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INVESTIGATION OF PEAT STRATIGRAPHY IN TIDAL MARSHES ALONG COOK INLET, ALASKA, TO DETERMINE THE FREQUENCY OF 1964-STYLE GREAT EARTHQUAKES IN THE ANCHORAGE REGION

by

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INTRODUCTION

Evaluating future earthquake risk in the region affected by the great Alaska earthquake of 1964 (moment magnitude 9.2) requires knowing how frequently events of this magnitude occur. The 1964 event was accompanied by tectonic uplift and subsidence that affected an area of more than 140,000 km^2 along 800 km of the Alaska-Aleutian subduction zone (fig. 1) (Plafker, 1969). Historic records and instrument monitoring show that no other earthquake of magnitude M≥7.4 ruptured the northern portion of this segment for at least 180 yr before the 1964 event (Sykes and others, 1980). However, there is no reason to doubt the inevitability of future earthquakes similar to the 1964 event. Adjacent areas of the Alaska-Aleutian arc have ruptured during at least one great earthquake (magnitude M≥7.8) in historic time. Considering that about 11 percent of the world's earthquakes have occurred in Alaska, including three of the ten largest events (Davies, 1984), the potential for future great earthquakes in the region is clearly high. Given the limitations of instrument and historic records to resolve the recurrence times of great earthquakes, only geologic investigation can disclose the long-term record of sudden tectonic changes and earthquake effects.

This report synthesizes the results of field studies the Alaska Division of Geological & Geophysical Surveys (ADGGS) conducted in 1985 and 1988-1992 to collect evidence of major prehistoric earthquakes in the Cook Inlet region. Combellick (1991) described studies of tidal marshes in upper Turnagain and Knik Arms in Cook Inlet (fig. 1, sites 1, 2, 4, and 5). Combellick and Reger (1993) collected data from four additional tidal marshes along eastern and upper Cook Inlet and re-examined sites 2 and 4. ADGGS conducted these studies to document sediment types, stratigraphy, and radiocarbon ages of the deposits. In this report, I present the key results of these studies and attempt to interpret their significance in deciphering the paleoseismic record.

Results of previous ADGGS studies in upper Turnagain and Knik Arms indicate that, although there are uncertainties in the radiocarbon-age data and imperfect correlation between marshes, the average recurrence interval of probable earthquake-related subsidence was 590-780 calendar yr during the past 4,700 yr (Combellick, 1991). As reported here, subsequent studies of tidal marshes at Chickaloon Bay, Kenai River flats, Kasilof River flats, and Fox River Flats (fig. 1) provide corroborative age data for some of the most recent events and allow generalizations to be made about regional tectonic deformation during the late Holocene.

VERTICAL CHANGES DURING AND AFTER THE 1964 EARTHQUAKE

The 1964 earthquake released accumulated stresses on the Alaska-Aleutian subduction zone, where the North American and Pacific plates converge at about 6 cm/yr (DeMets and others, 1990). The associated pattern of uplift and subsidence (fig. 1) resulted from regional crustal warping and from displacements on subsurface portions of the northwest-dipping Aleutian megathrust and subsidiary reverse faults (Plafker,

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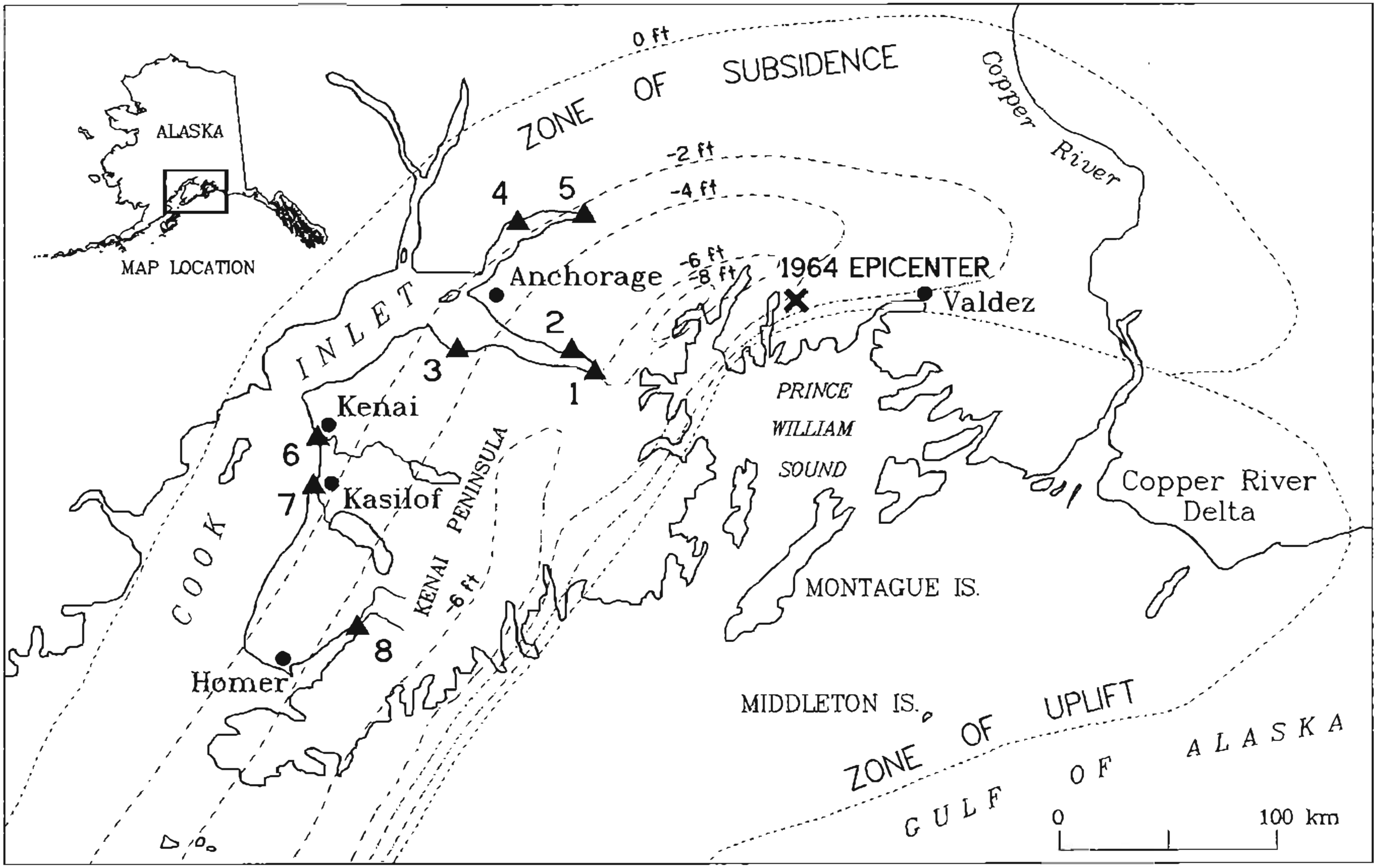

Figure 1. *Map of northern portion of region affected by tectonic deformation during the 1964 great Alaska earthquake (M_W=9.2), showing contours of measured subsidence (1 ft≈0.3 m). Tidal marshes studied for this report: 1—Portage flats, 2—Girdwood flats, 3—Chickaloon Bay, 4—Goose Bay, 5—Palmer Hay Flats, 6—Kenai River flats, 7—Kasilof River flats, 8—Fox River Flats. Modified from Plafker (1969).*

1969). Downwarp of as much as 2 m occurred over an elongate region including Kodiak Island (south of the study area), Kenai Peninsula, most of Cook Inlet, and Copper River Basin. Uplift as much as 11.3 m occurred seaward of the subsidence zone in an elongate region including Middleton Island, Montague Island, most of Prince William Sound, and Copper River Delta. Superimposed on this pattern of coseismic deformation is regional interseismic subsidence (Plafker and others, 1992). The long-term net vertical displacement is the sum of coseismic and interseismic displacements. Therefore, some areas undergo coseismic and long-term subsidence (upper Cook Inlet), others coseismic and long-term uplift (Middleton Island), and still others coseismic uplift and long-term subsidence (Copper River Delta) or coseismic uplift and long-term stability (Montague Island).

Postearthquake changes have restored tidal marshes at Portage and Girdwood (fig. 1, sites 1 and 2) to near pre-earthquake conditions. Subsidence totaled as much as 2.4 m at Portage, including about 1.6 m of regional tectonic subsidence and 0.8 m of local surficial compaction (McCulloch and Bonilla, 1970). During the decade following the earthquake, as much as 0.55 m of rebound occurred near Girdwood (Brown and others, 1977). Additionally, intertidal silt deposition began in submerged areas immediately following the earthquake and by 1980 had nearly restored the tidal flats to pre-earthquake levels (Bartsch-Winkler and Garrow, 1982). This postearthquake silt overlies grasses, mosses, herbaceous plants, peat, and root systems of spruce and cottonwood trees on the high marsh[2] that was submerged in the Portage and Girdwood areas during the earthquake. Similar studies were not undertaken in other tidal marshes that may have been submerged during the 1964 earthquake.

[2]In this report, ***high marsh*** refers to the vegetated upper portion of the intertidal zone that is primarily influenced by terrestrial conditions (infrequently flooded by salt water). ***Low marsh*** refers to a topographically lower part of the intertidal zone that is primarily influenced by marine conditions (flooded at least daily by salt water).

PALEOSEISMOLOGY AND RADIOCARBON DATING

Determining the effects and timing of prehistoric earthquakes depends on (1) correct interpretation of the geologic evidence of earthquakes and (2) accurate dating of the affected rocks or sediments (Allen, 1986). In the case of subduction-zone earthquakes like the 1964 Alaska event, the geologic evidence is usually related to sudden coastal uplift or subsidence (Plafker and Rubin, 1978; Lajoie, 1986) but may also be related to shaking effects, such as liquefaction (Obermeier and others, 1993).

