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Widespread methane leakage from the sea floor on the northern US Atlantic margin

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Methane emissions from the sea floor affect methane inputs into the atmosphere[1], ocean acidification and de-oxygenation[2,3], the distribution of chemosynthetic communities and energy resources. Global methane flux from seabed cold seeps has only been estimated for continental shelves[4], at 8 to 65 Tg CH_4 yr^{-1}, yet other parts of marine continental margins are also emitting methane. The US Atlantic margin has not been considered an area of widespread seepage, with only three methane seeps recognized seaward of the shelf break. However, massive upper-slope seepage related to gas hydrate degradation has been predicted for the southern part of this margin[5], even though this process has previously only been recognized in the Arctic[2,6,7]. Here we use multibeam water-column backscatter data that cover 94,000 km^2 of sea floor to identify about 570 gas plumes at water depths between 50 and 1,700 m between Cape Hatteras and Georges Bank on the northern US Atlantic passive margin. About 440 seeps originate at water depths that bracket the updip limit for methane hydrate stability. Contemporary upper-slope seepage there may be triggered by ongoing warming of intermediate waters, but authigenic carbonates observed imply that emissions have continued for more than 1,000 years at some seeps. Extrapolating the upper-slope seep density on this margin to the global passive margin system, we suggest that tens of thousands of seeps could be discoverable.

Reducing uncertainty in estimated global methane (CH_4) emissions from the sea floor[4] requires better constraints on seep distribution, integrated gas flux and the processes controlling methane leakage. To investigate seepage on the US Atlantic margin (USAM), we used data acquired by *Okeanos Explorer* between September 2011 and August 2013. North of Cape Hatteras, data coverage (Fig. 1) is complete from the shelf break at ~180 m below sea level (mbsl) to the mid-continental slope (1,500 mbsl). South of Cape Hatteras, surveys focused on the Cape Fear and Blake Ridge Diapir seeps[8]. Before this study, the only seep areas verified beyond the shelf break lay in Baltimore Canyon[9] (400 mbsl) and on the deepwater Blake Ridge and Cape Fear diapirs[8]. As the USAM is a tectonically inactive passive margin that is not associated with a major hydrocarbon basin, widespread seepage had not been expected.

Analysis of the backscatter data reveals at least 570 previously unrecognized water-column anomalies between Cape Hatteras and Georges Bank (Fig. 1 and Supplementary Table 1). These anomalies, which correspond to gas plumes, can be traced up to hundreds of metres above the sea floor and are often deflected by ocean currents. Remotely operated vehicle (ROV) exploration of one upper-continental-slope plume site (~425 mbsl) and four deepwater clusters (1,100–1,450 mbsl; Supplementary Table 2) discovered bubble streams, chemosynthetic communities, authigenic carbonates, and occasional deep-sea corals and/or gas hydrates (Fig. 2).

The bubbles that comprise the plumes have not been sampled, but most likely contain methane. Microbial methane, which is produced during the degradation of organic matter in the sea floor, is widespread in the sediments of many continental margins beneath the sulphate reduction zone, where anaerobic oxidation of methane (AOM) is most active[10]. Some chemosynthetic organisms (for example, *Bathymodiolus* mussels, bacterial mats) observed during ROV dives are metabolically dependent on methane or on hydrogen sulphide, a by-product of AOM. AOM also produces authigenic carbonates in sediments, and the extensive exhumed carbonates discovered at some seeps imply methane emissions, although not necessarily continuously, for more than 1 kyr on the basis of carbonate growth rates measured elsewhere (0.4–5 cm kyr^{-1}; ref. 11). High methane concentrations (1.75×10^4 ppm at 6.6–72.6 m below the sea floor) were encountered in sediments on the upper slope offshore New Jersey[12]. In the water column, methane concentrations reach 100 nM or more in Hudson Canyon[13] and on the Virginia outer shelf[14], although seafloor seeps and/or water-column plumes were never identified. Quantitative resource assessments for the margin yield 6.14×10^{14} m^3 methane sequestered in gas hydrates[15], which is a frozen form of water and concentrated methane stable in sediments at relatively low temperatures and moderate pressures.

