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Critical review

J. Shaw

Authors

K.W. Conway (kim.conway@canada.ca)
J.V. Barrie (vaughn.barrie@canada.ca)
Geological Survey of Canada
9860 West Saanich Road
Sidney, British Columbia
V8L 4B2

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Abstract: Very large (>60 x 10^6 m^3) submarine slope failures occur in Douglas Channel, British Columbia. Geophysical and core data suggest that these failures were episodically active between 13 ka and 11 ka radiocarbon years BP. Radiocarbon ages indicate that regionally, near continuous sedimentation has been ongoing for approximately the last 10 000 a and that this deposition has not been interrupted by sedimentary units indicative of large-scale slope failures. The new data support an inferred bedrock sagging or sackung origin for the bedrock slides that occurred along bounding faults after support by buttressing glacial ice had been removed. Faulting, observed in seismic data affecting the Late Glacial section south of the slide area, may have contributed to slope instability along the southeastern shoreline of Douglas Channel. The observed fault may have been reactivated during glacial loading and unloading or may result from an existing regional, north-south–oriented, dextral-shear stress regime.

Résumé : Des ruptures de versant sous-marines ayant mobilisé de très grands volumes (>60 x 10^6 m^3) sont survenues dans le chenal Douglas en Colombie-Britannique. Selon les données géophysiques et les données tirées de carottes de sédiments, ces ruptures se seraient produites de façon épisodique entre 13 et 11 ka en années radiocarbone BP. Les âges radiocarbone indiquent que la sédimentation à l'échelle régionale a été presque continue au cours des 10 000 dernières années environ et que celle-ci n'a pas été interrompue par le dépôt d'unités sédimentaires signalant des ruptures de versant sous-marines à grande échelle. Les nouvelles données appuient l'hypothèse voulant qu'un affaissement du substratum rocheux, ou sackung, serait à l'origine des éboulements rocheux s'étant produits le long des failles bordières suite à la disparition de la glace de glacier qui servait de contre-fort. Le jeu de failles, dont les traces sont observées dans les données sismiques de la coupe tardiglaciaire au sud de la zone de glissements, pourrait avoir contribué à l'instabilité des versants situés le long du rivage sud-est du chenal Douglas. La faille observée pourrait avoir été réactivée lors de l'ajout et du retrait de la charge glaciaire ou être le produit d'un régime existant de contraintes de cisaillement dextre, suivant une orientation nord-sud, à l'échelle régionale.

INTRODUCTION

As part of the Public Safely Geoscience Program in natural hazards research the Geological Survey of Canada undertakes studies in support of the effective management of natural hazards such as slope instability, tsunamis, and near-surface fault rupture. The municipality of Kitimat, British Columbia and the Kitimat Arm shoreline are the sites of ongoing and proposed construction for several industrial developments including multiple oil and gas infrastructure projects such as liquefied natural gas export facilities and pipeline termini for both heavy oil and natural gas. Douglas Channel is the seaward extension of this fiord system (Fig. 1) and the proposed transport corridor for the products to be exported from these facilities. In coastal areas in general, and more specifically in fiords, submarine landslides or landslides entering the water from a landward source, may cause damaging tsunamis (Mosher, 2009; Bornhold and Thomson, 2012). Some of the largest tsunamis ever recorded have occurred in fiords as a result of slope failures entering the ocean (Bornhold and Thomson, 2012). Previous studies identified large submarine bedrock slides located in Douglas Channel (Conway et al., 2012) and the age and mechanism of the slides has been regarded as important to understand and define any potential tsunami threat to local communities and infrastructure developments. Work modelling the specific failures presented in Conway et al. (2012) indicated that they could generate very large (>30 m) tsunamis were the submarine slides to be emplaced in one large rapid event (Thomson et al., 2012). Understanding the process and timing of the submarine slides is thus critical to understanding the hazard represented by any similar future failures and the processes that drive them. The tsunamigenic potential of creep or slow-sliding failures is much reduced compared to any rapidly occurring event. In addition, it is understood that slope instability and failure was much more common during the immediate postglacial time period than during recent (Holocene) time (St. Onge et al., 2004). The presence of a submarine slide in the present-day landscape is not necessarily an indication of ongoing hazard (Conway et al., 2013).

The physiographic origins of the north-south–oriented Douglas Channel are thought to have been fault controlled (Duffell and Souther, 1964; Roddick, 1970; Holland, 1976) with a sense of fault motion of up and to the north of the east side relative to the west side (Roddick, 1970). Involvement of large bedrock masses as submarine slope failures originating on the Hawkesbury Island shoreline led Conway et al. (2012) to propose that a faulted bedrock shoreline as a failure mechanism was possible, and these authors pointed to extensive north-south–oriented lineaments as evidence for such faulting.

Specific marine geoscience work has been undertaken to address issues related to previously defined slides (Conway et al., 2012, 2013; Thomson et al., 2012) to provide an assessment of the nature of these features and determine the age and origin, and to assess the possibility of slide recurrence and active faults in the vicinity. The purpose of this report is to provide a summary of the timing and character of the previously identified submarine slope failures, and present evidence of nearby faults that may have been active during the late Quaternary.

METHODS

Marine geoscience surveys were undertaken during Canadian Coast Guard Ship (CCGS) *Vector* cruise 2013007PGC in November 2013 and from CCGS *John P. Tully* in October 2014. Approximately 220 line kilometres of high-resolution seismic (sparker) data were collected using a 400 J Huntec deep-tow system during the 2013 survey (Fig. 2). An additional 500 line kilometres of hull-mounted Chirp data, operating a frequency range centred on 3.5 kHz, were collected during both cruises. Cores were collected using a Benthos split piston coring system with a 1000 kg head weight and barrel assemblies up to 12 m (for core locations *see* Fig. 2). A digital still camera (GSC-A 4000) was used to acquire seabed images in 2014 and a large volume (0.5 m^3) grab sampler was deployed during the 2013 cruise. Sparker and Chirp subbottom profile data were analyzed using Kingdom Suite software. Two multisensor core logger systems were used to analyze the cores for physical properties including gamma-ray density, magnetic susceptibility, and high-resolution image data collection. Cores were split and visually described and accelerator mass spectroscopy radiocarbon dating of selected samples was undertaken at Beta Analytic Inc. (Miami, Florida). Ages are presented and discussed in conventional radiocarbon years BP (BP). A reservoir correction of 800 a was applied to shell dates (410 global reservoir and a 390 year local marine reservoir Delta-R correction). Conversion of radiocarbon years to calendar years, required for assessing rates of geological processes, was accomplished using the method of Fairbanks et al. (2005).

