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Résumé de l'article

Vingt-quatre nouvelles dates au ^{14}C provenant de carottes sédimentaires de bassins isolés, d'excavations, de coupes naturellement exposées et archéologiques permettent de cerner les changements du niveau marin relatif depuis la dernière glaciation dans la partie nord du détroit de Géorgie, en Colombie-Britannique. Le niveau marin relatif a rapidement passé de 150 m à 45 m d'altitude entre 11 750 et 11 000 ans BP (13 750-13 000 cal. BP), le taux d'abaissement ayant ralenti par la suite. L'émersion initiale rapide correspond à la fin de la sédimentation glaciomarine distale qui accompagnait le retrait du front glaciaire. Un bas niveau de quelques mètres sous le niveau actuel a pu s'instaurer durant l'Holocène inférieur, jusqu'en 2000 ans BP. Au début, le soulèvement isostatique a accusé un retard de quelques siècle sur celui de la zone du détroit à 80 km plus au sud. Le bas niveau de la partie nord du détroit est survenu plus tard et fut moins prononcé. Les données indiquent un enfoncement isostatique de type exponentiel avec des constantes de désintégration de 500 et de 2600 ans ^{14}C. Le taux le plus rapide correspond à une viscosité du manteau terrestre d'environ 10^{19} Pa s, ce qui concorde avec les résultats de la modélisation glacio-isostatique. Le taux de soulèvement glacio-isostatique actuel résultant de l'inlandsis de la Cordillère s'établit à environ 0,25 mm/a. Ce taux ne peut contrer les effets du rehaussement du niveau marin prévu pour cette région en raison des faibles mouvements de la croûte terrestre qui y sont envisagés.

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RELATIVE SEA-LEVEL CHANGE IN THE NORTHERN STRAIT OF GEORGIA, BRITISH COLUMBIA*

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ABSTRACT Twenty-four new radiocarbon dates from isolation basin cores, excavations and natural exposures, and an archeological site, constrain relative sea-level change since the last glaciation in the northern Strait of Georgia, British Columbia. Relative sea level fell rapidly from about 150 m elevation to 45 m elevation from 11 750 to 11 000 BP (13 750 to 13 000 cal BP), then its rate of fall slowed. The initial rapid emergence began soon after the transition from proximal to distal glaciomarine sedimentation, when the glacial front retreated from the Strait of Georgia and the Earth's surface was unloaded. A sea-level lowstand a few metres below present-day sea level may have occurred in the early Holocene, but sea level was near its present level by 2000 BP. Sea-level change in the northern Strait of Georgia lagged the mid Strait of Georgia, 80 km to the south, by a few hundred years during initial emergence. The lowstand in the northern strait was later and probably shallower than in the mid strait. Isostatic depression inferred from the sea-level observations can be fit with two decaying exponential terms with characteristic decay times of 500 and 2600 years. The faster decay time corresponds to a shallow mantle viscosity of about 10^{19} Pa s, consistent with previous glacio-isostatic modelling. The present-day crustal uplift rate from the residual isostatic effects of the Cordilleran Ice Sheet is about 0.25 mm/a. Crustal uplift is not expected to significantly ameliorate projected sea-level rise in the mid and northern Strait of Georgia because present-day vertical crustal movements are inferred to be small.

RÉSUMÉ *Changement du niveau marin relatif de la partie nord du détroit de Géorgie, Colombie-Britannique*. Vingt-quatre nouvelles dates au ^{14}C provenant de carottes sédimentaires de bassins isolés, d'excavations, de coupes naturellement exposées et archéologiques permettent de cerner les changements du niveau marin relatif depuis la dernière glaciation dans la partie nord du détroit de Géorgie, en Colombie-Britannique. Le niveau marin relatif a rapidement passé de 150 m à 45 m d'altitude entre 11 750 et 11 000 ans BP (13 750-13 000 cal. BP), le taux d'abaissement ayant ralenti par la suite. L'émersion initiale rapide correspond à la fin de la sédimentation glaciomarine distale qui accompagnait le retrait du front glaciaire. Un bas niveau de quelques mètres sous le niveau actuel a pu s'instaurer durant l'Holocène inférieur, jusqu'en 2000 ans BP. Au début, le soulèvement isostatique a accusé un retard de quelques siècle sur celui de la zone du détroit à 80 km plus au sud. Le bas niveau de la partie nord du détroit est survenu plus tard et fut moins prononcé. Les données indiquent un enfoncement isostatique de type exponentiel avec des constantes de désintégration de 500 et de 2600 ans ^{14}C. Le taux le plus rapide correspond à une viscosité du manteau terrestre d'environ 10^{19} Pa s, ce qui concorde avec les résultats de la modélisation glacio-isostatique. Le taux de soulèvement glacio-isostatique actuel résultant de l'inlandsis de la Cordillère s'établit à environ 0,25 mm/a. Ce taux ne peut contrer les effets du rehaussement du niveau marin prévu pour cette région en raison des faibles mouvements de la croûte terrestre qui y sont envisagés.

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INTRODUCTION

Sea-level change provides a fundamental control on the paleogeography of coastal areas, and thus helps to determine habitat distribution, including areas available for human settlement (Hetherington *et al.*, 2003). The development of coastal landforms is intimately related to sea level (Hart and Long, 1996), and the engineering properties of sediments are affected by the history of subaerial exposure and marine inundation. Projections of future crustal movements and sea-level change are aided by information on past sea-level change. Knowledge of sea-level history consequently benefits coastal and marine planning and engineering efforts.

Sea level in coastal British Columbia rapidly dropped from a late-Pleistocene highstand immediately following deglaciation to a minimum level below the present-day ocean surface in the early Holocene (Mathews *et al.*, 1970; Clague *et al.*, 1982). Sea level then gradually recovered to the present elevation in concert with the rise in global, or eustatic, sea level. The early sea-level fall is due to postglacial rebound, in which the land rose in response to the removal of the ice load.

Sea-level histories developed recently for Victoria and the eastern Strait of Juan de Fuca (James *et al.*, 2002; Mosher and Hewitt, 2004) and the mid-Strait of Georgia (Hutchinson *et al.*, 2004a) follow this pattern. Although less constrained, the early sea-level history of the Queen Charlotte Islands and adjacent continental shelf areas also features sea-level fall (Barrie and Conway, 2002a) to a pronounced sea-level low (Josenhans *et al.*, 1997), possibly related to a crustal forebulge generated by the retreating ice sheet (Luternauer *et al.*, 1989).

Computer modelling of sea-level change provides information on the rheology (flow properties) of the Earth's mantle. For southern British Columbia, the modelling indicates a low-viscosity mantle, but with limited available data, vertical and horizontal variations in mantle viscosity were not discriminated (James *et al.*, 2000; Clague and James, 2002). Viscosity values inferred from modelling of sea-level observations have been used in tectonic models to explain features of the tectonically active Cascadia subduction zone (Wang *et al.*, 2001). Postglacial rebound modelling also provides estimates of the present-day residual crustal motion due to the melting of the ice sheets. More sea-level observations would improve these estimates of mantle viscosity and residual crustal motion.

To address these issues, systematic efforts have been made to improve the observational record of sea-level change in southern coastal British Columbia. The first results provided new information for Victoria and Vancouver (James *et al.*, 2002) and have generated a well-constrained sea-level history for mid-Strait of Georgia (Hutchinson *et al.*, 2004a). Here we present a complementary study for the northern Strait of Georgia and briefly discuss the implications for mantle flow properties and projections of future sea-level change.

GLACIAL HISTORY AND TECTONIC SETTING

GLACIAL HISTORY

During the last ice age, the Cordilleran ice sheet nucleated at high altitudes in the Coast Mountains. Ice accumulated, flowed down, and spilled out onto coastal lowlands (Clague, 1989). The ice front advanced south along the Strait of Georgia, reaching its maximum extent around 14 000 BP in southern Puget Sound (Fig. 1). Peak ice thicknesses in the Strait of Georgia were about 2 km (James *et al.*, 2000). Vancouver Island was covered with ice, and ice flowed out the Strait of Juan de Fuca. Retreat was rapid, with the southern Strait of Georgia deglaciating earlier than 12 000 BP. Present-day ice cover was established by about 10 000 BP (Clague and James, 2002).

TECTONIC SETTING

The region comprises the northern part of the Cascadia subduction zone, where the oceanic Juan de Fuca plate subducts beneath North America at about 4 cm/a. Farther north, the Explorer microplate underthrusts northern Vancouver Island, although at reduced rates compared to the Juan de Fuca plate. Inland, the Cascades volcanic chain indicates dehydration of the subducting oceanic lithosphere and partial melting of the overlying mantle. The subducting oceanic lithosphere is relatively young, aged 6 Ma at the trench, and consequently the shallow mantle beneath the oceanic lithosphere is expected to be relatively hot and to have a low viscosity. The Cascadia subduction zone is tectonically active and is a region of enhanced earthquake hazard. Geodetic observations measure the crustal strain leading to earthquakes, but must be corrected for postglacial rebound and non-tectonic processes.

The study area is located at the northern end of the Strait of Georgia (Figs. 1-2). It lies in the Cascadia forearc, above and near the northern limit of the subducted Juan de Fuca Plate. Because heat flow values are relatively low in the forearc (Hyndman and Lewis, 1995), crustal temperatures are also expected to be low. Consequently, in the Strait of Georgia, it is probable that the entire thickness of overriding continental lithosphere (60-70 km) responded elastically, and not viscously, to the bending and flexure induced by the Cordilleran ice sheet.

