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Dear Dr. Lutz,

Attached is our manuscript submitted to the Deep Sea Research II Special Volume in honor of Dr. Peter Rona entitled “Hudson Submarine Canyon Head Offshore New York and New Jersey: A Physical and Geochemical Investigation of a Fertile Habitat Space”. The manuscript contains exciting new results concerning the geology, geochemistry, and the physical oceanography of the Hudson Canyon region. We expect that our findings will help to motivate and formulate future interdisciplinary investigations of the Hudson Canyon ecosystem.

The Hudson Canyon has held Peter’s interest for decades. In 2007, Peter brought together an interdisciplinary team of scientists and engineers with expertise in geological, chemical, physical oceanography, and fisheries to begin a multi-year investigation of the upper reach of the canyon. Through Peter’s perseverance and persistence, this project became a reality. We honor him with the completion of this manuscript. Peter was was our dear friend and we miss him.

Sincerely,

Donglai Gong
Hudson Submarine Canyon Head Offshore New York and New Jersey: A Physical and Geochemical Investigation of a Fertile Habitat Space

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Abstract

Hudson Canyon is the largest shelf-sourced canyon system off the east coast of the United States, and hosts a productive ecosystem that supports key commercial and recreational fisheries. Here we report the results of a multi-year interdisciplinary study of the geological, physical oceanographic and geochemical features and processes in the canyon that underpin that ecosystem. Multibeam bathymetric and backscatter data show that the contrasting morphology of the two perpendicularly oriented branches at the head of the Hudson Canyon is related to different state of activity and sediment transport. Tightly spaced ridges and gullies extend perpendicularly towards the canyon axis from the canyon walls. Numerous circular depressions are found at the base of the canyon walls or along the canyon axis at depths between 300 to 700 m. The depressions likely represent active and/or inactive pockmarks. Direct measurement of dissolved methane concentration in the water column suggests that methane is actively venting in the portion of the canyon where the most depressions are distributed. The presence of methane maxima in a region of strong advective currents requires that methane supply is continuing and is likely to be large. Together, the sharp contours, smooth margins, steep walls, reflective floors, and associated methane anomalies of the circular depressions suggest that the presence of active methane gas release-collapse pockmarks with carbonate floors. Hydrographic observations in the canyon show that multiple layers of distinct inter-leaved shelf (cold, fresh) and slope (warm, salty) water masses occupy the head of the canyon during the summer. Their interactions with each other produce shifting fronts and strong currents that flush the canyon and can support canyon upwelling and mixing. These physical processes help to drive increased supply of materials into the water column to help support the rich canyon ecosystem.
1. Introduction

A vast ocean frontier in an early stage of exploration lies at the doorstep of the New York-New Jersey metropolitan area seaward of the Hudson River and dominated by a submarine valley and canyon system that connects with the channel of the Hudson River (Figure 1). The Hudson River channel extends about 500 km southward from its watershed in the Adirondack Mountains to New York Bay where it links with the submarine Hudson Shelf Valley (HSV). The HSV extends southeast as a shallow trough (5-40 m below the surrounding shelf surface; width ~4-16 km; mean axial seaward inclination ~1°) about 150 km across the continental shelf to a shelf edge delta complex (Ewing et al., 1963; Butman et al., 2003; Thieler et al., 2007). The HSV then connects with Hudson Canyon which begins as a smooth semi-circular indentation at the seaward edge of the shelf (water depth ~80-100 m; Figure 1). The canyon continues seaward, cutting through the continental shelf and slope for ~ 50 km as a gorge whose floor ranges from water depths of 120 to 2000 m with walls attaining a maximum relief of about 1200 m and rim-to-rim width of ~5-10 km. The mean inclination of the axis in this stretch of the canyon is about 5° (Pratson and Haxby, 1996). The canyon extends another ~450 km down the continental rise (water depth down to ~5000 m; mean seaward inclination ~1°) to the Hatteras Abyssal Plain, linking the Hudson River channel to the deep ocean basin (Heezen and Tharp, 1957). Hudson is the largest of 23 major submarine canyons that incise the seaward edge of the continental shelf on the eastern U.S. continental margin between Maine and Virginia, and is comparable in size to Monterey Canyon, the largest canyon on the western U.S. margin. While Monterey Canyon is designated by the National Oceanic and Atmospheric Administration (NOAA) as the Monterey Bay National Marine Sanctuary, has been extensively explored and is the subject of an initiative
to improve ecosystem-based management of its resources (Brown et al., 2011), our knowledge of
the Hudson Canyon system remains limited by the lack of appropriate observations that would
allow us to address interdisciplinary questions concerning the canyon’s geology, physics,
geochemistry, and biological productivity.

The head of Hudson Canyon is highly productive and is of interest to both commercial
and recreational fisheries for a number of reasons. First, it is recognized as a commercial fishing
“hot spot” that contains essential habitats for a number of finfish species (summer flounder,
silver and red hake, black sea bass, butterfish, tilefish), long fin squid, and shellfish (lobster,
depth sea red crabs) that contribute to a local and regional commercial fisheries.

Commercial catches in the surrounding fisheries statistical area (SA616) in the period 2008-2012 suggest a
strong and persistent role of this canyon in enhancing fisheries on the surrounding shelf. This is
particularly evident from fisheries-dependent data for bottom trawl fisheries for summer
flounder, squid, butterfish, and hakes and the trap fishery for American lobster (NEFMC 2014).
Indeed, the northern terminus of the canyon has yielded particularly large catches (Figure 2).
Corroborating the “hot spot” status of the canyon based on industry catches, fisheries-
independent catch-per-unit-effort (CPUE) data from the Northeast Fisheries Science Center
(NEFSC) spring trawl survey suggest substantially higher densities of several managed fisheries
species than on the shelf in general (Table 1). Second, despite its distance from land, the Hudson
Canyon has been a popular venue for sport fisheries involving a variety of fish species for
several decades. Record size fishes from several large pelagic predatory fishes (blue and white
marlin, yellowfin and bigeye tuna) in the New Jersey recreational fishery are all from Hudson
Canyon. Limited observations at higher trophic levels suggest increased concentrations of krill
attracting larger numbers of marine mammals in Hudson and other east coast canyon systems
(Greene et al., 1988; Hooker et al., 1999, Waring et al., 2001). Finally, the New England Fisheries Management Council found Hudson Canyon may merit deep sea coral protection under the Magnuson-Stevens Fishery Conservation and Management Act Reauthorization of 2006 based on inferred habitat suitability, although coral survey work there was deemed inadequate (NEFMC 2012).

The eastern US continental margins and the submarine canyons are also potential sites of a large methane hydrate repository. Recent multibeam sonar mapping surveys found evidence for over 500 putative methane gas bubble plumes along the upper slope between Georges Bank and Cape Hatteras (Skarke et al., 2014). A concentrated cluster of the gas plumes was observed inside the shelf-segments of Hudson Canyon (http://woodshole.er.usgs.gov/project-pages/hydrates/seeps.html). The multibeam study, however, did not include direct measurement of dissolved methane concentration in the water column.

