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WHITE PAPER

Powering the Deep

The Science and Strategy Behind Transoceanic Interconnectors

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1. Introduction

Faced with the uncertainties across the global geopolitical arena, nations are focussing on their energy security and futureproofing energy supply. With this in mind, and the push for decreased reliance on fossil fuels, subsea cross-border interconnectors act as vital arteries for distributing renewable energy. These interconnectors will rival telecommunication cables in terms of length and engineering ingenuity.

From Table 1 it is clear that Europe leads the field for electrical interconnector cables. This is not entirely surprising given that Europe is amongst the leaders in the offshore wind industry and has strong grid synchronisation policies.

The longest interconnector in the world at present is the Viking Link between the UK and Denmark, at 765km long. The project faced several seafloor challenges across this long stretch of the southern North Sea during its construction. The seabed preparation, burial, and protection works involved a 3-yr campaign and required the handling of variable seabed conditions, including glacial till, high-strength clay, and soft sand. Apart from the challenge of the glacial sediments, however, one could consider the North Sea seabed relatively homogeneous to deal with (Senior et al., 2017). Water depths do not vary dramatically and there are limited geological hazards such as faults, seismicity, volcanism or gravity driven landslide processes. In addition, the North Sea has been the focus of exploration for decades, the stratigraphy is well known and documented.

Plans for much longer interconnectors, across oceans connecting continents are being discussed and tested for feasibility (Table 1). These ambitious plans for cross-oceanic, continental scale interconnectors spanning thousands of kilometres will face more complex seabed conditions. Those challenges have already been faced and mitigated by telecommunication cables so there is a lot of knowledge that can be adopted from decades of telecommunications cables planning, laying and operating (Figure 1).

Longer routes can introduce new challenges, including more variable seabed conditions and a wider range of geohazards. Ternan Energy is an independent marine geoscience and engineering consultancy with a team of highly experienced scientists and engineers specialising in de-risking marine projects. The author holds a PhD in marine geohazards and has more than 20 years' experience conducting and being part of marine expeditions and geohazards research in the world's oceans. Ternan's team has been entrusted with numerous route engineering designs, cable burial risk assessments, and burial assessment studies as well as the design and oversight of site investigations for inter-array, export and interconnector cables. Ternan also regularly conducts data adequacy and data gap analyses and acts as Expert Witness in high value disputes.

Table 1: Operational, under construction and planned interconnectors

INTERCONNECTOR	COUNTRIES CONNECTED	LENGTH (KM)	CAPACITY (MW)	YEAR COMMISSIONED
OPERATIONAL				
Skagerrak 1-4**	Norway and Denmark	240	700 (total)	1977-2014
Spain-Morocco HVDC	Spain and Morocco	59	1400	1997/2006
SACOI**	Italy, Sardinia and Corsica	385	300	1968
IFA	Great Britain and France	73	2000	1986
Baltic Cable	Sweden and Germany	260	600	1994
SwePol Link	Sweden and Poland	254	600	2000
Moyle	Northern Ireland and Scotland	63.5	500	2001
GRITA	Italy and Greece	300	500	2001
NorNed	Norway and Netherlands	580	700	2007
BritNed	Great Britain and Netherlands	260	1000	2011
East-West	Ireland and Great Britain	262	500	2012
SAPEI	Italy and Sardinia	435	1000	2012
Estlink 2	Estonia and Finland	105	350	2014
COBRAcable	Netherlands and Denmark	325	700	2016
Nemo Link	Great Britain and Belgium	140	1000	2019
North Sea Link	Great Britain and Norway	720	1400	2021
NordLink	Norway and Germany	623	1400	2021
IFA2	Great Britain and France	204	1000	2021
ElecLink*	Great Britain and France	51	1000	2022
Viking Link	Great Britain and Denmark	765	1425	2023
Greenlink	Great Britain and Ireland	190	500	2025
UNDER CONSTRUCTION				
Celtic Interconnector	Ireland and France	575	700	2028
Biscay Gulf	France and Spain	400	2000	2028
NeuConnect	Great Britain and Germany	725	1400	2028
EuroAfrica	Cyprus and Egypt	1396	1000	2029
Great Sea Interconnector	Greece, Cyprus and Israel	1208	2000	2030
Green Energy (GREGY)	Greece and Egypt	950	3000	2031
PLANNED/CONCEPTUAL				
LionLink	Great Britain and Netherlands	–	2000	2030-2032
AQUIND	Great Britain and France	–	2000	2030
FAB Link	Great Britain and France	220	1250	2030-2031
IceLink	Iceland to Great Britain	1200	1200	?
Xlinks	Great Britain and Morocco	4000	3600	Abandoned
AAPowerLink	Australia and Singapore	4300	3000	?
Baltic-German PowerLink	Lithuania, Latvia and Germany	600	2000	2037
NATO-L	Canada and Europe	>4000	3 x 2000	2040

Table excludes within-country interconnectors
*Through Channel Tunnel
**A mix of overhead and submarine cable

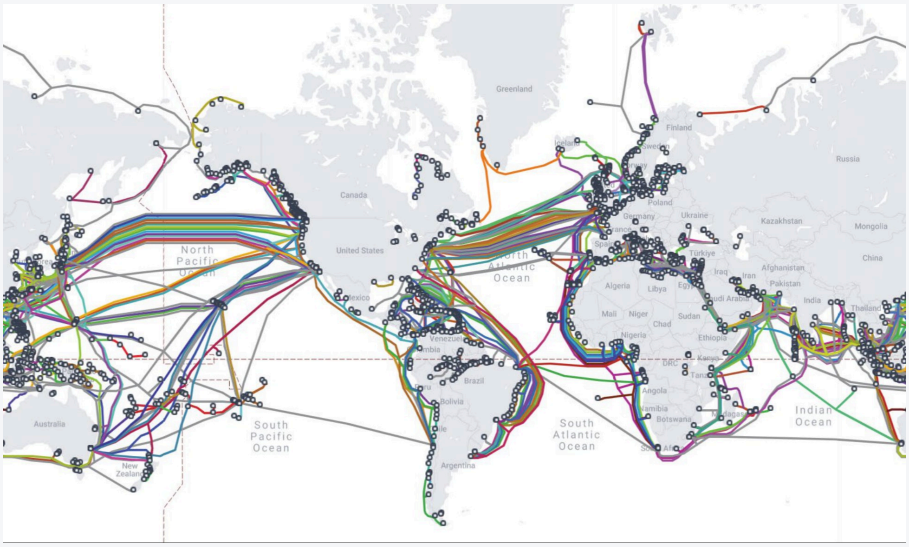

Figure 1 Global distribution of telecommunication cables (from TeleGeography)

Our independence ensures that our advice remains objective, practical and useful. This White Paper examines the most significant geological challenges facing transoceanic cable projects and discusses mitigation strategies, informed by decades of experience from the telecommunications industry. The list of challenges presented is not exhaustive and is certainly not prescriptive, but knowing what to anticipate helps inform survey design and appropriate specifications. For any cable route, a dedicated route-specific assessment is a necessary next step to identify the relevant seabed challenges and for mitigation strategies to be put in place (Figure 2).

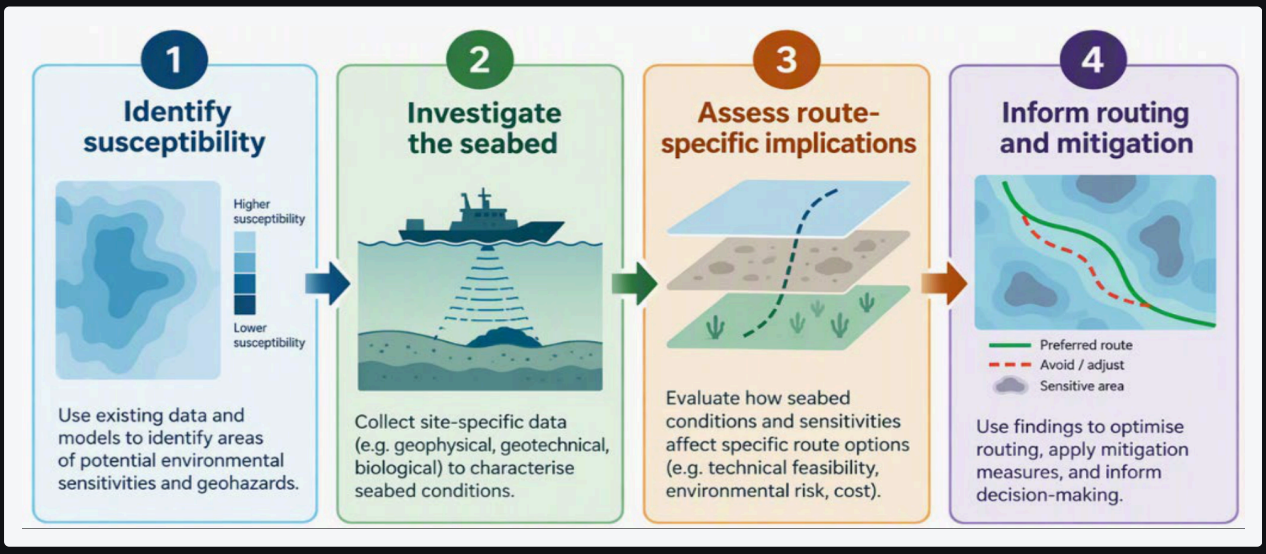

Figure 2 Workflow towards mitigation

2. Continental Shelf

Continental shelves represent the transitional zone between the coastal and infralittoral areas and the shelf break, an area characterised by a marked change in slope that signals the abrupt deepening of the ocean basin across the continental slope. Globally the shelf break varies in water depth from 20m in tropical continental shelves to 550m in polar regions. The global average is 140m water depth. Continental shelf width is typically 30-60km but can vary significantly. Slope gradients are on average very low, less than 0.5°.

