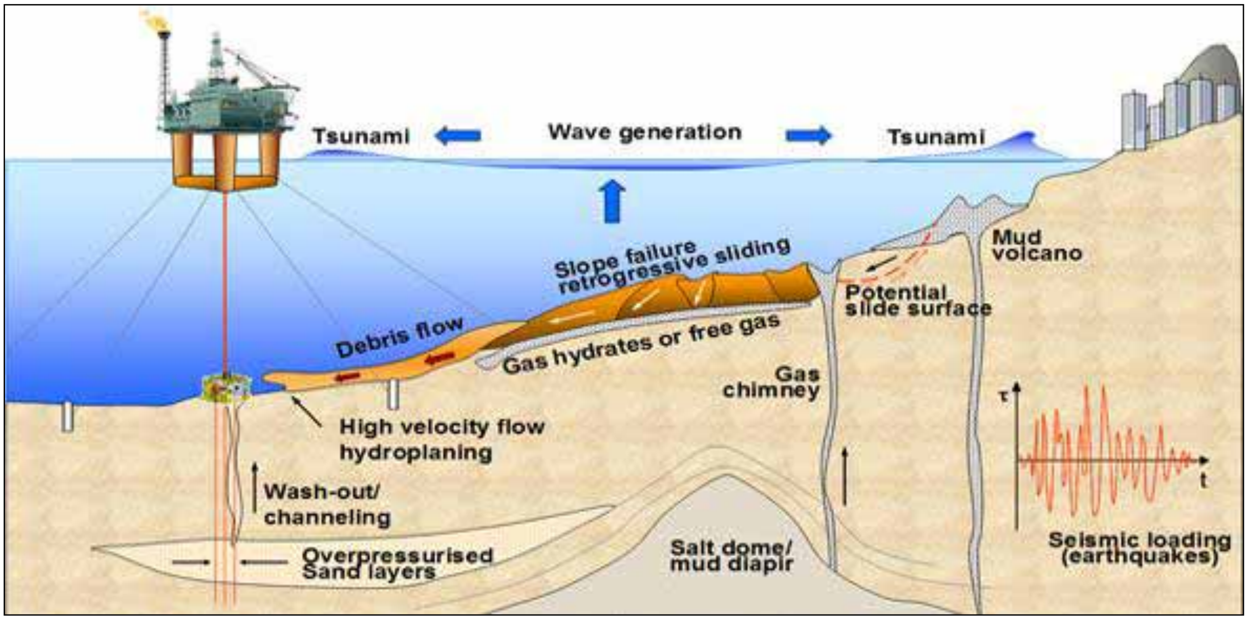
4.1.4 Natural Hazards Affecting the Seafloor (Attachment A)

Natural hazards affecting the seafloor are referred to as geohazards. A geohazard is defined as "A geological state, which represents or has the potential to develop further into a situation leading to damage or uncontrolled risk". Geohazards are found in all parts of the Earth and are always related to specific geological conditions and geological processes, either recent or past. Important offshore geohazards include: (i) seabed instabilities and mass wasting processes including debris flows and gravity flows (submarine slope failures); (ii) pore pressure phenomena (e.g., shallow gas accumulations, gas hydrates, shallow water flows, mud diapirism and mud volcanism, fluid vents, pockmarks); and (iii) seismicity (Figure 4.6).



Source ICG 2010.

Figure 4.6 Main Offshore Geohazards

A drilling hazards and constraints assessment of the proposed Old Harry exploration well was conducted in October 2010 (FGI 2010). Constraints are features or conditions that may affect drilling or installation operations, but do not constitute a safety hazard and include such items as localized near-surface boulders that might cause refusal during drilling or affect structural alignment of casing during installation, thereby requiring respud or reinstallation. A hazard by comparison may present a safety risk, such as the presence of over-pressured shallow gas within the “open hole” drilling interval, which would have potential to cause a blow-out. Hazards may be assessed qualitatively as having either low or high probability of occurrence, based on interpretation of the available geological and geophysical data. High probability is assessed if geologic conditions are conducive and the data support the presence of a specific hazard. In this case, the hazard occurrence is considered probable. In the case of low probability, the observed geologic conditions may be conducive and, although the data do not necessarily support the presence of a hazard, the data do not exclude the possibility of a hazard (FGI 2010).

High-resolution geophysical site survey data were acquired over the proposed well site for the purpose of a shallow drilling hazards assessment (FGI 2010). Geophysical data were acquired within a 22.5 km^2 rectangular survey site, aligned north-northwest-south-southeast. The site dimensions are 4.5 km (west-southwest-east-northeast) by 5 km (north-northwest-south-southeast). The assessment was performed to identify geological hazards and constraints on the seabed and in the shallow sub-surface relevant to the safety and efficiency of proposed exploration drilling operations. The assessment was limited to the "open hole" drilling interval (approximately 600 m below seafloor). Natural hazards that may affect the seafloor are described and discussed in the following sections, with results from the Old Harry geohazard survey (FGI 2010) included for appropriate site context.

4.1.4.1 Seabed Conditions

The regional surficial and shallow geology in EL 1005 reflects processes of Pleistocene glaciation and subsequent marine sedimentation (FGI 2010). The ultimate retreat of Late Wisconsinan ice from the Laurentian Channel is recorded by the near-surface sedimentary succession, which consists of glacial diamict (till), overlain by glaciomarine muds (Emerald Silt) and draped by Holocene surficial silty clays (LaHave Clay) (Fader et al. 1982; Grant and Morrison 1996). The LaHave Clays are distal equivalents of sand-rich slope deposits (Sambro Sands) on the flanks of the Laurentian Channel, which were derived from transgressive erosion of St. Pierre Bank and adjacent shelf areas as sea level rose from a post-glacial lowstand of -110 m (Fader et al. 1982; Josenhans and Lehman 1999; Quinlan and Beaumont 1981).

Josenhans and Lehman (1999) describe a typical succession of ice contact and till deposits, proximal and distal glaciomarine clay deposits and surficial marine muds. Three till sub-units relating to multiple glacial advances have been defined, with only the oldest (Lower Till) present in the region of the Old Harry prospect. The tills form a discontinuous cover over bedrock, and are draped by glaciomarine sediments and Holocene muds (FGI 2010).

The Old Harry prospect is situated within the Magdalen Basin (FGI 2010). Basin formation was initiated during the waning stages of the Acadian Orogeny in an extensional setting, with periods of dextral transpression (Williams 1995; Hayward et al. 2002). Within the Old Harry prospect area, the Basin hosts Upper Carboniferous sedimentary strata consisting of multi-storied channel sandstones interbedded with fine-grained siltstones, shales and mudstones (Giles and Utting 1999, 2003). The formerly flat-lying to gently dipping strata have been folded and faulted by salt-motivated tectonism, resulting in a system of fault-bounded anticlines and synclines, providing structural closure for prospective hydrocarbon systems (Hayward et al. 2002).