METHODS

SAMPLE COLLECTION

As noted by Hutchinson *et al.* (2004a), isolation-basin coring is a preferred method for obtaining high-resolution information on sea-level change. As sea level changes, an isolation basin undergoes a transformation in the character of sedimentation when it passes through the marine-freshwater transition. In coastal British Columbia, a typical isolation basin is a lake, marsh, or bog located below the limit of glaciomarine inundation. An ideal basin has a rocky sill that has not experienced significant erosion; in early deglacial times, when sea level was high, it underwent glaciomarine and marine deposition, then, as sea-level dropped, it emerged from the ocean and freshwater sedimentation commenced.

Shallow marine basins can also record the time of sea-level lowstands, when sea level dropped below present. In exceptional circumstances, a core may recover evidence of the initial marine deposition when sea level was high, the transition from marine to freshwater conditions when sea level dropped below

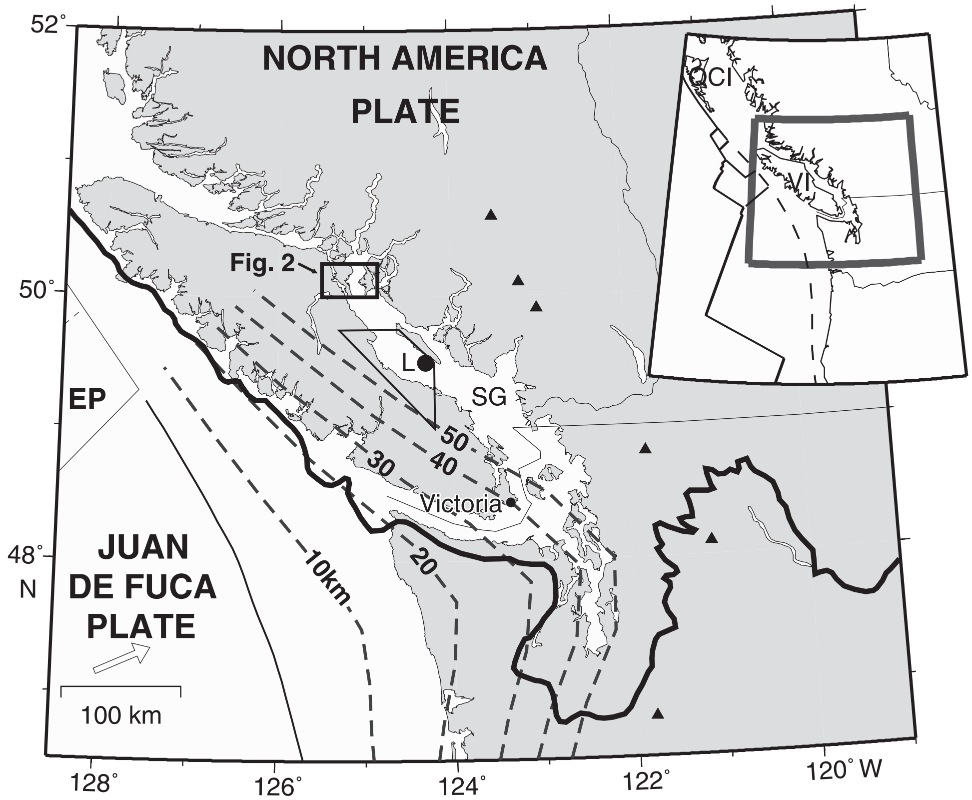

FIGURE 1. Location map for the northern Cascadia subduction zone, where the Juan de Fuca plate subducts beneath western North America (after James *et al.*, 2000). Dashed contour lines show the depth to the top of the subducting oceanic lithosphere (Fluck *et al.*, 1997). Thick solid line shows the maximum extent of the Cordilleran Ice Sheet around 14 000 BP (Clague, 1983). The study region is located at the northern boundary of the Strait of Georgia (SG), and detail is given in Figure 2. L is Lasqueti Island, and the quadrilateral shows the region for which a sea-level curve was developed for mid-Strait of Georgia (Hutchinson *et al.*, 2004a). Filled triangles are volcanic centers. (inset) Location map of western North America. QCI is Queen Charlotte Islands and VI is Vancouver Island.

Carte de localisation de la zone de subduction de Cascadia-nord, où la plaque Juan de Fuca *plonge sous la plaque nord-américaine occidentale (d'après James* et al.*, 2000). Les lignes pointillées montrent la profondeur à laquelle le haut de la lithosphère océanique entre en subduction (Fluck* et al.*, 1997). La ligne pleine délimite l'étendue maximale de l'inlandsis de la Cordillère il y a 14 000 ans (Clague, 1983). La région à l'étude se situe dans la partie nord du détroit de Géorgie (SG), d'autres détails se trouvent à la figure 2. L fait référence à l'île Lasqueti et le quadrilatère montre la région pour laquelle une courbe du niveau marin a été développée pour le détroit de Géorgie (Hutchinson* et al.*, 2004a). Les triangles représentent des centres volcaniques. (Insertion) Carte de localisation de l'ouest de l'Amérique du Nord. QCI désigne les îles de la reine Charlotte et VI l'île de Vancouver.*

the sill, and a second transition from freshwater back to marine conditions when sea level rose again (*e.g.* Johnson Lagoon on Lasqueti Island, Hutchinson *et al.*, 2004a).

Four freshwater basins and three marine basins were cored in this study. Coring methods included percussion coring (Reasoner, 1993) (one lake, one marine basin), vibracoring on marshes and bogs (three sites), and piston coring (two marine basins). Vibracores were extruded onto plastic gutters, logged, and sampled for radiocarbon and diatom analyses in the field. Piston and percussion cores were sectioned and transported to cold storage for later splitting, logging, and sampling. Samples were selected for radiocarbon dating to determine the age of possible marine-freshwater transitions, or, if material was lacking near the inferred transition, to determine the age and time span of lithostratigraphic units. When possible, the species selected for radiocarbon dating was identified.

Elevations were determined by calibrating an altimeter to the high-tide line. Sill depths for marine basins were determined from bathymetric charts, and were adjusted to reflect the tidal range (difference between higher high water and lower low water for a large tide) at Campbell River of 4.6 m (Canadian Hydrographic Service, 2001).

A classified advertisement was placed in a local newspaper, seeking information on marine shells found at high elevations. Response from local residents was good, and samples for radiocarbon dating were collected from a recently dug well, two dug ponds, a gravel pit, and a stream bed. The elevation and location of the samples were noted, and the samples were identified and radiocarbon dated.

Two radiocarbon samples were obtained from a recent archeological excavation indicating human habitation near the present-day shoreline.

PALEOENVIRONMENTAL INTERPRETATION

Frequently, the paleonvironmental interpretation was straightforward, as the clastic marine sediments often contained marine shells, and the overlying freshwater organic sediments (gyttja, peat) exhibited strong colour and textural contrasts with the marine sediments. For two cores, however, a diatom analysis was done to test possible marine-freshwater transitions.

Organic matter in diatom samples was removed by H_2O_2 digestion, and the remaining material was washed in distilled water, decanted to remove fines, and brought to a near-neutral pH. Aliquots of suspended material were dried on glass slides and mounted in Hyrax. At least 100 specimens or, in diatom-poor samples, the number of specimens counted on 10 random traverses, were identified for each sample.

Diatoms were identified from standard taxonomic sources, principally Sims (1996) and Witkowski *et al.* (2000). Species were assigned to habitat groups based primarily on information on salinity tolerance (van Dam *et al.*, 1994; Sims, 1996).

RADIOCARBON ANALYSIS

In selecting samples for radiocarbon dating, articulated shells were preferred over single valves, shell fragments, or shell hash. For terrestrial samples, macroscopic material (seeds, twigs, wood fragments) was preferred over bulk organic material, such as gyttja or peat. Samples were sent to IsoTrace Laboratory (University of Toronto) for radiocarbon dating by the accelerator mass spectrometry (AMS) method.

The marine reservoir correction has varied in the Strait of Georgia since late-glacial time (Hutchinson *et al.*, 2004b). Radiocarbon ages on marine shells with uncorrected ages older than 10 000 years were corrected by -950 ± 50 years. Ages on younger marine shells were corrected by -720 ± 90 years. Radiocarbon ages on basal freshwater bulk organic material are systematically older than macrofossils recovered from the same level (Hutchinson *et al.*, 2004b). Consequently, ages on bulk organic material (gyttja) retrieved from immediately above the marine-freshwater transition were corrected by -625 ± 60 years (Hutchinson *et al.*, 2004b).

RESULTS

The sample sites range east to west from Cortes Island, across Quadra Island, to near Campbell lake (Fig. 2). They encompass a distance of about 40 km in an east-west direction and about 20 km south to north. The following site descriptions are ordered from highest to lowest elevation. Core stratigraphy is given in Figure 3 for sites above sea level and Figure 4 for sites below sea level. Radiocarbon results are given in Table I. In the following discussion, ages are in corrected radiocarbon years.

