Section 4

Subchapter 5J

Continental slopes and submarine canyons

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Key points

- Continental slopes and submarine canyons are increasingly affected by direct anthropogenic impacts and by climate change.
- Fishing, waste dumping, litter and plastic pollution, oil and gas exploration and exploitation, placement of seafloor infrastructures, noise generation and tourism appear as the human activities with the most impact.
- Submarine canyons are highly valuable biodiversity hotspots, including corals, sponges and cetaceans.
- Little is known about the capability and time scales of continental slopes and submarine canyons to recover after disturbance, but they are generally much slower compared to shallow waters. The recovery of habitats affected by bottom trawling can take decades while key ecosystem engineers rebuild.
- Despite substantial advances in slope and canyon knowledge, conservation and management, many of the gaps identified in the second *World Ocean Assessment* remain.
- Most continental slope and submarine canyon habitats remain unexplored and mid- to long-term data is limited, making it difficult to assess changes over the past 5 to 10 years.

1. Introduction

The continental slope represents the seafloor province extending from the shelf edge (100–1,000 m depth or more) to the upper limit of the continental rise (1,000-4,000 m or more). Continental slopes vary in width, gradient and length, covering 19.6 million km^2, or 5.2% of the global ocean floor, and are often incised by submarine canyons (Anell, 2024), which are slope dissecting steep-walled valleys varying in shape, length and configuration. Canyons serve as drainage networks conveying sediments, organic matter and pollutants from shallow to deep (Canals and others, 2006; Zhong and Peng, 2021; Jones and others, 2022). Intense hydrodynamic processes may occur in canyons eventually involving different water masses. Over 10,000 submarine canyons are known, with more yet to be mapped in underexplored oceanic regions.

2. Developments in understanding of continental slopes and submarine canyons

Functioning

The continental slope is a depocenter where sedimentary and organic particles can accumulate and be buried due to a hydrodynamic regime weaker than that on the shelf (Bianchi and others, 2018; Ausín and others, 2021). Longshore hydrographic fronts and the balance between the horizontal pressure gradient and Coriolis force, create major water flows along isobaths. By promoting the slow, long-term sorting and redeposition of seafloor sediments, these currents create large deposits (contourite drifts) (Thran and others, 2018; Wilckens, 2023), that can trap substantial amounts of organic carbon (Yin and others, 2024).

Submarine canyons enhance the connectivity between coastal and deep realms (Maier and others, 2019) and accelerate the transfer of material from the shelf to deep waters, which promotes carbon sequestration (Baker and others, 2024). Canyon dynamics can encompass strong and deep tidal currents, local upwelling, bringing nutrients into the euphotic zone enhancing primary production (Saldías and others, 2021; Brun and others, 2023) and deep upwelling that can contribute to global diapycnal mixing (Wynne-Cattanach and others, 2024). Canyons also channel dense waters that cascade down continental slopes, enhancing cross-margin export of matter (Luneva and others, 2020; Durrieu de Madron and others, 2023). At high latitudes, shoreward cross-isobath flows may transport warm currents to the continental shelf, thus easing the melting of sea-terminating glaciers (Wynne-Cattanach and others, 2024; Donda and others, 2024). Marine heatwaves can reach upper continental slope and submarine canyon depths (Amaya and others, 2023).

Submarine canyons are also loci for the reflection and refraction of internal waves and tides that could exceed 100 m in amplitude, leading to increased energy focusing and dissipation, resuspension and mixing (Hall and others, 2017; McPhee-Shaw and others, 2021; Tian and others, 2024), thereby affecting resident benthic communities (Pearman and others, 2023).

Episodic gravitational processes, some of which could generate tsunamis, help shape continental slopes and canyons. Land-detached canyons can be as active (Heijnen and others, 2022) as those connected to the biggest river systems on Earth (Azpiroz-Zabala and others, 2017).

Effects of climate change

Canyon inhabitants are vulnerable to climate change given they often live near their tolerance limits of temperature, aragonite saturation, oxygen concentration and nutrient levels. By 2100, significant increases in temperature with decreases in pH, dissolved oxygen and particulate organic carbon (POC) in canyons and continental slope areas are projected under the high CO_2 emissions scenario RCP8.5 especially, with atmospheric CO_2 at approximately 940 parts per million and mean global temperature of approximately 3.7°C above pre-industrial levels (Levin, 2018, 2019; Bindoff and others, 2019). However, the heterogeneous, synergistic and compounding effects of climate change-related processes will be highly variable, spatially defined and species-dependent.

