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Geology of Holocene Liquefaction Features Along the Lower Columbia River At Marsh, Brush, Price, Hunting, and Wallace Islands, Oregon and Washington

Compiled by Brian F. Atwater[1]

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[1] U.S. Geological Survey at Department of Geological Sciences, University of Washington, Seattle, WA 98195

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ABSTRACT

An earthquake about 300 years ago produced many liquefaction features now exposed at low tide along the lower Columbia River. These bodies of intruded and extruded sand were discovered in 1992 by Stephen Obermeier. Reconnaissance by Obermeier and several coworkers in 1992, and field work by a larger field party in 1993, led to the findings compiled in this report.

The field work in 1993 comprised geologic surveys of low-tide outcrops, collection of core samples of underlying deposits, and engineering tests of the underlying deposits. It was carried out by some 20 geologists, civil engineers, and volunteers. The work was done at three pairs of islands: Marsh and Brush Islands (33-34 km inland), Price and Hunting Islands (44-45 km inland), and lower and upper parts of Wallace Island (57-59 km inland). The outcrops surveyed at these islands were selected for maximum low-tide exposure of deposits old enough to record shaking from the most recent major plate-boundary seismicity at the Cascadia subduction zone, which has been dated elsewhere to within a few decades of A.D. 1700. For the six islands together the length of surveyed shore totals nearly 3 km and the outcrop area about 10,000 m^2. A dozen vibracores 7.5 cm in diameter provided samples of deposits as much as 6 m beneath surveyed outcrops, and a portable penetrometer gave readings of resistance to penetration to depths of 4-6 m at 29 sites among the six islands.

All the surveyed outcrops are located along eroded banks of infrequently inundated, shrubby or forested wetlands of low relief along tidal channels of the Columbia River. These wetlands, herein termed swamps, are part of an along-the-river transition from floodplain to tidal marsh.

As of A.D. 1700, the sites of the surveyed outcrops were probably hundreds of meters from large channels toward which land could have spread during liquefaction. Such distances are implied by shoreline erosion since 1870, which has exceeded 100 m at surveyed parts of most or all the six islands. The greatest of this historical erosion occurred at Marsh Island (up to 350 m), Price Island (up to 250 m) and upper Wallace Island (up to 350 m along the Columbia River side, and about 600 m at the upriver tip).

The surveyed islands are founded on sand many meters thick and are widely capped by mud a few meters thick. The sandy foundation contains lenses of mud and of plant fragments, and the muddy cap at many of the surveyed outcrops contains two marker beds about 500 years old beneath a buried soil that is probably about 300 years old. The lower marker bed dates to the 1400s if, as is likely, the upper marker bed consists of ash and pumice probably erupted from Mount St. Helens beetween A.D. 1479 and 1482.

The sandy foundation and muddy cap together record the construction and maintenance of marshes and swamps at sites that had been occupied by channels or subtidal bars within the past 2000 years. Most of the muddy cap at many or all of the surveyed outcrops accumulated within and just above the intertidal zone. The lower part of the muddy cap at Marsh, Price, and Hunting Islands contains growth-position fossils that record upward shoaling from a tidal flat to a marsh or swamp.

The muddy cap at Marsh Island, and perhaps at most of the surveyed other islands as well, contains evidence for renewed intertidal submergence after construction of a marsh or swamp. Such evidence at Marsh Island consists of growth-position tubers of a tidal-flat plant, *Scirpus fluviatilis*, in mud above a buried soil that contains tree roots in growth position. Radiocarbon ages, tree-ring counts, and inferred stratigraphic correlations together suggest that the submergence resulted from a plate-boundary earthquake about A.D. 1700.

Surveyed parts of all six islands display bodies of sand that were emplaced through liquefaction. About 200 of these are intrusions--mainly vertical dikes no more than a few centimeters wide--exposed at low tide. Extruded sand crops out above the level of the highest intrusions at Marsh, Brush, Price, and Hunting Islands; it forms lenses less than 2 cm thick that mantle the buried soil within a few meters of a high-level intrusions. Additional liquefaction features are present beneath the surveyed outcrops, where they have been identified in vibracore by continuity with an exposed dike, by lack of lamination, by presence of angular clasts of mud, and

(or) by contacts at high angle to bedding. The deepest of these, found beneath Hunting Island 3-4 m below modern low-tide level, include a probable dike that cuts through nearly 30 cm of horizontally laminated mud.

All the liquefaction features seen in outcrop probably formed within a few decades of A.D. 1700, particularly those intrusions and extrusions in contact with the buried soil. The liquefaction features seen in vibracore from Hunting Island formed either at that time or earlier in the past 2000 years; the probable dike seen cutting through laminated mud is situated 1.5 m above laminated sand from which a stick gave an age of 1670 ± 70 ^{14}C yr B.P.

The bodies of intruded and extruded sand resulted from earthquake-induced liquefaction. All of them formed far from any natural levees tall enough to produce sand boils during floods; some of them taper upward as if injected from below; and some can be shown to date to a time of an earthquake about 300 years ago. It is unclear, however, which of the dikes welled passively upward into cracks that had been opened by lateral spreading, and which occupy cracks that had been forced open by high-pressure water.

The shaking responsible for the liquefaction probably came from a chiefly offshore rupture at the boundary between the subducting Juan de Fuca plate and the overriding North America plate. A plate-boundary source is likely because the features probably date to the time of plate-boundary seismicity about 300 years ago at the Cascadia subduction zone. A chiefly offshore location for the rupture is consistent with--but not strongly indicated by--differences among the surveyed islands in the size and abundance of intrusions. These differences may depend less on distance from the earthquake source than on such local factors as the thickness of the muddy cap, the properties of the sandy foundation, and the distance from channels toward which land could have spread 300 years ago.

The combination of geologic and engineering data from the surveyed islands allows identification of plausible source sand for the liquefaction features seen in outcrops and cores. The loosest plausible source is the sand with the lowest blow counts beneath areas with exposed liquefaction features. Denser but still-plausible source sand underlies the lowest parts of probable dikes seen in vibracores at Hunting and Marsh Islands. Shaking within the past 2000 years probably liquefied some of the densest of the tested sand beneath the surveyed islands.

INTRODUCTION

Liquefaction features along the lower Columbia River are important for several reasons. As of early 1994 these bodies of intruded and extruded sand offered the only strong evidence for inland shaking from prehistoric plate-boundary seismicity at the Cascadia subduction zone (Obermeier and others, 1993). Engineering interpretation of the features may yield numerical estimates of that shaking (Palmer and others, 1993) for comparison with ground motions that geophysicists have deduced from speculation about source parameters and attenuation of plate-boundary earthquakes at the Cascadia subduction zone (Heaton and Hartzell, 1989; Wong and Silva, 1990; Crouse, 1991; Youngs and Coppersmith, 1989).

Study of liquefaction features along the lower Columbia River began in the summer of 1992 when they were discovered by Stephen F. Obermeier, a civil engineer with the U.S. Geological Survey. Follow-up study in 1993 included field work focussed on six islands between about 30 and 60 km from the coast (Figure 1). The 1993 work included geologic surveys of low-tide outcrops, engineering tests of underlying deposits, and collection of core samples of the tested deposits.

This report presents most of the information gathered during the 1993 work at the six islands. It tells who did the work, how it was done, and what was learned about the geology of the liquefaction features. The report also includes a few 1992 findings that bear on the age of the features.

The report offers no numerical estimates for the shaking recorded by the liquefaction features. It does provide, however, some of the information upon which such estimates could be based.

ACKNOWLEDGMENTS

Although I did some of the field work, compiled the illustrations, and wrote the text, this report is based mainly on work by many other people: Lorin Amidon (volunteer, 1992), Patricia Atwater (11-year-old daughter), Boyd Benson (U.S. Geological Survey [USGS] in 1992, volunteer in 1993), Catherine Chatfield (USGS), John Bertelling (Portland State University [PSU]), Scott Craig (PSU), Stephen Dickenson (Oregon State University [OSU]), Murray Hay (University of Calgary [UC]), Eileen Hemphill-Haley (USGS), Harry Jol (UC), Roger Lewis (USGS), Ian Madin (Oregon Department of Geology and Mineral Industries), Richard McMullen (Nuclear Regulatory Commission), Mary Meek (PSU), Richard Meyers (UC), Coby Menton (USGS), Lynn Moses (Washington Department of Transportation), Stephen Obermeier (USGS), Stephen Palmer (Washington Division of Geology and Earth Resources), Curt Peterson (PSU), James Phipps (Grays Harbor College), Timothy Roberts (OSU), John Shulene (volunteer), Daryl Smith (UC), Maureen Soar (PSU), David Tabaczynski (USGS in 1992, volunteer in 1993), Paul Travis (PSU), and Daryl Wieneke (PSU). Some of these persons worked on the project for many weeks, others for as little as day. The section below on methods spells out roles played by most of them.

Access to the outcrops depended largely on loans of two motorboats and a canoe. One of the motorboats came from the National Oceanic and Atmospheric Administration through Lew Consiglieri. Pat Gearin of the National Marine Fisheries Service provided a trailer for it, and Bill Wollenzier of Longview, Washington, fixed its motors. The other motorboat came from the Washington Department of Natural Resources, courtesy of Bud Clark. Eileen Hemphill-Haley loaned the canoe.

Steve McLane of Skamokawa Vista Park set aside camping space for many in the field party. He and his staff graciously allowed several of us to compile and plot survey data on a computer owned by Wahkiakum County Port District Number 2.

Funding for engineering tests by Steve Dickenson and Tim Roberts, and for vibracoring by Curt Peterson and his students, came indirectly from the Nuclear Regulatory Commission through grants to Steve Obermeier and me. State transportation departments of Oregon and Washington loaned the portable penetrometers used for the engineering tests.

Steve Palmer reviewed this report, Steve Dickenson provided insightful comments on early drafts of Figure 3 and Table 7, and Pat Pringle contributed Table 4.

METHODS

Selection of outcrops

In July of 1993 I selected outcrops for surveys that would lay geologic groundwork for engineering studies planned for later in the summer. These outcrops are located on three pairs of islands: Marsh and Brush Islands, 33-34 km inland from the coast; Price and Hunting Islands, 44-45 km inland; and lower Wallace Island (three outcrops) and upper Wallace Island (two outcrops), 57-59 km inland (Figure 1, Figure 2; Table 1). Many of them had been recommended by Steve Obermeier, who in 1992 found prehistoric liquefaction features along the Columbia River from a few kilometers west of Marsh Island to an inland limit at lower Wallace Island (Figure 1).

In selecting outcrops I sought maximum low-tide exposure of deposits old enough to record shaking between A.D. 1680 and 1720, which is the time of the most recent major plate-boundary seismicity along t he southern Washington and northern Oregon coast (see "Buried soil" beginning on p. 17). Such antiquity can be widely inferred in outcrop from the presence of a pair of marker beds. The upper of these marker beds probably correlates with a volcanic eruption about A.D. 1480 (see "Beige layer" on p. 19).

Various additional factors influenced the selection of certain islands and outcrops:

- Marsh Island is located near the western limit of the liquefaction features recognized by Steve Obermeier in 1992. The outcrop selected at Marsh Island displays the largest dike that he had found.
- Brush Island provided a second western outcrop. Parts of that outcrop are more riddled with dikes than any other outcrop selected.
- Price Island was as far from Skamokawa as the field party dared take an unreliable motorboat. The outcrop selected at Price Island borders a stand of ancient Sitka spruce, ring counts of which provide limiting ages for marker beds and a buried soil used to date some of the liquefaction features (see "Age" beginning on p. 19 and on p. 23).
- Hunting Island offers a wave-washed, nearly horizontal outcrop at least six times larger than any of the other outcrops surveyed (Table 2).
- Outcrop B at lower Wallace Island includes the most inland of the liquefaction features that Steve Obermeier found along the Columbia River in 1992. Outcrops A and C are the only other large ones on the island that display the marker beds.
- The two outcrops at upper Wallace Island add to the evidence for liquefaction near the inland limit of liquefaction features recognized in 1992. Outcrop A contains a dike about half as wide as the widest recognized dike at Marsh Island.

Additional field work in 1993 showed that liquefaction features are present along the Columbia River farther inland than Wallace Island. Some are at Deer Island, where they were discovered by Lynn Moses (Obermeier and others, 1993); others are near Portland (Siskowic and others, 1984). Description of these features is beyond the scope of this report.

Surveys of outcrops

Detailed surveys of the outcrops selected in 1993 began in early July and continued intermittently through the middle of August. Most of the work was done during six-hour intervals centered on daytime low tides with predicted levels a few tenths of a meter below mean lower low water. The main tasks were to set up horizontal and vertical coordinates and to measure low-tide levels, stratigraphic features, liquefaction features, and outcrop dimensions. Most of the results of the surveys, and of accompanying subsurface studies, are plotted with great vertical exaggeration in Figure 3. Additional diagrams summarize outcrop and subsurface stratigraphy (Figure 4) and the orientation and abundance of intrusions (Figure 5, Figure 6).

Coordinates and low tides

Catherine Chatfield, John Shulene, Coby Menton, and Dave Tabaczynski established the horizontal coordinate systems for Figure 3 by setting stakes at 10-m intervals from arbitrary starting points. They made most of the stakes from flotsam and flagging and positioned them along tape-measured lines. The tape-measured lines were straight or gently curved; they did not closely follow irregularities of the shoreline, and they ran tangent to promontories on embayed shorelines. Horizontal coordinates for surveyed features were estimated or measured from the nearest 10-m stake.

Vertical control came from leveling by instrument and water surface. Most of the leveling was done by Catherine Chatfield, Patricia Atwater, John Shulene, Coby Menton, Eileen Hemphill-Haley, and me. We used a tripod-mounted level to measure differences in height with respect to a local datum for each outcrop. We created the local datum by assigning an arbitrary height of 10.00 m to the first bench mark that we set on an outcrop. Distances between bench marks at individual outcrops did not exceed 90 m, and closure errors did not exceed 5 cm. Closure errors were measured by sighting back to the day's initial bench mark, or by sighting to water and measuring its level with respect to that bench mark.

Meter sticks served as tide gages monitored chiefly by Catherine Chatfield, John Shulene, and me. At each island we measured low tide, in relation to the local datum, on several different days (Figure 3). The tide usually stayed within a few centimeters of the plotted level for at least 1/2 hour.

Stratigraphy

To document the stratigraphic setting of liquefaction features the leveling party measured the horizontal and vertical positions of marker beds, plant fossils, and soils. Catherine Chatfield and I identified most of these stratigraphic features. Some are plotted with unshaded symbols on the cross sections in Figure 3: marker beds (polygons), tree roots (concentric circles), herbaceous tubers (hearts). The others, plotted solid black, are modern and buried soils (rectangles; plotted at top of soil), localized sheets of extruded sand (circles), and mud beds (ovals; plotted from outcrop at upper Wallace Island only).

The surveyed soils, extruded sand, tree roots, and marker beds provide the vertical control for the hachured line that denotes the approximate or inferred level of the swamp surface during the liquefaction inferred to date from about A.D. 1700 (Figure 3, parts a-f). I plot this line through the top of the buried soil, immediately beneath the extruded sand, through or slightly above the roots, and above the marker beds. At the west-northwest end of the Hunting Island outcrop, however, I drew the hachured line beneath an enigmatic spruce root that is apparently in growth position. This root is not superposed with a buried soil but is situated entirely above the level of a buried soil seen only a few meters to the east (Figure 3d).

I plotted the stratigraphic features on cross sections with the vertical scale expanded about fiftyfold. This vertical scale greatly exaggerates slope of the inferred swamp surface and of other stratigraphic boundaries.

Liquefaction features

The leveling party also surveyed most bodies of intruded and extruded sand noted in outcrop. The intrusions were mainly identified by Catherine Chatfield, John Shulene, Steve Obermeier, Eileen Hemphill-Haley, Roger Lewis, Dave Tabaczynski, Dick McMullen, Patricia Atwater, and me. Using shovels we followed most intrusions to their highest observable level and noted whether this level marks the top of the intrusion (dark gray squares on the cross sections in Figure 3, parts a-f) or is merely a modern erosional surface that intersects the intrusion (light gray squares on those cross sections). We routinely noted dike width only where it exceeded 2 cm.

We recorded strike for most of the planar dikes (gray squares on graph above cross sections, Figure 3; summary in Figure 5). But we rarely noted dip, which for most of the intrusions is nearly vertical.

Outcrop dimensions

To gage the abundance of intrusions the field party measured the approximate area of outcrop in which intrusions could be both present and observable. Those mainly responsible for the outcrop-area measurements are Catherine Chatfield, John Shulene, Boyd Benson, Dave Tabaczynski, Coby Menton, Patricia Atwater, and I. The measurements, plotted on the lower bar graphs in Figure 3, can be compared with the tally of intrusions, which is shown on the upper bar graphs in those figures. Figure 6 presents such a comparison for each surveyed island, paired by distance from the Pacific coast.

The outcrop whose area we measured extends upward from low tide to the lower of the marker beds (the gray layer) or, at upper Wallace Island, to the highest observed dike at the outcrop. Ideally, we would have measured low-tide outcrop to the level of the land surface that dates from the time of liquefaction. However, a buried soil from such a land surface is not evident anywhere at Wallace Island, nor is one widely mappable at any of the other surveyed outcrops except at Marsh Island. The gray layer, by contrast, is the most obvious stratigraphic marker at most of the surveyed outcrops, and it is old enough--it is probably 500-600 years old (p. 19)--to predate the probable time of liquefaction by at least 200 years.

We made two separate measurements of outcrop area for each 10-m interval along the line of horizontal-control stakes: horizontal outcrop, for slopes averaging less less than 45 degrees and typically less than 10 degrees (filled bars on lower bar graphs in Figure 3); and vertical outcrop, for steeper slopes (open bars on those graphs). The measurements included intervals where the shoreline was several meters longer than 10 m because the trend of the shoreline diverged from the trend of the staked line. For such intervals I have reported the total area measured, without adjustment for shoreline trend (Figure 3, Figure 6; Table 2, Table 6).

Whatever the trend and condition of the outcrop, I report the length of the surveyed shore as the length measured along the line of horizontal-control stakes. The length of outcrop may be greater than that length where the outcrop deviates from the trend of the staked line. Conversely, the length of outcrop is less than the reported shoreline length where much of the outcrop is covered by modern intertidal deposits.

For the six islands together the length of surveyed shore totals nearly 3 km and the outcrop area totals about 10,000 m^2 (Table 2). At all but upper Wallace Island the length of surveyed shore exceeds 300 m. Horizontal outcrop at Hunting Island accounts for three-quarters of the six-island total of outcrop area.

Subsurface studies

Among a total of 200 sand intrusions noted at the surveyed outcrops, only a few intrusions at upper Wallace Island have probable source beds shallow enough for inspection at low tide. To learn about potential source beds the field party probed deeper deposits by means of hand augers, vibracores, and penetration tests. Results of these tests are plotted on the cross sections in Figure 3.

Auger borings

Hand augering with a narrow cylindrical barrel revealed depths to sand beds thicker than a few tenths of a meter at Marsh, Price, Hunting, and lower Wallace Islands. Most of this augering was done by Coby Menton, Boyd Benson, and Dave Tabaczynski. They used a steel half-cylinder 1 m long and 2 cm in diameter (Dutch corer), to which they attached standard soil-auger extension rods and a T-shaped handle. The Dutch corer does not easily penetrate sand more than 0.3 m thick.

Hand augering with a bucket 8 cm in diameter cut through sand beds the Dutch corer could not penetrate. Such augering was done at all penetration-test sites at Price, Hunting, and lower Wallace Islands and at the Washington-penetrometer sites at Marsh Island (see p. 8). Steve Palmer, Tim Roberts, Steve Dickenson, Steve Obermeier, and Coby Menton did the work.

Results of both kinds of augering are represented by gray circles on the cross sections in Figure 3, parts a-f. The circles approximate the depth to the highest sand bed greater than 0.3 m thick. Where depths differ greatly among nearby sites, the difference may be largely due to a gradational and (or) steeply inclined contact between mud above and sand below (see p. 14), or to the Dutch corer's failure to penetrate a lens of sand.

Vibracores

Aluminum irrigation pipe vibrated into the ground provided scarcely disturbed samples 7.5 cm in diameter through as much as 6 m of sandy section. A total of 13 such cores were obtained from five of the six islands. The location and depth range of the cores are shown by dashed vertical lines on the cross sections in Figure 3, parts a and c-g.

Marsh, Hunting, and Wallace Islands

Eleven vibracores were drilled at Marsh, Hunting, lower Wallace, and upper Wallace Islands by Curt Peterson, Scott Craig, Mary Meek, Paul Travis, and Daryl Wieneke. Curt and coworkers drilled the cores in multiple segments; for example, they would obtain a core of the uppermost 2 m, then put a fresh barrel into the open hole and vibrate it into deeper deposits. In most cases they measured the depth to the bottom of only the lowest segment.

Maureen Soar, Scott Craig, and Curt Peterson logged the cores in Portland a few weeks after collection. The sandy parts of a core from Hunting Island (VB-7) and two from Marsh Island (VB-9, VB-14) were logged further by Steve Palmer, Curt Peterson, and me four months after collection. Accompanied by Maureen Soar and Scott Craig, we brought out sedimentary structures by brushing damp sand with a soft paintbrush.

Price Island

Daryl Smith, Murray Hay, Harry Jol, and Rick Meyers drilled two vibracores at Price Island. Daryl and coworkers used a single barrel for each core and extruded both cores on the island, where I logged them.

Uncertainties in depth

Depths assigned to most features in the vibracores are imprecise because the thickness of the cored deposit commonly differs from the length of the recovered core. Labels in Figure 3 (parts a, c-e, and g) state the resulting uncertainties for most of the mud beds and liquefaction features seen in the cores.

For many cores the uncertainties in depth result from differences of about 0.5 m between the thickness of the cored deposit and the length of recovered core. Some of the recovered samples exceeded the combined length of the penetrated segments by as much as 0.6 m, while others were too short by as much as 0.6 m (Hunting Island) or 1.0 m (Price Island). Such differences are shown by downward arrows and upward arrows, respectively, in Figure 3 (parts a and c-g).

Reasons for the differences are poorly known. The excessive samples probably include material that fell into an open borehole between drilling of successive segments. For the samples that are too short, mud may have flowed around a barrel plugged with sand, sampled deposits may have fallen from the barrel as it was lifted from the hole, and (or) sand may have compacted while being vibrated by the barrel.

Penetration tests

Susceptibility to liquefaction is commonly estimated from the degree to which granular deposits resist penetration by steel cylinders or rods. In most commonly used method, termed the standard penetration test, a 130-pound (59 kg) weight is dropped onto a rods connected to a core barrel with an outside diameter of 2 inches (5 cm). The number of such hammer blows needed to advance the core barrel into a standard thickness of deposit tends to vary inversely with susceptibility to liquefaction (Seed and Idriss, 1982).

For slippery low-tide outcrops Tim Roberts, Steve Palmer, Steve Dickenson, Steve Obermeier, and Coby Menton used non-standard but portable penetrometers, herein termed the Oregon penetrometer and the Washington penetrometer. They recorded the number of blows required for a free-falling weight to drive the penetrometer 6 inches (15 cm).

