Vol 448 | 19 July 2007 | doi:10.1038/nature06018

LETTERS

Catastrophic flooding origin of shelf valley systems in the English Channel

Sanjeev Gupta[1], Jenny S. Collier[1], Andy Palmer-Felgate[1] & Graeme Potter[2]

Megaflood events involving sudden discharges of exceptionally large volumes of water are rare, but can significantly affect landscape evolution, continental-scale drainage patterns and climate change[1]. It has been proposed that a significant flood event eroded a network of large ancient valleys on the floor of the English Channel—the narrow seaway between England and France[2–4]. This hypothesis has remained untested through lack of direct evidence, and alternative non-catastrophist ideas have been entertained for valley formation[5,6]. Here we analyse a new regional bathymetric map of part of the English Channel derived from high-resolution sonar data, which shows the morphology of the valley in unprecedented detail. We observe a large bedrock-floored valley that contains a distinct assemblage of landforms, including streamlined islands and longitudinal erosional grooves, which are indicative of large-scale subaerial erosion by high-magnitude water discharges. Our observations support the megaflood model, in which breaching of a rock dam at the Dover Strait instigated catastrophic drainage of a large pro-glacial lake in the southern North Sea basin[2]. We suggest that megaflooding provides an explanation for the permanent isolation of Britain from mainland Europe during interglacial high-sea-level stands[7], and consequently for patterns of early human colonisation of Britain together with the large-scale reorganization of palaeodrainage in northwest Europe[4].

The geographic isolation of Britain from continental Europe is a consequence of high interglacial sea levels that led to marine flooding of the shallow shelf areas of the English Channel and the North Sea[7]. Before the formation of the Dover Strait, however, Britain remained connected to Europe by means of a structural ridge, the Weald–Artois anticline, which extends from southeast England to northwest France (Fig. 1). During interglacial high-sea-level stands, this Chalk ridge formed a narrow isthmus separating marine embayments to the north (North Sea) and to the southwest (English Channel)[4]. To form 'island' Britain it was thus necessary to breach the Weald–Artois ridge; however, the mechanism of the breach remains speculative[4].

Early marine geophysical investigations of the English Channel revealed a ~400-km-long network of submerged and partially infilled valleys carved into the bedrock floor of the shelf[8–10] (Fig. 1). This network extends westwards from the Strait of Dover, collecting the drainages of southern England and northern France before eventually amalgamating to form a single prominent valley, the Hurd Deep[2,8,10]. Formation of the network was explained by a variety of mechanisms: fluvial erosion in response to late Quaternary sea-level lowering[9], glacial erosion[5,6], tidal scouring[11] and erosion by catastrophic flooding[2–4]. However, testing these competing hypotheses has awaited detailed mapping of the sea floor. Here we analyse a regional high-resolution bathymetric grid of the north-central

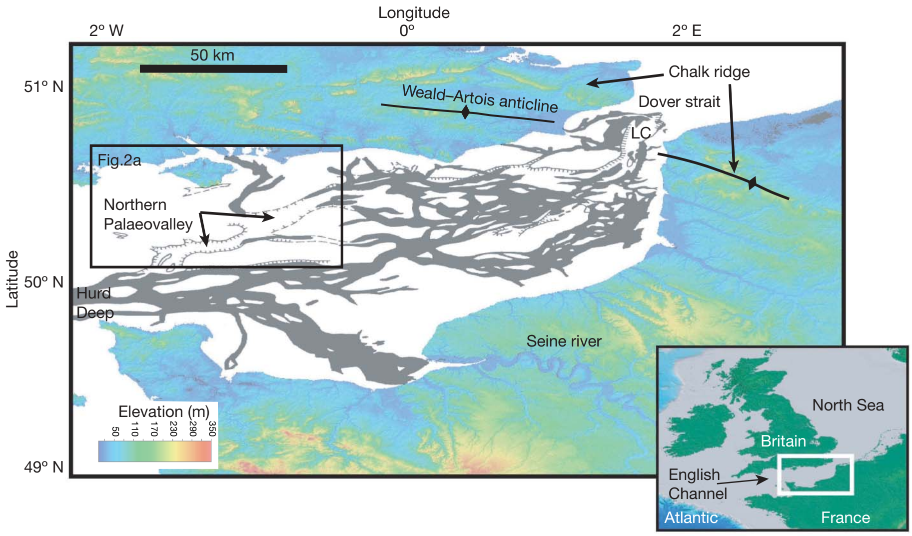

Figure 1 | Location map and inferred distribution of palaeovalleys on the English Channel shelf. Grey indicates valleys filled with sediment; white and hatched, unfilled valleys. The box shows the location of the segment of Northern Palaeovalley that we studied. Onshore topography is shown as a coloured and shaded relief image; data are derived from the NASA Shuttle Radar Topography Mission elevation model. There is a prominent topographic escarpment formed by the Weald–Artois anticline that extends from southeastern England into northwestern France. The Lobourg Channel (LC) in the Dover Strait extends westward into the Northern Palaeovalley. The inset shows the location of the study area with respect to northwest Europe. The map of palaeovalleys is reproduced with permission from ref. 2.

