FINAL TECHNICAL REPORT

External Grant award number 00HQGR0067

Title of Recipient's application:
Investigation of Late Holocene Fault Displacement on the Southern Whidbey Island Fault Zone in the Northern Puget Lowland: Collaborative Research Between Humboldt State University and U. S. Geological Survey

Title of Final Technical Report:
Late Holocene displacement on the Southern Whidbey Island fault zone, northern Puget lowland, Washington n

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Program Element: Element II

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TECHNICAL ABSTRACT

Although there is no fault scarp at the location where the Southern Whidbey Island fault zone crosses Whidbey Island, we infer that about 3,000 years ago, there was an earthquake in the northern Puget Lowland that resulted in 1 to 2 meters of tectonic uplift on the northern side of the north strand of the fault zone. Evidence for the earthquake comes from different relative sea level histories and paleoecologic records of two coastal marshes immediately to either side of the inferred fault. Hancock marsh relative sea level rises without interruption for the period 3500 to 2500 year BP at the same time that Crockett relative sea level undergoes a period of no change. Furthermore, Crockett marsh show an abrupt transition from scrub-shrub wetland to forested wetland about 3,000 years ago whereas Hancock marsh, 8 km to the southeast and on the other side of the fault zone, shows evidence for disturbance but no evidence for a change in land level at the same time. The lack of a fault scarp on Whidbey Island at likely locations for the transition from positive vertical displacement to no land level change implies that tectonic displacement of Crockett marsh was the result of folding above the tip of a fault that did not reach the ground surface.

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NON-TECHNICAL ABSTRACT

Although there is no fault scarp at the location where the Southern Whidbey Island fault zone crosses Whidbey Island, we infer that about 3,000 years ago, there was an earthquake in the northern Puget Lowland that resulted in 1 to 2 meters of tectonic uplift on the northern side of the north strand of the fault zone. The evidence for 1 to 2 meters of uplift comes from a tidal marsh at Crockett Lake whose stratigraphy shows an abrupt transition from wetland to forest about 3,000 years ago. This paleoenvironmental change at Crockett is in contrast to the environment at the nearby Hancock tidal marsh, 8 km to the southeast and on the other side of the fault zone, where there was evidence for disturbance but no evidence for a change in land level at the same time. Because of a lack of a fault scarp at the likely location of the south margin of the uplift, we infer that the deformation at the surface was folding rather than faulting. In summary, our investigations show that there was a tectonic vertical displacement up to the north about 3,000 years ago at the likely site for the trace of the north strand of the southern Whidbey Island fault zone. The lack of a fault scarp implies that tectonic displacement of Crockett marsh was the result of folding above the tip of a fault that did not reach the ground surface.

INTRODUCTION

The Puget Lowland, northwest Washington, is contracting south to north (Wells et al., 1998; Miller et al., 2001) and crustal structures that accommodate this contraction (Figure 1A) are a seismic hazard. Best known of these structures are the Seattle fault and the Tacoma fault (Johnson et al., 1999; Brocher et al., 2001; Blakely et al., 2002; Nelson et al., 2003). Recognized but less understood fault zones lie further north in the lowland and include the Southern Whidbey Island, Utsalady Point, Strawberry Point and Devils Mountain fault zones (Johnson et al., 1996; 2001a).

The Southern Whidbey Island fault zone is a major basin bounding structure both identified in offshore seismic reflection profiles and having a pronounced gravity and aeromagnetic signature (Johnson et al., 1996; Blakely and Lowe, 2001; Johnson et al., 2001b). The Southern Whidbey Island fault zone bounds the Everett Basin to the south. Where the fault zone likely projects across Whidbey Island, based on mapped offsets of seismic stratigraphy in the offshore, there is no recognized Holocene surface trace. We provide relative sea level and paleogeodetic data based on paleoecology and geochronology of coastal marshes to demonstrate late Holocene vertical tectonic displacement, up to the north, at the latitude where a strand of the fault zone crosses Whidbey Island.

