Chapter 2

Terrain Analysis for Pipeline Corridor Selection

This chapter focuses on:

1. What tools and techniques are used in terrain analysis for pipeline corridor selection?
2. What terrain features must be evaluated for characterization and assessment of pipeline routes?
3. How is terrain analysis applied to the pipeline corridor selection process?
CHAPTER OVERVIEW

This chapter focuses on the science and technology of terrain analysis and how terrain mapping is an important component in the selection of routing corridors and final alignments for pipelines. It introduces the reader to the definition of terrain analysis and its role in both pipeline corridor selection and geohazard assessment, as well as the various tools and data sources used in desktop terrain analysis studies. The various types of terrain features that must be evaluated during pipeline terrain analysis studies and other key considerations in the application of terrain analysis to pipeline are also discussed. Nine of the global terrain types that may be encountered during pipeline routing are summarized in detail.

CHAPTER LAYOUT AT A GLANCE:

2.1 INTRODUCTION
This section introduces readers to the definition of terrain analysis and its role in both pipeline corridor selection and geohazard assessment.

2.2 TERRAIN MAPPING AND GEOHAZARD ASSESSMENT
This section describes the general principles and data tools used in terrain mapping and geohazard assessment, including air photo and satellite image interpretation, digital surface modeling, integration of existing terrain data into a geographic information system (GIS), and the use of 3D visualization in the interpretation and mapping process.

2.3 TERRAIN FEATURES EVALUATED FOR GEOHAZARD MAPPING AND ASSESSMENT
This section discusses the main features of terrain that must be considered when carrying out terrain analysis and geohazard mapping for pipelines, including surface materials and their geotechnical properties, topography, drainage, groundwater, known geohazards, and cultural and environment constraints.

2.4 APPLICATIONS OF TERRAIN ANALYSIS TO PIPELINE ROUTING, CONSTRUCTION AND OPERATION
This section discusses the application of terrain analysis and its role in the corridor and route selection process, design, construction and operational phases of a pipeline. The importance of understanding scale in terrain analysis studies is also discussed.

2.5 ASSESSING GEOHAZARDS IN DIFFERENT REGIONS
This section summarizes nine of the most common terrain types that may be encountered during terrain analysis for pipeline corridor and route selection, design, construction and operation, including glaciated terrains, fluvial terrain, permafrost, peatlands and organic terrains, coastal terrain, karst terrain, mountains, volcanic terrain, and deserts.

2.6 SUMMARY
This section provides brief concluding remarks emphasizing the key messages.

A list of references and suggested further reading is provided for the reader at the end of the chapter. Green highlight boxes are used in this chapter to emphasize key concepts or lessons learned, and to suggest links to other chapters or additional reading.
2.1 INTRODUCTION

Geohazard risk assessment is essential to meet the significant engineering, environmental and socioeconomic challenges involved with the routing, construction and operation of pipelines. Although identifying and mitigating the risk of geohazards has long been part of geotechnical studies for the pipeline industry (Mollard, 1959; Mollard, 1972; Mollard et al., 2008), pipeline geohazard assessment has become increasingly important with greater public awareness and scrutiny of environmental conditions, public safety, and integrity management (Kerr, 2004; Leir, 2004; Cosford et al., 2014).

Geohazards are natural geological processes and features with the potential to cause death or injury to persons and damage or loss to property and infrastructure (Komac et al., 2013). Buried pipelines in particular are susceptible to many geohazards (Figure 2-1). Assessing and managing the threat of these geohazards involves recognizing and delineating specific geohazard mechanisms, estimating the frequency and magnitude of occurrence of these processes and events, and assessing the vulnerability of the pipeline to specific geohazards. Based on this information it is possible to conduct qualitative, semi-quantitative and quantitative geohazard risk assessments to pipeline infrastructure (Rizkalla and Read, 2007; Rizkalla, 2008; Rizkalla and Read, 2013; Read and Rizkalla, 2015; Read et al., 2017). These references provide detailed lists of geohazards, affected pipeline elements and mitigation options and emphasize the importance of assessing pipeline vulnerability in risk assessment.

Among the tools used in geohazard assessments of pipelines is terrain analysis, which involves the study of surficial characteristics and the interpretation of landforms from geospatial data for geoscience and engineering applications (Mollard et al., 2008). Terrain analysis is an essential and cost-effective component of pipeline routing, design, construction, and operational studies (Figure 2-2). When evaluating alternative routes and corridors for new pipelines, terrain analysis is used to identify and avoid problem areas, and to generate geotechnical data and maps to support the successful design, construction and operation of pipelines. For existing pipelines, terrain

![Figure 2-1: Some potential pipeline geohazards (adapted from Porter et al., 2008)](image-url)
analysis can be used to assess and monitor the effect of changing landscapes on pipeline integrity. It is, therefore, the purpose of this paper to provide a general overview of the application of terrain analysis to geohazard assessment and management for pipelines.

2.2 TERRAIN MAPPING AND GEOHAZARD ASSESSMENT

Terrain mapping involves the delineation and classification of the landscape based on landforms, surficial materials, and geomorphic processes. From these generalized terrain inventory maps it is possible to produce more specialized or derivative maps (e.g. geohazards, landslide inventory, permafrost, organic soils and wetland, geotechnical characteristics and suitability, etc.) that support specific applications. While terrain analysis describes existing conditions, the information gathered can assist with evaluating how conditions may change over different stages of the project and with assessing potential environmental and social impacts of the project.

Historically, terrain maps were generated primarily from stereoscopic air photo interpretation supported by reference to published maps and field observations. Today, advances in remote sensing technology have provided a wider range of geospatial data including high-resolution and multispectral satellite imagery, digital aerial imagery (from both conventional aircraft and unmanned aerial systems) and detailed digital surface models (derived from LiDAR or from photogrammetric techniques). Geographic Information Systems (GIS) provide a means to integrate these data types and to evaluate the spatial relationship between landforms (and their associated engineering and geohazard properties) and the surrounding environmental, cultural and socioeconomic conditions.

2.2.1 Terrain Analysis Tools

Geospatial data used for terrain analysis and geohazard assessment includes air photo, satellite and ground-based imagery interpretation, digital surface models (and derived data), and the integration of existing maps and field studies (Figure 2-3). A GIS can be used to create, analyze and manage the various types and scales of geospatial data applied to the route planning and geotechnical design process. Technological advances in Unmanned Aerial Vehicles (UAVs) and ground-based
systems are already transforming both the delivery and nature of many types of geospatial information. However, while advances in remote sensing systems continue to improve the quality of geodata available, the geological and geotechnical interpretation of the data will always rely on the basic principles of terrain analysis.

2.2.2 Air Photo Interpretation

Terrain analysis traditionally involves the interpretation of stereo aerial photos for the recognition of landforms and the subsequent prediction of the associated materials and properties. The ability to recognize landforms in air photos – and thus infer their material properties – is based on an understanding of key air photo identifying features including topographic relief, photo tones and textures, patterns of erosion, drainage and land use, amounts and types of vegetative cover, etc., as well as on an understanding of the geological, environmental or anthropo-morphic processes at work in the present study area or in the recent past. Where available it can be extremely useful to obtain multiple ages and scales of air photos – the historical photos serving as a valuable archive of past conditions and providing evidence for changes in the landscape within the study area.

Among the key objectives of terrain analysis for pipeline engineering is the identification and avoidance of natural hazards to ensure pipeline integrity and public safety. Terrain analysts study air photos to recognize indicators of constructability and maintenance hazards, such as active riverbank erosion and channel migration, actively sinking ground, or a slowly creeping slope (Figure 2-4). These manifestations of terrain instability may not appear on maps nor be discernible from the ground, yet they can be identified from studying sets of multidate and/or multiscale aerial photographs. Among the more noteworthy advantages of sequential air photo terrain analysis is the detection of landscape change over time, such as the subtle changes in a creeping landslide or eroding shoreline, change in the appearance of sediment in water bodies, or the anthropogenic or natural changes in land use and land cover over time. These changes are usually detectable from comparing terrain detail in different ages and scales of air photo stereopairs -- in effect viewing Earth’s landscape in four dimensions: three spatial dimensions plus time. Integrated spatial and temporal analysis of Earth surface change is possible because, in most areas of the world, air photos are available from photo mapping programs carried out over the past 80 or more years. Most countries will have an air photo archive that can be searched for suitable imagery; these archives are typically maintained by government but may also be available from some universities or other institutions.

In the past, aerial photos were typically taken with specialized, high resolution film cameras mounted in aircraft, and delivered as stacks of paper photographs printed at a standardized (predetermined) scale. Most...
aerial photography companies or air photo archive centers can still provide paper prints at customer request. However, modern aerial photographs are taken using sensors mounted on aircraft or unmanned aerial vehicles (UAVs) and provided direct to the customer as digital image files, usually with associated metadata such as camera and/or aircraft parameters, lens calibration data, and geolocation information (from on-board GPS systems). UAVs also capture oblique air photos that provide useful perspectives for interpretations (Figure 2-5).

Legacy (film) aerial photographs can also be scanned and captured as digital images, and many government and academic institutions with archival aerial photography are starting to provide digital copies at or comparable in cost to paper prints. Digital aerial imagery, whether acquired from aircraft / UAV flights or scanned from historical archives, can be brought into specialized photogrammetric and/or stereo photo mapping software packages for further analysis and interpretation, or used as a base layer against which other geospatial data can be displayed.

### 2.2.3 Satellite Imagery

Space-borne imagery has been commercially available (in one form or another) for nearly 50 years. Multispectral and multitemporal satellite imagery is routinely used to assess changes in soil moisture, discriminate between diverse soil and rock types, map vegetation and land use patterns, study changes in snow, ice and water cover over time, and detect and monitor environmental conditions or disturbances and destruction from human activities or natural disasters. Imagery acquired from satellite is often the preferred image type for large, regional-scale studies, such as those undertaken during the early stages of routing for long-distance pipelines, electrical transmission lines, and transportation infrastructure (Figure 2-6).

Most satellite remote sensing systems are passive, meaning they rely on reflected sunlight or emitted radiation from the earth. This includes most of the mid-resolution (regional-scale) earth observation systems such as the Landsat series (administered by the United States Geological Survey), the French SPOT satellite series, and the wide variety of high-resolution (submeter) commercial satellites launched by private companies over the past two decades. Passive satellite imagery is often captured as a set of images that correspond to specific wavelengths of light (visible light, near infra-red, thermal infra-red, etc.); analysis of the relative amounts of reflection between

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**Figure 2-5:** Oblique aerial image of river scour and slope collapse captured by an unmanned aerial vehicle (UAV) during field studies. Image © 2018 J.D. Mollard and Associates (2010) Limited

**Figure 2-6:** Regional-scale satellite image mosaic of the Mackenzie Valley, Northwest Territories, Canada. Landsat 5 Thematic Mapper (TM) satellite image courtesy United States Geological Survey (USGS); data available from the USGS Earth Explorer web portal.

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**Aerial and Satellite Imagery**

A key decision in terrain analysis is the selection of appropriate imagery. The factors which dictate which imagery is appropriate for a specific study include:

- Availability
- Cost
- Scale/spatial resolution
- Date of acquisition/age
- Spectral resolution
- Stereo capability
different wavelengths of light can yield clues to the materials, geology, moisture content and vegetation condition at the Earth’s surface within the study area. In some of the more remote areas of the world satellite imagery may be the only form of repeat imagery available, as remote conditions, poor weather, and/or sensitive or dangerous environments may make conventional aircraft photography programs impractical or prohibitively expensive.

A few satellite systems, most notably RADAR satellites such as Canada’s RADARSAT-1 and -2, are classed as active sensors – they generate a signal which is reflected off the Earth’s surface and detected by sensors onboard the spacecraft. RADAR and other forms of active remote sensing data are much more complicated to process and interpret compared to passive imagery but can yield important information on shallow subsurface geology and geological structures, moisture and hydrological regimes, or hidden / subtle cultural or terrain features. It is even possible to measure millimeter-scale ground movements over large areas using interferometric techniques.