LOVELAND MARSH

An undrained, open marsh north of Loveland Bay (Campbell Lake) at 190 m elevation was vibracored. The core features coarse clastic sediments at the base that fine upwards from gravel to fine to medium sand overlain by gyttja and peat (Fig. 3). Diatom analyses of three samples near the transition from sand to gyttja indicate a freshwater environment. Two diatom samples below the transition in a silty, very fine sand,

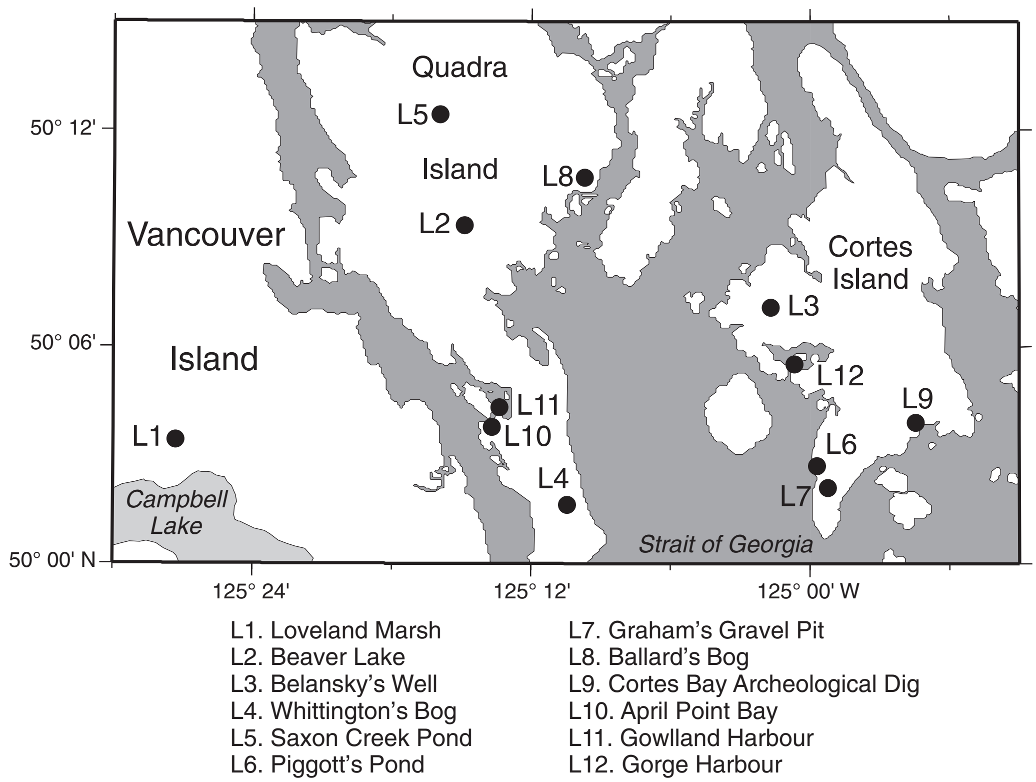

FIGURE 2. Sea-level sites in the northern Strait of Georgia.

Sites de la partie nord du détroit de Géorgie.

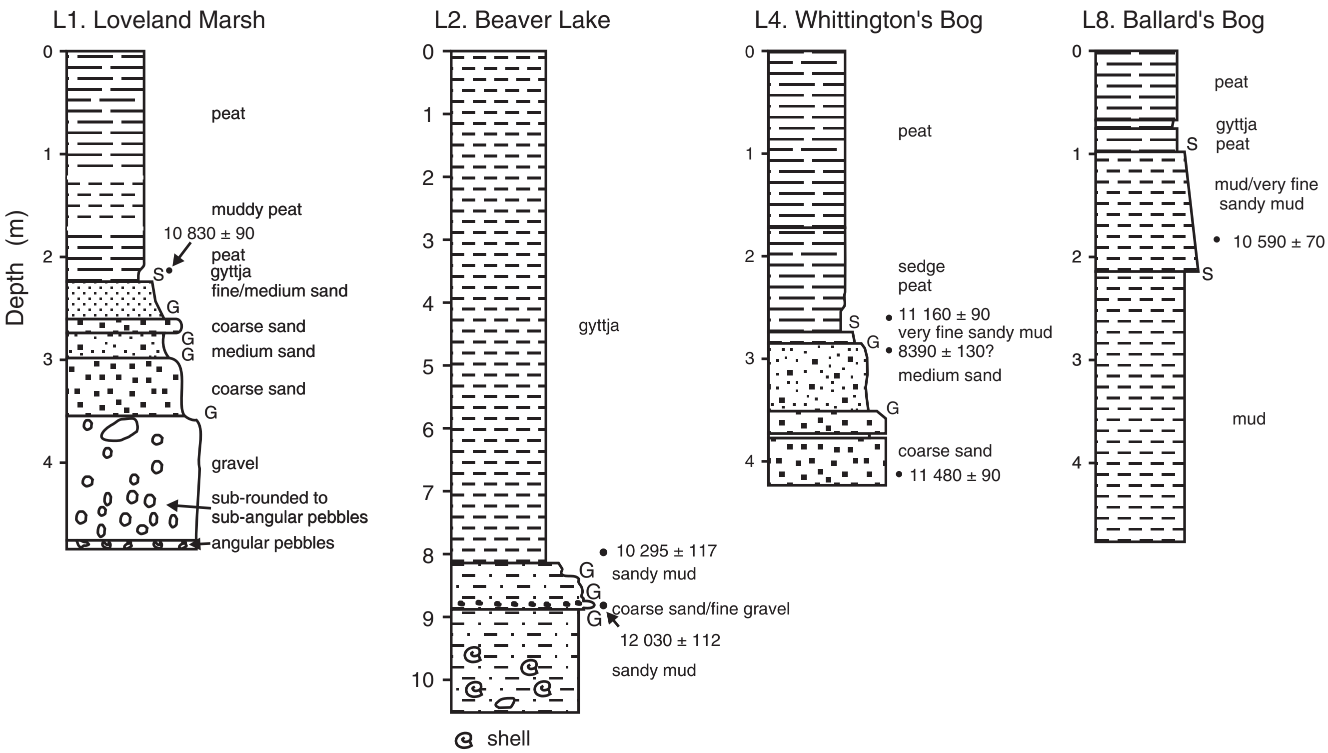

FIGURE 3. Sediment cores from isolation basin sites above sea level. Ages are in corrected radiocarbon years. The letters S and G indicate sharp and gradual contacts, respectively.

Carottes de sédiments en provenance de sites isolés situés au-dessus du niveau marin. Les âges au radiocarbone sont en années étalonnées. Les lettres S et G montrent respectivement les zones de contact brusques et graduelles.

feature a few, commonly fragmented diatoms. The diatom species present are typical of a cool, oligotrophic lake. A sample from gyttja above the transition shows an extremely rich and diverse freshwater diatom assemblage.

The apparent absence of a marine phase at Loveland Marsh is consistent with the mapped marine limit of 175 m in the Campbell River area (McCammon, 1977; Clague, 1981). Loveland Marsh is located in a shallow, elongated depression. The depression may be a former meltwater channel, in which case the fining-upward clastic sediments indicate the decreasing energy levels of waning meltwater flow as the glacial front retreated from the area. A radiocarbon age on seeds of the yellow pond-lily (*Nuphar lutea*) from gyttja 10-20 cm above the gyttja-sand contact is 10 830 ± 90 BP, giving a minimum age for establishment of pond vegetation following deglaciation.

BEAVER LAKE

A percussion core from Beaver Lake, at 145 m elevation, produced a sandy mud containing a coarse sand to fine gravel layer which is overlain by a thick sequence of gyttja (>8 m) (Fig. 3). A shell age from the coarse unit is 12 030 ± 112 BP. The age of the basal gyttja is 10 295 ± 117 BP.

BELANSKY'S WELL

A well dug at 107 m elevation yielded marine shells in a blue-grey clay at depths of 4.3 to 5.5 m. The time of marine conditions is given by an age on a scallop valve (*Chlamys rubida*) of 11 670 ± 121 BP.

WHITTINGTON'S BOG

A vibracore from a drained bog at 75 m elevation features mud and sand overlain by nearly 3 m of peat (Fig. 3). The clastic sequence fines upwards from a coarse to medium sand to a very fine sandy mud. A wood fragment from the base of the peat yielded an age of 11 160 ± 90 BP. In the coarse sand near the bottom of the core, a poplar bud scale yielded an age of 11 480 ± 90 BP. Apparently, sea level dropped below 75 m between 11 160 and 11 480 BP.

A small sample of plant material (12 mg) from the top of the clastic sediments yielded an anomalous age of 8390 ± 130 BP. The sample was formed by combining two smaller samples and was near the minimum weight recommended by IsoTrace for radiocarbon dating (10 mg). The anomalous age is probably due to contamination.

SAXON CREEK POND, PIGGOTT'S POND AND GRAHAM'S GRAVEL PIT

Three ages on marine shells give the time of marine conditions for elevations ranging from 45-50 m. A *Clinocardium nuttallii* valve recovered from the bed of Saxon Creek on Quadra Island at the outlet of a small pond at 50 m elevation has an age