RESEARCH APPROACH

If the northern strand of the southern Whidbey Island fault zone, as mapped by Johnson et al. (2001b) based on seismic reflection profiles, has been active in the Holocene, then two coastal wetlands on either side of the northern fault strand should have different relative sea level histories. The Crockett marsh wetland is ca. one km north of the northern fault strand and the Hancock marsh wetland is ca. 1 km south of the northern fault strand (Figure 1B). However, barring any Holocene fault displacement between the wetlands, they should have the identical relative sea level history because they are close (8 km) to each other. Any glacio-isostatic influence on relative sea level should be reflected identically in both wetlands and any tectonic influence on relative sea level resulting from strain accumulation and release on the underlying subduction zone similarly should result in identical relative sea level perturbations at both sites.

The only event that could produce different relative sea level histories in the late Holocene is vertical tectonic displacement of one wetland relative to the other. If relative sea level curves for the two marshes are not the same, then divergence of the two curves would indicate the timing and magnitude of the vertical displacement on the intervening fault.

In order to determine sea level histories at the wetlands, cores were taken in a transect across each wetland perpendicular to the barrier sand bar that separates the Puget Sound (Admiralty Bay) from the wetland (Figure 2). The core transects start at the sand bar and proceed inland across the wetland with cores every 50 m until reaching the dry upland.

GEOLOGIC CROSS SECTIONS AND RELATIVE SEA LEVEL CURVES

At each marsh, the geologic cross section (Figure 2) indicates relative sea level rise over time. The sand barrier in front of each marsh has built upward over the late Holocene. As the barriers built upward, peat wetlands aggraded behind them (Figure 2).

Paleo sea level index points define a relative sea level curve at each site. Sea level index points are at the contact of the peat with the underlying substrate (Figure 2), which is beach sand, sandy gravel or a thin veneer of beach sand over Pleistocene glacial sediment. The sand-peat contact is a paleo sea level indicator because the underlying sand has marine diatoms and the overlying peat has freshwater and brackish-water plant macrofossils. The sand-peat contact in the modern marsh (located by the asterisk on each cross section in Figure 2), based on level surveys, has the same elevation at each marsh within 0.2 m and is at the approximate level of mean high water (MHW) (Figure 2).

The sea level curves for the two marshes (Figure 3A) are depicted based on the age and depth of paleo sea level index points relative to modern mean lower low water (MLLW). AMS ^{14}C dating of plant macrofossils (seeds) in the peat within 30 mm of the contact provides age control. Age ranges in Figures 2 and 3 are years before A.D. 1950 (equivalent to "years ago" as used in the text) and are converted from the 2-sigma-reported laboratory ^{14}C age using Stuiver et al. (1998) (Table 1). The height and width of the rectangles (data points, Figure 3) express the magnitude of the error in locating the relative sea level curve in time-depth space. The width of the rectangle is the age range of the sand-peat contact (Figure 2). The height of the rectangle is the uncertainty in elevation of the sand-peat contact, ± 0.3 m, calculated as the square root of the sum of the squares of the three variables that determine elevation relative to mean lower low water (MLLW): survey error (± 0.01 m), tidal measurement at site (± 0.20 m) and variation in elevation of the modern sand/peat contact (± 0.20 m).

NORTH-SIDE-UP DISPLACEMENT ON THE SOUTHERN WHIDBEY ISLAND FAULT ZONE 3,000 YEARS AGO: PALEO ECOLOGIC EVIDENCE

The two relative sea level curves are not the same. Superposition of the Crockett and Hancock curves (Figure 3) shows that, for ages older than 3,000 years, equivalent-age sea level index points at Crockett are 1 to 2 m higher than at Hancock. Also, there is a 500 to 1,000 year interval of time, after 3,000 years, when the Crockett site shows no change in relative sea level, or a relative sea level fall, whereas there is no period of time at Hancock when relative sea level is not rising. The two relative sea level curves in the last 2,000 years are similar within limits of sea level resolution.