Within the Laurentian Channel, the strata have been deeply eroded by Pleistocene glaciation. In the Old Harry well site area, the shallow sedimentary succession comprises partially eroded, sandstone-dominant Cable Head Formation at the top, underlain by the finer grained Green Gables Formation, and the more interbedded Bradelle Formation, which is interpreted to host prospective reservoir quality sandstones (Hayward et al. 2002; Hu and Dietrich 2008, 2009;).

The Old Harry site is situated on the floor of the Laurentian Channel, a large-scale, glacially overdeepened u-shaped valley separating the Magdalen Shelf and the narrow shelf of southwest insular Newfoundland (FGI 2010). Water depths within the surveyed Old Harry well site area range from 462 m in the northwest to 482 m in the east; and the seabed dips regionally to the southeast at an average of less than 1°. The seabed displays a gently undulating topography with a broad, low relief “ridge” trending southeastward through the centre of the site, with low-lying troughs on each side. The proposed well surface location is situated near the crest of the “ridge” at 470 m water depth. The local seabed dip is <1° SSW (FGI 2010).

Seabed sediments in the Old Harry site investigation area consist mainly of soft glaciomarine to post-glacial muds with occasional coarse granular material derived from ice rafting (FGI 2010). The muds (>60 percent clay, >30 percent silt and <5 percent sand) are interpreted to have been deposited by gradual, deep-water pelagic sedimentation during the Late Wisconsinan to Holocene period. Far offset piston core data suggest that the surficial muds are bioturbated and contain occasional ice-rafted clasts. Seabed video images show a generally smooth mud seabed with common burrows formed by benthic infauna. Isolated clusters of ice-rafted pebbles are seen in places (FGI 2010).

Anchoring conditions are considered to be generally favourable within the Old Harry well site area. There are no identified or charted man-made features or obstructions to drilling and anchoring in the well site area (FGI 2010).

Boulders

There is potential for occasional ice-rafted cobbles and/or boulders within the near-surface Unit 1 deposits, down to the Base Quaternary glacial unconformity. Holocene surficial marine mud deposits vary from approximately 9 to 28 m thick across the Old Harry site, and are estimated to be 15 m thick at the proposed well location. Potential for coarse granular material generally increases below the Holocene surficial marine muds, within the proximal glaciomarine sediments and basal tills. There may be potential for fragmented bedrock on the glacially eroded, buried bedrock surface. While isolated boulders may occur, there is considered to be a low probability of drilling refusal or casing problems caused by near-surface boulders at the Old Harry well site (FGI 2010).

Faults

A southwest-northeast trending system of normal faults occurs in the southern part of the site investigation area, forming a graben-like structure (FGI 2010). Faulting was likely associated with salt-motivated tectonism and uplift. These faults are not considered active. It is noted that the proposed well site at Old Harry is located approximately 1,200 m northwest of the fault system and does not intersect interpreted faults.

4.1.4.2 Pore Pressure Phenomena

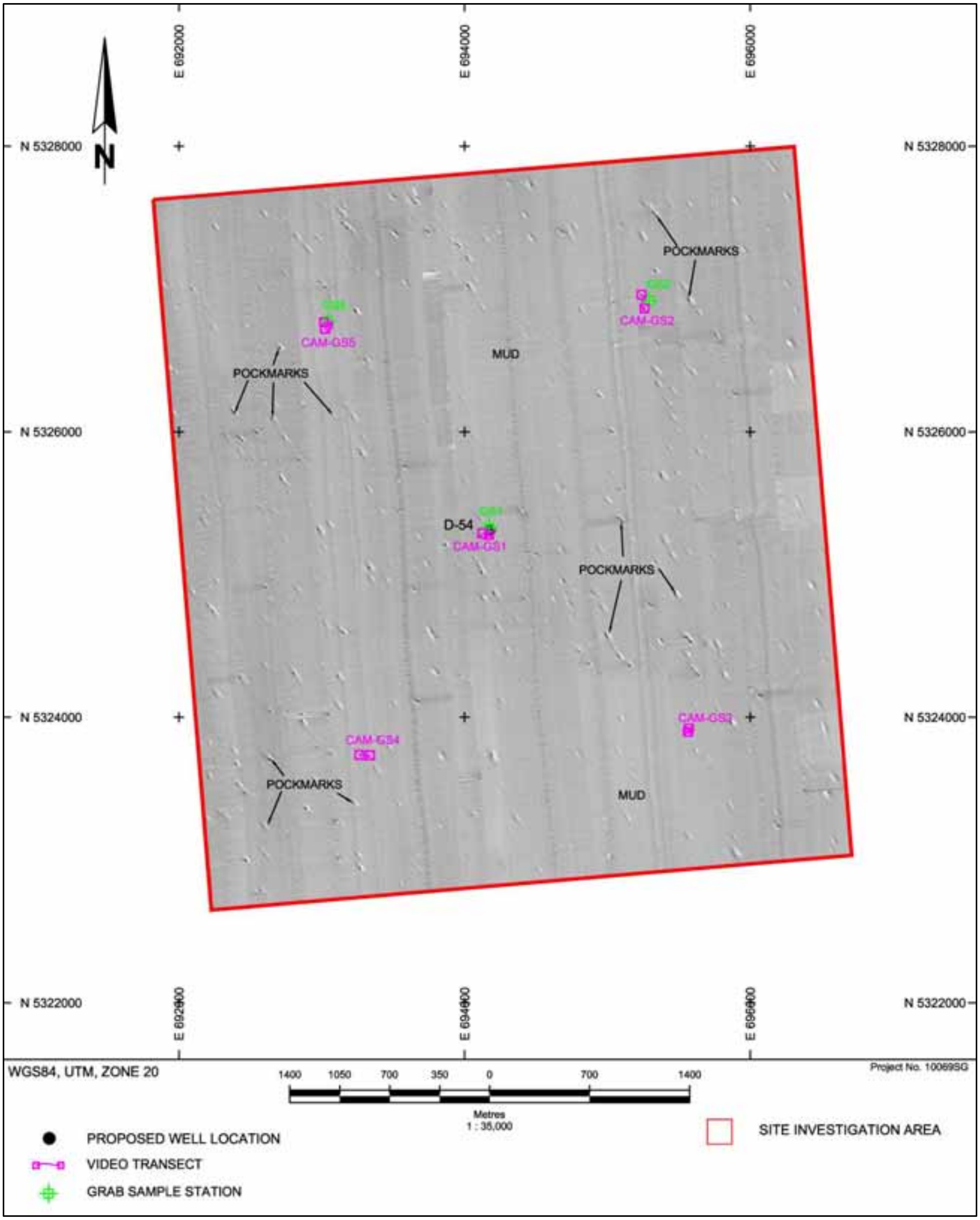
The pore pressure phenomena considered in this report include shallow gas accumulations, gas hydrates, shallow water flows, mud diapirism, mud volcanism, fluid vents and pock marks. While all are individual phenomena, they are related, and are an expression of former or present day activities of fluid flow related to conduits such as faults or sedimentary discontinuities. Fluid flow within sediments, exploiting pathways of permeable sediments or faults, results in upward migration of gas and water expelled from sediments at depth. The end result of these extrusions is pockmarks and mud volcanoes and diapirisms, which form where entrained sediment erupt at the seafloor. These processes are related to excess pore pressure at depth, which decreases sediment strength and increases slope failure potential. The use of high-resolution seafloor mapping tools has permitted identification of submarine slides, pockmarks, mud volcanoes and active faults in unprecedented detail. The morphologic evidence suggests that all these features should be considered as common rather than exceptional on the seafloor (Cochonat et al. 2007).