With an ever-increasing number of Earth-observation satellites in orbit, and increased sophistication in both space sensors and image processing software, satellite imagery can be extremely useful in pipeline engineering studies. The best satellite imagery provides an incredibly detailed synoptic view over large areas. However, information interpreted from this perspective is still best when correlated and integrated with data interpreted from 3D (stereoscopic) air photos and other existing geospatial data.

2.2.4 Digital Surface Modelling

The surface of the Earth within a study area can be represented by a computer using a Digital Surface Model (DSM). The common types of DSM for terrain analysis studies is the Digital Elevation Model (DEM), in which elevation values (typically captured in feet or meters above mean sea level) are contained within a regular array (i.e., a raster file). DEMs of a project study area can often be obtained from the same agencies / organizations that provide air photos, satellite imagery or other geospatial data. They can also be generated from photogrammetric analysis of high-resolution air photo stereopairs, from gridding of existing ground survey or topographic maps (using existing contours, benchmarks, spot heights, etc.), or processed from airborne LiDAR or ground-based laser surveys. As with satellite imagery, the resolution of DEMs must be considered when interpreting specific terrain features. Coarse resolution DEMs, such as the USGS Shuttle Radar Topography Mission (SRTM) dataset, provide a good view of regional-scale trends in topography, information useful when routing long-distance pipelines or identifying areas for further study. High resolution (typically sub-meter) DEMs from LiDAR surveys can highlight small, localized terrain features that may be important to pipeline design or geohazard assessment.

LiDAR, in particular, is becoming the most popular data source for topographic modelling, both because of its high-level of accuracy (typically submeter) and because the surveys can return not just the elevation of the underlying ground (i.e., the ‘bare earth’ model) but also heights and density of existing vegetation, the heights and shapes of man-made structures, and the presence of discrete topographic features that may be too small to be detected by conventional ground surveys or photogrammetric analysis (but which may still provide clues as to underlying geological processes; Figure 2-7). These high-resolution surface models can also be used to identify stratigraphic contacts and to generate detailed cross-sectional profiles to produce an interpretation of stratigraphy (Figure 2-8).

Because of its expense and high data-storage requirements, however, LiDAR surveys are generally not done over large (regional-scale) study areas, but are more suited to narrow, well-defined paths, such as a pipeline corridor or right-of-way. Because of this, preliminary pipeline studies will likely draw on coarser DEMs (such as SRTM data or those generated from existing topographic maps), with LiDAR brought in to the final design phase.

Modeling the Earth’s surface in a computer as a DSM allows for the generation of ancillary data sets such as slope maps (either as percentage slope or in degrees), aspect maps (typically in direction referenced to true north), average or mean relief (or levels of variation from), even levels of shading or light intensity (for use in generating shaded relief maps). Analysis of such ancillary data gives the terrain analyst a more complete understanding of the topography of the study area and may yield clues to geological, environmental or man-made processes that may not be detectable from visual observation alone (Figure 2-9).
Figure 2-7: Shaded-relief DEM generated from aerial LiDAR survey data (grey swath) and overlaid on Google Earth imagery (tilted to show an oblique perspective). The DEM clearly shows collapse structures and massive earth flows on the side of the river valley. These features were not visible from air photos or field visits because of the heavy forest cover on the valley slopes. Image © 2018 J.D. Mollard and Associates (2010) Limited. Google Earth imagery © 2018 Google, Inc.

Figure 2-8: Oblique image of a landslide face taken by an UAV during field studies (LEFT) was combined with high-resolution elevation data obtained from LiDAR surveys to produce a cross-section and profile of the slope and to identify stratigraphic contacts (RIGHT). Figure © 2018 J.D. Mollard and Associates (2010) Limited.
2.2.5 Existing Maps and Reports

Existing maps and scientific reports can provide data on soils, geology, topography or other types of physical and human data that can guide, support and supplement air photo and satellite imagery analysis. Maps are necessary to show administrative areas and protected lands that may limit pipeline route options and are best examined during the early stages of pipeline engineering studies. Other maps may show existing transportation and communication infrastructure corridors and networks that can also impact pipeline route selection, construction and operation. Maps of a given study area can often be obtained from various relevant government agencies, universities or commercial map resellers; many of these maps may also be available online in interactive web-mapping applications or can be downloaded as image files for direct import into a GIS.

2.2.6 GIS and Geospatial Data Visualization

A Geographic Information System (GIS) is a suite of software applications which allow a user to create, import, process, query and display data in a geographic (i.e., spatial or location-based) form. One of the great strengths of GIS applications is their ability to store information of virtually any type or form provided the information itself can be geolocated (i.e., can have geographic coordinates attached to it). The addition of geographic location to data allows the GIS user to explore the spatial relationships between various features on the Earth’s surface, compare maps or overlay images regardless of original scale or projection, and identify trends or processes that may not be apparent by looking at each feature separately. All of the data sets described in Sections 2.2.1 through 2.2.4 – digital air photos, satellite imagery, digital surface models and digitized maps -- can be included in a GIS (Figure 2-10).

Figure 2-9: (Left) Shaded-relief DEM of a river meander, generated from LiDAR survey data; (Right) slope raster computed from the DEM. Slope rasters are one of several ancillary datasets that may highlight subtle terrain features not readily apparent on conventional imagery or DEM views. Figure © 2018 J.D. Mollard and Associates (2010) Limited

Figure 2-10: Combining several types of geospatial data in a GIS to produce ancillary data – in this case a soil erodibility potential map – to assist with pipeline routing and corridor selection. © 2018 J.D. Mollard and Associates (2010) Limited.
Within a GIS, datasets can be overlain on other data to assist with interpretation of features or relationships. For example, the planned alignment of a new pipeline could be overlain on a terrain map containing information on known and interpreted geohazards, allowing planners and designers to immediately see and assess potential future risks to the construction or operation of the pipeline. The ability of GIS to present technical or abstract data in a form that is easily recognizable and/or visually appealing is especially important when communicating projects to affected stakeholders, regulators, elected officials and the general public. Satellite or aerial image mosaics overlain with existing map data and design plans can help put the location and extent of a pipeline project into perspective for residents of surrounding communities or other interested parties. High-resolution imagery draped over detailed surface models and annotated with appropriate data can help regulators visualize the physical appearance and potential impacts of an industrial facility. Immersive (360°) video and rendered 3D fly-throughs can be provided to the public through online map and video viewing applications, to keep everyone updated on project progress or to present the facts related to a particular issue. Even open-source or public web mapping applications such as GoogleEarth can be leveraged to present project data to the public in a format that is both effective and easy-to-use (Figure 2-11).

Figure 2-11: Challenging terrain for pipeline routing, represented in a 3D visualization by draping satellite imagery over digital elevation data in a GIS. Landsat 7 ETM+ satellite imagery courtesy United States Geological Survey (USGS); data available from the USGS Earth Explorer web portal.
2.3 TERRAIN FEATURES EVALUATED FOR GEOHAZARD MAPPING AND ASSESSMENT

Geohazard mapping and assessment relies on evaluating multiple features of the landscape through terrain analysis. Landform interpretation provides the foundation for delineating the location and extent of various terrain units that represent surficial materials and associated geotechnical properties, such as topography, drainage, vegetation, geohazards, and cultural or environmental restraints. Specific features or constraints, such as river crossings or unstable slopes, can be further studied with more detailed data collection and field studies. GIS analysis and other geospatial tools can be used to generate maps specific to certain aspects of the terrain, improving the pipeline planning and design process and providing information for effective communication within the project team and with project stakeholders, regulators and the public.

2.3.1 Surficial Materials and Geotechnical Properties

Terrain analysis provides valuable information on surficial materials and conditions essential to pipeline geohazard mapping. With a background in geomorphology and geology, the terrain analyst can interpret surficial materials from remotely sensed imagery based on recognition of various landforms and understanding the processes of their formation (Figure 2-12). In glaciated terrain, for example, hummocky moraines are recognized by morphology, tone, drainage patterns, etc., and an understanding of the process of formation allows for the material composition to be interpreted as ablation till, which exhibits certain geotechnical properties.

2.3.2 Topography

Topography is an essential aspect of terrain and is commonly expressed through elevation, relief, slope, aspect and surface roughness by processing digital surface models or other topographic data in a GIS. In some areas, where unconsolidated sediment (e.g., Quaternary deposits) overlies bedrock, surface roughness can be used as a measure of overburden thickness (Schwab et al., 2004). When routing pipelines or evaluating geohazards within a corridor, topographic constraints must be evaluated because they impact factors such as design, constructability, access, and drainage.

2.3.3 Drainage

River crossings pose unique geotechnical, environmental, and social challenges to pipeline routing and operations. Because flowing water is an active geomorphic agent, river crossings pose geotechnical challenges associated with scour, bank erosion, slope instability, channel avulsion, and debris impact. From an environmental and social perspective, however, the most significant problem with river crossings is the potential for...
leakage from the pipeline and contamination of water. Recent examples of pipeline failures along the North Saskatchewan River in Canada and protests over the Dakota Access Pipeline in the United States highlight the paramount importance of limiting the number of river crossings and selecting geotechnically suitable crossing sites.

When routing a pipeline, all attempts should be made to minimize the number and length of river crossings. Where crossings are unavoidable, detailed terrain analysis using topographic models and hydrological data, including historical stream discharge and watershed characteristics, can identify the most favorable crossing locations for more detailed geotechnical investigations. Crossings are often classified in terms of length, from minor crossings (less than a few hundred meters), intermediate crossings (from a few hundred meters up to about 1.5 km), and major crossings (greater than 1.5 km). While shorter crossings are obviously preferred, other terrain considerations such as geotechnical properties, geohazards, and environmental sensitivity must also be considered. Once necessary crossings are identified, the most suitable and cost-effective construction methods can be determined. In cases where horizontal directional drilling (HDD) is used to bore under streams, important factors to consider include geological stratigraphy, cover thickness, groundwater conditions, ground stability, geological and geotechnical properties affecting drilling methods, the need for casing, stability of the hole and the potential loss of drilling fluid into geological formations intersected by the well bore (see Chapters 6 and 7 for more details).

2.3.4 Groundwater Conditions

Subsurface water conditions influence pipeline routing, construction, and operation. Where shallow water wells or other borehole data exist, data on groundwater conditions should be compiled and evaluated, including depth to water table, seasonal fluctuations, oxidizing and reducing conditions, hydraulic conductivity and connectivity, etc. These factors affect geotechnical design, construction methods, and operations and maintenance. Because of the relatively shallow depth of pipeline placement, it is necessary to characterize the shallow groundwater regime, which is strongly controlled by surficial materials and drainage conditions. Terrain mapping of surficial materials provides information on soil conditions, porosity and permeability, permafrost, wetlands and organic soils, etc. Topographic information can be used to assess groundwater recharge and discharge areas and the direction of shallow groundwater flow. Direct evidence for groundwater discharge from contact or artesian springs, and the elevation of the water table, can sometimes be revealed by surficial morphological features.

Groundwater conditions are particularly important for evaluating and planning HDD crossings to help select drilling parameters and to ensure that aquifers are not contaminated by drilling fluid.

2.3.5 Geohazards

Geohazards are caused by various earth system processes (geological, geomorphological, hydrological, etc.) that pose challenges or risks to lives, infrastructure, and the environment. For the pipeline industry, geohazards are a primary concern because of the potential effects on pipeline integrity, which impacts public safety, the environment, and the reliable and cost-effective delivery of products to customers. Identification and assessment of geohazards and their risks is thus given high priority during both the initial corridor and route selection, geotechnical design and construction processes as well as for long-term operation and maintenance. Terrain mapping provides a basic approach to identify geohazards and to conduct geohazard risk assessments on pipeline infrastructure (Mollard, 1977).