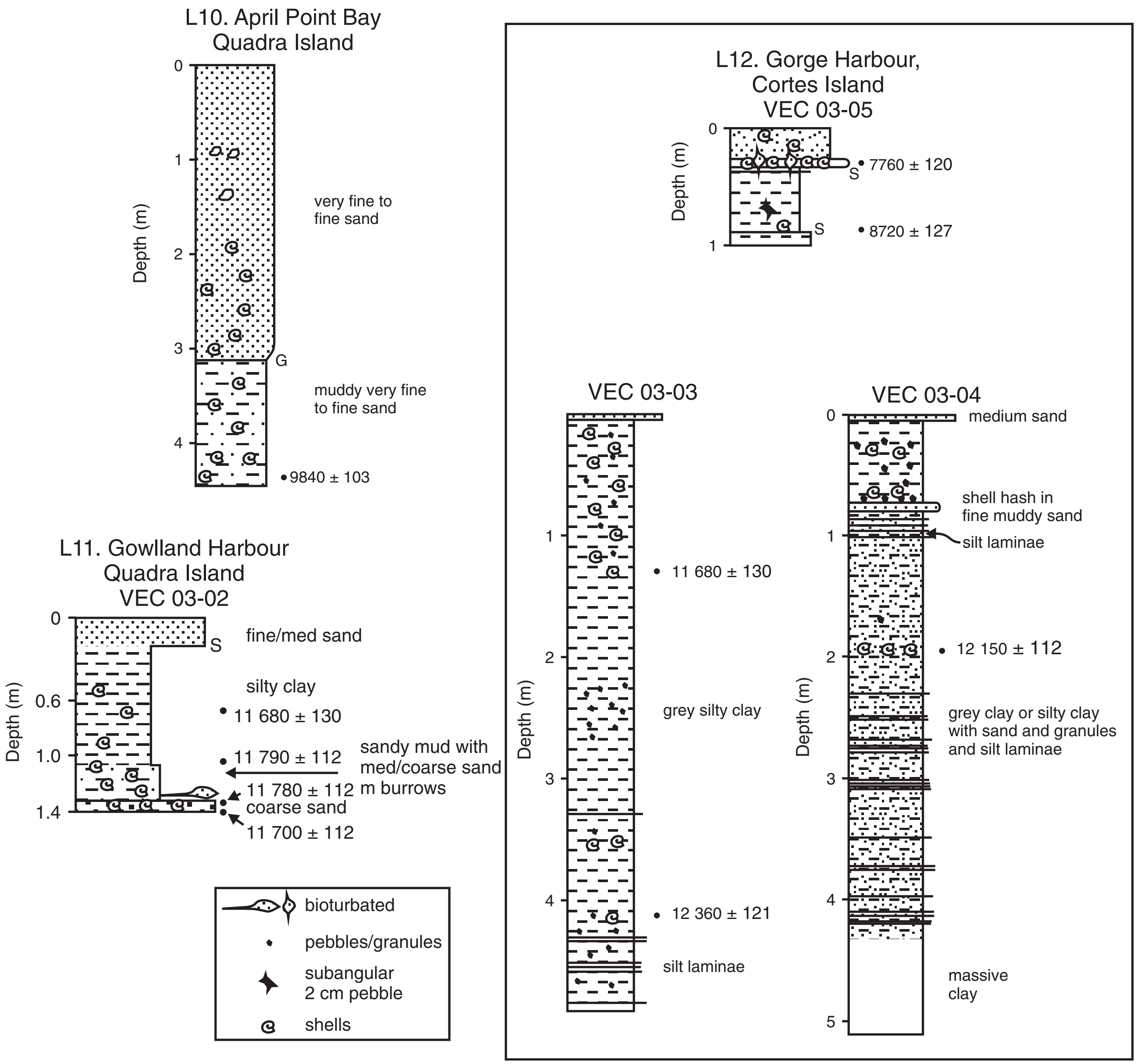

FIGURE 4. Sediment cores from sites below sea level. Ages are in corrected radiocarbon years. The letters S and G indicate sharp and gradual contacts, respectively.

Carottes de sédiments en provenance de sites situés sous le niveau marin. Les âges au radiocarbone sont en années étalonnées. Les lettres S et G montrent respectivement les zones de contact brusques et graduelles.

of 11 880 ± 103 BP. A *Chlamys rubida* fragment from Piggott's Pond dug at 47 m elevation has an age of 11 660 ± 112 BP. An age on a marine shell valve and fragments from the steeply-dipping foreset beds of a glaciofluvial sand and gravel delta (Graham's gravel pit) is 11 140 ± 103 BP. This age probably closely dates the time that sea level dropped below 45 m, which is the approximate elevation of the contact between topset and foreset beds.

BALLARD'S BOG

A vibracore from a drained bog by 23 m elevation features mud to very fine sandy mud overlain about 1 m of peat (Fig. 3). The upper 1.2 m of the clastic sediments fines upwards from very fine sandy mud to mud. Wood or bark fragments 80 cm below the mud-peat transition are dated to 10 590 ± 70 BP.

Diatom analysis of sediments surrounding the transition from mud to overlying peat and gyttja indicate that the top of the mud was deposited in a brackish to freshwater pond or marsh (Fig. 5). Above the mud the basal peat freshens upwards from a freshwater to brackish marsh or pond to a freshwater marsh or pond.

A pond dug on the edge of Ballard's bog yielded marine shells at 5 to 6 m depth in a blue-grey mud. The age of a *Tectura persona* valve is 11 740 ± 112 BP. Apparently, this site

TABLE I

Radiocarbon Ages

Site	Name[a]	Latitude (deg. min. N)	Longitude (deg. min. W)	Altitude or sill elevation (m)	Depth in core (cm)	Material dated[b]	Weight used (mg)	Lab No.	Radiocarbon age	Corrected age[c]	Calibrated age (1 S.D.)
1	Loveland Marsh	50 03.39	125 27.30	190	215-220	*Nuphar lutea* seeds[1]	15	TO-10818	10 830 ± 90	10 830 ± 90	12 795-12 891
2	Beaver Lake	50 09.35	125 14.89	145	815-817	Gyttja[3]	925	TO-9910	10 920 ± 100	10 295 ± 117	11 826-12 380
2	Beaver Lake	50 09.35	125 14.89	145	869-874	*Mya truncata valve* and sh. fragments[2]	242	TO-9911	12 980 ± 100	12 030 ± 112	13 774-13 996
3	Belansky's Well	50 07.07	125 1.67	107	n/a	*Chlamys rubida* valve fragments[2]	735	TO-9897	12 620 ± 110	11 670 ± 121	13 392-13 656
4	Whittington's Bog	50 01.62	125 10.41	75	265	Wood fragment[3]	31	TO-9912	11 160 ± 90	11 160 ± 90	12 959-13 134
4	Whittington's Bog	50 01.62	125 10.41	75	287-291	Wood and plant fragments[3]	12	TO-9913	8390 ± 130	8390 ± 130	9259-9530
4	Whittington's Bog	50 01.62	125 10.41	75	412	Poplar bud scale[1]	36	TO-10817	11 480 ± 90	11 480 ± 90	13 249-13 408
5	Saxon Creek Pond	50 12.40	125 15.93	50	n/a	*Clinocardium nuttallii* valve[2]	416	TO-9895	12 830 ± 90	11 880 ± 103	13 618-13 849
6	Piggott's Pond	50 02.68	124 59.68	47	n/a	*Chlamys rubida* fragments[2]	205	TO-9915	12 610 ± 100	11 660 ± 112	13 389-13 641
7	Graham's Gravel Pit	50 02.07	124 59.22	45	n/a	*Saxidomus giganteus* valve and *Humilaria kennerleyi* fragments[2]	308	TO-9916	12 090 ± 90	11 140 ± 103	12 939-13 120
8	Ballard's Bog	50 10.70	125 09.72	23	179	Wood or bark fragments[3]	216	TO-9914	10 590 ± 70	10 590 ± 70	12 406-12 777
8	Ballard's Bog	50 10.72	125 09.65	23	n/a	*Tectura persona* valve[2]	312	TO-9896	12 690 ± 100	11 740 ± 112	13 458-13 707
9	Cortes Bay[1]	50 03.92	124 55.44	1.5	n/a	Charcoal[4]	378	TO-11643	1950 ± 60	1950 ± 60	1825-1985
9	Cortes Bay[2]	50 03.92	124 55.44	1.3	n/a	Clam shell fragments[4]	998	TO-11644	2980 ± 60	2260 ± 108	2190-2510
10	April Point Marina	50 03.78	125 13.67	-8	427	*Macoma* sp. valve[2]	411	TO-9909	10 790 ± 90	9840 ± 103	11 123-11 361
11	Gowlland Harbour	50 04.44	125 13.43	-17	66	Pelecypod valves[5]	478	TO-11632	12 630 ± 120	11 680 ± 130	13 396-13 673
11	Gowlland Harbour	50 04.44	125 13.43	-17	106	*Macoma nasuta*[5]	579	TO-11633	12 740 ± 100	11 790 ± 112	13 501-13 756
11	Gowlland Harbour	50 04.44	125 13.43	-17	137	Pelecypod valve[5]	494	TO-11634	12 730 ± 100	11 780 ± 112	13 492-13 745
11	Gowlland Harbour	50 04.44	125 13.43	-17	140	Pelecypod valve fragment[5]	504	TO-11635	12 650 ± 100	11 700 ± 112	13 425-13 673
12	Gorge H.-V0303	50 05.51	125 00.69	-22	133	Pelecypod valves, shell fragments[5]	202	TO-11636	12 910 ± 100	11 960 ± 112	13 713-13 946
12	Gorge H.-V0303	50 05.51	125 00.69	-22	415	Paired pelecypod valves[5]	32	TO-11637	13 310 ± 110	12 360 ± 121	14 102-14 611
12	Gorge H.-V0304	50 05.54	125 00.82	-22	188	Shell fragments[5]	120	TO-11638	13 100 ± 100	12 150 ± 112	13 859-14 122
12	Gorge H.-V0305	50 05.51	125 00.46	-22	31	Shell fragments[5]	434	TO-11639	8480 ± 80	7760 ± 120	8510-8850
12	Gorge H.-V0305	50 05.51	125 00.46	-22	85	Shell fragments[5]	341	TO-11640	9440 ± 90	8720 ± 127	9702-10 088

a. Archeological designations for Cortes Bay (Mathews, 2003) are (1) EaSf-36, Unit 5, Stratum 6, (2) EaSf-36, Unit 2, Level 8, Stratum 8.

b. Sample identification by (1) Hebda, (2) Hetherington, (3) James, (4) Mathews, (5) Conway

c. Marine reservoir corrections are -950 ± 50 and -720 ± 90 years for laboratory radiocarbon ages older and younger than 10 000 BP, respectively. The reservoir correction for basal gyttja is -625 ± 60 years. Corrected uncertainties are determined by adding in quadrature the laboratory radiocarbon uncertainties and reservoir correction uncertainties.