Radiocarbon dating can provide a minimum or maximum age for an earthquake recorded in coastal sediments if organic material overlies or underlies the earthquake-related horizon. If organic material predating and postdating the horizon can be obtained, the age of the event can be bracketed. Alternatively, if it can be shown that the dated organisms died as a result of the earthquake, then the age of the youngest tissue approximates (very closely postdates) the age of the event.

Several sources of error make radiocarbon dating a relatively crude method for dating earthquakes and even less reliable for determining whether earthquake effects observed at different locations are attributable to a single event (Atwater and others, 1991). Bulk samples of organic material, such as peat, may predate or postdate the event by many years. Contamination by younger roots, detrital organic material, or bacterial decomposition can introduce significant error. Some tree species die rapidly after immersion and burial; others survive and propagate new roots for several years (Bartsch-Winkler and Schmoll, 1992). Quoted laboratory errors on reported ages are normally at least several decades and may be understated because of unknown analytical errors (Scott and others, 1990). Different laboratories analyzing splits of the same or stratigraphically equivalent Holocene samples have reported ages that fail to overlap even at two standard deviations and may differ by up to 700 yr (Nelson, 1992). Finally, because of natural variation of ^{14}C content of atmospheric carbon through time, calibration to calendar years using dendrochronology is not linear and can result in a radiocarbon age yielding several possible calendar ages (Stuiver and Quay, 1980; Stuiver and Becker, 1986).

Despite these problems, conventional radiocarbon dating is a useful tool for determining approximate ages of earthquakes and their average recurrence interval. In some circumstances, high-precision radiocarbon dating of very carefully selected and prepared materials can provide ages with quoted errors on the order of one or two decades (Atwater and others, 1991).

REGIONAL STUDIES

Numerous studies have documented repeated sudden vertical tectonic displacements in south-central Alaska during the past 5,000 yr, or late Holocene (Plafker and Rubin, 1967, 1978; Plafker, 1969; Plafker and others, 1992; Combellick, 1986, 1991; Bartsch-Winkler and Schmoll, 1987, 1992). Although the timing of all events is not yet clear, the distribution of prehistoric uplift and subsidence appears consistent with the pattern of 1964 deformation.

Radiocarbon dating of submerged peat layers in estuarine sediments of upper Cook Inlet indicates that the area probably subsided coseismically six to eight times during the 4,700 yr prior to the 1964 event, implying recurrence times on the order of 600 to 800 yr (Combellick, 1991). Elevated terraces on Middleton Island record five pre-1964 uplifts during the past 4,300 radiocarbon yr (Plafker and Rubin, 1978), or 4,900 calendar yr. The most recent uplift preserved by Middleton Island terraces was about 1,300 yr ago. At Copper River Delta, which undergoes net long-term subsidence punctuated by coseismic uplift, buried peat and forest layers record four pre-1964 uplifts during the past 3,000 yr (Plafker and others, 1992). The most recent event represented in the Copper River Delta sequence was about 800 yr ago.

Karlstrom (1964) dated and briefly described a buried forest layer in tidal sediments at Girdwood and recognized that it recorded a period of lower relative sea level. He obtained an age of 700±250 radiocarbon yr (510-910 calendar yr) for wood from a rooted stump at about 0.8 m below the pre-1964 surface and 2,800±180 yr (2,750-3,200 calendar yr) for wood from a peat layer about 4 m lower in the section. Karlstrom, whose report was prepared prior to the 1964 earthquake, did not attribute burial of the forest layer to possible coseismic subsidence.

Plafker (1969) used Karlstrom's dates to infer a regional average subsidence rate of 2-30 cm per century between 700 and 2,800 radiocarbon yr ago. He also concluded that gradual tectonic submergence prevailed in Prince William Sound as much as 1,180 yr prior to the 1964 earthquake. Plafker and Rubin (1978) inferred that the lowest elevated terrace at Middleton Island, dated at 1,360 radiocarbon yr, represents the last coseismic uplift in the region prior to 1964. However, Plafker and others (1992), reported new evidence of widespread coseismic uplift with a calibrated age of 665-895 yr in the Copper River Delta. Combellick (1993) reported evidence from Portage, Girdwood, Chickaloon Bay, Palmer Hay Flats, and Goose Bay (fig. 1, sites 1-5) that coseismic subsidence occurred during approximately the same period in the upper Cook Inlet region. This event about 700-900 yr ago was probably the penultimate, or second to last, 1964-style earthquake in the Anchorage region.

FIELD AND LABORATORY METHODS

To obtain evidence of coseismic subsidence in the Cook Inlet region, my colleagues and I examined bank exposures or hand-auger cuttings at 41 sites and drilled hollow-stem boreholes at 24 sites in eight tidal marshes along eastern and upper Cook Inlet between 1985 and 1992. Samples we collected during this field program yielded 129 radiocarbon-age determinations and 142 grain-size analyses. Numerous additional samples were collected for possible future studies of micropaleontology and tephrochronology. Samples for radiocarbon dating were collected from the upper 1-3 cm of buried peat layers and from the outer 10-25 growth rings of rooted stumps. Because tidal-marsh vegetation is suddenly submerged and killed by salt water as a result of coseismic subsidence, radiocarbon dating of vegetation killed by this process provides maximum ages that closely approximate the ages of the events.

Combellick (1991) and Combellick and Reger (1993) describe the field and laboratory procedures, provide detailed stratigraphic sections and descriptive logs for all field sites, and present results of laboratory analyses for all samples. In this report, only representative or diagnostic results are presented for each tidal marsh as a basis for interpreting the paleoseismic record.

The radiocarbon-age ranges I report here represent the 1-sigma limits of tree-ring calibrated age ranges determined using a computer program by Stuiver and Reimer (1993) and are rounded to the nearest 10 yr. The age ranges incorporate a conservative error multiplier of 2 in the absence of an error multiplier specified by the two commercial laboratories that performed the radiocarbon-age determinations. Although this multiplier has the effect of doubling the quoted standard deviation, the probability that the true sample age is within the calibrated age range remains at 68 percent. The error multiplier compensates for the fact that the quoted standard deviation typically is not large enough to account for all sources of laboratory error (Stuiver and Pearson, 1986). Laboratory sample numbers and noncalibrated radiocarbon ages are given in Combellick (1991) and Combellick and Reger (1993).

I provide calibrated weighted-average radiocarbon ages in some cases where (1) multiple age determinations were performed on separate splits of the same sample, (2) where age determinations were performed on multiple samples that are clearly contemporaneous, such as at the top of the same peat layer or from different trees rooted at stratigraphically equivalent positions, or (3) where age determinations were performed on multiple samples from apparent age-correlative layers in different marshes. Before averaging the ages, I performed a chi-squared test to ensure that the ages used for averaging are statistically compatible with a single sample population. Ages that I otherwise describe as well correlated also satisfy this chi-squared test. Both the chi-squared test and the weighted averaging were performed using the Stuiver and Reimer (1993) program. Weighted-average ages for case 3 (samples from apparent age-correlative layers in different marshes) should be regarded with great suspicion because the chi-squared test does not guarantee that the dated event occurred simultaneously in different marshes. Indeed, the chi-squared test cannot distinguish between some closely spaced radiocarbon ages from different layers in a single stratigraphic section where the layers clearly represent nonsynchronous events.

PEAT STRATIGRAPHY

PORTAGE FLATS

Maximum subsidence during the 1964 earthquake was in the vicinity of Portage (fig. 1, site 1). Shallow drill holes and tidal-bank exposures along Portage Creek indicate that the pre-1964 ground surface is now buried beneath as much as 2.6 m of postearthquake intertidal silt (Bartsch-Winkler and Ovenshine, 1977). Two adjacent boreholes on the tidal marsh at Portage (fig. 2) show the greatest number of older distinct peat layers and the largest vertical inter-peat separation of all eight sites studied by the ADGGS team. This observation is not surprising if we accept the ideas that these peat layers were buried as a result of coseismic subsidence and that tectonic deformation was similar during prehistoric earthquakes, with the greatest subsidence near Portage. The pre-1964 ground surface was not buried by postearthquake sediment at the site of the Portage boreholes, probably because this site was protected from tidal deposition by highway and railroad embankments built before 1964. Therefore, a distinct peat layer representing the 1964 event is not present at this location.

