The Central English Channel troughs: major source-to-sink remnants or giant tidal scours?

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The Central English Channel troughs: major source-to-sink remnants or giant tidal scours?

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ABSTRACT

The Central English Channel troughs correspond to elongated incisions up to 250 m-deep, at several locations at the bottom of this sea corridor. Depending on their location, they are usually interpreted as part of the submerged quaternary paleovalley network or as resulting from megaflood events. Shedding light on these features, their age, and the processes underlying their development is key for understanding their significance in terms of event geology. The interpretation of a dense grid of high-resolution marine seismic data acquired in the Bay of Seine area reveals that the extensive Quaternary paleovalley and trough network commonly as associated to the "Channel River" system is actually subdivided into at least two superimposed and unrelated incised networks. The overlying network corresponds to fluvial incisions developing during low sea-level conditions of Pleistocene time and connects to the present day fluvial network. The underlying network corresponds to the troughs and appears as a complex, deeper, relatively discontinuous and isolated network. This older network shows unexpected local incision depth up to c.350-400 m-deep and complex sedimentary infill involving several sedimentary processes and environments from fluvial to tidal and shallow-marine. We discuss these observations and their implications for understanding the origin, age and development of the troughs all over the English Channel, from the Dangeard Troughs in the Dover Strait to the Hurd Deep at the western end. We also raise questions about the significance of these large incised features in terms of source-to-sink system of northwestern Europe.

1. Introduction

Incised networks are common landforms resulting from a variety of erosion and sediment transport processes that locally affect Earth's surface. They develop onshore as rivers adapt their profiles to maintain an equilibrium state while external conditions change such as local or regional uplift, relative base level falls, and/or water-sediment flux ratio is modified. It thus can be caused by the following controlling parameters and their interactions: climate and eustasy (global sea-level) that are considered as global controls (Fisk, 1944; Posamentier and Vail, 1988a; 1988b; Molnar and England, 1990) and/or tectonics, isostasy, and geomorphologic parameters (topography, drainage area …) that are considered as local controlling parameters (Hack, 1960; Summerfield, 1985; Molnar and England, 1990; Dalrymple et al., 1998). In submarine environments, channelized erosion occurs due to gravity processes and density currents in slope canyons and gullies and turbidite channels (Farre et al., 1983; Pratson and Coakley, 1996), or to current acceleration as for contourite moats (Rebesco et al., 2014), or tidal scours (Hamblin et al., 1992; Harris et al., 2005).

The English Channel has been an area of intense geological investigation for decades, spanning various subjects such as structural and basin evolution between variscan and alpine orogenic cycles, or sediment transport over a wide platform under strong tidal and storm current influences (see Evans, 1990; Hamblin et al., 1992; Reynaud et al., 2003; Collier et al., 2006 and reference herein). These successive studies progressively shed light on this area and provided a complete overview of the English Channel Geology (Fig. 1). Among the addressed subjects, one specific feature of the English Channel is the occurrence of a complex network of channels (Fig. 1) with clear morphological expression at the seabed (Fig. 2). Since the beginning of the 20th century, and more efficiently since the 1970s thanks the development of high-resolution seismic acquisition, this network has been the focus of several studies

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that proposed various scenarios for its origin (glacial to marine) and age (Miocene to Pleistocene; see Hamblin et al., 1992). It is now commonly accepted that these incised features developed as part of the "Channel River" paleovalley network when the area emerged during one or more successive Pleistocene low sea level periods (Lericolais, 1997; Lautridou et al., 1999; Lericolais et al., 2003; Bourillet et al., 2003; Ehlers and Gibbard, 2004; Toucanne et al., 2010). Large, significantly deeper, and partially filled depressions – known as the Channel Troughs - have been described along this valley network. Several studies focus on these features to understand their development (incision and infill) as well as their link with the submerged valley network. Several studies including the latest ones propose that troughs develop locally where river current accelerate and cut through softer material with possible involvement of catastrophic flooding (Auffret et al., 1980; Collier et al., 2015; Gupta et al., 2017). Nevertheless, few authors pointed out that the Channel Troughs may be older and completely disconnected from the paleovalley network (Hamilton and Smith, 1972; Alduc, 1979; Hamblin et al., 1992). Seismic interpretation of recent data during updating of the geological mapping provides evidences of this disconnection. We thus propose to test the various hypotheses by reassessing morphological, erosional and sedimentary characteristics of valleys and troughs as well as their potential linkage. We use high-resolution seismic data acquired by academics and BRGM in the framework of PhD projects and as part of the French marine geological mapping project carried out by BRGM. The area of study is restricted to the French waters of the Central English Channel in front and within the Bay of Seine area, offshore Normandy.

2. Geological settings

The English Channel, also referred as "La Manche" in French, is a sea corridor connecting the Atlantic Ocean to the North Sea, between northwestern France and southern England. From a geological point of view, the area of the English Channel recorded several events since the middle Paleoproterozoic including Icartian cycle (around c. 2 Ga), the Neoproterozoic Cadomian orogeny (part of the Panafrican Cycle around c. 600 Ma), and the Variscan orogeny (Devonian to Carboniferous – c. 420-300 Ma) (Inglis et al., 2004; Linnemann et al., 2014; Ballèvre et al., 2001; Ziegler, 1990). Neoproterozoic is characterized by the deposition of a thick siliciclastic series (Brioverian) that is deeply affected (deformation, metamorphism, and magma emplacement) during the Cadomian orogeny that took place during Ediacaran time (Neoproterozoic). From Cambrian to Devonian, deposition occurred over the area before

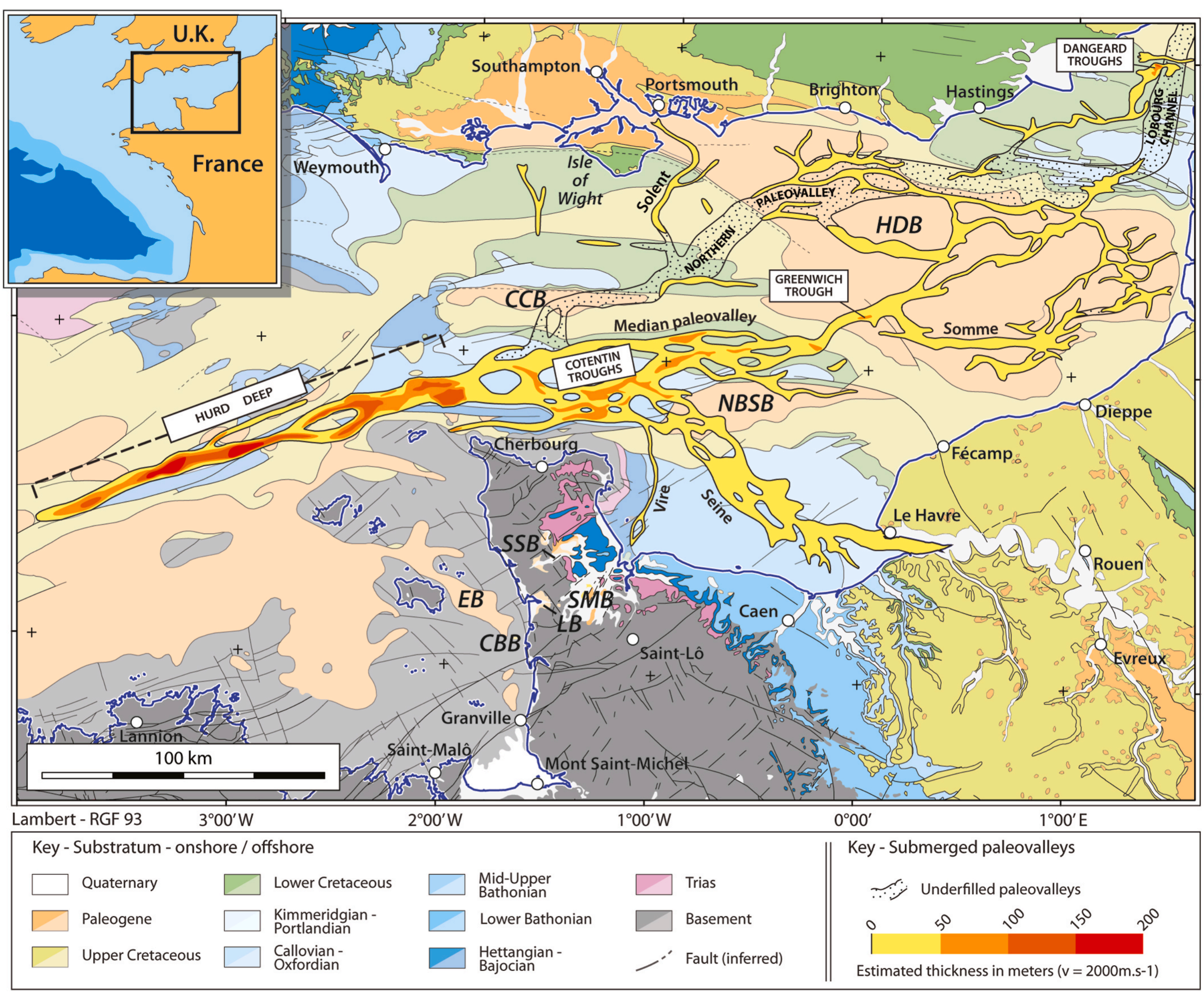

Fig. 1. Map of the geographic and geological contexts of the area of study (modified and simplified from Larsonneur et al., 1982; Hamblin et al., 1992; Chantraine et al., 2003). HDB: Hampshire-Dieppe Basin; CCB: Central Channel Basin; NBSB: North Bay of Seine Basin; SSB: Saint-Sauveur-le-Vicomte Basin; SMB: Sainteny--Marchésieux Basin; LB: Lessay Basin; EB: Echréou Basin; CBB: Chaussée-des-Bœufs Basin. Quaternary deposits appears in white (bay, coastal and fluvial deposits).

the onset of the Variscan orogeny (Devonian-Carboniferous). This complex orogeny characterized by the collage of several micro continental plates (Armorica, Iberia, Bohemia, …) to major ones (Avalonia, Laurentia, Baltica, Gondwana) is often referred as the most significant event that re-organized and consolidated the Western Europe basement (Ziegler, 1990; Ballèvre et al., 2009). Major Variscan crustal structures (and Cadomian ones to a lesser extent) delineating basement blocks (former micro plates) will be reactivated later as inherited structures during late Paleozoic, Mesozoic, and Cenozoic tectonic events (Mégnien and Mégnien, 1980; Guillocheau et al., 2000; Ballèvre et al., 2009; Averbuch and Piromallo, 2012; Briais et al., 2016). The collapse of the Variscan belt during late Carboniferous-Permian times is followed by the development of an intracratonic sedimentary basin – the Anglo-Parisian Basin – that covers a large part of Western Europe (Ziegler, 1990). This basin evolved from Triassic to Neogene and was subject to series of geodynamic events affecting the European plate and its margins such as the opening of the Atlantic Ocean and Bay of Biscay, and both Pyrenean and Alpine orogenies. These later events are recorded as major tectonic inversions during Paleogene and early Neogene along major structures (Weald-Artois, Bray, Portland-Wight, Central Channel, Fécamp-Lillebonne, …) that are inherited from Variscan orogeny (Ziegler, 1987, 1990; White and Lovell, 1997; Rosenbaum et al., 2002; Lagarde et al., 2003; Biteau et al., 2006; Vissers and Meijer, 2012). Paleogene deposits (Thanetian-Rupelian) originally deposited over much larger area are thus progressively deformed, eroded, and finally preserved in the core of asymmetric synclines (Dieppe-Hampshire Basin - DHB, Nord Baie de Seine Basin - NBSB, Central Channel Basin - CCB) along these main structures (Fig. 1). The younger attested deposits within these “basins” are the Bembridge and Bouldnor formations (Solent Group) of Oligocene age (Rupelian) in the Isle of Wight area (King, 2016). Nevertheless, Rupelian marine and lacustrine deposits may covered a much larger area as they are also preserved around the English Channel, in the central Paris Basin, and in the Cotentin (Pomerol, 1973; Dugué et al., 2009). A long erosional-depositional hiatus (Chattian to mid Miocene) is attested in the eastern English-Channel area (Dugué et al., 2009; Hamblin et al., 1992), and understood as the result of a main tectonic inversion period. Deposition occurs during Middle or late Miocene as shelly sands (Falun de Bléhou Fm., Middle Miocene; Falun de Fécamp Fm., Late Miocene) with remnants attested onshore only in the Cotentin and near Fécamp (Dugué et al., 2009). Paleogeographic reconstructions for the period from late Oligocene to Miocene propose that deposition often occurred within narrow seaways (Gibbard and Lewin, 2003 and references herein). Another hiatus exists from late Miocene to lower Pliocene prior to the deposition of continental to shallow marine Pliocene and Pleistocene deposits (Dugué et al., 2009). Pliocene and Pleistocene deposits are dominated by siliciclastic material (Sables de Lozere Fm.; Sables de St Vigor Fm.) with few local occurrences of shelly sands (Falun de Bohon Fm.). The paleogeographic reconstructions for Pliocene-early Pleistocene (Dugué, 2003; Jamet, 2015) also shows restricted areas of deposition that prefigure the modern landscape distribution. Throughout Quaternary and the onset of fluctuating glacial climate (Head and Gibbard, 2015), glacio-eustasy deeply affects the English Channel landscape. The area experiences successive almost complete emersion during glacial maxima (water locked up in ice-caps) and rapid flooding as the ice cap melts and sea level rises. with a c. 100 m amplitude (Shackleton, 1987).

