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Marine cores from the continental shelf edge of British Columbia (Canada) demonstrate that sea level at the shelf edge was 153 meters below present 14,000 calendar years ago and more than 30 meters lower than the maximum eustatic low of −120 meters. Dated artifacts, including stone tools, indicate that humans occupied this region by at least 10,200 calendar years before present (B.P.). Local sea level rose rapidly (5 centimeters per year) during the period of early human occupation as a result of eustatic sea-level rise and glacio-isostatic forebulge movement. This shelf edge site was first elevated and then subsided. The exposed shelf edge was available for human occupation and may have served as a migration route during times of lowered sea levels between 13,500 and 9500 ^{14}C years B.P.

The continental shelf of British Columbia and the coastal fjord embayments reveal evidence of postglacial sea level that changed rapidly about 14,000 years ago (*1–4*). Contemporaneous but regionally tilted paleoshorelines are documented at elevations from +200 m (*5*) at the head of Kitimat Fiord (Fig. 1) to −140 m at the continental shelf edge, a distance of 200 km.

Mapping the paleoenvironments and locating early human remains along these inferred paleocoastlines is of special interest with respect to extending the possible human migration routes to North America beyond those recently reported (*6*) in the Bering Strait. Here we combine data from seismic reflection mapping and piston coring in the offshore with archaeological, faunal, floral, and ^{14}C analysis to reconstruct the postglacial sea-level history and paleoenvironments of the Gwaii Haanas (*7*) region of the Queen Charlotte Island archipelago (Figs. 1 and 2) and specifically Juan Perez Sound.

To establish the age and elevation of paleoshorelines, we identified and cored formerly subaerial basins (Fig. 2) with sills at different elevations and dated the paleocontacts between freshwater and marine sediments (*8, 9*). In the study area, numerous isolated basins formed during glaciation with sills at different elevations. The transition from freshwater basinal sedimentation to marine deposition was determined by analysis of diatoms from core samples. The age of the marine inundation was determined mostly from ^{14}C-dated wood fragments. We preferentially dated twigs and cones to avoid errors introduced by ancestral wood. Sill depth was obtained from hydrographic field sheet data, published charts, and sounding data obtained along seismic profiles (Fig. 3). Seismic reflection data collected across the sills were used to determine their composition and relative age. Bathymetric data were merged with terrestrial elevation data (1:20,000) to develop a digital terrain model around the Queen Charlotte Islands (*10*).

Five isolation basins within a 50-km radius (Fig. 2) were located by high-resolution seismic profiling and sidescan sonar. These were sampled by piston or vibracore (*4*). We also cored and dated several lakes near the coast to define the maximum elevation of raised shorelines (*11*). In Juan Perez Sound (Fig. 3), a submerged delta (depth = 153 m) and paleoriver system are evident in seismic data; we sampled these with a vibracore to establish the time of marine transgression. We obtained 267 radiocarbon dates (*12, 13*). The data set consists of 86 dates on archaeological sites, 52 dated raised paleobeach deposits, 30 from lake cores, and 99 from marine cores. Dates on 72 shell-wood pairs indicate a marine reservoir correction of 600 years for shell dates (*12, 14*).

Changes in the ^{14}C production rate or disturbances in the carbon cycle during deglaciation, or both, have affected radiocarbon levels in the atmosphere and produced substantial age plateaus at ^{14}C ages of 9600, 10,000, and 10,500 ^{14}C years before present (B.P.) (*15–17*). We used dendrochronological and U-Th radiocarbon calibrations (*16, 18–21*), plus additional data from European lake sediment records (*15, 17*), to convert the ^{14}C ages to calendar ages.

The data show that sea level varied from −153 to +16 m between 14,600 and 10,100 calendar years B.P. (Fig. 4 and Table 1). Drowned isolation basins with sills at −107, −80, −45, and +16 m define four of the sea-level curve points. For example, marine incursion of the fjord embayment of Logan Inlet, which has a sill height of −80 m (site 4, Fig. 2, and Fig. 3, left), occurred 12,300 calendar years B.P. Diatom analysis indicated that marine incursion is marked by the transition from a freshwater diatom assemblage including *Tabellaria fenestrata,*

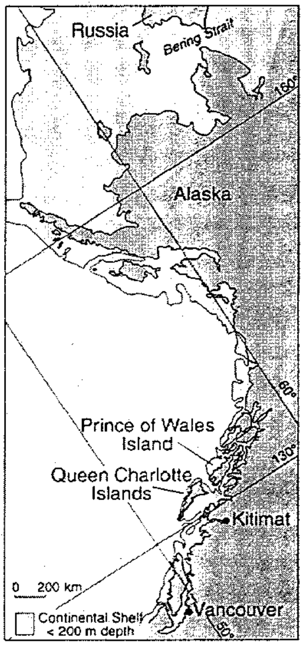

Fig. 1. Index map of the study area showing continental shelf areas shallower than −200 m that may have served as a coastal migration corridor during times of low sea level.