The blow counts that record resistance to penetration are plotted beside thin vertical lines on the cross sections in Figure 3. Each vertical line shows only the range of levels tested with the penetrometers; the top of the line is no more than a few tenths of a meter below the uppermost sandy deposits judged in the field to be thick and clean enough to be candidates for liquefaction. Such deposits are commonly at least 1 m below the level of the low-tide outcrops. Tim and coworkers identified the sandy deposits in samples retrieved in Dutch corer (Oregon-penetrometer sites at Marsh Island) or bucket auger (all other penetrometer sites).

In all cases I have plotted the counts as recorded in the field. I did not adjust them for calibration with standard penetrometer tests, nor did I adjust the counts for depth.

Oregon penetrometer

Most of the blow counts were made with the Oregon penetrometer--a probe with a conical tip 1 inch (2.5 cm) in diameter driven by a 20-lb (9.1-kg) weight dropped 18 inches (46 cm). Tim Roberts and his coworkers counted blows in a total of 654 six-inch intervals among 29 Oregon-penetrometer holes (Table 2; Figure 7). Nearly one-third this effort was devoted to Hunting Island.

The small diameter of the Oregon penetrometer allowed continuous blow-count measurement to considerable depth with little or no resistance from friction against the side of the probe or extension rods. Tim and his coworkers checked for friction by making sure that the string of probe and rods spun freely. They made such a check once for every 4 feet (1.2 m) of penetration.

Reproducibility of the Oregon-penetrometer blow counts was checked by making penetration tests at a pair of sites a few meters from one another at Hunting Island (OR-H-4 and OR-H-8, Figure 3e). The paired tests, made three days apart, gave conflicting results in the upper few meters; in one case a blow count of 5 at OR-H-4 aligns with counts in the high 20s at OR-H-8. The conflicts are probably due to complex subsurface geology: mud lenses or beds are abundant and are cut by sand intrusions in a vibracore drilled within a few meters of both penetrometer holes (VB-7). I doubt the conflicts are due to error in vertical coordinates for the plotted counts. The blow counts from OR-H-4 would agree better with those from OR-H-8 if the former were moved upward by 0.5 m. But depths below ground surface are recorded clearly in notes of the penetrometer party, and those depths put the conflicting blow counts side by side if the ground-surface levels are about the same for the two penetrometer sites. I believe that the ground-surface levels are about the same, for the outcrop had little relief, and surveying notes indicate that the top of OR-H-4, as leveled August 15, is 3 cm higher than the top OR-H-8, leveled August 18.

To summarize blow counts from the Oregon penetrometer I plot the counts from each surveyed island against an approximate or inferred outcrop-wide average for the level of the land surface about A.D. 1700 (Figure 7). I do not omit any counts that were probably made for layers of mud or plant fragments, such as the eight successive counts of 0 at Price Island site OR-P-4. All counts are also included in the statistical summaries to the right of the graphs. I use a land-surface datum from A.D. 1700 because that is the probable round-number age of most or all of the exposed liquefaction features at each island (see "Age" on p. 23). For each of four islands--Marsh, Brush, Price, and Hunting--I estimate an average land-surface level ca. 1700 from the levels of buried soils observed in outcrop (solid rectangles in Figure 3, parts a-d). For lower Wallace Island I assume that the 1700 land surface, like the 1700 land surface at those four islands, is located a few tenths of a meter above the upper marker bed (the beige layer). For upper Wallace Island I plot the 1700 land surface just above the highest level to which I traced dikes in outcrop.

Washington penetrometer

The Washington penetrometer consists of a conically tipped probe 2 inches (5 cm) in diameter that was driven by a 35-lb (16 kg) weight dropped 30 inches (76 cm). Steve Palmer led in the use of this not-so-portable device at Marsh, Hunting, and Wallace Islands. I plot his results only for Marsh and lower Wallace Islands (Figure 3, parts a and e); elsewhere the Washington-penetrometer data are obviated by more comprehensive and reliable data from the Oregon penetrometer.

The Washington penetrometer has a diameter large enough for friction along the side of the probe to increase the blow counts above what would be obtained from resistance at the tip alone. To minimize such friction Steve and coworkers used a bucket auger to create an open hole above each tested interval. Each tested interval comprised three sections 6 inches long. The highest of these sections commonly contained loose material from the walls of the hole. Only the counts from the other two sections are plotted in Figure 3 (parts a and e). In all cases the count for the bottom section is as high (2 cases) or higher (28 cases) than the count for the middle section. In some cases the downward increase in blow counts may be due to the skin-friction problem. A test at upper

Wallace Island showed that skin friction greatly increased blow counts with the Washington penetrometer if the probe was driven without prior augering to the top of the tested interval.

Additional studies

Particle-size analysis

Steve Palmer and John Bertelling checked for interstitial silt and clay, which can retard the liquefaction of sand (Seed and Idriss, 1982), by measuring the particle-size distribution of some of the sand beneath the surveyed outcrops. Steve used carefully trimmed samples from bucket augering at lower Wallace Island; John used vibracore samples from upper Wallace, lower Wallace, Hunting, and Marsh Islands. Owing to uncertainties in depths of vibracore samples (see "Vibracores" above), the vertical positions of most of John's samples are plotted less precisely than Steve's.

Both Steve and John made their particle-size measurements with sieves. For the boundary between sand and silt John used 0.063 mm, while Steve used 0.063 mm for some samples and 0.074 mm for others.

The percentage of mud (silt and clay) is plotted in Figure 3 (parts a, c-e, and g) within circles for the 0.063-mm boundary and within squares for the 0.074-mm boundary. Steve's numbers appear in italics.

Correlation and dating

Limiting ages of liquefaction features along the lower Columbia River have been obtained by correlation of soils and tephra, by radiocarbon analysis, and by counting of tree rings. The ages are important for estimating the extent of shaking that could have occurred during a single earthquake, and for identifying the source of the shaking as an earthquake at the boundary between the Juan de Fuca and North America plates (see p. 25).

Soils

Stratigraphic markers juxtaposed with the liquefaction features include a buried soil at Marsh, Brush, Price, and Hunting Islands (Figure 3, parts a-d; Figure 4). The soil, and the presence of sand vented upon it, were recognized in 1992 by Steve Obermeier, Dave Tabaczynski, and Curt Peterson.

The buried soil probably correlates with the uppermost buried soil at other Pacific coast estuaries in southern Washington and northern Oregon (Obermeier and others, 1993), which records abrupt lowering and consequent tidal submergence of coastal land about 300 years ago (Atwater, 1987, 1992; Darienzo and Peterson, 1990; Darienzo and others, 1994). Eileen Hemphill-Haley and I tested this inferred correlation by asking whether tidal submergence triggered burial of the soil at Marsh, Brush, Price, and Hunting Islands. We looked for contrasts like those at the nearby estuaries, where the uppermost buried soil contains growth-position remains of plants that live at or above high-tide levels, and where deposits above the soil have the lithology and fossils of tidal flats (Atwater, 1987, 1992; Grant and McLaren, 1987; Darienzo and Peterson, 1990; Hemphill-Haley, 1992; Darienzo and others, 1994). I checked the buried soil for growth-position fossils of vascular plants--especially the roots of spruce and cottonwood, which at today's Columbia River estuary live only at or above high-tide levels (Thomas, 1983, 1984). I also checked mud above the soil for tubers of *Scirpus fluviatilis* (Figure 8), a sedge which at today's Columbia River estuary flourishes only on freshwater tidal flats (Thomas, 1984). The fossils I recognized are plotted in Figure 3 and Figure 4 (see p. 17). Eileen studied diatoms in soil and mud samples smeared on glass slides and viewed under a petrographic microscope at Skamokawa (p. 17). Interpretation of all the fossils is discussed under "Paleobathymetry" beginning on p. 18.

Tephra

Some of the liquefaction features intrude a pair of marker beds that underlie the buried soil. These beds were recognized widely in 1992 by Curt Peterson, Steve Obermeier, and Dave

Tabaczynski. The upper of the beds contains abundant volcanic ash and, at Marsh and Brush Islands, locally contains pebbles of pumice.

To test possible correlation with tephra identified and dated elsewhere, Pat Pringle checked the mineralogy of pumice from the upper marker bed at Marsh Island. He crushed the pumice and compared its mafic-phenocryst mineralogy with that reported for tephra layers from the three volcanoes nearest the surveyed islands: Mounts Rainier, St. Helens, and Hood (Figure 1; Table 4). His findings are discussed under "Marker beds" (p. 16) and "Beige layer" (p. 19).

Radiocarbon ages

Deposits in contact with the liquefaction features commonly contain plant fragments suitable for radiocarbon dating. Along with Eileen Hemphill-Haley and Patricia Atwater, I collected radiocarbon samples from outcrops at Marsh, Price, Hunting, lower Wallace, and upper Wallace Islands. In addition, Curt Peterson, Steve Palmer, and I took radiocarbon samples from vibracores at Marsh and Hunting Islands. Results of the dating are plotted in Figure 3 and Figure 4, and details are listed in Table 5.

I obtained radiocarbon ages on single sticks; on sedimentary peat composed of twigs, spruce needles, and other millimeter-size plant fragments; and on tubers of *S. fluviatilis*. The sticks and the plant fragments in the sedimentary peat took their carbon from the atmosphere before they were deposited; they provide limiting-maximum ages for deposition. By contrast, the tubers provide limiting-minimum ages for the deposits into which they grew.

All the ages were measured by benzene methods at a commercial laboratory, Beta Analytic, Inc. The ages were calculated for the Libby half-life and an assumed $\delta^{13}C$ value of -25 parts per thousand. I report all the ages in conventional radiocarbon years before A.D. 1950 (^{14}C yr B.P.), along with the standard error quoted by the laboratory. For some ages I also mention in the text corresponding ranges of approximately calendric years (in years A.D. or in years ago; for the latter I use round numbers referenced to the 1990s). These ranges are based on radiocarbon-calibration data of Stuiver and Pearson (1993), as used in revision 3.0.3 of the calibration program of Stuiver and Reimer (1993). Each range includes the 95-percent confidence interval if the error quoted by the lab equals no less than 0.5 standard deviations of the age measurement (I used an error multiplier of 2.0).

Tree-ring counts

Although killed forests are rooted in the uppermost buried soil at Pacific coast estuaries in southern Washington (Yamaguchi and others, 1989; Atwater, 1992), some trees at the edges of the killed forests have managed to survive in what is now a transition from floodplain to tidal swamp (Benson and others, 1992). Several such survivors bordered the surveyed shore of Price Island in 1992 and 1993 (Figure 9).

The survivor spruce at Price Island are useful for dating liquefaction features because they have multiple levels of roots. The live roots of the trees rarely extend more than a few tenths of a meter below ground level--a growth habit typical of Sitka spruce on wet soil (Day, 1962). However, similarly horizontal but dead roots are attached to the trees about 3/4 m below present ground level, at the approximate level of a buried soil onto which liquefied sand vented (Figure 3c). Because the lower roots probably originated while the soil was forming, and because inner rings within the trunks of the trees probably formed early in the lifetime of the lower roots, the innermost rings of the trunks predate deposits that overlie the soil (see p. 20), including extruded sand.

Rings of survivor spruce at Price Island were first cored and counted in 1992 by Boyd Benson and Lorin Amidon. One of these cored trees fell over less than a year later, probably during the Inauguration Day windstorm of January, 1993 (Figure 3c, tag number 60). Boyd and I sawed slabs from the trunk and roots of this fallen tree in August, 1993. Boyd subsequently checked ring counts both in the tree cores and on sanded slabs. All the counted samples from trunks were collected 1-2 m up the trunks from the 1992 ground surface.

Boyd used the ring counts to assign calendar dates to inner rings of several of the survivors (Figure 3c). He dated the innermost ring (the pith) in cores of one standing tree (tag number 70) and in a slab of the fallen tree (tag number 60). For a third tree the core did not reach the pith, so the date plotted is later than the date of the pith (tag number 99).

Historical changes in shorelines

Distance to shorelines can affect the amount by which land spreads through gravity-driven flow within underlying liquefied deposits. During the 1964 Alaska earthquake, level alluvial ground along The Alaska Railroad cracked most commonly within 150 m of streams and rarely cracked more than 300 m from them (McCulloch and Bonilla, 1970, p. D54). Lateral spreading observed for this and other earthquakes further shows that total horizontal displacement above liquefied deposits tends to increase toward channels that provide an unsupported (free) face toward which the liquefied deposits can flow (Bartlett and Youd, 1993, their chapters 3 and 4).

For prehistoric liquefaction features exposed along the lower Columbia River the relevant shorelines are those of A.D. 1700--the likely round-number date of the shaking responsible for most or all of the liquefaction features described in this report (see "Age" on p. 23). Although the locations of such prehistoric shorelines can only be inferred from geologic evidence, shorelines of the lower Columbia River were mapped accurately about 175 years after 1700. These nineteenth-century shorelines can be compared with modern shorelines to provide limiting minimum estimates for the distance to free faces ca. 1700.

The earliest historical maps that accurately depict the shorelines, bathymetry, and vegetation of the surveyed islands are 1:10,000-scale hydrographic and topographic sheets made in the 1860s and 1870s by the U.S. Coast Survey (Table 3). Although such Coast Survey maps can be subject to large errors (Shalowitz, 1964), accuracy of shorelines shown on the Columbia River maps has been demonstrated through comparison with modern photographs, maps, and larger-scale topographic surveys (Thomas, 1983, App. B). Furthermore, in their portrayal of wetland vegetation the U.S. Coast Survey maps far surpass modern topographic maps of the lower Columbia River; the Coast Survey topographers drew separate symbols for unvegetated tidal flat, unvegetated sandy flat above high tide, patchy incipient marsh on tidal flat, continuous marsh, shrubby wetland, and forested wetland. The Coast Survey maps provide no key to these symbols, but most of the symbols resemble natural features that can be seen today along the lower Columbia River. Along with the accuracy reported by Thomas (1983), that resemblance makes me confident in the comparisons shown in Figure 2.

Catherine Chatfield and I obtained paper copies of the historical maps by means of a microfilm printer at the National Oceanic and Atmospheric Administration library in Seattle. I reduced these copies to about 1:24,000 scale by means of an ordinary photocopier. To register the historical maps with the modern maps I matched junctions or sharp meanders of small sloughs that I assume to have undergone less historical change in location than have shorelines exposed to large wind waves and ship wake. Owing to uncertainties in registration and in the maps themselves, my estimates of shoreline change might be wrong by as much as 75 m for Hunting Island and by as much as 50 m for the other islands.

SETTING

Landforms and vegetation

All the liquefaction features surveyed are located along eroded banks of infrequently inundated, shrubby or forested wetlands of low relief beside tidal channels of the Columbia River. These wetlands, herein termed swamps, are part of an along-the-river transition from floodplain to tidal marsh.

Few if any of the surveyed islands are likely to have had modern or historical natural levees more than a meter high. Natural levees and crevasse splays are evident in modern riverside topography--at former swamps that have been diked and cleared--no farther downstream than the upstream end of Wallace Island (south side of river on Oak Point 7.5-minute quadrangle; contour interval 5 ft [1.5 m]). Natural levees at Wallace Island itself can be inferred from vegetation mapped in the 1870s (Table 3); these maps depict the fringe of the island as more heavily wooded than the interior. But such woodlands did not border any of the other surveyed islands about 1870, and with respect to low tide the modern swamp surface stands only about 1 m higher at upper Wallace Island than at the other surveyed islands (Figure 3, Figure 4).

The most conspicuous plants of the surveyed islands are willow and dogwood at Marsh and Brush Islands, Sitka spruce at Price and Hunting Islands, and cottonwood at Wallace Island. Details about the botany of swamps and marshes seaward of Hunting Island have been presented by Thomas (1984) and Macdonald (1984).

Tides and floods

The river water that surrounds and occasionally overtops the surveyed islands is both fresh and tidal. River flow keeps the water fresh (year-round salinity <0.5 parts per thousand) as far downriver as Marsh Island, the most seaward of the surveyed islands (Columbia River Estuary Data Development Program, 1984, pl. 3-5). But tides largely control the level of the water: the range between the average of the lower of the two daily low tides (mean lower low water) and the corresponding average for high tides (mean higher high water) increases seaward from 1.7 m near upper Wallace Island to 2.5 m near Marsh Island (National Oceanic and Atmospheric Administration, 1993). Owing to river flow, the level of mean lower low water is about 0.4 m higher at Wallace Island than at Marsh Island, as measured with respect to a geodetic datum (Simenstad and others, 1984, p. 89).

Large historical floods along the lower Columbia River probably crested several meters above the swamp surface at the surveyed islands. An estimated profile for the largest such flood, in June of 1894, shows crest heights of about 5 m in the vicinity of Wallace Island and about 4 m near Marsh Island, with height referenced to local mean lower low water (Simenstad and others, 1984, p. 89). Corresponding figures for the largest twentieth-century flood along the lower Columbia, in June of 1948, are about 4 m and 3 m. By contrast, the modern swamp surface at the surveyed outcrops stands about 2 m above mean lower low water except at upper Wallace Island, where the swamp surface is closer to 3 m above mean lower low water (Figure 3). I saw no sign of inundation of the swamps by high tides in the summer of 1993, but at most of the surveyed islands I noted plenty of bank-top flotsam that could have been deposited during floods.

Historical changes

Marsh, Brush, Price, Hunting, and Wallace Islands contain among the largest remnants of marsh and swamp that bordered waterways of the lower Columbia River in the 1800s. U.S. Coast Survey maps made in the 1860s and 1870s depict about 70 km^2 of marsh and about 120 km^2 of swamp on Columbia River floodplains and islands downstream of Wallace Island. About half that marsh and three-quarters of the swamp disappeared by 1980 (Thomas, 1983, p. 18).

Although human diking and draining account for most of the historical reduction in wetland area (Thomas, 1983), some swamp has also disappeared through erosion. Between about 1870 and 1980 the shoreline retreated at least 100 m at surveyed parts of all the studied islands with the possible exception of Hunting Island (Figure 2; Table 3). The greatest of this erosion occurred at Marsh Island (up to 350 m), Price Island (up to 250 m, about 1/3 of that since 1959; Table 3) and upper Wallace Island (up to 350 m from the northwest, and about 600 m from the northeast).

Inferred shorelines of 300 years ago

The large amounts of historical erosion can be used to guess the location of the surveyed outcrops with respect to the nearest waterway that could have provided a free face for lateral spreading during liquefaction about A.D. 1700 (see p. 11). The erosion suggests that during the liquefaction about 1700, most or all of the surveyed outcrops were hundreds of meters from the such a free face. Moreover, except perhaps at Hunting and upper Wallace Islands, the erosion since 1870 has been so rapid that the channels now beside the surveyed outcrops may have been farther from them in 1700 than were other, lesser waterways:

- For most of the surveyed parts of Marsh and Brush Islands the nearest major free face in 1700 may have been an ancestral Marsh Island Creek rather than a larger waterway to the northwest (Figure 2). Marsh Island Creek has not shifted enough since 300 years ago to remove the marker beds about 500 years old that crop out on both banks of the creek (gray and beige layers in Figure 3, parts a and b; age inferred under "Age" beginning on p. 19). I am aware of no strong evidence, however, that Marsh Island Creek even existed about 300 years ago.

- Similarly at Price Island, the nearest free face may have been an ancestor of Steamboat Slough rather than the main river channel to the southwest (Figure 2). Situated on the cut-bank side of a major bend in the Columbia River and also subject to attack by wind waves from the west (Figure 1b), Price Island in the past 300 years has doubtless undergone more than the 200-250 m of erosion along the Columbia River since the 1870s.
- The free face in 1700 nearest the Hunting Island outcrop could have been the main channel of the Columbia River, or it could have been an ancestor to the slough southeast of the southeast end of the surveyed outcrop (Figure 2).
- At lower Wallace Island the nearest free face in 1700 may have been either to the northwest or to the southeast of the surveyed outcrops. If the lower Wallace Island of 1700 extended as far north as the elongate islet of swamp entirely removed by erosion since 1874 (Figure 2), the nearest free face in 1700 probably lay to southeast, where the shore of Wallace Island has been stable or has prograded slightly since the 1870s.
- The historical shoreline changes at upper Wallace Island are too great to provide much guidance about the location of free faces in that area in 1700. Possibilities include a nearby free face to the southeast of both surveyed outcrops.

Sites with historically stable shorelines would probably offer better control on the location of free faces 300 years ago. However, I do not know of any such sites that have extensive low-tide outcrop of deposits at least 300 years old.

STRATIGRAPHY

The surveyed islands are founded on sand many meters thick and capped by mud a few meters thick. The sandy foundation contains lenses of mud and of plant fragments, and the muddy cap at many of the surveyed outcrops contains marker layers about 500 years old and a buried soil that is probably about 300 years old. The deposits record the construction and maintenance of tidal marshes and swamps at sites that had been occupied by channels or subtidal bars within the past 2000 years.

Sandy foundation

Thickness and composition

Vibracores show that deposits dominated by sand are at least 4 m thick beneath Marsh, Price, Hunting, lower Wallace, and upper Wallace Islands (Figure 3, parts a, c-e, g; Figure 4). The maximum thickness documented at the surveyed outcrops is 7 m at upper Wallace Island, where the uppermost part of the sandy foundation is exposed at low tide (Figure 3g). Sand probably continues to depths greater than those reached in the subsurface studies; none of the vibracores bottomed in non-sandy deposits except at Price Island, where mud makes up most of the lowest 1.5 m of vibracore VB-G4 (Figure 3c).

Most of the sandy foundation consists of arkosic, micaceous, fine to coarse sand that is distinctly stratified. Horizontally laminated, fine and medium sand predominates in the lower two-thirds of vibracore VB-14 at Marsh Island and in many other vibracored sections as well. Fine and medium sand with inclined lamination is exposed at low tide in a horizontal bed at least 0.3 m thick at upper Wallace Island, outcrop B (Figure 10). Inclined lamination is also present in coarse sand in the lowest meter of Hunting Island vibracore VB-7.

The sandy foundation contains local concentrations of mud, plant fragments, and gravel. Mud beds less than 10 cm thick are common high in the sand at upper and lower Wallace Islands (Figure 3, parts e and g). Mud beds or lenses are also present lower in the section in some cores at other islands, especially in Hunting Island vibracore VB-7 (Figure 3d) and in the lowest 1.5 m of Price Island vibracore VB-G4 (Figure 3c). The mud low in the section at Price Island may be continuous with the deposits through which the Oregon penetrometer was pushed (blow counts of 0) at nearby penetrometer site OR-P-4. Plant fragments a few millimeters long abound in two of the mud beds exposed at upper Wallace Island outcrop A, and they form layers interbedded with sand in upper Wallace Island vibracore VB-4 and in Marsh Island vibracores VB-9, -10, and -14. Two beds of pebbly sand are present in the lowest meter of Hunting Island vibracore VB-7 (Figure 3d).

Contact between sandy foundation and muddy cap

The upper part of the sandy foundation commonly grades into the muddy cap. At most places the gradation is accomplished by interbedding, but at some places the sand itself becomes muddy. To depict gradation, and to allow for uncertainties in delineating the top of the sandy foundation, I use a dotted line to represent the contact between sandy foundation and muddy cap in Figure 3.