The present study focuses on the head of the canyon from its landward terminus (water depth ~80 m) about 30 km seaward (to water depth of the canyon axis of ~700 m: Figure 1), since this section of the canyon is considered most important for supporting local and regional recreational and commercial fisheries (Figure 2). This paper reports results of high-resolution bathymetric mapping to delineate seafloor morphology on a scale approaching fish habitat (meters), summertime temperature-salinity-depth profiling of the water column to delineate water masses and their flow in the canyon head, and water column measurements of methane concentrations. These conditions form the physical background that supports the fertility of the canyon and structures its habitats (Pierdomenko et al., 2014, this issue).

2. Background
Hudson Canyon has been the site of numerous partially published investigations, including dives by Human Occupied Vehicles DSV Alvin, DSV Johnson Sea Link, and the former US Navy NR1 (Stanley & Freeland 1978; Cacchione et al., 1978; Keller & Shepard 1978; Able et al., 1982; Twichell et al., 1985). Yet because of the canyon’s large size, until very recently, most of its geological features remained poorly mapped. A regional surface ship multibeam bathymetric survey mapped the canyon from the shelf edge to within kilometers of the boundary of the US Exclusive Economic Zone at the mid-continental rise about 185 km seaward of the shelf edge (Butman et al., 2006). In addition, a portion of the canyon head was mapped as part of a program to map the adjacent Hudson Shelf Valley (Butman et al., 2003). Hudson Canyon was again mapped from a surface vessel in 2012 and 2013 as part of the NOAA Atlantic Canyons Undersea Mapping Expedition (ACUMEN), although results for Hudson Canyon have not yet been published. The geomorphology of four other large U.S. Mid-Atlantic shelf-sourced canyons mapped during that expedition (Obelcz et al., 2014) provides a basis for comparison with Hudson Canyon. In this study, we used an Autonomous Underwater Vehicle (AUV) equipped with a multibeam system to map the Hudson Canyon region during a series of cruises from 2007 to 2009. The AUV multibeam mapping improves the bathymetric resolution of seafloor features from tens of meters (typical of surface ship multi-beam) to just few meters. The resulting bathymetric map reveals diverse morphological features in the floor and walls of the canyon head approaching the habitat scale of finfish, shellfish and deep water corals (Figure 3). Hydrographic and geochemical measurement of water column properties at stations along and across the canyon axis were made during each of the AUV cruises as well as an additional cruise in 2011.
2.1 Geologic Setting and Hydrocarbons

The formation of Hudson canyon is attributed to a complex history of multiple glacioeustatic lowerings of sea level (Ericson et al., 1952; Tucholke 1987). A lowering of about 120 m during the Wisconsin Stage of the Last Glacial Maximum (26,000 to 13,300 BP) shifted the Hudson River discharge to the seaward edge of the continental shelf via the HSV. The occurrence of turbidity currents, presumably loaded with glacial debris, would have contributed to erosion of the canyon (Thieler et al., 2007). Subsequent rise in sea level has contributed to depositional construction of the canyon walls consistent with Shepard’s (1952) composite hypothesis of canyon formation. That hypothesis invokes erosion by sediment mass transport in concert with oceanic currents flowing along the axis together with up-building by pelagic deposition of sediment on the walls.

The continental shelf, slope and rise in the Hudson Canyon region lie within the Baltimore Canyon Trough, one of five major Mesozoic and Cenozoic basins of the U.S. Atlantic margin. Sediment accumulation in the basins increases with seaward tilting and subsidence from a tectonic hinge line near the current coastline and increases seaward beneath the adjacent continental shelf and slope to thicknesses that may exceed 16 km beneath the continental rise (Sheridan et al., 1982). A series of petroleum exploration wells (1978-1982) drilled from the outer shelf to the lower slope in the Baltimore Canyon Trough revealed marginal to excellent organic richness in the Jurassic through Cenozoic sedimentary section (to ~5000 m below sea floor) (Libby-French 1984; Mattick et al., 1981; Poag 1979; Smith et al., 1976). While most of the wells were dry, a cluster of five wells drilled in the outer continental shelf (water depths 100
to 200 m) 15-25 km southwest of the head of Hudson Canyon (Figure 1) produced major shows of natural gas (primarily methane).

In addition, the continental rise in this region (water depths >2000 m) is at least partially underlain by gas hydrates based on multichannel seismic detection of a bottom simulating reflector about 500 m beneath the sediment-water interface of the rise (Tucholke et al., 1977; Dillon et al., 1994). Analysis of high-resolution multichannel seismic profiles by Brothers et al., (2014) revealed the presence of previously undetected gas hydrates on the upper continental slope of the U.S. Atlantic margin (Figure 4). These authors found more than 5000 pockmarks at water depth ranging from 120 m and 700 m and observed the presence of gas-charged sediments and probable fluid chimneys within the calculated Gas Hydrates Stability Zone (GHSZ), whose up-dip extent coincides with a seaward transition to lower pockmark density, at about 600 m depth.

Water sampling by Gulf Research and Development Corporation in the early 1970s detected plumes of methane, ethane and propane at a water depth of about 80 m water on the outer shelf near Wilmington Canyon, south of Hudson Canyon off New Jersey (Richard Mousseau, pers. comm., 1977 and 1993). These plumes were confirmed by water sampling during a 1994 research dive with the U.S. Navy NR-I submarine on the shelf near the head of Wilmington Canyon which measured a methane maximum with concentrations up 300 nM (M. Scranton, unpublished data).

Other studies have also hinted at widespread methane sources to the water column in this region. Water column samples collected during cruises of the Shelf Edge Processes (SEEP) program contained anomalously high dissolved methane concentrations at water depths between 50 m and 300 m near the shelf break and upper continental slope at sites between Cape Cod and
Chesapeake Bay (M. Scranton, unpublished data). More recently, the NOAA Ship *Okeanos Explorer*, using the ship’s multibeam sonar, imaged 25 distinct gas bubble plumes rising as high as 1 km in the water column from seafloor depths of 1.0 to 1.6 km on the continental slope off Cape Henry, Virginia and Nantucket Island Massachusetts (Skarke et al., 2014). The multi-beam survey along the east coast margins identified numerous methane bubble plume sources inside Hudson Canyon at depths ranging from shallower than 200 m to 600 m (http://woodshole.er.usgs.gov/project-pages/hydrates/seeps.html; Skarke et al., 2014).

Thus it is clear that a regional source of methane exists in this area, although prior to this work, no localized seep sites had been identified. Physical oceanographic processes such as upwelling, mixing, and advection in and around the canyon are expected to drive the dispersal and distribution of methane gas in the water column. Studies in hydrothermal and cold vent systems suggest that methane can be an important substrate for benthic communities (Dando et al., 1991; Bogdanov, 2002).

### 2.2 Physical Oceanographic Setting

The advection, upwelling, and mixing of water masses due to flow interaction with canyon topography are the major physical drivers of canyon biogeochemistry. Advection and mixing can drive the dispersal of dissolved material and gases in the water column, while upwelling can drive nutrient delivery into the euphotic zone. Forcing processes such as winds, tides, storms, internal waves, and rings/eddies, determine the temporal and spatial variability of flow within the canyon (Butman 1986). Geological observations in the canyon suggest that there is a net down-canyon transport of material (Butman 1986) and that the bottom sediments are
likely activated by breaking internal waves, boundary layer shear flows, and energetic turbidity currents (Puig et al., 2004). Most of the time, however, energetic currents (> 20 cm s\(^{-1}\)) are observed in the inertial, semidiurnal, and higher-frequency bands (Butman 1986, Csanady et al., 1988). Mixing events driven by internal tides and waves are connected to the enhanced delivery of nutrients into the upper water column at the head of canyon (Shea and Broenkow, 1982).

