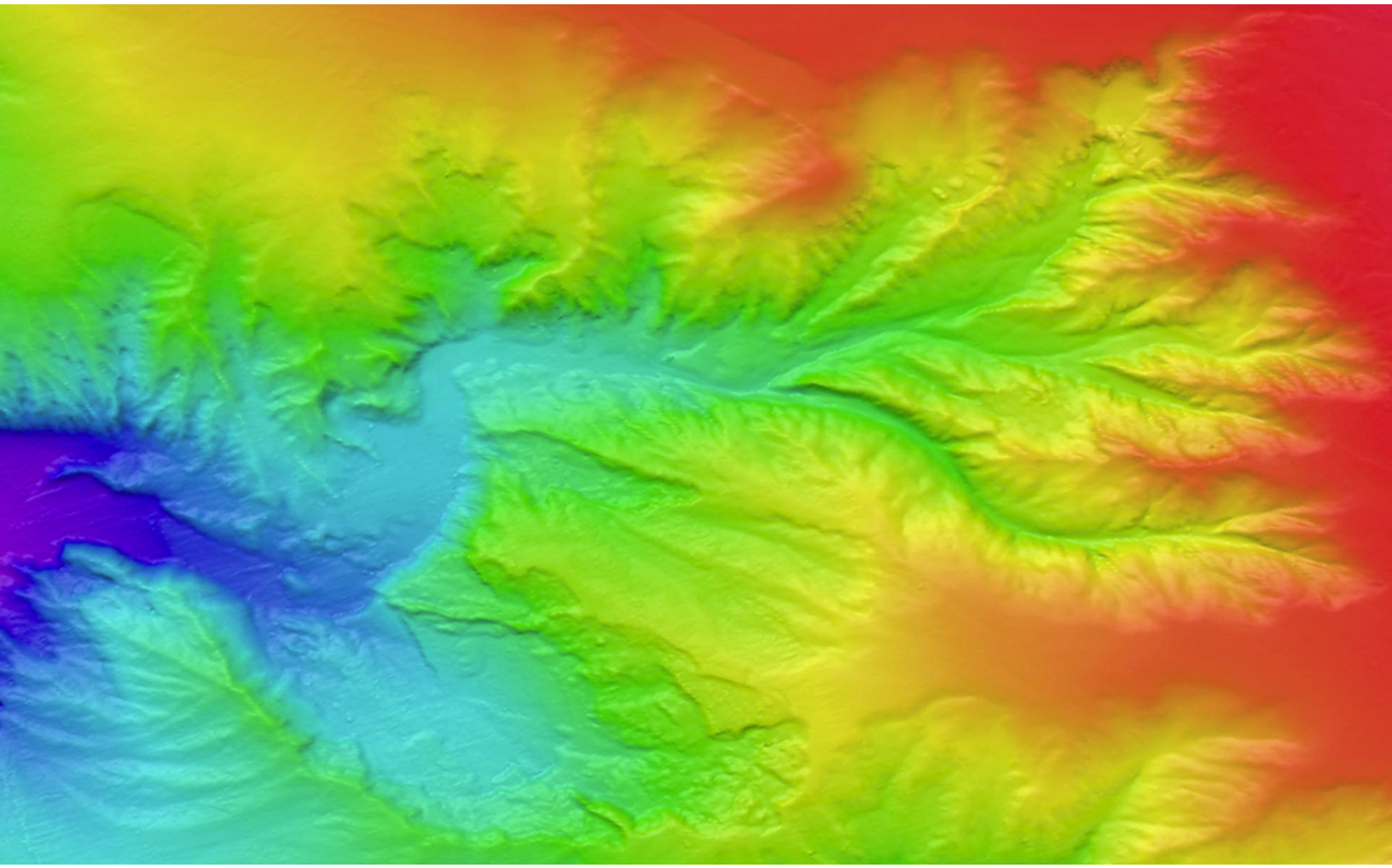
3RD INCISE INTERNATIONAL
SUBMARINE CANYON SYMPOSIUM

25 - 27 JULY 2016
VICTORIA, BC CANADA



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International Network for submarine Canyon Investigation and Scientific Exchange

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Front Cover: Shaded relief image of multibeam bathymetry data acquired over Barkley Canyon, ~100 km Southwest of Vancouver Island, BC, Canada. Water depths displayed are between ~150 and 1400 m. Figure produced by Ocean Networks Canada using data from Ocean Networks Canada TN282, TN266, TN269, TN254, Ocean Networks Canada/Schmidt Ocean Institute FK009A/B, Canadian Hydrographic Service Tofino Basin 5028091/5027560, J.R. Delaney, D.S. Kelley, and D. Glickson, University of Washington, TN175. This figure has been produced by the University of Victoria based on Canadian Hydrographic Service (CHS) data, pursuant to CHS Direct User License No. 2016-0506-1260-V.

INCISE International Network for submarine Canyon Investigation and Scientific Exchange

According to recent studies derived from high-resolution seafloor mapping, in the order of 10,000 submarine canyons exist worldwide. Less than one hundred canyons (only 1%) have been studied with some level of detail in terms of geology, physical oceanography, or habitat heterogeneity and biodiversity. Submarine canyons are very important features along the world's continental and island margins. They create terrain habitat heterogeneity and provide the main pathway for sediments, detrital organic matter, pollutants and marine debris from the shelf to the deep sea. Canyons often concentrate organic matter enhancing overall ecosystem biomass and fisheries and acting as biodiversity hotspots.

Recent advances in technology (e.g., ROVs, AUVs, gliders, cabled observatories, etc) have allowed the expansion in the exploration of submarine canyons, revealing exuberant ecosystems with never-seen before life forms and entire habitats. However, while the scientific exploration of canyons advances, so does the human footprint into the deep sea, canyons in particular, with the increased worldwide demands for oil and gas, mineral deposits and fisheries. Therefore, the scientific community in particular the INCISE network, has the responsibility to prepare a comprehensive assessment of the role submarine canyons in generating and maintaining deep-sea biodiversity, ecosystem function and services; in support of marine spatial planning aiding to marine policy and conservation strategy development.

This is the 3rd edition of the INCISE Symposium, and the first to be hosted in North America. Previous symposia were hosted by Ifremer in Brest, France, in 2012 and by the British Geological Survey in Edinburgh, Scotland, in 2014. Publication outcomes from previous symposiums include a special issue published in *Deep Sea Research II* (Huvenne & Davies, 2014) and two review papers by Amaro et al., 2016 in *Progress in Oceanography* and by Fernandez-Arcaya et al., submitted to *Frontiers in Marine Science*. Other outputs from the INCISE working groups include an extensive bibliography of submarine canyon publications. The INCISE network of experts on submarine canyons continues to grow as new collaborators join from various parts of the globe. In this 3rd edition we have specific contributions investigating canyon systems located in various countries in Europe, Asia and North America and a global analysis on canyon geomorphology that will support various marine spatial planning initiatives, helping to narrow conservation efforts in many countries' economic exclusive zones. Moreover, and in addition to the four main INCISE working group themes, the symposium will have two specific sessions dealing with "Sediment transport monitoring in submarine canyons" and on "Interdisciplinary studies in Barkley Canyon", monitored by Ocean Networks Canada NEPTUNE Cabled Observatory. The 2016 INCISE Symposium organizing and scientific committees welcome you to Victoria, British Columbia, Canada. The symposium will prove to be an interesting arena for the exchange of ideas between the interdisciplinary participants. With the impressive lineup of keynote speaker, talks and discussion sessions, we hope you enjoy.

Local Organizing Committee (ONC):

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OPENING KEYNOTE

A tribute to Francis Parker Shepard, father of marine geology, and insights of his work on submarine canyons

PRESENTED BY H. GARY GREENE

AUGUST 1980; PHOTO COURTESY OF SCRIPPS INSTITUTION OF OCEANOGRAPHY

Fran Shepard was a pioneer in the study of Submarine Canyons and marine geology. He was a gentleman geologist interested in marine geology that stemmed from his exposure to the sea through his father's company, the Shepard Steamship Line, and sailing on his father's yachts along the east coast of the U.S. He was Professor of Geology at the University of Illinois after graduating from the University of Chicago in 1922 focusing on structural geology, and later became Professor of Marine Geology at Scripps Institution of Oceanography. In his own words he stated ". . . in spite of being at the University of Illinois, a long ways from the ocean, I became the first geologist who took up marine geology as his main scientific interest." Among his students were Robert Dietz, K.O. Emery, Bruce Martin, and Robert Dill, all who advanced marine geology and the study of submarine canyons. Fran published the first textbook on marine geology and with one of his students, Robert Dill, published a book on Submarine Canyons and Other Sea Valleys.

Fran's work on submarine canyons initiated with a sabbatical he took at Scripps from 1933 to 1934 when he studied submarine canyons in southern California and then branched out to study other world ocean canyons after that. He essentially transferred his knowledge of canyon and valley geomorphology from what he learned on land to the marine environment to describe submarine canyons. He proposed that all submarine canyons were subaerially

eroded during the low stands of sea level in the Pleistocene. Later, near the time he retired in 1966 Fran became frustrated with the lack of interest in submarine canyons and the inability to relate canyon morphologies to the new sciences of plate tectonics. My encounters with Fran occurred after his retirement and our mutual interest in the origin of, and processes associated with Monterey Canyon and other submarine canyons along the California coast. The evolution of thought between us in regard to how canyons form on passive, convergent, and transform plate margins will be presented along with humorous antidotes that Fran shared in regard to his career in marine geology.

Dr. H. Gary Greene

Professor Greene obtained a PhD degree in Marine Geology from Stanford University in 1977. He has over 50 years of experience in mapping the geology of the seafloor, which he gained while working in industry as an undergraduate, with the U.S. Geological Survey from 1966 to 1994 and in academia thereafter. From 1994 to 2000 he was Director of Moss Landing Marine Laboratories (MLML) of the California State University system where he taught geological oceanography and established the Center for Habitat Studies. Dr. Greene retired from teaching in 2006 to devote full time to running the Center for Habitat Studies and the newly established Tombolo institute on Orcas Island in Washington State, USA. He now heads the SeaDoc Society Tombolo Mapping Lab, is a research faculty member at Friday Harbor Labs (University of Washington), and Emeritus Professor at MLML.

He first became interested in submarine canyons during his tenor with the USGS and while working on a Masters Degree at Moss Landing Marine Labs (San Jose State University) in 1966. His PhD dissertation was on the geology of the Monterey Bay region where he intensely studied Monterey Canyon, relating it to an origin and evolution along a transform plate margin. Since that time he has continued to study submarine canyons along the California margin and elsewhere in the Pacific and has published over a dozen papers on the subject. Dr. Greene is also continuing to do research in marine benthic habitat mapping and geohazards evaluation within submarine canyons. He pioneered deep-water marine benthic habitat mapping in the United States and has contributed to many habitat-mapping efforts globally, including the mapping of submarine canyon heads.

KEYNOTE SPEAKERS

Dr. Susan E. Allen

Dr. Susan Allen, Professor and Associate Dean at the University of British Columbia, is a physical oceanographer who uses all types of models including scaling, analytics, laboratory and numerical to understand, and predict coastal oceanographic processes and biogeochemical-physical interactions in the ocean. Her longest standing obsession has been the flow over and around topography, particular submarine canyons. The goal is to be able to understand the rotationally dominated flow over topography and quantitatively estimate the cross-bathymetric gradient flows and the scalar fluxes they generate. The SCOR working group on Deep Ocean Exchange with the Shelf invited a review paper, which she co-wrote with Xavier Durrieu de Madron. In this paper, they reviewed and synthesized the community's accomplishments in understanding and quantifying flows over canyons.

Dr. Veerle A. I. Huvenne

Dr. ir. Veerle A.I. Huvenne is based at the National Oceanography Centre, Southampton, UK, where she coordinates the Seafloor and Habitat Mapping Team. She is Principal Investigator on the ERC Starting Grant CODEMAP and has >15 years of experience in habitat mapping and sediment dynamics, mainly focussing on complex deep-sea environments such as submarine canyons, cold-water coral settings, hydrothermal vents and seamounts. She has extensive expertise working with new technologies and marine robotic systems such as AUVs and ROVs (Autonomous Underwater Vehicles and Remotely Operated Vehicles) and often works closely with the engineering teams on the development of new sensor or vehicle capabilities.

Dr. Craig R. Smith

Dr. Craig Smith obtained his Ph.D. from Scripp's Institution of Oceanography in 1983 and is currently a Professor of Oceanography at the University of Hawai'i. He has strong interests in biodiversity, disturbance ecology, and human impacts in seafloor ecosystems. Craig has conducted research in Antarctica, mangroves, submarine canyons, organic-fall communities, cold seeps, continental slopes, and abyssal plains to obtain a broad perspective of natural and stressed marine ecosystems. He has lead over 50 research expeditions from the equator to Antarctica, and has conducted over 100 HOV, ROV and AUV dives. Craig has also published over 140 papers in the scientific literature on seafloor ecology, biodiversity, climate-change impacts, and the design of marine protected areas.

Derek Fenton

Mr. Derek Fenton works with the Marine Protected Areas (MPA) Program of Fisheries and Oceans Canada in Dartmouth, Nova Scotia, Canada. He has 20 years of experience with the identification, establishment and management of protected areas under the Oceans Act, the Fisheries Act and the Canada Wildlife Act. Coming from a fishing family he dedicated his education at Saint Mary's University and Dalhousie University on marine applications, with particular focus on coastal mapping, public involvement and environmental policy implementation. As part of team at Fisheries and Oceans, he is responsible for the ongoing management of the Gully Marine Protected Area, the Musquash Estuary Marine Protected Area, deep-sea coral and sponge conservation areas and the establishment of new protected areas under the Oceans Act. This involves directing and participating in public outreach, implementation of regulations, management planning, surveillance and enforcement, research planning and evaluating the effectiveness of these areas.

Dr. Charlie Paull

Dr. Charlie Paull is a Senior Scientist at the Monterey Bay Aquarium Research Institute (MBARI). His career as a Marine Geologist has involved an unusually broad diversity of research topics including gas-hydrates, cold seep vents, canyon processes, neotectonics and submarine landslides. He's played an integral role in many research projects including being co-chief scientist for ODP Leg 164, developing and installing cable-connected sea floor observing infrastructures, and leading numerous expeditions using ROVs, HOVs, and AUVs. These efforts are documented in over 200 peer-reviewed publications. He is currently leading the Monterey Bay Coordinated Canyon Experiment, a multi-institute, international research program focused on making physical measurements within turbidity flows in-situ.