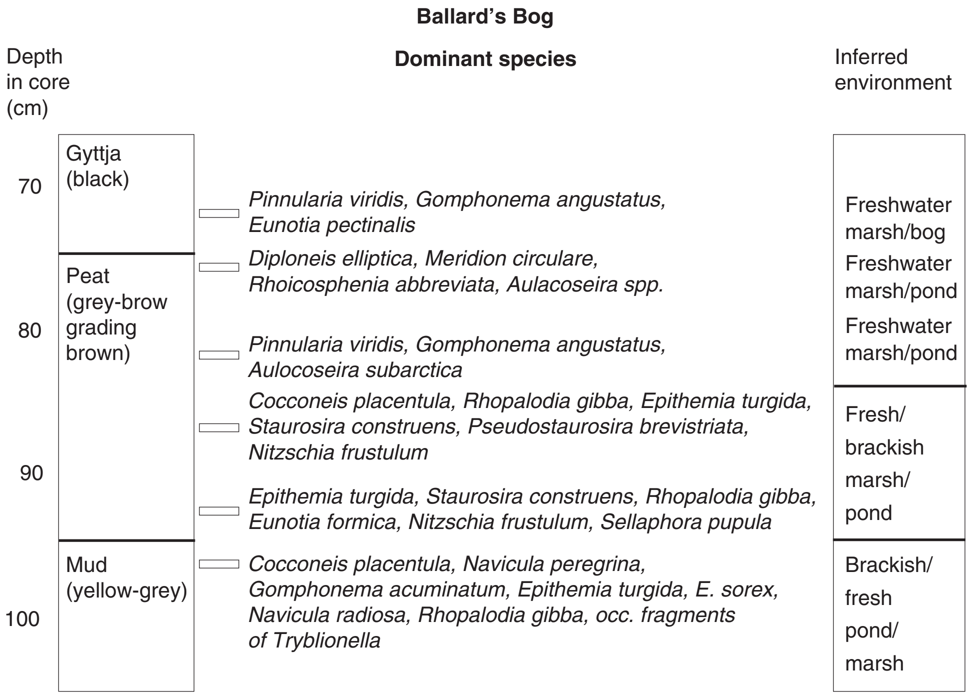

FIGURE 5. Dominant diatom species and inferred paleoenvironment, for a selected interval of a vibracore from Ballard's Bog.

Diatomées dominantes et les conditions paléo-environnementales estimées d'une partie spécifique de la carotte de Ballard's Bog.

experienced marine and brackish conditions from earlier than 11 740 BP to later than 10 590 BP. The site probably fully emerged from saltwater soon after 10 590 BP.

CORTES BAY ARCHEOLOGICAL DIG

An archeological excavation (EaSf-36) on Cortes Island revealed cultural deposits, generally about 1 m thick, overlying a former beach (Mathews, 2003). The earliest occupation was probably during the Marpole Period (2500-1000 cal BP), although earlier occupation is not ruled out. The site was occupied sporadically up to the early Historic Period (Mathews, 2003).

Two samples from this excavation were radiocarbon dated. A mixed sand-shell horizon at the base of the cultural deposits is probably littoral. Slightly wave-worn shell fragments at 1.3 m elevation (Unit 2, Level 8, Stratum 8; Mathews, 2003), taken from near the landward margin of this horizon, are 2260 ± 108 BP old. The stratum contains a burnt clamshell and wave-rolled mammal bone fragments, indicating probable human occupation at slightly higher elevations when the stratum was deposited. Charcoal (Unit 5, Stratum 6; Mathews, 2003) at 1.5 m elevation may have been water-deposited, and is 1950 ± 60 BP old. The ages are consistent with earliest occupation occurring during the Marpole Period.

If the littoral deposits are high-tide deposits, then this suggests that sea level was at about 1.5 m elevation at 2000 BP. Alternatively, if the site is an area of cultural accumulation on a former storm beach, then sea level may have stood lower at 2000 years ago, perhaps near its present level. In either case, at 2000 BP sea level probably stood less than 1.5 m higher than its present level.

APRIL POINT BAY

A percussion core from April Point Bay (sill at about -8 m) has about 3 m of very fine to fine sand overlying about 1.5 m of muddy very fine to fine sand (Fig. 4). Shells are present from about 1.75 m depth to the base of the core. An age on a *Macoma* sp. valve from the base of the core is 9840 ± 103 BP. The relatively homogeneous character of the core suggests a uniform depositional environment, and may indicate that sea level did not drop below -8 m during the Holocene.

GOWLLAND HARBOUR

Four radiocarbon dates on marine shells from a 1.4 m long piston core (sill at about -17 m) range from 11 680 to 11 790 BP (Fig. 4). One age is from an articulated shell. The core fines upwards from a coarse sand to a sandy mud (with medium to coarse sand in clam burrows) to silty clay. The texture and radiocarbon ages are consistent with the distal glaciomarine unit described by Barrie and Conway (2002b). The core is capped with fine to medium sand, which is probably a Holocene lag deposit.

GORGE HARBOUR

Three piston cores were taken in Gorge Harbour (sill is at approximately -22 m) in 30-40 m of water (Fig. 4). The two longer cores (VEC03-03 and VEC03-04) grade upwards from a silty clay with silt laminae, sand, granules, and pebbles, to a shell-rich mud. Three radiocarbon ages determined from marine shells range from 11 680 to 12 360 BP. The textures and radiocarbon ages are consistent with the cores grading upwards from proximal to distal glaciomarine sedimentation

(Barrie and Conway, 2002b). Both cores are capped with a thin layer of medium sand.

The third core (VEC03-05) records a period of early Holocene sedimentation. It contains a stiff silty clay overlain by an olive-coloured clay. Shell fragments from the base of the olive-grey clay have an age of 8720 ± 127 BP. An olive-grey medium sand at the top of the core yielded shell fragments with an age of 7760 ± 120 BP.

SEA-LEVEL CURVE

A sea-level curve for the northern Strait of Georgia, based on the foregoing descriptions and corrected radiocarbon ages, is given in Figure 6. Sea level fell rapidly from above 145 m to below 50 m between about 11 800 and 11 000 BP. The rate of sea-level fall then slowed substantially, reaching 15 or 20 m elevation by 10 000 BP. Sea level is relatively unconstrained in the early and mid-Holocene, but probably did not drop below 8 m depth, or rise above 20 m elevation. A shallow lowstand phase in the early Holocene is possible but, if so, sea level recovered in the mid or late Holocene. Sea level stood at, or slightly below, 1.5 m elevation by 2000 BP. In the last 2000 BP, sea level dropped to its present level.

The laboratory radiocarbon ages were calibrated using Calib 5.01 (Stuiver and Reimer, 1993; www.calib.org) to determine the corresponding calendar ages. The ages of marine and terrestrial samples were calibrated with the Marine04 (Hughen *et al.*, 2004) and IntCal04 (Reimer *et al.*, 2004) calibration datasets, respectively. The calibration program assumes a global marine reservoir value of about 400 years. Consequently, a regional reservoir correction DR = 550 ± 50 years was used for marine ages older than 10 000 BP; for younger ages, DR = 320 ± 90 years. The age of the basal gyttja sample from Beaver Lake was corrected for a 625 ± 60 year reservoir effect before calibration (Hutchinson *et al.*, 2004b).

The calibrated ages, expressed as probability density functions, determine sea-level change in calendar years (Fig. 7). Sea level fell from above 145 m around 13 750-13 500 cal BP to 75 m at about 13 250 cal BP. In the next 250 years sea level dropped another 25 m to about 50 m elevation. Sea-level fall

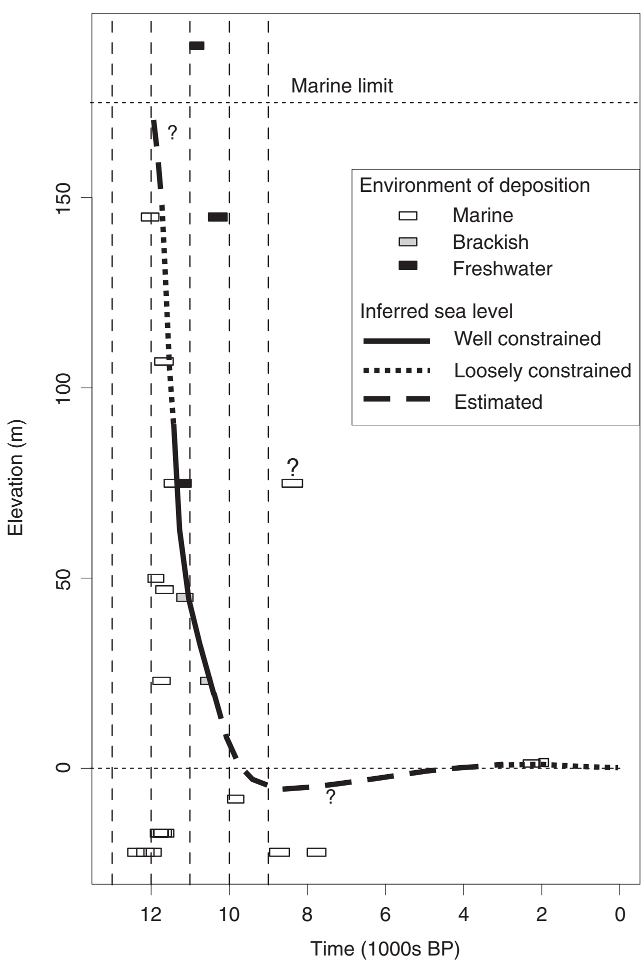

FIGURE 6. Inferred relative sea-level curve, in corrected radiocarbon years, for the northern Strait of Georgia.