Geohazard assessments for pipeline infrastructure should begin during the selection of a corridor, within which the types of geohazards present are identified and characterized based largely on terrain mapping. While some geohazards, such as an existing slope failure or a tectonic fault, appear as discrete features others extend over broader areas, such as valley bottoms affected by flooding of a particular magnitude, or areas of permafrost. Once the geohazards within a study area are identified and delineated, they can be characterized by their causal mechanisms, frequency, and magnitude, all of which provide the necessary physical inputs to a geohazard risk assessment.

Mass movement of unstable slopes, ground subsidence and heave are among the most common geohazards affecting pipelines (Figure 2-13). Along unstable slopes, movement can range from barely perceptible soil creep to the catastrophic failure of an entire slope. These features may have direct impacts to the pipeline as well as indirect impacts affecting access to the pipeline and related infrastructure (e.g., roads, power lines and compressor stations). Terrain mapping allows for the identification and classification of existing slope failures and the characterization of slopes for potential instability along with determination of the mechanisms of failure and assessments of the frequency and magnitude of these events. Identifying risk factors that may lead to slope failure, such as stream erosion and over-steepening of slopes, thawing of ice-rich permafrost, freezing of frost susceptible soils, and changes in groundwater conditions are key components of terrain mapping for pipeline engineering studies (Sneed, 1972).
Figure 2-13: TOP: Annotated air photo showing mass wasting (LS) and other geohazards along the slopes of a river valley in glaciated terrain. BOTTOM: Oblique aerial views of some of the mass wasting events identified in the main air photo. Airphoto A12518-113(top) © 2018 Her Majesty the Queen in Right of Canada, available from the National Air Photo Library, Ottawa, Ontario. Oblique aerial photos (bottom) © 2018 J.D. Mollard and Associates (2010) Limited.
2.3.6 Cultural and Environmental Constraints

When selecting a pipeline route, increasing attention is paid to environmental and social concerns. Incorporating environmental and cultural constraints into the route selection process can, at least in part, limit or mitigate these concerns. Obviously, sensitive or restricted areas should be avoided altogether, but where this is not possible terrain analysis can assist with selection of a route that minimizes the impacts. For existing pipelines, it is important to maintain an up-to-date inventory of environmental and cultural information along and in vicinity of pipeline rights-of-way to ensure potential impacts are identified, monitored, and addressed during operational and maintenance activities.

2.4 APPLICATIONS OF TERRAIN ANALYSIS TO PIPELINE ROUTING, CONSTRUCTION AND OPERATION

2.4.1 Scales of Terrain Analysis – From the Desktop to the Field

Terrain analysis can be conducted at different scales of study, typically at either a regional scale or at local or landform scale, depending on the purpose of the project. Often a multi-stage approach is used that begins at a high-level to establish the overall terrain conditions and geohazards and to determine locations where low-level or more detailed investigations are required. Pipeline route selection, for example, begins with a high-level evaluation that allows several potential route corridors to be identified, followed by progressively more detailed low-level analysis, finally leading to selection of a specific right-of-way (Mollard and Janes, 1984). Similarly, the evaluation of geohazards along pipeline routes is initially conducted at a regional scale to identify the various types of hazards and their geographic distribution, before evaluating individual hazards at a local level.

After the completion of a "desktop" terrain study, field observations are required both to validate the analysis ("ground truthing") and to collect new data to refine and revise the interpretations.

Prior to going to the field, specific sites are identified based on such criteria as the nature of issues to be investigated, the type of terrain in which these issues are likely to be encountered, a representative distribution of sites along the pipeline, exposure of materials for observation and testing, accessibility, and the availability of complementary data. Along with identifying specific locations, a list of conditions and features to be observed or sampled should be made before visiting the study area.

Field reconnaissance along a selected pipeline corridor to check terrain types and geohazards is often conducted from a helicopter, landing at sites of interest or at predetermined locations. Following aerial reconnaissance, particular sites accessible by road can also be visited on the ground. Depending on the nature of the site and the objectives of the field investigation, individual sites or lengths of the corridor can be visited by all-terrain-vehicle, by UAV, or by foot. While on the ground, the terrain analyst refers to air photos or satellite images and terrain maps so that direct comparisons can be made with features identified during desktop studies. Observations are documented with ground photographs with recorded GPS locations that can be integrated with geospatial data such as detailed topography from LiDAR and high-resolution images to create 3D geological and geohazard models of specific features of interest.

2.4.2 Corridor and Route Selection Process

The objective of pipeline corridor and route selection studies is to determine the optimal centerline for the pipeline, the one that satisfies technical and engineering requirements while best limiting environmental impacts and potential risks, minimizing costs, and addressing stakeholder interests and concerns (Mollard, 1971). Seldom is a single route option apparent at the outset. Instead, most pipeline routing studies begin with regional considerations that involve the identification and assessment of several competing corridors, followed by more detailed evaluation of a specific route within the selected corridor that ultimately becomes the final pipeline right-of-way (Mollard et al., 2008).

Identifying potential corridors typically begins with regional terrain and constraint mapping within a defined study area, with consideration of engineering parameters and requirements, geotechnical conditions (surface materials, topography, hydrology, etc.), geohazards (slope stability, permafrost, karst, etc.), and cultural and...
environmental constraints. While some preferred corridors can be immediately apparent based on engineering or terrain conditions, it is not uncommon for corridors to be constrained in order to avoid “no-go” or restricted areas.

Regional data are then compiled to facilitate high-level comparisons to select a preferred corridor option or several viable alternative options (Figure 2-14). Once competing corridors have been selected, stakeholder engagement activities are often initiated to seek input on issues and concerns with the different options. When comparing different corridor options, it may be necessary to acquire more detailed desktop data (high-resolution imagery, LiDAR surveys, environmental field surveys, etc.) and to conduct field reconnaissance as required to ensure sufficient information is available to evaluate and select a preferred corridor.

After a preferred corridor is selected, the next step is to identify potential route centerlines within the corridor, which may require acquisition of higher resolution imagery and topographic data along with field observations to support detailed mapping of terrain, geohazards, infrastructure and environmental constraints within the corridor. Potential route centerlines are then segmented and attributed based on these parameters. Spatial data are then analyzed in a GIS to help evaluate construction costs, stream crossings, geohazard risk assessments, environmental mitigation requirements, etc. Ranking these factors allow for comparisons of competing route options. With this information, stakeholder engagement activities can be conducted to seek additional input on routing options being considered and to assist with the selection of a final preferred route centerline.

Corridor and route selection studies require different approaches and levels of investigation depending on the specific project requirements, availability of existing data, geographic location, and the nature of routing constraints. Among the most immediate considerations in the study approach is deciding whether there is a need to consider alternative corridors and routes, the number of alternatives to consider, and the widths of the corridors. The process of corridor and route selection is commonly iterative, requiring several rounds of consultations with stakeholders, the public, government agencies and regulators.

Advantages using this progressive approach to corridor and route selection include controlling upfront costs and data requirements during earlier corridor studies which often coincide with parallel studies aimed at assessing the financial, environmental and regulatory viability of the project. Larger investments associated with

Figure 2-14: Index map showing the competing route alternatives identified for a pipeline along a portion of the Mackenzie River Valley, from San Sault Rapids to Fort Simpson to the Fort Liard River, Northwest Territories, Canada. (Mollard, 1971).
more detailed routing studies can be deferred until overall project feasibility becomes more certain. This approach also has advantages with respect to stakeholder engagement as the details of the project are introduced to stakeholders in stages allowing time for people to understand the need for the project and options being considered, and to provide input for assessment of corridor and routing options.

Where long routes and extensive study areas are involved in a pipeline project, the most efficient and economical means of capturing route characteristic data is by remote sensing. Trained analysts use air photos, satellite imagery and other geospatial data to identify Earth surface features and conditions and the genetic processes and environments that created them. From this information they can infer the geoenvironmental characteristics of the terrain along every segment of a potential route option. Desktop (i.e., in office) remote sensing studies reveal difficult terrains and geohazards that can be avoided in initial corridor selection and guide follow-up site-specific field investigations along competing and selected pipeline routes.

2.4.3 Design and Construction

Terrain analysis is essential not only to corridor and route selection, but also to pipeline design and construction. Pipeline design must meet engineering criteria within the constraints imposed by terrain and geotechnical conditions. At the design stage, detailed terrain and supplementary data collected for the centerline routing can be used to develop the pipeline design. The selected pipeline centerline sets the horizontal and vertical routing can be used to develop the pipeline design. The locations and length of pipeline affected), statistical conditions along the pipeline centerline (geographic requirements in organic terrain, insulation in weightings), and describe factors that have design and cost implications (e.g., slope, geotechnical properties, surface and subsurface hydrology, meteorology and climatology, vegetation, and other environmental factors. Within each physiographic region, one can expect different terrain conditions that influence pipeline routing strategies, geotechnical design and construction, and long-term operation and maintenance (Barnett et al., 2004; Rizkalla and Read, 2007; Porter et al., 2014). For this reason, the following sections provide detailed lists and summaries of global geohazards and pipeline mitigation options.

2.4.4 Operation

Terrain and geohazard data developed during routing, design and construction activities can be incorporated in a pipeline integrity database to provide timely access to information that supports the safe operation and maintenance of a pipeline. With the benefit of well mapped and attributed terrain data, pipeline operators can quickly and effectively determine surficial materials, soil types, stratigraphy, hydrological conditions, environmental sensitivities, geohazards, and access routes at specific locations along the entire length of a pipeline. As new information becomes available through regular aerial and ground-based monitoring, the system is updated to capture changes at prioritized geohazard sites and flagged locations where maintenance or other corrective action may be required. Used in this way, terrain analysis can assist with geohazard risk assessments on operating pipelines, planning and implementing protective and mitigative measures on a prioritized pre-scheduled basis and responding to emergency situations as needed.

2.5 ASSESSING GEOHAZARDS IN DIFFERENT REGIONS

Terrain analysis is a well-established approach to geohazard risk assessment in diverse physiographic regions throughout the world. Although a variety of terms and definitions are used, physiographic regions are largely differentiated by geomorphology (landforms and landscapes), surficial and bedrock geology and associated geotechnical properties, surface and subsurface hydrology, meteorology and climatology, vegetation, and other environmental factors. Within each physiographic region, one can expect different terrain conditions that influence pipeline routing strategies, geotechnical design and construction, and long-term operation and maintenance (Barnett et al., 2004; Rizkalla and Read, 2007; Porter et al., 2014). For this reason, the following sections describe major physiographic regions, implications for pipeline routing and characterization, and strategies to avoid and mitigate associated terrain and geohazard challenges. Others (Rizkalla and Read, 2007; Rizkalla, 2008) also
2.5.1 Glaciated Terrain

Over the past 2.5 million years (the Quaternary Period) continental ice sheets expanded across the northern reaches of North America and Europe, along with portions of Asia and mountainous regions throughout the world (Figure 2-15). During the most recent glaciation, ice covered nearly one-third of Earth's land surface, compared to about one-tenth today, mainly in Antarctica, Greenland, and high alpine environments. Glacial processes sculpted landforms and deposited eroded materials over extensive regions, resulting in distinctive glaciated terrains.

In North America, the Laurentide Ice Sheet formed from multiple coalescing sectors and advanced from the continental interior, eroding the underlying bedrock and transporting the material toward the margins of the ice sheet. Glacial erosion affected much of the Canadian Shield, over which the ice sheet was centered, resulting in eroded landforms and widespread bedrock exposure. Melting of the ice sheet, particularly around the margins, left a legacy of undulating, hummocky, ridged, and ground moraines composed of till and smaller areas of glaciofluvial and glaciolacustrine landforms and stratified material (Figure 2-16). While some glaciofluvial, glaciolacustrine and glaciomarine deposits were laid down in direct contact with the ice, most of this waterlaid material was carried and deposited far from the retreating ice margin.