We infer that the explanation for the dissimilarity of relative sea level curves is vertical tectonic displacement associated with a structure that trends between Crockett and Hancock marshes. The apparent upward shift of the Crockett relative sea level curves is caused by upward vertical displacement at Crockett relative to Hancock about 3,000 years ago (Figure 3). Reconstructing one relative sea level curve common to both sites requires vertically lowering the Crockett curve onto the Hancock curve by 1.0 to 2.1 m (Figure 3), which implies that the amount of vertical displacement is 1.5 m ± 0.5 m up to north.

Paleoecologic data from cores at the two marshes provide corroborative evidence for upward displacement of Crockett versus Hancock marsh ca. 3000 years ago. At Crockett marsh a 2-cm thick clean, fine sand layer occurs within the peat sequence in core J ca. 25 cm above the tide flat to marsh wetland contact (Figure 2); the sand layer contained 2,780-3,130 year-old detrital seeds (Figure 2). The thin sand layer separates an underlying herbaceous and detrital peat from an overlying peat containing woody detritus from a forested wetland. Similarly, in adjacent core IJ, 25 m farther north, a contact of the same age as the sand layer separates an underlying herbaceous peat from an overlying peat containing coarse woody detritus (Figure 2). At the time of deposition of the thin sand layer, the wetland at Crockett emerged suddenly, changing from a scrub-shrub wetland to a relatively drier forested wetland at core site J and from a peat wetland to a forested wetland at core site IJ. We infer that tectonic displacement, which is evident from the sea level curves, produced rapid emergence and a change to drier site conditions at the Crockett wetland relative to the Hancock wetland. The drier environment at Crockett persisted for about 500 to 1,000 years, based on sedimentation rate from ^{14}C ages, at which time the Crockett marsh again responded to relative sea level rise through peat aggradation. This 500-to-1,000-year interval roughly is equivalent to the time interval when relative sea level at Crockett was static or fell slightly (Figure 3).

At Hancock marsh, diatom assemblages profoundly change at about 2,800 to 3,200 years ago (352 cm depth, core R, Figure 2), which is synchronous, within limits of the calibrated radiocarbon ages, with the time of abrupt relative sea level fall at Crockett marsh. Prior to this time, the Hancock diatom assemblage is dominated by the intertidal diatom flora Paralia sulcata and Trachyneis aspera. At about 2,800 to 3,200 years ago, the assemblage becomes dominated by Fragilaria construens. The change in diatom assemblage indicates a change in intertidal environment. Fragilaria construens is a cosmopolitan diatom that characteristically lives in lower intertidal environments in northern Puget Sound (Rao and Lewin,1976), and may have become dominant 2,800 to 3,200 years ago due to a local site disturbance to Hancock marsh.

Although it may be tsunami generated, there is no evidence to support a tsunamigenic origin for the sand layer at 1.5 m depth in core J at Crockett (Figure 2). The sand layer that separates underlying herbaceous and detrital peat from overlying peat containing woody detritus was only found in one core at Crockett and no sand layers were found in the Hancock peat sequence. If a tsunami accompanied the tectonic displacement that raised Crockett's marsh floor, the tsunami was too small to entrain and deposit sand extensively over the Crockett or Hancock marsh surfaces.

DISCUSSION

The structure that caused the 1 to 2 m of north-side-up displacement must lie between the two marshes, which are within 8 km of each other. The structure responsible for the displacement is most probably the northern strand of the Southern Whidbey Island fault zone because the northern strand projects, from offshore seismic profiles, into that part of Whidbey Island between the two marshes. If this fault strand is the causative structure, then slip on the fault did not reach the ground surface because no fault scarp is apparent on Airborne Laser Swath Mapping (ALSM) imagery that covers the mid-Whidbey Island region where the structure must cross (ALSM imagery provided by S. Johnson, March, 2003). We infer slip below the surface produced a fold at ground level that accounts for the 1 to 2 m of vertical displacement.