[1]Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK. [2]UK Hydrographic Office, Admiralty Way, Taunton, Somerset TA1 2DN, UK.

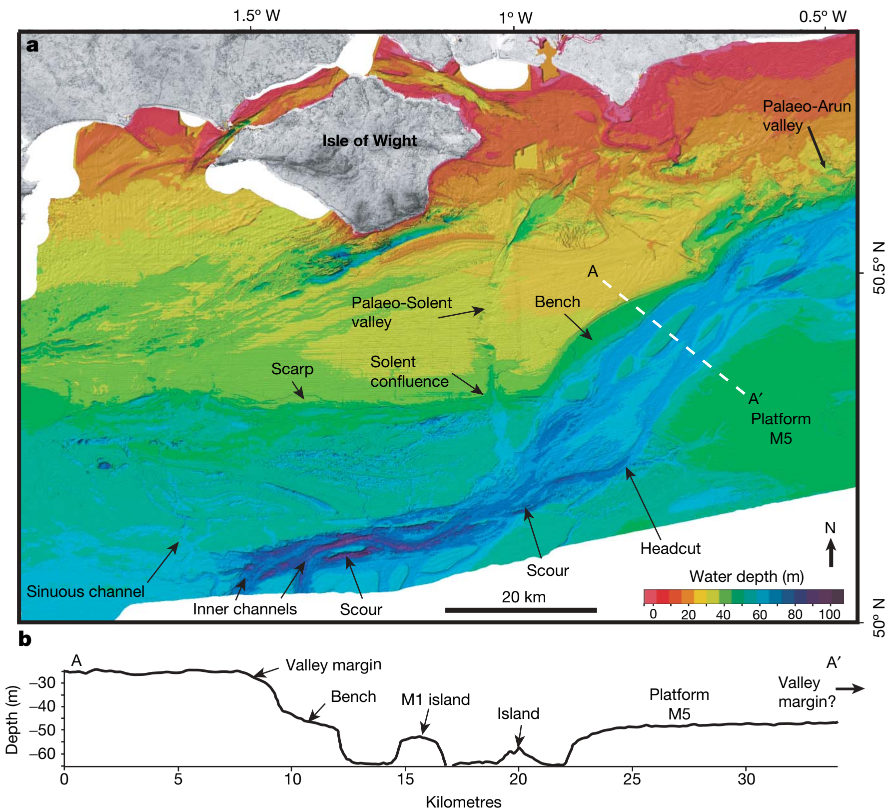

Figure 2 | Sonar bathymetry of the north-central English Channel shelf. **a**, Coloured and shaded relief bathymetry map. Onshore topography is shown as black and white shaded relief. A headcut is a small cataract at the upstream termination of inner channels. Scours are elongate hollows eroded into the channel floor. The scarp is an east–west-trending escarpment defining the northern limit of the palaeovalley. The white dashed line shows the location of the bathymetric profile A–A′. The east–west and east northeast–west southwest striping (closely spaced lines) in the image is an artefact of survey vessel tracks. **b**, Bathymetric profile across the Northern Palaeovalley showing valley margin, bedrock bench and streamlined islands.

English Channel shelf (see Methods). The data show a collection of landforms that, taken together, indicate a catastrophic flood origin.

The bathymetry shows a prominent ~100-km-long, northeast–southwest-trending, linear valley that is eroded into the gently southward-sloping shelf (Fig. 2a). This feature, called the Northern Palaeovalley[11], represents the northern branch of the Channel valley system (Fig. 1) and forms a bedrock-floored valley that is largely devoid of sediment infill. Inner channels within the valley show an anabranching planform. In the northeast, the valley is up to 50 m deep with a floor width of <15 km (Fig. 2a). Traced westwards, it narrows to a prominent <10-km-wide and 40-m-deep inner channel bounded to the north by a 12-km-wide bench. Cross-sections across the valley show rectangular profiles, with valley walls of ~2°, flat valley floors and high width-to-depth ratios (Fig. 2b). In the east, valley margins show streamlined edges (see TL in Fig. 3a and b), which are sharp and erosive (Supplementary Fig. 1). The valley cross-cuts a variety of bedrock lithologies[12], ranging from soft Palaeogene rocks to more resistant Chalk bedrock, indicating that lithology does not significantly control valley morphology.