Landscapes created by continental ice sheets and their products are characterized by numerous lakes, bedrock exposures, and different varieties of supraglacial, englacial and subglacial till and ice-contact and proglacial stratified deposits. There are also areas of extensive permafrost. In North America, the Laurentide Ice Sheet accumulated over the Precambrian Shield and while this was largely a zone of erosion, discontinuous silty sandy gravelly till and stratified drift overlie eroded basement rocks. South of the Shield, the glaciated landscapes are dominated and characterized by sandy, silty and clayey till deposits that overlie extensively flat-lying younger and softer Paleozoic and Mesozoic sedimentary rocks. The grain-size compositions of these tills reflect the compositions of their source bedrock, which was eroded by advancing glacial ice. In general, glacier-eroded clay shales give rise to clayey till, carbonate rocks to silty carbonate-rich till, sandstones to sandy till, and igneous and metamorphic rocks to a silty sandy gravelly till with little clay - each till type containing glacial boulders, a potential problem in pipe trench excavation and trenchless crossing installation in some locations (see Chapter 6).

A summary of glacial terrain characteristics and potential implications for pipelines is provided in Tables 2-1, 2-2 and 2-3.
Primary constraints of morainal landforms on pipeline route selection, construction and maintenance are associated with the topography, stratigraphy and material properties associated with these deposits. In most cases morainal sediments represent relatively stable materials with good bearing capacity and open trench properties. However, randomly occurring water-bearing stratified layers in ablation till may be sources of water in-flow into trenches, as numerous small closed water-bearing basins in hummocky or knob-and-kettle morainal topography. This includes moderate relief hummocky moraine, with locally steep-sided mounds and ridges, and kettleholes that commonly flood during spring snowmelt, moderate relief end moraine ridges, and deeply kettled kame moraine, where spring runoff collects in kettleholes leading to seasonally fluctuating water tables. Topography in high-relief drumlin terrain may represent a significant routing issue especially where pipeline routes are oriented mainly perpendicular to the dominant drumlin orientation.

Figure 2-16: Air photo showing fluted moraine and glaciolacustrine plain topography. Air photo A19784-113, © 2018 Her Majesty the Queen in Right of Canada, available from the National Air Photo Library, Ottawa, Ontario.
### Table 2-1: Glacial Moraines

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Till</td>
<td>Generally good foundation conditions but may contain boulders which can damage coatings and which may require additional costs for excavation</td>
</tr>
<tr>
<td>Topography</td>
<td>Rolling to ridged</td>
<td>High relief may result in increased vertical bends and increased construction costs</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Includes areas with poorly drained conditions</td>
<td>Seasonal flooding and soft wet ground; may contain water bearing stratified layers that result in trench flooding and caving</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>Usually cultivated in agricultural areas but high relief and boulder areas may be left uncultivated</td>
<td>Increased likelihood of archaeological and environmental sensitivities in uncultivated areas which may represent the only remaining natural habitat</td>
</tr>
</tbody>
</table>

**Comments**

Attempt to maintain straight horizontal alignments while minimizing crossings of poorly drained depressions and areas of natural habitat. Detailed remote sensing and ground reconnaissance are required to identify areas with high concentrations of surface boulders, especially in Rogen and de Geer moraines and eroded till plains.

### Table 2-2: Glaciolacustrine Landscapes

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Fine-grained stratified sediments (clay, silt, fine sand)</td>
<td>Clay-rich sediments susceptible to high swell and shrinkage potential with changes in moisture content. Silty sediments are susceptible to frost heave and thaw settlement in northern locations. Wet clay sediments have high compressibility and low bearing strength</td>
</tr>
<tr>
<td>Topography</td>
<td>Level to gently undulating</td>
<td>Minor issues related to topography. Susceptible to shallow failures on slopes.</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Poorly drained, low groundwater potential</td>
<td>Poorly drained, high moisture conditions common in low-lying areas. Susceptible to failures in trench excavations. Capillary rise in may lead to corrosive conditions, especially in saline areas. Low-lying areas in areas of groundwater discharge may be susceptible to saline conditions.</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>Poorly drained, highly plastic soils</td>
<td>Potential environmental impacts where highly plastic soils are located in low-lying wet areas due to disturbance by construction equipment (rig mats required) and increased construction costs, particularly during seasonally wet conditions.</td>
</tr>
</tbody>
</table>

**Comments**

Attempt to maintain straight horizontal alignment while avoiding low-lying, poorly drained areas.
In northern Precambrian Shield and glaciated mountain terrain rough, bumpy, bedrock-controlled relief may require additional heavy rock blasting and excavation for the pipe trench. In Rögen (ribbed) and de Geer (washboard) moraines, surface boulders 1 to 2 m in diameter create obstacles to pipeline construction. Ice-thrust moraine often has rafted inclusions of dislocated bentonitic marine shale that can be unstable and prone to slope movement. A general characteristic of all morainal deposits is the heterogeneous nature of the material and the possibility that boulders of varying sizes can be encountered in pipeline excavations and bores.

Stratified sand and gravel deposits occur in ridged and hummocky ice-contact glaciofluvial terrains (kames and eskers) and in level and kettled proglacial glaciofluvial terrains (outwash plains and outwash deltas). All are potential sources of construction aggregate and groundwater supplies for pipeline construction and maintenance. Because of the dominance of granular sediments in glaciofluvial deposits, groundwater is often encountered in pipeline trenches which may require pumping during construction. Trench walls in coarse, well-graded stratified sediments tend to be stable at fairly steep slopes, however, fine clean sands are subject to collapse. Outwash plains and deltas tend to have relatively little

### Table 2-3: Glaciofluvial Plains And Valleys

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Stratified drift (dominantly sand and gravel) in glaciofluvial plains; Interbedded glacial sediments and bedrock in meltwater channel valley sides; Alluvial sediments on floors of meltwater channels</td>
<td>May encounter soft weak glacial and bedrock sediments on valley slopes and wet compressible sediments on valley floors.</td>
</tr>
<tr>
<td>Topography</td>
<td>Level to undulating on glaciofluvial plains and floodplains; gentle to steep slopes on meltwater channel valley sides</td>
<td>Valley slopes may be subject to landslides where meltwater channels are eroded in to underlying weak bedrock sediments (e.g., clay shales with bentonitic layers) or cut through weak glaciolacustrine or glaciomarine sediments.</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Generally well-drained; may encounter contact springs, intertill and bedrock aquifers on meltwater channel valley sides</td>
<td>May encounter high watertables and collapsible sands in fine-grained glaciofluvial deposits. Local high moisture conditions and unstable trench walls may occur where pipeline cross aquifers on valley sides.</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>Often uncultivated in agricultural areas resulting in higher percentage of natural habitat</td>
<td>May encounter environmental sensitivities related to near surface groundwater conditions, natural habitat and archaeological sites and artifacts. Pipelines crossing glaciofluvial plains may also have economic resource implications because this landform often has a valuable aggregate resource potential.</td>
</tr>
<tr>
<td>Comments</td>
<td>In many cases, glaciofluvial plains represent areas with good pipeline engineering characteristics (well-drained with good bearing potential and low compressibility). However, care must be taken to assess potential impacts to aggregate resources and environmental sensitivities related to potential groundwater contamination, loss of natural habitat and impacts to archaeological sites and artifacts.</td>
<td>Construction issues may also be encountered due to high watertables and collapsible sands in trench walls. Considering these factors, while glaciofluvial plains don’t necessarily need to be avoided, proper terrain studies are required to understand local conditions and possible implications. In some environments (e.g., northern permafrost affected areas) glaciofluvial plains may represent a preferred terrain while in others it may be less desirable. Careful terrain evaluation is required when crossing meltwater channels to avoid historical and active landslides and to assess the potential for re-activation of dormant landslides and initiation of new landslides.</td>
</tr>
</tbody>
</table>
relief offering good access, ease of selecting a good alignment and good construction conditions. Topographic relief is higher in ice-contact glaciofluvial terrain and materials are more variable leading to more difficult and field and trenching conditions. All glaciofluvial terrain types have greater environmental sensitivity owing to permeable soils and near-surface ground water tables that are susceptible to contamination from surface spills or pipeline leakage.

Glaciofluvial deposits are often associated with meltwater channels formed by proglacial meltwater erosion. Most of these meltwater valleys are partly filled with stratified fine and coarse fluvial and lacustrine waterlaid sediment. Where meltwater channels have eroded through a cover of glacial deposits and into underlying Cretaceous and Tertiary bentonitic clay shale and mudstone, large rotational slump and translational slides are common occurrences along valley sides. These landslides commonly creep at rates of a few centimeters to as much as 1 m a year, especially where the valley sides and riverbanks are actively eroded by rivers (Figures 2-17 and 2-18).

Figure 2-17 (LEFT): Small-scale air photo showing two pipeline routes (yellow lines) avoiding a large, actively moving landslide on the side of the South Saskatchewan River near Outlook, Saskatchewan, Canada. The landslide is located in till overlying slide-prone Cretaceous clay shale with thin bentonite seams. A large-scale view of the main portion of the landslide (within the black box) is shown in Figure 2-18.

Figure 2-18 (RIGHT): Large-scale air photo showing retrogressive failures along a valley side in glaciated terrain. The main landslide area is outlined in Figure 2-17. Identification of this geohazard allowed route planners to avoid constructing pipelines crossing this area. Features marked ‘C’ are fresh cracks, visible in the air photos; features marked ‘G’ are sinking graben below the headscarp. Air photos © 2018 Her Majesty the Queen in Right of Canada, available from the National Air Photo Library, Ottawa, Ontario.
2.5.2 Fluvial Terrain

The term “fluvial terrain” includes landscapes eroded by running water or built up by accreting deposits over time, both of which can influence pipeline location and design. Pipeline river crossings in different valley and channel types represent a major challenge for hydrological engineers deciding whether the pipeline will be stable if installed in alluvium under a riverbed, or whether it is more desirable to bore under the river channel alluvium in dense till or bedrock. Erosion of stream banks and stability of the adjacent valley side must also be assessed to ensure long-term pipeline integrity. Table 2-4 provides information on fluvial terrain and associated potential issues.

Common river channel types can be identified and their behavior provisionally predicted and evaluated using map and 3D air photo terrain analysis (Figure 2-19; Mollard, 2013).

Figure 2-20 provides examples of meandering and braided river channels. It is also important to have a basic understanding of typical environments and typical bed and bank materials that create different planforms and types of river channels, which affect channel bank and riverbed stability tendencies. These kinds of data are helpful in selecting pipeline routes and avoiding pipeline integrity problems at valley and channel crossings.