Upper Wallace Island most clearly displays interbedding of mud and sand high in the sandy foundation. Nearly all the mud beds in the sandy foundation at upper Wallace Island are confined to the upper 2 m of the sand (Figure 3g). Most of them are exposed at low tide (Figure 10, Figure 13).

Muddy sand is common in the upper 2 m of the sandy foundation at lower Wallace Island outcrop B. In that interval the sand commonly contains more than 10 percent interstitial or thinly interbedded mud, as shown by particle-size analysis (Figure 3e).

Overall upward gradation from sand to mud probably contributes to differences among nearby auger borings, vibracores, and penetration-test holes in the vertical position of the uppermost mud-poor sand plotted in Figure 3 for Marsh, Brush, Price, Hunting, and lower Wallace Islands. Such differences are shown in Figure 3 by scatter among shaded circles, which represent the uppermost sand thicker than about 0.3 m in augers and vibracores (see p. 6, 7), and by their vertical separation from the highest blow counts, which were measured on the shallowest sand estimated to be clean enough to liquefy (p. 7). Circles near one another horizontally commonly differ in vertical position by several tenths of a meter, and similar differences are common between circles and highest blow counts. Some of the differences are probably due to inclined contacts, which needn't have much dip to appear steep at the fifty-fold vertical exaggeration of the cross sections in Figure 3. In addition, differences involving vibracores might be due entirely to uncertainties in assigning depths to the recovered cores (see p. 7).

Resistance to penetration

Deposits in the upper few meters of the sandy foundation yielded Oregon-penetrometer blow counts less than 25 per 6 inches at all surveyed islands (Figure 7). Some of the counts associated with mud-poor or mud-free sand are less than 10 (Table 7).

Deposits low in the sandy foundation, however, yielded much higher blow counts at Price and Hunting Islands than at the other islands (Figure 7). Many of the Oregon-penetrometer counts at Price and Hunting Islands are in the 30s and 40s per 6 inches.

Although I do not know what accounts for the high blow counts at Price and Hunting Islands, I doubt that absence of mud, depth of burial, age, or seismic history play much of a role:

- Mud-free sand typically has blow counts less than 20 per 6 inches in the sandy foundation at Marsh and upper Wallace Islands (Figure 3, parts a, g). Conversely, mud beds are present in sand cored a few meters horizontally from deposits that yielded blow counts near 30 per 6 inches (Hunting Island, vibracore VB-7 and penetrometer tests OR-H-4 and OR-H-8; Figure 3d).
- Depths to the high blow counts at Price and Hunting Islands are in the range of depths of lower blow counts at Marsh, lower Wallace, and upper Wallace Islands, whether measured with respect to the modern land surface (Figure 3, parts a, c-e, g) or to the land surface about 300 years ago (Figure 3, parts a, c-e, g; Figure 4, Figure 7).
- Radiocarbon ages differ little between sand at the depth of blow counts in the 30s and 40s per 6 inches beneath Hunting Island and sand with blow counts near 10 per 6 inches at Marsh Island. The ages, which are the only ones available from the sandy foundation (Figure 4), are 1670 ± 70 ^{14}C yr B.P. at Hunting Island and 1300 ± 90 ^{14}C yr B.P. at Marsh Island. Both ages were measured on plant fragments likely to have formed shortly before deposition--a single bark-bearing stick at Hunting Island, many fragments of leaves and twigs at Marsh Island (Table 5).

The dated stick at Hunting Island came from core VB-7, and the high blow counts there came from the nearest deep penetrometer holes, OR-H-7 and OR-H-9 (Figure 3d). The dated plant fragments at Marsh Island came from core VB-9, the blow counts from OR-M-1 (Figure 3a).

- The sand with high blow counts beneath Hunting Island is unlikely to have had much greater opportunity to densify during earthquakes than has the sand with low blow counts beneath Marsh Island. Among the two to four major earthquakes that may have occurred along the lower Columbia River since deposition of the dated sand at Hunting Island, two have occurred since the deposition of the dated sand at Marsh Island. I estimate two to four major earthquakes since 1670 ± 70 ^{14}C yr B.P. by extrapolation from the Copalis River. There, about 100 km north of the mouth of the Columbia River (Figure 1a), one or two plate-boundary earthquakes probably occurred between 1500 and 2000 years ago, additional seismicity probably occurred between 900 and 1300 years ago, and another plate-boundary earthquake occurred close to 300 years ago (Atwater, 1992).

Depositional environment

Several points suggest that the sandy foundations of the surveyed islands were constructed mainly in subtidal water:

- Sand is the main bottom sediment along the lower Columbia River at low-tide water depths greater than 1 m (Hubbell and Glenn, 1973; Sherwood and others, 1984; Columbia River Estuary Data Development Program, 1984). This modern sand ranges from very fine to coarse, with particle size tending to increase upriver between Marsh Island and Wallace Island (Simenstad and others, 1984, p. 203-209). Typically it is laminated and commonly it is interbedded with mud (Hubbell and Glenn, 1973, p. 20-22).
- Mud beds within the sandy foundation lack intertidal fossils in growth-position, particularly the *Scirpus fluviatilis* tubers that in the Columbia River estuary are indicative of muddy intertidal flats (see p. 9).
- Now situated below low-tide level, most of the sand sampled beneath the islands could not have formed within or above the intertidal zone unless relative sea level[2] during deposition was improbably low. Relative sea level at nearby estuaries in Washington and Oregon has undergone only a few meters' rise in the past 2000 years (Hutchinson, 1992; Peterson and Phipps, 1992). Along the lower Columbia River itself, a net rise of barely 1 m in the past 1000 years is suggested by the radiocarbon-dated *S. fluviatilis* tubers in the muddy cap at Marsh, Price, and Hunting Islands. The age and present intertidal position of these fossil intertidal indicators shows that that the intertidal zone has risen by no more than about 1 m since sometime between 350 and 800 years ago at Marsh Island, 750 and 1350 years ago at Price Island, and 600 and 1000 years ago at Hunting Island (see "Age" on p. 15).

Deposition in an abandoned slough far from the main channel of the Columbia River may best explain the thick mud deep beneath Price Island at vibracore site VB-G4 (Figure 3c). Later migration of the river, such as the 200-m shift since 1871 (Figure 2, Table 3), could easily account for the present riverside location of the site.

The main exception to a probably subtidal origin is upper meter or two of the sandy foundation at upper Wallace Island. This interbedded sand and mud probably accumulated within and perhaps partly above the intertidal zone. U.S. Coast Survey map T-1401b (Table 3) shows a possible historical analog for such deposition: unvegetated sand above high tide at the upstream tip of Wallace Island in 1874 (Figure 2). I assume that this nineteenth-century sand accumulated during floods, historical examples of which crested several meters above the forested surface of upper Wallace Island (see p. 12).

Age

The sampled part of the sandy foundation is probably less than 2000 years old beneath all surveyed outcrops (Table 5, Figure 4). This estimate is based on the dating of two samples: the

[2] Relative sea level denotes the level of the sea with respect to the local land.

stick in the lowest meter of sampled sand beneath Hunting Island that yielded an age of 1670 ± 70 ^{14}C yr B.P., and the plant fragments higher in sand beneath Marsh Island that yielded an age of 1300 ± 90 ^{14}C yr B.P.

Ages from the muddy cap show that the upper part of the sandy foundation is more than 500 years old at Marsh, Brush, Price, Hunting, and lower Wallace Islands (Figure 4). Radiocarbon ages of tubers and sticks in the muddy cap show that the uppermost part of the sandy foundation accumulated before 1140 ± 70 ^{14}C yr B.P. at Price Island, before 780 ± 60 ^{14}C yr B.P. at Hunting Island, and before 590 ± 70 ^{14}C yr B.P. at Marsh Island (Table 5). In addition, radiocarbon ages on twigs or individual bark-bearing sticks deposited in the muddy cap--detritus unlikely to be much older than their time of deposition--imply that the uppermost part of the sandy foundation accumulated before 880 ± 50 ^{14}C yr B.P. at Hunting Island and before 630 ± 50 at lower Wallace Island outcrop C. Converted to calendric years, the ages imply that the sandy foundation had been completed by 750-1350 years ago at Price Island, by 700-1000 (stick) or 600-900 (tubers) years ago at Hunting Island, and by 350-800 years ago at Marsh and lower Wallace Islands. All the radiocarbon ages are consistent with the presence of a marker bed close to 500 years old in the muddy cap at Marsh, Brush, Price, Hunting, and lower Wallace Islands. This marker bed, the beige layer, probably accumulated within a few years of A.D. 1480 (see p. 19).

For upper Wallace Island, by contrast, absence of the beige layer and its accompanying marker bed, the gray layer, suggests that the upper part of the sandy foundation there originated less than 500 years ago. Both the beige layer and the gray layer are conspicuous in the muddy cap at all the other surveyed outcrops, including those at lower Wallace Island (see "Marker beds" on p. 16). Their absence anywhere in the surveyed outcrops at upper Wallace Island suggests that all the exposed deposits at the upper Wallace outcrops accumulated after A.D. 1480. This timing is consistent with a radiocarbon age on plant fragments in a mud bed near the top of the sandy foundation at upper Wallace Island outcrop A (Table 5; Figure 3g, Figure 4). The age, 420 ± 60 ^{14}C yr B.P., implies that the uppermost part of this sandy foundation postdates A.D. 1300.

Muddy cap

Thickness and composition

The muddy cap at the surveyed islands ranges in typical thickness from 2 to 4 m. The cap is thickest at Price Island and thinnest at upper Wallace Island.

The cap consists primarily of clayey silt. Sand is mostly restricted to beds and lenses less than 0.3 m thick within 0.5 m of the contact with the sandy foundation. Sand high in the cap is common only at upper Wallace Island, where the muddy cap contains beds of silty fine sand and fine sand as much as 0.3 m thick.

Much of the muddy cap at all the surveyed islands lacks obvious bedding with a few exceptions--the bedding defined by the marker beds, by the buried soil, and by extruded sand that locally mantles the buried soil.

Marker beds

A pair of distinctive beds crops out in the muddy cap at all the surveyed outcrops except on upper Wallace Island. The lower of these beds consists of gray silt and clayey silt (the gray layer); the upper contains much pale brown volcanic ash (the beige layer). Where coarser than other deposits in the muddy cap, the marker beds can be traced for many meters as wave-etched notches. Such notches highlight the gray layer at lower Wallace Island and at the southeast end of Price Island, and they characterize both the gray layer and the beige layer at Marsh and Brush Islands.

The thickness of the marker beds, and of the intervening mud, varies among the surveyed outcrops and also tends to vary with height (Figure 11). Each bed is commonly 1-3 cm thick, but the gray layer is typically 8 cm thick at lower Wallace Island, and the beige layer attains a maximum thickness of 5 cm at Marsh and Brush Islands. The thickness of the intervening mud ranges from 2 to nearly 20 cm. At Marsh and Brush Islands the thickness of the intervening mud tends to decrease with height relative to a low-tide datum, as does the beige layer at these islands.

At Price Island the intervening mud is thickest where the marker beds are low (horizontal coordinate 231 m in Figure 3).

Neither marker bed shows much sedimentary structure except where the bed is at least 2 cm thick. Structure in the gray layer is most apparent and variable at lower Wallace Island. There, along tens of meters of outcrop B, a basal layer of clayey silt 0.3-1.0 cm thick is overlain by medium to coarse silt 2-3 cm thick, which is in turn overlain by clayey silt 3-4 cm thick. The internal contacts appear gradational. The simple upward coarsening and upward fining at outcrop B contrast with the structure at nearby outrop C, where the gray layer contains two 3-cm-thick laminae of silt among three thinner laminae of clayey silt.

The beige layer displays little horizontal lamination except at Marsh and Brush Islands, where tens of meters of wave-etched outcrops reveal alternating laminae defined by slight differences in particle size. I noted distinct laminae farther east in the beige layer only at Price Island, and there only at horizontal coordinate 231, where the lamination is defined by intercalated leaves.

Pumice pebbles as much as 3 cm in diameter are concentrated here and there in the beige layer at Marsh and Brush Islands. Pumice from the beige layer at Marsh Island contains phenocrysts of hypersthene and hornblende (Patrick T. Pringle, written communication, 1994).

Buried soil

Outcrops of the muddy cap locally display a buried soil about 1/3 to 1/2 m above the beige layer at Marsh, Brush, Price, and Hunting Islands (Figure 3, parts a-d). Only at Marsh island does the soil crop out continuously along more than 10 m of surveyed shoreline.

The soil is marked by its A horizon--dark peaty mud or mud that has an abrupt upper contact and a gradational lower contact. At Marsh Island the A horizon is as much as 20 cm thick; elsewhere it is less than than 10 cm thick. The soil is most evident where mantled by extruded sand (see p. 22).

Fossils

Large fossils of vascular plants

The muddy cap contains vascular-plant fossils that can be seen in outcrop at all the surveyed islands. Many of these fossils are pieces of transported wood, the largest accumulations of which crop out below the marker beds at Price Island, Hunting Island, and outcrop C of lower Wallace Island. Others are woody roots and herbaceous tubers in growth position.

The lowest woody roots are based within the uppermost 0.1 m of the buried soil. Those at Marsh Island are attached to a single dead stump and have the shiny, papery below-ground bark of cottonwood. The woody roots at Price and Hunting Islands, by contrast, have the black bark and resinous odor of Sitka spruce. Most come from dead stumps but a some, at Price Island, are attached to living trees (Figure 3c; see p. 10).

Tubers of *Scirpus fluviatilis* (Figure 8) crop out below the marker beds at Marsh, Price, and Hunting Islands, and they also crop out above the buried soil at Marsh Island (Figure 3, parts a, c, and d). Locally at Marsh Island the tubers are accompanied by rhizomes that probably belong to *Carex lyngbyei*, a sedge common in both low and high parts of freshwater tidal wetlands of the Columbia River estuary (Thomas, 1983, 1984; Macdonald, 1984).

Diatoms

Diatoms are present within the buried soil and within overlying mud at Marsh Island (horizontal coordinate 0 m), Price Island (horizontal coordinate 275 m), and Hunting Island (horizontal coordinate 17 m). Eileen Hemphill-Haley, in a quick inspection of smear slides (see p. 9), noted no major difference between diatom assemblages below the buried soil and those above it.

Depositional environment

Paleobathymetry

Most of the muddy cap at many or all the surveyed outcrops probably accumulated within and just above the intertidal zone. *S. fluviatilis* tubers demonstrate fully intertidal, probably freshwater deposition of much of the mud that crops out below the marker beds at Marsh, Price, and Hunting Islands, and also of mud that crops out above the buried soil at Marsh Island (see p. 9). Such tubers also indicate freshwater intertidal conditions for deposition of mud just above the buried soil at Marsh Island. Less-frequent inundation, probably also by freshwater, is indicated by the buried soil on Marsh, Brush, Price, and Hunting Islands, and by the tree roots in this buried soil at Marsh, Price, and Hunting Islands.

Whereas the lower part of the muddy cap at Marsh, Price, and Hunting Islands records upward shoaling from a tidal flat to the marsh or swamp recorded by the buried soil, the *S. fluviatilis* tubers above the buried soil Marsh Island indicate renewed intertidal submergence. Such submergence occasioned the burial of the soil at Marsh Island; it may have also led to burial of the soil at Brush, Price, and Hunting Islands, for the buried soil at these islands probably correlates with the buried soil at Marsh Island (see "Buried soil" on p. 20); and it may further account for the death of the lowest horizontal roots of the oldest spruce trees at Price Island. Subsequent shoaling at Marsh Island, and perhaps at the other surveyed islands as well, led to establishment of the swamps and marshes mapped in the 1870s.

The submergence marked by the buried soil and overlying tubers at Marsh Island happened abruptly enough to produce a sharp, non-erosional contact between the soil and overlying intertidal mud. I did not note evidence that the mud accumulated around delicate stems and leaves of herbaceous plants that had been living on the soil just before the onset of burial. Such entombed herbs have provided confirmation of abrupt, probably earthquake-induced submergence of unoxidized buried soils at other estuaries in southern coastal Washington (Atwater and Yamaguchi, 1991; Atwater, 1992), northern Oregon (Nelson and Atwater, 1993), and northern California (Carver and others, 1992). Their probable absence at the surveyed outcrops need not signify gradual submergence, however, for deposits immediately above the buried soil at Marsh, Brush, Price, and Hunting Islands are riddled with rootlets injected from above, and such rootlets are typical of sites at the other estuaries where entombed herbs are absent in mud immediately above the uppermost buried soil. I suspect that the rootlets inject or open pathways for oxygen that destroys herbaceous fossils after their entombment.

Brief study of diatoms has not confirmed that submergence of any kind accounts for burial of the soil in the muddy cap at Marsh, Price, or Hunting Islands. However, little is known about the diatom assemblages of modern swamps along the lower Columbia River, and it is possible that the main swamp species are common on adjacent tidal flats as well (Eileen Hemphill-Haley, oral communication, 1993).

Special conditions for the marker beds

Special conditions allowed the marker beds to form distinct layers within the largely non-bedded muddy cap. These conditions probably involved rapid deposition and, for the beige layer, they also involved fluvial redeposition of volcanic ejecta.

The gray layer evinces flow of muddy water across marshes and swamps of the lower Columbia River. The single upward coarsening and then upward fining in the gray layer at lower Wallace Island outcrop B may mean that the flow had a single main peak, but the multiple silt layers at nearby outcrop C imply additional peaks.

The distribution of pumice suggests that the beige layer was also delivered by running water, not by air. If derived from Mount St. Helens (see p. 19), the pumice could not have blown westward to Marsh and Brush Island (where it is present in the beige layer) without falling at least as heavily onto Wallace, Price, and Hunting Islands (where it is absent from the beige layer) (Figure 1b).

Age

Deposition of the muddy cap has probably spanned the last 1000 years at the surveyed parts of Price and Hunting Islands and less time at the other surveyed outcrops. As judged from radiocarbon dating (Figure 4, Table 5), deposition of the muddy cap began before 750-1350 years ago at Price Island, before 600-1000 years ago at Hunting Island, and before 350-800 years ago at Marsh and lower Wallace Islands (see "Age" on p. 15). The maximum limiting range of 350-800 years ago for the muddy cap at Marsh Island probably applies as well to the nearby and stratigraphically similar cap at Brush Island. The muddy cap at upper Wallace Island originated less than 500 years ago (p. 16).

The muddy cap at most of the surveyed outcrops contains three stratigraphic levels that probably can be dated with high precision. The gray layer predates the beige layer by less than about 70 years; the beige layer almost certainly dates to within a few years of A.D. 1480; and deposits immediately above the buried soil probably date to within a few decades of A.D. 1700.

Gray layer

The gray layer accumulated sometime between 1410 and 1480 if the age assigned to the beige layer is correct, and if mud between the gray and beige layers at most parts of the Price Island outcrop accumulated at average rates of 1-4 mm/yr.

I use Price Island for such dating by average sedimentation rate because the exposed muddy cap there has yielded the oldest radiocarbon age among all the surveyed outcrops. This antiquity gives Price Island the best chance of having been a slowly, steadily accreting wetland through the time of deposition of the gray and beige layers.

An average sedimentation rate in the range 1-4 mm/yr is indicated by the 1-m thickness of mud between the radiocarbon-dated tubers (about 1350-750 years old) and the overlying beige layer (about 500 years old; see "Beige layer" below) in the southeastern part of the Price Island outcrop (Figure 3c). An average rate between 1 and 2 mm/yr is further suggested by the 0.2-0.4 m of mud between the beige layer (about 500 years old) and the top of the buried soil (probably about 300 years old; see p. 20) at horizontal coordinate 275 in that outcrop.

Except in a probable tidal-creek fill at horizontal coordinate 231, the mud between the gray and beige layers exposed at Price Island is 2-7 cm thick (Figure 11). At 1-4 mm/yr that thickness makes the gray layer between 5 and 70 years older than the beige layer.

Beige layer

Limiting ages show that the beige layer accumulated sometime between about 800 and 400 years ago. The maximum age of 800 years ago is the earliest likely calendric age corresponding to the two youngest radiocarbon ages on plant remains below the beige layer (590 ± 90 ^{14}C yr B.P.at Marsh Island, 630 ± 50 ^{14}C yr B.P. at lower Wallace Island outcrop C). The minimum age of 400 years ago comes from the A.D. 1607 date of the innermost ring counted in the oldest spruce tree at Price Island (Figure 3c, tag 60). The lowest horizontal roots of this tree, as measured after the tree fell over in 1992 or 1993, grew chiefly or entirely above the level of the beige layer surveyed at 7 places within 20 m of the tree. This vertical position implies that the beige layer predates all the nearly 400 rings in the tree.

Several additional points show that the beige layer probably correlates with Mount St. Helens tephra set W:

- Mount St. Helens is among the volcanoes best situated to send water-borne tephra to the lower Columbia River. The Columbia River can carry tephra from more-remote volcanoes, as shown by the deposits of Mazama ash (erupted at Crater Lake, southern Oregon) in submarine canyons off the mouth of the Columbia River (Griggs and Kulm, 1970). But Mounts Rainier, St. Helens, and Hood are the Cascade volcanoes nearest the surveyed islands (Figure 1), and tephra from Mounts Rainier and St. Helens could reach these islands via the Cowlitz River, which has headwaters at those volcanoes and flows into the Columbia River at Longview.
- Among recognized tephra layers and tephra-producing eruptive periods at Mounts Rainier, St. Helens, and Hood (Table 4), only Mount St. Helens tephra layers Wn and We are in the 400- to 800-year-ago age range of the beige layer.

- The pumice sample from Marsh Island studied by Pat Pringle has the mafic-phenocryst mineralogy of set-W tephra--hypersthene and hornblende without much if any augite or cummingtonite (Table 4). Pat further noted that the similarity with set-W tephra extends to the crystal size and abundance of these mafic phenocrysts (Patrick T. Pringle, written communication, 1994.)
- Much of the set-W tephra layer fell in the drainage basin of the Cowlitz River (Crandell and Mullineaux, 1978, p. C6).

If composed mainly of set-W tephra, the beige layer dates to within a few years of A.D. 1480. The earlier of the major set-W eruptions, which produced tephra layer Wn, occurred late in 1479 or early in 1480 (Fiacco and others, 1993; Yamaguchi, 1983, 1985). The later eruption, marked by tephra layer We, followed soon thereafter, in 1481 or 1482 (Yamaguchi, 1985). I assume that the Cowlitz River and its tributaries promptly delivered much debris from these eruptions to the Columbia River. Such was the case in 1980, when the Corps of Engineers dredged 11.5 million cubic meters of debris from the Columbia River near Longview in the aftermath of the Mount St. Helens eruption of May 18, 1980 (Schuster, 1981, p. 711).

As the larger of the two major set-W tephra layers, layer Wn is the one more likely to correlate with the beige layer. The area of airfall tephra more than 20 cm thick is nearly four times greater for layer Wn than for layer We (Crandell and Mullineaux, 1978, p. C6), and the estimated volume of the Wn eruption is about five times that of the We eruption (Pringle, 1993, p. 28). The area thickly covered by layer Wn also exceeds comparable areas for the main 1980 eruption of Mount St. Helens: layer Wn more than 20 cm thick blanketed nearly twice the combined area of 1980 lateral-blast and airfall-tephra deposits thicker than 20 cm, and it covered nearly 40 times the area of those 1980 airfall deposits alone (Sarna-Wojcicki and others, 1981, Table 67).