RESULTS

Sedimentary units and geochronology

The sedimentary sequences recovered in cores from Douglas Channel comprised three units (Fig. 3). The lowermost unit was laminated to massive grey clay with minor sand and gravel that was up to 8 m thick (2013007PGC cores). The sand grains and lithoclasts of variable lithology were matrix supported in the clay. Unit 1 was dated to 10 110 ± 30 BP to 10 950 ± 40 BP (Fig. 2; Table 1). In addition, one anomalously young age of 4630 ± 30 was obtained in this unit. Overlying the gravel clay unit an interbedded silty clay to variably coloured clay (unit 2), up to 1 m thick, was dated from 10 470 BP to 10 200 BP. The clay beds vary from 10 cm to 40 cm in thickness and are burrowed in some

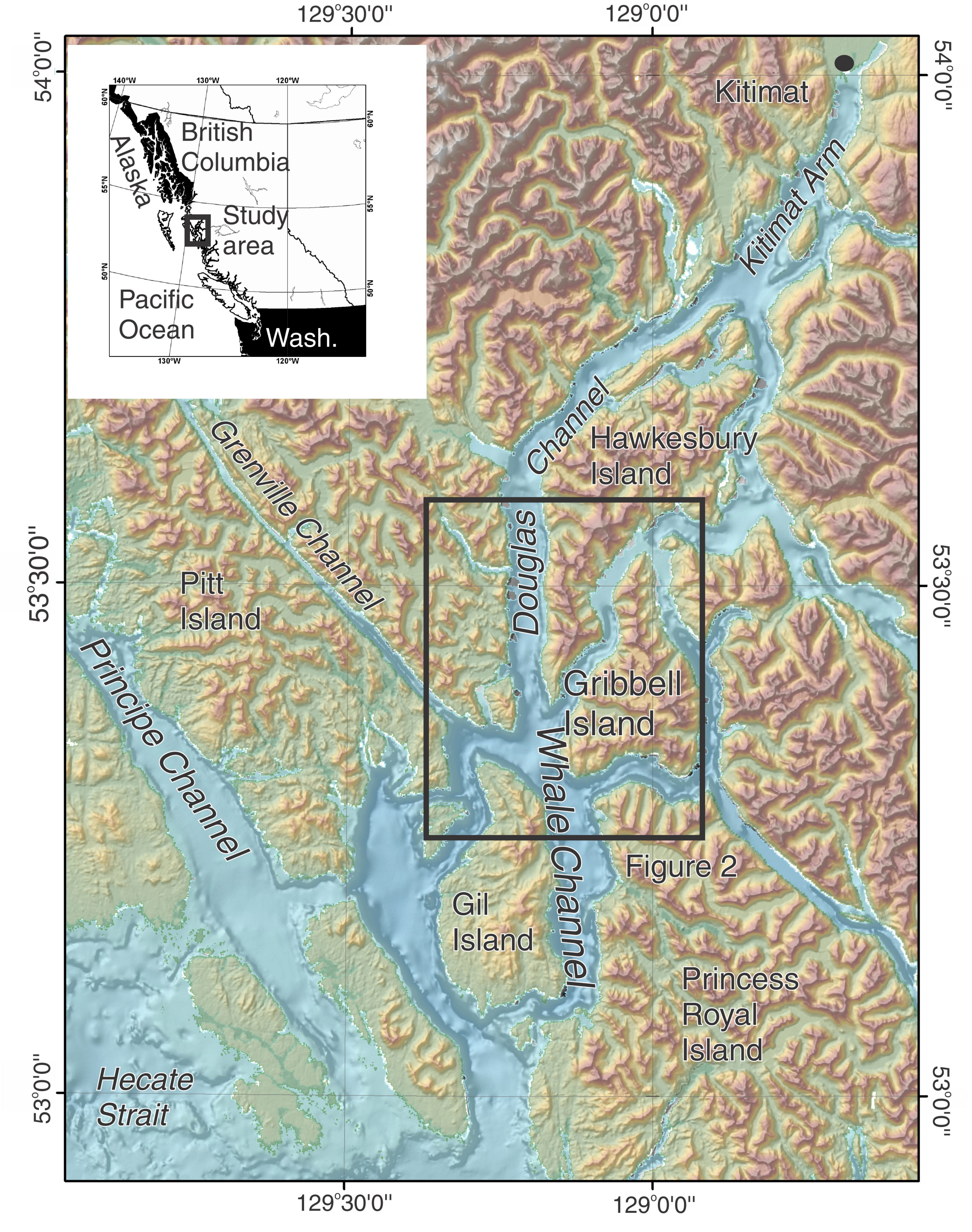

Figure 1. Location of Douglas Channel, Kitimat, Kitimat Arm, and Hawkesbury, Gil, and Princess Royal islands. Study area is indicated. Wash. = Washington