Pockmarks

Pockmarks are concave, crater-like features on the seafloor, generally up to several hundreds of metres in diameter and tens of metres in relief (King and MacLean 1970; Kelley et al. 1994). The formation of pockmarks is mostly caused by the seepage of thermogenic and biogenic gases (Rogers et al. 2006) and the release of pore water (Harrington 1985). Pockmarks have been described in areas that have been affected by the up-drift of ice that detached from the sub-seafloor (Paull et al. 1999) and decomposing gas hydrates (Solheim and Elverhøi 1993). Pockmarks are also induced by grounded moving icebergs or anthropogenic activities such as trawling and ship anchoring (Harrington 1985; Fader 1991).

Approximately 250 seabed pockmark depressions occur across the Old Harry survey site (FGI 2010) and their distribution is shown in multibeam and side scan sonar imagery (Figure 4.7). The features are asymmetrical with a dominant elongation to the south-southeast, in the direction of prevailing bottom currents. They are typically on the order of 50 m wide and 100 m long, and commonly less than 2 m deep. The smallest pockmark features imaged by multibeam data are approximately 20 m in diameter. Isolated pockmark features reach depths of approximately 5 m below the surrounding seabed. The inner sidewall slopes of pockmarks are typically <2° but exceed 5° in places (FGI 2010).

The areal density of pockmarks within the survey site is approximately 11/ km^2. The pockmark distribution does not show well-defined patterns, though they appear to be most abundant southeast of the proposed Old Harry well location (FGI 2010). A few of the pockmark features are aligned with each other and have coalesced to form longer seabed depressions oriented with the dominant current direction, as seen mainly in the northeast part of the site. It is not known whether any of the features are actively venting; however, some are distinct while others appear muted and are potentially older (FGI 2010). Fluid expulsion would likely be gradual and intermittent (Grant and Morrison 1996).



Source FGI 2010

Figure 4.7 Side Scan Sonar Mosaic Depicting Pockmarks at Old Harry

Side-scan sonar imagery shows locally high acoustic reflectance in many of the pockmark depressions, suggesting that accumulations of coarse granular material may have formed at the base of the features, due to progressive winnowing of fine-grained sediments by fluid expulsion (FGI 2010). The coarse granular (ice-rafted) material, previously embedded in a mud / clay matrix, settled to the bottom of the pockmarks as the fine sediments were suspended by venting and then transported down-current. Some of the pockmark features show local seabed mounding on the down-current fringes, where some of the suspended sediment load has been rapidly deposited close to source (FGI 2010).

Pockmarks should be avoided when selecting well spud locations. In the event that an anchored MODU is used for drilling, the deepest pockmarks should be avoided during anchor placement.

Shallow Gas Accumulations

Shallow gas, which occurs at depths less than 1,000 m below seafloor (Floodgate and Judd 1992), may pose a hazard to offshore open-hole or riserless drilling operations, such as geotechnical drilling or drilling of the tophole section of oil and gas wells. There are two different types of shallow gas, defined by origin: thermogenic and biogenic. Thermogenic gas forms at depth under high temperatures and pressures. It may be present in the shallow subsurface where it has migrated up from a deeper reservoir (Floodgate and Judd 1992). Thermogenic gas can migrate upward along natural pathways, through porous strata or along faults, or along leaking wells. Biogenic gas forms at shallow depths through bacterial activity.

Biogenic gas is by far the most common gas in shallow sediments (Lin et al. 2004). Biogenic gas requires a sufficient supply of organic matter and a rapid sedimentation rate to bury organic material before it is oxidized. The gas accumulates when it can migrate in a free gas phase (Rice 1993), with this occurring when the concentration in the pore fluid exceeds gas solubility, or when gas exsolves due to reduction of hydrostatic pressure, which could be caused by erosion of the seabed or a fall in relative sea level.

Shallow gas accumulations require a reservoir, a seal and gas. Shallow gas reservoirs are most commonly formed by coarser-grained materials such as sand, and seals by fine-grained sediments such as clay (Kortekaas et al. 2011).

Geophysical observations suggest that there is possible near-surface gas in places within the Old Harry survey site, as indicated by seabed pockmarks and localized columns of attenuated amplitudes in Huntec sub-bottom profiler data, which commonly occur below the pockmark features (FGI 2010). Acoustic attenuation in proximity to pockmarks suggests the possible occurrence of gas (probably methane) within the dominantly fine-grained near-surface sediments, with potential seepage at the seabed. However, it is noted that the possible near-surface gas interpreted within the Old Harry survey area does not produce widespread acoustic wipe-out with loss of acoustic stratigraphy and structure, which typically occurs in high frequency sub-bottom profiler data where shallow sediments are extensively gas-charged (FGI 2010).

