GUIDANCE NOTES ON

SUBSEA PIPELINE ROUTE DETERMINATION

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Foreword

The ABS Classification of a subsea pipeline system requires review of data and analysis results concerning conditions along the selected route of the pipeline. Prior to the final selection of the route and detailed design of the pipeline system, different routes will be considered and assessed. A method for route determination is presented in these Guidance Notes where candidate routes are selected and assessed. The method relies on the use of available Geographic Information System (GIS) technology and risk assessment techniques. An example of the method's application is provided.

The ABS *Guide for Building and Classing Subsea Pipeline Systems* is the controlling standard for the ABS Classification of such a system. The process of pipeline route determination is not in the scope of ABS' Classification of a pipeline system. However, the contents of these Guidance Notes provide a suggested approach to this topic that should be beneficial to readers.

It is acknowledged that methods of survey data collection and interpretation, data assessment and routing techniques, and risk assessment are constantly evolving. Improvements in these subjects are encouraged, and the publication of these Guidance Notes is not to inhibit the use of applicable, proven technology.

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GUIDANCE NOTES ON

SUBSEA PIPELINE ROUTE DETERMINATION

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SECTION 1 Criteria for Pipeline Route Determination

1 Introduction

These Guidance Notes are developed to support the selection of subsea pipeline routes by systematically evaluating geological, geotechnical, ecological, and cultural factors that determine pipeline route suitability and assessing the risks of pipeline route selection.

The procedures to determine a pipeline route in these Guidance Notes are built upon the important concept using a geocost map, which is established on a project basis to reflect the quantified geo risks corresponding to geometric and geologic hazards. Favorite route can be determined by selecting a path which causes the least accumulated geocost.

1.1 Purpose and Scope

The purpose of these Guidance Notes is to assist in pipeline route determination by recognizing and categorizing potential geological hazards (geohazards) as well as constraints ranging from cultural, ecological, pipeline, and/or project specific constraints. Consideration of such geohazards and constraints will help to reduce, control, or avoid potential engineering, construction, and operational problems.

These Guidance Notes are applicable to the offshore pipelines that are defined in ABS *Guide for Building and Classing Subsea Pipeline Systems*. The pipelines can be trenched, buried, as-laid, or even anchored.

The objectives of these Guidance Notes are to:

- Specify appropriate data to be collected and interpreted as part of a phased approach for selection of potential pipeline corridors or routes.
- Provide a representative but not exhaustive list of potential geohazards, ecological, cultural, and economic constraints, and possible effects on pipeline development and related infrastructure.
- Describe options for pipeline route selection and evaluation of route alternatives.
- Establish a general risk assessment procedure that can be used as a guide for specific projects.

1.3 Pipeline Route Selection Criteria and Determination Flowchart

The favorable pipeline route is the shortest path that minimizes the summation score of geocost between two termini. But the design working space for the route determination is bounded by applicable constraints that restrict the pipeline from passing through.

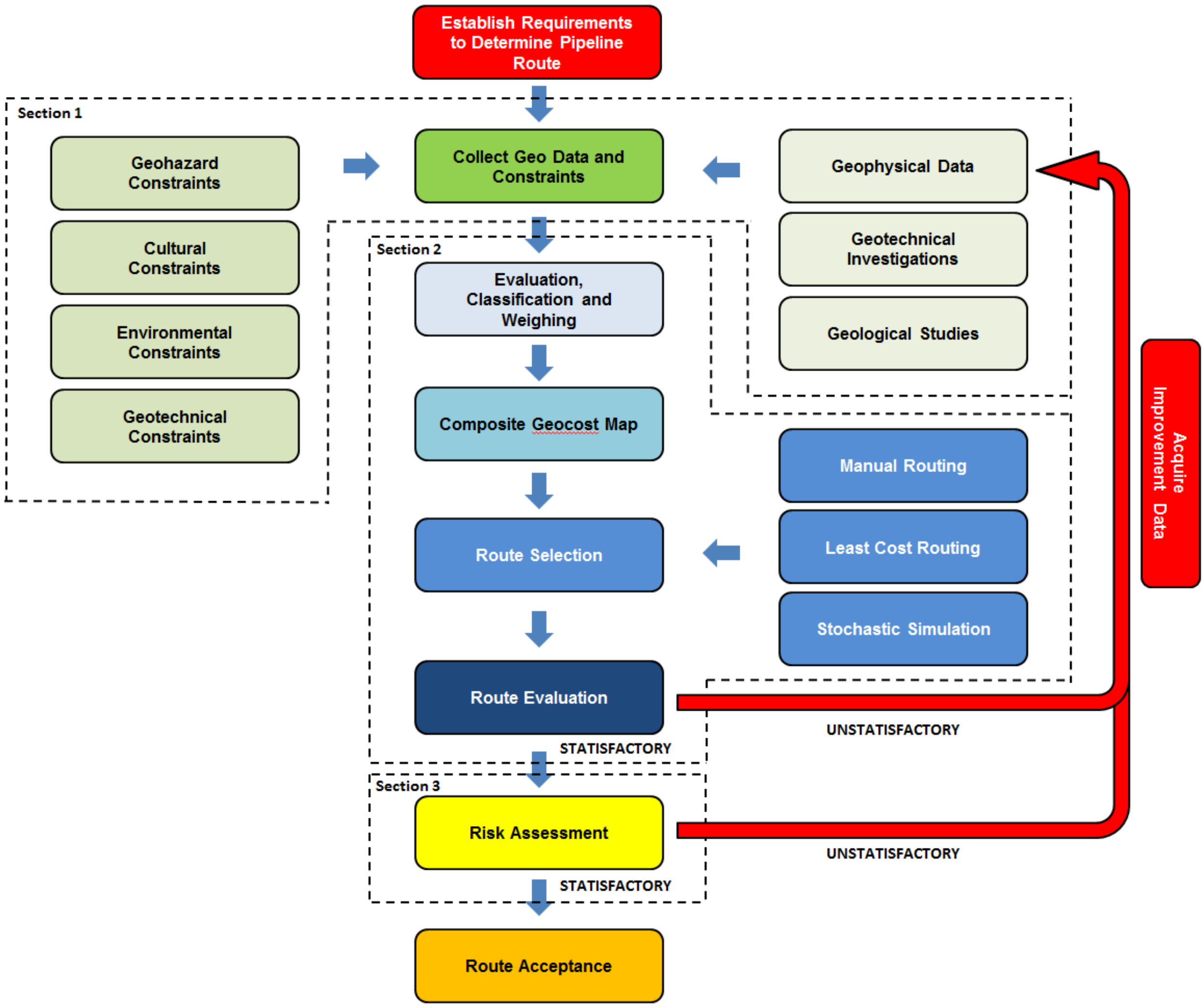
Pipeline route determination flowchart, Section 1, Figure 1, illustrates a systematic approach of selecting pipeline route. This systematic approach consists of a series of steps that are grouped into three sections within these Guidance Notes.

In the beginning, geo data collection and route constraint recognition are performed to collect information within the project working area. The general required information such as geophysical data, geotechnical investigations, and geological studies are stated in Subsection 1/3. Geohazard constraints are discussed in Subsection 1/5. Cultural, environmental, and geotechnical routing constraints are covered in Subsection 1/7.

Following that, geohazard classification and weighting procedure are conducted which are described in Subsection 2/3 and the development of the geocost map is stated in 2/3.1. Route determination methods (manual, least geocost, stochastic) are then discussed in Subsection 2/5 followed by route evaluation given in Subsection 2/7.

Finally, risk assessment and route acceptance are performed in accordance with Subsection 3/1.

FIGURE 1
Pipeline Route Determination Flowchart



1.5 Required Documentation

Recommended procedures for subsea pipeline route determination are based primarily on the following kinds of data and documents in order to demonstrate that the route selected meets all pertinent acceptance criteria:

- Data required to assess seabed conditions where a pipeline will be installed: 2-D or 3-D seismic, multibeam bathymetry, multibeam backscatter, side scan sonar, geotechnical or geological cores, pipeline termini, manifold locations, existing infrastructure, envrionmentally sensitive areas, pipe geometry and properties, loads and load matrix (pressure and temperature at installation, testing, and operation conditions).
- Specialist reports on geophysical surveys
- Specialist reports on geotechnical or geological cores
- Specialist reports on soil sampling/testing and pipe-soil interaction, including sea-bed and near sub-surface soil conditions as well as pipe-soil interaction.
- Special study reports (if applicable) to identify parameters and/or actions that require special consideration and/or monitoring during soil sampling/testing, material testing, fabrication, installation, post installation survey and and operation.

The data and documents listed above are those required for route determination. In the case of routes that have been determined, a route determination report describing the procedures used and a risk assessment report are also expected.

1.7 Pipeline System Design Guides and Standards

For subsea pipeline engineering standards and codes focusing on engineering design, material selection, installation, inspection, and soil site investigation, references can be made to the following:

- ABS *Guide for Building and Classing Subsea Pipeline Systems (Pipeline Guide)*
- ABS *Rules for Building and Classing Offshore Installations*
- API RP 1111
- API RP 2RD
- API 5L
- ASME B31.4
- ASME B31.8

3 Data Acquisition and Site Characterization

This Subsection describes methods used to collect the data necessary to evaluate potential pipeline routes and discusses aspects pertinent to subsea pipeline route selection. 1/3.1 discusses regional geophysical surveys required for optimal assessment of seafloor and shallow subsurface geological conditions. 1/3.3 addresses the importance of collecting relevant metocean data for assessment of conditions prior to pipeline selection. 1/3.5 emphasizes the importance of collecting geological and geotechnical core samples to obtain design level information once a preliminary pipeline route or corridor has been determined.

Pipeline route selection as outlined in Section 1, Figure 1 is an iterative process in which the quality of the information collected is refined as the cycle is repeated. For example, during the first iteration a provisional route might be determined on the basis of a desktop study and existing regional geophysical data with little route-specific geotechnical information. Such a provisional route, or more likely a corridor several kilometers wide, can then be used to target collection of more detailed geophysical and geotechnical information to further refine the route until uncertainty and risk are reduced to an acceptable level.

A desktop study is an initial step that can define the regional geologic setting within the area of a potential pipeline route, using existing information. The desktop study should involve an understanding of the regional geology from published studies, nearby locations, and analogous sites. Integration of all available data is important at this point. The information that is considered in a desktop study can include public domain bathymetric (water depth) maps (e.g., GEBCO – General Bathymetric Chart of the Oceans, Admiralty e-Nautical Publications) produced using different methods, scientific publications, or regional information such as 2-D or 3-D seismic reflection data used to guide petroleum exploration and development.

Regional geophysical surveys are a convenient starting point for route selection because, having been collected to support oil and gas exploration, they are typically available early in the process. They can therefore be used to support determination of one or more preliminary route corridors along which additional geophysical, geotechnical, and geological information can be collected and used to refine the route. One disadvantage of regional geophysical data is that they may be available over the reservoir or field development area but perhaps not along the full length of any export route corridors. Additional data may be required in order to properly evaluate export route corridors or other areas of concern such as the source areas of long-runout slope failures (e.g., debris flows) that may affect pipeline operation.

Additional high-resolution geophysical surveys, geotechnical in-situ testing and sampling, and geohazard cores are required for optimal assessment of seafloor and subsurface conditions. However, they are generally obtained only after a preliminary route corridor is established. Additional data that can be helpful during the assessment process consists of regional seismicity data, metocean criteria, tsunami hazard and risk assessment, and environmental data.

3.1 Regional Geophysical Surveys

Regional surveys cover hundreds to thousands of square kilometers and are a minimal requirement for route selection. Regional surveys most typically consist of 3-D seismic reflection and hull-mounted or towed reconnaissance multibeam echosounder (MBES) surveys obtained for oil and gas exploration. However, high-resolution bathymetric and subsurface data obtained from autonomous underwater vehicles (AUVs) may be obtained to support major subsea developments and thus, be available for pipeline route selection (Tootill et al., 2004). AUV and hull-mounted data typically comprise MBES bathymetric or water-depth coverage, backscatter data, side scan sonar (SSS) seafloor imagery, and sub-bottom profiler (SBP) lines that depict shallow (e.g., < 50 m) subsurface strata and other geologic features. Sub-bottom profiling is a simple but very high resolution variation on seismic reflection.

The kinds and sizes of features that can be identified with these surveys depend on the resolution of the data. Several survey types are listed in Section 1, Table 1 along with their uses, features that can be identified, typical resolution limits and advantages and limitations. The smallest features that can be mapped and confidently interpreted by an experienced geologist typically have characteristic lengths on the order of ten times the bin or raster size of the survey grid. Smaller seafloor features may exist but are not likely to be mappable. For 3-D seismic reflection surveys, bin sizes typically range from 10 m to 20 m. However, bin sizes as small as 0.5 m to 2 m are common in AUV surveys. Thus, features with characteristic lengths less than 200 m or areas smaller than 40,000 m^2 may be difficult or impossible to discern using 3-D seismic reflection data with a 20-m bin size. The equivalent thresholds for AUV bathymetric data with a 2-m bin size, in contrast, would be 20 m characteristic length and 400 m^2 area. Section 1, Figure 2 illustrates the difference in resolution between AUV MBES data, using different bin sizes over the same geologic feature. Smaller bin sizes will display more detail. Some effects that may limit interpretation to much lower resolutions include excessive biogenic gas that may affect the quality of the geophysical data or high shear strength glacial deposits, boulders, authigenic carbonate hardgrounds, or sub-cropping bedrock that may affect the penetration limit of SBP thus eliminating detailed subsurface interpretation.

Similar limits exist for the vertical resolution of regional geophysical data sets, and are commonly expressed in terms of the vertical limit of separability (VLS). The VLS is an estimate of the thinnest layer or stratum for which both the top and bottom of a layer can be delineated on a particular geophysical survey. It will depend on the frequency of the sound waves used during the seismic survey and the speed at which the sound waves are transmitted through the strata. For 3-D seismic surveys used in oil and gas exploration, the VLS may be on the order of 8 m to 10 m. For sub-bottom profiles, which use a much higher frequency energy source, the VLS is on the order of several tens of centimeters and are generally considered more appropriate for detailed pipeline route assessment.

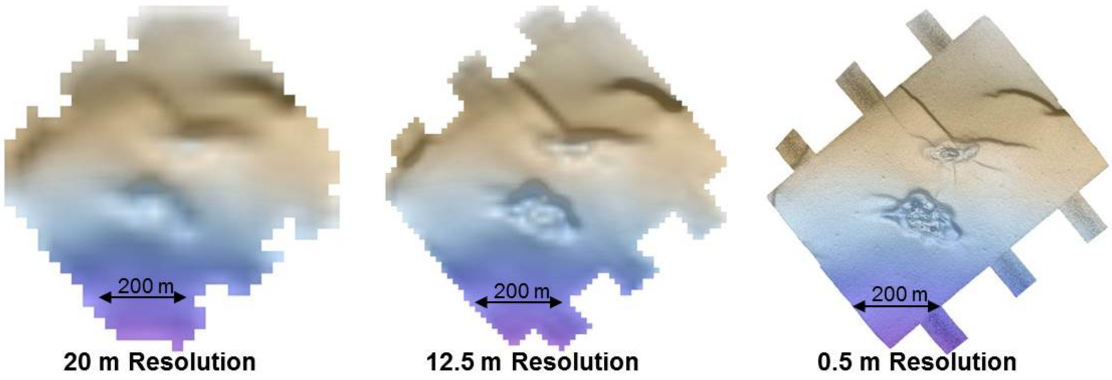
TABLE 1
Geophysical Survey Types

Survey Type	*Uses*	*Features Identified*	*Typical Horizontal Resolution*	*Typical Vertical Resolution*	*Advantages*	*Limitations*
3-D Seismic	Identifying stratigraphy and structural, regional bathymetry, exploration for hydrocarbon reservoirs	Faults, landslides, mass transport deposits, fluid expulsion features, channel systems, buried structure (faults and folds), buried stratigraphy, buried gas/hydrate	10 m to 25 m	10's to 100's of meters	Regional coverage and regional geologic interpretation	Lower resolutions compared to other surveys
HR or UHR 2-D seismic reflection	High resolution of stratigraphy and structure	Shallow seafloor features, buried structures, buried structure (faults and folds), buried stratigraphy, buried gas/hydrate	N/A	2 m to 4 m	Provides higher resolution than 3-D seismic to resolve subsurface conditions	Time consuming and costly to cover a large area
Sub-Bottom Profiler (SBP)	Identify near-seabed shallow stratigraphic and structural horizons	Manmade objects, faults, fluid expulsion features, shallow buried structure (faults and folds), shallow buried stratigraphy	N/A	10's of centimeters to 10's of meters	Provides higher resolution than 2-D and 3-D seismic to resolve shallow subsurface conditions	Features may not be detected depending on line spacing
Multibeam Echosounder (MBES)	High resolution bathymetry, backscatter (intensity showing hard or soft material), water column data	Faults, landslides, mass transport deposits, fluid expulsion features, channel systems at the seafloor	0.1 m to 15 m	N/A	Provides high resolution imagery of the seafloor	Resolution decreases with water depth depending on sensor height (e.g., hull-mounted versus AUV)
Side Scan Sonar	Detection of manmade objects, assess harder material versus softer material	Manmade objects, faults, fluid expulsion features, hardground	centimeters to decimeters	N/A	Provides high resolution imagery of seafloor objects	May not resolve features on steep slopes due to data shadows

3.1.1 3-D Seismic Reflection

3-D seismic reflection surveys are based upon sound waves passing through geological strata. Energy that is reflected off the interfaces between strata with different material properties is recorded by receivers known as hydrophones, and used to create a 3-D model of the strata. Marine 3-D seismic surveys also provide data that model the seafloor as well as subsurface geological conditions, because sound waves are reflected by the seafloor and interfaces between strata. These data are processed into seismic cubes or volumes for interpretation using specialized software. 3-D seismic data can be conventional exploration data or further processed to enhance geological features of interest for early stage interpretations (Section 1, Figure 3). The amplitude or strength of the seafloor reflection can sometimes be used to infer the nature of sediments in the few meters directly beneath the seafloor. Sandy seafloor sediments, for example, may have much higher amplitudes than clayey seafloor sediments. Information on line spacing, data processing, frequency of the seismic source signal, and quality (e.g., VLS) should be provided in any geological interpretation of 3-D seismic data.

FIGURE 2
Geophysical Survey Data Resolution Comparison



3.1.2 High-resolution or Ultra-high-resolution 2-D Seismic Reflection

High-resolution (HR) or ultra-high-resolution (UHR) 2-D seismic reflection surveys are generally required for advanced pipeline development if 3-D seismic surveys are not sufficient to resolve shallow subsurface conditions beyond the depth limits of sub-bottom profiles. The vertical resolution of HR or UHR 2-D surveys is generally 2 m to 4 m and several hundred meters of depth penetration can be obtained.

Section 1, Figure 3 compares the resolution of typical 3-D exploration seismic, 2-D UHR seismic, and sub-bottom profiles. Section 1, Figure 3(a) shows how AUV SBP data provide a better image of the top 30 m of the subsurface and help to delineate multiple geological layers compared to the exploration 3-D seismic data. Section 1, Figure 3(b) illustrates how 2-D UHR seismic data provide a better image the deeper subsurface and help to delineate multiple geological layers compared to the exploration 3-D seismic data.