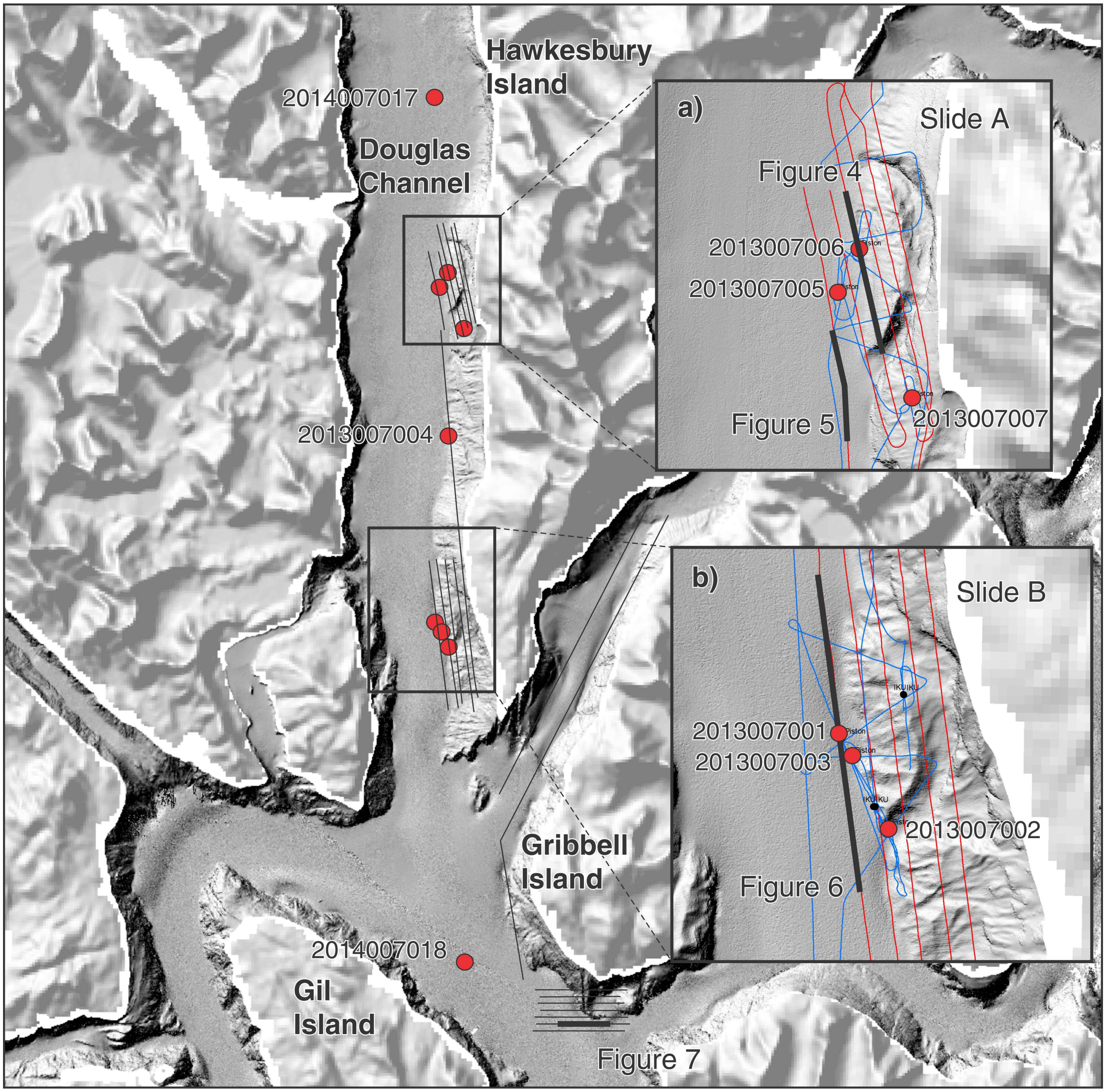

Figure 2. Douglas Channel study area. Insets show location of cruise 2013007 cores and figures relative to **a)** slide A and **b)** slide B. Huntec deep-tow seismic profiles are shown in red and Chirp subbottom profiles are shown in blue.

intervals. The clay units are blue-grey to blue-green and are a different colour than the bracketing grey to dark grey mud units.

The uppermost unit (unit 3) is an olive, soft, massive bioturbated silt that is up to 5.5 m thick (Fig. 3). Each core site has a variable unit 3 sediment thickness, but none show discrete bedding planes or laminations in the unit. The age range in unit 3 is from 4250 ± 30 BP at 144 cm depth in core 2014007018 to 10 230 ± 30 BP at 429 cm depth in core 2013007003. Radiocarbon ages indicate that the uppermost unit sediment has been accumulating in the channel at different rates. The range of ages indicates sedimentation throughout much of the Holocene.

At two sites (cores 2013007006 and 2013007007) proximal to the slides (Fig. 2) no recent sediments have accumulated and only unit 1 (glaciomarine) gravelly and laminated grey clay was recovered at these sites. Two cores (2014007017 and 2014007018) distal to the large slides, were collected to examine regional sedimentation patterns and these recovered a very similar sequence with similar radiocarbon ages and estimated sedimentation rates (0.7 mm/a and 0.9 mm/a)