Within the Bay of Seine area, authors identify several paleovalleys including the Seine, the Vire and the Orne rivers (Fig. 2 – Larsonneur, 1971; Alduc, 1979; Auffret et al., 1980; Antoine et al., 2003). In the larger Seine paleovalley, Alduc (1979) and Benabdellouahed et al.

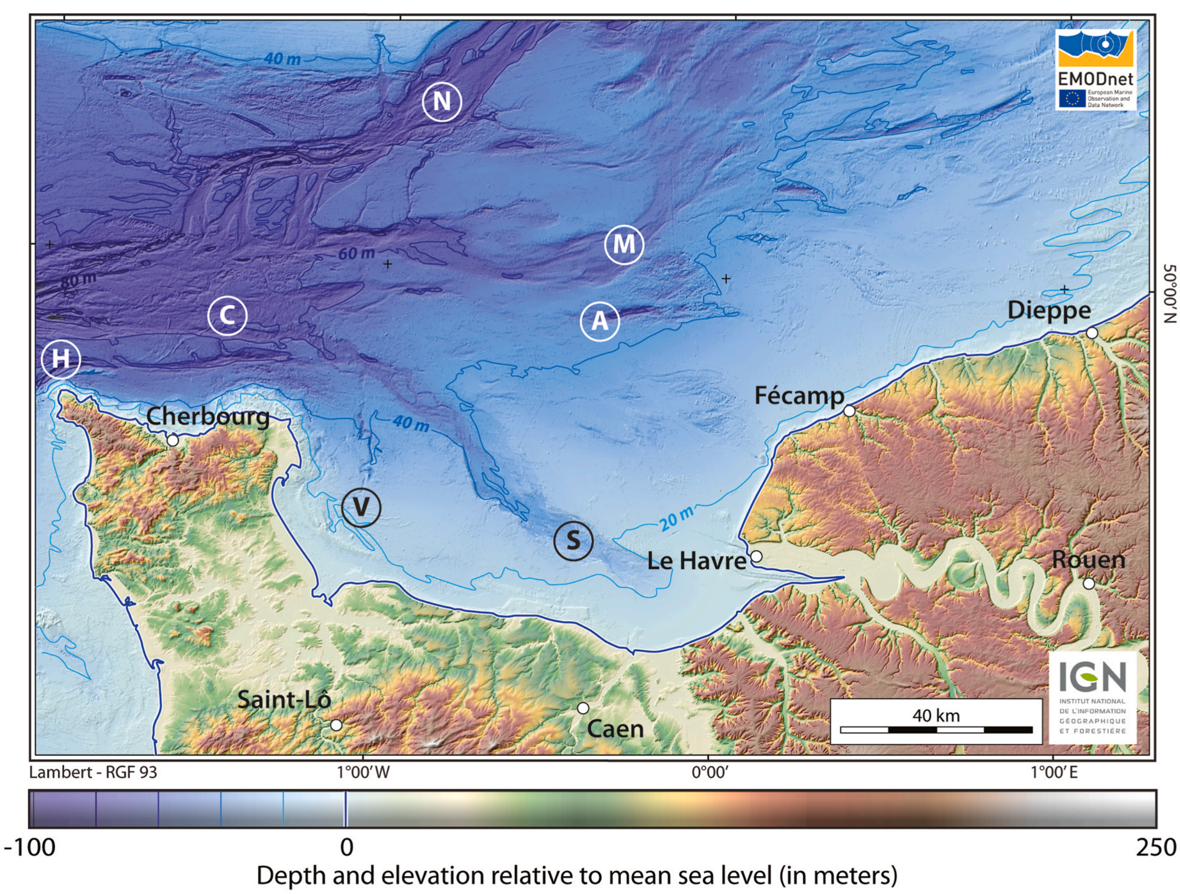

Fig. 2. Topo-bathymetric map of the area of study (©IGN for topography and ©EMODnet, 2018, for bathymetry). Circled letters refer to Seine (S), Vire (V), Median (M) and Northern (N) paleovalleys, and Hague (H), Cotentin (C) and Antifer (A) troughs.

(2013) recognized two to three main cut and fill terraces that reveal a progressive migration toward the southwest. In the absence of critical sediment samples offshore, terrace ages are inferred from correlation with dated onshore terraces (Antoine et al., 1998; Lautridou, 2003; Cordy et al., 2003). Benabdellouahed et al. (2013) propose mid-Pleistocene, Saalian, and Weichselian ages for the three successive terraces.

The Vire and Seine valleys merge outside the bay, 15 km north-eastward from Cotentin Peninsula (Fig. 2). The course and morphology of these valleys are partly controlled by the regional slope of the shelf and locally by the structurally controlled distribution of contrasted Mesozoic lithologies (Alduc, 1979; Benabdellouahed et al., 2013). Further north, the Seine Paleovalley connects with the Median and the Northern Paleovalleys. This area of converging paleovalleys is also the area where the deep troughs (Cotentin Troughs and Hurd Deep further west) are described (Figs. 1 and 2). The idea of the present study is to reassess the relation between these paleovalleys and troughs in the light of new very-high-resolution data.

3. Data and method

This study relies on the interpretation of a dense grid of more than 6000 km of very-high resolution marine sparker seismic dataset (Fig. 3). These data have been acquired from 2007 to 2015, during six surveys (see Table 1) in the framework of BRGM's geological mapping initiative and in collaboration with several research institutes and universities including UMR 6143 M2C and UMR 8187 LOG (see Table 1). These data offers a unique image of sedimentary series and structural features with meter-scale vertical resolution. The downside of such kind of data is that interpretation is mostly limited to the section above the first multiple. It means that over continental shelves, where bathymetry ranges from 0 to c.200 m, the investigation depth within the substratum usually ranges from few tenths to three hundred meters. To reach greater depths of investigation, we purchased a conventional oil exploration seismic dataset acquired in 1993 by Britsurvey for Jebco Seismic Ltd/Svitzer Ltd and provided under specific licensing by IHS Global SA for scientific purpose (Fig. 3). Seismic data are complemented by vintage and newly

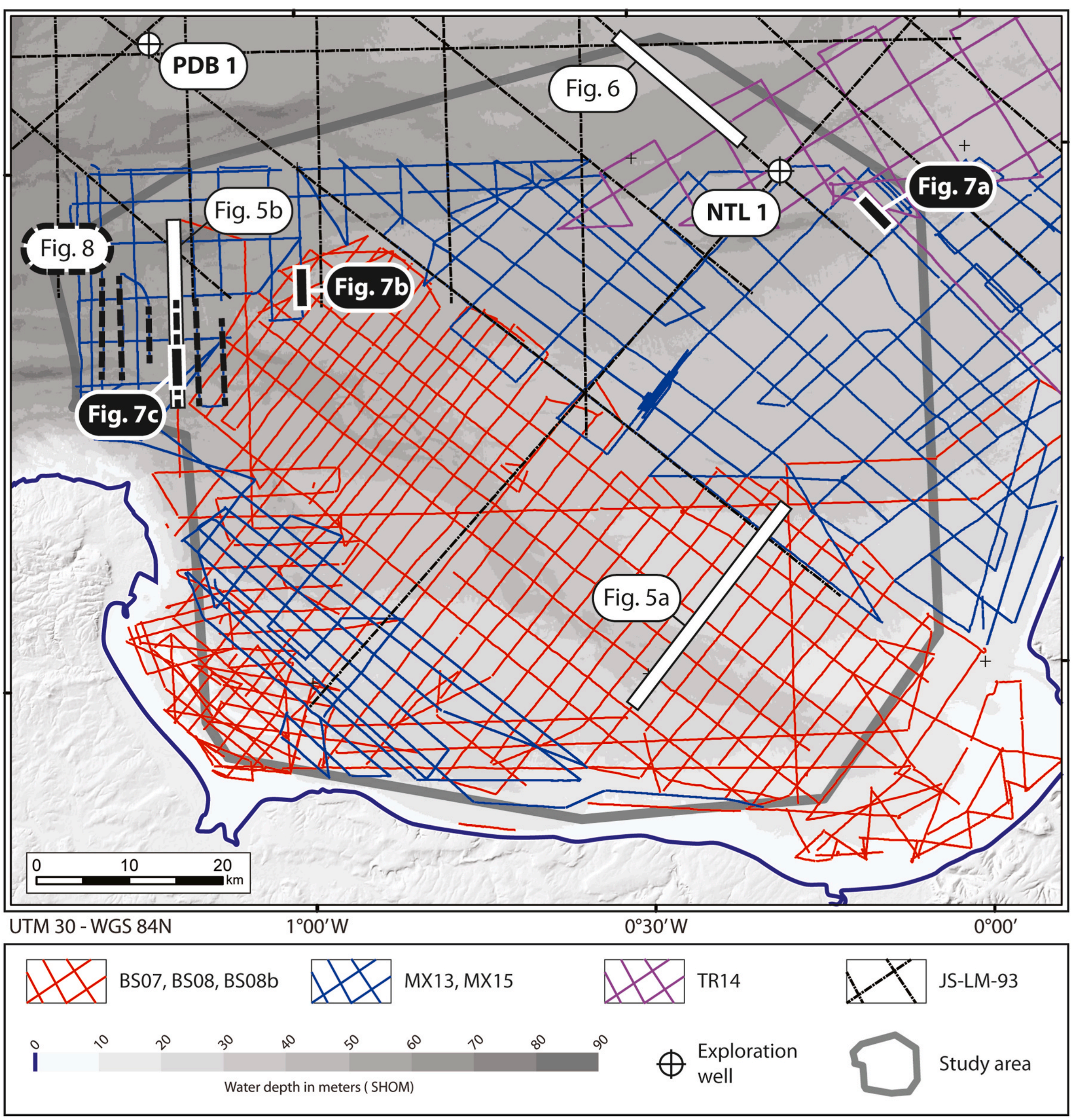

Fig. 3. Location map showing the dense grid of very-high-resolution seismic profiles (color lines) as well as oil exploration seismic (thin dashed lines) and wells (PDB-1: Pointe de Barfleur 1; NTL 1: Nautile 1). Thick lines with labels correspond to the location of interpreted seismic profiles with related figure number (Background image from ©IGN and ©EMODnet).

Table 1
Seismic surveys and data main characteristics used in this study. For additional details on surveys BS07 to MX15, visit https://campagnes.flotteoceanographique.fr/. For additional details on survey JS-LM 93 as well as exploration wells, visit http://www.minergies.fr/en.