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Diatoma tenue, and freshwater *Cyclotella* species to a marine assemblage dominated by *Chaetoceros lorenzianum*. We determined the elevation and age of the raised marine limit by analyzing a core from Arrow Lake (site 1, Fig. 2, and Fig. 5), which lies 16 m above present-day mean sea level. Here a marine incursion is marked by the transition of a freshwater diatom assemblage dominated by *Frustulia rhomboides* and species belonging to the genera *Aulacoseira* and *Eunotia* to a brackish water assemblage including *Rhopalodia gibba*, *Mastogloia* spp., and *Gyrosigma*, as well as some planktonic marine species, such as *Paralia sulcata*. The return to freshwater conditions is marked by the disappearance of brackish and marine taxa and the reappearance of freshwater species of *Aulacoseira*, *Frustulia*, and *Tabellaria*.

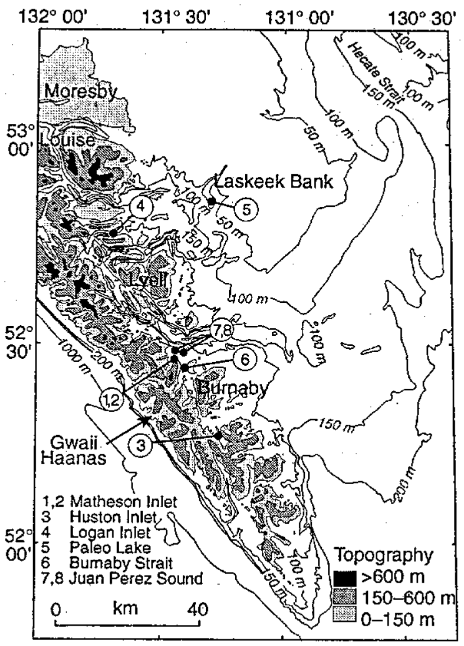


Fig. 2. Relief map of southern Queen Charlotte Islands and bathymetry map of adjacent Laskeek Bank and Hecate Strait. Numbers show the location and names of individual study sites referred to in the text.

Two cores from Matheson Inlet with a paleodelta at −25 m (site 2, Fig. 3, right) record the marine inundation. Fauna in core M1 (Fig. 3, right) shift from the intertidal mollusk *Mytilus edulis* in a coarse gravel matrix to the subtidal mollusks *Lucina annulata*, *Chlamys rubidus*, and *C. hericus* in a mud matrix. In core M4, the transition is marked by a shift from the upper intertidal agglutinated foraminifer *Trochammina pacifica* to marine foraminifera.

Seabed mapping, based on high-resolution seismic reflection and sidescan sonar and swath bathymetry data, revealed a meandering drowned river sequence in a depth up to 153 m (Fig. 3, right) that drained into the glacially overdeepened central fjord basin (*22*). The seismic and vibracore data define the transition from delta topset to foreset beds at a depth of −153 m. This drowned river was also sampled 1 km and 6 km upstream from the paleodelta at water depths of −141 m (core 59) and −110 m (core 11). All three cores show a similar division into lower, middle, and upper units, corresponding to transitions from freshwater to brackish and then to marine conditions. The observed diatom assemblage successions are coincident with marked changes in lithology, from relatively fine-grained sequences at the sea floor to variable but generally sandy mud with abundant organic debris within the brackish to freshwater interval (*23*). In all three cores, siliceous microfossils of diatoms were sparse in the lowermost coarse sediments (sandy gravel). The transition between this lowermost unit and the overlying unit is very abrupt, both in the core and seismic profiles, suggesting that this unit has been rapidly transgressed by the sea.

The diatom record at the marine inundation in core 59 (*23*) reflects a brackish to marine, shallow nearshore environment. The finer silty sediments contain a more diverse assemblage of diatoms dominated by *Cocconeis scutellum*, *C. stauroneiformis*, *Rhoicosphenia curvata*, and *Paralia sulcata*. The fossil diatom assemblages preserved in the uppermost unit of all five cores are typical of offshore marine (neritic) environments.

