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Thomas S. James, Ian Hutchinson, and John J. Clague

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Authors' addresses

T.S. James *(tjames@nrcan.gc.ca)*
Geological Survey of Canada
9860 West Saanich Road
Sidney, British Columbia V8L 4B2

I. Hutchinson *(ihutchison@sfu.ca)*
Department of Geography
Simon Fraser University
8888 University Drive
Burnaby, British Columbia V5A 1S6

J.J. Clague (*jclague@sfu.ca*)
Department of Earth Sciences
Simon Fraser University
8888 University Drive
Burnaby, British Columbia V5A 1S6

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Thomas S. James, Ian Hutchinson, and John J. Clague
GSC Pacific, Sidney

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Abstract: Freshwater sediments in low-elevation lakes and bogs in southwestern British Columbia are commonly underlain by marine and glaciomarine deposits. Radiocarbon ages from the marine-freshwater transition define the time that basins became isolated from the sea. Data from five lakes and bogs in the Victoria area, combined with earlier results, indicate that sea level fell from above 60 m a.s.l. to below present sea level between 12 500 and 11 500 ^{14}C years ago. In the Fraser Lowland, data from seven lakes and bogs show that sea level fell from above 180 m a.s.l. to about 80 m a.s.l. between 12 500 and 12 000 ^{14}C years ago, to 20–30 m a.s.l. by 11 000 ^{14}C years ago, and to about 10 m a.s.l. by 10 000 ^{14}C years ago. A previously proposed secondary resubmergence of the Fraser Lowland of 100 m or more is ruled out by the radiocarbon ages and by diatom analyses.

Résumé : Dans les lacs et les tourbières à faible altitude du sud-ouest de la Colombie-Britannique, les sédiments d'eau douce reposent généralement sur des dépôts marins et glaciomarins. La datation au radiocarbone de la zone de transition entre les sédiments marins et les sédiments d'eau douce permet de déterminer à quel moment les bassins ont été isolés de la mer. Des données provenant de cinq lacs et tourbières de la région de Victoria, combinées à celles d'études antérieures, montrent que le niveau de la mer est passé de plus de 60 m au-dessus du niveau actuel à un niveau plus bas que le niveau actuel entre 12,5 et 11,5 ka (^{14}C). Les données provenant de sept lacs et tourbières dans les basses terres du Fraser montrent que le niveau de la mer est passé de plus de 180 m au-dessus du niveau de la mer actuel à environ 80 m au-dessus de ce niveau entre 12,5 et 12 ka (^{14}C), puis à 20-30 m au-dessus de ce niveau à 11 ka (^{14}C) et à environ 10 m au-dessus de ce niveau à 10 ka (^{14}C). Une proposition antérieure relative à l'existence d'une nouvelle submersion secondaire des basses terres du Fraser sous 100 m d'eau ou plus est exclue d'après les radiodatations et des analyses des diatomées.

INTRODUCTION

The general character of relative sea-level change in south coastal British Columbia since deglaciation in the Late Pleistocene has been understood for some time (Mathews et al., 1970; Clague et al., 1982). Sea level fell rapidly during and immediately following deglaciation, dropping below its present level within 1000–2000 years. The amount of sea-level fall ranges from about 50 m on western Vancouver Island to about 200 m along the mainland coast. Sea level fell because removal of the ice load allowed the Earth's crust to rebound to its former position of isostatic equilibrium. Sea level then gradually approached its present position in the middle Holocene as eustatic sea level rose.

Data showing the spatial variability of sea-level change and providing tight constraints on timing are, however, not available for southern British Columbia. For example, the marine limit at Victoria is thought be at about 75 m a.s.l., based on the elevation of the late Pleistocene Colwood delta (Mathews et al., 1970), but there are no published dates on the age of this feature and, until this study, no other sea-level information existed between 30 and 75 m a.s.l. In the Fraser Lowland and adjacent northern Puget Lowland in Washington state, a period of rapid resubmergence and re-emergence shortly after initial emergence has been proposed (Easterbrook, 1963; Mathews et al., 1970; Armstrong, 1981), although not generally accepted (e.g. Clague et al., 1982).