Jay Ritchlin

Jay leads the Western Canada team at David Suzuki Foundation in its efforts to achieve sustainable practices in the western provinces. He has a biology degree from Kenyon College in the U.S. and over 15 years' experience working on solutions to environmental challenges. Before becoming Director, Jay led the Foundation's aquaculture and offshore oil and gas campaigns and shared responsibilities on marine fisheries and sustainable seafood campaigns. Prior to that, Jay worked on pulp, paper and toxics issues in Canada and the U.S. and spent four years working in commercial fisheries. He has also worked in the U.S.Congress on foreign policy and military issues and spent several years working with Greenpeace in the U.S. and Canada.

THEME 1: CANYON PROCESSES IN THE SPACE-TIME CONTINUUM (FORMATION, EVOLUTION, + CIRCULATION)

Flow patterns, nutrient fluxes and biological aggregation in submarine canyons

SUSAN E. ALLEN

UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

Fluid dynamics forces geostrophic flows along isobaths, limiting exchange between the shallow shelf and the deep ocean. Submarine canyons are important conduits between these two domains. Exchange flows can generated by strong upwelling and downwelling currents, rapidly changing currents and by enhanced mixing due to internal wave trapping and focusing, local internal wave generation or tidal resonance. These enhanced exchange flows can be conduits for nutrients or low oxygen water onto the shelf, or in the other direction, for cascading flows carrying high organic carbon loads to the deep ocean. The dynamics of the flows in the canyons cause small spatial scales and strong vertical flows. The first leads to heterogeneity in habitats and the latter to aggregation of zooplankton or small fish. In this talk, we will discuss flow patterns, nutrient fluxes and biological aggregation giving quantitative estimates where possible.

Mean circulation and high-frequency flow amplification in the Sable Gully

BLAIR GREENAN, BRIAN PETRIE, DIANA CARDOSO

FISHERIES AND OCEANS CANADA, BEDFORD INSTITUTE OF OCEANOGRAPHY, DARTMOUTH, CANADA

The Sable Gully, a broad, shelf break submarine canyon approximately 40 km east of Sable Island on the eastern Scotian Shelf, separates Banquereau and Sable Island Banks. Unique among canyons on the eastern Canadian continental shelf because of its depth, steep slopes and extension far onto the shelf, its ecological significance and increasing human pressures led to its designation in 2004 under Canada's Oceans Act as the first Marine Protected Area (MPA) in the Atlantic Region. To improve the state of knowledge of the Gully MPA, a multi-disciplinary field program was carried out in 2006–07; the physical oceanographic component consisted of a 16-month deployment of four current meter moorings and two CTD surveys. Analysis of the mooring deployment demonstrates that the mean circulation above the canyon rim (~200 m) is characterized by a southwestward flow that appears unaffected by the canyon topography. There is also some indication of the existence of an eddy at rim depth. Below 500 m, the circulation is dominated by an upcanyon flow (of order 0.02 m/s) at the mooring array (halfway between the canyon head and mouth). The mean, 200 m-bottom transport towards the head of the Gully was estimated as 35,500 m^3/s, implying an upwelling velocity of 14 m/day over the area. Results also show bottom-intensified tidal flows and nonlinear constituents due to the interaction of K1, O1, M2 and S2 components along the thalweg of the canyon; the strong overtides and compound tides observed in the Gully make it unique among canyons. Further analyses provide evidence of enhanced mixing in the Gully which is approximately 20 times that observed on the adjoining Scotian Shelf. Total variance of the currents in the Gully is about 2.5 times greater than that observed on the nearby continental slope with an equivalent water depth.

Observations of nonlinear internal tides and turbulence in a steep canyon

MADELEINE HAMANN, MATTHEW ALFORD, ANDREW LUCAS, VERONICA TAMSITT, CELIA OU, SAM BILLHEIMER, MARION ALBERTY

SCRIPPS INSTITUTION OF OCEANOGRAPHY, US

Submarine canyons are common features of the coastal ocean. Their complicated topographies host dynamical processes with a wide range of temporal and spatial scales, many of which give rise to small-scale turbulence. Previous research has shown that canyons can focus internal wave energy propagating from the open ocean and dissipate that energy very efficiently. However, previous research has been limited to a few large canyons with slopes that allowed the propagation and/or breaking of linear internal waves.

In order to investigate mixing dynamics in canyon smaller and steeper (arguably more "generic") than those studied to date, a process study was conducted in the La Jolla Canyon (LJC) off the coast of La Jolla, CA. CTD, velocity, and temperature microstructure data were taken at two 24-hour shipboard stations and a 54-hour profiling mooring along the canyon axis. KE/PE ratios at all stations indicate that the steep canyon axis was indeed reflective to the M2 internal tide giving rise to a partially standing wave. Velocity and isopycnal displacements were dominated by the M2 frequency, but the variance explained by the M2 signal decreased up-canyon, suggesting that this reflection also caused scattering into higher harmonics and a visible steepening of the internal tide waveform.

Baroclinic energy flux was oriented up-canyon and decreased from 182 W/m at the canyon mouth to 46 W/m near the head, and the convergence of up-canyon baroclinic energy flux roughly balanced the observed dissipation rates. Two maxima were apparent in the vertical distribution of energy flux averaged over an integral number of M2 periods. The depths of these maxima corresponded to the depths at which oscillations of the steep, nonlinear waveform gave rise to periods of high shear and strain. These events at mid-depth coincided with observations of enhanced dissipation rates O (10-7 -- 10-5 W/kg). While previous canyon studies observed enhanced dissipation near the bottom primarily due to bottom-trapped bores or topographically controlled hydraulic flows, here we observed elevated dissipation and periods of weak stratification at mid-depths. This suggests a different breaking mechanism where the superposition of incident and reflected waves gives rise to mid-column rather than near-bottom mixing.

Our results provide evidence that narrow, steep canyons that are expected to reflect that energy back out to the open ocean are able to focus and dissipate internal wave energy locally through nonlinear processes. Despite their size, they produce significant energy dissipation that is underrepresented or inappropriately distributed in ocean models on a variety of scales. Because such canyons are much smaller in scale than the current resolution of climate models, it is vital to parameterize this mixing for global simulations of climate, circulation, and biological productivity. Regionally, this dissipation is critical for mixing of tracers including heat, carbon and nutrients. In particular, mid-depth mixing near the nutricline may significantly alter the local nutrient distribution, with important but understudied impacts on local ecology.

Inhomogeneous internal wave generation and propagation at a shelfbreak canyon

WEIFENG (GORDON) ZHANG, TIMOTHY F. DUDA

WOODS HOLE OCEANOGRAPHIC INSTITUTION, US

This study focuses on the tidal generation of internal waves at a shelfbreak canyon and the subsequent wave evolution around the canyon. Hydrodynamic models with idealized (but typical) canyon bathymetries and forced by a barotropic (surface) tide are used to simulate the internal wave generation and propagation processes. Model simulations show that the forcing of internal waves by barotropic tides is strongly asymmetrical with respect to the canyon axis even though the canyons are symmetrical in structure. This leads to internal waves of much larger amplitude on one canyon side-slope than the other. The resulting onshore-propagating internal waves are strongest along beams in the horizontal plane, with the stronger beam lying on the side with higher energy conversion. Analysis of the simulation results suggests that multiple-scattering effects on one canyon side-slope cause the cross-canyon asymmetrical energy conversion. As opposed to a single-scatter model where the conversion of surface tide energy to internal waves depends only on the surface tides, the multiple-scatter model allows the internal waves to affect the conversion process (feedback). Essentially, the phase variation in the spatially distributed collection of internal-wave sources, governed by variations in the orientation of the bathymetry gradient vector, allows resonant internal-wave generation on one canyon side-slope, but not the other. The cross-canyon phase variations of the internal wave sources also cause phased array-like behavior, forming the internal wave radiation beam and leads to localized formation of high-frequency solitary internal waves. Presumably, the asymmetrical internal wave generation leads to water mixing occurring preferentially on one side of canyons, which may have important biological implications. The asymmetrical internal wave generation can also induce inhomogeneous sediment transport within the canyon through the localized strong near-bottom oscillatory flows. Results of this modeling work call for more dedicated field studies of circulation and internal wave processes in shelfbreak canyons.

Upslope vs downslope asymmetric bedforms at the head of a submarine canyon

CLAUDIO LO IACONO[1], JENNY GALES[1], TAHMEENA ASLAM[2+3], ROBERT HALL[2], QUERALT GUERRERO[4], GARETH CARTER[5], KATLEEN ROBERT[1], JORGE GUILLÉN[4], TIM LE BAS[1], RUSSELL WYNN[1], VEERLE A.I. HUVENNE[1]

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Sediment transport from shelf to deep ocean is mostly controlled by gravitational flows, but this simple pattern can become more complex in the vicinity of submarine canyons. Here we document uncommon asymmetric bedforms that are interpreted to represent a pattern of both upslope and downslope flows connecting the upper reaches of the Whittard Canyon to the outer shelf on the northern Biscay margin. During the JC125 CODEMAP expedition, funded by ERC Starting Grant 258482 and the NERC MAREMAP programme, high-resolution data were collected from two sandwave fields along the outer shelf adjacent to the head of Whittard Canyon. Data include shipboard MBES bathymetry (5 m res) and sub-bottom profiles, AUV sidescan sonar (0.15 m res), 3 ROV-mounted vibrocores, and 2 box cores, allowing a multi-resolution analysis of the mapped bedforms in both space and time. The sandwave fields are 7 km apart, occur at 170-220 m depth, and display wavelengths ranging from 300 to 700 m and wave heights of 3 to 8 m. One field of well-developed sandwaves has an unusually pronounced upslope asymmetry, facing the shallower regions of the shelf. Contrastingly, the second sandwave field has similar morphometric characteristics but shows a downslope asymmetry, facing the head of the canyon. AUV sidescan sonar mosaics show, with unprecedented quality, spectacular trains of fresh megaripples with an average wavelength of 10 m, overprinting the large sandwaves. The megaripples reflect the same asymmetric trends, suggesting a constant hydrodynamic regime in the region. AUV-derived images also show unusual lenticular features along the wave crests, which have not been described previously. Comparison with a bathymetric grid acquired 15 years earlier does not reveal any significant migration of the sandwaves. Nonetheless, differences in sediment grain size and composition between crests and troughs suggest that the crests may be controlled by active processes. The spatially-variable regime of the internal tide may be one of the mechanisms involved in the generation and maintenance of the mapped sandwaves. Concurrent hydrographic observations within the canyon using an autonomous ocean glider indicate large-amplitude semidiurnal internal tides are present, possibly transitioning to asymmetrical-shaped internal bores in the upper reaches. Moreover, preliminary results from a numerical model of the semidiurnal internal tide within the canyon suggest a dynamic environment with internal tide energy fluxes directed both up- and down-canyon. This work highlights the local importance of uncommon and still not fully characterized sedimentary dynamics, which are likely related to a complex interaction between canyon morphologies and tidally-driven oceanographic regimes. These results challenge traditional notions of gravity-driven processes being dominant in canyon head environments, and have implications for geo-hazard assessment of mobile substrates in outer shelf settings and quantification of offshore sediment and carbon fluxes.

Geomechanical properties of submarine bedrock cliffs: controls on rock slope failures within the Whittard Canyon, Celtic Margin

GARETH CARTER[1], VEERLE A.I. HUVENNE[2], JENNY GALES[2], CLAUDIO LO IACONO[2], LEIGH MARSH[2], KATLEEN ROBERT[2], RUSSELL WYNN[2]

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Large-scale mass wasting of slopes within submarine canyon environments is well-documented (e.g. Cunningham et al., 2005; Sultan et al., 2007; Lastras et al., 2009). However, at present research has almost exclusively focused upon unconsolidated, loose sediments that form the canyon head and flanks, and produce large slumps and turbidity currents that transport huge quantities of sediment to the canyon floor. This is perhaps due to the relative abundance of geophysical data which can be acquired from research vessels, enabling the detailed geomorphological mapping of large landslide scars and debris lobes at the base of slopes. In contrast, very few studies have previously attempted to assess bedrock rockwall behaviour within a submarine canyon, which could have significant implications for canyon evolutionary processes and, subsequently, regional geohazard assessments for offshore infrastructure. During the CODEMAP 2015 research cruise to the Whittard Canyon, Celtic Margin (funded by ERC Starting Grant 258482 and the NERC MAREMAP programme), a Remotely Operated Vehicle (ROV) gathered High Definition (HD) video footage of the canyon rockwalls over the course of more than 20 individual dives; this dataset was supplemented by rock samples collected during these dives and by shipboard geophysical datasets. The extremely high-resolution video footage revealed small-scale rockwall slope processes that would not have been visible if shipboard geophysical equipment was solely relied upon during the survey. Of particular interest was the apparent spalling failure of mudstone and chalk rockwalls, with fresh superficial "flaking" scars and an absence of sessile fauna indicating relatively recent mass-wasting activity. Extensive talus slopes, often consisting of coarse gravel, pebble and occasionally boulder-sized clasts, were observed at the foot of slopes impacted by spalling failures; this debris was rarely colonised by biological communities which could be an indicator of frequent rockfall events. It is suggested that hydrodynamic stresses could exacerbate the spalling process, and bio-erosion was noted on many of the walls prone to this form of rock slope failure (RSF). Undercutting of cliffs was noted, particularly in carbonate-rich lithologies, which resulted in the failure of large (>1 m) blocks from the overhanging ledge of resistant Fe-oxidised bedrock. Internal fracture networks impose a major control on the observed RSF processes, often resulting in cubic and tabular blocks (0.2-1.0 m scale) of bedrock toppling or sliding out of the cliff face. These discontinuity jointsets were evaluated and modes of failure (e.g. planar, toppling or wedge) were assessed against each lithology where structurally-controlled mass wasting was observed. The rock samples were sent to the British Geological Survey (BGS) geotechnical laboratory for testing in order to ascertain the tensile strengths of the different lithologies present within the canyon. By combining the ROV observations, discontinuity assessments and laboratory testing results, an understanding of the geomechanical properties of the bedrock can be obtained and linked with past and ongoing rock slope processes within the Whittard Canyon. These conclusions will have a wider implication for ongoing geomechanical processes within submarine canyons on a global scale.

Reveal the full extent of submarine canyons; The application of Drainage Network Analysis to the Gollum Canyon System, NE Atlantic

PAUL K. MURPHY, ANDREW J. WHEELER

UNIVERSITY COLLEGE CORK, IRELAND

The Gollum Canyon System (GCS) is the largest submarine canyon system in European waters extending 250 km from the shelf break to the Porcupine Abyssal Plain. Commonly referred to as the Gollum Channel, the morphometric analysis presented here suggest that it is infact a submarine canyon and therefore best referred to as the Gollum Canyon System. An analysis of regional multibeam echosounder data for the entire Porcupine Seabight was conducted with drainage network analysis revealing the true dendritic canyon system present. The GCS is far more expansive than previously thought, proving that GIS-based flow accumulation models as seabed mapping analytical tools reveal significantly more information not possible by visual inspection of sun-illuminated DTMs.