The present-day geomorphology of most continental shelves results from combinations of relict and modern features. This is an area that is very sensitive to sea level cyclicity and the morphology and substrate reflect that. During the Quaternary, sea-level cycles were characterised by slow, stepped sea-level falls and abrupt sea-level rises with short-lived lowstands and highstands (Siddall et al., 2007). As a result, most continental shelves were subaerially exposed multiple times during sea level lowstands and then flooded rapidly when sea levels rose.

Continental shelves are most commonly classified by the climate zone in which they are. There are high latitude continental shelves, influenced by glacial processes, mid-latitude shelves, influenced mostly by sea-level changes, and tropical shelves, influenced by carbonate sediment production (Figure 3).

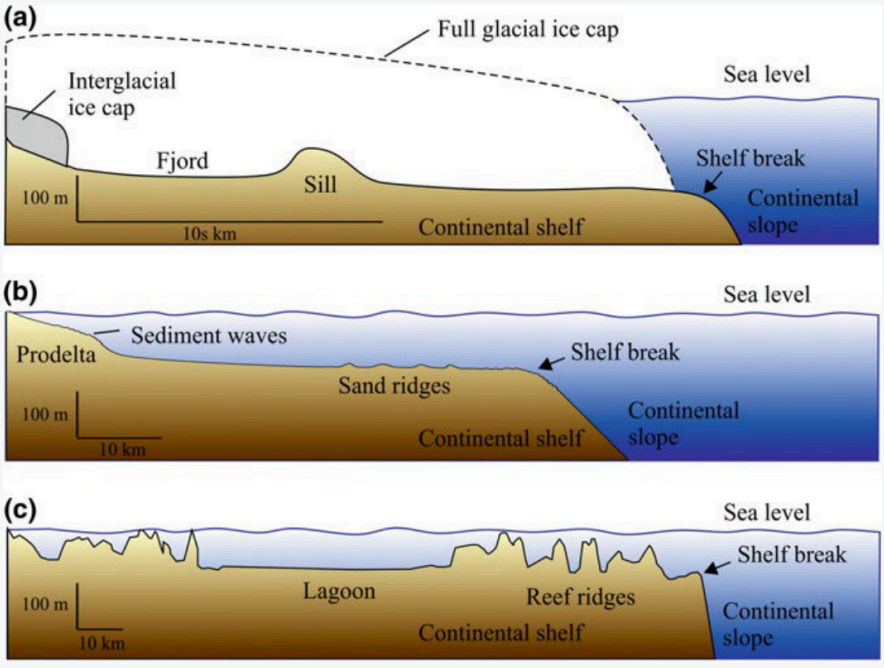

Figure 3 Schematic representation of the three shelf types based on climatic classification. (a) Glacial shelf, (b) mid-latitude shelf, (c) tropical (carbonate) shelf. (From Durán and Guillén, 2018).

Continental shelves in high latitudes have experienced entirely different processes as they were often occupied by thick marine based ice sheets (Figure 3). The present-day equivalent would be the West Antarctic ice sheet and the impact it has on the continental shelf underneath it. The best examples of continental shelves that have inherited morphologies and lithologies associated with the former presence of ice are the North Sea, the Baltic Sea, offshore Atlantic Canada and Greenland. Relic morphologies such as moraines, eskers, drumlins and filled or partially filled glacial valleys are common. Hard substrates generated by the presence of till and particularly high-strength clay are often encountered, and boulders of various sizes, from 0.3m to several metres in diameter are a common constraint for any offshore infrastructure project and specifically cable installation.

Mid-latitude continental shelves that have been subaerially exposed several times throughout their geological history host highly complex geologies. Shoreline and associated landforms (e.g., barrier islands, spits, beachrocks, sand ridges, sand dunes, etc.) migrating across the shelf, fluvial channels and sediment dispersal shifting patterns contribute to generating highly variable seabed and sub-seabed ground conditions. With changing sea levels tidal and wave patterns also shift, not only positioning on the shelf but also dynamics and sediment depocentres. The across- and along-shelf sediment fluxes caused by the interplay of hydrodynamic processes determine the sediment distribution, the development and/or evolution of bedforms and the presence of sedimentary structures on the seafloor.

Tropical or carbonate continental shelves grade very gently from the shoreline or lagoon to the shelf break (commonly less than 0.1°). Shelf sediment is predominantly characterised by biogenic material with minimal contributions from terrigenous sediment. Carbonate continental shelves commonly include features such as spurs, terraces, reef ridges, platforms, shoals and lagoons.

2.1 Common continental shelf constraints

Common constraints across continental shelves are rocky outcrops (exposed bedrock or ridges) and hydrodynamic conditions, the impact of which depends on the water depth and the tidal regime at each different geographic location.

Exposed bedrock is usually found where there is low sediment supply and/or where erosional processes, i.e., local currents, prevent sediment from settling. Erosional processes can also create other morphologies, including channels, scours, and large-scale lineations and furrows. On the other hand, currents can generate depositional bedforms with long histories of progradation. These include deltas (small or large, depending on amount and history of sediment supply), shore parallel swales and ridges, and large fields of sediment waves and dunes. It is important to consider these bedforms as transient as they are often mobile. The rate of migration is important to determine in the context of the lifetime of an offshore infrastructure project to determine the impact.

Fluid escape features in the form of mud volcanoes and pockmarks are often found on continental shelves. Mud volcanoes are observed on various settings around the world and they are attributed to processes of overpressurised mud migrating to the seabed either as diapirs or via fault and fracture networks. They are not related to volcanism, but they derive their name from their similar shape and mode of formation, i.e., extrusion or eruption of material onto the seabed. They are often conical or dome-shaped with diameters up to a few kilometres and heights up to 200m. Seeping through mud volcanoes can be continuous with intermittent major eruptive stages. The outputs are sediments often rich in methane and mud breccia is deposited on the flanks.

Pockmarks are seafloor depressions, usually circular or elliptical, with steep sides and flat floors. Pockmarks are only found in fine-grained sediments (clay and silt). They can be up to 700m wide and 45m deep (Hovland et al., 2002). Where they coalesce, they form elliptical depressions or chains that may resemble channels (Figure 4) (Pilcher and Argent, 2007). The type of venting fluid is either gas or water from sources buried below. Pockmarks are indicative of deep fluid pressure build-up (Hovland et al., 2002).

Fluid escape features are not unique to continental shelves as they are not related to water depth or slope angle. They can be found in deeper water too as the conditions for their formation essentially lie in deep sub-seabed formations.

