GEOLOGICAL SURVEY OF CANADA
OPEN FILE 3748

A preliminary assessment of the occurrence of submarine slope failures in coastal British Columbia by analysis of swath multibeam bathymetric data collected 2001-2011

K. W. Conway, R. B. Kung, J.V. Barrie, P.R. Hill, and D.G. Lintern

2013

Natural Resources Canada   Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 3748

A preliminary assessment of the occurrence of submarine slope failures in coastal British Columbia by analysis of swath multibeam bathymetric data collected 2001-2011

K. W. Conway, R. B. Kung, J. V. Barrie, P. R. Hill, and D. G. Lintern

2013

doi:10.4095/292370

This publication is available for free download through GEOSCAN (http://geoscan.ess.nrcan.gc.ca/).

Recommended citation
Conway, K.W., Kung, R.B., Barrie, J.V., Hill, P.R., Lintern D. G., 2013. A preliminary assessment of the occurrence of submarine slope failures in coastal British Columbia by analysis of swath multibeam bathymetric data collected 2001-2011; Geological Survey of Canada, Open File 7348. doi:10.4095/292370

Publications in this series have not been edited; they are released as submitted by the author.

ABSTRACT

An inventory of submarine slope instability features has been compiled for coastal areas of British Columbia based on morphologic analysis of regional multibeam bathymetric data. The slope instability features are classified as submarine slides, debris flows, rock avalanches and associated features including fan deltas, sediment cones and channel complexes. In addition, the study provides an initial assessment of the size and distribution of these geohazards, with a particular focus on identifying large features that are the result of a single failure event because these would have the greatest potential to generate a damaging tsunami. Submarine landslide deposits have been identified in all fjords and inlets examined including Bute, Knight, Toba and Jervis Inlets and Howe Sound. Douglas Channel, Kitimat Arm and Alberni Inlets also have significant landslide derived sediment bodies on the margin and floors of these inlets. In the Strait of Georgia extensive failures have been identified along the Fraser River delta and on slopes where sediment accretion has occurred in the Holocene, including spits and other coastal landforms. The locus of nearly all submarine slope failures in Juan de Fuca Strait has been along the edge of a terrace landform associated with sea level lowstand. Whereas the age of some features can be tentatively inferred by association with modern or postglacial morphology, the exact age of the instability features documented in this study cannot be determined from this morphologic analysis alone. The accompanying ArcGIS document allows each instability feature to be located and queried for information such as morphologic classification, surface area, possible age, and other details.

INTRODUCTION

The Earth Science Sector's Public Safety Geoscience Program undertakes research in support of the effective management of natural hazards in Canada. The program delivers improved national-scale assessments of selected natural hazards (earthquakes, tsunamis, volcanoes, landslides, and space weather events) to inform decision-making. The assessment of Canada's susceptibility to terrestrial landslides was recently completed and efforts are now focused on slope failures in Canada's marine lands.

Assessment of submarine slope failures or submarine landslides has become important because expansion of oil and gas exploration onto the continental slope, the development of coastal infrastructure at pipeline terminals and the planning of marine transportation routes all require an understanding of these potentially unstable environments. In addition to the direct threat posed by submarine slope failures, large submarine slides have the potential to trigger tsunamis, This was catastrophically demonstrated in 1998 when a slide-generated tsunami devastated large areas in Papua New Guinea (Tappin, 1999).

The glacial and geological history of BC, along with the other major fjord landscapes in the world, including Alaska, Chile, Greenland and Norway, renders these coastal settings susceptible to this landslide and tsunami geohazard (Bornhold and Thomson, 2012; Leonard, 2012). Failures of the steep fjord walls can lead to extremely high tsunami waves as has been documented in several case histories (Bornhold and Thomson, 2012). The highest tsunami ever recorded reached 524 m above sea-level in coastal Alaska at Lituya Bay in 1958 as a result of a very large landslide (Miller, 1960). This landslide itself followed an M 7.7 earthquake on the Fairweather Fault, which is an extension of the Queen Charlotte Fault in British Columbia (BC). Some numerical modelling work has been undertaken to assess the probable size of tsunamis generated by coastal landslides on the west coast of North America (Thomson et al., 2001; Thomson et al., 2012).

In addition to the fjord walls, slope instability is common on geomorphological features such as fan deltas, delta and channel systems and submarine alluvial fans that are associated with fiords (Nemec and Steel, 1988; Bornhold and Prior, 1990).

The regional compilation of multibeam data has now enabled the preliminary assessment of submarine landslide occurrence in coastal BC . The collection of swath multibeam data in BC waters was first undertaken in 1994 (Currie and Mosher, 1996), and systematic regional surveying has accelerated over the past decade. The collection of these data is ongoing and it will be many years before the coverage is complete (R. Hare pers. comm. 2011). However, the main areas proximal to population centres and of highest seabed usage have been surveyed, and these form the basis of this report.

The objectives of this report are to contribute to the inventory of submarine slope failures in coastal BC, provide a general overview of the distribution, size range, morphology and styles of past submarine slides and to suggest possible targeted studies in the future. For a full hazard assessment, knowledge of the age and frequency of occurrence of the submarine slides is required. However, the age of most slide events and other features documented here is largely unknown, although it is likely that most have occurred in postglacial times (since 12,000 years ago). It is known that submarine slides in many glaciated regions occurred more frequently in the period immediately following deglaciation (e.g. St. Onge et al., 2004), so the presence of a submarine slide in the present-day landscape is not necessarily an indicator of hazard. The present study is therefore only a first step in hazard assessment, with other information being required to assess what, if any, hazard is associated with the mapped features. Other important information would include better characterization of the slide through sub-bottom profiling and constraining the age of the slide through strategic coring of the seabed in and around the slide (Piper et al., 2012).

Setting

British Columbia is characterized by a fjordic coastline comprising about 150 individual inlets (Thomson, 1981; Dallimore and Jmieff, 2008). Fjords are high-latitude estuaries, which have been excavated and modified by glacial ice sheets (Syvitski et al. 1987; Syvitski & Shaw 1995). The fjords of coastal British Columbia are situated in the transition zone between the ocean-influenced temperate mountain belt of Vancouver Island and Haida Gwaii and the cold continental, high elevation, glacier-capped mountains (rising to 3300 m) to the east . Slope stability in this large region is likely influenced by a broad range of factors including topography, geology, tectonic stress regime, soil composition, and watershed hydrology. However, the high seismicity of the region provides a critical mechanism for triggering submarine slides.

Seaward of BC's continental margin, there are complex plate boundaries that cause variable but intense seismicity within the region. In the north of the province, movements on the plate boundary transform fault, the Queen Charlotte Fault, cause frequent earthquakes including a recent M 7.7 earthquake (Oct 27, 2012), which was the largest quake in Canada for 60 years. Further south, larger quakes (M 8.9 to 9) are thought to occur in the Cascadia subduction zone at a recurrence interval estimated at 350 to 500 years (Atwater, 1987). Seismicity has large implications for the timing and distribution of slope failures as submarine failures may be initiated by seismicity (Mosher et al., 2004). However the detailed relationship between landslides and earthquakes in this region is beyond the scope of this study.