The drainage network analysis has provided modelled proof of hydrological links between the previously separate Elven, Kings and Gollum Canyon Systems. Evidence is also provided of sediment transfer shutdown in canyons due to canyon capture overtime. Additional morphometric analysis has revealed that channel morphologies and orientations are controlled in part by the shallow sub-surface geology within the basin. Tectonic inversion and compressional reactivation of former rift margin faults in the Neogene generating stages of tectonic uplift appear to have occurred concurrently with the development of the GCS, with channels showing evidence for morphological responses to steepening slopes. Evidence of a northward shutdown of the system, with canyons becoming infilled, is also seen, likely tracking changes in sediment supply routes across the shelf in response to the development of Northern European ice sheets.

Towards an understanding of the long-term evolution of submarine canyons

DAVID AMBLAS[1], THOMAS P. GERBER[2], STEVEN Y.J. LAI[3], MIGUEL CANALS[4], JULIAN A. DOWDESWELL[1]

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This abstract contains an image which is displayed at: http://incise2016.oceannetworks.ca/abstracts

The morphology of Earth's continental slopes is in many ways similar to that observed in terrestrial uplands. Where the seafloor descends from coastal to abyssal depths it is sculpted by submarine canyons that in both form and scale are comparable to river valleys in erosional landscapes. Yet the continental slope is also a site of long-term sediment accumulation and, as such, contains a record of its surface evolution beneath the present-day seafloor. Though it can be helpful to draw on surface process models developed for upland landscapes to explain the evolution of continental slopes, a deeper understanding of canyon development requires models for the submarine processes that build and shape the slope.

In this contribution we summarize a number of recent studies that together have shed new light on canyon form and growth. We document observations and measurements from the Catalano-Balearic Basin (NW Mediterranean) that relate the long-profile form of canyons and channels to the processes that control their evolution. We briefly present a model for the long-profile curvature of submarine canyons that includes the combined effects of turbidity currents and background (i.e. hemipelagic) sedimentation, and compare the range of model profile shapes with those observed on the present-day NW Mediterranean slope. Finally, we report on a new line of experimental research aimed at producing canyon morphologies at reduced-scale (Figure). We show that by isolating two key processes – the progressive growth of slope relief and a constant source of unconfined gravity flows – we are able to produce a canyon growth sequence and morphologies that appear similar to what's observed at field scale. We conclude our discussion with some remarks on our view of the outstanding problems and critical research questions related to canyon geomorphology and stratigraphy that will motivate future lines of research.

The Avilés Canyon system: morphology and sediment transport

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POSTER

The Avilés submarine canyon system is one of the largest in Europe. It INCISEs the high-energy central Cantabrian margin in the Bay of Biscay extending down to the Biscay abyssal plain where it opens at 4765 m of water depth. It displays a complex morphology with three main branches, namely Avilés, El Corbiro and La Gaviera, and a large number of smaller tributaries, of which the most significant ones are those forming La Vallina branches entering the main Avilés Canyon trunk through its western side. Several of the reaches of the Avilés Canyon systems have a fairly evident structural control.

A detailed multibeam bathymetry mapping of this canyon system was carried out in the frame of the Spanish DOS MARES research project, jointly with a year-round (from March 2012 to April 2013) monitoring of environmental variables and particle fluxes. Furthermore, remote sensing images and meteorological and hydrographical data were also incorporated, thus constituting one of the most complete datasets on a large submarine canyon in Spain's Atlantic margins.

In this contribution we will present the main results of such a study, with a focus in the information provided by seafloor backscatter imagery and its fit with the measured particle fluxes and the main factors controlling them. Particle fluxes are mainly driven by direct delivery of river-sourced material to a narrow continental shelf and by major resuspension events caused by large waves and near bottom currents developing at the occasion of the rather frequent severe storms that commonly occur in the Cantabrian Sea. Atmospheric and oceanographic conditions and associated Ekman transport largely determine whether or not sedimentary particles may easily reach the main canyon head, with two main modes that tend to follow a seasonal pattern. Tides add an extra amount of energy to the prevailing bottom currents within each transport mode, thus contributing to a permanent background of suspended particles in near-bottom waters and to the winnowing of the finer fraction, especially in the main canyon heads and upper courses. Organic matter, opal and calcium carbonate fluxes representing more than 30% of the total mass flux translate the impact of seasonal high primary production events. We will finally consider the atmospheric teleconnections linking the oceanographic conditions in the Cantabrian margin with those in the Northwestern Mediterranean margin, where other submarine canyons were monitored in parallel.

Numerical simulation exploring the mechanisms driving upwelling in Mackenzie Canyon, Beaufort Sea

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POSTER

Submarine canyons support thriving ecosystems by enabling the exchange of nutrients between the deep ocean and the continental shelf. In regions of low nutrient supply, such as the Arctic Ocean, canyons play a significant role in the regulation of primary productivity by enhancing upwelling in the region. Analytical and laboratory studies of the flow dynamics in idealized canyons indicate that upwelling is driven by three mechanisms: the time-dependent response of flow to an initial forcing, the advective response, and the convergence of isobaths along the canyon walls. These mechanisms coexist in Mackenzie Canyon, which is located on the southeastern edge of the Beaufort Sea in the Arctic Ocean. The three mechanisms are reviewed, and their implications for the circulation around Mackenzie Canyon are explained. Furthermore, a description of the regional configuration of the NEMO (Nucleus for European Modelling of the Ocean) model that will be used to test their relative strengths will be provided, along with a preliminary evaluation of the model using observational data collected in the region.

The Porcupine Bank Canyon, NE Atlantic: A natural laboratory to study the potential of Cold-Water Corals as archives of environmental change

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POSTER

The Porcupine Bank is a section of continental crust partially split form the Irish continental shelf by an aulacogen formed during the opening of the Atlantic, beginning in the Permo-Triassic roughly 250 million years ago. Incised into the bank are several submarine canyons, the largest of which is the Porcupine Bank Canyon, 48 km long and 29 km at its widest, and between 3000 and 700 mbsl at termination and head respectively. Around the lip of the canyon, scleractinian Cold-Water Corals (CWC) have thrived for some time, leading to the development of carbonate mounds; large build ups of anastomosing coral framework, baffled sediment and coral skeleton fragments. These unique habitats support increased local species abundance and diversity, acting as a shelter for communities of fishes, crustacea, porifera, echinoderms and actinians.

With no direct connection to a river or land-contiguous shelves, exchange processes occurring at the canyon are hypothetically devoid of any terrestrial and anthropogenic signals. By investigating the palaeorecord of biomineralised CWC skeletons and their associated carbonate mound build-ups, in-situ spectators of flushing and upwelling events, it is anticipated that new insights will be gained into the natural functioning of the upper canyon system and the development of these CWC habitats.

This study aims to assess the validity of signals for environmental change, water mass and nutrient exchange, and sediment flux, preserved in carbonate mounds at the Porcupine Bank Canyon head. This will be achieved through analysis of the geochemistry of live coral skeleton extracted from the canyon edge, as well as fossil coral through the length of a core, and examining microfaunal assemblages present in the sediment record. Here, preliminary results from the research are presented.

Active processes influencing the morphology of submarine gullies – new insights from marine robotics

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POSTER

Processes operating on the flanks of submarine canyons are often overlooked with attention focused on large-scale events in the axis of a canyon. This is because in-situ monitoring studies and evidence from sediment cores have shown that these can be hugely dynamic and active environments. Turbidity currents transport the highest volumes of sediment on earth, can reach speeds of 20 m/s and are able to travel on seafloor gradients as low as 0.3°. They can impact the location of hydrocarbon reservoirs, are responsible for cable breaks which disrupt internet traffic and can lead to slope failure and thus pose risk of tsunami. How the flows initiate, their behaviour and the influence they have on seafloor morphology still remain poorly understood. Using new evidence collected by a fleet of marine robotic systems in Whittard Canyon, Celtic margin, we highlight the importance of canyon-flank processes, specifically the role that gullies play in the formation and maintenance of canyon morphology. We show that these systems are highly active, may have significant influence on canyon-axis processes, and may be operating on significantly shorter time-scales compared to major down-canyon events. These processes are likely to be integral to canyon evolution and have greater influence on canyon biota compared to less frequent down-canyon events. We identify distinct canyon flank morphologies from quantitative analysis of geophysical data and attempt to link morphology with formation mechanisms. Processes controlling canyon morphology are poorly constrained with suggested mechanisms including turbidity currents, debris flows, slides, slumps and oceanographic processes such as dense water overflows, internal tides and contour currents. We use data collected by Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and shipboard systems, providing ultra-high (cm-scale) resolution geophysical data, targeted ROV-operated vibrocores, multicores and piston cores from gully flanks, axis and fans, and high-resolution video footage showing fine-scale canyon flank morphology. We show evidence for active processes influencing canyon flank morphology, including debris flows and debris fan formation, small-scale mass wasting, turbidity currents and potentially a new mechanism of gully formation through dissolution. We discuss how these processes are influenced by the underlying lithology, internal tide energy and canyon flank gradient, orientation, roughness and geometry, and examine the effect this has on flank morphology. We show that these processes may be fundamental in contributing to the evolution of continental margins, are active today and highlight their importance compared to well-documented canyon-axis processes. Understanding how these mechanisms differ is fundamental in understanding seafloor erosion patterns, basin-ward sediment transport, factors influencing turbidity current evolution and behaviour, continental margin and canyon evolution and factors influencing slope instability.

Origin, transport and burial of organic matter in the Whittard Canyon, North East Atlantic

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POSTER

Submarine canyons are often considered efficient conduits of material to the deep sea that can also harbour varied and well developed ecosystems. Recent work from canyons of the European and N. American margins has revealed highly heterogeneous environments that can also function as important depocentres and are homes to diverse habitats. However little is known about the drivers for such variability and a more comprehensive understanding of the processes within canyons is much needed. The Whittard submarine canyon (Celtic Sea, North East Atlantic) is one of the largest (~100 km across, down to 4500 m depth) and most complex underwater features in the North Western European Margin being home to an array of diverse benthic ecosystems and the focus of much recent research. This project is part of the effort to elucidate the biogeochemical processes that drive variability in the Whittard canyon and assess its significance in marine biogeochemical cycling and deep-sea benthic ecosystem functioning. This will be attempted by examining the provenance, transportation, burial potential and ecological function of sedimentary organic matter from targeted sites of this system. 40 sediment cores, down to ~50 cm, were collected during three surveys in 2013, 2014 and 2015 at depths up to 4210 mbsl across the four main branches and the main channel. Sedimentological (grain size) and geochemical (XRD, XRF, organic Carbon and Nitrogen, lipids) analyses are in progress. Initial grain size results from few cores of the upper western branches have provided a glimpse of the sharp energy changes of the system. Total organic carbon (TOC) concentrations were within already published ranges (0.2-0.6% TOC of dry sediment), but did not correlate well with grain size. At this point it is not clear whether these preliminary results reflect processes related to sediment transport and/or deposition within the canyon at different time scales, local benthic bioturbation, or anthropogenic activities. Future work will focus on the more detailed evaluation of the fluxes, origin, nutritional value and burial potential of the organic material (OM) within the specific sedimentological and geomorphic context of each sampling site.

A middle Pleistocene outcrop analogue of submarine canyon fill along the Ionian side of Calabria (southern Italy): depositional processes and relationships with the modern submarine canyons

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POSTER

The Crotone Basin is a forearc basin located on the Ionian side of the Calabrian Arc (southern Italy) that was active from Serravallian to middle Pleistocene. In the northern sector of the basin, behind the modern Neto delta north of the town of Crotone, there crops out a coarse-grained canyon fill succession (the Serra Mulara Formation) of middle Pleistocene age. The canyon fill is up to 178 m thick and consists of a NW-SE elongated body (4.25 km long and up to 1.5 km wide) laterally confined by a deep-water succession of clays and silts. The lower part of the canyon fill is dominated by gravelly to sandy density-flow deposits containing abundant bivalve and gastropod fragments, passing upwards into a interval composed of metre- to decimetre-scale density-flow deposits forming sandstone-mudstone couplets. Sandstone deposits are mostly structureless and planar laminated, while the clayey layers record hemipelagic deposition during quieter phases. This interval is overlain by another composed of thicker, structureless sandstones alternating with layers of interlaminated mudstones and sandstones, which contain leaf remnants and freshwater ostracods and can be directly linked to river floods. The canyon fill is overlain by gravelly to sandy continental deposits recording a later stage of emergence. Overall, the Serra Mulara Formation records a relative sea-level rise related to the transition from MIS 12 to MIS 11, followed by a generalized relative sea-level lowering mostly related to regional uplift. The Serra Mulara Formation is the only known example of outcropping submarine canyon fill along the Ionian side of Calabria and is not connected to the present-day network of submarine canyons. However, seismic profiles available on the Neto alluvial plain and off the modern coast suggest that all canyons post-date the lower Pleistocene. We propose that the Serra Mulara canyon records a response to middle Pleistocene tectonic events that culminated in the uplift of Calabria, resulting in the incision, infill and beheading of a canyon system that has continued to develop in the adjacent offshore. The Serra Mulara canyon is similar in size to the largest active submarine canyons found along the Ionian margin of Calabria, and may be profitably used as an outcrop analogue to study both erosional and depositional processes acting within these large features.

Seabed imprint of dense shelf water cascading

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POSTER

Dense shelf-water cascading (DSWC) is an atmosphere-driven seasonal phenomenon that occurs in marine regions around the globe. DSWC starts when surface waters over the continental shelf become denser than surrounding waters (by cooling, evaporation or sea-ice formation with brine rejection) and sink, generating a near-bottom gravity flow that moves downslope along the seabed, often using submarine canyons as preferential conduits. This process contributes to deep-ocean ventilation, plays a role in the global thermohaline circulation (and hence global climate), and involves the massive transfer of energy and matter (including sedimentary particles, organic carbon and pollutants) from shallow to deep waters.

DSWC is highly sensitive to temperature change in both the lower atmosphere and the sea surface. In the coming decades global warming will likely modify the frequency and intensity of DSWC, which could significantly affect the functioning of the deep-sea ecosystems. Overall, dense-water formation is expected to decline over both continental shelves and offshore, particularly in Arctic and sub-polar latitudes where sea-ice production is declining.