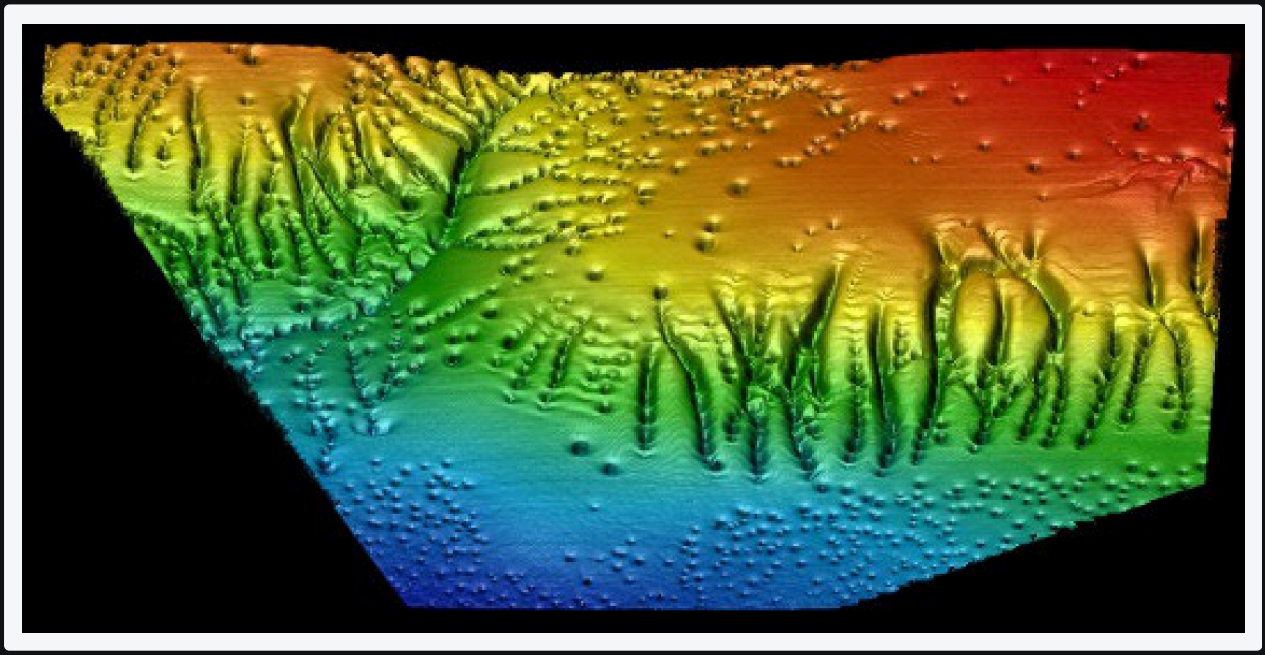

Figure 4 Pockmark trails offshore Gabon, West Africa in water depths 540-1860m (From Pilcher and Argent, 2007)

2.2 Mitigation

The continental shelf is the most easily accessible area for surveying. Many datasets already exist and much knowledge is already published that can be utilised. National Geological Survey institutes, such as the British Geological Survey, Geological Survey Ireland, US Geological Survey, the French

Geological Survey (Bureau de Recherches Géologiques et Minières – BRGM), Geoscience Australia, etc., have extensively surveyed their own continental shelves and have made data publicly available. Other data exchange databases, such as EMODnet (European Marine Observation and Data Network), the IRIS Earthquake Browser, NOAA's Bathymetry Portal, etc., also exist.

In addition, due to the relatively shallow water depths and proximity to the coast, the continental shelf can be relatively easily mapped in detail by geophysical techniques and sampled by geotechnical surveys, assessing seabed conditions and bedform migration against the project's design life (e.g., the previously mentioned Viking Link's three-year pre-lay seabed preparation and burial campaign involving geophysical surveys of the entire offshore cable corridor to map seabed morphology, sediments, boulders, sediment mobility, shipwrecks, UXO risks and existing infrastructure; geotechnical investigations to determine burial feasibility and cable protection requirements; cable crossing investigations using ROVs at locations where the route intersected existing pipelines, telecom cables or power cables; benthic and environmental surveys to characterise seabed habitats and support permitting).

3. Continental Slopes

The continental slope connects the shallow continental shelf to the deep ocean floor. It is typically narrow, about 20km and has an average gradient of 4° with many local variations. Water depths change across these 20km from 140-150m at the shelf break to more than 3000m where there is another marked slope change at the base of the continental slope. Conditions here are very different to the continental shelf. Tides and waves have limited impact at these water depths. However, slope parallel bottom currents can sweep the seabed and control sediment distribution. The steeper gradients mean that gravity is a very important factor on the slope morphologies and sediment that is not "trapped" on the continental shelf and makes it to the shelf edge and beyond onto the continental slope is subject to gravitational forces. Moreover, the previously subaerially exposed continental shelves that were traversed by fluvial systems could have allowed for river mouths to reach the shelf break and carve deep submarine channels (Figure 5). These are large scale morphologies impacting extensive areas of the seabed.

3.1 Submarine landslides

Submarine landslides are among the largest natural events on the planet. They are found on all continental margins, at all water depths and on slope gradients as low as 2° (Georgiopoulou et al., 2020). They can travel very large distances, in the order of >1000km, and can mobilise volumes of sediments more than three orders of magnitude larger than their terrestrial counterparts (Talling et al., 2014). They can be very dynamic phenomena with significant destructive ability for any seafloor

infrastructure and have been responsible for many telecommunication cable damages. Hundreds (ca. 400) of cable breaks globally have been attributed to submarine landslides in recent decades and account for roughly 20% of all cable faults (Carter et al., 2009).

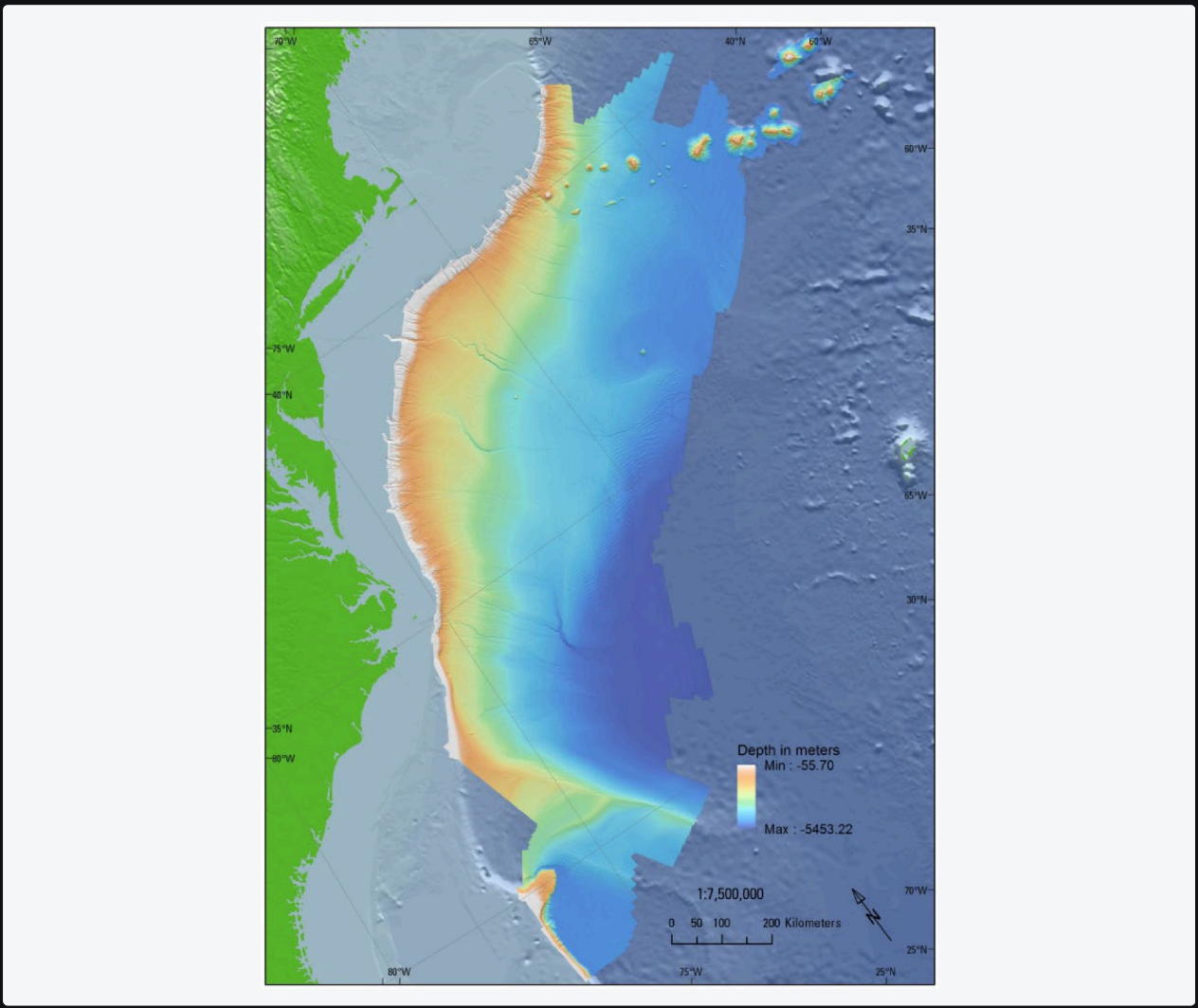

Figure 5 Bathymetric terrain model of the US Atlantic margin (From USGS)

The term submarine landslide is used here as a generic term encompassing all displacements of a mass of soil or rock when the downslope driving force (gravity) exceeds the resisting forces. Submarine landslide classification is not always easy as they can be classified based on velocity, mass coherency, the ratio of solid material vs. fluid (water) and/or the internal flow forces. Terminology has not been entirely consistent amongst researchers but the most widely accepted and used terms are: *slide* for the movement of a relatively coherent mass of sediment moving on a distinct failure plane; *debris flow* for a laminar and cohesive flow of clasts in a fine-grained matrix; *debris avalanche* for a rapid flow of cohesionless rock fragments, blocks, and clasts, in which energy dissipates through grain to grain contact; and *turbidity current* for a gravity flow in which sediment grains are maintained in suspension through fluid turbulence.