The water-column gas plumes on the northern USAM originate at ~50–1,700 mbsl and are distributed in 69–87 seep clusters, as well as at solitary seeps. The patchy along-margin seep distribution reflects variations in sediment lithology, erosional history, methane availability, and interaction with ocean currents. The most notable feature is the concentration of >240 plumes on the upper continental slope between Washington and Baltimore canyons (along-margin distance ~92 km) compared with none (except in Hudson Canyon) in the sector stretching ~415 km from Wilmington Canyon (Mid-Atlantic Bight) to Atlantis Canyon (Southern New England margin). On the basis of the analysis of 3.2×10^5 km of multichannel seismic data[15], the plume-free Wilmington to Atlantis canyons sector has thinner post-Cretaceous sediment cover (hundreds of metres compared with >1,000 m), higher sand content (particularly south of Hudson Canyon) that would promote diffuse (non-seep) gas emission, and lower sediment methane charge than the Washington to Baltimore canyons sector. The absence of plumes between Wilmington and Atlantis canyons may also reflect the presence of relatively intact and continuous

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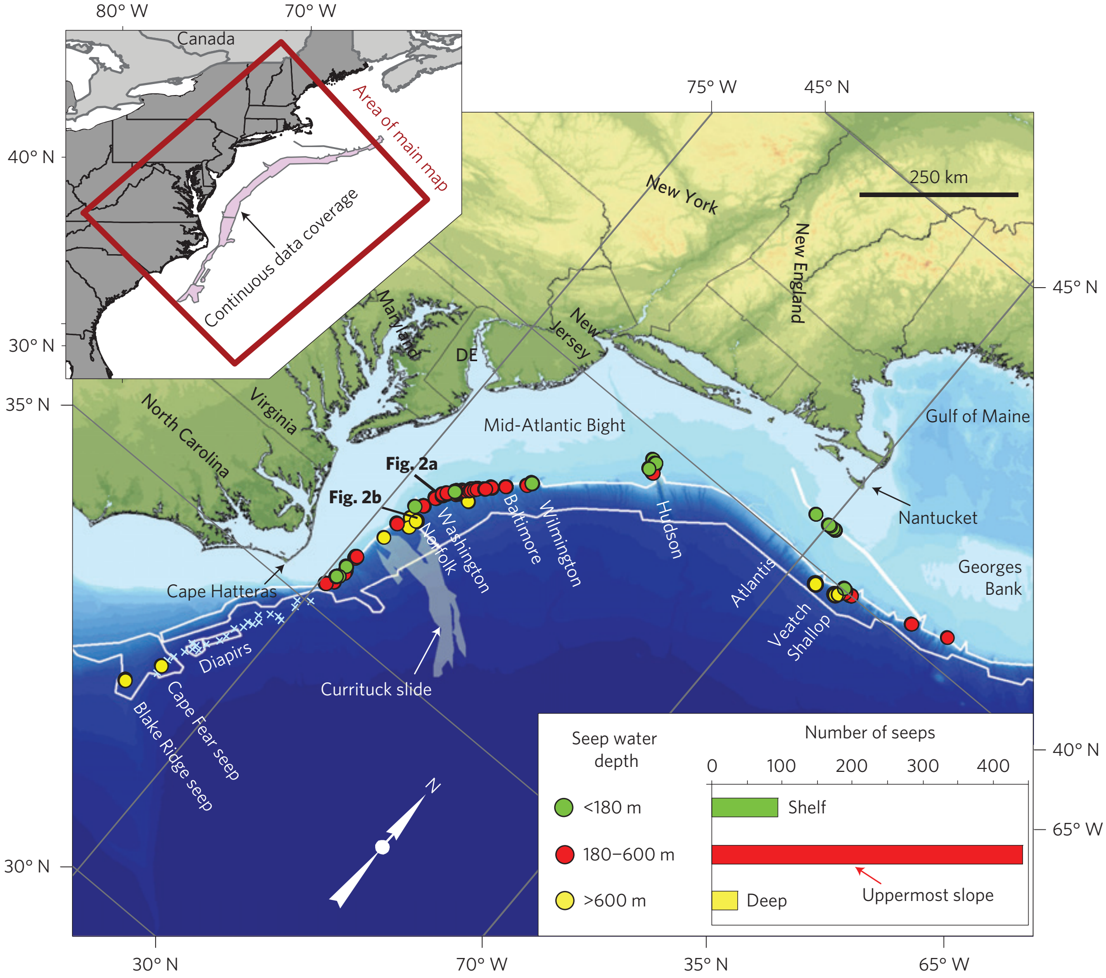