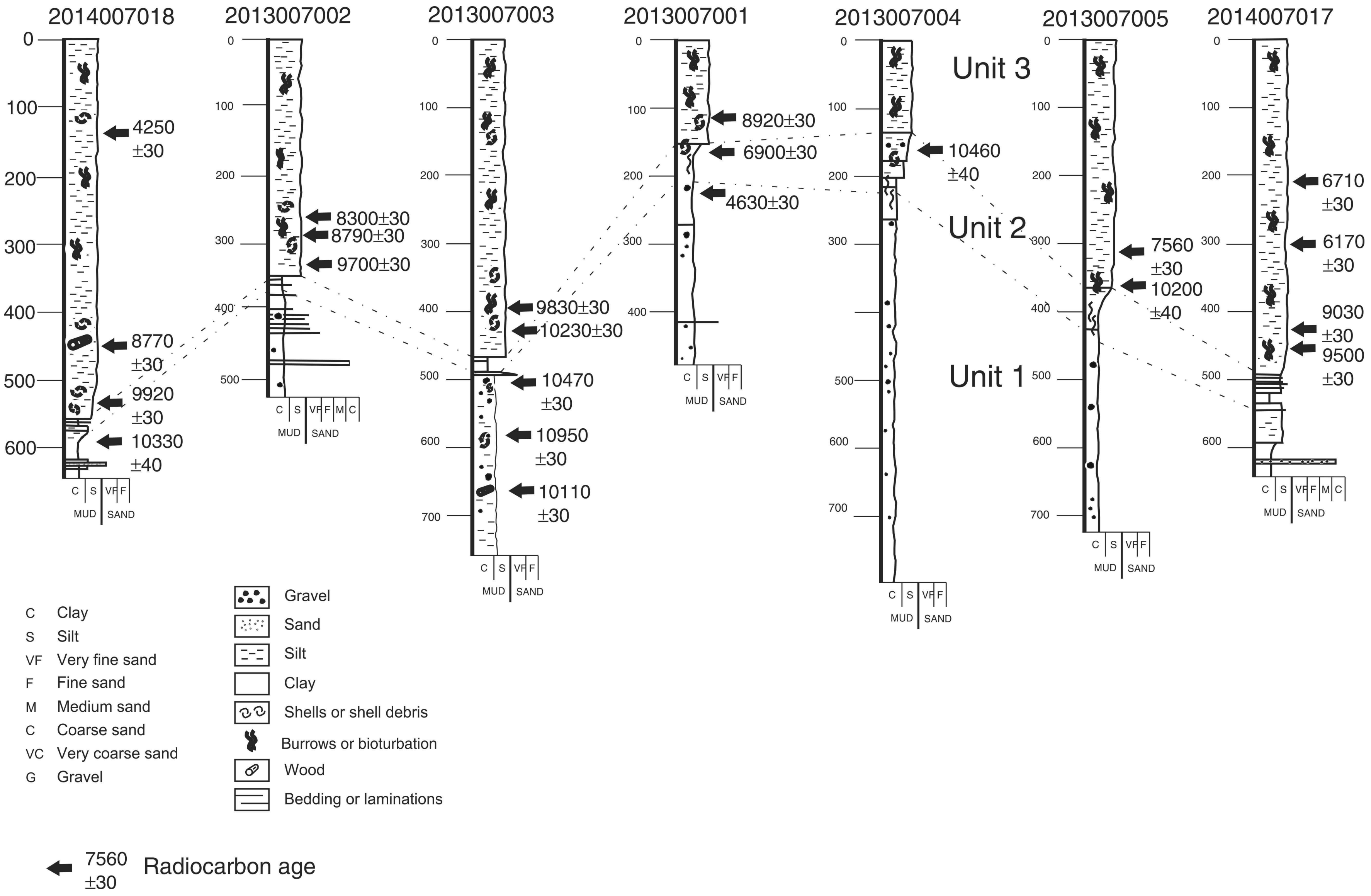

Figure 3. Douglas Channel piston core lithology, ages, and correlation. *See* Figure 2 for locations.

Table 1. Radiocarbon ages of samples from Douglas Channel piston cores. A local marine reservoir correction (Delta-R = −390 a) and global reservoir correction (−410 a) was applied to shell dates for a total radiocarbon marine reservoir correction of −800 a.

Core number	Depth in core (cm)	Beta Analytic Inc. lab number	Material	Conventional radiocarbon age (BP)	Calendar age* (BP)
2013007001	113	384642	Shell	8920 ± 30	10096 ± 87
2013007001	156	384643	Shell	6900 ± 30	7714 ± 33
2013007001	226	384644	Wood	4630 ± 30	5362 ± 55
2013007002	266	384645	Shell	8300 ± 30	9315 ± 58
2013007002	282	384646	Shell	8790 ± 30	9798 ± 81
2013007002	340	384647	Shell	9700 ± 30	11160 ± 34
2013007003	394	384648	Shell	9830 ± 30	11229 ± 15
2013007003	429	384649	Shell	10230 ± 30	11977 ± 62
2013007003	502	384650	Shell	10470 ± 30	12415 ± 60
2013007003	581	384651	Shell	10950 ± 40	12834 ± 46
2013007003	667	384652	Wood	10110 ± 30	11729 ± 77
2013007004	160	384653	Shell	10460 ± 40	12393 ± 81
2013007005	311	384654	Shell	7560 ± 30	8377 ± 16
2013007005	363	384655	Shell	10200 ± 30	11922 ± 73
2014007017	208	405125	Shell	6710 ± 30	7576 ± 19
2014007017	301	405126	Wood	6170 ± 30	7065 ± 60
2014007017	432	407367	Shell	9030 ± 30	10209 ± 14
2014007017	453	405127	Shell	9500 ± 30	10755 ± 80
2014007018	144	405128	Wood	4250 ± 30	4832 ± 19
2014007018	450	405129	Wood	8770 ± 30	9753 ± 72
2014007018	536	405130	Shell	9920 ± 30	11292 ± 37
2014007018	592	407368	Shell	10330 ± 40	12124 ± 78

*Fairbanks et al. (2005) calibration algorithm

during the deposition of the uppermost unit. These cores also record no stratified events in the unit 3 (Holocene) portion of the recovered section. Multisensor core-logger data shows that the uppermost unit is massive and unstratified, consistent with uninterrupted bioturbated sedimentation.

Sedimentary sequence

The basal unit (unit 1) is related to the late stages of deglaciation of Douglas Channel. Abundant gravel, occurring as isolated clasts, represents ice-rafted debris. Laminae and coarse sand beds probably represent glaciomarine sediment pulses and underflow deposition from turbid meltwater. The radiocarbon ages obtained on shells and wood in this unit are consistent with a late deglacial sequence deposited from about 11–10.5 ka BP.

The stratified clay unit, unit 2, overlying unit 1 is a well stratified, somewhat anomalous unit because of the variable colour in the well sorted clay beds. The radiocarbon ages of 10.5 ka BP to about 10.2 ka BP, grey sediment colours, and only slightly bioturbated appearance of the unit indicate that it records the terminal phase of deglaciation, before the onset of true Holocene climatic and oceanographic conditions.

The uppermost sedimentary unit (unit 3) is Holocene and is typically pervasively bioturbated, structureless, and olive. The recent (Holocene) sediment accumulation rate is variable throughout the Douglas Channel due to variability in the strength of tidal currents and to geostrophic effects that deflect currents and impact deposition in the fiord. At some locations, the Holocene sediments are up to 60 m thick, but elsewhere, where currents are focused, no sediment has accumulated and the seabed may be subject to localized scour. At all core sites recent sedimentation rates in unit 3 were found to be less than 1 mm/a and sedimentation was much less in the approaches and overlying slides A and B. Core data in all cases indicate that the fine massive Holocene sequence (Table 1) was not interrupted by graded sandy or stratified events that would imply more energetic depositional events such as would be deposited by turbidite sequences or debris flows.