Bedrock geology is complex within the region. Much of Vancouver Island, Haida Gwaii and the continental shelf consists of volcanic and sedimentary rocks forming the Insular Belt. On the mainland, the Coast Mountain Belt consists of granitic intrusions forming the Coast Plutonic Complex (Gabrielse et al., 1991).

Hydrology is variable in the region with larger snowfall-dominated rivers located in the north and interior (Skeena, Nass and Fraser). These rivers generally reach their highest flows during spring freshet due to the initial melt of the snow pack, and their flow rates taper off through the summer (Johannessen and Conway, 2006 and references therein). Submarine slide occurrences at the heads of some fjords (Bute, Knight and Toba inlets) have been shown to be dependent on seasonal hydrologic effects (Prior et al., 1984; Ren et al., 1994).

Previous Studies

Whereas Howe Sound has been the subject of a comprehensive inventory of submarine slide features (Jackson et al. 2008) other areas have seen limited systematic analysis of multibeam data for the purpose of identifying the distribution of submarine slope failures. However, there is a large body of work on submarine slope processes in BC fjords and in the Strait o Georgia. A detailed bibliography will not be provided here but some key studies that may point interested readers towards additional resources are listed below.

Early work defining slope stability and sedimentation processes in BC fjords was undertaken by Prior et al. (1981) and Syvitski and Farrow (1983). In the Bute and Knight inlets, the annual cycle of sedimentary inputs and related submarine channel evolution was established by direct measurements of turbidity current events (e.g. Prior et al. 1986, 1987; Bornhold et al. 1994; Ren et al. 1996). The submarine channels in Bute Inlet were described by Prior et al. (1987) and in Knight Inlet by Ren et al. (1996). A detailed analysis of the evolution of the large fan delta at Bear River, Bute Inlet was provided by Prior and Bornhold (1989). There is a large literature on the Fraser Delta channel system and slope failures on the delta front (Mathews and Shepard, 1962; Hart et al., 1992; Hill et al. 2008 and references therein). Slope failures generated by specific earthquakes have been identified in the Strait of Georgia (e.g. Rogers, 1980, Mosher et al., 2004).

Intervals of massive units interpreted to be the result of submarine sliding and/or gravity flows have been identified in Saanich Inlet (Bornhold and Kemp, 2001) and Effingham Inlet (Dallimore et al., 2005), some being tentatively interpreted to be related to earthquake events.

METHODS

Swath multibeam bathymetric surveys were undertaken by the Canadian Hydrographic Service (CHS) and the Geological Survey of Canada - Pacific between 2001 and 2011 using a Kongsberg-Simrad EM 1002, 100 kHz system mounted on the CCGS *Vector*, until 2009 when a Kongsberg-Simrad EM 710 multibeam system operating at 70-100 kHz was installed. Data were gathered using the Kongsberg SIS system and processed using the CUBE extension of the CARIS-HIPS software package. Data were then exported as 5 m resolution grids with confidence intervals of 2 m laterally, due to navigational limitations, and 0.1% of water depth vertically. In shallow water the motor launch *Otter Bay* was used to collect data with a Kongsberg-Simrad EM 3002 system in water depths from 5 to 150 m. Backscatter data were also acquired during surveys from both vessels. The data represent approximately 450 sea days of data collection.

The gridded bathymetry data were imported into ESRI ArcGIS software and are included as background layers in the GIS atlas accompanying this paper. They are rendered as high resolution images combining colour-ramped, hypsometric depths with “hill-shaded” relief. For the purpose of this paper and the accompanying GIS atlas the sun azimuth is set at 315 degrees and the sun angle at 80 degrees, not far from vertical. This unconventional sun angle is used because the narrowness and great depths of the channels and inlets of coastal British Columbia would render much of the hillshaded relief in complete shadow at lower sun angles.

In addition to the swath multibeam data, digital topographic data and SPOT satellite air photo imagery were used to identify streams and rivers entering coastal water bodies. These data were used to define such features as fan deltas, delta and channel systems as well as alluvial aprons and fans.

The features described in this paper are represented as polygons and classified in the accompanying ArcGIS digital atlas entitled “Submarine_Landslides_BC_Atlas. A folder for installing

ArcReader is provided. ArcReader will allow users who do not have access to ArcGIS to open the read-only .pmf file version of the Open File.

Cross references to the digital atlas are provided in the Results section of this paper as 23 spatial bookmarks, accessed from the "Bookmarks" menu in ArcGIS. This facilitates working with both the text and atlas files open simultaneously so that the description of each geographic area can be read as the ArcGIS digital atlas is examined. The reader is invited to turn layers on and off as required, and zoom in and out of the bookmarked map areas, to enhance the viewing of the submarine slope failures and related features described. The digital atlas is designed to be a dynamic and interactive component of this report.

Definition of slope failures and slope instability features

The submarine landslide classification system of Locat and Lee (2002) has been adopted with slight modifications for the purposes of this report. The results are based on interpretation from the morphologic seabed expression of landslide deposits, the adjacent source area and related features in the multibeam data. In this study the resultant deposit is examined and classified without consideration of the possible flow mechanisms and transformations that may have occurred prior to deposition, though such interpretations might be possible in some cases.

Types of Submarine Slope Failures

Translational slide: (USGS Definition http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html) In this type of slide, the landslide mass moves along an approximately planar surface with little rotation or backward tilting. The moving mass typically consists of a single unit or a few closely related units that move down slope as a relatively coherent mass. In this study, the translational slide classification is used where the slide plane is clearly visible and planar in form.

Rotational slide: (USGS Definition http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html) A slide in which the surface of rupture is curved concavely upward and the slide movement is approximately rotational about an axis that is parallel to the ground surface and transverse across the slide. In this study, the rotational slide classification is used where the slide plane is clearly visible and concave in form.

Undifferentiated slide: a slide where downslope displacement in a single event is evident, but where the form of the slide plane cannot be unambiguously determined. The planar or rotational aspect of some slides may be difficult to establish in multibeam data. Here these are classed as undifferentiated slides.

Rock avalanche: A lobate deposit of coarse blocky material characterized by angular, sharp crested linear ridges in areas of steep bedrock slopes. These are inferred to be the result of single events and are limited to those where the fallen debris is clearly lithified rock. Debris avalanches, where the blocks are interpreted to consist of unlithified sediment are here assigned to the debris flow class (see below).

