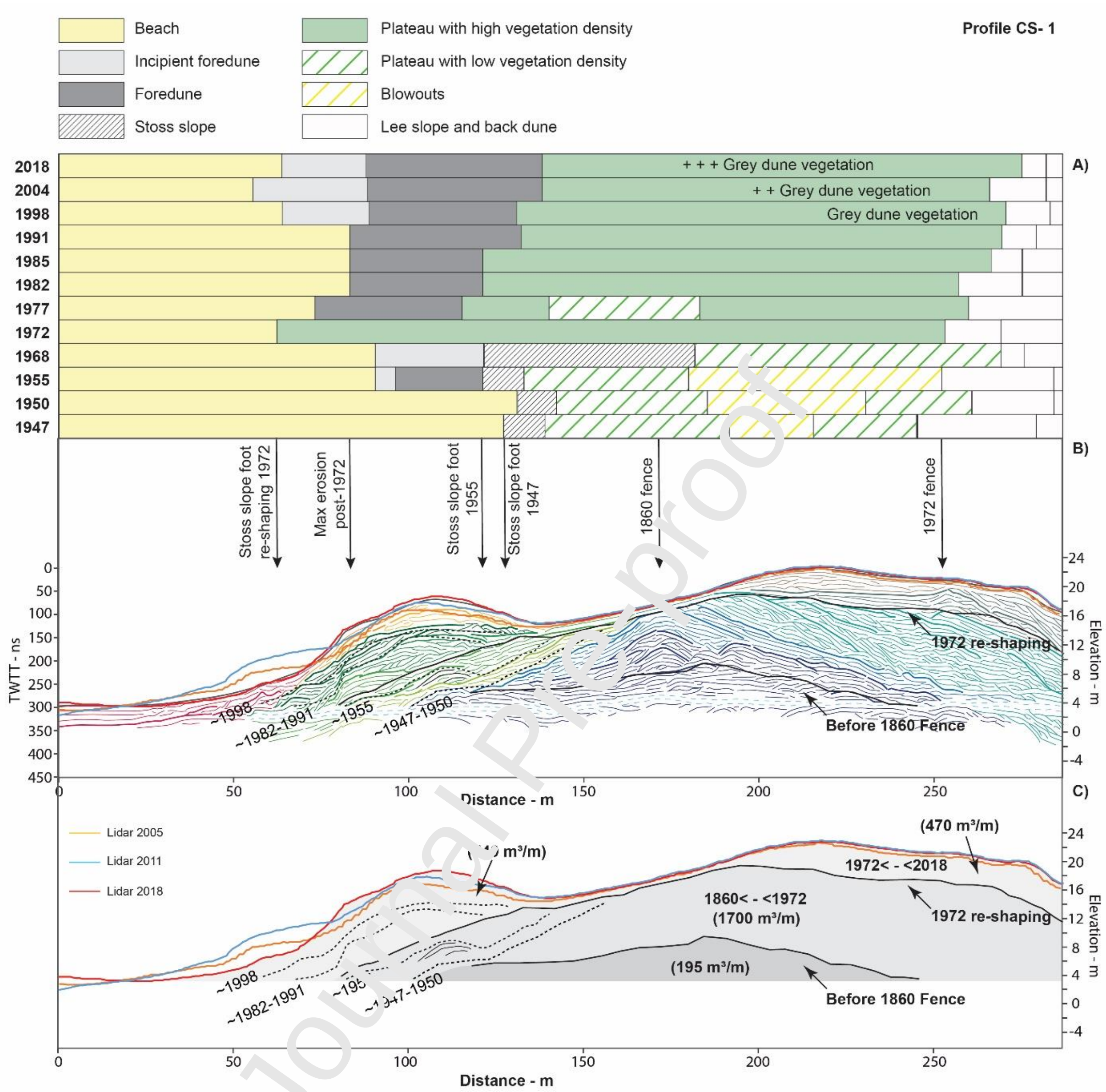

Fig.10: CS-1 profile with (a) geomorphology and interpretation of dune morphology between 1947 and 2018; (b) reflection-traced version of radar units and interpretation of several paleo-topographic profiles; (c) estimation of dune volume during several periods (before 1860, between 1860 and 1972, post 1972). Elevation in meters above mean sea-level (amsl).