Characteristics of glaciomarine sequence impacted by slides A and B

The deformation caused by the emplacement of slide A as imaged in subbottom profile data indicate impact along a deforming front of stratified glaciomarine sediments (unit 1). Folded and deformed glaciomarine sediments parallel the leading edge of the slides. The folds appear as gentle anticlines from 100 m to 300 m wide with some evidence of brittle deformation forming the boundaries of the poorly developed folds that are up to 50 m thick in section (Fig. 4). The folds and deformed intervals do not appear as one deformed unit, but as several that form a deformed sequence overlying the bedrock landslide body. Intervals of localized folding are capped in some cases by debris flows. Where the profile data cross the boundary of the slide blocks, a clear brittle deformation of the glacial section may be seen at slide A (Fig. 5). The deforming front is also draped and then subsequently the upper sequences were folded and deformed successively at slide B (Fig. 6). This also implies that the slides were not a rapid instantaneous event during one massive dislocation. Brittle deformation along a set of faults is capped off by a sequence at slide B that shows subsequent events of draping and folding followed by debris-flow activity (Fig. 6). The draping of the glacial sequence by the later units that are not deformed includes the uppermost part of the glaciomarine section.

Identification of late Quaternary faults

Three areas show evidence of active faulting in the seismic sections. An obvious offset in the glacial sediments is seen at one location (Fig. 5) that forms the southern edge of the area of impact of slide A. This represents the southern edge of the slide block where there is an interface with the undeformed glaciomarine unit. Farther south, slide B is seen to be bounded by significant offsets that penetrate from the bedrock to the overlying glaciomarine section (Fig. 6) where the offset is approximately 60 m. This faulted block represents the detachment zone of the bedrock block that has dislocated overlying sediments in a brittle fashion. The available data does not image the base of the fault, which is presumably deeper in the bedrock unit.

At the south end of Gribbell Island subbottom profile data suggests that faulted and deformed sediments occur in the glaciomarine section beneath the seafloor (Fig. 7). The deformation coincides with a well defined, previously identified lineament that bisects Gribbell Island (Conway et al., 2012). The deformation of the section is postdepositional and not a draping relationship of reflectors to an underlying hard surface. The identified fault does not completely penetrate the glacial section and the Holocene unit is also not deformed (Fig. 7). The top of the affected portion of the section has been eroded and this truncated zone underlies subsequent uneroded and undeformed glacial and Holocene sediments. The faulted sequence has limited expression of vertical offset.

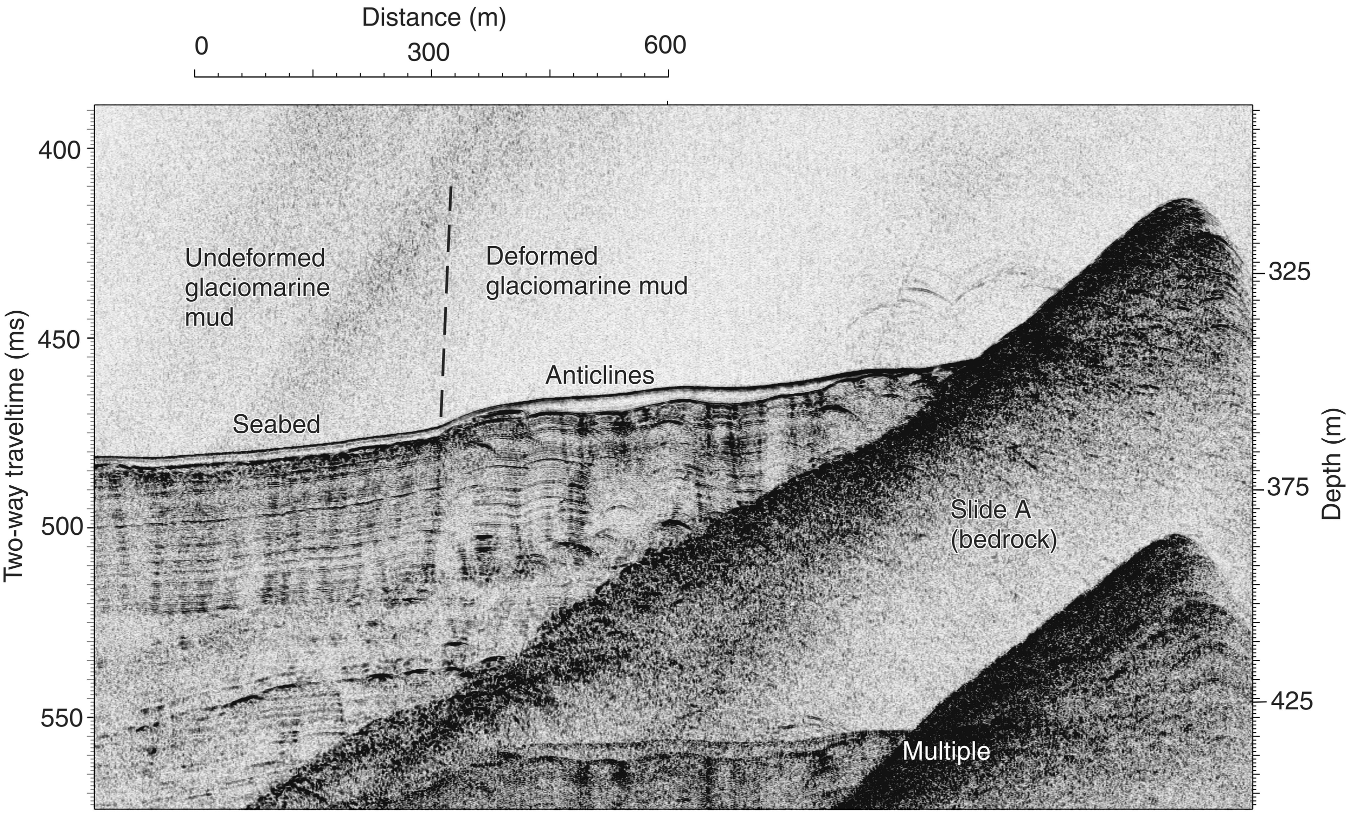

Figure 4. Huntec DTS profile showing stratified and deformed glaciomarine sequence at slide A. *See* Figure 2 for location.