*Debris flows(includes turbidity current channels, gullies, and debris flow depositional lobes)***:** Debris flows (also referred to in the literature as mudslides, mudflows, or debris avalanches) are fluid sediment masses that flow as an unsteady, very poorly sorted sediment slurry. Consistency ranges from watery mud to thick, rocky mud (like wet cement). The behaviour of the flow depends on the composition , which varies widely. In this study debris flow deposits are interpreted where individual blocks can be distinguished in a lobe of massive matrix (Prior et al., 1981). Debris flows commonly result from transformation of slides when partial or complete liquefaction of the slide mass occurs and they may themselves be transformed into turbidity currents (Piper et al., 2012). Debris flows may therefore be located in and around submarine channels that have been incised by the turbidity current phase of the flows. Submarine channels occur in various settings, including deltas, but where the morphology is dominated by debris flow deposits, the feature is assigned to this category. Debris flow channels and lobes are well described in Howe Sound by Jackson and others (2010) and in several other coastal fiords by Bornhold and Prior (1990).

Other Morphologic Features Related to Submarine Slope Stability

Submarine Alluvial Fan/Composite slide: a slide complex resulting from several events associated with a submarine channel or channels, but where no single, dominant river sediment source is apparent. These occur along steep fjord walls and may be associated with subaerial alluvial fans or alluvial aprons. They include features such as ephemeral stream deposits (Prior and Bornhold, 1988) and variable size aprons, fans and channelized slope surfaces. Submarine alluvial fan/composite slides are distinguished from *fan deltas* (see below) by the lack of a permanent river source and are interpreted to indicate ongoing slide activity of significant magnitude.

Fan delta: A coastal prism of sediments derived from an alluvial fan feeder system and deposited mainly or entirely subaqueously at the interface between the active fan and a standing body of water (Nemec and Steel, 1988). These are characterized by fan shaped deposits often channelized with several types of landslide deposits associated with the fan delta (Prior and Bornhold, 1988). Fan deltas are constructed by a combination of slope instability processes including debris flows, debris avalanches, turbidity flows and settling from suspension and there is therefore “a great variety of fan-delta architecture” (Prior and Bornhold, 1990).

*Delta and channel complex***:** Deltas are constructed by the deposition of fluvially transported sediment in the marine environment. They are typically characterized by low relief delta plains and where constrained by steep valley walls they grow rapidly into deep water (Syvitski and Farrow 1983; Prior et al. 1987). The submarine slopes of deltas are commonly characterized by submarine channels which may converge to form one predominant channel that captures and funnels turbidity currents and debris flows from the delta front to deeper water. These features are especially well developed in Knight (Ren and Bornhold, 1994) and Bute inlets (Prior and Bornhold, 1984) and off the mouth of the Fraser River (Kostachuk et al., 1992). Slope failures are common in the delta and channel complexes as delta fronts become oversteepened.

*Cone***:** an undifferentiated cone shaped deposit that may be a result of recurrent alluvial processes or a large landslide event or events. This feature is distinguished from submarine alluvial fans and fan deltas by the absence of channels. For example the deposit inferred to have been the landslide that caused the destruction of the first nations village of Kwalate is a cone deposit (Bornhold et al., 2007), and is without distinguishing characteristics apparent from multibeam data alone.

Bedrock Creep (Sackung): A sackung is a large bedrock area undergoing slow deformation by sagging (Zischinsky, 1966). Sackung is a German term meaning sagging. Such areas can be difficult to distinguish from simpler kinds of rotational sliding. Although to date bedrock sackung have not been described from the marine environment (Conway et al., 2012), such a possibility cannot be precluded and in this study two possible examples are indentified.

Sources of error

Interpretation of landslide deposit type based exclusively on multibeam bathymetry is often ambiguous and incorporates several sources of error, so that the results presented here should be considered preliminary. The classification of submarine slide deposits described is tentative and as new data, including sub-bottom data and cores, become available, the classification of some of these slides may change.

The multibeam resolution limits identification of blocks to those greater than 5 m in size. This would tend to impede identification of *debris flows* relative to other kinds of deposits. In addition, the use of rafted blocks as an indicator of a debris flow deposit may lead to the mis-classification of some debris flows as translational slides. *Rotational slides* are classified where the source area is clear and the slide mass basal plane is readily identified to specify the rotational nature of the slide. A sub-bottom profiler is normally required to determine the basal plane of the slide and for this reason many rotational slides will be classified as undifferentiated slides in this report. Slides are placed in the *undifferentiated slides* category when they cannot be assigned to a specific class. The slide categories rotational, translational and undifferentiated are all inferred to be the result of a single event. Multiple event slides are classed as *composite slides.* An additional complication in using only multibeam bathymetry to classify landslide deposits is that many are buried or partially buried by subsequent sedimentation.

Well-developed *channels* are interpreted to be indicators of repeat or ongoing slide or flow emplacement and so indicate that more than one event may have occurred at a site. This interpretation does not imply age or duration of processes. Using channels to identify possible slides is problematic because deposits resulting from one only failure event may create a channel. *Cone* features may also be the result of one or many landslides, whereas areas with well developed channels and channel systems such as the *delta and channel complex* and *fan delta* classifications are more readily interpreted to be multi event deposits.

RESULTS

The results are compiled for each of five geographic areas: Strait of Georgia, Vancouver Island, south coast fjords, central coast fjords, and north coast fjords. These areas are further partitioned geographically and are meant to be displayed with the spatial bookmarks in the accompanying ArcGIS digital atlas, that define the extent of each of 23 classified water bodies. A spatial bookmark is provided from the "Bookmarks" drop down menu in the digital atlas for each area being discussed to facilitate ease of viewing by zooming into that specific area. Each of the 1184 submarine landslide area polygons may be queried to see notes regarding the classification and spatial parameters, such as area, of the feature. Table 1 describes the types and numbers of land slide and instability features identified and classified in the study. In total 1184 features were classified with fan deltas and submarine alluvial fans/composite slide catgories making up about 55% (648) of the features described. All three types of slides (rotational, translational and undifferentiated slides) made up about 23% (266) of the features identified. When debris flows (137 occurrences) are included about 34% of all the features identified in this study are thought to have been the result of single event submarine slope failures. No mathematical treatments of the slide volumes, slides by area or slope calculations and slide volumes were undertaken.

Table 1. Submarine slope failures and related morphologic features**.**

Feature type	**Number of occurrences**
Debris flow	137
Rotational slide	3
Translational slide	191
Rock avalanche	44
Undifferentiated slide	72
Bedrock creep/sackung	2
Debris flow – inferred Pleistocene age	12
Submarine alluvial fan/composite slide	382
Cone	50
Delta and channel complex	25
Fan delta	266
TOTAL	**1184**

Synopsis of regional submarine slope instability by area

A brief description of the main types of slope instability found in each area surveyed to date is provided below. The most frequent type of slope instability feature is listed for each area and large or anomalous slides are also described. The geographic areas are selected to provide a sensible overview for each area and these are in each case associated with a bookmark reference in the Arc GIS document. The upper case letter in each case corresponds to labeled slide features in the bookmarked area being described.

Strait of Georgia

Strait of Georgia – North – see bookmark in digital atlas

Numerous debris flow deposits with channels and lobes are seen where unconsolidated sediments have failed in nearshore areas. These deposits are channelized and numerous lobes are apparent. It is possible that the debris flows are initiated as small slides that then become debris flows, which then transform to turbidity currents. The Quadra Sand (Clague, 1977) is the deposit that forms many islands in the Strait of Georgia islands including Quadra Island (A), Hernando (B), Savary Island (C), and Harwood (D) islands and also provides material for the construction of many littoral features such as spits and beaches. Quadra Sand deposits are typically very steep in sections and these are the source of the many failures in this area.