Buried soil

The buried soil is probably less than 500 years old at Marsh, Brush, Price, and Hunting Islands because at each of these islands the beige layer is at least a few tenths of a meter below the top of the buried soil. A maximum limiting age of 500 years ago is also consistent with each of two radiocarbon ages on sticks within 1 cm of the top of the soil--the age of 320 ± 50 ^{14}C yr B.P. at Marsh Island, and the age of 240 ± 60 ^{14}C yr B.P. at Hunting Island.

Tree-ring counts further limit the top of the buried soil at Price Island to a time between the early 1600s and the early 1800s. The early 1600s include dates when trees sprouted on the soil, as approximated by dates of the pith (see p. 10) in two trees at a height of a few meters above the level of the soil. These dates are 1607 and 1631 (Figure 3c, tags no. 60 and 70, respectively; Boyd E. Benson, written communication, 1994). The early 1800s include the pith date of a root that formed entirely above the level of the buried soil. Roots of that kind, sampled only from the tree with tag no. 60, must entirely postdate the buried soil.

A still narrower range, between 1680 and 1720, applies to the top of the buried soil at all four islands if the soil correlates with the uppermost buried soil at nearby estuaries. This correlation is likely for several reasons:

(1) Some of the soils at the nearby estuaries are probably similar in origin to the soil at Marsh Island and perhaps also to the buried soil at Brush, Price and Hunting Islands. Coastal subsidence during a plate-boundary earthquake, or during a brief series of plate-boundary earthquakes, best explains the submergence and burial of the uppermost buried soil at many estuaries along the southern Washington and northern Oregon coast (Atwater, 1987, 1992; Darienzo and Peterson, 1990; Darienzo and others, 1994). Such earthquake-induced submergence probably initiated burial of the soil at Marsh Island, and it may have also occasioned burial of the soil at Brush, Price, and Hunting Island (see p. 18).

(2) There is no known difference in age between the onset of burial of the uppermost buried soil at the nearby estuaries and the onset of such burial along the lower Columbia River. Burial began within the past 500 years at nearly all the estuaries where it has been dated in southern Washington and northern Oregon (Atwater, 1992; Darienzo and Peterson, 1990). Where dated most precisely the burial appears to have begun between 1680 and 1720 quite widely along the Cascadia subduction zone--at central Willapa Bay and at the Copalis River estuary in Washington (Atwater

and others, 1991), on the northern Oregon coast near Nehalem (Nelson and Atwater, 1993), and at Humboldt Bay, California (Carver and others, 1992) (localities shown in Figure 1). All these ranges are consistent with the ages estimated above for the onset of burial at the surveyed islands along the lower Columbia River--the maximum limit of 500 years ago for Marsh, Brush, Price, and Hunting Islands, and the range between the early 1600s and early 1800s for Price Island.
(3) Earthquake-induced submergence and burial near the Columbia River about 300 years ago was extensive enough to have reached at least as far inland as Marsh Island, which is nearly 35 km from the coast. Although their inland limit is poorly known, earthquake-induced submergence and burial about 300 years ago extended at least 20 km inland at southern Willapa Bay (to Naselle; Figure 1b) and at least 35 km inland to the north at Grays Harbor, as judged from permissive stratigraphic and radiocarbon correlation of the buried soil probably produced by that submergence and burial (Atwater, 1992).

LIQUEFACTION FEATURES

Surveyed parts of all six islands have bodies of sand that were emplaced through liquefaction. About 200 of these are intrusions--mainly vertical dikes no more than a few centimeters wide--that are exposed at low tide. Such intrusions are known from all the surveyed outcrops except outcrops A and C of lower Wallace Island. Above the level of the highest intrusions at Marsh, Brush, Price, and Hunting Islands is sand that was extruded; it forms a localized layer less than 2 cm thick that mantles the buried soil within a few meters of a high-level intrusion. Additional liquefaction features are present beneath the surveyed outcrops, where they have been identified in vibracore (Craig and others, 1993).

Below I further describe the liquefaction features by composition, orientation, abundance, size, and age. I also discuss several interpretations: why the features can be ascribed to liquefaction from seismic shaking; where that shaking may have originated; and what parts of the sandy foundation may have liquefied.

Composition

Intrusions seen in core

The vibracores contain two bodies of sand that can be confidently called intrusions. Both consist of arkosic sand that lacks lamination and contains scattered clasts of mud.

One of these intrusions is a subsurface part of the 30-cm-wide dike into which Curt Peterson and his students drove vibracore VB-14 at Marsh Island. That core followed the dike downward for nearly 2 m before exiting, perhaps through an sidewall of the dike, into horizontally laminated sand (Figure 3a).

The other, more inferential intrusion was sampled beneath Hunting Island in core VB-7 (Figure 3d). It displays a vertical contact 28 cm high midway across the 7.5-cm-diameter sample and midway along a core section 2.0-2.5 m long. On the other side of this vertical contact is mud with tens of horizontal laminae of coarse silt. The non-laminated sand extends 0.5 m below and at least 0.5 m above the vertical contact. Below the vertical contact it contains two angular, rotated clasts of laminated mud and coarse silt; both clasts are at least 5 cm long.

The vibracores also contain wispy bodies of very fine sand that appear to have been injected into mud. Such injections are plotted as probable liquefaction features in several vibracores, including Marsh Island core VB-9 (Figure 3a).

Intrusions seen in outcrop

The intrusions seen in outcrop consist mainly of fine sand and very fine sand. Whereas fine sand is typical of the widest dikes, very fine sand is typical of the tapered, non-eroded uppermost parts of dikes. I noted upward fining of sand within an individual dike at Price Island, where fine sand grades upward into silty very fine sand in an upward-tapering dike nearly connected with extruded sand (Figure 3c, horizontal coordinate 275 m). I recognized no mud clasts within exposed intrusions except in the 30-cm-wide dike at Marsh Island, which also contains pumice pebbles. Nor did I note flow banding except, as noted below, at upper Wallace Island.

Most of the intrusions can be spotted as slots eroded into a wave-washed outcrop (Figure 12; Stephen F. Obermeier, oral communication, 1992). Flanked by cohesive mud, the intrusions at most of the surveyed outcrops are more readily eroded by waves than are the intruded deposits. The exceptions to this rule are the dikes at upper Wallace Island. There, iron oxide has cemented silty, flow-banded margins of dikes that cut across interbedded sand and mud. As a result, dikes at upper Wallace Island can be spotted as paired sets of ridges that stand a few centimeters above the level of the intruded deposits (Figure 13; see also Figure 10).

Extrusions

Like the high parts of nearby intrusions, the sand that was extruded at Marsh, Brush, Price, and Hunting Islands is dominated by very fine sand. Some is silty and micaceous, as near the 30-cm-wide dike at Marsh Island, where silty sand forms a distinct lamina in the lowest few millimeters of a bed 2 cm thick.

The extruded sand at Marsh, Brush, Price, and Hunting Islands further resembles intrusions at those islands in cropping out as a slot that has been etched by waves. Wave-etched sand is also typical of probable tsunami deposits seen in outcrop elsewhere along the Cascadia subduction zone (Atwater and Yamaguchi, 1991; Atwater, in press). At the surveyed outcrops, however, I doubt that any tsunami about 300 years ago did any more than spread out sand that had already been extruded. The sand mantling the buried soil at these outcrops is too localized around high-level intrusions to resemble the sand sheets probably deposited by tsunami; these sand sheets extend for hundreds to thousands of meters on buried soils at Willapa Bay and the Copalis River, Washington (Atwater, 1987, 1992; Reinhart and Bourgeois, 1987), at the Salmon River and Alsea Bay, Oregon (Grant and McLaren, 1987; Peterson and Darienzo, in press); and at Port Alberni, British Columbia (Clague and Bobrowsky, 1994).

Extruded sand may also be present at upper Wallace Island, above the highest surveyed dike at outcrop A. Alternatively, this sand was deposited by the river.

Orientation

The strike of intrusions seen in the surveyed outcrops varies much more than does the dip, which for nearly all the intrusions is close to vertical. Dikes have similar strike only along parts of outcrops, as at Price, Hunting, and upper Wallace Island (Figure 3, parts c, d, and g). Otherwise I see little tendency for dikes to parallel one another (Figure 5).

The overall scatter in strike precludes strong correlation with the trend of a potential free face toward which land could have spread during liquefaction. However, the strike of the widest dike at Brush Island is nearly parallel to the modern trend of Marsh Island Creek, and the widest dikes at Price and upper Wallace Island strike within 30 degrees of the trends of nearby modern channels (Figure 5). Some of those trends may lie close to the trends of free faces of about 300 years ago (see "Inferred shorelines of 300 years ago" on p. 12)--a coincidence that may implicate lateral spreading in some of the diking (p. 24).

Size and Abundance

Width of dikes

Among the roughly 200 surveyed dikes, most are no more than 3 cm wide where seen in outcrop, and more than 90 percent are less than 5 cm wide. At the surveyed outcrops the field party found only 8 dikes that are chiefly wider than 5 cm (Table 6). Two of these, one each at Marsh and Brush Islands, are as much as 30 cm wide; another, at Hunting Island, is up to 20 cm wide; and one at upper Wallace Island is 15 cm wide.

Abundance of intrusions

Tallies for 10-m stretches of shore

The number of intrusions noted along each 10-m stretch of surveyed shore ranges from 0 to 8. At all the surveyed outcrops the intrusions are typically fewer than 5 per 10 m, and all but the short outcrops at upper Wallace Island have many 10-m stretches without any observed intrusions despite excellent horizontal and (or) vertical outcrop.

The number of intrusions per 10 m tends to increase with outcrop area at parts of Marsh, Price, and lower Wallace Island (Figure 3, parts a, c, e). However, many of the stretches without observed intrusions have outcrop areas of 50 m^2 or more, and the number of intrusion per 10-m stretch at Hunting Island does not increase much with area where the area exceeds 50 m^2 (Figure 6).

I doubt that orientation of intrusions accounts for much of this scatter in the relationship between abundance and area (Figure 6). The main effect of orientation may be to place the upper limit on the number of intrusions per 10-m stretch of the wide horizontal outcrop at Hunting Island, where many of the dikes are long and strike at high angle to the shore. Such dikes cannot greatly increase in number as an outcrop widens. However, there is little if any correlation between strike and abundance at the wide outcrops at Hunting Island (Figure 3d), which is the only surveyed island with enough horizontal outcrop for such correlation to be easily tested. Another possible effect of orientation is to prevent recognition of dikes where dikes strike parallel to mainly vertical outcrop. But strikes of the observed dikes are widely scattered (Figure 5), and most of the observed dikes are in horizontal outcrops that could have revealed a tendency for shore-parallel strikes had such a tendency existed.

Averages by outcrop or island

For all six islands together the abundance of intrusions averages nearly one intrusion for every 10 m of surveyed outcrop and nearly two intrusions for every 100 m^2 of surveyed outcrop (Table 6; for definition of outcrop length and outcrop area see "Outcrop dimensions" on p. 5). However, abundance varies greatly both at individual outcrops (Figure 3, lower bar graph in parts a-e and g) and among outcrops (Table 6). By length the intrusions are least abundant at outcrops A and C of lower Wallace Island (no intrusions noted) and most abundant nearby at upper Wallace Island (average of 3.2 per 10 m). By area the average abundance ranges from 0 at lower Wallace outcrops A and C, through the next-least value of 1.2 intrusions per 100 m^2 at Hunting Island, to maximum values of 9.5 and 12.1 intrusions per 100 m^2 at upper Wallace outcrop A and Brush Island, respectively.

All these averages are potentially misleading because each reduces many scattered measurements to a single number. Furthermore, where normalized only to length, average abundance does not express variation in the width of outcrop at which intrusions can be observed. That variation can be enormous, as shown by the contrast between Marsh Island (631 m^2 of outcrop along 678 m of shore) and Hunting Island (7494 m^2 of outcrop along 660 m of shore).

Age

All the liquefaction features seen in outcrop probably formed within a few decades of A.D. 1700, particularly those features in contact with the buried soil. The liquefaction features seen in vibracore from Hunting Island may have also formed at that time but could just as well have formed earlier in the past 2000 years.

Features seen in outcrop

The liquefaction features most convincingly dated to about 1700 are the bodies of extruded sand that mantle the buried soil at Marsh, Brush, Price, and Hunting Islands. The stratigraphic position of this sand shows that it was extruded at or about the time when the soil began to be buried. At least at Marsh Island, and perhaps at the other three islands as well, the burial probably resulted from submergence (see "Paleobathymetry" on p. 18). Limiting ages on the soil at all four islands permit correlation with a earthquake-induced submergence and consequent burial of a marshes and swamps at nearby Willapa Bay between 1680 and 1720 (see "Buried soil" on p. 20).

The intrusions most directly dated to about A.D. 1700 are the few recognized as having entered the buried soil. Such intrusions are present in surveyed outcrops at Marsh, Price, and Hunting Islands. Some of the other intrusions can be shown to postdate A.D. 1400; they cut across one or both of the marker beds, the lower of which formed less than 600 years ago (see "Gray layer" on p. 19) and the upper about 500 years ago (see "Beige layer" on p. 19). The remainder of the intrusions seen in outcrop postdate deposits with age ranges of 750-1350 years ago at Price Island, 350-800 years ago at Marsh, Price, and lower Wallace Islands; 600-1000 years ago at Hunting Island; and less than 700 years ago at upper Wallace Island (see "Age" on p. 19).

Two points suggest that all these exposed intrusions are coeval. First, many of the intrusions would have younger limiting ages were they more fully exposed. Such intrusions--all the ones shown with light-gray squares in Figure 3--could not be traced upward to where they tapered or vented; they are exposed only where they have been eroded to lower levels. Second, the surveyed outcrops provide no evidence for multiple times of intrusion. I do not know of any cross-cutting dikes, nor am I aware of any systematic difference in width or composition between dikes that entered the buried soil and dikes that did not. Multiple bodies of extruded sand may be present at a southeastern part of Hunting Island (Stephen F. Obermeier, oral communication, 1992), but no one in the field party reported multiple extrusions at any of the surveyed outcrops.

Intrusions seen in core

An age near A.D. 1700 need not apply to the liquefaction features seen low in core VB-7 beneath Hunting Island (see p. 24). For them a generous maximum limiting age is 2000 years ago, from the radiocarbon age of 1670 ± 70 ^{14}C yr B.P. on an underlying stick (Figure 3d,Figure 4).

This maximum limiting age permits those liquefaction features beneath Hunting Island to correlate either with seismicity about 300 years ago or with any of two or three earlier earthquakes inferred from coastal deposits 100 km north of the Columbia River. These earlier earthquakes occurred between 900 and 2000 years ago (see p. 15).

Inference of seismic shaking

Bodies of intruded and extruded sand can form without the earthquake-induced compaction that causes sand to liquefy. In one example, sand boils formed in a California desert where stormwater coursed through desert cracks unrelated to earthquakes (Holzer and Clark, 1993). In another example, I mistakenly blamed ordinary earthquake-induced liquefaction for intrusions and extrusions of sand that probably resulted from resulted from abrupt tectonic squeezing of sandy aquifers beneath the Copalis River (Atwater, 1992).

Several points, however, show that earthquake-induced liquefaction almost certainly produced the intruded and extruded sand seen in outcrop at the surveyed islands along the lower Columbia River:

- The intruded sand was injected from below, as shown by the common upward tapering of intrusions and by the upward fining of sand within an intrusion on Price Island (see p. 21).
- The features cannot record sand boils from water that rose high against levees, for natural levees are low or absent at the surveyed islands (p. 11).
- The features probably date to the time of an earthquake, as shown by their stratigraphic position with respect to a buried soil that probably records earthquake-induced submergence about 300 years ago (p. 23). That correlation is strongest for Marsh Island, somewhat weaker for Brush, Price, and Hunting Islands, and weakest for Wallace Island.

There remains much room for doubt, however, about the means by which the sand was intruded along the lower Columbia River. Did the sand passively well upward into cracks that had been opened by lateral spreading, or was the sand entrained in high-pressure water that forced open the cracks that became dikes? Lateral spreading may account for the widest dikes, particularly at Brush Island where the widest surveyed dike is 70 m north of and nearly parallel to a modern shoreline (the north side of Marsh Island Creek) that may approximate a free face of 300 years ago (p. 22). However, most of the surveyed outcrops are probably hundreds of meters from the nearest free face 300 years ago (p. 12)--a distance greater than was typical of lateral spreads along The Alaska Railroad during the 1964 Alaska earthquake (p. 11). If this Alaskan analog applies to islands of the lower Columbia River, forceful injection probably contributed to the emplacement of many of the intrusions at the surveyed outcrops.

Source of the inferred shaking

The Cascadia subduction zone provides several options for the source of seismic shaking along the lower Columbia River. The likely source for the shaking 300 years ago is a rupture between, rather than within, the subducting Juan de Fuca plate and the overriding North America plate. Although this rupture was probably located mostly or entirely offshore, available statistics on size and abundance of intrusions provide little if any confirmation of a consequent eastward attenuation of shaking between Marsh Island and upper Wallace Island.

Rupture at the plate boundary

A series of interpretations points to the plate boundary as the likely source of the shaking responsible for the exposed liquefaction features along the lower Columbia River:

- The features probably date to a time of abrupt coastal submergence about 300 years ago at the Cascadia subduction zone (see p. 23).
- In southern Washington and northern Oregon that submergence was probably caused by widespread tectonic subsidence attended by tsunami (Atwater, 1987, 1992; Darienzo and Peterson, 1990).
- Such a combination of subsidence and tsunami is best explained by one or a brief series of thrust earthquakes on the plate boundary (Atwater, 1992).

Alternative sources

An earthquake from within the subducted Juan de Fuca plate could cause liquefaction along the lower Columbia River, as happened at Longview during the magnitude-7.1 Puget Sound earthquake of 1949 (Murphy and Ulrich, 1951; Hopper, 1981). However, that earthquake was nowhere reported to have been accompanied by widespread lowering of land into the intertidal zone (Thorsen, 1986). I therefore doubt that an earthquake like the 1949 event could account for the liquefaction that probably accompanied widespread submergence along the lower Columbia River.

Slip on faults within the North America plate may account for some of the abrupt coastal submergence about 300 years ago along the Cascadia subduction zone (Nelson, 1992; Nelson and Personius, in press; Clarke and Carver, 1992; Goldfinger and others, 1992). But such localized deformation explains that submergence less simply than does slip at the boundary between the Juan de Fuca and North America plates, for several reasons:

- The plate boundary is the only recognized, recently active fault beneath all the sites with strong evidence for sudden, earthquake-induced submergence about 300 years ago. The best-dated of these sites are scattered along hundreds of kilometers of the Cascadia subduction zone (see p. 20).
- Some of the areas submerged about 300 years ago at northeastern Willapa Bay rest on a structural high marked by an antiformal body of the Crescent Basalt, a basement unit atypical of young synclines in the area (Walsh and others, 1987). This setting would not be expected of submergence caused by localized downwarping along a fault in the North America plate. The structurally high areas submerged at northeastern Willapa Bay have a buried soil widely overlain by tsunami-laid sand (Atwater, 1987; Atwater and Yamaguchi, 1991; Reinhart and Bourgeois, 1987).
- Faults in the North America plate may play a merely secondary role in generating earthquake-induced submergence at the Cascadia subduction zone. As happened at the Alaskan subduction zone during the great 1964 earthquake (Plafker, 1969), plate-boundary slip at the Cascadia

subduction zone may sometimes trigger ancillary movement on faults and folds in the overlying North America plate (Clarke and Carver, 1992; Goldfinger and others, 1992).

Chiefly offshore location

The inferred plate-boundary rupture should have been located mainly or entirely offshore. Geodetic and heat-flow evidence suggests that the plate boundary is too warm for brittle rupture far inland from the coast in the northern part of the Cascadia subduction zone (Savage and others, 1991; Hyndman and others, 1993). Offshore rupture is further suggested by the lack of earthquake-induced uplift about 300 years ago along the Pacific coast of southern Washington and northern Oregon. By analogy with the pattern of uplift and subsidence during the 1964 Alaska earthquake (Plafker, 1969), that coast should have undergone uplift had seismic slip occurred on the plate boundary many tens of kilometers inland.

Eastward attenuation of shaking from a chiefly offshore source may explain a few trends in the size and abundance of liquefaction features. As first recognized by Stephen F. Obermeier (oral communication, 1992), such attenuation may account for the systematic eastward decrease in the number and width of the widest dikes at islands grouped by distance from the coast, and it may further explain an overall eastward decrease in the average abundance of intrusions (Table 6b).

Alternatively, the size and abundance of liquefaction features at the surveyed outcrops depend on factors so numerous and poorly understood that the available statistics on size and abundance reveal little if anything about the location of the inferred earthquake:

- The most complete measures of size and abundance provide little if any evidence that shaking diminished eastward. The percentage of wide dikes at the surveyed islands is everywhere low and varies erratically with distance from the coast (Table 6). Counts of intrusions along 10-m stretches of shoreline likewise show little if any overall difference between 33 and 59 km from the Pacific coast (Figure 6; p. 23).
- Geologic effects of earthquake-induced liquefaction can depend on many factors in addtion to distance from earthquake source (Bartlett and Youd, 1992). Those considered important by Bartlett and Youd include distance to free face, local amplification of shaking, and the thickness, density, and particle size of the source of the liquefied sand. An additional factor for intrusions along the lower Columbia River is the mechanism of emplacement--which intrusions resulted from lateral spreading, which from forcible injection (see p. 24). Without evaluation of each of these factors there seems little hope of isolating evidence for eastward attenuation.
- Enigmatic variation in the size and abundance of dikes at individual islands is as great as the variation among islands. Outcrop near horizontal coordinate 500 m at Marsh Island displays a dike 30 cm wide and another one 10 cm wide; outcrop 175 m to the west displays no dike wider than 5 cm; outcrop still farther west, near horizontal coordinate 100 m, has no recognized dikes at all; yet these parts of the outcrop hardly differ in outcrop area, thickness of muddy cap, blow counts of the sandy foundation, or distance to a possible free face about 300 years ago (Figure 3a). Similarly at Hunting Island I see no reason why dikes turn out to be so much scarcer between coordinates 200 m and 400 m than they are between 400 and 500 m (Figure 3d).

Blow counts for calculation of shaking

Shaking had to exceed minimum combinations of acceleration and duration for sand to liquefy beneath the surveyed islands. In a preliminary estimate these minima, Palmer and others (1993) approximately converted representative blow counts to standard units of penetration resistance and then used modern calibration data of Seed and Idriss (1982) to calculate minimum combinations of acceleration and earthquake magnitude (the latter taken as a proxy for duration) that could have liquefied the sand.

The compilations of geologic and engineering data in Figure 3 could lead to improved estimates of shaking because those data aid in identifying specific sources for the liquefaction features. Table 7 gives depths and blow counts for two such sources at each of the five islands for which vibracore data are available. One source is loose and shallow--the loosest sand at least 0.3 m thick within 1 m of the muddy cap. The other source is denser and is located beneath probable dikes seen in vibracores (Hunting and Marsh Islands), beneath sand that may be too muddy to account for all the liquefaction features seen in outcrop (Wallace Island), or within the only thick sand bed seen in a vibracore (Price Island).

