New perspectives on the English Channel megaflood hypothesis: high-resolution multibeam and seabed camera imaging of submarine landforms in the Northern Palaeovalley

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ABSTRACT

A network of large, bedrock-incised valleys is preserved on the seabed of the English Channel. Based on analysis of a 30x30 m bathymetric grid, the morphology of the valleys was interpreted to be a consequence of erosion by catastrophic flood processes from overspill of a large proglacial lake in the Southern North Sea. The significance of the "megaflood features" has since been recognized by the UK Government with the designation of their protected status in one of three Marine Protected Areas (MPAs) within the palaeovalley in the central English Channel. Here, we analyse recent multibeam bathymetry data (2x2 m DEM) from these MPAs, together with backscatter and high-definition seabed camera imagery. The new data allow us to ground truth and refine the earlier interpretation and recognize previously undiscovered finer features. Streamlined valley margins, streamlined islands and metres-deep scours eroded into the valley floor are described at higher detail, while new subtle features on the valley floor such as kilometre-long, sub-parallel inner channels and streamlined bedrock ridges are identified for the first time. These features are consistent with a high energy erosion origin. We also identify isolated large boulders (> 1 m length) on flat seabed on the flanks of the palaeovalley, which are consistent with deposition from megaflood processes, although wave action during transgression/regression cannot be ruled out. Our new results enable more robust morphological evidence to support the influence of catastrophic flooding on bedrock valley incision in the English Channel.

1. INTRODUCTION

The mechanism and history of the Late Quaternary separation of Britain from continental Europe is a topic of considerable importance for understanding northwest European palaeogeographic evolution, and in particular the large-scale routing of northwest European drainage and meltwater to the North Atlantic via the English Channel. The discovery of an extensive anabranching network of valleys (Fig. 1) eroded into the bedrock seafloor of the English Channel (Auffret et al., 1980) led Smith (1985) to postulate that the valley system had been carved by overspill of a lake in the southern North Sea over a rock barrier at the Dover Strait. This idea was based on the planform similarity of the valley system to those in the Channeled Scabland (eastern Washington state, USA) that have been interpreted to have been eroded by the Missoula floods (Baker 2009). Gupta et al (2007) and subsequently Collier et al. (2015) analysed the morphology of these valley systems in the central English Channel from a 30 x 30 m bathymetric grid derived from single beam sonar data. They showed for the first time landscape elements preserved on the seabed that are characteristic of bedrock erosion by high magnitude flood flows. These interpretations were in accordance with a model of catastrophic drainage of a pro-glacial lake as postulated by Smith (1985). Alternative models for the breaching of the Dover Strait suggest more incremental models for landscape evolution by fluvial erosion during lowstands and marine erosion during transgression and at highstands (Hijma et al., 2012; Mellett et al., 2013; Westaway and Bridgland, 2010). The interpretation of the subaerial Quaternary geomorphological history of the English Channel is complicated because the features now lie under water and the role of marine transgressions, wave and tidal action in the generation of the present-day landscape is debated.

Recent analyses of marine geophysical data from the Dover Strait region have added significant new evidence to the discussion. Gupta et al. (2017) and García-Moreno et al. (2019) presented sub-bottom profile records revealing a set of sediment-infilled depressions (the Fosse Dangeard) that are deeply incised into bedrock that are interpreted as giant plunge pools formed at the foot of the original pro-glacial lake dam. These support a model of initial erosion of the Dover Strait by lake overspill, plunge pool erosion by waterfalls and subsequent dam breaching. In addition, the two papers documented the presence of a prominent bedrock-eroded valley – the Loboug Channel - running through the centre of the Dover Strait that is characterised by features associated with catastrophic flooding and indicative of final breaching of the Strait by high-magnitude flows. These studies indicated that the palaeovalley network in the Channel was carved by at least two catastrophic megaflood events. The first megaflood is envisaged to have been the result of overspill of a proglacial lake in the southern North Sea that was dammed to the south by a chalk rock ridge that extended from Dover to Calais (Gupta et al. 2017; García-Moreno et al., 2019). The second megaflood, inferred from cross-cutting geological relations in the Dover Strait, may have originated within the North Sea itself (for example, overspill of a moraine dammed lake) and reoccupied and further eroded the terrain carved out during the first event (Gupta et al. 2017). This model is consistent with an observation of two spikes in sediment delivery to the Celtic Sea deep fans during Marine Isotope Stages (MIS) 12 (~450 ka) and 6 (~160 ka) (Toucanne et al., 2009a, 2009b). Pleistocene palaeogeographical reconstructions also indicate merging of the Fennoscandian and British ice sheets at these times, which would have blocked northwards drainage and so provided the conditions to form pro-glacial lakes (Busschers et al., 2008; Cohen et al., 2014; Hijma et al., 2012).

The original understanding of the proposed megaflood terrain in the central English Channel was based on a bathymetric grid that was made from single-beam echo sounding data gathered between 1979-2003 (Collier et al., 2006; Gupta et al., 2007). These soundings were collected along 62.5 m spaced transects together with 2.5 km cross-lines and were presented as a 30x30 m grid. A direct comparison between this grid and a modern 100% coverage multibeam echosounder (MBES) dataset collected in 2003 in part of the area showed the mean vertical accuracy of the older grid to be 0.6 m, but with differences of up to +/- 3 m across patches of mobile seabed (sandwaves) and along the edges of some of the prominent bedrock topography. Therefore, whilst the single-beam grid provided the first mapping of the key landforms such as the kilometre-scale streamlined islands, smaller and more-subtle features such as scours around the islands, longitudinal grooves and secondary drainage channels could not be fully resolved, hence leaving interpretations on classification and formation open to critique and discussion (Fig. 2). In 2012 a number of transects of modern MBES and sub-bottom profiler data were collected across the terrain (James et al., 2011a) and these were used to confirm the bedrock-carved origin of the streamlined islands (Collier et al., 2015). Further geomorphological investigations in the central Channel have been hindered by a general lack of data, especially continuous, single survey high-resolution bathymetry.

Between 2006 and 2019, benthic habitat monitoring by the UK government included the collection of high-resolution (1 to 2 m/pixel, 0.25 m vertical accuracy, Fig. 2) MBES data and high definition (HD) video camera tows in three Marine Protected Areas (MPAs), known as Offshore Overfalls, Offshore Brighton and Wight Barfleur Reef, that correspond to portions of the Northern Palaeovalley (Fig. 1). In this paper, taking advantage of these high resolution data, we present a new investigation of seabed morphologic features in the area to provide a nested (i.e. multi-level) description of the seabed geomorphology and composition.

Previous studies of catastrophic flood terrains preserved on land have identified an association of landforms that are typically encountered in such landscapes. The features have been grouped according to size, from macroscale landforms such as cataracts and anastomosing channels (kilometres), to mesoforms such as streamlined islands and boulder bars (kilometres to hundreds of metres), to microforms such as boulders, potholes and flutes (metres) (e.g. Baker (2009, 1978); Baynes et al. (2015)). Many of these landforms are not exclusive to the action of extreme flood flow, and their presence within a landscape does not necessarily lead to the conclusion that an extreme flood event has taken place. A thorough inspection will have to consider the landscape as a whole and how multiple landforms are ‘associated’ with each other across a range of spatial scales, to give an insight into the magnitude of the events that formed them (Carling et al., 2009a). The aim of this study is to use the newly available multibeam bathymetry and backscatter data together with video images of the seafloor to investigate whether meso and microscale seabed forms consistent with the megaflood hypothesis are present or not, to correlate them with the macroscale features of the bathymetry data and thus test the megaflood hypothesis.