Areas of recent active landsliding have been related to the 1946 Courtenay earthquake which resulted in liquefaction and slide /flows at spits, beaches and spit platforms near Comox (E) and other recent sand and gravel deposits (Mosher et al., 2004) including near Powell River (F). One composite slide area, an alluvial apron feature, is found along the eastern shore of Texada Island (G).

Strait of Georgia – Central – see bookmark in digital atlas

Numerous translational slides off the ice streamlined banks such as Halibut Bank (H) and other deep banks date possibly from immediately post glacial time. There is a post glacial sediment drape of recent muddy sediments over some of these slides. As in the northern strait thick unconsolidated Quadra Sand deposits are subject to localized translational slides and debris flows, which are common around the Thormanby Islands (I). An area of abundant composite slides with many old channels exist between Qualicum Beach (J) and Parksville. These are possibly late stage deglacial channels that are relict features which are no longer active. Just north at Deep Bay recent debris flow deposits some of which were derived from the 1946 earthquake (JJ) have been well described by Mosher and others (2004).

Southern Strait of Georgia and the Fraser Delta- see bookmark in digital atlas

The Fraser Delta is the site of ongoing slope instability at the main channel as sand is moved through the river channel as bedload and a very large delta and channel complex has formed (K). A buoyant plume moves the mud fraction away from the delta front while tractive transport of the sand fraction results in scour by turbidity currents within the main channel (L) (Hill et al., 2008). Many of the obvious channel features are inactive (M) and have been abandoned since the river was fixed in position by walls that prevent the river from changing course (Barrie and Currie, 2000) early in the last century.

English Bay/Burrard Inlet - see bookmark in digital atlas

Burrard Inlet has several moderate sized fan deltas and alluvial fans entering from large watersheds (A). Several good examples of translational slides are found (B). No slides are seen in English Bay while three small slides are found east of Vancouver Harbour near where Burrard Inlet turns north (C).

Desolation Sound - see bookmark in digital atlas

The margins of the sound are lined by composite slides or alluvial aprons and fan deltas (A). The steep mainland slopes are the source of many of these where drainage areas are larger than the island shorelines. Many fan deltas and alluvial fans or composite slides are apparent in Ramsay Arm (B). The Quatam River (C) has constructed a well developed fan delta.

Vancouver Island Fjords

Saanich Inlet- see bookmark in digital atlas

The inlet has many small to medium size slope failures along shore parallel steps in deep water (A), as well as a few slides originating from the subaerial fiord wall (B). The much steeper western wall of the fiord has been subject to more instability, and slides on that side are larger and form a nearly continuous apron of slide material (C). The slides are classified as all the main types including translational, rotational, composite and undifferentiated. Some of the slides are draped by recent sediment (D). Many of the best examples seem to originate on a (muddy?) terrace feature (E) in about 120 m water depth that occurs along the eastern edge of the inlet.

Alberni Inlet- see bookmark in digital atlas

Near the head of the inlet a large debris flow occurs (A). The inlet has several small slides as well as one very large translational slide in the centre of the inlet (B). This is one of the best examples of a translational slide seen in the present study. Two large fan deltas have merged and covered the central portion of the floor of the inlet (C).

Effingham Inlet- see bookmark in digital atlas

The small number of slope instability features in this inlet are fan deltas or alluvial fan type deposits. Small rivers enter this inlet and consequently no large fan deltas have developed nor has a large fiord head channel system developed. One very good example of a large translational slide was noted (A).

Juan de Fuca Strait - see bookmark in digital atlas

Juan de Fuca seabed instability is related to small translational slides coming off the edge of shore parallel terraces that demark the old shoreline (A) that existed during a regional 50-60 m lowstand of sea level at the close of the last glaciation (Linden and Schurer, 1988; Mosher and Hewitt, 2004). A significant portion of the shoreline, possibly 30-35 % of the total length of the nearshore area, has been subject to these type of small failures. At Swiftsure Bank (B) the same type of slides appear to have occurred along the bank edge failing into deeper water, originating at 80 m water depth.

Goletus Channel- see bookmark in digital atlas

Due to the low relief drainage area of Vancouver Island – the Nahwitti Lowland and the opposite Hope and Nigel islands that form the margins of the channel few fan deltas or large alluvial fans have developed. Small composite slides, a few small alluvial fans and aprons and a few small fan deltas characterized Goletus Channel seabed instability features (A).

Lower Mainland Fiords

Howe Sound - see bookmark in digital atlas

Howe Sound landslides in the marine are mainly derived from terrestrial slides entering the water from steep river born debris torrents or flows (A). These tend to be concentrated along existing stream courses and rivers along the sea to sky corridor (Jackson et al., 2008). In addition numerous debris torrents, flows and landslides have occurred along the route of Highway 99 at several creeks where prior to installation of control measures seasonal debris torrents frequently destroyed bridges. The subaqueous delta of the Squamish River has grown into the fiord and has developed an extensive channel system (B). Some of the deadliest subaerial slides in Canadian history have occurred along stretches of the fiord edge in such areas as Britannia Beach (C). An interesting slide area exists at Britannia Beach mine site where decades of mine tailings disposal into the Howe Sound has created a complex of landslides and channels (Jackson et al., 2008) much larger than would normally be expected form a watershed of rivers of similar size. Several older slides are apparent along the eastern edge of the Porteau Cove terminal moraine (D) and these likely occurred shortly after deglaciation when supporting ice receded leaving over steepened coarse sediment piles susceptible to sliding. Similar older deposits may also occur at the north side of Keats Island (E). A recent overview of slope stability, including submarine evidence, comparing Howe Sound to Knight Inlet has been accomplished (Van Zeyl, 2009).

Small fan deltas with channel systems are found at Port Mellon (F) and also at several small rivers. Intermediate size failures have occurred adjacent to several islands in the southern part of the Howe Sound (G). These were probably emplaced during deglaciation of the sound.

Jervis Inlet - see bookmark in digital atlas

A channel complex of modest size is growing into the head of Jervis Inlet (A). Down slope of the channel system swales and sediment waves and small failures are present (B). Many slides and fan delta complexes enter the fiord along both margins in the upper reaches of the fiord (C). A unique feature is a fan delta that has developed as an ebb tidal delta as a result of ebb tides through Malibu Rapids which has been constructed at the junction of Jervis Inlet and Princess Louisa Inlet (D). This delta has seen several slides excavate channels down the delta front. These masses are apparent as bulbous deposits at the base of the delta (E). There are several similar buried deposits as well. The channels created by these slides are up to 900 m long and 8 m deep.