As listed in Table 7 the densest source sand is located beneath Hunting Island at vibracore site VB-7 (Figure 3d). Although this sand is old enough that the liquefaction feature just above it could have formed almost 2000 years ago (see p. 24), comparison with Marsh Island suggests that the sand was not much denser 300 years ago than it was whenever the overlying liquefaction feature formed (see p. 15). Shaking 300 years ago may have liquefied some of the densest sand tested beneath any of the surveyed islands.

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Table 1. Location of outcrops surveyed in 1993 at Marsh, Brush, Price, Hunting, lower Wallace, and upper Wallace Islands.

Island	Distance east of coast (km)	USGS 7.5-minute quadrangle	Location in land grid*
Marsh	33	Knappa	West end of outcrop: 2900 ft N, 3050 ft W of SE corner sec. 32, T9N, R7W
Brush	34	Knappa	Southwest end of outcrop: 100 ft N, 4500 ft W of SE corner sec. 29, T9N, R7W
Price	44	Skamokawa	Northwest end of outcrop: 1900 ft S, 150 ft E of NW corner sec. 21, T9N, R6W
Hunting	45	Cathlamet	Northwest end of outcrop: 250 ft S, 50 ft E of NW corner sec. 34, T9N, R6W
Lower Wallace	57	Nassa Point	Outcrop A: west end 100 ft S and about 2200 ft W of NE corner sec. 35, T8N, R5W Outcrop B: east end about 200 ft west of west end of A Outcrop C: 300 ft S, 1700 ft E of NW corner sec. 35, T8N, R5W
Upper Wallace	59	Oak Point	Outcrop A: 1450 ft N and 550 ft E of SW corner sec. 30, T8N, R5W Outcrop B: east end about 300 ft west of west end of A

* Distances in feet for ease of reading from 1:24,000-scale map. Abbreviations: sec., section; T, township; R, range

Table 2. Dimensions of outcrops and level of effort with vibracores, penetration tests, and particle-size analysis

Island and outcrop		Length of surveyed shore* (m)	Outcrop area† (m^2)			Vibracores		Penetrometer tests (Oregon penetrometer only)		Particle-size analyses
			Horizontal	Vertical	Total	Number	Total length (m penetrated)	Number of holes	Number of 6-inch intervals counted	
Marsh‡		678	446	185	631	5	23	6	170	9
Brush		310	187	69	256	0	0	4	50	0
Price		390	1042	169	1211	2	11	5	88	0
Hunting		660	7420	74	7494	3	12	9	205	9
Lower Wallace§	A	270	4	53	57	0	0	0	0	0
	B	219	83	72	175	1	6	2	48	15
	C	143	495	18	513	0	0	0	0	0
Upper Wallace	A	60	200	0	200	2	10	3	93	4
	B	40	n.d.	n.d.	<200	0	0	0	0	0

* Measured along straight or gently curved line of stakes; outcrop may be longer or shorter, depending on its curvature and exposure
† Measured between low tide and highest intrusion (upper Wallace Island) or between low tide and gray layer (other islands)
‡ Tallies include one 1.6-m vibracore and one particle-size analysis not plotted in Figure 3a
§ n.d., not measured, but by casual inspection I estimate that the sum of horizontal and vertical areas is less than 200 m^2

Table 3. Historical changes in shorelines and channels at surveyed parts of islands shown in Figure 2

Island	Maps compared (and year of survey)*		Maximum estimated error in registration (m)	Approximate retreat of shoreline between 1870 and 1980 (m)	Remarks
	Earliest	Later			
Marsh (Fig. 2a)	T-1235 (1870) T-1234 (1870) H-1015 (1867-1868)	Knappa (1977-1980)	50	150-350	
Brush (Fig. 2a)	T-1235 (1870) H-1015 (1867-1868)	Knappa (1977-1980)	50	50-150	
Price (Fig. 2b)	T-1250 (1871) H-1335 (1875-1876)	T-9268 (1959) Skamokawa (1980)	50	200-250	Widest part of island about 650 m wide in 1871, 500 m wide in 1959, and 425 m wide in 1980
Hunting (Fig. 2c)	T-1331 (1872) H-1335 (1875-1876)	Cathlamet (1980)	75	50-150	
Lower Wallace (Fig. 2d)	T-1401a (1874) H-1336 (1876)	Nassa Point (1977-1980)	50	100-150	
Upper Wallace (Fig. 2e)	T-1401b (1874) H-1336 (1876)	Oak Point (1980)	50	300-350	Retreat on northwest side of island and progradation on southeast side; in 1870s, site of outcrop A was ~150 m from tidal flat and shallow channel along opposite (southeast) side of island

* Maps denoted T- and H- are topographic maps and hydrographic maps, respectively, by the U.S. Coast Survey (1800s) and U.S. Coast and Geodetic Survey (1959), scale 1:10,000; dates for U.S. Coast Survey maps are those of the field surveys on which they are based. Named maps are 7.5-minute quadrangles of the U.S. Geological Survey, scale 1:24,000, prepared from air photos taken in years noted.

Table 4. Tephra layers and tephra-producing eruptive periods considered for correlation with the beige layer
[leaders (--), no data]

Volcano (Fig. 1)	Tephra layer or eruptive period	Mafic phenocrysts in tephra* Hyper-sthene	Augite	Horn-blende	Cum-ming-tonite	Age	Reference for age
				Eruptions less than 400 years ago			
Mount Rainier	X	yes	yes	trace	no	A.D. 1820-1854	Mullineaux and others (1969)
Mount St. Helens	unnamed	--	--	--	--	A.D. 1842	Yamaguchi and Lawrence (1993)
Mount St. Helens	T	yes	yes	yes	no	A.D. 1800	Yamaguchi (1983)
Mount Hood	Old Maid	yes	no	yes	no	A.D. 1760-1800	Cameron and Pringle (1987); P.T. Pringle (written commun., 1994)
Mount St. Helens	Kalama (late part)	--	--	--	--	A.D. 1647	Yamaguchi (1986)
				Eruptions 400-1000 years ago			
Mount St. Helens	We	yes	no	yes	no	A.D. 1481 or 1482	Yamaguchi (1983, 1985)
Mount St. Helens	Wn	yes	no	yes	no	A.D. 1479 or 1480	Yamaguchi (1983); Fiacco and others (1993)
				Eruptions more than 1000 years ago			
Mount St Helens	Sugar Bowl	yes	no	yes	no	~1200 ^{14}C yr B.P.	Mullineaux (1986)
Mount Hood	Timberline	yes	no	yes	no	~1400-1800 ^{14}C yr B.P.	Crandell (1980); Cameron and Pringle (1986)
Mount Rainier	C	yes	yes	yes	no	~2300 ^{14}C yr B.P.	Mullineaux (1974)
Mount St. Helens	P	yes	no	trace?	no	~2500-3000 ^{14}C yr B.P.	Mullineaux (1986)
Mount St. Helens	Y	trace?	trace?	yes	yes	~3500-3900 ^{14}C yr B.P.	Mullineaux (1986)

*After Mullineaux (1974, p. 69) and P.T. Pringle (written commun., 1994)

Table 5. Radiocarbon ages from outcrops shown in Figure 3

Island (and outcrop)	Location of sample: Coordinates relative to local datums (m)[†] Horizontal	Coordinates relative to local datums (m)[†] Vertical	Vertical position relative to other datums (m): Beige layer	Vertical position: Inferred swamp level ca. A.D. 1700	Vertical position: Lowest tide in 1993[‡]	Material dated: Kind	Material dated: Inferred depositional environment	Age (^{14}C yr B.P.)[*]	Lab no. (Beta-)
Marsh	236	11.1	0.6	0.05	1.5	Stick 1 cm in diameter	Intertidal flat	320 ± 50	65607
	86	9.80-10.00	~ -0.7	~ -1.0	0.17-0.37	Tubers of *Scirpus fluviatilis*	Incipient marsh in middle of intertidal zone	590 ± 70	65606
	505	~ 8.0	~ -2.7	~ -3.0	~ -1.6	Detrital plant fragments	Subtidal bar or channel	1300 ± 90	70250
Price	310	7.27-7.57	-1.2	-1.5	0.0-0.3	Tubers of *Scirpus fluviatilis*	Incipient marsh in middle of intertidal zone	1140 ± 70	65603
Hunting	17	9.96	0.3	-0.01	1.47	Stick 2 cm in diameter	Swamp high in intertidal zone	240 ± 60	65600
	248	8.53-8.66	-1.0	-1.3	0.04-0.17	Tubers of *Scirpus fluviatilis*	Incipient marsh in middle of intertidal zone	780 ± 60	65604
	248	8.6	-1.0	-1.3	0.1	Stick 1.0-1.5 cm in diameter	Same as for Beta-65604	880 ± 50	65605
	348	between 3.65 and 4.05	between -5.6 and -6.0	between -5.9 and -6.3	between -4.4 and -4.8	Stick ~2 cm in diameter	Subtidal bar or channel	1670 ± 70	70251

Table 5, *continued*. Radiocarbon ages from outcrops shown in Figure 3

Location of sample						Material dated		Age (^{14}C yr B.P.)*	Lab no. (Beta-)
Island (and outcrop)	Coordinates relative to local datums (m)†		Vertical position relative to other datums (m)			Kind	Inferred depositional environment		
	Hori-zontal	Ver-tical	Beige layer	Inferred swamp level ca. A.D. 1700	Lowest tide in 1993‡				
Lower Wallace (C)	40	~9.2	~ -0.5	~ -0.8	~ 0.4	Branch 3 cm in diameter	Unvegetated intertidal flat	630 ± 50	65602
Upper Wallace	9	9.68	n.a.	~ -1	0.71	Detrital plant fragments	Unvegetated intertidal flat	420 ± 60	65601

* Conventional radiocarbon years before A.D. 1950. Uncertainty is error quoted by laboratory; this error may be less than one standard deviation of the age measurement

† Shown on diagram for island (Fig. 3, parts a, c-e, g)

‡ Observed in July or August; date and predicted level shown on diagram for island (Fig. 3, parts a, c-e, g)

Table 6. Summary statistics about size and abundance of intrusions

(a) Individual islands and outcrops

Island and outcrop		Number of intrusions noted in outcrop	Size		Average abundance of intrusions		Dimensions of surveyed shore (Table 2)	
			Number of dikes chiefly wider than 6 cm	Maximum width of widest dike (cm)	By length (number per 10 m)	By area (number per 100 m^2)	Length (m)*	Total outcrop area (m^2)†
Marsh		28	2	30	0.4	4.4	678	631
Brush		31	2	30	1.0	12.1	310	256
Price		27	1	8	0.7	2.6	390	1211
Hunting		‡ 87	1	20	1.3	1.2	660	7494
Lower Wallace	A	0	0	0	0	0	270	57
	B	5	0	5	0.2	2.9	219	175
	C	0	0	0	0	0	143	513
Upper Wallace	A	19	2	15	3.2	9.5	60	200
	B	§ 7	0	3	1.7	3.0	40	** 150

* Measured along straight or gently curved line of stakes; outcrop may be longer or shorter, depending on its curvature and exposure
† Measured between low tide and highest intrusion (upper Wallace Island) or between low tide and gray layer (other islands)
‡ Excludes 7 additional intrusions found along 200 m of shoreline searched more carefully than most (Fig. 3d)
§ Includes only the largest dike in each of four clusters of en echelon dikes; excludes total of 7 dikes from these clusters
** Generous estimate

Table 6, *continued.* Summary statistics about size and abundance of intrusions

(b) Islands paired by distance from coast

Islands	Distance from coast (km)	Number of intrusions noted in outcrop	Size			Average abundance of intrusions		Dimensions of surveyed shore (Table 2)	
			Dikes chiefly wider than 5 cm		Maximum width of widest dike (cm)	By length (number per 10 m)	By area (number per 100 m^2)	Length (m)	Total outcrop area (m^2)
			Number	Percent					
Marsh and Brush	33-34	59	4	7	30	0.6	6.6	988	887
Price and Hunting	44-45	114	2	2	20	1.1	1.3	1,050	8,705
Wallace	57-59	31	2	6	15	0.4	2.8	732	1,095
TOTALS AND AVERAGES		204	8	4	--	0.7	1.9	2,768	10,687

Table 7. Properties of plausible source sand for liquefaction features from seismicity ca. A.D. 1700 along the lower Columbia River

Island[*]	Relative density of source	Horizontal location (core)	Height in 1993[†] (m)	Depth ca. 1700[‡] (m)	Blow count[§]	Silt and clay[**] (%)	Assumptions
Marsh	Loose	VB-9	8.6-8.9	2.5	3	6	Source is sand with low blow counts immediately below intrusion inferred in VB-9
	Denser	VB-14	8.2-8.5	2.5	11	n.d.	Source underlies deepest part of 30-cm-wide dike inferred in core
Price	Loose	VB-G5	5.6-5.9	3.5	4	n.d.	
	Denser	VB-G4	5.0-5.3	3.5	20	n.d.	Source is sole body of sand >0.1 m thick in core, and this sand body accounts for blow counts in 20s at penetrometer site OR-P-1
Hunting	Loose	VB-6	7.0-7.3	3.0	3	0	
	Denser	VB-7	4.1-4.4	5.5	20-30	0	Source is at level of lowest thick candidate for liquefied sand in VB-7. Density of source approximated by blow counts at same level in penetrometer (OR-H) holes 10, 9, 4, 7, 3, 6, 1, and 2.
Lower Wallace	Loose	VB-5	7.8-8.1	2.0	8	2	Sand higher in VB-5 may be looser but commonly contains >10% silt and clay
	Denser	VB-5	6.8-7.1	3.0	13	n.d.	Source is deeper than most mud beds and muddy sand seen in VB-5 and also sampled nearby in WA-W-3, -4, and -5
Upper Wallace	Loose	VB-2	8.2-8.5	2.0	3	n.d.	
	Denser	VB-4	6.8-7.1	3.0	8	0	Source underlies possible intrusion seen in VB-4

[*] Outcrop A at upper Wallace Island; outcrop B at lower Wallace Island
[†] Interval 0.3 m (1 ft) thick for blow counts that are presented two columns to the right; height expressed in coordinate relative to local datum at outcrop; thickness of sand that liquefied is probably greater than 0.3 m, especially for deepest and densest hypothetical sources
[‡] Relative to inferred or approximate level of swamp surface ca. A.D. 1700; rounded to nearest 0.5 m
[§] Average of counts, in blows per six inches, from two successive six-inch intervals
[**] Sample from or near blow-count interval; n.d., not determined for lack of such sample

Figure 1. Index maps. (a) Cascadia subduction zone. Most or all of the faults shown have been active within the past 2 million years and probably also within the past 10,000 years. The map omits additional faults of this kind where such faults are too numerous to show at the map scale (off Oregon and California) or where detailed mapping has not been published (off Washington and Vancouver Island). Faults from compilations by Rogers and others (in press), Goldfinger and others (1992), Clarke and Carver (1992), Wagner and others (1986), and Wagner and Tomson (1987). (b) Lower Columbia River. Solid dots denote outcrops portrayed in larger-scale maps (Figure 2) and stratigraphic cross sections (Figure 3).

Figure 2. Maps of shorelines and bathymetry ca. 1870, and of major changes in shorelines since ca. 1870, at Marsh, Brush, Price, Hunting, and Wallace Islands. Compiled from sources and subject to errors listed in Table 3 and discussed under "Historical changes in shorelines" (p. 11).

Figure 3. Stratigraphic cross sections and graphs of dike orientation, number of intrusions, and outcrop area. Symbols keyed to separate legend and further explained in the text under "Methods". (a) Marsh Island. (b) Brush Island. (c) Price Island. (d) Hunting Island. (e) Lower Wallace Island, outcrop B. (f) Lower Wallace Island, outcrops A and C. (g) Upper Wallace Island.

Figure 4. Generalized stratigraphic columns. Compiled from cross sections in Figure 3.

Figure 5. Strikes of dikes. Compiled from data graphed immediately above stratigraphic cross sections in Figure 3.

Figure 6. Abundance of intrusions at islands paired by distance inland from the Pacific coast. Compiled from data shown on bar graphs in Figure 3, and subject to uncertainties discussed in text (see "Outcrop dimensions" on p. 5).

Figure 7. Summary of blow counts measured with Oregon penetrometer. The counts include several probably measured on mud (see "Penetration tests" on p. 7).

Figure 8. Fossil tubers of *Scirpus fluviatilis* from Marsh Island. These and other tubers collected about 1 m below the land surface of ca. A.D. 1700 gave an age of 590 ± 70 ^{14}C yr B.P. (Table 5; Figure 3a). Scale is 15 cm long.

Figure 9. Grove of ancient Sitka spruce at Price Island. Tree at left with double trunk began growing no later than A.D. 1631 (Figure 3c, tag number 70). View to northwest; man at right gives scale.

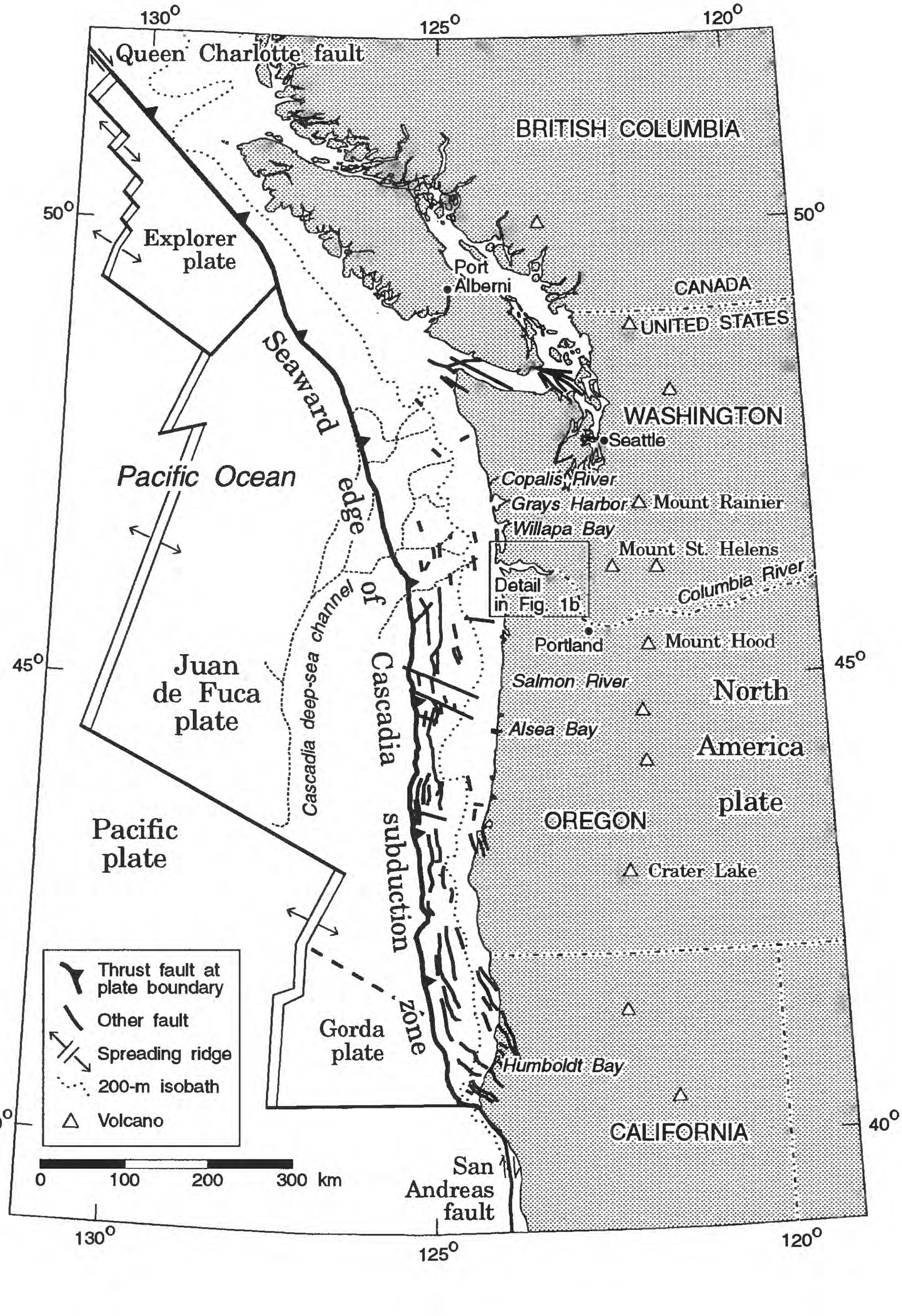
Figure 10. Sand with inclined lamination at upper Wallace Island, outcrop B. Apparent dip to the right (west). Small dike at right intrudes overlying mud, which displays horizontal lamination. Bands on shovel handle are 10 cm long.

Figure 11. Common thicknesses of the gray and beige layers, and of the mud between them, at Marsh and Brush Islands, Price and Hunting Islands, and outcrops A-C of lower Wallace Island. Thicknesses plotted against tide level a few tenths of a meter below mean lower low water.

Figure 12. Eroded dike at Hunting Island. Waves have washed sand from the dike, leaving a slot in the intruded mud. Shovel handle is 0.5 m long.