Survey code	Survey name	Year	Seismic source	Vessel	Channel(s)	Institute(s)	References/DOI
Very-High resolution seismic surveys – meter-scale resolution							
BS07	BaiSeine	2007	Sparker 50 J	Côte D'Aquitaine	Single	UMR 6143 M2C - BRGM	Tessier and Guennoc (2007) 10.17600/7410020
BS08	SEINE THR	2008	Sparker 50 J - Boomer 200 J	Côte D'Aquitaine	Single	UMR 6143 M2C	Tessier (2008) 10.17600/8410090
BS08b	SEINE HR	2008	Spaker 50J	Côtes De La Manche	Single	BRGM	Guennoc (2008) 10.17600/8480120
MX13	MERCAUX 2013	2013	Spaker 50J	Côtes De La Manche	Single	BRGM	Paquet (2013) 10.17600/13480060
TR14	TREMOR 1	2014	Spaker 50J	Côtes De La Manche	Single	UMR 8187 LOG	Gaullier (2014) 10.17600/14010400
MX15	MERCAUX 2015	2015	Spaker 50J	Thalia	Single	BRGM	Paquet (2015) 10.17600/15010000
Oil industry seismic survey – decametre-scale resolution							
JS-LM 93	La Manche Trans-Median Line	1993	Air Gun 320 ci	SV/Svitzer Mercator	120 channels	Jebco-Svitzer	14-0811 (Minergies.fr/en)

acquired geological samples (e.g. Benabdellouahed et al., 2014 and references therein ….) and by lithostratigraphic data from two oil-exploration wells Nautile-1 (14–3577) and Pointe de Barfleur-1 (14–4476) that reached depth of respectively 1050 m and 1212.5 m, and helped in the lithostratigraphic identification of substratum seismic units. Digital bathymetric maps have been produced using Digital Terrain Models from EMODnet Bathymetry (2018 release -https://www.emodnet-bathymetry.eu/) (Fig. 2). The complete dataset is shown on Fig. 3 and described in Table 1.

Seismic data has been interpreted using classical methodology from Mitchum et al. (1977). Full description of all seismic units and the resulting geological map are not described here as we only detail the recent incised features. Alternatively, we show simplified geological maps including basement and main sedimentary series that characterize the substratum of the area.

The interpretation work of incised features follows previous works carried out in the area (Larsonneur et al., 1982; Auffret et al., 1980; Lericolais, 1997; Alduc, 1979; Benabdellouahed et al., 2013). Incised features are correlated and associated as networks on the basis of their (i) shape and depth of incision, (ii) sedimentary fill thickness, (iii)

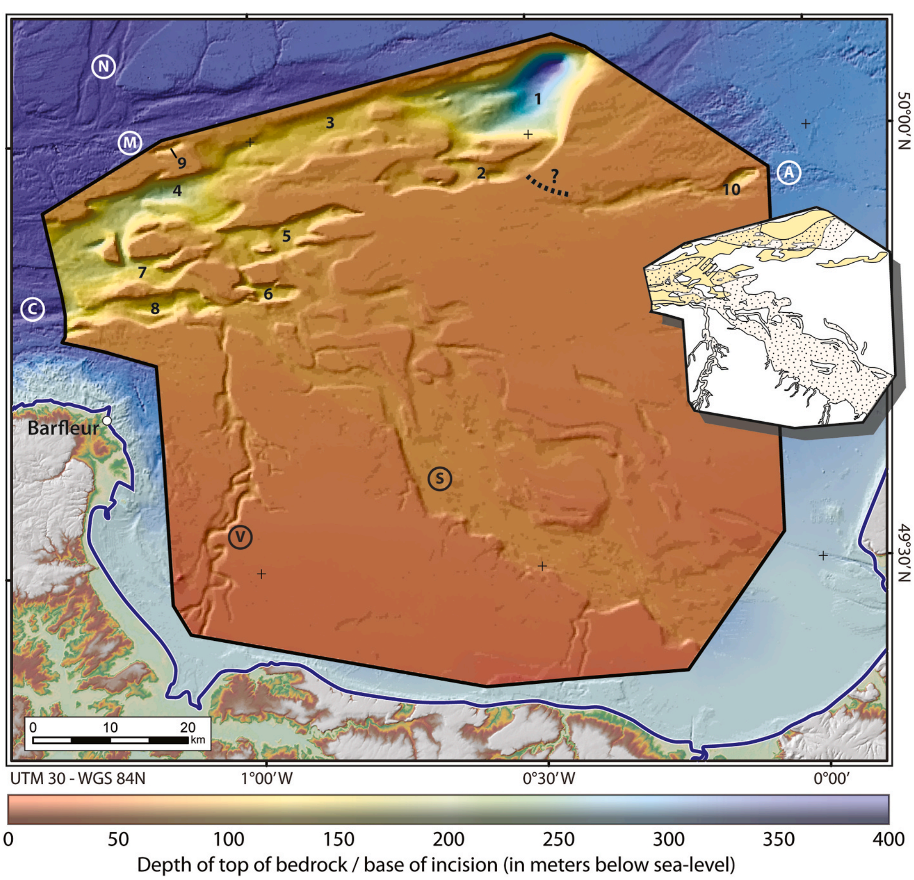

Fig. 4. Isohypse map of the top bedrock surface showing the imprint of both network incisions on the pre-Neogene substratum (Background topography and bathymetry from ©IGN and ©EMODnet Bathymetry (2018)). The inset shows the contour of Network 1 (dotted transparent pale beige) and Network 2 (pale yellow). Labels correspond to trough numbers used in the text. Circled letters refer to Seine (S), Vire (V), Median (M) and Northern (N) paleo-valleys, and to Cotentin (C) and Antifer (A) troughs.

seismic facies, and (iv) mapping coherency.

We produce a 200 m-resolution isohypse map of the top of bedrock (base of incisions) in order to reveal the morphology and amount of downcutting, as well as the complexity of all erosion features, and finally, to highlight the differences between networks. We use a sound velocity value of 2000 m s^{-1} for the incision infill in order to estimate its thickness and to render the bedrock isohypse map. This sound velocity value is comprised between usual values for unconsolidated sediments (1500–1600 m.s-1), and measured interval velocity for Jurassic series in Nautile-1 (2355 m.s-1).

4. Results

The interpretation of bathymetry and seismic profiles in the Bay of Seine area allow identifying several incision surfaces and associated infill. According to their location, stratigraphic relationship and main morphological (depth and shape of incision) and sedimentary infill characteristics (thickness, seismic facies), these incisions can be grouped in two main networks later referenced as networks 1 and 2. Both of these channelized erosion surfaces and associated infill are described below. The isohypse map of the top of bedrock highlights the distinctive incision characteristics of both networks (Fig. 4).

4.1. Network 1 – the paleovalleys

The first incised network is well developed in the core of the Bay of Seine. It consists in a 20–40 m deep incision cutting through the surrounding plateaus (present day seabed) into the Meso-Cenozoic substratum. The actual depth below sea level ranges from −20 m near the present day river outlet to −70 m just outside the bay. It forms continuous, more or less sinuous channels that connect to the present day fluvial network at Seine, Vire, Seules, Orne, and Dives river mouths. This network has been studied in detail by Alduc (1979), Benabdellouahed (2011), Benabdellouahed et al. (2013). It is interpreted as the offshore continuation of present day fluvial valley that developed during successive glacio-eustatic sea level falls during Pleistocene (Auffret et al., 1977; Lautridou et al., 1999).

Channel width can vary from 500 m for the Seules paleovalley, to 1–2 km for the Vire, and up to 12–16 km for the Seine paleovalley. Several smaller branching ramifications develop around the Vire paleovalley and on the left bank of the Seine paleo-valley as revealed by both bathymetric and seismic data. Along the right bank of the Seine paleovalley, larger tributaries as well as connected or isolated sinuous channels are recognized. These tributary channels do not show clear connection to the present day fluvial network. Incised substratum is composed of lower to upper Jurassic carbonates, marls, mudstones, and sandstones, lower Cretaceous sands, upper Cretaceous chalk, and Paleogene mudstones and sands. The general course of each paleovalley follows the local slope of the shelf but lithological contrast and distribution also locally affect valley shape. Within the inner bay of Seine, the Seine paleovalley develops within the upper Bathonian limestones and Callovian marls whereas the Vire paleovalley develops over the Hettangian limestones and lower Bathonian Marls (Marnes de Port-en-Bessin Fm.). The Seine paleovalley shows a number streamlined island separating several narrow channels where the valley cuts through the upper Cretaceous chalk in the northern part of the Bay of Seine.

The sedimentary infill of the paleovalley network is characterized by chaotic high-amplitude seismic facies with few internal erosion surfaces with channels and lateral aggradation. The estimated thickness of this unit ranges from 10 to 30 m.

The fluvial terraces of the Seine paleovalley described by Alduc (1979) and Benabdellouahed et al. (2013) are clearly visible on seismic but somehow difficult to distinguish precisely along the whole valley. The older and higher terraces are preserved along the right bank (NE) although difficult to track all the way downstream as they are progressively eroded. The most recent terrace including incision and associated fill developed along the left bank (SW) where the paleovalley is clearly visible on bathymetry. It can be traced downstream on both seismic and bathymetry as a c. 20 m thick chaotic unit, until it reaches the bathymetric depressions, north of Cotentin (Figs. 4 and 5). Attentive look to the seismic data set (eg. profile BS08b_spk069 of Figs. 5b, 7c and 8) allows following this terrace on top of two c. 80-100 m-deep troughs of the second network. In addition, the isohypse map of the top of bedrock clearly shows that the Seine Paleovalley cross the area toward the NW whereas the deep troughs are E-W to ENE-WSW. These are key observations for understanding the relationships between both networks. .

The sinuous course of the Vire paleovalley over the Marnes de Port-en-Bessin Fm. displays small terraces and abandoned channels. It merges with the most recent channel of the Seine paleovalley 20 km NE of Barfleur (Fig. 4).

North of Bay de Seine, the Central (or Median) paleovalley, associated to the Somme River, appears as a smooth 5-10 km-wide valley developing along E-W direction on bathymetric data. Very few high-resolution seismic profiles are available over that area thus preventing precise mapping.

Further north, the Northern paleovalley that connects upstream to the Lobourg Channel and the North Sea through the Dover Strait merges with the Central paleovalley. As for the Central paleovalley, very few seismic images are available along the Northern paleovalley. Nevertheless, its lower part is deprived of sediments (Alduc, 1979; Auffret et al., 1980, 1982). Therefore, the trace of the valley corresponds to its bathymetric expression.

To summarize, the network of paleovalleys corresponds to a coherent set of continuous incised and partially filled valleys that connect to the present day fluvial network and merge north of Cotentin Peninsula. Depth of incision and sedimentary fill thickness vary from 10 to 40 m.

4.2. Network 2 – the troughs

The second network of incision is almost entirely located north, outside the Bay of Seine. There, it consists in a c. 20-25 km-wide corridor of WSW-ENE orientation, with anastomosed incised channels cutting through Jurassic, lower Cretaceous and Paleogene series (Fig. 1). The depth of incision in thalwegs of most of the network usually ranges from 50 to 150 m (Fig. 4). This observation is in agreement with previous studies (Dingwall, 1975; Alduc, 1979; Quesney, 1983). However Oil exploration seismic data interpretation reveals an unexpected depth of incision up to 350 m at the northeastern end of the corridor within the study area (Figs. 4 and 6). Inside this corridor, ten main troughs are distinguished (labelled from 1 to 10 on Fig. 4). They are almost parallel to each other along E-W to ENE-WSW direction (same as corridor), slightly sinuous with rather abrupt flanks (20° slope) and sharp terminations at bank' edges. Troughs show connection through several “passes” and local depressions. The overall morphology of the network incision is complex and do not evoke a single fluvial valley or fluvial network. The sedimentary infill revealed by seismic images is complex and diverse. We propose to distinguish four main seismic facies, as seen on very-high resolution data that fill the main trough channels and channelized incisions within the troughs (Figs. 5 and 7, Table 2). We tentatively suggest possible environment and process for each seismic facies. These interpretations are presented in the discussion section and should be taken with caution since groundtruthing is lacking.

We propose a rapid description of few troughs of the corridor based on their incision and fill characteristics.