The terrain analyst must not only recognize different channel types, but also recognize a variety of drainage patterns created by the erosion and deposition of different kinds of soil material in different geologic, topographic and climatic environments (Figure 2-21). For example, some

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Meandering streams tend to have granular material in the channel and fine (clay and silt) in the floodplain. Braided stream channels tend to be coarser with sand to cobble sized clasts.</td>
<td>Foundation materials generally good, but boulders can damage coatings and which may require additional costs for excavation. Erosion and shifting channels can undercut and expose the pipeline.</td>
</tr>
<tr>
<td>Topography</td>
<td>Generally flat floodplains with single or multiple channels; valley slopes vary from gently sloping to steep slopes in unconsolidated cohesive and non-cohesive sediments, to steep bedrock slopes.</td>
<td>Valley slopes may be prone to slope instability especially where weak layers and groundwater aquifers are present in the stratigraphy and where bank erosion undercuts slopes.</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Subject to flooding, high water tables and poor drainage on floodplains. May encounter artesian aquifers below stream beds and valley sides.</td>
<td>Seasonal flooding and soft wet ground on floodplains. Artesian aquifers may have implications for directional boring below streams.</td>
</tr>
<tr>
<td>Active processes</td>
<td>Bank erosion, bed scour, sediment deposition, seasonal flooding, ice jams, ice scour. Meandering streams will be subject to channel migration and seasonal flooding. Braided streams will be subject to shifting channels and flooding in multiple shallow channels and adjacent bars.</td>
<td>These processes may impact pipeline integrity at stream crossings. Mitigation options include avoidance of problem areas, deeper burial of pipelines and directional boring at stream crossings.</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>Valley crossings often have a higher probability of cultural and environmental issues.</td>
<td>Avoidance and mitigation of cultural and environmental sensitivities.</td>
</tr>
<tr>
<td>Comments</td>
<td>Stream crossings represent highly sensitive conditions from a terrain, geological, hydrogeological, long-term stability and cultural and environmental perspectives. Careful multidisciplinary study is required to assess potential crossing locations early in the planning process so that all issues can be identified and properly assessed. Often, optimum stream crossing locations will serve as pinch points that represent a major constraint in overall route location. Direction boring may represent the best alternative for stream crossings but geological and hydrogeological conditions must be carefully assessed.</td>
<td></td>
</tr>
</tbody>
</table>
Fluvial channels occupy narrow valleys and have little or no floodplain while others actively migrate back and forth across wide floodplains, forming meander scrolls and oxbows, which can undermine pipelines. In these locations one must also watch for dormant and active slope failures adjacent to undercut banks. These slopes may begin to creep or fail abruptly as undercutting of the slope toe progresses. Actively eroding or depositing alluvial fans, cones, terraces, deltas and pediments may also influence pipeline route selection.

Narrow channels may be characterized by a greater degree of bed erosion where riverbed sediments consist of highly mobile silt or fine-grained sand. Therefore, it is important to assess the potential depth of scour at pipeline potential crossings. It is also important to recognize locations with thick accumulations of loose riverbed silt and fine sand that are subject to scour during major flow events (Figure 2-22).

In some cases, riverbed aggradation may lead to the formation of overbank flooding and avulsions. One must also be aware of natural and human alterations, such channel straightening, dredging, and reservoir construction and degradation of sand riverbeds below dams that can lead to avulsions, increase erosion or cause flooding. Sedimentation may also cause abandoned meanders to infill with fine-grained sediment that is highly compressible, saturated and unstable in open excavations. Loose collapsible silt and fine sandy soils may also exist beneath alluvial floodplains. Where riverbeds consist of large boulders or erosion-resistant bedrock, rapids and falls may form; features that are usually easy yet important to routing. Lastly, during pipeline routing across northern rivers one must identify locations susceptible to the formation of ice dams, ice jams, and anchor ice.

**Fluvial Terrain**

Potential geohazards in fluvial terrain (Table 2-4) include:
- Channel bed scour
- Channel bank erosion / recession
- Flooding
- Environmental issues (esp. stream crossings)
- Issues resulting from seasonal variability in discharge rates
- Ice issues (in northern areas)
Figure 2-20: Stream channel types, environments and typical bed and bank materials. Figure © 2018 J.D. Mollard and Associates (2010) Limited.

<table>
<thead>
<tr>
<th>Channel appearance</th>
<th>Channel type</th>
<th>Typical environment</th>
<th>Typical bed and bank materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karst and Kettleshale Soluble rock (carbonates, evaporites) terrains. Also kettle ice-disintegration moraine and kettle supraglacial and proglacial outwash terrains.</td>
<td>Fine dendritic Clayey till plain, coastal plain, dissected clay shale and slate terrains.</td>
<td>Anular Uplifted interbedded sedimentary strata of varying hardness and erosion</td>
<td></td>
</tr>
<tr>
<td>Thermokarst Beaded, or buttonhole (B), drainage; and degraded ice-wedge polygons (P) in permafrost terrain.</td>
<td>Coarse dendritic Semipermeable (silty sand, sandy silt) Marine and lacustrine plains.</td>
<td>Radial Large domes, volcanic cones, small mesas, large buttes.</td>
<td></td>
</tr>
<tr>
<td>Shifting meanders with cutoffs and oxbow lakes Typically wide, low-gradient, unstable meander floodplains composed of a slightly cohesive topstratum over silty sand to fine sand.</td>
<td>Pinnate Dissected thick loessial deposits, dissected margins of terraced silty lacustrine and marine valley fills, and coastal plains.</td>
<td>Ditch Artificial surface drainage to lower water table.</td>
<td></td>
</tr>
<tr>
<td>Coarse subparallel Uniformly sloping marine and lacustrine plains. Eroded preferred joint set and subparallel faults.</td>
<td>Deranged Undulating and low relief hummocky till plain, with drainage into marshy</td>
<td>Tile Underground drains used to lower water table (lighter soil tones occur above tiles).</td>
<td></td>
</tr>
<tr>
<td>Fine subparallel Sheetwash, rillwash, alluvial aprons (coalesced fans).</td>
<td>Trellis Eroded, tilted alternating soft (valley) and hard rock materials (ridges).</td>
<td>Distributary (dichotomic) Bifurcating (splitting) channels on sloping alluvial fans and cones.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-21: Drainage patterns and their associated material types. Figure © 2018 J.D. Mollard and Associates (2010) Limited.
Figure 2-22: Plan and profile sketches illustrating the causes of riverbed scour (Top and center group of sketches from C.R. Neil, pers. comm.)
2.5.3 Permafrost Terrain

Permafrost is frozen soil, sediment, or rock that remains below 0°C for at least two consecutive years. The thermal conditions required for permafrost to form typically occur in climatic zones where the mean annual air temperature is below freezing (Figure 2-23). Because of this close relationship, permafrost is particularly sensitive to changing environmental conditions. Thawing of permafrost, whether naturally or induced, poses significant challenges to pipeline routing, construction and operation (Figure 2-24). Creep and caving of ice-rich stream banks are concerns in pipeline route selection and operation, as are ice-rich and ice-cored mounds and terrain environments that create frost heave, thaw settlement and thermal erosion. Chapter 10 covers geotechnical aspects of permafrost in detail.

For purposes of pipeline engineering studies, landscape features in permafrost terrain can be characterized as either favorable or unfavorable. Generally, landforms with frozen ground but which are ice-free are favorable because the potential volume change upon freezing or thawing is low. Examples include dense morainal deposits with low moisture content and well-drained outwash deposits. Many unfavorable permafrost terrain features, obstacles and hazards are recognizable in good quality 3D air photos and are ideally evaluated during corridor and route selection studies to minimize their impacts.

Sorted and non-sorted patterned ground stripes, steps, circles, nets, polygons and hummocks indicate surficial materials that are subject to intensive frost action processes. As an example, low-center and high-center ice wedge polygons near Tuktoyaktuk, NWT, are shown in Figure 2-25. Ground heave caused by aggradation of ground ice can form various types and sizes of ice-rich/ice-cored mounds, including open and closed pingos, palsas, earth hummocks, frost blisters, frost boils, peat plateau bogs and polygonal peat plateau bogs. These features are sensitive to ground disturbance and will settle or collapse when thawed. Frost heave and frost jacking can also result in the formation of Felsenmeer (frost shattered angular boulders) and blockfields of fractured bedrock that are difficult to excavate or clear from pipeline rights-of-way. Thermal transitions from frozen to unfrozen ground in discontinuous permafrost can create high thermal gradients along pipelines.

Table 2-5 provides a summary of permafrost terrain characteristics and potential implications for pipelines.

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Table 2-5: Permafrost Terrain Characteristics and Implications

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice-wedge polygons</td>
<td>Thermal transitions require careful consideration to avoid damage</td>
</tr>
<tr>
<td>Solifluction lobes</td>
<td>Slope instability can lead to landslide hazards</td>
</tr>
<tr>
<td>Pingos and palsas</td>
<td>Ground heave can result in pipeline displacement</td>
</tr>
<tr>
<td>Beaded drainage patterns</td>
<td>Frost heave can cause pipeline settlement</td>
</tr>
<tr>
<td>Horsetail drainage patterns</td>
<td>Frost boils can lead to pipeline degradation</td>
</tr>
<tr>
<td>Thaw collapse features</td>
<td>Impacts of ground disturbance may require mitigation efforts</td>
</tr>
</tbody>
</table>

---

Figure 2-23: Map of permafrost distribution in the northern hemisphere. (From Péwé, 1975)

Figure 2-24: Example of sensitivity of permafrost to disturbance by vehicle traffic. Photo © 2018 J.D. Mollard and Associates (2010) Limited.
A number of diagnostic slope movement features are indicative of permafrost. For example, solifluction lobes form where slow downward creep of shallow frozen ground on slopes results in the formation of lobate step-like features. Creep-type slope movements also occur in ice-rich streambanks and in rock glaciers and talus slopes. Bimodal flows, where the thawing horseshoe-shaped backscarp is nearly vertical, form because of high soil moisture following permafrost thaw and precipitation events with the resulting mud slurry flowing out of a gently sloping flow bowl through a narrow debris channel. Multiple retrogressive thaw slumps and active layer detachment (skin) flows are other slope failure types commonly found in permafrost terrain.
Hydrological indicators of permafrost include oriented lakes, which may be partly to entirely sediment-infilled, beaded (buttonhole) streams with roundish thaw holes at ice-wedge intersections along small streams, and horsetail drainage with closely spaced, subparallel surface drainage runoff lines. The presence of a “drunken forest” is an effect of permafrost thaw on vegetation where thawing of permafrost in ice-rich peat bogs and along lake, pond and stream shore cliffs undermines the ground in which the trees are rooted resulting in leaning and fallen trees above the thawing face (Figure 2-26).
2.5.4 Peatlands and Organic Terrain

Peatlands (bogs and fens) are one of the more common and important wetland landforms, which also include swamps and marshes (Figure 2-27). All can influence pipeline route characterization and pipeline operation. Canada has the most extensive peatlands in the world, covering roughly 12 percent (110 million hectares) of the Canadian landmass, with many existing and proposed major pipelines located in high water table, high compressibility peatlands, with contiguous frozen and unfrozen peat landforms, the majority of them located in boreal forest.

In northern areas where extensive peatlands cannot be avoided in pipeline routing, pipeline construction is usually undertaken in winter when construction equipment can travel on snow covered, frozen peat surfaces. Where peatlands form extensive bog blankets mantling mineral-soil surfaces, they are commonly used as “winter roads” when the ground is frozen. Ice roads over alternately frozen bogs and unfrozen fens are constructed by flooding packed snow to give a smooth ice riding surface. Watertrack fens usually freeze up a month or so later than bogs, which shortens the length of winter road trafficability.

A useful indicator of shallow versus deep peat is the envisioned topographic shape of the mineral soil surface underlying peatland. Shallow saucer-shaped mineral surfaces underlying peat, identifiable in 3D air photos and surface models created from DEMs, commonly correlate with thinner peat depths. Sharply depressed bowl-shaped hollows in the underlying mineral sediment surface correlate with thicker peat, especially in bogs (e.g., over deep kettleholes in outwash deposits and deep glacier-scoured rock basins). In general, bog peat landforms commonly reach significantly greater depths than fen peat landforms (Figure 2-28).

Peatland researchers have classified roughly 20 types of bog and 20 types of fen. In many cases, peatland is unavoidable in pipeline routing, and it is necessary to choose the shortest or the least hazardous route through it. The simplified peatland classification used in the James Bay Lowland of northern Ontario provides an example of peatland types and related features that can be identified from remotely sensed images. Include are permafrost features typically associated with certain peatland types in northern latitudes.

Table 2-6 provides peatland and organic terrain characteristics and potential implications for pipelines.