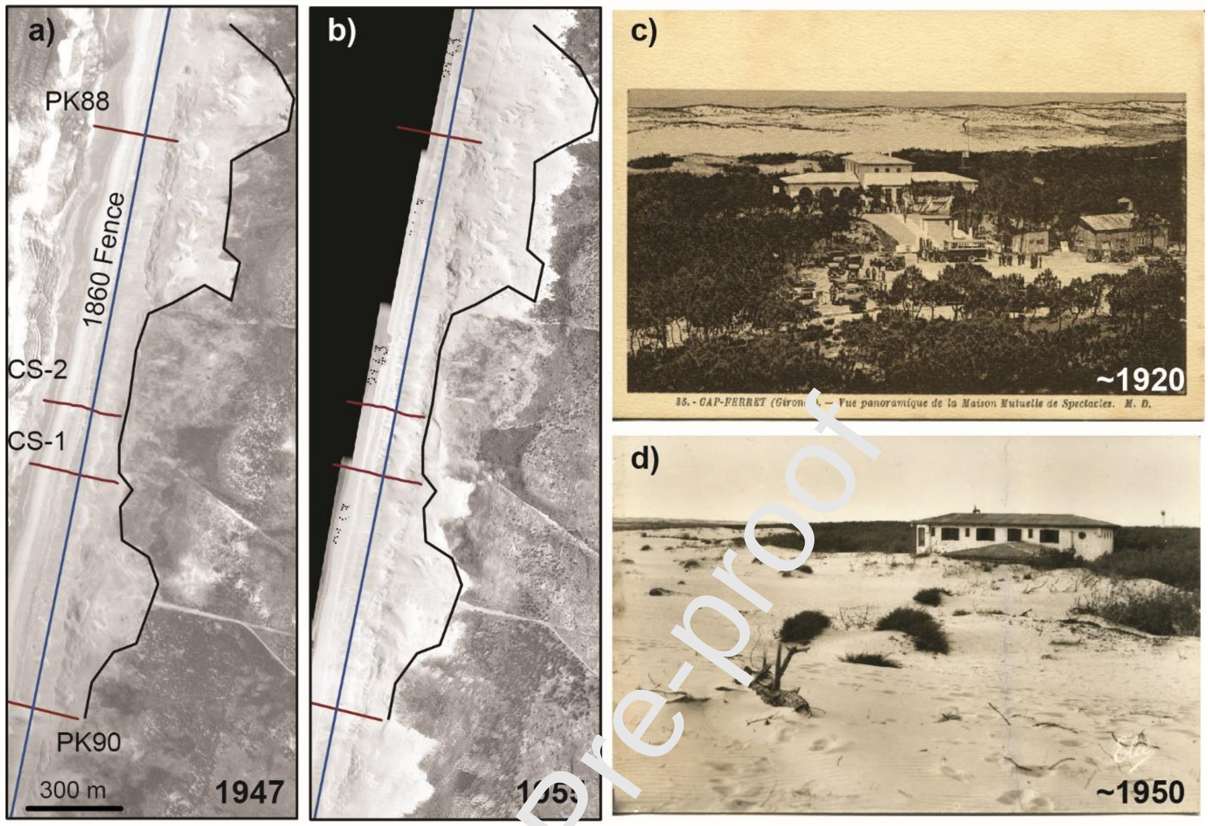

Fig.11: Historical evolution of the dune. (a), (b) Aerial photos illustrating the sand invasion during the 1940s; (c), (d) Field photos of the «Maison des spectacles» located 14 km southward of the study site (© Fabien Lasser, ONF)