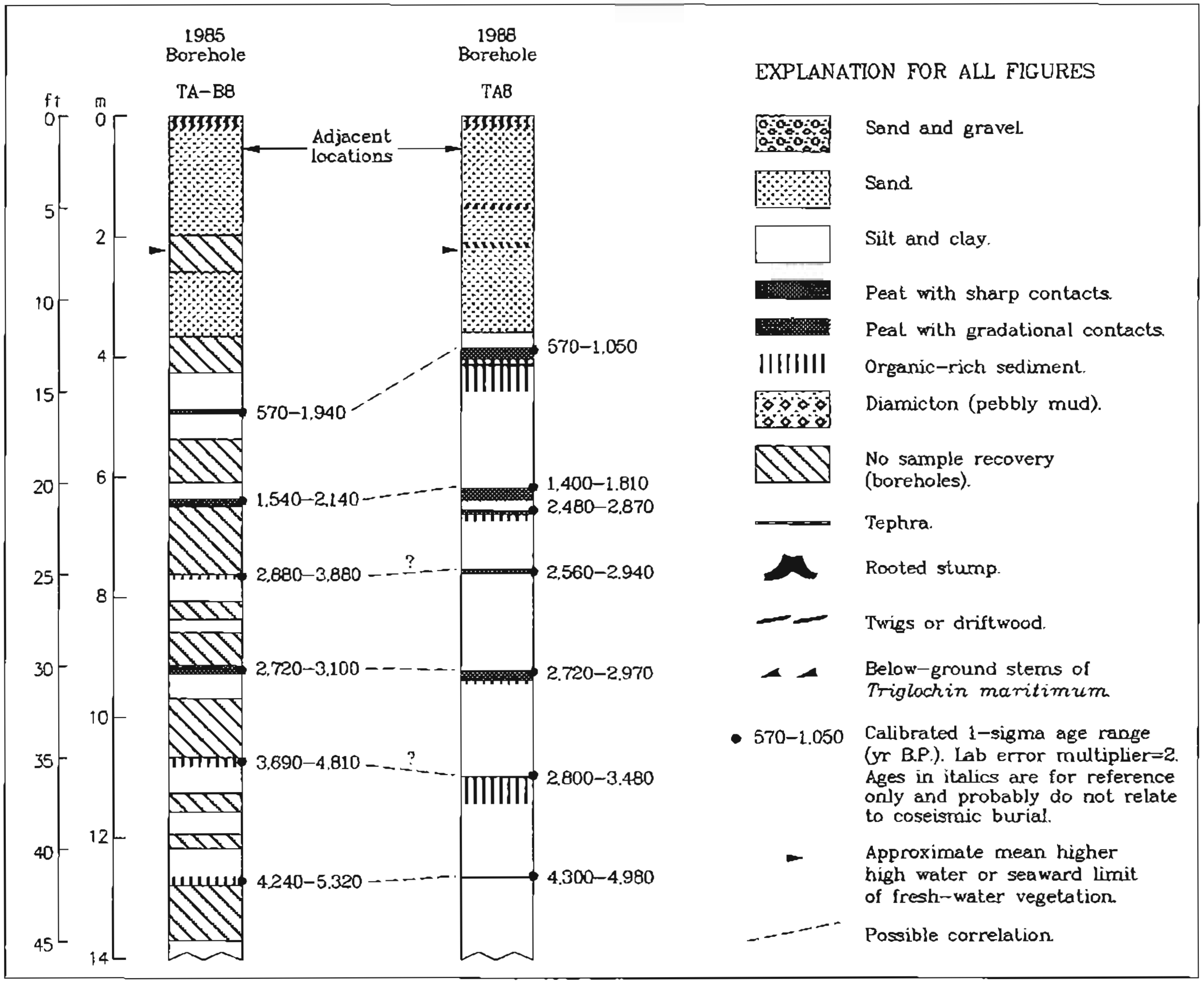

Figure 2. *Stratigraphic diagrams of boreholes at Portage flats (fig. 1, site 1) and explanation of symbols for figures 2-7 and 9.*

Because of the depth of pre-1964 peat layers and because all but the top 1-3 m of exposed stratigraphic section is covered by modern intertidal sediments, none of the older peat layers are visible in natural exposures at Portage. Additionally, eight other boreholes drilled by ADGGS (R.A. Combellick and R.G. Updike, unpublished data) and one borehole drilled by the U.S. Geological Survey (Bartsch-Winkler and others, 1983) indicate extensive reworking of late-Holocene sediments by three rivers that traverse Portage flats. Therefore, the site of adjacent boreholes drilled in 1985 and 1988 (fig. 2) is the only known location studied on Portage flats where an apparently undisturbed record of episodic pre-1964 coseismic submergence and interseismic marsh development has survived. However, interpretation of these events is limited by the small diameter of the cores (4 cm in the 1985 cores, 6.4 cm in the 1988 cores).

Most of the peat layers in the Portage boreholes show a gradual upward increase in organic content, a sharp upper contact, and are overlain by organic-poor silt and clay that increase upward in plant matter, culminating in the next higher peat layer. This pattern is consistent with repeated cycles of gradual marsh development followed by rapid submergence and burial.

Comparison of the radiocarbon ages of peat layers sampled in 1985 and 1989 demonstrates some of the difficulties of using conventional bulk radiocarbon analyses to date coseismic events (fig. 2). Large reported analytical errors produce calibrated age ranges up to several hundred years. Consequently, calibrated ages of different layers in one borehole show better correlation than samples from the same layer in adjacent boreholes. Four layers in borehole TA8 yield ages that are statistically equivalent at 95% confidence. Additionally, the two closely spaced peats at 6-7-m depth in borehole TA8, separated by a thin layer of mud, may represent one event or two. Although these problems preclude assigning precise ages to each event, the boreholes show evidence of seven or eight events during the past 5,000 yr (including the 1964 event). Total net subsidence at Portage has been 12.5 m during this period (5.0 m assuming average sea-level rise of 1.5 mm per year as estimated by Bard and others, 1990).

GIRDWOOD FLATS

Tidal banks at Girdwood (fig. 1, site 2) provide excellent exposures of as many as five buried peat and forest layers, including the layer buried in 1964 (fig. 3). Three of these layers and an additional older layer also appear in a borehole about 300 m inland from the shoreline. The 1964 peat layer underlies several tens of cm of postearthquake silt and contains the rooted stumps of many dead cottonwood and spruce trees that are still standing on Girdwood flats.

About 1 m below the 1964 peat layer is a second layer of stumps rooted in peat. This forest layer is discontinuously exposed for distances up to several hundred meters along the tidal bank. Mud above and below this peat layer locally contains below-ground stems of the halophytic plant *Triglochin maritimum*, which dominates vegetation only in low-marsh conditions (Atwater, 1987). The sharp upper contact and presence of *T. maritimum* in mud immediately above the contact indicate rapid transition from high-marsh to low-marsh conditions, as would occur during coseismic submergence. The weighted-average range of all radiocarbon ages from outer growth rings of rooted stumps and from peat samples at the surface of the layer is 730-900 yr B.P. This layer was probably buried as a result of the penultimate 1964-style earthquake (Combellick, 1993).

As many as four older peat layers with calibrated ages ranging to 4 ka appear in the exposures and in borehole TA1. As shown in figure 3, not all layers are continuous and the calibrated age ranges of samples from apparently correlative layers show considerable variation. However, ages from apparently correlative samples satisfy the chi-squared test for equivalence at 95 percent confidence and give weighted-average ages of 1,170-1,360, 1,930-2,120, 2,730-2,850, and 3,370-4,090 yr B.P. The 1,170-1,360-yr layer

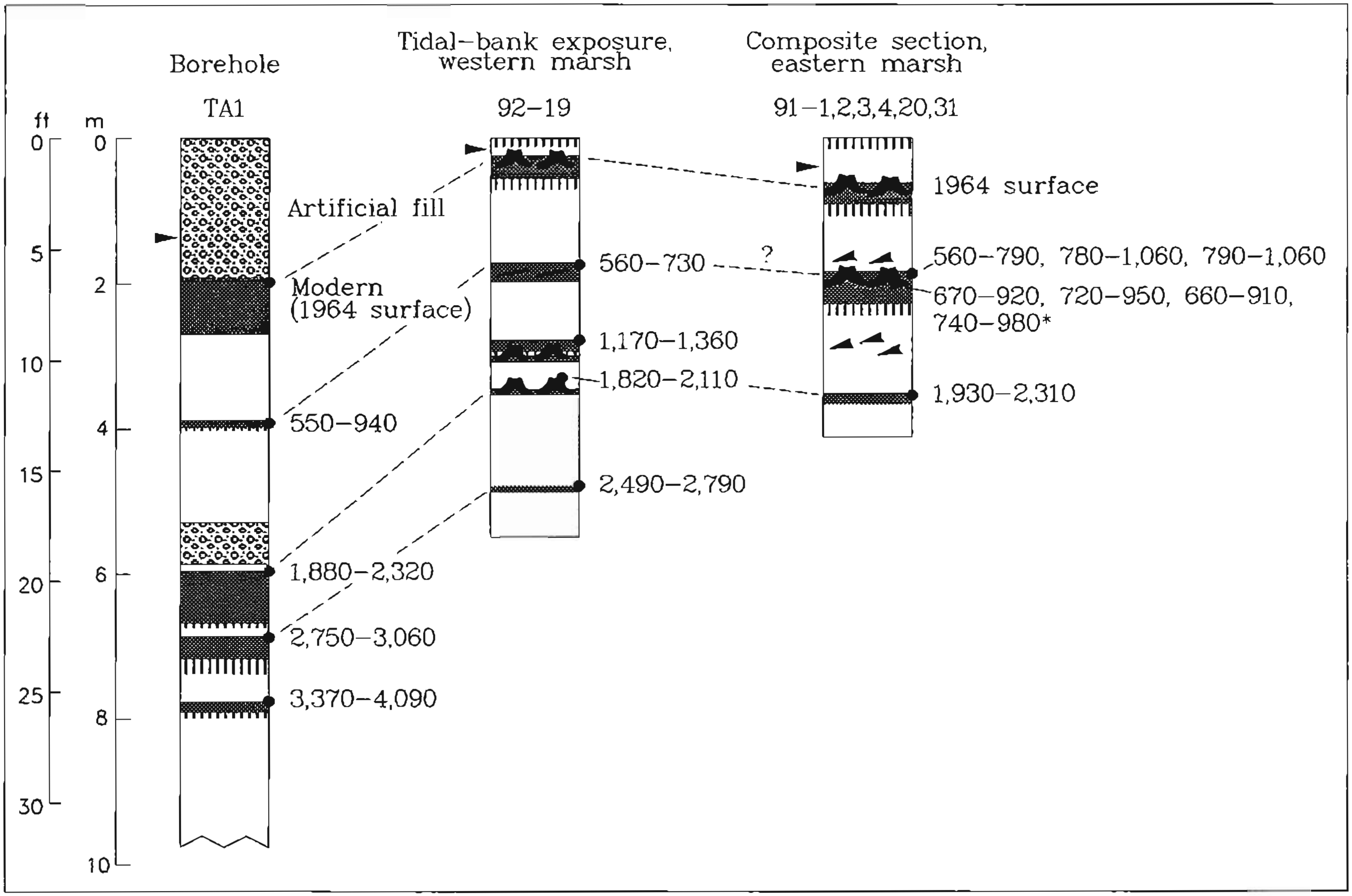

Figure 3. *Stratigraphic diagrams of borehole and tidal-bank exposures at Girdwood flats (fig. 1, site 2). *Radiocarbon age provided by Gordon Jacoby (personal commun.). See figure 2 for explanation of symbols.*

appears at only one exposure at Girdwood but may correlate with a 1,150-1,430-yr uplift event at Middleton Island (Plafker and others, 1992).