Figure 2-27: Air photos of peatland and organic terrain. Treed plateau bogs with collapse scars (white patches) are surrounded by string (ribbed) fens. The peat plateau bogs commonly contain ground ice. The fens are unfrozen and have a water-table at or near ground surface. Air photos A12942-158 (top) and A17887-115 (bottom) © 2018 Her Majesty the Queen in Right of Canada, available from the National Air Photo Library, Ottawa, Ontario.

Peatland Types

Peatland and Organic terrains (Table 2-6) include bogs, fens, swamps and marshes.

- **Bogs** are freshwater wetlands characterized by stagnant (standing) water, very low pH and thick accumulations of organic matter (peat).
- **Fens**, on the other hand, are fed from flowing ground or surface water, have a neutral or slightly alkaline pH, and with a high level of dissolved minerals but little organic matter.
- **Swamps** are wetlands dominated by woody vegetation such as trees and shrub. The water is stagnant to slowly-moving, and can be fresh, brackish or seawater, depending on the location. Similarly, marshes also feature stagnant to slow-moving waters, but are dominated by grasses, reeds and rushes.
Figure 2-28: Schematic illustrating the development of peat plateau bogs and thaw-collapse scar fens, a common peatland type in boreal forests. Figure © 2018 J.D. Mollard and Associates (2010) Limited.
Figure 2-29 provides an example of forested, semi-forested and non-forested black spruce/Sphagnum-dominated bogs, typically with slightly raised (domed and plateau) surfaces, from northern Ontario.

In the same region, water track and ribbed (string/ladderlike) sedge-tamarack dominated fens, typically occur on extensive regular smooth, low-gradient slopes (horizontal fens) and in channel ways (channel and water track fens) while sweeping water track fens enclosing teardrop-shaped and darker-toned forested bog islands are typically found across gentle slopes. Spring fens form where groundwater breaks through to ground surface giving a finely speckled pattern of small ponds and small raised peat forms. In many cases bogs and fens are found in large numbers located in close proximity to one another forming intricate mosaics of bog-fen and fen-bog complexes, with the dominant peatland type listed first.

Also found in these areas are northern swamps characterized by relatively thin peat accumulations, intermittent seasonal flooding and fluctuating water levels. Figure 2-30 shows the depth of peat measured in widespread blanket bog in northwestern Ontario.
Bogs in northern latitudes are often sites where ice-rich permafrost forms ground ice layers in peat plateau bogs, ice-wedges and patterned ground and ice-cored peat mounds called palsas. Melting of ground ice in peat plateau bogs creates small thaw basins called collapse scars. When viewed in air photos or satellite images the collapse scars create a speckled pattern due difference in the reflectance of vegetation within the collapse scar compared to the vegetation on the raised part of the peat plateau.

2.5.5 Coastal Terrain

Water currents tend to be more important than waves in creating erosion and deposition in rivers, whereas waves are more important than currents in creating erosion and deposition along ocean shore zones, developing different coastal types and continuously modifying their geometry in plan and profile (Figure 2-31). Table 2-7 describes coastal terrain characteristics.

The effects of wave action on shore zones in coastal areas are strongest between about 10 m below and 10 m above mean sea level. Beyond about 10 m below mean sea level, the wave base depth is insufficient to move sediment on the ocean floor. Along shoal coasts, waves break far from the shoreline creating a low wave-energy environment, where shore and ocean bottom erosion rates are lower.

Although they are relentlessly ongoing, the shorezone-altering effects of ocean wave and current erosion and deposition usually don’t exceed more than about 10 m above mean sea level. Exceptions are locations where tsunamis and wave action erode the toe of high shoreline bluffs, resulting in bluff failure, removal of failure spoil, and landward retreat of the bluff from ongoing erosion. Along ocean and lake shores, waves bend toward and erode headlands and other shoreline promontories. Eroded coarser sediment is transported into adjoining inlets and sheltered bays by wave-generated alongshore currents. In consequence, pocket beaches and sand dunes are characteristic depositional features in small coastal inlets. In contrast, barrier spits, islands, passes, flood and ebb tidal deltas, washover fans, lagoons and tidal marshes, commonly with associated sandy beaches and dunes, are characteristic features of large coastal embayments. Here, longshore currents strike gently shelving shores at an angle, moving sand particles along the beach while high

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Wave eroded and reworked sediment (sand to cobbles) near the shoreline and fine-grained sediment and organic deposits in lagoons and tidal marshes. Rock and boulders along rocky shorelines.</td>
<td>Compressible silty and clayey deposits require close balancing of pipeline weights. Expansive clays can cause pipeline heave. Rocky shores can damage coatings. Wind driven ice can cause damage to pipelines and associated infrastructure</td>
</tr>
<tr>
<td>Topography</td>
<td>From steep rocky cliffs to clayey tidal flats. Steep, wave-eroded bluffs are common with a gently sloping beach down to the water and in the nearshore.</td>
<td>Wave erosion undercutts coastal bluffs and leads to mass wasting.</td>
</tr>
<tr>
<td>Active processes</td>
<td>Wave erosion, tidal activity, storm surges, tsunamis, ice bergs, etc.</td>
<td>Potential impacts to pipelines near the shoreline include erosion of soil cover, periodic flooding and inundation of pipeline and related infrastructure, ice berg scour, exposure to natural events and human activity related to coastal development and ship traffic. High salinity may contribute to pipeline corrosion</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>Coastal zones often represent sensitive natural and cultural environments</td>
<td>Care must be taken to protect natural ecosystems, communities, infrastructure and heritage resources.</td>
</tr>
<tr>
<td>Comments</td>
<td>Transitions from onshore to offshore pipelines must be carefully considered to avoid potential issues within the coastal zone. Directional boring may alleviate many concerns. Care must be taken to eliminate potential issues with natural forces such as waves, tides and tsunamis, as well as human impacts related to coastal development and ship traffic.</td>
<td></td>
</tr>
</tbody>
</table>
velocity rip currents erode channels in the nearshore ocean floor, driving sediment directly offshore.

Onshore and nearshore underwater slopes on cones, fans, deltas, beaches, spits, bars and barrier islands require the special attention of air photo terrain analysts because they are continually modified by ongoing shore erosion and deposition processes. To estimate the average rate of annual shore recession or advance, changes in the shoreline position are plotted and measured from air photos, high-resolution satellite images and digital topographic models acquired at the same location a few years to several decades apart.

Deeply buried offshore clean sand shorelines along some of the world’s largest estuarine, birdfoot, tidal and arcuate deltas (Figure 2-32) are sites of major oil and gas exploration and discovery, and therefore the sites of subaerial onshore and subaqueous nearshore and offshore pipelines. Examples are the Mackenzie, Mississippi, Tigris/Euphrates Shatt-al Arab, Ganges, Ob, Niger, Congo-Luando and Amazon deltas. As major oil and gas fields are explored and developed in these coastal environments, pipeline route location and planning can be a major challenge. These coastal environments are particularly exposed to the ravages of tsunamis, hurricanes, strong winds, high waves and floating ice, any of which can create significant pipeline design, construction and operation issues.

As a result, coastal features to look for and assess from maps, satellite and air photo imagery include evidence of past tsunami damage and the effects of hurricanes, surging tides and wind damage (for example, the Mississippi Delta). It is also important to assess the extent of coastal erosion and deposition change over time by measuring shoreline recession and progradation, assessed from sequential air photo measurements. In northern coastlines it is particularly important to assess permafrost conditions, both onshore and offshore, and the potential damaging effects of climate change on coastal erosion rates.

Where coastlines are bordered by high steep slopes it is important to assess the potential for landslides, topples and falls and creep movements along eroding shore bluffs as well as the potential for subaqueous flowslides, which are often triggered by seismic activity. The potential for landslide-generated waves must also be assessed to determine potential impacts on pipelines in coastal zones.

Nearshore environments associated with river mouths, lagoons, tidal marshes, swamps and deltas require particular attention to assess shifting (eroding and depositing) distributary beds on shorezone fans and deltas, soft, weak compressible onshore and offshore silty and clayey deposits, requiring close balancing of pipeline weights, expansive clays which can cause pipeline heave, and the potential for flooding of onshore large fluvial-deltaic plains. High salinity and potential corrosive effects are also concerns in marine coastal environments.

Offshore pipelines present a unique set of terrain challenges. Where pipelines on the seafloor cross the seasonal paths of icebergs, there is potential for damage due to iceberg grounding (Barrette, 2011). Most icebergs are discharged into a path governed by bathymetry,
currents, and winds. In offshore areas, the water depth is great enough to preclude iceberg scouring of the seafloor. Near the shoreline, where the water is shallow, icebergs can become grounded with the potential for disrupting pipelines.

Early studies on the effect of iceberg scour on offshore pipelines sought to address the question of whether the iceberg keels scoured to sufficient depth below the seafloor to damage pipelines. Among the approaches used to determine the scour depth was to investigate ice keel markings noted on the glaciolacustrine plain of Lake Agassiz in southern Manitoba (Woodworth-Lynas and Guigné, 1990). Terrain analysis had noted that the otherwise low-relief and uniform character of the glaciolacustrine plain exhibited, in some locations, distinct curvilinear ice keel markings. More prominent features are over 5 km long and have surface expressions that are 20-100 m wide. Specific features mapped from air photos have been targeted for follow-up field investigations to determine the depth of disturbance below the ground surface [ibid].

2.5.6 Karst Terrain

The term “karst” is used to characterize sinkhole topography produced by surface and subsurface water flow, dissolution, subsidence and underground cave and cavern collapse in carbonate and evaporite strata. While dissolution is mainly chemical, caused by flowing acidic (CO₂) groundwater, it is also partly mechanical, the effects of flowing water physically wearing away carbonate rock. Although gypsum, anhydrite and halite evaporite formations are much more soluble than are carbonate (limestone and dolostone) formations, the more limited exposure of evaporites (except for very arid regions) makes the solution of limestone a greater worldwide concern in pipeline route selection and characterization. Table 2-8 summarizes karst terrain characteristics.

Sinkholes are mostly funnel-shaped circular depressions measuring a few meters to tens of meters across (Figure 2-33), formed by the downward seepage of water through residual soil overburden, enlarging fissures and cavities in the underlying soluble rock. In some cases, they can range up to 150 m in diameter. Sinkholes develop where the water table has lowered from above to below the soil-rock boundary, and where the rate of percolation has been accelerated by an increasing amount of water available at ground surface.

In air photos and satellite images, sinkholes may be marked by elongate (long and narrow) lakes that overlie solution-widened fractures in tilted carbonate strata, although steep-sided sinkholes may also be dry and vegetated yet subject to flooding during high precipitation events. In tropical climates high relief conical “haystack- and cucumber-shaped” residual hills (cone karst), separated by alluvial flats may present obstacles in pipeline route selection. Extreme caution is required when selecting routes where sinkholes are visible as underground cavities with uncollapsed roofs may exist in nearby adjacent areas. These are locations where sudden collapse or downdrops could occur during or after construction. Areas where residual or glacial soils overlie historical collapse depressions may result in a difficult-to-predict sharp, irregular contact between surficial soil overburden (up to 5 m deep but mostly much thinner) and underlying

![Figure 2-33: Cutaway view showing common surface and subsurface dissolution features in karst terrain. Figure © 2018 J.D. Mollard and Associates (2010) Limited.](image-url)
carbonate bedrock. For example, in northern Alberta, Canada, sinkholes in sand and till over carbonate beds are caused by solution collapse of highly soluble evaporite (salt, gypsum) interbeds in carbonate strata (e.g., Wood Buffalo National Park, northeastern Alberta). Thus a pipeline trench excavation in this type of terrain may alternate across abrupt contacts between soil and bedrock with corresponding abrupt changes in geotechnical properties. Another concern may be highly plastic residual clay formed from dissolved limestone at the base of residual soil over carbonate rock. Such clays are subject to significant swelling and shrinking with changes in moisture content.