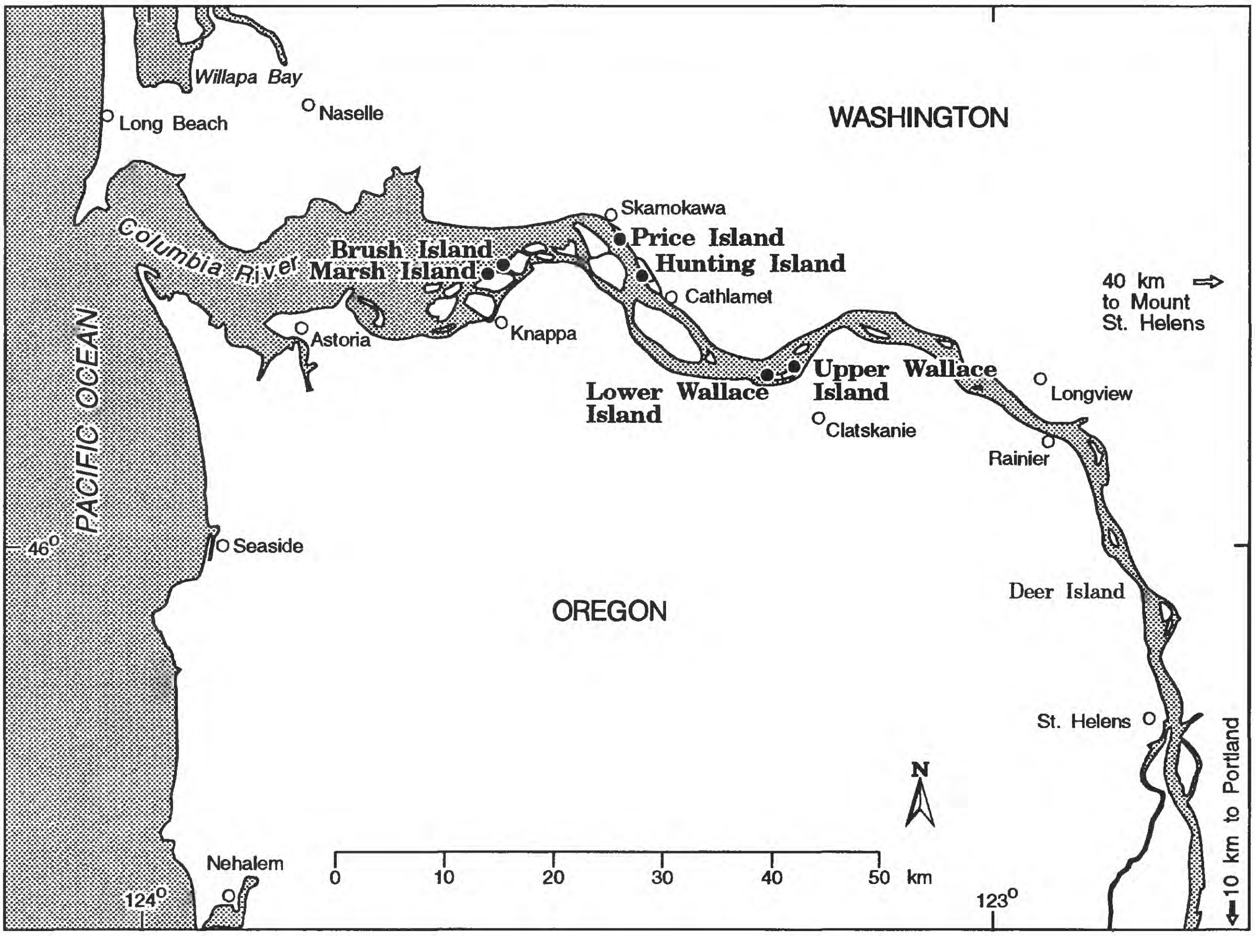
Figure 13. Dikes with raised edges at upper Wallace Island, outcrop A (Figure 3g). Shovel handle is 0.5 m long. (a) Overview eastward across dikes. The dikes transect mud beds that extend parallel to shoreline. Shovel handle for scale is behind dike at left center. (b) Closer view of one of the larger dikes.

Figure 1a



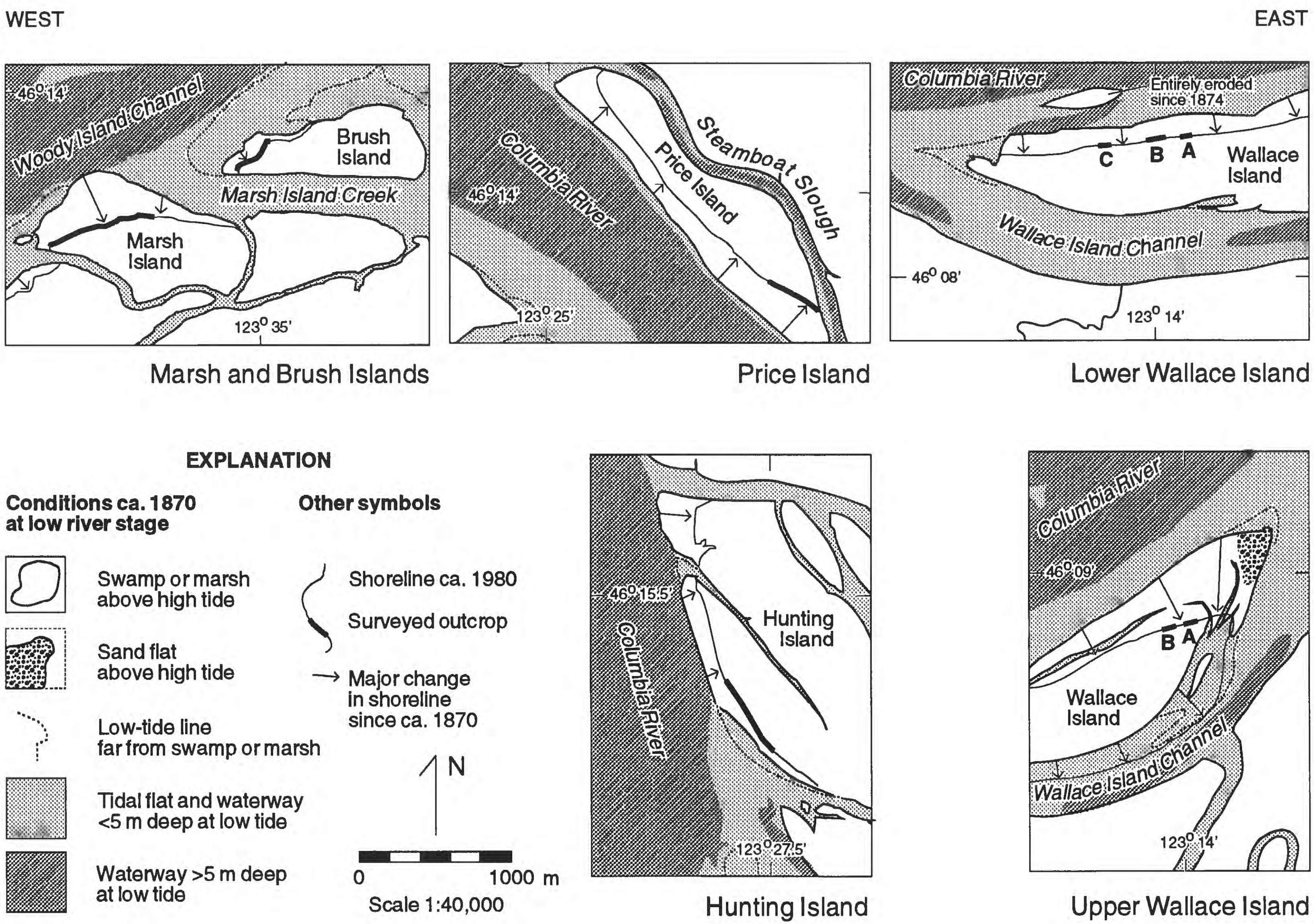
130°
125°
120°
Queen Charlotte fault
BRITISH COLUMBIA
50°
Explorer plate
Port Alberni
CANADA
UNITED STATES
Seaward edge of Cascadia subduction zone
WASHINGTON
Seattle
Pacific Ocean
Copalis River
Grays Harbor
Mount Rainier
Willapa Bay
Mount St. Helens
Detail in Fig. 1b
Columbia River
Cascadia deep-sea channel
Portland
Mount Hood
45°
Juan de Fuca plate
Salmon River
North America plate
Alsea Bay
Pacific plate
OREGON
Crater Lake
Thrust fault at plate boundary
Other fault
Spreading ridge
200-m isobath
Volcano
Gorda plate
Humboldt Bay
40°
CALIFORNIA
0 100 200 300 km
San Andreas fault

Figure 1b



Willapa Bay
Long Beach
Naselle
WASHINGTON
Skamokawa
Columbia River
Brush Island
Marsh Island
Price Island
Hunting Island
Cathlamet
40 km to Mount St. Helens
Astoria
Knappa
PACIFIC OCEAN
Upper Wallace Island
Lower Wallace Island
Longview
Clatskanie
Rainier
46°
Seaside
OREGON
Deer Island
St. Helens
N
10 km to Portland
Nehalem
124°
0 10 20 30 40 50 km
123°

b



WEST
EAST
46° 14'
Woody Island Channel
Brush Island
Marsh Island Creek
Marsh Island
123° 35'
Marsh and Brush Islands
Columbia River
46° 14'
Steamboat Slough
Price Island
123° 25'
Price Island
Columbia River
Entirely eroded since 1874
C
B
A
Wallace Island
Wallace Island Channel
46° 08'
123° 14'
Lower Wallace Island
EXPLANATION
Conditions ca. 1870 at low river stage
Swamp or marsh above high tide
Sand flat above high tide
Low-tide line far from swamp or marsh
Tidal flat and waterway <5 m deep at low tide
Waterway >5 m deep at low tide
Other symbols
Shoreline ca. 1980
Surveyed outcrop
Major change in shoreline since ca. 1870
N
0
1000 m
Scale 1:40,000
46° 15.5'
Columbia River
Hunting Island
123° 27.5'
Hunting Island
Columbia River
46° 09'
B
A
Wallace Island
Wallace Island Channel
123° 14'
Upper Wallace Island

Figure 2

Explanation for Figure 3

Upper bar graph

Outcrop area--Denotes area between low tide and the highest recognized intrusion (upper Wallace Island) or the gray layer (other islands)

Vertical outcrop--Steeper than 45 degrees

Horizontal outcrop--Gentler than 45 degrees, typically less than 10 degrees

Cross section

Swamp surface

Surveyed point--For buried swamp, denotes top of buried soil

Profile--For buried swamp, drawn above marker beds and at or just above level of lowest dead tree roots in growth position

Marker bed

Beige layer--Probably set-W tephra from Mount St. Helens

Gray layer--Provenance unknown

Fossils in growth position

Tubers of *Scirpus fluviatilis*--Symbol represents hundreds of individual tubers 1-2 cm in diameter within mud otherwise lacking in growth-position remains of vascular plants

Woody roots--Sitka spruce at Hunting and Price Islands; cottonwood at Marsh Island. Plotted only where part of large, horizontally aligned system. Additional dead roots are common but not plotted <0.3 m below 1993 swamp surface at Price Island

Liquefaction feature

Vented sand--Silty very fine sand or sandy silt less than 1 cm thick; mantles buried soil

Intrusion--Typically a vertical dike less than 2 cm wide. Symbol shows level of highest part of intrusion seen in outcrop, or of lowest part seen in core

Top seen--Tapers to less than 2 mm wide below eroded surface of outcrop

Top not seen--Transected by eroded surface of outcrop or by edge of core

Contact between muddy cap and sandy foundation--Measured in vibracore (where symbol is centered on vibracore line), in borehole made with bucket auger 5 cm in diameter (where symbol is centered above line for Washington [*WA*] penetrometer hole), or with push corer 2.5 cm in diameter (other symbols). Discrepancies among nearby measurements have one or more likely explanations: uncertainties in assigning depths to recovered cores (vibracore sites only), difficulty of penetrating sand beds >0.2 m thick (push-corer sites only), and gradational contacts due to interbedding of sand and mud

Other contact--Price Island only

Edge of inferred tidal-channel fill

Contact between relatively loose and relatively dense sand

Bed of mud or sandy mud in interval otherwise dominated by sand--Shown where documented by vibracoring (most islands) and where seen in low-tide or shallow subtidal outcrops (upper Wallace Island). Subject to errors due to difference between depth range of core and recovered thickness of core (difference noted beneath label for core). Symbol connected with solid line where mud bed continuously exposed at low tide (Fig. 13a)

Percentage of fine-grained sediment in sample of sand--Measured by sieving of sample from vibracore (upright numbers) or from bucket auger 5 cm in diameter (italicized numbers). Vertical position of most of the vibracore samples is subject to same error as noted above for mud beds

(0) [circle] <0.063 mm

11 [square] <0.074 mm

14
22
19
23

Penetration resistance--In blows per 6 inches. Not adjusted for depth, or for calibration with standard penetrometer. Adjacent vertical line shows depth range of measurements

15 Oregon penetrometer (borings labelled OR-)

15 Washington penetrometer (borings labelled *WA*-)

VB-10 0.4 m VB-14 0.5 m

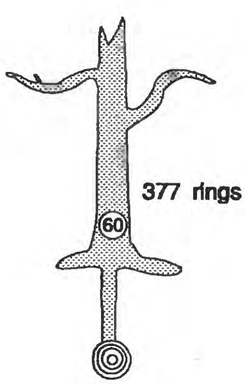
Vibracore--Heavy dashed vertical line shows depth range. Number at bottom gives length by which the recovered core is greater (arrow pointing downward) or less (arrow pointing upward) than the vertical range represented by the line

1140 ± 70 (tubers)

Radiocarbon age--In conventional radiocarbon years before A.D. 1950. Material dated in parentheses

July 30, -0.3

Low tide--Month, day, and predicted level at Astoria, in meters relative to mean lower low water



Sitka spruce--Live tree known or inferred to have originated before A.D. 1700 (seen at Price Island only). Number beside symbol denotes probable date, in years A.D., of innermost annual ring (pith) at height of 1-2 m above 19993 swamp surface; date determined by counting rings inward from bark in sanded slab (tag number 60) or core (other trees). Circled number denotes label on aluminum tag attached to trunk. Vertical stem below 1993 swamp surface connects with dead roots seen in bank except for tree with tag 99; this tree located too far back from bank for such roots to be seen

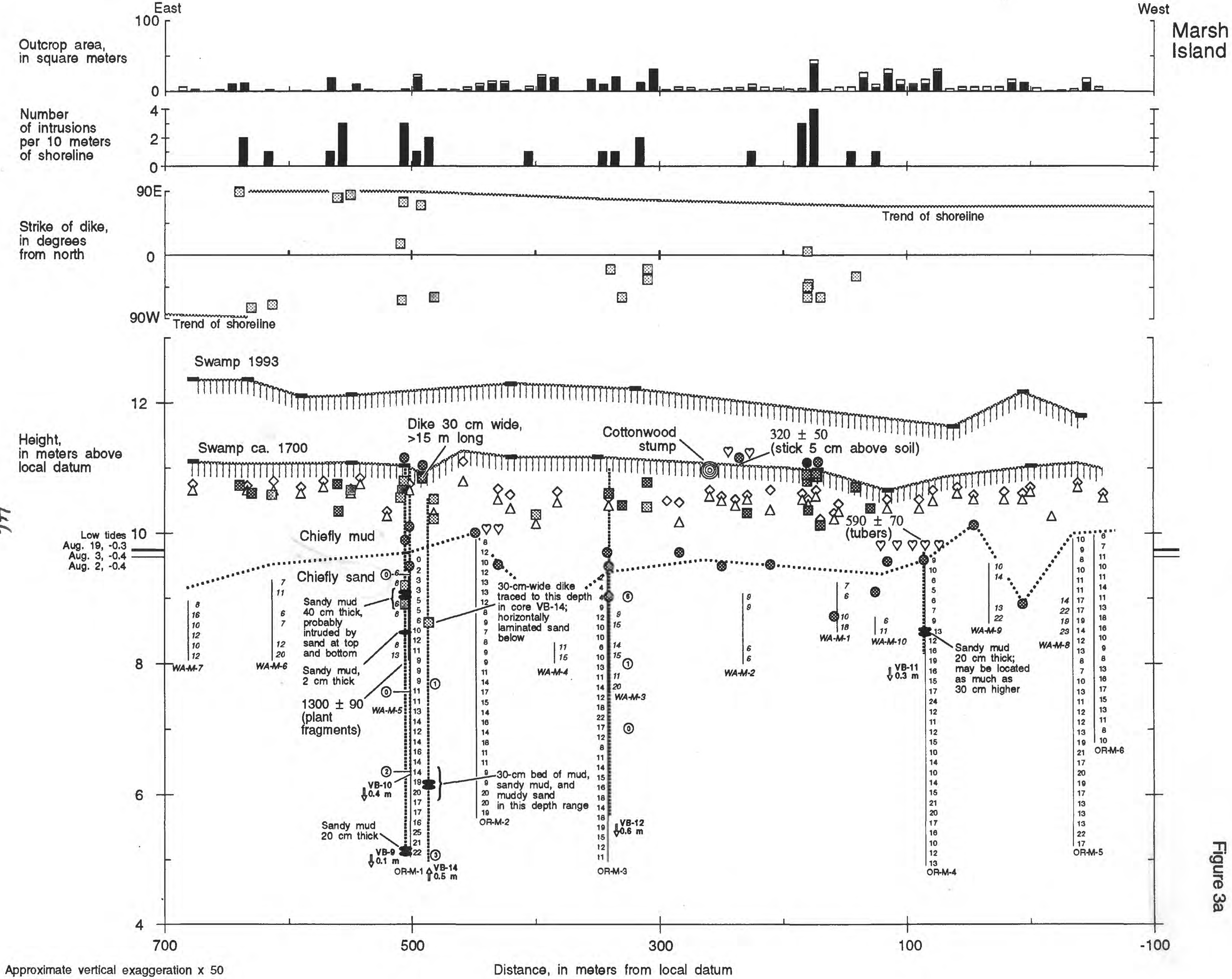

East
West
Marsh Island
Outcrop area, in square meters
Number of intrusions per 10 meters of shoreline
Strike of dike, in degrees from north
90E
90W
Trend of shoreline
Height, in meters above local datum
Swamp 1993
Swamp ca. 1700
Dike 30 cm wide, >15 m long
Cottonwood stump
320 ± 50 (stick 5 cm above soil)
590 ± 70 (tubers)
Low tides Aug. 19, -0.3 Aug. 3, -0.4 Aug. 2, -0.4
Chiefly mud
Chiefly sand
Sandy mud 40 cm thick, probably intruded by sand at top and bottom
Sandy mud, 2 cm thick
1300 ± 90 (plant fragments)
30-cm-wide dike traced to this depth in core VB-14; horizontally laminated sand below
30-cm bed of mud, sandy mud, and muddy sand in this depth range
Sandy mud 20 cm thick
Sandy mud 20 cm thick; may be located as much as 30 cm higher
WA-M-7
WA-M-6
WA-M-5
WA-M-4
WA-M-3
WA-M-2
WA-M-1
WA-M-10
WA-M-9
WA-M-8
OR-M-1
OR-M-2
OR-M-3
OR-M-4
OR-M-5
OR-M-6
VB-9 0.1 m
VB-10 0.4 m
VB-14 0.5 m
VB-12 0.6 m
VB-11 0.3 m
Approximate vertical exaggeration x 50
Distance, in meters from local datum