The significance of the seabed topography in the Northern Palaeovalley from a historical perspective of Island Britain as well as the seabed habitats they provide, has also influenced the level of policy making. The portion of the palaeovalley tract with streamlined islands within the Offshore Overfalls Marine Conservation Zone (MCZ) (Fig. 1), has been designated as a protected feature (English Channel Outburst Flood Features), following the UK Marine and Coastal Access Act (2009), and could be considered a *de facto* marine geopark. A secondary aim of this study is therefore an improved recognition of the megaflood-related features, both within the currently designed area (Offshore Overfalls) and in the other two MPAs where the protected status is not applied due to the present lack of detail.

2. GEOLOGICAL AND ENVIRONMENTAL SETTING

A key element for the identification and preservation of the English Channel geomorphology is that it is mostly carved into bedrock. Knowledge of the bedrock geology, and its various erosional properties, is therefore needed to interpret the features. The region is composed of several discrete sedimentary-rock-filled basins separated by major faults. During the Alpine Orogeny (Latest Cretaceous-early Tertiary) some of the basins were uplifted (exposing Mesozoic sedimentary bedrock at the seabed) while others underwent subsidence (allowing Palaeogene sediments to accumulate). The study area is mostly situated in the Channel Basin, where the upper Cretaceous white Chalk Group and the lower Cretaceous Greensand, Gault Clay and Wealden Group are exposed in a synclinal fold (Collier et al., 2006). The basin is bound to the east by the Wight-Bray Fault (Lagarde et al., 2003), a major NW-SE oriented structure that runs from the Isle of Wight to mainland France, and to the South by the Mid Channel Fault, which runs E-W parallel to the southern English coastline. Close to these faults the bedrock bedding can approach vertical. To the south of the Channel Basin is the Paleogene/Mesozoic Central Channel Basin and to the east the Paleogene Hampshire Basin. (Fig. 1, British Geological

Survey, 1995). The Palaeogene rocks comprise interbedded sandstones and claystones, which form an alternation of hard and softer layers, linked to fluvial to marine depositional successions (Hamblin et al., 1992). This hardness heterogeneity leads to an irregular seabed morphology, where more resistant strata protrude from the seabed (e.g. bed in Fig. 2). Conversely, the hard and massive Chalk Group outcrops show a generally flat or hummocky seabed morphology (Collier et al., 2006). The other main lithologies of the study area are the Upper Jurassic clays, sandstones and dolostones of the Mid Channel Anticline, which crop out north of the Mid Channel Fault. Like the Palaeogene lithologies, these outcrops produce a seabed with marked topographical expressions, in the form of ridges and depressions.

The seabed of the Northern Palaeovalley is mostly characterised by bedrock outcrops or veneers of coarse sediment (pebbles to cobbles), at times apparently cemented to form a compact rough layer (James et al., 2011a). This cemented gravel is particularly common in Offshore Overfalls (James et al., 2011b). In other places the seabed is covered by unconsolidated sandy deposits and sandwave fields, particularly towards the east of our study area (James et al., 2011a), hindering the interpretation of the underlying bedrock geomorphology.

The study area is dissected by the western part of the Northern Palaeovalley, the main unfilled valley of the English Channel (Auffret et al., 1980; Diesing et al., 2009), characterised by paleochannels bordered by terraced rock platforms. The valley segment described in this study is about 80 km long and varies in width from ~5 to 12 km. It is oriented mainly NE-SW, but changes orientation when it crosses the Mid Channel Fault, turning abruptly N-S (Fig. 1) before merging into the Central Palaeovalley. In turn, these two palaeovalleys merge into the structurally-controlled Hurd Deep about 50 km downstream of our study area (Fig.1, Lericolais et al., 1996). Streamlined islands have been previously mapped within the study area in the Northern Palaeovalley. They have been classified as bedrock islands carved by high magnitude flood events (Collier et al., 2015, also numbering in Fig. 3) because their lemniscate shape, k values (degrees of elongation) and shape factors Xm (location of their maximum width) are very similar to examples in the Channelled Scablands (Baker, 1978) and on Mars (Carling et al., 2009b). The chalk islands form a population distinct from the Palaeogene ones (the latter having smaller k values) which further supports their megaflood origin.

While post ice age marine transgressions have most likely affected the seabed, modern wave and tidal regimes are not strong enough to erode rock or rework large clasts (cobble or greater). Mitchell et al. (2013) show that Holocene tidal currents were ineffective at eroding bedrock in the English Channel, and this assessment can be projected at least to the Late Glacial Interstadial based on palaeotidal models for the British Isles (Uehara et al., 2006; Ward et al., 2016). At present, the greatest current speeds at the seabed occur to the south of the Isle of Wight, along a vertical transect to the Cotentin peninsula in France, where they are in excess of 1 m/s, mobilizing grains up to pebble size (Velegrakis et al., 1997). The transect acts also as a bedload-parting zone, where east of it, sediment is transported northeastward. Significant disturbance of the seabed by wave action is limited to waters less than 30 m (Grochowski and Collins, 1994), however, annual maximum significant wave heights can be higher than 2.5 m and are able to disturb the seabed up to 60 m deep (Connor et al., 2006).

3. METHODS

3.1. Data collection and processing.

The acoustic data presented here were collected between 2006 and 2019 onboard the Cefas RV Endeavour together with similar quality MBES archive data from the United Kingdom Hydrographic Office (UKHO). The Endeavour was equipped with a Kongsberg EM2040 system at 300 kHz, recording both bathymetry and backscatter. While full areal coverage was obtained at Offshore Overfalls, less than 50% of Wight Barfleur Reef's area was covered, and an even smaller proportion was surveyed at Offshore Brighton (Fig. 1). Ship motion and position were recorded using the SBG Systems Motion Reference Unit (MRU) and CNAV 3050 high precision GPS. Bathymetry data were processed using CARIS HIPS & SIPS™ and MBES backscatter data with the QPS FMGT™ software packages.

Seabed imagery stations were located either at features of interest for habitat monitoring or in a regular grid across the wider site (as per MPA monitoring protocol). Video and camera set-up and operation followed the Mapping European Seabed Habitats (MESH) guidelines (Coggan et al., 2007). Before 2017, standard-definition video footage was collected at an oblique angle to the seabed and recorded on a Sony GV-HD700 DV tape recorder and a computer hard drive. The video footage was interrupted momentarily to collect still images at points of interest for benthic ecology. From 2017 onwards, video and still imagery were acquired separately (resulting in seamless video footage) using a STR SeaSpyder "Telemetry" drop camera system, with a 1080p HD video camera, 18-megapixel digital stills camera, both orthogonal to the seabed (~1 m from it). A second video camera (referred to as the IP camera) was mounted on the exterior of the frame (40 cm above the orthogonal camera) in an oblique, forwards facing orientation, permitting the observation of the surrounding seabed. Overall, tows were from 5 to 15 minutes long, covering between 50 to 150 m of seabed. STR Subsea laser pointers (two to four points), with a wavelength of 650 nm and a spot size of ~6 mm, permitted an estimate to be made of the dimension of features on the seabed.

3.2. Interpretation

Processed MBES mosaics were displayed and analysed in ESRI ArcGIS™ 10.5. In some areas, bedrock texture from the new data could be used to improve the locations of geological boundaries obtained from the British Geological Survey (BGS, made available under the Open Government Licence, © NERC, 2020) and previous studies (Collier et al., 2015, 2006, Fig. 2). For this study, a total of 200 video files were reviewed, and occurrence of rock outcrops and boulders deposits mapped. Boulder dimensions were estimated using the laser scale, with an estimated uncertainty of 10 cm. In many cases the seabed bedrock geology could be identified in the visual imagery and so acted as ground-truthing of inferred seabed type from the bathymetry texture and backscatter values in areas without camera tows.