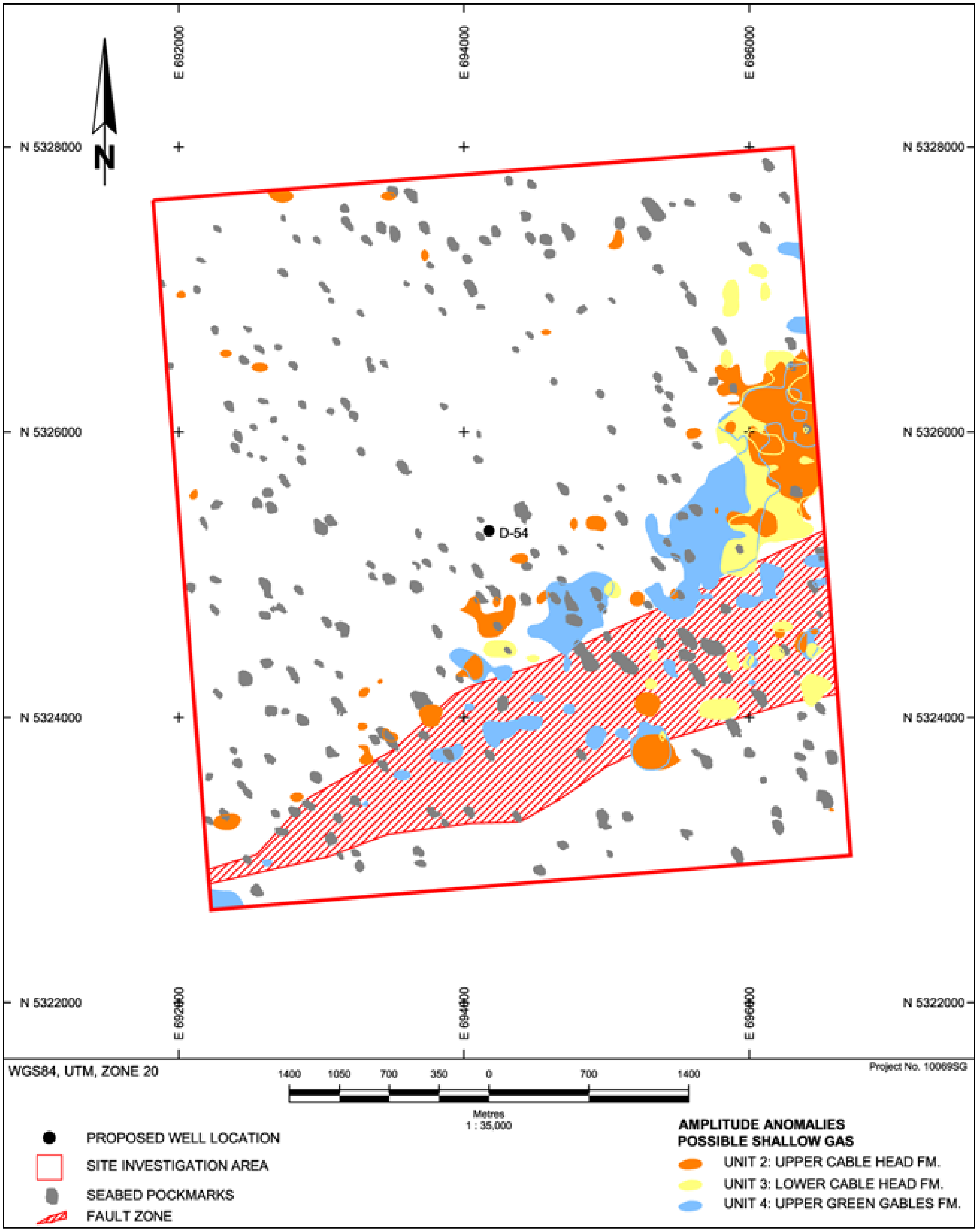
Localized, subsurface high amplitude anomalies indicative of possible shallow gas have been mapped within the Old Harry survey site (FGI 2010). These anomalies occur within shallow Carboniferous bedrockalong a southwest-northeast trend through the southern part of the site; mostly coincident with the mapped fault zone along the anticlinal structure that shallows to the north-northeast. High amplitude anomalies indicative of possible gas occur more than 200 m southeast of the well site location. These anomalies display a number of gas attributes, including trough-overpeak reflection pairing, sharp lateral gradients and possible frequency effects (FGI 2010). The anomalies occur up-dip of the proposed well site, within the truncated anticlinal structure. These anomalies, delineated on the hazards and constraints map, do not pose a hazard to drilling at the proposed well site (Figures 4.8 and 4.9) (FGI 2010).

It is noted that anomalous amplitudes occur near the up-dip limit of the trough reflector (Figure 4.8), which implies the possibility of gas migration up-dip along bedding planes (FGI 2010). The possibility of communication between the moderate amplitude bedding, the shallow amplitude anomalies (up-dip) and apparent fluid or gas escape pockmark features at the seabed suggests that the presence of gas cannot be excluded on the basis of the available data. However, the observed seismic attributes do not appear to be indicative of an overpressured gas zone below the Old Harry proposed well site. The reflector below the well site is therefore interpreted to have a low probability for shallow gas that is hazardous to drilling. As potential for shallow gas at the proposed well location cannot be excluded, it is suggested that mitigation options be considered (FGI 2010).

Gas Hydrates

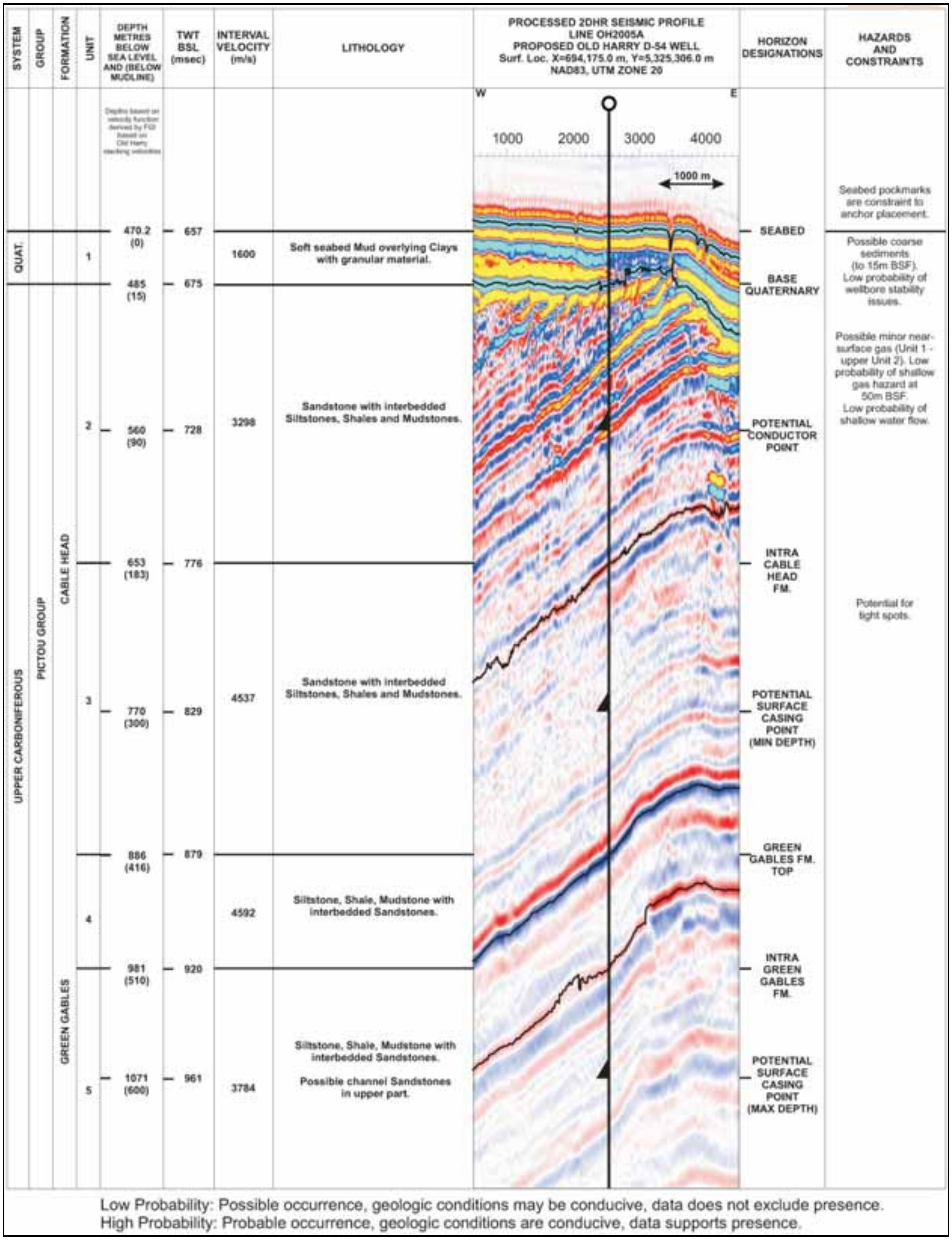
Gas hydrates occur naturally onshore in permafrost and at or below the seafloor in sediments where water and gas combine at low temperatures and high pressures to form an ice-like solid substance. Methane, or natural gas, is typically the dominant gas in the hydrate structure. In a gas hydrate, frozen water molecules form a cage-like structure around high concentrations of natural gas; specifically, they are non-stoichiometric, solid compounds similar to ice crystals (Sloan 1998).

