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Abstract: A new analysis of multibeam swath bathymetry data reveals evidence of large submarine slope failures in southern Douglas Channel, British Columbia. Specifically, two rotational submarine slides (A and B) formed by the failure of scallop-shaped blocks derived from the eastern margin of the fiord wall are identified. Slide A has an estimated minimum volume of 32 000 000 m^3 and Slide B of 31 000 000 m^3. The toes of the failures are buried by a thick cover of mud deposited from suspension, as are the edges of the slide masses, suggesting that the failures occurred during early to mid-Holocene time, i.e. 5000 to 10 000 years BP. Although the causes of the failures are not known at this time, their close proximity to an apparently active fault presents the possibility that they may have been triggered by ground motion or surface rupture of the fault during past earthquake events. Additional geological research is required to better delineate the age of the submarine failures, their triggers, and their mechanisms of emplacement. Nested failures, retrogressive and incipient slide blocks, and steep slopes are characteristic of the southeastern margin of Douglas Channel and present conditions conducive to future submarine failures.

Each of the newly identified slide volumes exceed that of the 25 000 000 m^3 slope failure that took place on 27 April 1975 along the inner slope of Kitimat Arm to the northwest of Douglas Channel. This latter failure generated a tsunami with a maximum recorded wave height of 8.2 m and damaged a First Nations village on the opposite side of the inlet. A fine-scale numerical model using high-resolution seafloor topography and detailed slide-volume characteristics has been initiated to better assess the generation, propagation, and along-channel impacts of tsunami waves that may have resulted from the Douglas Channel slope failures. The findings will provide important information needed to manage the potential impacts of any future event and to support the safe and sustainable development of the region.

Résumé : Une nouvelle analyse de données de bathymétrie multifaisceaux révèle les signes de vastes ruptures de talus sous-marines dans la partie sud du chenal Douglas (Colombie-Britannique). Plus précisément, on a identifié les traces de deux glissements rotationnels sous-marins (A et B) créés par la rupture de blocs en forme de festons sur le mur oriental du fjord. Le glissement A a mis en mouvement un volume minimal estimé à 32 000 000 m^3 et le glissement B, à 31 000 000 m^3. Le front des ruptures est enfoui sous une épaisse couverture de boue résultant du dépôt de particules en suspension, comme le sont les bordures des masses déplacées, ce qui donne à penser que les ruptures se sont produites à l'Holocène précoce ou moyen, c'est-à-dire, il y a de 5 000 à 10 000 ans BP. Bien qu'à ce moment-ci les causes de ces ruptures ne soient pas connues, l'étroite association spatiale entre les traces des glissements et une faille apparemment active soulève la possibilité que les ruptures ont pu être déclenchées par des mouvements de sol ou par le jeu en surface de la faille lors d'anciens séismes. De plus amples recherches géologiques seront nécessaires afin de mieux définir l'âge des ruptures sous-marines, les agents de déclenchement et les mécanismes de mise en place. Des traces de ruptures emboîtées, des blocs de glissements rétrogressifs ou embryonnaires, ainsi que des pentes raides sont caractéristiques de la marge sud-est du chenal Douglas et les conditions actuelles sont propices au déclenchement de nouvelles ruptures sous-marines.

Les volumes des glissements récemment reconnus sont supérieurs aux 25 000 000 m^3 mis en mouvement par la rupture de talus survenue le 27 avril 1975 le long du talus intérieur du bras Kitimat, au nord-ouest du chenal Douglas. Cette dernière rupture a provoqué un tsunami, avec des vagues d'une hauteur maximale enregistrée de 8,2 m, qui a causé des dommages au village des Premières Nations situé sur le côté opposé du bras de mer. Afin d'étudier la génération des ondes de tsunami qui ont pu être causées par les ruptures de talus récemment reconnues dans le chenal Douglas, leur propagation et leurs effets le long du chenal, on a entrepris la conception d'un modèle numérique à petite échelle ayant recours à la topographie haute résolution du fond marin et aux caractéristiques détaillées des volumes déplacés par les glissements. Les résultats attendus généreront de l'information de grand intérêt pour gérer les impacts potentiels de tout événement futur ainsi que pour appuyer le développement sécuritaire et durable de la région.

INTRODUCTION

The Earth Science Sector's Public Safety Geoscience Program undertakes research in support of the effective management of natural hazard risks in Canada. As part of the current program cycle, new and/or improved national-scale assessments of selected natural hazards (earthquakes, tsunamis, volcanoes, landslides, and space-weather events) are being developed to inform decision-making. The assessment of Canada's terrestrial landslide susceptibility was recently completed (Bobrowsky and Dominguez, in press) and efforts are now being focused on slope failures in Canada's marine lands. Specifically, high-resolution swath multibeam bathymetry and other available data sets are being analyzed for evidence of such failures. For the Pacific region, the analysis got underway in late 2011 utilizing data sets in nearshore and coastal areas that were collected and compiled between 2001 and 2011 (*see* for example Barrie et al., 2005).

The intent of the analysis is to provide an overview of the types, locations, and extents of submarine slope instability features. Particular focus is on submarine slope failures that could pose a risk to infrastructure or generate tsunamis. (Tsunamis are long, surface gravity waves with periods ranging from minutes to hours generated by earthquake-induced displacements or slope failures and rock falls. The wave heights, inundation, and currents associated with tsunamis can have major impacts for coastal communities and infrastructure.) The British Columbia coastal region is an area of steep slopes, seasonal extremes of soil moisture, large tidal ranges, and the highest seismicity in Canada, factors which increase the potential for slope failures. In coastal environments, both submarine and subaerial slope failures may be initiated, and in relatively shallow and/or confined waterways, they present a significant hazard for tsunami wave generation (Mosher, 2009; Bornhold and Thomson, in press). Submarine slope failures and associated tsunamis are well documented in the British Columbia coastal region (Bornhold et al., 2007; Bornhold and Thomson, in press). The Kitimat Arm and Douglas Channel fiord system (Fig. 1) is under consideration for the development of extensive shoreline installations and infrastructure for a variety of industrial projects.