Seabed erosional surfaces were isolated using the method presented by Mellett et al. (2013), with special focus on the uninterrupted MBES dataset in Offshore Overfalls. A frequency histogram of bedrock elevations was produced (Fig. 4), and multiple populations were distinguished by qualitatively identifying peaks in the distribution and placing separators between them. Groupings were adjusted to match geomorphological observations (e.g. consistent with general platforms extent bounded by slopes). Due to the natural E-W slope of the English Channel, surfaces are about 10-12 m deeper in Wight Barfleur Reef compared with Offshore Overfalls (compare palaeovalley floor depths in Fig. 3 against Fig. 5), so the group boundaries were lowered by this amount.

4. RESULTS

The new MBES data show a higher level of complexity in the macroscale features previously identified, while new smaller-scale features have been identified using both MBES data and camera imagery. Below we describe the morphology and landforms in the Offshore Overfalls and Wight Barfleur Reef study area to explore their processes of formation within the context of prior interpretations of the English Channel palaeodrainage system. Each section will contain the description of the feature/s followed by a brief interpretation of its/their genesis.

4.1. Macroscale Bedrock Erosional Landforms

4.1.1. Erosional Surfaces.

The seabed can be subdivided into five different erosional surfaces (ESs) (Fig. 4).

ES1 is the shallowest and most extensive of the erosional surfaces. It includes a bedrock platform gently sloping down to 39 m bsl in Offshore Overfalls, which stretches across the northern part of the study area. For most of the western and central part of the MBES data the chalk is cropping out, and it shows subtle E-W-trending bedding planes, more vertically pronounced and folded to the North and East (Sandown Anticline (Collier et al., 2006)) (Fig. 3). Sinuous or dendritic palaeochannels oriented roughly N-S cut the surface in different places. The most evident is the palaeo-Solent river (Fig. 1), but other small tracts, etched in bedrock and not tracing onto land, are visible at the southern edge of ES1 in Offshore Overfalls (at the border with ES2, Fig. 4). To the east ES1 is blanketed by sediment drift, forming elongated ribbons or irregular waves (Fig. 3 and 4).

ES2 extends between 39 and 52 m bsl and forms a distinct terrace in Offshore Overfalls, bound by ES1 to the northwest and the main channel of the Northern Palaeovalley (ES4) to the southeast. ES2 is also present southwest of the Northern Palaeovalley and extends beyond the region of MBES data of the study area. The ES2 terrace develops upstream of a constriction in the palaeovalley to the northeast of Offshore Overfalls; it is a crescent-shaped and planar surface ~25 km long and 4 km wide at its maximum, sloping very gently (0.005°) towards the SW and ~0.2° toward the palaeovalley (from NW to SE) and widely incised by secondary channels. Its surface is mainly covered by the cemented, coarse gravel pavement, but the presence of chalk bedrock can be determined from the HD photography (Fig. 6D) and BGS drill cores (Gupta et al. 2007). Further supporting evidence for bedrock presence is given by the "banded" MBES texture on the terrace and layering at the scarp border with the Northern Palaeovalley floor (ES4), which appears to be bedding in the Chalk bedrock (Fig. 3). The bounding scarp with ES1 is longitudinally curvilinear and exceptionally smooth, with no indentations. Scarp slopes are generally <10° and can be either smooth (Fig. 4C) or show a "stepped" vertical profile (Fig. 4A). More abrupt scarp slopes (>15°) are observed in some cases. Modern sediment drift, 1-3 m thick and rippled towards the southwest, is present along the scarp foot forming wide aprons; eastward the drift is not evident and both MBES texture and camera imagery do not indicate thick sediment cover (i.e. bedrock is visible). Nonetheless the channels, which are widely distributed across the lower part of the terrace, become more subtle or disappear completely closer to the ES1 scarp. The lower scarp separating the ES2 terrace from the Northern Palaeovalley floor (ES4) shows a different morphology to that between ES2 and ES1. It is characterised by an undulated (or "scalloped") longitudinal profile, with small (up to 1 km long) embayments and bedrock promontories (bedrock bedding is visible, see Fig. 3G). Most promontories correspond to the mouth of one of the various secondary palaeochannels incised in the terrace and directed into the NP (Fig. 4). Scarp slopes are generally <10° and typically have a “stepped” profile while descending to the NP floor, forming small minor arcuated terraces that belong to ES3 (Fig. 4).

ES3, between 52 and 58 m bsl (64-70 m bsl in Wight Barfleur Reef), includes Jurassic and lower Cretaceous bedrock successions in Wight Barfleur Reef, the flat tops of the streamlined islands and a ~5 km long and 800 m wide lunate terrace in the southern part of Offshore Overfalls, bound by the ES2 terrace to the north and Northern Palaeovalley to the south. The surface of the terrace is flat and presents a step-like transition to ES2. No camera tows were collected on the terrace so the seabed composition can only be inferred from the MBES bathymetry and backscatter texture, which does not appear to differ from ES2.

ES4 between 58 and 65 m bsl in Offshore Overfalls and down to 75 m bsl in Wight Barfleur Reef coincides with the NP floor. It is mostly flat and smooth to the NE, when on chalk bedrock, whereas to the SW, on older or younger lithologies, it becomes very irregular, showing a complex morphology of bedrock ledges, depressions and rises partly following the underlying geological structure. Bedrock scouring, that was poorly resolved in the earlier studies, is now visible with great clarity throughout ES4 (Fig. 3). Two elongated, shallow (2-3 m deep) and curvilinear scours occur SE of Island 25, following the shape of the streamlined island and that of ES3 scarp margin. Deeper scours are classified as ES5, as they appear as a separate population in the bathymetry histogram (Fig. 4). The most pronounced scours of ES5 are located in Wight Barfleur Reef, where the deepest can reach 20 m below the average ES4 surface. They are south of the Mid Channel Fault and correspond to outcrops of Eocene clay (London Clay Fm). A second set of deep scours is to the NE of Offshore Overfalls, east of the Wight-Bray Fault, and reach a depth of 72 m bsl in the Palaeogene formations (~10 m deeper than ES4).

4.1.2. Streamlined Islands.

The most distinctive evidence for a catastrophic flooding mechanism for erosion of the Northern Palaeovalley is the presence of streamlined islands or erosional bedrock remnants (Collier et al., 2015; Gupta et al., 2007). Our new data provides considerably more detailed information on the morphology of the islands by comparison to the original single beam data grid.

The islands form flat-topped, positive relief lenticular mesas that sit within the Northern Palaeovalley with long axes oriented approximately parallel to the valley axis. They are characterised by smooth, arcuate outlines. The islands sit up to 10-15 m above the valley floor. The new MBES data enables the planform shape of the islands to be clearly imaged. A variety of different forms are preserved. Many of the islands show a blunt or more rounded upstream end that narrow downstream to a pointed tail (islands 24, 25). These are classic tear-drop shaped islands (Baker 1978). Islands 23 and 24 meanwhile form part of a larger, quadrilateral shaped island.