Figure 1 | Distribution of methane seeps located on the US Atlantic margin using water-column backscatter data. Top inset: area of main map and the continuous surveys. On the main map, the white outline encloses the densely surveyed area. Individual seeps are colour-coded by water depth, and the locations of Fig. 2a,b are designated. Bottom inset: seep depth distribution for this data set plus previously located diapir seeps[8]. Approximately 440 of the 570 identified seeps lie on the upper continental slope between the shelf break (assumed ~180 m) and 600 m water depth, bracketing the zone across the updip limit of the gas hydrate stability zone (505–575 mbsl; ref. 17).

Pleistocene shelf-edge deposits[16] that may trap methane. In contrast, the shelf-break to upper-slope Pleistocene section is strongly eroded and/or missing east of Atlantis Canyon and especially south of Wilmington Canyon[16], and older, permeable strata that intersect the sea floor may feed seeps.

At a finer scale, seeps are spatially associated with canyons, occurring on promontories overlooking shelf-break canyon heads, on ridges within canyons, or where canyons have eroded upper-slope deposits (Fig. 2a,c). Canyon incision downward into older strata and landward into the upper slope and shelf break may physically disrupt gas hydrate or free gas deposits (Fig. 3). Hudson Canyon, the largest on the margin, has long been suspected to host seeps[13]. We discovered at least 25 seeps in the canyon's thalweg at 497–580 mbsl, which is a depth range spanning the updip limit (505–585 mbsl) of the gas hydrate stability zone[17] (GHSZ) calculated from observed bottom-water temperatures (BWTs). At least 25 more seeps occur between 97 and 368 mbsl.

Fifty-seven per cent of USAM plumes originate between Cape Hatteras and Hudson Canyon at 250–600 mbsl, which suggests a link to the dynamics of the GHSZ. The GHSZ thins to vanishing on upper continental slopes, rendering this part of the deepwater gas hydrate system sensitive to complete dissociation as impinging intermediate waters warm[18]. On the West Spitsbergen margin, recent methane emissions from seeps within and shallower than the upper-slope GHSZ limit have been linked to seasonal[6], decadal[7] and/or century-scale[2] ocean warming that drives gas hydrate dissociation. Data there also point to long-lived seepage (for example, from hundreds up to 8,000 yr; ref. 6) on which short-term warming events are superposed.

The northern USAM is the first mid-latitude region where widespread upper-slope seepage possibly linked to gas hydrate degradation has been recognized, indicating the importance of this process outside rapidly warming arctic areas. Bottom-simulating reflectors (BSRs)—negative-impedance seismic reflectors that separate hydrate-bearing sediments from underlying gas-charged sediments—have not been detected on USAM upper continental slopes; however, BSRs are rare on upper slopes[17], and gas hydrate frequently occurs where BSRs are lacking. Recent analyses indicate that the Mid-Atlantic Bight upper slope may host hydrate-charged sediments, some of which may have been stranded updip of the present-day GHSZ as it adjusted downslope during BWT warming[17]. These stranded hydrate-bearing sediments are no longer in equilibrium with overlying waters and could provide a ready source for methane to feed seeps.

Gas released during methane hydrate dissociation may be emitted locally, migrate through permeable strata to form seeps at shallower depths, or be retained in sediments, thereby increasing pore pressures and susceptibility to seafloor failure. Consistent with