CHICKALOON BAY

Meandering tidal and river channels at Chickaloon Bay (fig. 1, site 3) provide good exposures of as many as three distinct buried peat layers, some with rooted tree stumps and shrubs (fig. 4). Older, deeper layers may be present but were inaccessible because it was not possible to transport a drill rig to the area. Field observations at Chickaloon Bay were made primarily by examining tidal-bank exposures but were supplemented by hand augering at one location. The best exposures are as much as 3 m high; below 3 m depth from the marsh surface, the exposures are buried beneath modern tidal sediments.

The 1964 peat layer is overlain by as much as 1 m of tidal mud and contains many rooted stumps (fig. 4). The lower portion of the overlying mud layer is rich in below-ground stems of *Triglochin maritimum*, indicating transition from high-marsh to low-marsh conditions. Surprisingly, the depth of mud overlying the 1964 forest layer is greater than at Girdwood, where tectonic subsidence was nearly double that at Chickaloon Bay. The likely reason is that there was greater compaction-related subsidence at Chickaloon Bay, which covers an area about ten times as large as the marsh at Girdwood and is probably underlain by thicker unconsolidated sediments.

The next lower peat layer is prominently exposed at three widely separated locations at Chickaloon Bay and yields radiocarbon ages that are in close agreement. The weighted-average calibrated age of samples collected at the top of this layer is 760-930 yr B.P., which is also in close agreement with the age of the peat underlying the 1964 layer at Girdwood and lies within the age range of the uppermost buried peat at Portage. The contact with the overlying mud is sharp at all locations. At one location (fig. 4, 92-16), the overlying mud is rich in *T. maritimum* but at the other two locations the mud is largely free of organics.

At location 92-14R, a third peat layer is exposed at the base of the exposure and an additional layer or a continuation of it appears deeper in hand-auger samples. Ages at the tops of these lower two layers are virtually identical, suggesting that they represent a single buried marsh deposit. The uppermost layer has a sharp upper contact, is overlain by mud containing *T. maritimum* remains, and has a calibrated age of 1,810-2,000 yr B.P. This correlates closely in age with the 1,930-2,120-age peat layer at Girdwood (fig. 3) and may correlate with a peat layer at about 6-m depth at Portage for which one sample gives an age of 1,540-2,140 yr B.P. (fig. 2)

PALMER HAY FLATS AND GOOSE BAY

These two marshes lie along Knik Arm, which subsided about 2 ft (0.6 m) during the 1964 earthquake (fig. 1, sites 4 and 5). An extensive tidal-bank section is visible at Goose Bay, but exposures along estuary channels in Palmer Hay Flats State Game Refuge are very limited. Several boreholes were drilled to supplement natural exposures at both marshes (fig. 5).

Although postearthquake silt deposition was not documented in either of these marshes following the 1964 event, a peat layer yielding negative (modern) calibrated radiocarbon ages or an age range of 0-300 B.P. is present at most locations and is buried under as much as 1 m of organic-rich silt. This layer probably was buried as a result of subsidence in 1964.

At all but one location shown in figure 5 (KA1), a second thin peat layer appears at depths of 1.0-1.7 m and yields calibrated radiocarbon ages consistently within the period 300-670 yr B.P. The weighted-average calibrated age of these samples is 500-550 yr B.P. Stratigraphic evidence that this buried peat represents regional coseismic subsidence is weak. The peat layer is thin (2-10 cm), discontinuous where well exposed at location 92-20 (Goose Bay), and lies at the base of an interval for which no samples were retrievable

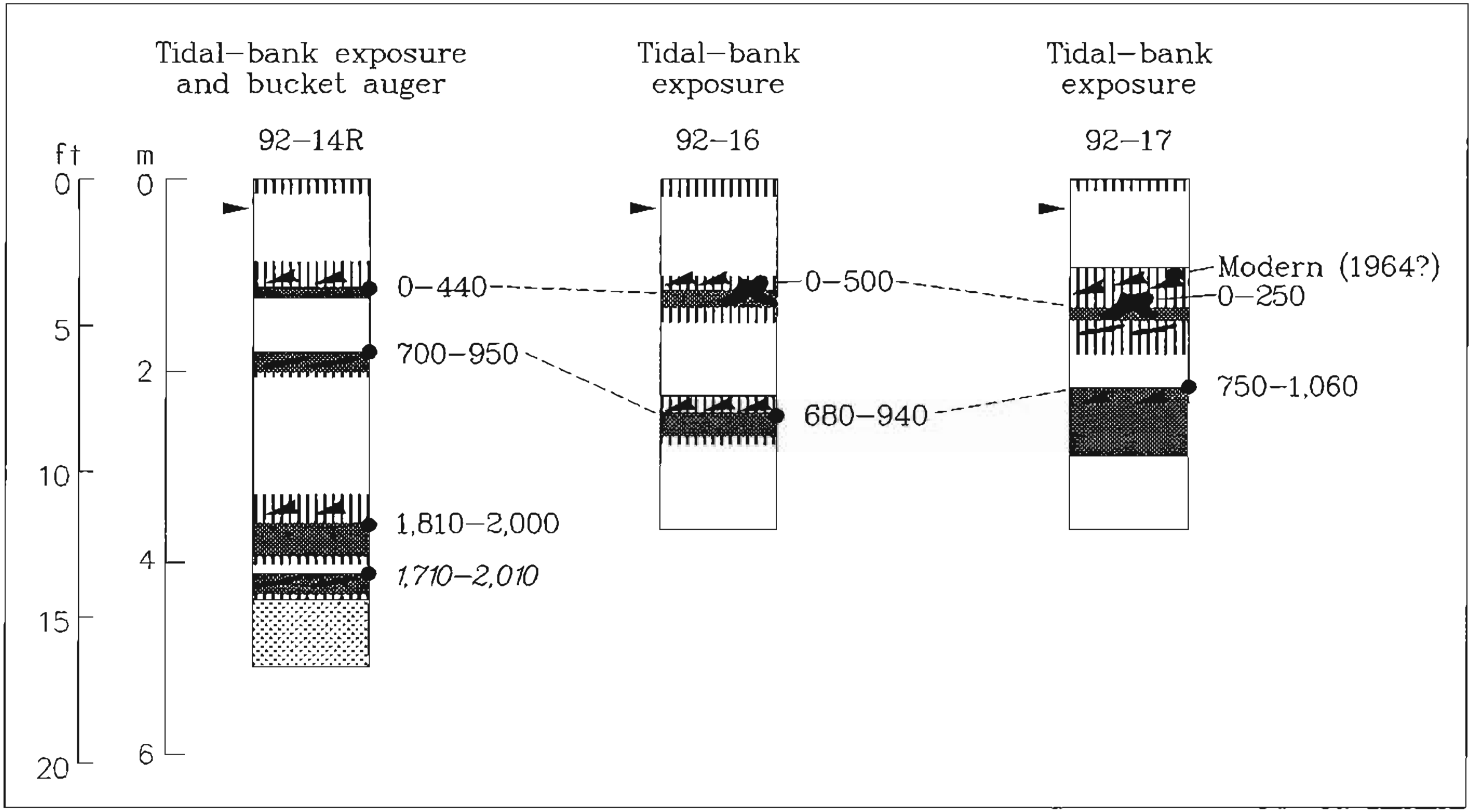

Figure 4. *Stratigraphic diagrams of selected tidal-bank exposures at Chickaloon Bay (fig. 1, site 3). See figure 2 for explanation of symbols.*