This paper presents the results of a preliminary investigation of geological hazards within this fiord environment. Specifically, a potentially active fault and two large slope failures discovered in this fiord are documented. A preliminary assessment of the potential tsunami hazard resulting from failures of this scale is provided and detailed numerical modelling has been initiated to provide greater insights. The results are intended to support land-use stewards, regulatory agencies, and others in making informed decisions about land-use development, environmental protection, and public safety.

PREVIOUS STUDIES

Bedrock geology of this portion of the Canadian Cordillera was studied by Roddick, (1970) and the overlying Quaternary geological history of the Kitimat region was elucidated by Clague (1985 and references therein). The marine geology of the fiord system was reviewed by Bornhold (1983). During deglaciation, the area experienced raised relative sea level by up to 200 m between 16 000 and 12 000 calendar years BP as a result of isostatic depression under the Cordilleran ice sheet. As ice margins retreated, thick sequences of muds, sands, and deltaic gravels infilled basins in coastal settings and relative sea level fell. Holocene (10 000 calendar years BP to present) sediments are up to 60 m thick in the deeper basin areas of Douglas Channel and overlie several hundred metres of older glacial sediments (Bornhold, 1983).

Kitimat Arm, which forms the northwest extension of Douglas Channel, experienced submarine slope failures in 1974 and 1975. The failure of 17 October 1974 generated a 2.4 m tsunami in the inlet at the time of low tide (Johns et al., 1986; Thomson et al., 2001). The failure of 27 April 1975 also took place near low tide on the northeast slope of the inlet (Luternauer and Swan 1978; Prior et al., 1982) and generated a tsunami with maximum recorded wave height of 8.2 m. Deposits resulting from the 1975 event have been well surveyed using a variety of geological methodologies (Prior et al., 1982; 1984) and shallow-water wave modelling has been undertaken in order to determine the height and propagation of the tsunami waves (Murty, 1979; Skvortsov and Bornhold, 2007). The 1975 slide, which involved a subaerial component of material, has also been used as a case study for estimates and mechanisms of tsunamis in coastal British Columbia waters (Fine et al., 2002; Bornhold and Thomson, in press).

DATA COLLECTION

Multibeam data were collected in Kitimat Arm and Douglas Channel in water depths greater than 50 m from the CCGS *Vector* between 2007 and 2009 using a hull-mounted Kongsberg-Simrad EM2002 multibeam echo-sounder system before 2009 and a gondola mounted Kongsberg-Simrad EM 710 system operating at 70–100 kHz system in 2010. Selected areas inshore deeper than 5 m were surveyed by the CCG Launch *Otter Bay* mounted with an EM 3002 multibeam system. 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 0.1% of water depth vertically and 2 m horizontally. The grids were then imported into ESRI ArcInfo™ GIS software to allow visualization. Perspective, three-dimensional views of portions of the multibeam data were created using Fledermaus™ software.

