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**New insights into the late Quaternary evolution of the
Bristol Channel, UK**

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Friday 3rd March, 2017

Dear Professor Duller,

We have revised our manuscript entitled “**New insights into the late Quaternary evolution of the Bristol Channel, UK**” for publication in *Journal of Quaternary Science*.

We have revised the manuscript taking into account all comments by the two reviewers and you as Editor. We provide details on these below. We would like to thank you and the reviewers for the very useful comments and these have helped improve the manuscript.

We look forward to seeing this published in *Journal of Quaternary Science*.

Yours Sincerely

Dr. Philip Hughes
Reader in Physical Geography

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Response to reviewer comments (**our comments in red bold font**):

Reviewer 1

This is an interesting paper that forms a useful addition to the late Quaternary history of SW England and South Wales and adjoining sea areas. The paper forms a good, general review that will be of interest to a wide range of Quaternary scientists working in the area and fills knowledge gaps in our understanding of the Quaternary history of South Wales, Lundy and the SW Peninsula. I think it should be published following some relatively minor changes to the manuscript. These are as follows:

1. The paper needs better context. It discusses the Quaternary history of land areas adjacent to the Bristol Channel but misses out recent research and publications on these areas. For a start it should cite the paper by Hubbard et al (2009) which produces numerical projections of ice sheet extent from the IIS covering much of the SW. (Hubbard, A.L., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M. 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British-Irish ice sheet. *Quaternary Science Reviews* 28 (7-8) pp. 758-776). The implications of these projections should be discussed.

The papers by Evans et al on Dartmoor ice (QSR 2012) and on Exmoor ice by Harrison et al (PGA 1998) should also be cited.

We have added in these references and also those suggested by the Editor and write:

“In a recent paper, Smedley et al. (2017) combined cosmogenic and optically stimulated luminescence dating (OSL) to confirm the Late Devensian (MIS 2) age of glaciation at the northern edge of the Isles of Scilly. This confirms predictions in a numerical model of glaciation for the Devensian which projects ice over much of the Celtic Sea (Hubbard et al. 2009). The model projections of Hubbard et al. (2009) also project ice into the Bristol Channel and they note (p. 774) that “the experiments presented also indicate significant excursions of wet-based ice into areas of southern England”. Independent ice masses have also been suggested to have existed on Exmoor (Harrison et al. 1998) and Dartmoor (Evans et al. 2012).”

Finally, the paper by Carr and Hiemstra on Lundy (2015 in Quaternary Newsletter) should also be cited as evidence that the glacial story of Lundy is contested (around page 9 line 3), even if you disagree with their views.

In the Introduction we now add this “Despite the widely reported evidence of glaciation in the Bristol Channel, Carr and Hiemstra (2015) still questioned the evidence for this in the vicinity of Lundy, although with no basis.”

2. There are a few typos here and there: p 9 line 42: insert ‘in’ after glaciations. p 15 line 25: insert ‘or’ after ‘one’. p 15 line 35: Explain ‘as low as 100m’. p 15 line 43: insert ‘the’ before ‘English’. p 15 line 46: delete ‘in’.

Done

3. There could also be mention of the glacial (?) erratic on the south coast of Cornwall (e.g. around Porthleven) in the context of the Quaternary history of the English Channel and Western Approaches.

We have added a range of references to studies of erratic boulders in the region: “Erratic boulders have been noted in this area (Taylor 1956; Madgett & Inglis 1987) as well as further south on the coast of Cornwall (Flett and Hill 1912; Ealey & James 2001).”

Reviewer 2

This manuscript presents a synthesis of newly-released borehole, bathymetric and other data from the Bristol Channel. The study area is at a critical location for understanding British-Irish glacial history as it lies close to the southern limit of at least two phases of ice-sheet advance. These glaciations have been mainly documented onshore, so the availability of new offshore data makes this paper a timely contribution to the topic. In general there is a current focus on completing our understanding of the NW European glaciations by including evidence from the shelf, so this is a welcome contribution to this broader focus. The work is well written and includes data from a large number of sources. There are three areas where I suggest improvements:

a) I would have liked to see a few more technical details about the datasets used, for example the cell size of the EMODNet bathymetry (0.125 arc min or 230m?) and what data types

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exactly were available via the Atlantic Array Project. Similarly I would be surprised if the EDINA bathymetric grid is at 10 m (I thought it was 30 m), and if so why wasn't that used for the zoom-ins rather than EMODNet! Similarly I found it difficult to follow the sedimentological argument presented in section 4.2.1 without being able to see the locations of the boreholes relative to the bathymetric moraines on a map. Perhaps all the boreholes could be marked and colour coded according to thickness of glacial deposits?

We have clarified the EMODNet data (0.125 arc min) and changed the caption to Fig. 1 – it is based on EMODNet. We have added an inset map to the borehole figure. We didn't go for colour coding as the new inset map should help and thickness is indicated on the borehole scales.

b) I found the main results (section 4) a little dense. I wonder if a few “sign-post sentences” could be added to help guide the more general reader through it and better capture the key points of the argument. Something like what is written at the start of the discussion would be ideal.

We have added text introducing each section now to make it clearer.

c) At the start of the discussion itself I would have liked to see a slightly clearer acknowledgement of what the new (post 2010 or so) data has contributed. Whilst I understand this study relies on integrating all available data, it would be useful to see what couldn't have been resolved before and so give encouragement (or otherwise) to re-look at other areas.

We have added this text:

“The recently available high-resolution bathymetric, borehole and geophysical data from the floor of the Bristol Channel has allowed for new analysis of the seafloor topography and Quaternary geology. This has revealed new information on the fluvial and glacial history of the Bristol Channel, especially evidence for glaciation and the former course of the River Severn.”

In the comparison between the Bristol and English Channels, I didn't understand why the additional deepening of the English Channel River was attributed to tidal scouring (Page 15, line 43-48), when in the next paragraph the existence of mega-flooding was acknowledged.

We have added in both to read “In the English Channel the valley extends to depths twice that in the Bristol Channel, possibly a consequence of the tidal scour during transgressions and also catastrophic flooding events.”

Small points

We have done all of these. Some edits have comments from us.

- 1) There is no section 2 ! The manuscript refers to a Table 1, but this seems to be missing.
- 2) There is some unnecessary repletion about data locations in the Methods and the preceding paragraph.
- 3) Did someone really count 22,214 boulders (line 30, page 8)?! Whilst I am confident this is what is written in the report, assuming this is an estimate, perhaps it would be better here to say 22k boulders.

Yes, 22,214 are individually logged in an excel file. We now refer to the Appendix D of the report to clarify. We now write: "Geophysical surveys reported by Channel Energy Limited (2010) and RWE npower renewables (2010) have revealed the presence of more than 22,000 boulders (> 0.3 m height) in the Atlantic Array survey areas. Each of these boulders have been identified and measured for height with data on each available in the report by Channel Energy Limited (2010, Appendix D)"

4) Page 15, line 25, one several.

5) Page 15, line 53, I think this should read "islands and scour pits" (not potholes).

6) Page 16, line 7, I think this should read "Arun" not "Adur".

7) Page 16, line 34, I was always told you are not allowed a paragraph consisting of a single sentence!

Editors Comments

We have undertaken all of the edits suggested below. Some edits have additional comments from us – see below.

Page 2, line 25: Remove the extraneous "the" so that it reads "... a further series of isolated, enclosed..."

Page 2, line 48: The recent paper by Smedley et al (2017) could be mentioned here as providing the first firm chronology for the most recent glaciation of the northern edge of the Scillies. The reference should also be included on page 13, line 43.

Smedley, R.K., Scourse, J.D., Small, D., Hiemstra, J.F., Duller, G.A.T., Bateman, M.D., Burke, M.J., Chiverrell, R.C., Clark, C.D., Davies, S.M., Fabel, D., Gheorghiu, D.M., McCarroll, D., Medialdea, A., Xu, S. (2017). New age constraints for the limit of the British–Irish Ice Sheet on the Isles of Scilly Journal of Quaternary Science 32: 48-62.