Evidence of irregular scalloping of the walls by mass movement processes, or spur and gully features typical of dissection by normal fluvial processes, is not apparent. A distinct sub-horizontal bench (~4 km wide, ~25 km long), cut into Chalk bedrock, is observed on the northern valley flank (Fig. 3a, b), indicating at least two episodes of downcutting: one to carve the bench and another to incise it further. The southern margin of the initial incision is not observed in the study area (Fig. 2b); accordance of the bedrock bench and platform M5 indicates that the initial valley was a minimum of 45 km in width. The large size, linear trace and anabranching morphology of the Northern Palaeovalley together with the presence of prominent streamlined valley margins is compelling evidence that valley incision was achieved by high-magnitude flood erosion rather than by normal fluvial processes[13,14] (see Supplementary Information). In contrast, the onshore Seine river valley shows a single-thread sinuous course where it is incised into Chalk bedrock (Fig. 1).

The most striking evidence that the Northern Palaeovalley was formed by catastrophic flooding is the presence of kilometre-scale streamlined islands or mesas (M1–M5 in Fig. 3) with characteristic elongate, lenticular to quadrilateral planforms (M2, M3 in Fig. 3b, c).

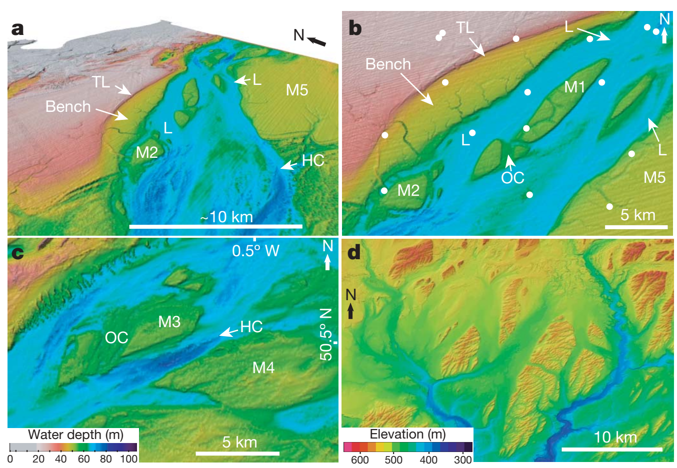

Figure 3 | Details of geomorphology of the Northern Palaeovalley. Location of images indicated in Supplementary Fig. 2. **a**, Three-dimensional perspective view of the Northern Palaeovalley looking northeast. Vertical exaggeration is approximately ×6. Water depth is indicated by the colour scale in **c**. HC, headcut; TL, trim line of valley margin. L, longitudinal lineations. **b**, Vertical view of the northeast reach of the Northern Palaeovalley. The northwestern valley margin shows the presence of a distinct bedrock bench. Prominent streamlined islands are present in the main valley. Flow lines are indicated by longitudinal lineations on the floor of the inner channel. OC, oblique channel. White circles indicate Chalk bedrock from shallow cores. **c**, Vertical view of streamlined islands (M3, M4) in the northeastern reach of the Northern Palaeovalley. There is an oblique channel dissecting island M3. **d**, A coloured and shaded relief image of streamlined islands in the Cheney–Palouse Scabland terrain (Channeled Scabland, Washington). Flood flow direction is to the south. Data are derived from a 10-m-resolution US Geological Survey digital elevation model.

These islands are up to 10 km long and 4 km wide (Fig. 3), with an average length-to-width ratio of 3–4. Shallow coring of the seabed[12] indicates that the islands are eroded into bedrock and do not represent depositional forms (Fig. 3b). The upper surface of the islands is generally smooth and flat, although locally oblique channels cut through small divides at their crest. The streamlined islands bear a striking resemblance to loess islands preserved in the Cheney–Palouse terrain of the Channeled Scabland of Washington, USA[13,14] (Fig. 3d). These formed when outburst flooding from the Pleistocene glacial lake Missoula eroded through loess cover into basalts[13]. The distinctive shape of the islands is thought to be a feature to minimize resistance in fluid flow[15].

Additional evidence for erosion by flooding comes from the presence of longitudinal lineations on the floor of the Northern Palaeovalley (L in Fig. 3a, b). These form alternating ridges and grooves that are oriented parallel to the channel gradient and have long axes sub-parallel to the channel walls (Fig. 3a, b). The grooves are typically <200 m wide, <2–3 m deep and 10–15 km long. They clearly show curvature around intra-channel topography, indicating that they approximate flow streamlines. Similar lineations in the Channeled Scabland are thought to result from erosion by longitudinal vortices developed in high-magnitude flood flows[13]. Also typical of flood erosion are crescent-like scours that taper upstream into V-shaped headcuts (Fig. 3c); we interpreted these to have formed by headward recession of small <10-m-high cataracts.