4.2.1. Trough 1 – the “deep groove”

Trough 1 is located in the northernmost part of the corridor within the study area and corresponds to the largest trough ever detected in the area. It is a newly discovered feature that reveals itself thanks to one seismic profile of conventional marine seismic data that provides deeper penetration than VHR sparker data. Along profile JS-LM93-05, the trough shows an incision depth of c. 350 m and a width of 8–10 km

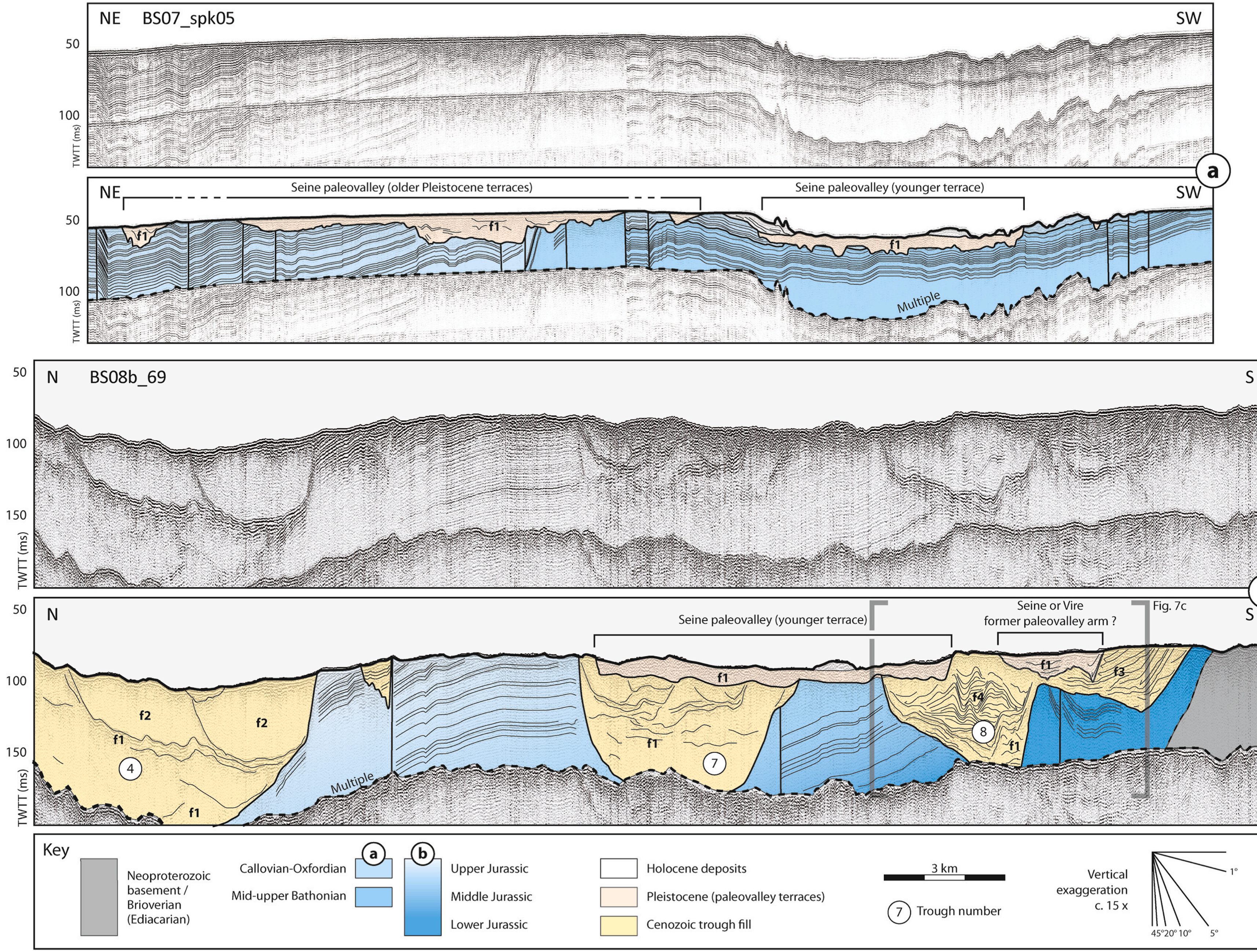

Fig. 5. Seismic profiles and interpreted sections showing the Seine paleovalley incision through Jurassic substratum within the Bay of Seine (a), and offshore Cotentin, where it develops on top of a set of trough incisions (b). "f" labels refer to seismic facies described on Table 2. See location on Fig. 3.

Table 2
Description of seismic facies as seen on very-high-resolution seismic data. Labels T4 to T10 correspond to trough numbers as seen on Figs. 4, 5, 7 and 8.

Seismic Facies	Configuration	Amplitude	Continuity	Context	Location on VHR seismic	Fig.	Proposed environment and process
f1	Chaotic with channels	Medium to high	Low	Paleovalley	Seine	5a, 5 b, 7c	Coarse grain fluvial braided with channels
				Base of trough	T4, T5, T7, T8	5 b, 7 b, 7c	Coarse grain cross-beds (fluvial, tidal, or shallow marine)
f2	Chaotic	Very low	Very low	Nested channels	T4	5 b	Mass flow/megaflood?
f3	Oblique, low angle	Medium	High	Trough and nested channels	T5, T8, T10	5 b, 7a, 7 b, 7c	Shallow marine/estuarine lateral accretion
f4	Wavy - mounded	Low to medium	Medium to high	Trough (above f1)	T5, T8	5 b, 7c	Shallow marine with tidal currents.

(Figs. 4 and 6). It exhibits almost symmetrical flanks of 5°–10° apparent slope interrupted by few irregular terraces or steps. The floor of the trough is flat and 2 km-wide along the NW-SE direction of the profile. The substratum consists of Upper Jurassic marine carbonates and marls overlaid by Lower Cretaceous "wealdian" continental deposits (fluvial and floodplain), and possibly the clayey Gault Formation. Jurassic is clearly dissected by normal faults with vertical displacement of c. 10–20 m. Despite the scarcity of data in the area, it appears that the Deep Groove extended exclusively on the Lower Cretaceous "wealdian" and aptian-albian deposits and did not extend either over the Upper Cretaceous chalk nor the Jurassic series.

The sedimentary fill of trough 1 is characterized by a rather chaotic seismic facies with few high-amplitude irregular reflectors that individualize at least four phases of deposition. The relatively low resolution of petroleum seismic does not allow further description of the sedimentary fill.

Toward the east, Trough 1 may connect to an unnamed trough of c. 100 m deep identified by Alduc (1979) and further east, to the Greenwich trough. Southward, a pathway is suspected between Trough 1 and Trough 2. Trough 1 seems to also connect to the Cotentin Troughs to the west through the shallower Trough 3 (50-100 m-deep). Trough 2 and 3 show very chaotic seismic facies on VHR seismic data.

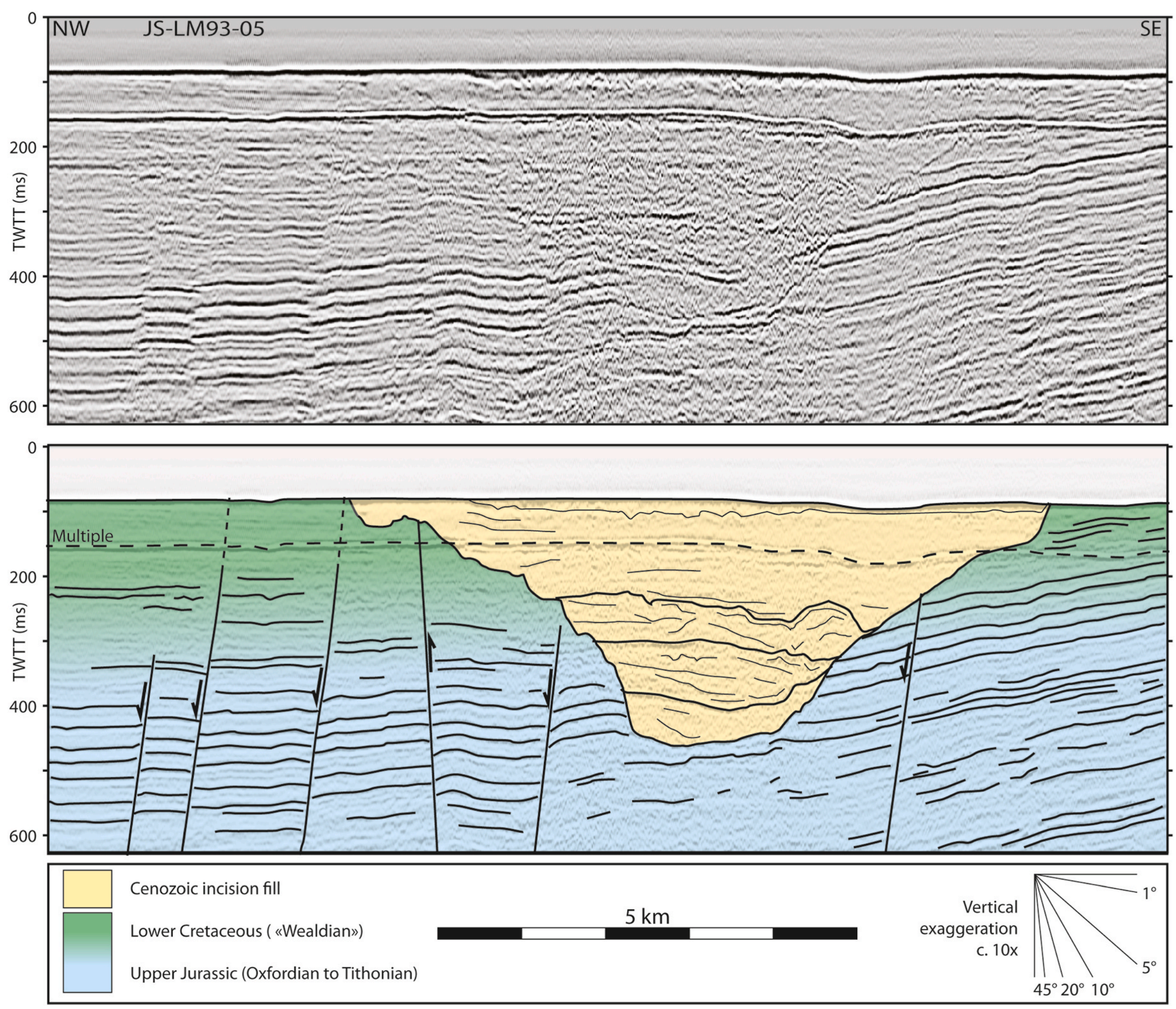

Fig. 6. The "deep groove" (Trough 1) located north of the Bay of Seine as seen on oil-exploration seismic profile JS-LM93-05. Data courtesy of IHS. See location on Fig. 3.

4.2.2. Trough 10 – the Antifer Trough

Southeast from the "Deep Groove" lies the easternmost trough of the study area (Fig. 4). It is located below the bathymetric depression known as Antifer Deep, a c. 60 m-deep trench (40 km NW from Antifer Cape and Étretat). The trough develops over Paleogene siliciclastic and calcareous deposits (mostly Eocene – Fig. 7a). It is an east-west elongated feature of 2 km by 30 km, and it reaches a maximum depth of 100 m below sea level (60 m-deep incision from surrounding plateaus). The deepest and easternmost part also shows the thickest sedimentary infill (c. 50 m), whereas the westernmost part is almost deprived of sediments thus forming the bathymetric Antifer Deep (Fig. 4). The sedimentary infill is characterized by 50 m-high low-angle oblique sets (2°–4°) showing internal erosional unconformities with progressive apparent migration of deposits toward the north (facies f3), ending up with a channel-like feature with apparent lateral migration toward the south (Fig. 7a). The "Antifer trough" appears isolated from both trough and paleovalley networks.

4.2.3. Cotentin Troughs

North of Cotentin Peninsula, several E-W troughs (4–9) develop over Mesozoic and Cenozoic successions. They show various sizes from 2.5 km by 8 km (Trough 6) up to 7 km by > 30 km (Trough 4). Depth of incision varies from 50 to 150 m from the surrounding area (−100 m to −200 m below sea level). Trough flanks are very steep with slope value locally reaching up to 45°–50°. Numerous pathways seem to connect troughs together thus creating an intricate pattern (Fig. 4). With the exception of Trough 4 that connect to Trough 3, all other troughs show abrupt terminations eastward without clear and progressive connection to the paleovalley network incision. Westward, troughs 4, 7, and 8 apparently merge to form a wider depression that connects to the Hurd Deep (Dingwall, 1975).