Anthropogenic CO_2 has already descended to canyon intermediate water depths (Trotter and others, 2019; Fontela and others, 2020). Climate velocity models have now identified the mesopelagic zone as highly susceptible to major shifts in biogeography (Brito-Morales and others, 2020). Since corals underpin deep-water reef ecosystems and local biodiversity hotspots, large reductions in coral habitat suitability predicted by 2100 (e.g. more than 79% in the north Atlantic) will have major ecological ramifications (Morato and others, 2020) (see sect. 4, subchap. 5E). In deep waters, ingress of CO_2 via overturning ocean circulation has caused shoaling of the carbonate compensation depth; canyons in the southwest Atlantic are deemed most vulnerable where substrates below the carbonate compensation depth have doubled since pre-industrial times (Harris and others, 2023b).

The Mediterranean Sea is at the forefront of climate change as it is warming faster than the global ocean. While invertebrate mass mortality events have occurred across the continental shelf, abrupt temperature increases and intensified oligotrophic conditions around canyons are now threatening deeper water communities (Bahamon and others, 2020). Globally, limited experimental and in-situ data show deep-water taxa are variably sensitive to warming at different life stages, thus reduced metabolic function, increased mortality and latitudinal or depth migration is expected under higher temperature conditions (Bindoff and others, 2019; Simões and others, 2021; Lang and others, 2023; Scanes and others, 2024). Together with Antarctic warming, sea-ice retreat will reduce nutrient-rich zones and biomass in canyons (FAO, 2018; Bindoff and others, 2019). Krill, a keystone species of marine food webs, have already responded by their poleward contraction (Atkinson and others, 2019; Kawaguchi and others, 2024); thus, canyons in lower latitudes may serve as future refuges for krill (Santora and others, 2018).

At oxygen minima zones (e.g. African margins), where colonial corals appear hypoxia-tolerant (Wienberg and others, 2023) (see sect. 4, subchap. 5E), greater sensitivities are expected in organisms living close to their metabolic thresholds. As these zones expand, the consequent impacts on mortality, reproduction and other physiological impairments, will restructure or potentially decimate canyon and slope ecosystems.

3. Value of continental slopes and submarine canyons as biodiversity hotspots

Continental slopes and submarine canyons can be biodiversity hotspots (De Leo and Puig, 2018; Ismail and others, 2018). Compared with continental slopes, canyons feature complex and dynamic environments with higher spatial heterogeneity and a wider range of habitats and communities.

Coral and sponge hotspots

Sediment-rich continental slopes host extensive soft coral communities, like bamboo corals, sea pens and sponge grounds that provide crucial habitats for invertebrates and fish (Santín and others, 2018; Compaire and others, 2021; Grinyó and others, 2021). Highly dynamic, nutrient-rich and morphologically complex canyons support hard corals and sponges and attract fish (Corbera and others, 2019; Saunders and others, 2021; Guy and Metaxas, 2022). Recent studies of the distribution of deep-sea habitats reveal new locations of cold-water corals (Bo and others, 2023; Trotter and others, 2019, 2022), soft-corals (Long and others, 2020) and biodiversity hotspots (Moccia and others, 2019, 2021; Gayá-Vilar and others, 2024), as well as changes in priority habitats (Moura and others, 2020; Nestorowicz and others, 2021). These discoveries show how depth, relief, local hydrodynamics and substratum collectively impact habitat distribution and emphasize the need for further exploration and extensive conservation (see sect. 4, subchap. 5E).

Recent discoveries of new deep-sea species (e.g. sponges, gastropods, octocorals and corals) including 111 unique taxa off the Western Antarctic Peninsula (Friedlander and others, 2020), highlight the need for ongoing taxonomic reviews (Addamo and others, 2024) (see sect. 4, subchap. 5E).