Southeast of the Isle of Wight, a north–south trending valley (2–4 km wide) is observed that is interpreted as the offshore course of the palaeo-Solent valley[9,11,16]. At its confluence with the Northern Palaeovalley it forms a hanging tributary with a series of south-facing knickpoints (Figs 2a and 4a), suggesting that the Solent was unable to regrade when the Northern Palaeovalley was abruptly incised to its current base level. Another tributary, the 2-km-wide palaeo-Arun (Fig. 2a), has incised a 600-m-wide gap into a prominent east–west-trending bedrock ridge at its confluence with the Northern Palaeovalley (Fig. 4b). Tributary erosion through the bedrock ridge is best explained by an abrupt base-level fall at the confluence caused by rapid incision of the Northern Palaeovalley by catastrophic flooding.

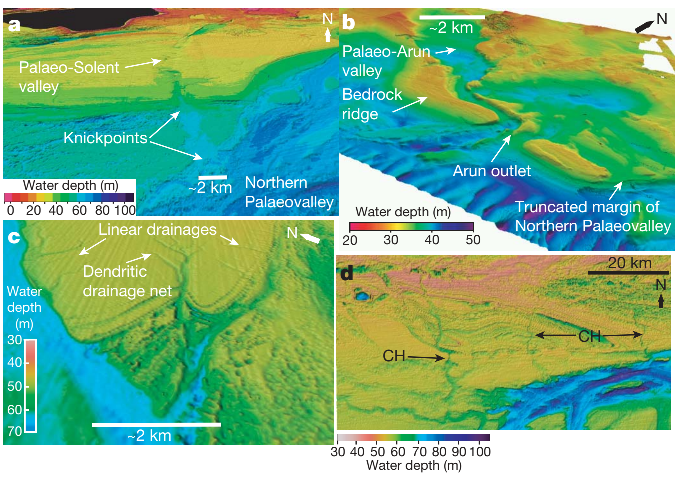

Figure 4 | Bathymetry images showing tributary confluence morphology and post-flooding secondary drainages. a, Three-dimensional perspective view of the palaeo-Solent confluence with the Northern Palaeovalley. Distinct knickpoint steps are present at the confluence. Vertical exaggeration is approximately ×6. **b**, Multibeam bathymetry perspective view of the palaeo-Arun confluence with Northern Palaeovalley. Vertical exaggeration is approximately ×6. **c**, Three-dimensional perspective view of post-flooding secondary drainage networks eroded into streamlined islands. **d**, Vertical view of sinuous secondary drainages in the southwestern part of the study area, indicating post-flooding erosion by small rivers. CH, sinuous channels.

Superimposed on the flood-carved topography are a series of dendritic and linear drainages (<250 m wide; <10 m deep) that were carved by normal fluvial erosion processes (Figs 3b and 4c). These debouch to the floor of the Northern Palaeovalley, indicating that they post-date final valley incision. To the southwest of the study area, ~30-km-long sinuous channels reveal evidence of more extensive streams on the English Channel floor (Fig. 4d). Preservation of post-flooding drainages confirms a subaerial setting for valley erosion.

Our study provides the first direct evidence that a megaflood event was responsible for carving the English Channel valley network. Normal fluvial processes cannot explain erosion of the Northern Palaeovalley, because before flooding no significant river was sourced from the Weald–Artois ridge to the east[16] (Fig. 1). Tidal scour is not a viable mechanism because the superposed dendritic drainages indicate subaerial exposure of the valley floor after incision. Erosion by glaciers[5,6] is untenable, because there is no evidence that these advanced into the English Channel[17]. Our observations are consistent with erosion by high-magnitude flood flows, as in the Channeled Scabland, in which analogous landforms were indisputably formed by catastrophic drainage of the glacial lake Missoula[1,13] (see Supplementary Information for additional discussion).

The continuity of the Northern Palaeovalley to the Dover Strait (Fig. 1) indicates an eastern source of floodwaters. Our analysis supports the hypothesis proposed in ref. 2, that catastrophic flooding was caused by overflow of a large pro-glacial lake in the southern North Sea[4]. This lake was impounded by the coalesced Fennoscandian and British ice sheets in the central North Sea and the Weald–Artois barrier across the Dover Strait, and was fed by the Rhine and Thames drainages[16] as well as from melting of the ice sheet itself. Before ice advance in the Elsterian/Anglian stage (conventionally equated to Marine Isotope Stage (MIS) 12), these rivers would have joined on the exposed North Sea shelf and drained northwards[16]. The rise in lake level eventually led to a catastrophic breach of the Weald–Artois structural barrier, with a consequent outburst of floodwaters into the subaerially exposed English Channel[2].