Field observations show that DSWC can rapidly reshape the seafloor, particularly in submarine canyons. It has been suggested that DSW fluxes could generate continental slope gullies in Polar Regions too. In situ near-bottom velocities up to 1.25 m s-1 have been measured for these currents, which are similar to those attained by turbidity currents. The large volumetric fluxes created by DSWC can result in appreciable sediment erosion and downslope transport. However, very few field studies discuss DSWC as an effective seafloor-sculpting agent, and none of them at global scale. Here we present a new project that considers the morphological signature of DSWC events on modern continental shelves and slopes. The project aims to contribute to a better characterization of the distribution, hydrodynamics and sculpting capacity of dense shelf water currents, as well as the long-term morphodynamics where they are or have been in action in geologically recent times. It also aims to better understand the past and future effects of climate change on the formation of DSWC, in addition to shedding new light to the on-going discussion about the potential vulnerability of deep-sea ecosystems that largely rely on the arrival of nutrients transported during DSWC events.

THEME 2: NEW WAYS TO STUDY SUBMARINE CANYONS: INTEGRATED PROGRAMS, NEW TECHNOLOGIES + COORDINATED MONITORING EFFORTS

Obtaining an integrated, multiresolution picture of a single submarine canyon system

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This presentation will give an overview of the most recent efforts to obtain a holistic understanding of Whittard Canyon, Celtic Margin, NE Atlantic. Whittard Canyon is a large, dendritic, shelf-incising canyon, currently located ca. 200nm from the closest shoreline. During glacial times, when sea level was much lower, the canyon frequently funnelled large catastrophic sediment flows to the deep sea. In recent times, this activity is much reduced, but this does not mean that the canyon is inactive. Integrating all existing knowledge about the canyon from different disciplines (geology, sedimentology, geomorphology, oceanography, ecology and benthic biology; Amaro et al., subm.), we will review the processes currently affecting canyon formation and sediment transport, and discuss their effects on the benthic communities.

The second part of this presentation will demonstrate how a combination of the latest developments in marine robotic technology can be used to obtain a complete, multiscale, 3-dimensional image of a submarine canyon and its benthic habitats. Expedition CODEMAP2015 made use of the Autosub6000 AUV, Isis ROV and a Seaglider to apply a nested mapping scheme in Whittard Canyon, including detailed side-ways mapping of vertical and overhanging canyon walls and continuous measurements of the water column structure.

The Whittard Canyon – a case study of submarine canyon processes

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Submarine canyons are large geomorphological features that incise continental shelves and slopes around the world. They are often suggested to be biodiversity and biomass hotspots, although there is no consensus about this in the literature. Nevertheless, many canyons do host diverse faunal communities but, owing to our lack of understanding of the processes shaping and driving this diversity, appropriate management strategies have yet to be developed. Here, we integrate all the current knowledge of one single system, the Whittard Canyon (Celtic Margin, NE Atlantic), including the latest research on geology, sedimentology, geomorphology, oceanography, ecology, and biodiversity in order to address this issue. The Whittard Canyon is an active system in terms of sediment transport. The net suspended sediment transport is mainly up-canyon causing sedimentary overflow in some upper canyon areas. Occasionally sediment gravity flow events do occur, some possibly the result of anthropogenic activity. However, the role of these intermittent gravity flows in transferring labile organic matter to the deeper regions of the canyon appears to be limited. More likely, any labile organic matter flushed downslope in this way becomes strongly diluted with bulk material and therefore of little food value for benthic fauna. Instead, the fresh organic matter found in the Whittard Channel mainly arrives through vertical deposition and lateral transport of phytoplankton blooms that occur in the area during spring and summer. The response of the Whittard Canyon fauna to these processes is different in different groups. Foraminiferal abundances are higher in the upper parts of the canyon and on the slope than in the lower canyon. Meiofaunal abundances in the upper and middle part of the canyon are higher than on adjacent slopes, but lower in the deepest part. Mega- and macrofauna abundances are higher in the canyon compared with the adjacent slope and are higher in the eastern than the western branch. These faunal patterns reflect the fact that the Whittard Canyon encompasses considerable environmental heterogeneity, related to a combination of organic matter trapping, current regimes (due to focused internal tides) and different substrates. We conclude that coordinated observations of processes driving faunal patterns are needed at a fine scale in order to understand the functioning of communities in this and other submarine canyons.

New insights into links between flow events, benthic biology and carbon fluxes: a proposal for co-ordinating international monitoring efforts at series of "global test sites"

PETER J. TALLING

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Turbidity currents play a key role in submarine canyon dynamics and genesis, carrying sediment into deeper water to form the largest sediment accumulations on our planet. These submarine flows also supply organic carbon and nutrients; thus affect the dynamics of benthic ecosystems. In a stark contrast to other sediment transport processes such as rivers, it is sobering to note quite how few direct measurements we have from turbidity currents in action. Sediment concentration is the critical parameter controlling such flows, yet it has never been measured directly for flows that reach and build submarine fans. How then do we know what type of flow to model in flume tanks, or which assumptions to use to formulate numerical simulations or analytical models?

It is proposed here that international efforts are needed for an initiative to bring together monitor active turbidity currents with studies of benthic ecosystems and carbon transport; at a series of global 'test sites'. Flows and ecosystems evolve significantly, such that source to sink data are needed. We also need to directly monitor flows and ecosystems in different settings with variable triggering factors and flow path morphologies because their character can vary significantly. Such work should integrate numerical and physical modelling with the collection of field observations in order to understand the significance of field observations.

This 'test site' initiative may be timely and feasible, due to recent technological advances in monitoring sensors, moorings and autonomous data recovery. This will be illustrated here by seminal field datasets recent collected by colleagues from the Squamish River Delta, Bute Inlet, Monterey Canyon, Congo Canyon and offshore SE Taiwan. This talk will conclude with some suggestions for appropriate test sites and collaborative approaches to future data collection. The initial phase of this proposal has been funded by the UK research councils, and input is sought into the design of the broader test site initiative.

Acknowledgements: This overview is based on a seminal body of recent flow monitoring work by international colleagues including John Hughes Clarke, Maria Azpiroz, Matthieu Cartigny, Michael Clare, Cortis Cooper, Stephanie Girardclos, Philip Hill, Gwynn Lintern, James Liu, Andrew Lin, Dan Parsons, Charlie Paull, Cooper Stacey, Esther Sumner, and Jingping Xu, amongst others.

Measuring powerful turbidity currents which leave no trace

D. GWYN LINTERN, COOPER D. STACEY, PHILIP R. HILL

GEOLOGICAL SURVEY OF CANADA, NATURAL RESOURCES CANADA, SIDNEY, CANADA

Turbidity currents are difficult to monitor directly. We have made direct and high bandwidth observations of turbidity currents using a cabled seafloor observatory. This talk outlines the techniques and instruments we are using. The main platforms have undergone several version changes. From 2008 to 2012 the platform had been almost completely buried and anchored into the seabed of the upper delta due to high sedimentation, and had been tumbled to its side by then unknown reasons. On 5 June 2012, a 2 tonne platform located in 107 m was displaced downslope and severed from its data cable. It was found 250 m downslope. A much more streamlined platform has replaced the original, but still undergoes movement during the strong turbidity currents. Lines of evidence indicate that the flows come in as a bed hugging wedge, and build up to between 1 m and 4 m in height as the head passed through. Curiously, these strong events failed to cause discernible seabed elevation change. This talk presents a newly instrumented platform which is specifically designed from a science perspective, from lessons learned regarding both the difficult environment, and the limitations of existing instruments.

Exploring the submarine canyons' scientific landscape

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This abstract contains an image which is displayed at: http://incise2016.oceannetworks.ca/abstracts

Submarine canyons are among the most studied geomorphologic structures in the deep sea. Around 9500 canyons have been identified worldwide to date. In a fraction of those, numerous studies across disciplines have been conducted, covering several structural and functional aspects of their nature and revealing their remarkable influence on the surrounding areas. Despite the vast literature published, and the valuable information that the study of past and present knowledge trends can yield, the canyons' scientific landscape delimitation through 'knowledge clusters' is still missing. Most scientific and technical literature is available in electronic format, allowing its analysis by powerful text retrieval techniques. Text mining offers powerful tools to organize, classify, label and retrieve previously unknown data patterns from large text collections. The INCISE canyons database, recently developed by Working Group 2, was structured into a textual corpus and updated with the corresponding abstracts to extract the most relevant terms in literature. Extraction of terms (single- and multiword) was carried out using natural language processing (NLP) methods, and the subsequent epistemic analyses were performed based on the frequency of terms occurrence. All the NLP tasks and co-word analyses were performed using the tools available in the open access platform CORTEXT Manager. In addition, the Gephi program was used to map the canyons scientific landscape while complementary analyses and data visualization processing were run using R software. In this study we addressed three main issues: 1) determine the main knowledge clusters of canyon research by scientific subject area and how they are interconnected; 2) identify which are the canyons and scientific subject categories well-covered in published literature and where are the main knowledge gaps in canyon research; and 3) reveal the dynamics and historic evolution of the canyons' science landscape. Although language ambiguity in multidisciplinary co-word analysis may be criticized, these studies provide systematized and useful information to scientists and science managers. The scientific landscape mapping and its complementary results will be available online in the near future, as an open interactive platform that can be used by canyon stakeholders as a tool for better planning of future research, management actions, and funding allocation.

THEME 3: BIOLOGICAL PATTERNS IN SUBMARINE CANYONS: ROLE OF SCALE + HETEROGENEITY

Early phytoplankton bloom and large seafloor productivity footprint in Andvord Bay fjord, Antarctica: results from the first FjordEco cruise

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Fjords are glacially cut submarine canyons that dissect polar margins. The West Antarctic Peninsula (WAP) has an extensive, rapidly warming system of sub-polar fjords with tidewater glaciers. These fjords appear to be hotspots of biomass and biodiversity, with sustained phytoplankton blooms, massive aggregations of krill and humpback whales, and high abundance and species richness of megabenthos. This spectacular marine life attracts >20,000 tourists to individual WAP fjords each summer. Nonetheless, drivers of high fjord productivity/biodiversity, as well as the sensitivity of WAP fjord ecosystems to climate warming, are very poorly understood. Within the FjordEco Project, we are conducting an integrated field and modeling program to evaluate physical oceanographic processes, glacial inputs, plankton dynamics, and benthic community structure and function in Andvord Bay, a sub-polar WAP fjord, to address two overarching questions: (1) What physical, glaciological, biological and chemical processes interact to enhance fjord productivity and biodiversity? (2) How sensitive are these fjord processes to increased glacial meltwater and sediment inputs expected from climate warming? Our field program will test mechanistic hypotheses concerning oceanographic/glaciological forcing and phytoplankton and benthic community responses, and includes: (1) Deployments of moorings (physical oceanographic, sediment traps, seafloor time-lapse camera), weather stations, and glacial and sea-ice time-lapse cameras to obtain an integrated view of ecosystem processes in the fjord and adjacent Gelarche Strait over 15 months; and (2) spring and fall process cruises using shipboard CTD, towed Acrobat system, AUV glider, and intensive studies of phytoplankton and benthic species composition and production/respiration to elucidate fjord ecosystem structure and function during different seasons. We will then use a coupled physical/biological modeling approach (ROMS/NEMURO) to evaluate drivers of biogeochemical cycles in WAP fjords and to explore their potential sensitivity to enhanced meltwater and sediment inputs.

Here we present results from our spring cruise to Andvord Bay in Nov-Dec 2015 to deploy instruments and evaluate ecosystem processes. The fjord proved physically dynamic, with glacial+sea ice filling/emptying the fjord within days due to tides and katabatic winds. Tabular icebergs with 30-m freeboard roved throughout the fjord, potentially stirring waters to >200 m. The spring phytoplankton bloom was well underway in the fjord by late November while it had not yet begin on the open shelf; the fjord bloom was unexpectedly dominated by cryptomonads which may be favored by meltwater conditions. Primary production was highest over sills in the outer fjord, and the fjord appeared to be exporting meltwater, phytoplankton and nutrients into the Gerlache Strait. Benthic megafaunal abundance was dramatically elevated throughout the fjord relative to Gerlache Strait, with extraordinary abundances occurring <1 km from rapidly flowing (>5 m/d) glacial termini. Sediment community respiration was also 4-fold higher in the fjord than on the open shelf, with the highest rates underlying the zone of high pelagic primary production. Our initial results confirm that Andvord Bay is productive early in the season, especially in the outer fjord, with the benthic footprint of this enhanced productivity extending into the fjord's innermost recesses.

A critical evaluation of methods to compare the diversity of 2 submarine canyons

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Submarine canyons are listed as potential biodiversity hotspots, however, to date there is very little data on canyon community composition of these features, or measures of diversity to assess their potential importance as features of conservation interest. For effective management of submarine canyons, we need a method by which they can be classified in terms of what is important for conservation. Diversity is a well used and accepted method for quantification and compatibility between habitats and features. Diversity indices such as Margalef (1958), Shannon-Wiener (1963) and Simpson (1949) index are commonly used in ecology and can measure richness, dominance and evenness.

These, as well as other (Simpson's reciprocal Index, rarefaction curves etc.) can be used to measure the alpha diversity of biotopes, but to date there is no standardised approach for comparing diversity of habitats/features. When comparing diversity, caution needs to be taken regarding which index is used, simply averaging species richness across samples can be misleading as no standardisation for sampling effort is made. Here we use data of 2 adjacent submarine canyons to critically evaluate the methods used to treat quantitative data for comparing biodiversity. Ultimately, a better understanding of the methods used to treat and compare the data for conservation allows more accurate predictive modelling in canyons.

The Lacaze-Duthiers canyon: a natural laboratory to study deep-sea ecosystem dynamics and functions in a climate change context

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Submarine canyons are ecological hotspots on continental margins sustaining a variety of services to marine ecosystems and human societies. Canyon ecosystems are exposed to cumulative climatic and direct anthropogenic pressures, particularly at places where extreme events propagate disturbances of the meteorological-hydrological regime down to hundreds or thousands meters depth (e.g.: through deep water convection or export of material during storms). The complex links between environmental fluctuations and ecological responses however remains largely undescribed in the deep-sea due to limited access. There are thus many critical gaps to fill in order to understand how climate forcing may challenge ecosystem resilience.

In this perspective, we established a multiannual integrated ecological study in the Lacaze-Duthiers submarine canyon (Western Mediterranean Sea), which aimed at investigating key ecosystem functions and their dynamic features in natural conditions. This canyon hosts abundant populations of deep-water corals, whose sensitivity to warming and acidification may further enhance ecosystem vulnerability. A first objective of our experimental approach was the study of the in situ growth dynamics of the two dominant coral species, M. oculata and L. Pertusa, in combination with changes in associated microbial communities. We also focused on microbial and animal plant macrodebris colonization, to examine the role of canyon in transferring energy from land to deep-sea and supporting deep-sea faunal diversity.

The first outcomes of this programme reveal unexpected rapid dynamics of key ecological processes, potentially reflecting the environmental instability at seasonal or event scales, resulting of atmospheric forcings in this area. While providing clues to explore the underlying mechanisms, these results set the basis for a long-term integrated study of a climate-sensitive deep-sea ecosystem, supporting the implementation of effective monitoring strategies by the Marine Protected Area of the Gulf of Lion (Parc Naturel Marin du Golfe du Lion).

