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May 1992

This is a preprint of a report accepted for publication in *Short Notes on Alaskan Geology*, to be released as a Division of Geological and Geophysical Surveys Professional Report in 1993.

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# THE PENULTIMATE GREAT EARTHQUAKE IN SOUTHCENTRAL ALASKA: EVIDENCE FROM A BURIED FOREST NEAR GIRDWOOD

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## INTRODUCTION

Determining the potential for future great earthquakes (Richter magnitude about 8 or 9) requires knowing how often they have occurred in the past. In the Anchorage, Alaska, region, only one great earthquake has occurred during historic time. This event, the great 1964 Alaska earthquake ($M_w$=9.2), 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 great earthquake ruptured this segment, roughly between Kodiak and Cape Suckling, 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 and, in some cases, several great earthquakes during 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. Recent geologic studies indicate that recurrence intervals for great earthquakes in this region range from about 400 to 1,300 yr (Plafker and others, in press). My purpose in this paper is to present evidence from a coastal marsh near Girdwood that the penultimate, or second to last, great earthquake in the Anchorage region occurred between about 700 and 900 yr ago. This evidence comes from a layer of high-marsh[1] peat and rooted trees that were submerged by subsidence, probably killed by salt-water intake, and buried by postseismic deposition of intertidal silt and clay. I present preliminary evidence that subsidence was substantial and sudden (coseismic), and suggest that this subsidence at Girdwood probably coincided with subsidence at Portage and Palmer Hay Flats and with uplift at Copper River Delta. If such a large area was deformed during a single event, it must have been a great earthquake similar to the 1964 event.

## 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, 1969). Downwarp of as much as 2 m occurred over an elongate region including Kodiak Island, 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

[1]In this paper, *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).

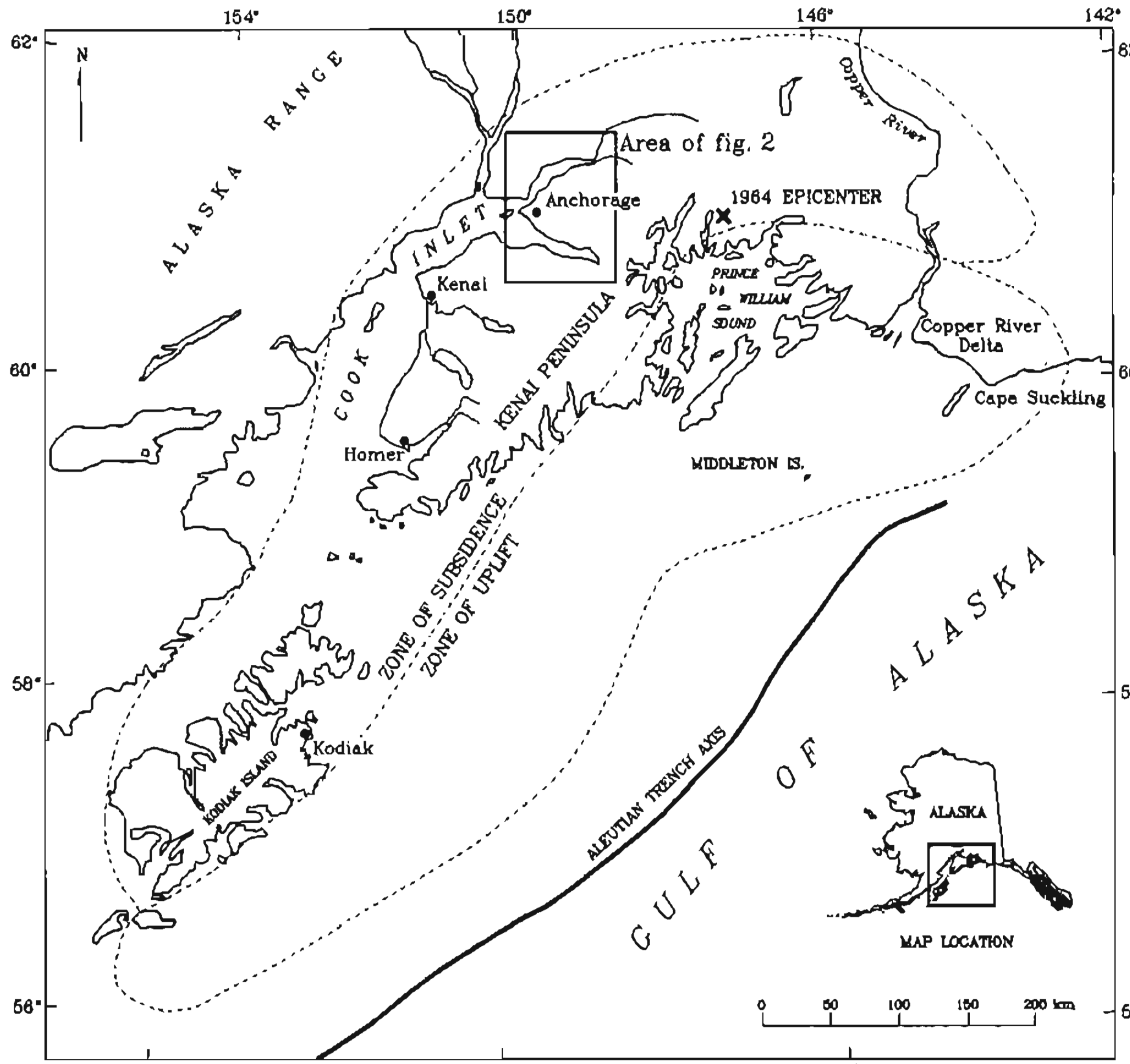


Figure 1. *Region affected by vertical tectonic displacement during the great Alaska earthquake of 1964 (modified from Plafker, 1969, fig. 3).*

Prince William Sound, and Copper River Delta. Superimposed on this pattern of coseismic deformation is regional interseismic subsidence (Plafker and others, in press). 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 much of the subsided area of Turnagain Arm (fig. 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 along Turnagain Arm (Brown and others, 1977). Additionally, intertidal silt deposition began in submerged areas immediately following the earthquake and by 1980 had nearly restored the

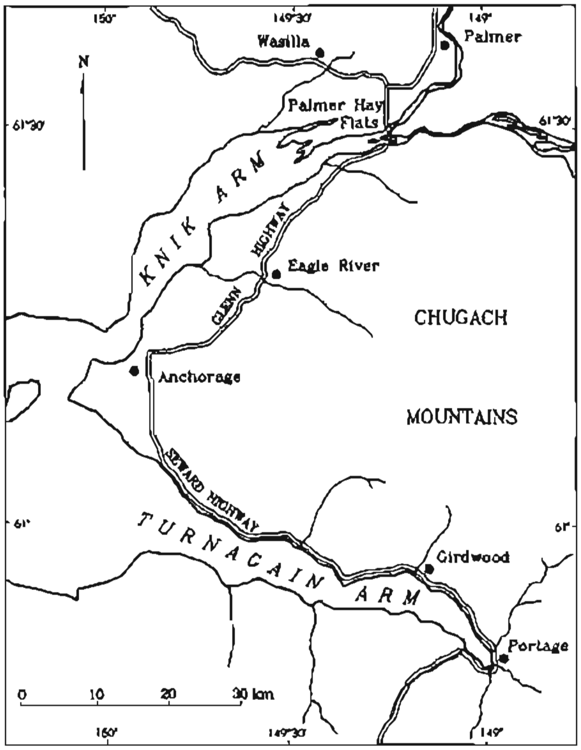


Figure 2. *Anchorage region and portion of upper Cook Inlet, including study area in vicinity of Turnagain and Knik Arms (see fig. 1 for map location).*

tidal flats to pre-earthquake levels (Bartsch-Winkler and Garrow, 1982). In the Portage area, Ovenshine and others (1976) mapped this deposit as the Placer River Silt. An equivalent but thinner deposit is present at Girdwood. This postearthquake silt overlies grasses, mosses, herbaceous plants, peat, and root systems of spruce and cottonwood trees on the high marsh that was submerged in the Portage and Girdwood areas during the earthquake.

## 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, 1985).

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. 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, in press). 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 frequency over long periods. 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 southcentral Alaska during the past 5,000 yr, or late Holocene (Plafker and Rubin, 1967, 1978; Plafker, 1969; Plafker and others, in press; Combellick, 1986, 1991; Bartsch-Winkler and Schmoll, 1987). 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 indicate 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, in press). 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 $700\pm250$ radiocarbon yr (510-920 calendar yr) for wood from a rooted stump at about 0.8 m below the pre-1964 surface and $2,800\pm180$ yr (2,759-3,207 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 (fig. 1), dated at 1,360 radiocarbon yr, represented the last coseismic uplift in the region prior to 1964. However, Plafker and others (in press), reported new evidence of widespread coseismic uplift with a calibrated age of 665-895 yr in the Copper River Delta.

## BURIED FOREST LAYERS AT GIRDWOOD

Erosion by waves and tidal currents has exposed two peat layers with rooted tree stumps along coastal banks at Girdwood (fig. 3). Trees rooted in the uppermost layer were killed as a result of submergence during the 1964 earthquake, probably by salt-water intake. Many of these dead trees remain standing but their root systems are partially or completely buried beneath postearthquake silt (equivalent to Placer River Silt) up to several tens of cm thick. Patches of bark remain on above-ground portions of some of the trees and are commonly well preserved on buried portions of the trunks.

Stumps rooted in the lower layer are broken or eroded to heights of less than 1 m and encased in about 1 m of gray clayey silt between the upper and lower forest layers. None of the lower stumps protrude through the modern marsh surface. No bark remains on the specimens I observed from the lower layer except for very few small, loosely attached patches. The lower stumps are rooted in a layer of mossy and woody peat 10-15 cm thick, which has been partly removed by tidal and wave erosion where the stumps crop out at the base of the bank (fig. 3B). This lower layer of rooted stumps is probably the same layer that Karlstrom (1964) dated at $700\pm250$ radiocarbon yr.

Several lines of evidence indicate that the lower forest layer was submerged and buried as

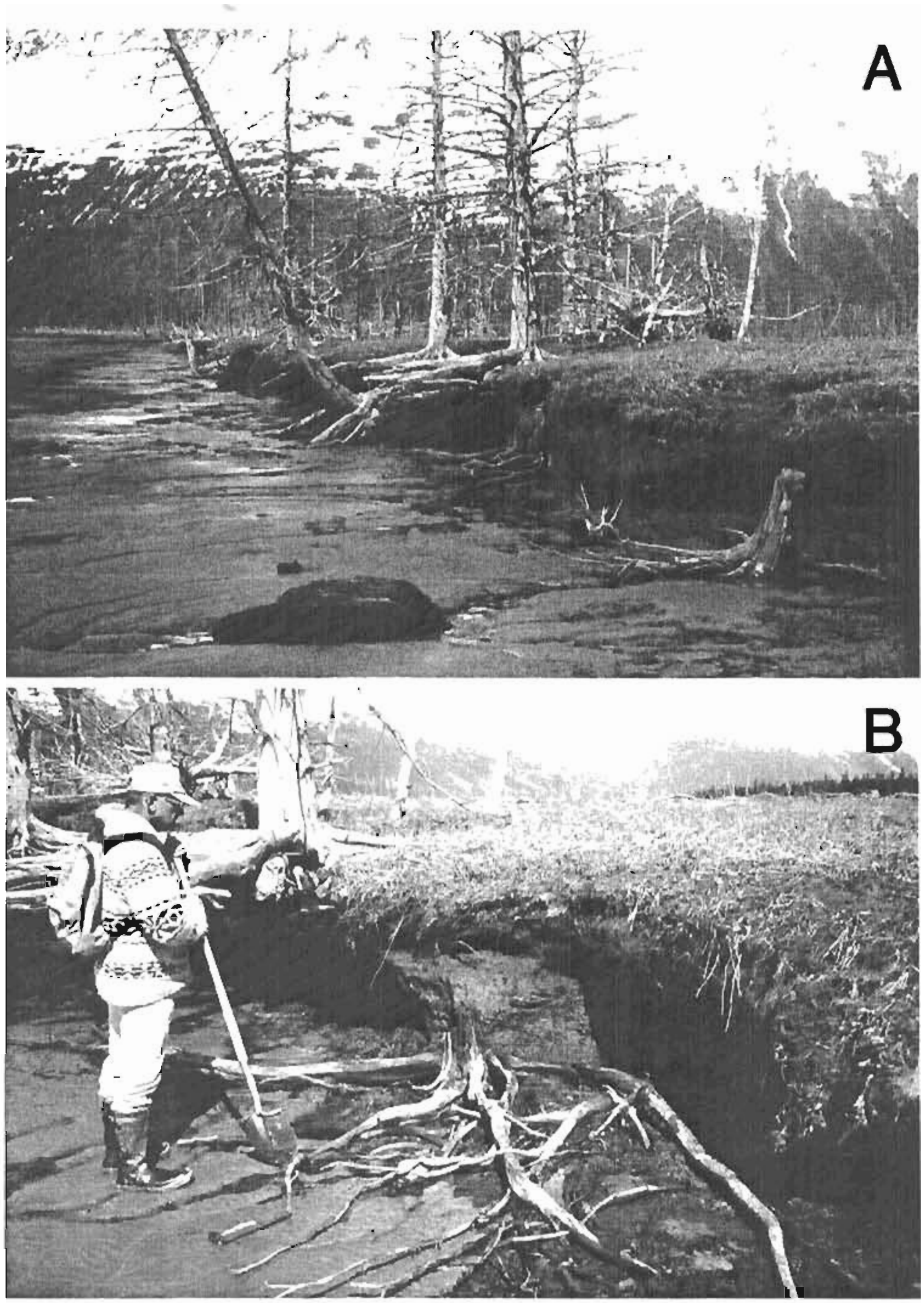


Figure 3. *Erosion has exposed root systems of two generations of dead spruce trees in coastal banks along upper Turnagain Arm near Girdwood. A, View of standing trees that probably died from salt-water intake following submergence during the 1964 earthquake. The roots of these trees and other contemporaneous vegetation were buried by postearthquake deposition of intertidal silt. Stumps along the base of the bank are rooted in an older peat layer, which is buried beneath about 1 m of intertidal silt. B, Closeup of older rooted stump showing intertidal mud that buried the root system and associated peat layer (erosion has removed much of the peat). Death of these older trees and burial of the peat layer within which they are rooted probably resulted from subsidence during the previous great earthquake (1991 photographs).*

a result of sudden subsidence: (1) the contact between the peat layer and overlying mud is very sharp, indicating rapid burial, as with the 1964 layer; (2) outer growth rings of the buried stumps are continuous and as wide as or wider than inner rings, indicating healthy growth until death, comparable to that observed in coastal Washington by Atwater and Yamaguchi (1991); and (3) the lower part of the overlying mud layer contains below-ground stems of the halophytic plant *Triglochin maritimum*, indicating submergence to a lower level in the intertidal zone. In southwestern Washington, where diurnal tide range is about 3 m, *T. maritimum* is dominant only in low-marsh areas that are 0.5-2.0 m or more below the typical high-marsh surface (Atwater, 1987). In upper Cook Inlet, where diurnal tide range is about 10 m, *T. maritimum* may indicate greater than 2-m depth below the high-marsh elevation. The overlying mud layer shows a gradual upward increase in roots, grass stems, and other plant material and grades into the overlying peat, suggesting a gradual return to the high-marsh environment.

Although alternating layers of peat and intertidal mud can be produced by nonseismic processes (Nelson and Personius, in press), the sharp peat-mud contact, presence of *T. maritimum* in mud above the contact, apparent sudden death of rooted trees, and gradual mud-peat transition are strong evidence of coseismic subsidence followed by gradual uplift or sedimentation that returned the tidal flat to high-marsh conditions. Still lacking, however, is convincing evidence of strong ground shaking in the form of liquefaction features associated with burial of the peat. This evidence may be very difficult to find; a 1991 reconnaissance of several km of tidal- and river-bank exposures in the Portage area, where liquefaction was extensive during the 1964 earthquake (McCulloch and Bonilla, 1970), revealed only a few sand dikes penetrating the 1964 soil (B. Atwater and R. Combellick, unpubl. data). Locating similar evidence of ground shaking during previous events will be even more difficult because previous coseismic subsidence is interpreted mainly from borehole samples (Combellick, 1991).

## Radiocarbon Ages

My estimate for age of burial of the lower forest layer at Girdwood is based on radiocarbon dating of two wood samples and three peat samples. The wood samples were collected from the outermost eight to ten growth rings of two rooted tree stumps. Because bark was not present on the sampled stumps, these may not be the last growth rings added before death. However, the well-preserved condition of the stumps, nearly continuous outermost rings, and smoothness of the outer surface suggest that few or no growth rings have been lost to decomposition. Considering the potential sources of error in conventional radiocarbon dating, the exact position of the dated wood relative to the outermost ring at time of death is probably insignificant. If my assumption is correct that these trees were growing normally at the time of submergence and died quickly as a result of submergence, the average age of these outer rings should predate the time of the event by no more than a few years. The potential for contamination of wood samples with older or younger organic material is far less than for peat samples. Therefore, the wood samples should provide a more reliable age estimate for submergence.

Two of the peat samples were collected from the upper 2-3 cm of the peat layer exposed near the rooted stumps, immediately below the abrupt contact between the peat and overlying tidal mud. The third peat sample was collected from an equivalent stratigraphic position in a nearby borehole (Combellick, 1991, table 2, sample GX-15210). If the peat is composed primarily of plant material that was growing at or shortly before submergence, these samples should provide a closely limiting maximum age for the event. However, possible contamination by older plant matter or younger roots may introduce unknown errors.

Two commercial laboratories performed the radiocarbon dating using standard pretreatment and gas-proportional counting techniques.

Reported radiocarbon ages (fig. 4) include a correction for natural $^{13}C/^{12}C$ isotopic fractionation and are referenced to A.D. 1950. Calibration to calendar years was based on tree-ring data of Stuiver and Becker (1986) and was performed using a computer program by Stuiver and Reimer (1986). The laboratories did not provide specific error multipliers to account for non-counting analytical errors, so I used a conservative value of 2 for all calibrated ages. Although this 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. This is because the quoted standard deviation may not be large enough to account for all sources of laboratory error (Stuiver and Pearson, 1986).

The wood samples yielded ages of 860±60 and 940±60 radiocarbon yr (670-930 and 730-970 calendar yr). The weighted average of these ages is 900±43 radiocarbon yr, which gives possible calibrated ages of 794, 814, and 817 yr and an error range probably within the interval 728-929 yr B.P. at 68 percent confidence (fig. 4). The calibrated age range is greater than the uncalibrated range because of multiple intercepts in the calibration curve and greater rate of change of calibrated age versus radiocarbon age during this period (fig. 5).

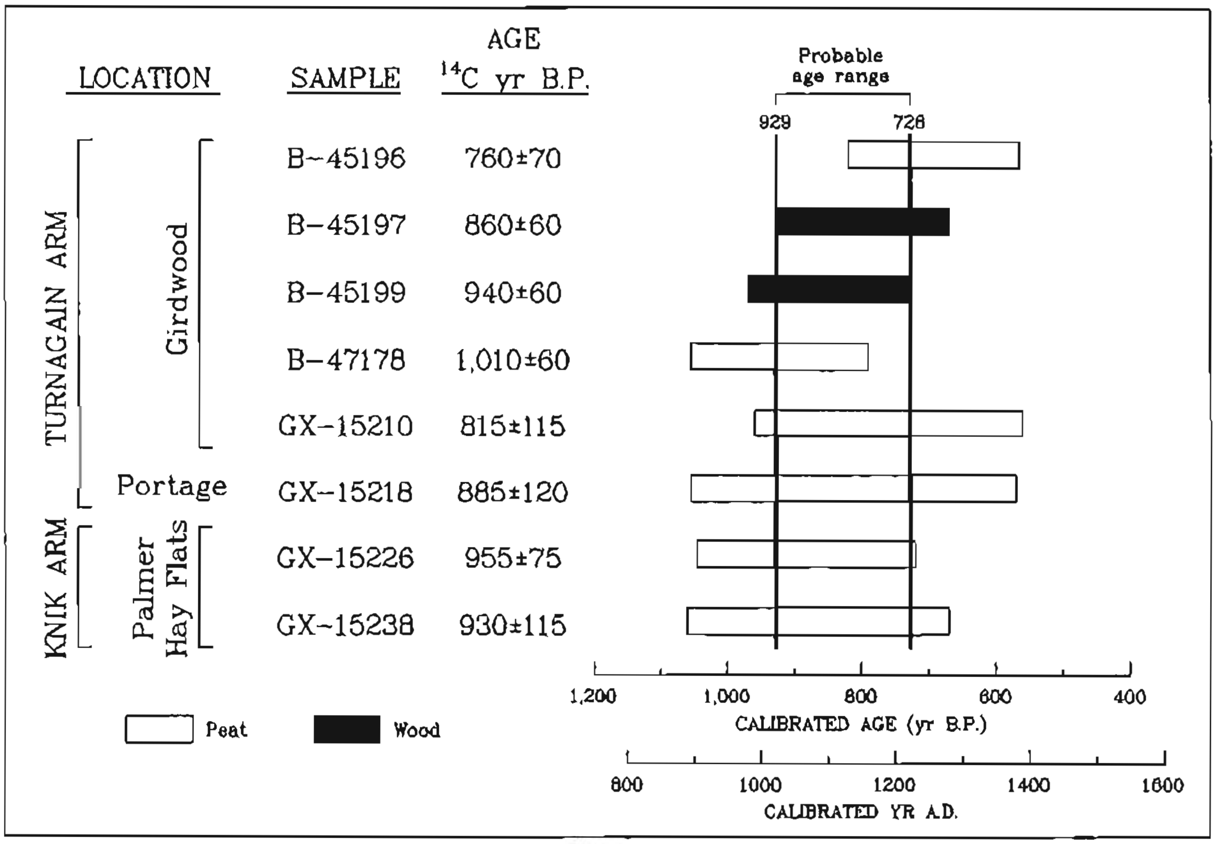


Figure 4. *Radiocarbon ages of wood and peat samples used in this study. Wood samples were collected from the outer 8-10 growth rings of rooted stumps. Peat samples were collected from the upper 2-3 cm of buried peat. Age in $^{14}C$ yr B.P. is conventional radiocarbon age in years before A.D. 1950 with quoted counting error of one laboratory standard deviation. Calibrated age ranges at right are based on tree-ring data of Stuiver and Becker (1986) and incorporate an error multiplier of 2 to account for possible non-counting sources of laboratory error. Probable range shown represents error limits of the average calibrated age of two wood samples at the Girdwood site, at 68 percent confidence (fig. 5).*

Ages of the peat samples were 760±70, 815±115, and 1,010±60 radiocarbon yr (563-818, 558-960, and 790-1,056 calendar yr, respectively)(fig. 4). These ages are consistent with the wood ages but show greater variation, probably because of the longer period spanned by each peat sample and, in the case of the 760-yr age, possible contamination by younger organic material.

## REGIONAL CORRELATION AND DISCUSSION

Buried peat layers with characteristics similar to the lower Girdwood forest layer, but without observed rooted stumps, occupy an equivalent stratigraphic position in estuarine sediments at Portage and Palmer Hay Flats (Combellick, 1991)(fig. 2). A sample from the top of the peat layer at Portage has an age of 885±120 radiocarbon yr (572-1,054 calendar yr). Samples from the top of the peat layer at two locations at Palmer Hay Flats yielded ages of 955±75 and 930±115 radiocarbon yr (720-1,047 and 670-1,060 calendar yr, respectively). These peat ages are consistent with the ages of wood and peat samples from the lower Girdwood forest layer (fig. 4). The reported 665-895-yr calibrated age for coseismic uplift in the Copper River Delta area (Plafker and other, in press) is also consistent with the wood and peat ages in upper Cook Inlet.

These data do not prove that vertical displacement was coeval in all areas; if the dated deposits were produced by events separated by only a few years or decades, these events cannot be resolved by conventional radiocarbon dating. However, because the current body of paleoseismic evidence indicates an average recurrence interval of 600-800 yr for great earthquakes in this region, it is reasonable to presume that the dated deposits represent a single event.

If vertical displacement was coeval, the minimum magnitude of this earthquake can be roughly estimated using an empirical relationship between magnitude of subduction-zone earthquakes and length of measurable deformation (West and McCrumb, 1988). Considering

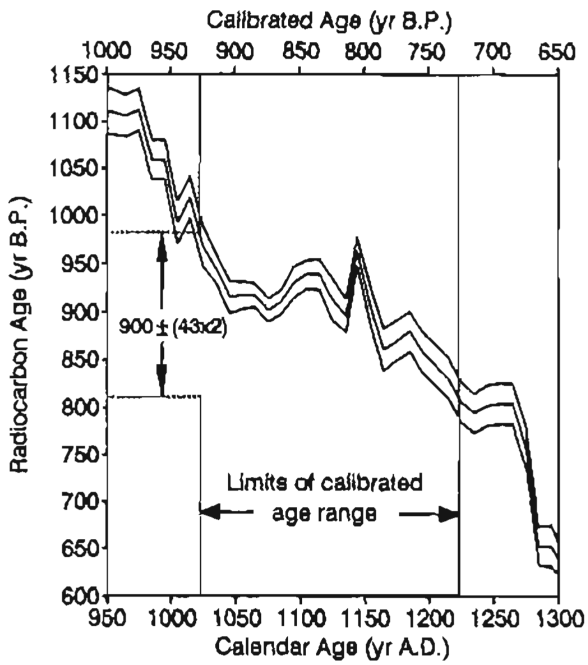


Figure 5. *Portion of tree-ring calibration curve showing translation of average radiocarbon-age range for the two wood samples to calibrated probable range shown in fig.4. Prior to calibration, the error calculated from the laboratory standard deviations is increased by an error multiplier of 2. The center line is the calibration curve and the outer lines represent uncertainty of one standard deviation in the calibration data set; this standard deviation incorporates a laboratory error multiplier of 1.6 (modified from Stuiver and Becker, 1986, fig. 1B).*

that deformation zones are elongated parallel to the trench axis, the deformation associated with the earthquake must have exceeded the 300-km distance between upper Cook Inlet and Copper River Delta because this line is roughly perpendicular to the trench axis. According to the graphic relationship of West and McCrumb (1988, fig. 1), the minimum earthquake magnitude for a 300-km-long zone of deformation is about 7.8.

High-precision dating involving much longer counting periods could provide radiocarbon ages with standard deviations on the order of one or two decades (Stuiver and Becker, 1986; Atwater and others, 1991). However, this technique may not improve resolution of the calendar age of the earthquake because of apparent wide variability of atmospheric $^{14}C$ between about 750 and 900 yr B.P. (A.D. 1050-1200). The resulting calibration curve (fig. 5) shows that radiocarbon ages between about 860 and 960 yr give multiple calibrated ages between 750 and 925 yr. As Atwater and others (1991) have demonstrated, it may be possible to precisely date older rings of rooted stumps, thereby obtaining radiocarbon ages on a steeper portion of the calibration curve (greater than 960 radiocarbon yr B.P.) where there are fewer multiple intercepts. Subtracting the number of growth rings between the sampled portion and the outer surface would then yield more precise calibrated ages for the samples. This method could help determine whether sudden vertical displacements in this region between 700 and 900 yr ago resulted from multiple great earthquakes.

## SUMMARY AND CONCLUSIONS

The last great earthquake that caused tectonic deformation in the Anchorage region prior to 1964 probably occurred between 700 and 900 yr ago. This inferred earthquake caused vertical shoreline changes extending at least from upper Cook Inlet to Copper River Delta. Evidence of these changes appears in tidewater banks at Girdwood, where a layer of peat and rooted tree stumps exposed about 1.7 m below the modern coastal high marsh is buried beneath intertidal mud. The abrupt upper contact of the peat, apparent sudden death of the trees, and presence of halophytic plant fossils in mud above the contact indicate submergence into the low-marsh environment more rapidly than would be expected as a result of nontectonic rise of relative sea level. As intertidal silt deposition and possibly postseismic rebound restored the tidal flat to dominantly subaerial conditions, the mud above this forest layer became increasingly rich in plant matter and a new brackish-water high marsh developed. Subsidence during the 1964 earthquake submerged this marsh in a similar fashion and resulted in burial by intertidal silt.

Age control for this penultimate earthquake comes from radiocarbon dates of outer growth rings from two rooted trees that were probably killed by salt water as a result of coseismic submergence. Mathematically combining these ages gives a calibrated age range probably within 728-929 calendar yr B.P. at 68 percent confidence. Peat samples from the top of the soil layer within which these stumps are rooted yield calibrated ages that are consistent with the wood ages but show greater variation. The wood and peat ages at Girdwood closely match ages obtained from similar buried peat layers at Portage and Palmer Hay Flats, and from deposits formed by coseismic uplift at Copper River Delta. Although I presume that these vertical displacements occurred during a single great earthquake, multiple earthquakes may have affected each area separately within a period that was too brief to resolve with conventional radiocarbon dating. If the vertical displacements occurred during a single earthquake, its magnitude was probably 7.8 or larger.

## ACKNOWLEDGMENTS

The U.S. Geological Survey, Department of the Interior, supported this study under National Earthquake Hazards Reduction Program award 14-08-0001-G1949 to the Alaska Division of Geological and Geophysical Surveys. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing official policies, either expressed or implied, of the U.S. Government.

I thank Richard Reger for his assistance in the field and for his knowledgeable insights. Beta Analytic, Inc. and Geochron Laboratories Division, Krueger Enterprises, Inc. performed all radiocarbon-age determinations. Reger, Brian Atwater, and George Plafker reviewed the manuscript and provided many valuable suggestions for improvement.

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