Detailed sea-level information is needed to understand the environments of deposition and the nature of the sedimentary processes operating in south coastal British Columbia during late Pleistocene and Holocene time. Knowledge of the depositional and postdepositional environments, in turn, assists in assessments of the stability and response of these sediments to earthquakes.

Precise relative sea-level observations can also assist with geophysical modelling. Recent postglacial rebound modelling (James et al., 2000; Clague and James, in press) of a limited number of relative sea-level observations from Vancouver Island indicates that mantle viscosity values are smaller than those generally adopted for global postglacial rebound models. Low mantle-viscosity values have been used in preliminary viscoelastic models of the subduction-earthquake cycle to explain horizontal crustal velocities observed using GPS (Wang et al., 2001). Tighter constraints on the depth-dependence of mantle viscosity are needed for this modelling and can be provided through additional relative sea-level observations.

To provide additional, high-quality sea-level data, fieldwork was undertaken in the summer of 2000 in the Victoria and Vancouver areas. The work was part of the first year of the Georgia Basin Geohazards Initiative, a three-year project focusing on geological hazards in and around the Strait of Georgia. Here we discuss the preliminary results of our work and propose revised relative sea-level curves for the Victoria area and the western Fraser Lowland.

METHODS AND PREVIOUS WORK

A paleo–sea-level observation consists of a radiocarbon age on organic material having a known position relative to sea level at the time of deposition. For example, a radiocarbon age on intertidal marine shells in growth position from a relict beach or strandline provides the time of beach habitation by marine organisms and hence the time that sea level was at the elevation of the beach. Frequently, however, the stratigraphic context is less precise, and it may only be possible to say that sea level was above or below the site elevation at the time the organic material was deposited. For example, a date on a marine shell may only indicate that sea level was above the level of the observation point because some molluscs live below the intertidal zone and because their shells can be reworked and carried to greater depths or lower elevations.

A core from a low-elevation lake or bog, or a shallow marine basin, can potentially provide precise information on past sea-level changes (e.g. Hafsten and Tallantire, 1978; Anundsen et al., 1994; Josenhans et al., 1997). If a transition from marine to freshwater sediments can be identified in a core, and if organic material can be extracted, it is possible to date the time at which the basin became isolated from the sea. The transition occurs when sea level drops below (or rises above) the sill elevation, which is the elevation of the outlet of a lake or bog or, for a marine basin, the deepest declivity in the basin walls. Consequently, in interpreting the age in terms of sea-level change, it is important to relate it to the sill elevation, not the elevation from which the dated material was extracted.

Lakes and bogs were cored in the summer of 2000 in the Victoria and Vancouver areas. The sea-level record below about 25 m a.s.l. at Victoria is reasonably well known (Clague et al., 1982), and consequently coring was limited to six sites ranging in elevation from 23 m to 75 m (Fig. 1).

The sea-level history in the Vancouver area is less well known. One proposed sea-level history features a fall in sea level from 200 m a.s.l. to about 50 m a.s.l., followed by a rise back to about 150 m a.s.l., and then a final fall to near present-day level, all between about 13 000 and 10 000 ^{14}C years ago (Mathews et al., 1970; Armstrong, 1981). Another proposed sea-level curve (Clague et al., 1982) shows sea level monotonically dropping from above 100 m a.s.l. before 11 ka to present levels by about 10.5–11 ka.

The late-glacial history of the Fraser Lowland is more complex than that of Victoria. A lobe of the Cordilleran ice sheet retreated to the eastern Fraser Lowland and then readvanced. The readvance featured at least two pulses (Clague et al., 1997), and the resulting stratigraphic complexities, including possible reworking of early glaciomarine sediments in ice-dammed lakes, has resulted in an ambiguous sea-level record. Because of this ambiguity, and to encompass the elevation range of the proposed resubmergence and re-emergence events, seven sites ranging in elevation from 9 m to 175 m were cored.