Courbe du niveau marin relatif estimée, en années ^{14}C étalonnées, de la partie nord du détroit de Géorgie.

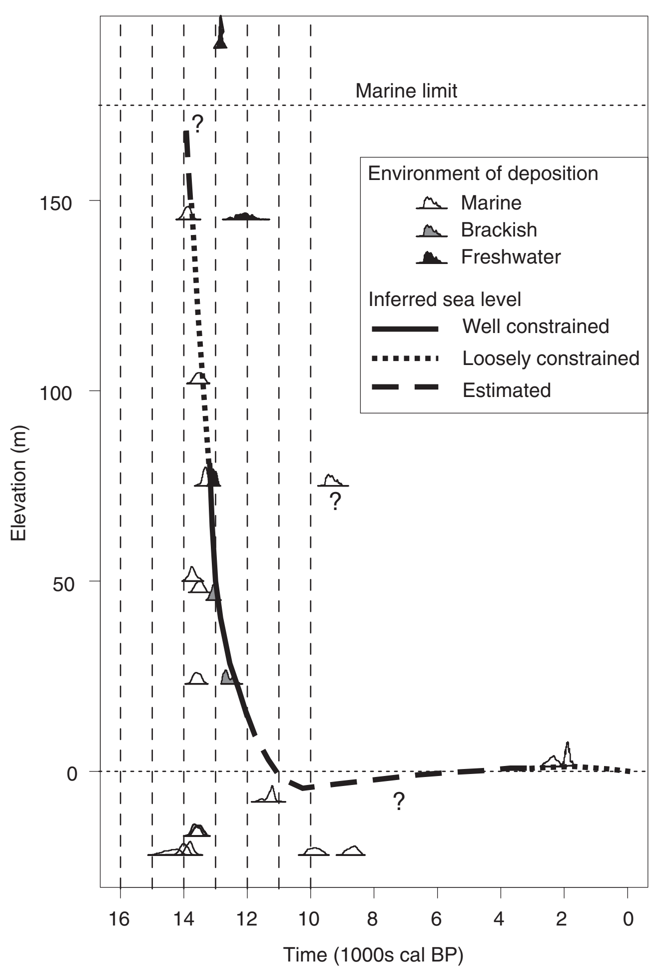

FIGURE 7. Inferred relative sea-level curve, in calendar years, for the northern Strait of Georgia.

Courbe du niveau marin relatif estimée, en années calendrier, de la partie nord du détroit de Géorgie.

then slowed substantially, and dropped to 15-20 m by 12 000 cal BP. Subsequent to 12 000 cal BP, sea level is uncertain, but probably did not drop below 8 m depth or rise above 20 m elevation. A shallow low-stand between 11 000 to 8000 cal BP is possible, but, if so, sea level recovered and stood at, or slightly below, 1.5 m elevation by 2000 cal BP. Sea level then dropped to its present position.

DISCUSSION

SEA LEVEL AND DEGLACIAL HISTORY

The sea-level curve presented here is consistent with the deglacial sedimentary and paleoenvironmental history of the Strait of Georgia (Barrie and Conway, 2002b; Guilbault *et al.*, 2003; radiocarbon ages given by Barrie and Conway (2002b) are corrected by an additional 150 years to reflect the larger marine reservoir correction assumed here). Following deglaciation, the Strait of Georgia experienced proximal glaciomarine sedimentation for a few hundred years centered around 12 250 BP (14 100 cal BP). The proximal phase occurred at the same time throughout the mid and northern Strait of Georgia, suggesting regional downwasting and stagnation of ice. Extensive gravel platforms built to the west of Campbell River that are graded to about 175 m elevation indicate the marine limit (McCammon, 1977; Clague, 1981), and were probably built during the proximal glaciomarine phase. A transition to distal glaciomarine sedimentation then occurred, which persisted until about 11 100 BP (13 000 cal BP).

Proximal glaciomarine sediments were rapidly deposited and feature abundant ice-rafted debris, well-sorted sand layers, and silt laminae deposited from turbid meltwater plumes. They indicate nearby, actively calving, tidewater glaciers and abundant meltwater input. The distal glaciomarine unit is bioturbated, indicating slower sedimentation rates. It generally contains finer sediments (80% clay and silt) but also contains minor ice-rafted gravel. The distal phase indicates that the Strait of Georgia was still connected to tidewater glaciers that generated icebergs. The absence of inferred meltwater plumes shows, however, that the glacial front had retreated, probably into fjord heads of the British Columbia mainland where they were fed by remnant ice in the Coast Mountains.

Sea level may have been maintained near 175 m elevation for a few hundred years during the proximal phase around 12 250 BP (14 100 cal BP). Around the time of the onset of distal glaciomarine sedimentation, or soon after, when tidewater glaciers retreated from the Strait of Georgia, sea level started to drop rapidly. The thinning and retreating ice sheet exerted a decreasing load on the lithosphere and caused the land to start rising. By 11 800 BP (13 700 cal BP) sea level had dropped 30 m to below 145 m. In the next 700 years, during the remainder of the phase of distal glaciomarine deposition, sea level dropped another 85 m to about 60 m elevation. The rate of sea-level fall then slowed.

Sea-level fall began to slow around 11 000 BP (12 900 cal BP), at the beginning of the Younger Dryas chronozone. The climatic cooling associated with the Younger Dryas was less severe in coastal British Columbia than in the North Atlantic (Mathewes *et al.*, 1993), but the slowing rate of sea-level fall could indicate that nearby ice masses stopped thinning or even thickened and advanced at this time in the northern Strait of Georgia. The stillstand or readvance would, however, have been short lived, as the Cordilleran ice sheet attained its present configuration shortly after 10 000 BP (11 450 cal BP) (Clague, 1989). As well, the cessation of glaciomarine sedimentation just before the beginning of the Younger Dryas indicates that the climatic cooling did not cause a return to earlier deglacial conditions. Instead, as discussed below, the slowing of sea-level fall may primarily be related to the Earth's response to the surface unloading.

CRUSTAL RESPONSE AND PROJECTED SEA-LEVEL CHANGE

The northern Strait of Georgia sea-level curve provides information on the amount of isostatic depression following deglaciation. It also indicates how isostatic depression has changed up to the present day. To a first order, postglacial sea-level change is a combination of changes to the volume of water in the oceans (eustatic sea level) and local changes in the elevation of the Earth's surface. Eustatic sea level can be approximated by sea-level observations from sites located far away from the continental ice sheets of the last ice age. Although the sea-level histories of "far-field" sites differ in detail (Milne *et al.*, 2002), for present purposes the Barbados sea-level record (Fairbanks, 1989) adequately represents eustatic sea-level change.

The isostatic depression was calculated by subtracting the Barbados sea-level curve from the observed relative sea-level change (Fig. 8). The resulting isostatic depression curve shows that the surface of the Earth was depressed by about 230 m at 13 750 cal BP at the northern Strait of Georgia. Since that time, the lithosphere has rebounded and the Earth's surface has risen. The amount of subsidence has decreased, up to the present, at an ever-slower rate.

The surface loading theory of a linear viscous or viscoelastic planet predicts that the Earth's response to glacial mass changes is composed of one or more decaying exponential terms (Peltier, 1985; Turcotte and Schubert, 2002). In the simplest case a single exponential term suffices, and the isostatic depression D decreases with time: $D = D_0 \exp(-t/\tau)$, where D_0 is the initial isostatic depression after deglaciation, and t is the decay time. The exponential decay constant depends on the viscosity of the Earth's mantle, showing why postglacial rebound analysis is a key method for inferring mantle viscosity.

Isostatic depression is shown in Figure 9A on a semi-logarithmic plot. The slope of the straight line through the points is the negative inverse of the decay time, $-1/\tau$, and here gives $\tau = 2500$ years. A single decaying exponential curve fit to the entire time series (Fig. 9B) under-predicts the observed early, large subsidence and over-predicts subsidence later on. If, however, only the post-13 000-year data is fit to the single exponential term, a relatively good fit is obtained.

The early, large subsidence values generate a break in slope on the semi-logarithmic plot (Fig. 9C). The apparent decay time at earliest times is about 1200 years, compared to

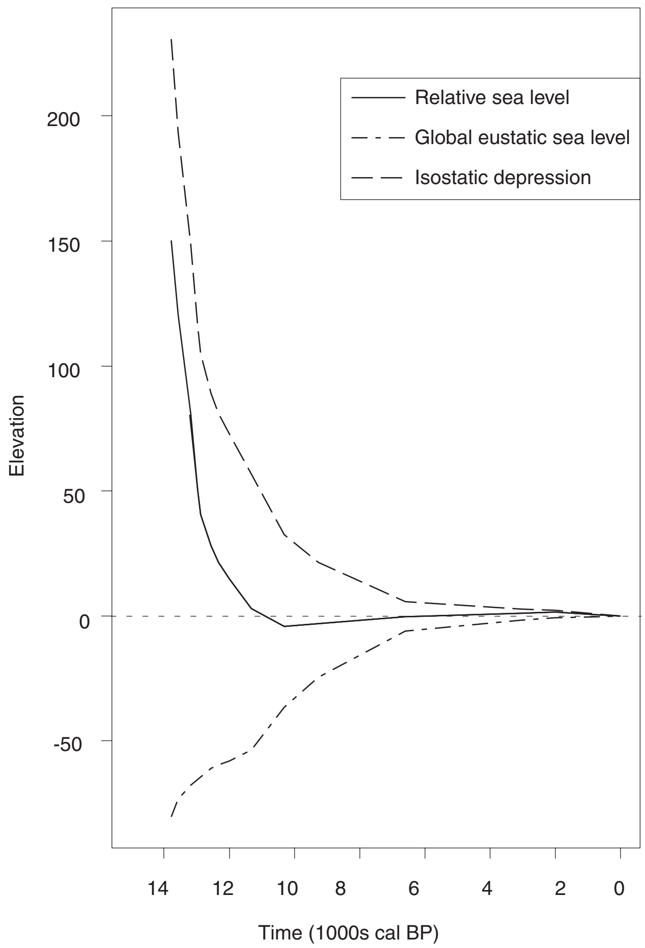

FIGURE 8. Isostatic depression (long-dashed line) obtained by subtracting an estimate of global eustatic sea level (short-dashed line; Barbados sea-level curve; Fairbanks, 1989) from the northern Strait of Georgia sea-level curve (solid line).