The development of karst is common in tropical and semitropical carbonate and evaporite regions, where dense forests, thick organic soils and heavy rains combine to produce carbonic acid groundwater. Cone (cockpit) karst is common in the tropics, characterized by clusters of cone-shaped hills surrounded by star-shaped alluvial flats. In southern and northern (e.g., arctic) arid desert terrains, where precipitation is low and the surface of carbonate terrains is dry and the organic topsoil is thin, classic karst terrain is less common.

There are two types of sinkholes in classic karst: solution sinkhole karst, caused by the dissolving action of acid groundwaters on soluble bedrock; and collapse sinkhole karst, created when the roof above underground cavities suddenly drops. As a result, most non-tropical karst topography is characterized by a pockmarked pattern of dimpled sinkholes and sparse surface runoff channels (Figure 2-34). The relatively few large valleys that do appear in air photos typically have steep-walls and flat bottoms, and a common absence of tributary gullies. Streams disappear into sinkholes, connecting with underground channels and cavities following solution-widened subvertical fractures and subhorizontal bedding planes, where the carbonate strata have not been significantly folded or tilted. Groundwater entering sinkholes often reappears downstream as flowing springs, which can disappear during dry weather and reappear during wet weather. Therefore, it is important to look for evidence of groundwater discharge into and out of sinkholes and large flowing springs in air photos and satellite images when evaluating pipeline routes in karst terrain. The surface hydrology may reveal disappearing and reappearing streams in this type of terrain. Pipeline leaks in karst terrain are particularly concerning as collapse cavities and associated karst features create direct pathways between the surface and underlying groundwater. Karst terrain may be underlain by large groundwater sources, although groundwater is susceptible to high hardness, pollution and contamination.

Groundwater levels may also experience large elevation fluctuations and, in areas of evaporate

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Dissolution of rock produces irregular topography, distinct landforms and drainage patterns controlled by fractures: sinkholes, grooves and gullies, dry valleys, conical hills, etc.</td>
<td>Routing can be challenging because of irregular topography and the risk of sinkhole collapse and encountering underground voids.</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Slow and gradual dissolution of rock at depth leading to rare but impactful solution collapse and altering of surface and groundwater drainage.</td>
<td>Potential for sudden collapse of ground above underground caverns. Leakage from pipelines can directly contaminate local and regional groundwater systems.</td>
</tr>
<tr>
<td>Active processes</td>
<td>Areas of sinkhole topography and subsurface cavities must be recognized and avoided</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-8: Karst Terrain
dissolution, saline groundwater may create corrosion issues on metal pipelines.

Long linear fracture-trace lineaments are a common feature over surficial and near-surface limestone and evaporite formations, reflecting the continuity of aligned sinkholes (Figure 2-35) and linear solution depressions. All karst terrains display them. Ground observations reveal sinkholes and elongate solution valleys to be aligned along surface lineaments that overlie narrow zones of solution-widened master joints, joint zones, and faults of minor displacement. Sinkholes are avoided in pipeline route selection where it is practical to do so, especially in locations where they are actively enlarging and deepening. Sinkhole topography is a serious pipeline routing impediment where sinkholes are deep, steep-sided and closely spaced, thus difficult to avoid along linear pipeline routes.

Figure 2-35: Air photo showing aligned sinkholes resulting from the dissolution of evaporite strata in carbonate beds underlying thick glacial till, in the Fort MacMurray oil sands area of northern Alberta, Canada. Air photo © 2018 Her Majesty the Queen in Right of Canada, available from the National Air Photo Library, Ottawa, Ontario.
2.5.7 Mountain Terrain

Mountain ranges with intervening valleys, lakes and smaller basins are typically located along continental margins where high rainfall and snowfall and a generally wet climate predispose the high relief and steep slopes to sudden slope failures, some small and others huge. Dormant slope failures can be reactivated by natural and human activities, creating pipeline integrity and public safety hazards (Figure 2-36). Glaciers are often present at high elevations and landforms associated with glaciation, fluvial morphology and slope stability dominate the landscape and geohazards to be identified and assessed.

Table 2-9 provides a summary of mountain terrain characteristics and potential implications. Examples can be found in the West Coast ranges of North, Central and South America, the Guiana Highlands of South America, the Alps, the Urals, the Caucasus, the Himalayas, Hindu Kush, Tian Shan, and parts of Indonesia, among others in the Americas, Europe and Asia.

Landslides ranging from rockfalls, rockslides and debris flows to slow and progressive types of slope movement associated with soil and rock creep (Mansour et al., 2011) are features that should be identified and avoided during pipeline routing. Numerous examples of pipelines being severed or damaged by landslides can be found. For example, a natural gas pipeline near Prince Rupert, British Columbia, was severed in November 2003 by an extremely rapid clay-flow slide, leaving Prince Rupert residents without natural gas heat for 10 days (Schwab et al., 2004). Slope instabilities can be identified from air photos, satellite imagery and digital elevation models. Landslides can also be inventoried along existing pipelines to identify
potential problem areas and to assess risks associated with landslides (Mollard, 1977). Standard techniques typically include mapping the geomorphic components of the slide (e.g., backscarp, failure bowl, debris track and failure debris), making inferences about the failure mechanism and geological controls and judging the relative rate of movement and current status of the failure (e.g., stable, recently active, currently active, etc.). This information then guides field reconnaissance and collection of drill hole and other data.

As an example, Figure 2-37 lists a variety of mountain geohazards along a short stretch of the proposed Alaska pipeline route, at Sheep Mountain where the Slims River delta enters Kluane Lake, Yukon, Canada. Three major slope failures on Sheep Mountain above the Alaska Highway and the proposed Alaska pipeline route are a massive rock avalanche, a rock glacier and a debris torrent, which failed a recorded eight times in 1,200 years, forming a debris cone above the highway (Figure 2-38).

The following paragraphs describe a range of pipeline geohazards in mountainous terrains, which can be assessed from maps and remotely sensed imagery and should be avoided where possible in pipeline routing.

Pipeline routing in mountainous terrain with high mountain peaks, steep slopes, sharp breaks in slope, steep sidehill ground focuses on identifying viable routes in intervening valleys and through mountain passes. As a result, geohazard assessment largely focuses on assessing the stability of slopes, potential debris pathways and runout, hydrologic geohazards and features associated with permafrost and glaciers such as outburst floods, over-steepened mountain and valley slopes, hanging valleys and fiords.

Slope instability features in mountainous terrain include large scale rock slides, slumps, falls and avalanches (c.f., Figure 2-38), including those associated with Sackungen lineaments (upslope-facing scarps) on upper
mountainsides, which signify slope dislocation and local topographic barriers for pipeline routing. Flow failures variously referred to as earthflows, lateral spreads, spreads, flowslides, debris torrents, debris flows, slab failures, piston failures and liquefaction failures also require assessment as do lahars on active volcanoes and solifluction and rock glaciers in permafrost at higher elevations.

Features associated with seismicity must also be assessed. For example, linear fault scarps, including offset topographic and drainage features, rock structures such as folds, faults and fractures, especially fault-rupture displacements in deformed layered rocks, and features associated with neotectonic uplift (caused by glacier-melt unloading and glacial rebound) and subsidence, mostly small and variable in magnitude along coastal mountains and other ranges, yet significant enough in places to predispose the terrain to landslide activity.

### 2.5.8 Volcanic Terrain

Volcanism occurs along the boundaries of tectonic plates that are converging (through the process of subduction) or diverging (mostly at mid-ocean ridges and in rift zones) and within plates over deep-seated hotspots. Many of the world’s active volcanic centers are located along the subducting tectonic margin of the Pacific Rim. Known as the “Ring of Fire,” this area extends along the west coast of the Americas from Chile to Alaska and the Aleutian Islands, and along the east coast of Asia south to the East Indies and New Zealand. Subduction of the Indo-Australian plate generates active volcanism in the Indonesian Archipelago. Scattered volcanoes also occur...
Volcanic terrains consist largely of lava flows and erupted airfall fragmental debris. Lava flows erupting through systems of deep fissures spread outward in sheets that can pile up to a thousand meters or so in thickness, forming extensive flood basalt plateaus and tablelands. Sheet-upon-sheet of stacked basaltic lava outpourings are exposed on near-vertical canyon cliffs in the states of Washington, Oregon and Idaho in the northwestern United States. As the molten lava congealed into hard basaltic rock, it developed hexagonal columns that resemble piles of cordwood set vertically on end (Figure 2-39). Locations where canyons have tall cliffs, ubiquitous high water-tables and highly plastic residual clay surfaces on buried subaerially weathered lava beds are susceptible to huge landslides. Networks of open fractures (fissures) in the flood basalts are capable of storing large volumes of groundwater and create large groundwater springs that may be visible in air photos and satellite images. Volcanic materials ejected into the air, ranging in size from dust to rounded and angular blocks larger than 64 mm across, are called pyroclastic and tephra deposits. Some volcanic terrains also consist of interbedded pyroclastic and lavas.

While active volcanic terrains are obviously poor places to locate a pipeline, even long extinct volcanoes pose hazards. Terrain obstacles and geohazards that the terrain analysts should assess when locating and planning pipeline routes over volcanic terrains are largely associated with surface topography, slope stability, erosion, seismicity, active volcanism and groundwater. Table 2-10 provides a summary of volcanic terrain characteristics.

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Extrusive volcanic rock including lava flows, fragmented pyroclastic debris and airfall deposits. Thick flood basalt deposits with weathered lava bed on subhorizontal contacts</td>
<td>Fragmented angular blocks of volcanic rock which can damage coatings and may require additional costs for excavation. Potential for large translational slides on weakness planes between flood basalt deposits</td>
</tr>
<tr>
<td>Topography</td>
<td>Volcanic cones can reach high elevations with steep slopes. Areas of extensive flood basalt plateaus can form relatively flat tablelands with steep slopes. Ropy lava fields with ridged topography</td>
<td>Vertical and horizontal bends in pipeline due to high relief and steep topography from volcanic cones and tablelands. Rock blasting required in ridgy topography. Potential for slope instability on steep slopes</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Extensive flood basalt plateaus with open fracture networks can store large volumes of groundwater and have large springs where water discharges. Potential for subsurface water-filled cavities in lava fields. Potential for high flows and flooding in streams.</td>
<td>High water table and potential for groundwater flow into open trenches. May encounter open cavities in the subsurface. Assess historical flood frequency information and potential for channel scour and bank erosion.</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>May represent locations of cultural importance. Potential for unusual habitats and rare species. Possibility of excessive ash, dust and toxic steam and gases in active volcanic areas.</td>
<td>May require heritage resource assessment studies and mitigation. May be a need for environmental protection and mitigation. Air quality issues may affect construction and maintenance activities.</td>
</tr>
<tr>
<td>Comments</td>
<td>Avoid areas with active or potentially active volcanism. Plan routes to avoid steep slopes, areas with high, irregular relief, and potential issues associated with near-surface fracture networks, subsurface cavities, ground water and slope stability issues.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-10: Volcanic Terrain

Volcanic terrain (Table 2-10) can be very challenging to the pipeline routing process, even if the volcano is long extinct!
High local topographic relief in wrinkled, ropy lava tongues with lava “squeeze-ups” and pressure ridges that can especially in young lava fields located in dry regions, creates a bumpy land surface that increases the volume of rock blasting required in trench excavations. Near-vertical stair-stepped, saw-toothed cliffs on canyon walls create challenging topographic obstacles for pipelines and fragmented pyroclastic debris that weathers to plastic clay and erodes into intricately dissected terrains can be difficult and costly to cross.