Gas hydrates are found abundantly worldwide in the top few hundred metres of sediment beneath continental margins at water depths between a 100 and 1,000 m (few hundred and a few thousand feet). The gas hydrate stability zone in the marine environment is determined by water depth, seafloor temperature, pore pressure, thermal gradient and the gas and fluid composition. The base of the zone in which hydrate can exist is limited by the increase in temperature with depth beneath the seabed (Sloan 1998). Currently, the principal indicator of marine methane hydrates is the detection of bottom-simulating reflectors on seismic data (CGG Veritas 2011).



Source FGI 2010

Figure 4.8 Hazards and Constraints Map of Old Harry Study Area



Source FGI 2010

Figure 4.9 Hazards and Constraints at Old Harry Proposed Drill Site

The presence of pockmarks at the seabed and locally attenuated amplitudes in sub-bottom data suggests potential for localized near-surface gas within the Old Harry site. If temperature and pressure conditions are favourable, there would be potential for gas hydrate formation (FGI 2010). Estimated parameters for the Old Harry site were plotted on the phase equilibrium curve(s) to provide an indication of potential for gas hydrate formation. Water depth at the Old Harry well site is 470 m. A water bottom temperature (near seabed) of 5°C was found at the Old Harry site. The subsurface geothermal gradient is not well constrained for the well site area. These parameters and assumptions confine the Old Harry site to the shallow limit of the gas hydrate phase equilibrium curve(s). For the "saline water" case, the geothermal trend is nearly tangential to the upper limb of the phase equilibrium curve and does not intersect, suggesting that conditions for hydrate formation are not satisfied. Given that near-surface sediment pore waters at Old Harry are likely to be saline to some depth, there is considered to be a low probability of gas hydrates forming and remaining stable on or near the seabed (FGI 2010).

In addition, near-surface (Quaternary) sediments within the well site area are interpreted to be predominantly fine-grained with a clay matrix, and therefore lack sufficient porosity for the development of massive hydrates. Also, there is no apparent bottom-simulating reflector that would indicate the presence of free gas accumulation beneath a potential gas hydrate stability zone (FGI 2010).

If gas hydrates are present, they are likely localized and disseminated within the fine-grained sediment in the form of small crystals, small to large nodules, lenses and partings, or thin veins. If free-phase gas (or mixed gas and hydrate) are present locally in the unconsolidated near-surface sediments, it is not expected to be overpressured (FGI 2010).

Potential hazards associated with gas hydrates include ground subsidence, methane release, seabed and slope instability. Offshore drilling operations that disturb gas hydrate-bearing sediments could fracture or disrupt the bottom sediments and compromise the wellbore, pipelines, rig supports and other equipment involved in oil and gas production from the seafloor. Problems stem from decreases in pressure and/or increases in temperature, which can cause the gas hydrate to dissociate and rapidly release large amounts of gas into the well bore during a drilling operation (Folger 2008). However, as noted above, there is a low probability associated with gas hydrates forming and remaining stable on or near seabed at Old Harry (FGI 2010).

Shallow Water Flow

Shallow water flow is defined as water flowing within and around the outside of structural well casing to the seabed (Alberty et al. 1997). Shallow water flows occur when fluids under greater than hydrostatic pressures are present in unconsolidated sands between approximately 90 and 500 m (300 and 5,000 feet) below the mudline. These highly permeable sands are widely referred to as shallow water flows because they are sufficiently geopressured to force water and sand into the lower-pressured well bores (Von Flatern 1997). Common deepwater shallow sediment traits are low fracture gradients with pore pressures greater than a seawater gradient. The high pore pressure relative to the fracture gradient causes difficult drilling conditions in the shallow regions of the well.

In the Old Harry well site area, the shallow stratigraphy is comprised of thin (<20 m) unconsolidated clay-dominant Quaternary deposits overlying truncated and dipping Carboniferous sandstone and mudstone beds. The sandstones may be sufficiently porous to host pore fluids. However, the Quaternary deposits are too thin to exert substantial overburden pressure, and the lithified sandstones are effectively incompressible. Any potential for shallow flow would likely arise from deeper geopressures causing upward fluid migration through porous (or fractured) sandstone beds. There is interpreted to be a low probability of shallow water flow associated with the high amplitude beds in the conductor interval at the Old Harry site (FGI 2010).

Other Pore Pressure Phenomena

Mud Diapirism and volcanoes are other pore pressure phenomena that may occur but are not expected to occur at the Old Harry site, based on the Old Harry Geohazard Survey (FGI 2010). A brief description of these pore pressure phenomena are included for completeness.

Mud diapirism is the extrusion of fluid rich, fine-grained sediment through an overlying lithologic succession with seismicity and/or hydrocarbon generation causing the timing and amount of extruded material (Yassir 1989). The actual location of the mud upwelling is often directed by confining structural elements or pre-existing weak zone (faults), which serve as dewatering pathways and conduits (Shipley et al. 1990).