Page 3, Section 3: Please avoid paragraphs consisting of a single sentence. These sentences could be combined into a coherent paragraph.

Page 7, line 25: Is the word "mapped" missing here? Should it be "...clay and/or sands mapped as glacial..."

Page 9, line 42: Is the word "of" missing? Should it be "...for glaciation of the Bristol district..."

Page 10, line 13: Add the word "by" so that it is "...also made by Stephens (1966, 1970)..."

Page 11, line 46ff: The sentence starting "The development of the lower Severn below Ironbridge..." is poorly phrased. Please check and consider rephrasing to make it clearer.

Page 11, line 52: A word is missing here. Is it "model"? "...presented a revised and elaborated model following..."

Page 12, line 6: Word "as" is missing. It should be "referred to as the Severn"

Page 12, line 30: Please gives units for the age. Is this in "C-14 a BP", or has it been calibrated?

Page 13, line 50: Add "ing" to "understanding"

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Page 15, line 18: Remove the extraneous "the"

Page 15, line 18: Please either give a reference to studies on the aeolian dunes, or specify some key localities.

We have edited this and corrected the text to read “However, possibly the most important development has been the accumulation of sand and gravel, mostly in active intertidal dune fields (Allen 1990; Allen & Fulford 1993; Carling et al. 2006).”

Page 15, line 25: There is an error in the text ("one several"): "...whilst the former has been subjected to one several glacial events during its history"

Page 15, line 47: Please add "that" so that it reads "...coarse fluvial sedimentation that took place..."

Figure 5: The caption only talks about borehole BH15A, but the diagram shows two other boreholes. Either remove the other two boreholes, or ensure that the caption and the main text refers to these other two boreholes.

New insights into the late Quaternary evolution of the Bristol Channel, UK

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ABSTRACT

A synthesis of new publically-available borehole and bathymetric data, combined with a wealth of other existing disparate data sources reveals new insights into the Pleistocene history of the Bristol Channel area. Sediment boreholes throughout the Bristol Channel confirm the area was glaciated in the Pleistocene. Till is present below marine deposits and, in some areas, is visible morphologically as submerged moraines. In the central and eastern Bristol Channel the submerged valley course of the palaeo-Severn is very clear in new high-resolution bathymetric surveys. This former river course and associated tributaries cross-cut through glacial sediments in the Bristol Channel. At least three phases of glaciation are recorded in the Bristol Channel, one related to the southern limits of a Late Devensian Substage (~MIS 2) Welsh Ice Cap which reached into Swansea Bay, an earlier Devensian (MIS 4 to 3) glaciation associated with Irish Sea ice, and another older glaciation that is associated with ice that filled the entire outer and central Bristol Channel. The age of the older Bristol Channel glaciation is still open, although it predates the Devensian (Late Pleistocene) and must date to the Middle Pleistocene. It is evident therefore, that Pleistocene glacial and fluvial activity, combined with subsequent post-glacial sea transgression, directly account for current morphometries of the Bristol Channel and Severn Estuary, and the current geography of SW British Isles.

1. Introduction

Detailed investigations over the past half-century have revealed remarkable evidence of the morphology and geology of shelf seas adjacent to northwest Europe (cf. chapters in Ehlers et al. 2011). For the British Isles this work has provided important insights into the relationship of the Quaternary sequences to those on land in adjacent regions and the interaction of land and sea through the period. The Bristol Channel (Figure 1) is one area that, although it has received some attention has not been systematically investigated as a whole, apart from by the surveyors of the British Geological Survey, who have published a map and accompanying memoir (Tappin et al. 1994).

In the west the Bristol Channel extends from "a line joining Hartland Point in Devon (51°01'N 4°32'W) to St. Govan's Head in Pembrokeshire (51°36'N 4°55'W)"

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(International Hydrographic Organisation). To the east, the landward limit of the Bristol Channel is taken as lying between Sand Point, Somerset (north of Weston-super-Mare) and Lavernock Point (south of Penarth in South Wales) from here the Channel passes into the estuary of the River Severn. Technically, western and northern Pembrokeshire, and north Cornwall lie beyond the limits of the Bristol Channel, and are considered part of the Atlantic Ocean coast, within the Celtic Sea. Overall therefore, the Bristol Channel extends for some 120 km from west to east, but if the eastward extent of tidal influence in the Severn Estuary is taken into account, today the Bristol Channel system extends a further 70-80 km NE almost to Gloucester.

The structural origin of the Bristol Channel and SW England is reviewed by Tappin *et al.*, (1994). In the Irish/Celtic Sea region there are a series of downfaulted basin structures infilled with later Paleogene to early Neogene sediments. These basins owe their origin to basin inversion during the post-Maastrichtian (latest Cretaceous) to pre-Middle Eocene period (cf. Tucker & Arker, 1987). Together with the Bristol Channel Basin, they include the St. George's Channel Basin, the North and South Celtic Sea basins, the Stanley Bank Basin and the Cardigan Bay basin (Tappin *et al.* 1994). They were infilled mainly by fluvial and related deposits. The later Oligocene to middle Miocene saw the main phases of the Alpine (Helvetic) Orogeny which was represented by inversion of the Bristol Channel and other basins in northwestern Europe (Tappin *et al.* 1994; Gibbard & Lewin 2003).

In the Palaeogene, a further series of isolated, enclosed basins developed along the major NW-SE-trending Sticklepath-Lustleigh wrench fault. Apart from the Stanley Bank Basin beneath the Bristol Channel, they include the Bovey, Petrockstowe and the minor Dutson basin on land. Each of these basins is infilled by terrestrial, largely fluvial sediments, the north-westward flowing rivers being aligned along the fault suture. According to Edwards & Freshney (1982), the lower, fine-grained fill of these basins is of Eocene-age, overlain by a complex sequence that is over 1000 m thick, the upper 300 m of which are Oligocene age. Following the earlier Neogene basin inversion, the late Pliocene to earliest Pleistocene (*c.* 3-2 my) saw the re-establishment of rivers in the down-faulted Bristol Channel and Irish Sea basins (cf. Tappin *et al.*, 1994; Gibbard & Lewin 2003), potentially linking the basins to the Celtic Sea shelf. However, the absence of a sedimentary record results in there being little known concerning the later Pleistocene evolution of the Bristol Channel until the late Middle Pleistocene.

The glaciation of the Bristol Channel area was first recognised by Strahan & Cantrill (1904), who identified erratics in the Vale of Glamorgan, and Maw (1864) who identified glacial deposits in the Barnstaple area. Erratic boulders have been noted in this area (Taylor 1956; Madgett & Inglis 1987) as well as further south on the coast of Cornwall (Flett and Hill 1912; Ealey & James 2001). Mitchell (1968) agreed with the idea of an ice sheet pushing up the Bristol Channel and also supported the idea of ice filling the southern part of the Irish Sea as far as the Isles of Scilly. The latter is now well established (Scourse 1991; Scourse & Furze 2001; Chiverrell *et al.* 2013), with ice reaching as far as the Celtic Sea shelf edge (Praeg *et al.* 2015) during the Late Pleistocene. In a recent paper, Smedley *et al.* (2017) combined cosmogenic and optically stimulated luminescence dating (OSL) to confirm the Late Devensian (MIS 2) age of glaciation at the northern edge of the Isles of Scilly. This confirms

predictions in a numerical model of glaciation for the Devensian which projects ice over much of the Celtic Sea (Hubbard et al. 2009). The model projections of Hubbard et al. (2009) also project ice into the Bristol Channel and they note (p. 774) that “the experiments presented also indicate significant excursions of wet-based ice into areas of southern England”. Independent ice masses have also been suggested to have existed on Exmoor (Harrison et al. 1998) and Dartmoor (Evans et al. 2012).