It is not uncommon for submarine landslides to experience flow transformation while moving through bulking up of the mass flow through erosion, or through reduction of the mass to fluid ratio through deposition or even through local seabed geomorphological changes, such as small gradient changes that may cause hydraulic jumps within the flow.

A wide variety of factors can contribute to preconditioning or triggering slope failure. These include inherent characteristics of the slope material (e.g., presence of weak layers that can act as failure planes), rapid sediment accumulation and overpressure development (e.g., at river deltas), external factors such as seismic activity, gas charging or storm-wave and tidal loading, volcanic processes, tectonic movements, and sometimes human activities (e.g., the Nice harbour catastrophe, Dan et al., 2007).

3.1.1 Mitigation

If areas of historic submarine landslides can be avoided then routing away from high-susceptibility corridors, using probabilistic hazard maps (e.g., EMODnet) built from decades of research and of telecom fault data is always preferable.

If avoiding certain areas is not possible, then extensive surveying with geophysical and geotechnical techniques and incorporating sedimentological investigations and dating of past events is advised (e.g., Georgiopoulou et al., 2019). This approach can reveal the factors that control slope instability and the frequency with which they occur.

3.2 Submarine Canyons

Submarine canyons are deep incisions present on all margins and slopes. Their relief is as dramatic as river valleys on land with depths of 100s to 1000s of metres and lengths of 10s of kilometres.

The dominant sculpting process that incises canyons and contributes to their growth is turbidity currents (Amblas et al., 2018). Turbidity currents are sediment-laden flows that make them denser than the surrounding seawater and causes them to flow downslope as an undercurrent, exchanging sediment with the seabed. Turbidity current flows bulk up by eroding sediment from the seabed and up to a point that can make them even more erosive. As they descend to lower slopes, come out of the confinement of the canyons and decelerate they tend to become depositional and eventually die out as the sediment driving the movement settles out.

Turbidity currents are not constant flows through the canyons. Instead, they are episodic. They are either generated by flood river discharges that traverse continental shelves or on canyon heads that are close to the coastline, or by the impact of storm waves on the shelf and shelf edge that resuspend sediment, or by landslides that take place within a canyon or tributary and while moving ingest enough ambient water into the flow to transform them into turbidity currents. Generally, any

process that can create an increase in density in the water mass has the potential to transform to a turbidity current. Crucially it is important to highlight that there is a very wide range of triggers, from weather and climate related to earthquake related.

3.2.1 Mitigation

Cable routes should generally avoid traversing canyons as turbidity currents, likened to snow avalanches in terms of power and impact on the bed on which they flow, are the most common natural cause of telecommunication cable failures. It was the breaking of a series of telegraph cables offshore Nova Scotia in 1929 that first revealed that this process was even taking place on the world's seafloors (Kuenen, 1952).

3.3 Contourites

Contourites are depositional systems on continental slopes that are affected, reworked and deposited by the persistent action of bottom currents (or otherwise known as contour currents). Contourites form large mounds, called drifts, they are large scale features affecting areas 1000s of km² and can be >1km thick. They are elongate in the direction of bottom current movement and may often be associated with an erosional moat to one side. Contourites develop along continental margins that have been influenced by bottom currents for long periods of time (>2–3 My). They often co-exist with other deepwater processes, including downslope moving turbidity currents.

3.3.1 Mitigation

To the best of our knowledge no cable faults have ever been attributed to contouritic deposition but considering the physical processes involved, any cables routed through or over contourite depositional systems will need to be able to withstand the ongoing bottom current activity and sediment eroding and depositing. Cables laid directly on the seabed will likely be subjected to scouring and lateral loads. We advise that the site should be investigated with geophysical and geotechnical techniques to establish the rate and speed of sediment movement. Accordingly, strategies involving burial/protection design rated for sustained scour and lateral current loading should be considered if required.

4. Mid-ocean ridges (MOR)

Mid-ocean ridges form at divergent plate boundaries, i.e., where tectonic plates move away from one another. These are the locations where new oceanic crust forms by way of volcanism, meaning magma rising to fill in the space created from the diverging plates. Seafloor morphology, crust and lithosphere structure, as well as tectonic styles are a function of spreading rate. The texture of the

seafloor at MORs is dominated by regularly spaced topographic highs that are elongated parallel to the spreading centre (abyssal hills) which can be straightforwardly related to the morphology of the MOR where they originated (Figure 6).

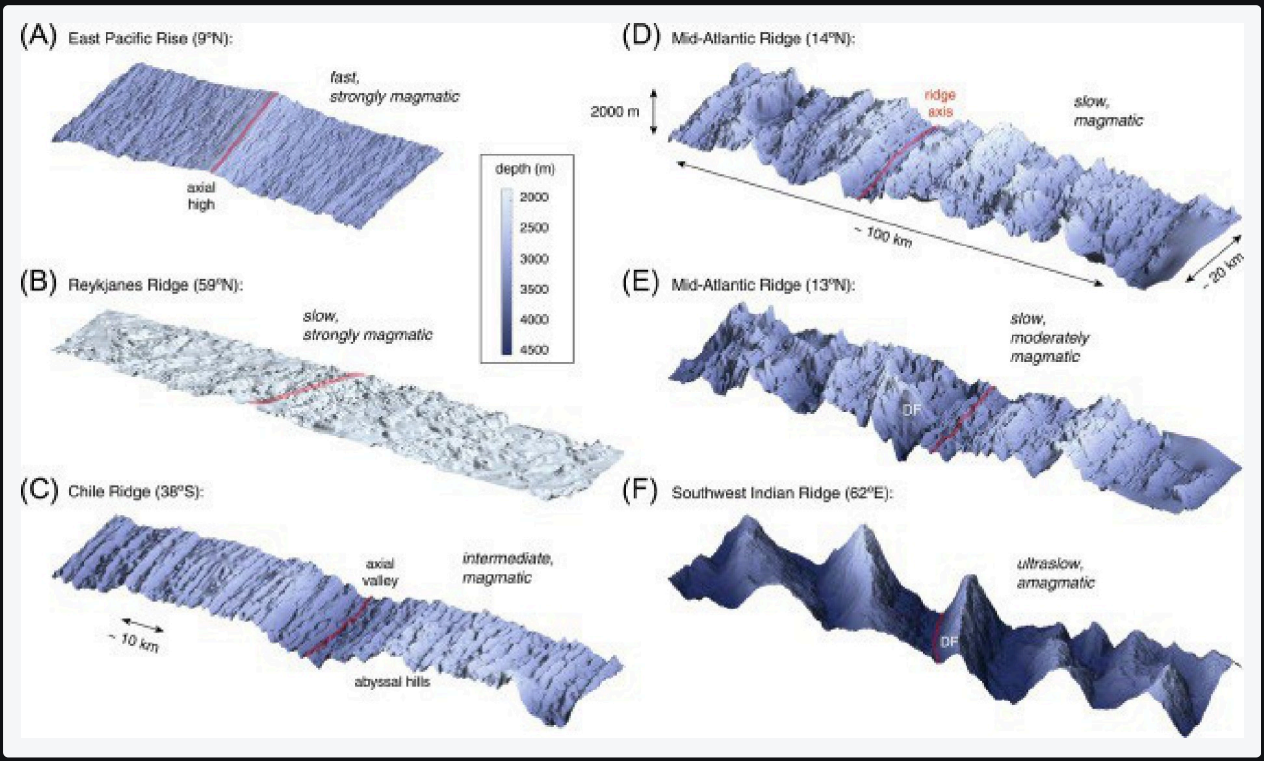

Figure 6 Axial morphology of various mid-ocean ridges. All panels are to scale. DF: Detachment fault. (A–F) are roughly ordered by decreasing magma supply. (From Olive, 2023).

MORs are classified based on the rate of spreading:

- Fast
- Intermediate
- Slow
- Ultra-slow

Fast-spreading ridges (e.g., the East Pacific Rise, Figure 7A and Figure 7) are typically associated with an axial high ~10 km wide and ~100s of meters high, whose flanks are dissected by many axis-facing and outward-facing faults. The axial high hosts multiple hydrothermal vents that spew metal-rich fluids at temperatures >350°C. These vents cluster within hydrothermal fields, each accounting for a heat flux on the order of ~100s of MW.

Intermediate-spreading ridges share many characteristics of fast-spreading ridges, with the main exception that they can be straddled either by an axial high or an axial valley (e.g., the Chile Ridge, Figure 6C and Figure 7D). In the latter case, the axis consists of a ~10-km-wide depression with ~1 km negative relief, bound on either side by axis-facing normal faults. High-temperature hydrothermal fields have also been extensively documented at intermediate-spreading ridges (e.g., Tivey and Johnson, 2002). At slower spreading rates the abyssal hills are more widely spaced (Figure 6D) and

magmatism is reduced. The most crucial change is the increased variability in ridge characteristics along axis. The centres of slow-spreading ridge segments show more intense magmatic activity compared to segment ends (located near transform faults or non-transform offsets).

