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Bay, Southern Coastal Alaska**

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ABSTRACT

A conifer forest on the shore of Verdant Cove, an inlet of Aialik Bay on the southeast coast of the Kenai Peninsula, was buried by high-energy beach sediments shortly after 860 ± 50 ^{14}C BP. The switch from ocean-distal forest to cobble beach indicates a radical change in depositional environment suggestive of rapid subsidence of 1-3.5 meters. The presence of hemlock, a tree taxon sensitive to salt-water exposure, and the preserved cast of a tree trunk suggest that subsidence and burial occurred rapidly. By 690 ± 60 ^{14}C BP, forest peat was accumulating atop the beach sediments burying the forest and rapid spit progradation was underway. Spit progradation implies land emergence or stable sea level, especially in this case where the spit has a limited sediment supply. We infer that subsidence of the spit ca. 860 ± 50 ^{14}C BP was followed by slow land emergence up to the time of the 1964 AD great earthquake, when the area subsided coseismically 1.4 m. The sudden drowning of the buried forest in Verdant Cove was probably caused by coseismic subsidence and later emergence by gradual, interseismic uplift. Comparison of the Verdant Cove record with previously reported data from south-central Alaska suggests that the penultimate great earthquake in the rupture zone of the 1964 Alaska earthquake occurred between 700 and 800 cal BP.

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Introduction

The 1964 Alaska earthquake ($M_w = 9.2$) affected a 450 x 850 km region of southern Alaska inland of the Aleutian trench between the Copper River delta and southwestern Kodiak Island (Plafker 1969) (Fig. 1). This is the area of highest density of human population in Alaska; consequently the 1964 earthquake caused widespread property damage and loss of human life (Plafker and Kachadoorian 1966; National Research Council 1972). The 1964 event was the largest earthquake occurring along the Queen Charlotte-Alaska-Aleutian seismic zone in historic time, and the second largest instrumentally recorded earthquake worldwide (Nishenko and Jacob 1990).

There is only limited data on the recurrence intervals of earthquakes in the rupture zone of the 1964 Alaska earthquake. Nishenko and Jacob (1990) estimate the recurrence time of great ($M_w \geq 8$) earthquakes there as 230 to 460 years. This estimate assumes no aseismic slip and is based on comparisons between the long-term rate that the Pacific plate converges on southern Alaska and a small number of estimates of coseismic horizontal displacement in 1964 (Plafker 1969; Nishenko and Jacob 1990).

Theoretical estimates differ by a factor of two from the geologic record of previous earthquakes in south-central Alaska. Raised marine terraces on Middleton Island (Fig. 1) record 6 coseismic-uplift events, including one in 1964, spaced 390 to 1300 years apart, with a mean interseismic interval of 1020 ± 360 years (Nishenko and Jacob 1990; Plafker et al. 1992). The ages of terrestrial peat layers in the intertidal muds of upper Cook Inlet suggest that 6 to 8

earthquakes occurred in the ca. 4700 years preceding 1964 AD (Combellick 1991). Also on the basis of intertidal peat stratigraphy in upper Cook Inlet, Bartsch-Winkler and Schmoll (1987, 1992) suggest that earthquakes caused coseismic subsidence at intervals of 400-500 years since at least 3200 ^{14}C BP. On the Copper River delta (Fig. 1), Reimnitz (1972) describes buried forest horizons dating to ca. 750 and 1700 ^{14}C BP. He suggests these forests established immediately after coseismic uplift, then died during slow subsidence caused by some combination of interseismic subsidence and delta compaction. Plafker (1990) and Plafker et al. (1992) interpret buried forest layers and terrestrial peat to indicate at least four coseismic uplift events on the Copper River delta occurring between ca. 3500 BP and 1964 AD.

Here we describe evidence for rapid subsidence of a cobble spit in Verdant Cove within Aialik Bay on the southeastern Kenai Peninsula 700 to 800 years ago (Fig. 1). After correlating this event with other paleoseismic records from southern Alaska, we suggest it represents the penultimate great earthquake in south-central Alaska.