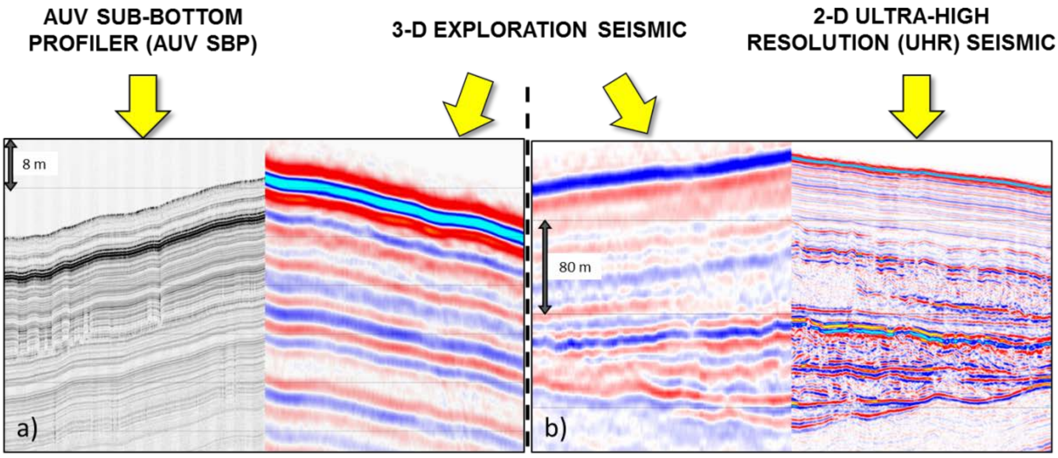
3.1.3 Sub-bottom Profiler

Sub-bottom profilers collect very high frequency single channel acoustic data to produce profiles similar to vertical seismic sections (Section 1, Figure 3). Penetration depths can range from less than 10 m to 100 m, depending on the energy source and the nature of the strata being profiled. SBP data can identify stratigraphic, structural, or geomorphological features, and help identify shallow hazards such as fluid expulsion features and faults. The high frequency signals used by sub-bottom profiles, which are in the kHz range, yield vertical limits of separability values typically on the order of decimeters.

3.1.4 Multibeam Echosounder

Multibeam echosounding sends an acoustic pulse to the seafloor and then records the reflected sound wave. This technique measures the travel time of the pulse from the MBES system to the seafloor, which is further processed to produce a bathymetric surface and a record of the acoustic energy (backscatter intensity) returned to the receiver. Strong backscatter anomalies can represent seafloor sediments that are coarser or denser than surrounding sediments and, in that regard, are similar to seafloor reflection amplitudes from 3-D seismic reflection data. Hull-mounted MBES systems are cost-effective and used for regional surveys because continuous surveying can be completed over a large area; however, their resolution is strongly depth-dependent. Shallow hull-mounted data can be quite good compared to deepwater hull-mounted data. AUV MBES surveys can provide much higher resolution than hull-mounted surveys because they collect data at heights of a few tens of meters or less above the seafloor; however, they are more expensive and time consuming than hull-mounted surveys, and thus, are often used for limited areas identified during preliminary studies.

FIGURE 3
AUV SBP, 3-D Seismic, and 2-D UHR Data Resolution Comparison



3.1.5 Side Scan Sonar

Side scan sonar (SSS) measures the relative reflection strength of sound pulses reflecting off the seafloor. Individual side scan sonar data lines can be overlain to create a mosaic image. The intensity of the reflection energy can give an indication of the composition of seafloor sediments and manmade objects on the seafloor. High reflectivity sonar anomalies (which are typically shown in darker tones on mosaic images) can represent harder or coarser (e.g., sandy) seafloor material when compared to surrounding sediments. Low reflectivity sonar (typically shown as lighter tones on the mosaic images) indicate softer or finer (e.g., clayey) sediments. Side scan sonar is capable of detecting very small and very large features however, specific requirements may request surveys that are capable of resolving features on the seafloor that are at least 1 m long by 1 m wide by 1 m high. The size of a feature that is resolved in side scan sonar is dependent on specific survey parameters such as the speed of the vessel and towfish height.

3.3 Metocean Data

The collection of metocean (meteorological and oceanographic) data should be considered in the early stages of development, because it can take a significant amount of time to obtain relevant data. Wind, waves, or currents can be measured and monitored from the surface to great depths and can change the geomorphic features on the seafloor over the life of a pipeline project. These changing conditions can lead to sediment scouring, static and dynamic loading, loss of support, supply of deposition, and pipeline free-spans that may give rise to damaging vortex-induced vibrations.

Wind, currents, and waves can affect pipeline installation and can also result in changing conditions after the pipeline has been installed. Winds can have a direct effect on currents during storm surges while waves can affect pipelines in shallower waters through soil liquefaction, for instance. Waves in waters less than 150 m are considered a major source of dynamic loads (see Chapter 3, Section 3 of the *Pipeline Guide*) and waves in any water depth will affect the transfer of lay vessel motions to pipeline motions at the seafloor, influencing the as-laid embedment of the pipeline. Currents can affect installation and lead to seafloor scouring, subsequent pipeline free-spanning, and vortex induced vibrations. It is therefore important to have statistical or historic data to properly characterize the metocean conditions along potential pipeline routes. If such data are available and suggest conditions conducive to excessive erosion or sedimentation, that information can be incorporated into the route selection process.

3.5 Coring and In Situ Testing

Thorough interpretation of geophysical surveys is essential for determining the optimal locations for geotechnical and geological cores.

Geotechnical cores are generally used to obtain design level information once a preliminary pipeline route or corridor has been determined to provide an early indication of soil conditions which may be necessary for conceptual design.

Geological cores are intended for detailed stratigraphic and sedimentological logging and age dating that can provide insights into types, numbers, magnitudes, and frequency of geologic events such as mass transport events or turbidity flows affecting a region. Geological cores provide a record of the recent geologic history of a development area or route corridor and changes in geologic conditions over time, which can be used to support decisions about the possible future conditions that should be anticipated. Geological cores can also be used to calibrate geophysical data or help to identify features that are not easily discernible using geophysical data. Geological cores should be used to test specific hypotheses about the geologic setting of the project area rather than to blindly collect information; they can be useful both before and after a preliminary route or corridor has been selected.

To specify the best location, quantity, and type of geotechnical and geological core locations a comprehensive assessment of the study area using the geophysical data and a desk study should be completed. Arbitrary or regularly-spaced core locations may not be optimal because important information may be missed. Cores should be taken where maximum information about the soil conditions and geological processes would be gained.

The different kinds of testing and logging performed on geotechnical and geological cores almost always make them mutually exclusive, and it is highly unusual to use a core for both geotechnical testing and geological logging without significantly compromising one or both aspects. Therefore, geotechnical cores and geological cores should be planned and located separately from each other; however, the cores can be taken close together to obtain information at the same location.

3.5.1 Geotechnical Cores and In Situ Testing

Geotechnical cores and in situ testing provide information about the sediment composition (e.g., carbonaceous versus siliceous), geotechnical index properties such as Atterberg limits, strength, and pore pressure. They can also provide valuable information for analysis such as scour and slope stability assessment.

Geotechnical cores can be taken using a variety of methods that include free-falling, gravity-driven boxes (box cores), piston cores, and jumbo piston cores (JPC), robotic seafloor drilling rigs, and geotechnical drill ships. The piston core (or JPC) device is lowered then gradually placed on the seafloor, at which point the device is triggered and the core barrel falls freely into the sediment. A piston within the core barrel helps to reduce sediment disturbance. A box core can obtain a sample that is 0.3 m wide by 0.3 m long by 0.8 m deep. Piston cores typically have a 3 inch diameter and are about 12 m long. A JPC has a 4 inch diameter and is 30 m long.

Soil samples are retrieved from geotechnical cores and are generally preserved in plastic cylinders or bags to minimize disturbance. Soil properties needed for pipeline design and route determination can be obtained either onboard the geotechnical survey vessel using handheld tools in a basic laboratory, or by returning cores to an onshore soil testing laboratory where both routine and specialized testing should be undertaken.

Piston gravity corers have been used extensively for pipeline soil investigations in deep water. Inspection of the top decimeters of samples, however, often discloses partial loss or remolding of the material, in which case the sample cannot be used for accurate measurements at very low stresses. Concerns have also arisen with jumbo piston corers regarding their capacity to capture subtle changes in the geotechnical parameters in the top decimeters below seafloor, due to possible washing-out of the extremely soft seafloor materials during the initial phase of free-fall penetration.

Box core samples are typically of high quality, but the extremely soft nature of seafloor soils does not allow any sub-sampling without disturbing the material. In situ testing inside the box (using a mini T-bar) is therefore the usual way to obtain relevant shear strength data.

In situ testing using a cone penetrometer (CPT) allows determination of key soil parameters such as undisturbed soil strengths and the soil relative density, and help classify the soils along a considered pipeline route. A piezocone penetration test (PCPT) can also measure excess pore pressure ahead of the cone, which is useful for determining the drainage properties of the soil. Cyclic ‘full flow’ penetrometer testing that uses larger instruments such as T-bars and ball-shaped tools allow for the assessment of strength degradation, which is useful for assessing pipe-soil interaction forces for use in pipeline design, but also for foundation design of related seabed infrastructure.

3.5.2 Geological Cores

Geological cores can provide information about the geological history along a potential pipeline route, for example the age, frequency, and types of depositional events such as mass transport events and turbidity flows; the geological nature of sediments comprising the cored interval; and the existence of geologic hazards that were identified from previous geophysical surveys. Interpretation of geological events from the sedimentary record is specialist work that requires trained and experienced geoscientists; it should not be confused with basic sediment or soil type descriptions obtained from geotechnical testing programs. Samples can be obtained for age dating techniques such as radiocarbon (^{14}C), micropaleontological, or other kinds of absolute dating methods in order to establish the frequency or recurrence intervals of dated events. Establishment of temporal frequencies or recurrence intervals relies on continuous undisturbed cores. Piston cores taken for geohazard logging should be paired with box cores so that the surface material is preserved which is of greatest interest.

3.7 Other Kinds of Surveys

Surveys that provide high-resolution imagery of the seafloor can be performed along a potential pipeline corridor, and can be particularly useful for identifying features that can only be inferred from geophysical data.

3.7.1 Seafloor Video Recordings

Remotely Operated Vehicles (ROVs) are tethered underwater machines controlled by a surface operator. ROVs provide visual access in areas where it would be difficult for other data collection platforms (e.g., AUVs) to maneuver, for example, around steep slopes, highly variable seafloor, or areas with existing infrastructure. ROVs can collect detailed video imagery of the seafloor that can be used to confirm geological or manmade features interpreted from the geophysical data.

3.7.2 AUV Photo Imagery

AUVs and ROVs can collect photographs close to the seafloor (typically from a distance of 7 m to 10 m) that can be geo-referenced and used to create a photomosaic image of the seafloor. A mosaic can be used to assist in calibration of side scan sonar data and verify geological, ecological, or cultural features inferred from geophysical data.

3.7.3 Magnetometer Surveys

Magnetometer surveys that measure magnetic field strength can help detect ferrous (iron-rich) or magnetically susceptible features lying on or buried into the seafloor. A magnetometer is typically towed no more than 6 m above the seafloor and several ship-lengths behind the vessel to avoid erroneous readings associated with the vessel’s magnetic field. Magnetometer surveys are useful for detecting manmade objects such as barrels or shipwrecks, igneous intrusions, and iron-rich channel infill sequences.

3.7.4 Seismic Refraction Surveys

Seismic refraction may provide increased resolution for the upper meters of soil and therefore refine assessment of the soft sediment cover thickness. Seismic refraction provides the compression wave velocity, V_p, of each soil layer. The velocity, V_p, is related to the compactness of sediments and the density, weathering, and fracturing of underlying bedrock. The more compact and the less weathered the rock, the higher the V_p. Compressive wave velocity alone does not differentiate between loose to medium sand and soft clay, and between dense to very dense sand, and firm to stiff clay. Hence CPT test data and cores are still necessary to verify refraction interpretation.

5 Hazard Identification

5.1 Geohazards

A geohazard can be an active geological event such as a landslide or movement along a fault, or a passive geologic attribute such as seafloor roughness (as caused by boulders or sediment waves) that can lead to damage of subsea infrastructure or make construction difficult.

Shallow water and deepwater marine geohazards can be identified using geophysical surveys and knowledge about them can be refined using geological and/or geotechnical cores. The distribution of geohazards varies throughout the world depending on the general and local geological and tectonic setting. Section 1, Figure 4 illustrates a variety of geologically-related hazards (geometric geohazards or geologic geohazards) and geohazard triggers relevant to subsea pipelines. Geometric geohazards are those that can be identified on the basis of calculations alone, for example slope angle or seafloor roughness. Geologic geohazards are modern or past processes such as slope failures, fluid expulsion, or gravity driven sediment flows; they generally cannot be identified on the basis of calculations alone, but instead require interpretation of a variety of geological data describing the nature of the seafloor and underlying strata.

5.1.1 Geohazard Triggers

Section 1, Figure 4 schematically shows geohazard triggers such as earthquakes, hurricane winds, tsunamis, and bottom currents. Natural events such as earthquakes are impossible to accurately predict and are usually analyzed as random processes with annual probabilities of occurrence. Hurricane prediction and trajectory are better understood today than in the past. However, warnings will not help to prevent damage to existing seafloor facilities that are in the path of the hurricane. Thus, historical records of hurricane occurrence must be used to estimate possible future events. Tsunamis are large, fast moving waves that result from earthquakes or landslides. Tsunamis can potentially lead to damage of a pipeline due to wave impact or currents. General metocean effects such as bottom currents can cause sediment mobility resulting in areas of scour on the seafloor.

5.1.2 Geometric Geohazards

Seafloor conditions can be assessed using geometric geohazards (Section 1, Figure 4). In the absence of a comprehensive geological assessment, geohazards that can be identified by calculating attributes from a digital elevation model (DEM) of the seafloor are considered geometric hazards (Section 1, Figure 5). These include seafloor slope (the first derivative of the digital elevation model), seafloor curvature (various formulations exist, but they are in general expressions of the second derivative of the seafloor), or seafloor roughness (also known as rugosity, and a measure of the local variability of the seafloor).

Section 1, Figure 5 provides some examples of geometric geohazards such as seafloor curvature [Figure 5(a)], seafloor roughness [Figure 5(b)], and seafloor slope [Figure 5(c)]. The colors on each example represent the variability of the geometric hazard across the study area. Areas in blue are considered less severe compared to areas in red which are more severe.

Seafloor roughness can be quantified using a variety of measures, each of which has advantages and disadvantages. Seafloor roughness is the variability of a topographic surface at a given scale and an example [shown below in Section 1, Figure 5(b)] can be calculated from the moving window standard deviation of the residual bathymetry. The residual bathymetry is derived from subtracting a geometrically smoothed (averaged) bathymetry from the original bathymetry. Low values of seafloor roughness correspond to areas of gentle sloping seafloor, whereas high values of seafloor roughness correspond to areas of erosion, buried mass transport deposits, sediment waves, or landslides.

Steep seafloor slopes [Section 1, Figure 5(c)] can indicate features such as areas prone to slope failure, seafloor undulations (e.g., sediment waves, buried landslides), edges of erosional channels, and seafloor mounds.

FIGURE 4
Geohazard Examples*

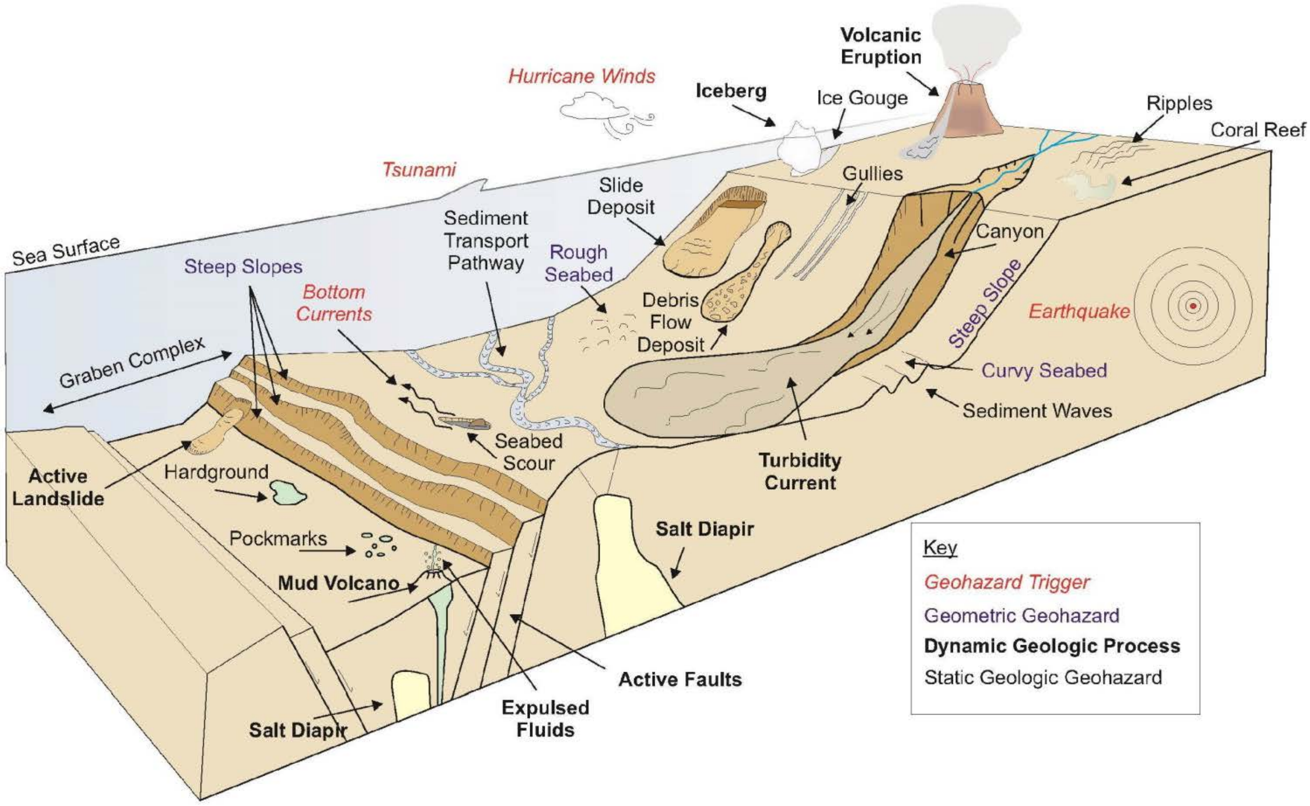
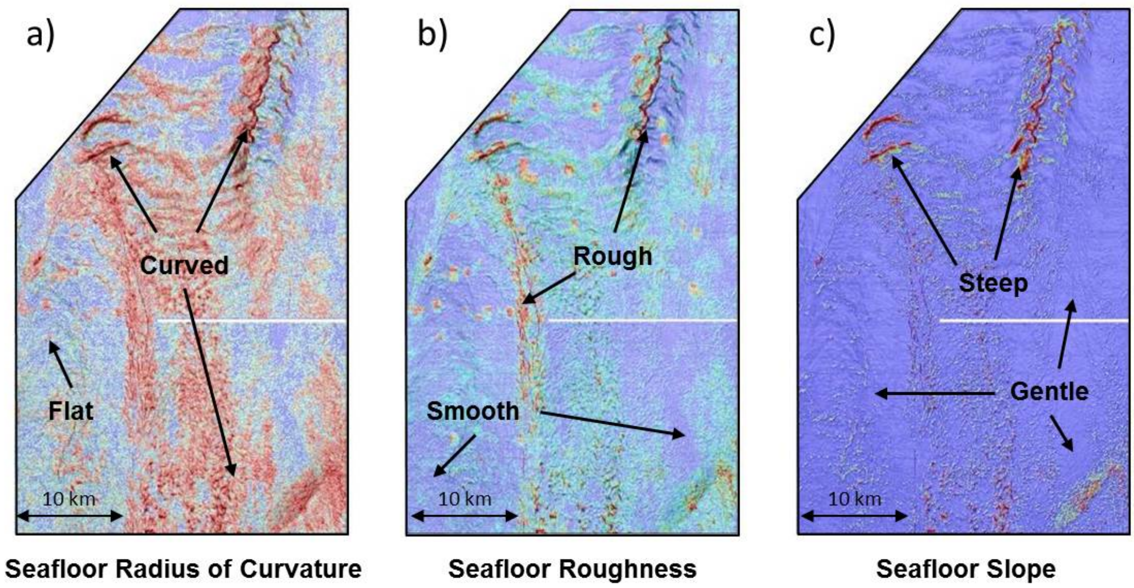


*Figure 4 modeled after: Thomas et al., 2010, Nadim and Kvalstad, 2007, and Chiocci et al., 2011.