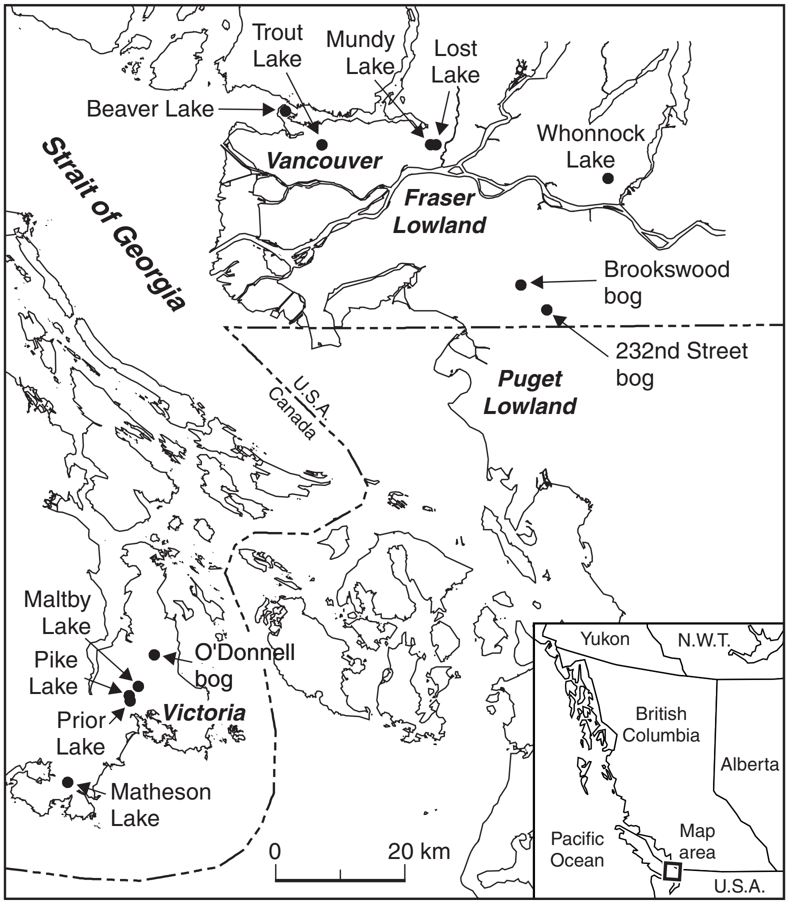

Figure 1.

Site map for isolation-basin coring done in the Victoria area and in the Fraser Lowland.

Lake cores were obtained using a percussion coring device (Reasoner, 1983) and bog cores were obtained using a vibracorer. The cores were transported to the Geological Survey of Canada laboratory at Sidney, British Columbia, split, and logged. Samples for radiocarbon dating were extracted from the base of the freshwater sequences (generally a compact gyttja), and, where present, from the underlying marine or glaciomarine sediments. In many cases plant macrofossils (plant detritus, twigs, coniferous tree needles, and seeds) were recovered from the basal freshwater sediments, and these were dated. Radiocarbon ages were also obtained on some bulk samples of gyttja or organic mud. Marine and glaciomarine sediments in cores from the Vancouver area were generally devoid of dateable organic material. In contrast, four of the five Victoria sites yielded marine shells or shell fragments. Thirty-two samples were radiocarbon dated at IsoTrace Laboratory (University of Toronto) for this study.

RESULTS

Preliminary revised sea-level curves, based on our study and earlier work, are shown in Figures 2 and 3. Our results extend the dated elevation range at Victoria and provide important new constraints for the western Fraser Lowland.

The marine reservoir correction for shell ages is assumed to be 800 years (Southon et al., 1990). Many radiocarbon age determinations in the 1950s and early 1960s, and, until recently, all GSC ages, were not normalized to -25 ‰ δ^{13}C, which is now the standard. Instead, they were not normalized at all or were normalized to 0 ‰. For marine shells, either of these approaches corresponds to about a 410-year correction. Consequently, marine shell dates from earlier studies were adjusted by 800-410 = 390 years.

Most of the Victoria and Vancouver cores feature a unit of grey, unmottled, glaciomarine, clayey silt sharply overlain by brown freshwater sediments. The basal freshwater sediments are commonly gyttja, which grades into peat at the bog sites. The gyttja shows minor differences in colour, a gradual upward increase in water content, and no evidence of a return to marine conditions following the initial, sharply defined emergence.