Recent modeling studies show that secondary circulation such as upwelling and downwelling are also important aspects of canyon circulation and dynamics (Klinck 1996). Upwelling in particular has been shown to drive enhanced primary productivity within canyon ecosystems (Allen et al., 2001). Canyon upwelling can result from interaction of the along-shore incident flow with the steep canyon topography which drives upwelling in the canyon (Hickey 1997). Most canyons that have been targeted for upwelling study are western margin canyon systems such as Astoria Canyon, with a seasonal mean flow direction favorable for upwelling. Eastern margin canyon systems, such as those on the Middle Atlantic Bight (MAB) have a mean along-shelf flow at the shelf-break that favors downwelling (Lentz, 2008). Upwelling-favorable conditions can occur in eastern margin canyons as measured by a recent glider survey when the flow at the MAB shelf break reverses from equatorward to poleward due to wind and/or offshore eddy forcing (Gong, unpublished data). Sub-surface primary production is expected to be a major contributor to the total water column productivity in the canyon region, but the measurement of such events are rare, except for a few synoptic surveys using ships and gliders (Glenn, unpublished data).

Despite the observational and modeling evidences suggesting strong mixing and upwelling events inside eastern margin canyons and the associated biogeochemical response, our knowledge of the dynamical connections among geology, physics, and ecosystem for eastern
margin canyon systems have not significantly advanced in recent decades due to a lack of integrated interdisciplinary investigation of these canyon systems.

3. Methods

We used a combination of bathymetric mapping, water column hydrographic measurements, and moored current measurements in our investigation of the Hudson Canyon. The high-resolution bathymetric mapping reported here was accomplished with a multibeam echosounder (MBES) (Kongsberg/Simrad EM-2000 200 kHz) mounted on an Autonomous Underwater Vehicle (AUV): National Institute for Undersea Science and Technology (NIUST), Explorer class AUV Eagle Ray (http://niust.org/uvtc/Eagle_Ray/). NIUST’s Eagle Ray AUV was programmed to fly in a grid pattern (150 m line separation at 50 m above the seafloor, providing 10 percent overlap of acoustic coverage) at a speed 1.75 m s⁻¹ (3.5 knots). The vehicle was guided by a Doppler Velocity Log (RDI Workhorse 600 kHz DVL) aided internal Inertial Navigation System (Kearfott KN-6053, Seaborne Navigation System Doppler Velocity Log, SEADeViL), running a Kalman Filter using the RDI DVL for position guidance to correct for instrument drift and Kalman filter error stacking. Acoustic Ultra-Short Baseline (LinkQuest 5000HA USBL) data of the AUV’s position, acquired by the surface vessel during the dive, were recorded and, during post processing, applied to correct the navigational track of the AUV. Eagle Ray mapped approximately 130 km² of seafloor within rectangular boxes typically 10 km along the canyon axis by 5 km wide on each of 10 dives made on the cruises in 2007, 2008 and 2009. The bathymetric data were processed to produce maps of seafloor relief (Figure 3), seafloor slope (Figure 5), and acoustic backscatter (Figure 6). GIS software was used to render
3D viewing of elevation and 3D vector data including draping of imagery and vector data over a 3D surface (e.g., Figure 7; Global Mapper; http://www.bluemarblegeo.com/products/global-mapper.php).

Hydrographic surveys of the Hudson Canyon region were conducted on a series of cruises aboard the NOAA Ship Ronald Brown (2007) and NOAA Fisheries Research Vessel Henry Bigelow (2008, 2009, and 2011). Water column properties were measured using a Conductivity-Temperature-Depth (CTD) (Sea-Bird Electronics model SBE-911plus) sensor. Data from the CTD were processed using standard Sea-Bird Electronic data processing software. A number of salinity samples were collected during each cruise for the purpose of calibrating the CTD data. Profiles were obtained at along-canyon axis and cross-canyon axis locations. Potential temperature and potential density anomalies were calculated using the TEOS-2010 Gibbs Equation of State for Seawater (http://www.teos-10.org, September 2011). The along and cross-canyon axis hydrographic sections were constructed from individual profiles using a Matlab-based linear 2-D interpolation scheme (http://www.mathworks.com/matlabcentral/fileexchange/8998-surface-fitting-using-gridfit, September 2011). The baroclinic component of the geostrophic velocity was calculated from the along- and cross-canyon axis density sections using the thermal wind relation (Gong and Pickart, in press). The geostrophic velocity calculation assumes zero bottom velocity. Currents near the bottom of the canyon were directly measured for a two day period during the August 2011 cruise using an upward looking ADCP (RDI Workhorse 300 kHz) deployed at 610 m in the central axis of the canyon.

Water samples for methane analysis were collected from ten 5-liter Niskin bottles mounted on the CTD rosette stand and stored in glass bottles. The glass bottles were filled from
the bottom and allowed to overflow about one bottle volume before capping. Samples were
preserved by addition of 10 N NaOH solution (2 ml/L) and sealed without headspace either in
ground glass stoppered bottles or in champagne bottles sealed with a metal cap using a bottle
capper. Methane analysis was carried out later in a shore-based laboratory using the bulb
extraction method of Herr and Barger (1978). Samples were injected through a fixed volume
loop into an HP 5890II Gas Chromatograph (GC) equipped with Flame ionization detector (FID)
and a 6 ft. x 1/8 inch column packed with Poropak R. The GC was calibrated for each run using
two standards, one containing 9.98 ppmv methane in nitrogen and the other containing 999.3
ppmv methane in nitrogen.

4. Results

4.1 Bathymetric Features

The AUV mapping of the first 30 km of the Hudson Canyon, starting at about 40 km
shoreward of the shelf margin, delineated three contiguous segments, each about 10 km-long
(Figure 3 and inset). The segments exhibit different orientations and morphologies from where
the canyon begins (terminus) on the outer continental shelf to ~30 km seaward, with an increase
in the water depth of the canyon floor from 100 m to 700 m. Bathymetric and backscatter data
revealed an increase in the complexity of canyon morphologies with increasing depth, along with
a marked asymmetry between the eastern and western flanks of the canyon:

1) Segment A (0 to 10 km along the canyon):
This segment includes the canyon head, which is composed of two branches, henceforward designated branch 1 and branch 2 (Figure 3), oriented respectively NW-SE and N-S, that merge at depth of about 120 m and display differing morphologies. Branch 1 begins as a smooth semi-circular indentation delineated approximately by the 100 m isobath on the outer continental shelf, with a break in slope at canyon margins (rims) characterized by low axial inclination (~5°). The initial 8 km of this branch connects with and continues the NW-SE trend of the Hudson Shelf Valley (Figure 1). In this segment, to a water depth of about 300 m, branch 1 exhibits a symmetric U-shaped cross-section about 3 km wide (Figures 3, 5, 8 profiles A-A’ and B-B’). Canyon sidewall relief and slope increase down-slope respectively to 150 m and to about 10°, with local facets up to 20° (Figures 3 and 5). The western wall lacks a sharp rim and is incised by a few gullies separated by small ridges and oriented orthogonal to the canyon axis, while on the eastern wall such features are absent. On the contrary, the eastern wall in this section displays sharp rims and two semi-circular reentrants about 3 km wide that appear to be generated by slumps (Figure 7A). No deposits were evident at the foot of the wall from bathymetric data.