A significant and important contribution to the debate on the Quaternary history of the Bristol Channel has been presented by John (1968; 2008) who argues that the area was glaciated from the west. Bowen (1994) also agreed that the Bristol Channel had been glaciated, arguing that the glaciation must date from the Middle Pleistocene, and suggesting that the most easterly glacial deposits, in the Bristol area, might even relate to Marine Isotope Stage (MIS) 16 (i.e. Cromerian/Donian Stage). However, earlier workers equated the glaciation of the Bristol Channel with a much later cold stage equivalent to MIS 6 (Late Wolstonian) (Hawkins 1972; Gilbertson 1974; Gilbertson & Hawkins 1978a); a useful review of the history of research in the inner Bristol Channel area is provided by Bridle (2012, Ch. 2). In the outer Bristol Channel area, Rolfe et al. (2012) found that glaciated granite surfaces on Lundy date to the Devensian Stage (Middle Devensian, MIS 3) indicating that they became ice-free at that time during a phase of deglaciation. Despite the widely reported evidence of glaciation in the Bristol Channel, Carr and Hiemstra (2015) still questioned the evidence for this in the vicinity of Lundy, although with no basis.

This article includes new evidence that has been revealed through offshore investigations as part of the Atlantic Array Offshore Windfarm Project. This project was cancelled in 2013. The survey data from the planning stages of this project were made publicly available in September 2014 and published by the UK Crown Estate. These data were combined with the geophysical information previously published by the Outer Bristol Channel Marine Habitat Study (BioMôr Project; Mackie et al. 2006) and new data (first published in 2015) from the EMODnet project (EMODnet 2016).

This paper examines the entire Bristol Channel area from Lundy and Swansea Bay in the west to the Severn Estuary and surrounding land areas. The palaeo-Severn catchment is also examined and linked with the evidence from the Bristol Channel.

2. Methods

Geological maps and borehole records were examined from the British Geological Survey (BGS). This included published surveys of the Bristol Channel area (BGS 1986) and also onshore borehole scans available from the BGS Borehole Record viewer (2016).

The recent data provided by the Atlantic Array Project and published on Crown Estate's Marine Data Exchange (<http://marinedataexchange.co.uk/>) supplemented the BGS information for the Outer Bristol Channel area. The Atlantic Array Project produced detailed survey data for an area between Lundy and the Gower (Figure 1). The Atlantic Array Project also includes geophysical data from the line of the proposed powerline cable corridor which was planned to run southeastwards from the windfarm between Lundy and the mainland reaching land in Barnstaple Bay (Channel Energy Limited 2010; 2011; RWE npower renewables 2010).

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Bathymetric data at 0.125 arc minutes resolution were obtained from the European Marine Observation and Data Network project (EMODnet 2016). Information on high-resolution morphometries of submarine landforms in the Outer Bristol Channel area was obtained from the BioMôr Project (Mackie et al. 2006). Palynological data from sediment stratigraphical sequences in the Swansea Bay area were obtained from Culver & Banner (1978) and Evans & Thompson (1979).

3. Results

The results presented here comprise three main types of information: 1) bathymetric and submarine topographic data from the floor of the Bristol Channel; 2) sedimentological information revealed in borehole cores and geophysical surveys from the sediments at the floor of the Bristol Channel, and; 3) onshore evidence from islands within and areas surrounding the inner Bristol Channel.

3.1 Bathymetry and submarine topography of the Bristol Channel

Examination of the recent bathymetric evidence has provided important new insights into the evolution of the Bristol Channel floor. A high-resolution bathymetric map of the Bristol Channel from the European Marine Observation and Data Network project (EMODnet 2016) is shown in Figures 2 and 3. Here a series of elements can be identified and their relative sequence established. A relative chronology of events represented by these individual elements is dependent on already available results from previous studies.

The most obvious principal element is the central valley. This narrow curvilinear to straight depression extends throughout the length of the Bristol Channel from the Severn Estuary to a line between Pembrokeshire and Cornwall (Figure 1), a distance of over 110 km (cf. Collins 1987). The valley is generally a constant width of c. 1.5 km and a single furrow, but in places, it appears to branch and reunite around obstacles, e.g. south of Swansea Bay. It passes between the islands of Flat Holm and Steep Holm at its eastern end off-Weston-super-Mare, and north of Lundy in the west. Cross-sections of the central valley demonstrate that it is steep-sided and grades from -14 m between Newport and Clevedon, to -27 m between Cardiff and Weston-super-Mare, -36 m south of Port Talbot, reaching in excess of -50 m at its westernmost point (Figure 4). Tributary valleys enter and are graded to the central valley incision from both the north and south sides as submarine extensions of rivers on the adjacent land areas, but the valleys on the northern side are the best developed. Of particular interest is the extension of the River Usk valley at Newport, into the Severn Estuary north of Clevedon, first described by Williams (1968). At its western end the central valley is buried by younger deposits, predominantly tidal flat deposits of clay, silt and sand (Edina Geology Digimap 2016). In many areas small stream valleys dissect the submarine surfaces. These courses do not reach the present land areas but indicate that the small streams were also graded to this central valley. The alignment of the central valley appears strongly controlled by outcrop and structures in the Mesozoic bedrock, in particular by the major E-W orientated faults (Tappin et al. 1994).

The second most obvious feature is the glacial moraine ridge in Swansea Bay (cf. Charlesworth 1929; Bowen 1974). Here a prominent arcuate ridge, c.1.5 km wide and 10-12 m high, projects across the Bay mouth at shallow depths of < 3 m O.D. The ridge has an asymmetric cross-profile with a markedly steeper south face. The ridge is dissected in three places on its western extremity, its south-west and south sides by what appear to be channels. South of the ridge a series of sinuous channels spread-out in a fan-like fashion, forming an apron-like structure. A second, more subdued, possible arcuate morainic ridge, 4 m high and of similar width and form, occurs at the outer margin of this apron (Figures 2 and 3). The fan-like apron is truncated where it meets the central channel, in all but one case, the channel from the south-west. This truncation indicates that the central valley post-dates the apron structure. The channel that passes through the ridges and appears to grade into the central valley may represent an extension of the current river valleys. Overall this landform assemblage represents a suite of glaciogenic deposits, which is covered in the east by thick accumulations of sand (the Scarweather Sands; Figure 3).

The general nature of the Bristol Channel floor, outside the incised valleys, comprises two types of surface. Firstly bedrock outcrop patterns are distinct in the Bristol Channel surface as a consequence of the general paucity of later sediment cover. These features form an undulating topographic expression. Secondly, there are several places where there are apparently wide, flat or very gently sloping surfaces, which possibly represent terraciform surfaces, e.g. off-Cardiff and the continuation off the coast of Barry to the west. They also occur on the south side north of Exmoor. These surfaces are incised by the younger channel or valley forms, indicating that they pre-date the latter.

Later sedimentation appears to be restricted to relatively few places. The largest spread is that west of Lundy in the widest area of the Bristol Channel where it meets the Celtic Sea - the Outer Bristol Channel (OBel) Sands. The surface of this sand formation bears an extensive assemblage of substantial sand waves (Figures 2 and 3). In fact, this is one of the most significant sand-wave fields on the British continental shelf, covering over 900 km². According to James et al. (2012) this extensive area includes sand waves up to 19 m high, although most are 5-10 m, predominantly elongated in a north-north-west to south-south-eastwards direction. The sand-wave field extends over 37 km from north-south and can be divided into a northern half, the NOBel Sands, where bedforms are densely concentrated on a sand substrate, and a southern half, the SOBel Sands, where isolated sand waves occur on a coarser, gravelly sediment substrate on the Lundy and Morte Platforms (James et al. 2012). The sand wave spread stretches west to east for about 40 km in the north, but narrows southwards to a width of about 12 km. In both areas, the sand waves are generally asymmetric in cross profile, with steep west-facing lee slopes, apparently indicating net sand transport towards the west by ebb-tidal currents. Geophysical evidence indicates that the uppermost metre of sediment of large sand waves is mobile, but that the overall structure and position of the landforms appear to be in equilibrium (James et al. 2012). Generally they appear to be static, no evidence being seen of their active migration. Indeed they are, in turn, buried by later landforms, including elongate, bar-like forms (linear tidal sandbanks, or banner sand banks) that have aggraded over the sand waves, e.g. Helwick Sands west of the Gower peninsula and Nash Sands off the Vale of Glamorgan (Schmidt & Mitchell 2014). A similar elongate tidal sandbanks occur between Cardiff and Newport (at -1m O.D.) and teardrop-shaped

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islands, that are emergent at low-tides, occur mid-Channel immediately off the Usk confluence. Elsewhere substantial sediment sand accumulations occur in embayments on both sides of the Bristol Channel, e.g. off the Cornish north coast, within Carmarthen Bay, Weston-super-Mare, inner Swansea Bay and off the Bristol district. Evidence of contemporary sediment movement is limited. Isolated sand accumulations are seen both to the east and the west of Lundy, in Bideford Bay and isolated in the middle of the Channel off-Barry.