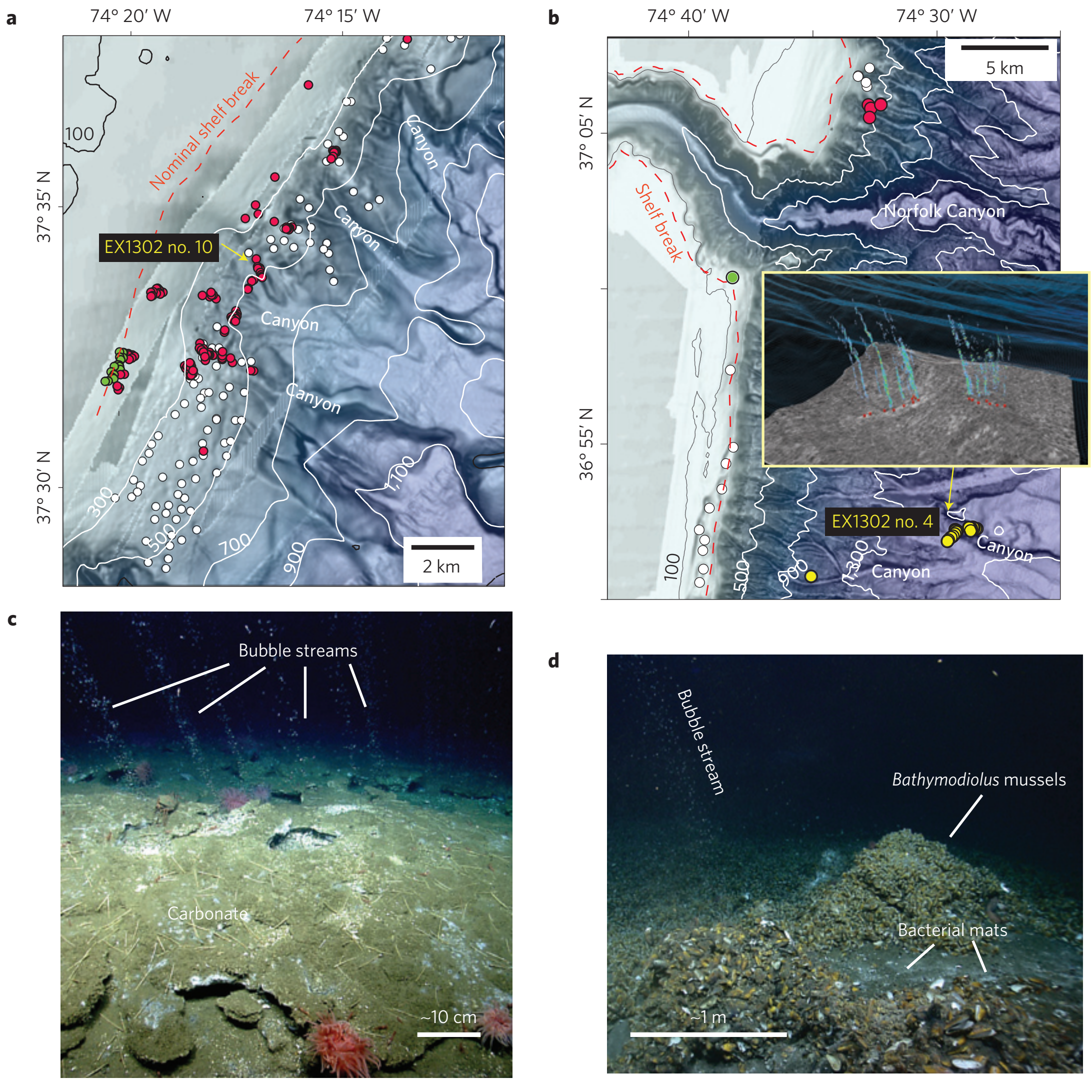

Figure 2 | Seep and pockmark distributions and seafloor photographs at upper-slope and deepwater seep sites offshore Virginia. a,**b**, Seeps (colour-coded as in Fig. 1) and pockmarks[17] (white) with bathymetry contoured at 200 m intervals north (**a**) and south (**b**) of Norfolk Canyon. Nominal updip limit of gas hydrate stability zone is 505–575 mbsl. In **a**, note the paired shelf-edge/upper-slope seeps and upper-slope seeps arrayed around a broad, pockmark-free canyon head. In **b**, the inset shows water-column plume visualization at ~1,400 mbsl, deflected westward by currents. **c**,**d**, Seafloor images from remotely operated vehicle dives EX1302 no. 10 and no. 4 (Supplementary Table 2 and Supplementary Movies) at sites marked by yellow arrows in **a** and **b**, respectively. Scales are approximate.