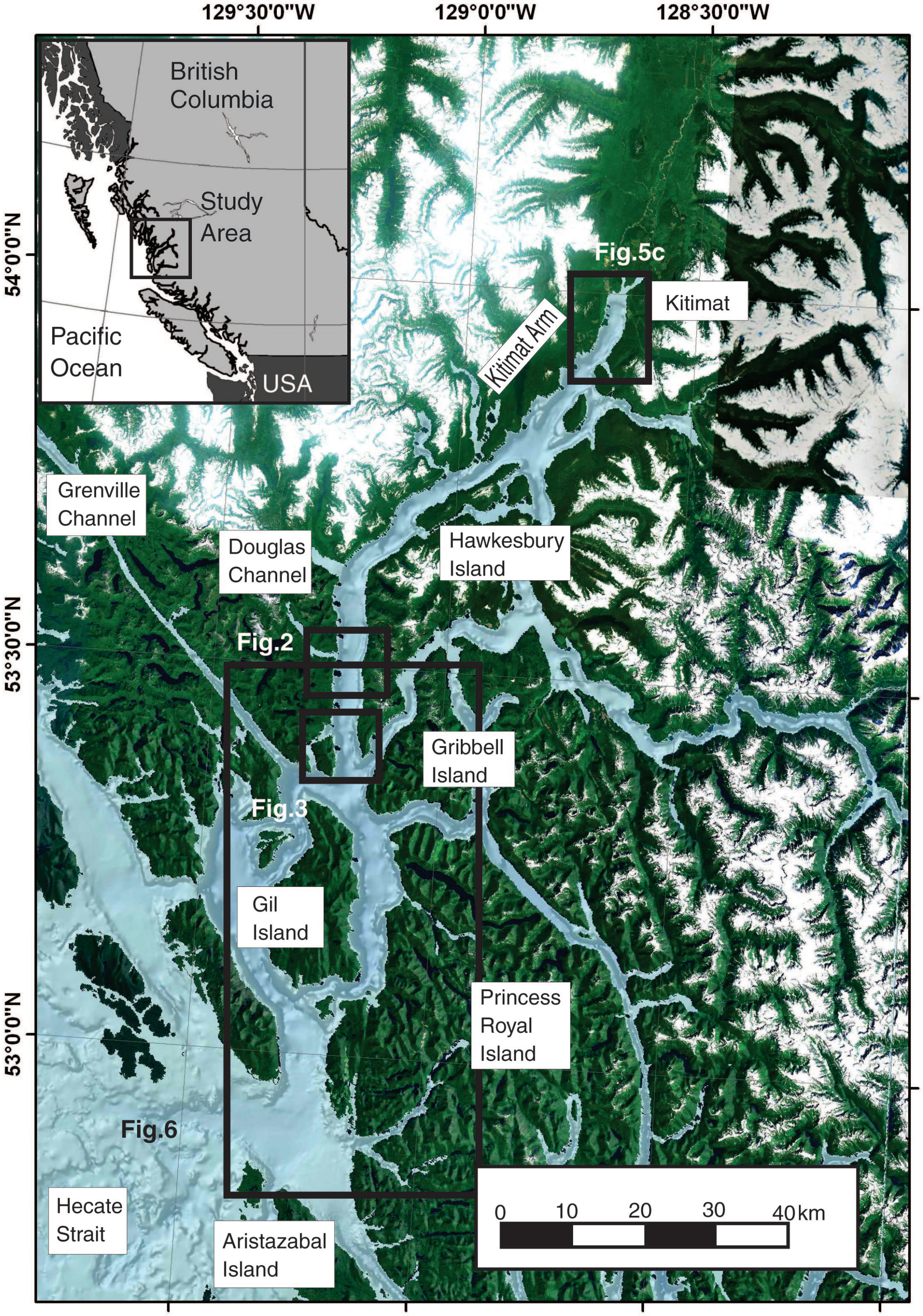

Figure 1. Location of the Douglas Channel/Kitimat Arm study area. Insets show locations for following figures.

RESULTS

Multibeam bathymetric data indicate the existence of previously unrecognized massive slope failures along the southeastern margin of Douglas Channel (Fig. 2, 3). Two scallop-shaped hollows located along the edge of the fiord wall are associated with detached blocks that extend out into the fiord. The blocks appear to be detached directly from the Hawkesbury Island nearshore which, by extrapolation from the mapping by Roddick (1970), probably consists of Cretaceous diorite. The more northern failure (Slide A) appears to have originated from water depths less than 60 m to 100 m (Fig. 2), whereas the more southern failure (Slide B) appears to have originated from depths between 75 and 100 m (Fig. 3). The failure blocks taper out onto the fiord floor at approximately 350 m water depth at Slide A and 400 m at B. The margins of the detached blocks appear to be mantled with an undetermined thickness of recent sediments (Fig. 2, 3) that infill the fiord and drape the distal ends of the slide blocks. The displacement of the blocks indicates that, in each case, a portion of the slide mass runs out for some distance onto the fiord floor, but has been buried by subsequent sedimentation (Fig. 2, 3). Perspective views of the slide block A, looking northward up the channel, assist in its visualization (Fig. 4). They show that the slide occurs in a zone of general slope instability where small failures are superimposed on larger failures. Nested failures occur on the backslope of Slide A and also on its crest (Fig. 4a). A developing scarp appears to define an incipient slide block adjacent to Slide A (Fig. 4b). This incipient slide is bracketed by Slide A to the north and retrogressive, smaller failures to the south. In addition, an older failure scarp is apparent.

Bathymetric profiles across the features (Fig. 2, 3) indicate that the blocks failed as rotational slides (Locat and Lee, 2002) with downslope horizontal displacements of up to 350 m (Block A) and 400 m (Block B). Relative block movements are not the same along the centre axes of the blocks relative to the source of the slide. Both failures indicate more downslope movement on the south side of the slide relative to the north side, suggesting some rotation in the along slope direction as well. The volumes of the two slides are estimated at 32 000 000 m^3 for Slide A and 31 000 000 m^3 for Slide B. These estimates are approximate and do not include buried debris that would have spread into the fiord after initial detachment and block sliding.

Comparison of multibeam data from the 1975 slide/debris flow in Kitimat Arm against the rotational slides in Douglas Channel at the same map scale reveals the deep-seated nature of the detached blocks compared to the surficial nature of the debris flow deposit in Kitimat Arm (Fig. 5). While the slide volumes of the 1975 Kitimat event and Slides A and B are the same order of magnitude, the nature of the material involved and the mechanism of slide emplacement of the 1975 event are distinct from the latter two. The differences would result in distinctly different tsunami generation potential and behaviour (*see* Discussion).

POSSIBLE ACTIVE FAULT

A north-south trending lineament or lineation apparent on bathymetric and topographic data suggests the possible existence of a fault immediately to the south of Slide B (Fig. 6). Multibeam swath bathymetry data indicate a north-south trending, linear zone of extensive deformation immediately south of the mapped slope failures (Fig. 6). Evidence for a continuous fault trace is observed in topographic data by features such as aligned stream beds crossing topographic and drainage divides. The total length of the lineation is 50 km and in the north the feature terminates near a zone of elongate, north-south trending, en echelon fractures at the south end of Hawkesbury Island within 4 km of Slide B (Fig. 3). The lineation appears to terminate in the south near Aristazabal Island. Eleven small (<M3) earthquakes have occurred within 20 km of the inferred structure in the past 25 years (J. Cassidy, pers. comm., 2012); however, none of these earthquakes can be directly linked to the inferred fault given the uncertainties in their epicentral locations. Nonetheless, in the absence of additional evidence, the fault must be considered a potential trigger for the submarine failure events.