Mud volcanoes can be large and long-lived geological structures that morphologically resemble magmatic volcanoes. Mud volcanoes are of two types, those associated with magmatic complexes and those related to petroleum provinces. The presence of mud volcanoes is distributed throughout the globe in both passive and predominantly active margins, often located along faults, fault-related folds and anticline axes. Mud volcanoes act as the preferential pathway by which deep fluids gather and ultimately reach the surface. Mud volcanoes episodically experience violent eruptions of large amounts of gas mixed with water, oil, mud and rock fragments, forming the ‘‘mud breccia’’. The periodic eruptions can produce volcano-shaped mountains that can reach kilometres in size (Mazzini 2009). The main cause of the eruptions is overpressured methane rising from source rocks and hydrocarbon reservoirs at greater depths.

Mud volcanoes may pose a geohazard for drilling and platform constructions due to the potentially violent release of large amounts of hydrocarbons and mud breccia. Eruption of greenhouse gases via mud volcanoes may influence global climate regimes and several attempts to estimate their contribution have been made. Offshore mud volcanoes are frequently associated with the presence of gas hydrates (Mazzini 2009).

4.1.4.3 Other Geohazards

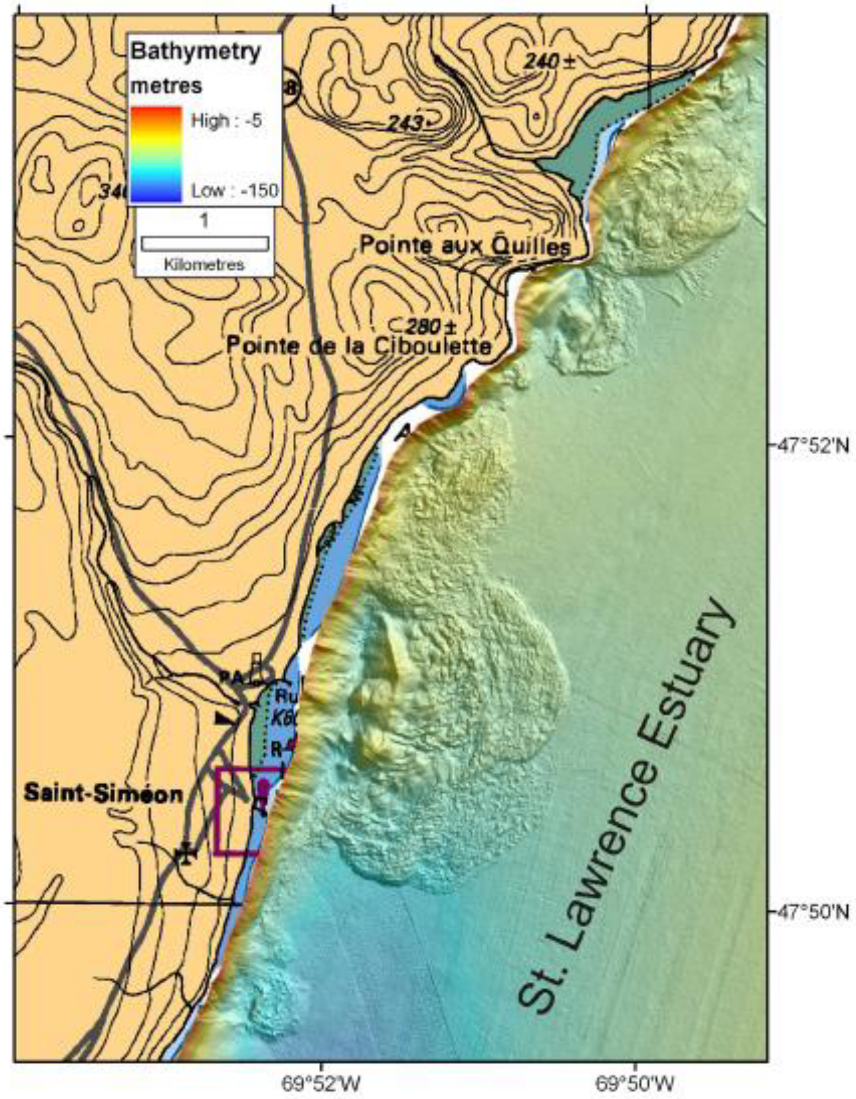
Canada’s coastline is over 243,000 km long, which is the longest in the world. As noted in Section 4.1.4.1, important offshore geohazards include seabed instabilities, pore pressure phenomena (discussed in Section 4.1.4.2), and (iii) seismicity (Section 4.1.2). Seabed instabilities including submarine slope failure is the most serious geohazard on both local and regional scales. Seabed instabilities have not been well researched because of their inaccessibility and general lack of direct societal consequence. With increasing awareness of the potential for offshore seabed instabilities (including slope failures) to potentially generate tsunami there is a need for better understanding of offshore seabed instabilities processes and potential (Locat and Lee 2002). The seabed instability geohazards are included for completeness and are not anticipated to occur at the Old Harry site for reasons noted below.

Seabed Instabilities

Seabed instabilities may occur near a coastal region and along continental slopes. Coastal seabed instabilities present a particular hazard as a result of their potential for tsunami generation as well as proximity to societal infrastructure. Coastal regions often exhibit a variety of factors that could result in the establishment of conditions for sediment mass-failure (Mosher 2008). As a result of wave, long-shore current and glacial erosion, coastal regions may have steep slopes. Coastal sediments arising from quaternary glaciations deposition have mixed lithologies that often lack cohesive strength as well as having endured episodes of sea level rise and fall, thus the sediments are of marine and lacustrine origin. This history results in sediments of variable adjacent geotechnical competency.

After British Columbia, the second highest earthquake prone area in Canada is the Laurentian Valley of Quebec (Mazzotti et al. 2005), which is located approximately 700 km from Old Harry. Numerous examples of sediment failure (Figure 4.10) can be found along the banks and submarine slope of the St. Lawrence estuary and the Saguenay Fjord (Urgeles et al. 2001; Levesque et al. 2006; Cauchon-Voyer et al. 2007). Most of the sediment failures are pre-historic but a few are recent events, 1663 and *circa* 1860 (Cauchon-Voyer et al. 2007). Depending upon conditions of failure and location, a modern instability event in these areas could readily cause damage to underwater structures and generate waves that will damage coastal infrastructure within a limited area.

It should be noted that the Old Harry site is not considered to be located in a coastal area as it is in the Gulf, approximately 80 km west of Cape Anguille, western Newfoundland, and 88 km northeast of the Magdalen Islands, Quebec, at a water depth of approximately 470 m (FGI 2010). The seabed slope at Old Harry is not steep, with the seabed dipping regionally to the southeast at an average of less than 1° (FGI 2010). The seabed at the Old Harry site displays a gently undulating topography with a broad, low relief “ridge” trending southeastward through the centre of the site, with low lying troughs on each side. The proposed well surface location is situated near the crest of the “ridge” at 470 m water depth and the local seabed dip is <1° south-southwest (FGI 2010).



Source: Mosher 2009.