Interpretation of these features indicates that the Bristol Channel is effectively an extension of the River Severn valley and estuary; the east to west-aligned central valley being the valley of the River Severn itself, as noted by earlier workers (e.g. North 1955; Tappin et al. 1994). This incised valley is clearly the youngest fluvial feature and its links with incoming tributaries on both sides of the Channel indicate that these streams were all graded into the central valley. Likewise small stream courses, which do not reach the present land areas but dissect the submarine surfaces, indicate that these streams were also draining to this central valley.

There can be little doubt that the group of landforms preserved in Swansea Bay can be interpreted as a glacial morainic assemblage, the apron-like channelled spread to the south being a meltwater fan complex. The second subdued ridge-like feature could represent a slightly older moraine that has been eroded and breached by the meltwater streams discharging from the retreated ice front, although the precise difference in age between the inner and outer moraines remains unknown. The Swansea Bay glacial suite is apparently truncated by the central valley and therefore it must be presumed that it pre-dates the latter, the exception being the stream that is graded into the central valley, which is probably of the same age.

The dissected terraciform surfaces, outside the valley areas are potentially modified fluvial terrace remnants, which are likely to relate to the Severn-system drainage. That they pre-date the central valley is demonstrated by the fact that the latter truncates these terrace-like areas. How they relate to the glacial deposits is not obvious.

These landforms must have all been formed during the period of low eustatic sea-level when the Bristol Channel formed a substantial valley-like land area (cf. Collins, 1987). The last time this occurred was during the Late Devensian (Late Weichselian) Substage. During this period the exposed surfaces, outside the valley channels and glaciated areas was subjected to periglacial weathering processes, such that it is in effect a drowned periglacial landscape, periglaciation being widespread across south-western Britain at this time (Jones & Keen 1993). This is a feature it shares in common with the English Channel floor and northern France (cf. Lericolais, 2003).

3.2 Sedimentological evidence from the Outer Bristol Channel: Swansea Bay, Atlantic Array and Lundy areas

This section looks at the sedimentological evidence, including borehole data and other geophysical evidence, for glaciation in the Outer Bristol Channel. This includes Swansea Bay in the north and the proposed Atlantic Array Windfarm in the central Outer Bristol Channel and Lundy in the south and the associated proposed cable route between Lundy and mainland Devon (Figure 1).

3.2.1 Swansea Bay and Gower

Boreholes from Swansea Bay indicate tills associated with the southernmost extension of the Welsh Ice Cap which reached c. 15 kilometres south of Swansea (Bowen 1970; 1973; 1974; Culver 1976; Culver & Bull 1979; BGS 1986). Sedimentological and microfaunal analyses indicate that these glacial deposits were *originally* land-based and were progressively submerged by a marine transgression between 10 ka and 2.5 ka ^{14}C a BP (Culver & Banner 1978). A series of rock basins in Swansea Bay were occupied by glacial lakes prior to marine transgression and are likely to have been present from glacier retreat at c. 16 ka ^{14}C a BP until marine transgression at c. 10 ka ^{14}C a BP (Culver & Bull 1979). As noted earlier, a clear end moraine is also visible at the sea-bed surface in high resolution bathymetric maps with a network of meltwater channels visible outside of this moraine (Figure 3). The eastern part of the moraine arc is covered in thick sand accumulations at Scarweather Sands. Glacial deposits have also been identified beyond the limits of the Swansea Bay moraines by Blackley (1978; his Fig. 11), south and southeast of the Scarweather Sands area based on continuous seismic profile records.

The Gower peninsula is well known for its Pleistocene sediment record, with glacial deposits and raised beach deposits recorded and reviewed in numerous publications (e.g. Bowen 1974; Bowen & Sykes 1988; Bowen et al. 1985). The Gower is important for glacial research because it marks the southern limit of the Devensian Welsh Ice Cap. A boulder associated with this limit has yielded a ^{36}Cl exposure age of 23.2 ± 2 ka (Bowen et al. 2002). On the south and west of Gower the Paviland Moraine, a marginal complex of meltwater gravels and sands, rests on a red clay till (Bowen, 1974, 1999), rich in Millstone Grit clasts derived from southern Welsh Carboniferous rocks. Raised-beach deposits date to the last interglacial and earlier. Uranium-series ages from a cave stalagmite interbedded with marine beds at Minchin Hole indicate a MIS 5 age (Stringer et al. 1986). Bowen et al. (1985) argued that at least three high stands of sea level are recorded, the older two of which are correlated to the interglacials of MIS 5e (Ipswichian, Eemian Stage) and MIS 7 (Late Wolstonian, Late Saalian Substage).

3.2.2 Atlantic Array and Lundy

Till is present throughout the Atlantic Array survey area (Channel Energy Limited 2010). This till (unit 3) is overlain by sand and gravel deposits (units 1 and 2). The till is present throughout the Atlantic Array survey area and according to the Channel Energy Limited (2010) report by Gardline Geosurvey reached no more than 4 m thickness. However, a later borehole report (Channel Energy Limited 2011) indicates a much thicker glaciogenic sequence (see below).

Three boreholes (BH 10, 12, 13), out of 15 proposed in a Senergy report for RWE npower renewables (2010), encountered glacial sediments in the Atlantic Array survey area. These include clay and/or sands logged as glacial (Pleistocene) with thickness of 2-8 m, underlying 2-18 m accumulations of sand. Data from four of the 15 proposed borehole locations (BH 6, 11, 12, 15) is presented in a later report by the Danish Geotechnical Institute (GEO) for Channel Energy Limited (2011) and in three of these boreholes glacial deposits are reported (BH 6A, 12, 15A). The locations of

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the GEO boreholes are given in Figure 1. Summaries of the borehole logs are illustrated in Figure 5.

The thickest glacial deposits in the Bristol Channel are reported between Lundy and the mainland (BH 15A) where 37.9 m of glacial deposits are logged (Figure 5) (Channel Energy Limited 2011). In this borehole the top 1.9 m is composed of sand. This is underlain by three units of silt/clay deposits with occasional subangular and subrounded cobbles. The silt/clay units (1.9-12.7 m, 17.2-23.0 m and 24.5-39.0 m depths) are separated by sand/silt and gravel units. The middle silt/clay units (17.2-23.0 m) and also the sand and gravels separating this unit from the upper silt/clay unit contain “rare seams of fine to medium gravel and lignite”. The upper silt-clay unit is predominantly grey although grades upwards into reddish and dark brown gravelly/sandy/silty clays. The lowermost silt/clay unit is reddish grey and olive-grey in colour.

The borehole log from BH 15A records the entire sediment sequence below 1.9 m as from a glacial environment (Gl) and of glacial age (Gc) (Figure 5) (Channel Energy Limited 2011). Some units are logged exclusively as glacial (1.9-5 m), whilst below this the sediments are recorded as both glacial and marine (Ma) or freshwater (Fw), sometimes all three simultaneously. However, the lithostratigraphy of the borehole log is interpreted in this paper as representing three till units separated by sand/gravel units. The middle till unit and overlying sand and gravels contain organic materials (lignite). Neither the upper or lower tills contain any references to lignite. Whilst no geochronology is available, it is possible that the lower till unit is Middle Pleistocene in age and the middle and upper tills are of Late Pleistocene (Devensian Stage) age. The middle till may be Early or Middle Devensian in age, with lignite seams (< 1 cm) being derived by reworking of interglacial deposits, possibly of freshwater origin. However, further research is required to determine the age and nature of these deposits. Nevertheless, it does appear that multiple till units are recorded in BH 15A.