Cetacean hotspots

Submarine canyons, due to their complex topography and enhanced nutrient cycling provide productive conditions for marine mammals, whereas continental slopes serve are important feeding grounds and corridors for migratory cetaceans (Cannaby and others, 2023; Loutrage and others, 2023; Ransier and others, 2024). Temperature and productivity influence cetacean distribution (Granata and others, 2020; Salgado Kent and others, 2021) and their higher diversity in canyons (Hodge and others, 2022), highlighting their importance for cetacean conservation. The use of species distribution models (Feyrer and others, 2024) and environmental DNA (Boldrocchi and others, 2024; Jeunen and others, 2024) has improved habitat characterization for various cetacean species along continental slopes.

4. Natural resources and ecosystem services

Continental slopes and submarine canyons sustain many supporting, provisioning, regulating and cultural services that are crucial to human well-being. These include: (i) seafood (Fanelli and others, 2018; De Leo and Puig, 2018; Clavel-Henry and others, 2020); (ii) non-renewable resources, in particular oil and gas and possibly gas hydrates and deep-sea minerals in the future (Miller and others, 2018; Weaver and Billett, 2019; Zhang and others, 2019); (iii) bioactive compounds from prokaryotes (Wang and others, 2020), fungi (Ogaki and others, 2020; Varrella and others, 2021) and invertebrates, especially octocorals and demosponges (Zhang and others, 2024); (iv) space for offshore energy and communication infrastructure (Bosch and others, 2018; Danovaro and others, 2024); (v) carbon sequestration (Graves and others, 2022); (vi) nutrient cycling (Chen and others, 2022); (vii) biodiversity enhancement (De Leo and others, 2020; Ramirez-Llodra, 2020); and (viii) ecological refuges and habitats for spawning of commercial species (Ramirez-Llodra, 2020).

High-resolution data from continental slopes and canyons has identified new functions and services, some already threatened. Fisheries have moved to deep ocean environments, with documented impacts on single species and whole ecosystems (Oberle and others, 2018; Paradis and others, 2018, 2021; Taviani and others, 2023), even if new regional regulations limit their effects, such as the total closure of 87 sensitive zones between 400 and 800 m deep in the north-east Atlantic (European Union, 2022). Increasing anthropogenic impairment of the services provided by slopes and canyons, exacerbated by climate change, has prompted research on environmental management issues (Thiele, 2019; Baker and others, 2020; Amon and others, 2022).

5. Human activities and associated impacts

Loss of seafloor integrity and associated impacts

Continental slope and canyon floor integrity refers to the maintenance of the characteristic functioning of natural ecosystem processes and spatial connectedness, including the physical structure and biotic composition of the benthic community (Rice and others, 2010). Many human activities impact the seafloor and associated communities, causing disturbance or physical loss (ICES, 2019) and compromising the provision of ecosystem services. Loss involves sealed (e.g. pipelines, cables) or unsealed (e.g. bottom trawling) disappearance of the natural seafloor, which can occur over different time intervals (Buhl-Mortensen and Buhl-Mortensen, 2018). Other harmful activities include mining of hydrothermal sulphide fields, crusts and phosphates on continental slope settings (Curric, 2016; Carver, 2019; Galley and others, 2020; Jones and others, 2020; van Putten and others, 2023). The International Seabed Authority (ISA) has discussed on the draft regulations on exploitation of mineral resources in the Area —which might include continental slope settings beyond the limits of national jurisdiction — in order to ensure effective protection for the marine environment from harmful effects which may arise from such activities.

Fishing

Bottom trawling is the most significant human activity on continental margins and in canyons (Tiano and others, 2024). It disrupts benthic habitats by destroying them and resuspending and overturning sediments, with impacts far surpassing natural processes like currents, especially at greater depths (Puig and others, 2012; Schönke and others, 2022). Effects extend beyond fishing grounds, as resuspended particles spread impacts across large areas, including canyon axes (Pusceddu and others, 2014; Daly and others, 2018; Bradshaw and others, 2021).

Waste dumping

Deep submarine canyons and adjacent continental slopes used for domestic and industrial waste disposal are "out of sight, out of mind" (Vare and others, 2018; Vogt and Skei, 2018; Pierdomenico and others, 2020). Canyons near populated and industrial areas especially can become conduits for land-sourced waste (Fabri and others, 2017; Bouchoucha and others, 2019). Industrial waste can spread well beyond the initial discharge site (Fontanier and others, 2020).