A large complex slide, which may be the result of one event, is seen in upper Jervis Inlet (F). The slide involves the upper slope of the fiord and translates into a debris lobe well out onto the fiord floor. Slide blocks up to 5 m in height and 70 m across are seen on the mid slope. The length of the slide is about 2 km. Further south along the fiord numerous (>20) fan deltas mantle slopes (G) with channelized deposits apparent at most of these sites.

In deeper water an unusual slide mass is apparent in southern Jervis Inlet (H). This slide travelled at least 2700 m along the fiord floor. The source is not obvious. The scarp created in the slide tack is at least 15 m in height and the distal lobe is 8 m thick. This is one of very few slide deposits seen to reach the centre of any southern mainland fiord.

Toba Inlet - see bookmark in digital atlas

Some landslides in Toba Inlet are associated with a large and growing channel complex at the mouth of the fiord (A). The channel system extends for 20 km down the inlet carrying debris flows and turbidity currents which result in an incised channel to 30 m deep. Thin channelized deposits and some small fan deltas exist on both sides of the fiord (B). A larger fan delta is found at the Brem River (C). Numerous smaller fan deltas occur further seaward (D).

Bute Inlet - see bookmark in digital atlas

Landslide deposits in Bute Inlet are concentrated in the upper portion of the fiord where The Southgate (A) and Homathko (B) rivers deliver large volumes of sediment. These have created deep turbidity current channels that funnel material derived from the delta front to deep water up to 40 km down the fiord (C). The channel system is itself a source of small slides at the outer bends of channels where so-called “nested slides” occur at the bend in the channel as erosion destabilizes the channel slope (Conway et al, 2012). Very large rock avalanche deposits are found along the south eastern margin where very steep slopes forming the southeast side of the fiord (D). Some of these are very large and probably quite recent based on contiguous terrestrial slide morphology that has limited forest growth. It is likely that several of these are the result of one landslide event based on the morphology of the deposit including crest lines that result from one event and the lack of channels indicating successive landslides. Channelized deposits of slides and fan deltas exist (E) along the opposite slope. Other landslide deposits are found where fan deltas have been constructed and where rock avalanches enter the fiord, such as the large delta at Bear Bay (F). One very large hook shaped landslide covers the floor of much of the inlet further south (G) A large series of what appear to be detached blocks are seen at one location (H). This style of deformation has not been observed elsewhere in these data sets.

Knight Inlet - see bookmark in digital atlas

Only the upper 70 km of Knight Inlet has been multibeam surveyed to date. An elaborate channel system delivers turbidity currents up to 30 km from the head of the inlet (Ren et al., 1994) . This extensive channel system is up to 40 m deep (A). A large number of rock avalanches are apparent opposite the complex delta area (B) on the south side of the inlet. A tributary river (Sim River) enters the channel system with a channel system of its own and associated sediment transport by tractive flows (C). Further south small fan deltas and chutes bring sediment to the fiord floor. One conical landslide deposit (D) is thought to represent the source of a large tsunami about 500 years ago that destroyed the village of Kwalate (Bornhold et al., 2005) on the opposite shore (E). Some large landslides that failed as one unit are seen further seaward (F) in an area that also shows surface roughness of the seabed from possible decomposing gas hydrates (G) or other phenomena (Bornhold and Prior, 1986).

Johnstone Strait- see bookmark in digital atlas

The slope instability in Johnstone Strait is determined largely by drainage from the steep Vancouver Island side of the strait with almost no riverine input from the mainland island side which is generally much lower lying (A). No large single event slides are present, although one extensive debris flow deposit or possibly a slide (B) has been recognized in the southern strait immediately south of West

Thurlow Island (C). Deposits are reworked by currents (D) in much of Johnstone Strait which make the recognition of failure deposits more difficult than in other areas of lesser current velocities.

Seymour/Belize Inlets- see bookmark in digital atlas

Seymour Inlet is the southerly inlet in this complex waterway (A) and is somewhat larger than Belize Inlet (B). Much of the margins of these inlets are lined by alluvial apron deposits of composite slide materials (C). Numerous short feeder channels move debris to the aprons. Few individual slides were resolved. Where slopes are steep these aprons are well developed (D). In the seaward portion of the system these deposits are much less common a function of the low relief and limited drainage areas (E).

Smith Inlet - see bookmark in digital atlas

Smith Inlet has a large delta and channel complex developing at the head of the inlet (A). Nearby there are several fan deltas (B) which have grown as a consequence of the large drainage hinterland. A variety of slope failure types and sizes including translational and composite slides occur in the central portion of the inlet (C). Seaward of this area a group of composite slides are found (D) part of an area of complex morphology.

Northcoast Fjords

Kitimat Arm and Approaches - see bookmark in digital atlas

Well described debris flows that caused tsunamis have occurred at the head of Kitimat Arm in 1974 and 1975 (Luternauer and Swann, 1979; Prior et al., 1981; Bornhold et al., 1980; 2009). This large deposit derived from these two events is very well imaged on the multibeam data and blankets much of the upper portion of the fiord (A). Several fan deltas are adjacent to the debris flow deposit. Further south in the channel small translational or undifferentiated slides enter the fiord (B). One large translational slide nearly crosses the width of Devastation Channel (C), and an area of large fan deltas is seen (D). Small failures are distributed along much of the length of the western side of Kitimat Arm and Douglas Channel. Kildale Arm extending off of Kitimat Arm to the east has a developing channel and delta complex at its head (E).

Douglas Channel- see bookmark in digital atlas

The southern part of Douglas Channel is quite different than the northern portion. An area of undifferentiated slides and two very large arcuate translational slides (A;B) occur at the southeast end of Douglas Channel (Conway et al., 2012) and these are the largest single event landslides identified in this study. These appear to be related to ongoing slope instability along most of the eastern shoreline of Douglas Channel. This slope instability is possibly related to a fault trace that extends for approximately 50 km to the south (Conway et al., 2012). The eastern wall of the fiord flanking Hawkesbury Island has been subject to slope instability at several scales. In the northern part of the channel much smaller translational slides, rock avalanches and fan deltas are apparent (C). Much smaller translational slides are found on both sides of the channel system.

Skeena River/Prince Rupert and Approaches- see bookmark in digital atlas

The Skeena River delta has a widely distributed active delta front among inshore coastal islands such as Smith, Kennedy and de Horsey islands (Luternauer, 1980; Conway et al., 1996). Instability along this front is apparent as small slides and debris flows with minor channel development (A). Debris flows originate from the delta front at some sites (B). Indications of ubiquitous gas seen as extensive gas pockmark fields (C) suggest rapid deposition of fine organic material beyond the zone of slope failures (Conway et al., 1996). Along the Prince Rupert water front very small slides are seen along the foreshore which may be due to construction debris dumping or small scale slides due to other processes (D).

Grenville and Principe Channels- see bookmark in digital atlas

Grenville Channel joins the Skeena River delta and Prince Rupert area to the south end of Douglas Channel so is an important waterway. The main feature on the seabed of this waterway is several small fan deltas (A) which have limited drainage areas coming from Pitt Island to the west and a small mainland hinterland to the east. An interesting feature at the north end of the channel are a large array of seabed pockmarks which are water or gas escape features (B). A portion of the Skeena River delta and channel complex is adjacent to the north entrance of the channel. Where the channel becomes narrow and steep walled several rock avalanches, debris flows and one translational slide are found (C).