The presence of a bedrock bench at the valley margin indicates that at least two episodes of flooding eroded the valley. The preservation of small truncated and beheaded channels on the upper surface of island M1 (Fig. 3b) is evidence that an interlude of normal fluvial processes operated on the valley floor following the initial episode of flooding but before final valley incision by a second flood episode. We cannot resolve the absolute timing of the flooding events. An Elsterian/Anglian stage (MIS 12) age was initially proposed for overflow of a southern North Sea lake[4]; however, a Saalian/Wolstonian stage (MIS 10–6) age has also been suggested[18]. The Dover Strait was certainly open by the Eemian/Ipswichian stage (MIS 5e)[19]. Our topographic data permit estimation of the water discharges associated with the flooding (see Methods). Maximum peak discharges for the flood events range between $\sim 0.2 \times 10^6\, m^3\, s^{-1}$ and $\sim 1 \times 10^6\, m^3\, s^{-1}$, making them some of the largest megafloods on Earth[20].

Our discovery has several wider implications. The breach of the Weald–Artois anticline reorganized the palaeodrainages of northwest Europe[16] by re-routeing the combined Rhine–Thames river system through the English Channel to form the Channel river, one of the largest palaeodrainages of Europe during late Quaternary low-sea-level stands[21–23]. The breach also led to the permanent separation of Britain from continental Europe during interglacial high-sea-level stands, thus providing an explanation for its recent geographic insularity[7]. These palaeotopographic changes seem to have influenced patterns of early human occupation of Britain. Lower Palaeolithic records of early human activity in southern Britain indicate regular episodes of colonization from Europe[24,25]. Early human populations peaked between the end of MIS 13 and MIS 10, then showed a decline into MIS 8, followed by a sharp drop from MIS 7 (refs 26, 27). From MIS 6 there is a period of human absence of about 100,000 years (ref. 27). We speculate that flooding-induced changes in topography together with post-flooding diversion of the Rhine–Thames river system created notable barriers to migration across the subaerial Channel floor, thus contributing to the observed pattern of decline and absence. The clear absence of early humans (and also of other mammals such as horses[28]) during MIS 5–4 is a consequence of Britain's resulting isolation from mainland Europe during the last interglacial highstand.

Finally, our results have potential palaeoclimatic significance. It is widely held that massive freshwater pulses into the North Atlantic following outburst flooding from the glacial lake Agassiz caused the Younger Dryas and 8.2 K climatic cooling events through weakening or shutdown of the Atlantic meridional overturning circulation[29,30]. Our discovery of significant flood events in the English Channel that probably discharged into the eastern North Atlantic offers the possibility that outburst flooding from a southern North Sea lake could have forced previous episodes of abrupt climatic cooling.

METHODS SUMMARY

Data acquisition and processing. The bathymetry data were collected for navigational charting purposes by the Maritime and Coastguard Agency and are archived at the United Kingdom Hydrographic Office. The bathymetric soundings were collected during 36 surveys over a 24-year period (1979–2003) with a hull-mounted, single-beam echo-sounder, with individual soundings being converted to depth using measured water sound–velocity profiles. Vessel positioning for the pre-1996 surveys was, in general, by range and bearing from onshore trisponders, and for the post-1996 surveys was by differential global positioning system (GPS). The datasets were generally acquired along transects spaced 62.5 m apart on a bearing of 080° together with 2.5-km-spaced cross-lines. The raw data were hand-edited to remove bad navigational and depth points, reduced to Admiralty Chart Datum using tide gauge measurements, and interpolated onto a 20-m-cell-size digital terrain model. The data set has a horizontal accuracy of ±20 m and vertical accuracy of ±10 cm. East–west and east north-east–west southwest striping observed in bathymetry images is an artefact of survey vessel tracks. See Methods for additional details.