With no more than two meters of vertical displacement at the surface and an unknown length of subsurface rupture, the size of the earthquake that caused the displacement is unknown. Based on vertical displacement alone, earthquake moment magnitude may be on the order of ca. 6.5 (Wells and Coppersmith, 1994).

Secondary effects of a moderate sized crustal earthquake in central Whidbey Island were probably minor and not recorded regionally. The earthquake did not trigger a sizable tsunami, which would have left an extensive record of sand deposition in nearby marshes. Although Jacoby et al. (1992) have identified a submerged forest on a landslide lobe that translated into Lake Washington ca. 2,850-3,250 years ago, the central Whidbey Island ca. 3,000-year-ago earthquake is probably one of several seismogenic sources that could have triggered the Lake Washington landslide in the 2,850-3,250 year-ago time interval.

CONCLUSION

A structure in central Whidbey Island, most probably the northern strand of the southern Whidbey Island fault, slipped coseismically about 2,800 to 3,200 years ago, generating a fold at the surface that produced 1 to 2 m of vertical displacement up to the north that halted relative sea level rise at Crockett marsh immediately north of the fold trace but did not affect ongoing relative sea level rise at Hancock marsh immediately south of the fold trace. Macrofossil observations at Crockett confirm abrupt uplift to a drier environment at the time of the relative sea level perturbation, and diatom flora at Hancock show disturbance to Hancock's marsh surface at the same time. Although a sand layer occurs at the contact that defines the interruption in rise of sea level at Crockett, there are no additional field observations that would support a tsunamigenic origin for this sand. Abrupt tectonic displacement is the only explanation that can satisfy the relative sea level and paleoecologic changes ca. 3000 years ago in central Whidbey Island; however, the causative tectonic structure and the extent of secondary effects associated with the tectonic displacement cannot be conclusively resolved. Most significantly, the coastal marsh relative sea level and paleo ecologic data demonstrate that the northern Puget Lowland, in the late Holocene, has been the site of at least one M 6+ earthquake on a crustal fault that caused abrupt sea level change and vertical ground displacement.

ACKNOWLEDGMENTS
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TABLE 1. RADIOCARBON AGES, CROCKETT AND HANCOCK MARSHES, WHIDBEY ISLAND