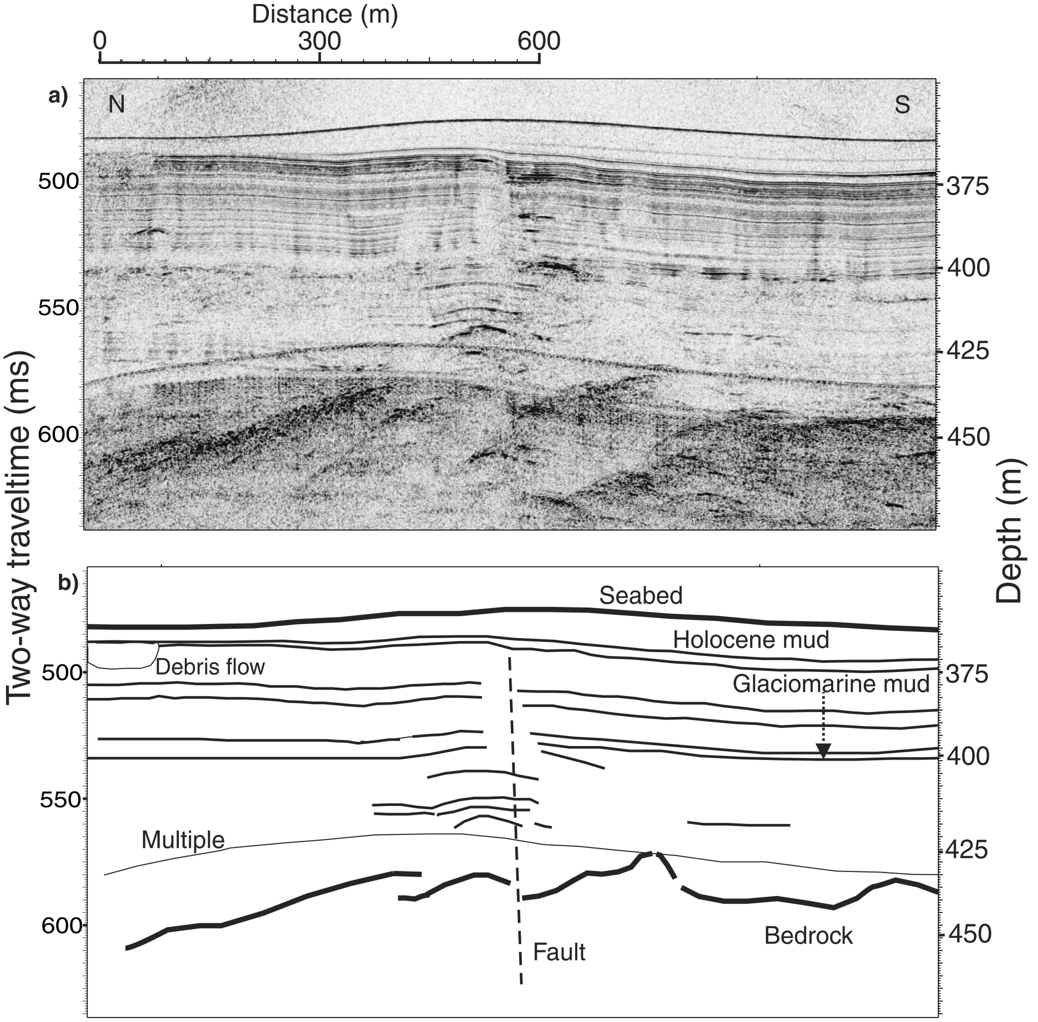

Figure 5. High-resolution subbottom profile adjacent to slide A; **a)** Huntec DTS geophysical profile and **b)** interpreted section showing faulted sediments. *See* Figure 2 for location.

DISCUSSION

Slope instability: slides A and B

The large slides in Douglas Channel, slides A and B, were emplaced during and after deglaciation of the Douglas Channel. High-resolution subbottom profile data consistently show deformation of Late Glacial sediments, whereas the Holocene sediments are not affected. Timing of the slides would have had to have been after ice had left the Douglas Channel after 13 ka BP (Bornhold, 1983), but well before the onset of Holocene conditions. The uppermost part of the glaciomarine section is not affected by the bounding faults related to slides A and B. Ice had receded to the Kitimat Arm by about 11.5 ka BP (Bornhold, 1983), and this would have corresponded to approximately the age of the faulted or undeformed glaciomarine section that caps the deformed and faulted slide section. The age proposed for the active period of the slides would thus be estimated at between 13 ka BP and 11.5 ka BP.

The deformation in the glacial and glaciomarine section overlying the bedrock slides could be interpreted as intervals or pulses of deformation as the sliding blocks were pushed into the deforming stratified pile. The nature of the deformation would be the expected result of incremental successive thrust events that dislocated the glacial section into small folds bracketed by local, small-scale brittle deformation. If one event were to catastrophically impact such a well stratified sequence, it would be anticipated that a thrust plane or planes would develop that would incorporate and stack stratified sediments as the sequence was sheared and transported into the deeper water of the fiord by the slide mass. Contrary to this, the relatively gentle folds and discontinuous deformation of the section is observed. No distal chaotic mass is associated with the periphery of the slides as would be anticipated in the event of one massive movement. Massive intervals are associated with the shoreward limit of the deformed zone, however.

Slides A and B were initially interpreted to be rotational slides that probably failed in a rapid fashion (Conway et al., 2012) or as bedrock sagging or sackung features that may also have been emplaced quite rapidly. Sackungen are