In BH 12 the clay unit, described as exclusively glacial, is much less thick than in BH 15A and is present for nearly 4 m between 14.6-18.5 m and is characterised by many colour variations (Channel Energy Limited 2011). The clay unit is overlain by 14.6 m of sand with shell fragments. Borehole 12 is associated with a prominent asymmetrical ridge. This has smaller ridges superimposed onto it (ripples) but the main core of the ridge itself could be a moraine associated with ice coming from the west. The prominent ridges in the area of Borehole 12 (and to the east) look different to other large ripples and large sand waves of the area. The steep western slope of the ridge is consistent with a steeper ice-contact moraine slope.

In BH 6A records just over 3 m of clays/silts between 3.5-7.6 m. They are described as mudstone and siltstone but are considered glacial in environment and age (with codes Gl and Gc), although codes indicating marine (Ma) and Jura[-ssic] (Ju) are also used (Channel Energy Limited 2011). These fine-grained deposits are overlain by 3.5 m of sand and gravel mixed with cobbles and boulders. In the borehole log notes these deposits are considered to be marine/recent or glacial environment/age and the interpretation that is “very uncertain”.

The upper contacts of glacial silt and clay deposits in all three cores are similar elevations at -49.1, -48.9 and -48.6 for boreholes 6, 12 and 15A. Sand and gravel with shell fragments overlies this lower unit (Fig. 5) (Channel Energy Limited 2011).

Geophysical surveys reported by Channel Energy Limited (2010) and RWE npower renewables (2010) have revealed the presence of more than 22,000 boulders (> 0.3 m height) in the Atlantic Array survey areas. Each of these boulders have been identified and measured for height with data on each available in the report by Channel Energy Limited (2010, Appendix D). This includes the cable routes through Barnstaple Bay. Two concentrated clusters of boulders occur in the Atlantic Array survey area, one in the west and a larger cluster in the east. The extent of the eastern boulder cluster can be extrapolated southwards since concentrations of boulders are also revealed in the three cable routes between Lundy and the mainland (Figure 1).

The origin of the boulder clusters can be attributed to either marine or glacial origin, or both. In the former case boulder concentrations may be related to transient shoreline positions. The boulders could also be glacially-transported. The fact that till is reported in boreholes in areas where no surface boulders are present whereas no till is reported in areas where boulders are found suggests that either the boulders are not of glacial origin or that they represent boulder remnants of a pre-existing till layer, where the fine matrix has been winnowed out. Pleistocene tills are often relatively thin in the central Bristol Channel and no more than 2-8 m in the cores reported from the Atlantic Array survey area (although 16.1 m thick between Lundy and mainland Devon - see above). Another possibility is that the boulders are ice-rafted, since erratic boulders are commonly found on shorelines along the coast of Devon and elsewhere in the Bristol Channel, including as far east as Flat Holm (see section 3.3.2).

Boreholes from the British Geological Survey north and west of Lundy also report glacial deposits. These include reports from Borehole 72/49 (51° 0.86' N, 4° 54.82' W), Borehole 72/52 (51° 23.03' N, 4° 54.45' W), and Borehole 73/60 (51° 24.93' N, 4° 44.80' W). Borehole 72/49 is situated c. 25 km due west of Hartland Point in Devon. This borehole revealed sand and gravel (0-3 m) underlain by poorly sorted unconsolidated sediments (3-6 m), including clay with numerous rounded, subangular and angular rock fragments. The latter includes "broken cobbles and pebbles of igneous material". These unconsolidated sediments are considered to be Recent and Pleistocene, whilst underlying bedrock revealed in the borehole is Carboniferous mudstone. Boreholes 72/52 and 73/60 are situated west of the Atlantic Array survey area between Lundy and the Gower peninsula. In borehole 72/52, deposits are entirely "Pleistocene and Recent" (i.e. Pleistocene and Holocene), the top 0.5 m recorded as sand, underlain by 3 m of brown-grey "Boulder Clay". In borehole 73/60 the top 0-2.5 m is "Recent" sand and gravel, below which "Pleistocene: Till, red-brown, stiff with small rounded pebbles" is recorded between 2.5-9.5 m.

The offshore evidence clearly illustrates that the Outer Bristol Channel was glaciated during the Pleistocene (Figure 6). As noted above, Lundy also shows clear evidence of glaciation (Mitchell 1966; Rolfe et al. 2012; 2014; Figure 1). The island has large areas of ice-scoured granite bedrock with perched boulders (local lithology) and extensive areas of erratic gravels. Rolfe et al. (2012) dated the granite bedrock surfaces using paired $^{10}\text{Be}/^{26}\text{Al}$ analyses, the results demonstrating that there was no

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evidence of long-term complex exposure (i.e. exposure, burial and then re-exposure etc). However the island had been exposed for c. 40 ka, i.e. since the Middle Devensian.

3.3 Inner Bristol Channel: Somerset/Vale of Glamorgan to the Severn Estuary

The Vale of Glamorgan lies beyond the limits of the so-called South Wales end moraine (Charlesworth 1929). In the Cardiff area, the Late Devensian ice formed a lobe that reached off the current shore (Figure 6). The BGS (1986) sample map shows till present in the lower Severn Estuary in the area immediately SE of Cardiff, as depicted in maps by Bowen (1973). However, the BGS (1986) sample map also shows till beyond the traditional Devensian limits between Lavernock Point and Flat Holm offshore of Penarth.

3.3.1 Bristol and Somerset

Palmer (1931, p. 358) argued that there is no evidence of glaciation in the Bristol area. However, Hawkins & Kellaway (1970) concluded the opposite and presented evidence for glaciation of the Bristol district, a situation further advocated by Kellaway (1971). This was then disputed by Kidson & Haynes (1972) who pointed out that the Burtle beds were estuarine sediments containing Quaternary microfauna from both the current and last interglacial (i.e. the Ipswichian). Thus, they are not related to glacial processes, as had been suggested by Kellaway (1971). The nature of the glacial record in the Bristol area has since remained unclear and the evidence for ice reaching this area is patchy. The best evidence for glaciation in this area, the easternmost reaches of the Bristol Channel, is at Court Hill and Kenn, near Clevedon where erratic boulders and till are exposed (Hawkins and Kellaway 1971; Gilbertson & Hawkins 1978a,b). Whilst it is likely that ice did reach the Bristol area based on this evidence there is no strong evidence for ice reaching further east into Wiltshire (Scourse 1997) (Figure 1), although boulders at megalithic sites such as Stonehenge are attributed by some to have been transported by ice (e.g. Thorpe et al. 1991; John 2008). As for the age of the Bristol and Somerset glaciation, this remains unknown. In the Gordano Valley, a few kilometres NE of Clevedon, Bridle (2012) dated intertidal and alluvial sediments using amino-acid analyses showing that they date from MIS 7 or 5e. However, the amino acid chronology is contradicted by younger radiocarbon and OSL ages from the same deposits dating to the Devensian Stage (MIS 5d-2) and thus the geochronology remains open to interpretation. Whilst this geochronology, does not confirm the specific age of the pre-interglacial sediments, any glaciation in this area must at least pre-date the Devensian Stage.

On the southern coast of the Bristol Channel the evidence for glaciation is limited, although valleys appear to be truncated or aligned parallel to the coast, such as at Lynton. Similar channels can be seen along the coast as far as Ilfracombe to the west and Minehead to the east. Some of these are consistent with ice-marginal meltwater channels when the Bristol Channel was filled with ice, an argument also made by Stephens (1966, 1970). This has been the focus of recent unpublished research (Rolfe 2015). OSL ages from Doniford, close to the north Somerset coast in the Inner Bristol Channel, indicate a semi-continuously aggrading fluvioperiglacial sequence dating from the Middle Devensian, MIS 4 to 3 (Basell et al. 2011a,b). Any glaciation that penetrated into Somerset must pre-date this, although it is possible that these

sediments built up whilst ice was present to the northwest in the Outer Bristol Channel. The Doniford fluvioperiglacial sequence has yielded mammoth fossils and also Lower Palaeolithic implements (Wedlake 1950; Basell et al. 2011a,b). This environment is likely to have been characteristic of the fluvial environments of the Inner Bristol Channel at this time. Since the current river at Doniford is much smaller than the valley it occupies, Basell et al. (2011a) considered it to be a misfit stream with the palaeovalley and associated sediments associated with a much larger river that drained eastern Exmoor and the Quantock Hills. This river may be associated with a major river channel, south of the palaeo-Severn river channel, both of which are visible in the central Bristol Channel (Figures 2 and 3).