findings in other regions, pockmarks do not seen to be active seep loci[19]. Comparing the locations of mapped plumes (10 m resolution) and those of more than 5,000 upper-slope Pleistocene to Holocene pockmarks (10–20 m resolution)[17] yields only 17 pockmarks occurring within 70 m of a seep. All such features are in the Washington to Baltimore canyons sector (<95 km), which is characterized by ~250 plumes and ~630 pockmarks in the 150–600 mbsl interval. The high density of pockmarks and seeps, and not a causal relationship between contemporary seepage and pockmark formation, may explain the spatial proximity of some pockmarks and seeps in this sector.

Oceanographic processes drive BWT warming that can lead to episodes of methane emissions from dissociating upper-slope gas hydrate[2,5]. South of Cape Hatteras, the northward-flowing Gulf Stream brings warm waters into contact with the upper-continental-slope GHSZ on both short- and long-term (Holocene) timescales[5]. This is predicted to lead to future, large-scale dissociation of southern USAM gas hydrates[5], although no upper-slope seeps have yet been recognized there. North of Cape Hatteras, upper-slope perturbations cannot be attributed directly to the Gulf Stream, which peels northeastward towards Georges Bank at these latitudes. Warm-core rings spawned by the Gulf Stream sometimes become trapped on the New Jersey continental slope (no seeps) and occasionally affect the southern New England shelf break[20] (some seeps). Currents offshore New York and New England are also influenced by the North Atlantic Oscillation, which has experienced a strong positive shift since the 1970s (ref. 21). The positive North Atlantic Oscillation state causes warm Atlantic slope waters to dominate over cold, southward-flowing Labrador waters, increasing BWT at intermediate water depths. Such oceanographic processes may explain decadal-scale forcing for upper-slope seepage on the New England margin, but not as far south as the Washington to Wilmington canyons sector. At intra-annual timescales, the sparse data available there indicate upper-slope BWT variations of 1 °C or more[22], which could repeatedly destabilize upper-slope gas hydrates.

The backscatter analysis also reveals 38 new deepwater (1,000–1,700 mbsl) seeps. Some are solitary (for example, within the Currituck slide scar), but most occur in sublinear clusters.

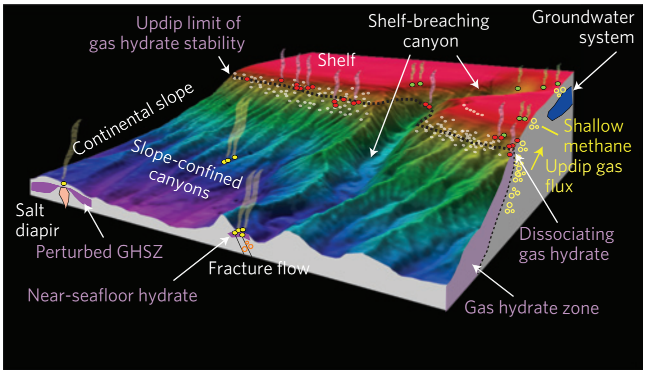

Figure 3 | Schematic showing the relationship of the US Atlantic margin seeps to morphologic and geologic features. The distributions of seeps and pockmarks are shown with respect to canyons, the updip limit of the gas hydrate stability zone, shallow shelf and hydrate-associated free gas, a shelf groundwater system, salt diapirs, and fractured rock.

Pressure (10–17 MPa) and BWT (3.5–4.5 °C) place these seeps far within the GHSZ. Although gas hydrate was discovered during ROV exploration of some deepwater seeps, BWT is so stable at these depths that gas hydrate degradation is an unlikely primary cause for methane plumes. On the southeastern US margin[8], deepwater seeps occur where high-thermal-conductivity salt diapirs cause warming of overlying, hydrate-bearing sediments[23], but salt diapirs have never been mapped on the northern USAM continental slope. Most of the deepwater seeps occur in eroded sections of the mid-slope, where gas migrates through fractured, shallowly buried Eocene rocks.