The thalweg, about 2 km wide, is characterized by a low backscatter facies associated with a smooth seafloor and poorly defined axial incision (Figure 6). Branch 1 is intersected by a second channel (designated branch 2, Figure 3) at about 8 km downslope along axis (at arrow on profile 1 in Figure 8). The morphology of branch 1 changes near the intersection with branch 2; specifically, widening and steepening of the eastern wall may be observed from bathymetric data (Figure 4).

Branch 2 is about 2 km wide between canyon rims, has sidewall relief up to 150 m (Figure 8 profile DD’) and trends NE-SW, parallel to the regional trend of the shelf edge and
nearly orthogonal to branch 1. **Branch 2 abruptly bends NW-SE nearly 90° just south of the intersection with branch 1.**

The floor and walls of branch 2 display a **more complex morphology** (Figure 3), being characterized by a **V-shaped cross section and asymmetric flanks** (Figure 8, profile D-D′). The steeper north wall (inclination to 22°; Figure 5) is affected by several coalescent landslide scars, each a few hundreds of meters wide (Figure 7D). The **backscatter map** shows relatively higher backscatter intensities along the thalweg of branch 2 as compared with branch 1 (Figure 6).

A distinct circular depression interpreted as a pockmark was mapped in smooth sediment on the west side of the canyon floor near the seaward end of segment A (position 39°37.98′ N, 72°26.29′ W). The depression is about 100 m in diameter and displays poorly defined rims at 345 m and a flat floor at 360 m water depth.

2) **Segment B (10-20 km down-slope along the canyon):**

The orientation of the second segment **abruptly changes to nearly N-S** after the confluence of the two branches (Figure 3) and bathymetric data reveal a **more complex morphology** with respect to the previous segment. The canyon is about 4 km wide from rim to rim and **wall relief** increases with increasing depth from 300 to 450 m.

In this segment canyon the walls **have** slope very gently (about 3°) in the **upper portion**, while **gradients** increase abruptly (up to 30°) below 150 m depth. This feature is clearly visible from bathymetric (Figure 3), **slope map** (Figure 5) and cross sections (Figure 8 E-E′, F-F′ and G-G′). **Distinct features** project from the east and west walls of segment 2 (Figure 3B and 7C, D, and E). There are a series of gullies that may act as short tributaries, incised into the underlying strata at a regular spacing of about 0.7 km, and are separated by parallel small ridges. Despite **similar spacing**, the morphologies of these features are different along the two **flanks**. On the
west wall gullies are shorter (500 to 800 m), less incised, and seem partially buried under a
smooth cover of sediment (Figure 3 and 7D). Ridges have gently rounded crests and extend
down to 350 m depth. On the contrary, the ridges separating the gullies on the east wall are
narrower and characterized by sharp crests that extend down to 450 m depth, where consolidated
strata crop out near the base of the wall (Figure 3, 7C and 7E). The gullies are narrower and
more incised; the most pronounced ones start at the base of coalescent landslide scars few
hundreds of meters wide (Figure 7C), and incise fan-like deposits with lower slopes (10°-15°)
that occur at the base of the wall, consistent with mass wasting events of the east wall.
Backscatter data show a pattern with low backscatter within the gullies, in contrast with a higher
backscatter facies in correspondence of the ridges (Figure 6).

The width of the thalweg decreases in this segment from about 2 km to less than 1.5 km
and displays an axial channel, 500 to 700 m wide, up to 60 m deeper than the surrounding
seafloor, which runs close to the base of the eastern wall down to 500 m depth (Figure 3 and
Figure 8 profiles E-E’, F-F’, and G-G’). This entrenched thalweg is connected to branch 2
through a knickpoint 30 m high, while the branch 1 gently merges to this channel without sharp
breaks in slope (Figure 8 profile 1). The channel, which is characterized by medium to high
backscatter facies (Figure 5), re-incises the thalweg and appears to be an active transportation
conduit for sediment derived from upslope input and mass wasting of the adjacent east wall.

At least three pockmarks were mapped in segment B. Two of them are situated near the
base of the east wall (position 39° 35.24’N, 72° 24.12’W; 39° 34.86’N, 72° 23.65’W). The other
depression lies at the base of the west wall (position 39°33.87’N, 72° 25.66’W). Both east wall
depressions are situated along the axis of gullies in the walls. All three at about 350 m depth and
are each about 150 m in diameter, with 20 m relief between rim and floor.
(3) Segment C (20 to 30 km down-slope along the canyon):

The orientation of the third segment abruptly changes back to NW-SE as with segment A. The progressive development of features in the floor and walls of the canyon, as well as the asymmetry of the two flanks, already observed from segment A to segment B, continues in segment C, where the canyon displays the highest morphological complexity within the mapped area (Figure 3). The network of gullies continues on both walls with a slightly denser spacing (~0.6 km). However, on the west flank the zone of distribution of these features, as well as the width of the walls, expands, from about 1 km width in segment B, to 2 km width in segment C suggesting that the wall has receded and still appears to be smoothed by a sediment cover, as also confirmed by backscatter data (Figure 5).

In contrast, on the east wall the width of this gully zone remains about 2 km from segment B to segment C, but the sharpness of incisions increases, along with an increase in area of slopes exceeding 30° (Figure 3, 5 and 7G). In this segment, near the base of the wall, ridges are characterized by a rough morphology and by high backscatter intensities, suggesting outcrops of consolidated substrata.

Bathymetry (Figure 3) and cross sections (Figure 8 H-H’, I-I’ and L-L’) of segment C show the entrenched channel within the thalweg as a rough trough along the base of the east wall. Profiles constructed along the thalweg show that the gradient of the channel is continuous between the three segments with a mean inclination of 1.66°, with the exception of the branch 2, which shows a mean axial inclination of 2.70°. Sedimentary features at mid-depth on the east wall comprise three fields of bedforms with the crests oriented parallel to the canyon axis (Figure 7F and 7G) and potential bottom current deposits (Figure 7G), suggesting the flow of contour currents along this wall.
Two areas characterized by rough topography on a scale of meters in sediment on the upper margin of both walls (Figure 7I) resemble features described as hummocky terrain associated with long-term burrowing by tilefish (*Lopholatilus chamaeleonticeps*) (Twichell et al., 1985).

Seafloor video and photo images collected within 1 km SE of the mapped area confirm the presence of semi-lithified clay substrate and tilefish burrows (Pierdomenico et al., 2014).