Close observation of the MBES texture of the islands confirms that they are formed of layered bedrock (islands 22, 23 and 24). For example, the tip of Island 24 seems to be coincident with deformation within the chalk beds (Fig. 3D). Moreover, the improved spatial resolution of the MBES data enables different stages of bedrock island evolution to be now clearly deduced. Island 25 comprises an upper elongated blade-like form overlying a larger, leminiscate platform, the contour of which can be made out in the bathymetry data within ES4 (Figure 3A). Continued flood erosion can be invoked as the cause for the narrowing of the upper section of the island. The same can be seen for islands 26, 27 and 28, which were possibly united as a single structure before new channels – divide crossings – sub-divided the island into smaller fragments (Fig. 3). Similarly, the quadrilateral island structure (formed of islands 22 and 23) is dissected by a 1.7 km wide, ~5 m deep channel that is hanging relative to the surrounding main valley floor (surface ES4). This feature is interpreted as a spillover channel where flood waters overflowed across the island carving a new channel and dissecting the island into two (islands 22, 23); subsequent flood erosion and deepening of the main valley floor caused the spillover channel to be abandoned. The new data therefore enhances the previous interpretation of these features as having been carved by megaflooding and suggests that the islands evolved and fragmented during the high magnitude flood erosion.

Two additional teardrop-shaped hills, tapering towards the WSW, and located in the chalk bedrock area of Offshore Overfalls close to the southern flanks of the lower ES2 terrace (Fig. 3E and F) have been identified. They rise from ES4 and their axes orientations follow closely the curvature of the scarp border with ES2 and ES3. Linear benches (visible in Fig. 3F) on the flanks of the northernmost hill indicate a bedrock composition for the feature. We compared the geometrical indices of these newly discovered features to the streamlined island population analysed by Collier et al. (2015). The larger of the two hills is 1.3 km long and 300 m wide (elongation ratio = 4.3, elongation factor k = 4.77, shape factor Xm = 0.82, see Komar, 1984 for full description of these indices), its maximum height is 5.2 m. The smaller hill is 0.94 km long, 167 m at its widest (elongation ratio = 5.6, elongation factor k = 4.83, shape factor Xm = 0.62), and up to 4.5 m high. These shape measurements are all higher than the average of the streamlined islands in the chalk regions of the Northern Palaeovalley (elongation ratio = 3.21, k = 3.5, Xm = 0.5, Collier et al., 2015), and are found at the extremes (and beyond the extremes for Xm) of the chalk population limits provided by Collier et al. The airfoil shape and small size of the teardrop-shaped hills make them comparable to type A loess islands in the Cheney-Palouse tract (Patton and Baker, 1978), interpreted as erosional remnants that were completely covered by the flood. They contrast with islands interpreted as having been only partially submerged or unsubmerged (Type B and C), which are typically larger, show more developed flanking scarps, rhombohedral shapes and may preserve pre-flood topography on their top (such as seen on Channel island 26). We interpret therefore the newly observed small islands as subaqueous remnants, while the other major islands in the study area belong to Type B and C (*sensu* Patton and Baker, 1978).

4.1.3. Secondary Palaeochannels

Superimposed onto the bedrock surfaces of the Northern Palaeovalley in the Offshore Overfalls area are a network of small, secondary branching and sinuous channels that are incised into chalk bedrock (Fig. 3 and 4). Given their relatively small size (on average 80 m wide and ~3 m deep), the new multibeam data allow their detailed analysis for the first time. We identify two different groups of incised channels: (1) channels incised into the northeastern side of the palaeovalley, and (2) those incised into bedrock of Island 26 and the southeastern side of the palaeovalley.

The first group comprises simply branching, dendritic channels up to 10 km in length, up to 9 m deep and with a depth:width ratio of ~0.03 (Fig. 4). Despite the partial sediment cover, several of these channels can be traced crossing multiple erosional surfaces in their course, i.e. dissecting the south-east edge of ES1, then continuing on the ES2 terrace and then parts of ES3. Their longitudinal profiles are generally linear to slightly convex up (e.g. Fig. 4, profile 3-4), except two major unburied remnants on ES1, which show a marked knickpoint (convexity upward) near their mouths, i.e. at the ES1-ES2 scarp, and the steepness of the profile downstream of the knickpoint is much higher than that found in the main trunk (Fig. 4, profile 1-2). Moreover, a semi-rounded “pool” feature is found at the corresponding scarp foot on ES2 for both channels (Fig. 4A, C).

The second group of incised channels comprises subtle or shallow features, with a depth:width ratio of ~0.01. The channel remnants on Island 26 are sharply truncated at the edges of the island indicating that the drainages pre-date island formation.

The channels draining from SE show quasi-linear longitudinal profiles and a significant convexity upward/knickpoint at the boundary between ES3 and ES4, although not a truncation as abrupt as for Island 26 or the channels in the NW group on ES1. The knickpoints observed for the group 1 channels on ES1 and the group 2 channels suggests a truncation and the lack of readjustment to the new lowered base level at either ES2 (for group 1) or ES4 (for group 2), leaving the channels hanging. All the other incised channel sections that terminate at ES4 had apparently more time to readjust to the new base level, as shown by their linear or quasi-linear longitudinal profile.

The hanging nature of the incised network superimposed onto Island 26 is explained by its location and correlation with the streamlined island. The size of the drainage is much larger than the area of the island and only a part of the network is preserved – the boundaries of the island clearly truncate the channel network. This indicates that the channel network formed originally on a larger surface (an extended ES3) than currently expressed on the island, and it was possibly a palaeoriver flowing congruently to the palaeovalley axis. The carving of surface ES4 and the formation of the island caused the drainage net to be truncated and abandoned.

The hanging channels incised into the edge of ES1 are instead puzzling, considering that in a fluvial/megaflood model they have the same age or are older than those on ES2, and they should have had the same or more time to re-equilibrate their profiles. The option of abandonment after truncation for the ES1 channels is not satisfying, as the plunge pools and their clear connection to continuing channels on ES2 indicate that they were active after the truncation and creation of the ES2 terrace. The alternative explanation of time-transgressive truncation by wave action is also not a suitable option, as cliffs are not present at the marine mouths of channels and erosion is driven by a combination of wave and fluvial processes (Anderson et al., 1999; Snyder et al., 2002).

Overall, the secondary incised channels are interpreted as palaeochannels formed by subaerial fluvial incision processes acting during lowstand phases after ES1 and ES2 formation, or as ephemeral drainage of megaflood water than carved ES2 and ES4.

4.1.4. Submarine terraces

In Wight Barfleur Reef, submarine bedrock terraces, generally 100s m wide and a few kms long are observed (Fig. 5A and B). Their surface slopes away from the outer edge towards the inner margin, and they are bound by steep scarps. In some places the outer edge has a planar (truncated) top. Figure 5A clearly shows the presence of boulder accumulations across the edge of the western terrace, and Figure 7F confirms the presence of large boulders also on the eastern terraces. The eastern terraces are located in the deepest scours of WBFR (ES5) forming a stepped-like bathymetry with a concave profile towards the inner part.

Overall the terraces may be explained as wave-cut platforms due to their geometry, with some underlying structural control as the inclination away from the presumed shoreline is very atypical (Stephenson, 2000). However, this explanation is insufficient to fully account for the morphology of the eastern terraces:

1. the concave profile is indicative of enhanced erosion in the inner part of the terraces;
2. the terraces have an average depth of 85 m bsl, which means that they would have been already under 17 m of water at marine transgression, as encroaching sea water from the West would have had to cross the shallower mouth of the Northern Palaeovalley at its conjunction

with the Central Palaeovalley, approximately 68 m bsl. This means that the terraces could not have possibly formed by wave cutting. Following this evidence an alternative freshwater origin is suggested, with this stepped bathymetry possibly indicating waterfall action.