About 90 seeps are identified landward of the shelf break (~180 mbsl), an area that was minimally surveyed. Most of the shelfal gas plumes detected with the multibeam surveys are near canyon heads, and a few shelfal seep clusters are paired with nearby upper-slope seeps (Fig. 2a), implying updip gas migration. Mid-shelf seeps (~50 mbsl) south of Nantucket occur in sediments known to host a shallow Pleistocene-aged groundwater system[24], and at least 12 seeps at 97–138 mbsl in the upper reaches of Hudson Canyon may also be loci of groundwater discharge[25]. Such discharge must entrain gas and/or be significantly colder than surrounding waters to produce the observed water-column backscatter signal. For this data set, ~1.2% of the estimated methane flux originates at shelfal seeps, which are the most critical for atmospheric methane inputs[1]. More extensive surveys will be required to thoroughly map shelfal seep distributions and to assess ocean–atmospheric methane flux.

Methane emissions from the northern USAM seeps are conservatively estimated at ~15–90 Mg yr^{-1}, corresponding to 0.95–5.66 × 10^6 mol yr^{-1}. The range in the estimates reflects variations in bubble sizes, emission rates, number of emission sites per seep, and BWT scenarios (Supplementary Table 3). The estimated flux is a fraction of that determined from careful quantification in 12 seep areas on the Makran margin[26] (~40 ± 32 ×10^6 mol yr^{-1}). The greatest uncertainty in the northern USAM flux calculation is the number of emission sites that contribute to a single water-column gas plume. The seeps explored by the ROV are associated with the best quality (strongest) and thus highest flux[27] plumes, yet the number of seafloor emission sites varied from 1 to more than 15 (Supplementary Table 2). Where few emission sites were found, the ROV probably missed some or surveyed when some were dormant.

Upper-slope USAM seeps contribute ~67% of the total estimated emissions, implying that substantial methane is injected into intermediate waters, where it may enhance oxidation[28]. Between Washington and Baltimore canyons, ~13.8 Mg yr^{-1} CH_4 is emitted by upper-slope seeps for the base case calculation. Even if this represents only 10% of the methane released in the sediments by dissociating gas hydrates (assuming 80% consumed by AOM and 10% retained in sediments) and the flux continues unabated for 10^4 yr, dissociation would have liberated only 0.0014 Gt CH_4 that was previously sequestered in gas hydrates. As upper-slope gas hydrates in this sector are estimated to sequester many times more methane (0.053–0.105 Gt), the seepage can plausibly be attributed to gas hydrate dissociation.

The approach used to map widespread methane seepage on the northern USAM can be applied to other regional-scale surveys. The northern USAM averages 0.46 upper-slope seeps per kilometre between Cape Hatteras and Georges Bank (~440 seeps in ~950 km). Extrapolating to the 6 × 10^4 km length of global passive margins implies that ~29,500 upper-slope seeps may be discoverable in areas with appropriate lithology, geologic history, sufficient methane charge, and warming BWT conditions. Such seeps would represent a source of global seabed methane emissions that have not been fully accounted for in previous carbon budgets.

Methods

Plume identification. The backscatter data were acquired aboard *Okeanos Explorer* using a hull-mounted 30 kHz Kongsberg Simrad EM302 multibeam swath bathymetric system. Tracklines provided 120–150% seafloor coverage. Using QPS Fledermaus Midwater software, the water-column backscatter data were evaluated parallel and perpendicular to tracklines to identify anomalies. The locations of these anomalies, which correspond to gas plumes, were recorded in a geodatabase (Supplementary Table 1). For quality control, a second, independent analysis was conducted, and a subjective quality factor (1 = high; 5 = low) was assigned to each plume (Supplementary Fig. 1). Seeps designated as diffuse are several pixels wide in the backscatter imagery, whereas discrete seeps are a single pixel (10 m by 7 m) in the imagery. The bubble streams shown in Fig. 2c,d and in Supplementary Movies 1–6, which were acquired at a different time than the backscatter surveys, correspond to discrete plumes.