FIGURE 5
Example Geometric Geohazards



5.1.3 Geologic Geohazards

Geologic geohazards that can affect pipeline installation and development come in a variety of forms (Section 1, Figures 4 and 5) and can be interpreted from 2-D and 3-D seismic data, AUV MBES bathymetry and backscatter, side scan sonar, and sub-bottom profiler data as well as from geotechnical and geological core logging. Geohazards can be dynamic (or potentially dynamic) or static. It is important to recognize and accurately map the seafloor and shallow subsurface affected by geohazards.

i) *Dynamic and Static Geohazards.* Features or processes that actively affect the modern seafloor such as active fluid expulsion or an area of ongoing sediment deposition (e.g., Mississippi Delta) are considered dynamic geohazards. Dynamic geohazards are associated with geologic processes such as submarine landslides, debris flows, fluid expulsion at the seafloor, and movement along faults. Dynamic geohazards generally cannot be directly observed. Instead, their past occurrence must be inferred from the nature of geologic deposits or stratigraphic relationships produced by the hazardous processes. If dynamic geohazards can be shown to have occurred in the recent geologic past, they must be considered as possible future hazards and incorporated into the pipeline route selection process. If there is no evidence for a geologically recent occurrence of the process, the seafloor geohazards can be considered to be static rather than dynamic. Static geohazards are interpreted geologic features that have a geomorphological influence on the seafloor. These hazards were, at one time, active processes that were forming on or depositing on the seafloor. A feature may be identified as a static geohazard and will likely not be active within the life of an offshore project; however, conditions can change due to unforeseen circumstances such as anthropogenic activity or earth-driven events (meteorological/seismic) and the static hazard could be regenerated and considered dynamic.

Some examples of geohazards are discussed below and are supported with figures or images illustrating an example of the geohazard. Geohazards can be complex entities of process versus depositional unit or feature. The geohazards outlined below define how common nomenclature of geohazards can be interpreted as either dynamic or static. This is not an exhaustive list of geohazards and it is important to recognize that every project area will be unique and have a variety of hazards that require a thorough assessment by an experienced team of geoscientists and engineers.

ii) *Mass Transport Deposits (MTDs)*

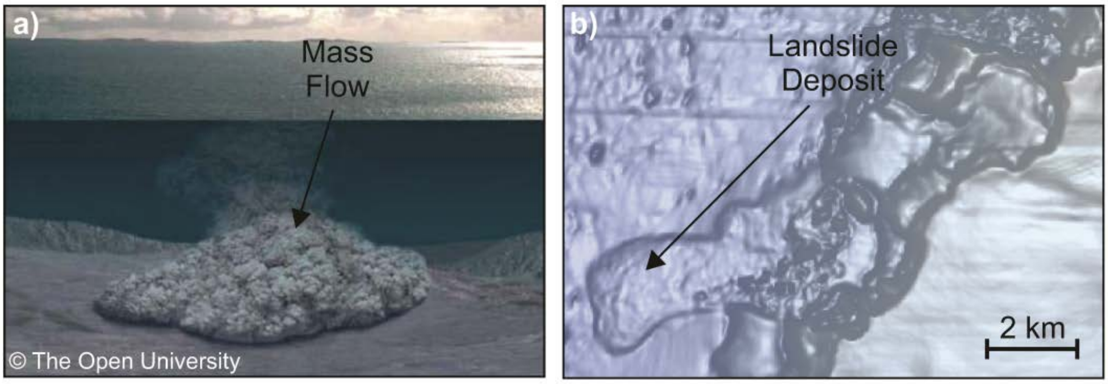
a) *Dynamic:* MTDs result from gravity-driven movement (i.e., a mass flow or failure) of large amounts (millions of cubic meters) of material that is deposited downslope [Section 1, Figure 6(a)]. Some examples of mass flows or failures include: landslides, slumps, debris flows, rockfall, or topple (Section 1, Figure 4). A landslide occurs when a main body detaches from a main scarp along a rupture plane or several rupture planes and stays intact as is moves down slope. Slumps or creep can occur gradationally over time. Debris flows consist of complex mixtures of sediment and debris. These sediment mixtures are dependent on grain to grain contact to support the continuous flow of the debris, which can be transported great distances from their source. Rockfall occurs when material falls from steep slopes and is deposited as large, rubbly blocks. Topple implies masses of material that have detached along a surface and have fallen or toppled onto the seafloor. Mass flows or failures can be generated by tectonic uplift, seismicity, or gravitational collapse due to over-steepening of sediments along steep slopes. Mass failures are prevalent along steep escarpments, canyon walls, or along the margin of graben complexes. MTDs in an area may indicate the potential for future occurrences that may damage pipelines.

- *Effect on Pipeline:* The placement of a pipeline near areas prone to gravity-driven, mass transport events should be carefully evaluated. A pipeline in the direct path of a mass transport event can be moved or seriously damaged. Depending on the orientation of the pipeline relative to the direction of the mass flow, the pipeline may be displaced, compressed, buried, ruptured or scoured if the movement of the mass flow is perpendicular to the pipeline. If the movement of the mass flow is parallel, the pipeline may experience stretching, compression, burial, compression, rupture, or scour.

b) *Static:* The irregular topography and variable geotechnical properties of a mass transport deposit or landslide deposit [Section 1, Figure 6(b)] on the seafloor can have an effect on pipeline route determination. The principal static geohazards associated with mass transport deposits at or directly below the seafloor are moderate to steep-sloped mounds due to bouldery surfaces or deep, steep-sided depressions due to the hummocky nature.

- *Effect on Pipeline:* The steep slope angles associated with the irregular surface of a mass transport deposit can create pipeline free-spans. The heterogeneous nature of mass transport deposits consisting of hard and soft sediments can lead to highly variable geotechnical properties and result in possible displacement or differential embedment of the pipeline.

FIGURE 6
Mass Transport Deposits



Mass Transport (Dynamic)
Mass flows
Image courtesy of The Open University

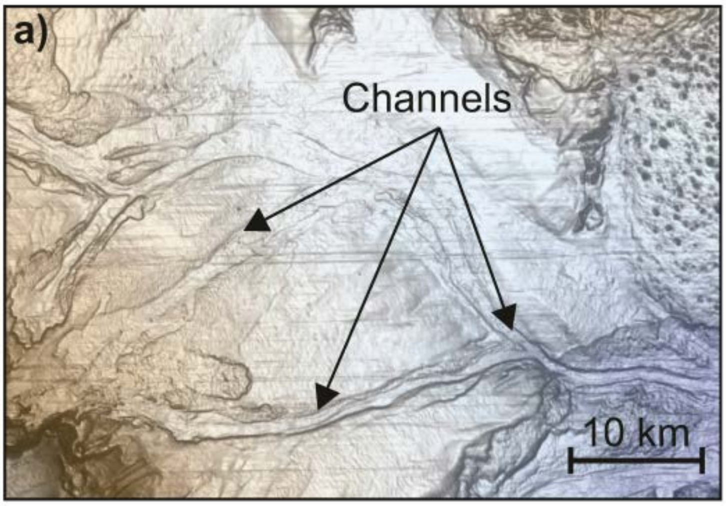
Mass Transport Deposit (Static)
Landslide deposits
Image courtesy of Fugro

iii) *Sediment Transport Pathways*

a) *Static:* Examples of sediment pathways include subsea canyons, complex channel systems [Section 1, Figures 4 and 7(a)], and smaller gullies. Although the pathways themselves are static features, processes that utilize the pathways – such as mass flows or turbidity currents – are dynamic. Flows can move rapidly through the pathways, depositing large amounts of sediment downslope. Canyons and deeply incised channels can range from tens of meters to kilometers in width and have steep, unstable slopes. Gullies can be tens of meters wide and have steep to moderate slopes.

- *Effect on Pipeline:* Potential problems that may arise from placement of a pipeline within or across a sediment transport pathway need to be considered when selecting a route. The location and direction of the crossing are critical. Steep slopes and slopes prone to mass failures should be avoided to the extent possible in order to minimize impact on the pipeline if a failure were to occur. If a pipeline crosses a steep slope it may be susceptible to pipeline free-spans or may become buried, dislocated, or scoured by mass transport deposits due to failure along unstable slopes and flows moving through the sediment transport pathways.

FIGURE 7
Sediment Transport Pathways



Sediment Transport Pathways (Static)
Channels
Image courtesy of Fugro

iv) *Sediment Erosion and Deposition*

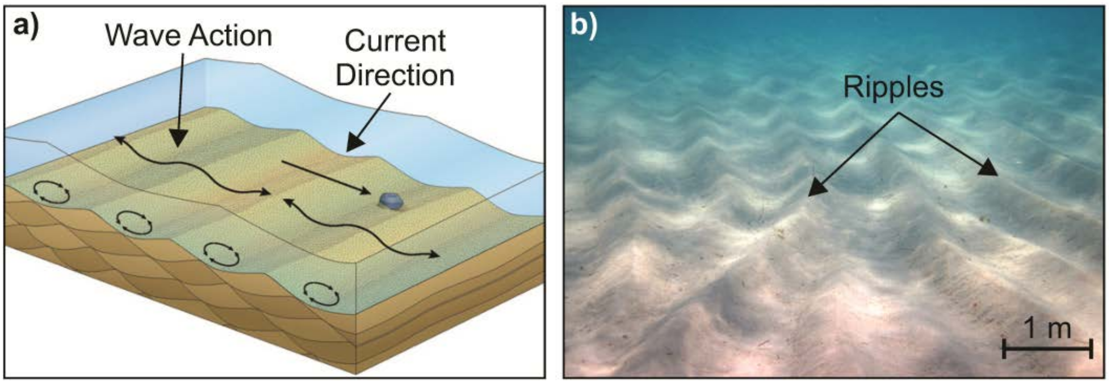
a) *Dynamic:* Active processes such as hurricanes, tsunamis, wave action, or bottom-currents [Section 1, Figures 4 and 8(a)] can cause erosion and deposition through the initiation of turbulent fluidized flows and sediment mobility. Active processes can occur as a consequence of tidal or wave action and currents, which can generate undulating deposits of ripples, sand waves, or sediment waves. Sediment waves are undulating, depositional and dynamic bedforms that are formed beneath a current flowing at, or close to, the seafloor. Sediment waves are thought to have formed from repeated downslope-flowing turbidity currents or along-slope-flowing bottom currents. Turbidity currents are fast-moving, fluidized flows comprising a turbulent mixture seawater and sediment. Continuous deposition from turbidity currents results in a seafloor that is typically scoured or covered by depositional lobes of sediment known as turbidites.

- *Effect on Pipeline:* Erosion can lead to burial, displacement, scour and undercutting of the seafloor below the pipeline, creating unsupported pipeline spans and loss of support. Deposition of sediment can lead to compression, burial, or possible rupture of a pipeline or differential loading of slopes, potentially making the slopes unstable. Continuous sediment deposition or movement of sediment waves may lead to pipeline free-spans, and can create difficulties in designing reliable solutions for a pipeline that expand and contract during cycles of thermal loading.

b) *Static:* Ripples [Section 1, [Figure 8(b)], sand waves, or sediment waves (Section 1, Figure 4) that have resulted from past erosion and deposition can produce undulating or irregular seafloor topography. The geotechnical properties of the seafloor may be quite variable due to the heterogeneity of the sediments.

- *Effect on Pipeline:* Undulating seafloor is generally not considered a significant hazard to pipelines; however the uneven nature of the seafloor can lead to pipeline free-spans. Areas that are not obviously mobile may become so post-installation due to changes in the local hydraulic regime.

FIGURE 8
Erosion and Deposition



Erosion and Deposition (Dynamic)
Waves, currents
Image courtesy of Fugro

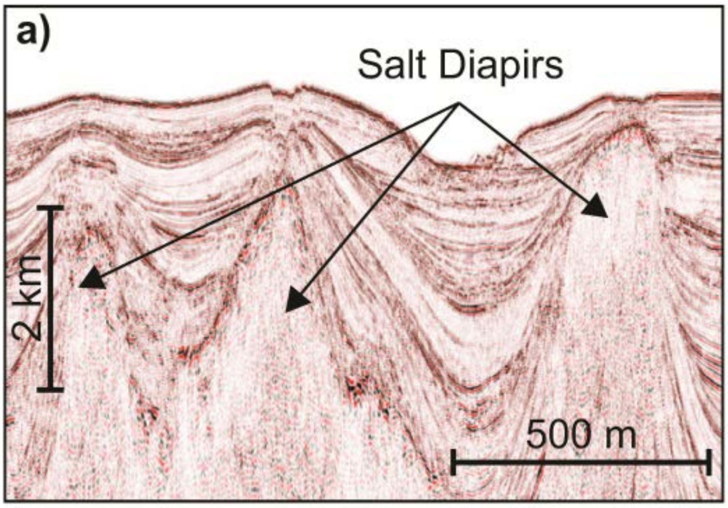
Undulating Seafloor (Static)
Ripples/sand waves
Photograph courtesy of James St. John, Ohio State University at Newark.

v) *Tectonic Effects*

a) *Dynamic:* Active tectonic processes can lead to earthquakes, liquefaction on the seafloor, strain softening of sediments, and long term excess pore pressures. Salt upwelling (known as diapirism) is common in some sedimentary basins such as the Gulf of Mexico. Salt is more buoyant than the overlying sediments and can move upward to create domes and ridges on the seafloor [Section 1, Figure 9(a)], or outwards and can withdraw leaving behind significant basins. Salt tectonic activity is, in many ways, different to regional plate tectonics; it is governed more by the effects of regional slope, vertical loading (in response to fluctuating sediment input), and the nature of the original salt deposit. Uplift zones associated with ongoing tectonic activity are dynamic geohazards because they may create conditions conducive to chronic large-scale slope failure. Many tectonically active basins (e.g., along the Banda Arc) feature recurrent, small landslides. Whereas passive margins slopes may have low angle slopes, slow rates of sediment accumulation, limited tectonic modification (if any), yet they feature some of the largest mass movements on Earth (e.g., Storegga, Norway, or the northwest African margin).

- *Effect on Pipeline:* Earthquake activity can liquefy the seafloor, leading to pipeline displacement, free-spans, possible rupture, and overstressing of connections to other infrastructure. Areas with active salt movement can have steep slopes prone to landslides that can result in burial, compression, or rupture to the pipeline.

FIGURE 9
Tectonic Effects



Tectonic Effects (Dynamic)
Salt diapirs
Image courtesy of Fugro

vi) *Faults*

a) *Dynamic:* Faults form in environments such as subsiding basins or areas of uplift associated with salt diapirism. Faults can be normal, reverse, growth, strike-slip, or polygonal or a combination of any of these. Normal faults [Section 1, Figure 10(a) and 10(b)] form when a large mass (hanging wall) moves downward relative to another mass (footwall) along a fault plane, and are most common in areas undergoing uplift or regional extension. Reverse faults form when the hanging wall moves upwards relative to the footwall and tend to be common in regional fold belts. Strike-slip faults have only horizontal movement along the fault plane. Polygonal faults can form as a result of sediment compaction and dewatering.

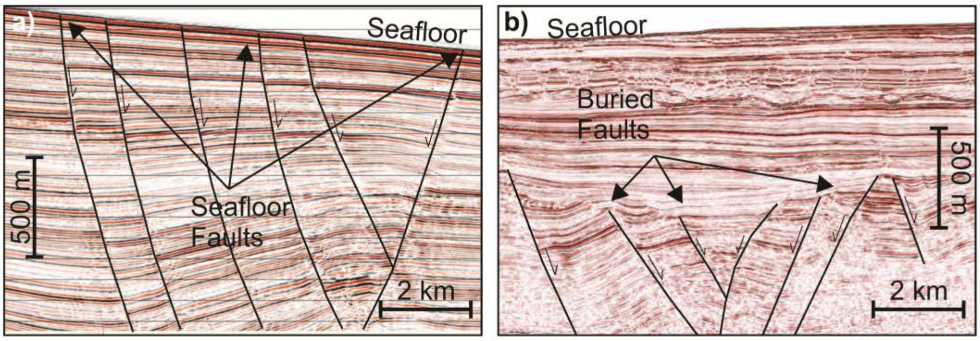
Different criteria may exist for what is considered a dynamic or active fault. The California Department of Conservation and California Geological Survey (CGS) considers a fault active when it has had recent geological movement, for example, evidence of movement within the Holocene (< 11,000 years before present) (CGS, 2007) or potentially active if there was any surface displacement during the Quaternary (< 1.6 million years). With the absence of age-dating to verify the last movement or recurrence interval on a fault, other indications such as the offset of the hemipelagic drape or faults that extend to the seafloor [Section 1, Figure 10(a)] may be considered active. These faults require additional investigations to establish their date of last movement, average slip rate, and likelihood of movement during the life of a pipeline. If such investigations cannot be undertaken prior to pipeline route determination, faults cutting the seafloor should be considered active.

- *Effect on Pipeline:* A pipeline that is laid across a fault may be susceptible to pipeline free-spans, stretching, displacement, or rupture if there is any significant movement along the fault during the life of a pipeline. The distinction between normal and reverse faults is important because normal fault movement will stretch a pipeline built over a fault scarp whereas reverse fault movement will shorten or buckle a pipeline built over a fault scarp. The can also affect the stability and integrity of any structure connected to the pipeline.

b) *Static:* A fault with no recent geological movement (> 1.6 million years before present) is considered an inactive fault [Section 1, Figure 10(b)]. Typically these faults have been significantly buried by younger sediments and have no direct impact on a pipeline, however may have had an impact on the current topography of the seafloor.

- *Effect on Pipeline:* A pipeline that is laid across an area where an inactive fault has previously shaped the seafloor, such as along steep fault scarps, may be susceptible to pipeline free-spans.