3.3.2 Cardiff and the Vale of Glamorgan

The Welsh Ice Cap reached beyond Cardiff during the Late Devensian (Bowen, 1974; Kendall 2015) (Figure 6). Till is recorded offshore between Flat Holm and Cardiff (BGS 1986) and can be attributed to this phase of glaciation. However, it is only here and in Swansea Bay that Welsh ice reached offshore during the Devensian. Between Cardiff and Swansea, as well as east to Newport and the English border, the southern limits of the Welsh Ice Cap follow a line described by Charlesworth (1929), as marked by the South Wales Moraine. These moraines contain material from the South Wales coalfield area and are especially rich in Pennant Grit boulders which are widespread in this area at the heads of the glaciated South Wales valleys.

Older glacial deposits are present at Pencoed (Figure 1), where erratic boulders were revealed in an open-cast coal mine. Bevins & Donnelly (1992) re-examined 21 boulders from this site and confirmed that these were erratics from sources surrounding the Irish Sea. These authors argued that this observation reinforced the view that Irish Sea ice had penetrated this far east during an older glaciation to the Devensian moraines described above. Other evidence for moraines and erratics associated with the west in the Vale of Glamorgan is scarce.

Meltwater channels are widespread in the Vale of Glamorgan. They are usually attributed to meltwater associated with Devensian ice which had its limit in the north and east of the Vale (Bowen 1967). The morphology of these channels is consistent with this at sites such as Thaw valley and in the area bounding the Ely valley, immediately west of Cardiff. However, Crampton (1966) argued that two meltwater channels, at Cwm Alun and Pant St Brides, 2-3 km south of Bridgend, were formed by overflow channels when Welsh ice abutted Irish Sea ice in the Bristol Channel during an older glaciation.

3.3.3 The islands: Steep Holm, Flat Holm and Denny Island

Erratic pebbles and boulders are present on Flat Holm. Many of these are present on the beaches surrounding the island (John, 2014). They are also described in Whittaker and Green (1983). The morphology of the three islands is marked by distinct west-east asymmetry, with a gentler western than eastern slope profile. Both Flat Holm and Steep Holm display ovoid planform, especially the latter island. Denny Island also has a west-east asymmetry, although the island is aligned SSW to NNE. These morphologies are consistent with ice-moulding by ice flowing from the west.

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3.4 The Late Pleistocene palaeo-Severn

The River Severn is one of the longest rivers in Britain. Rising above the Ironbridge gorge, after following a meltwater channel, its lower course then continues in a wide erosional valley which includes a system of terrace deposits, finally entering its tidal estuary that grades into the Bristol Channel. The Pleistocene terrace sequence in the Severn catchment is discussed by Bridgland et al. (2004) who suggest that there is evidence for inputs from three glaciations. This includes deposits associated with the last cold stage, the evidence of which is reviewed in detail below.

The catchment of the River Severn would have been similar to today during the Late Pleistocene, although the upper reaches and western tributaries would have been fed by the melting margins of the Welsh Ice Cap. This ice cap was retreating and rapidly thinning by 20 ka and ice had retreated to the headwaters of the mountains by 16-15 ka (Glasser et al. 2012; Hughes et al. 2016). The Severn catchment would have been ice-free after this time, except for some minor cirque glaciers during the Younger Dryas Stadial in the Severn tributaries, such as in the Berwyns (Hughes 2009). The middle reaches of the Severn were complicated by the northward blocking of drainage into Shropshire and Cheshire by the Irish Sea ice sheet. This caused the formation of glacial Lake Lapworth (Wills, 1924).

3.4.1 Late Pleistocene terrace deposits and drainage evolution of the Lower Severn Valley

Late Pleistocene terrace deposits provide insight into the drainage evolution of the Lower Severn Valley. The drainage history of the Severn was established by Wills (1924, 1938) and Whitehead & Pocock (1947). Subsequently research by Beckinsale & Richardson (1964) presented a revised and elaborated model following the emergence of new evidence on the river's development. Subsequent investigation of the Severn Estuary by Williams (1968) further elaborated the evolution of the valley, and most recently dating of the pre-Late Pleistocene terrace deposits was presented by Maddy et al. (1995) and Maddy (1999) and their sedimentation was discussed by Dawson (1985; 1989). Here the river's Late Pleistocene history, based upon the investigation from Worcester to the estuary at Gloucester, is summarised for comparison and interpretation of the form and development of the Bristol Channel.

The terrace deposits are collectively referred to as the Severn Valley Formation (Maddy 1999). They comprise predominantly gravels and sands deposited under cold-climate conditions. The Late Pleistocene sequences include three major units that underlie respectively, the Main Terrace (Wills 1938) or Third Terrace, the Worcester Terrace (Wills 1938; Dawson 1989) or the Second Terrace and the Power House (Power Station) Terrace surfaces (Wills 1938; Barclay et al. 1997; Maddy 1999). Of these the oldest unit, the Main Terrace member relates to the Maximum of the Late Devensian 'Irish Sea' (i.e. Stockport Formation) glaciation of the Upper Severn and the drainage of Glacial Lake Lapworth. The unit occurs up to 30 m above the present river floodplain. Incision following abandonment of the Main Terrace resulted in the coarse gravel and sand aggradation of the Worcester Member, its uppermost surface occurring at c. 20-22 m above the present river. At Worcester the unit is 6 m thick but it thickens downstream to over 12 m near the Severn Tunnel (Williams 1968; Barclay et al. 1997). The Worcester gravels are interpreted as late-

Devensian outwash possibly related to the Ellesmere (Welsh) ice re-advance (Shotton & Coope 1983; Beckinsale & Richardson 1964; Thomas 1989). The youngest gravel and sand unit is the Power House (Power Station) Terrace Member which rests in a channel excavated into the previous unit (Shotton & Coope 1983). Downstream of Worcester, it underlies the Holocene alluvium, where it is 2-3 m thick and can be traced throughout the Lower Severn (Wills, 1938; Beckinsale & Richardson 1964). Locally it reaches thicknesses of 12 m. According to (Shotton & Coope 1983), a radiocarbon date from the overlying alluvial sediments of $12,570 \pm 220$ ^{14}C a BP indicates that the Power House gravels accumulated immediately before the Devensian Late-glacial Substage. Moreover, these authors conclude that the deposition of the three terrace members discussed here "can have taken no more than 12,000 years and possibly as little as 5,000 years to accomplish" (p. 33). However, this chronology is based on only one radiocarbon date, from what is potentially complex valley-fill sequence. By analogy with sequences further east (cf. Lewin & Gibbard 2010), it is conceivable that the deposition of the Power House Member continued into the Devensian Late-glacial. By contrast, radiocarbon dates from organic materials in the Main Terrace, and its equivalent the River Avon Terrace No.2, indicates that the whole scheme from Main Terrace Member times relates to the last 38 to 42 ^{14}C ka BP (Coope et al. 1961). However, Dawson (1989) suggested that the Main Terrace dated from 25 to 18 ^{14}C ka BP.