Oil and gas exploration and exploitation

The oil and gas industry has continued its expansion into continental slopes (Zhang and others, 2019; Wen and others, 2023). Incidents with oil spills from drilling rigs and seabed pipelines (e.g. the Deepwater Horizon disaster) continue to pose severe environmental threats (Girard and Fisher, 2018; Kujawinski and others, 2020; Cavcic, 2023). Sediment resuspension, burial from anchoring and pipeline installation and discharges of drilling muds and produced water typically affect areas within 100 to 2,000 m (Cordes and others, 2016). Hard structures, like pipelines, can become growing substrata for organisms, which should be considered during decommissioning (Rouse and others, 2019; McLean and others, 2022).

Submarine cables

The submarine communication cable industry is growing, driven by increasing demand for content and data transmission, carrying over 95% of worldwide communications. Most new installations focus on mid and low latitudes,[1] often connecting data centre hubs rather than traditional population centres (Submarine Telecoms Forum, 2024). Power cables are mostly installed in shallow waters, with some deep-water examples mostly in the Mediterranean Sea (Ardelean and Minnebo, 2015);[2]. Power cables often incorporate fibre optics for communication purposes. Cable routes in deep-water are chosen to minimize environmental impact and avoid geohazard-prone areas (e.g. landslides and canyons) (Clare and others, 2023)[3] Disused cables are increasingly recovered for recycling (see second *World Ocean Assessment*).

Noise

Human-driven underwater noise pollution modifies marine soundscapes (Bayrakci and Klingelhoefer, 2024), impacting marine organisms across various trophic levels (Duarte and others, 2021). Shipping, geophysical surveys, drilling and military sonars are major sources of this pollution. While monitoring

[1] See https://subtelforum.com/submarine-cable-map/.
[2] See https://cyprus-mail.com/2022/10/14/euroasia-interconnector-ready-for-construction-historic-day-president-says/.
[3] https://www.internetsociety.org/resources/doc/2024/2024-west-africa-submarine-cable-outage-report/).

efforts are increasing, in particular for impulsive noise sources like seismic surveys (Merchant and others, 2020), data on continuous noise from shipping are limited (Jalkanen and others, 2022).

Litter and plastic pollution

Seafloor litter accumulates in submarine canyons, being greatest near populated coastlines and tourism hotspots (Canals and others, 2021; Hernandez and others, 2022; Pierdomenico and others, 2023). These include mainly single-use plastics, microplastics and lost fishing gear, which are transported by canyon hydrodynamics (Galgani and others, 2022; Harris and others, 2023a). Plastic degrades into micro and nanoplastics, threatening marine life and ecosystems, with accumulations in deep-sea sediments and biota showing alarming increases (Fossi and others, 2018; Kane and others, 2024). The persistence timescales of litter depend on composition, with those of plastics unknown but likely longest in deep-sea environments (Ward and Reddy, 2020), posing serious concerns for canyon ecosystems (Pierdomenico and others, 2019).

Tourism

Dolphin and whale-watching along the continental margins is a booming industry that supports local economies, but it can also negatively impact marine mammals. Other wildlife species can also be affected by boat-based and in-water tourist activities (Convention on the Conservation of Migratory Species of Wild Animals (CMS) Secretariat, 2025). Boat presence, noise pollution and close encounters can disrupt the behaviour of cetaceans and other species, causing stress, altering feeding and socializing patterns, and even leading to habitat abandonment (Schuler and others, 2019; Sprogis and others, 2020). However, efforts are underway to promote more sustainable and ecologically respectful tourism practices (Amerson and Parsons, 2018; Suárez-Rojas and others, 2023) (see subsect. 5A, chap. 4). It is of the utmost importance to ensure that wildlife interactions driven by tourism are conducted sustainably (CMS Secretariat, 2025).

Recovery from disturbance

While evidence of anthropogenic impacts on continental slopes and submarine canyons is growing, little is known about the recovery of these habitats. Studying deep waters is challenging and repeat surveys at impacted sites are scarce. Habitat recovery affected by bottom trawling, for example, can take decades while key ecosystem engineers like cold-water corals and sponges (CWCS) rebuild (Huvenne and others, 2016; Clark and others, 2022; Goode and others, 2024) (see sect. 4, subchap. 5E). However, once impacts are removed and conditions are favourable, recolonisation by species can occur (Strong and others, 2023).