Sample ID *	Laboratory ID †	Date §	^{14}C age #	Calibrated age range**	Dated material
Crockett Marsh					
CR01 B 123	GX-29065	7.02	940±30	772-928	seeds
CR98 C 168	B 125102	1.99	2500±50	2360-2750	seed
CR98 G 407	B 125103	1.99	4140±90	4410-4860	seeds
CR00 E 215	GX-27608	2.01	2950±40	3990-4250	seeds
CR00 G 365	GX-27614	2.01	4230±40	4620-4860	seeds
CR00 H 482	GX-27613	2.01	4200±40	4580-4840	seeds
CR00 J 121	GX-27612	2.01	2860±30	2870-3130	seeds
CR00 J 173	GX-27611	2.01	3030±30	3080-3340	seeds
CR00 J 193	GX-29990	4.03	12740±230	13950-15770	shell
CR01 I/J 74	GX-29058	7.02	1780±50	1566-1821	seeds
CR01 I/J 124	GX-29059	7.02	2240±50	2129-2345	seeds
CR01 I/J 161.5	GX-29989	4.03	2870±50	2850-3200	seeds
CR01 I/J 184	GX-29060	7.02	3090±30	3212-3376	seeds
CR01 I/J 224	GX-29061	7.02	3690±30	3926-4144	seeds
CR01 I/J 266	GX-29062	7.02	3700±30	3929-4145	seeds
CR01 S 260	GX-29066	7.02	13720±60	15720-16700	shell
Hancock Marsh					
HA98 G1 257	B 125100	1.99	1110±50	930-1130	Scirpus stem base
HA98 B2 443	B 125101	1.99	3450±60	3560-3850	resinous herb stem
HA00 DD 52	GX-27610	2.01	2520±40	2360-2750	seeds
HA00 CC 81.5	GX-27340	11.00	2480±40	2360-2720	seeds
HA00 E 212	GX-27609	2.01	2950±40	2960-3310	seeds
HA01 G 377	GX-29064	7.02	3090±30	3212-3376	seeds
HA00 K 420	GX-27339	11.00	3170±40	3270-3470	seeds
HA00 O 447	GX-27336	11.00	3470±40	3640-3830	seeds
HA00 R 50	GX-29051	7.02	800±40	665-787	moss
HA00 R 102.5	GX-29052	7.02	1520±40	1315-1517	seeds
HA00 R 155	GX-29053	7.02	2160±50	2003-2312	seeds
HA00 R 205	GX-29054	7.02	2440±50	2352-2711	woody stem
HA00 R 240	GX-29055	7.02	2700±50	2746-2918	seeds
HA00 R 273	GX-29056	7.02	2990±30	3076-3320	seeds
HA00 R 349.5	GX-29057	7.02	3420±60	3480-3830	seeds, Thuja plicata stem
HA00 T 446	GX-27337	11.00	3400±40	3480-3820	seeds
HA01 U/V 422	GX-29063	7.02	3420±30	3574-3819	seeds
HA00 W 172	GX-27338	11.00	2070±30	1950-2120	seeds

* Sample code includes: site designation; year sampled; core designation; depth (cm) to top of sample.

† Laboratory prefixes and measurement methods: B, Beta Analytic, accelerator mass spectrometry; GX, Geochron Laboratories, accelerator mass spectrometry.

§ Laboratory run date: month, year

\# Laboratory reported ^{14}C age (one standard deviation).

** Calibrated years before A. D. 1950, using calibration program of Stuiver et al. (1998). Calibration incorporates two standard deviations and an error multiplier of one. We use a reservoir correction for marine shells of 800±25 years (Robinson and Thompson, 1981).