Cold-water coral ecosystems in Cassidaigne Canyon (Mediterranean Sea): an assessment of their environmental living conditions

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The Cassidaigne canyon is one of the two canyons (together with Lacaze-Duthiers) of the French Mediterranean coast in which cold-water corals have settled and formed large colonies, providing a structural habitat for other species. Nevertheless, the communities settled in the Cassidaigne canyon are physically impacted by discharges of bauxite residues.

New information on the distribution of the species Madrepora oculata and the associated species diversity in Cassidaigne canyon was provided by videos and photos acquired in 2013. An area investigated at 515 m depth harbored a high density of small colonies of M. oculata. The water column structure of the area was described by using a CTD transect deployed along the axis of the canyon. High resolution (10 m and 2 m) bathymetric data were collected in the Cassidaigne canyon in 2010 and 2014. Seafloor characteristics were derived from the 10 m resolution bathymetric data. Data on local hydrodynamic conditions in the first 10 meters above the seafloor were produced by applying the MARS3D hydrodynamic model in the Cassidaigne canyon at a horizontal resolution of 80 m (CASCANS model configuration). These environmental datasets combined with the geographic coordinates of the known occurrences of dense M. oculata colonies in the canyon allowed establishing a model using the MaxEnt software package to predict the habitat distribution in terms of probability of occurrence.

According to the water mass analysis, M. oculata habitats are mainly located in the layer of the Intermediate waters originating from the Eastern Mediterranean Basin. A high concentration of suspended sediment due to the bauxite residues expelled into the canyon was observed in the axis of the canyon where we measured 1 NTU (2.5 mg/l) at 100 m above the bottom while concentrations were even higher (2NTU; 5mg/l) closer to the bottom. The habitat suitability model indicates that the living conditions of M. oculata can be found in areas of the Cassidaigne canyon where the substratum shows irregularities, slopes and topographic highs. Concerning environmental variables resulting from the hydrodynamic model, temperature and high current velocities were identified as explanatory factors of the distribution of M. oculata. Suitable areas for M. oculata habitat settlement were mapped at the scale of the canyon.

This study gathers multiple disciplines combined to consider a submarine canyon as a global functioning system and is an approach intended to promote the management of sensitive ecosystems in complex topographic features such as canyons.

Whittard Canyon's eastern branch: zooming in from tidal models to fine-scale photogrammetry

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The complexity of submarine canyons is well known and in order to address how this heterogeneity affects species spatial patterns, it is important to consider this habitat in three dimensions and at multiple scales. At the broader scale, the accidented topography results in an array of benthic habitats, but also significantly affects the hydrodynamics of the overlaying waters. At the finer-scale, complex three dimensional features such as vertical and overhanging cliffs are colonized by a wide diversity of organisms, often including vulnerable marine species such as cold-water corals. In this study, we build on previous work which had used ROV video surveys to predict spatial patterns in abundance, species richness and diversity across the four main branches of Whittard Canyon. However, these past studies were mostly carried out at an intermediate scale and focused on the importance of bathymetry (ship-mounted) and derived terrain variables. We now revisit these predictions, and demonstrate the importance of also considering hydrodynamic variables. Investigation of the M2 internal tide in the canyon, using the Princeton Ocean Model, showed clear differences in internal tidal energy between the canyon branches. The inclusion of the resulting internal tide driven currents (magnitude and direction) helped increase the amount of variation explained in predictive habitat models of species richness and diversity. In addition, the habitat predictions highlighted the importance of vertical structures, we employed recently developed photogrammetry approaches (structure from motion) to reconstruct sections of canyon walls in three dimensions from ROV video footage. These very high resolution reconstructions were used to position very accurately in three-dimensional space individual organisms and derive terrain variables on scales similar to those experienced by megabenthic individuals (<20cm for sonar and <1cm for photogrammetry). Using this information we explore fine-scale spatial partitioning of cliff environments for a variety of organisms including Acesta clams, the cold-water coral Lophelia pertusa and a few different morphotypes of soft corals. The large amount of work having been carried out within Whittard Canyon allows for the integrated multi-disciplinary studies needed to examining the complex biological spatial patterns often observed within submarine canyons.

This work is part of the ERC CODEMAP project (Starting Grant no 258482) and data were collected during the CODEMAP2015 cruise.

Benthic Polychaete Assemblage Patterns in the Whittard Canyon System

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Deep-sea macrofaunal polychaete species assemblage characteristics were examined in the Whittard Canyon system (NE Atlantic). Replicate Megacore samples were collected, from three canyon branches and one site on the continental slope to the west of the canyon (~ 3500 m water depth).

A total of 110 polychaete species were morphologically identified. Paramphinome jeffreysii was the most abundant species (2326 ind m-2) followed by Aurospio sp. B (646 ind m-2), Opheliidae sp. A (393 ind m-2), Prionospio sp. I (380 ind m-2), and Ophelina abranchiata (227 ind m-2). Species composition varied significantly across all sites. From east to west, the dominance of Paramphinome jeffreysii decreased from 39.6 % in the Eastern branch to 12.9 % on the slope. Environmental variables depth and clay % best explained patterns in species composition. Species diversity between branches inside the canyon was roughly similar. Richness and diversity indices were higher on the slope compared with inside the canyon. Forty-six of the ninety-nine polychaete species found in the Whittard Canyon were not present on the adjacent slope site, suggesting that the canyon may increase beta diversity and enhance the regional species pool.

Additional polychaetes were collected for a preliminary molecular analysis (CO1 and 16S genes) from the shallower parts (~ 1000 m) of the canyon and nearby Goban Spur to the northwest of the canyon. A total of 109 sequences were obtained from 139 specimens. This resulted in the identification of 33 polychaete species, of which 5 could be assigned Latin binomial names based on phylogenetic analyses. Only two of these species (P.jeffreysii, Aurospio dibranchiata) occurred at the deeper (3500 m) sites, suggesting that polychaete assemblages in the shallower regions of the canyon are different from the deeper assemblages. However, more samples from shallower regions would be needed to confirm this conclusion.

This study highlights the variability of polychaete assemblages within the soft-sediment habitat of a submarine canyon. This variation probably reflects the dynamic environmental conditions, which are influenced by the topographic profiles of individual canyon branches.

Food quantity and quality available for benthic communities within Pacific and Atlantic submarine canyons

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Benthic communities respond to food availability, among other environmental variables. Higher food quantities usually support higher benthic biomasses and/or abundances. Although usually neglected, food quality can also play a role in structuring benthic communities based on nutritional value and food preferences of different species. Submarine canyons provide traps and conduits of organic matter from shallow to deeper waters depending on topography and circulation patterns. In this study we compare the quantity and quality of food within submarine canyons from the Gulf of Maine in the Atlantic (North East Channel, Corsair and Heezen Canyons) and Pacific (Barkley Canyon) at different depths. Total sedimentary organic carbon and nitrogen were low at the head of the canyons and increased with depth. These results correlate with sediment grain size, which was coarser at the head of the canyon, suggesting strong currents transporting organic matter and sediments down the canyon to ~1000 m where major deposition occurs. The increased total lipids and chlorophyll/phaeoforbides ratio, a metric of food quality, at about 400-600 m, suggests higher nutritional value at that depth. Complex circulation in submarine canyons likely contributes to this result. Similarly, phospholipids (indicative of live or recently deceased organisms) in bottom water particulate organic matter increased at about 400 m. Despite generally lower food quantities in Barkley Canyon than in the Atlantic canyons, low amounts of high-quality food characterize all canyon heads of this study and contrast more abundant but lower quality food below 1000 m depth. Other characteristics of organic matter differ in each of the canyons. For example, high levels of wax esters occurred in bottom water samples from 800 and 1500 m, coinciding with zooplankton migration depths in Barkley Canyon. Abundant hydrocarbons in Barkley canyon at 900 m coincided with methane hydrates in sediments; we also observed abundant hydrocarbons at Heezen Canyon, although we did not observe hydrates or seeps. Therefore, the physical, geological, and biological characteristics of submarine canyons complicate any simple linear decrease in degradation of organic matter with depth contrary to expectation. These results suggest food availability (amounts and quality) change along submarine canyons with depth in unusual ways, and such changes should be considered when trying to understand patterns in benthic communities and food webs.

Effects of sediment source-sink dynamics on deep-sea benthos in the Gaoping Submarine Canyon

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With rising demands and capability to exploit the deep sea, the deep ocean has become a frontier for economic development; however, such exploitation remains highly controversial because the associated risks and environmental impacts are not well understood and the baseline data is usually lacking. There is also a mismatch between the scale of our current knowledge and the scale of the potential impacts, because the large-scale and long-term manipulative impact experiments are practically impossible. To bridge the gap between the mesocosm experiments and the real-world problem, it is important to understand the cumulative impacts and recovery processes of benthic communities undergo large-scale natural disturbance or submarine geohazards.

Gaoping Submarine Canyon (GPSC) off the SW Taiwan (NW Pacific) has been an instructional example of the source-to-sink sediment pathway from the high mountain (head water of Gaoping River at ~4000 m) to the deep South China Sea (> 5000 m to the Malina Trench) and thus an ideal natural laboratory to study the impacts of land-sea interactions on deep-sea benthos. A total of 5 research cruises were conducted during 2014 and 2015 to sample the upper GPSC and the adjacent slope between 200 to 1000 m. The densities of larger macrobenthos (>300 um) were consistently lower in the GPSC than that on the slope, while the densities of smaller meiofauna (>40 um) appeared very similar between the slope and canyon in August 2015 but significantly lower in the GPSC than on the slope in November 2015. The compositions of both size classes were distinctively different between the slope and canyon with more co-occurring taxa on the slope than that in the canyon. Molluscs and paracarid crustaceans did not appear to survive in the canyon, but polychaetes, harpacticoids, nematodes and kinorhyncha seemed to flourish in both the canyon and slope environments.

Our preliminary results suggested that the benthos were likely stressed by the dynamic environments in the GPSC. The effects were more pronounced and consistent for the larger macrobenthos than for the smaller meiobenthos. In contrast to the elevated benthic standing stocks reported in most of the submarine canyons worldwide, the GPSC consistently had lower macrofauna densities than that on the slope throughout the year, suggesting that the benthic communities cannot recover from large-scale and frequent disturbances in the GPSC and the communities remain in early successional stages. Our results also imply that the hyper sedimentation associated with deep-sea mining or mine tailing placements likely have negative impacts on the surrounding benthic communities throughout the length of their operations.

Crinoid fauna of the NE Atlantic

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POSTER

During two cruises aboard RV Celtic Explorer to the Celtic margin, crinoid imagery and specimens were collected using the Irish deep-water ROV Holland I. The cruises explored two submarine canyon systems comprising two unnamed canyons to the north of the Porcupine Bank and the Whittard Canyon, a dendritic system south of the Goban Spur. We observed over 8000 individual crinoids representing species from eight families. Voucher specimens of Anachalypsicrinus nefertiti, Atelecrinus helgae, Endoxocrinus (Diplocrinus) wyvillethomsoni, Koehlermetra porrecta, Neocomatella europaea, Pentametrocrinus atlanticus, Porphyrocrinus thalassae, Zeuctocrinus gisleni were collected, allowing confirmation of the video identifications. We observed a further 900 specimens that could only be identified as 'comatulid sp.' or 'stalked crinoid sp.' due to poor imagery or lack of identifying characteristics. We describe the identifying features of the species collected, their habitat, and report their abundance. We also provide in situ photographs of every species to facilitate future identifications by non specialists.

La Fonera canyon, northwestern Mediterranean: A threatened cold-water coral habitat

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POSTER

Submarine canyons are known to be one of the morphological features where cold-water coral (CWC) ecosystems develop in the Mediterranean Sea, as observed in Cap de Creus and Lacaze-Duthiers canyons. La Fonera canyon, in the Catalan margin, Northwestern Mediterranean Sea, also was a good candidate to host such communities. Its head incises 28 km into the Catalan continental shelf and is formed by a complex network of three main branches (Cap de Begur, Illa Negra and Sant Sebastià) and many minor branches and gullies, with a rough terrain, high slope gradients and rock outcrops suitable for coral growth. The tip of Illa Negra branch is located at 60 m water depth at a distance of barely 800 m from the coastline.

After being mapped in detail in 2007 using a multibeam echosounder, the canyon head was the target of a systematic ROV survey, using a Seaeye Lynx 1500, at different environments and depths ranging between 79 and 401 m. ROV images evidence the presence and the status of CWC species Madrepora oculata and Dendrophyllia cornigera, gorgonian red coral Corallium rubrum, as well as human impacts taking place in their habitats. Terrain classification techniques have been applied to high-resolution swath bathymetric data to obtain semi-automatic interpretative maps to identify the relationship between coral distribution patterns and canyon environments.

Large, healthy colonies of M. oculata occur on abrupt, protected, often overhanging, rocky sections of the canyon walls, especially in Illa Negra branch. D. cornigera is sparser and evenly distributed at depth, on relatively low sloping areas, in rocky but also partially sedimented areas. C. rubrum is most frequent between 100 and 160 m on highly sloping rocky areas. The probable extent of CWC habitats has been quantified by applying a maximum entropy model to predict habitat suitability: 0.36 km2 yield M. oculata occurrence probabilities over 70%.

All ROV transects document either the presence of litter on the seafloor or pervasive trawling marks, with nets and longlines entangled on coral colonies, coral rubble observed at the foot of impacted colonies and partial burial of some colonies that could be the result of the resuspension generated by bottom trawling on neighboring fishing grounds, which has been demonstrated to be responsible of daily increases in sediment fluxes within the canyon.