In addition to the general complexity of trough distribution, seismic images reveal a large variety of sedimentary features in the infill of the troughs (Figs. 5b, 7b and c, and Fig. 8) that were already noticed by Dingwall (1975), Alduc (1979), Quesney (1983), Lericolais (1997), and Lericolais et al. (2003). The sedimentary fill of the Cotentin troughs starts with a 10 to 30 m-thick high amplitude discontinuous reflection with channel features that covers the bottom of each trough (f1). Above these first deposits, troughs are then filled up by large kilometer-scale imbricated channels with either chaotic facies (f2, Troughs 4 and 7 on Fig. 5), or sets of low-angle oblique reflections migrating laterally (f3, Troughs 5 and 8 on Fig. 7b and c) somehow similar to Antifer Trough (Fig. 7a). Trough 8 also exhibits pronounced wavy stratification in its deeper area (f4, Figs. 5 and 7c). These wavy features filled the trough by progressive buildup of mounds/levees separated by channels. These undulating bodies once reached 10 to 20 m-high and a width varying between 250 and 500 m along a north-south section.

4.2.4. Other troughs

The seismic record shows few other potential trough candidates surrounding the area of study. Several aligned 50 to 100 m-deep incisions and associated infill are visible on several oil-exploration seismic profiles, north of the main trough corridor, along the contact between lower and upper Cretaceous series. They correspond to the "bras septentrional" (northern arm) described by Alduc (1979). We propose to conserve this interpretation of an elongated channel as part of the trough network (Fig. 9). Within the area of study, an E-W elongated and arcuate feature is found 25 km WNW of Etretat. It is a rather shallow incision

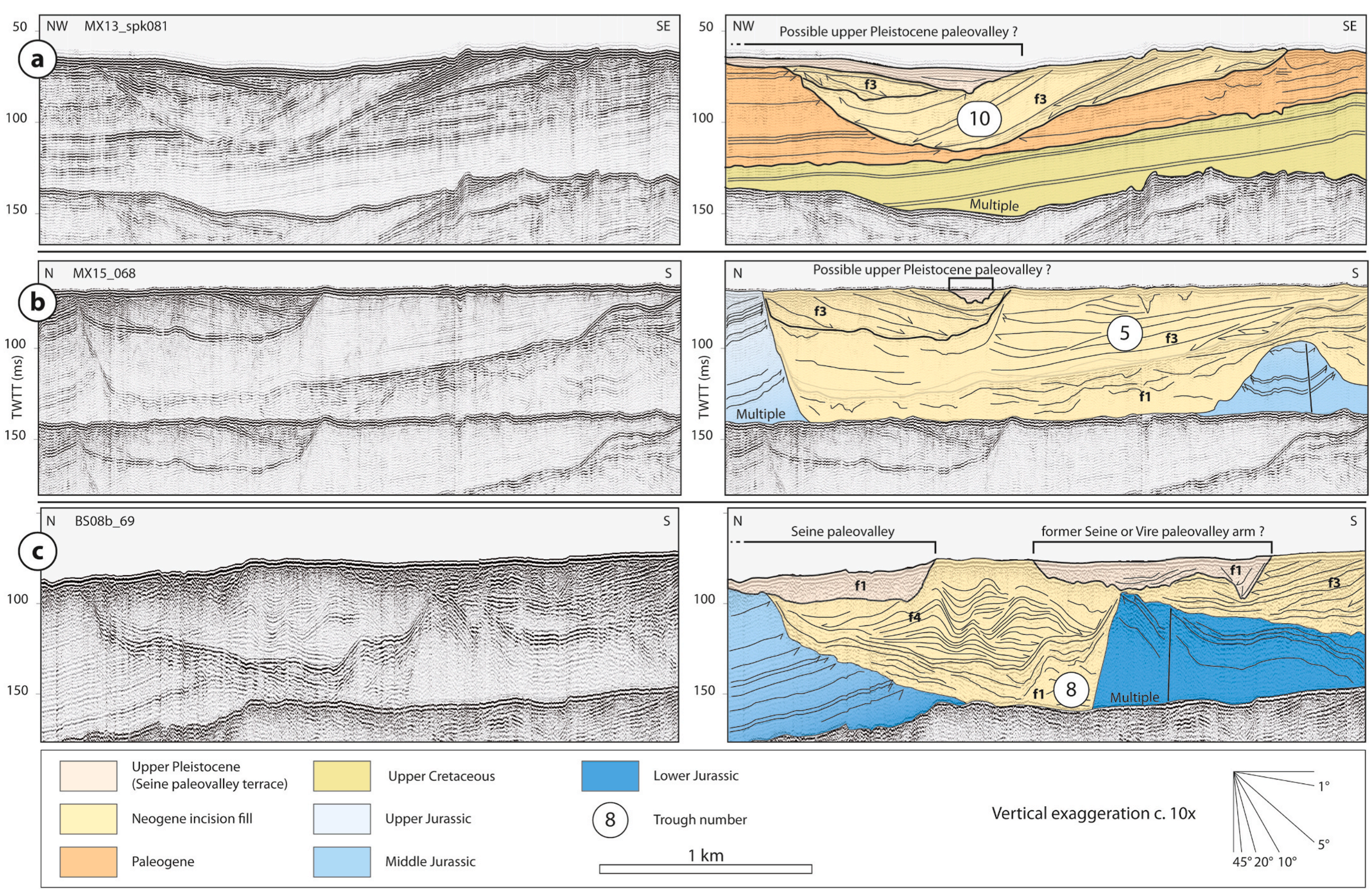

Fig. 7. Very-high-resolution seismic sections showing the morphology and infill geometries of troughs10 (a), 5 (b), and 8 (c). Fig. 7c shows the overlying "upper Pleistocene" paleovalley network. Fig. 7a and b shows possible upper Pleistocene paleovalleys that do not show the distinctive trough seismic facies, though not showing connection to the paleovalley network. "f" labels refer to seismic facies described on Table 2. See location on Fig. 3.

(10–15 m) developing over upper Jurassic (Kimmeridgian), along its boundary with lower Cretaceous deposits (Aptian-Albian). The thin sedimentary fill does not show clear geometry. Finally, one last candidate lies below the deposits of the Seine paleovalley in the core of the Bay of Seine. Already noticed by Benabdellouahed et al. (2014), this feature is a 5 by 2 km NE-SW elongated incision that cut 30 m-deep into the middle Jurassic series. It developed in parallel to a set of faults and fold affecting the Jurassic in the inner part of the Bay (Fig. 9).

4.3. Stratigraphic relationship between networks

The relationship between paleovalleys and troughs is the subject of debates for decades as mentioned in the introductive section. We propose to test this relationship with the help of newly acquired data. The quality and density of seismic data indeed allow a rather precise and confident mapping of the contour of both networks within the study area. This mapping confirms that networks converge offshore Cotentin, NE of Barfleur (Fig. 4 – Auffret et al., 1977; Lericolais, 1997). In that area the Seine-Vire paleovalley system "joins" the Cotentin Troughs. Whereas

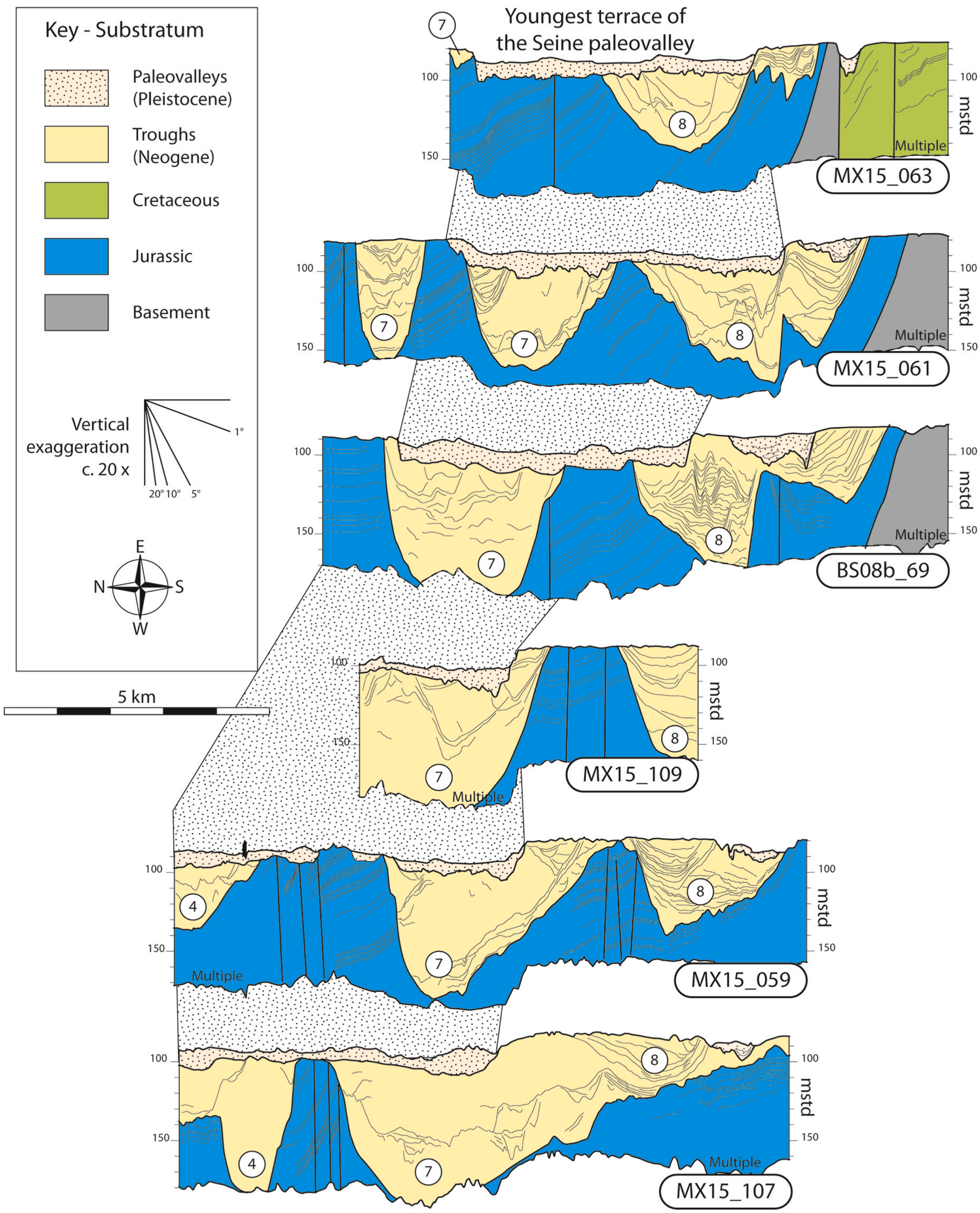

Fig. 8. E-W succession of parallel N–S trending interpreted seismic sections showing stratigraphic relationships between the pre-Neogene substratum, the trough network, and the Pleistocene Seine-Vire paleovalley network. See location on Fig. 3.

the older terraces of the Seine paleovalley are poorly preserved due to later erosion and are thus difficult to identify in this area, the youngest terrace is clearly visible from one seismic profile to the next from within the inner part towards the outer part of the Bay of Seine. This terrace and associated incision constitute an obvious and continuous channel on bathymetric data (Fig. 2). Seismic profile BS08b_69 (Fig. 5b) already offers an opportunity to understand stratigraphic relationships between the paleovalley network and the trough network. On this profile, Cotentin Troughs 4, 7 and 8 cut through Jurassic series with an average incision depth of c. 100 m. Above them, the typical youngest cut and fill terrace of the Seine paleovalley (c.10 km-wide and 10 to 20 m-thick) appears to incise equally Jurassic and troughs (7 and 8), thus forming a distinct erosional unconformity. The Seine Paleovalley incision and subsequent fill seems to develop relatively independently from the trough network. In order to validate this relationship semblance, we propose to zoom out and verify the network distinctiveness by observing them on a serial sectioning of seismic profiles (Fig. 8). The succession of interpreted profiles clearly shows that the youngest terrace of the Seine paleovalley developed northwestward downstream over and across EW elongated troughs. First over trough 8, then over both trough 7 and 8, and finally ovet troughs 7 and 4. Thus, Seine paleovalley cut and fill system does not merge and connect with troughs as proposed by several authors (Auffret et al., 1980; Lericolais, 1997) but rather remains a distinct and more recent system with fluvial incision and subsequent fill developing over a substratum made of deformed Pre-Neogene series and a trough network (Alduc, 1979). This distinction between both networks appears clearly once their respective distribution is cartographically highlighted (Fig. 9).