5 Conceptual model of Truc Vert dune evolution since 1860: Natural and Anthropogenic processes

At Truc Vert beach, the comparison between radar facies and historical data (literature, maps, state archives and aerial photographs) allows us to identify a substantial portion of the stratigraphic signature of large anthropogenic coastal dune profiling and construction that interferes with natural accretional and erosional processes. The Truc Vert dune evolved under natural and anthropogenic forcing in the last 150 years (Figure 12). In the 1860s the first dune was established on a relatively flat surface and low topography by erecting a sand trapping fence (and planting vegetation) (Figure 12a). Further fences were built as the initial and subsequent ones were buried and a large (12 m thick) and wide (~140m) foredune system was created (Figure 12b). From the late 19th century to the mid 20th century the foredune progressively evolved towards the desired engineering profile of Goury (Figure 3) with a gentle stoss slope and a sub-horizontal plateau (Figure 6 and Figure 10a). However, the dune also suffered erosion with the plateau incised by blowouts and gullies. Mining of the coastal dune sediments to build the Nazi blockhouses along the Aquitaine coast during WWII may have favored the dune destabilization, although it is unknown if sand mining occurred at Truc Vert despite the presence of two buried blockhouses. In addition, the absence of coastal dune management between WWI and WWII combined with the great storms of 1912, 1917, 1924 and 1927, (Barrère, 1992; Bossard and Nicolae Lerma, 2020) were dominant factors favoring the destabilization of the coastal dune (Figure 12c).

The next key phase was the massive mechanical reshaping which took place in 1972, with the formation of a wide plateau surface which was planted with Marram grass (Figure 4 and Figure 12d). Subsequently, significant seaward accretion took place (Figure 12e), which was interrupted by storm wave driven erosion in the late 1970s. Brushing (surface covering with branches) was applied in 1979 to mitigate the aeolian erosion initiated on the seaward part of the plateau (Figure 2 and Figure 12f). The next phase is characterized by seaward accretion and further growth in both height and width of the establish foredune (Figure 12g). The modern phase is characterized by alternating periods of formation and erosion of an incipient foredune, accretion of the established foredune toe, and accretion on the upper established foredune stoss slope (Figure 12h).

Therefore, three primary periods dominated by natural evolution can be depicted (*i.e.* with no signature of prominent human intervention): (i) in the period between the ~1860's and

1939 when the foredune prograded considerably, and blowouts and erosional gullies eventually developed. Post 1939, there is evidence of probable human interventions during WWII at Truc Vert (e.g. mining; construction of bunkers), as with other areas on the Aquitaine coast, (Barrère, 1992; Bossard and Nicolae Lerma, 2020) (ii) between 1947 and 1972 when considerable stoss face accretion occurred, and (iii) since the post 1972 reshaping period, characterized by large horizontal and vertical growth of the foredune (Castelle et al., 2019), although inherited management influences the natural behavior of the system to a degree.