DISCUSSION

Age of the slope failures

The age of the two newly identified failures cannot be determined with precision using available data; however, our analysis suggests a probable early- to mid-Holocene (i.e. 5000–10 000 calendar years BP) age for both. The bedrock walls of Douglas Channel would have been eroded during glacial ice movement through the fiord system prior to 17 000 calendar years BP (Clague, 1985). If the slides had occurred prior to glaciation, the slide scars would have been removed during the glacial carving of the fiord. This suggests that the slides occurred after deglaciation, i.e. post-14 000 calendar years BP, and places a maximum age constraint on the features. One possibility is that the failures detached immediately after deglaciation when the ice withdrawal suddenly reduced the horizontal stress on the near-vertical fiord walls. At this time, significant seismicity related to the postglacial isostatic recovery of the lithosphere was likely and may have triggered the failures. However, examination of multibeam data from other fiords surveyed to date do not reveal similar submarine slope failures of this scale elsewhere (Geological Survey of Canada, unpub. data, 2001–2011) in areas where the processes of ice sculpting and deglaciation would have been quite similar. This argues against very early Holocene deglacial failures.

Sedimentation rates are variable in the Douglas Channel, with some areas experiencing erosion while others experiencing sedimentation of several centimetres per year (Bornhold, 1983). The smooth seafloor at the base of Slides

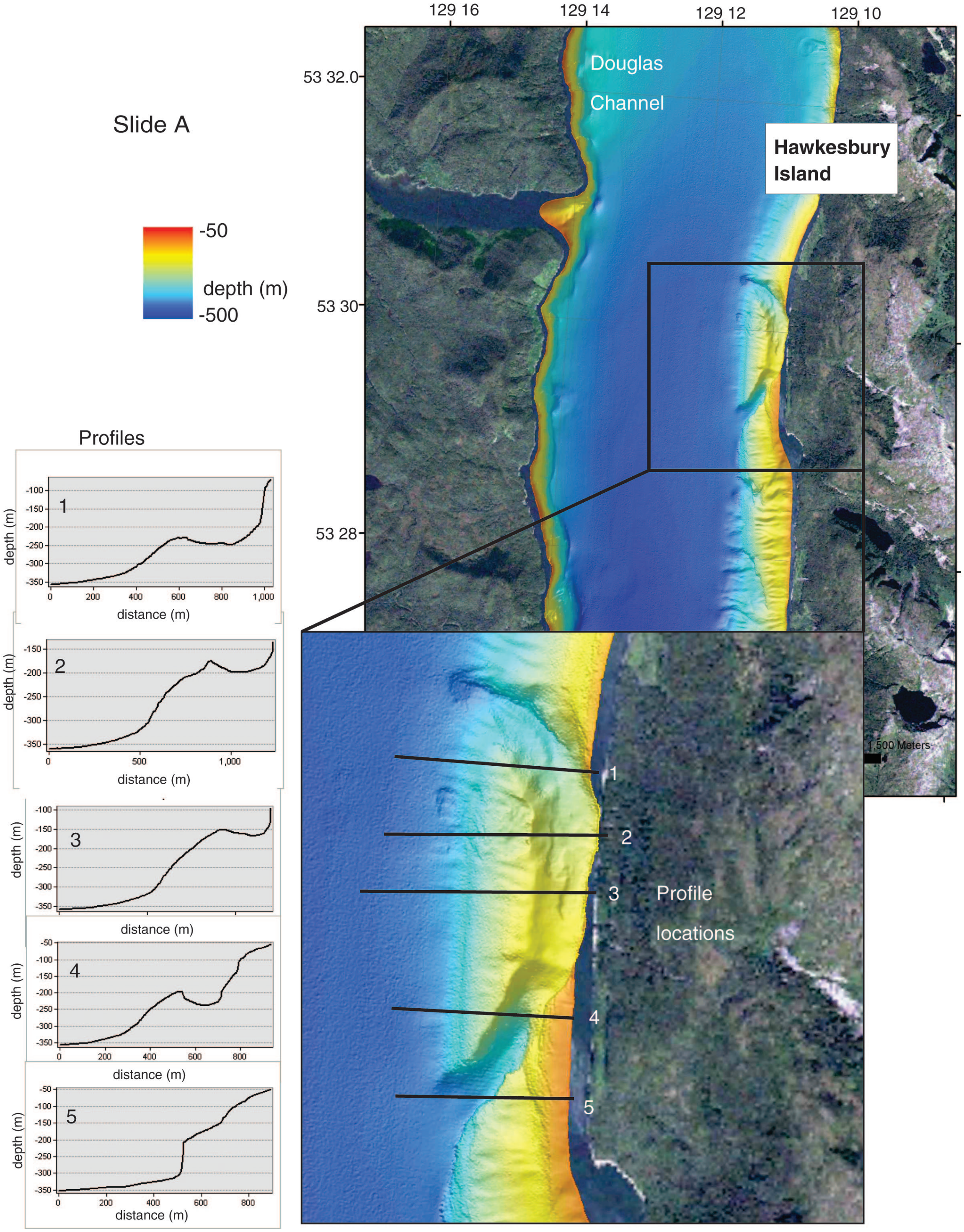

Figure 2. Detailed multibeam imagery of landslide A. Bathymetric profiles extracted from multibeam bathymetry data are shown with locations at right. *See* Figure 1 for location. Profiles show general shape of slide detachment from Hawkesbury Island. Profile 5 shows 100 m scarp where slide block was removed.