The Severn Valley Formation units rest on eroded bedrock surfaces, the youngest of the units, the Power House Member, filling a continuous deep channel previously termed the 'buried valley'. Cross-sections by Beckinsale & Richardson (1964) and modern borehole records demonstrate that this valley has a downstream gradient of 0.34 m km^{-1} and it is incised into the wider valley occupied by the Worcester Terrace form. At Upton-on Severn the buried valley floor occurs at -1.0 m OD, whilst downstream at Gloucester it occurs at -2.5 m O.D. At the Severn Tunnel (Figure 1), the buried bedrock surface underlying the gravel units is described as an c.11 km wide trough with an undulating floor, according to Beckinsale & Richardson (1964, p. 97). The deep channel of 'buried valley' here is incised into this surface to a depth of -6 to -12 m O.D. 10-20 m thick Worcester Member which overlies the trough (Wills 1938; Williams 1968). The buried valley is filled by 3 m of Power House Gravels in this transverse section. This final phase of gravel aggradation in the lower Severn, was terminated by the Holocene eustatic sea level transgression which, with minor fluctuations, continued into historic times (cf. for details: Beckinsale & Richardson 1964), the gravel units being buried by Holocene sediments that range from 6-15 m thick.

According to Beckinsale & Richardson (1964, p. 96) the change in the valley width from the wide Worcester Terrace channel, probably occupied by the river in braided form, to the narrower, well-defined channel occupied by the Power House gravels, seems to reflect a considerable decrease in run-off, velocity and probably sediment supply, potentially related to the deglaciation history of the Severn catchment. Moreover, these erosional phases may be correlated with that when valleys in lowland Somerset were cut down to c. -27 m O.D. and sea level was below -30 m O.D. The period may be represented in the Severn by the deep excavations beneath the estuary and by the strong valley-in-valley form cut in the bedrock surface underlying the Worcester Terrace gravels. That this valley form continues offshore into the Bristol Channel was already demonstrated by North (1955), whilst Anderson & Blundell

(1965) identified a former confluence of the Severn and Taff c. 9 km south of Penarth at -30 m O.D. Moreover, according to Williams (1968) the possible confluence of the River Usk with the Severn occurred at similar depth south-southwest c. 9.5 km from its present mouth.

4. Discussion

The recently available high-resolution bathymetric, borehole and geophysical data from the floor of the Bristol Channel has allowed for new analysis of the seafloor topography and Quaternary geology. This has revealed new information on the fluvial and glacial history of the Bristol Channel, especially evidence for glaciation and the former course of the River Severn.

4.1 Glaciations of the Bristol Channel

Overall, three glacial stratigraphical units can be recognised in the Bristol Channel: 1) the southernmost deposits of the Welsh Ice Cap offshore of Swansea and Cardiff, which is Late Devensian in age; 2) thick glacial deposits, surface boulders and erosional features in the outer Bristol Channel, which is dated to the Middle Devensian, and; 3) glacial deposits in the inner Bristol Channel that are more sporadically preserved, and likely to date from the Middle Pleistocene (Figure 6). The age of these older glacial deposits remains unknown and open to speculation.

The geochronology of the Bristol Channel glaciations, and relating this to glacial evidence elsewhere, remains one of the biggest challenges, even for the outer Bristol Channel. Glaciation as far south as the Isles of Scilly and the Celtic Sea shelf has been shown to date from the Late Devensian, MIS 2 (Cofaigh & Evans, 2007; Chiverrell et al. 2013; Praeg et al. 2015; Smedley et al. 2017), close in time to the global LGM (cf. Hughes & Gibbard 2014). However, the glaciation of the outer Bristol Channel appears to have occurred earlier in the Devensian, with ice retreating over Lundy in MIS 3 (Rolfe et al. 2012) from a larger ice extent that was reached sometime earlier, probably in MIS 4.

Despite the challenges in understanding the timing and regional patterns of glaciation in the south-western British Isles, it is clear that glaciers have sculpted the Bristol Channel on at least two occasions, with a third glaciation shaping its northern margins. This has profound implications for ice-sheet dynamics in south-west Britain, since the Bristol Channel embayment was a major outlet route for the Irish Sea Ice Sheet. This outlet for glaciation not only moulded the Bristol Channel itself, but also directly affected fluvial systems draining into it. If the Bristol Channel glacier had blocked the drainage it would have potentially caused the formation of a glacial lake east of the ice front.

4.2 Linking the Late Pleistocene Lower Severn record with the Bristol Channel

Based on these observations a relative chronology of events can be established for the time represented and compared to that of the River Severn upstream of the estuary. The oldest features identified on the Bristol Channel floor appear to be the fluvial terraciform remnants of the palaeo-Severn Worcester Member, how they relate to the

next oldest landforms, the Swansea Bay suite of glacial deposits, as already stated, is yet to be clarified. Previous evidence indicates that the Welsh ice reached the end moraine in what is now Swansea Bay at c. 23 ka (Bowen 1994; 1999) and Carmarthen Bay (Bowen 1974; 1999) during the Late Devensian but did not cross the Severn Estuary/Bristol Channel (Clark et al. 2004). The Swansea Bay meltwater presumably discharged into the River Severn flowing during the Worcester Terrace phase (cf. above). As noted, the Worcester Member gravels include a substantial input from Late-Devensian outwash sourced from the Ellesmere (Welsh) ice re-advance (cf. Thomas 1989) into the upper Severn catchment. It therefore appears that the advance to the Swansea Bay moraines occurred at much the same time as that further north.

Following glacial recession from the Swansea coastal area, which began at 16 ka (Culver & Bull, 1979), glaciolacustrine deposits accumulated in the basin between the moraine and the land until c.10 ka B.P. At a similar time, fluvial incision initiated the central valley infilled by gravels and sands. Corresponding downcutting from the Worcester Terrace by the Severn and its tributaries upstream gave rise to the 'buried valley' which is infilled by the laterally equivalent Power House Member gravels (cf. above), of Devensian Late-glacial age. As North (1955) recognised, there is no reason not to consider the Bristol Channel central valley as the extension of the Severn buried channel and by implication that the incision and contemporaneous deposition of the overlying gravels to be of Late-glacial age. Equally the tributary valley buried valleys and their basal gravel fills, such as that of the rivers Usk, Taff, etc. (Wills 1938; Beckinsale & Richardson, 1964; Anderson & Blundel 1965; Williams 1968), almost certainly also date from this interval. Throughout these phases the river was graded to low eustatic sea-level below -50 m O.D. and almost certainly substantially lower. A final phase of rejuvenation on the lower Severn, termed the Forest-period, excavation appears to have intervened between the Late-glacial and initiation of Holocene sedimentation. This is thought to have been halted by the Holocene eustatic sea-level rise (Beckinsale & Richardson, 1964; Kidson 1977, 1982).

Marine transgression associated with the Holocene interglacial climatic amelioration began at between 10.5 and 9.8 ka at - 35 m O.D., near Scarweather Sands, according to Evans & Thompson (1979) and Kidson (1982). The drowning of the river valley proceeded rapidly with freshwater materials being buried over a vertical range of over 47 m (Kidson 1977, p. 286). The substantial tidal fluxes associated with this transgression resulted in scouring, almost certainly removing and recycling the sediment and regolith cover of the bedrock surfaces (cf. Campbell et al. 2012). This scouring also appears to have removed sediments that accumulated within the central and associated valleys as the transgression progressed. Associated with this transgression was the influx of sand/silt sediments which provided the materials for the substantial sheet of deposits in the westernmost part of the Bristol Channel and upon which the migrating sand waves were developed. Later, as the transgression reached its maximum level by c. 6 ka (Kidson 1977; Heyworth & Kidson 1982), with water depths increasing markedly in the west, these sand waves ceased migrating and later coastal sediment accumulations were laid down, a process that continues today in embayments and similar places. For example, according to Beckinsale & Richardson (1964), the mouth of the River Severn proper, close to the Severn Tunnel, the present river is 11 km in width, its undulating floor being buried by patches of gravels and deep deposits of silt. As Campbell et al. (2012, p.39) note, the general

regional environmental and landscape evolution during the middle to late Holocene has been minor, the main coastal impacts being the re-occupation of old cliff and shorelines, the development of littoral landforms, including beaches, spits, bars, etc. and sedimentation in the estuaries. However, possibly the most important development has been the accumulation of sand and gravel, mostly in active intertidal dune fields (Allen 1990; Allen & Fulford 1993; Carling et al. 2006).