Principe Channel parallel and seaward of Grenville Channel is broad and open to Hecate Strait at both ends. Several small composite slides or alluvial fans and seen along the western margin of the channel (E). Current scour is prevalent throughout much of the channel based on the seabed morphology (F and G).

Squally Channel, Whale Channel, Verney Passage and Campania Sound- see bookmark in digital atlas

Several small slides are seen in the southern part of Squally Channel (A). At the north end of Whale Channel two areas with debris flow channels gullies and lobes are seen (B). Several small fan deltas occur in the area as well. It is inferred that slope stability features in this area are few due to the limited drainage areas of Princess Royal and Gil Islands.

DISCUSSION

The coastal areas assessed include major BC inlets and channels as well as some of the large inshore areas such as the Georgia Basin. A clear trend is towards the concentration of slope instability features in areas with large sediment input in coastal watersheds such as at the heads of fiords. Many fan deltas and submarine alluvial fans/composite slides are identified and these appear to be largely controlled by drainage area and slope. This correlation between watershed size and submarine alluvial landform is obvious in areas where valleys on coastal islands develop much fewer or smaller features than adjoining coastal areas which drain larger hinterland areas. The fan delta and submarine alluvial fan composite slide categories comprise more than half of the features identified.

Small slides, both rotational and translational, as well as debris flows are common in areas where Quaternary unconsolidated sections, such as the Quadra Sand (Clague, 1977) are found. These deposits and the slides associated with them are found in the northern Strait of Georgia where islands are predominately formed of this Quaternary unit. Holocene spits and beaches in the Northern Strait of Georgia have been sites of slides related to recent earthquakes (Mosher et al., 2004).

The northern margin of Juan de Fuca Strait has a very large number of small slides derived from a series of sea level terraces along this shoreline that probably relate to the last sea-level low stand during the late Quaternary (Linden and Schurer, 1988; Mosher and Hewitt, 2004). These numerous slides are individually inconsequential in terms of volume, but collectively form a widespread series of possibly related deposits.

Translational and even rotational slides are apparent and a single event is assumed where no channel, overlapping lobes or obvious multiple source or river is associated with the feature and where a source of the slide volume is clearly seen.

Features such as fan deltas normally have many associated individual instability events such as channels or debris flow lobes (Prior and Bornhold, 1988). River delta and channel complexes may contain a wide variety of instability features including debris flows constrained within the channel and nested slides at outer channel bend positions (Conway et al., 2012). Cones having no obvious channels are particularly hard to classify. A cone type deposit has been tied to the only catastrophic coastal landslide BC tsunami tied to a given event (Bornhold et al., 2007). Age assignment is also problematic as a drape of sediment may be hard to infer from multibeam alone, especially in deeper water.

Large (approximately 10 million cubic metres) translational slides are found on the floor of Alberni Inlet and Jervis Inlet, at two locations and are reported here for the first time. Very large slides (> 65 million cubic metres) have been noted on the margin of Douglas Channel (Conway et al., 2012). These kinds of very large events are rare and slides of this size have not been observed elsewhere in the regional study area. The Douglas Channel is notable for the numerous and large slides found along the eastern margin of the inlet compared to all the other inlets examined in this study. The maximum size of the largest translational slides described in Douglas Channel is over 65×10^6 m^3, and were these large failures to occur today very large tsunamis would have been generated (Thomson et al., 2012).

Debris flows are common features associated with fan deltas as well as single events such as occurred at Kitimat (Bornhold et al., 2007). Long (>10 km) and deep (> 10 m) turbidite and debris flow channels occur in Knight, Bute and Toba Inlets and are well developed in Howe Sound at the Squamish river delta. In Howe Sound, the Squamish River is especially active and instability events may be measured on a near daily basis (Hughes-Clarke et al., 2010; Hughes-Clarke pers. comm.. 2012). Avulsion of the main river mouth channels appears to control sub-tidal channel development. Several channels are inset in the main channel system in Bute and Knight while these are not well developed in the other fiords. Many side entering debris flow/turbidite channels are apparent in Howe

Sound and are less prevalent in the more northerly fiords. Abandoned channel segments are apparent in four fiords reflecting rapid evolution of the channel systems. Several large scale (> 10^6 m^3) rock avalanche deposits are apparent in Bute Inlet, but are not seen in the other study areas. Large fan deltas occur in all of the studied fiords. Jervis Inlet appears to be somewhat unique as it is relatively sediment starved and has a large ebb-tidal fan delta where Princess Louisa Inlet marine waters enter the fjord. Howe Sound has been subdivided by a large late advance moraine at Porteau Cove that has probably affected the post glacial development of seabed channels. Proximity to large ice fields and large hinterland watersheds appear to account for differences in the development of fiord floor channel systems. Dune formation in areas of the delta and channel complexes appears to occur in each fiord studied, reflecting the importance of this process in sediment transport in these systems.

Blocky collapse seabed areas have been described for lower Knight Inlet. These collapse areas, attributed to either subsurface gas hydrate formation or in situ liquefaction during earthquakes (Bornhold and Prior, 1989) are also seen in Bute Inlet but are not apparent in Howe Sound, Toba, or Jervis inlets.

Along the delta front of the Fraser River many channel segments have been abandoned both through natural channel avulsion but also as the channel was fixed in place early in the last century (Hart, 1992 and references therein). The bedload and much of the suspended loads are delivered to only a few of the many channels on the delta front resulting in dynamic processes in these areas. The main channel is a site where sandy sediments bypass the delta slope in the main channel (Hill et al., 2008) and is an area of active deposition of turbidity current deposits.

The overall distribution of the mapped submarine slope failures reflects a trend towards more slope failures in areas with the steepest slopes and largest watersheds. In addition geological composition of each seafloor area determines to a large extent the style of slide deposits encountered. For example the abundant slope failures in Quaternary sediments in areas of the Straits of Georgia and

Juan de Fuca as compared to the relative abundance of rock avalanche and debris flow deposits in the steep slopes of the mountainous regions that host the southern mainland fjords is an illustration of this geological and topographic control.

CONCLUSIONS

Confidence in the classification of the identified landslides would be improved if a number of case studies were selected for follow up work, using sub-bottom profiles and cores to determine ages and validate process interpretations. Very large (>10 x 10^6 m^3) translational slides and debris flows are not numerous relative to the large number (approximately 1200) of submarine slope failures and related features identified. These slides could potentially have caused tsunamis during the failure events.

The wide distribution of the channel and delta complex features at the heads of many of the inlets would suggest that ongoing processes of sediment transport in these channels and delta fronts are critical features of BC fjord systems. The numerous small slides in Juan de Fuca Strait may possibly originate from a single earthquake event. It would be informative to establish a chronology to date these and other regional events to determine if they are synchronous and related to the mega thrust Cascadia subduction zone earthquake cycle. The large number of alluvial fan and apron deposits lend themselves to more quantitative assessments of these areas using a GIS approach and drainage area criteria.