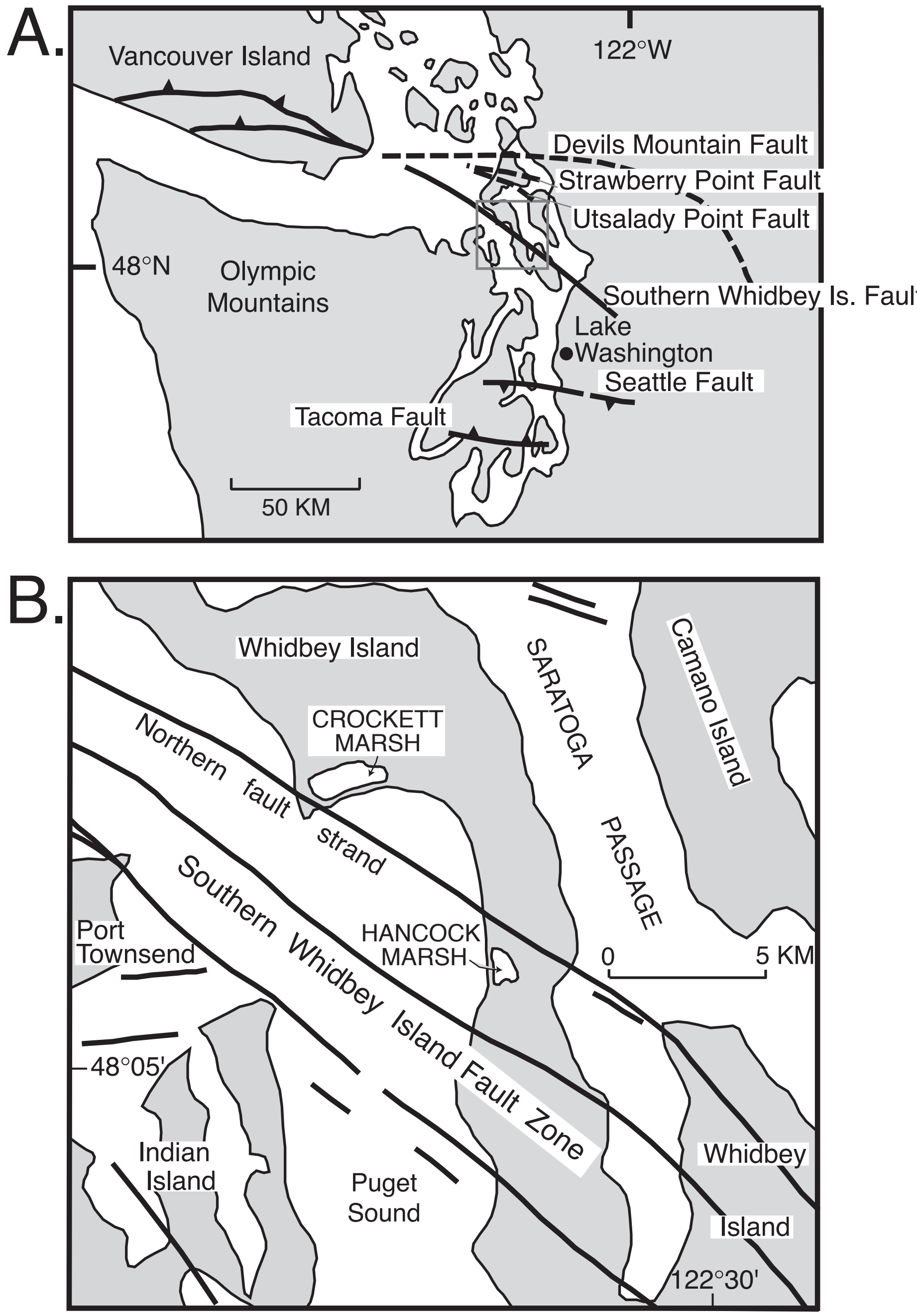

Figure 1. A. Location map of northwest Washington state and southern Vancouver Island, modified after Johnson et al. (1996), showing location of faults in the Puget lowland that can accommodate north-south contraction. Also shown is the Lake Washington site that shows evidence for landsliding approximately 3,000 year ago. B. Tectonic map showing the three main fault traces of the Southern Whidbey Island fault zone, adapted from Johnson et al. (1996; 2001b). Crockett coastal marsh and Hancock coastal marsh straddle the on-land projection of the offshore seismically imaged trace of the northern strand of the Southern Whidbey Island fault zone.