4.3 Comparison with the English Channel

Comparison of the Bristol Channel with the English Channel might not seem immediately obvious, the latter being considerably larger, being an open seaway rather than an extended estuary, whilst the former has been subjected to several glacial events during its history. However, scale aside, the Severn Estuary-Bristol Channel complex has much in common with the English Channel, including origin and shared Quaternary history. In fact, it is possible to consider the Bristol Channel as a partial analogue for what the English Channel might have looked today if it were not for the opening of the Dover Strait.

The first, and most obvious point is that during periods of low global sea-levels the floors of both channels are exposed as dry land. In the case of the English Channel, at sea-level minima, surfaces as low as -100 m were exposed. During this period, most recently during the Late Devensian, the floors were subjected to subaerial periglacial weathering. At this time, the rivers extended their courses across the emergent surfaces causing substantial incision, and associated sedimentation in the valleys. The English Channel Central Palaeovalley is 6-8 km wide in the west on the Palaeozoic rocks, and even wider in the east (c. 10 km) on the Mesozoic substrate. By contrast, the Severn/Bristol Channel central valley remains remarkably constant at c. 1.5 km throughout the submarine area. In the English Channel the valley extends to depths twice that in the Bristol Channel, possibly a consequence of the tidal scour during transgressions and also catastrophic flooding events. As Antoine et al. (2003) showed, the valley systems are characterised by deposition of coarse fluvial sedimentation that took place in predominately under cold climates at low sea-level, with the rivers adopting braided or wandering courses.

The notable contrast between the palaeo-Severn, incised into the Bristol Channel floor, and the English Channel Northern Palaeovalley, is the occurrence in the latter of a characteristic channel morphology including diamond-shaped intra-channel islands and scour pits. These features have been described in detail by Gupta et al. (2007) and Collier et al. (2015), who interpreted them as resulting from catastrophic flooding events ('mega-flood'), associated with overspill of glacially dammed lake water in the southern North Sea and formation of the Dover Strait/Pas de Calais (cf. Gibbard 1988; 1995, 2007; Gibbard & Cohen 2015). No such features have been observed in the Bristol Channel central valley in the bathymetric maps currently available. Moreover, in this context, it is interesting to note that the characteristic catastrophic ('mega-') flood channel morphology seen in the Northern Palaeovalley of the English Channel floor is absent from tributary valleys in the same system, e.g. the Seine (Benabdellouahed et al. 2016) and the Arun (Gupta et al. 2007). This indicates that the palaeo-Severn valley and its tributaries are 'normal' fluvial systems. However, according to Mellett et al. (2013), erosion of the eastern English Channel floor following the major-flooding event during the Late Wolstonian (MIS 6) was

composite, the morphology of the Northern Palaeovalley also in part resulting from later normal fluvial processes.

In common with the English Channel, occupied by the Channel River, the Bristol Channel palaeo-Severn discharged into the Atlantic Ocean during low sea-level stands, their material in transport contributing to the sediment accumulated on the continental slope and adjacent ocean floor, as described by Bourillet et al. (2003) and Toucanne et al. (2009, 2010).

Tectonic activity has played a significant role in the long-term, controlling the development of the river evolution in both channel systems. The long-term tilting of Britain determined a broad N–S alignment of drainage lines in the non-glaciated southwest and southern Wales. Broadly southward tilting of the Cornish Massif along a WSW–ESE to W–E axis has determined the N–S alignment of the Cornish streams and the occurrence of the characteristic drowned river valleys (or rias) on the English Channel coast. In contrast, in Cornwall, as in northern Brittany, the profiles of the coastal rivers are steeply sloping and the valleys are deeply incised into the plateaux surfaces owing to a strong uplift of the northern coast. This strong uplift potentially also explains the poor preservation of Pleistocene fluvial sequences in this area.

In both channels interglacial deposits are rare in the fluvial sequences and are mainly restricted to estuarine or coastal raised-beach areas. Regarding the marine re-flooding of the channels, the occurrence of sand waves developed on sand-sheet spreads is common to both systems. According to Reynaud et al. (2003) the thickest deposits are bank systems in the English Channel Western Approaches, comparable to those in the westernmost Bristol Channel-Celtic Sea zone. As noted above, these static southern Celtic Banks are interpreted as having been constructed during the last, post-glacial sea-level rise (e.g. James et al. 2012). In that case the Celtic Banks and the OBel sands of the western Bristol Channel would represent the tidal transgressive systems tract accumulations confirming the observations from this study. By contrast, the substantial bar, dune to fan-shaped accumulations observed in the Bristol Channel reflect fully marine deposits active sediment migration processes linked to tidal flux. The sediment is almost certainly derived in both the Bristol and English Channel examples from the offshore reworking of older littoral deposits or incised valley fills (cf. Reynaud et al. 2003).

5. Conclusions

At least three phases of glaciation can be recognised in the Bristol Channel region. The earliest recorded glaciation occurs in the Inner Bristol Channel where ice filled the entire area between the Vale of Glamorgan and Somerset and reached beyond the Severn Estuary to a point between Bristol and Weston super Mare. A second phase, dating from earlier in the Middle Devensian (MIS 4/3), occurred where ice overrode Lundy and deposited thick accumulations of glacial sediments in the Outer Bristol Channel. The most recent glaciation occurred during the Late Devensian Substage (MIS 2) and is associated with the southern limits of the last Welsh Ice Cap in South Wales. This event has produced a striking submarine morphology in Swansea Bay.. H, where, two end moraine assemblages are evident.

The Bristol Channel contains a bedform morphology that reveals clear evidence of major fluvial systems. The most striking feature is the evidence for the palaeo-Severn channel which is visible on high-resolution bathymetry throughout the inner and central Bristol Channel. This palaeochannel cross-cuts earlier deposits, including glacial sediments and is overlain in the Outer Bristol Channel by thick accumulations of marine sands.

Whilst the long-term evolution of the Bristol Channel has been influenced by tectonic processes, the morphology of the current channel has been directly shaped by glaciation and subsequent fluvial processes during the Pleistocene. This was followed by inundation by rising glacio-eustatic sea levels in the early Holocene with the River Severn retreating to its current course leaving a palaeo-River Severn Channel clearly imprinted in the submarine bathymetry of the Bristol Channel.

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Figures

Figure 1. Location of the Bristol Channel area showing key locations mentioned in the text. The Atlantic Array survey area is shown along with the cable routes to Devon. The bathymetry data is from EMODNet (2016).

Figure 2. High-resolution submarine and bathymetry of the Bristol Channel. Image from EMODnet (2016).

Figure 3. Detailed focus on high-resolution submarine and bathymetry of the outer, central and inner Bristol Channel areas. Images from EMODnet (2016).

Figure 4. Cross-profiles of the inner, central and outer Bristol Channel. The palaeo-Severn river channel is clearly visible in each cross-section. Data from EMODnet (2016).

Figure 5. Boreholes BH 6A, BH 12 and BH 15A in the Outer Bristol Channel (see Figure 1 for locations). Borehole BH 15A contains the thickest accumulation of glacial deposits recorded in the Bristol Channel. The Pleistocene glacial sediments between 6 and 36 m include occasional seams (<1 cm) of reworked freshwater lignite. These logs are from a report by the Danish Geotechnical Institute (GEO) for Channel Energy Limited (2011).

Figure 6. Glacial phases and associated limits in the SW British Isles. Adapted from Scourse et al. (1997) including new annotations on glacial limits in the Bristol Channel region.

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104x62mm (300 x 300 DPI)

Figure 2. High-resolution submarine and bathymetry of the Bristol Channel. Image from EMODnet (2016).

104x62mm (300 x 300 DPI)

Figure 3. Detailed focus on high-resolution submarine and bathymetry of the outer, central and inner Bristol Channel areas. Images from EMODnet (2016).

208x247mm (300 x 300 DPI)

Figure 4. Cross-profiles of the inner, central and outer Bristol Channel. The palaeo-Severn river channel is clearly visible in each cross-section. Data from EMODnet (2016).

65x24mm (300 x 300 DPI)

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121x83mm (300 x 300 DPI)

Figure 6. Glacial phases and associated limits in the SW British Isles. Adapted from Scourse et al. (1997) including new annotations on glacial limits in the Bristol Channel region.

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