Dates on the transgressive sequences indicate that shorelines were 140 m below

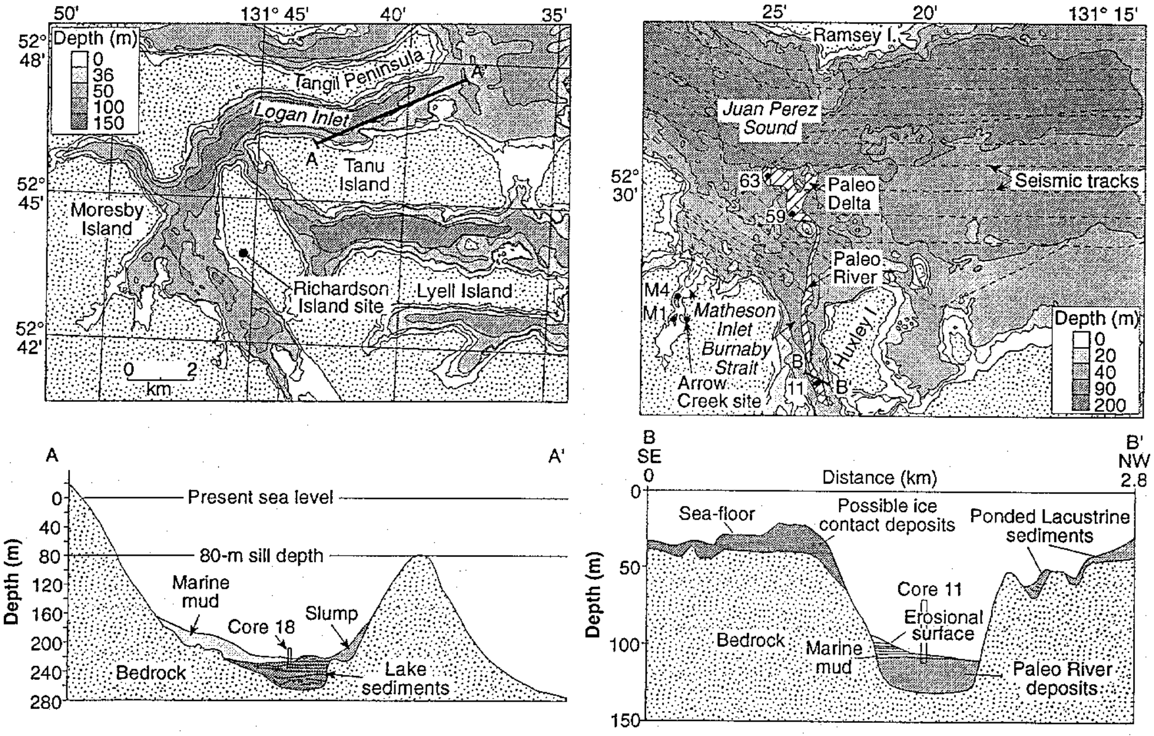
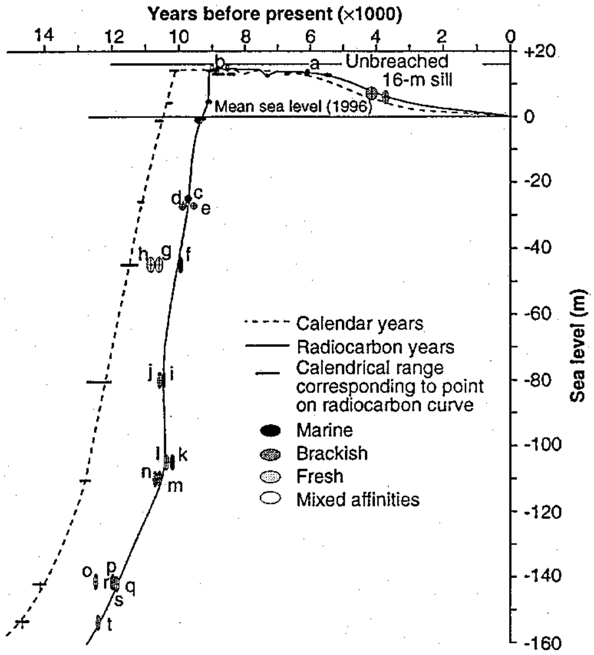


Fig. 3. (**Left**) Bathymetric map of Logan Inlet (site 4) and interpreted geological cross section (A-A') of the fjord and sill. The interpretation is based on 630-cm^3 airgun and 3.5-kHz seismic reflection profile data. A 12-m piston core penetrated the marine and paleolake sediments and reveals a sharp contact between horizontally stratified lacustrine deposits and the overlying slumped marine deposits. (**Right**) Bathymetric map of Juan Perez Sound and Burnaby Strait showing location of cores as well as the interpreted extent of a paleoriver–delta deposit. Seismic reflection tracks, which consisted of Huntec Deep Tow System high-resolution sparker, Seistec, and 3.5-kHz subbottom profilers, as well as 100-kHz sidescan sonar, are shown as dashed lines. The interpreted cross section of Burnaby Strait (B-B') shows the paleoriver deposits sampled by core site 11.