4.2. Mesoscale Bedrock Erosional Landforms

4.2.1. Inner curvilinear scours

Gupta et al. (2007) identified as additional evidence for catastrophic flooding the presence of longitudinal lineations or grooves on the floor of the Northern Palaeovalley. However, these features were very much at the limit of resolution in their data. We find that the valley floor (ES4) is eroded into inner scours that are up to 10 kilometres long, several hundred metres wide and several metres deep. The scours are oriented parallel to the valley long axis and show curvature around intra-valley topography or follow valley margins. This is clearly illustrated in the Offshore Overfalls area adjacent to islands 24 and 25 (Fig. 3) and in Wight Barfleur Reef, around island 33 (Fig. 5). Southeast of island 24, a ~5 m deep, ~400 m wide (at its base) linear inner channel is observed. This is truncated by a prominent 10 km long, 400 m wide, and ~3 m deep NE-SW oriented inner channel that curves convex downward at the margin of island 24 and then curves to the southeast around island 25. Adjacent to the northwestern margin of the Northern Palaeovalley, we observe metre-deep scours that extend for kilometres parallel to the valley margins and following its curvature.

The orientation of these scours parallel to the valley gradient, with long axes sub-parallel to valley walls and showing curvature that follows wall and intra-valley topography strongly indicates that their formation is linked to the same processes that formed the valleys. In particular, the formation of scouring around streamlined islands indicates that they were formed by similar flow processes and their curvature should approximate flow streamlines. The form and length scale of the inner scouring does not resemble fluvial forms arising from normal fluvial processes; for example, no sinuous channel forms are observed. Additionally, the scours are not congruent to the tidal ellipsoids for this area (cf. Kirby et al., 2011) or to the axis of megaripple trains that cross the palaeovalley, suggesting an independent formation from bottom currents. Inner scouring is interpreted as distinct evidence for erosion by high-magnitude flood flows, perhaps by localized erosional deepening during flood flow. Similar forms have been reported in the Channeled Scablands (Baker 1978), though their mechanism of formation remains enigmatic.

4.2.2. Streamlined bedrock ridges

In the Offshore Overfalls area, the older singlebeam data showed a constriction in the Northern Palaeovalley where it crosses from Palaeogene to chalk strata across the Wight Bray Fault (Fig. 3). The new data reveals the detailed morphology of this constriction in the valley planform. Firstly, it shows that the actual Wight Bray Fault and the geological boundary with the massive chalk is located slightly further south than originally interpreted (Fig. 2, cf. Collier et al. (2015)). The previously interpreted fault line is now reinterpreted as a hard, protruding Palaeogene bed which crosses the region from NW to SE (Fig 2 and 3).

Secondly, a distinct set of bedforms – streamlined bedrock ridges – are found associated with the valley constriction. The first set of streamlined bedrock ridges are associated with a gap in the stratigraphically higher Palaeogene hard bed (Fig. 3C). The gap is 500 m wide and ~5 m deep. The smooth texture on the MBES data and the presence of ribbon-like features suggest that the centre of the gap is covered by sediment, which makes 5 m only a minimum value for the depth to the bedrock surface. Deep scours, partly filled with sediment, are found in the palaeovalley floor (ES5) to the NE and SW of the gap. The SW scour, 8-10 m deeper than the surrounding ES4 seabed, stretches until the WBF, where the seabed regains quickly the average ES4 depth of

~64 m bsl. The small set of partly buried streamlined rock ridges in the gap are oriented parallel to the palaeovalley axis; they are up to 100 m long, 30 m wide and 1 m high, have been clearly sculpted against (i.e. perpendicular to) the NW-SE bedding direction.

The gap, streamlined remnants and deep scouring are consistent with intense flow and erosion through the palaeovalley constriction during a flood (Carling et al., 2009b). The protruding Palaeogene hard bed would have provided a temporary barrier to the water flow, however the gap formation could have been facilitated by the presence of a NE-SE fault or weakness in the Palaeogene bed at that location. This proposition is supported by the presence of a fault just 1.8 km NW, at the flank of the palaeovalley, where displacement of the Palaeogene bed is visible, and a second smaller gap in the bed 2 km further NW (Fig. 3).

The second set of streamlined bedrock ridges forms a constrained fan-like structure eroded into the chalk bedrock (Fig. 3B). They originate at the trace of the Wight Bray Fault and are also coincident with the southwestern end of the scour in the Palaeogene rocks described above, and a straight line can be projected from that point for ~1.5 km NE, to the centre of the gap in the hard Palaeogene bed (Fig. 3). The ridges are oriented parallel or only a few degrees oblique to the axis of the palaeovalley channels, they are up to ~700 m long, 30 m wide but all less than a metre high and with a symmetrical, rounded profile. HD camera images confirm the chalk outcrop composition (Fig. 6A) and the analysis of MBES texture in the area suggests that they follow at least partly the chalk bedding at the site.

Other large, streamlined ridges on ES4 have also been mapped outside of the Offshore Overfalls, in the southern reaches of WBFR within the Central Channel Fault zone (Fig. 5C). These features appear again to be congruent to the local bedding structure of the area and on the sides of the palaeovalley; however, their rounded profiles suggest erosion by water. They are more than 1.5 km long, and vary in dimensions, the largest being 300 m wide and 4 m high.

The streamlined bedrock ridges are interpreted as lineations or furrows sculpted by high energy, sediment-laden flood waters, possibly linked to longitudinal vortices in the flow (Carling et al., 2009b). Similar ridges have been observed in the Channelled Scablands (Baker, 2009), parallel to the palaeoflow direction. The occurrence of the fan-like streamlined ridges structure at the SE edge of the palaeovalley constriction in the Offshore Overfalls, following the gap in the Palaeogene bed, a deep scour in the seabed and also in correspondence of the WBF (a lithological boundary), suggests a strongly channelised water flow and possibly a drastic change in water flow regime with the change in bedrock competence at the boundary.

4.3. Depositional Landforms

In megaflood landscapes, depositional landforms and sedimentary deposits provide important clues to flood processes, flow dynamics and sediment transport (Carling et al., 2009a). Indeed, flood-formed deposits such as large bars and gravel dunes have often provided critical evidence to infer megaflood processes. Unfortunately, palaeo-depositional landforms are very rare in the Northern Palaeovalley, possibly because any such forms originally deposited were subsequently erased during marine transgressions or by tidal action. Nevertheless, we identify two distinctive landforms in the study area that likely represent palaeodepositional features: (1) a set of relict coarse-grained dunes and (2) boulder deposits.

4.3.1. Relict coarse-grained dunes

In the southwestern portion of the Offshore Overfalls study area, a train of short, subdued linear ridges are observed on the channel floor, along the edge of the small ES3 terrace (Fig.3E). These ridges have along crest lengths of ~400 m, amplitudes of ~60 cm to 1 m and a wavelength that ranges between 80-160 m. The most prominent ridges are observed at a depth between -56 and -58 m, on ES3, but similar features appear to continue northeastwards into deeper waters (-60 to -62 m) on ES4. The ridges have an asymmetric topographic profile with steeper, lee sides facing to the northeast and a mean crest orientation of 125° N. While no bottom imagery was collected across these deposits, the backscatter acoustic texture is similar to the general palaeovalley floor, which is characterised by cobbles and pebbles. This suggests that these ridges may also comprise sediments with a cobble- and pebble- surficial grain size.

We interpret these ridges as relict coarse-grained dunes based on their inferred grain size and subdued and "broken" texture, very different from the clear modern mobile sedimentary features, for example, the dune trains that obliquely cross the floor of the Northern Palaeovalley and from the prominent transverse dune field in the north-eastern part of Offshore Overfalls area (Fig. 3). Their orientation is roughly congruent to tidal ellipses modelled for the area, (cf. Kirby et al., 2011), so they are tentatively interpreted as tidal submarine in origin.