5. Discussion

This study addresses paleovalleys and troughs within the Bay of Seine and Central English Channel area with unprecedented details. Results show that paleovalleys and troughs represent two distinct networks that differentiate one to the other from their respective morphology (incision and sedimentary fill characteristics) and stratigraphic relationship. This observation somehow invalidates the hypothesis of a direct link between troughs and middle to upper Pleistocene paleovalleys (Hamilton and Smith, 1972; Auffret et al., 1980) but rather promote the distinction made by Alduc (1979). Whereas the postulated middle to late Pleistocene age and fluvial origin of paleovalley network is broadly accepted, thus forming part of the quaternary "Fleuve Manche" (Lautridou et al., 1999; Lericolais et al., 2003; Antoine et al., 2003; Bourillet et al., 2003; Mellett et al., 2013; Toucanne et al., 2010; Benabdellouahed et al., 2013), trough network appears as an older geological object that need to be addressed properly. In this discussion section, we propose to evaluate several scenarios for the origin and age of the trough network (incision and infill) and to address the resulting implications of these scenarios in terms of regional geological significance. With the absence of critical sample within the trough sedimentary fill, our interpretation relies on trough distribution and morphology, as well as infill main characteristics on seismic. We first address the age constraints, then origin of incision event(s), and finally the sedimentary processes and environment(s) responsible for the fill characteristics.

Without any robust timing constraint and ground truthing, hypotheses remain speculative.

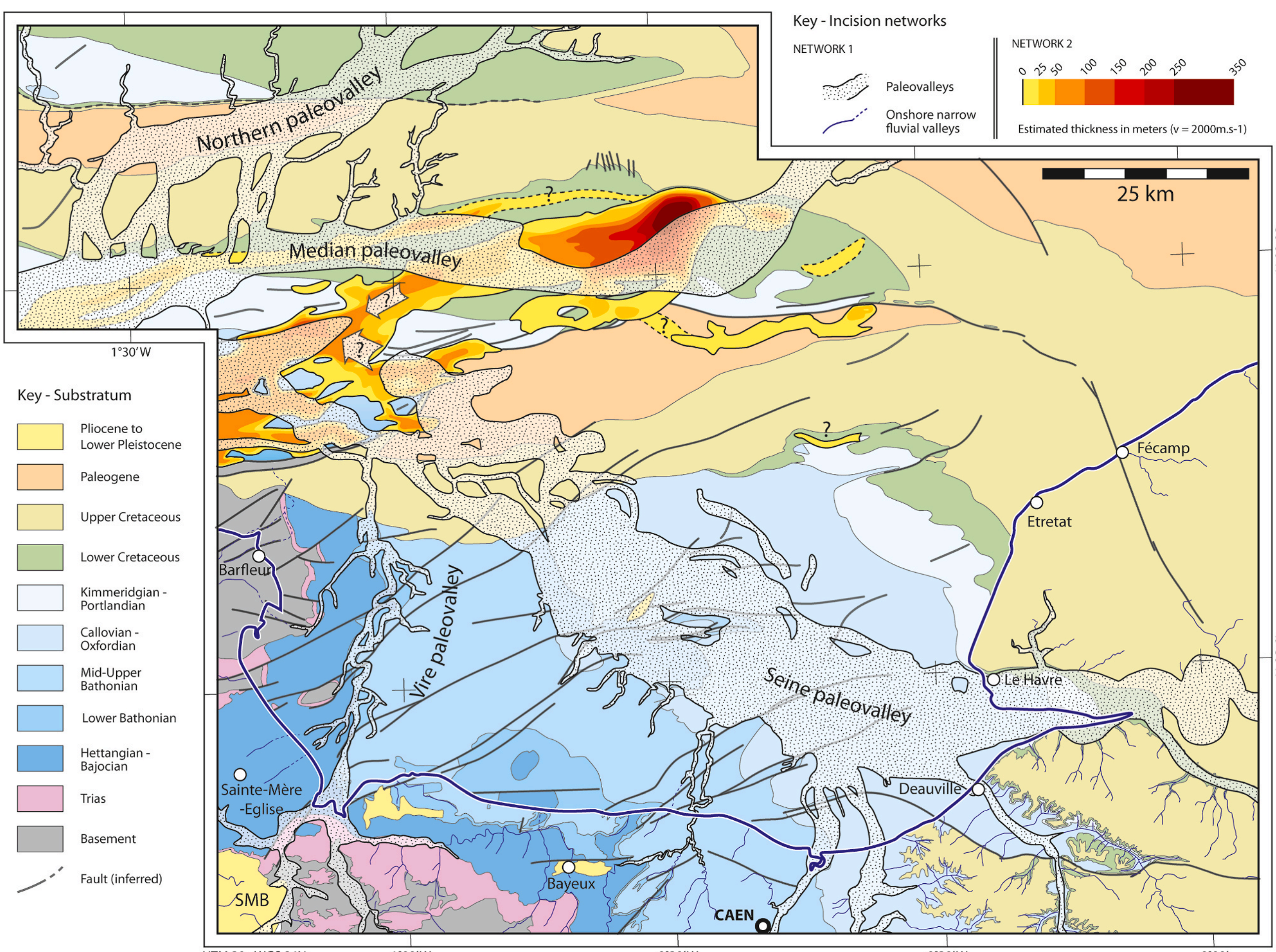

Fig. 9. Updated simplified geological map of the area adapted from Chantraine et al. (2003) and Paquet et al. (In prep.). Troughs (figured as isopach shading) and valleys (dotted area) are resolved as two distinct and superimposed networks. SMB: Sainteny-Marchésieux Basin.

5.1. Age constraint for trough development

English Channel trough infill has never been successfully sampled despite several attempts during the past decades (Auffret and Gruas-Cavagnetto, 1975; Larsonneur, 1971). This is mostly due to technical difficulties to traverse and recover samples trough unconsolidated sandy and gravelly sediment cover of the area (Vaslet et al., 1979) using gravity-based corers or vibro-coring devices. Therefore, in the absence of actual stratigraphic constraint the timing of trough incision and fill events remains relative. This study shows that the troughs already exist prior to the development of the mid-late Pleistocene paleovalley network. The youngest sedimentary formations incised by troughs within the study area belong to the Cenozoic basin in the northern Bay of Seine (Fig. 9) and correspond to folded Bartonian shelly sands (Benabdellouahed et al., 2014). Troughs apparently cut through a large set of tectonic structures that bounds the northern part of Bay of Seine (Fig. 9) without being affected by deformation. These E-W and NE-SW structures belong to the widespread English Channel inverted structures (e.g. Central English-Channel Fault, Purbeck-Wight Fault). They have been reactivated during late Paleogene-early Neogene because of tectonic events affecting the whole European plate (Pyrenean and Alpine orogenies, Icelandic Plume – Ziegler, 1987; Ziegler, 1990; Hillis, 1995; White and Lovell, 1997; Rosenbaum et al., 2002; Biteau et al., 2006; Hillis et al., 2008; Vissers and Meijer, 2012; Westhead et al., 2018). Recent vein calcite U–Pb dating by Parrish et al. (2018) in southern England reveals that the culmination of deformation occurred during late Eocene-early Oligocene (Priabonian-Rupelian/34-31 Ma). In the Cotentin area, Dugué et al. (2009) propose that the erosional hiatus from Chattian to middle Miocene indicates the continuation of deformation in the area. This mean that trough incision could have initiated as early as the Chattian-early Miocene period, and subsequent infill starting during early to mid- or upper Miocene while deformation ceased. The age of troughs (incision and infill) cannot be younger than mid Pleistocene that corresponds to the age of the overlying fluvial network terraces.

5.2. Origin of trough incision

The main morphological characteristics of troughs are their depth of incision reaching locally several hundred meters, the discontinuous aspect of the network and its isolated character in the deepest part of the English Channel without any connection to the present day fluvial network. These are key aspects to understand the processes that may have originated the troughs. Several theories emerged throughout the years including (i) subglacial tunnel-valley or glacial lake outbursts (Berthois and Furnestin, 1938; Destombes et al., 1975; Kellaway et al., 1975; Wingfield, 1989, 1990), (ii) karst generation (Boillot, 1963a, 1963b, 1964), (iii) thermokarsts (for small 100 m-scale troughs only - Lericolais et al., 2003), (iv) tectonic collapse along major faults (Dangeard, 1929; Hinschberger, 1963), or (v) fluvial to marine hydrodynamic processes (Auffret et al., 1977, 1980; Larsonneur and Walker, 1982; Hamilton and Smith, 1972; Smith, 1985; Mitchell et al., 2013). Subglacial processes are now ruled-out since successive Pleistocene ice sheets never reached the English Channel (Ehlers and Gibbard, 2004; Clark et al., 2004). The generation of karsts would have implied a systematic location of troughs over carbonate series. However, several troughs develop over siliciclastic deposits such as lower Cretaceous series (e.g. Alduc, 1979; this study). We would rather emphasize the role of unconsolidated lithology in the preferential location and development of troughs knowing that several deep troughs cut through lower Cretaceous sands. Finally, the tectonic collapse hypothesis would require the systematic presence of faults along trough flanks, steep sides, and syntectonic sedimentary geometries (growth strata). None of these features can be found in or along the troughs of the Central English Channel area (this study). Alternatively, as deformation (faults and folds) determines the distribution of lithologies at seabed, it may have played a passive though key role in the location of sedimentary formations prone to erosion and consequently, the trough location itself. We thus favor hydrodynamic processes, either fluvial or marine, to explain trough incision. We propose to review several erosion contexts that could generate incision using modern or ancient examples and analogs.

5.2.1. Fluvial incision

Trough incision usually reaches more than 100 m and the present study reveals that the base of one of the troughs, informally called “Deep Groove”, is reaching the unforeseen value of 350 m-depth below the surrounding plateaus (Figs. 4, 5b and 6, 7 and 8). The actual depth of incision at time of erosion is even larger than observed nowadays as the surrounding plateaus are certainly lower than the actual topography at the time of incision. This latter point is highly conceivable when looking at how flanks connect to either buried topography or to the present day seabed with almost systematical sharp angular edges (Figs. 5b, 6 and 7 and 8). In addition, the trough network does not form a clear continuous pattern of classical fluvial valleys but a set of more or less connected adjacent deeps (Fig. 4). If we nevertheless consider fluvial incision as the main driver for down cutting 100–350 m, several aspects and conditions need careful considerations. First, trough depth values have to be compared to the incision depth of the overlying fluvial paleovalley that reach locally 20–40 m (Dingwall, 1975; Alduc, 1979; Auffret et al., 1982; Benabdellouahed et al., 2013; Mellett et al., 2013). These latter values are indeed compatible with Pleistocene sea-level fluctuations of c. 100–150 m (Waelbroeck et al., 2002; Lisiecki and Raymo, 2005; Spratt and Lisiecki, 2016). Incision up to 350 m cannot be explained by any of the Pleistocene or the middle Cenozoic eustatic variations (Miller et al., 2005; Cramer et al., 2011). This means that other controls need to be involved such as tectonics or autogenic processes, or a combination of both. Tectonics alone would require at least one regional uplift phase responsible for incision followed by at least one local subsidence phase of equivalent range allowing partial preservation. The discontinuity of the trough network would then reflects the variation in the distribution of subsiding loci and the whole network would correspond to the remnant of a deformed fluvial network. Such tectonic events and vertical displacements of hundreds of meters during Neogene continuing into Quaternary are documented in adjacent areas as the St. George’s Channel Basin (Holford et al., 2008), the Western Approaches (Menpes and Hillis, 1995; Le Roy et al., 2011), the Dover Strait (Van Vliet-Lanoë et al., 2004) and Cotentin (Pedoja et al., 2018).