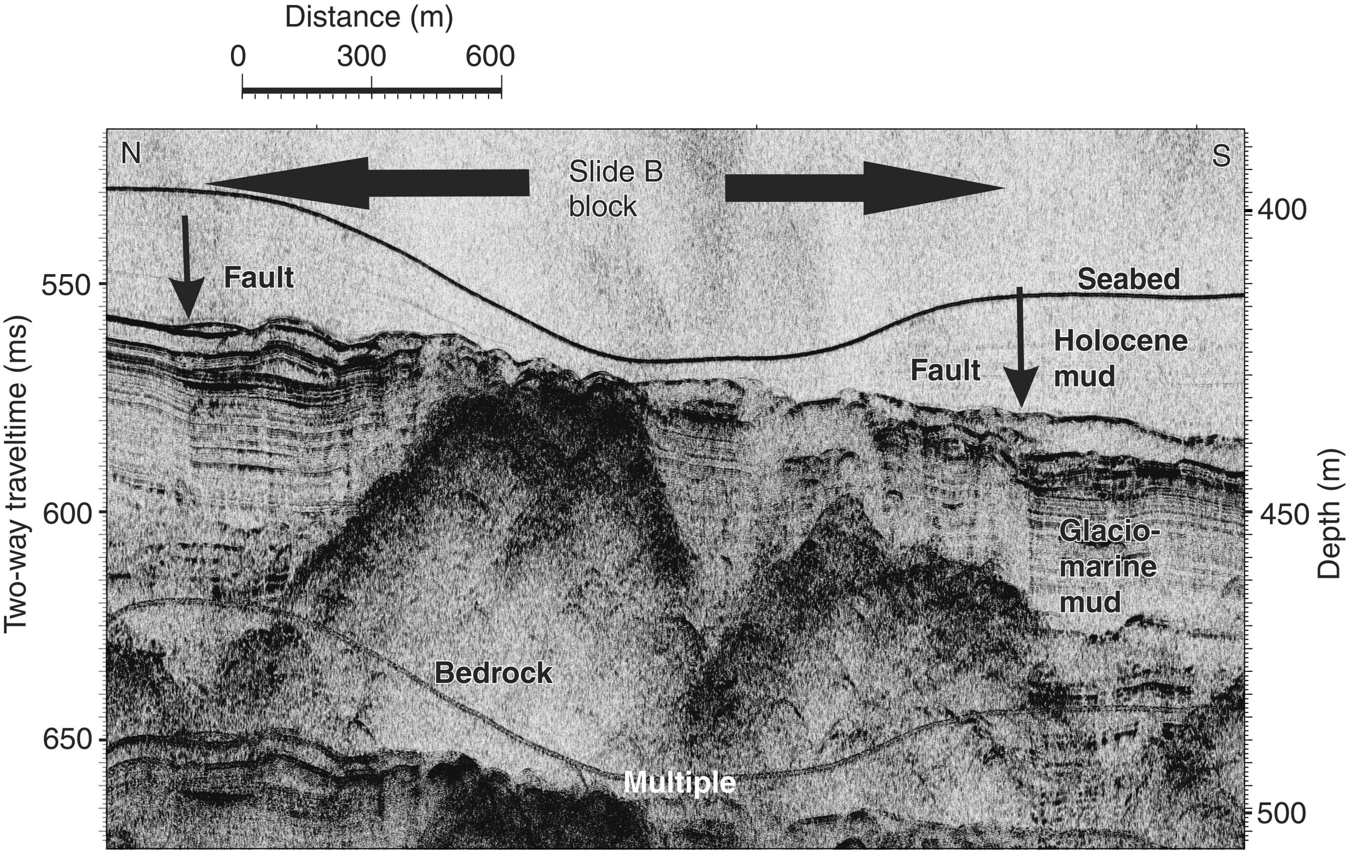

Figure 6. High-resolution subbottom profile adjacent to slide B showing faulted strata below the Holocene and Late Glacial section. *See* Figure 2 for location.

large bedrock gravitational sliding features of mountainous regions that are common in tectonically active alpine areas. These new data suggest that slides A and B were emplaced in a punctuated fashion and not catastrophically. The deformation observed in the glaciomarine sediments peripheral to the slide blocks is consistent with an interpretation of creep as opposed to catastrophic failure.

Sackungen are well described on land, but have not been identified in a submarine setting. These bedrock sagging features are found in alpine areas globally including California (McCalpin and Hart, 2002), Italy (Ambrosi and Crosta, 2006), Alaska (Li et al., 2012), and on land in British Columbia (Schwab and Kirk, 2002). Whereas bedrock sagging is normally considered to be a slow creep process, serious landslide hazards related to such bedrock instability may still exist (Forcella, 1984). Dating of sackungen rates of sliding on land is normally accomplished by boreholes collected in the back scarp of the slide area, which is typically infilled during development of the slide. Typical rates of movement measured on land at sackungen are a few millimetres to a few centimetres per year (Forcella, 1984). In the case of the Douglas Channel slides, the back scarps are not infilled so this method of dating is not possible. The area is nondepositional due to high ambient seabed tidal currents keeping the slide masses swept clear of recent sediments. Slides A and B have downslope dislocations of 300–400 m (Thomson et al., 2012). If slides A and B represent sacking-style deformation then 300–400 m of movement would have been accommodated between about 13 000 BP and 11 000 BP (15 140 cal years BP and 12 900 cal years BP) when ice receded from outer Douglas Channel landward to Kitimat Arm (Bornhold, 1983), and before the latest glaciomarine sediments were deposited. This would give an estimated slide movement rate of about 13–17 cm/a. The typical appearance of sackungen on land is somewhat different than these examples as normally an uphill-facing scarp is the principal indication of the structure. In addition the developing upslope gap or head scarp is normally infilled to some extent by slopewash and other processes. In the marine examples in the present study, a deep and vertical head scarp remains. The sackung style of sliding and bedrock deformation has not been observed in other British Columbia fiords examined (Conway et al., 2013).

Inset smaller slides located at the top and sides of slide A (Conway et al., 2012) were found to be composed of gravelly grey clay inferred to be glaciomarine. The small glaciomarine slides are exposed at the seabed and dating of the identified slides could thus only be constrained