4.3.2. Boulder Deposits

A key novel finding of our study is the occurrence of boulders, either isolated or in deposits, from observations of video tow data on the seabed in several parts of the study areas (Fig. 6, 7 and 8). Boulders were identified at 58 of the 172 stations analysed, 24% of which are within Palaeogene and 55% in the Lower Cretaceous (Wealden Group) provinces (Fig.8), suggesting a strong lithological control on their presence or formation. In most cases, the lithology of the boulders themselves was impossible to determine, due to covering by encrusting benthos, water turbidity, or distance of the camera. Therefore, the nature of boulder transport was determined by examination of their shape (angularity etc.) and their relation to the surrounding seabed (presence of nearby rocky scarps etc.). We identify three different classes of boulder deposits based on clast size, abundance and morphology together with the relationship of clasts to surrounding seabed topography (Fig. 8):

- Type A boulder deposits mainly consist of piles of clasts, many of which appear to be related to nearby planar or protruding bedrock outcrops. When associated with scarps, clasts can be more than a metre long, angular, tabular and weathered, showing extensive boring and fractures. Locally they form chaotic clusters, with angular to subangular, parallelepipedal boulders piled up very closely or on top of each other (for example in Fig. 7G, H), with some observed with still attached sides to the original outcrop, indicating minimal transport. Accumulations on flat seabed occur when bedrock show jointing or fracturing on its surface, and small planar boulders detach and pile on it. Type A is observed in all the study area apart from the chalk outcrops. Its origin appears to be related to the bedrock lithology and geotechnical properties, with the massive and resistant chalk formations less prone to form Type A than the bedded Jurassic or Palaeogene formations. Either periglacial fracturing, bedrock jointing and heaving and wave cutting or a combination of these processes are suggested as a mechanism for its formation (Ballantyne, 2018; Dionne, 1983).
- Type B deposits comprise small to very large (>2 m in diameter) boulders separated by barren seabed (for example Fig.7E or F, in contrast to the Type A deposit shown in Fig.7G, where clasts form piles). Clasts are angular to subrounded (Fig. 7C), mostly tabular or slab-like, laying on bare bedrock or coarse-grained sediment. These deposits are not directly related to fracturing in

subjacent bedrock outcrops, as in Type A, however they often occur not far from bedrock scarps (cf. bathymetry in Fig. 5 and position of boulders shown in Fig. 7E, F). Overall, it is hard to assess how far the boulders have been transported, because they are all heavily encrusted by sponges or weathered; a lithological determination was not feasible. Figure 5A and B show the relationship between Type B deposits and a set of small submarine terraces, where the deposits occur close to the outer edge of the terrace and on the scarp. While the formation of the terraces is not unequivocal, the morphology of the deposits and their association with the scarps supports either an origin as debris arising from subaerial scarp erosion or as boulder beaches on wave-cut platforms (Buchanan et al., 2020; Causon Deguara and Gauci, 2017). Boulders were detached from the rocky scarps and reworked by waves, which could account for the rounded shape of some of the clasts.

- Type C boulder deposits include isolated or very sparsely clustered boulders. These boulders are angular to subrounded, subspherical to elongate, and they sit on sub-horizontal seabed, either coarse-grained sediment or directly on bedrock (Fig. 6E, F). The largest boulder seen belonging to this group has the longest axis >1.5 m (Fig. 6G, H). In a few cases it was possible to detect that the boulders had a different lithology from the underlying bedrock. For example, in Figure 6B, an angular small block of possibly dark mudstone is found on chalk bedrock ~4 kilometres away from the closest possible source of the boulder (Palaeogene rocks, see Fig. 3). Similarly, coarse-grained pinkish boulders are found on grey Lower Cretaceous bedrock in Figure 7A and B (location on Fig. 8). In all occurrences, no nearby elevated outcrops are observed either on the video tow or from interpretation of the MBES data (when available); the closest scarp was found more than 100s metres away. Type C deposits occur predominantly along the margins of the Northern Palaeovalley, either where the valley shows widening (samples in Offshore Brighton), or where the palaeovalley bends abruptly and changes direction to N-S (samples in Wight Barfleur Reef, Fig. 8). Two possible origins are proposed for Type C deposits. The first is a megaflood-related origin, with the boulders representing erratics that were transported by high magnitude flood flows. This interpretation is supported firstly by the consistent distribution of Type C deposits along the margins of the Northern Palaeovalley, in places where decrease in flow velocity leads to clast deposition, as documented in other studies (Waitt et al., 2019). This interpretation is also reinforced by the documented cases of boulders that are lithologically different from the underlying bedrock. Although normal Pleistocene fluvial processes could account for the transport of the smaller boulders (e.g. Fig 6B), such processes cannot explain the presence of the metre-sized clasts that are frequently observed (cf. De Brue et al., 2015). A glacial erratic or iceberg dropstone origin can be readily ruled out, as palaeogeographical reconstructions of the English Channel during the Pleistocene suggest that the local (southern British and Fennoscandian) ice sheet margin during stadials was either far or land-locked (Hijma et al., 2012). The second possible origin for Type C deposits is wave-related detachment and movement of boulders during powerful storm events. Previous studies have recorded movement and transport of very large boulders along different European coasts (Causon

Deguara and Gauci, 2017; Cox et al., 2018), with single massive boulders having moved for 100s m. This explanation does not justify the very far transport distance observed and the marked distribution along the palaeovalley margin. However, with the present data it is not possible to ascertain lithology and distance from origin in most of the cases, so the interpretation remains inconclusive.

5. DISCUSSION

5.1. Weighing up the evidence: megaflood geomorphology in the Northern Palaeovalley

The results presented in this study show evidence for both megaflood and normal marine-related erosion. Five erosion surfaces (ES1-6) have been mapped in the Offshore Overfalls and extended to the Wight Barfleur Reef region, where data are more fragmentary. Of the erosional surfaces analysed, only ES4 and ES5 (scours), which form the current floor of the Northern Palaeovalley, show strong evidence for formation by high magnitude flood erosion. Surface ES1 lies outside the limits of the Northern Palaeovalley so beyond any effects of flood erosion. Surfaces ES2 and ES3 comprise bedrock terraces or the tops of streamlined islands and do not show any evidence of flood erosion in the form of flood-eroded grooves or scours although these may have been obliterated by subsequent processes. A summary of the observed features within the context of the megaflood model is given in Table 1. Below we present the key features, building on the list proposed by Baynes et al. (2015), observed in the new data that support a megaflood model for erosion of the Northern Palaeovalley in the central English Channel.

1. Streamlined bedrock islands whose morphology and distribution is diagnostic of megaflood-affected terrains (Baker, 1978; Burr, 2005). The islands show evidence

of progressive fragmentation with creation of divide-crossings and subdivision of larger original structures. Newly observed small teardrop-shaped islands with marked differences in shape parameters from the general large island population may correspond to totally submerged island types proposed by Patton and Baker (1978).

2. Inner channels that are up to 10 km long are eroded into the floor of Northern Palaeovalley. They are oriented parallel to valley topography and show curvature around valley margins indicating that the processes that formed them are sensitive to valley topography. We interpret these features as forming by progressive valley erosion by high magnitude flood processes as also observed in the Channeled Scablands (Baker 1978). The features do not show planform geometries and dimensions associated with normal fluvial processes (ie., sinuous channel form). Nor can they be readily explained by marine erosion processes; it seems unlikely that marine erosion would carve narrow kilometres long channel form geometries.
3. Streamlined bedrock ridges evidently formed by a process strongly constrained to geological structure and local topography, as they have been observed downstream of prominent hard layers or geological boundaries consistent with temporary damming and then outburst carving (fan-shaped streamlined bedrock ridges at WBF, a water “breakout” feature?). Glacial influence is discounted because of palaeogeographical reconstructions and different morphology of megascale glacial lineation in palaeoglaciated settings (Bradwell et al., 2008; Krabbendam et al., 2016). Longitudinal lineations have been used to infer catastrophic flood terrain in the Channelled Scablands (Baker, 2009).