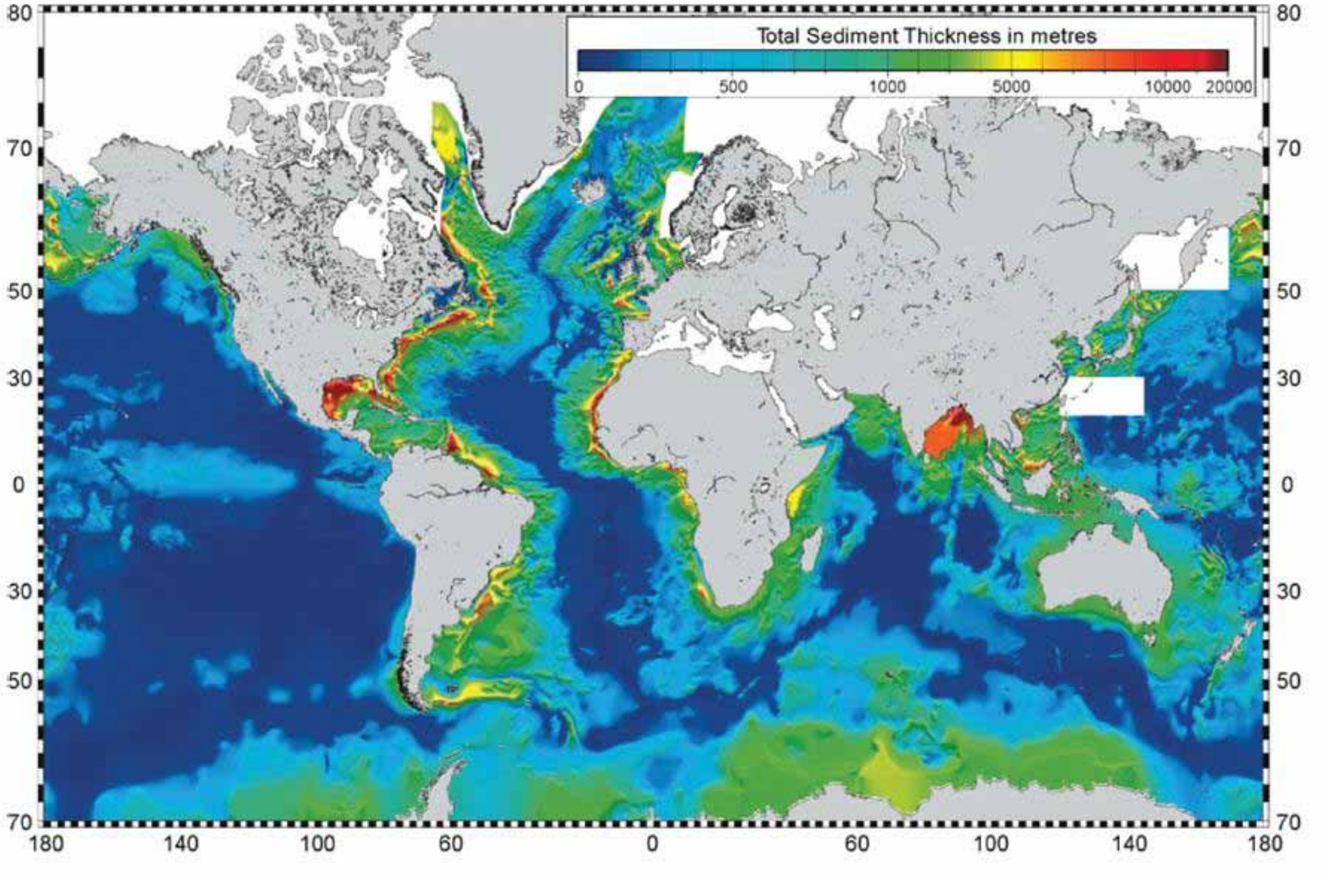
Figure 4.10 Physical Features Present in the Gulf of St. Lawrence

Continental Shelf Seabed Instabilities

Canada's underwater landmass below the 200 m (approximate depth of the shelf break) and above the 3,000 m isobath represents an area of 2,960,000 km^2, which is the largest of any country in the world. The seabed slope angles within this zone typically range between <1° and 4°, although canyon and channel wall or subduction thrust ridge slope angles can exceed 45° (Mosher et al. 2004a). The continental slope typically supports a stable, thick, unconsolidated sediment overburden (Mosher et al. 1994). Other factors that may result in seabed and slope instability potential include interstitial biogenic or hydrocarbon free gas, gas hydrate, salt mobility, high sedimentation rates (e.g., deglacial periods), high pore pressures and vertical lithologic (porosity / permeability) variability (Mosher et al. 2004b). Lykousis et al. (2007) indicate that for continental margin settings, seismicity, or ground shaking due to earthquakes, is required to initiate seabed instability. It is acknowledged that the main triggering mechanisms of sediment failures are seismic shaking, overloading, gas hydrate dissolution and excess pore pressure (coastal flow regime), wave loading, erosion and human activities such as coastal construction (Locat and Lee 2009).