Figure 3a

Figure 3b

Brush Island

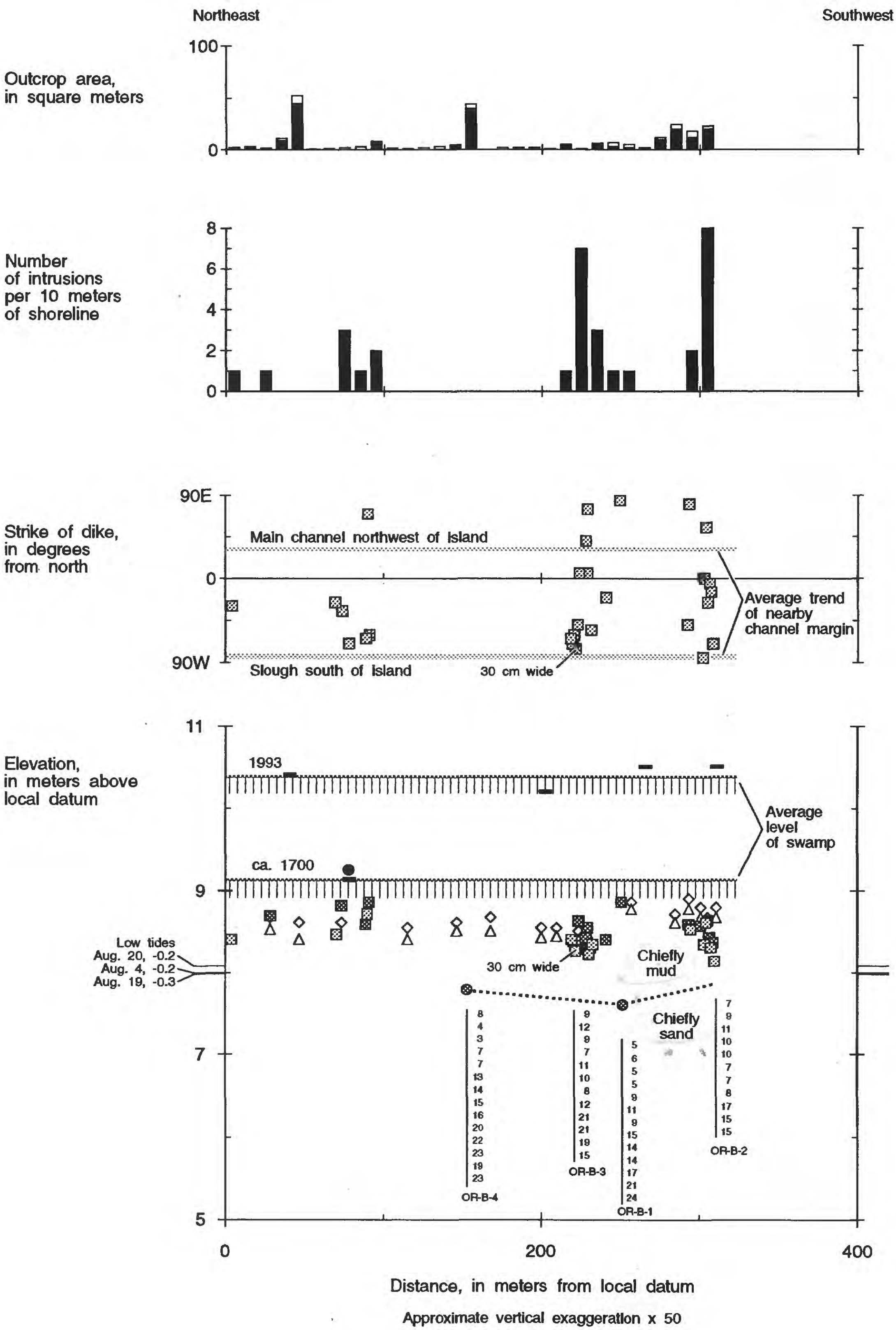


Figure 3c
Price Island

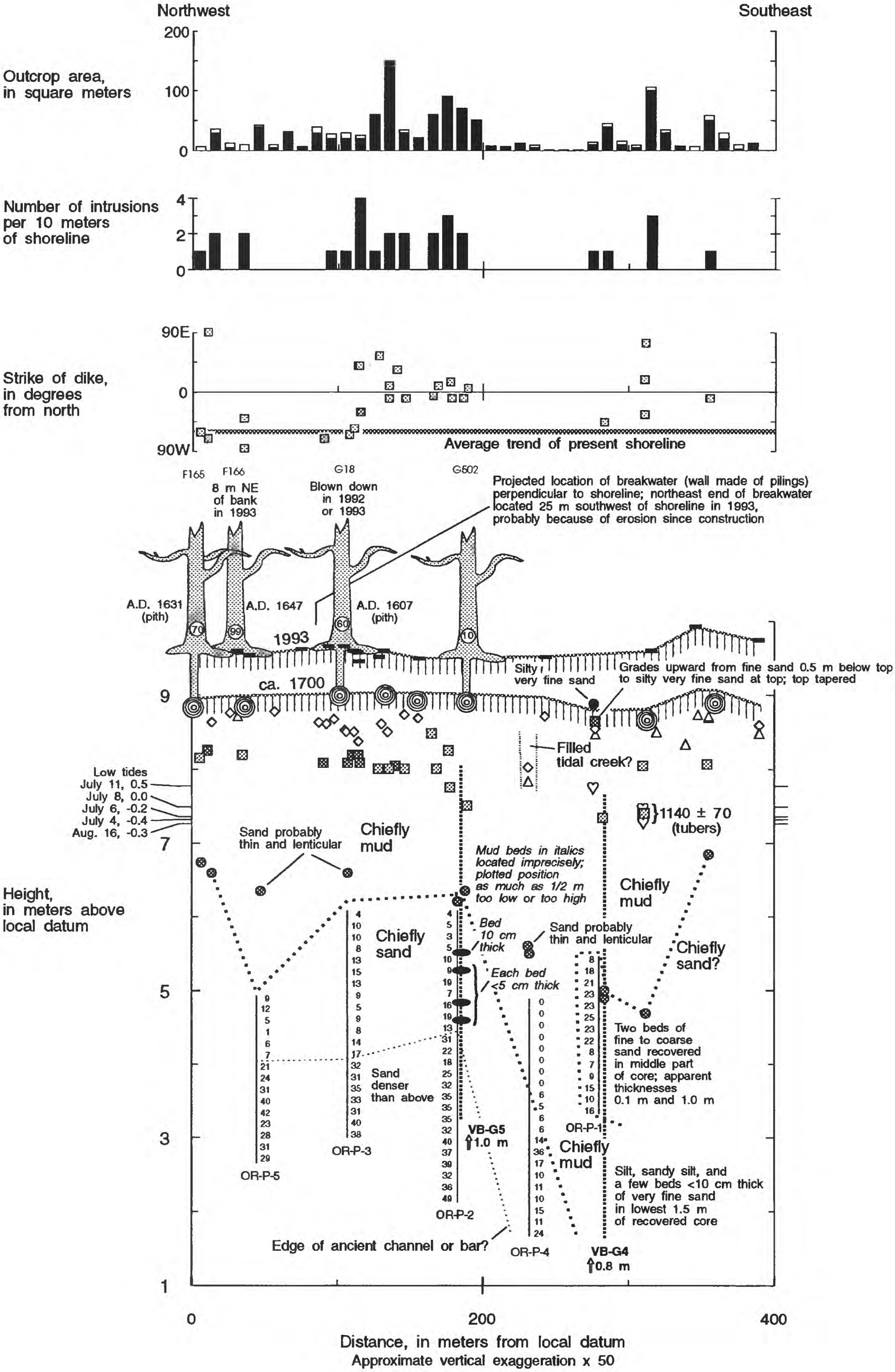
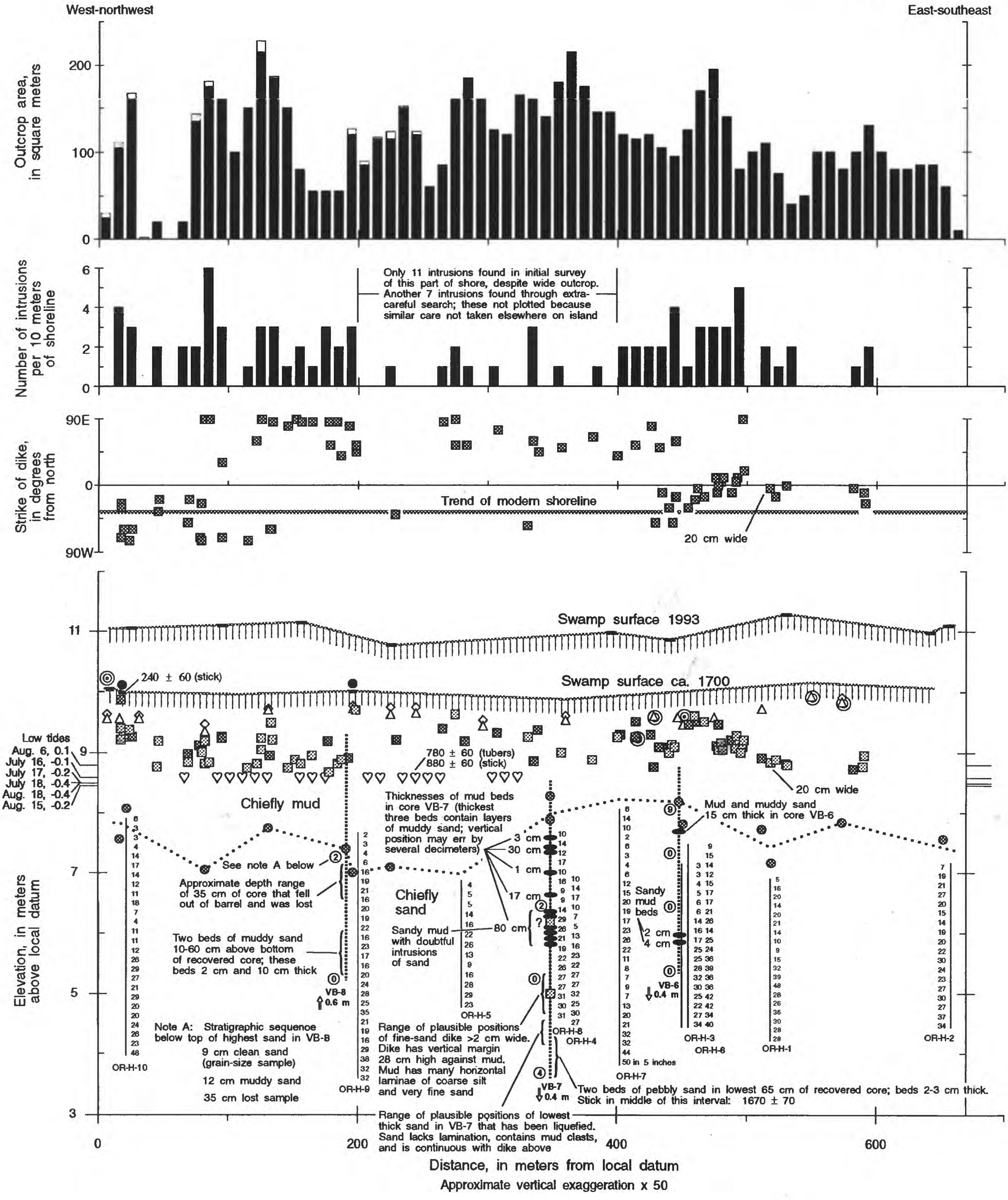


Figure 3d

Hunting Island



Lower Wallace Island

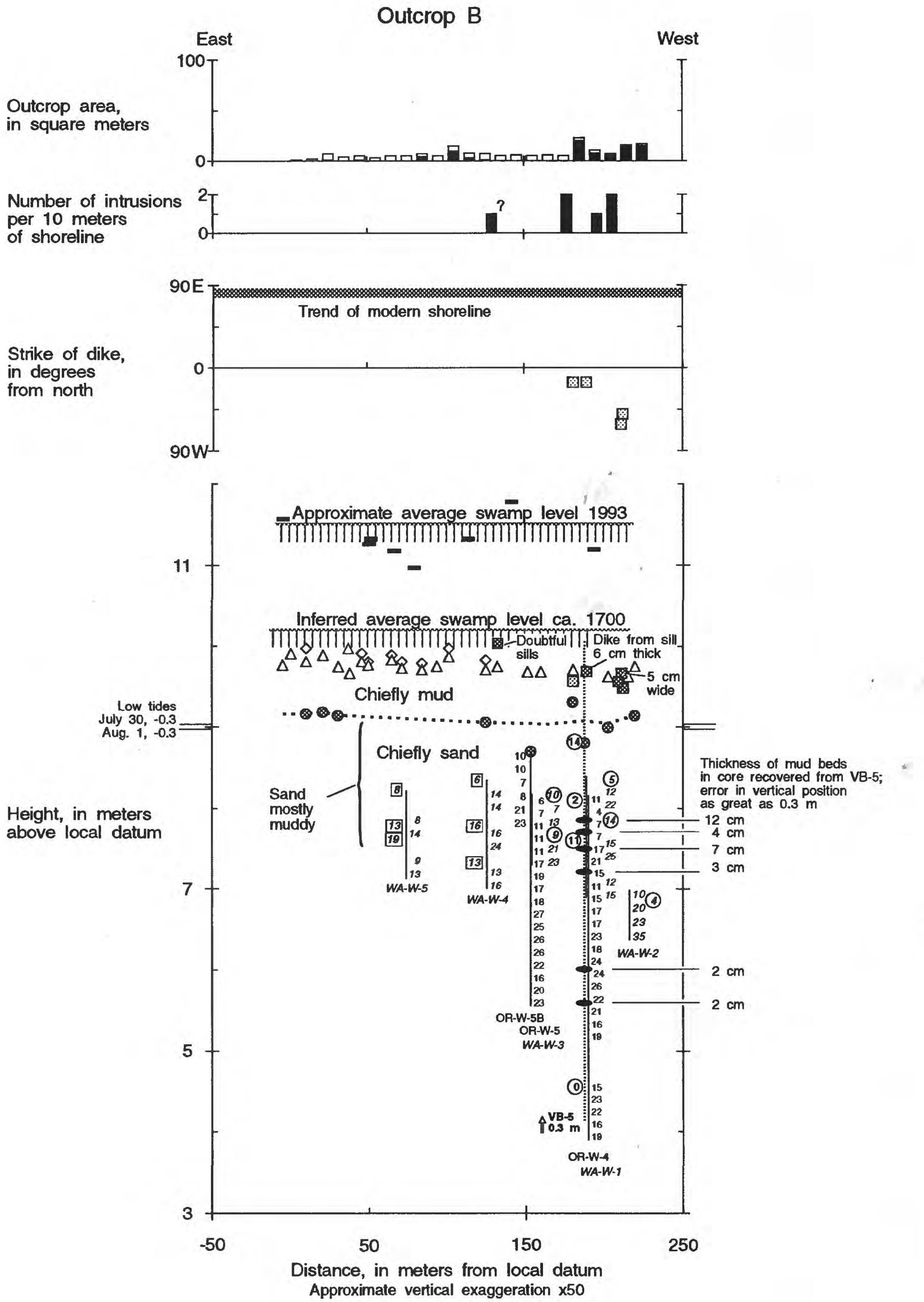
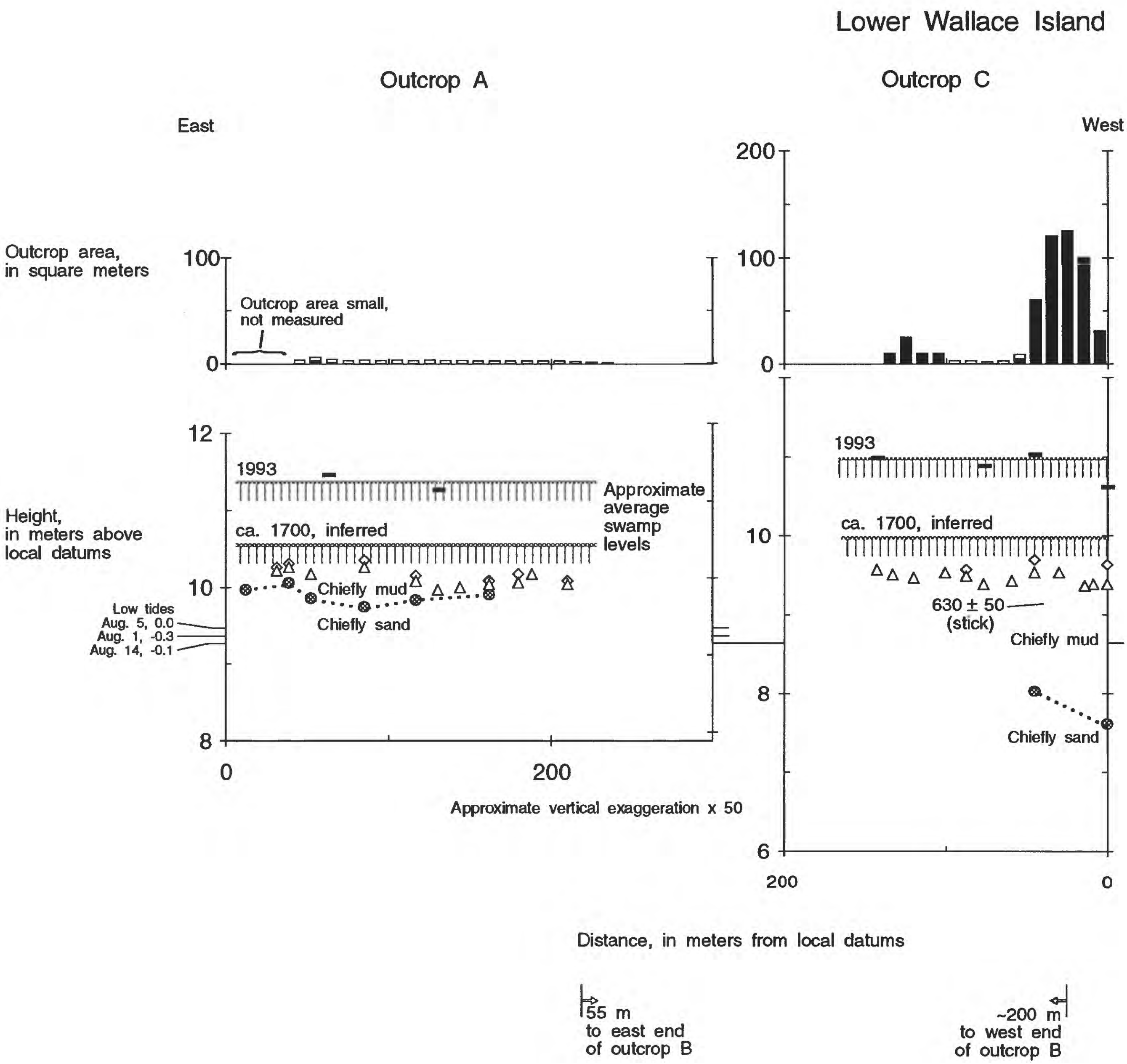


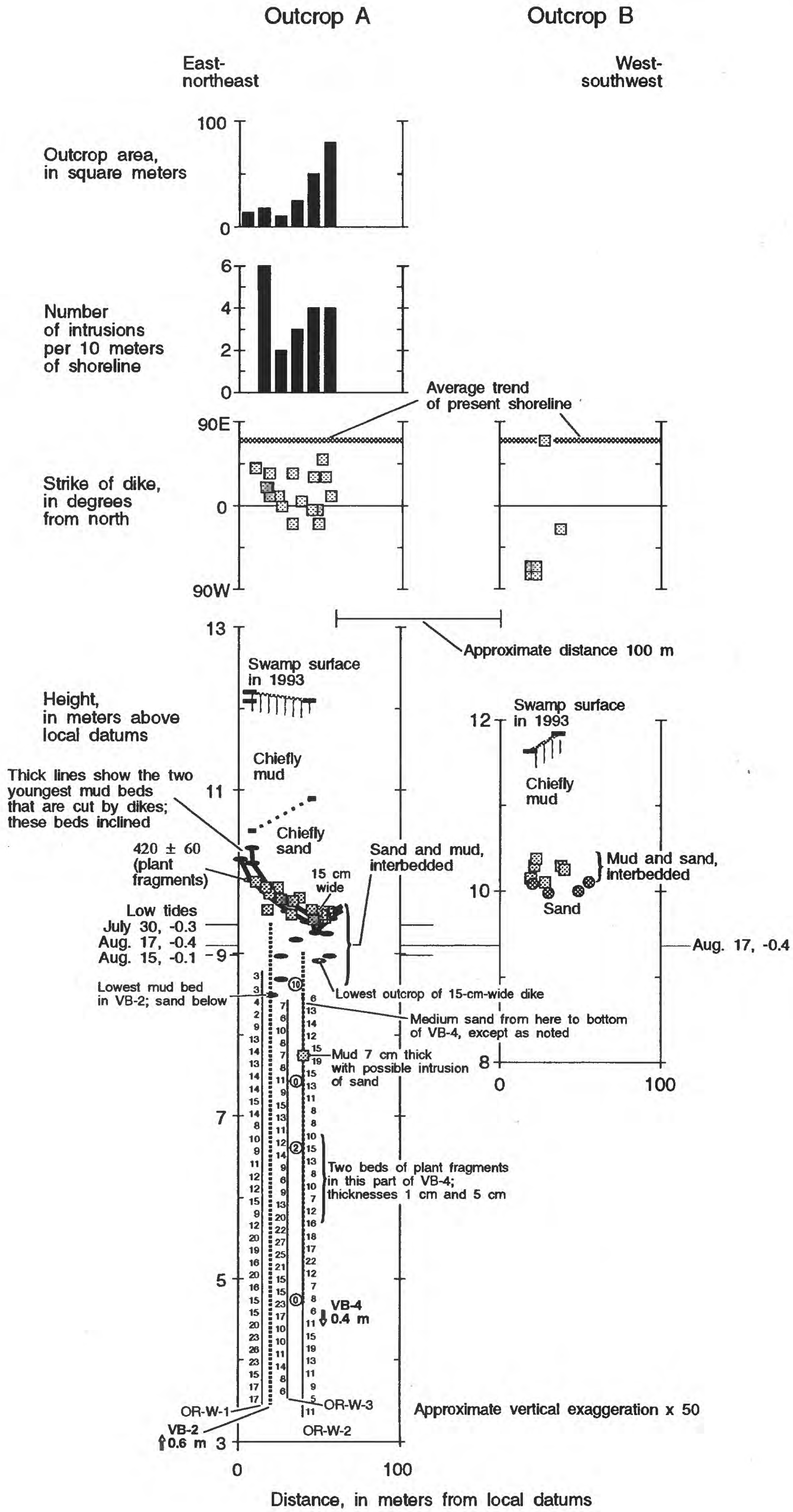
Figure 3f



Lower Wallace Island
Outcrop A
Outcrop C
East
West
Outcrop area, in square meters
100
0
200
Outcrop area small, not measured
Height, in meters above local datums
12
10
8
6
1993
ca. 1700, inferred
Approximate average swamp levels
Chiefly mud
Chiefly sand
Low tides
Aug. 5, 0.0
Aug. 1, -0.3
Aug. 14, -0.1
630 ± 50 (stick)
Approximate vertical exaggeration x 50
Distance, in meters from local datums
55 m to east end of outcrop B
~200 m to west end of outcrop B

Figure 3g

Upper Wallace Island



Explanation for Figure 4

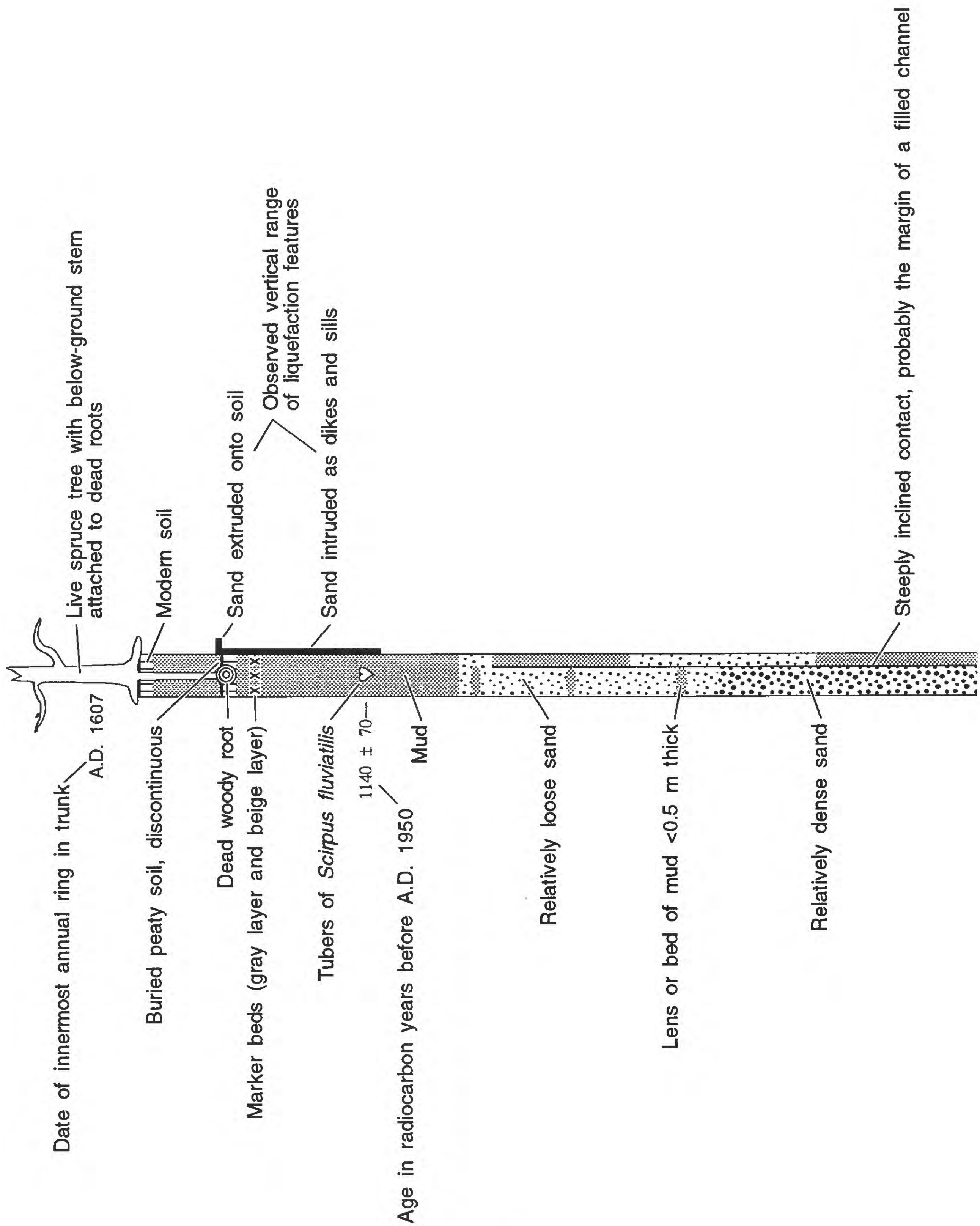
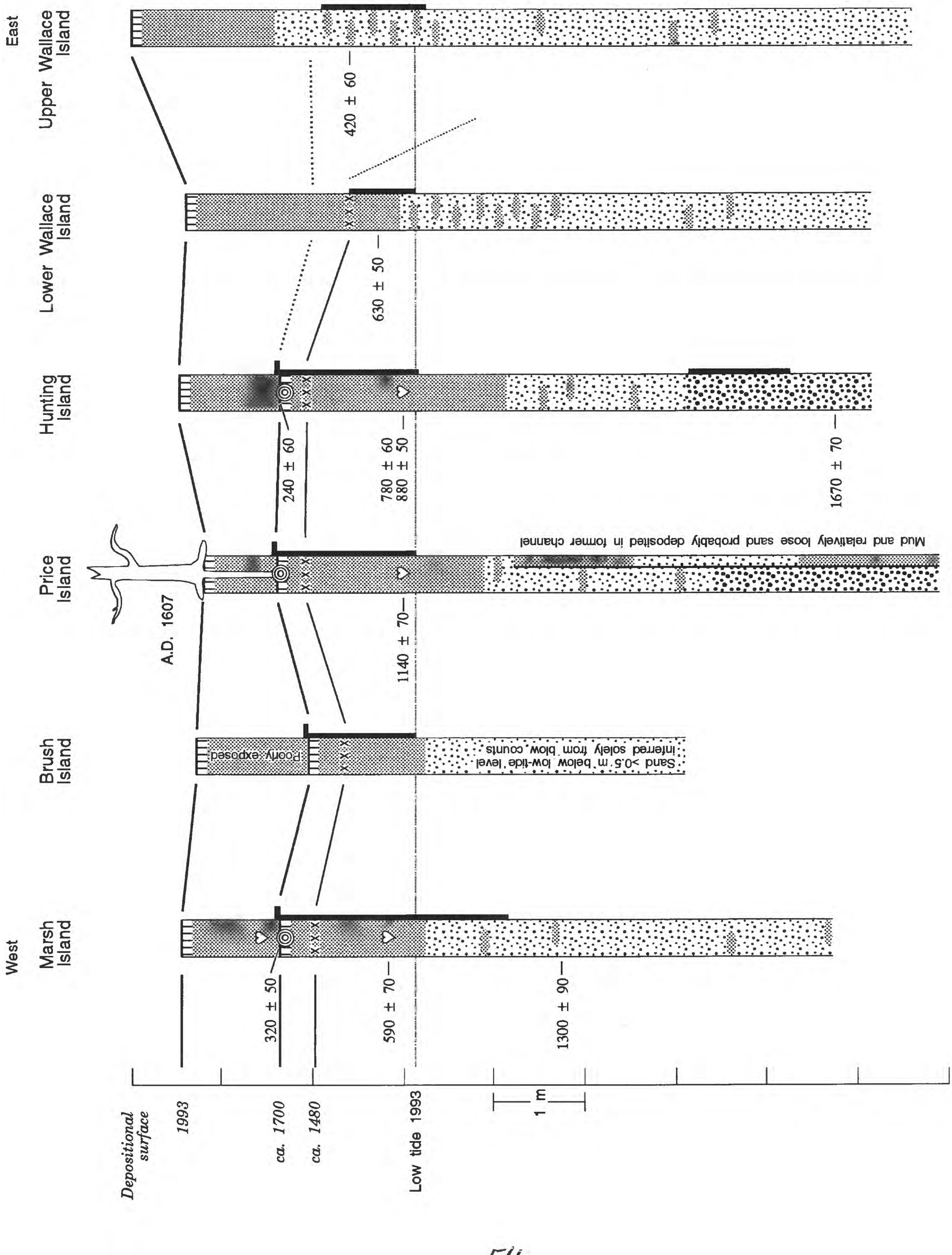