Palaeohydrological estimation of flood discharge. We estimated the peak discharge of the Northern Palaeovalley using the uniform flow Manning's equation[31], with the slope, channel width and channel depth derived from the sonar bathymetry (see Methods for details of assumptions and uncertainties in the calculation). By substituting mean flow velocity from Manning's equation in the continuity equation, flow discharge at a discrete point was calculated using $Q = dWn^{-1}R^{2/3}S^{1/2}$, where Q is the discharge ($m^3 s^{-1}$), d is the mean channel depth, W is the mean channel width, n is Manning's roughness coefficient, R is the hydraulic radius (taken to be mean channel depth) and S is the down-flow slope of the channel bed ($m\,m^{-1}$). We used a Manning's n of 0.04 estimated for rock-bound channels[32], consistent with previous studies of floods in bedrock channels[13,14]. We estimated discharges for the two episodes of flood erosion identified and assumed bankfull flow in each case (that is, water entirely filled each palaeochannel to its rims): event one involved erosion from the trim line to the upper surface of the bench, and event two eroded to the inner channel floor. For event one (at line of cross-section A–A′, Fig. 2a), $d = 20$ m, $W = 20{,}000$ m (a minimum width because the southern channel margin is not observed in the survey area, and is likely to be much greater) and $S = 0.0002$. For event two, we estimated discharges for a maximum and minimum width of the valley. A maximum width of $W = 12{,}000$ m was measured immediately downstream of island M1, and a minimum width of $W = 7{,}000$ m was obtained at the prominent constriction in the valley just upstream of M1. Channel depth was measured as $d = 15$ m and slope was $S = 0.0002$. From these measurements, we estimate peak discharge Q_{event1} of $\sim 1 \times 10^6\ m^3 s^{-1}$, and Q_{event2} between ~0.2 and $0.4 \times 10^6\ m^3 s^{-1}$.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

Received 18 September 2006; accepted 11 June 2007.

1. Baker, V. R. The study of superfloods. *Science* **295,** 2379–2380 (2002).
2. Smith, A. J. A catastrophic origin for the paleovalley system of the eastern English-Channel. *Mar. Geol.* **64,** 65–75 (1985).
3. Roep, T. B., Holst, H., Vissers, R. L. M., Pagnier, H. & Postma, D. Deposits of southward-flowing, Pleistocene rivers in the Channel region, near Wissant, N.W. France. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **17,** 289–308 (1975).
4. Gibbard, P. L. in *Island Britain: a Quaternary Perspective* (ed. Preece, R. C.) 15–26 (Geological Society Special Publication, London, 1995).
5. Destombes, J. P., Shephardthorn, E. R., Redding, J. H. & Morzadeckerfourn, M. T. Buried valley system in strait of Dover. *Phil. Trans. R. Soc. Lond. A* **279,** 243–256 (1975).
6. Kellaway, G. A., Redding, J. H., Shephardthorn, E. R. & Destombes, J. P. The quaternary history of the English Channel. *Phil. Trans. R. Soc. Lond. A* **279,** 189–218 (1975).
7. Preece, R. C. (ed.) *Island Britain: a Quaternary Perspective* (Geological Society Special Publication, London, 1995).
8. Hamilton, D. & Smith, A. J. The origin and sedimentary history of the Hurd Deep, English Channel, with additional notes on other deeps in the western English Channel. *Mem. Bur. Rech. Geol. Min.* **79,** 59–78 (1972).
9. Dingwall, R. G. Sub-bottom infilled channels in an area of eastern English-Channel. *Phil. Trans. R. Soc. Lond. A* **279,** 233–241 (1975).
10. Auffret, J. P., Alduc, D., Larsonneur, C. & Smith, A. J. Maps of the paleovalleys and of the thickness of superficial sediments in the eastern English-Channel. *Ann. Inst. Oceanogr.* **56,** 21–35 (1980).
11. Hamblin, R. J. O. *et al. United Kingdom Offshore Regional Report: the Geology of the English Channel* (HMSO for the British Geological Survey, London, 1992).
12. British. Geological Survey *Wight. 1:250,000 (Solid Geology) map* (British Geological Surveys, Edinburgh, 1995).
13. Baker, V. R. & Nummedal, D. (eds) *The Channeled Scabland; a Guide to the Geomorphology of the Columbia Basin, Washington* (National Aeronautics and Space Administration, Washington DC, 1978).
14. Baker, V. R. *The Channels of Mars* (Univ. Texas Press, Austin, Texas, 1982).
15. Komar, P. D. Shapes of streamlined islands on Earth and Mars — experiments and analyses of the minimum-drag form. *Geology* **11,** 651–654 (1983).
16. Gibbard, P. L. The history of the great northwest European rivers during the past 3 million years. *Phil. Trans. R. Soc. Lond. B* **318,** 559–602 (1988).
17. Ehlers, J. & Gibbard, P. L. (eds) *Quaternary Glaciations—Extent and Chronology. Part I: Europe* 251–270 (Elsevier, Amsterdam, 2004).
18. Meijer, T. & Preece, R. C. in *Island Britain: a Quaternary Perspective* (ed. Preece, R. C.) 89–110 (Geological Society Special Publication, London, 1995).
19. Keen, D. H. in *Island Britain: a Quaternary Perspective* (ed. Preece, R. C.) 63–74 (Geological Society Special Publication, London, 1995).
20. O'Connor, J. E., Grant, G. E. & Costa, J. E. in *Ancient Floods, Modern Hazards—Principles and Applications of Paleoflood Hydrology* (ed. House, P.) 359–385 (American Geophysical Union, Washington DC, 2002).
21. Antoine, P. *et al.* The Pleistocene rivers of the English channel region. *J. Quat. Sci.* **18,** 227–243 (2003).
22. Lericolais, G., Auffret, J. P. & Bourillet, J. F. The Quaternary Channel River: seismic stratigraphy of its palaeo-valleys and deeps. *J. Quat. Sci.* **18,** 245–260 (2003).
23. Menot, G. *et al.* Early reactivation of European rivers during the last deglaciation. *Science* **313,** 1623–1625 (2006).
24. White, M. J. & Shreve, D. C. Island Britain–peninsula Britain: palaeogeography, colonisation and the lower palaeolithic settlement of the British Isles. *Proc. Prehist. Soc.* **66,** 1–28 (2000).
25. Parfitt, S. A. *et al.* The earliest record of human activity in northern Europe. *Nature* **438,** 1008–1012 (2005).
26. Ashton, N. & Lewis, S. Deserted Britain: declining populations in the British Late Middle Pleistocene. *Antiquity* **76,** 388–396 (2002).
27. White, M., Scott, B. & Ashton, N. The Early Middle Palaeolithic in Britain: archaeology, settlement history and human behaviour. *J. Quat. Sci.* **21,** 525–541 (2006).
28. Sutcliffe, A. J. in *Island Britain: a Quaternary Perspective* (ed. Preece, R. C.) 127–140 (Geological Society Special Publication, London, 1995).
29. Barber, D. C. *et al.* Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* **400,** 344–348 (1999).
30. Broecker, W. Was the Younger Dryas triggered by a flood? *Science* **312,** 1146–1148 (2006).
31. Manning, R. On the flow of water in open channels and pipes. *Trans. Inst. Civ. Eng. Ir.* **20,** 161–207 (1891).
32. Chow, V. T. *Open Channel Hydraulics* (McGraw-Hill, New York, 1959).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements The bathymetry surveys were funded by the Maritime and Coastguard Agency under the UK Civil Hydrography Programme; we thank J. Collins and R. Spillard for support. Data acquisition for Fig. 4b was funded by the Aggregates Levy Sustainability Fund through English Heritage and by the Joint Research Equipment Initiative (HEFCE/HEFCW). We thank B. Coakley, A. Densmore, R. S. Anderson, P. A. Allen, C. Paola, S. Parfitt, R. Preece and N. Ashton for discussions, and V. Baker and P. Gibbard for their comments.