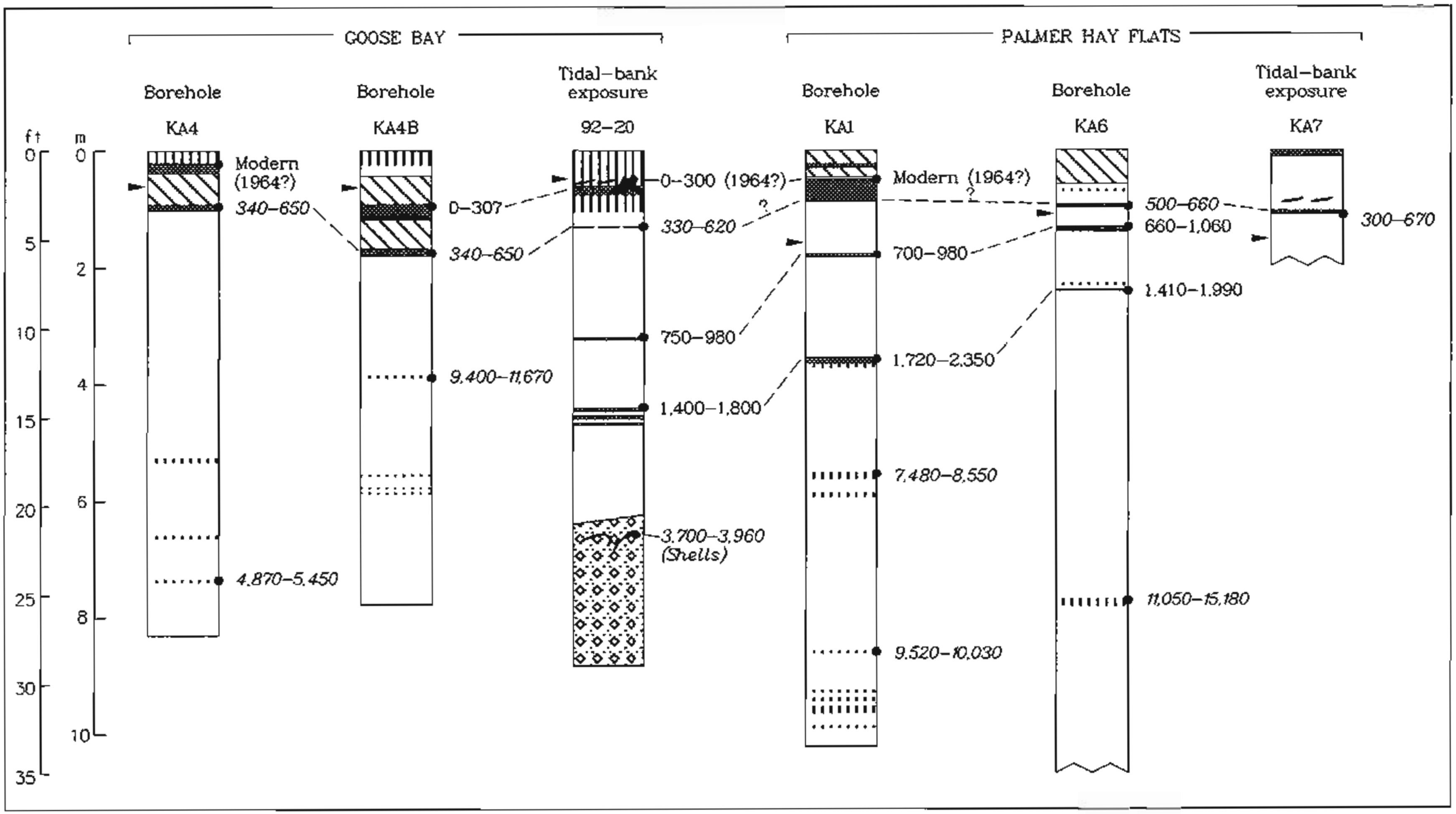

Figure 5. *Stratigraphic diagrams of selected boreholes and tidal-bank exposures at Goose Bay and Palmer Hay Flats (fig. 1, sites 4 and 5). See figure 2 for explanation of symbols.*

at locations KA4 and KA4B. At these two locations, the nonsampled interval may be peat, implying that the dated samples came from the base of a thicker peat layer. If this is true, the radiocarbon ages do not approximate age of burial.

No buried peat layers with a top-surface age in the range 300-670 yr B.P. appear consistently at any other marshes studied in Cook Inlet. Two explanations other than subsidence during a subduction earthquake may account for the presence of this buried peat at Goose Bay and Palmer Hay Flats. The first is possible displacement on the Castle Mountain fault, which traverses NE to SW about 25 km northwest of Goose Bay. Displacement on this high-angle fault has been mostly dip-slip with downward motion on the south side (Detterman and others, 1974, 1976; Bruhn, 1979). Major offset on this fault could cause sufficient local subsidence to result in submergence of the tidal marshes at Goose Bay and Palmer Hay Flats. Limited geologic-age control along the fault indicates that the most recent surface rupture occurred 225-1,700 yr ago (Detterman and others, 1974).

The second possible cause of extensive shallow burial of the marsh surface in Palmer Hay Flats is glacial-outburst flooding of Knik River. Outburst floods were recorded nearly annually between 1948 and 1966 (Post and Mayo, 1971). A very large outburst flood could have resulted in widespread silt deposition, burying all or most of the marsh surface.

Exposed in the tidal bank at Goose Bay and appearing in two boreholes in Palmer Hay Flats is a deeper buried peat layer that may correspond to the pre-1964 buried peat at Portage, Girdwood, and Chickaloon Bay (fig. 5, locations 92-20, KA1, and KA6). The weighted-average calibrated age of samples from the top of this layer at these three locations is 780-950 yr B.P.

One more older peat layer that may correlate among the same three locations has an average age of 1,550-1,870 yr B.P. This layer may be equivalent to layers with average ages of 1,540-2,140, 1,930-2.120, and 1,810-2,000 at Portage, Girdwood, and Chickaloon Bay, respectively. However, this correlation is weak and is by no means sufficient evidence that regional coseismic subsidence occurred as a single regional event during this period.

KENAI AND KASILOF RIVER FLATS

Good exposures up to 2 m high are present along the banks of both the Kenai and Kasilof River estuaries (fig. 1, sites 6 and 7) and show similar tidal-marsh stratigraphy. Borehole drilling and hand augering supplemented examination and sampling of these exposures (fig. 6).

The striking feature of tidal-marsh stratigraphy in the Kenai and Kasilof River flats is that deposits spanning the late Holocene are much thinner and shallower than those in other tidal marshes of upper Cook Inlet. Additionally, peat deposits with radiocarbon ages between about 900 and 7,000 yr B.P. are not interlayered with organic-poor mud as in the other marshes. The peat is nearly continuous and contains one or more layers of rooted tree stumps, indicating that the marshes, which are largely nonforested now, supported forests at various times during that period. These alternations between forested and nonforested conditions may have resulted from climatic variations, minor changes in elevation during earthquakes, or minor changes in sea level.

Without interlayered mud deposits to indicate submergence to lower intertidal conditions, it is not possible to decipher a paleoseismic record from the peat stratigraphy with the possible exception of an event that resulted in burial of the entire sequence. Samples from the top of the thick buried peat sequence at locations 90-2 (Kenai), 91-16 (Kenai), 91-15 (Kasilof), and KS1 (Kasilof) yield statistically equivalent calibrated ages between 930 and 1,400 yr B.P. and have a weighted-average range of 1,160-1,290 yr B.P. This age correlates well with a 1,170-1,360-yr-old peat at Girdwood and with the 1,150-1,430-yr uplift event at Middleton Island (Plafker and others, 1992). However, the case for coseismic subsidence in the Cook Inlet region is weak because peats indicating possible sudden submergence at

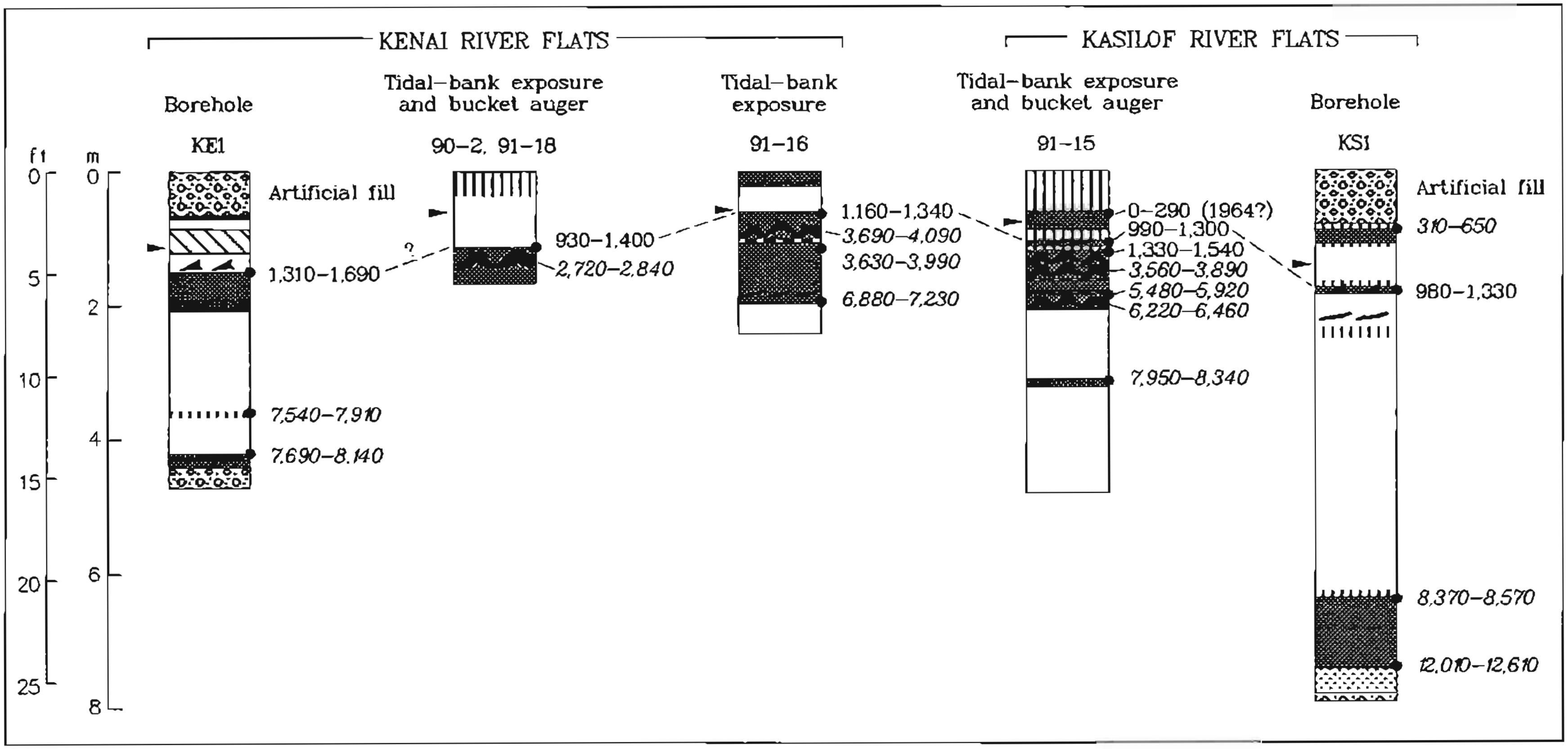

Figure 6. *Stratigraphic diagrams of selected boreholes and tidal-bank exposures at Kenai and Kasilof River flats (fig. 1, sites 6 and 7). See figure 2 for explanation of symbols.*

this time are present only at Kenai and Kasilof River flats and at one location at Girdwood flats; no convincing evidence for coseismic subsidence 1,100-1,400 yr ago was found at Portage, Chickaloon Bay, Palmer Hay Flats, or Goose Bay.