Even more spectacular variability can be observed from segment to segment along slow and ultraslow MORs. About 50% of the Northern Mid-Atlantic Ridge axis is populated by “symmetric” segments with a well-defined axial valley that is ~10 km wide and >1 km deep (Escartín et al., 2008). These sections produce abyssal hills that are ~2–8 km apart and reach amplitudes of ~1 km (Figure 6D). The hills are bound by axis-facing normal faults. By contrast, the remaining ~50% of the Northern Mid-Atlantic Ridge axis consists of highly asymmetric sections where there are greater seismicity rates and stronger hydrothermal activity.

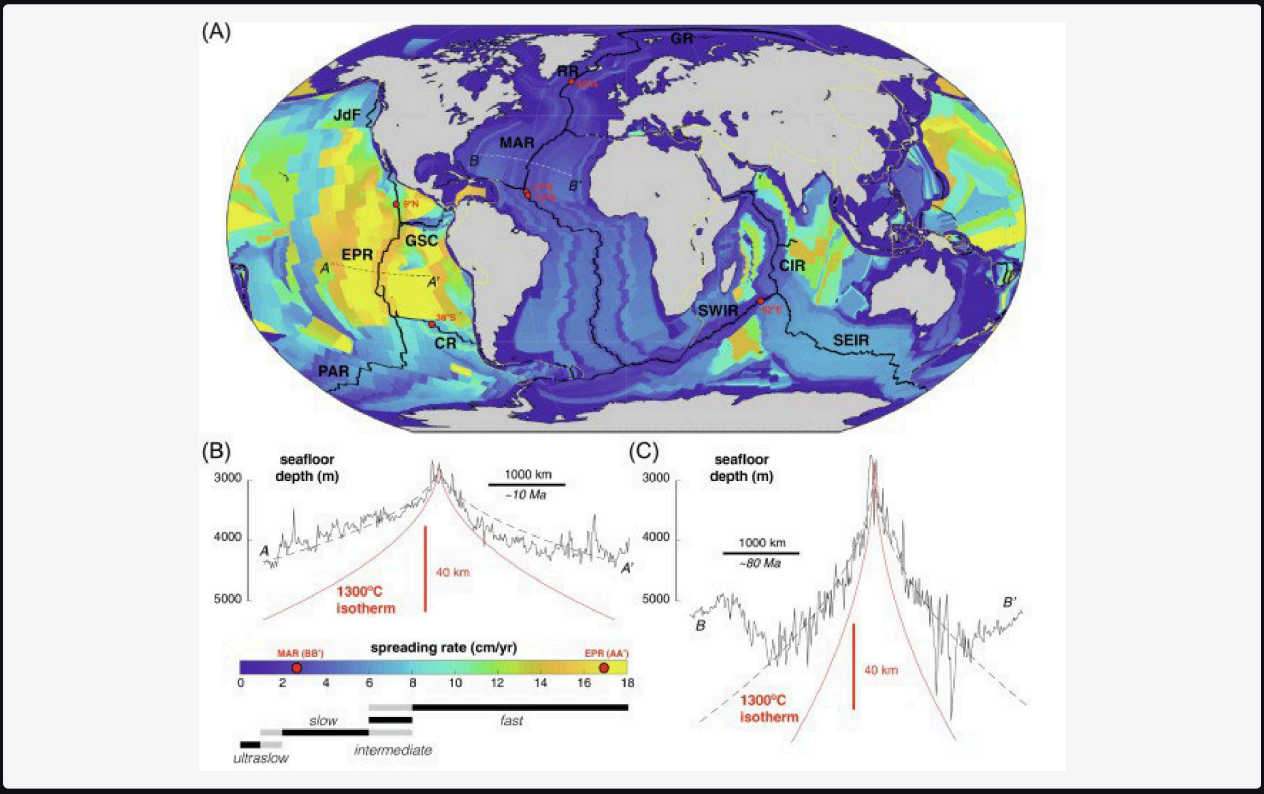

Figure 7 (A) Map of seafloor spreading rates. MAR: Mid-Atlantic Ridge. RR: Reykjanes Ridge. GR: Gakkel Ridge. JdF: Juan de Fuca Ridge. GSC: Galapagos Spreading Center. EPR: East Pacific Rise. CR: Chile Ridge. PAR: Pacific–Antarctic Ridge. SWIR: Southwest Indian Ridge. SEIR: Southeast Indian Ridge. CIR: Central Indian Ridge. Red dots are sites shown in Fig. 2. Dashed lines are transects shown in panels B and C. (B) Bathymetric transect across the EPR (Ryan et al., 2009). (C) Same across the Mid-Atlantic Ridge. Half-space cooling model assumed a full spreading rate of 2.5 cm/year. (From Olive, 2023).

4.1 Mitigation

Multiple telecommunication cables traverse MORs, in the Atlantic, the Pacific and the Indian Ocean (Figure 1). Recently the route planned and used for the EllaLink used seismic and volcanism monitoring to select the “quieter” parts to route cables through, to minimise the likelihood of impact of such processes on cables (EllaLink, 2019).

5. Abyssal Plains

Deep abyssal plains are the flat deep-water areas either side of a MOR. Dynamically they are the least active zones (quiet zones), but due to distance from the coastline and the deep waters they are very poorly imaged. Very large sediment flows (turbidity currents) may reach them, but by this point these flows are expected to be significantly weakened with only the fine-grained components remaining in the flow and depositing. Seamounts may be present.

5.1 Mitigation

A significant risk is data gaps from unmapped seafloor. Any knowledge / impression we have of the deep seafloor is at very low resolution. Surveying of a possible corridor required for route planning should precede any route lock-in.

6. Volcanic Islands and Seamounts

Volcanic marine environments mainly include volcanic cones that usually appear in clusters, lava flows and deposits of pyroclastic flows that have entered the sea. The flanks of volcanic islands include morphological features that record their history of constructive and destructive processes, such as guyots, insular shelves and evidence of flank collapses (landslide scarps and scars) and channels or gullies. The growth and morphological evolution of volcanoes are, in fact, the result of interaction between constructive and destructive forces. The constructional processes prevail during the relatively short periods of eruptive activity, whereas destructive forces become dominant during the longer inter-eruption periods or when volcanic activity has ended (Casalbore, 2018).

Cables traversing active submarine volcanic areas will need to contend with tectonic movements, routing through hard bedrock exposures, potential future lava flows or pyroclastic flows and the not so uncommon mass wasting from flank collapses. These include multiple constraints and geotechnically challenging conditions. Unless volcanic islands are part of the interconnection these are areas preferably avoided.

A recent example of telecommunication cables being impacted by volcanic activity comes from the Hunga Tonga-Hunga Ha'apai eruption in January 2022. The collapse of the eruption plume of Hunga Volcano triggered fast-moving density currents that entered the sea and severed both of Tonga's domestic and international submarine cables (Clare et al., 2023). There are many other historical examples of telecommunication cables impacted either directly by the eruption or by subsequent events caused by an eruption. A study on the impact of volcanic eruptions to the global telecommunications network highlights that usually the causes of damage relate mostly to secondary hazards that occur either at the same time as the eruption climax or some time after the eruption (Clare et al., 2025).

6.1 Mitigation

Mid-ocean volcanic islands or submarine volcanoes should be avoided unless the island is itself a landing point for the cable. Inhabited volcanic islands are usually monitored for seismic and volcanic activity. This monitoring could help determine whether some part of the island is more stable and therefore more favourable as a landing point.

7. Transatlantic interconnectors: A Case Study

The US continental slope hosts canyons and landslide scars shown on Figure 8 (Twitchell et al., 2009). The European Atlantic margin likewise hosts large canyons and the scars and deposits of giant submarine landslides (Hühnerbach et al., 2004). A map of submarine landslide susceptibility for the European margin has been produced by the European Marine Observation and Data Network (EMODnet) (Figure 9). These large-scale landslide events are not frequent and are controlled by multiple factors. The likelihood of an event of this scale happening in the next 100 years is very small, however, the scarps can be unstable and reactivate multiple times and the deposits present high lithological variability (e.g., Georgiopoulou et al., 2019).