At some sites the boundary between the marine/glaciomarine and freshwater units is more complex, and includes muddy laminations (Whonnock Lake, Fraser Lowland), transitions from gyttja to organic mud and back (O'Donnell bog, Victoria area; 232nd St. bog, Fraser Lowland), or gravel within the peat (Brookswood bog, Fraser Lowland). For these sites, diatom analyses were performed on selected intervals to confirm the depositional environment. In all cases, diatom

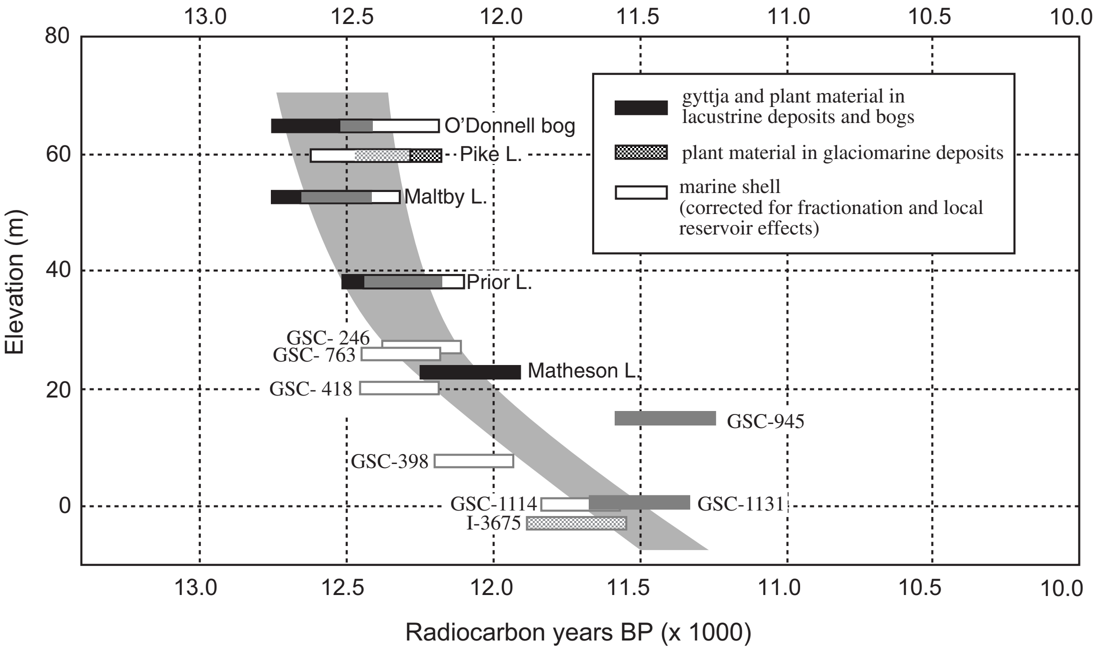

***Figure 2.** Age-elevation plot of relative sea-level observations (rectangular boxes) and inferred sea-level curve (shaded region) for Victoria. Data acquired for the present study are identified by the place names of the isolation basins. Previously published data are identified with the laboratory numbers. The width of each box corresponds to twice the reported analytical uncertainty of the radiocarbon age.*

analyses revealed a single transition from marine to freshwater conditions with no suggestion of a return to marine or brackish conditions.

Victoria

Sea level at Victoria fell from above 60 m a.s.l. to its present level between about 12.5 and 11.5 ka (Fig. 2). A 75 m site (Florence Lake) was cored twice, but we were unable to penetrate below the level of a prominent tephra (Mazama ash; 6.7 ka; Hallett et al., 1997) owing to the thickness of the freshwater sequence. The initial sea-level fall at the end of the Pleistocene was apparently quite rapid (100–200 years?), as the corrected marine radiocarbon ages are essentially equivalent at sites above 20 m elevation. Radiocarbon plateaus at this time may, however, make the duration of this initial sea-level fall longer.