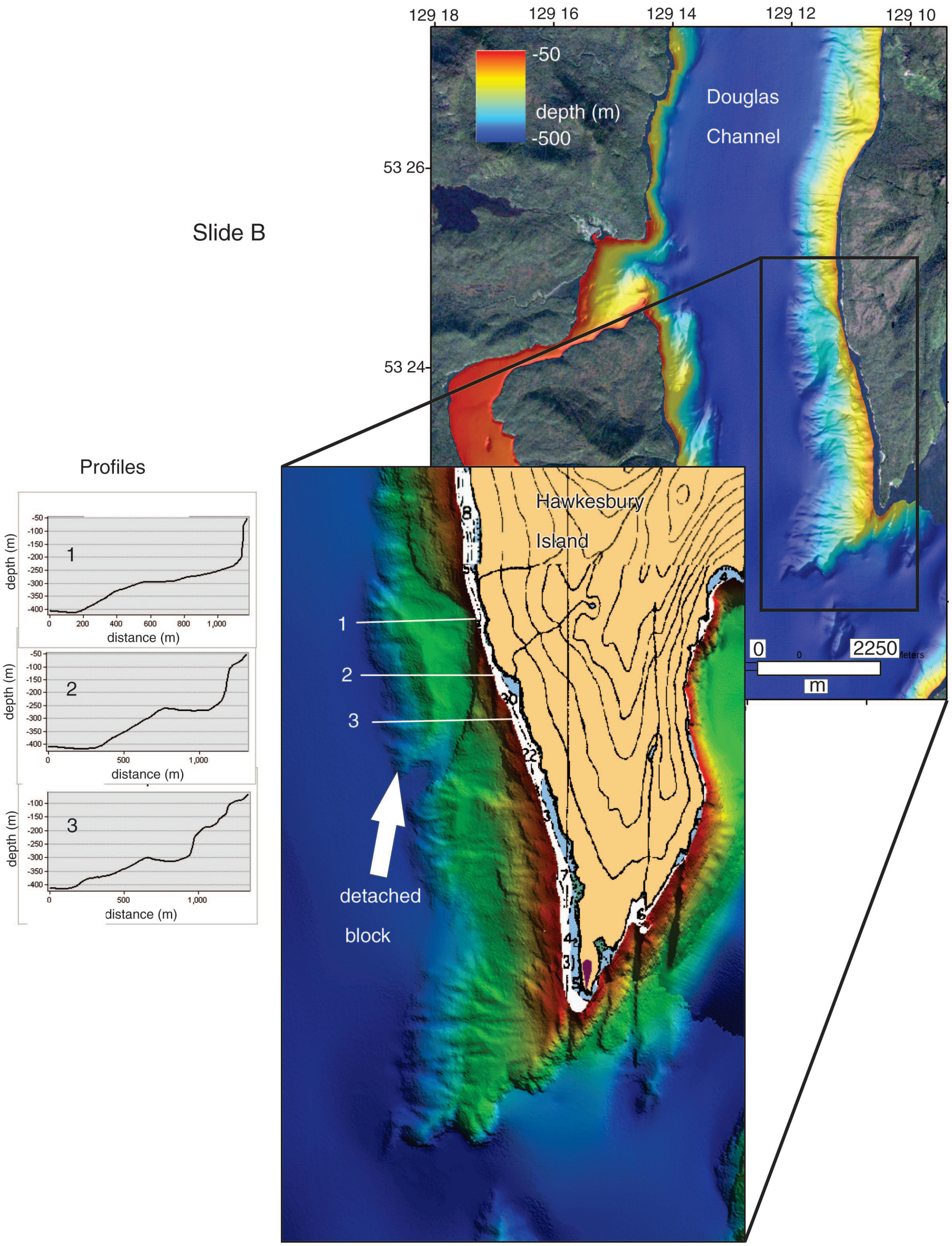

Figure 3. Detailed multibeam imagery of landslide B showing detached block. Bathymetric profiles extracted from multibeam bathymetry data are shown with locations at right. *See* Figure 1 for location. Note pronounced north-trending submarine fractures at the south end of Hawkesbury Island.