The unusual depth of the troughs could also result from local deepening and scouring of the longitudinal profile occurring either at confluence or where the river(s) cut(s) through contrasted lithologies thus forming giant riffle-pool sequences. This may partially explain the network discontinuity with preserved deep pools and progressively eroded riffles sections. Nevertheless, considering the depth of the troughs, the associated river should have exhibited extreme water discharge values. Such water discharge conditions may be achievable if the drainage area extends dramatically to match the characteristics of the potential Pleistocene “Fleuve-Manche” with its partially glaciated drainage area reaching up to 2.56×10^6 km^2 (Patton et al., 2017). By comparison, the present day Congo River, the second largest drainage basin (c. 4.10^6 km^2), and second highest average discharge in the world after the Amazon River (c. 46,000 m^3 s^{-1}; Runge, 2007), is actually the world’s deepest river. Along the lower reach of the Congo River, its water depth ranges from few tens of meters to maximum values of 164 m in a pool near Bulu (up to unconfirmed value of 220 m - Jackson et al., 2009). Considering the surrounding plateaus lying approximately 150 m above the river itself, the total drop due to incision of Proterozoic bedrock reaches between 300 and 400 m. However, such a dramatic incision is usually explained by authors as resulting from the Congo River downcutting through the uplifting series of the Niari Basin and West-Congo Fold Belt since the early Neogene (Dadet, 1969; Runge, 2007). Moreover, incision may have been enhanced by the catastrophic drainage of a possible dammed Malebo Pool lake (Runge, 2007). In the case of the troughs, the existence of a proto "Fleuve Manche" would also require an earlier breaching of the Dover Strait before late Pleistocene.

A fluvial origin scenario for trough development would therefore imply either a large ancient and deformed incised network or a "giant" riffle-and-pool system, or a combination of both. This would relate with the idea of Dingwall (1975) that "Cotentin Troughs" correspond to a fluvial paleo-network that could initiate during Miocene. Several fluvial remnants are indeed described in Brittany (Gibbard, 1988; Guillocheau et al., 1998; Van Vliet-Lanoë et al., 1998; Brault et al., 2004; Paquet et al., 2010) and over the Paris Basin (Dugué et al., 2012) from Miocene to Pliocene. Upper Miocene-lower Pliocene Proto-Seine River then consisted in wide sand spreadings located directly to the north of the Pleistocene Seine valley (Sables de Lozère Fm.). Nevertheles, this network is nothing comparable to the deeply incised troughs. Moreover, paleogeographic reconstruction studies for that period indicate that troughs of the Central English Channel were below sea level or at least in coastal environment (Gibbard and Lewin, 2003 and references herein; Dugué et al., 2012; Jamet, 2015). This is attested by the occurrence of Middle Miocene faluns de Bléhou Fm. (marine shelly sands) in the Cotentin are (Sainteny Marchésieux Basin; Fig. 9). Finally, assuming hypothesis of a fluvial origin, the resulting network would correspond to a major source-to-sink system across northwestern Europe with large clastic discharge to both Celtic and SW Approaches Margins. There, Miocene bioclastic limestones of the Cockburn Formation is dissected by an erosion surface showing channelized features (Evans and Hughes, 1984, Peyre, 1997; Reynaud et al., 1999; Bourillet et al., 2003; Le Roy et al., 2011). The overlying Pliocene Little Sole Formation located on the outer shelf may record the increase of siliciclastic input to the shelf from a possible fluvial system (Evans and Hughes, 1984; Bourillet et al., 2003; Le Roy et al., 2011; King, 2016). The continuity of few Pliocene channels with slope canyons is in favor of a sediment routing connection between the shelf and the Celtic and Armorican deep sea fans (Bourillet et al., 2003). However, sedimentary successions at DSDP sites 400 and 402 do not evidenced a clear increase of terrigenous inputs between Miocene and Pliocene (Montadert and Roberts, 1979) but the location of wells may place them off the main clastic sediment routing system.

5.2.2. *Megafloods*

Another and complementary origin to the fluvial hypothesis for trough incision may involve one or several catastrophic flooding events. This hypothesis has been proposed by several authors to explain the development of part of the English Channel paleovalley network (including troughs). Smith (1985, 1989) favors a breaching of the Dover Strait and the draining of an Ice-dammed lake located in the southern North Sea. The released waters would have flooded the emerged English Channel floor, probably using pre-existing fluvial network, reshaping it, and forming a succession of overdeepened troughs from the Dover Strait to the Hurd Deep. This hypothesis, latter promoted by Gupta et al. (2007), Collier et al. (2015), and Gupta et al. (2017), is based on similarities between morphological features of English Channel valley floors (e.g. streamlined islands) and the jokülhlaups (megaflood events usually associated with collapse of ice-dammed lake) related Channeled Scablands in the northwestern USA (Bretz, 1969; Baker, 1973; Waitt, 1980; 1985). In the scenario of megafloods affecting the English Channel, recent studies by Gupta et al. (2007) and Gupta et al. (2017) propose that the opening of Dover Strait occurred in two major episodes at MIS 12 (478–424 ka) and MIS 6 (191–130 ka – ages from Lisiecki and Raymo, 2005).

The first opening event would be responsible of the formation of the 100 m-deep Dangeard Troughs as series of plunge pools when the proglacial lake waters started to spill over the Weald-Artois high thus forming large waterfalls during MIS 12. The Dangeard Troughs are located along the boundary between the lower Cretaceous sandy-clayey deposits and the upper Cretaceous chalk, where spillovers occurred according to Gupta et al. (2017). Central English Channel troughs also developed over the area dominated by lower Cretaceous deposits (including Gault clays, Greensands and wealdian facies). This implies that in the case of the English Channel, the distribution of contrasted lithologies have a strong influence on the location of deep incision features.

The second opening event would correspond to the final breaching of the Dover Strait during MIS6 with the drainage of a Saalian lake(s) (Busschers et al., 2008; Meinsen et al., 2011; Murton and Murton, 2012) and the development of Lobourg Channel and Northern Paleovalley over both the Dangeard Troughs and the pre-existing fluvial network. The two-stage opening scenario is also supported by evidences of terrigenous inputs in the sediments of the Bay of Biscay at c. 455 ka and c.150 ka (Toucanne et al., 2009). As stated above, Smith (1985) proposed that these events may be responsible for the development of other troughs in the English Channel including the Cotentin Troughs and the Hurd Deep. These troughs are indeed relatively similar in terms of depth range and sediment infill geometries to the Dangeard Troughs (multi kilometric scale and up to 140 m-deep). In addition, the proposed middle-Pleistocene age (MIS12, Gupta et al., 2017) is coherent with the trough stratigraphic position, directly under the late-Pleistocene Seine and Vire paleovalley terraces (Figs. 5, 7 and 8). The estimated peak discharge of the last event ranges from c. 0.2 to 1.0 $\times$ 10^6 m^3 s^{-1} (Gupta et al., 2007). This value is equivalent to the estimated water discharge of the Channeled Scabland megaflood events that occurred in the northwestern U.S.A. (Baker, 1973), actually 10 times higher than the Congo River mean annual water Discharge.

In such scenario, the "Deep Groove" which is located downstream from the mapped boundary between upper Cretaceous chalk and the lower Cretaceous sandy and clayey deposits would be an equivalent of the Dangeard Troughs. This "plunge pool" origin would make it the deepest plunge pool discovered to date. It is therefore tempting to imagine a succession of large troughs from the Dover Strait until the Hurd Deep, all resulting from the catastrophic flooding events. However, several questions remain if considering the correlation between the Dangeard Troughs and the other troughs located further west:

- (i) If the "Deep Groove" is a true plunge pool resulting from water overflowing a cuesta ridge of upper Cretaceous chalk, this would imply another local breaching and enormous waterfalls to create such a wide c. 350 m-deep incision, three times deeper than the Dangeard system itself?
- (ii) Presence of such a topographic barrier is not attested and should have been already cut across and locally erased by the Pleistocene Somme river that dates back since at least early Pleistocene time (MIS 21/22; Antoine et al., 2000; Bahain et al., 2007).
- (iii) Cotentin Troughs and Hurd Deep do not show plunge pool characteristics and rather elongate along E-W and WSW-ENE directions, parallel to the presumed flood flow (Fig. 9). The flow dynamic of the flood would need to be sufficiently high to incise 100–200 m down into the bedrock along more than 200 km by itself without invoking the effects of successive waterfalls, important knickpoint regression, or simply an unexpected river profile favoring incision in this otherwise relatively flat part of the continental shelf.
- (iv) The comparatively shallow Lobourg Channel and Northern Paleovalley system that shows robust evidence of catastrophic flooding (e.g. streamlined islands, benches, Gupta et al., 2007; Collier et al., 2015) developed tens of kilometers north away from the trough corridor. This observation raises the question as to why two almost successive flooding events did not follow the same pathway and did not produce equivalent features.

Whereas we do not rule out the scenario of catastrophic flood at the origin of the troughs in the Dover Strait (Gupta et al., 2017) and over the English Channel, the connection and correlation of all troughs, as proposed by Smith (1985) are somehow uncertain. The “Deep Groove”, the Cotentin Troughs and the Hurd Deep could then developed during one or several extreme flooding events prior to MIS 12, meaning that the Dover Strait area underwent at least one more breaching and opening event than previously proposed (Gupta et al., 2007, 2017; Gibbard, 2007; Toucanne et al., 2009; Collier et al., 2015; Catt et al., 2006) perhaps from MIS 19 to MIS 6–2. However, no evidence exists of such a succession of catastrophic outbursts of lakes located in the southern North Sea into the English Channel during Quaternary.

5.2.3. Tidal scouring

Previous scenarios consider that troughs incision occurred as fluvial or flooding processes when the English Channel was partially emerged due to lower relative sea level. An alternate hypothesis invoke tidal currents as main erosive factor and implies the immersion of the English Channel. The area is now characterized by a macro-tidal environment with a maximum tidal range reaching more than 13 m in the Mont-Saint-Michel Bay (Fig. 1). This theory of tidal scouring is partially promoted or discussed by several studies for the Hurd Deep (Donovan and Stride, 1961; Stride, 1963; Smith and Hamilton, 1970; Larsonneur, 1971; Hamilton and Smith, 1972) and for the whole area (Dingwall, 1975; Hamblin et al., 1992). For these authors, after an initial period of regression (climatically or tectonically controlled) and possible fluvial erosion initiating the incision, the following transgressions and emplacement of strong tidal currents dramatically widened and deepened the valleys to form the trough network we see today. Hamilton and Smith (1972) proposed an initial phase of fluvial incision as they linked both fluvial valleys and troughs. Our observations tend to reject this connection between networks. Thus, in the absence of other obvious valley network remnants connecting to the troughs, we consider that invoking an initial fluvial incision phase is possible though speculative and non-critical here. To support this assertion, we would mention several closed-contour depressions such as the St Catherine’s Deep (south of the Isle of Wight), the Hague Trough at Alderney Race (Raz Blanchard, northwest of Cotentin; Furgerot et al., 2019), or the Ouessant and the Virgin Island Troughs (northwest of Brittany) that do not show any connection to fluvial valleys (Andreieff and Lefort, 1972; Hamblin et al., 1992). Authors propose that the presence of contrasted lithologies at seabed resulting from Cenozoic inversion tectonic phase favoured a differential erosion of the bedrock, causing a localized acceleration of tidal currents and subsequent excavation and scouring of these isolated deeps (Smith, 1985; Hamblin et al., 1992; Mitchell et al., 2013). We could thus generalize this approach and consider troughs to be the result of tidal scouring on specific lithologies by acceleration of tidal currents at narrows, straits, and around promontories and islands (Johnson et al., 1982; Howarth, 1982) as the sea progressively flooded the developing English Channel. This would also explains why troughs developed along directions that almost perfectly and systematically follows the main tectonic structures (Hamilton and Smith, 1972; Evans, 1990; Lericolais et al., 1996). Lericolais et al. (1996) already proposed that late Paleogene-Neogene tectonic played an active role by shaping an initial morphology in which the Hurd Deep subsequently developed. Such scenario is also compatible with paleogeographic and paleoenvironmental reconstructions proposed from middle Miocene to middle Pleistocene by several authors (Gibbard and Lewin, 2003; Dugué et al., 2012, and references herein). They depict the area as large embayment located east of Cotentin and connected to the Atlantic Ocean through a seaway that was narrower than the present day configuration and located where troughs are observed. The length of the whole system from the Western Approaches to the end of the embayment was then ranging from 300 to 400 km, which allows the onset of tidal resonance (REF). In addition, the width of seaway would have played a role in tidal current acceleration.