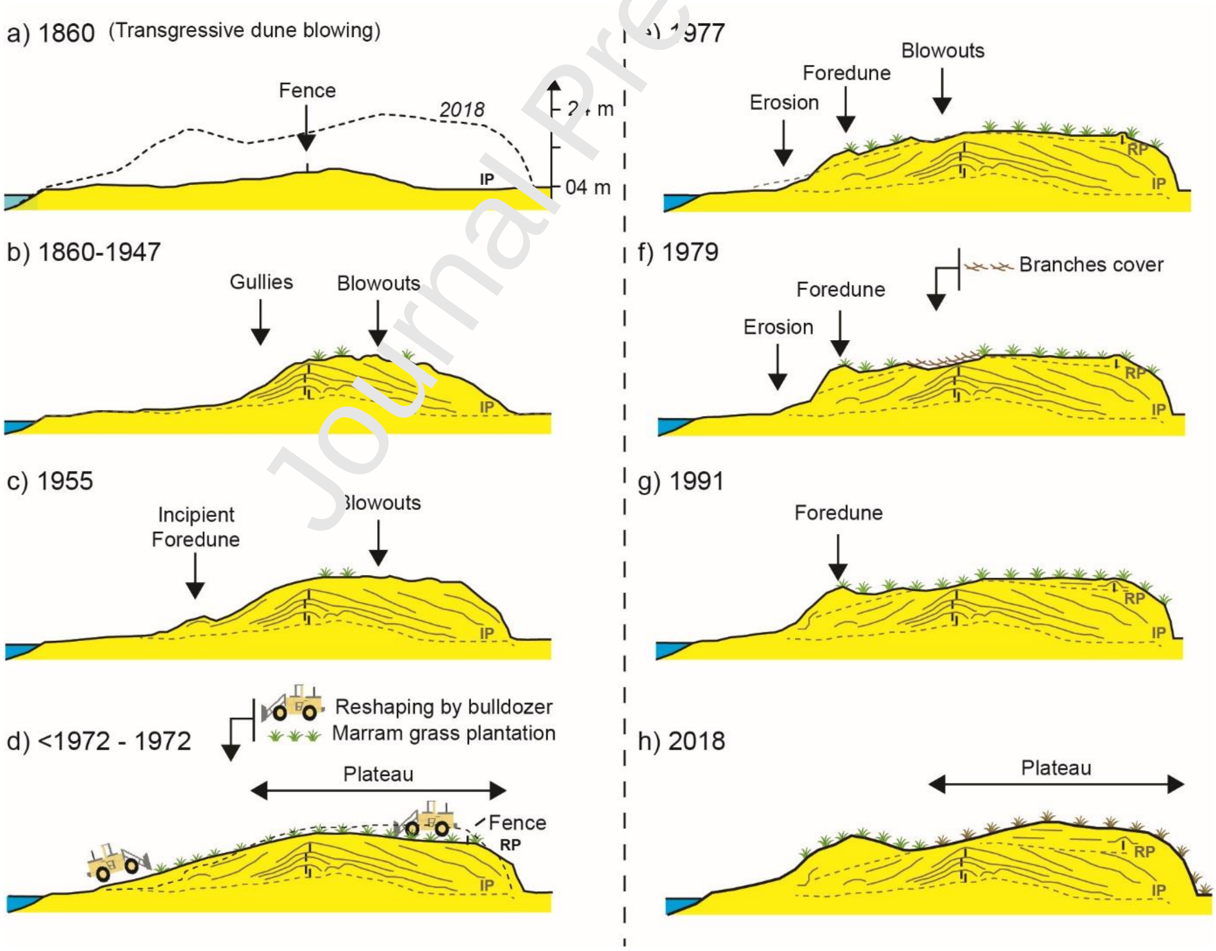

Fig.12: Conceptual model of the evolution of the Truc Vert dune between 1860 and 2018 (IP = Initial Profile of 1860's, RP = Reshaped Profile).

6. Discussion

6.1 Dune architecture: the melding of natural and anthropogenic processes

GPR is widely used in studies focusing on the evolution of Holocene dunes and other systems. GPR investigations on modern coastal dunes at a decadal scale are limited, although they have the potential to provide new insight into coastal change. Moreover, these studies do not generally mention anthropogenic influences on their field sites. So it is not known if and how human intervention can be, archived in the stratigraphy of the dune.

At Truc Vert beach, the contemporary coastal dune has experienced a long history of anthopogenic works since more than a century. The installation of large (1860) or small (1972) fences caused (with vegetation planting) the construction of a particular dune shape, with the additional contribution of a massive mechanical reshaping in 1972. These interventions are clearly observed in the stratigraphy of the CS-1 and CS-2 profiles. More GPR surveys spread alongshore would allow a better characterization of the alongshore variability of the respective contributions of anthropogenic and natural forcing. GPR can therefore provide fresh insight into multi-decadal to centennial coastal dune changes, including the influence of coastal management strategies pending reliable historical documents are available for interpretation and dating (Figure 10b).

Due to the fact that human interventions can be recorded in the coastal dune stratigraphy, interpretation of GPR radar facies must be done with care. The current dune landscape does not suggest any abvious anthropogenic shaping. This impression is supported by the remoteness of Truc Vert, which is located tens of kilometers from the first coastal resorts (Figure 1). Moreover, each unit, contact, truncation of erosion recorded by the GPR herein have equivalent units observed in natural environments (Van Heteren et al., 1998; Bristow et al., 2000a; Jol and Bristow, 2003; Neal, 2004). Thus, the interpretation of the internal coastal structures assuming te operation of natural processes only is possible, but can be misleading. Therefore, holistic studies of modern coastal dunes, say post 15th century, combined with stratigraphy, absolute dating, and historical archives are encouraged to better identify and further assess the influence of anthropogenic actions on coastal dune evolution. In the absence of a high resolution and multi-source historical data base, interpretations of these modern dune facies must be done with care, at the risk of reducing interpretation to pure speculation. Thus, the identification of the anthropogenic impacts by GPR investigations allows the inclusion of a new method of chrono-stratigraphy of the dune if interventions can be dated by historical documents (Figure 10b).