The number and size of circular depressions interpreted as pockmarks markedly increases in segment C (Figure 3 and 9). At least 23 large pockmarks are present in segment C at depth between 300 and 500 m, preferentially aligned along the axis of the gullies in the lower portion of the west wall (Figure 9A). A larger semi-circular depression near the base of the west wall is about 300 m long (E-W), 150 m wide (N-S) and about 15 m deep, with a rim at 500 m and floor lying at 515 m water depth (Fig 9B). A smaller pockmark, with 10 m relief from rim to floor, lies 400 m upslope from the semi-circular depression (Figure 9B). Pockmarks in segment C range up to 700 m in diameter and 80 m in relief between rim and floor, most clustered within the 150 m diameter and 15 m relief size (Figure 10). Diameter and relief of the depressions increase linearly, suggesting that they are of similar origin (Figure 10). The depressions display steep walls (15° to 25°; Figure 9C) and flat floors with higher backscatter facies with respect to the surrounding sediments (Figure 9D). Strings of small, shallow circular-to-elongated pockmarks (with dimensions on the scale of meters) lacking raised rims lie on the canyon floor oriented parallel to the canyon axis (Figure 7H and 9A). These small features lie on the thalweg near the base of the walls and may be an early stage in the development of the circular depressions, or they may reflect differing origins or developmental environments (e.g. high vs. low velocity current regimes in the open thalweg channel vs. in the shelter of gullies). In the case
of the thalweg pockmarks, the elongated depressions may be generated by the coalescence of adjacent circular depressions.

4.2 Water Chemistry

Water samples from CTD-rosette samples taken in 2007 revealed small methane maxima on the shelf (water depth ~100 m), and at water depths of about 1200 m and 2600 m. Additional methane measurements were made in 2009 and 2011 in water samples recovered at multiple stations along the axis and near the base of walls of segments 1, 2 and the northern end of segment 3 of the canyon between water depths of 100 m and 550 m and between 1300 m and 1700 m. Most methane values at these stations were only slightly above background (5 nM to 10 nM; Figure 11). An exception is an interval between water depths of 450 m and 520 m at the seaward end of segment B (Figure 11 and 12). There, anomalously high methane anomalies (to 100 nM), two orders of magnitude above background, were measured in near-bottom water samples at the canyon axis. Methane anomalies were mostly clustered within the sector of the canyon axis where pockmarks were observed (Figure 12) and were absent in the near bottom water samples recovered in the 1300 m to 1700 m depth range (Figure 11). The water depth interval between 550 m and 1300 m has not yet been sampled.

4.3 Physical Oceanography

The hydrographic survey data revealed significant interannual variability in water mass distribution and circulation over Hudson Canyon. The water column over Hudson Canyon is strongly stratified in the upper 100 m with a density difference of 4 kg m\(^{-3}\) across the seasonal thermocline and weakly stratified below 100 m with a density difference of 1 kg m\(^{-3}\) between
100 and 400 m of depths (Figure 13). **Five major water masses** identified near the head of Hudson Canyon are: surface shelf water (warm and fresh), bottom shelf water (cool and fresh), Gulf Stream water (warm and salty), intermediate slope water (cool and salty), and deep slope water (cold). A large part of the hydrographic variability in the upper water column can be attributed to the presence of (or lack of) Warm Core Rings that can carry warm and salty Gulf Stream to the canyon.

Comparing the three survey years, 2008 and 2009 had the warmest and freshest surface water, which created a strong pycnocline, whereas 2007 and 2011 surveys found cooler and saltier surface water (Figure 13 A-D). Water with Gulf Stream properties (T > 15 °C, S > 35) was observed in the upper water column (down to a depth of 100 m) during 2007 and 2008 surveys, but was completely absent during the 2011 survey. This can be clearly seen in the Temperature-Salinity plots in Figure 14. There are hints of Gulf Stream water in the 2009 survey as well, but the survey did not go **far enough offshore** to confirm its presence in the mid and lower canyon. Associated with the Gulf Stream water mass is **displacement** of upper water column isopycnals consistent with either a Warm Core Ring (WCR) or a smaller warm core eddy. The close proximity of the WCR or eddy and the head of the Hudson Canyon modified the spatial distribution of both shelf and slope water masses.

Below the pycnocline, shelf bottom water, commonly known as the ‘cold pool’, occupies most of the lower water column on the outer shelf. The cold pool is **nutrient rich** and has a core temperature of **less than 8°C**, which is significantly cooler than the surface water as well as all water masses surrounding it. On the shelf, the cold pool typically resides between the 30 and 70 m (Houghton *et al.*, 1982). Due to the sudden steepening of the topography at the head of the canyon, the **offshore edge of the cold pool detaches from the bottom and can extend over the**
canyon axis to an isobath of over 500 m. The temperature, salinity and volume of the cold pool vary from year to year. Based on the Temperature/Salinity plot in Figure 14, the average salinity of the bottom shelf water at the head of Hudson Canyon was estimated to be 34 in 2008, 33.5 in 2007 and 2009, and 32.7 in 2011. These variations are due to the combined effect of the size and location of the cold pool and the presence of rings/eddies nearby. Mixing between shelf water and the offshore waters likely contributed to the observed difference in salinity for the 4 sampling years. The warm-core eddies in 2008 and 2009 also appear to have severely limited the cold pool’s offshore extent over the Hudson Canyon, whereas the lack of major offshore features in 2011 allowed the cold pool to extend more than 25 km from the head of the canyon (Figure 13 g, h).

The intermediate slope water, with salinity of 35.5 +/- 0.2 and density of 26.5 kg m\(^{-3}\) < \(\sigma_0\) < 27.2 kg m\(^{-3}\), generally resides at depths between 75 and 250 m. In the Hudson Canyon, the intermediate slope water was observed in the along-canyon axis section for all four sampling years but the presence of cold pool at the head of the canyon displaced the intermediate slope water to depths between 125 and 250 m. Nutrient measurements at the head of the canyon in 2011 indicated that the phosphate concentration of the intermediate slope water was between 1 and 1.5 \(\mu\)M (not shown). Assuming an N:P ratio of 13:1 (Jahnke and Jahnke, 2000), the slope water represents a significant nitrogen source at the base of the euphotic zone in the slope sea. Below the intermediate slope water in the deeper portion of the canyon is the deep slope water, with \(\sigma_0\) of 27.2 kg m\(^{-3}\). The T-S property of the deep slope water was relatively steady over the different years, but the isopycnals (\(\sigma_0 \sim 27.2\) kg m\(^{-3}\)) varied by up to 50 m from year to year (Figure 13), possibly due to eddies (2008, 2009) or internal tides (2011).
High-resolution across and along-canyon axis hydrographic transects from each of the survey years revealed significant spatial and interannual variability (Figure 13, 15). Large isopycnal displacement of 50 m on length scale 1-3 km was observed across the canyon axis, and similar displacement on length scale of 5-10 km was observed along the canyon axis. We applied the thermal wind relation and calculated the geostrophic velocity for both along and across canyon axis flows (Figure 16). The calculated velocities are referenced to zero at the bottom or 600 m (maximum). The across-canyon (along-shelf break) velocity sections show equatorward flowing (positive) shelf-break-jet-like structure right over the head of the canyon, located in the upper 100 m of the water column with a speed of 5-20 cm s\(^{-1}\). This feature was observed in all years of the study. Further offshore, a poleward-flowing current of similar magnitude was also observed during all survey years. The strong opposing equatorward and poleward currents observed in 2008 and 2009 are consistent with the water column’s T/S properties indicating a small slope water eddy carrying Gulf Stream like water residing over the canyon each year. The origin and time evolution of these eddies is not known and beyond the scope of this study.