Testing the hypothesis of tidal scouring would require modelling the erosive effect of tidal currents on local lithologies varying from indurated to unconsolidated, weathered, and fractured chalk, limestone, marls, sandstone or conglomerates. However, input parameters such as the initial morphology of the area, actual velocity, and duration of processes are lacking so evaluating this hypothesis is only possible through comparison to existing tidal scour examples.

One of the largest tidal scours ever described on a shelf are the scour holes of the Bungo Channel, at Hayasui Strait between the Suo-Nada Sea and the Pacific Ocean in Japan (Ikehara, 1998). These twin holes reach impressive depth values of c. 350 and c. 450 m below m.s.l. (c. 250 m and 350 m below surrounding shelf depth) very similar to the “Deep Groove” off Bay of Seine. Ikehara (1998) proposes that these scour holes developed during Quaternary transgressions and highstands as tidal eddies estabished between Suo-Nada Sea and the Pacific Ocean. Another example is located in the Bay of Fundy area, Nova Scotia, Canada, where world’s maximum present day tidal range is recorded with a maximum value of c. 16.3 m (Archer and Hubbard, 2003). In the upper bay, a 5 km-wide narrow, known as the Minas Passage, separates the main water body of the Bay of Fundy from the Minas Basin. There, a series of large tidal scours developed through Quaternary glaciomarine muddy deposits down to the Paleozoic-Mesozoic bedrock, 170 m below mean sea-level (Todd et al., 2011; Shaw et al., 2012). The largest scour centered on the Minas Passage is 30–35 km-long by 5 km-wide. A second scour, located directly to the west (west) is approximately a quarter of the Minas Passage scour. They elongate in the tidal stream direction and are slightly arcuate. Shaw et al. (2012) propose that tidal scouring and removal of Quaternary sediments occurred as sea-level rose during Holocene. Other tidal scours and hollows have been described worldwide including the North Hollow in the Guayaquil Gulf (Reynaud et al., 2018), or the Golden Gate tidal inlet (Barnard et al., 2013; Dartnell et al., 2015). By their morphologies and sizes, giant Quaternary tidal scours of Bungo Channel, Minas Passage North Hollow, and Golden Gate inlet are indeed very similar to most troughs in the English Channel thus making them potential recent analogs.

Reconstructions of the regional English Channel paleogeography by several authors (Bignot, 1972; Larsonneur, 1972; Gibbard and Lewin, 2003; Gibbard and Levin, 2016) between Chattian and Pleistocene all propose the presence of a proto-English channel embayment or seaway at the location of troughs. This is in accordance with the tidal scour scenario and leave a long time interval for multiple complex trough development as we see in both their distribution and sedimentary infill.

5.3. Trough sedimentary infill

The sedimentary infill of the troughs as revealed by high-resolution seismic imaging proves to vary drastically from one trough to the other. Former studies already proposed various hypotheses for the depositional environments ranging from fluvial to shallow marine (Hamilton and Smith, 1972; Auffret et al., 1977; Alduc, 1979; Lericolais et al., 1996; Lericolais et al., 2003; Benabdellouahed et al., 2013; Gupta et al., 2017). In absence of critical sampling, we also rely on seismic images to interpret possible sedimentary environments. Four main seismic facies are recognized from very-high-resolution data (Table 2): We here propose a tentative interpretation of these facies based on their characteristics or similarities with sedimentary features described elsewhere.

Facies 1 represents the first deposits for two troughs (T4, T7, Fig. 5) and can account for most of trough infill (T7, Fig. 5). It exhibits chaotic, medium to high amplitude reflections, with concave-up and –down reflection features. These observations suggest rather complex deposits with small sedimentary bodies and possible reworking. F1 thus indicates that the early deposition in troughs involved repeated cycles of erosion and deposition under dynamic flow. Due to similarities of this facies to the seismic images of the Pleistocene alluvial terraces of the Seine River, it has been previously interpreted as fluvial deposits. However, we prefer to remain cautious as tridimensional geometry of these features is yet unknown. Indeed, if troughs correspond to deep tidal scours incised in the lithified meso-cenozoic substratum, the early deposition could still imply strong tidal currents that may be responsible for this chaotic facies infill interpreted as coarse deposits reflecting high-energy environments. A present day example of such deposits is found on the floor of the Hague Trough in the Alderney Race area, where sets of large tidal dunes composed of pebbles are found (Furgerot et al., 2019).

Very chaotic and low amplitude reflections of facies 2 are often associated to massive unsorted sediments such as mass flow deposits. It occurs only within the c. 50 m-thick nested channels that form the sedimentary infill of Trough 4 above facies 1. One tempting idea would be to associate this facies to catastrophic flood events and to bring a new consistent element to the megaflood scenario of Gupta et al. (2017). Thus, trough 4 may represent a potential path for the first flooding event, while the second one would have flown through the Northern Paleovalley. We understand this hypothesis as rather seducing but still very speculative without any ground-truthing.

Facies 3 displays continuous, oblique, and low angle reflections with downlap terminations filling entire troughs or channels on top of facies 1 (T5, T8, T10; Fig. 7). These oblique reflectors form continuous sets that can reach up to 50 m-thick and develop across the trough over kilometric scale. The height of these sets thus implies a water column of at least 50 m. F3 is present on top of F1 within trough 5 whereas it seems to be directly above the substratum within troughs 8 and 10. The initial sets show apparent lateral migration from south to north in T5, T8 and T10 (Fig. 7). Secondary sets filling channels of T5 and T10 show apparent lateral migration toward the south. These geometries are very similar to those described by Houthuys (2011) in the mid Eocene Brussel Sands (Belgium). This formation is interpreted as tidal sands progressively filling submerged pre-existing incised valleys by lateral migration and accretion under the influence of tidal currents. Internal channelized incisions in the infill sequence of several troughs could correspond to a new phase of tidal scouring followed by lateral infilling as visible in troughs 10 and 5 an Fig. 7a and b respectively. In this context, the low angle and lower amplitude reflections visible in T5 may correspond to tidal mud or sand flats developing laterally to the channel (Fig. 7b). The 80 m-deep enclosed Murray Pit, offshore Belgium, below the Lobourg Channel, also shows similar oblique reflections that may develop as tidal currents affected the area during Pliocene according to several authors (De Batist, 1989; Balson, 1989; Liu et al., 1993).

Facies 4 corresponds to wavy reflections with building-up mounds or levees and adjacent channels. The height of the mounds reaches up to 20 m and the spacing between mounds varies from 100 to 300 m. F4 is encountered in trough 8 where it shows onlap characteristics on both northern and southern flanks of the trough. F4 is best expressed within T8 although crude wavy reflections are suspected within T5 and T10 in few bottom sets of F3. There, they develop in the progressively narrowing channel. F4 in T8 was already noticed by Lericolais (1997) and Lericolais et al. (2003) and interpreted as part of an alluvial system. The actual configuration of channels and mounds (eg. elongation direction, shape) within T8 is yet unclear. Nevertheless, the undulating geometry itself is uncommon for river system. We would rather prefer a shallow marine-shelf environment with persisting bottom currents and sufficient water column height to develop 20 m-high mounds. Tidal currents can be responsible for such geometry development as observed within the Holocene deposits of the Gadoek Waterway system in southeastern Korean peninsula (Lee et al., 2005) or in the tidal channels of the Gulf of Morbihan (Menier et al., 2011).

The speculative interpretation of seismic facies as deposits and environments points toward two type of scenarii. The first one, from fluvial (possibly followed by catastrophic mass flow(s)) to tidal and shallow marine corresponds to the classic record of a transgression (Zaitlin et al., 1994). The second scenario explores the marine-tidal hypothesis alone to explain both the incision and the fill of troughs. This idea had been rejected in former studies because tidal currents were supposedly not efficient enough to cut into the hard substrate of the English Channel. Nevertheless, the studies of giant tidal scours such as Minas Passage and Golden Gate prove otherwise. Thus the incision and fill of the troughs would rather reflect the onset of strong tidal currents and their progressive weakening. This can thus be interpreted either as an effect of one or several transgressions or a progressive change in the shape and size (coastline and bathymetry) of involved water bodies.

Concerning the age of trough's sedimentary fill, the time interval also ranges from Chattien to early Pleistocene.

5.4. Onshore analogs

Whereas this study provides new insights into the understanding of Central English Channel troughs as distinct geological objects, critical aspects of their development are missing. Without direct ground-truthing, these aspects can be addressed by finding accessible onshore regional analogs.

Potential regional targets may be found in the Cotentin area, between Cherbourg and Saint-Lô (Fig. 1). There, several elongated channel and basin remnants are described (Sainteny-Marchésieux (SMB), Lessay (LB), Saint-Sauveur-le-Vicomte (SSB)), with a depositional history spanning Néogène-Pleistocene stages, and a strong tidal influence throughout their development (Garcin et al., 1997; Baize, 1998; Dugué et al., 2000, 2009). According to Baize (1998) and Estournès (2011), these basins have offshore extensions surrounding the Island of Jersey and found within the Ecréhou (EB) and Chaussée des Boeufs (CBB) basins. Within these basins, authors describe infill showing morphology and sedimentary geometries comparable to those of the trough network, and that overlie the stratified Eocene deposits. Maximum depth of incisions varies from one sub-basin to the other from c. 60 m at CBB (Estournès, 2011), 70–80 m at LB and SSB (Baize, 1998), c. 110 m at EB (Estournès, 2011), and c. 170 m at SMB (Vittecoq et al., 2015). In the Cotentin, these small basins developed from middle Miocene (Falun du Bléhou Fm.), and throughout upper Pliocene and lower Pleistocene (Baize et al., 1997, Dugué, 2003). Several arches of possible tectonic origin (horsts) separate the sub-basins from one to another even if connection in proposed (Baize, 1998). As for Central English Channel troughs, their distribution and extension seems to relate on the structural pattern and show very few connections to the present day fluvial network (Fig. 9). The onshore SMB, LB and SSB may be southern equivalent to the trough network described in this study and could be the focus of more accessible studies. This indeed would have to be tested by offshore drilling and sampling of the trough network infill.

6. Conclusion

This study revisits a renowned trough network that has been the subject of several studies for decades. Better constrain the origin and the time of the networks is essential to understand the evolution of the English Channel and part of the NW Europe during a geodynamically significant though poorly known and recorded Late Paleogene-Neogene time interval in that area. Thanks to a dense grid of very-high-resolution seismic lines and oil industry profiles, we propose to distinguish the older deep trough network from the mid-to late-Pleistocene paleovalley network over the Central English Channel. The absence of critical sample in the trough network limits our understanding of the origin and timing of trough development. However, based on seismic imaging and worldwide possible analogs, we propose two distinct scenarios to explain the origin and the spatio-temporal evolution of these networks. The "fluvial" scenario would see the troughs as the remnants of a large and deformed Miocene or Pliocene river network that developed prior to the mid-late Pleistocene one. Taking into account the size and distribution of these remnants, this initial fluvial network would be one of the largest in Europe, thus acting as a long-lasting major source-to-sink element of the whole continent. However, there is a lack of evidence for such a large fluvial network. The "Megaflood" scenario, while tempting, would imply several earlier breaching events of the Dover Strait before MIS12 to explain stratigraphic relationships and the complex distribution of troughs. Otherwise, the "giant tidal scour" scenario would probably reflect the initiation of the connection between the Atlantic Ocean and the English Channel area and its evolution leading to the emplacement of strong tidal currents accelerated within narrow seaways developing preferentially over lithologies prone to erosion. Whereas we do not discard a possible fluvial influence during the trough network evolution, as sea level fluctuations may have emerged the area, the tidal origin *s.l.* for both incision and part of the infill is the enticing scenario we would favor here.

Only direct sampling by offshore drillings could however fade away uncertainties in both timing and processes associated to trough development, as well as evaluating its paleogeographic significance.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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