6.2 Reshaping impact and lessons

Natural evolution of coastal dunes in many parts of the world was significantly altered by human intervention in an attempt to stabilize them (Hesp and Hilton, 2013). The short term impact of beach and coastal dune management strategies such as for instance, beach nourishment, grass planting, sand fencing or reshaping is well known and documented (e.g. Arens et al., 2001; Jackson and Nordstrom, 2011; Bakker et al., 2012; Portz et al., 2015; Itzkin et al., 2020). Their impact on dune evolution on longer time-scales (decades to centuries) is less understood, as monitoring programs have been implemented too recently to cover these time scales (Bochev-van der Burgh et al., 2011; Hesp, 2013; Doyle et al., 2019). Truc Vert beach with over 150 years of interspersed, large-scale, anthropogenic work is an ideal site to explore the impact of such actions on the system at a longer time scale.

The fence installed around 1860 and successively raised at the same location associated with intense marram planting, created the conditions for a large dune to build with a volume estimated at 650 m^3/m on CS-1 ($U1_{bcd}$, 22% of the actual volume of the dune; Figure 10c). It resulted in sand accumulations upwind and downwind of the defense line. The slightly asymmetrical shape and the order of magnitude of the height to width ratio are in line with the smaller scale models of Li and Sherman (2015). Dune managers met their objectives by erecting this dune system to trap sand and initiate foredune development in order to act as a barrier to protect the landward forest plantation. Such approach has been successful earlier elswhere (e.g. Sherman and Nordstrom, 1994; Miller et al., 2001; Itzkin et al., 2020). Nevertheless, maintaining such a fixed dune system over long periods (probably several decades) in a system with a large sediment supply results in a significant increase in height (at least 12 m before the 1972's reshaping) of the dune. Thus, this height prevented a greater transfer of sediment towards the back of the dune and plateau, and the widening of the dune system (Figure 1). However, the construction of a wider dune system (rather than very high) would have been beneficial compared to the current situation of the system. Indeed, at present and into the future, the erosive trend of the majority of the Aquitaine coast (Castelle et al., 2018; Nicolae-Lerma et al., 2019; Bossard and Nicolae Lerma , 2020) and an increasingly narrowing dune will produce a very challenging future management dilema for managers who will have to fight against the rising sea levels and potentially greater erosion.

At Truc Vert beach, the intense mechanical reshaping of the dune profile of 1972 by bulldozers, enabled managers to obtain the theoretical profile idealized by Engineer J.S.Goury and to reduce the erosion on the plateau. Coupled with intense marram planting and in an environment with a significant sediment supply, it proved to be a positive management practice to help the system to build a residual sediment budget of 1010 m^3/m on CS-1 between 1972 and 2018 (representing 35% of the actual volume of the dune; Figure 10c). The imprint of this intervention and those of the 1860's underline that the morphology, the evolution and the resilience of the foredunes are inherited from their past and from the anthropogenic interventions. This is consistent with Bossard and Nicolae Lerma (2020) who observed that the majority of the foredunes of the Aquitaine coast meets the "ideal profile" from almost 40 years ago. Moreover, the results presented here show that similar studies would be useful elsewhere, in certain coastal sectors which underwent similar management interventions since the last centuries (e.g. Arens and Wiersma, 1994; Nordstrom and Arens, 1998; Zaromskis, 2007; Clarke and Rendell, 2009; Pranzini et al., 2015). These perspectives will potentially help refine coastal management strategies.