FIGURE 10
Faults



Active Faults (Dynamic)
Normal seafloor faults
Image courtesy of Fugro

Inactive Faults (Static)
Buried normal faults
Image courtesy of Fugro

vii) *Fluid Expulsion Features*

a) *Dynamic:* Actively forming features created by gas, fluid, or sediment expulsion onto the seafloor include mounds, craters (mud volcanoes), or depressions (pockmarks). Fluid expulsion mounds form as fluid is discharged onto the seafloor to create a mound higher than the surrounding seafloor. Expulsion features commonly occur near or along faults that provide fluid migration pathways from deep petroleum paleobasins, and are most common above subsurface accumulations of pressurized fluid. Mud volcanoes [Section 1, Figure 11(a)] are conical shaped mounds that have a central crater or flanking feeder pipes that discharge fluid. Pockmarks are localized, circular to elliptical seafloor depressions interpreted as seafloor expressions of hydrocarbon-bearing fluid expulsion. The elongated shape of many pockmarks may be controlled by seafloor currents or be evidence of fluid flow along buried faults. Pockmarks are typically tens to hundreds of meters in diameter and tens of meters deep, however, can become in-filled with mobile sediments over time, creating highly heterogeneous soil conditions along a pipeline route.

Hardgrounds around seafloor gas vents may consist of deepwater benthic communities. Upwelling fluids containing chemically reduced hydrocarbons may react with shallow sulfate-rich pore fluids to create carbonate nodules, chimneys, and mounds at or near the seafloor and are often associated with active or fossil chemosynthetic communities. These communities may also be associated with gas hydrate accumulations and/or outcrops of authigenic carbonate. Deepwater benthic communities typically include tubeworms, clams, mussels, bacterial mats, and/or other types of burrowing invertebrates. In some regions such as the Gulf of Guinea, these communities can create stiff surficial crusts due to overconsolidation of fecal pellets, for example.

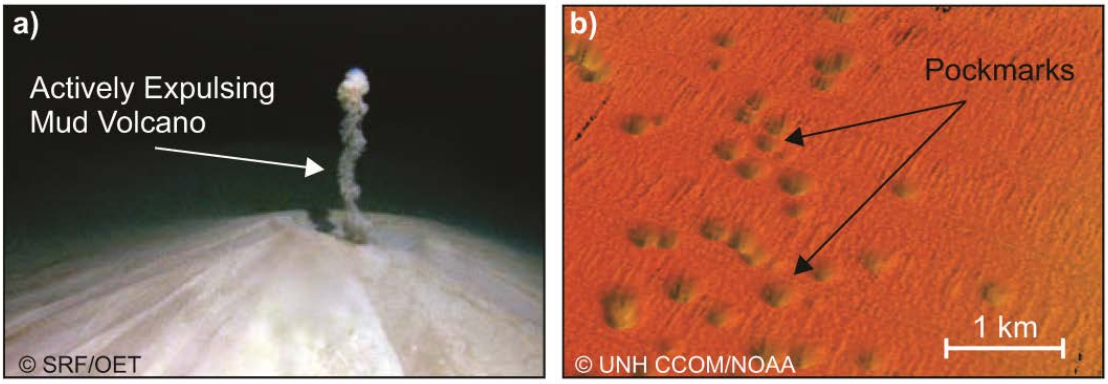
It is also important to consider the potential corrosive effects, variable soil conditions (e.g., hardgrounds or soft gassy soils), and environmental issues (e.g., chemosynthetic communities that may be protected by law) of active expulsion areas.

- *Effect on Pipeline:* In addition to the possibility of future fluid expulsion, seafloor expulsion features such as pockmarks may cause vertically, laterally, and temporally variable soil strength, which might create difficulties for the installation of pipelines. Pipeline free-spans may result from the steep sides associated with fluid expulsion features. Hardgrounds may lead to abrasion or differential embedment on the pipeline if the pipeline walks or laterally buckles during the lifetime of development. Surficial crusts can also impact the pipe-soil resistance used in lateral buckling analysis.

b) *Static:* Features created by past expulsion of gas, fluid, or sediment onto the seafloor include mounds, craters, or depressions [Section 1, Figure 11(b)]. These remnant expulsion features lead to irregular seafloor, steep-sided mounds, and steep-sided depressions. Areas with fossil chemosynthetic communities may have resultant hardground with variable geotechnical properties.

- *Effect on Pipeline:* Remnant expulsion features that have no evidence of current activity may cause problems such as pipeline free-spans. Hardgrounds may lead to abrasion or differential embedment on the pipeline if the pipeline walks or laterally buckles during the lifetime of development.

FIGURE 11
Expulsion Features



Fluid Expulsion (Dynamic)
Mud volcano
Photo courtesy of Sea Research Foundation (SRF) and the Ocean Exploration Trust (OET)

Past Fluid Expulsion (Static)
Pockmarks
Image courtesy of Center for Coastal and Ocean Mapping (CCOM) Joint Hydrographic Center (Mayer et al., 2010)

viii) *Volcanic Activity*

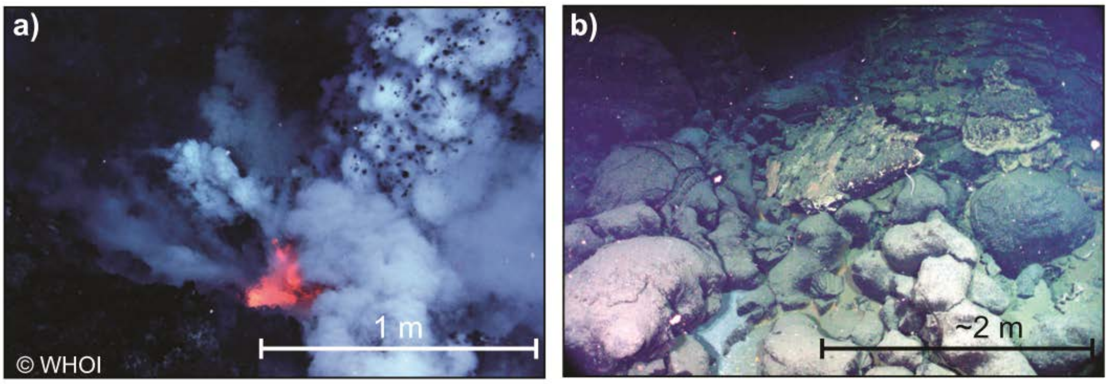
a) *Dynamic:* Petroleum pipelines would typically not be routed in areas of active volcanism; however it is important to know the regional setting and whether the possibility of volcanic eruptions exists. The seismic activity associated with volcanic eruptions may be important, as is the triggering of flank failures that may be caused by eruptions, growth and instability of the magma chamber in the period preceding an eruption (e.g., Canary Islands, NW Africa). An active eruption can eject lava or create subsea pyroclastic flows [Section 1, Figure 12(a)]. Effusive subsea volcanic eruptions originate from an active volcanic vent and form massive to pillowed lava flow deposits. Explosive or pyroclastic subsea volcanic eruptions are violent occurrences that discharge ash, gasses, and tephra. Subsea pyroclastic flows can move like mass flows and deposit large amounts of material far from the volcanic vent. Subaerial pyroclastic eruptions are initially deposited on land; however, these fast moving flows can enter the sea and continue as subsea mass transport deposits.

- *Effect on Pipeline:* A subsea pyroclastic deposit could bury, compress, and/or rupture a pipeline due to their speed, density, and abundant debris. An active, underwater volcanic effusive flow may bury, compress, and/or rupture the pipeline.

b) *Static:* A seafloor comprised of volcanic deposits is generally irregular, hard, and rough with steep topography [Section 1, Figure 12(b)]. The principal static geohazards associated with volcanic deposits at or just below the seafloor are moderate to steep-sloped mounds due to blocky surfaces or deep, steep-sided depressions due to the hummocky nature and heterogeneity of the deposit.

- *Effect on Pipeline:* Volcanic extrusions and resultant material from past eruptions can be a routing hazard due to rock strength and the irregular shape of the seafloor topography. Pipelines may be susceptible to displacement or pipeline free-spans.

FIGURE 12
Volcanic Activity



Volcanic Activity (Dynamic)
Active lava eruptions
Photo courtesy of Joseph Resing, Univ. of Washington NOAA, NSF/AIVL/ ROV Jason©2009 Woods Hole Oceanographic Institution (Resing et al., 2011)

Volcanic Seafloor Deposits (Static)
Volcanic Flow deposits
Image courtesy of Submarine Ring of Fire 2002, NOAA/OER.

ix) *Sea Ice*

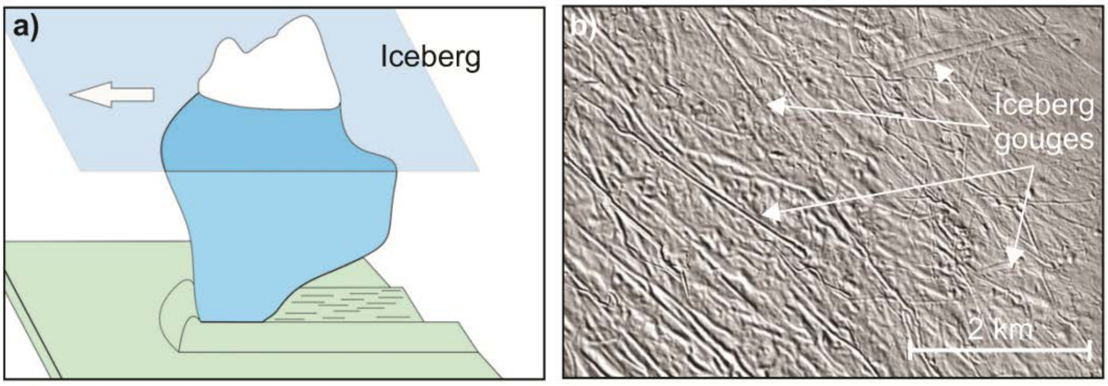
a) *Dynamic:* Ice pans or icebergs are large floating masses of ice derived from arctic environments. Near-shore sea ice can build up pressure ridges. In shallow water environments, both icebergs and sea ice can lead to scouring or ice gouging of the seafloor [Section 1, Figure 13(a)]. Scouring can also occur when a vertical hole is present in sea ice and a downward jet-like, buoyancy-driven drainage of flood water creates a vortex and results in a scoured depression on the seafloor. These features, known as strudel scours, can be more than 4 m deep and as much as 20 m wide.

- *Effect on Pipeline:* Icebergs and sea ice are not considered geohazards to pipelines in deepwater settings (in water depths in excess of 200 m). However, icebergs and pressure ridged sea ice in shallow waters may scour around or rupture an existing pipeline. A buried subsea pipeline may become exposed and lead to an unsupported span if a sufficiently deep strudel scour develops directly above the pipeline. A strudel scour located directly above a buried pipeline can also remove the backfill material that is needed to prevent damage from ice gouging and upheaval buckling. Areas of intense ice gouging and strudel scouring should be avoided when selecting a subsea pipeline route.

b) *Static:* Past evidence of ice effects such as gouges [Section 1, Figure 13(b)], strudel scours, and deposition of large debris such as boulders (dropstones) can have a pronounced effect on the shape of the seafloor. Areas that were once shallower may have been more prone to ice gouging or strudel scours; however are deep enough at present to not be affected by dynamic ice effects.

- *Effect on Pipeline:* Pipeline free-spans can occur in bouldery areas or areas of intense ice gouging and strudel scouring.

FIGURE 13
Sea Ice



Ice Transport (Dynamic)
Iceberg actively scouring seafloor
Image courtesy of Fugro

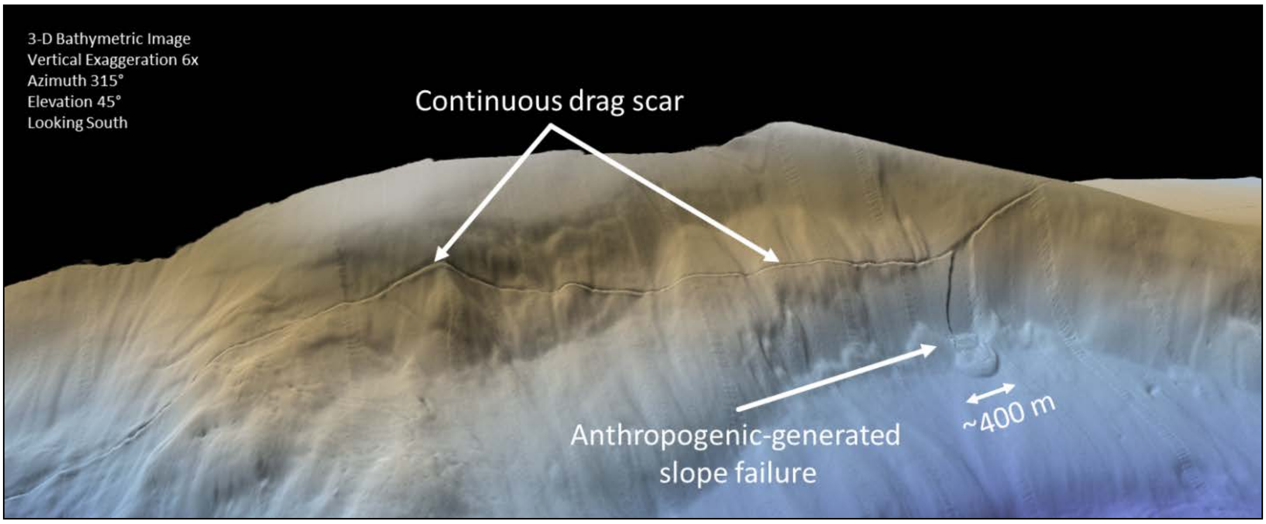
Ice Geohazards (Static)
Ice gouges
Image courtesy of the Geological Survey of Canada and C-CORE

5.3 Manmade Hazards

Manmade hazards can include subsea infrastructure (e.g., existing pipelines, manifolds, platform legs), areas affected by marine industries (e.g., fishing/trawling/shipping activities), military debris (e.g., unexploded ordnance), drag scars, and industrial debris or waste. Anthropogenic loading of, or impact along, steep unstable slopes may lead to slope instability and subsequent mass failure events (Section 1, Figure 14).

Geometrically intricate features identified on high-resolution geophysical surveys such as SSS, MBES and SBP can be interpreted as manmade objects. Magnetic anomalies on the seafloor may also be interpreted as possible manmade objects. Manmade objects identified from the geophysical data can be validated with ROV or AUV surveys using video or photography of the seafloor to accurately identify manmade hazards of significance. Certain areas throughout the world, for example former war zones or areas plagued by shipwrecks, may require specific avoidance criteria of manmade hazards by subsea infrastructure which can be taken into consideration during the pipeline route determination.

FIGURE 14
Anthropogenic-Generated Slope Failure



5.5 Effect of Geohazards on Pipelines and General Responses

The most important reason for properly selecting a pipeline route is to minimize, if not eliminate, the risks associated with hazards identified between pipeline termini. Route selection should reduce the number of hazards encountered while also considering their possible effects on the pipeline.

Section 1, Table 2 summarizes a number of geohazards and the effects they might have on a pipeline during or after construction. If geohazards cannot be avoided, additional and more detailed geophysical surveys, an ROV inspection, and geohazard or geotechnical core samples should all be considered as part of the route selection, evaluation, and refinement process. Engineering design and, most specifically the analyses performed in order to assess the effects that the identified geohazards may have on the pipeline, must also consider the possibility of variable soil geotechnical properties associated with static and dynamic geohazards.

TABLE 2
Potential Pipeline Geohazards and Manmade Hazards and Response to Their Effect

Hazards	*Effect on Pipeline*	*Response*
	Geohazards (Dynamic and Static)	
Shallow water	Susceptible to near-shore oceanic conditions and anthropogenic activities in shallow water	Trench or bury pipelines
Deepwater	High pressures, lack of visibility, difficult environment in deep water	Avoid deepwater routes if possible
Seafloor curvature	Development of pipeline free spans.	Avoid or mitigate for curved seafloor
Seafloor roughness	Development of pipeline free spans.	Avoid or mitigate for rough seafloor
Seafloor slope	Development of pipeline free spans, pipeline stretching.	Avoid or mitigate for steep slopes
Mass transport deposits	Burial, compression, pipeline displacement, pipeline-structure connection overstress, stretching, rupture, scour, development of pipeline free spans.	Avoid areas of known mass transport deposits and mitigate for rough terrain
Sediment transport pathways	Burial, compression, pipeline displacement, pipeline-structure connection overstress, rupture, scour, development of pipeline free spans.	Avoid sediment transport pathways or mitigate to cross pathways at an optimal angle
Sediment erosion/deposition	Burial, pipeline displacement, pipeline-structure connection overstress, rupture, scour, development of pipeline free spans.	Avoid or mitigate. Metocean monitoring and modeling is required.
Tectonic Effects	Burial, compression, pipeline displacement, pipeline-structure connection overstress, rupture, scour, development of pipeline free spans.	Avoid or mitigate
Faults	Pipeline displacement, pipeline-structure connection overstress, stretching, rupture, development of pipeline free spans.	Avoid or mitigate to cross faults at an optimal angle
Fluid expulsion features	Pipeline displacement, pipeline-structure connection overstress, development of pipeline free spans.	Avoid or mitigate
Volcanic activity	Burial, compression, rupture, pipeline displacement, pipeline-structure connection overstress, development of pipeline free spans.	Avoid areas with active volcanism
Sea Ice	Scouring, rupture, development of pipeline free spans.	Avoid areas with frequent ice or bury pipeline to appropriate depth below potential gouge
	Manmade Hazards	
Military debris (e.g., unexploded ordnance)	Pipeline displacement, rupture	Avoid by specific distance criteria
Industrial debris	Development of pipeline free spans, pipeline displacement, rupture	Avoid by specific distance criteria
Marine industries	Pipeline displacement, rupture	Avoid by specific distance criteria
Subsea infrastructure	Development of pipeline free spans, rupture	Avoid by specific distance criteria

7 Other Routing Considerations

7.1 Ecological and Environmental Constraints

Ecological constraints can affect route selection by prohibiting or limiting installation across environmentally sensitive areas. Certain ecological habitats are protected throughout the world and specific areas may require protection and specific avoidance criteria by subsea infrastructure. These may include but are not limited to protected waters and near-shore areas, environmentally sensitive areas, fishing areas, benthic communities in deepwater settings, and coldwater corals.

7.3 Cultural Constraints

Cultural constraints must be considered during route selection because they can directly affect the prosperity and well-being of the public and communities in the vicinity of the development. Installation and operation of a pipeline, for example, can affect commercial or subsistence fishing opportunities. Shipwrecks, ordnance disposal areas, chemical waste disposal areas, tourist attractions or other features of historical or archaeological significance may also have specific avoidance criteria. Mining or dredging operations, existing infrastructure, pipelines or cables on the seafloor, and oceanographic monitoring devices are other examples of cultural constraints that may be affected by development of a new pipeline. Respect of cultural values is important if agreeable relationship between industry and the general public is to be maintained.

7.5 Pipeline Curvature Constraint

Pipeline curvature constraint is the minimum acceptable horizontal radius of a pipeline, which is, in general, the minimum radius a pipeline installation vessel can lay the pipeline. The radius can be considered in both route selection and optimization so that the installation can be carried out along the proposed route option.

7.7 Project-Specific Constraints

The stakeholders may add project-specific constraints related to internal policies, project requirements, industry standards, or local regulations. Project-specific constraints may include: user defined avoidance distances of specific features; specific angles at which the route must cross faults, canyons, or steep slope avoidance of land crossings (e.g., an island along an otherwise optimal route); avoidance of existing third-party infrastructure (or connection to existing third-party infrastructure); or avoidance of specific geologic, ecological, or cultural features not already restricted by governing agencies. Project-specific constraints can be incorporated into the route selection process to satisfy the requests from the Owner.

7.9 Onshore Routing

Many subsea routes tie back to onshore facilities and onshore geohazards, cultural, and environment constraints must be taken into consideration when selecting a route. This can be done following procedures similar to those outlined for subsea routing; however, a detailed discussion of onshore route determination is beyond the scope of these Guidance Notes.