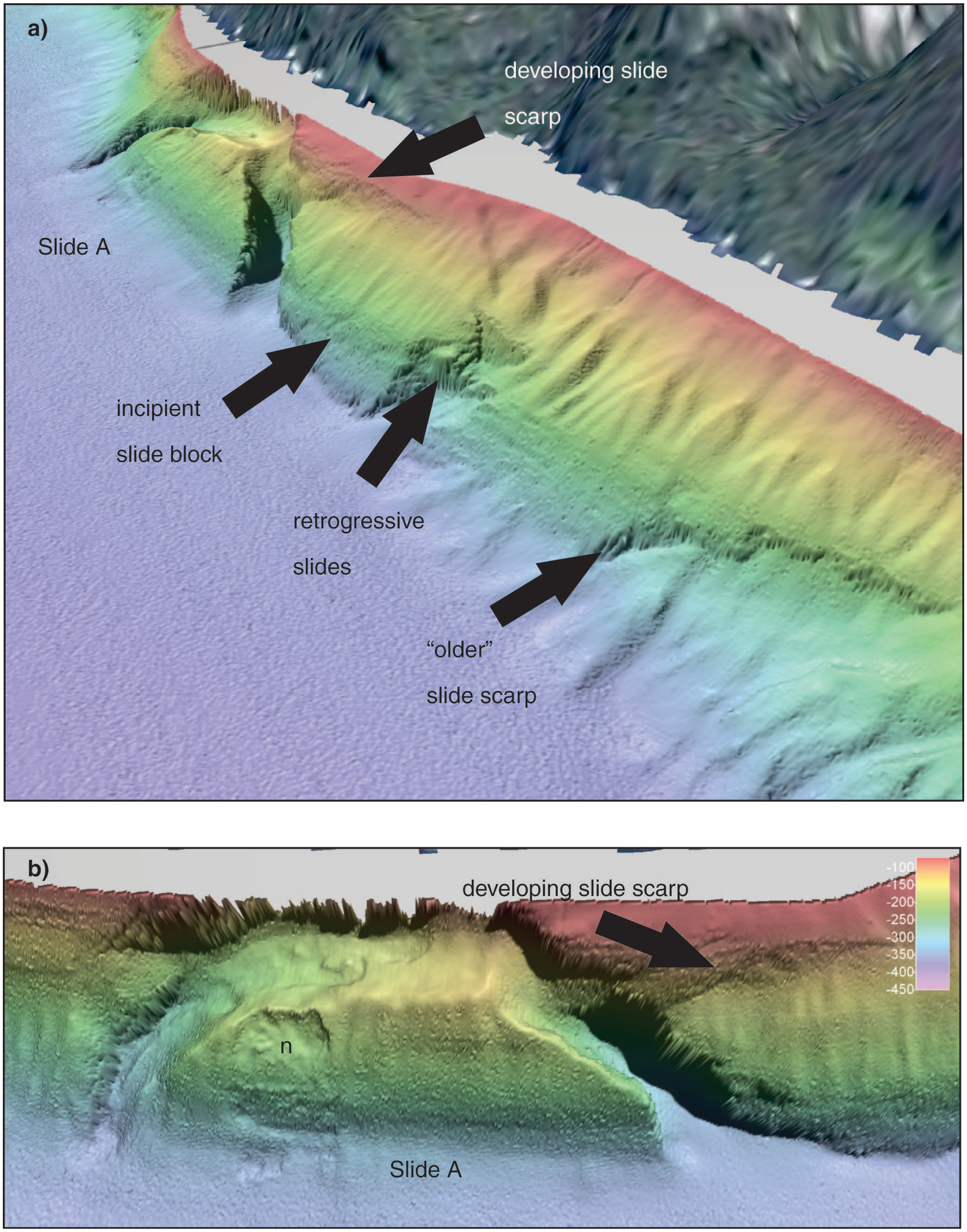

Figure 4. Perspective views of Slide A and surrounding area using Fledermaus™ software; **a)** oblique view looking north shows several instability features adjacent to Slide A, including an older slide scarp and a possible incipient slide that has been bracketed by Slide A and smaller retrogressive slides; **b)** oblique view looking east toward Slide A shows several smaller slides (at ‘n’) have occurred on the top and backslope of the main slide and a close view of what may be a developing slide scarp.