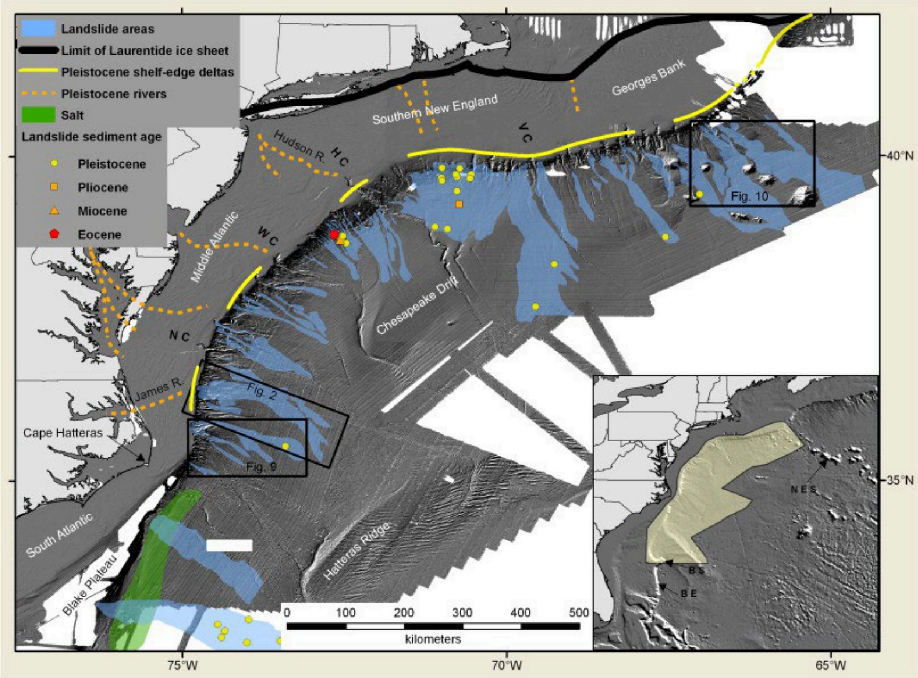

Figure 8 Regional morphology and landslide and canyon distribution on the US Atlantic margin. NES: New England Seamounts; BOR: Blake Outer Ridge; BS: Blake Spur; BE: Blake Escarpment; VC: Veatch Canyon; HC: Hudson Canyon; WC: Wilmington Canyon; NC: Norfolk Canyon. From Twitchell et al., 2009.

In addition, there are large deposits of contouritic drifts along the entire length of the European continental slope which have been building up for millions of years, since the northward flowing currents were established in Late Eocene (Georgiopoulou et al., 2021).

Any cables traversing the Atlantic will have to contend with what is considered the longest mountain range on the planet, the Mid-Atlantic Ridge, extending from the Arctic to the southern tips of Africa and South America. As Figure 10 shows, it is impossible to avoid it. For most of its length it comprises two parallel ridges with a valley in the middle and numerous MAR parallel ridges of lower amplitude, as can be seen in the variable morphology of the profiles of Figure 10.

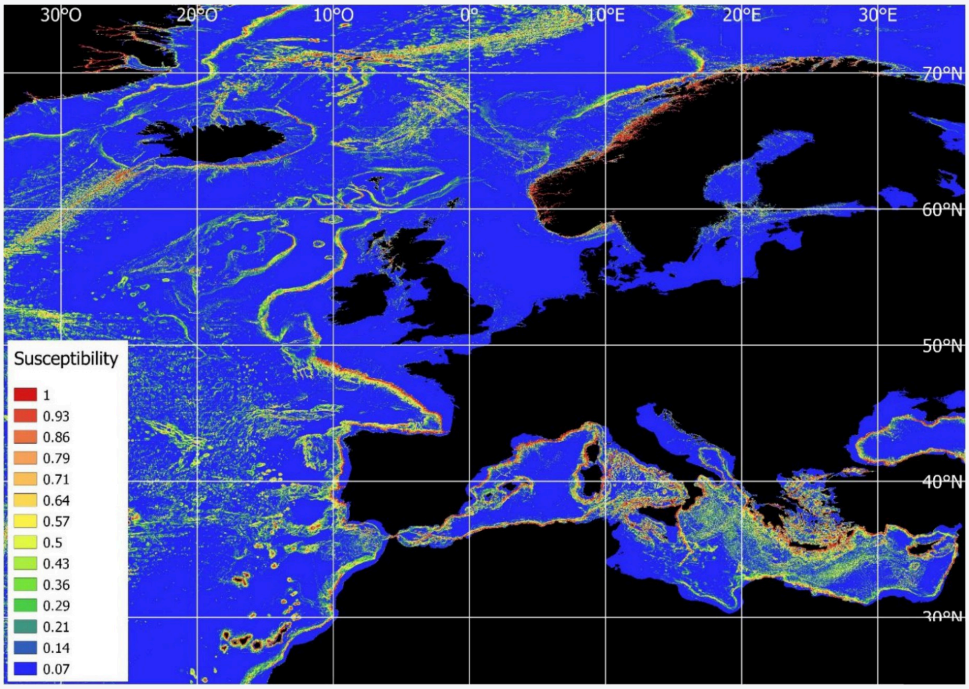

Figure 9 Submarine landslides susceptibility map (EMODnet Geology)

The Mid-Atlantic Ridge (MAR) is a formidable barrier for transatlantic submarine cables. Historically, these systems routed cables through the North Atlantic, linking Europe to North America, establishing a strong foundation for global communications. The path across the MAR presents a host of engineering and environmental challenges:

- Steep slopes: peaks rising 2,000-4,000m above the adjacent seafloor, with water depths in excess of 5,000m
- Rift valleys: the MAR is in fact made of two parallel mountain ranges separated by a deep valley. From about 56°N at the Bight Fracture Zone and northwards towards Iceland sits the Reykjanes Ridge, which is a single elevated axial high rather than a rift valley with no lateral offsets by any large transform faults.

- Seismic activity: earthquakes take place daily along the length of the MAR. 4-6 Mw are common. However, there are sections of the MAR that are less active than the rest
- Hydrothermal activity: as active spreading takes place and the magma is very close to the surface there are parts of the MAR that show hydrothermal activity with chimneys spewing hot, mineral-rich fluids
- Volcanism: parts of the MAR show active volcanism at the seabed, but this is not taking place currently along the entire length of the ridge.

In the past, cable routings have used seismic and volcanism monitoring to select the “quieter” parts to route cables through, to minimise the likelihood of impact of such processes on cables (EllaLink, 2019).

The deeper parts of the Atlantic, on either side of the MAR are considered the least dynamic areas. However, these parts of the seafloor are very poorly imaged to date. Seamounts and other unknown hazards and constraints may be present.

Four arbitrary examples have been drawn to connect North America (USA and Canada) to Northeast Europe (France, Belgium, and Ireland) to illustrate the hazards and constraints that could be encountered (Table 2 and Figure 10).

Table 2 Example interconnectors between US/Canada and Western Europe

ROUTE WESTERN END	ROUTE EASTERN END	LENGTH (KM)	DEPTH RANGE (M)
New York City, NY, US	Brittany, France	5,830	4,900
Boston, MA, US	Le Havre, France	5,450	4,590
Québec City, Canada	Bruges, Belgium	5,660	3,850
St John’s, Canada	Cork, Ireland	3,215	4,900

Of the four examples only one does not exceed 4000m water depth. Water depth affects the static and dynamic tensile loads encountered during installation. 4000m is a likely development for HVDC cable technology in the early 2030s. The longest route is between New York City and Brittany in France, whereas the shortest route is between Newfoundland and Ireland.

The profiles in Figure 10 show the variable morphology of the Atlantic Ocean seabed from the continental shelves to the Mid-Atlantic Ridge. On both continental shelves constraints for mid-latitude and northern latitude continental shelves as described in Section 2 may apply.

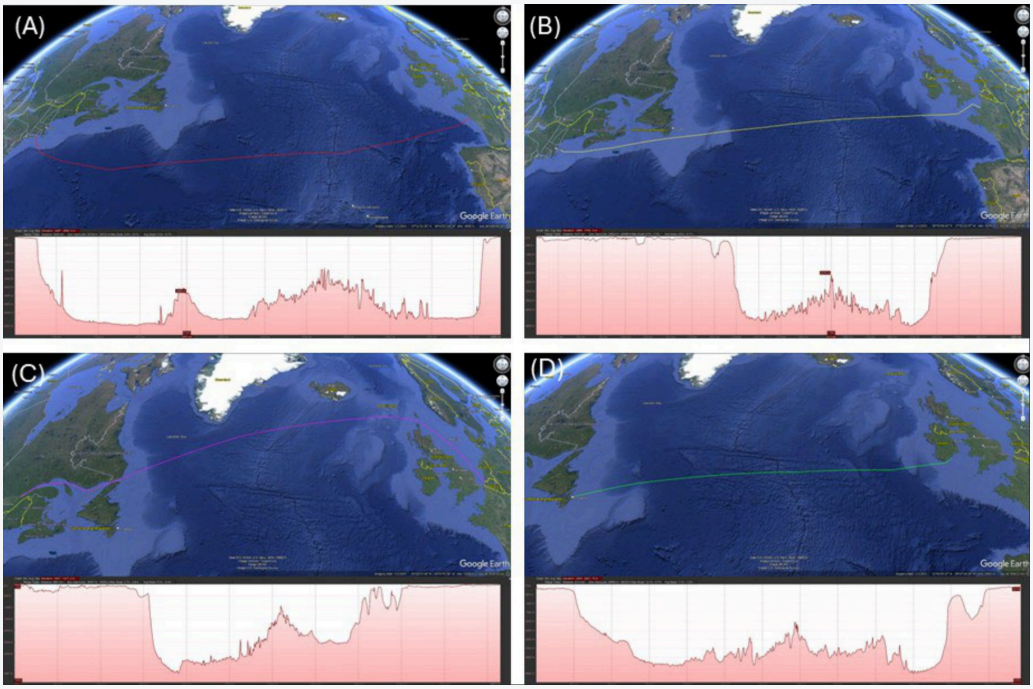

Figure 10 Interconnectors across the Atlantic Ocean. (A) New York to Brittany; (B) Boston to Le Havre; (C) Québec to Bruges; (D) St John's to Cork (bathymetry source: Google Earth)