SECTION 2 Methods for Route Determination

1 Route Determination Options

Because the evaluation of different factors constraining route determination is a specialized task that lies beyond conventional geotechnical and pipeline engineering activities, the project Owner or its engineering consultant may need additional specialty consultants or in-house experts to assist in the route selection or optimization process and to guide the selection of the optimal route from a limited set of feasible routes.

Qualitative route selection can be performed based on visual assessment of geohazard, geological, or other types of supporting maps and by subsequently drawing a line on the map between two termini and avoiding hazardous areas. This method is solely based on the experience and judgment of experts. This kind of qualitative route selection is not recommended because it is highly subjective, its results are generally not easily reproducible, and it is difficult to assess the sensitivity of the selected route to uncertainty in the information used to guide route determination.

Semi-quantitative route selection can be based on the construction of a composite cost surface, as described in Subsection 3/1, and then using the cost surface to guide manual selection of a route. Although considerable subjectivity remains, the composite cost surface approach introduces a logical structure that is much more amenable to sensitivity analysis than purely qualitative route selection. It is considered to be an acceptable approach in an early stage, notional evaluation of routes; or for more advanced stages in areas of limited geological, ecological, and cultural complexity.

The quantitative method of route selection suggested in these Guidance Notes uses the “least-geocost path techniques” to determine the optimal route across a composite cost surface. Although it cannot completely remove all subjectivity from the process it relies upon a structured logical framework to create a composite cost surface (which facilitates revisions as new information becomes available and is also amenable to sensitivity analysis) with quantitative determination of the lowest cost route for the available input. Least-geocost path optimization methods have been used to evaluate options for a variety of transportation corridors including deepwater petroleum pipelines, onshore petroleum pipelines, power lines, sewer lines, and roads.

Advanced applications of this method have incorporated resampling based geostatistical simulation of equally probable cost surfaces as a means of evaluating sensitivity of the optimal route to input cost surface uncertainty.

1.1 Required Input

The input required for the route determination procedure suggested in these Guidance Notes includes the locations of two pipeline termini and a composite geocost map as described in the following section. GIS software (as listed above) with the capability to perform raster analysis and least-geocost path optimization is also required in order to apply the described procedures.

1.3 Required Software

The methods described in this document are best implemented using GIS (Geographic Information System) software to store, organize, and analyze the geospatial data supporting the route determination. Several free open-source (e.g., GRASS, QGIS, and SAGA) and commercial (e.g., ArcGIS, ERDAS Imagine, and IDRISI GIS) options are currently available. GIS software is highly specialized and, like many other kinds of specialty software, requires significant training and experience to be properly used to its full potential. This is particularly true if the input map data uses different map projections, coordinate systems, data types, file formats, or resolutions. The project owner may find it useful to retain qualified GIS analysts to support the work.

3 Geocost: Geohazard, Cultural, and Ecological Classification

Geohazards, cultural constraints, and ecological constraints can be classified and weighted after they have been mapped. Because each project will be different, not all of the hazards described in Subsection 1/5 will be encountered in all projects nor will they always receive the same weights. Ranking and weighting of individual geohazards should be performed collaboratively by a project team that includes, as appropriate: specialists in engineering geology, geotechnical engineering, pipeline engineering, geohazard assessment, seafloor geomorphology, marine geology, marine ecology, and marine archeology.

Geocosts are typically classified from low to high using a weighting scheme, for example with 1 as low and 10 as high based upon inferred significance (see Section 2, Table 1). Section 2, Table 1 gives examples for landslides deposits with variable radiometric ages and recurrence intervals and variable geomorphological signatures. A landslide deposit that is smooth and geologically old will have a lower geocost compared to a landslide deposit that is rough and geologically young. The weight assigned to any particular hazard will likely vary from project to project because the geological details and context will differ.

TABLE 1
Descriptions for Geocosts

*Geocost**	*Hazard Level*	*Geohazard Example – Landslide Deposit*	*Mitigation*
1	Negligible	Smooth surface, inferred to be geologically very old, radiometric age dates suggest no geologically recent movement.	Avoidance unnecessary. Possible to mitigate using engineering solutions if necessary.
2	Low Hazard	Smooth surface, inferred to be geologically old, no radiometric data available.	Mitigation using engineering solutions depends on site specific details, avoidance should be considered but not necessary.
3			
4			
5	Moderate Hazard	Rough surface, inferred to be geologically young, geological evidence (seafloor fractures) suggests movement in the past 11,000 years.	Mitigation using engineering solutions depends on site specific details, avoidance recommended
6			
7			
8	High Hazard	Rough surface, inferred to be geologically very young, radiometric age dating suggest evidence of geologically recent movement, geological evidence of recent movement (numerous seafloor fractures).	Mitigation is not practical – avoidance strongly recommended
9			
10			
N/A	Impermissible Zone	Geological evidence suggests frequent occurrence of landslides, area deemed to be impassable.	Mitigation not applicable - complete avoidance

* *Note:* The allocation of geocosts is dependent on the specific site details and the experience and preference of the project team assessing the geohazards. The geocost values used in this example (1 to 10) are arbitrary. However, all assessed geohazards must comply with a consistent numerical assignment. The assignment of numerical geocosts to specific geohazards is based upon the size or potential severity, likelihood of future occurrence, and geological age of the hazards as they may impact the performance or safety of a pipeline.

Geohazards can be classified by assigning geocosts based on the severity of the impact to the pipeline. For example, development of pipeline free-spans as a consequence of an irregular seafloor is not as hazardous as a debris flow or landslide that could impact and rupture the pipeline. Therefore, the irregular seafloor will have a lower geocost compared to an area with known past occurrences of potentially damaging subsea landslides. The likelihood of occurrence and magnitudes of events, both important elements of hazard assessment, should be incorporated into the weighting scheme to the extent possible.

Cultural or ecological considerations should likewise be classified based on their degree of sensitivity. Areas designated as restricted can be completely omitted from the routing analysis, such that no routes are permitted through those areas. Areas across which passage is strictly forbidden can be assigned an effectively infinitely high cost by assigning Null or No Data values in GIS maps, thus completely eliminating them from consideration.

Section 2, Table 2 shows some typical geocosts used in a deepwater pipeline routing project, sorted by geohazard type then severity of impact to the pipeline. The listed costs consider a scale from 1 to 10 for all geohazards. Hence, additional proportional weighting can be used to differentiate between each geohazard.

TABLE 2
Examples of Typical Geocosts for Subsea Geohazards

Geohazards	*Geocost*
Seafloor Slope 0° to 3°	1
Seafloor Slope 3° to 5°	2
Seafloor Slope 5° to 10°	4
Seafloor Slope 10° to 15°	8
Seafloor Slope 15°+	10
Older Seafloor Scours	3
Older Sediment Wave Area	3
Young Mass Transport Deposit	10
Large Landslide Deposit	10
Seafloor Fault	10
Active Fluid Expulsion Feature	10
Active Seafloor Channel	10

3.1 Composite Geocost Map

A composite geocost map is typically a combination (e.g., sum, product, or average) of several coincident individual or component geocost maps with geohazards compiled into one map. Various types of combinations exist and rely on Multi-Criteria Decision Methods (MCDM) or Multi-Criteria Decision Analysis (MCDA), Analytical Hierarchy Process (AHP), or Multiple Attribute Utility Theory (MAUT).

The creation of a digital composite map can be accomplished in a GIS program by adding individual stacked raster cells (Section 2, Figure 1). Each box of the composite map should represent a corresponding area of the seafloor. Rasters represent geographic features by dividing them into discrete square or rectangular cells (pixels) laid out in a grid. The raster cell size is primarily based on the resolution of the data from geophysical survey. Resolution of the prevailing survey practices are listed in Section 1, Table 1.

Each pixel has a value that is used to represent some characteristic of that location, such as elevation or slope angle. Geological features depicted as vector features in GIS comprising polygons, lines, and points can be converted to raster maps and included in the composite. Section 2, Figure 1 demonstrates how raster cells with the same spatial reference can be combined to create a geocost composite map. The upper left corner square in Component Map 1 (Geocost 5) is added to the upper left corner square in Component Map 2 (Geocost 1) to total 6. The value 6 is averaged using the number of raster maps used (in this example, 2 maps are used) to give a Geocost of 3 in the upper left corner of the Geocost Composite Map. The composite map delineates areas of high cost (low favorability) and low cost (high favorability) across the project area and serves as a critical piece of input for the route determination.

FIGURE 1
Composite Geocost Map Premise

5	6	5
1	3	8
6	8	9

Geocost Component Map 1

+

1	8	7
7	7	8
6	2	5

Geocost Component Map 2

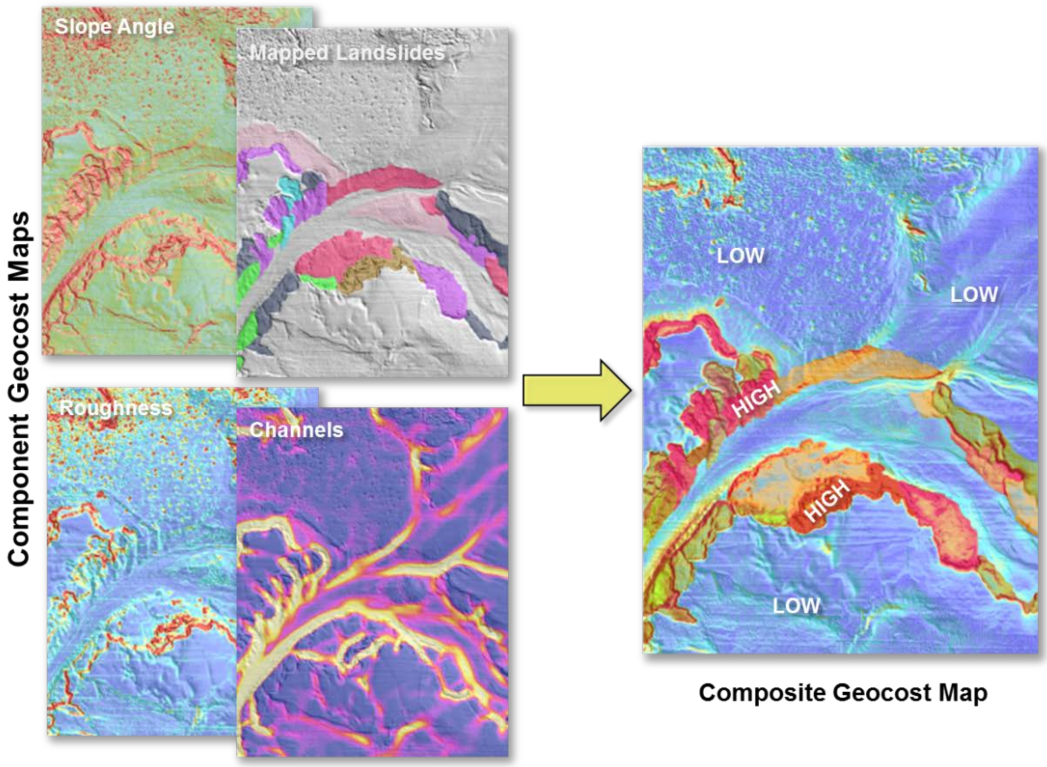
=

3	7	6
4	5	8
6	5	7

Averaged Geocosts Composite Map

Section 2, Figure 2 illustrates how multiple weighted individual geocost component maps are added together to create a composite geocost map. Implicit in the method is the assumption that the distribution of values across the composite geocost surface is proportional to the combined costs of characterizing, designing, building, operating, and maintaining the pipeline being routed. The composite geocost map is the fundamental input for least-geocost path determination of optimal pipeline routes; however, it can be used to evaluate pipeline routes that have been selected by manual approaches as well.

FIGURE 2
Composite Geocost Map



5 Route Selection

There are three acceptable methods to identify and select potential routes once the relevant geohazards in the project area have been mapped and classified, and once a geocost composite surface has been generated:

i) Using manual route selection guided by a composite cost surface

ii) Using least-geocost path route optimization based upon one or multiple composite cost surfaces

iii) Using stochastic simulation

5.1 Manual Route Selection

One or more candidate pipeline routes can be developed using the available hazard maps to create a composite geocost map; then pipeline route options are manually drawn on the composite geocost map from terminus to terminus. This form of route determination is simplistic. However, if hazard maps are constructed with care, the constraints are limited, and the route crosses uncomplicated areas of seafloor, it may be sufficient.

5.3 Least-geocost Path Optimization

Least-geocost path routing uses GIS processing to define an optimized route between two points located on a geocost composite surface. Given a set of individual geocost maps as described above, a least-geocost pipeline route is calculated using the following steps illustrated conceptually in Section 2, Figure 3:

i) Create a composite geocost map as described above in 2/3.1.

ii) An appropriate point is selected from the pipeline termini as the best anchor point or, in GIS terminology, source point (e.g., a manifold to which multiple pipeline segments could connect).

iii) Run least-geocost path route optimization in a GIS program (e.g., ArcGIS). The composite geocost map and source point are used for two intermediate cost distance calculations in ArcGIS:

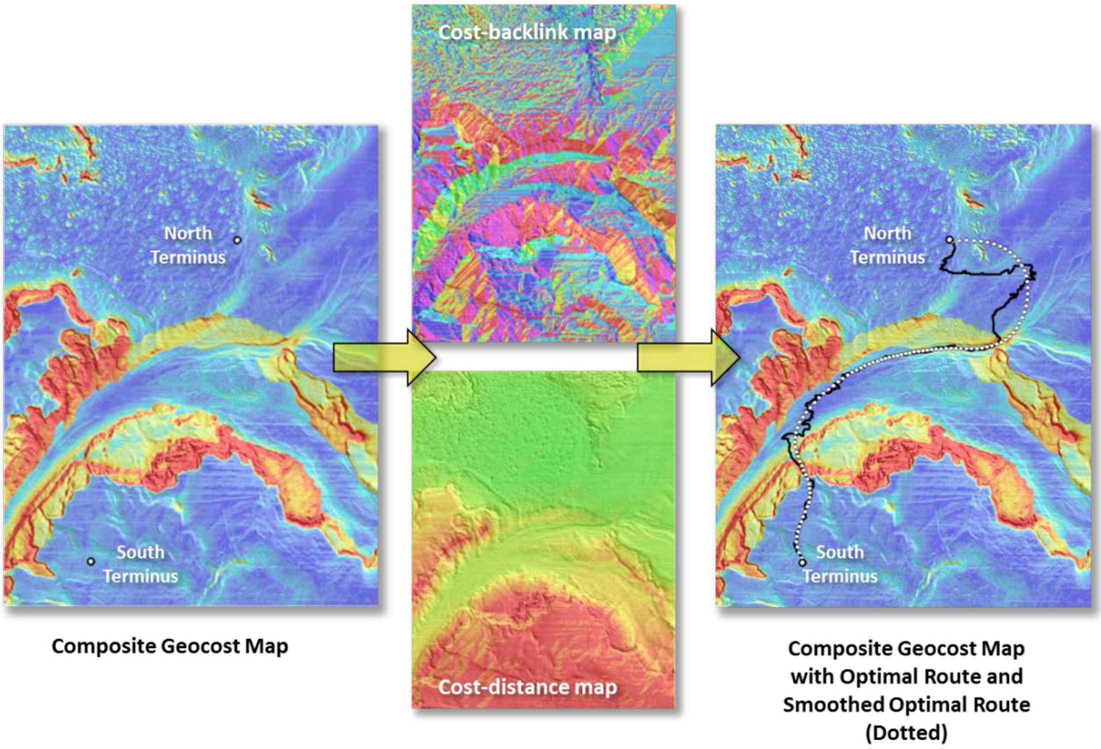
a) A cost-distance map that shows the least accumulative cost distance for each raster to the nearest source (e.g., a manifold or pipeline terminus) over the specified cost surface, and

b) A cost-backlink map that defines, for each raster, the neighbor that is the next cell on the least accumulative cost path to the nearest source (e.g., the travel direction from each cell to the nearest source point). The cost-distance and cost-backlink maps are used to calculate the least-cost path from a specified point to the source point. Next, a least-cost path algorithm is used to determine the most efficient route across the cost surface between two specified points.

iv) The optimized route polyline can be converted to points on a meter by meter basis and the cell values of the composite geocost surface can be extracted to the individual points. The total geocost can be calculated as a function of the distance along the entire route.

v) Post-processing can be applied to the optimized least-geocost route such as adjusting the route to project specific constraints.

FIGURE 3
Least-Geocost Path Pipeline Routing



5.5 Stochastic Simulation for Sensitivity Analysis

Regardless of the care taken in preparation of the component and composite geocost maps, they will always carry some uncertainty as a consequence of human judgment, data resolution, and other issues. The number of individual component maps, the complicated spatial distribution of the features and attributes contributing to geocost variability, and a currently incomplete understanding of the ways in which uncertainties in the component geocost maps interact with each other to create uncertainties in the composite geocost maps; make traditional approaches to sensitivity analysis impossible. One solution is to use resampling based stochastic simulation of the composite geocost surface.

In resampling based stochastic sensitivity analysis, the original geocost surface is sampled at a large number of random locations (Section 2, Figure 4). The number of locations selected will depend on the complexity of the composite geocost surface, and the number of points should be chosen to adequately represent the first-order variability of the surface. This will always be a subjective decision. However, the adequacy of the number of points selected can be visually assessed by plotting the random sample points on the composite geocost surface to ascertain whether a reasonable degree of coverage has been achieved. It is suggested that values be within the range:

$$L_c/10 < \sqrt{A/N} < L_c/2$$

where

L_c	=	characteristic length or dimension of the important seafloor features affecting pipeline route determination
A	=	size of the study area being sampled
N	=	required number of sample points.

Typical values for that range of points as a function of L_c are shown in Section 2, Table 3. The smaller the features to be simulated and the more fidelity desired, the higher the number of recommended sample points.