Seep cluster analysis. Using ESRI ArcGIS software, circles of varying radii (for example, 50–5,000 m) were ascribed around each seep to analyse seep clustering. Seeps with overlapping circles were assigned to a single cluster, representing a unique methane emission area and implying that the same process or gas source could be responsible for all clustered seeps. This approach does not account for geologic processes that may have length scales shorter or longer than those ascribed. We also applied multi-distance spatial cluster analysis based on Ripley's K-function and found statistically significant ($p = 0.01$) spatial clustering of seeps at all length scales for both the entire seep database and for the subset of diffuse seeps. Thus, there is no specific distance at which clustering processes are especially pronounced. The various approaches yielded an estimated 69–87 seep clusters, each containing 1 to more than 12 seeps. Some solitary seeps (for example, 17 for cluster radius of 500 m) remain following the analyses. These may indicate a single area of seafloor leakage or a seep within a cluster where other seeps were inactive at the time of the surveys.

Methane emissions. Six dives (three ROV engineering tests and three exploration dives) were conducted at five seep sites (Supplementary Table 2) during the initial cruises with the National Oceanic and Atmospheric Administration's *Deep Discoverer* ROV in 2013. With less than 1% of the ~570 seep sites explored and only limited information about bubble sizes, emission rates and the number of distinct emission sites per seep (Supplementary Movies 1–6) from these dives, we have few constraints on methane emissions compared with more thorough studies[26]. The amount of methane contained in a single bubble is determined from the compressible gas law ($n = ZPV/RT$), where n is the number of moles of methane in a spherical bubble of volume V emitted at a given temperature (BWT) T in Kelvin and hydrostatic pressure P in pascals (ref. 29), Z is the compressibility of methane[29], and R is the universal gas constant (8.314 m^3 Pa mol^{-1} K^{-1}). Multiplying by an assumed number of emission sites and rate of bubble production at each seep yields estimated methane emissions for a seep, and contributions are summed to determine total annual emissions, assuming that the bubbles contain pure methane (16.04 g mol^{-1}) at the sea floor. BWTs at greater than 250 mbsl were determined using a high-order polynomial fit to CTD (conductivity, temperature and depth) temperatures recorded within 10% of full ocean depth on the northern USAM in the World Oceans Database. Owing to high geographic and intra-annual BWT variability at <250 mbsl, BWT of 281 K was assumed at these seeps. A higher BWT would reduce the volume of gas in a bubble. Lacking data on the temporal variation in seep emissions on the

USAM, we assumed constant and continuous leakage for the methane emission calculation. The calculations were repeated for various values of bubble radii, number of emission sites per seep, bubble production rate and BWT conditions (Supplementary Table 3).

Methane hydrates. The program CSMHYD (ref. 30) was used to calculate pressure–temperature conditions for stability of Structure I methane hydrate in equilibrium with 33‰ NaCl sea water. Following convention in the gas hydrate literature, pressure in the sediments is assumed hydrostatic. Combining the stability constraints with BWT yields an estimated updip limit for methane hydrate stability[17]. The amount of methane sequestered in upper-slope methane hydrates between Washington and Baltimore canyons is based on a 3.75×10^4 m^2 cross-sectional area for hydrate-bearing strata on the upper slope south of Hudson Canyon[17]. Assuming these strata are continuous between Washington and Baltimore canyons (~92 km) and that they have 50% porosity, 2.5–5% of which could be filled with gas hydrate, yields the gas hydrate volume, which is converted to mass using gas hydrate density of 910 kg m^{-3}. Structure I methane hydrate ($46(H_2O)\cdot 8(CH_4)$) is 13.4% methane by mass for completely filled hydrate cages, yielding 0.053–0.105 Gt as the estimated mass of methane within the Washington to Baltimore canyons upper-slope sector.

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Author contributions

A.S. collected some of the multibeam data, devised the approach for analysis of the water-column anomalies, conducted the second full analysis of the plumes, completed the cluster analysis and prepared the plume database. C.R. wrote the paper, prepared most of the figures, and performed the video analysis and flux calculations. M.K. completed the first full analysis of the backscatter data set. D.B. contributed the pockmark database and assisted with geologic interpretations and map preparation. E.L. collected some of the multibeam data and analysed the episodicity of some seeps using repeat multibeam data sets.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.S.

Competing financial interests

The authors declare no competing financial interests.