4. Deeply scoured channels in bedrock (ES5) (‘bedrock basins’ - Baker, 1978), curvilinear scours flanking the streamlined islands (Offshore Overfalls) and stepped profile with possible plunge pools (Wight Barfleur Reef). Flow through channel constrictions causes intense erosion of bedrock and modelling studies have indicated that Missoula flood flows through the scabland constrictions would have been characterised by a hydraulic jump with critical or supercritical flow within the constrictions (Carling et al., 2009b). Measured tidal currents are not sufficiently erosive or correctly aligned to explain these over-deepenings (Mitchell et al., 2013), thus the scours are best interpreted as the product of high energy floods.
5. Secondary drainage with hanging channels and possible plunge pools which indicate rapid base level lowering and channel abandonment (e.g. on Island 26) or inability of the channel to readjust its longitudinal profile (hanging channels on ES1 and the SE).
6. Type C boulder accumulations have been mapped predominantly on or near the flanks of ES4 (Fig. 8). The accumulations occur at a constriction point and at the outside bends of the palaeovalley where sharp changes in channel orientation are observed. These are locations where currents would be expected to show reduction in flow velocities. The presence of isolated boulders on low gradient, sub-horizontal bedrock terrain could be explained by deposition from high magnitude currents, however clast provenance reconstruction has proven mostly impractical, with only one case in ES4 (small mudstone in Fig. 6B) where the lithology was positively identified and associated with outcrops at least ~4 km

away. By contrast with boulders clearly transported by megaflood processes observed in the Channeled Scablands (Balbas et al., 2017; Waitt et al., 2019), our evidence in the English Channel cannot rule out Pleistocene and Holocene marine processes as the cause for boulder formation and transport.

5.2. Evidence for two episodes of flood erosion?

Gupta et al. (2017) and García-Moreno et al. (2019) demonstrated a two-stage opening of the Dover Strait by high magnitude flood processes based on stratigraphic and morphological evidence from the Dover Strait. Gupta et al. (2007) had inferred a two-step carving of the Northern Palaeovalley based on the presence of the prominent bedrock terrace (ES2) at the margin of the Northern Palaeovalley and the cross-cutting relation of palaeodrainages preserved on the upper surface of island 26. Nevertheless, our new data cannot conclusively demonstrate flood erosion as a mechanism for formation of surfaces ES2 and ES3 and thus an older megaflood episode. For example, no flood eroded grooves or scours are preserved on these surfaces. The presence of hanging secondary drainage on ES1 with associated plunge-pools is evidence for abrupt base-level fall that could be possibly linked to a high energy water discharge preceding the formation of surface ES4. Moreover, the large dimensions of the ES2 bedrock terrace, with a gentle SW-oriented slope in agreement with the palaeoflow direction and the smooth curvilinear shape of the inner scarp bounding with ES1 may suggest a rapid formation by strong erosional forces. However, the terrace is also sloping from NW to SE towards the outer margin with the Northern Palaeovalley, it presents stepped profiles at both ES1 and ES4 bounding scarps and does not preserve any mesoscale erosional feature as those encountered on

ES4. Shape and slope are not dissimilar from other wave-cut platforms described in previous studies (Alvarez-Marrón et al., 2008; Buchanan et al., 2020).

Further evidence that may clarify the origin of the ES2 terrace is given by the planform profile of its bounding scarps. The inner scarp is consistently smooth for tens of kilometres and does not show the small shallow bay-and-promontory ("scooped") planform profile that is seen in the outer scarp bounding (i.e. with ES3 and ES4, the Northern Palaeovalley floor). The "scooped" geometries are best interpreted as created by wave erosion, with sediment input from the secondary drainage mouths buffering the erosion of the rock platform creating the stubby promontories (e.g. Fig. 3G). If ES2 was formed by wave cutting, it is not clear why a similar scooped geometry is not observed on the inner margin. A model for a two megafloods is thus proposed:

1. Prior to the breach of the northern limb of the Weald-Artois anticline that formed the rock ridge at the Dover Strait, the river occupying the English Channel/La Marche was relatively modest. On the English side the largest contributor was the River Solent, and on the French side the Rivers Seine and Somme (Antoine et al., 2003; Gibbard, 1988). Other major rivers, including the Thames and Rhine, drained northwards through the North Sea. Therefore, at the time of release of a possible first megaflood, the water may initially have been unchannelised and the resulting sheet flows would have covered an extensive region (Carling, 2013). Evidence for this stage is seen in the presence of "blind" tributaries eroded into platforms in the offshore Kent and East Sussex areas (Collier et al., 2015; Gupta et al 2017).
2. During this early stage of the megaflood, the ridges of Palaeogene rock that are near-vertical close to the WBF in Offshore Overfalls would likely have formed a

temporary barrier. The new MBES shows the most prominent of these to rise to 6 m from the surrounding seabed today. Temporary damming at this feature may have contributed to the unusual seabed morphology seen in the northeastern corner of the Offshore Overfalls area (Fig.3). In this model, the ES2 terrace carved immediately south of the obstacle may be well linked to temporary obstruction of early flows. The smooth "trimline" form of this feature is unlike any geomorphology elsewhere imaged on the floor of the English Channel and its spatial relationship with the rock-ridges close to the WBF is consistent with a short-lived pulse (or pulses) of high-volume water as the barrier was overcome. Multiple flood water pulses could be responsible for the stepped profile observed in the new data. The trimline is also constrained to chalk bedrock, tapering at the junction with Lower Cretaceous downstream, implying that pre-flood geomorphology and/or bedrock properties also influenced its formation.

3. Between this possible first event and the more established megaflood that carved the streamlined islands and ES4, normal riverine erosion was restored and produced a sinuous channel network of which one remnant is observed on top of Island 26 (ES3) in Offshore Overfalls.
4. In the subsequent megaflood event(s), the initial Northern Palaeovalley was further deepened, and streamlined islands and inner channels were eroded to form the morphology currently observed. Secondary drainage channels formed by headward retreat were eroded across the newly formed scarp.

6. CONCLUSION

1. The fidelity of reconstruction of past geomorphic processes from landforms is highly dependent on the resolution of the data being analysed – improved resolution permits finer scale detail to be observed, generally enabling improvement in process interpretation. Our new multibeam bathymetry data (multibeam bathymetry and backscatter at 2x2 m ground resolution) show a much higher level of detail and complexity in the morphology of macroscale landforms that were previously identified in the central English Channel The current analysis supports the conclusion that at least one high energy flood discharge is the cause for the formation of the Northern Palaeovalley.
2. Additional stages of streamlined island erosion were found, confirming them to be formed by erosion during high water flow conditions.
3. Previously undescribed sets of landforms were found in the Offshore Overfalls and Wight Barfleur regions, including sets of streamlined bedrock ridges that relate to deep bedrock scours and palaeovalley constrictions, indicating channelised flow and enhanced erosion as observed on other megaflood terrains.
4. Analysis of video tows at seabed has led to the identification of isolated large boulders (> 1 m length) on the flanks of the palaeovalley and unrelated to bedrock scarps. The distribution correlates with locations where the water velocity would have dropped – where the bedrock geology caused a constriction and two changes in azimuth. These boulders are related to large scale flooding; however, storm wave action cannot be ruled out. The study also shows areas of boulder deposits

including large accumulations of angular clasts that can be instead explained by periglacial fracturing and wave erosion forming boulder beaches.