North American Margin (Figure 11):

New York, NY, USA – Brittany, France: Coming out of New York City the cable would be routed through the Mid-Atlantic continental shelf encountering constraints such as lithological variability due to the area's subaerial exposure during the lower sea levels in the LGM. Across the slope the route would contend with numerous canyons and extensive larger and smaller scale submarine landslides (Figure 11A). This margin and slope have been researched extensively with data and published scientific work available to use and consult (NOAA, USGS, and published scientific work). In the deeper water the cable(s) would have to be routed through the New England Seamount Chain and further to the east, potentially the Corner Rise Seamount Chain. Those have also been mapped and some of the seamounts have even been videoed (e.g., Kelvin Seamount with Okeanos Explorer[1]). All the existing data would be considered dated and new surveys will need to be conducted, but the existing knowledge helps with route planning and survey design.

Boston, MA, USA – Le Havre, France: For a large part of the route the cable could stay on the continental shelf offshore NE US and Canada. That would allow the cable to avoid the large scale geohazards on the slope in the form of canyons and submarine landslides. The continental shelf in this area was previously occupied by the Laurentide Ice Sheet (Figure 11B) and as a result constraints associated with the presence of large ice sheet are anticipated. The area has been mapped at relatively high resolution, and a lot of data and knowledge are already available, that would help with routing and survey planning.

[1] NOAA Ocean Exploration, Our Deepwater Backyard: Exploring Atlantic Canyons and Seamounts 2014

Québec, Canada – Bruges, Belgium: Coming out of Québec City the cable(s) would be routed through the St Lawrence Channel. Shallow water depth, vessel traffic, highly variable ground conditions and likely iceberg scouring during winter and spring months.

St John's, Newfoundland, Canada – Cork, Ireland: This is the closest point to Europe from North America. The risk of icebergs and scouring is present for this route too, but the length of the cable(s) on the continental shelf is shorter. All the constraints associated with a previously glaciated area will be present too on the continental shelf. The transition to the slope and deeper water is smoother here than on the US slope. No large canyons or obvious landslide scarps, but a site-specific survey will be required to confirm that.

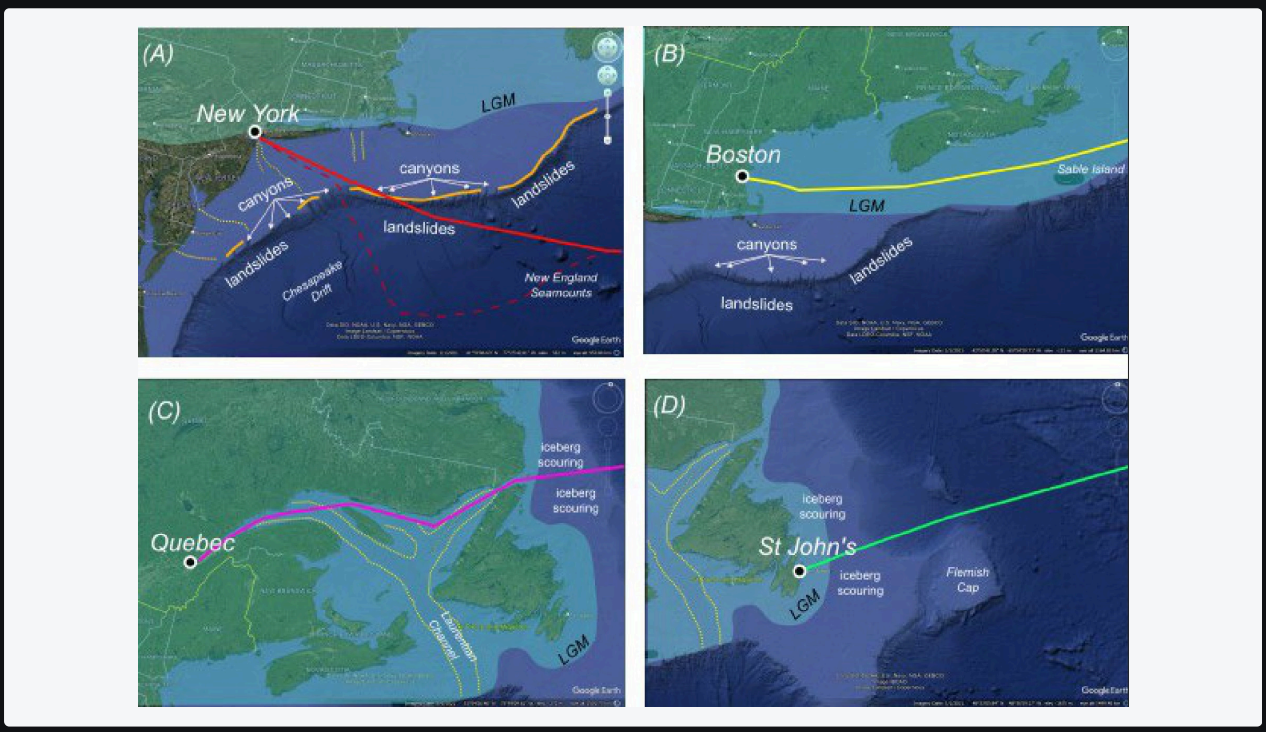

Figure 11 Geohazards and constraints on the North American margin associated with the four examples. (A) Route between New York, USA, and Brittany (Nantes), France, (B) between Boston, USA, and Le Havre, France, (C) between Québec, Canada, and Bruges, Belgium, (D) between St. John's, Newfoundland, and Cork, Ireland. Red line: possible interconnector route; dashed red line: more realistic route across the shelf and slope; yellow dotted lines: channels; yellow solid lines: shelf edge deltas; light blue transparency: maximum ice sheet extent during the Last Glacial Maximum (LGM)

Mid-Atlantic Ridge crossing (Figure 12):

Across the Mid-Atlantic Ridge all four routes would contend with very patchy data, numerous mapped and unmapped seamounts, potential volcanic and seismic activity (Figure 12). The route between Québec and Bruges crosses the MAR over the Reykjanes Ridge, which is a part of the MAR that differs both morphologically and in terms of activity from the rest of the MAR in the North Atlantic. At this location there are no fracture zones, and there is no While some parts of the Mid-Atlantic Ridge have been mapped, the deeper water areas away from the MAR on either side are lacking any data of useful resolution. Choosing the right location for the crossing will need to rely on long-term

monitoring of the Mid-Atlantic Ridge, through existing databases and networks such as the IRIS earthquake database. A dedicated deep-water survey will allow for engineering the rest of the route safely in the deep Atlantic.