At one location on Kenai River flats (KE1) and one location on Kasilof River flats (91-15), buried peats have a top-surface calibrated age between 1,300 and 1,700 yr B.P. (weighted average range is 1,350-1,540 yr B.P.). At location KE1, this may simply be an erroneously older age for a peat surface that correlates with the top of the buried sequence at the other four locations. However, at location 91-15, this peat (calibrated age 1,330-1,540 yr B.P.) is stratigraphically below the 990-1,300-yr peat and clearly represents an earlier burial event. Although the older peat has a sharp upper contact with the overlying mud, indicating probable rapid burial, the mud is very thin (6 cm) and could be a overbank deposit resulting from a river flood rather than an intertidal deposit resulting from coseismic submergence.

Although there was minor (<0.6 m) subsidence along this portion of the Kenai Peninsula coast during the 1964 earthquake (Plafker, 1969), there was no documented postearthquake tidal deposition on the Kenai or Kasilof River flats. However, a buried peat layer with a surface age of 0-290 yr B.P. is exposed at location 91-15 and a peat dating 310-650 yr B.P. appears beneath artificial fill at location KS1. The latter may represent peat within a thicker layer that was disturbed or partially excavated during fill emplacement. The 0-290-yr-old peat at location 91-15 may have been buried during the 1964 event or during an earlier flood. Neither likely indicates pre-1964 coseismic subsidence.

A prominent tephra layer that appears in bank exposures in both estuaries (fig. 6, locations 91-15 and 91-16) is well dated at 3,640-3,840 (weighted average of samples above and below the tephra at both locations). This tephra correlates closely in age with regional tephras of Mt. Hayes that were deposited 3,650±150 yr B.P. (calibrated age 3,730-4,150 yr B.P.; Riehle, 1985). Electron-microprobe analyses demonstrate that the tephra is essentially equivalent in chemical composition to the Hayes tephra (R.A. Combellick and D.S. Pinney, unpub. data). A lower, older tephra layer at location 91-15 is also chemically equivalent to the Hayes tephras. Although these tephras provide good stratigraphic markers and age control, they do not provided any information relating to paleoseismicity.

Assuming constant sea level during the late Holocene, the data at Kenai and Kasilof River flats indicate net subsidence of about 2 m during the past 7,000 yr (roughly 0.3 mm/yr). If sea-level rise is assumed to be 1.5 mm/yr during this period (Bard and others, 1990), the data indicate net uplift of about 8.5 m (1.2 mm/yr).

Deposits older than about 7 ka beneath the near-surface peat layers indicate long-term rapid submergence, probably due to postglacial sea-level rise. Peat overlying sand and gravel at the bottom of boreholes KE1 and KS1 may represent an estuarine marsh that developed during a temporary sea-level stillstand between about 12 and 8 ka or during postglacial isostatic uplift that kept pace with sea-level rise.

Fox River Flats

Nine boreholes, twelve hand-auger holes, and two tidal-bank exposures in the Fox River Flats Critical Habitat Area (fig. 1, site 8) failed to reveal any laterally extensive or continuous buried peat layers or any other clear evidence of prehistoric great earthquakes. Radiocarbon ages of some shallow samples are anomalously old, probably due to contamination by older carbon from nearby coal deposits (Combellick and Reger, 1993). Subsurface sediments in most areas contain much sand and gravel, reflecting dominance of deltaic processes and probable reworking of any preexisting tidal flat sediments by lateral migration of three major streams that cross the flats. Four locations with buried organic layers that appear to correlate in age to buried peats elsewhere are shown in figure 7. A layer of *Triglochin maritimum* stems at location 91-11

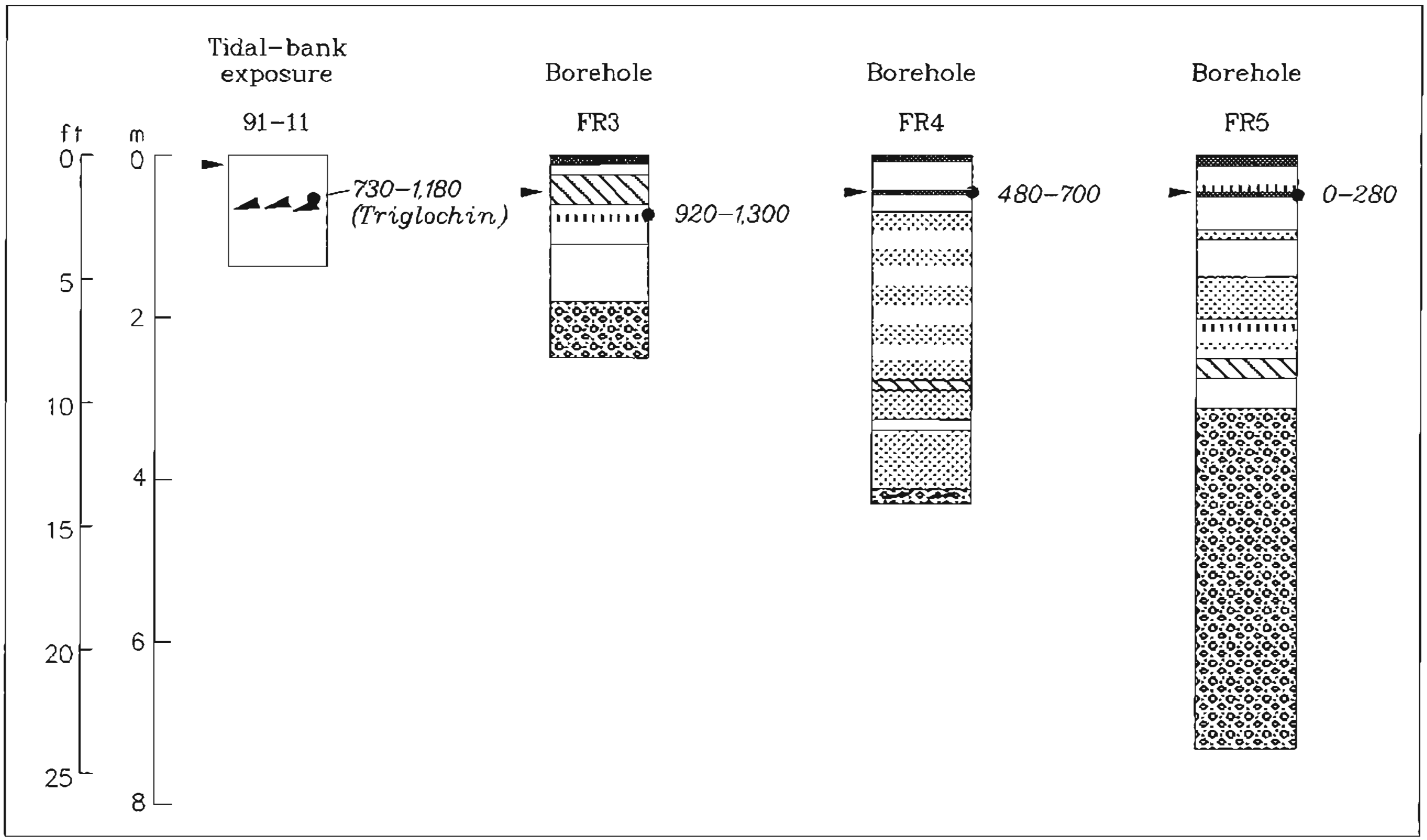

Figure 7. *Stratigraphic diagrams of selected boreholes and tidal-bank exposure at Fox River Flats (fig. 1, site 8). See figure 2 for explanation of symbols.*

and a peaty mud layer at approximately the same depth (0.7 m) at location FR3 yield radiocarbon ages that correlate with pre-1964 buried peat layers at Portage, Girdwood, Chickaloon Bay, Palmer Hay Flats, and Goose Bay. However, there is no stratigraphic evidence at Fox River Flats that these layers were buried as a result of coseismic subsidence; apparent correlation of their radiocarbon ages may be fortuitous. Boreholes FR4 and FR5 encountered shallow buried peat layers with calibrated ages of 480-700 and 0-280 yr B.P., respectively. No credible argument can be made for coseismic submergence on the basis of these two isolated peats, which show no diagnostic evidence of sudden burial. The shallow organic horizons at all four locations may simply represent burial of former marsh surfaces by overbank flood deposits.

PALEOSEISMICITY

Interbedded peat and mud layers in the tidal marshes of eastern and upper Cook Inlet provide at least a partial record of subsidence associated with major, probably great, prehistoric earthquakes. Marsh-peat deposits submerged and buried as a result of the 1964 great earthquake at Portage and Girdwood provide a visible stratigraphic model of coseismic subsidence and postearthquake tidal deposition that can be used as an analog for interpreting older deposits. The main elements of this stratigraphic model are: (1) gradual upward increase in organic content associated with high-marsh development on an emerging tidal flat, (2) sharp upper contact of the peat layer with the overlying mud, indicating rapid burial, and (3) dominance of plant fossils with salt-water affinity (*Triglochin maritimum*) in mud immediately above the contact, indicating transition to low-marsh conditions. Repetition of this stratigraphy occurs where interseismic rebound is less than coseismic subsidence, resulting in long-term net subsidence (fig. 8). Superimposed on this process may be long-term gradual rise in sea level, resulting in thicker peat and mud layers than if sea level was constant.

Highly desirable evidence that peat burial was earthquake-related includes liquefaction deposits resulting from major ground shaking. These deposits would appear mainly as planar sand or gravel dikes bisecting the peat layer and either truncated by erosion or terminating in sand-boil deposits on top of the peat layers (Obermeier and others, 1993). A few clastic dikes associated with liquefaction during the 1964 earthquake are visible in the Portage area (B.F. Atwater and R.A. Combellick, unpub. data), but no irrefutable liquefaction-related deposits were observed at any other study sites in conjunction with buried tidal-marsh peats.