Author Contributions S.G. and J.S.C. analysed the bathymetry data and wrote the paper. G.P. compiled and processed the data, together with A.P.-F. who also aided the analysis.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to S.G. (s.gupta@imperial.ac.uk).

METHODS

Multibeam data acquisition and processing. High-resolution swath bathymetric data were collected in March 2003 across an 8 × 17 km patch of sea floor off Littlehampton, UK, using a Reson 8101 multibeam echosounder, and were used to generate Fig. 4b. Operating at 240 kHz, the system formed 110 1.5° × 1.5° - beams over a 150° swath, producing a footprint of 0.5–3.5 m^2 in water depths ranging from 18 m to 55 m. The Reson 8101 was mobilized on the 12-m-long catamaran *Explorer of Portsmouth* using an over-the-side pole mounting. Vehicle motion was measured using an Applanix POS MV 220 integrated motion sensor, gyrocompass and GPS positioning system. A CSI Wireless differential GPS receiver using Trinity House RTCM corrections determined vessel position with sub-metre accuracy. The Reson SVP-C sensor continuously monitored sound speed at the transducer head, and a Reson SVP-14 sound-speed profiler was lowered to measure velocity profiles to the seabed.

Offsets between all of the sensors were carefully measured, and standard hydrographic patch test and calibration procedures were followed to correct for any misalignment between the sonar head and the survey vessel. A Valeport pressure-type tide gauge was installed in Brighton Marina, and measurements were made at ten-minute intervals throughout the survey period. A Reson 6042 data acquisition system was used to digitally acquire data, integrate data from the ancillary sensors, and to store raw data files. Data from the 6042 were exported into an eXtended Triton Format for processing with CARIS HIPS, which produced cleaned and gridded data. The data were gridded at a 3-m cell size.

Data visualization. The coloured and shaded relief bathymetry and onshore digital terrain images used in Figs 1–4 were generated using Interactive Visualisation Systems' (IVS 3D) visualization software Fledermaus.

Uncertainties and assumptions in estimation of flood discharge. There are many uncertainties inherent in reconstructing palaeo-flood discharges from the geological record, so our discharge estimates can be considered only a first approximation. Although more sophisticated methods for modelling flow conditions are available, these require additional assumptions and thus are not warranted for a preliminary understanding of flood discharge. In the future, more detailed characterization of the topography of the valleys (for example, more accurate determination of flood-stage indicators) and identification of sedimentary bedforms and deposits associated with flooding may permit more accurate reconstruction of flood discharges.