^{14}C age (years B.P.)	Calibrated age (years B.P.)	Uncertainty (years)*	Sea level (m)	Rate of sea-level rise (m/year)
9,050	10,100	75	+14	0.038 ± 0.010
9,150	10,200	75	+4	
9,400	10,500	75	-1	0.045 ± 0.009
9,800	11,100	75	-26	0.051 ± 0.009
10,000	11,450	250	-45	
10,500	12,300	350	-80	
10,700	12,750†	150	-110	0.023 ± 0.003
12,000	14,100	200	-142	
12,400	14,600	200	-153	

*Uncertainties are based on an assumed sea-level versus radiocarbon age curve (Fig. 4) and estimated uncertainties in the calibration data. †Based on extrapolation of coral data from about 11,000 ^{14}C years B.P. (*18–20*).

Table 1 (above). ^{14}C to calendar year correction table showing calculated rate of relative sea-level rise measured between data points shown on the sea-level curve. **Fig. 4 (right).** Sea-level curve plotted against radiocarbon years B.P. The dashed line shows sea levels plotted against calendar years. Letters refer to particulars of dates shown in (*13*). Cross hairs in ovals indicate errors in ^{14}C dating and definition of sill depth.



present at about 12,000 ^{14}C years B.P. Contemporaneous deltas are exposed 200 m above sea level at the fjord head near Kitimat, 200 km to the east-northeast (Fig. 1) (*5*). This significant tilt in coeval shorelines is attributed to the presence of a thick Cordilleran ice sheet, which depressed the Coast Range mountains and interior of British Columbia by as much as 250 m (*2*). This load displaced the underlying mantle to the glacier margin at the shelf edge to form a peripheral bulge. Because glacial ice on the continental shelf was limited to localized piedmont lobes and local ice caps in Gwaii Haanas (*22*), it did not significantly load the outer shelf, thus allowing a forebulge to develop.

Postglacial isostatic recovery at Kitimat was rapid; the maximum rate of relative sea-level fall was about 10 cm/year (*5*). The associated collapse of the forebulge caused a rapid rise in relative sea level at the shelf edge (*4*). The paleodelta in Juan Perez Sound at −153 m marks the maximum lowstand and is about 33 m deeper than the maximum last glacial-eustatic lowering of 120 m (*20, 24*) and 63 m deeper than the predicted eustatic sea level of 90 m at 12,400 ^{14}C years ago. We suggest that the crust may have been locally elevated to 63 m, the height of the glacial forebulge. (We have not attempted to correct for hydroisostatic effects, in view of the limited ice volumes interpreted for the area.)

Detailed examination of the ^{14}C ages reveals that some ages are out of sequence; however, all of these are within the 30 to 50 cm range of biogenic reworking from mollusk burrowing. Some of the apparent rapid jumps in the raw sea-level curve (Fig. 4) may be an artifact of nonlinearities in the radiocarbon calibration curve. Apparent rapid sea-level jumps from −26 to 0 m, −40 to −26 m, and −110 to −80 m correspond to plateaus in the calibration curve at 9600, 10,000, and 10,500 B.P. and probably span several hundred calendar years. Conversely, the apparent stillstands at −26 and 0 m lie on steep portions of the curve at radiocarbon ages of 9000 to 9500 years B.P. and 9600 to 10,000 years B.P. and represent very short calendar intervals. Despite a dense network of ^{14}C dates, the extremely rapid rate of sea-level rise (maximum = 5 cm/year), combined with biogenic reworking and ^{14}C uncertainties (plateaus), leads to insufficient precision needed to identify potential stepwise tectonic crustal movement. Regional seismic reflection surveys (*4*) show no evidence of faulted postglacial deposits. A comparison of postglacial crustal adjustment rates with rebound on