5. The previously proposed two-stage megaflood model in the English Channel cannot be completely confirmed with the evidence provided in this study, as the geomorphological record for a first, older megaflood remains partly ambiguous and other processes, in particular platform cutting by wave action, could still be invoked.
6. Finally, this study improves our understanding of protected geomorphological features in Offshore Overfalls and identifies other megaflood-related features in other two marine protected areas. The interplay between megaflood processes and fluvial to marine action has created a diverse submarine landscape which has major significance for the type and distribution of seabed habitats in the central English Channel. Erosion of Northern Palaeovalley geomorphic features together with deposition of boulder fields has created topographical “oases” of substrate and topographic heterogeneity on otherwise relatively homogenous seabed. In such a setting a high diversity of epifaunal species assemblages can attach and thrive. The relationship between seabed heterogeneity and epifaunal diversity is well understood at both the small and medium scale – however heterogeneity at the “landscape” level, such as provided by large-scale features such as the Northern Palaeovalley, is less well understood (Pittman, 2017). Anecdotal observations of the epifaunal assemblages from this study across the three MPAs highlight the importance of including geomorphological features in national level conservation measures, such as the UK Marine Protected Area programme.

7. APPENDIX

Table with the boulder analysis (excel file)

8. ACKNOWLEDGMENTS

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FIGURE AND TABLE CAPTIONS

Figure 1. Geographical overview of the study area, with the extent of the analysed MBES and camera tow survey data (Defra’s Marine DEM 1 arc second in the background). The geological

boundaries are improved after British Geological Survey (1995) and Collier et al. (2006, 2015). WBF: Wight-Bray Fault; MCF: Mid Channel Fault; MCA: Mid Channel Anticline; Bedrock geology is as follows: Pa: Palaeogene formations; Cha: Chalk Group (upper Cretaceous); L.Cr: Lower Cretaceous formations (including Wealden Group); Ju: Jurassic formations. In the inset map to the upper left-hand side, the generalised location of the paleolake (P. lake) which drainage ruptured the Dover Strait (D.S.) land bridge is shown. The Cotentin peninsula (C.P.) and Hurd Deep (H.D) are also shown.

Figure 2. Comparison of the new high resolution 2x2 m DEM with vertical accuracy ±0.25 m (left) and the previous 30x30 m DEM with vertical accuracy of ±0.6-3 m (right). The new data allows the recognition of new features on the seabed (e.g. NW-SE lineaments crossing the area), and improved definition of others (e.g. scouring), and the observation of fine details (e.g. fragmentation of a bedrock island), which are all critical to assess the megaflood hypothesis. WBF: Wight-Bray Fault

Figure 3. Geomorphology of Offshore Overfalls MCZ. ESx are Erosional Surfaces (see text for details). WBF: Wight-Bray Fault; A: streamlined bedrock island no 25, notice the fragmented tip and the broad profile of a larger island (labelled “original island 25”), suggesting a multiphase erosional history, and the broad curvilinear and elongated scours on the Northern Palaeovalley floor south of the island. B: Fan-shaped set of ridges emanating from the mapped location of the WBF. Note how the Paleogene strata is relatively overdeepened, suggesting that a rock-unit at the base of the Paleogene sequence acted as a temporary barrier to the flow. More streamlined bedrock ridges, this time parallel and shorter, are observed in C (arrow indicating), coinciding

with a gap in a prominent (harder) Palaeogene bed. D: streamlined bedrock island no 24, with indication of structural control (arrows) on its formation, where bedrock bedding appears to indicate the presence of a fold hinge. E: streamlined, possibly bedrock, hill in an almost perfect lemniscate shape. North of it, a series of relict dunes crosses on a small terrace (ES3) and encroaches on ES4, the Northern Palaeovalley floor, with steep stoss sides directed NE. The texture and morphology are clearly different from the other constructional current-induced sediment forms to the top right corner of the map (black arrow) and the megaripple train in box A. F: smaller streamlined bedrock hill, close to the margin of ES3, its bedrock nature is suggested by the benches indicated by the black arrow. G: example of a bedrock promontory corresponding to a secondary channel mouth. Chalk bedding is clearly visible (indicated also with a black arrow on the main map, next to the box), as the embayments in the rock platform to both side of the promontory. Similar examples of promontory-embayment are visible along the entire length of the lunate terrace.

Figure 4: Left – secondary palaeodrainage system on ES2. Colour-coded slope is shown when exceeding 5 degrees. A, B and C: examples of secondary palaeochannel mouths when reaching the bounding scarp. Profile 1-2: example of hanging channel. Profile 3-4: example of channel with a normal longitudinal profile. Right: erosional surfaces identified in Offshore Overfalls. WBF: Wight-Bray Fault.

Figure 5. Geomorphology of Wight Barfleur Reef characterised by deep scouring in bedrock and very irregular bathymetry compared to Offshore Overfalls. Island numbering is based on Collier et al. (2015). ESx: Erosional Surface. A: bedrock platform characterised by squared margins

(probably fault boundings) and an abundant cover of boulders. B: stepped bathymetry forming sickle-shaped platforms sloping towards the interior. A high abundance of boulders has been observed in this location. C: elongated bedrock ridges before the breaking of the palaeovalley into separate channels, at a sharp southward turn in its overall direction.

Figure 6. Photos and video snapshots showing seabed images at Offshore Overfalls and Offshore Brighton. Their location is shown in Fig.3 and Fig.8. A: chalk outcrop confirming the bedrock nature of the fan-shaped bedrock ridges (Fig.3B). B: small dark green-bluish boulder, possibly a Palaeogene mudstone, on sand and gravel. It is located in the Channel Basin (chalk), about 4 km away from Wight Barfleur Reef. C: hard (possibly cemented) cobble pavement (mostly flintstones) with interstitial loose sandy gravel, typical composition of the seabed in Offshore Overfalls and Offshore Brighton. D: chalk outcrop on the lunate terrace (ES3), supporting its bedrock nature. E, F, G and H: large, isolated boulders (Type C), possibly sandstone, observed on flat bathymetry in Offshore Brighton. G and H are the same boulder from two different perspectives (top and front respectively).

Figure 7. Video snapshots showing seabed images at Wight Barfleur Reef. Their location is shown in Fig 5 and Fig.8. A and B: Coarse-grained pink to red boulders (Type C) sitting on grey to beige featureless bedrock with clear different lithology. C: Large isolated boulder (Type C) on a streamlined island (see Fig. 5). D: Very irregular and bored bedrock outcrop, very common throughout Wight Barfleur Reef. E and F: boulder accumulations encountered at the outer edge of the small bedrock platforms to the south of Wight Barfleur Reef and classified as Type B. G

and H: examples of a Type A accumulation, with very angular boulders detached from a bedrock outcrop and probably remained in situ.

Figure 8. Boulder distribution divided for the three recognised types; maximum boulder size observed at each station is depicted using increasing size of the symbols. Boulder deposit type C, which may have been moved and deposited by high energy flood events, are coloured green to differentiate them from other types. The distribution is overlaid on NP morphology and lithological boundaries. Locations of snapshots in Fig.6 and 7 are also shown. OOVR: Offshore Overfalls MCZ; OBRG: Offshore Brighton MCZ; WBFR: Wight Barfleur Reef SAC. NP: Northern Palaeovalley; WBF: Wight-Bray Fault; MCF: Mid Channel Fault; Pa: Palaeogene formations; Cha: Chalk Group (upper Cretaceous); Wea: Wealden Group (lower Cretaceous); L.Cr: other Lower Cretaceous formations; Ju: Jurassic formations.

Table 1. Summary of the features and sequence of events described in this paper in relation with features observed elsewhere in the English Channel and the main events as described in Collier et al. (2015), García-Moreno et al. (2019) and Gupta et al. (2017). A tentative correlation to Marine Isotope Stages (MIS) is also presented.