ACKNOWLEDGEMENTS

The Canadian Hydrographic Service, under the leadership of Rob Hare and Ernest Sargent, is recognized for extraordinary dedication to the long term vision of providing complete and seamless mapping of the many seaways and coastal passages of British Columbia. Thanks to David Piper, GSC-Atlantic, for numerous suggestions which improved the report.

REFERENCES

Atwater, B. F., 1987. Evidence of great Holocene earthquakes along the outer coast of Washington State, Science 236, 942–944.

Barrie, J.V., Hill, P.R., Conway, K.W., Iwanowska, K and Picard, K, 2005. Environmental Marine Geoscience 4: Georgia Basin: Seabed features and marine geohazards. Geoscience Canada, Vol. 32, No.4.

Bornhold, B. D., Harper, J. R., McLaren, D. and Thomson, R. E., 2007. Destruction of the First Nations village of Kwalate by a rock avalanche-generated tsunami. Atmosphere-Ocean, 45, 123-128.

Bornho1d, B. D., 1983. Sedimentation in Douglas Channel and Kitimat Arm in Canadian Technical Report of Hydrography and Ocean Sciences No. 18 (1983) Proceedings of a Workshop on the Kitimat Marine Environment. Canadian Technical Reports Hydrography and Ocean Sciences v. 18, p. 1-218.

Bornhold B.D. and Kemp A.E.S. (eds), 2001. Late Quaternary sedimentation in Saanich Inlet, British Columbia, Canada – Ocean Drilling Program Leg 169S. Marine Geology v. 174, p.1–387.

Bornhold B.D. and Prior B., 1989. Sediment blocks on the seafloor in British Columbia fjords. Geo-Marine Letters v. 9, no. 3, p. 135-144.

Bornhold B.D. and Prior B., 1990. Morphology and sedimentary processes on the subaqueous Noeick River delta, British Columbia, Canada. In: Colella A, Prior DB (eds) Coarse-grained deltas. International Association of Sedimentologists Special Publication 10:169–181.

Bornhold B.D., Ren P., and, Prior D.B. 1994. High-frequency turbidity currents in British Columbia fjords. Geomarine-Marine Letters, v. 14, p. 238–243. doi:10.1007/BF01274059.

Bornhold, B.D. and Thomson, R.E., 2012. Tsunami hazard assessment related to slope failures in coastal waters *in:* Clague, J.J. and Stead, D. (eds) Landslides: Types, Mechanisms and Modeling. Cambridge University Press. p. 108-120.

Clague, J.J., 1977. Quadra Sand: a study of the late Pleistocene geology and geomorphic history of coastal southwest British Columbia. Geological Survey of Canada, Paper, no. 17- 77.

Clague, J.J. , 1985. Deglaciation of the Prince Rupert - Kitimat area, British Columbia Canadian Journal of Earth Sciences, v. 22, p. 256-265.

Conway, K.W., Barrie, J.V., and Thomson, R.E., 2012. Submarine slope failures and tsunami hazard in coastal British Columbia: Douglas Channel and Kitimat Arm; Geological Survey of Canada, Current Research 2012-10, 13p.

Conway, K.W., Bornhold, B.D. and Barrie, J.V., 1996. Surficial geology of the Skeena River delta. Geological Survey of Canada, Open File 3307.

Conway, K.W., J.V Barrie, Picard, K and Bornhold, B.D., 2012. Submarine channel evolution: active channels in fjords, British Columbia, Canada. Geo-Marine Letters, v. 32, no. 12, p.301-312.

Currie, R.G. and Mosher, D.C., 1996. Swath bathymetric surveys in the Strait of Georgia, British Columbia. Current Research 1996- E, Geological Survey of Canada, p. 33-40.

Dallimore A., and Jmieff G.G., 2010. Canadian west coast fjords and inlets of the NE Pacific Ocean as depositional archives. Geological Society of London Special Publication no. 344(1), p. 143–162.

Dallimore, A., Thomson, R.E., and Betram, M., 2005. Late Holocene laminated sediments of Effingham Inlet, Vancouver Island, British Columbia: Implications for regional geologic, paleoseismic, oceangraphic and climatic history. Marine Geology, v. 2 19(1) p.47-69.

Fell, R., Stapledon, D, MacGregor, P., 2012. Landslides and geologic environments *in:* Clague, J.J. and Stead, D. (eds) Landslides: Types, Mechanisms and Modeling. Cambridge University Press. p. 134- 143.

Gani, M. R. 2004: From Turbid to Lucid, A straightforward approach to sediment flows and their deposits. The Sedimentary Record (SEPM) 2, 4 – 11.

Hart, B.S., Prior D.B. Barrie, J.V., Currie, R.G., and Luternauer, J.L., 1992. A river mouth submarine channel and failure complex, Fraser Delta, Canada. Sedimentary Geology, v. 81, 1–2, p. 73–87.

Hill, P.R., Conway, K.W., Lintern, D.G., Meulé, S., Picard, K., Barrie, J.V., 2008. Sedimentary processes and sediment dispersal in the southern Strait of Georgia, BC, Canada. Marine Environmental Research, v. 66, p. S39–S48.

Hughes Clarke J.E., Brucker S., Hill P., Conway K., 2009. Monitoring morphological evolution of fjord deltas in temperate and Arctic regions: international conference on seafloor mapping for Geohazard assessment, Editors: Chiocci FL, Ridente D, Casalbore D, Bosman A, Rendiconti online della Societa´ Geologica Italiana , v. 7(4), p. 147–150.

Jackson, L. E. Jr., Hermanns, R.L., Courtney J. E., Conway, K.W. and Kung, R., 2008. Annotated images of submarine landslides and related features generated from swath multibeam bathymetry, Howe Sound, British Columbia. Geological Survey of Canada, Open File 5662.

Johns, M.W., Prior,D.B., Bornhold, B.D., Coleman, J.M. and, Bryant W.R.. 1986. Geotechnical aspects of a submarine slope failure, Kitimat Fjord, British Columbia. Marine Geotechnology, v. 6, no. 3.

Kostachuk R.A., Luternauer J.L., McKenna G.T., and Moslow T.F., 1992. Sediment transport in a submarine channel system: Fraser River delta, Canada. Journal of Sedimentary Research, v. 62(2), p. 273-282.

Leonard, L.J., Rogers, G.C. and Mazzotti, S. (2012). A preliminary tsunami hazard assessment of the Canadian coastline. Geological Survey of Canada, Open File 7201.

Linden, R.E. and P.J. Schurer, 1988. Sediment characteristics and sealevel history of Royal Roads Anchorage, Victoria, British Columbia. Canadian Journal of Earth Sciences, v. 25, p. 1800-1810.

Luternauer, J.L., 1980. Skeena, Nanaimo and Cowichan River deltas and offshore environs, British Columbia: surficial sediment distribution and locations of other available data types collected by the Geological Survey of Canada. Geological Survey of Canada, Open File 1112.