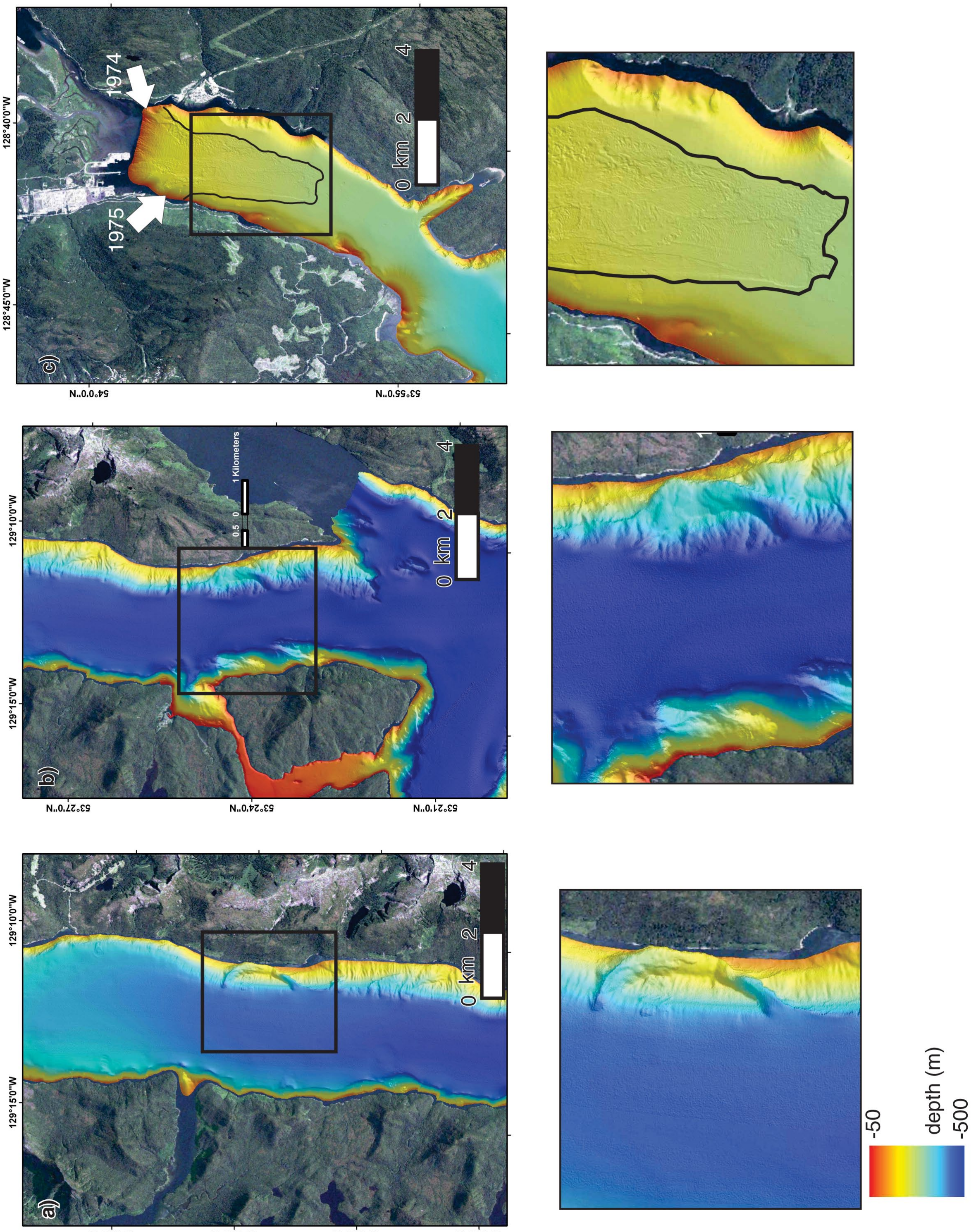

Figure 5. Submarine slides in Kitimat Arm and Douglas Channel at the same scale, with detailed inset showing difference in morphology of the landslides; **a)** Slide A; **b)** Slide B; and **c)** Kitimat slide. The Kitimat slide morphology represents a composite geomorphic feature as the 1975 slide overlaps the 1974 slide and they cover much of the same area of the seabed in Kitimat Arm. The failure zone of each landslide is shown. *See* Figure 1 for locations.

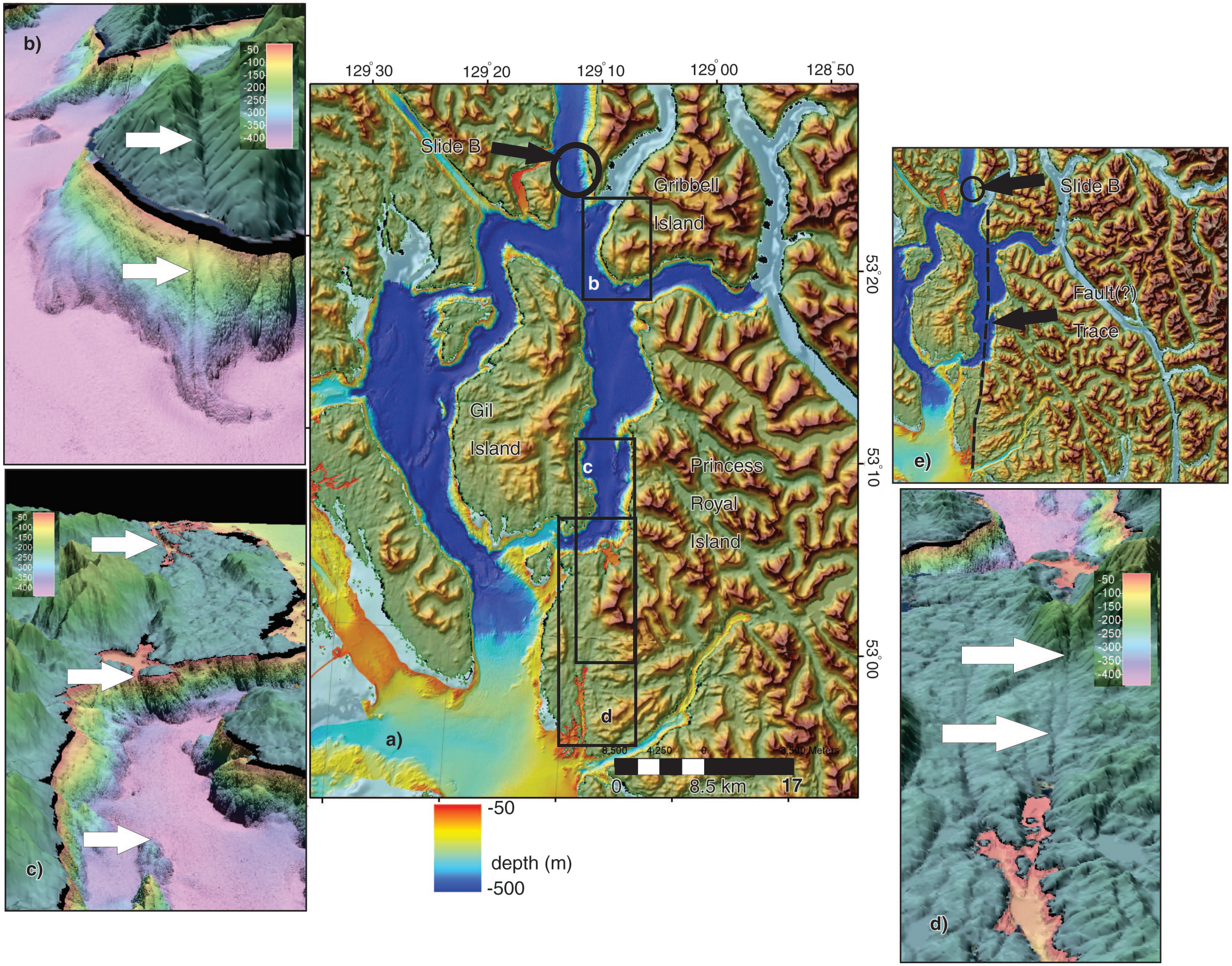

Figure 6. **a)** Possible active fault south of slide area B, visible in topographic and bathymetric data. Insets show details of fault trace. **b)** 3-D perspective view looking north to Gribbell Island showing stream beds aligning across a divide with a corresponding lineation in the multibeam bathymetric data. **c)** 3-D perspective view looking south to Princess Royal Island showing alignment of linear features. **d)** 3-D perspective view looking north across Princess Royal Island showing pronounced alignment of features (streams, bays, and ridges). **e)** Total extent of fault trace adjacent to Slide B. The lineation is approximately 50 km in length.