In the along-canyon axis (across-shelf break) sections, the surface intensified geostrophic flow was directed offshore (negative) on the eastern side of the canyon and onshore (positive) on the western side of the canyon for 2008 and 2009 with speeds of 5-30 cm s\(^{-1}\) (Figure 16C,16E,16G). The opposing currents were asymmetrical with stronger offshore flow than onshore flow. In 2011, an onshore geostrophic flow up the central axis of the canyon was observed. The enhanced flow along canyon axis is consistent with the common expectation that canyons are locations of enhanced cross-shelf break transport. Furthermore, the along- and across-canyon axis flows can also support can drive upwelling and downwelling circulation
inside the canyon. Another factor that drives enhanced biological activity and dispersion of material is tidal mixing. A brief mooring deployment of a bottom-mounted ADCP made direct observations of flow inside the Hudson Canyon in 2011. The mooring was deployed for 2 days at a depth of 600 m and covered the bottom 100 m of the water column. During the two tidal cycles observed, the maximum flow speed observed was 18 cm s\(^{-1}\) (Figure 17). Principal Component Analysis indicates that depth-averaged current along the canyon axis accounted for 93% of the total variance. The flow was consistent with diurnal tidal oscillations although the flow direction change was sudden from up-canyon to down-canyon. The tidal excursion length scale associated with the oscillating currents is +/- 3 km. A significant amount of super-tidal variability was observed in both the current velocity as well as the vertical velocity structure with bottom intensification. A gradient Richardson number calculation using both a nearby shipboard CTD profile collected during mooring deployment (Figure 17B) and the ADCP time series data show banded structures of stable and unstable regions to vertical mixing within the lower 100 m of the water column. The bands had vertical length scales of 10 to 30 m (Figure 17C).

5. Discussion

The bifurcation of the canyon head into two branches, where it indents the outer edge of the continental shelf seems to be related to two distinct regimes for the canyon in space and in time. Specifically, the contrasting morphology and acoustic seafloor response of the two branches indicates different states of activity and suggest that distinct sedimentary processes may have contributed to their evolution.
The smooth rounded profile of branch 1, the weak axial incision and the low backscatter facies within the thalweg (Figure 4 and 5) suggest that a cover of fine sediment is accumulating on the floor and that this branch is presently inactive as a sediment conduit. Presumably, branch 1 was active during times of glacioeustatically lowered sea-level when sediment supplied by glacial erosion was transported across the shelf, deltas were formed near the shelf edge, and the canyon was excavated by erosion. The head of Norfolk Canyon, offshore of Chesapeake Bay, shares a similar geometry as the channel 1 of Hudson Canyon. It is reasonable to speculate that they shared a similar set of geomorphologic forcing conditions that led to their formation. Although geological evidence suggests that the head of branch 1 is not currently actively transporting sediment, the hydrographic observations nevertheless suggest there is bi-directional flow on opposing sides of the canyon that can support upwelling of nutrient rich intermediate slope water.

By contrast, the second of the bifurcated branches, which trends NE-SW until it abruptly turns NW-SE downslope continuing as an erosive channel that re-incise the thalweg up to 60 m deep, shows a rough morphology, a V-shaped section and an higher backscatter intensity along the thalweg; these observations indicate absence of a fine sediment cover and suggests that this branch is presently active as a sediment conduit. The north wall of branch 2 appears to be undergoing steepening by undercutting, presumably by sediment transport The steepening of the walls of the two branches near where they join, the widening of branch 1, the sharp intersection at the join (Figure 4) indicate that slumping and related slope recession have occurred on these walls.

Among the numerous shelf break canyons south of Hudson Canyon, Wilmington, Baltimore, and Washington Canyons share canyon-head geometries similar to branch 2 of the
Hudson Canyon where the canyon axis at the head is aligned in the along-shelf break direction (Obelcz et al., 2013). This alignment of the canyon head suggests that erosion by strong current(s) paralleling shelf contours is responsible for this type of canyon head geometry. The presently active flow in branch 2, deduced from geological evidence, is consistent with geomorphological interactions with an energetic boundary current. This current, largely in geostrophic balance, is a direct result of the density difference between shelf and offshore water. If large glacial floods in the past resulted in exceptionally fresh shelf waters adjacent to the open ocean, the resulting boundary current formed at the shelf break could have been strong enough to help carve branch 2-like features at these canyon heads. The idea that a sediment laden shelf-break boundary current may have played a prominent role in the geological evolution of the canyon head for major east coast canyons is new and has not been explored as a mechanism of canyon evolution. To check whether shelf-break boundary can be actively influencing the flow and sediment transport in the along-shelf break channels of the different canyons, future studies would need to make direct observations in both branches of Hudson Canyon as well as in other major canyons with similar canyon head geometries.

Oceanographic evidences of asymmetrical geostrophic flows in the along-canyon axis sections, with stronger flows on the eastern side of the canyon, are consistent with the geomorphological observation. Indeed, we observed the presence of morphological features suggesting higher-energy sedimentary dynamics, such as bedform fields and bottom current deposits, only along the eastern flank. Sediment distribution also confirms the presence of coarse-grained sediment at the canyon rims and walls mostly along eastern side, while a cover fine sediment tends to accumulate prevalently on the western flank of the canyon (Pierdomenico et al., 2014, this issue).
Energetic tidally-driven internal waves likely drive mixing inside the canyon. Although we did not directly measure turbulence in this study, there were hints of internal tides in our along-canyon axis hydrographic transects. The deep isopycnals (> 100 m) were oscillating on a length scale of 5-20 km with amplitude of 50 m. Our data, however, do not have the resolution to resolve any high frequency internal waves. It has been shown that a significant amount of internal wave energy is directed and focused toward the head of the Hudson Canyon with eventual dissipation source attributed to internal wave breaking (Hotchkiss and Wunsch, 1982), and that internal tides and waves can drive mixing events that can enhance the delivery of nutrients from depths into the upper water column at the head of a submarine canyon (Shea and Broenkow, 1982). We expect that the mixing mechanism of nutrient delivery at the head of the canyon to be a major contributor of enhanced biological productivity at Hudson Canyon. The time series Richardson Number analysis of the lower water column provides an intriguing view of the near bottom potential for mixing inside the canyon. The cause of the observed banded structure, however, is not clear. The along-canyon axis flow along with shear driven mixing can drive methane plume dispersal, while the asymmetry of the geostrophic currents along the two sides of the canyon axis suggests differences in flow dynamics that may drive the evolution of the canyon geology on the long term.