Submarine canyons, naturally prone to disturbances (e.g. slope failures and sediment flows), offer insights into natural recovery processes. The meiofauna of the Kaikoura Canyon nearly completely recovered within four years after the 2016 M_w 7.8 earthquake, nematode communities still differed from pre-earthquake conditions and complete megafauna recovery is projected to take between 4.5 and 12 years (Bigham and others, 2023, 2024).

6. Future trends and need for conservation

Most continental slope and submarine canyon habitats remain unexplored and mid- to long-term data are limited, making it difficult to assess changes over the past 5 to 10 years. Natural disturbances and those derived from human activities can have immediate and widespread effects, but recovery and shifts in these deep-sea ecosystems are generally much slower compared to shallow waters (Da Ros and others, 2019).

Evidence of climate change-induced shifts in marine species is emerging. Tropicalization of demersal megafauna along the Brazilian Meridional Margin has occurred since 2013 (Alvarez Perez and Sant'Ana, 2022). European Seas (e.g. the Mediterranean, Black and Baltic seas), have been warming since the 1980s, leading to tropicalization and deborealization (Chust and others, 2024) and the expansion of non-indigenous species (NIS) (Galil and others, 2018, 2021). Sea pens and shrimps are expected to shift to higher latitudes, while most cold-water corals will move to lower latitudes in the Atlantic (Morato and others, 2023) (see sect. 4, subchap. 5E).

Improved waste management and recycling could reduce the amount of waste reaching coastal areas and nearby canyon heads (Willis and others, 2022; Bruemmer and others, 2023). Greater enforcement of and amendments to international agreements aim to curb marine pollution.[4]

However, debate continues over the disposal of hazardous waste like radioactive materials (Buser and others, 2020; Dabrowska and others, 2021). Conservation efforts have advanced with many continental slopes and canyons now within exclusive economic zones (EEZs) and cross-boundary agreements aiming to extend conservation efforts into international waters (Fernandez-Arcaya and others, 2017).

Despite substantial advances in slope and canyon knowledge, conservation and management, many of the gaps identified in the second *World Ocean Assessment* remain. With new technologies, coordinated funding initiatives and new regulatory frameworks, major progress is anticipated to better understand canyon processes (Demopoulos and others, 2024; Wynne-Cattanach and others, 2024), quantify ecosystem functioning and services and better predict ecosystem adaptations under climate change (Sweetman and others, 2017). Marine litter and pollution research is shifting from identifications and inventories to investigations into ecotoxicological and species behavioural effects (Bruemmer and others, 2023). The expansion and increased accessibility of new technologies (e.g. automated underwater vehicles, remotely operated vehicles) and artificial intelligence-based data analysis, together with increased time series observations (Chauvet and others, 2018), will further support evidence-based management of continental margins.

7. Knowledge and capacity-building gaps

The major imbalance in data availability and access to key observational equipment and research capacity still hampers the progress to fully understand the world's continental slopes and submarine canyons. Research efforts remain focused on only a limited number of study sites, mostly within the EEZs of developed nations. The 10 most prominent institutions in submarine canyon research are based in the United States of America, Spain, France, the Kingdom of the Netherlands and the United Kingdom of Great Britain and Northern Ireland. The most studied canyons are all along the continental margins of North America (six canyons), southern Europe (four canyons) and Taiwan Province of China (one canyon) (Matos and others, 2018). Specialized vocational and university training is closely connected to marine research, industrial development and management capabilities. While there are diverse strategies and initiatives to address these imbalances (e.g. greater access to the best universities, research centres and modern infrastructure), challenges remain (Barnhill and others, 2023; Howell and others, 2020; Roberts and others, 2023).

[4] See https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx; https://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Pages/LDC-LC-LP.aspx.

Ocean literacy campaigns are also important for societies to understand the benefits of, and provide support to, deep-sea research, which is especially critical given the general lack of interest in protecting the deep sea (Carlesi and others, 2023), despite scientists increasingly advocating its importance (Niner and others, 2018; Da Ros and others, 2019; Fanelli and others, 2021).

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