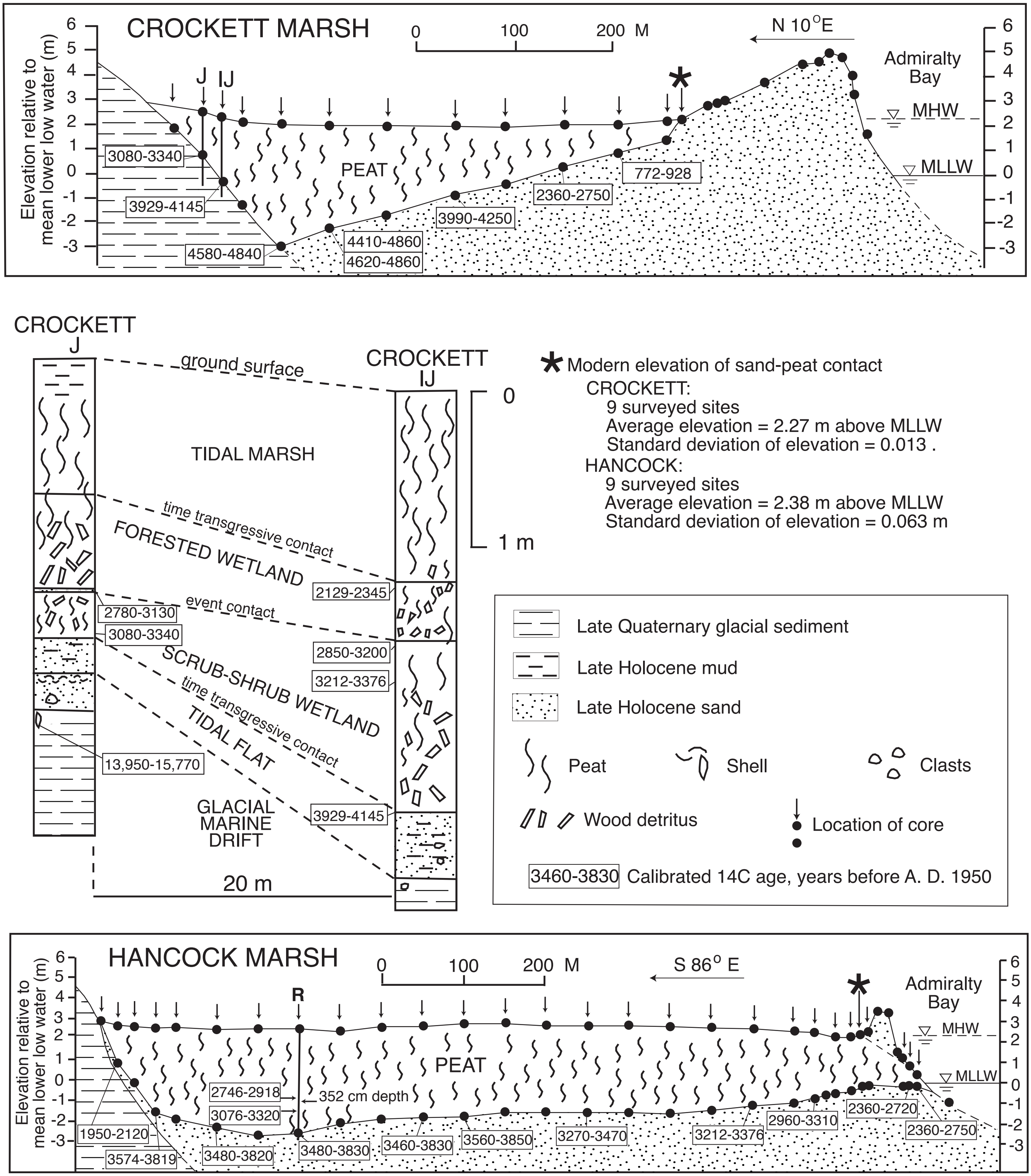

Figure 2. Geologic cross section of Crockett and Hancock marshes, and stratigraphic data from Crockett cores J and IJ. The Hancock marsh cross section is different from the section at Crockett in that peat is exposed in the intertidal zone. At Hancock, the sand barrier is underlain by peat because the sand barrier first built up and prograded seaward and then while the barrier continued to build upward, it started to migrate landward eroding peat that had been previously deposited behind the barrier. At Crockett, the barrier built upward and seaward as sea level rose.