A corrected radiocarbon age on *Nuculana* sp.(?) shell fragments from Pike Lake (12 440 ± 80 BP, TO-9192) is 160 years older than plant fragments (12 280 ± 120 BP, TO-9191) from the same depth in the glaciomarine deposits. In contrast, corrected marine shell ages from O'Donnell bog and Maltby Lake are 250 and 100 years younger, respectively, than bulk dates on the overlying gyttja. These data are consistent with other published results indicating that radiocarbon ages on bulk gyttja are hundreds of years too old (Tornqvist et al., 1992; Wohlfarth et al., 1993). At Prior Lake, a corrected shell age from marine sediments (12 270 ± 90 BP, TO-9189) is 50 years younger than a date on a twig from the overlying gyttja (12 320 ± 100 BP, TO-9187). The discordance between the shell and gyttja ages is probably due to errors in the latter, although a marine reservoir correction less than 800 years cannot be ruled out.

Radiocarbon ages from earlier studies define the sea-level curve below 30 m elevation and are consistent with the upper part of the curve developed here. They suggest that the rate of sea-level fall may have decreased after 12 ka.

Fraser Lowland

We were unable to date the mineral-rich glaciomarine/marine sediments at most of the Vancouver-area sites, but basal ages on the freshwater sequences, together with previously published marine shell ages (Clague, 1980), allow preliminary definition of a sea-level curve (Fig. 3). It features rapid sea-level fall from above 175 m a.s.l. to 80 m a.s.l. in a few hundred years between 12.5 and 12 ka. In the next 500 years sea level may only have fallen another 20 m, before accelerating again and dropping to 30 m a.s.l. by about 11.3 ka. Sea level then fell slowly to about 10 m elevation at 10 ka.

This interpretation relies heavily on basal dates from freshwater sediments at Whonnock Lake (175 m a.s.l.; organic mud, 11 870 ± 90 BP, TO-9214), 232nd St. bog (79 m a.s.l.; gyttja, 11 920 ± 80 BP, TO-9206), Brookswood bog (60 m a.s.l.; herbaceous plant tissue and wood fragment, 11 410 ± 110 BP, TO-9209), and Trout Lake (30 m a.s.l.;

gyttja, 11 140 ± 100 BP, TO-9198) and on evidence for persistence of a freshwater environment once the transition from marine to freshwater conditions was achieved. No mineral-rich sediments were recovered from either Lost or Mundy lakes, thus the basal dates from these sites are minima for the onset of freshwater conditions. Diatom analysis showed that mottled silt underlying gyttja at Beaver Lake is marine in origin. A radiocarbon age on a twig (10 030 ± 90 BP, TO-9197) extracted from this unit probably closely dates the time of emergence of this site.

Most previously published radiocarbon ages agree with our results. Most marine shell ages lie below or at the boundary of the inferred sea-level curve, and most ages on freshwater sediments fall above or near the boundary of the curve. The large elevation range of marine shell dates older than 12 ka may be due to the fact that the molluscs lived in a range of water depths. In addition, dated molluscs may have been redeposited after death in deeper water. Our results imply that two anomalous ages on plant material (L-331A at 160 m and GSC-1695 at 100 m; Fig. 3) were extracted from till and not