Dépression isostatique (ligne en long pointillé) obtenue par la soustraction d'une estimation du niveau marin global (ligne en court pointillé; courbe du niveau marin de la Barbade; Fairbanks, 1989) à celle de la courbe du niveau marin de la partie nord du détroit de Géorgie (ligne pleine).

2600 years for the rest of the record. Fitting two exponential terms to the isostatic depression, and varying the decay time of the faster term, yields the best fit shown in Figure 9D. A 500-year decay time, combined with the slower 2600-year term, fits the entire time series well. At early times, the 500-year and 2600-year decay times combine to produce the apparent decay time of 1200 years shown in Figure 9C.

The fit with two exponential terms provides an estimate of the crustal uplift rate (Fig. 10) due to glacio-isostatic adjustment following the deglaciation of the Cordilleran ice sheet. The crustal uplift rate was at least 100 mm/a and may have exceeded 200 mm/a during early emergence. The rate of crustal uplift dropped below 10 mm/a by 10 000 cal BP and below 1 mm/a by about 3000 cal BP. The present-day rate of postglacial crustal uplift is about 0.25 mm/a.

Over the last 2000 years, postglacial uplift has produced about 55 cm of crustal uplift, causing 55 cm of relative sea-level fall (Fig. 10). The contribution of other processes (tectonics, sedimentation, mountain glacier growth and retreat, changes in oceanographic circulation) to relative sea-level change is uncertain. The sparse late-Holocene data from Cortes Bay, showing that sea-level has dropped by 1.5 m or less in the past two thousand years, suggests, however, that the net contribution from other processes is no more than about twice that of postglacial rebound.

The inferred slow rate of present-day postglacial crustal uplift and the small amount of observed late-Holocene sea-level change have implications for projections of future sea-level change in the mid and northern Strait of Georgia. The Intergovernmental Panel on Climate Change (IPCC) projections of global sea-level rise from the year 1990 to 2100 range from 9 to 88 cm, with the averages of the projections falling the range of 30-50 cm (IPCC, 2001). Most of the projected sea-level rise is due to the warming of ocean water (steric effect) and the melting of glaciers and ice caps. The actual sea-level change in the Strait of Georgia will be affected by changes in regional oceanographic conditions (circulation, temperature) and may deviate from the global average.

In 110 years (the time elapsed from 1990 to 2100) the amount of postglacial uplift is only 3 cm. This slightly reduces the IPCC projected global sea-level rise to 6 to 85 cm. Crustal motion from other processes may also contribute, but crustal uplift is not expected to strongly ameliorate sea-level rise in the mid and northern Strait of Georgia. This is in contrast to some parts of Canada, where postglacial uplift occurs at much larger rates. For example, the port of Churchill on Hudson Bay is rising at about 10 mm/a (Lambert *et al.*, 2006). Here, local sea level would be expected to continue to fall, even at the largest projected values of global sea-level rise.

EARTH RHEOLOGY

The early, rapid crustal uplift and corresponding small decay time of about 500 years could be related to transient rheology or non-linear mantle flow (Ranalli, 1995), but could also indicate a layered mantle viscosity. Commonly, geodynamic models of postglacial rebound and mantle convection feature mantle viscosity increasing with depth. If this is the case for the mantle underlying the Strait of Georgia, then the 500-year decay time is representative of a shallow, low-viscosity zone, and the 2600-year decay time represents deeper, high-viscosity mantle.

Numerical techniques are required to rigorously compute the spectra of decay times for layered viscous or viscoelastic Earth models, and are beyond the scope of this paper. However, an analytical formula gives the relation between decay times and mantle viscosity for a uniform incompressible viscous half-space (Turcotte and Schubert, 2002) and provides insight into Earth rheology. The decay time τ is given by $\tau = 2\eta k/(\rho g)$, where η is mantle viscosity, k is the spatial wavenumber ($=2\pi/\lambda$, where λ is wavelength), ρ is density of the halfspace, here taken to be the density of shallow mantle (3 300 kg/m^3), and g is the acceleration due to gravity (9.82 m/s^2). Assuming the shallow mantle responds to ice load

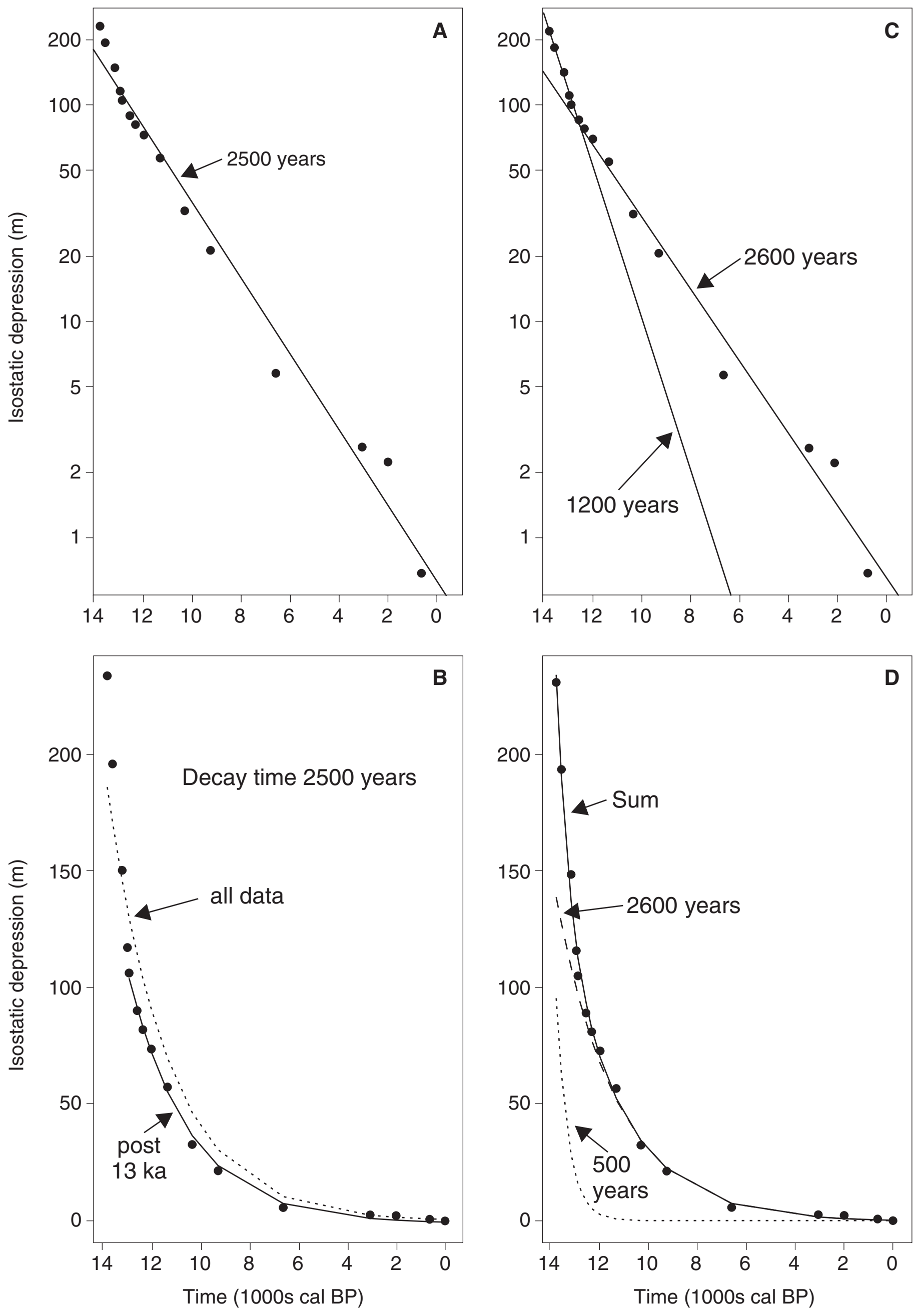

FIGURE 9. Analysis of isostatic depression to determine exponential response times for the Earth's mantle. (A) Regression of isostatic depression with a single decay constant. (B) The resulting fit for a 2500 year decaying exponential to all data (dashed line) and without data before 13 000 cal BP (solid line). (C) Regression of isostatic depression, allowing a faster decay time for the early emergence. (D) The best fit to isostatic depression with two exponential decaying terms. The slow decay time of 2600 years was assumed from (C), and the fast decay time was varied to obtain the best fit at 500 years.

Analyse de la dépression isostatique pour déterminer le temps de réponse du manteau terrestre. (A) Droite de régression avec une constante. (B) Résultat de l'application d'une demi-vie de 2500 ans sur l'ensemble des données (ligne pointillée) et sans les données d'avant 13 000 cal. BP (ligne pleine). (C) Droite de régression de la dépression isostatique permettant une émergence plus rapide. (D) Meilleur modèle d'ajustement de la dépression isostatique avec deux constantes. La demi-vie lente de 2600 ans est obtenue à partir de (C) et la demi-vie rapide a été sélectionnée en fonction du meilleur ajustement à 500 ans.

changes on the scale of the Strait of Georgia, giving λ = ~200 km, the viscosity of the shallow mantle is about 10^{19} Pa s. Deeper parts of the mantle have a viscosity at least five times larger, and perhaps significantly more than five times, because the deeper mantle responds to longer-wavelength components of the surface load.