FIGURE 4
Stochastic Simulations

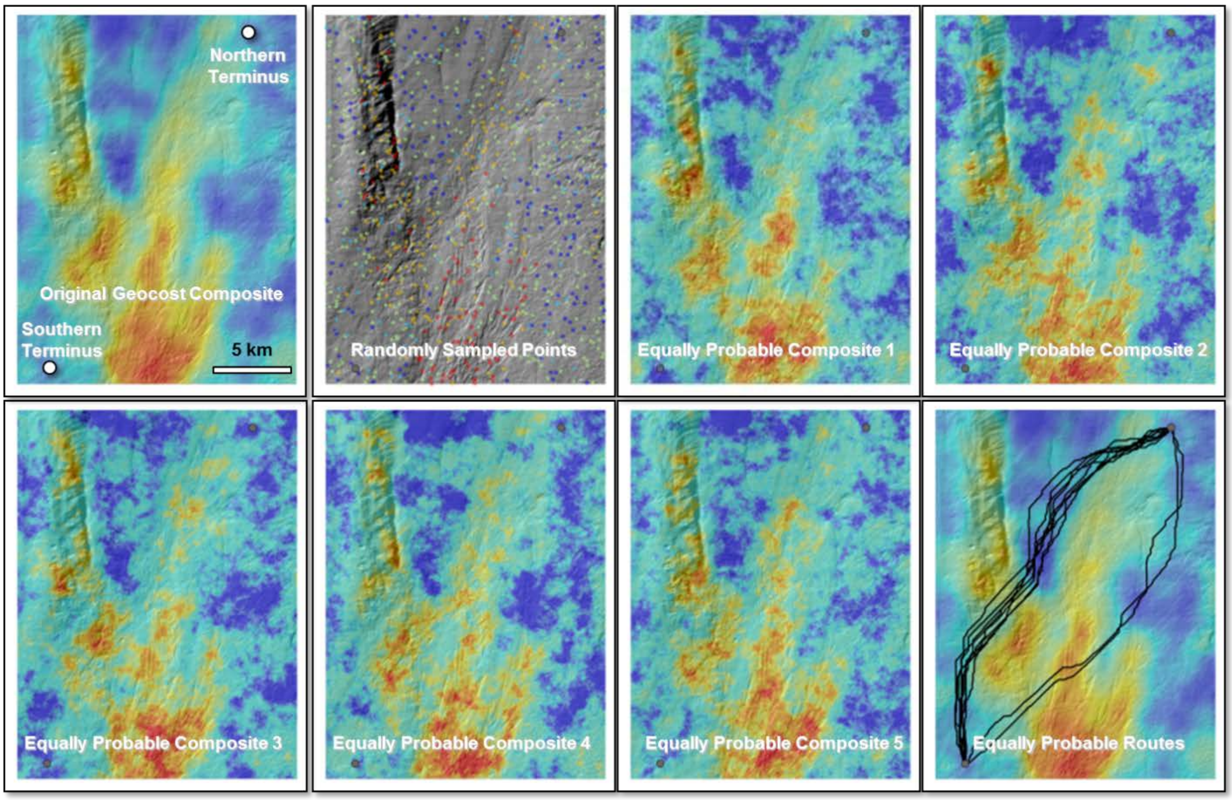


TABLE 3
Ranges of Sample Points Recommended for Stochastic Simulation of Cost Surface Uncertainties

Characteristic Length of Seafloor Features (m)	*Recommended Number of Sample Points per Square Kilometer*	
	Minimum	*Maximum*
500	16	400
1000	4	100
1500	0.64	16
5000	0.16	4

The geocosts and locations of the sample points are then used as input for conditional simulation of the cost surface, which can be accomplished using GIS or other widely available geostatistical simulation software. After values at the chosen number of random points are sampled, a large number (100 or more) of equally probable versions of the cost surface are generated using conditional simulation, and a least-geocost path route is calculated for each version. The result is a cloud of possible routes, the dispersion of which reflects the sensitivity of the routing process to changes in the input geocost map. The width of the cloud of routes can then be used to define a corridor for additional data collection and route refinement. In a typical application, the first attempt at routing might be based upon a 3-D seismic-derived seafloor surface with 15 m to 20 m cell size, and stochastic simulation might be used to determine a corridor for subsequent and more detailed AUV data collection using a 2 m or 3 m cell size, allowing the route to be evaluated in more detail and with more confidence.

7 Route Evaluation

Route evaluation is to verify that the selected route meets all applicable criteria. It is possible that the output from least-geocost path routing, for example, may not satisfy requirements that the route crosses faults or slopes at the required angles or passes too close to runout zones for debris flows. In such a case, a decision is made to either refine the route using existing data or to collect additional, more resolute or detailed, data. Route evaluation can also include a risk assessment. Route evaluation should be performed by the same multidisciplinary project team that performed the initial geocost assignments, with additional input from project managers and risk assessment professionals. If all applicable criteria are satisfied, then the process can move on to risk assessment without further iteration.

SECTION 3 Risk Assessment

1 Principles

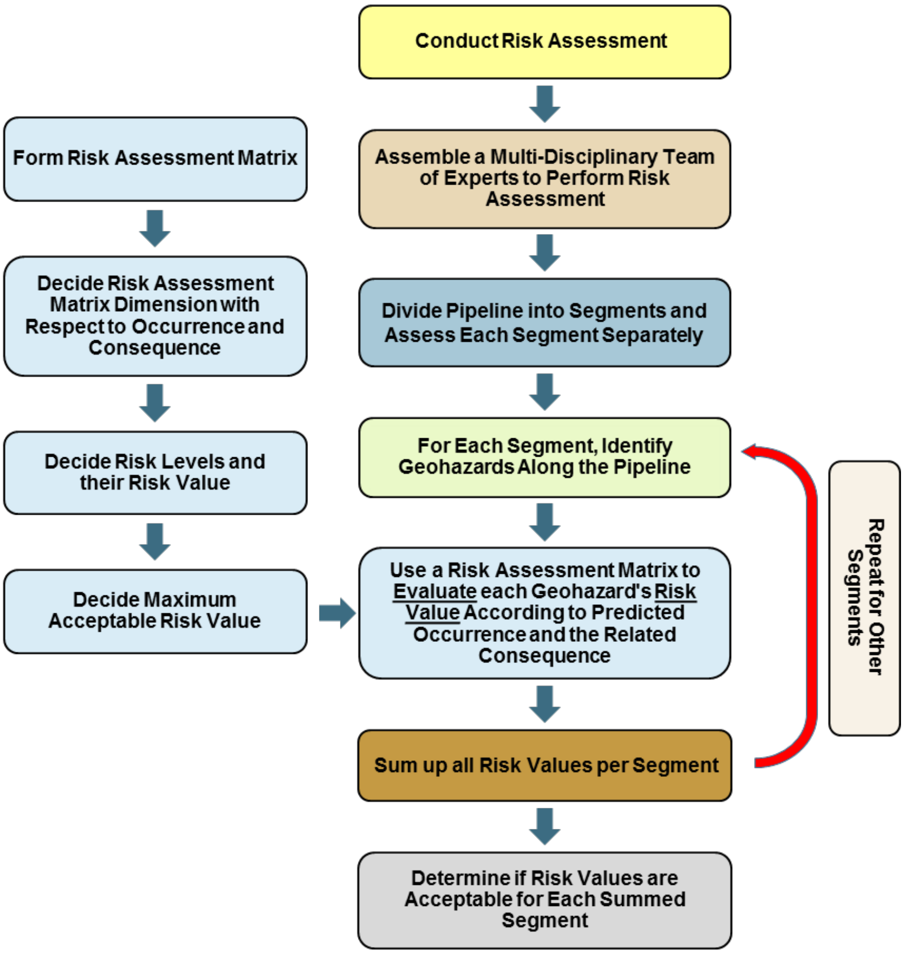
Risk assessment is an essential element of the route determination and acceptance process. The methods described in these Guidance Notes are intended to reduce, but cannot completely eliminate, hazards along pipeline route. As long as hazards exist, there will also be potential consequences that lead to risks for the project Owner, the public, and the environment. This includes events for which there may not be current evidence in the project area or which may originate far beyond the project area, or unpredictable human activities like accidents or terrorism. Moreover, there may be different thresholds for the risks that various stakeholders are willing to accept on different projects.

Risk has historically been defined as a function of 1) the likelihood of an occurrence (e.g., the hazard) and 2) the losses anticipated upon occurrence (e.g., the consequence). Some practitioners explicitly separate the vulnerability of the asset at risk from the consequences and consider it a third variable, but the underlying principle remains unchanged. ISO 31000 proposed a significantly different and more abstract definition of risk – the effect of uncertainty on the attainment of an objective - with the purpose of including positive as well as negative aspects of the problem. These Guidance Notes use the more traditional definition of risk.

Although a variety of geohazards as well as ecological and cultural constraints are incorporated into pipeline route selection as described in these Guidance Notes, ecological and cultural constraints will typically not be included in risk assessment (although, as described below, the potential for environmental and social damage as a consequence of geohazards is incorporated). This is because ecological and cultural constraints such as a shipwreck or protected benthic community do not present the potential for unacceptable consequences such as pipeline rupture, loss of containment, injury, or loss of life as long as they are recognized and avoided during the route selection. If known ecological or cultural constraints cannot be avoided by the route, then they should also be considered as hazards and the attendant risks evaluated.

Section 3, Figure 1 illustrates the steps required to conduct a risk assessment discussed in 3/1.1 and 3/1.3. As is the case for the classification and weighting of component hazard maps, risk assessment is best performed collaboratively by a multi-disciplinary team that includes expertise in marine engineering geology, geotechnical engineering, pipeline engineering, marine ecology, marine archeology, health/safety/environmental (HSE) compliance, and project management. On large or complicated projects, this may be best accomplished in a professionally facilitated workshop with experienced professionals to guide the discussion and verify that all requirements of the risk assessment process are met.

FIGURE 1
Risk Assessment Flowchart



1.1 Hazard Identification

The first step in the risk assessment is identification of geohazards along the route. Although the cost surface approach illustrated in these Guidance Notes is intended to minimize the number of geohazards along the route, it does not guarantee a route completely free of hazards. Hazards may be encountered because there are so many that they cannot be completely avoided or because the pipeline route would have to be impractically long in order to completely avoid all possible hazards.

Hazard identification as part of the risk assessment requires the un-weighted component geohazard maps used to create the composite cost surface. These maps will show the locations and sizes of seafloor and shallow subsurface geohazards that are identifiable using geophysical data available when the route was selected. At this stage, the task is to identify specific hazards with the potential to adversely affect the pipeline, their magnitudes, and their likelihoods of occurrence. This may be best accomplished by creating a tabular hazard or (if consequences are included) risk register for the pipeline route. For long pipelines or pipelines passing through areas of complicated seafloor geology, this may be best accomplished by breaking the route into segments and assessing each segment separately. The location, volume or magnitude, and expected frequency of each hazard that might affect the safe and successful operation of the pipeline over its intended useful life should be tabulated in a spreadsheet or database. This process is repeated for each segment of the route.

One of the unique challenges of geohazard and georisk assessment compared to other kinds of risk assessment is that geologic information is almost always fragmentary and subject to considerable uncertainty. Thus, even in the most comprehensive of integrated subsea site investigations it will likely be impossible to precisely define an annual probability of occurrence of hazards such as subsea landslides, let alone secondary attributes such as runout distance, velocity, and, ultimately, the impact force if a pipeline is impacted by a landslide. In many projects, annual likelihoods for entire classes of geohazards may be quantifiable only within one or two orders of magnitude.

1.3 Risk Matrix

Once hazards have been tabulated for the entire pipeline route, the likelihood and consequences of each hazard should be evaluated using an 'industry standard risk matrix' such as the one illustrated in Section 3, Table 1. Risk matrices are common in government and industry and, as such, there are many sources of information about their creation and use.

Using the example risk matrix in Section 3, Table 1 and the steps outlined in Section 3, Figure 1, risk values can be established by an experienced project team and assigned to each cell in the matrix starting with low values that increase as the level of risk increases to the unacceptable level. As discussed above, the pipeline is assessed by segment and risk values summed for each segment. The project team will determine whether the summed risk values are acceptable based on a maximum acceptable risk value adopted for that project. Matrices are project specific and can be modified to suit the needs of the project team (See Appendix 2, "Case Study").

In cases where an average annual probability of occurrence can be calculated, for example using radiocarbon dates of debris flow deposits, this can be used to classify the likelihood from Rare to Likely. In cases where it is not possible to calculate annual probability of occurrence, the likelihood will have to be estimated on the basis of the collective experience of the project team and the industry in general. For example, if a hazard has no known history of occurrence anywhere in the offshore oil and gas industry then it might be assigned a likelihood of Rare with the understanding that this loosely corresponds to an event with an annual probability on the order of 10^{-5}/yr. If it is expected to occur repeatedly on the project under consideration, then it would be classified as Likely with the understanding that this corresponds to an annual probability on the order of 10^{-1}/yr.

After the likelihood of each tabulated hazard along the route has been estimated, its consequences relative to health and safety, environmental quality, social issues, and financial loss must be estimated. As illustrated in Section 3, Table 2, different criteria will be used for each aspect and potentially for each project; hence, Section 3, Table 2 should be used only as a guide and specific thresholds developed for each project using input from all stakeholders. Acceptable levels of health and safety, environmental, and social risk may be defined by society with little or no room for modification by the project Owner and Operator. The acceptable level of economic risk, however, can be defined only by the project Owner and Operator who will bear the consequences of a failure.

After both the likelihood and the consequences of each hazard remaining along the route after its selection are estimated, the risk associated with each can be classified as acceptable (green), marginal (yellow), or unacceptable (red). No further action is required for acceptable risks. Unacceptable risks require a written plan of action from the risk assessment team, which may include options such as reducing vulnerability through specific engineering measures or re-routing the pipeline to avoid the hazard altogether. The re-routing option is generally not preferred at this stage, because an optimal route has already been selected based upon available information, evaluated, and judged to be generally satisfactory. Re-routing to avoid a hazard not already accounted for may affect a large length of the pipeline to the point that a complete re-routing may be required. Because of the difficulty in mitigating most subsea geohazards, especially in deep or ultra-deep water, removal or neutralization of the hazard is generally not an option and if it is, then it can be quite costly and time-consuming. Marginal risks require more detailed evaluation at an 'executive' level in order to make a holistic decision to either accept or reduce the health and safety, environmental, social, and/or financial risks.

TABLE 1
Example Risk Matrix

Risk Likelihood

Risk Consequence	Rare	Very Unlikely	Unlikely	Possible	Occasionally	Likely
	Has not occurred in the industry	Has occurred in the industry	Has occurred on a similar project	Likely to occur in 10% of similar projects	Likely to occur 1-2 times on this project	Likely to occur repeatedly on this project
	< 10^{-5}/yr	**10^{-5} - 10^{-4}/yr**	**10^{-4} - 10^{-3}/yr**	**10^{-3} - 10^{-2}/yr**	**10^{-2} - 10^{-1}/yr**	**> 10^{-1}/yr**
Catastrophic						
Severe						
Major						
Moderate						
Minor						
Negligible						

TABLE 2
Example Risk Levels for Health and Safety, Environmental, Social, and Financial Consequences

	Health and Safety	Environmental	Social	Financial (millions of US $)	Other
Catastrophic	> 10 fatalities or > 100 hospitalizations (workers and community)	Long term damages (> 10 year recovery) or no potential for recovery to pre-incident state.	Public outrage, sustained international news coverage, little chance of community recovery.	> 1000	
Severe	2 – 9 fatalities or 50 – 100 hospitalizations (workers and community)	Medium term damages (3 – 10 year recovery) or degradation of economic or conservation value.	Local public outrage, national news coverage, 1-10 year community recovery	100 - 1000	
Major	1 fatality or multiple disabilities or < 50 hospitalizations (workers and community)	Short term damages (1 – 3 year recovery) and no degradation of economic or conservation value.	Regional to national news coverage, public opposition, < 1 year community recovery.	10 - 100	
Moderate	1 disability or multiple cases of short-term health effects (workers and community)	Detectable effects beyond incident location but no environmental damage (< 1 year recovery).	Local to regional news coverage, little to no public opposition, 1-12 month community recovery.	1 -10	
Minor	1 case of short-term health effects or multiple first-aid cases	Effects detectable only at incident location with cleanup in days to weeks.	Limited local news coverage, minor inconvenience to most people, < 1 month community recovery.	0.1 - 1	
Negligible	Single case requiring first-aid.	No effects.	No news coverage, very minor inconvenience to most people, no community impact.	< 0.1	

1.5 Site or Component Specific Risk Analysis

Although these Guidance Notes discuss risk assessment at the route level, they do not include information about site- or component-specific risk analysis because these activities should occur only after a route has been determined and design is underway. Few geohazards, especially in deep water, can be effectively mitigated. Instead, the available responses are generally limited to avoidance (which is largely accomplished during route selection) or design of the pipeline to resist the loads associated with the geohazards (such as debris flow impact). Design, in turn, should not begin in earnest until the hazards to be addressed have been identified and characterized on a site-specific level after the route has been determined. Detailed risk assessment, moreover, requires knowledge of vulnerability and consequences to the pipeline in the event a hazardous event occurs; however, neither vulnerability nor consequences are known until design is well underway.

APPENDIX 1 Acronyms and Abbreviations

ABS	American Bureau of Shipping
ADCP	Acoustic Doppler Current Profiler
AIVL	Advanced Imaging and Visualization Laboratory
ASME	American Society of Mechanical Engineers
AUV	Autonomous Underwater Vehicle
BS	British Standards
CCOM	Center for Coastal and Ocean Mapping
C-CORE	Centre for Cold Ocean Resources Engineering
CPT	Cone Penetrometer
DEM	Digital Elevation Model
ft	Feet
MBES	Multibeam Echosounder
MTD	Mass Transport Deposit
GEBCO	General Bathymetric Chart of the Oceans
GIS	Geographic Information System
GRASS	Geographical Resources Analysis Support System
HR	High Resolution
ISO	International Organization of Standards
JPC	Jumbo Piston Core
kHz	Kilohertz
OER	Ocean Exploration and Research
m	Meter(s)
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PCPT	Piezocone Penetration Test
ROV	Remotely Operated Vehicle
SAGA	System for Automated Geoscientific Analyses
SBP	Sub-bottom Profile
SSS	Side Scan Sonar
UHR	Ultra-High Resolution
VLS	Vertical Limit of Separability
WHOI	Woods Hole Oceanographic Institution
yr	Year
^{14}C	Carbon-14

APPENDIX 2 Case Study

This case study uses a combination of real and hypothetical data to illustrate the selection of a subsea pipeline route using methods outlined in these Guidance Notes. Using the pipeline route determination flowchart (Appendix 2, Figure 1) as a guide, the following steps will be used to determine a subsea pipeline route:

Step 1 – Collect, and evaluate available geological, geophysical, geotechnical, and metocean data.

Step 2 – Collect, evaluate, classify, and weight geohazard, cultural, environmental, and geotechnical constraints.

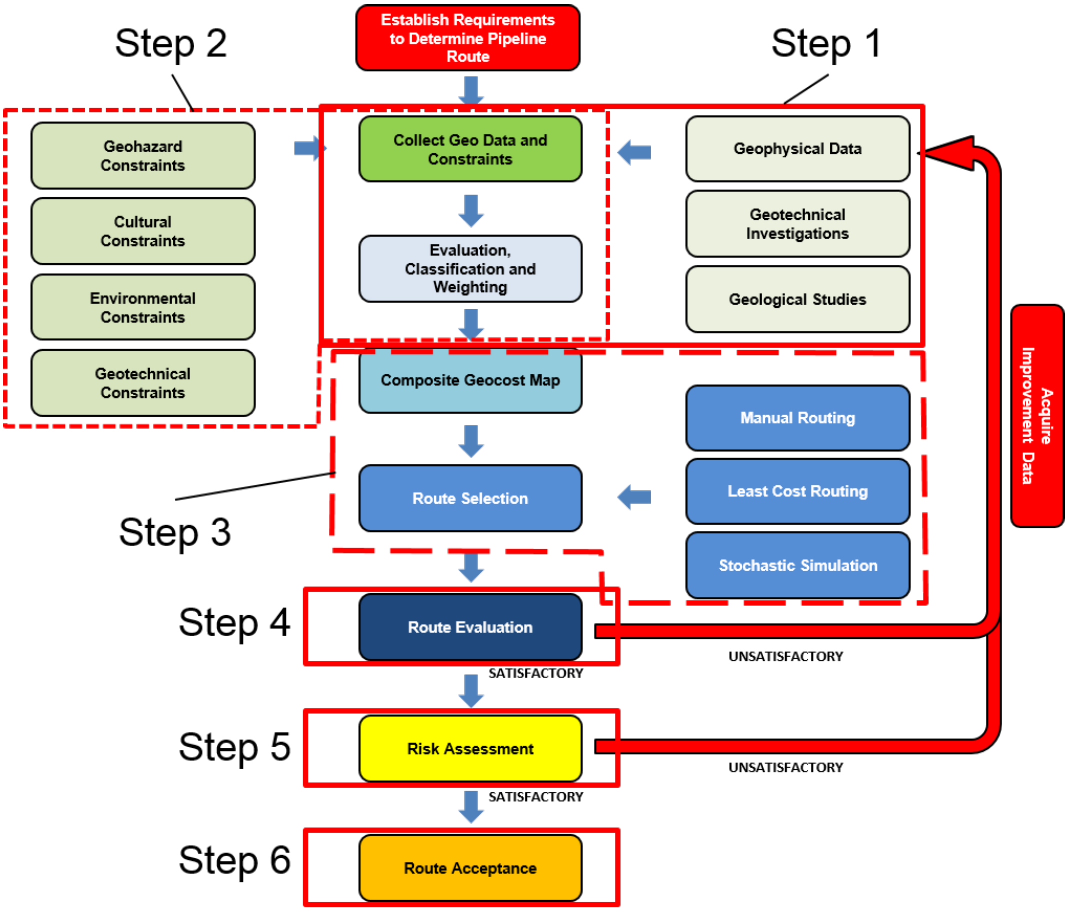
Step 3 – Create a geocost composite map and perform manual routing, least-geocost routing, or stochastic simulations and select the route.