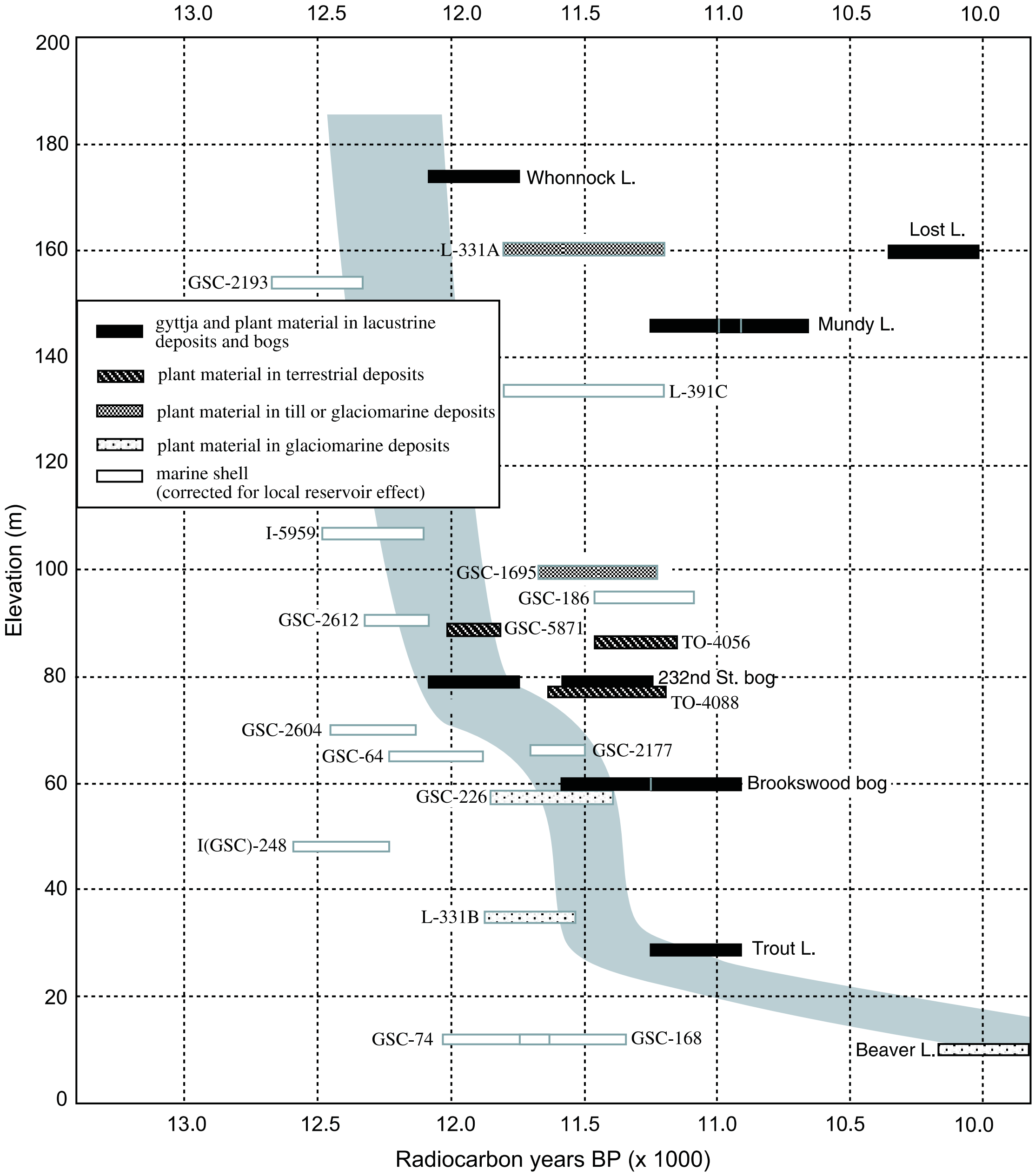

Figure 3. Age-elevation plot of relative sea-level observations and inferred sea-level curve for the Fraser Lowland. Figure conventions as in Figure 2.