A and B suggests that they are covered by a significant thickness of postglacial sediment. Whereas the exact thickness cannot be determined with present data, the sediment mantle suggests that the slides did not occur in the late Holocene. The presence of smaller landslides within the sediment drape on the surface of Slide A (Fig. 4) also suggests an early- to mid-Holocene age. In addition, Slide B appears to be eroded on the flanks (Fig, 3) which suggests an early Holocene age. Geological research by coring of deposits draping slides A and B would allow determination of their ages and seismic profiling would allow their structure in the subsurface to be examined.

Classification of slope failures and possible failure mechanism

The type of slope failure for both slides A and B is classified as a rotational slide (Locat and Lee, 2002). In some alpine terrestrial environments, large bedrock areas are documented to have undergone slow deformation known as 'sackung' — a German term meaning 'sagging' (Zischinsky, 1966) — that can be geologically difficult to distinguish from simpler kinds of rotational slides (Ambrosi and Crosta, 2006). In a few cases, a sudden devastating slide of the sagging block has been documented (Forcella, 1984; Brückl, 2001). Although to date sackung have not been described in a submarine setting, the available date do not exclude the possibility that Slides A and B represent sudden failures of sackung blocks. The horizontal translation of the slides A and B appear limited, a significant difference from the 1975 Kitimat event that was mainly emplaced as a debris flow that travelled more than 4 km down the fiord. However, as the toes of Slides A and B are buried, it is not presently possible to determine if either transformed downslope to a debris flow.

The structural control on major physiographic elements in the Douglas Channel–Kitimat Arm region is inferred to trend north-south (Duffell and Souther, 1964; Bornhold, 1983). Although no faults are indicated on geological maps of the area (Roddick, 1970), a series of coast-parallel foliation directions in the Cretaceous diorite are indicated in the area close to slides A and B on Hawkesbury Island. Duffell and Souther (1964) and Roddick (1970) suggested that faults offset the two sides of Douglas Channel, which is interpreted to be a structurally controlled north-south physiographic landform (Holland, 1976). The sense of motion of the inferred faults is up and to the north on the east side relative to the west side of Douglas Channel (Roddick, 1970). These geological data are compatible with the presence of a fault as interpreted from bathymetric and topographic lineations (Fig. 6). An assessment of the composition and geotechnical properties of the materials in the failure deposits would further constrain the failure mechanisms and support an assessment of their potential tsunami impacts. Similarly, a structural-geology field study of the inshore coastal zone would identify pertinent rock lithology characteristics of the slide source area and in situ strain rates and assist in determining if motion on the inferred fault structure is recent, and could have contributed to the failures in southern Douglas Channel.

Possible associated tsunami hazards

The maximum wave height and energy of tsunami waves generated by submarine failures (including the strength of the currents associated with the waves) depends on a number of slide parameters and associated factors, including slide volume, slide density, the location of the slide volume on the slope, the slope angle, and the type of failure (Fine et al., 2002). According to these authors, rigid-body slides produce much higher tsunami waves than viscous slides of the same volume. For rigid-body slides, the higher the initial slide above sea level, the higher the generated waves. For a viscous slide there is a specific slide position (elevation) which produces the largest waves. An increase in slide volume, density, and slope angle always increases the energy of the generated waves. The added volume associated with a subaerial slide entering the water is one of the reasons that subaerial slides are much more effective tsunami generators than submarine slides. Theoretical investigations and laboratory modelling indicate that tsunami wave heights are inversely related to the initial depth of the submarine slide and that subaerial slides are much more effective at tsunami wave generation than purely submarine slides.

There are several significant differences between the slides that occurred in Kitimat Arm in 1974 and 1975 and the newly identified slides failures (A and B). Whereas the former are characteristic of fluid, or viscous flow, submarine slides (Jiang and LeBlond, 1992, 1994), the latter are characteristic of rigid-body submarine slides. The former occurred close to sea level and involved subaerial components. The latter originated at depths of ~60 m or more and do not appear to have involved subaerial components (as indicated by the apparently undisturbed coastlines adjacent to these slides). Detailed tsunami modelling is required to assess the relative contributions of these factors and the overall probable impacts of tsunamis that may have resulted from slides A and B.

CONCLUSIONS

Multibeam swath bathymetric data indicate that two large submarine slides (A and B) have occurred in southern Douglas Channel. The ages of the failures can be constrained to less than 14 000 calendar years BP, but based on evidence of sediment cover, an early- to mid-Holocene age, i.e. 5000 to 10 000 years BP is favoured. The mechanisms of failure appear to involve rotational sliding of competent blocks from near the shoreline, but the degree to which the slides may have translated downslope into block glides or debris flows or other types of failures is unknown due to the burial of the bases of the slides by subsequent sedimentation.

The slides appear to have left very steep slopes at or near the shoreline susceptible to future failure events. A large incipient failure has been tentatively identified immediately adjacent to Slide A. The triggers for the failures have not been defined; however, their proximity to a potentially active fault represents one potential source. The failures probably generated tsunamis during emplacement and conditions exist for similar failures and associated tsunamis to occur along this segment of Douglas Channel in the future.

Detailed tsunami modelling based on modern numerical simulation methods has been initiated to provide an improved understanding of the generation, propagation, attenuation, and likely coastal inundation of tsunami waves that would have been created by slides A and B, or that could be generated from similar future events. Only through the development and application of this type of tsunami modelling will it be possible to gauge the level of hazard posed by the identified submarine slope failures to shore installations and infrastructure, or to devise ways to effectively mitigate the impacts of future such events.

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Canadian Hydrographic Service personnel Rob Hare and Ernest Sargeant made this analysis possible by their diligent survey work. Geological Survey of Canada colleagues, including Kim Picard, Robert Kung, and Sean Mullan are thanked for technical assistance and John Shaw, Philip Hill, and John Cassidy provided valuable reviews that improved the paper.

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