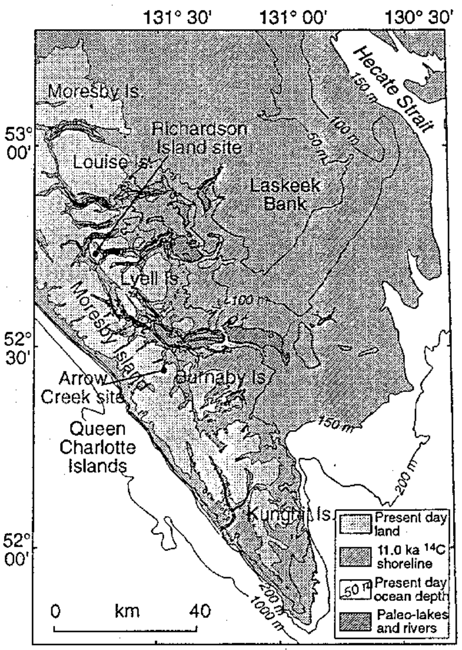


Fig. 5. Inferred areas of terrestrial exposure on Laskeek Bank during times of maximum lowered sea level as indicated by the sea-level curve.

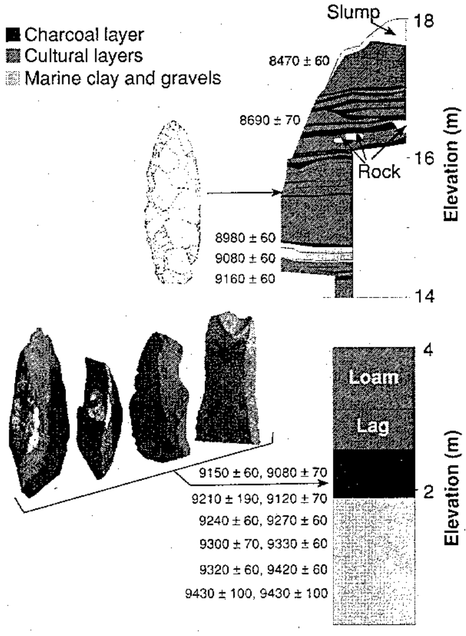


Fig. 6. Archaeological evidence for early human occupation of the study area within the period of rapidly changing sea levels. Details are given in (*34*).

passive margins [for example, Maine, maximum = 2.2 cm/year (*25*)] and mid-ocean ridges [for example, Iceland, maximum = 6.9 cm/year (*26*)] illustrates the influence of mantle viscosity and tectonic setting on the rate of recovery.

The recent discovery of human remains (9880 ± 50 ^{14}C years B.P.) in a cave on Prince of Wales Island (*27–29*) immediately north of the Queen Charlotte Islands (Fig. 1) highlights the potential for eventual discovery of early postglacial human occupation of Gwaii Haanas and the adjacent submerged areas of Hecate Strait. Our evidence for marked paleoenvironmental changes in Gwaii Haanas from late-glacial to mid-Holocene time offers insights into the distribution of habitable landscapes (Figs. 5 and 6) along the northern Northwest Coast. Paleobotanical analyses have demonstrated that the Northwest Coast was suitable for human habitation by 13,000 years B.P. (*30, 31*). Stone tools found on paleobeach sites confirm human occupation by 9300 ^{14}C years B.P. (Fig. 6). The lack of evidence for human use of the early postglacial landscape may be largely attributable to the drastic and rapid changes in past sea levels. Gwaii Haanas coastlines dating from 9300 to 9100 years B.P. coincide with those of today, coastlines dated before 9300 are deeply drowned (to −153 m), and those dating from 9100 to 5000 years B.P. are stranded in the rainforest some 15 m above current levels. In this context, it is interesting that the Gwaii Haanas Haida Indian oral history abounds in legends of rapidly rising seas (*32*).

The sea-level curve (Fig. 4) provides an important tool that enables archaeologists to focus their studies in search of paleobeaches and paleohabitats (*33, 34*). The opportunity to locate evidence of human activity dating to the period of lowered sea levels may be better some 150 km to the east, along the British Columbia coast, where isostatic dynamics resulted in coeval raised marine deposits now situated >200 m above modern sea level.

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13. Table of sample parameters and dates that bracket the interval of marine versus brackish or lacustrine conditions recorded in the piston or vibracore samples. The sill height is shown for sites where the constraining sill depth is shallower than the core site. Many of the ^{14}C dates were derived from young wood fragments to avoid errors introduced by dating of ancestral wood. Table available to *Science* Online subscribers at www.sciencemag.org/
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23. Composite diagram of core 59 showing the relations between lithology, diatom assemblages, interpreted depositional environments, and ^{14}C age. The age of marine inundation was plotted against water depth at the core site to develop the sea-level curve. Figure available to *Science* Online subscribers at www.sciencemag.org/
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