Luternauer, J.L. and Swan, D., 1978. Kitimat submarine slump deposit(s): a preliminary report. Geological Survey of Canada Paper 78-lA, p. 327-332.

Locat, J. and Lee, H.J., 2002. Submarine landslides: advances and challenges Canadian Geotechnical Journal, v. 39, p. 193–212.

Mathews, W.H. and Shepard, F.P., 1962. Sedimentation of the Fraser River delta, British Columbia. American Association of Petroleum Geologists Bulletin v. 46, p. 1416-1438.

Miller, D.J., 1960. The Alaska earthquake of July 10, 1958: giant wave in Lituya Bay. Bulletin of the Seismological Society of America, v. 50, no. 2, p. 241-250.

Mosher, D.M., 2009. Submarine landslides and consequent tsunamis in Canada. Geoscience Canada. V. 36, No 4.

Mosher, D.C. and Hewitt, A.T., 2004. Late Quaternary deglaciation and sea-level history of eastern Juan de Fuca Straight, Cascadia. Quaternary International. v. 121, p. 23–39.

#

Mosher, D.C., Monahan, P.A., Barrie J.V., and, Courtney, R. C., 2004. Coastal Submarine Failures in the Strait of Georgia, British Columbia: Landslides of the 1946 Vancouver Island Earthquake Journal of Coastal Research, v. 20, no. 1, p. 277-291.

Niedoroda, A.W., Reed, C., Das. H., Hatchett, L., & Perlet, A.B.: Controls of the behavior of marine debris flows. Norwegian Journal of Geology,Vol. 86, pp. 265-274. Trondheim 2006. ISSN 029-196X.

Nemec, W. and Steel, R.J. (eds) 1988. Fan Deltas: Sedimentology and Tectonic Settings. Blackie and Sons.

Piper, D.J.W., Mosher, D.C., and Campbell, D.C., 2012. Controls on the distribution of major types of submarine landslides *in:* Clague, J.J. and Stead, D. (eds) Landslides: Types, Mechanisms and Modeling. Cambridge University Press. p. 95-108.

Prior, D.B. and Bornhold, B.D., 1988. Submarine morphology and processes of fjord fan deltas and related high-gradient systems: modern examples from British Columbia *in:* Nemec, W. and Steel, R.J. (eds*)* Fan Deltas: Sedimentology and Tectonic Settings. Blackie and Sons.

Prior, D. B., Bornhold, B. D. and Johns, M., 1984. Depositional characteristics of a submarine debris flow. Journal of Geology, v. 92, p. 707-727.

Prior, D.B., Bornhold, B.D., Coleman, J.M., and Bryant, W.R., 1982. Morphology of a submarine slide, Kitimat Arm, British Columbia. Geology, v. 10, p. 588–592.

Prior, D,B, and Bornhold B.D., 1989. Submarine sedimentation on a developing Holocene fan delta. Sedimentology, v. 36, p. 1053–1076.

Prior, DB, Bornhold, B.D. and, Johns M.W.1986. Active sand transport along a fjord-bottom channel, Bute Inlet, British Columbia. Geology, v. 14, p. 581–584.

Prior D.B., Bornhold B.D., Wiseman W.J., Lowe D.R., 1987. Turbidity current activity in a British Columbia fjord. Science, v. 237, p. 1330–1333.

Ren P., Bornhold B.D., and Prior D.B., 1996. Seafloor morphology and sedimentary processes, Knight Inlet, British Columbia. Sedimentary Geology, v. 103, p. 201–228.

Rogers, G.C., 1980. A documentation of soil failure during the British Columbia earthquake of 23 June, 1946. Canadian Geotechnical Journal, v. 17, p. 122-127.

Southern California Earthquake Center, 2012. A Comparison of the February 28, 2001, Nisqually, Washington, and January 17, 1994, Northridge, California Earthquakes http://www.scec.org/news/01news/feature010313.html. Accessed Dec 10, 2012.

St-Onge, G., Mulder, T.Piper, D.J.W., Hillaire-Marcel, M., 2004. Earthquake and flood induced turbidites in the Saguenay Fjord (Quebec): a Holocene paleoseismicity record. Quaternary Science Reviews, v. 23, p. 283-294.

Syvitski, J.P.M., and Farrow G.E., 1983. Structures and processes in bayhead deltas: Knight and Bute inlets, British Columbia. Sedimentary Geology, v. 36, p. 217–244.

Syvitski, J.P.M., Burrell, D.C. and Skei, J.M., 1987. Fjords: Processes and Products. J. P. Springer-Verlag, New York 1987.

Syvitski, J.P.M. and Shaw, J., 1995. Sedimentology and geomorphology of fjords. *in*: G.M.E. Perillo, G.M.E. (ed), Geomorphology and Sedimentology of Estuaries, Elsevier Publ., 113-178 pp.

Tappin, D. R., Matsumoto, T., Watts, P., Satake, K., McMurtry, G. M., Matsuyama, M., Lafoy, Y., Tsuji, Y., Kanamatsu, T., Lus, W., Iwabuchi, Y., Yeh, H., Matsumotu, Y., Nakamura, M., Mahoi, M., Hill, P., Crook, K., Anton, L., and Walsh, J. P.: Sediment slump likely caused 1998 Papua New Guinea Tsunami, EOS, Transactions of the American Geophysical Union, 80, p. 329, 334, 340, 1999.

Thomson, R.E., 1981. Oceanography of the British Columbia coast. Canadian Fisheries and Aquatic Sciences Special Publication, no. 56.

Thomson, R.E., Rabinovich, A.B. Kulikov, E.A. I.V. Fine, I.V., and Bornhold, B.D., 2001. On numerical simulation of the landslide-generated tsunami of November 3, 1994 in Skagway Harbor, Alaska. In *Tsunami Research at the End of a Critical Decade*, Advances in Natural and Technological Hazards Research, v. 18, (ed) Hebenstrait, G.T. Kluwer Academic Publishers, Netherlands, 304 p.

Thomson, R., Fine, I., Krassovski, M., Cherniawsky, J., Conway, K., and Wills, P. 2012. Numerical simulation of tsunamis generated by submarine slope failures in Douglas Channel, British Columbia. DFO Canadian Science Advisory Secretariat Ressearch Document 2012/155.

Tipper, H. W., Woodworth, G. J., and Gabrielse, H., 1981. Tectonic Assemblage Map of the Canadian Cordillera. (1505A), Geological Survey of Canada.

Van Zeyl, D.P., 2009. Evaluation of subaerial landslide hazards in Knight Inlet and Howe Sound, British Columbia. Unpublished M. Sc. Thesis. Department of Earth Sciences, Simon Fraesr University.

Wheeler J.O., Brookfield A.J., Gabrielse, H., Monger J.W.H., Woodsworth G.J., 1991. Terrane map of the Canadian Cordillera. Geological Survey of Canada Map 1713A, scale 1:2,000,000.