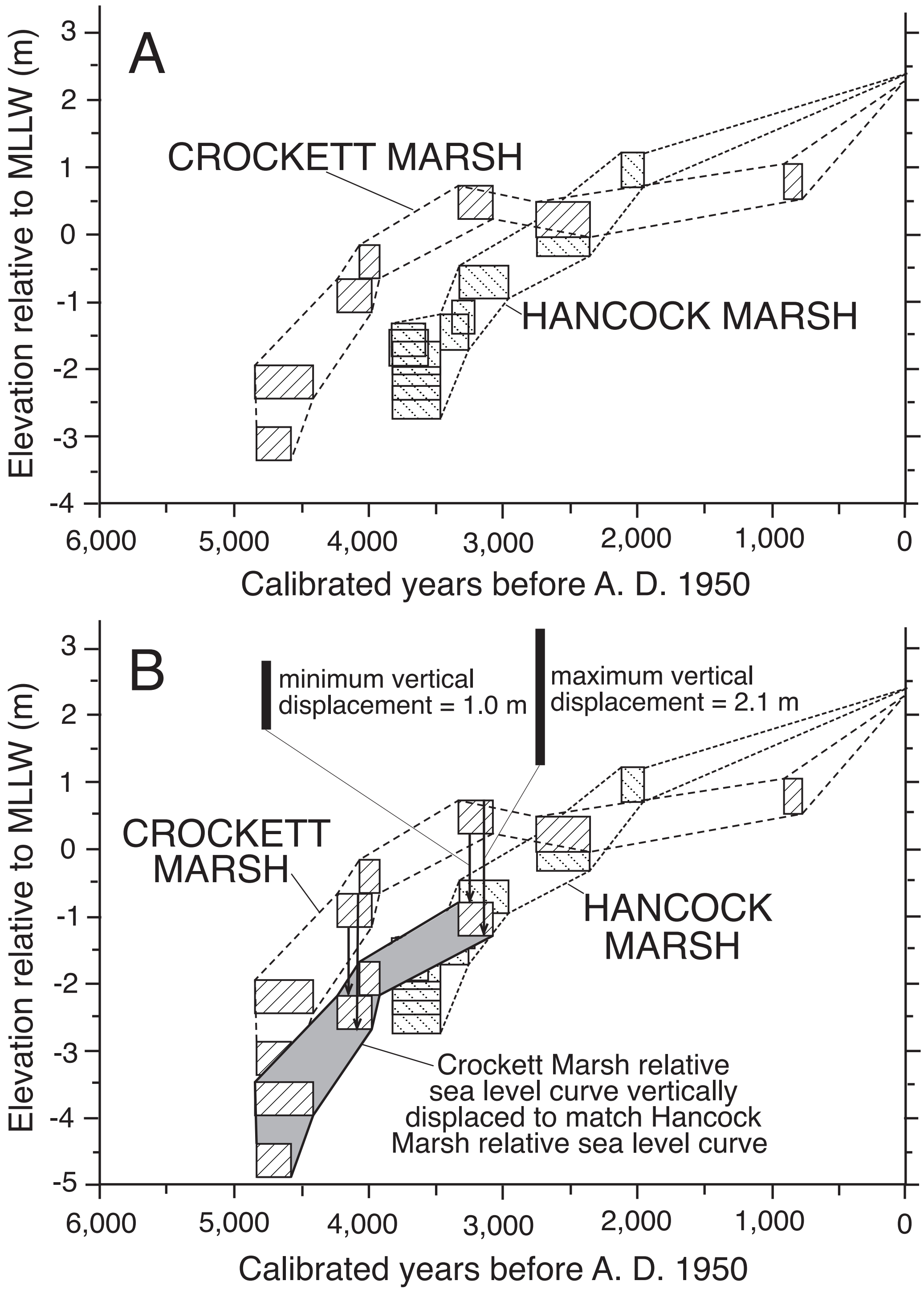

Figure 3. A. Relative sea level curves for Crockett and Hancock coastal marshes. B. Combined relative sea level curves for Crockett and Hancock coastal marshes, showing a reconstruction of a single sea level curve (Hancock curve with superposed, displaced Crockett curve) if there had been no vertical displacement of Crockett versus Hancock marshes. In the reconstruction, the Crockett curve was shifted down 1.5 ± 0.5 m, which is the estimated vertical displacement, up to the north, on the north fault strand of the Southern Whidbey Island fault zone. The estimated time of the crustal earthquake, equivalent to the time of divergence of the sea level curves, is ca. 2,800 to 3,200 years before A. D. 1950.