A viscosity of 10^{19} Pa s is consistent with mantle viscosity inferred from the tilts of relict proglacial lake shorelines in Puget Sound (James *et al.*, 2000). Clague and James (2002) showed that the lake shoreline tilts are only sensitive to the viscosity of the shallow mantle, above 670 km depth. In the future, detailed numerical modelling could determine the thickness of the low-viscosity zone needed to satisfy both proglacial lake shoreline tilts and the new relative sea-level data.

As discussed above, the slowing of sea-level fall at the beginning of the Younger Dryas at 11 000 BP (~12 900 cal BP) could indicate that remnant ice masses near the study area slowed melting or even thickened for a few hundred years. However, the good fit with two decaying exponential terms suggests that this effect, if present, was not large.

COMPARISON WITH MID-STRAIT OF GEORGIA SEA LEVEL

A comparison of the mid-Strait of Georgia sea-level curve (Hutchinson *et al.*, 2004a) to the northern strait shows a similar pattern of sea-level fall (Fig. 11). In the northern Strait of Georgia, sea-level fall lagged the mid-Strait of Georgia by only

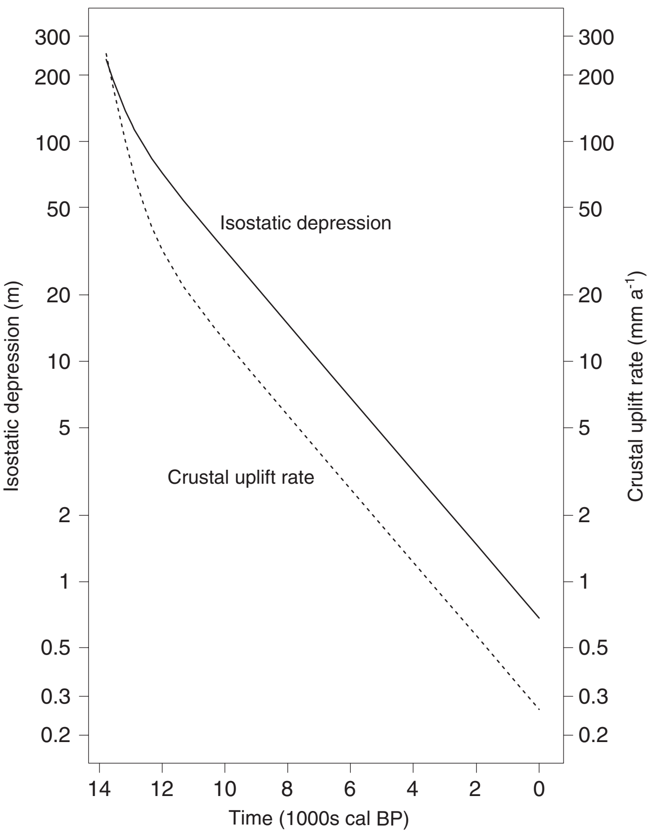

FIGURE 10. Isostatic depression (m) and crustal uplift rate (mm/a) from the best fit to the isostatic depression given in Figure 9D.

Dépression isostatique (m) et taux de soulèvement de la croûte terrestre (mm/a) calculés à partir du meilleur modèle d'ajustement de la dépression isostatique présenté à la figure 9D.

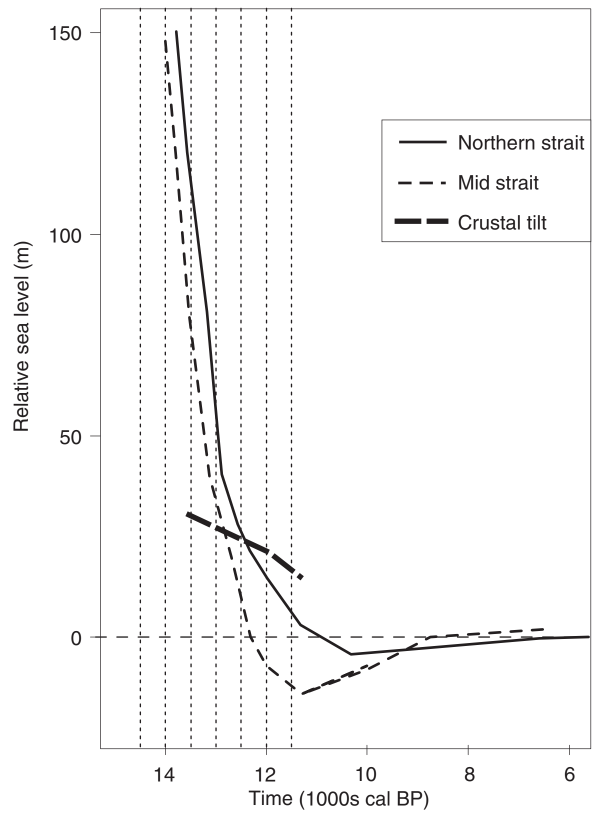

FIGURE 11. Comparison of sea-level curves for the northern and mid-Strait of Georgia. The difference between the curves gives the amount of crustal tilt (down to the north) between the two regions.

Comparaison des courbes du niveau marin relatif entre le nord et le centre du détroit de Géorgie. La différence entre les courbes donne l'inclinaison de la croûte terrestre (vers le nord) entre les deux régions.

200-300 years during early emergence. After 13 000 cal BP, sea-level fall in the mid-strait continued at a faster rate than the northern strait, and it underwent an earlier, and probably larger-magnitude, lowstand than the northern strait.

Crustal tilt between the mid and northern Strait of Georgia is given by the difference in sea-level curves. The largest difference occurred at the earliest time at about 13 500 cal BP, and amounts to about 35 m, or only about 15% of the initial isostatic depression of 230 m. The distance between the middle and northern strait is about 80 km, and this gives crustal tilt of 35 m per 80 km = 0.45 m/km. This is less than one-half of the peak crustal tilt of about 1.15 m/km observed in Puget Sound soon after the Cordilleran ice sheet started retreating from its maximum position (Thorson, 1989; James *et al.*, 2000). The smaller values of crustal tilt for the Strait of Georgia compared to Puget Sound are consistent with rapid deglaciation of the Strait of Georgia (Barrie and Conway, 2002b; Guilbault *et al.*, 2003) and a thicker lithosphere (60-70 km compared to 35-40 km for Puget Sound). A thicker lithosphere has greater flexural rigidity and bends less readily. The mid and northern Strait of Georgia responded to glacial unloading nearly uniformly, with a relatively small amount of crustal tilting compared to the total vertical subsidence.

CONCLUSIONS

The sea-level observations described here are based on isolation basin coring and other information. They provide constraints on deglacial and postglacial sea-level change for the northern Strait of Georgia, a region previously lacking any information on past sea-level change. The observations indicate that:

1- Initial emergence was rapid, with sea level falling about 100 m between 13 750 and 13 000 cal BP. Sea level may have dropped to a lowstand of a few metres depth between about 11 000 and 8000 cal BP. It recovered and may have stood slightly above its present level by 2000 cal BP. It then dropped to its present level.

2- Sea-level fall in the northern Strait of Georgia closely paralleled, and slightly lagged, sea-level fall in the mid Strait of Georgia (Hutchinson *et al.*, 2004a). The time lag was only 200-300 years during early emergence. The mid Strait of Georgia probably experienced an earlier, and slightly larger magnitude, sea-level lowstand than the northern strait.

3- The initial rapid sea-level fall began at about the time that sedimentation in the Strait of Georgia changed from proximal to distal glaciomarine, consistent with retreat of the ice front from the Strait of Georgia and ensuing unloading of the Earth's surface.

4- The peak isostatic depression inferred from the sea-level observations is about 230 m. Comparison of the mid and northern Strait of Georgia sea-level curves shows that the crust was tilted down to the north by about 35 m during initial emergence, about 15% of the peak isostatic depression. The Strait of Georgia responded to glacial unloading relatively uniformly, with little crustal tilt compared to the amount of isostatic depression.

5- The crust was tilted down to the north by about 35 m over a distance of 80 km between the mid and northern Strait of Georgia during initial emergence, giving a crustal tilt of 0.45 m/km. For comparison, crustal tilts from Puget Sound were much larger (0.8 and 1.15 m/km), a consequence of the thinner lithosphere underlying Puget Sound and the larger nearby load.

6- The isostatic depression can be fit with two decaying exponential terms with decay times of about 500 and 2600 years. The response times may relate to a shallow, low-viscosity mantle layer, and deeper, high-viscosity mantle, respectively. The mantle viscosity inferred from the faster decay time is 10^{19} Pa s, consistent with earlier analyses of tilted relict proglacial lake shorelines in Puget Sound (James *et al*., 2000; Clague and James, 2002).

7- Initial rates of crustal uplift from the glacio-isostatic response to the Cordilleran ice sheet exceeded 100 mm/a at the northern Strait of Georgia. The rate of crustal uplift has decayed since then to the present-day rate of about 0.25 mm/a. This value can be used to correct present-day observations of sea-level change and crustal uplift for glacio-isostatic adjustment to isolate the tectonic signal.

8- The potential of crustal uplift to ameliorate projected global sea-level rise is limited in the mid and northern Strait of Georgia because present-day crustal movements are inferred to be small.

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