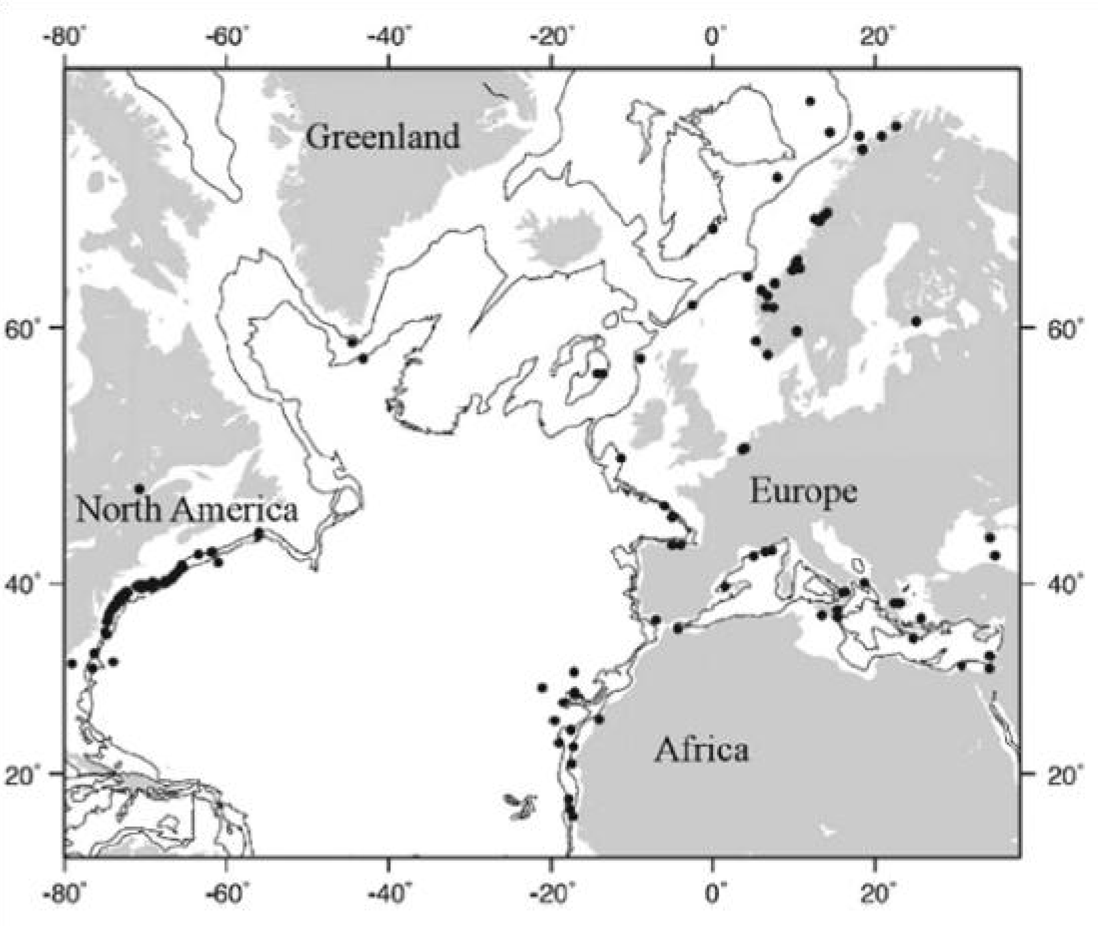
Canada's eastern continental margin is a tectonically-passive margin where seismicity is rare (Adams and Halchuk 2003). However, earthquakes up to M7+ can be expected (Mazzotti and Adams 2005) and have occurred, such as the 1929 M7.2 event off the southern tail of the Grand Banks (Bent 1995). In the past, seismicity was probably more common due to deglacial isostatic rebound, or periods when possible ocean basin scale tectonism was active (Weaver 2003). The 1929 Grand Banks landslide is perhaps the most famous historic submarine mass-transport deposit. It led both to the first formal recognition of naturally-occurring turbidity currents (Piper et al. 1988), and that seafloor displacements due to seabed sediment failure can cause damaging tsunamis at great distance from their source (Ruffman and Tuttle 1995; Ruffman 2001; Fine et al. 2005).

Lee et al. (2007) noted that submarine landslides (sediment instabilities) are not distributed uniformly over the world's oceans, but instead tend to occur commonly where there are thick bodies of soft sediment, where the slopes are steep and where the loads exerted by the environment are high. It should be noted that Old Harry is not situated in an area with this type of seabed morphology. A compilation of sediment thickness for the main oceans is illustrated in Figure 4.11 (areas coloured red denote a zone of substantial deltaic accumulation (such as the Gulf of Mexico) or thick glacial sequences (that would be found off the eastern coast of Canada)). The St. Lawrence Estuary is located in a glaciated area in which the land has risen faster than sea level, resulting in large terraces that were cut and are now exposed. A compilation of landslide distribution for the North Atlantic had been described in Hunerbach and Masson (2004) and is presented in Figure 4.12. Since the production of this figure, the St. Lawrence estuary was mapped and more than 30 slides were identified in that area (Campbell et al. 2008).



Source: Locat and Lee 2009

Figure 4.12 Total sediment Thickness for the Main Oceans



Source: Locat and Lee 2009

Figure 4.12 Slope Failures in Western and Eastern North Atlantic and Adjacent Seas

Slope instabilities occur mainly in two settings, on open continental margins and on oceanic island flanks, which appears to be a function of specific aspects of the geology and morphology of these areas. Slope failures associated with continental margin slopes are typically of low gradient with gentle topography; however, the 'drop' from shelf edge to basin floor can be up to 5 km over distances of a few hundred kilometres (Masson et al. 2006). Parallel-bedded sediment sequences with little variability over large areas characterize their subsurface structure, with the result that, should the conditions for slope failure occur, they can simultaneously affect large areas.

The hazard posed by submarine landslides will vary according to landslide scale, location, type and process and are such that even small submarine landslides can be dangerous when they occur in coastal areas. Slope failures can be divided into two types, those related to the geological characteristics of the landslide material (e.g., overpressure due to rapid deposition or the presence of a weak layer) and those driven by transient external events (e.g., earthquakes or climate change).

Many sedimented slopes prone to submarine landslides show a history of landsliding that extends back through geological time. This observation can often be applied at quite local scales, with areas showing stacked landslide deposits sharply demarcated from those showing long-term stability (Solheim et al. 2005). The importance of tsunamis generated by slope instabilities has only become widely recognized during the last 15 years or so, when it became apparent that a landslide source could explain the unusual run-up distributions and propagation characteristics of certain particularly deadly tsunami, such as the 1998 PNG event (Ward 2001; Okal and Synolakis 2004).

Seabed Instabilities Generated Tsunamis

Considerable evidence suggests that 'unusual' tsunamis, particularly those with high near-field run-ups that decay rapidly away from source, are directly caused by seabed and slope failures (landslides) (Bardet et al. 2003; Okal and Synolakis 2004). Rotational slides (often referred to as slumps), where a thick slide block with a steep headwall can move rapidly downward, may be particularly effective in generating tsunamis, even when the lateral distance moved is small and little effect is seen on the seafloor downslope of the immediate landslide site. As noted previously, the Old Harry site displays a gently undulating topography with a broad, low relief "ridge" trending southeastward through the centre of the site, with low lying troughs on each side. The proposed well surface location is situated near the crest of the "ridge" at 470 m water depth and the local seabed dip is <1° south-southwest (FGI 2010). This type of topography generally does not support seabed or slope failures.

Slope failure volume, velocity, initial acceleration, length and thickness all contribute to the determination of tsunami character (Masson et al. 2006). The best indicator of tsunamigenic potential is the product of volume and initial acceleration (Lovholt et al. 2005). An abrupt deceleration might also contribute to larger surface elevations. The slide length affects both the wavelength and the maximum surface elevation (Haugen et al. 2005), while the wavelength is also determined by the travel time or run-out distance of the slide. Submarine slides are normally clearly subcritical, implying that the tsunami will run away from the wave-generating slide, limiting the build-up of the wave. Slides in shallow waters are more critical, since the speed of wave propagation is lower. Moreover, shallower water normally means less distance to the coast and a shorter distance available for radial damping (Masson et al. 2006). In contrast, tsunamis generated by earthquakes are more critical when the seabed displacement occurs in deeper waters, as the initial wave will become shorter and more dangerously amplified when propagating from deeper to shallower waters (Masson et al. 2006). The area in which Old Harry is located is of low seismicity potential and in an area with gentle undulating topography, so slope failures in the immediate area would not be expected.