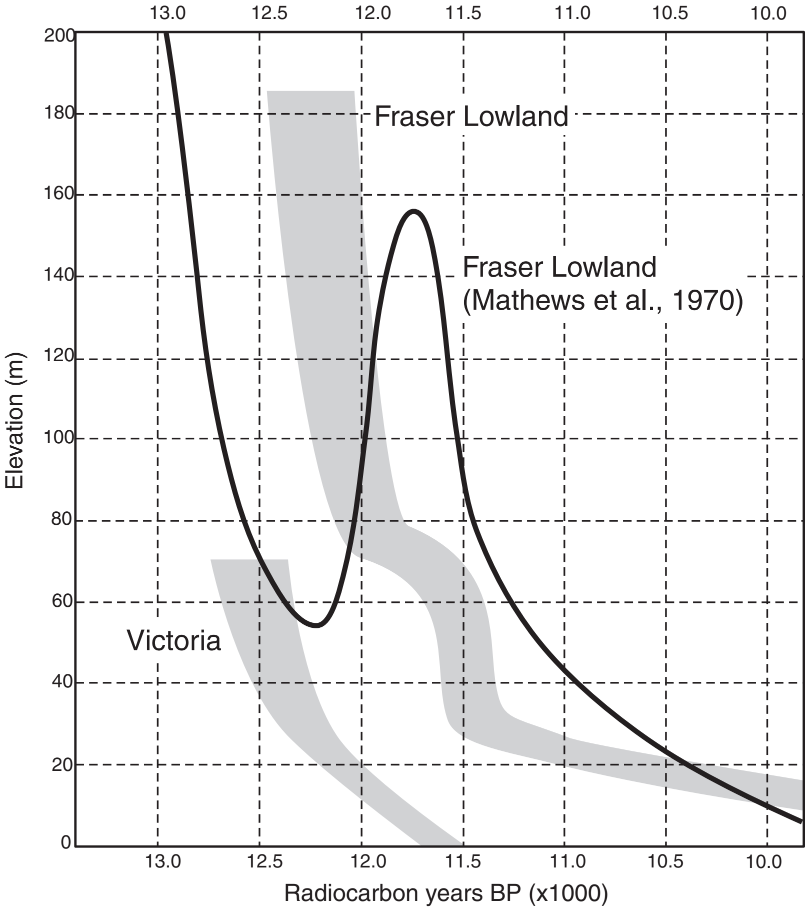

Figure 4. *Inferred relative sea-level curves for Victoria and the Fraser Lowland based on this study and curve for the Fraser Lowland proposed by Mathews et al. (1970).*

glaciomarine sediments. Two ages on plant material from glaciomarine sediments at elevations of 35 and 57 m (L-331B and GSC-226) probably closely date the time of emergence of these sites, and provide evidence for the second phase of rapid sea-level fall around 11.5 ka.

Two dates on marine shells conflict with our results and require explanation. GSC-186 (Dyck et al., 1965) and L-391C (Mathews et al., 1970), at 95 m and 135 m, respectively, are younger than basal freshwater ages from Whonnock Lake (175 m) and 232nd St. bog (79 m). An explanation for this inconsistency may lie with the amount of leaching of the shell samples that was done prior to dating. For example, marine shells dated for this study were leached by 20 to 50% to remove possible contamination of the outer layers of the shells. Dyck et al. (1965) report that the sample that yielded GSC-186 was leached by only 10%. L-391C is a Lamont age. From comments of Olson and Broecker (1959), it is clear that pre-leaching was not standard treatment at that laboratory at the time. It is possible, therefore, that L-391C was not pre-leached.

DISCUSSION AND CONCLUSION

Isolation-basin coring in the Victoria and Vancouver areas has provided important new information on the history of relative sea-level changes. Our preliminary results are summarized in Figure 4.

The new radiocarbon ages from Victoria sites define a fall in sea level from above 60 m a.s.l. to below present level between 12.5 and 11.5 ka. In the Vancouver region, uninterrupted freshwater sequences at two sites at 79 and 175 m indicate that sea level had dropped from above 175 m a.s.l. to about 80 m a.s.l. by 12 ka and did not subsequently rise above this level. The rate of sea-level fall may have slowed shortly after 12 ka for a few hundred years, but sea level continued to drop to 20 to 30 m a.s.l. by 11 ka and to about 10 m a.s.l. by 10 ka.

The apparent slowing of sea-level fall in the Fraser Lowland after 12 ka could be due to the Sumas advances, which occurred before about 11.9 ka and shortly after 11.3 ka (Clague et al., 1997). Postglacial rebound modelling could test this hypothesis and could also indicate whether low-amplitude (a few metres to 10 or 20 m?) resubmergence and subsequent emergence events are possible.

Our results differ from the 100 to 200 m resubmergence and re-emergence event around 11 to 12 ka previously proposed for the Fraser Lowland and adjacent Puget Lowland (150–200 m, Easterbrook, 1963; about 100 m, Mathews et al., 1970; about 130 m, Armstrong, 1981). Comparison of Fraser Lowland sea-level curves (Fig. 4) reveals that the initial emergence of Mathews et al. (1970) is about 400 years earlier than suggested by this study, probably because marine-reservoir corrections were not applied to their marine-shell ages. The resubmergence event is based on radiocarbon ages that disagree with our isolation-basin results. As discussed above, the disagreement may stem, at least in part, from evolving radiocarbon-laboratory protocols in the 1950s and 1960s.

Ice loading during the Sumas advance was suggested as a mechanism to produce this large vertical displacement (Easterbrook, 1963). However, the thickness and areal extent of the Sumas advance seems too small to produce 100 m or more of vertical motion. With the new data presented here, large-amplitude resubmergence and re-emergence can be ruled out, resolving a fundamental problem.

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