Step 4 – Perform an evaluation of the routing results.

Step 5 – Perform a risk assessment on the least-geocost route.

Step 6 – Route Acceptance.

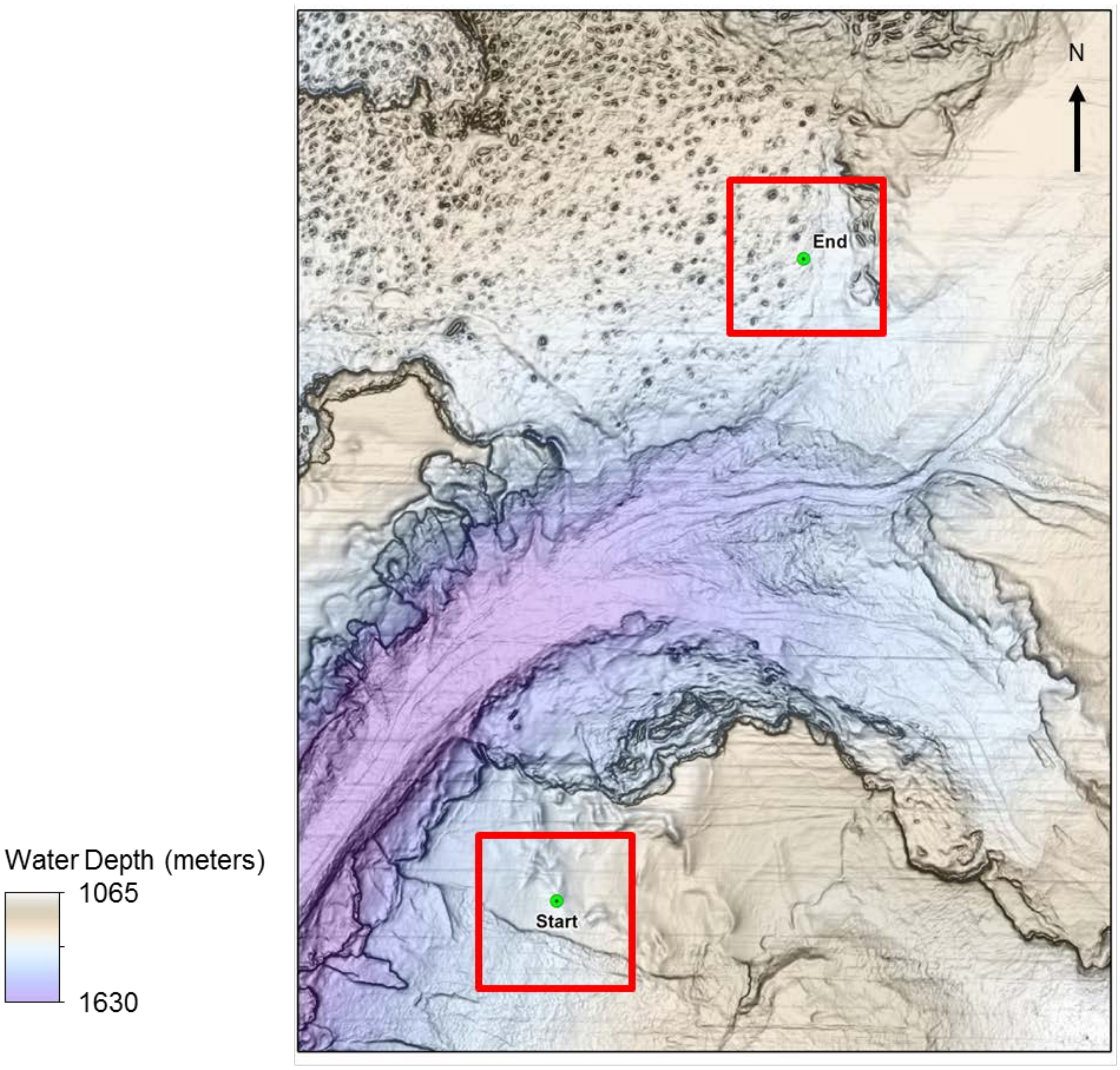
FIGURE 1
Pipeline Route Determination Flowchart



The case study area is located 100 km offshore in a geologically complicated area with water depths ranging from about 1000 m to 1600 m. The goal is to select a subsea pipeline route between two manifolds representing the pipeline termini (Appendix 2, Figure 2).

The procedures discussed below will use ArcGIS to support geohazard identification, mapping, and pipeline route determination. Previous experience with ArcGIS or other GIS software is strongly recommended.

FIGURE 2
Study Area and Manifold Termini

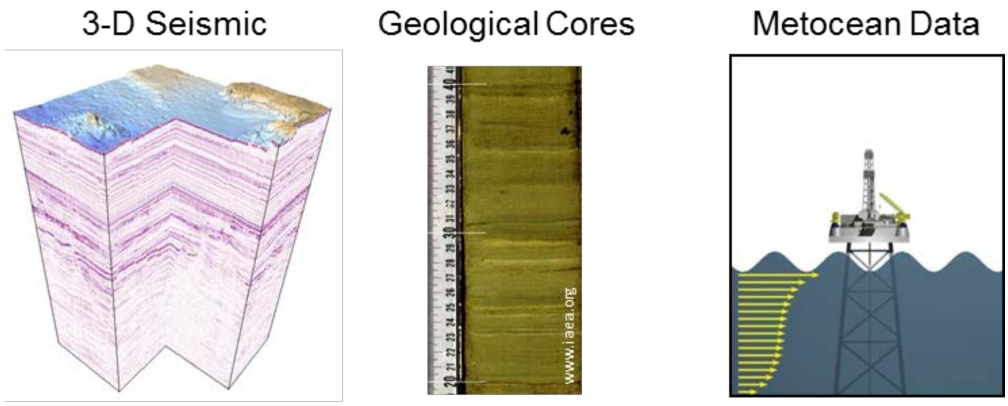


Step 1 Collect and evaluate available geological, geophysical, geotechnical, and metocean data

In most cases, collection, evaluation, and interpretation of geological, geophysical, and metocean data requires the use of data from specialty contractors and consultants. Data available (Appendix 2, Figure 3) for this case study include:

- 3-D seismic volume (with extracted bathymetric surface for import into ArcGIS)
- 6 geological cores
- Metocean measurements

FIGURE 3
Available Data



The 3-D seismic data have a bin spacing of 20 m and a vertical limit of separability of about 10 m. The size of geocost unit cell is therefore taken as 20 m. The seafloor surface extracted from the 3-D seismic data was exported from a 3-D modeling program and imported into ArcGIS for creation of seafloor maps. Faults with seafloor expressions, a channel system, landslide deposits, buried mass transport deposits with near-surface boulders, and fluid expulsion features such as pockmarks were identified in the seafloor rendering and verified with the 3-D seismic data.

In this example, geohazard core logging and radiocarbon age dates were obtained from 6 geological cores collected throughout the study area. Four age dates were taken from landslide deposits and two age dates were taken along faults. The radiometric age dates indicate two landslides have occurred within the last 10,000 years (before present) and are considered geologically young. However, the rate of recurrence of these geologically young landslides is considered infrequent (e.g., there has not been more than one landslide in the last 1.6 million years before present). Two landslide deposits are geologically older and also have a low rate of recurrence. One fault has experienced recent movement within the last 10,000 years before present and is considered geologically young and potentially active. Another fault that was age-dated has not had any movement in recent geological time and is considered geologically old and inactive. Geologically young and active landslides and faults are considered dynamic geohazards.

Metocean data was collected in the northern part of the study area to assess ocean current conditions. The data collected indicate that bottom currents are not actively scouring the seafloor and therefore, seabed scour is not considered a hazard to the installation or development of a subsea pipeline in the northern part of the study area.

High resolution geophysical data such as MBES, SBP, or SSS and geotechnical data are <u>not</u> available for this example project.

Data provided for this case study are sufficient for the determination of a <u>preliminary</u> pipeline corridor and route. Additional high-resolution geophysical surveys, ROV video, geotechnical in-situ testing and sampling, and geohazard cores are essential to adequately assess seafloor conditions and determine a final pipeline route.

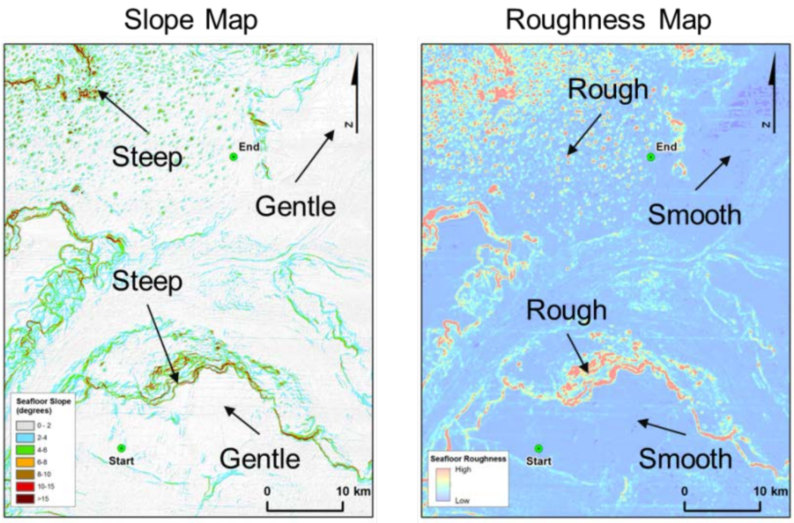
<u>Step 2</u> Collect, evaluate, classify, and weight geohazard, cultural, environmental, and geotechnical constraints

Seafloor conditions and geohazards can be quickly assessed using maps that show geometric geohazards. For example, the bathymetric (water depth) map is used to calculate seafloor slope angles and seafloor roughness using procedures in ArcGIS. The slope map indicates steep angles occur along the failure surfaces of landslide deposits, channel margins, and steep-sided boulders and pockmarks (Appendix 2, Figure 4). A roughness map indicates that rough areas of the seafloor occur in the northern boulder field and along steep failure planes along the channel system (Appendix 2, Figure 4).

Using the bathymetric surface and 3-D seismic data, geologic geohazards are also identified. A prominent seafloor channel system with steep walls defines the central and southern parts of the study area (Appendix 2, Figure 5). Landslide scarps and resulting landslide deposits along the steep walls of the channel system suggest that the slopes are unstable. Faults with seafloor expression, related to periods of regional geological deformation, are evident in the central and southern parts of the study area. The northern part of the study area has an overall rough topography and consists of many boulders and pockmarks (Appendix 2, Figure 5).

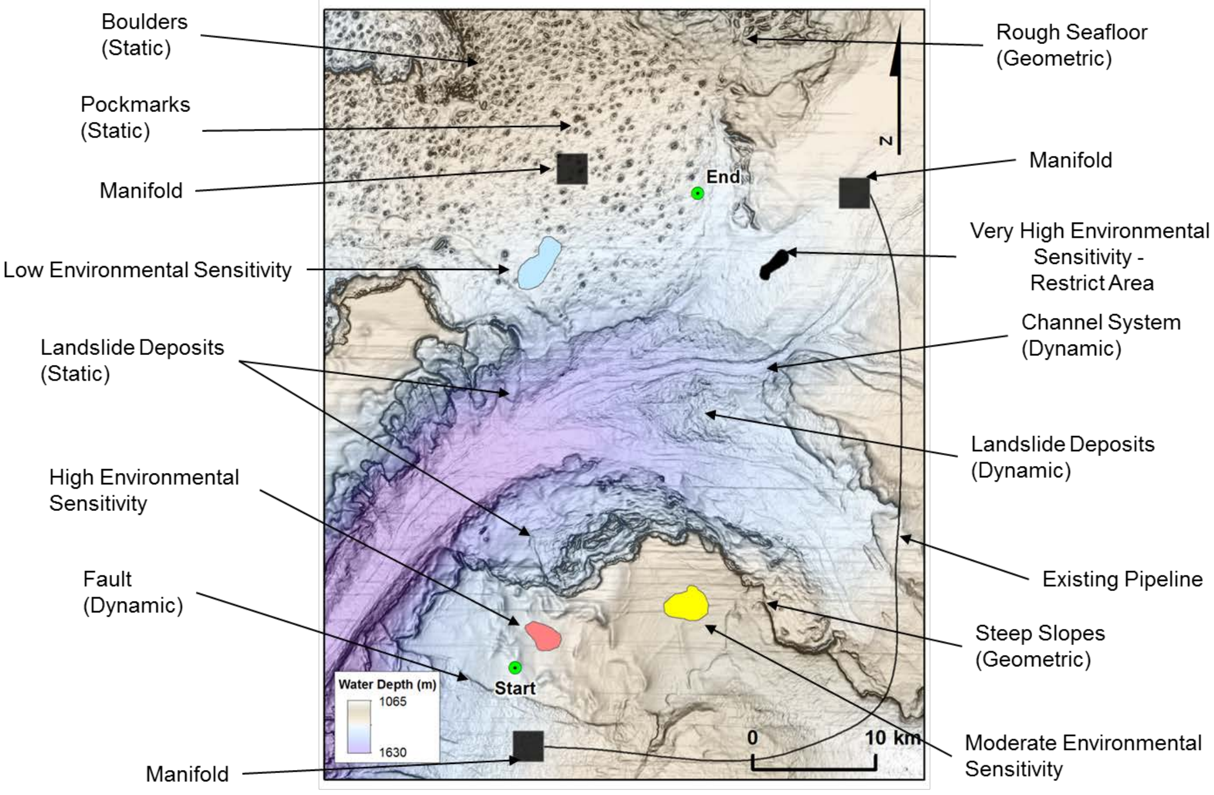
Manmade hazards within the study area consist of three manifolds and an existing pipeline (Appendix 2, Figure 5). For the purposes of this example project, we assume that both the manifolds and the pipeline each require a 1 km buffer and are restricted zones; therefore, the route cannot pass through those areas.

FIGURE 4
Geometric Hazards



The example data also include outlines of 4 environmentally sensitive areas to be considered during route selection. The sensitivity of each area is ranked as low, moderate, high, and very high; the very high area is considered a restricted area for the route assessment (Appendix 2, Figure 5). It is recommended (but not required) to avoid the non-restricted environmentally sensitive areas. However, if necessary, the pipeline may be routed through, or near, these areas to avoid a hazard.

FIGURE 5
Geohazards, Manmade Hazards, and Environmental Constraints



Using a scale of 10 = high to 1 = low, geocosts are allocated (Appendix 2, Table 1; Appendix 2, Figure 6) to identified geohazards by a team of experienced geoscientists and geotechnical engineers, who assess the severity of each hazard and rank them relative to one another in the project's study area.

To emphasize the effect that slopes would have on pipeline route selection, low slope angles (0° to 5°) are classified with a geocost of 1, moderate slope angles (5° to 10°) are classified with a geocost of 5 and higher slope angles (> 10°) are classified with a geocost of 10.

Roughness values within the range of 0 to ±0.6 m are smoother parts of the seabed and are assigned a geocost of 1 (Appendix 2, Table 1; Appendix 2, Figure 6). Roughness values greater than ±0.6 m are considered rougher parts of the seabed and are classified with a geocost of 10.

Faults that were determined to be geologically active based on radiometric age dates were assigned a geocost of 10 and faults that were determined to be geologically inactive were assigned a value of 2.

Geologically older deposits are not considered dynamic geohazards during the life of the project and they are assigned lower geocost values between 2 and 6. The range in values represents the complexity of the landslide deposit and the availability to properly assess the landslide deposit. For example, a landslide that has been determined to be geologically old may be assigned a geocost of 2 and a landslide deposit that has similar characteristics to the old landslide but does not have a confirmed radiometric age date may be assigned a geocost of 6. Geologically younger deposits, which may indicate the potential for future landslides, are considered potentially dynamic and assigned higher geocosts (Appendix 2, Table 1).

The 3-D seismic data indicate the channel system may be considered inactive. However, there is not enough data collected within the channel system to determine the activity of the channel, therefore, the channel system is assigned a value of 8.

The steepness of the boulders and potential for pipeline spanning results in an allocated geocost value of 10.

Pockmarks were created by past expulsion of gas, fluid, or sediment onto the seafloor. These remnant expulsion features lead to irregular seafloor and steep-sided depressions. Remnant pockmarks that have no evidence of current expulsion may cause problems such as pipeline free-spans and results in an allocated geocost value of 10.

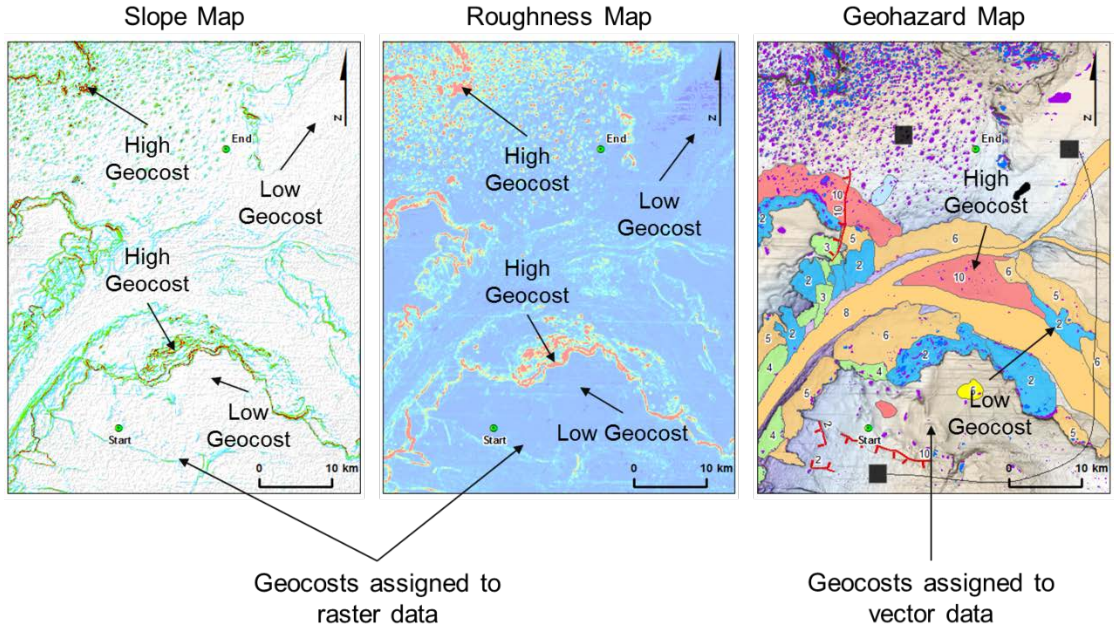
TABLE 1
Geocosts for Geohazards, Manmade Hazards, and Environmental Constraints

Geometric Hazards	*Geocost*
Seabed Slope Angle	
0° to 5°	1
5° to 10°	5
> 10°	10
Seabed Roughness	
±0 to ±0.6 m	1
±0.6 to 16+ m	10
Sensitive Areas	*Geocost*
Very High Sensitivity	Restricted
High Sensitivity	9
Moderate Sensitivity	5
Low Sensitivity	2

Geologic Hazards	*Geocost*
Static Hazards	
Inactive Fault	2
Landslides (geologically old)	2 to 6
Boulders (individual)	10
Pockmarks (individual)	10
Dynamic Hazards	
Channel System	8
Active Fault	10
Landslides (geologically young)	10

Manmade Features	*Geocost*
Manifolds	Restricted
Pipeline	Restricted

FIGURE 6
Allocation of Geocosts to Seafloor Slope, Roughness, and Geologic Hazards



Step 3 Create a geocost composite map and perform manual routing, least-geocost routing, or stochastic simulations and select the route.