Other nutrient delivery mechanisms at work in the canyon include upwelling supply of nutrient rich water from below the euphotic zone. Canyon upwelling and downwelling is driven by along-shelf-break flows (Allen and Hickey, 2010). Equatorward flow tend to drive axis-symmetrical upwelling and downwelling response on opposite sides of the canyon while poleward flow tend to drive upwelling response across most of the canyon (Klinck 1996). An estimate of the depth of upwelled water at Hudson Canyon can be obtained using scaling
relations derived by Allen and Hickey (2010) for ideal axial symmetric canyons assuming steady, spatially-uniform incident flow. The depth at which upwelling occurs (Z) can be parameterized by canyon geometry, flow velocity, and water column stratification: $Z = 1.4 \frac{U}{N} (L/R)^{1/2}$, where $U$ is the along-shelf flow speed, $N$ is the Brunt-Väisälä frequency, $L$ is the length of the canyon, and $R$ is the radius of curvature of the canyon at the shelf-break. For Hudson Canyon, $L = 30$ km, $R = 7$ km at the shelf-break, $U = 10$-20 cm s$^{-1}$ and $N = 0.01$-0.02 s$^{-1}$ below the canyon rim depth of 100 m. The calculated upwelling length scale is approximately 20-60 m. This is consistent with isopycnal displacement of 50 m at depths between 100 to 200 m in 2008 and 2009 surveys. Given that the bottom of the euphotic zone is located at depths of approximately 100 m, it is certainly possible for canyon upwelling to bring nutrient-rich upper slope water above the rim of the canyon into euphotic zone driving enhanced primary productivity.

If indeed upwelling of nutrients leading to phytoplankton blooms, these do not appear to contribute appreciably to annual cycles in chlorophyll $a$ or overall annual primary production in Hudson Canyon based on satellite measurements. Monthly mean chl. $a$ for canyon waters between 1997 and 2010 ranged 0.3 to 1.0 mg m$^{-3}$ based on NASA SeaWiFS ocean color satellite data. Annual production for the same period based on the employment of SeaWiFS data with the Ocean Production and Absorption of Light (OPAL) model was about 0.6 mgC m$^{-2}$ d$^{-1}$. Both chl $a$ annual production values were small, much lower than for the well-characterized bloom area on Georges Bank (3.0 to 5.0 mg m$^{-3}$ chl $a$ and ~1.3 mgC m$^{-2}$ d$^{-1}$ annual production). Furthermore, chl $a$ and production values for the Hudson Canyon vicinity were not distinguishable from those of the rest of the mid-Atlantic continental margin (NEFSC/NERO 2011). This does not mean that upwellings did not occur or that they were not an important forcing factor, but simply that
they were not of such magnitude or duration as to show up in long term course-resolution satellite analyses. Water-column fluorimetry measurements using glider in Norfolk and Washington Canyons suggest significant phytoplankton biomass residing below the surface layer of the canyons (Gong, unpublished data). It is entirely possible that satellite remote sensing does not capture the high primary production in the east coast canyons.

Methane maxima were detected in the near bottom water column near the canyon axis between 300 m and 600 m water depth but were absent between 600 m and 1000 m of the upper continental slope (Figure 11 and 12). The depth of the methane maximum is roughly at the upper depth of the hydrate stability zone in this region, which is controlled largely by bottom pressure and bottom water temperature. According to the interpretation of pockmark distribution and fluid expulsion by Brother et al., (2014), methane venting in the depth range between 300 m and 600 m could be related to the combined effects of pore fluid overpressure and gas hydrate dissociation due to transient changes in intermediate water temperature, while the disappearance of venting downslope may be explained by the absence of free gas once the Gas Hydrates Stability Zone is encountered.

In this scenario, the methane could be released through permeable pathways produced by faulting through the underlying sedimentary strata and flow through the truncated ends of sedimentary strata exhumed by the incision of the canyon into the continental slope. Indeed incision by the canyon is likely critical to methane venting in the canyon because cover by fine-grained sediment with low permeability typical of the areas between canyons could effectively seal the underlying sediment layers from venting. Study of fluid flow in this sedimentary framework indicates pressure gradients outward through the truncated strata beneath the continental slope (Dugan and Flemings, 2000) and is supported by patterns of mass wasting on
the slope (Rona and Clay, 1967) and direct observation of fluid discharge from the adjacent continental rise (Rona, 2000). Recent studies by Skarke et al., (2014) have found numerous bubbling seeps along the US Atlantic margin between Cape Hatteras and Georges Bank, including from within the Hudson Canyon, supporting the hypothesis of active methane venting from strata along the margin.

Results from 2011 strongly suggest that the circular depressions are associated with the methane anomalies. It was not feasible to control the position of the rosette closely enough to determine that the Niskin bottles sampled within a circular depression, and because of water movement, the source of methane for a particular maximum could be located at some distance from the position of the rosette cast. Advection and mixing in the bottom of the canyon driven by tides and lateral shear associated with the bi-directional flow inside the canyon can help to disperse the water column methane derived from localized seeps up and down the canyon. Methane can disperse on length scale significantly longer than the tidal excursion distance (+/- 3 km) when the oscillating tides are combined with a constant background flow. The lateral flow shear can help to disperse the methane both up and down canyon of the source locations.

Based on worldwide observations of methane associated with depressions on sedimentary continental margins, we infer the circular depressions belong to the class of features described as “pockmarks” that may be active or inactive loci of methane discharge. The absence of ejecta around the rims of the circular depressions, which would be visible if present at the resolution of the mapping, suggests that the circular depressions were formed by collapse of underlying strata rather than blowing out. Collapse could be caused by destabilization of hydrates (the depth of methane maximum at about 500 m is coincident with the upper limit of methane hydrate stability) or by dissolution of underlying sediments if predominantly carbonates by upwelling of
corrosive solutions. The high backscatter consistently observed from the floors of the circular depressions may be due to precipitation of calcium carbonate, possibly produced as a result of methane oxidation, in the circulating solutions, as has been observed at other such depressions (Hovland et al., 1987) although so far we have been unable to confirm this by direct sampling. Alternatively it could be related to the presence on the floor of the depressions of remoulded sediment, following collapse or blowout events.

Methane, like primary production, is a potential source of energy that may help fuel the canyon ecosystem via the microbial food chain. To assess its potential as an energy source we used the estimated annual carbon flux associated with methane seeps on the northern U.S. Atlantic margin (USAM) (Skarke 2014) with estimated annual phytoplankton production for the same 94,000 km² strip of the continental margin in which the seeps were found. We assumed a production rate of 0.5 gC m⁻² d⁻¹ that appears to typify average production over the continental slope in this region (NEFSC/NERO 2011). The estimates for methane release on the slope ranged from 15 to 90 MgC y⁻¹ (Skarke et al., 2014). Our estimates for primary production for the same area was 17.16 million MgC y⁻¹. If this is correct, methane seep production thus accounts for no more than 0.0005% of overall carbon production on the continental margin. Here again, this does not mean that methane contributed by seeps is unimportant, particularly in the localities of seeps, but only that investigation of this phenomenon needs to be made on smaller spatiotemporal scales.

There is another explanation for why Hudson Canyon is a fisheries “hot spot” that does not require enhanced productivity to support it. Perhaps the canyon simply attracts a diverse biota as a result of its habitat structure. The productivity (energy) to supports its biota comes in large part from elsewhere. Highly mobile fauna are attracted to the physical habitat space
seasonally from other areas and aggregate there temporarily. The question then becomes: what is it about this feature that makes it a more favorable habitat for a variety of species? We explore this question further in this volume (Pierdomenico et al., 2014).