Although this direct proof of earthquake shaking has not been observed in older tidal-marsh deposits, the similar stratigraphy of older buried peats to the peat layer buried at Portage and Girdwood in 1964 combined with the known seismically active environment of the Cook Inlet region make it highly likely that at least some of the observed peat layers were buried as a result of regional earthquake-related subsidence.

PROBLEMS

In addition to the previously discussed limitations of radiocarbon dating, lack of preservation of some or all of the evidence of coseismic subsidence and problems in interpreting the stratigraphy add to the difficulties of deciphering the paleoseismic record (see also Bartsch-Winkler and Schmoll, 1992):

1. If all or part of a submerged marsh did not become reestablished before the next subsidence event, evidence of that event would be lacking or very difficult to identify.

2. Many peat layers are not continuous in a marsh. As a result, evidence of one or more subsidence events may be missed altogether.

3. Peat layers cannot be positively correlated between marshes without clear stratigraphic markers like tephra layers, which are rarely present in key stratigraphic positions. Consequently, buried peat layers with equivalent radiocarbon ages in different marshes may represent one event

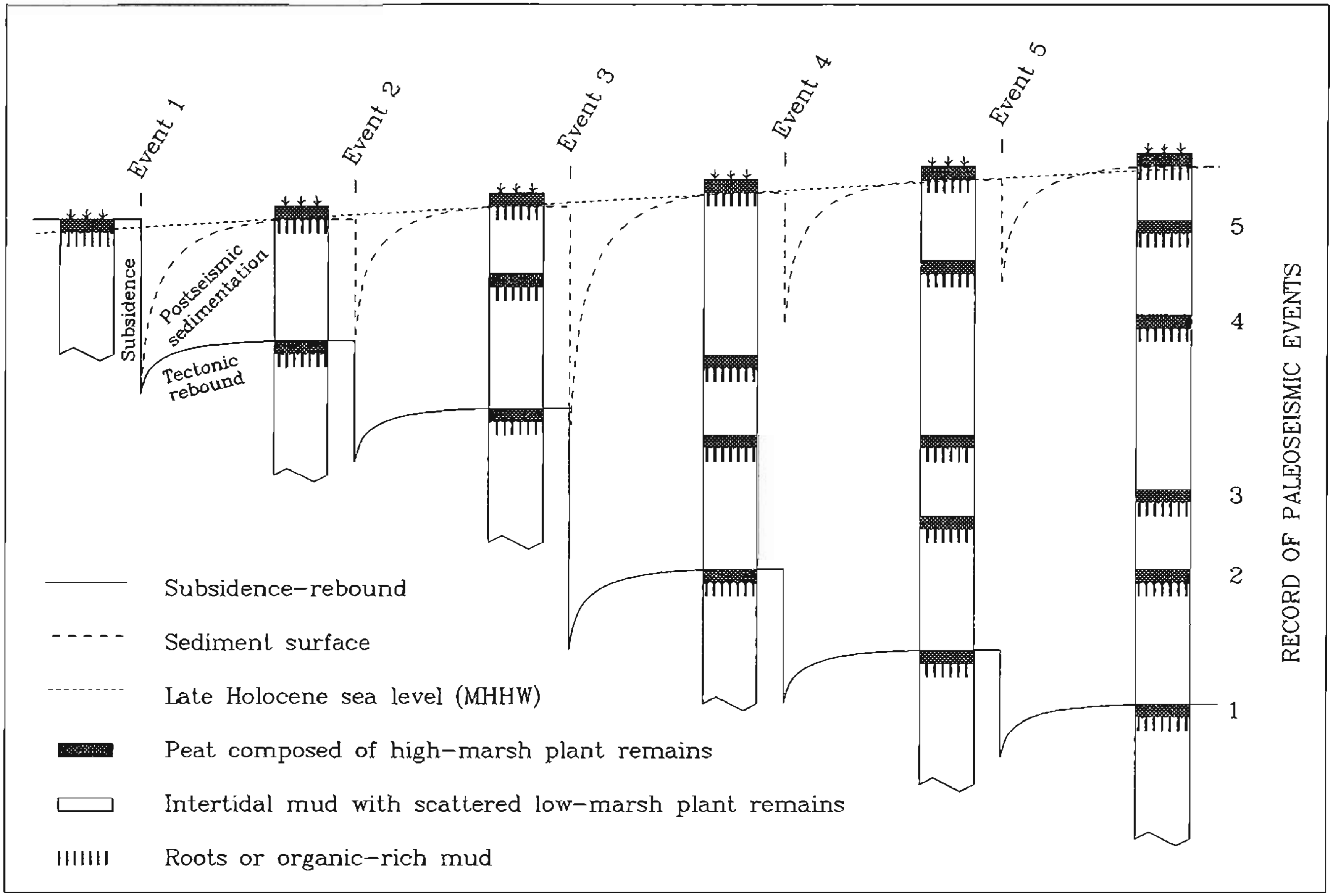

Figure 8. *Model of tectonic subsidence, rebound, sedimentation, and marsh burial in a region undergoing coseismic and long-term subsidence.*

or several events that are not distinguishable by radiocarbon dating.

4. Postearthquake processes like erosion, compaction, and reworking can remove or modify stratigraphic features so that some or all evidence of coseismic subsidence is lacking.

5. Some peat layers may have been submerged and buried by processes other than coseismic subsidence, like nonuniform sea-level rise. Interlayered peat and mud appear in many intertidal deposits along passive continental margins (for example, van de Plassche, 1991). A sharp upper contact of a widely mapped peat and dominance of halophytic plant fossils in the overlying mud are convincing evidence of coseismic subsidence (Atwater, 1987; Nelson, 1992). Lack of this evidence does not rule out coseismic subsidence but, unless a peat that does not show the evidence in one location can be reasonably correlated with peats in other locations that do, the case for earthquake-related burial is weak.

6. Below some threshold magnitude there is insufficient vertical deformation to submerge the marsh vegetation and allow burial beneath tidal mud, so there is no clear stratigraphic record of the event. West and McCrumb (1988) indicate that for historic subduction-zone events along the Pacific margin, measurable permanent crustal deformation does not occur below a threshold magnitude of about magnitude 7. A higher magnitude is probably necessary to cause enough submergence to bury marsh vegetation beneath tidal mud. If a buried peat layer can be correlated widely enough to delineate the entire zone of deformation, empirical relations can be used to estimate magnitude (West and McCrumb, 1988; Wyss, 1979). With the possible exception of the penultimate Cook Inlet event, which I estimate had a magnitude of at least 7.8 (Combellick, 1993), there is too little information on the lateral extent of subsidence to allow reasonable estimation of magnitude.

These limitations essentially mean that there may be some great earthquakes for which no stratigraphic evidence exists or has not been observed and that some buried peat layers, particularly those that appear only in one marsh, were buried by processes other than coseismic subsidence. The former case would cause underestimation of the number of earthquakes, whereas the latter would cause overestimation.

EVENTS AND RECURRENCE INTERVALS

As a result of earlier studies of buried peats at sites 1, 2, 4, and 5 (fig. 1) and correlation with other regional studies, I previously estimated a maximum recurrence interval of about 600-800 yr for subsidence events in upper Cook Inlet during the past 5,000 yr (Combellick, 1992). Bartsch-Winkler and Schmoll (1992) estimated an average recurrence interval of 400-500 yr, with a probable range of 200-800 yr, based on weak clustering of peat radiocarbon ages from their data set. Recent ADGGS studies of tidal marshes along the west coast of Kenai Peninsula support my earlier estimate of an average 600-800-yr recurrence interval. This estimate is based on the possible range in number of events represented in seven of the eight tidal marshes studied (no credible evidence of coseismic subsidence was observed at Fox River Flats). Possible correlations of peat layers in representative stratigraphic sections from each marsh are shown in figure 9.

Besides inevitable differences in data sets and how they were evaluated, the smaller recurrence interval estimated by Bartsch-Winkler and Schmoll (1992) may be an artifact of the clustering method. Because of inherent errors in radiocarbon dating, this method of pooling all radiocarbon ages and grouping those with similar ages creates two kinds of errors that offset each other only if neither error dominates: (1) in a single stratigraphic section, different layers that clearly show evidence of multiple events will be grouped as one if their reported radiocarbon ages are similar; and (2) a layer that appears at multiple locations and was buried by a single event may yield sufficiently different radiocarbon ages to result in clustering as multiple events. Case 2 has been demonstrated by tests showing that splits of the same or stratigraphically equivalent samples have yielded ages that fail to overlap even at two standard deviations (Nelson, 1992).

For dating probable earthquake-related subsidence events, I have attempted to rule out peat layers that do not display evidence of sudden burial, rapid submergence to a lower position in the intertidal zone, or at least good stratigraphic or age correlation with peats in other locations that show stronger evidence of these processes. One of these selected peat layers, the lowermost layer at Portage (~4,300-5,300 yr B.P.), lacks possible counterparts at other marshes in upper Cook Inlet but agrees in age with earthquake-related uplift 4,850-5,130 yr B.P. at Middleton Island (Plafker and others, 1992).

Although not perfect, this selective approach should result in a more realistic estimate of the average recurrence interval of prehistoric earthquakes based on the available data. Because of the possibility that great earthquakes occurred for which stratigraphic evidence has not been observed, the 600-800-yr average recurrence interval should be regarded as a maximum.

Despite uncertainties that preclude precise dating of most paleoseismic events in the Cook Inlet region, some conclusions can be drawn from the available data:

1. Strong regional evidence indicates that earthquake-related subsidence occurred 700-900 yr ago. Buried peat and forest layers with top-surface and outer-wood radiocarbon ages in this range are present at Portage, Girdwood, Chickaloon Bay, Palmer Hay Flats, and Goose Bay. The weighted-average of 18 calibrated radiocarbon ages from 10 different sites is 770-910 yr B.P. The age of this event is consistent with the 665-895-yr calibrated age for coseismic uplift in the Copper River delta area (Plafker and others, 1992). The lack of strong evidence of a more recent pre-1964 event implies that this event was probably the penultimate 1964-style earthquake in the Cook Inlet region (Combellick, 1993). The data still do not rule out the possibility that subsidence resulted from more than one event during this period, perhaps affecting different parts of the region at different times.