Slope stability issues that require careful assessment include volcanic cones with steep slopes (commonly 30° to 35°) and locations where layers of highly plastic residual clay create potential sliding surfaces between lava flows. The presence of former and possible future outpouring of hot lava flows interbedded and mixed with fragmental airfall ejecta are particularly hazardous where such deposits form steep slopes and are overlain by thick snow cover. Debris avalanches on cinder cones and lahars consisting of hot lava flows and pyroclastic ejecta on cones must also be assessed as do potential landslides and topples on upper basalt cliffs, creating piles of loose broken columns of talus below. Efforts should also be made to identify any potential lava channels, tubes and tunnels that may be subject to collapse. Locations with a high seismicity hazard (strong-motion earthquakes) and especially where there is a prospect of significant fault displacement movements during large magnitude earthquakes must be carefully assessed as seismic motion may destabilize slopes in the area (see Chapter 11).

In terms of erosion, loosely cemented ashfall deposits are subject to deep gully dissection on steep slopes and young weakly cemented pyroclastic deposits are also easily and excessively eroded. For example, fragmented pyroclastic debris that weathers to plastic clay can erode into intricately dissected terrains, which can be difficult and costly to cross with a pipeline.

Lastly, the potential for active volcanism such as volcanic dome and cone lava eruptions should be assessed based on historical and locally available data. Locations near active volcanoes may be problematic due to high concentrations of volcanic ash and dust, toxic steam and gases (e.g., Mount St. Helens), which are corrosive and a potential health hazard to humans and other living things.

2.5.9 Desert Terrain

A high proportion of the world’s largest oil and gas fields are located in desert terrains, most notably in North Africa, southwest Africa, the Middle East, and parts of southwestern United States, southwestern Canada, Mexico, southwestern South America, southeastern Europe, southern Russia, western China and Australia (Figure 2-40). Desert terrain characteristics and implications for pipelines are summarized in Table 2-11.
Figure 2-40: Arid and extremely arid lands around the world appear as light tan colored areas on this satellite image mosaic, standing out in stark contrast to forested / vegetated lands (green) or ice (white). NASA Blue Marble, Next Generation: Land Surface, Shallow Water and Shaded Topography version, © 2018 NASA Earth Observatory, Goddard Space Flight Centre, USA.

Table 2-11: Desert Terrains

<table>
<thead>
<tr>
<th>Terrain Characteristic</th>
<th>Description</th>
<th>Potential pipeline issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Coarse clasts to bare rock where deflation has removed fines. Accumulations of sand forms dunes in some areas.</td>
<td>Erosion of sand cover, exposure of pipe, difficult working conditions for construction and maintenance. Dune migration results in changes in conditions over time. Fine loose sand may have poor traffiability and be difficult for maintenance of equipment. Extreme heat, dust storms, wind erosion, shifting dunes can have an abrasive effect on pipeline coatings. Migrating dunes can expose pipelines. Saline soils and playas can cause pipeline corrosion.</td>
</tr>
<tr>
<td>Topography</td>
<td>Generally, low relief areas of deflation. Dunes form at angle of repose for clean sand (30-35 degrees).</td>
<td>Minor issues related to topography. Active dune ridges may be more problematic than sand plains.</td>
</tr>
<tr>
<td>Drainage and groundwater</td>
<td>Ephemeral discharge forms alluvial fans and migrating channel beds</td>
<td>Flash floods can cause washouts that expose the pipelines.</td>
</tr>
<tr>
<td>Cultural and environmental</td>
<td>Deserts may host sensitive plant and animal species and traditional land uses.</td>
<td>Timing and routing restrictions to avoid impacts to cultural and environmental features. Assessment of mitigation options to minimize impacts.</td>
</tr>
<tr>
<td>Comments</td>
<td>Minimize crossing high relief active dunes, soil remediation maybe required to protect against wind erosion over pipelines. Planning to minimize terrain impacts during construction and challenges related to construction equipment and personnel.</td>
<td></td>
</tr>
</tbody>
</table>
Deserts cover about 30 per cent of the Earth’s continental surface and occur where the average annual precipitation is arid (less than 250 mm) to semiarid (250 to 500 mm). Some desert landscapes receive as little as 110 mm a year total precipitation. Deserts are also regions of high evaporation: 800 to 4000 mm a year. As a result, they are characterized by few plants, strong winds, rare torrential rainstorms, playa lakes, salt flats, thin soil profiles, and lime-cemented subsoils called “calcrete”. Much of desert terrain consists of extensive sand sheets and sand seas, although only about 20 per cent of the world’s deserts have sand dunes. In the giant dune fields in the Sahara, Middle East and South Africa, dunes can exceed 100 m high, several kilometers long with basal widths as much as a kilometer, forming long subparallel chains one to three kilometers apart. Sand seas consist of more than 40 per cent coarse sand and gravel, whereas sand dunes can have up to 80 per cent fine sand (0.1 to 0.2 mm approximately), the remainder being medium sand (0.2 to 0.6 mm). Nearly 50 per cent of all desert surfaces are wind-eroded (deflation) areas, where wind has removed the fines (silt and clay) and sand, leaving bare rock or a surface layer composed of pebbles and cobbles on top of bedrock, the landscape called a “hammada”.

Many deserts are isolated, inhospitable, inaccessible regions. Strong winds create environmental effects that negatively affect pipeline construction and pipeline maintenance: dust storms, low visibility, a hot dry climate, excessive wind erosion, shifting dunes. And dust storms and heat can affect the health of pipeline workers.

There are two main types of wind erosion: deflation and abrasion. Deflation is the removal of material and abrasion is the sand-blasting or abrasive effect of wind-carried material. An important aspect of terrain analysis in desert terrain is identification of active dune, including blowouts and migrating dunes, where removal and transport of sand can result in exposure of buried pipelines.

Blowing and drifting fine sand can abrade above ground pipeline infrastructure while sand can get into and accelerate wear on pipeline construction and maintenance machinery. Dust storms also pose a health and safety hazard, largely caused by severely reduced visibility and potential inhalation of fine particles. Wind erosion also creates bare rock and surfaces veneered with gravel and cobble lag deposits which may require specialized construction equipment for trenching. In areas with deeper sand deposits are subject to caving of the trench walls, both where clean fine sand is dry and where it is saturated below the near-surface water table.

There are two main types of wind (aeolian) deposit: sand dunes, consisting of ridges and mounds of windblown dominantly fine and medium sand; and loess, a homogenous silt-rich, buff-colored, loose and porous windblown deposit. Loess is estimated to mantle one-tenth of the Earth’s land surface, ranging in thickness from less than 1 m to over 100 m. Notable examples are found in China, central Europe, southern Russia and northwestern and central parts of North America. High streambanks, gully sides and highway ditch backslopes in thick loess deposits can often be observed in near-vertical slopes. Deep deposits of loess, especially where denuded of vegetation are susceptible to excessive gully erosion and to collapse and piping from wetting of in situ loess and redeposited colluvial loess (Figure 2-41).

Figure 2-41: Development of piping and roof collapse in thick, silty, waterlaid (i.e., fluvial, lacustrine or marine) and silty, windlaid (loessal) deposits, characteristic of extremely arid, arid and semi-arid lands. Figure © 2018 J.D. Mollard and Associates (2010) Limited.
also susceptible to sudden subsidence from earthquake ground-shaking in seismically active locations.

There are several common types of dunes: barchan, longitudinal, star (pyramidal), parabolic and domal (Figure 2-42) as well as transverse (normal to the prevailing wind direction). Each dune type has a distinctive shape, often occurring within a particular region of the world and physical environment and influenced by the availability of sand supply, wind strength, annual moisture and thus vegetation cover. Parabolic dunes (U-shaped dunes with horns pointing upwind) are a common dune formed during the Pleistocene under moister periglacial climatic conditions. One of the more impressive dunes is the long and narrow longitudinal (seif) dune, where dune crests parallel the dominant wind direction, thought to be formed by counter-rotating turbulent roles of spiral wind vortices. Some dunes are “fixed” by vegetation while others are sheltered by topographic relief, and still others are constantly reshaped and shifted around by the wind. During pipeline construction and maintenance, disruption of the vegetation can result in stabilized dunes becoming reactivated (Figure 2-43).

On high dunes, clean, loose sand on downwind steep (~34°) lee-slopes is subject to slipping which can cause slumps that expose the pipe and wheeled vehicles to becoming easily bogged down in the loose sand. This is because the void ratio, porosity and looseness of sand are greater on lee slopes than on windward slopes that are impacted, compacted and densified by strong winds.

Hydrologic features that must be mapped and assessed in desert regions include alkali lakes and saline soils that induce pipeline corrosion. Repeated flooding of the surface and subsequent drying by evaporation may form calcrete deposits, consisting of lime-cemented crusts, that can present a difficult-to-excavate hardpan. In some cases, hard saline crusts form over soft unstable soil deposits leading to problematic foundation conditions for construction equipment and trench walls below the thin surface crust.

In some locations there is also the possibility of rare torrential rains that may result in flash floods that divert

Figure 2-42: The six dune types: a) parabolic; b) barchan; c) longitudinal; d) transverse, e) domal, and f) star (pyramidal). Figure © 2018 J.D. Mollard and Associates (2010) Limited.
distributaries on alluvial fans, leaving bridges abandoned and culverts filled with sand and gravel debris and forming new channels and washouts that expose pipelines. Terrain features to watch for include ephemeral sand and gravel streambeds—variously called arroyos, wadis and nullahs—which are typical desert watercourse features and channels subject to migration. In areas with shallow groundwater tables, desiccation and lowering of the water table may cause ground subsidence that either exposes shallow pipelines or imposes bending stresses on the pipe.

### 2.6 SUMMARY

Terrain analysis is an essential and cost-effective means to identify and evaluate alternative pipeline routes, avoid geohazards and other problem areas, and generate geotechnical data and maps to support the successful design, construction and operation of gas and oil pipelines. Terrain information is drawn from interpretation of aerial photographs, satellite imagery, digital surface models, existing geospatial datasets, and from field studies.

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*Figure 2-43: TOP: Slope raster (grey swath) generated from aerial LiDAR surveys, showing the size, shape and orientation of stabilized sand dunes in an area of extensive oil and natural gas production; BOTTOM: eolian dunes stabilized by vegetation are susceptible to disturbance and reactivation during pipeline construction, operation or maintenance.*
Geographic information system (GIS) mapping tools and 3D visualization can improve pipeline planning and design, and aid effective communication of information to members of the project team, contractors, regulators and affected stakeholders. Studies generally begin with high-level assessments utilizing regional-scale imagery and complementary geospatial datasets. High-level studies are followed by more detailed low-level studies that draw on higher resolution datasets. High and low-level studies are accompanied by corresponding field reconnaissance and collection of geotechnical, geological and geomorphic data to support detailed design and geohazard risk assessment and mitigation.

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CHAPTER SUMMARY

This chapter describes how terrain analysis is an essential and cost-effective means to identify and evaluate alternative pipeline routes, avoid geohazards or other problem areas, and generate geotechnical data and maps to support the successful design, construction and operation of oil and gas pipelines.

KEY POINTS AT A GLANCE:

• **Among the techniques used in geohazard assessments of pipelines is terrain analysis, which involves the study of surficial characteristics and the interpretation of landforms.**

• **The “tools” (data types) used by the terrain analyst include aerial photography, satellite imagery, digital surface modelling, existing maps and field report, and 3D data visualization in a GIS.**

• **Pipeline terrain studies generally begin with high-level assessments using regional-scale imagery and geospatial datasets, then progress to more detailed (low-level) studies using higher-resolution data.**

• **Desktop studies should be accompanied by field reconnaissance and the collection of geotechnical, geological and environmental data to support detailed design, risk assessment and mitigation studies.**

• **Terrain analysts should be familiar with the types of terrain that may occur in their study area and their associated geohazards. This includes geohazards in glaciated, fluvial, permafrost, peatlands, coastal, karst, mountain, volcanic and desert terrains.**