Early benthic successional processes at implanted substrates in Barkley Submarine Canyon affected by a permanent oxygen minimum zone

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POSTER

With the advent of cabled observatories scientists are now able to have a permanent presence in the deep-seafloor, being able to reveal previously unseen faunal behavior as well as to track long-term changes in biodiversity and ecosystem function. The Ocean Networks Canada 800-km loop regional seafloor observatory array located in the NE Pacific has instruments measuring a variety of environmental variables ranging from temperature, salinity, oxygen, currents, turbidity, fluorescence, etc, at multiple and very high temporal resolution scales. High-definition video cameras also monitor benthic communities in multiple deep-sea habitats, all at some extent influenced by an oxygen minimum zone (OMZ). In the present study, whale-bone and wood substrates are being used to evaluate bathymetric, regional and inter-basin variations in benthic biodiversity and connectivity, as well as interactions between biodiversity and ecosystem function. In May of 2014 three humpback whale (Megaptera novaeangliae) rib sections, one 20x20x10 cm block of Douglas Fir (Pseudotsunga meniziesii), and a ~ 30x30x30 block of authigenic carbonate were placed with the use of an ROV at 890 m depth inside Barkley Canyon. The substrate packages were placed concentrically, 45-cm away from a HD video camera. Five-minute videos were captured at 2-hr intervals. Moving averages (12 and 48 hr) were calculated for abundance and species richness, and waveform analysis at a 24-hr time scale was used to assess the relationship between animal activity (abundance counts) and tidal regimes. We used pressure data from a CTD as a proxy for tidal dynamics. Bacterial mat coverage at the surface of the whale bones was measured by means of manual image analysis using a masking tool on image J software. Environmental variables measured from ONC's Barkley Canyon POD3 CTDs (temperature, pressure, dissolved oxygen, fluorescence, turbidity) were used to explore environmental variability. Data analysis from 8 months of deployment showed very distinct early community succession patterns between the two organic substrates (bones and wood) and the authigenic carbonate. Whalebones and wood showed amphipod (Orchomene obtusa) abundance peaks mostly contained during the first 60 days after deployment; Amphipod peak abundance rapid decline coincides with rapid growth of bacterial mat on whalebone and wood surfaces. Specifically for the whale bones, community composition seems to be responding to sulfide build up from bacterial mat degradational processes, and switching from a mobile-scavenger directly into a sulfophilic stage (sensu Smith and Baco 2003). Absence of Osedax and Xylophaga on whale bones and wood, respectively, concur with our hypothesis of OMZ effects in reducing colonization rates by specialized macrofaunal decomposers. Low abundance, species richness and substrate degradation rates are in agreement with a low oxygen environment of the OMZ in the canyon. Even though data analysis is still underway, this experiment demonstrates how cabled observatories are suited for conducting experiments in the deep-sea, where researchers gain full control of observation parameters and benefit from high-frequency measuring of environmental fluctuation.

Smith, CR., Baco, AR, 2003. Ecology of whale falls at the deep-sea flloor. Oceanography and Marine Biology, An Annual Review, 41, 311–354

Connecting dots across Mediterranean seascape: the role of submarine canyons on Lophelia pertusa connectivity

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POSTER

The importance of submarine canyons in the benthic and pelagic ecosystem functioning has attracted the scientific attention in the recent years. Awareness on the need for protection and conservation of various habitats occurring in canyons, such as the cold-water corals classified as Vulnerable Marine Ecosystems, has grown progressively with our perception of the anthropogenic impacts. Canyons occur in the Mediterranean Sea in high number and they are more closely spaced here then in other areas of the world which may be a crucial factor for the connectivity of their communities. Knowledge on the spatial dynamics and limitations of this key process for community resilience and metapopulation persistence is fundamental for implementing effective conservation measures. Being a sessile species when adult and having a larval dispersal stage, Lophelia pertusa is an attractive species to model connectivity in the deep sea. Understanding the importance of the seascape configuration on the L. pertusa connectivity is the main objective of this work. A multidisciplinary approach is used to assess the role of habitat availability and suitability in the dispersal capability of the species. We integrated habitat suitability and biophysical dispersal modelling with graph analysis in order to explore the interaction between the seascape (habitat structure and oceanography) and L. pertusa potential connectivity. Graph-based analysis emerged in ecology as a promising tool to study the functional and structural connectivity. The habitat suitability map was produced using MaxEnt, a niche ecological model, and the output was obtained with the lagrangian-based system "Connectivity System Model". A geographically explicit network was generated based on the potential connectivity output and the relative importance of the habitat patches in the seascape configuration was analysed. The network analysis allows the characterization of the spatial structure of population sources and sinks, the occurrence of corridors or barriers and provides hypotheses on L. pertusa connectivity across the Mediterranean, which can be empirically tested.

THEME 4: PHYSICAL + ANTHROPOGENIC DISTURBANCE IN SUBMARINE CANYONS, CONSERVATION + MARINE POLICY

The Gully Marine Protected Area: reflections on 20 years of conservation efforts for Canada's largest submarine canyon

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The Gully submarine canyon is well-known for its habitat complexity and species diversity. For example, it is a nationally significant as a habitat for cold-water corals and rare cetaceans, such as the endangered population of northern bottlenose whales. Recently, the Gully celebrated its first decade as a Marine Protected Area (MPA) under Canada's Oceans Act. Since the initial conservation interest in the early 1990s to today, the management of this canyon ecosystem, and the supporting science activities, have evolved. Great strides have been made to understand the canyon ecosystem, to develop and report on ecosystem indicators, and to address key conservation priorities. This talk will introduce the audience to the Gully and its inhabitants, the history and evolution of management and science efforts, and present the key challenges and opportunities of management and research in an offshore setting in eastern Canada. These include ensuring enforcement and compliance with the MPA Regulations; managing research and tourism through an application and evaluation process; developing and implementing an ecosystem monitoring program; engaging the public in education and outreach efforts; and implementing and evaluating a variety of management activities. The talk will conclude with a look ahead to the next decade of canyon management and priorities for research and management.

Passive acoustic monitoring of cetaceans in the Gully Marine Protected Area and adjacent areas of the Scotian Slope

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The Gully Marine Protected Area (MPA) is a large submarine canyon located south of Nova Scotia, Canada. It was designated as a Canadian Oceans Act MPA in 2004 in part due to the abundance and diversity of cetaceans that occur in the canyon. The core region of the Gully has been identified as critical habitat of Endangered northern bottlenose whales. Other at-risk and rare species such as Sowerby's beaked whales and blue whales are also more frequently observed within the canyon than in other areas off eastern Canada. Investigating the occurrence of cetaceans in the Gully throughout the year has been identified as a research priority for the MPA. Traditionally, most information on whales in the Gully has been collected during summer months due to the difficulties of conducting field studies when weather conditions are more adverse. To fill in this important knowledge gap, two years of near-continuous acoustic data has been collected from the Gully and adjacent slope areas using bottom-mounted Autonomous Multichannel Acoustic Recorders (AMARs, © JASCO Applied Sciences). The hourly occurrence of specific species vocalizations throughout the year was investigated both within and outside the canyon. The results of this study indicate that many species occur in the Gully throughout the year, including a variety of baleen, beaked, and sperm whales, and delphinids, and some species are detected more often within the canyon. In addition, this long-term acoustic data set is being analyzed to establish baseline information on the year-round acoustic environment of the Gully MPA, including natural background ambient noise levels and anthropogenic noise sources, the latter constituting an important potential threat to cetaceans. This presentation will review some preliminary results of the long-term acoustic monitoring study and discuss implications for future research and monitoring efforts within the MPA.

Anthropogenic impacts on the megafauna of vulnerable marine ecosystems along the Gioia Canyon (Southern Tyrrhenian Sea)

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The Gioia Canyon is a submarine canyon of the Tyrrhenian Calabrian Margin (Central Mediterranean) presently characterized by active sediment transport processes. The canyon head indents the continental shelf up to very shallow depths of about 10 m and it is composed of two branches located just few hundred meters off the entrance of the Gioia Tauro harbor, one of the largest shipping terminals of the Mediterranean Sea. Furthermore, the canyon head is located close to the mouth of a gravel-bed stream known as fiumara, characterized by torrential discharges and high sediment yields.

The Gioia Canyon was selected as a pilot area in the framework of the National Project RITMARE, aiming at a comprehensive characterization of the physical and biological processes in deep sea environments, including the potential alterations of benthic habitats caused by anthropogenic activities. To assess the human impacts on the Gioia Canyon an extensive dataset was collected, including multibeam data, video surveys, sediment samples and oceanographic measurements. Vessel Monitoring Systems data were used to determine the spatial distribution of the fishing effort in the area, to constrain the effects of trawling disturbance on the benthic fauna.

Main results indicate the occurrence of sensitive habitats along the canyon margins, hosting the seapen Funiculina quadrangolaris and the octocoral Isidella elongata, species indicative of Vulnerable Marine Ecosystems. The General Fisheries Commission for the Mediterranean considers these two species relevant in terms of management priorities since they constitute essential habitats for certain crustacean species of commercial interest and are extremely vulnerable to the effects of commercial fisheries.

On the other hand, evidence of multiple anthropogenic activities along the canyon are also present, that may influence the integrity of the described benthic assemblages. Remote Operated Vehicle observations provide clear evidence of diffuse trawl marks over soft sedimentary bottoms and show remarkable quantity of litter within the thalweg area. Litter is mainly distributed at the canyon head, likely due to the very shallow setting and the proximity with the mouth of the Petrace fiumara and the Gioia Tauro harbor. Potential sites of sediment disposal from dredging operations in the harbor are also detected along the outer shelf and at the canyon margins.

Intense trawling activity may be the main factor responsible for the low abundances of megabenthic species observed locally, although the relationship between faunal abundance and intensity of fishing effort is not always univocal. Diffuse epibiosis and necrosis observed on Isidella elongata colonies also outside the trawled area suggest a critical state of health for these communities, arising concern regarding the conservation status of the benthic ecosystems of the canyon.

Litter peak concentrations in submarine canyons of the Northwestern Mediterranean Sea and the critical role of hydrodynamic processes in their dispersal

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In this contribution we report litter abundance, type and distribution in three large submarine canyons of the NW Mediterranean Sea, namely Cap de Creus, La Fonera and Blanes canyons based on direct seafloor observation with a Remotely Operated Vehicle (ROV). One common feature of the investigated canyons is that the three of them have their heads deeply INCISEd on the continental shelf, with their heads at short distance (<4 km) from the shoreline. The main aim of the work performed was determining the relationships between active hydrodynamic processes and litter distribution, thus going beyond previous, mostly descriptive studies on litter occurrence in the deep-sea.

Litter was monitored using the Liropus 2000 ROV at water depths ranging from 140 to 1731 m. Most litter consisted of plastic objects (72%), which were followed by lost fishing gear of different types (17%) and metal objects (8%). La Fonera and Cap de Creus canyons showed the highest mean concentrations of litter ever seen on the deep-sea floor, with 15,057 and 8090 items per km2, respectively. The largest concentrations (i.e. "litter hotspots") of litter were found on canyon floors at depths in excess of 1000 m. In contrast, litter objects were much less abundant on the canyon walls.

The analysis of litter objects in the studied canyons and their potential sources suggest a land source for the majority of the debris. The land-to-ocean transport of litter is assumed to involve wind transport, river discharge and direct dumping along the coastline, with coastal urban and industrial concentrations representing a permanent source of litter, in contrast with a seasonal component essentially driven by tourism and associated activities during summer months.

The finding of litter hotspots formed by mixtures of land-sourced litter items but also natural debris such as sea urchin carcasses requires efficient transport processes down to the deeper canyon reaches. Such hotspots may also involve marine-sourced litter (e.g. fishing gear) that enhance the trapping efficiency of further debris by such concentrations.

High-energy, down canyon near-bottom flows associated to seasonal dense shelf water cascading and severe coastal storms are known to occur in the investigated canyons where peak near-bottom current velocities in excess of 1 m s-1 have been measured in situ. Since these flows are seasonal, and occur with different intensities from one year to another, we hypothesize that the transfer of large amounts of light litter object to the deep reaches of the investigated canyons occurs episodically during relatively short periods of time (days to several weeks). In between "litter transfer events", debris tend to accumulate on the shallower continental shelf and canyon heads, which behave as temporary "debris accumulation zones" that discharge at the occasion of such high-energy events.

Conservation priorities of submarine canyons from analysis of a global seafloor geomorphic features map

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GRID-ARENDAL, NORWAY

A new global database of submarine canyon geomorphic metrics has been produced based on the analysis of the SRTM30_PLUS bathymetric grid1. "Large" canyons2 were mapped, including 2,076 shelf-incising and 7,401 blind canyons. Measurements were taken of canyon area, length, depth of incision and percentage area of steep-slope (escarpments), exceeding 5o (methods described in Harris et al., 2014). The 9,477 individual canyons cover a total area of 4,393,650 km2 (i.e. 1.2% of the total ocean area). This database allows estimates to be made of the area of canyons within each country's EEZ (the area of canyon habitat in each country) as well as the area of canyon that is currently protected within MPAs.

In order to estimate the area of canyons within national EEZs (that is, canyons that it is possible to protect within the jurisdiction of countries, as opposed to those located in areas beyond national jurisdiction, or the "high seas"), global EEZ boundaries were downloaded from the VLIZ database3 and used to calculate the areas of canyons within EEZ's. In addition, a summary of global MPA boundaries was downloaded from the IUCN and UNEP-WCMC database4 and used to calculate the areas of canyons within MPA's. It was found that, of the 4,037,764.35 km2 (91.9% of canyon area) of submarine canyon area in EEZs, about 5.0% is protected in MPAs (218,960 km2).

Canyon habitat that is most productive and contains the greatest biodiversity is undoubtedly the steepest (often rocky and cliff-like) section that commonly occurs towards the canyon head, in water depths of <1,000 m, found particularly in the case of shelf-incising canyons just below the shelf break. The steepest areas of seafloor, comprising a category termed "escarpments" (a seafloor gradient exceeding 5o over an area >100 km2), were also mapped by Harris et al. (2014) in their global assessment of seafloor geomorphic features. Overall it is found that 820,960 km2 of canyon area (i.e. about 18.7%) is escarpment. When we ask how much of that area is found inside existing MPAs we see that only 8,760 km2 of canyon area protected in MPA's is escarpment located above 1,000 m. That is to say, of the most potentially ecologically valuable area of canyons, only about 0.22% is protected within MPAs.

This analysis demonstrates that, on a global basis, the design of MPA's is biased against selection of canyon habitats most likely to be the most productive and biologically diverse. In fact, most MPA's that overlap with canyons (and presumably are intended to protect them) protect those parts of canyon habitats that are likely to be less productive and contain less biodiversity.

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Collecting evidence to inform management discussions within deep-sea canyon environments

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Submarine canyons are renowned for their importance to benthic biodiversity, promoting conservation efforts to secure their protection and management. However, policy makers require adequate evidence (for example physical and biological datasets) in order to underpin the protection and management of these submarine canyon environments.

In 2013 the Department for Environment, Food and Rural Affairs (Defra) designated The Canyons Marine Conservation Zone (MCZ) to protect a unique area of submarine canyons to the south-west of the UK. This MCZ is designated for its cold-water coral reef communities, amongst other features. These vulnerable cold-water coral communities need protection from potentially damaging human activities, but before management measures could be developed, further data collection was required.