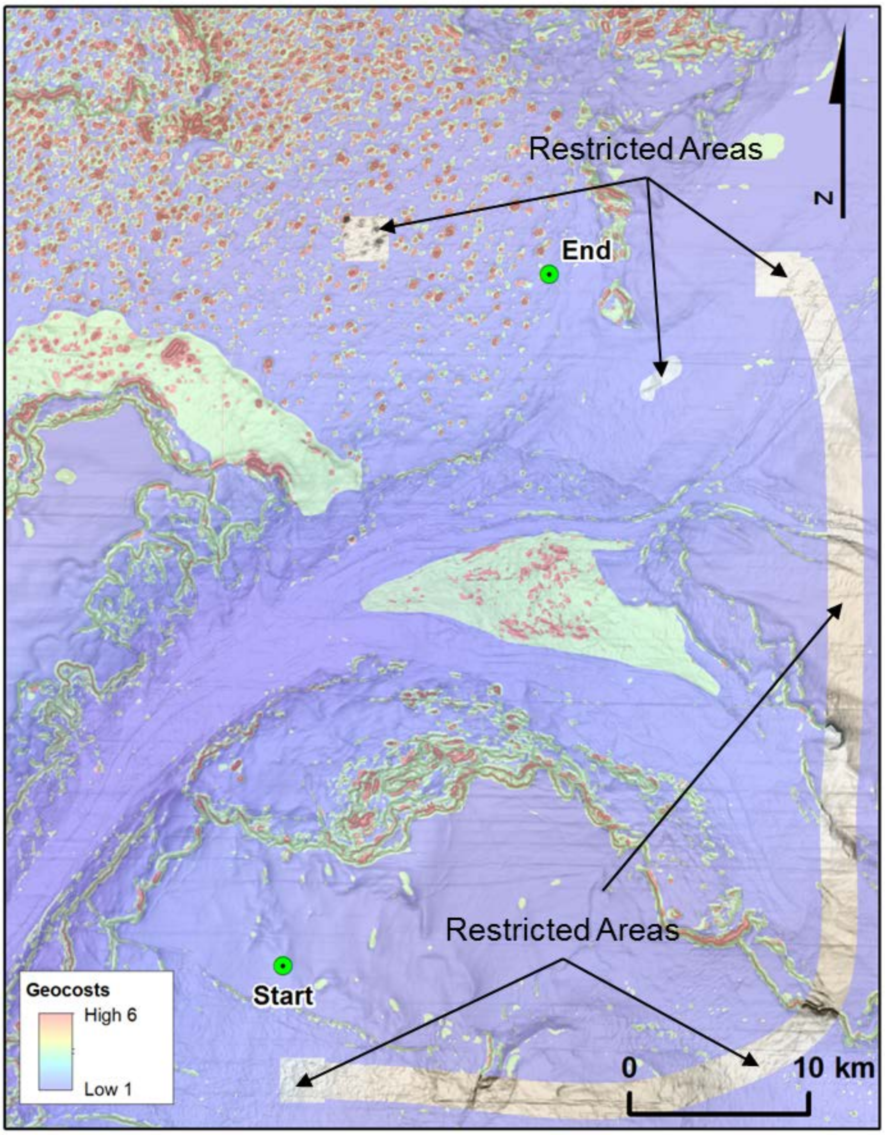
In this example, all geological features are depicted as vector features in GIS and comprise polygons, lines, and points. Vector geohazard polygons/lines/points and environmentally sensitive areas were converted from a vector file to a raster file to create geocost component maps. The slope angle map and roughness maps were already raster files.

For this example, a total of 9 geocost component maps were added together and averaged:

- Seafloor Slope
- Seafloor Roughness
- Landslides
- Faults
- Pockmarks
- Boulders
- Channel System
- Environmentally Sensitive Areas
- Manmade Hazards

The averaged geocosts produce a value range of 1 = lowest to 6 = highest. The restricted zones (existing infrastructure and very high environmentally sensitive area) were omitted from the data and shown as gray-scale areas in the resulting geocost composite map (Appendix 2, Figure 7).

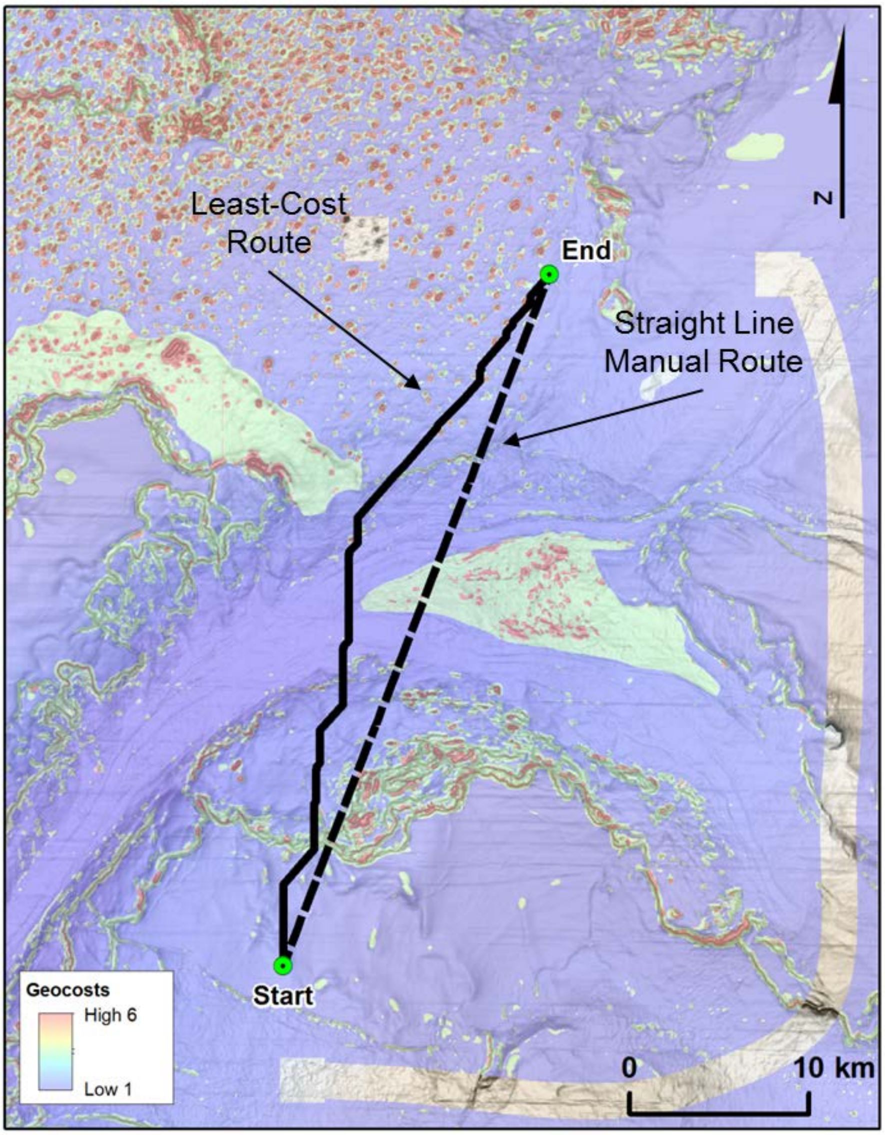
FIGURE 7
Geocost Composite Map



For this example, manual routing is shown in Appendix 2, Figure 8. This route is the shortest distance (straight line) between the start and end termini and would be ideal if no geohazards were present along the route. However, as seen in Appendix 2, Figure 8 the straight line route crosses several high geocost areas.

The geocost composite map was used for least-geocost path routing as described in 2/5.3 of these Guidance Notes. As seen in Appendix 2, Figure 8, the optimized route travels through low geocost areas.

FIGURE 8
Manual Route and Least-Geocost Route



Step 4 Perform an evaluation of the routing results

Geocosts along the manual and least-geocost routes were extracted from the composite geocost map at 1 m intervals, integrated over the length of the route, and compared in Appendix 2, Table 2. The least-geocost path is 2.9 km (7%) longer than the manual, straight line route. Although the length of the manual route is shorter than the least-geocost route, the geocost values for the manual route are 13% higher. Because the manual route passes through areas identified as high geocost geohazards, the least-geocost route is a more favorable pipeline route option. A risk assessment on the least-geocost route is addressed in the following sections.

TABLE 2
Geocost Comparison

	Least-Geocost Path	*Straight Route*
Length (km)	44.2	41.3
Geocost	44,644	51,377
	Manual Route Length Difference from Least Cost Route	–7%
	Manual Route Geocost Difference from Least Cost Route	13%

Step 5 Risk Assessment

For this example, the significant hazards that could affect the pipeline are evaluated with several risk assessment levels (Appendix 2, Table 3) within the risk assessment matrix shown in Appendix 2, Table 4. A green risk level is considered acceptable without any further action required, yellow and orange risk levels are marginal and require management review, and red levels are considered unacceptable. Values established by an experienced project team are assigned to each cell in the matrix for example: starting at 1 and increasing to 2000 as the level of risk increases to the unacceptable level. The risk assessment matrix (Appendix 2, Table 4) used in this example assesses the potential for damage to the pipeline from the hazards considered, and the environmental impact with respect to the amount of oil that could be spilled. This is only one example of a type of risk matrix that can be applied to assess a pipeline route. Matrices are project specific and can be modified to suit the needs of the project team.

TABLE 3
Risk Assessment Levels

Risk Level	**Risk Management Action**
Very High	Unacceptable (mitigation of risk required)
High	Marginal (detailed evaluation and management permission required)
Moderate	Marginal (management review required)
Low	Acceptable (no further action required)

To perform the risk assessment the route was divided into 5 (10 km × 10 km) equal size areas to assess the geohazard impact to pipeline infrastructure (Appendix 2, Figure 9). The number and size of the areas can also be project specific and decided upon by the project team. In this example, the total risk value for each area should be no greater than 500 to be considered an acceptable or marginally acceptable route. **This limit may vary from project to project, can be based on corporate policies or industry examples, and decided upon by the project team or Owner prior to the risk assessment.** Using Appendix 2, Table 4, geohazards in each of the five areas were assessed and assigned a value based on the potential impact the geohazard would have on a pipeline. For example, the impact of a large (> 100 km^2) landslide in Area 1 would be catastrophic. However, the likelihood of this happening is very unlikely during the life of the project because no landslides occur in this area and the geomorphology is not considered landslide-prone. Therefore, landslides would be assigned a value of 100. This process continued for each geohazard in each of the five areas along the proposed route (Appendix 2, Table 5).

TABLE 4
Risk Assessment Matrix

Risk Likelihood

Risk Consequence

		Rare	**Very Unlikely**	**Unlikely**	**Possible**	**Occasionally**	**Likely**
		Has not occurred in the industry	Has occurred in the industry	Has occurred on a similar project	Likely to occur in 10% of similar projects	Likely to occur 1-2 times on this project	Likely to occur repeatedly on this project
Infrastructure Damage and Environmental Impact	**Qualification**	**< 10^{-5}/yr**	**10^{-5} - 10^{-4} / yr**	**10^{-4} - 10^{-3}/ yr**	**10^{-3} - 10^{-2} /yr**	**10^{-2} - 10^{-1} /yr**	**> 10^{-1}/yr**
Catastrophic pipeline rupture and oil spill (500,000 US gallons)	**Catastrophic**	50	100	250	500	1000	2000
Severe pipeline rupture and oil spill (250,000 US gallons)	**Severe**	25	50	100	250	500	1000
Major pipeline damage and oil spill (100,000 US gallons)	**Major**	10	25	50	100	250	500
Moderate pipeline damage and oil spill (50,000 gallons)	**Moderate**	5	10	25	50	100	250
Minor pipeline damage and oil leakage (1,000 gallons)	**Minor**	2	5	10	25	50	100
Minor pipeline damage – no leakage	**Negligible**	1	2	5	10	25	50

For each area, the consequence of a landslide is considered catastrophic. However, the likelihood of a landslide varies depending on the geological terrain and whether landslides are already present. Landslides are considered very unlikely to possible. The consequence of an active channel is considered moderate to major and the likelihood is very unlikely in some areas where the channel is not present to possible where the channel is present but there is not enough data to determine whether it is active or not. The consequence of a pipeline laid across a boulder is considered minor. The likelihood varies depending on the presence of boulders in the area. The consequence of a pockmark is considered minor and the likelihood of encountering a pockmark varies from unlikely to possible.

Area 3 is considered the highest risk area because a geologically young landslide is present within the 10 km by 10 km area around the proposed pipeline route. Another landslide occurring in this area could strike and rupture the pipeline. Because the landslide in this area is considered a high cost geohazard, the landslide is assigned a risk value of 500 based on available data for this feature and in this area. Area 4 also contains a geologically young landslide. However, if another landslide occurred in this area, it is interpreted to be parallel to the pipeline and may not impact the pipeline like a landslide in Area 3 and is therefore assessed as a marginal risk.

Step 6 Route Selection

When all the data are summed for each area (Appendix 2, Table 5), it is determined that Areas 1, 2, 4, and 5 of the optimized, least-geocost route are considered acceptable, based on route evaluation and the risk assessment. Upon additional collection of high resolution geophysical data including MBES, SSS, or SBP, additional geotechnical cores and tests, and additional geological cores with geohazard core logging and radiometric age dates; design aspects, materials, and installation can be considered. These data may supply enough information to determine whether the area along the proposed pipeline route is deemed marginal or acceptable for final pipeline route selection. Area 3 has a total risk value that falls within the unacceptable range. Therefore, further mitigation is required for this portion of the pipeline route, including but not limited to additional data as mentioned above, a risk assessment with involvement from management, or design of the pipeline to withstand a landslide impact.

FIGURE 9
Risk Assessment Areas along Least-Geocost Route

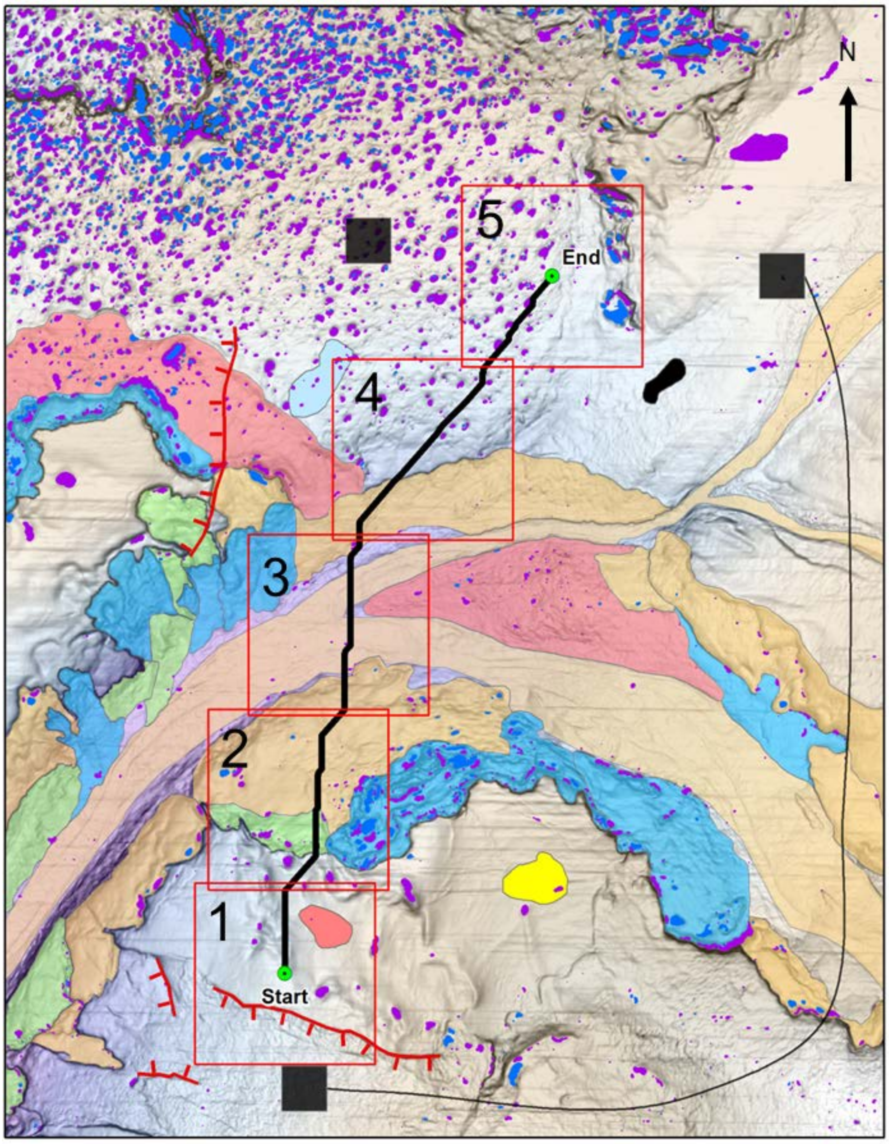


TABLE 5
Geohazard Risk Values for Areas 1 through 5

		Geohazards					
Area		*Landslides*	*Channels*	*Boulders*	*Pockmarks*	*Faults*	*Total*
1	Risk Value	100	25	5	10	25	165
2		250	25	25	10	25	335
3		500	25	5	25	10	565
4		250	25	5	25	10	315
5		100	25	25	25	10	185

Step 7 Recommendations

Four out of the five risk assessment areas are considered acceptable based on the maximum of 500 risk value per area. The presence of a younger and potentially active landslide in Area 3 deems the route through this area marginally unacceptable based upon the available data. Further investigations – including site-specific geotechnical and stratigraphic investigations of the landslide complex – may help to further refine the hazard and reduce risk through improved understanding of the hazard. If the results of such studies do not reduce risk to an acceptable level, either another route must be considered or the pipeline must be engineered and constructed to resist landslide movement. However, discussion of such engineering design options is beyond the scope of route determination. Because the route under consideration was selected based on existing knowledge of geohazards, it is unlikely that a markedly better route can be determined and mitigation by engineering the pipeline to resist the hazard is the most viable solution. If additional information becomes available and the route becomes unacceptable on the basis of that new information, the route determination procedure can be revised.