Figure 4


West
East
Marsh Island
Brush Island
Price Island
Hunting Island
Lower Wallace Island
Upper Wallace Island
Depositional surface
1993
ca. 1700
ca. 1480
Low tide 1993
1 m
320 ± 50
590 ± 70
1300 ± 90
Poorly exposed
Sand >0.5 m below low-tide level inferred solely from blow counts
A.D. 1607
1140 ± 70
Mud and relatively loose sand probably deposited in former channel
240 ± 60
780 ± 60
880 ± 50
1670 ± 70
630 ± 50
420 ± 60

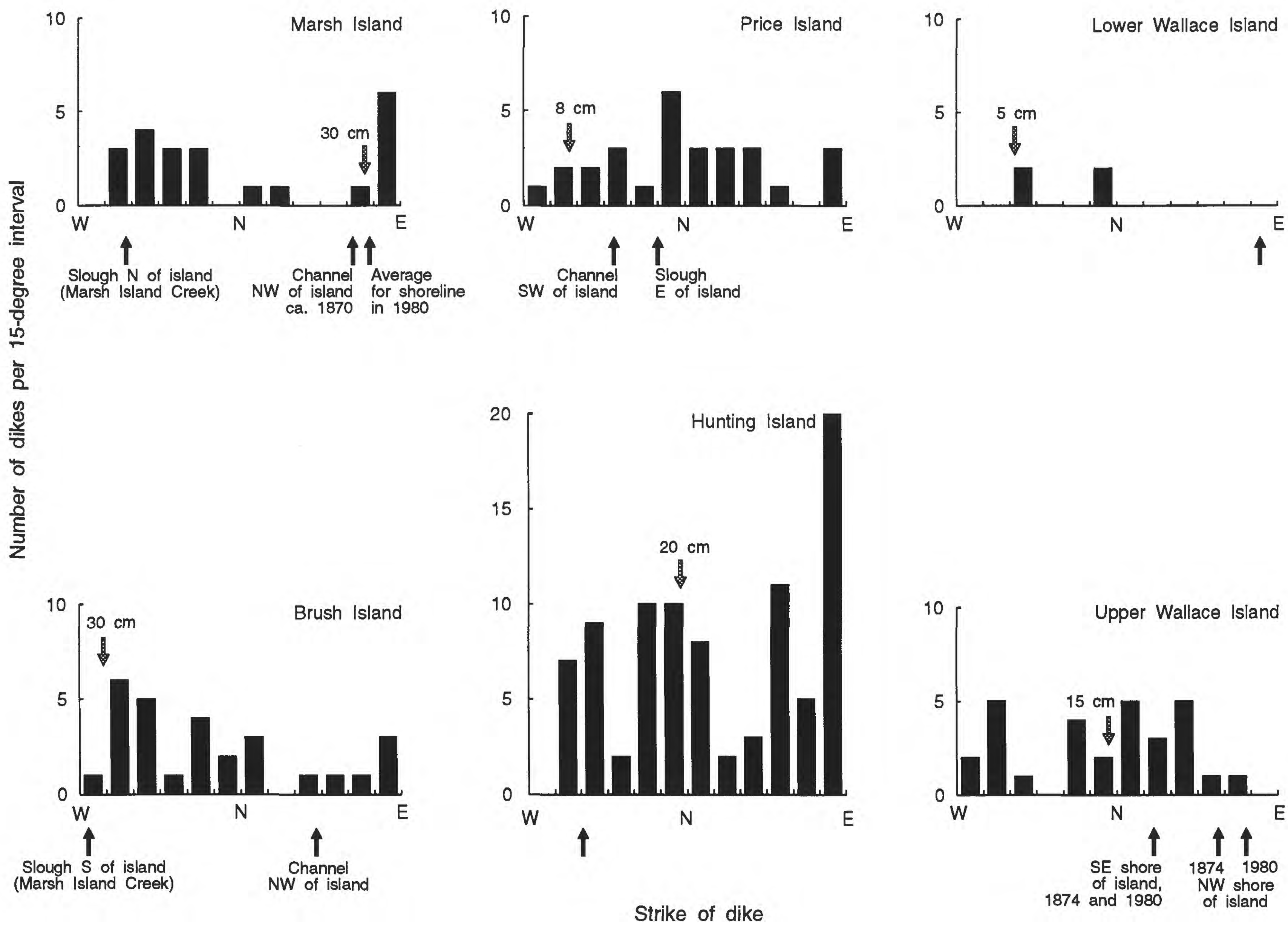

Number of dikes per 15-degree interval
Marsh Island
30 cm
Slough N of island (Marsh Island Creek)
Channel NW of island ca. 1870
Average for shoreline in 1980
Price Island
8 cm
Channel SW of island
Slough E of island
Lower Wallace Island
5 cm
Hunting Island
20 cm
Brush Island
30 cm
Slough S of island (Marsh Island Creek)
Channel NW of island
Upper Wallace Island
15 cm
SE shore of island, 1874 and 1980
1874 1980 NW shore of island
W N E
Strike of dike

Figure 5

Figure 6

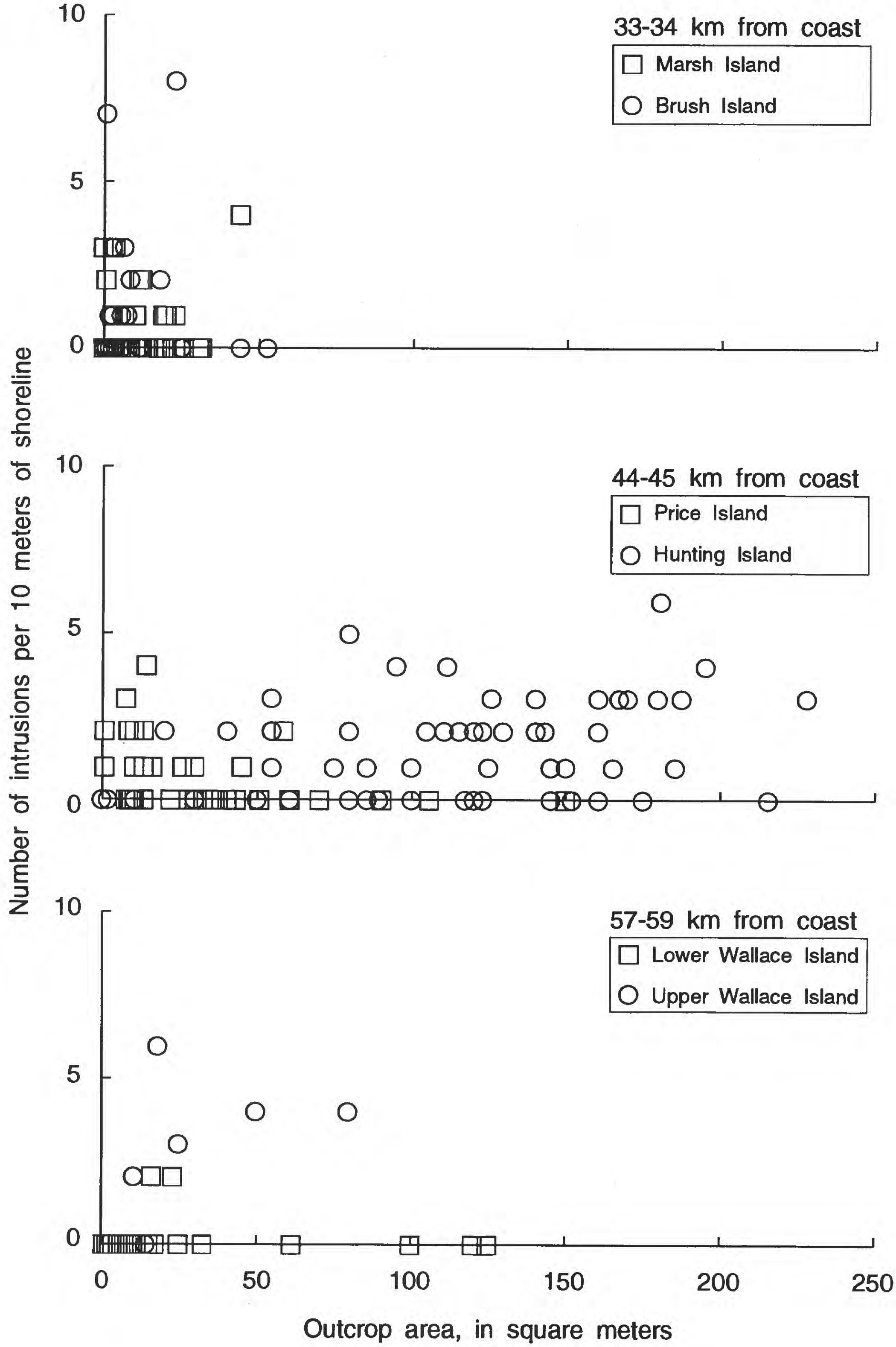

33-34 km from coast
Marsh Island
Brush Island
44-45 km from coast
Price Island
Hunting Island
57-59 km from coast
Lower Wallace Island
Upper Wallace Island
Number of intrusions per 10 meters of shoreline
10
5
0
0
50
100
150
200
250
Outcrop area, in square meters

Figure 7

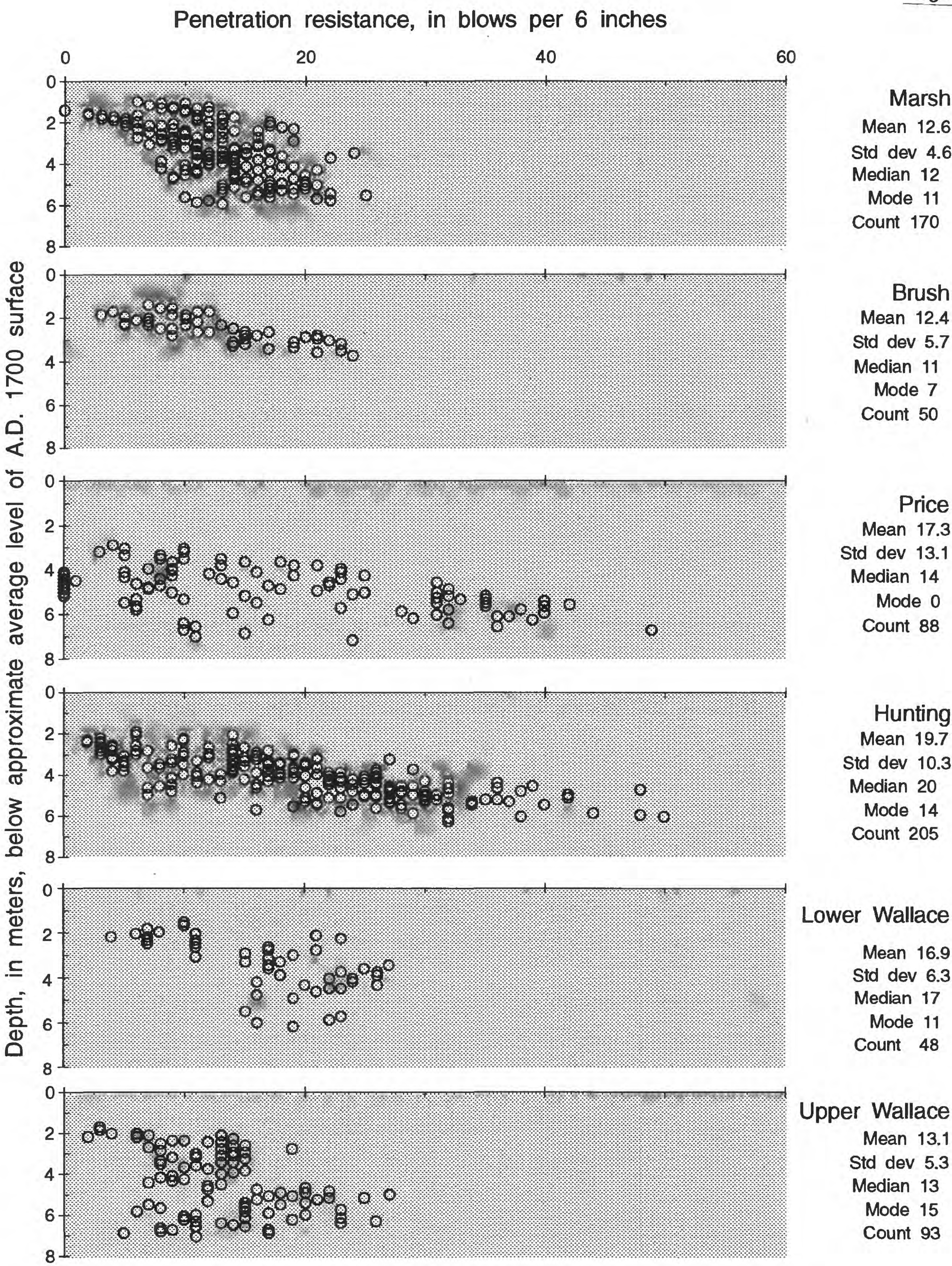

Penetration resistance, in blows per 6 inches
0
20
40
60
Depth, in meters, below approximate average level of A.D. 1700 surface
Marsh
Mean 12.6
Std dev 4.6
Median 12
Mode 11
Count 170
Brush
Mean 12.4
Std dev 5.7
Median 11
Mode 7
Count 50
Price
Mean 17.3
Std dev 13.1
Median 14
Mode 0
Count 88
Hunting
Mean 19.7
Std dev 10.3
Median 20
Mode 14
Count 205
Lower Wallace
Mean 16.9
Std dev 6.3
Median 17
Mode 11
Count 48
Upper Wallace
Mean 13.1
Std dev 5.3
Median 13
Mode 15
Count 93

Figure 8

Figure 9

Figure 10

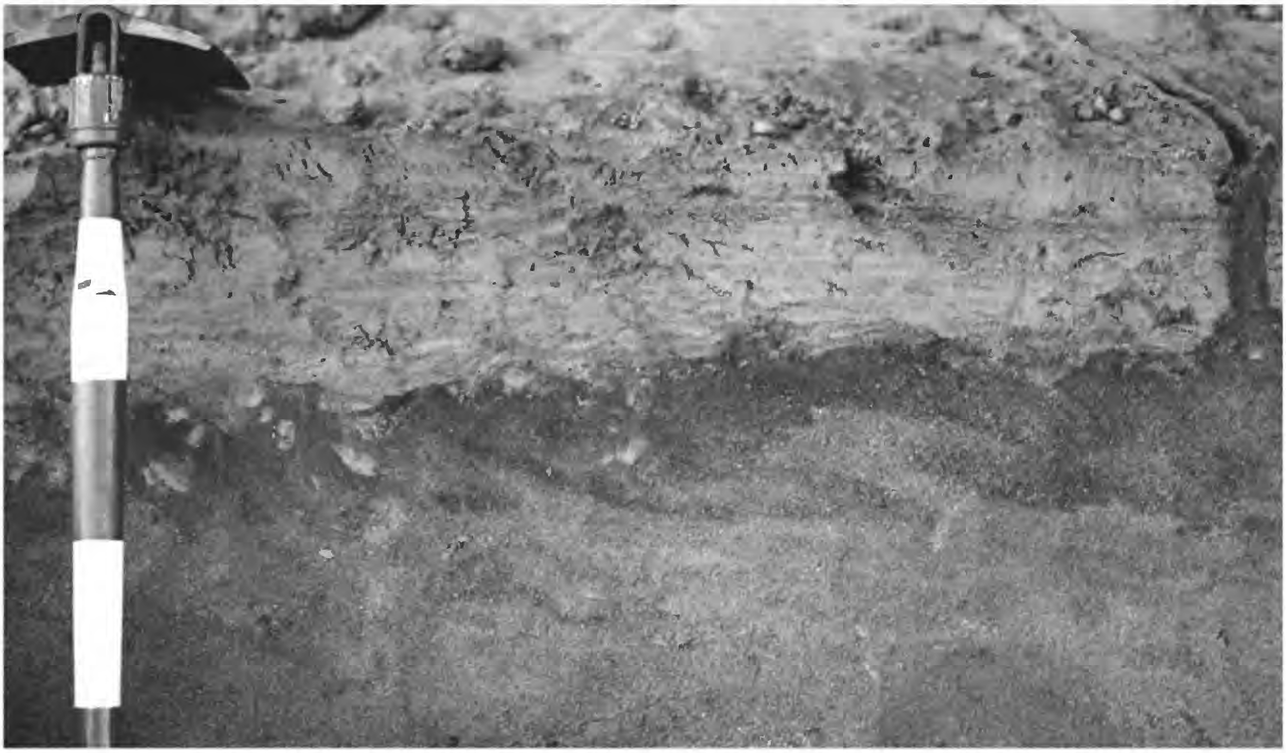
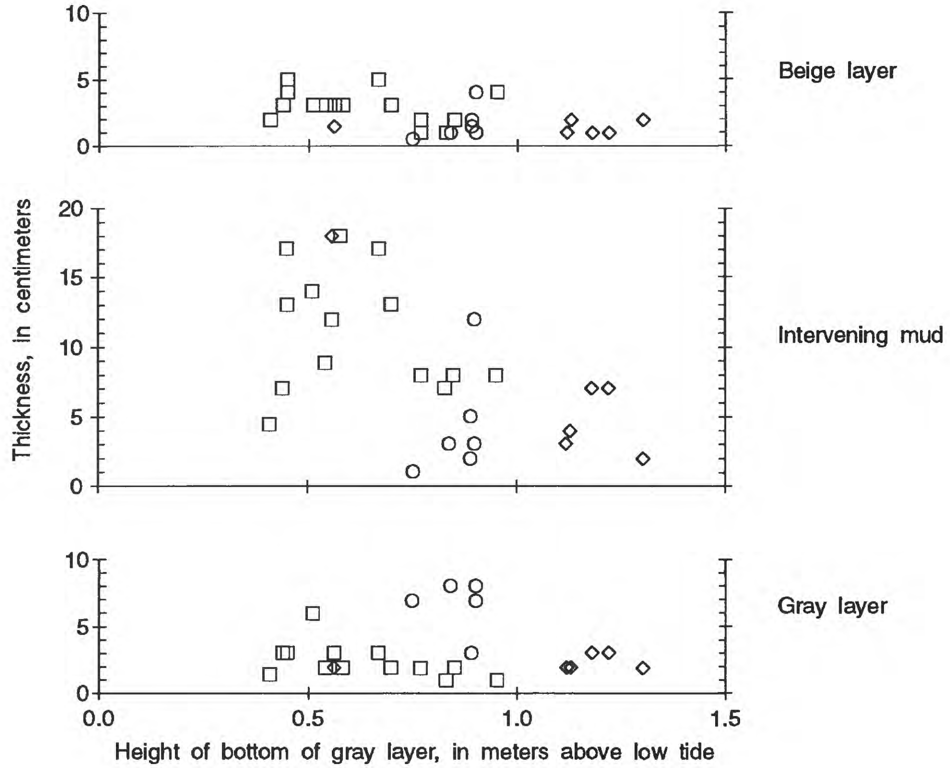


Figure 11



EXPLANATION

Location	Date of low tide
□ Marsh and Brush Islands	August 19
◇ Price and Hunting Islands	August 15 (Hunting) and 16 (Price)
○ Lower Wallace Island	August 1

Figure 12

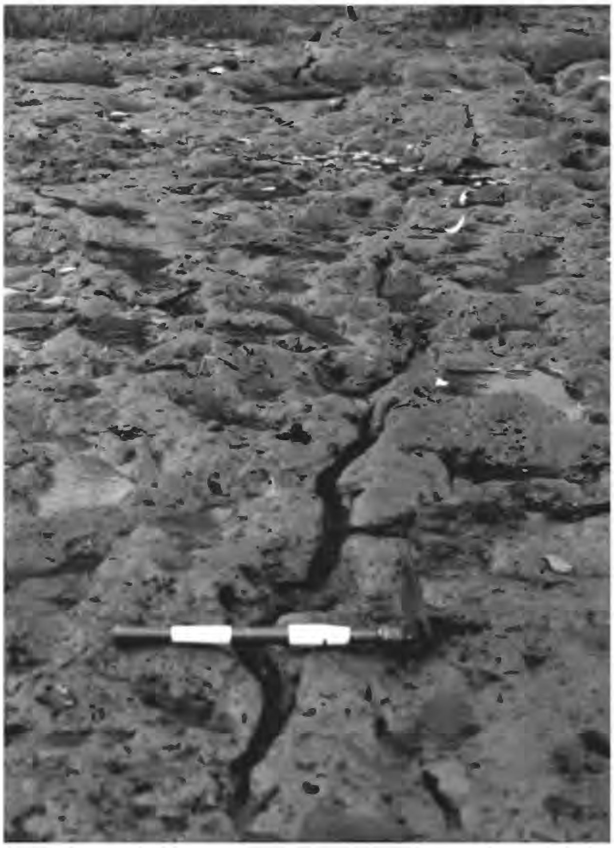


Figure 13a

Figure 13b