Defra, in collaboration with other partners, undertook survey work in 2015 during a CODEMAP cruise. The aim was to improve our understanding of the habitats and species found within the Explorer and Dangeard canyon systems in The Canyons MCZ, and in particular the distribution, extent and condition of the cold-water coral reef communities. The Remotely Operated Vehicle (ROV) ISIS was deployed three times within Explorer Canyon, in the north of the MPA. The primary target was a known cold-water coral reef, first discovered in 2007 as part of the MESH project. Using ISIS ROV, the colony was mapped in high resolution for the first time, and covered an area approx 200m x 700m. This knowledge was used along with the MESH project bathymetry data and a predictive Lophelia pertusa reef model developed by the University of Plymouth, to aid the transect design for subsequent ISIS ROV deployments to search for coral reef in other areas of the canyon flanks.

The Autonomous Underwater Vehicle (AUV) Autosub 6000, was also deployed to collect side-scan sonar on a section of the interfluve between Explorer and Dangeard Canyon, allowing high resolution mapping of a field of mini-mounds, co-located over an area where Vessel Monitoring System (VMS) data suggests that fishing activity from multinational fleets occurs. In addition, the vessel mounted EM120 multibeam echosounder system collected imagery from the deeper canyon areas within the MCZ, which had previously not been surveyed in detail.

This successful collaboration between a number of organisations utilised novel technologies in a time efficient manner, producing a range of high quality datasets. This new evidence will be used to inform the development of fisheries management measures for The Canyons MCZ, and will form part of the wider evidence base presented by the UK Government during multinational fisheries management stakeholder events; these discussions will inform the need, location and degree of fisheries restrictions required to protect features within the MCZ.

Meeting the challenges and opportunities of ocean conservation

JAY RITCHLIN

DAVID SUZUKI FOUNDATION, CANADA

The David Suzuki Foundation is a charity that helps Canadians find solutions to living within the limits of nature. We focus on environmental rights, climate and energy solutions and protecting and restoring biodiversity. We have a long history of protecting oceans and working for healthy marine spaces to support communities and ecosystems. This presentation will discuss our work to reform destructive fishing practices such as trawling, fix systemic problems like the lack of recognition for the importance of habitat as essential to species recovery and advocate for innovative approaches to marine spatial planning and protection. Our work supports engaged community leaders, implementation of evidence-based scientific policies and practices and collaboration with First Nations to achieve environmental goals in their traditional territories.

Assessing anthropogenic impacts in the deep-sea: Marine litter along submarine canyons of the Central Mediterranean Sea

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POSTER

Determining the anthropogenic impacts on marine ecosystems is becoming a key scientific topic, specifically considering the increasing human pressures on these ecosystems and the valuable goods and services they provide. Among the many anthropogenic alterations of ecosystem, marine litter is of global concern, since it is present in all the world's oceans, including deep benthic habitats, where the extent of the problem is still largely unknown. Most studies on marine litter have investigated floating debris and coastal areas, whereas little is known about the types, quantities, or impacts litter may have on habitats beyond the continental shelf. A knowledge gap exists about the transfer mechanisms of litter to the deep sea, that could help to better understand their distribution and impacts.

In the framework of the National Project RITMARE, a study on marine litter in geologically active areas is recently started to reconstruct sedimentary and hydrodynamic processes responsible for its emplacement in deep-sea. Three areas (i.e. the Gioia and the Caulonia canyons in the Tyrrhenian and Ionian Calabrian margin respectively, and the Messina Strait) were selected because of the occurrence of submarine canyons deeply indenting narrow continental shelves, thus acting as preferential pathways for transport of sediment, and potentially litter, from the coast toward bathyal areas. It is also noteworthy that these canyons are directly connected with steep and narrow gravel-bed streams (locally named fiumare), characterized by long periods of inactivity, during which their beds are completely dry and are often used as abusive wastes area, alternated to episodic flash floods, where a large amount of debris is transported into the sea possibly evolving into hyperpicnal flows. Based on previous reports of marine litter recovered in these areas, new data have been collected in February 2016 using remote sensing, ROV video transects, sediment samples and oceanographic measurements. The aim of this presentation is to show the preliminary results obtained during the cruise as well as to present the ongoing activities related to the definition and monitoring of the impact of deep-sea marine litter in geologically-active areas.

SPECIAL SESSION 1: SEDIMENT TRANSPORT MONITORING IN SUBMARINE CANYONS

The challenge of monitoring sediment flows within submarine canyons: lessons learned in Monterey Canyon

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Submarine canyons are conduits in which sediment-laden gravity flows swiftly transport massive amounts of sediment from the shallow ocean to the deep sea. While these flows are among the most important processes by which sediments are carried across the Earth's surface and are credited for forming the canyons, very few direct measurements have ever been made of what actually happens within these flows during transport events. The lack of empirical data on sediment flows is a consequence of the difficulty in accessing canyon floors, the inability to predict when flows will happen, and the reality that energetic flows put monitoring equipment at risk.

Documenting and directly measuring the passage of sediment-laden flows through the axis of a submarine canyon is the goal of a currently ongoing multi-institution program, called the Coordinated Canyon Experiment (CCE). The CCE is coordinated by the Monterey Bay Aquarium Research Institute, with partners and partial support from the National Oceanographic Center and Hull University in the UK, the US Geological Survey, and Ocean University of China.

The vision for the CCE is to deploy multiple types of sensors in Monterey Canyon over two winter seasons, extending from October of 2015 to the spring of 2017. This includes an array of six traditional moorings carrying downward looking vertical current velocity profilers and near bottom sediment traps distributed along the axis of the canyon, down to 1,900 m water depth. These are augmented by a series of novel sensors. Among them is a Benthic Instrument Node (BIN) designed to capture the details of the passage of a turbidity flow. The BIN includes four vertical current-velocity profilers of different frequencies running continuously at maximum sampling rates and recording on a common time base, as well as salinity, temperature, and turbidity sensors. A McLane profiler is monitoring the current velocities and temperatures in the benthic boundary layer directly upstream of the BIN. An array of benthic event detectors, (smart boulders that record their own motion) were initially buried within the floor and are designed to record their transport down canyon within a flow. An array of three precision-triangulation beacons was deployed to assess seafloor creep within the sediment fill of the canyon floor. The data series from instruments deployed throughout the canyon will be coupled with repeated high resolution AUV mapping of the canyon floor allowing changes in the canyon floor morphology to be related to the sediment-flow characteristics, as documented in multiple platforms. The CCE is arguably the most comprehensive source-to-sink monitoring of submarine sediment-laden flows that has ever been attempted. While still early in the experiment, two events within the canyon floor have been already recorded. Progress in this on-going experiment and lessons learned to date will be presented.

Tidal versus hyperpycnal regimes in the dynamics and sedimentation in the Gaoping Submarine Canyon off SW Taiwan

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The Gaoping Submarine Canyon (GPSC) is a river-fed canyon, whose head is located 1 km off the mouth of the Gaoping River, a small mountainous river in SW Taiwan, and meanders SW and SE that eventually merges into the northern end of the Manila Trench over a course of 260 km. The sediment dynamics and sedimentation in the canyon are dominated by the episodic hyperpycnal process triggered by typhoon floods in the river; and earthquakes and by normal tidal oscillations. These processes also create sediment records in the substrate of the canyon.

Sediment trap mooring studies in the GPSC have shown that under normal tide-dominated conditions, the net sediment transport direction near the canyon floor is up-canyon. The deployments of T6KP and T7KP moorings for two months each provide valuable contrasts in the net sediment transport in the near-bottom part of the GPSC under normal and hyperpycnal conditions. During the deployment of T6KP between Jan. 8-March 8, 2008, the net sediment transport was up-canyon, superimposed by tidal oscillations, both of which followed the orientation of the canyon axis at the mooring site. This net transport pattern is mainly controlled by the tidal regime.

The T7KP mooring (July 18-Sept. 18, 2008) reveals a complicated net sediment transport pattern, which shows that the normal up-canyon directed tidal regime was interrupted by a typhoon-triggered down-canyon hyperpycnal regime (July 18-25); that was followed by a transitional period of recovery (July 25-Aug. 24); after which the normal up-canyon tidal regime resumed.

The steady tidal oscillations and episodic gravity-driven hyperpycnal and gravity flows leave two distinct types of sedimentary signatures in the seafloor deposits of the canyon conduit. Trends similar to those observed in the sediment trap moorings were also observed in piston cores taken at three locations along the GPSC. They were taken in the 1) proximal, upper reaches (OR1-811 K08P), 2) at the transition between the upper and middle reaches (OR1-820 35), and more distally, 3) at the transition between the middle and lower reaches (OR1-811 K31A) of the GPSC. They are used to illustrate gradual down-canyon changes in the seafloor lithology in response to the relative dominance of these two sediment transport processes.

The sedimentary lithology observed in these three cores shows that the grain size decreases down-canyon in both the fine-grained hemipelagic sediments and in the coarse-grained gravity flow deposits. This demonstrates the down-canyon decrease in the strength of the fluvial-fed sediment load and/or the episodic gravity-driven turbidity currents. Due to the reduced dilution effect by these gravity flow deposits farther away from the head of the canyon, the fine-grained hemipelagic mud becomes the dominant lithology in the more distal, down-canyon sediments which is comparable to the hemipelagic sediments of the basin that ultimately form the deposits on the abyssal plain and in the Manila Trench in the SCS (the ultimate sink for sediments).

How accurately can the structure of turbidity currents be reconstructed from their deposits?

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Most of our understanding of highly energetic sediment-laden flows (turbidity currents) in the oceans results from analysing the deposits that these flows leave behind in the sedimentary record. It is therefore important to understand how accurately the dynamics of turbidity currents can be reconstructed from their deposits. We used a Remotely Operated Vehicle to collect across canyon transects of push cores in Monterey Canyon, California at the same locations (and others) that the USGS collected flow data in 2002. We find strong correlation between the facies and grain sizes deposited on the canyon walls and measurements of the grain sizes and thickness of flows. Synthesis of deposit data and flow data reveals turbidity currents that experience three phases: 1) flows begin life in the upper canyon as thin, high-energy, high-sediment concentration surges that can transport 1000 kg moorings and deposit chaotic sands and gravels; 2) as flows evolve over both time and space they transform into more dilute sand-rich flows with an expanding head that deposits thin-bedded graded sands and silty mud on the canyon walls; 3) finally the flow expands along its length lofting silty mud that is deposited at high elevations (at least 70 m) on the canyon walls.

Canyon filling and flushing along the California Margin

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This study presents the results of a ten-year coring and mapping campaign that collected 110 precisely located cores from 21 submarine canyons along the northern California Margin, enabling a holistic analysis of the gamut of processes operating within submarine canyons. (I) Canyons with their heads on the shelf, or at the shelf break, contain fine-grained sediments of both hemipelagic origin and those deposited from relatively dilute turbidity currents. These are the types of turbidity currents that have been successfully monitored by anchoring moorings in submarine canyons. (II) Canyons, with their heads close to the shoreline, intersect littoral cells and contain chaotic deposits of sand, gravel and boulders in their axes, thus providing evidence of extremely high-energy, high-concentration flows. The only measurements yet made of these high-concentration axial flows are the displacement of heavy instruments e.g. 60 kg instrument frames and moorings with 1000 kg anchors. (III) Finally, one of the studied canyons contained a series of giant scours in its axis that were up to 790 m long, 670 m wide and 50 m deep that cut down to bedrock and were draped by a veneer of 20th century flow deposits. These scours are inferred to represent a flow of sufficient size and energy to rip pre-exiting deposits out of the canyon axis and flush them out onto the submarine fan. These flows have never been observed but are probably responsible for both carving submarine canyons and providing sediment to construct submarine fans.

Evolution of a recent channel-levee complex inferred from levee deposits on the Fraser Delta front, British Columbia, Canada

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The Fraser Delta hosts a population of over 500,000 including the municipalities of Richmond and Delta. The main arm of the Fraser River has been fixed in place by construction of a jetty focusing sediment deposition at the mouth of the main distributary channel. There is a history of submarine slide events at the delta crest which pose substantial risk to coastal infrastructure near the delta front. Natural Resources Canada has a project aimed at determining the causes and risks associated with these slides. A submarine channel-levee complex extends seaward from the main distributary channel.

Sediment cores from the levee deposits indicate that sedimentation is characterized by sandy mud, interpreted as continuous deposition by river plume suspension fall-out, and two distinct kinds of sand beds which represent two different processes. The first type of sand bed (facies 6) is interpreted as the deposit of channelized turbidity currents from slides involving large volumes of material at the upper reaches of the tributary channels. The second type of sand bed (facies 5) is interpreted as a deposit from river generated turbidity currents. Facies 6 beds are restricted to the channelized margin of the delta front and the upper delta in areas where gully formation is prevalent. Facies 5 beds are distributed across the active delta front and likely represent deposition from sheet-like flows. Ages of sand beds were resolved by establishing a sediment accumulation rate using excess 210Pb activity from mud intervals inferred to represent constant deposition from the Fraser River.

Facies 6 sand beds often occur in sets of 2 to 4 beds and individual bed sets correlate to known large slide events with a return interval of 10 to 15 years during the past 40 years. Deposits of smaller events, including Facies 5 beds, occur on average every four to five years. Event ages are compared to large spring floods from the Fraser River and seismic activity to determine any causal relationship. It is concluded that there are likely a combination of other factors which determine the volume of slope failure including cumulative over-steepening and increased pore pressure.

Levee sedimentation is linked to channel-levee construction and three phases of evolution, characterized by a general fining up, are identified. The first phase corresponds to the installation of the Steveston Jetty from 1912-1932 and the establishment of a new channel position. During this phase channel relief was low and overspill deposits were frequent resulting in very thick sand deposits on the levees. During the second phase of levee growth channel relief increased and overspill events were less common resulting in deposits that are not as thick. During the third and current stage, channel relief has increased to a point where channel overspill events are far less common resulting in levee deposits that are characterized by thick mud sequences with thinner, less frequent sand beds.

Sediment density flow activity in sediment-starved submarine canyons (Pointe-des-Monts, Eastern Canada)

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Submarine canyons are known to be main conduits for the transport of sediments to deep-sea basins. Sediment density flows occurring in submarine canyons are mostly triggered by river floods, small to large slope failures and advection of shelf sediment offshore. In these contexts, sediment supply is necessary to maintain canyon activity over time. In 2007, a high-resolution mapping of small-scale submarine canyons offshore Pointe-des-Monts (NW Gulf of St. Lawrence, Eastern Canada) revealed a series of incisions characterized by the presence of confined crescentic bedforms. The repeat mapping of the canyons in 2012 and 2015 revealed that the bedforms migrated upslope, indicating that they are cyclic steps produced by supercritical flows. Surprisingly, the comparison of multibeam surveys revealed the absence of slope failures that could have triggered the sediment density flows responsible for the migration of the bedforms. Additionally, the rocky shores and sediment-starved coastal shelf do not supply sediments to the canyons, thus excluding hyperpycnal flows or sediment density flows triggered by advection of shelf sediment. We thus suggest that hydrodynamic processes are responsible for suspending in-situ sediments, which then may flow as turbidity currents. ADCPs deployed for 3,5 months during the summer of 2015 revealed along-canyon currents following tidal cycles with speeds up to 0.4 m/s, which were not strong enough to produce bedform migration. Therefore, the currents responsible for bedforms occur during infrequent events or during winter conditions, both of which require longer instrument time-series to be observed. The retrieval of a 1 year long mooring ADCP during the summer of 2016 will hopefully allow us to gain insights on the triggers of turbidity currents in a sediment-starved shelf.

Submarine canyon-head morphologies and inferred sediment transport processes in the Alías-Almanzora canyon system (SW Mediterranean)

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Submarine canyons are morphological incisions into continental margins that act as major conduits of sediment from shallow- to deep-sea regions, involving different sediment transport processes and triggering mechanisms operating at various time-scales. Canyon head regions are key areas for understanding the shelf-to-canyon sedimentary dynamics and assessing the predominant hydrodynamic and sedimentary processes shaping their morphology. High-resolution multibeam bathymetries were conducted along the main thalwegs of the Alías-Almanzora submarine canyon system to recognize their specific morphological features. Various canyon head morphologies were observed at 80-90 m water depth, incising the outer shelf off the Almanzora River prodelta. A direct connection from the river is evidenced by the coalescence of cyclic steps on the prodelta deposits and their continuation towards the Almanzora canyon head. This suggests the occurrence of flood events causing hyperpycnal flows that progressed directly into the canyon. Processes linked to seepage and groundwater sapping also seems evident in this prodelta, which results in pockmark alignments and formation of elongated narrow canyon heads. At the southern limit of the prodeltaic deposits another type of canyon head results from the formation and merging of linear gullies. These have been interpreted as the morphological expression of the distal off-shelf transport of flood-related hyperycnal flows, potentially transformed into wave-supported sediment gravity flows. Most of the canyon heads of this canyon system, however, are found at much shallower water depths (10-20 m), some of them being disconnected from any major river source, but showing a continuation in land with intermittent creeks that experience flash flood events. They cut into the infralittoral prograding wedge, displaying feeder channels with oval depressions indicative of sediment littoral drift interception. Some tributaries show crescent shaped bedforms over the shelf and along their axis, which have been observed until a water depth of 80 m and interpreted as the result of storm-induced sediment gravity flows. An instrumented mooring was deployed from October 2014 to April 2015 to monitor the contemporary sediment transport processes through a canyon axis with bedforms. No flash floods or major storms occurred during the deployment period and the sedimentary dynamics was governed high-frequency current fluctuations along the canyon, which caused several minor down-canyon transport events.

Tracer and nutrient transport through upwelling submarine canyons

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The exchange of water and solutes between the coastal area and the open ocean is of great importance to biogeochemical fluxes, nutrient budgets and their response to climate change and human activities. On a regional scale, submarine canyons are known to enhance physical processes such as shelf-slope mass exchange and mixing. There is good understanding of the flow around upwelling submarine canyons; however, the flux of biologically relevant tracers such as oxygen and nitrate is less understood. Tracer and nutrient transports are usually inferred from water transports. Although this assumption is a reasonable approximation, it does not take into account the contribution of mixing to the distribution of tracers. The objective of this work is to characterize the combined effect that enhanced mixing within the canyon and the specific initial profile of a tracer have on the spatial and temporal distribution of the tracer during an upwelling event. For that purpose, numerical experiments simulating an upwelling event near an idealized canyon with locally enhanced vertical diffusivity were performed using realistic nutrient and tracer profiles from Barkley Canyon, BC taken during the Pathways Cruise 2013.

This work presents results from numerical experiments using the community model MITgcm when varying the initial concentration profiles for six different tracers; it also suggests a physical mechanism through which each final distribution is reached. We find that for all tracers, the depth of strong gradients is key to the exchange process, allowing more tracer transport when located deeper than the shelf break. Added to this, enhanced mixing within the canyon drives a higher diffusive transport, while the lower background diffusivity allows relatively unmixed ocean water onto the shelf, near the bottom. Thus, the regime that leads to the lowest, deep oxygen concentration on the shelf, is not the same as that which leads to the highest shelf nitrate inventory. Taken together, our work shows that the tracer pathways developed by the canyon dynamics, locally enhanced mixing and initial tracer profile have significant implications for the final tracer distribution on the shelf.

Sediment dynamics within Barkley Canyon: impact of dynamical processes on particles in suspension and their potential sources

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Many canyons incising continental slopes are disconnected with their sediment source, yet may remain sites of active dynamics due to potential transport pathways on the continental shelf and focusing of energy within the canyon. Thus, they remain conduits for particulates that contribute to deep-sea sedimentation. Canyons are logical settings to study impacts of many seabed environments within a temporally varying hydrodynamic regime, and have great potential for studying interactions between lithogenic, pelagic-organic, and benthic-organic particles. Active processes in Barkley Canyon located off Vancouver Island, Canada, along with strong physical forcing and regions of stable gas hydrates at the seafloor provide an ideal environment to investigate linkages between a range of benthic environments and aggregate/sediment dynamics.

Using nearbed current, turbidity, and chlorophyll data collected using sensors mounted on a remotely operated vehicle tethered to the Ocean Networks Canada observatory in the winter 2010-2011, we performed initial analyses to investigate sediment dynamics on a small plateau located at 870 m depth within the canyon. At this site during the winter season, persistent down-canyon (~230°) flows that oscillate on tidal frequencies lead to downcanyon net fluxes of particles, and are effective at all times over the winter period. The negative correlation between turbidity and current speed implies a settling signal for these particles in suspension, not resuspension from the bed, and suggests that particles are being held in suspension in the bottom boundary layer, which builds and collapses with current speed. The temporal change in turbidity response to tidal velocity throughout the winter further suggests that particles of variable density are in suspension. Potentially denser, faster settling particles associated with very low chlorophyll signals near the seabed are likely sourced from other locations within the canyon; and less dense, slower-settling particles associated with higher levels of chlorophyll may be sourced from outside the canyon. The rich data set that has been collected at this NEPTUNE observatory site provides novel and effective means of studying active sedimentary processes within canyon environments with limited sediment supply, a topic of interest in a variety of modern global environments.

Yearly epibenthic megafaunal community dynamics at a cold seep (Barkley Canyon) using a tracked sea crawler

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Canyons systems extreme topography may entrain diverse and variable current regimes. In some locations this lead distinct sub-habitats within, such as the cold seep provinces within the Canyon Pacific canyons which knowledge on the functioning is scarce. Cabled multiparametric platforms allows real-time monitoring of fauna and environmental processes through discrete seabed windows. By attaching a tracked Internet Operated Vehicle (IOV) to one of these platforms, the ecosystem variability can be investigated in real from anywhere in the world. In this study, we used a deep sea crawler attached to the Ocean Networks Canada (ONC) at a cold-seep site at 890m depth in the Barkley Canyon, NE Pacific; the first seasonal megafaunal study using this technology. Video transects were run with a 4-h frequency, over 15 months, with both video and environmental data collected in order to determine the modulator effect of oceanographic parameters on animal behavior (i.e. seasonal periodicities). We acquired a total of 890 (over 93 h of footage) video-transects and imaged 7698 individuals, from 7 phyla representing 23 taxa. The abundance of the various fauna were logged over time, with the 6 most abundant faunal groups (rockfish, sablefish, hagfish, buccinids, grooved Tanner crab, small crabs, ctenophores and true jellyfish) exhibiting significant seasonal abundance patterns. We found the species assemblage structure significantly linked to the sampling month, to water temperature, current velocity and dissolved oxygen. Video footage revealed the reproduction behavior of the grooved Tanner crab from February to March and the ecological function of the ctenophore Bolinopsis infundibulum in northern temperate deep sea waters peaking in November-December, followed by a dramatic reduction, presumably explained by predation from the true jellyfish Poralia rufescens. Such information is important for biodiversity conservation and the sustainable management of deep sea fisheries.

Characterization of factors controlling the macrofaunal communities dynamic and biodiversity of Barkley Canyon

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The Barkley canyon area, located along the active continental margin of the Northeast Pacific within the Pacific Oxygen Minimum Zone, provides ideal settings to study factors controlling biodiversity along diverse abiotic gradients. Part of the Ocean Networks Canada deep-sea cabled observatory, the study area encompasses a wide range of environments from the continental shelf (400m) to the continental slope (900m). Since 2010, instruments deployed on the seafloor give access to high frequency, continuous and concomitant environmental and biological data. Previous studies on Barkley canyon (BC) communities were able –on a short term, hourly sampling basis, to show that temporal structures coincided with the ambient current oscillation1. In order to detect temporal structures at larger scales and to increase our knowledge about benthic community dynamics in relation with environmental changes, one year of video (2012-2013) from the upper slope, the wall and axis of Barkley canyon were analyzed. Results revealed a clear distinction between shallow (400m) and deep (900 and 1000m) macrofaunal communities that could be related to environmental factors (i) varying along the depth gradient, such as temperature, or (ii) affected by the canyon's topography, such as bottom current. . The analysis of recruitment substrates (INDEEP project) also showed some distinctions between sites with a higher diversity on the upper slope. The decomposition of temporal structure at the three locations highlighted three significant times scales in the community variations. While the finest scale (14-30 days) was probably due to biotic interactions currents and changes in water mass significantly contributed to community variation at broader scale, especially on the almost seasonal cycle of 2.5 to 5 months. This seasonal pattern was supported by the occurrence of a seasonal variation in the grooved tanner crabs Chionoecetes tanneri population structure, with the recruitment of small individuals in the fall followed by growth and migration away from the camera, suggesting a seasonal reproduction for this species. Understanding variations in community dynamics at seasonal and inter-annual scales is essential to understand long-term changes in response to environmental forcing and anthropogenic pressure.

[1] Matabos, M. *et al.* High-frequency study of epibenthic megafaunal community dynamics in Barkley Canyon: A multi-disciplinary approach using the NEPTUNE Canada network. *J. Mar. Syst.* 130, 56-68 (2014).

Do Barkley Canyon trap overwintering populations of Neocalanus plumchrus (Copepoda, Calanidae) at depth? Insights into particulate organic carbon flux to deep-sea sediments based on video imagery from a seafloor cabled observatory

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It is well documented in the literature that submarine canyons may enhance local productivity by topographically constraining surface ocean currents and therefore triggering local upwelling, as well as by trapping populations of diel-vertically migrating zooplankton, which in turn act as trophic subsidies for larger top predators such as seabirds and marine mammals. Little is known however, about how submarine canyon water column productivity is exported down to deep-sea sediments considering the high-level of topographic heterogeneity found among different canyon systems, and the varying levels of connectivity between canyons and respective adjacent continental shelves. Here we report for the first time, to the best of our knowledge, video observations of dense deep scattering layers composed primarily of ontogenetic migrating copepods (Neocalanus spp.) from various seafloor cameras installed in a deep-sea cabled observatory, around 1000 m of depth in Barkley Canyon. We developed an automated video image analysis protocol for estimating copepod abundances at the benthic boundary layer, and tested the protocol robustness in reproducing the natural ontogenetic migration cycle of Neocalanus spp (most likely N. plumchrus). We discuss the use of our proposed video imaging technique as a complementary measure to traditional estimates of particulate organic carbon (POC) flux from sediment traps, which seldom capture the contribution from larger zooplankton. We analyzed videos from May 2013 to January 2015 (~575 days) from three high-definition cameras installed in Barkley Submarine Canyon, at its axis (890 m), at the northern canyon wall (890 m), and in a control area in the nearby slope (400 m). Videos were captured for 5 minutes at two-hour intervals. A total of 33,486 still images were extracted from 1,674 videos and used in a computer-automated image analysis protocol implemented in the software Image J. The protocol followed several steps, which included image transformation to 8-bit, sharpening, and thresholding, and finally a particle count analysis that fitted an ellipsoid function to any particle below a threshold of maximum diameter size fitting Eucalanus spp. size range distribution. Our results showed a seasonal distribution of copepod abundances at the benthic boundary layer in Barkley Canyon that tightly mirrored the ontogenetic cycle of Eucalanus spp. From spring to early summer, particle counts were lower as copepods are dominating the upper ocean mesozooplankton biomass, being part of the diets of juvenile salmon, myctophids, baleen whales, and seabirds. However, copepod abundances were statistically significantly higher during late summer through autumn, and winter, matching the descent of Neocalanus spp. populations of non-feeding fifth-stage (C5) copepodites to deep waters. Between autumn and early winter, abundances remained high, representing the molting and non-feeding adult stages, which then spawn at or near the overwintering depth, and remain at depth until they die. We believe our observations using seafloor cameras connected to a cabled observatory are capturing a major missing link in the carbon flux estimates from the upper ocean to the deep-sea in the NE Pacific. We plan to further improve our video analysis protocols to continue monitoring this carbon export flux throughout the life span of the observatory, building a multi-decadal data set.

High-frequency Patterns in the Abundance of Benthic Species near a Cold-seep – An Internet Operated Vehicle Application

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Three abundant benthic megafaunal species (i.e. sablefish Anoplopoma fimbria; pacific hagfish Eptatretus stoutii and a group of juvenile crabs) were tested for diel (i.e. 24 h based) behavioral patterns at the methane hydrate site of Barkley Canyon (890 m depth), off Vancouver Island (BC, Canada). Fluctuations of animal counts in linear video-transects conducted with the Internet Operated Deep-Sea Crawler "Wally" in June, July and December of 2013, were used as proxy of population activity rhythms. Count time series were analyzed together with environmental parameters under the hypothesis that the environmental conditioning of activity rhythms depends on the life habits of particular species (i.e. movement type and trophic level). Non-linear least squares modeling of biological time series revealed significant diel periods for the sablefish in summer months and for the hagfish and crabs in December. Combined cross-correlation and multiparametric methods (RDA) analyses revealed strong relationships among environmental fluctuations and observed megafauna. In particular, sablefish presence in the field of view during the summer months was related to flow magnitude, while the activity of the pacific hagfish and the juvenile crabs in December correlated with change in chemical parameters (i.e. chlorophyll and oxygen concentrations, respectively). Waveform analyses of animal counts and environmental variables confirmed the differences of phase during the 24 h cycle. The timing of detection of sablefish further supported a previously reported diel population displacement within the canyon. Their movement occurred under low flow conditions and against the current direction, a possible behavioral adaptation to the general hypoxic conditions. The proposed effect of chlorophyll concentrations on hagfish counts highlights the potential role of phytodetritus as an alternative food source for this opportunistic feeder. The juvenile crabs seemed to display a cryptic behavior in order to avoid predation, though this was suppressed at early night hours when oxygen levels were at a minimum. Our results highlight the potential advantages such mobile observation platforms offer in multiparametric deep-sea monitoring, in terms of both spatial and temporal resolution.

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