2. Regional evidence for one or two events during the period 1,100-2,300 yr B.P. appears at numerous sites where a peat layer is visible below the 700-900-yr peat. At most of these locations there is a single peat layer with an age in this range, although the ages are fairly evenly distributed throughout the period. At Chickaloon flats (fig. 4, site 92-14R) two peats in this age range are separated by a thin layer of mud but have equivalent radiocarbon ages. At only one location on Girdwood flats (fig. 3, site 92-19) are there two distinct peats with significantly different ages indicating two burial events at that site. The age of the uppermost layer, 1,170-1,360 yr B.P., agrees closely with a 1,150-1,430-yr uplift event at Middleton Island (Plafker and others, 1992). Ages at the top of a thick buried peat sequence at Kenai and Kasilof River flats are also consistent with an event at this time (1,160-1,340 yr and 990-1,300 yr B.P. at sites 91-16 and 91-15, respectively; fig. 6)

3. Similarly, there is evidence at Girdwood and Portage of one to as many as four events during the period 2,400-3,000-yr B.P. At Girdwood sites TA1 and 92-19 (fig. 3) there is a single peat layer with an age in this range. At Portage site TA8 (fig. 2), there are four peats with overlapping, statistically equivalent ages in this range. Although stratigraphy at the Portage site indicates four possible burial events, the thin mud layer overlying the uppermost of the four peats may be a result of local nonearthquake-related burial. There is evidence of coseismic uplift 2,200-2,600 yr B.P. at Middleton Island and Copper River delta and 2,820-3,180 yr B.P. at Copper River delta (Plafker and others, 1992), but no evidence at a single site for multiple events during this period. Either (1) multiple events are recorded at the Portage site and have not been preserved or recognized elsewhere, (2) the radiocarbon ages at Portage are in error, or (3) not all of the peat layers at Portage represent earthquake-related burial.

4. The oldest buried peat layer at Girdwood (fig. 3, site TA1) shows strong stratigraphic evidence of sudden burial 3,370-4,090 yr B.P. This event agrees well in age with coseismic uplift

3,360-3,940 yr B.P. at Middleton Island (Plafker and others, 1992). One of two radiocarbon ages from the second-oldest peat at Portage (fig. 2, site TA8) overlaps the peat age at Girdwood and is statistically equivalent. The other age at Portage fails to overlap by more than 200 yr at 1 sigma and may be erroneous. The strong evidence for earthquake-related burial at Girdwood and close correlation with uplift at Middleton Island justify tentative acceptance of a regional event 3,400-4,000 yr B.P.

On the basis of arguments 1-4 above, I believe the data indicate a total of six to nine subsidence events related to major, probably great, earthquakes during approximately the past 5,000 yr, including the 1964 event. This gives an average recurrence interval of 560-830 yr, or 600-800 yr when rounded to the nearest 100 yr to account for the large uncertainties in the data.

TECTONIC DEFORMATION

Data now available from tidal marshes in Cook Inlet indicate that the pattern of tectonic subsidence during the late Holocene was probably similar to that associated with the 1964 great earthquake. Subsidence during the 1964 event was greatest (>2 m) along a NE-SW axis near Portage flats and decreased westward to <0.6 m along the west coast of Kenai Peninsula (fig. 1). A cross section of tidal marshes across the western limb of the 1964 subsidence zone shows that the thickness of tidal-marsh sediments that accumulated during this period is greatest at Portage flats and generally decreases westward (fig. 9), which is consistent with greatest subsidence at Portage flats and least at Kenai and Kasilof River flats.

Peat stratigraphy at the Portage site indicates net submergence and sediment accumulation there of about 12 m during the past 5,000 yr. In contrast, peat stratigraphy at Kenai and Kasilof River flats indicates that these sites have been relatively stable in relation to sea level, showing only 2 m of net submergence during the past 7,000 yr. Although the Kenai-Kasilof area underwent more than 100 m of isostatic rebound following maximum late-Wisconsin glaciation 18-21 ka (Reger and Pinney, in press), tidal-marsh data indicate that the area has been relatively stable during the late Holocene.

CONCLUSIONS

Given the known tectonic environment of the Cook Inlet region and the observed subsidence, marsh burial, and peat preservation resulting from the 1964 great earthquake, it is reasonable to assume that some or most of the buried peat layers in tidal marshes along upper Cook Inlet represent similar coseismic subsidence during previous events. Many, although not all, of these peat layers exhibit evidence of sudden submergence and burial, including a sharp upper contact and dominance of halophytic plant fossils in the overlying mud. Some layers lack this evidence possibly because they have been buried by nontectonic processes or the evidence has been removed or modified by postburial erosion. On the other hand, evidence of some subsidence events may be lacking because marshes had not become fully reestablished before sudden subsidence and, therefore, no peat layer was buried and preserved.

Although uncertainties in radiocarbon dating and imprecise stratigraphic correlation make the data difficult to evaluate, there is sufficient regional evidence to conclude that (1) there have been six to nine earthquake-related subsidence events during approximately the past 5,000 yr, giving an average recurrence interval of 600-800 yr, (2) the most recent pre-1964 event was 700-900 yr ago, and (3) the pattern of tectonic subsidence during the late Holocene was similar to that associated with the 1964 earthquake.

Lacking magnitude information for these prehistoric earthquakes, I maintain a conservative interpretation that the 600-800-yr recurrence interval represents $M_W \approx 9$ 1964-style earthquakes; "smaller" great earthquakes in the magnitude 8 range probably occur more frequently.

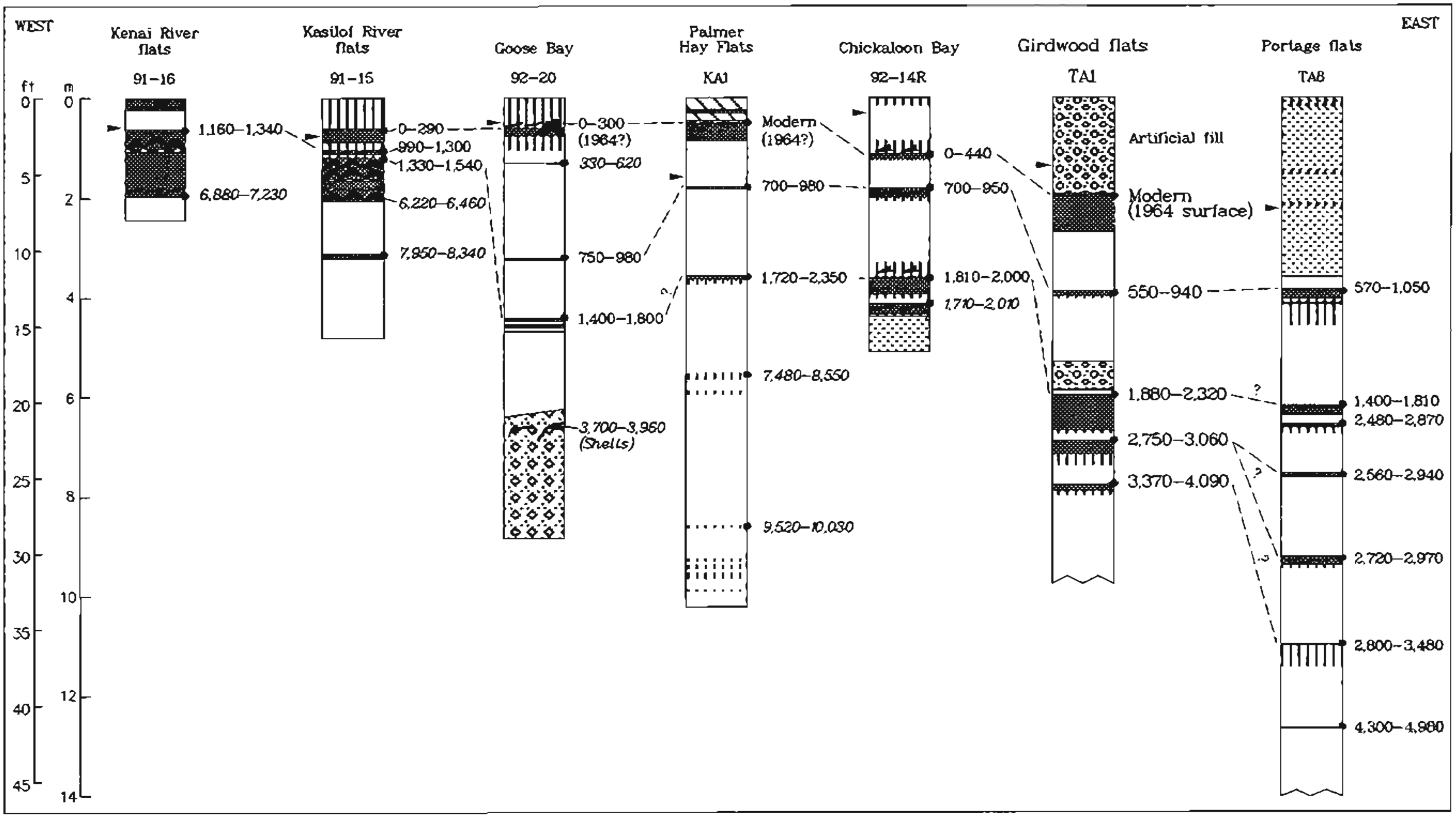

Figure 9. *Comparison of representative stratigraphic sections from tidal marshes studied for this report. Sections are arranged east to west across the western limb of the 1964 subsidence syncline. See figure 2 for explanation of symbols.*

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