The obvious limitation of this study, which was conducted using very limited resources, is that there was no biological sampling at the lower trophic levels, such as primary productivity or zooplanktons. These would have provided the data needed to study the linkage between physics, geochemical, and higher trophic levels. Future interdisciplinary studies should take a multi-trophic level approach and target the processes that couple water column physics and biogeochemistry.

6. Conclusions

We investigated the head of Hudson Canyon to define the conditions and processes that contribute to the productivity that make the canyon a habitat feature that appears to enhance local and regional commercial and recreational fisheries and protected marine mammal species. Key geological, physical oceanographic and geochemical features and processes identified include:

1. Several different geological processes contribute in shaping the head of Hudson Canyon. Two bifurcating branches showing contrasting morphology indent the outer continental shelf in the initial 10 km long section of Hudson Canyon (axial water depth 100 to 300 m). One was likely active during glacioeustatically lowered sea level, and the other is active at present sea level. The larger of the two branches aligns and connects shoreward with the Hudson Shelf Valley which extends NW as a shallow trough about 185 km
across the shelf to the mouth of the Hudson River. The floor of this branch is smoothed
by accumulating sediment, and presently appears to be inactive as a conduit for sediment
transport in contrast to its inferred active role during prior intervals of glacio-eustatically
lowered sea level. The second branch is oriented N-S along the shelf, exhibits rough
terrain, and appears actively moving sediments. In the second and third canyon sections,
narrow ridges with intervening erosive gullies extend orthogonal to the canyon axis from
the walls where they are regularly spaced about 1 km apart. The circular depressions
preferentially occur along the axis of the gullies.

2. Circular depressions are present at specific locations within the canyon and likely
represent both active and inactive pockmarks. A population of pockmarks occurs in
sediment on the canyon floor near the base of the walls. The pockmarks that are
distributed in the lower portion of the walls, aligned along the axis of the gullies, exhibit
diameters from 50 to 700 m and rim-to-floor relief up to 80 m, with relief increasing
directly with diameter. Pockmark along the thalweg are smaller (on the scale of few tens
of meters) and aligned along the canyon axis. Both features have flat high-reflectivity
floors, and steep walls (15° to 25°). The sharp contours of the depressions, their
expression through diverse terrains, and the absence of ejecta around their rims suggests
that they may be actively forming. Formation may be by collapse by dissolution of
underlying carbonate sediments (sinkhole mechanism) although we have no direct
information on the presence of carbonate layers.

3. Multiple layers of distinct inter-leaved shelf (cold, fresh) and slope (warm, salty) water
masses occupy the water column at the head of the canyon during the summer. Their
interactions with each other produced shifting fronts and strong currents that flushed the
canyon and can support canyon upwelling and mixing. Opposing flows on the two sides of the canyon and laterally offset in the along-shelf direction suggest complex flow dynamics likely associated with frontal and topographic interactions with nearby rings and eddies. The observed circulation could produce upwelling with magnitude of 20-60 m in the upper 200 m of the water column, potentially delivering nutrient rich water from below the euphotic zone into the euphotic zone. Tidal transport and mixing combined with the sheared lateral flow can help distribute methane released from point sources into the water column and up and down the canyon axis.

4. Methane is actively venting in the portion of the canyon where there are the most depressions. The presence of methane maxima in a region of strong advective currents requires that methane supply is continuing and relatively large. Methane oxidizing bacteria supported by oxidation of the methane flux can provide a food source to enhance the fertility of the canyon and by adding a chemosynthetic biota. Although we do not have sediment data, it is also possible that the high backscatter at the center of the depressions might be due to authigenic carbonates associated with sites of methane oxidation. Methane anomalies of up to 100 nmol L⁻¹, close to two orders of magnitude above background, were measured in near-bottom water samples between water depths of 300 m and 600 m at the canyon axis at the seaward end of the second segment of the canyon head. Methane anomalies were also measured associated with certain of the circular depressions in the same area. The sharp contours, smooth margins, steep walls, reflective floors, and associated methane anomalies of the circular depressions suggest that they are active methane gas release-collapse pockmarks with carbonate floors.
The dynamic interactions between the hydrographic regime, methane discharge and varied terrains create fertile habitats for biodiversity and development of fish stocks within the canyon. Enhanced shelf-slope exchange of water masses, facilitated by the conduit form of the canyon apparently influences adjacent shelf circulation, and impacts ecosystems including commercial fish stocks well beyond the canyon.

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http://www.nefmc.org/habitat/index.html


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Table 1. Average catch-per-unit-effort (CPUE) from fisheries-independent data for the 36 trawls made by the NEFSC random stratified spring trawl survey with nine ten-minute squares surrounding Hudson Canyon (Figure 2) from 2003 to 2012 (n = 36) versus all trawls in the mid-Atlantic region (Narragansett Bay to Cape Hatteras, n = 5,133) during the same period. Species above the line (HCE:MAR CPUE ratio >1.0) demonstrated enhanced catches in the Hudson Canyon Region.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mean NEFSC CPUE Values</th>
<th>Hudson Canyon Environ (HCE)</th>
<th>Mid-Atlantic Region (MAR)</th>
<th>HCE: MAR mean CPUE ratio</th>
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<tr>
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Table 2. CTD stations with Niskin rosette water sample depths and measured concentrations of dissolved methane.

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Table 2. (continued). CTD stations with Niskin rosette water sample depths and measured concentrations of dissolved methane.

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Figure 1: Regional map of the continental margin off New York and New Jersey showing study area at head of Hudson Canyon where the canyon indents the outer edge of the continental shelf about 185 km (100 nm) seaward of the mouth of the Hudson River in New York harbor. A shallow trough, the Hudson Shelf Valley connects the canyon head to the river mouth. Positions of exploratory oil wells and a multi-beam seismic profile (US Geological Survey Line 25) are shown.
Figure 2: Hudson Canyon fisheries-dependent data. Diagram of 10-minute latitudelongitude squares in NMFS Statistical Area 616 showing Hudson Canyon contours (dashed yellow lines, depths in meters) and mobile gear commercial catch (columns). Light green columns: annual catch exceeding 1 million lbs. (>453 metric tons), medium green: annual catch 50 thousand to 1 million lbs. (22 - 453 metric tons), dark green: annual catch less than 50 thousand pounds (<22 metric tons). Green arrow shows maximum 10-minute square annual catch: 2.174 million lbs. (986 metric tons) in the canyon head region. The red box outlines an area of 9-square region used for comparison of canyon fisheries-independent data in Table 1.
Figure 3: High-resolution shaded relief map (left) and 3D views (right) of the upper reach of Hudson Canyon from MBES data acquired with AUV Eagle Ray. Inset: location of the three main segment of the canyon characterized by different orientation and morphologies, discussed in the text.
Figure 4. Multichannel seismic reflection profiles along the Hudson Apron (OC270 Profile-61). Enhanced reflectors (high energy, high frequency) are concentrated above the base of the gas hydrate stability zone (BGHS) and are inferred to represent hydrate-bearing sediments. Hydrate-bearing strata out of equilibrium with present bottom water conditions are bounded by labels “1,” the maximum upslope extent of hydrate-bearing sediment, and “2,” the top of the gas hydrate stability zone. Inset: Three-dimensional perspective of pockmarks (red dots), landslide scarps (black lines), and Pleistocene strata (colored lines). From Brothers et al. 2014.