In our discharge estimation, we applied Manning's equation at discrete points along the channel (for example, cross-section A–A′, Fig. 2b) using the conveyance-slope method. Estimation of discharge and palaeoflow velocity requires estimates of channel cross-section dimensions, energy slope (S) and Manning's roughness coefficient (n). Below, we discuss some of the key assumptions and uncertainties in our discharge reconstruction.

It is uncertain whether the empirical Manning equation is appropriate for flows that are several orders of magnitude larger than any flow that has been directly measured. For example, the Manning equation assumes uniform flow, which is highly unlikely during catastrophic floods. Reference 33 indicated that there is no way to evaluate such assumptions; however, they noted that the Manning equation has proved appropriate for flows over several orders of magnitude (albeit much smaller). Our estimates thus enable an order-of-magnitude approximation of palaeo-flood discharge, but should nevertheless be treated as preliminary.

Key assumptions in discharge estimation. Accurate definition of the geometry and dimensions of channels is important for palaeo-discharge estimation. The channel dimensions were obtained from topographic profiles determined from the bathymetric data. The two-level channel geometry of the Northern Palaeovalley is interpreted as resulting from two episodes of valley incision caused by separate flooding events. We thus treat the valley as being comprised of two channels, with the second having incised into the base of the first, and we estimate discharges for each of the flood events. Event one carved the valley from the upper edge of the northern valley margin (the trim line TL) to the level of the bedrock bench (Fig. 2b). Clear evidence for high water marks is not apparent in our data; however, multibeam data from further to the northeast of the valley (Fig. 4b and Supplementary Fig. 1) indicate sharp erosion at the upper edge of the valley that we interpret as evidence of flood erosion. There is no evidence that the flood overspilled the rims of the valley, so the valley edge provides an upper flood stage indicator. Thus, we consider flow to have been bankfull between the bench level and the valley edge. For event one, we cannot constrain the width of the valley accurately because only one valley margin is observed in the survey area. We use a width of 20 km along the line of section A–A′; however, the valley width was almost certainly much greater (Fig. 2a).

Event two eroded the valley from the level of the bedrock bench down to the present floor of the channel. The cross-sectional morphology of this channel and the truncation of drainage nets on island M1 suggests that, for event two, flow was bankfull during flood erosion. That the upper edge of the Northern Palaeovalley and the bedrock bench maintain similar elevations, and that we do not see evidence of additional terracing, suggest that our assumption of bankfull flow may be appropriate. The geometry of the channels at each of these stages is assumed to represent the palaeogeometry of the channel at the time of flooding. The first flood event may initially have occupied a 'normal' fluvial bedrock channel, and thus the depth of flood erosion of the first channel may be lower than indicated. However, discharge estimates are more affected by the great width of the flows. It is very unlikely that a pre-flood river attained such a great width. Another assumption is that the measured cross-section approximates channel geometry at peak flood stages, that is, there has not been any significant post-peak downcutting, filling or valley widening. The geomorphic evidence indicates that this is the case.

Application of Manning's equation requires determination of the channel's hydraulic radius R. In channels that are much wider than they are deep, the depth of the channel can be used as a proxy for R. Application of Manning's equation also requires determination of the energy slope of the flood flow. The water surface slope and the resulting energy slope could not readily be determined so we used the present channel gradient as a proxy. This slope is probably less than the energy slope, and thus the discharge is likely to be an underestimate. We estimated channel slope by using the average gradient of the bedrock bench.

The selection of a Manning roughness coefficient (n) for the English Channel valleys is difficult because the empirical Manning equation derived for normal rivers has to be scaled to the large depths of flood flows. We used a value of $n = 0.040$ from the empirical table for rock-bound channels described in ref. 32. References 13 and 34 used this value of n to estimate roughness for basalt bedrock in the Channeled Scabland. The Chalk bedrock in the Northern Palaeovalley may have a lower value of n, but this would only serve to increase the discharge values obtained.

The application of both Chézy's equation and the Darcy–Weisbach equation to estimate palaeo-flow velocities and subsequently flood discharges in the Northern Palaeovalley yields results of a similar order of magnitude to those obtained using the Manning equation. We are thus confident in the approximate range of the discharges estimated.

33. O'Conner, J. E. & Baker, V. R. Magnitudes and implications of peak discharges from glacial Lake Missoula. *Geol. Soc. Am. Bull.* **104,** 267–279 (1992).
34. Baker, V. R. *Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington* (Geological Society of America, Boulder, Colorado, 1973).