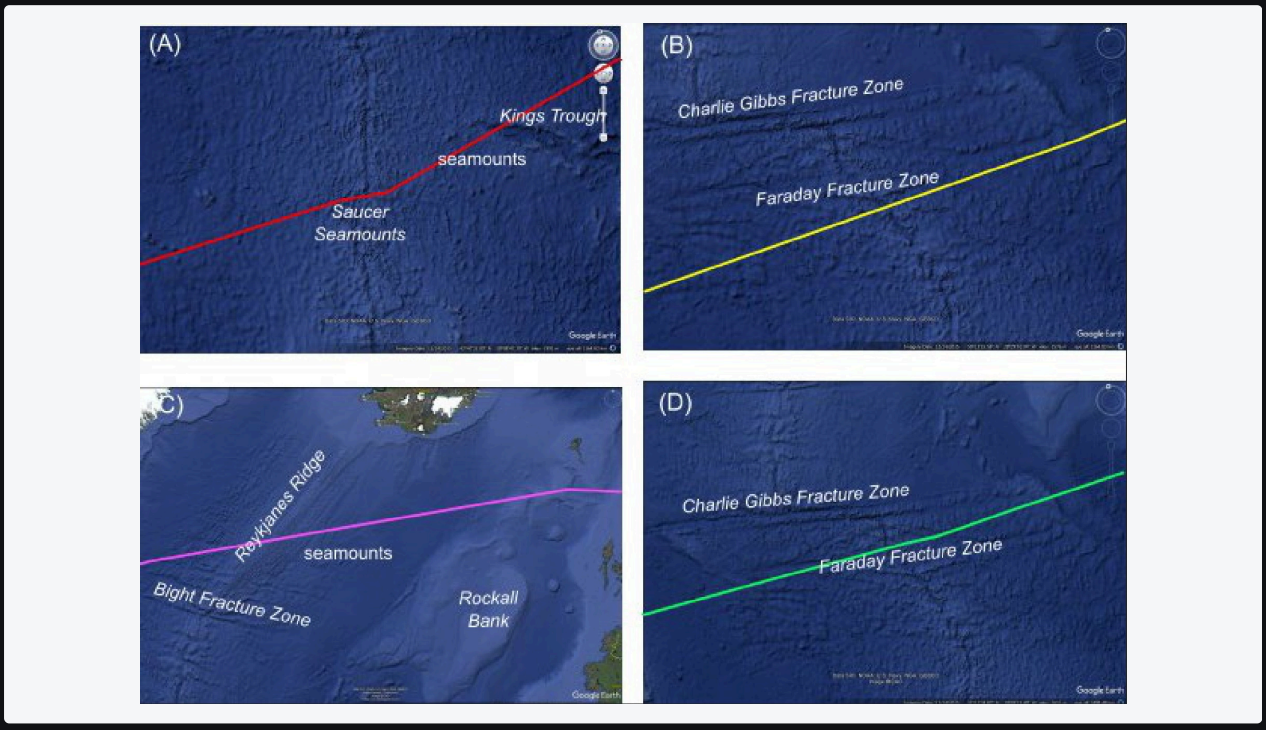

Figure 12 Crossing of the Mid-Atlantic Ridge (A) Route between New York, USA, and Brittany (Nantes), France, (B) between Boston, USA, and Le Havre, France, (C) between Québec, Canada, and Bruges, Belgium, (D) between St. John's, Newfoundland, and Cork, Ireland. Highlighted on the panels are fracture zones and known seamounts

North European margin (Figure 13):

New York, NY, USA – Brittany, France: Numerous canyons, steep slopes and submarine landslides will be encountered on this slope, as well as known exposed bedrock offshore Brittany.

Boston, MA, USA – Le Havre, France: This route goes through the Porcupine Seabight and over the Goban Spur, potentially encountering steep scarps, and to the south of the Gollum Channel Complex. On the Celtic Sea continental shelf there is a series of long relic ridges (Figure 13B), formed during the rising sea levels after the LGM as tidal ridges. They are no longer active, but they are morphologically prominent and consist of harder materials than the inter-ridge areas. Cable(s) can be routed through the ridges. Many telecom cables have been routed across the Celtic Sea continental shelf and through the English Channel.

Québec, Canada – Bruges, Belgium: The cable(s) routed through the north will need to negotiate a route through or over Lousy Bank, Bill Bailey's Bank, Faroe Bank, the Wyville-Thomson Ridge, and the Faroe Bank Seachannel (Figure 13C). These are remnant volcanic highs that are no longer active but are topographically prominent and are very important in bottom current circulation and sediment mobility and for habitats. A few telecom cables follow a route around the north of the British Isles

and over the north or south of Faroe Islands, such as the Atlantic Crossing 1 cable system that ended operation in 2024 and the presently operational HAVFRUE/AEC-2. The cable(s) will then cross the North Sea to head south to Belgium. This entire area was occupied by ice sheets during the Pleistocene glaciations (Figure 13C), which have left their imprint morphologically with glacial tunnel valleys, moraines and ridges, but also lithologically with hard till soils or very soft clays and numerous boulder fields. The area is also utilised by numerous telecom cables, pipelines and power cables and sees a lot of fishing and vessel traffic.

St John's, Newfoundland, Canada – Cork, Ireland: The Irish continental slope will be traversed at the Porcupine Seabight where there are a number of channels, canyons and carbonate mounds (Belgica, Moira, and Hovland Mound Provinces) (Figure 13D). There has been a lot of scientific research for this area (e.g., Van Rooij et al., 2003; Verweirder et al., 2023; Matossian and Van Rooij, 2024; Verweirder et al., 2026) and there are a lot of data that will allow careful planning of the route(s) and site-specific surveys.

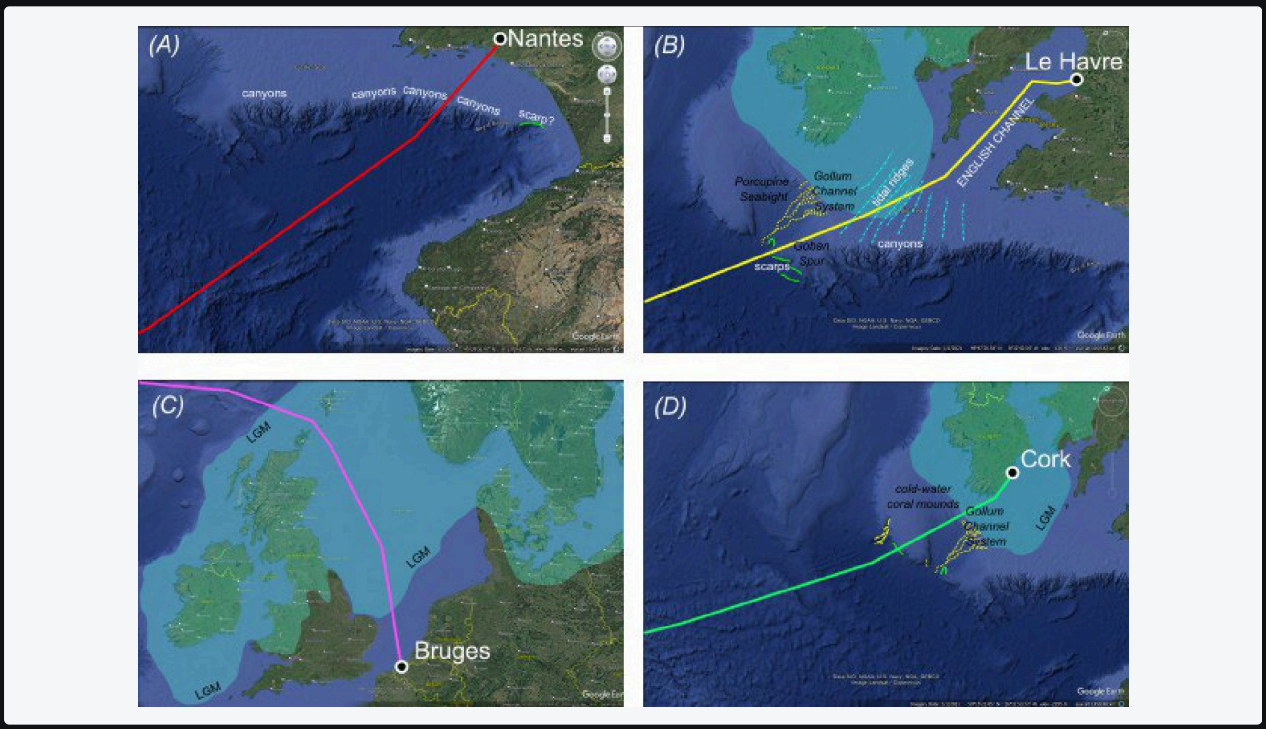

Figure 13 Geohazards and constraints on the North European margin associated with the four examples. (A) Route between New York, USA, and Brittany (Nantes), France, (B) between Boston, USA, and Le Havre, France, (C) between Québec, Canada, and Bruges, Belgium, (D) between St. John's, Newfoundland, and Cork, Ireland. Green solid lines: scarps; yellow dashed lines: channels/canyons; blue dashed lines: relic tidal ridges; light blue transparency: maximum ice sheet extent during the Last Glacial Maximum (LGM).

8. Conclusions

Transoceanic electrical interconnectors represent an exciting opportunity to strengthen global energy connectivity and support the transition towards a more integrated, resilient, and sustainable energy system. As projects extend across thousands of kilometres of ocean, understanding the geological and environmental conditions along their routes will be fundamental to successful design, installation, and long-term performance.

The challenges are significant, but they are not insurmountable. Decades of experience from the submarine telecommunications industry, combined with advances in marine geoscience, geophysical surveying and geotechnical investigation, provide a strong foundation for identifying, assessing, and mitigating potential hazards. Applying this knowledge at the earliest stages of project development can inform route selection, optimise survey strategies, and support robust engineering decisions.

Every interconnector route presents a unique combination of seabed conditions and geological constraints. A dedicated, route-specific assessment is therefore essential to establish the relevant hazards, inform cable specifications and develop effective mitigation strategies. By anticipating these challenges and integrating geoscientific understanding into project planning from the outset, developers can reduce uncertainty and build greater confidence in project delivery.

The future of transoceanic energy connectivity depends not on avoiding complexity, but on understanding it. With the right data, expertise and planning, the challenges of the deep ocean can be translated into informed engineering decisions, helping turn ambitious interconnector concepts into reliable, long-term energy infrastructure.

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