6.3 New insight of paleo-topographic profiling

Advances in GPR technology over the past few decades have provided a much clearer picture of the architecture of coastal systems and become essential in coastal research to highlight the complex evolution of foredunes for example (Dougherty et al., 2004). Nevertheless, it is still underused in the study of the evolution of modern foredunes, although it improves fundamental knowledge of dune history and behavior (e.g. Bristow et al., 2000a; Costas *et al*., 2006, Ramos et al., 2011, Gonzalez-Villanueva *et al*., 2011; Dougherty, 2014; Robin et al., 2020) or knowledge for management purposes (Cunningham et al., 2011; Bakker et al., 2012; Robin et al., 2018; Billy et al., 2020). The study shows that GPR coupled with historical documents (to obtain absolute dating of reflectors), is a useful tool to understand the 2DV evolutionary mechanisms of modern dunes. This holistic method illustrates the continuous evolution of around 250 m of the beach-dune system over the last 150 years including natural and anthropogenic evolutions (Figure 10c). This approach is complementary to information provided by the study of diachronic aerial (or satellite) photographs since the 1940s (Navaro-

Pons et al., 2016; Rader et al., 2018; Doyle et al., 2019; Jackson et al., 2019; Moulton et al., 2019) and makes it possible to extend the more recent 2DV database obtained using traditional topographic instruments and surveys (e.g. Bochev-Van der Burgh et al., 2011; Hesp, 2013, Houser et al., 2015; Castelle et al., 2017b; Brodie et al., 2019; Nicolae Lerma *et al*., 2019).

Combining all this archival, historical and GPR data enables one to estimate the volumetric changes of the dune over a medium time scale (decade to century). This approach has also been successful for Lindhorst and Betzler (2016) to retrieve a subdecadal wind record off the dune archive. At the Truc Vert dune, it is possible to characterize two periods: 1860/1972 and 1972/2008 (Figure 10c). The erosion truncation linked to the reshaping of the dune in 1972 makes it impossible to estimate the age of the reflectors of unit 2. Results indicate a positive sediment budget with + 1700 m^3/m between 1860-1972 (15,2 m^3/year/m), and + 1010 m^3/m between 1972-2018 (21,9 m^3/year/m). This is in accordance with the work of Froidefond and Prud'homme (1991) who estimate a sediment budget of 20-40 m^3/year/m between 1875/1966 and 19-29 m^3/year/m by sediment trap at La Salie (15 km away of Truc Vert beach).

7. Conclusion

This study provides fresh and quantitative insight into foredune formation and subsequent evolution over a 150-year period combining GPR data with historical documents (topographic surveys, ground and aerial photographs, literature). These data allow an assessment of the various stages of morphological development of the Truc Vert foredune (Aquitaine coast) driven by human and natural processes. This study complements those performed at shorter time scales on the Aquitaine coast (Castelle at al., 2017b; Nicolae Lerma et al., 2019; Bossard and Nicolae Lerma, 2020) and more broadly, the literature in relation to dunes evolving naturally without anthropogenic impact (Short and Hesp, 1982; Hesp, 1988, 2002, Psuty, 1988, 1992; Sherman and Bauer, 1993 ; Dougherty, 2014; Pellon et al., 2020). More specifically, key findings of this study include:

1) The GPR surveys allows the identification of 6 units through a 20 m thick sequence including the initial nucleus of the foredune/dune system. Historical information accords very well with GPR reflective units and so greatly improve the ease and quality of the interpretation of internal structures. Indeed, this study underlines that human interventions can be recorded in the coastal stratigraphy and in the absence of a more holistic approach, the reconstruction of the foredune evolution by GPR interpretation alone must be done with care.

2) The respective contribution of anthropogenic and natural forcing to coastal dune changes can be addressed. Results indicate that while some natural aeolian processes occurred and have been preserved in the record, human actions, primarily fence erection in the 1860s, foredune creation, and large mechanical reshaping in the 1970s, have had a profound influence on coastal dune changes and, in turn, on current coastal dune morphology. In Truc Vert beach as on many coasts, the current coastal dune landscape is strongly inherited from previous and sometimes very old anthropogenic actions.

3) The dune behavior revealed by the GPR also allows one to illustrate the continuous evolution of the beach-dune system over 150-year. Coupled with detailed historical documents which provide an absolute time scale, the study highlights that it is possible to extend the more recent 2DV database obtained using traditional topographic instruments and survey. An estimation of dune volume during several periods is then also possible. It reveals that the sediment budget is positive with + 1700 m^3/m between 1860-1972, and + 1010 m^3/m between 1972-2018.

4) Ultimately, this study shows the possibility of improving knowledge on the resilience of the system with 2DV data over 150 years, in order to better predict future evolutionary trajectories and support future coastal management strategies.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: