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DSRII Special Issue: towards a new and integrated approach to submarine canyon research

Veerle A.I. Huvenne[a] *& Jaime S. Davies*[b]
[a]National Oceanography Centre, Southampton. European Way, Southampton, SO14 3ZH UK
[b]Plymouth University, Drakes Circus, Plymouth, PL4 8AA, UK
Corresponding author : vaih@noc.ac.uk; 0044 (0)2380 59 6575

1. Background

Submarine canyons, steep-walled valleys that cut across virtually every continental margin around the world (Harris & Whiteway, 2011), are considered major sediment transport pathways between continental shelves and the deep sea (e.g. Shepard, 1963; Puig et al., 2014). Owing to their steep topography and high terrain heterogeneity, in addition to their unique current patterns and episodic down-canyon flushing events, which result in locally increased nutrient concentrations and food availability, submarine canyons are often considered as biodiversity hotspots (e.g. Tyler et al., 2009; De Leo et al., 2010). On the other hand, considerable differences have been observed between individual canyon systems, and between different faunal groups in terms of their response to the typical canyon environment (e.g. Cunha et al., 2011; Ingels et al., 2011; Schlacher et al., 2007). Unfortunately, in addition to transporting sediment, submarine canyons also tend to funnel our human litter and pollutants into the deep sea, extending the anthropogenic impact on the oceans far beyond our shores (e.g. de Jesus Mendes et al., 2011; Mordecai et al., 2011; Schlining et al., 2013).

Submarine canyons have been the subject of research for a long time. Shepard (1972) refers to a study from as early as the late nineteenth century, carried out by Milne (1897), which looked at the instability of canyon floor sediments as a possible cause for the repeated breaking of submarine cables that had been laid across a canyon. However, as a result of the steep terrain, locally enhanced currents and occasional down-canyon flushing events, the initial submarine canyon investigations were extremely challenging, and the number of studies was limited. Acoustic methods had to deal with excessive scatter and noise, in-situ instruments were regularly washed away and the coarse canyon thalwegs and rocky walls proved difficult to sample (e.g. Paull et al., 2003; Shepard, 1972. Direct observations were limited to shallow waters, within reach of divers or early submarines. With the increasing availability of new sampling and surveying technologies (deep-towed acoustic instruments, drop-down video systems, and eventually robotic vehicles), submarine canyon research increased dramatically (Fig. 1). Particularly the advent of

Remotely Operated Vehicles (ROVs) in many research institutes in the last ~10 years opened up a new perspective on submarine canyons, allowing a wider community of researchers to access parts of the deep ocean that had been hidden until then (Tyler et al., 2009).

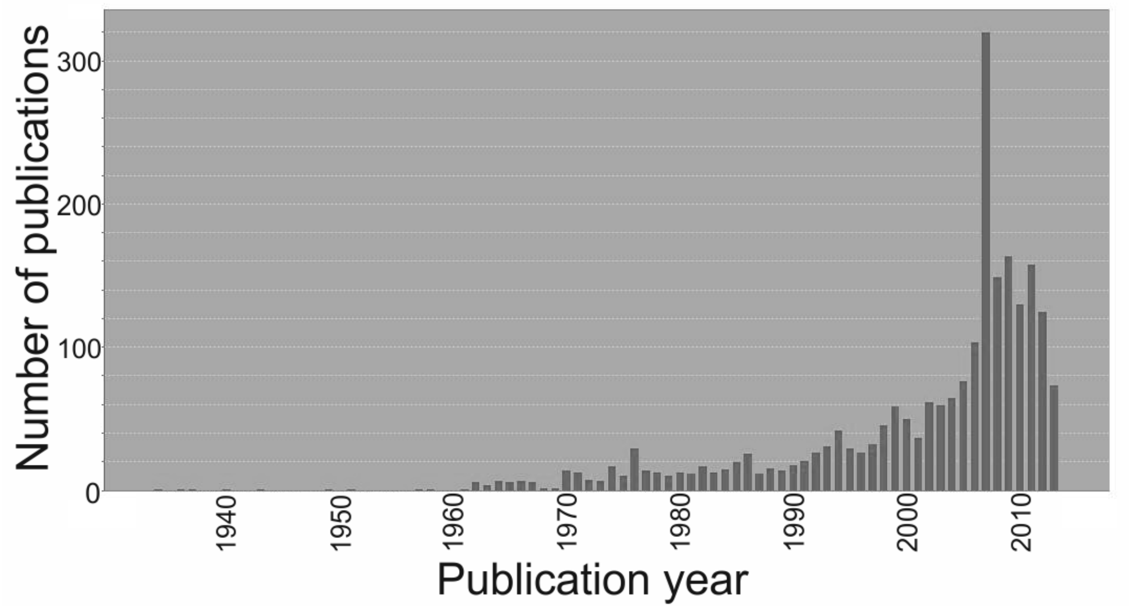

Fig. 1 Number of publication records in the Web of Knowledge database related to the search topic 'submarine canyon' as of 5 August 2013. Source: Thomson Reuters

As a result of this increased research effort, our understanding of submarine canyons is gradually growing. A number of individual canyon systems have received considerable attention (e.g. the Portuguese Canyons offshore Lisbon & Nazaré (Masson & Tyler, 2011 and references therein); Monterey Canyon (e.g. Hall & Carter, 2011; Paull et al., 2011; Robinson et al., 2010) or the Cap de Creus Canyon and the other canyons in the Gulf of Lions (e.g. Canals et al., 2006; Lastras et al., 2007; Orejas et al., 2009; Palanques et a.l, 2008)), but most canyons around the world have not yet been studied, or only to a very limited extend. Furthermore, many of the studies carried out so far are focussing on one aspect (geology, geomorphology, sediment dynamics, hydrography, current patterns, mega-, macro-, meiofauna distribution, biogeochemistry…) of a single canyon or canyon system. The time seems right to start putting all those pieces of the jigsaw together, and to start looking at canyons in a more holistic way. To this end, the first International Symposium on Submarine Canyons was organised in Brest, France in July 2012. Canyon research from all over the world was presented, followed by cross-disciplinary discussions and networking. A good proportion of those studies are presented here, in this Special Issue. In addition, the meeting resulted in the formation of INCISE: the International Network for submarine Canyon Investigation and Scientific Exchange (www.incisenet.org).

Further meetings and sessions at international conferences are planned, and an active forum has been set up, with the aim to stimulate cross-disciplinary discussions and research activities.

2. Integrated submarine canyon research

This Special Issue presents submarine canyon research from all over the world (Fig. 2). Particularly the large number of studies on the Sable Gully, off Nova Scotia, illustrates the type of integrated picture INCISE hopes to achieve for many individual canyons, and for submarine canyons as a whole. The Sable Gully was the first Canadian Marine Protected Area (MPA) to be designated in the Atlantic. The area is known to be an important cetacean habitat; especially northern bottlenose whales seem to have a great affinity for this canyon and similar canyons in the region (Moors-Murphy, 2013). Oceanographic/hydrographic observations by Greenan et al. (2013) illustrate the unique tidal environment of the canyon, which is dominated by unusual non-linear constituents that create overtides and compound tides. In addition, there is strong evidence for enhanced mixing and up-canyon flow within the canyon. The surface waters, however, do not seem to be very much affected by the presence of the canyon: they are mainly influenced by the regional NE-SW current pattern. To further enhance our understanding of the 3-dimensional circulation throughout the canyon, Shan et al. (2013) applied a multi-nested ocean circulation model, investigating the influence of shelf-scale circulation, tide-topography interaction and wind forcing on the circulation within and above the canyon. The authors found that wind, especially during storm events, is a significant factor affecting the circulation above the canyon, while especially the tide-topography interaction is a dominant factor within the Gully. This water mass structure and current pattern may well affect the pelagic fauna. For example, the crustacean micronekton and macrozooplankton are mainly structured by depth and diel cycle (MacIsaac et al., 2013). The upper waters (<750 m) are dominated by species typical of the mid- to higher latitudes in the N. Atlantic, which spend part of their daily cycle in the surface waters brought in by the overall NE-SW current. Inter-annual variability in species abundance is limited, however, despite substantial changes in oceanographic conditions during the 3 year study by MacIsaac et al. (2013). In contrast, Kenchington et al. (2013) looked at the epibenthic macrofauna living in the tidally dominated deeper parts of the canyon, beyond 1000 m depth. They found that those fauna mainly consist of filter-feeders, which probably reflects the influence of the tidal currents in the canyon. Furthermore, apart from depth, benthic communities are also structured by food availability (total organic carbon and labile carbon) at a spatial scale of 10s of km, while on shorter distances (10s of m) substratum seems to be an important factor determining species associations.

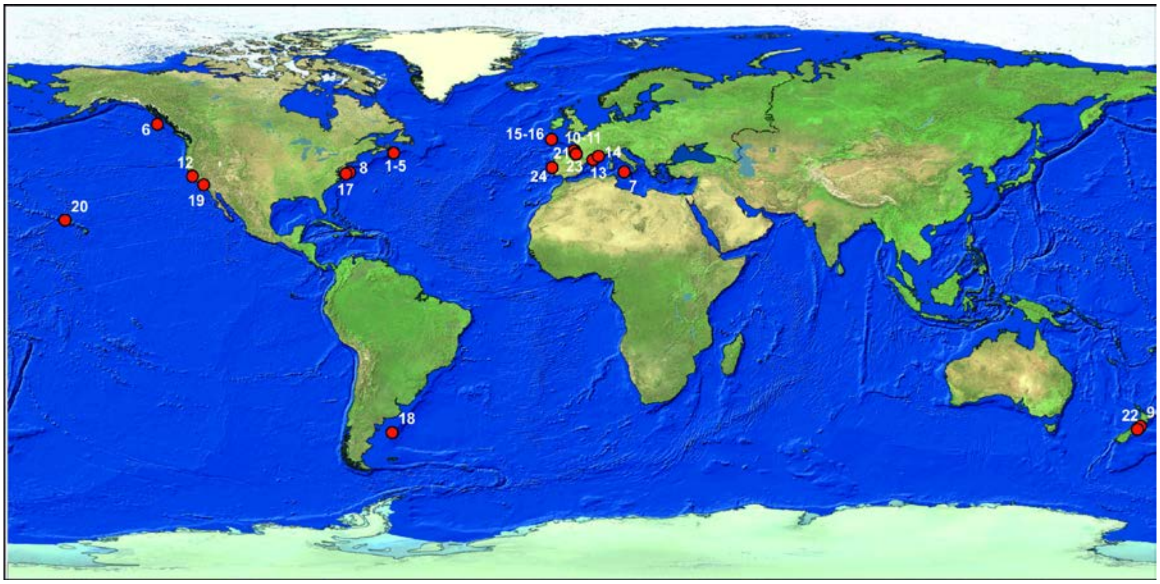

Fig. 2 Locations of submarine canyon studies published in this Special Issue. Labels refer to the order of the papers in this journal.

Of course, as indicated before: patterns emerging from a single canyon system may not necessarily be universal. Comparing canyons located on the active transform margin off Haida Gwaii, British Columbia, with the Sur Canyon system on the other well-known transform margin south of Monterey Bay, California, Harris et al. (2013) demonstrate that several factors are at play in the creation of canyon morphologies. Considerable variability has also been found between canyons as close as a few 10s to 100s of kilometres apart. For example, Lo Iacono et al. (2013) present two submarine canyons located offshore N Sicily. Although both are placed within the same tectonically active geological setting, the canyons have a very different morphology, and are governed by different sedimentary processes. Bottom-up, retrogressive slope failures have driven the formation of the Palermo Canyon, while top-down, erosive turbidity currents, linked to fluvial sedimentary input, have shaped the meandering Castellamare Canyon. Similar, although less extreme, differences were found by Obelcz et al. (2013) in the fine-scale morphology of four submarine canyons, spaced over 200 km along the US Mid-Atlantic passive margin, pointing to slightly different levels of canyon activity and sediment transport processes.

However, in terms of recent, short-term sediment transport in shelf-incising canyons, most observations seem to confirm the overall two-step mechanism already hinted by Shepard (1963), and recently reviewed by Puig et al. (2013). For example, tidally mobilised shelf sediments are intercepted by the Cook Strait Canyon heads offshore New Zealand, and accumulate in depocentres in the upper/central part of the canyon system. They are then remobilised in more catastrophic events and transported towards the lower canyon and deep ocean as a result of tectonic (earthquake) processes with a return period of ca. 100 years (Mountjoy et al., 2013). Similarly, the middle Cap-Ferret Canyon (Bay of Biscay, N Atlantic) acts as a depocentre for material that has been intercepted from outer shelf and upper slope transport by the canyon head and has bypassed the upper canyon. The lower canyon only receives sediment input in the form of gravity flows on timescales of decades or more (Duros et al., 2013; Schmidt et al., 2013).

On even shorted timescales, observations in countless submarine canyons (including the work by Greenan et al. (2013) and Shan et al. (2013) in the Gully) have shown that internal tides and waves are some of the most important factors in the daily (re)-suspension and flux of canyon sediments. Hall et al. (2013) now demonstrate that the nature of this internal tidal driving force can change from a standing to a progressive wave as the result of a change in watercolumn stratification. Using a numerical model of Monterey canyon, they show that an observed change in depth of the main pycnocline from 200 m (below the canyon rim) to 50 m (above the canyon rim) decreases the supercritical reflection of the up-canyon travelling internal tidal wave, allowing it to become dominant over the reflected down-canyon wave. This affects the energy flux through the canyon, and the spatial pattern of current amplification and sediment resuspension at the seabed. However, in addition to natural processes, there is increasing evidence that daily sediment resuspension and transport may also be caused by anthropogenic activities such as deep-water bottom trawling. Martin et al. (2013) present a stunning dataset illustrating the daily occurrence of increased water column turbidity and the associated sediment gravity flows in La Fonera Canyon (NW Mediterranean). The phenomenon occurs exclusively during the working days/hours of the bottom trawling fleet that fishes on the upper canyon flanks. The process is gradually reshaping the canyon morphology, but also influences faunal communities in the deeper reaches, by creating increased disturbance and sediment turbidity compared to the natural state.

Sediment resuspension is not the only type of anthropogenic impact reported in the submarine canyon studies of this Special Issue. Lost fishing gear is very common, as is litter (e.g. Fabri et al., 2013; Davies et al., 2013). Fabri et al. (2013) carried out a comprehensive study of 17 canyons along the French Mediterranean margin in order to evaluate the occurrence and status of Vulnerable Marine Ecosystems (VMEs) in the area. They found that sea pen grounds (Pennatulacea) and Alcyonacea grounds were fairly rare, and presented lower faunal densities than expected. This could be related to trawling pressure. Cold-water corals such as *Lophelia pertusa* and *Madrepora oculata* were not very common, and in addition to damage by lost fishing gear, were also affected by the discharge of bauxite mud in Cassidaigne Canyon. A similar benthic megafauna biotope study was carried out by Davies et al. (2013) in the upper part of a submarine canyon system along the Celtic Margin, NE Atlantic. They found 12 biotopes, of which

4 can be classified as VMEs. Especially *Kophobelemnon* (sea pen) grounds were specific for the canyons, but biotopes harbouring *L. pertusa* were present as well. In addition, Stewart et al. (2013) report the discovery of large numbers of small mounds in the same area (up to 4 m high and 150 m across, located at water depths of 250-400 m) covered with cold-water coral rubble. It is not clear if the coral died as a result of natural causes (change in environmental conditions over the last 1000s of years) or of deep-water trawling, which is very intensive in the area. Given the struggle of scleractinian corals to survive anthropogenic impacts in the European canyons, the discovery of *L. pertusa* in canyons on the US margin of the N Atlantic is a positive finding (Brooke & Ross, 2013).

Although studies like those by Davies et al. (2013) and Fabri et al. (2013) are invaluable for marine conservation, they only cover a small part of the world's oceans and submarine canyons. Nearly every biological survey of a (new) submarine canyon results in the discovery of new species (e.g. Kenchington et al., 2013; MacIsaac et al., 2013; Schejter et al., 2013). It will be clear that much more information is needed, including a deeper understanding of canyon biology and ecology, before policy-makers will be able to design the optimal submarine canyon management plans and conservation measures. Integrating the range of biological studies presented in this Special Issue (in addition to the wider submarine canyon literature), some patterns begin to emerge, although a lot of uncertainty still exists about the details. It is obvious that, as reported by Kenchington et al. (2013) and MacIsaac et al. (2013) for the Sable Gully, depth is the main structuring factor in the distribution of most canyon fauna/groups (Duffy et al., 2013; De Leo et al., 2013; Frutos & Sorbe, 2013). However, further driving factors remain difficult to ascertain. Duffy et al. (2013) could not find a statistically significant difference between the epibenthic megafauna communities of 5 canyons with different sediment transport regimes offshore California. However, the authors admit that the nature of their dataset (opportunistic ROV-based video rather than imagery transects conducted according to a rigorous sampling design) may play an important role in this result. This was not an issue in the work of De Leo et al. (2013), who sampled infaunal macrobenthos in 6 Hawaiian canyons, using a depth-stratified scheme. They found that habitat heterogeneity at medium and large spatial scales, in addition to Particulate Organic Carbon (POC) and distance from shore (both proxies for food input) seem to be good predictors of macrobenthic biodiversity. Food availability even seems to be the main structuring factor in Kaikoura Canyon, offshore New Zealand (Leduc et al., 2013). This canyon is characterised by unusually high food availability for benthic fauna, probably due to a combination of increased primary production and downwelling/topographically steered funnelling of surface-derived organic matter. The authors looked at free-living nemathodes in the canyon, and found an exceptionally high biomass, reduced diversity and specific nematode community structure. On a more local scale, disturbance has also been reported as an influencing factor in submarine canyons.

Although less than a kilometre apart, benthic foraminifera in samples from the Capbreton Canyon thalweg show a distinctively different assemblage than those on the lower canyon flank. They have a lower diversity and are dominated by pioneer species, illustrating that the community stays in an early stage of ecosystem colonisation as a result of the regular deposition of turbidite sequences (Bolliet et al., 2013). Taking an entirely different perspective, Guerreiro et al. (2013) present one of the first studies to characterise surface water coccolithophore assemblages in the context of an active submarine canyon and its associated physical oceanography. They find that the waters around Nazaré Canyon, offshore Portugal, are dominated in winter by two assemblages, distinguishing slightly more nutrient-rich coastal-neritic waters (influenced by surface water runoff) from the mixed oceanic waters advected onshore by the canyon. In addition, they report that the canyon head is often a location of high productivity between March & October, creating a coccolithophore diversity hotspot, mixing both the oligotrophic-oceanic and opportunistic coastal taxa. Such an increased productivity will have a strong influence on the benthic environment in the upper-middle Nazaré Canyon, where an extremely rich depocentre has been reported at ca. 3400 m water depth by several authors (e.g. Amaro et al. 2010; Cunha et al., 2011; Masson et al.. 2010).

3. Outlook

As demonstrated by the case studies of the Sable Gully (Greenan et al., 2013; Kenchington et al., 2013; MacIsaac et al., 2013; Moors-Murphy, 2013; Shan et al., 2013), in order to obtain a better understanding of submarine canyon systems as a whole, more integrated research efforts are needed, combining insights on canyon geology, sedimentology and oceanography with observations of biology and ecology. Also human activities and impacts should be included in the picture (Martin et al., 2013). Deriving universal patterns of canyon processes and characteristics will require such integrated research efforts to be repeated in several canyons, for several tectonic and environmental settings. To achieve comparable results, the submarine canyon research community will have to work towards comparable and compatible methodologies, including the set-up of (or continuation of) long-term monitoring programmes to assess the temporal aspects of canyon processes (Juniper et al., 2013; Martins et al., 2010). Understanding the scale (both spatial and temporal) at which canyon processes shape the canyon environment is key to understanding the biological and ecological patterns. Only when we understand the frequency, extent and biological response to natural disturbance events, will we be able to assess the real impact of anthropogenic disturbance in this unique environment. Obtaining an insight in the connectivity of submarine canyons will be necessary to devise viable networks of marine protected areas. The International Symposium on Submarine Canyons in Brest has set in motion a dynamic and ambitious community of researchers working towards these goals, aiming to increase the understanding of submarine canyons in a holistic way. We hope this Special Issue will be a first step, stimulating further cross-disciplinary discussions and investigations.

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