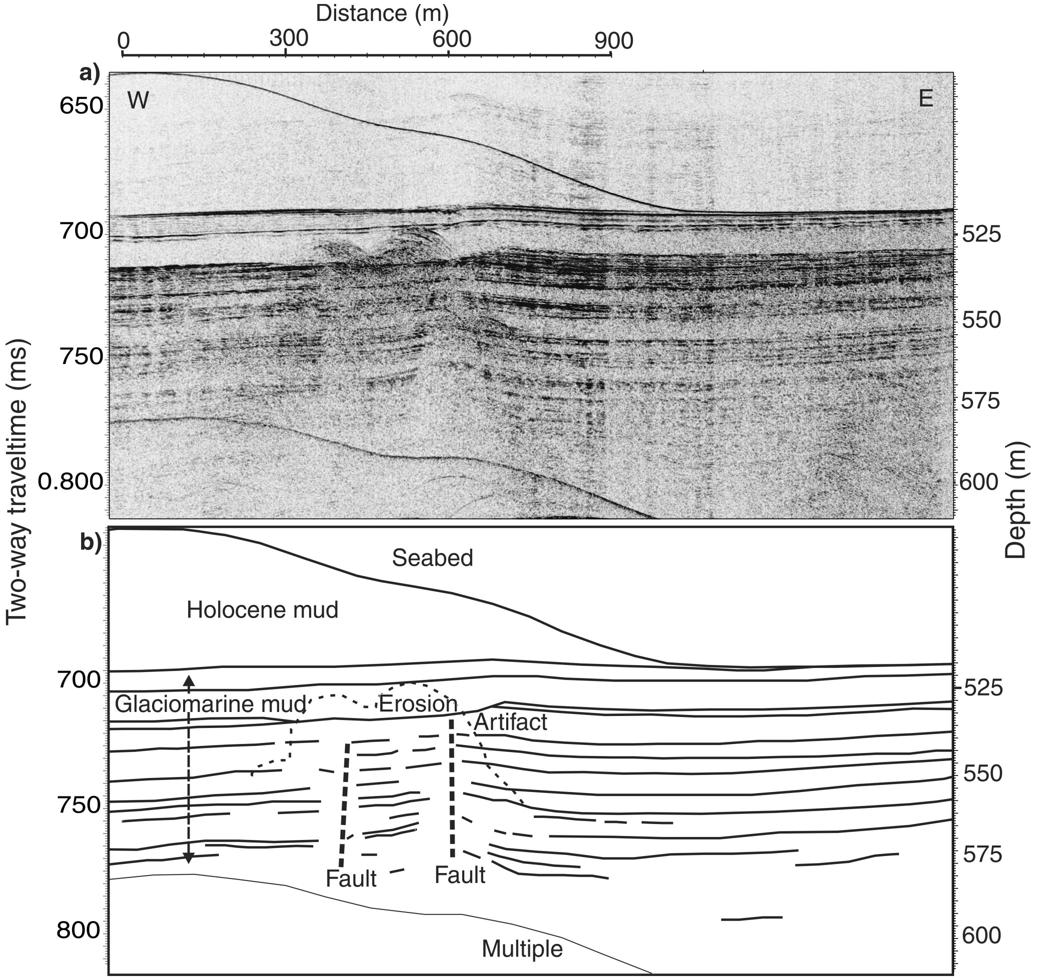

Figure 7. High-resolution subbottom profile south of Gribbell Island; **a)** Huntec DTS geophysical profile and **b)** interpreted section showing faulted sediments. *See* Figure 2 for location.

generally to a postglacial timing. These slides may thus originate from the initial activity of the sagging block during Late Glacial time or be related to later slope instability in the Holocene. Slides derived from the perimeter of the bedrock slides are hosted in glaciomarine sediments and the age of these smaller features is thus problematic as the area proximal to the slides is nondepositional today due to high tidal current velocities. Other evidence of instability may include unit 2, which is a somewhat anomalous clay interval. This unit is similar in appearance and stratigraphic position to clay units that record outburst flood events in southern British Columbia shelf and fiord areas (Conway et al., 2001; Blais-Stevens et al., 2003). Pollen and microfauna analysis would be required to determine if clay intervals in this section were related to these types of events, however.

Recent faulting

Examples of brittle deformation offsets in the Late Glacial sediments is seen at three locations in the deep-tow high-resolution data acquired. The offsets indicate about 10 m of vertical offset at one site adjacent to and offshore of the southern extension of slide A and at slide B (Fig. 5, 6). One other area where faulting may affect glacial sediments is at the south end of Gribbell Island, where evidence for faulting is seen. The faulting adjacent to slides A and B is related to the bedrock sagging feature and is directly offshore of the large landslides. The deformation of the glacial section related to emplacement of the bedrock masses is apparent at both slides. The sediments here down to the base of the resolved section record a brittle style of deformation related to faulting. The style and orientation of the faults suggests that these slides may be related to synthetic or normal faults as these are oriented at a roughly 30° to 45° angle to the inferred orientation of the main system of north-south faults. The orientation of lines is critical to properly image the fault traces at these locations. The nature of the shallow faults combined with the geomorphology of the channel and shorelines suggest a distributed style of deformation may be present in a broadly deformed zone.

The identified Gribbell Island fault trace shows very little vertical offset. If this fault were part of a strike-slip system of faults, vertical offset would not necessarily be expected. The alignment of the Gribbell Island Fault with the previously described (Conway et al., 2012) lineament that bisects Gribbell Island is also seen in multibeam data south of the island. These independent data sets are evidence that a north-trending fault existed that was possibly reactivated by ice-sheet dynamics during the last glaciation. Alternately, the fault is related to the modern stress regime. Geodynamics work using precision GPS monitoring has determined that the north coast region is being subjected to broadly north-south–directed dextral shear (Mazzotti et al., 2003, 2011), which is opposite to the sense of motion (left lateral strike-slip) inferred for Douglas Channel. These interactions are not mutually exclusive; however, any left-lateral motions must be accommodated by block rotation with the larger right-lateral shear tectonic environment.

CONCLUSIONS AND FUTURE WORK

The Douglas Channel submarine slides A and B were emplaced during deglaciation of the area in an intermittently sliding or creeping fashion over a period of several hundred years to possibly as long as 2200 a. These slides thus represent bedrock sagging features or sackungen that were a consequence of debuttressing of steep slopes during deglaciation. Radiocarbon dating of recent sediments indicates that they were either inactive or only slowly creeping during the last 10 000 a. Faults detected in the subbottom seismic data are evidence of bedrock structural control of detached blocks that form the seafloor along the eastern Douglas Channel shoreline. It is possible that glacial loading and unloading would have initiated reactivation of these faults. Future work will include installation of satellite RADAR reflectors at points along the fiord shoreline to determine if ongoing motion is indicated for the slides. In addition, light detection and ranging surveys (LIDAR) will be undertaken on Hawkesbury and Gribbell islands to examine slide and lineament, and possibly fault-scarp traces. Repeat multibeam surveys will be undertaken to determine if ongoing slope instability is detectable. Examination of the large slide blocks will be done using a remote-operated vehicle, and installation of a seabed-monitoring cable observatory system will help determine the nature of seabed slope instability processes.

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