Study Area

The Kenai Mountains rise abruptly out of the northern Gulf of Alaska to summit heights of 1800 to 2000 m (Fig. 1). Bedrock is flysch of the Chugach Terrane, including argillite, graywacke, and slate, with minor volcanics (Beikman 1994; Plafker et al, 1994). Extensive ice fields exist today above 1000 m (Wiles and Calkin 1994). Deep U-shaped valleys are confluent with fjords extending onto the continental shelf (von Huene 1966) and evidence extensive Pleistocene glaciation of the Kenai Mountains. Tertiary granitic plutons within the flysch bedrock of the Kenai Mountains form erosion-resistant massifs retaining abundant geomorphic evidence of glacial erosion. Although previously described as drowned cirques (Plafker 1969;

Péwé 1975), most of the steep, amphitheater-form headwalls along the Kenai coast in fact are confluent with submerged U-shaped valleys characterized by basin and riegel topography and probably resulted from intense erosion under valley glaciers.

Verdant Cove (informal name) is one of the drowned, glacially-carved valleys in granitic bedrock on the Harris Peninsula between Aialik and Harris Bays (Fig. 2). Measurements at a temporary tide-gauge station at Verdant Island on the north side of Verdant Cove showed 1.4 m of coseismic subsidence during the 1964 earthquake (Plafker 1969; Hicks 1972). Two kilometers away on the southeastern shore of Verdant Cove is a cusped spit built largely from cobbles eroding from headlands of mudstone and shale to the east and transported into Verdant Cove by the predominant southerly wave approach. The sediment-source area for the spit is limited in extent and borders closely the deep water of Aialik Bay, suggesting that input of new material to the spit is relatively slow.

The Verdant Cove spit is approximately 200 m wide and 600 m long (Fig. 3). Cobble beach ridges on its surface support two contrasting vegetation types. Highest above sea level and furthest from the sea, the Tsuga surface is comprised of shore-parallel beach ridges composed of small to medium cobbles and supporting a forest dominated by mountain hemlock (Tsuga mertensiana) with an understory of huckleberry (Vaccinium spp.). The Elymus surface consists of mostly shore-perpendicular beach ridges of small to medium cobbles and is densely vegetated by rye grass (Elymus arenarius) growing amid the snags of a conifer forest killed following the 1964 earthquake, as a result of salt water inundation. A leveling transect across the Verdant Cove spit illustrates the altitudinal differences between the higher Tsuga surface and the mostly lower Elymus surface (Fig. 4). A prominent storm berm parallels the modern shore and

encloses the Elymus surface (Figures 3 and 4). This storm berm is actively moving inland, as evidenced by overwash fans burying living vegetation. The modern storm berm is slightly higher than the highest of the Tsuga-surface ridges.

At the rear of the Tsuga surface is a tidal pond, approximately 45 m long and 5 to 20 m wide (Fig. 5). Although unconnected by surface flow to the sea, the water in the pond follows with a slight lag the tidal cycles in Verdant Cove. Salt water percolates freely through the cobble substrate of the intervening spit. The tidal pond is 5 - 6 m deep below the level of the highest Fucus distichus (rock weed), which grows up to approximately the level of mean high water (Plafker 1969). Spring-tide range in Verdant Cove is 4-5 m.

Results

Stratigraphy on the Shore of the Tidal Pond

A buried forest bed crops out on the inland side of the tidal pond about 1 m below the mean high water line (Fig. 6). We excavated 6 stumps from this buried forest, 4 spruces and two hemlocks. A trench dug perpendicular to the pond shore, 6 m long by 2 m deep, uncovered a spruce stump 6 m inland and at the same elevation as the outermost stump on the pond shore, indicating that a nearly level, buried forest layer underlies the inland margin of the tidal pond. Sediments enclosing the innermost stump of the buried forest contained a meter-long, air-filled cavity extending upwards from the stump, representing the cast of the freshly buried tree. Traces of an organic-rich soil are preserved in protected niches around the bases of the buried stumps. It is noteworthy that the wave-washed root crowns of trees killed after the 1964 earthquake around the tidal pond similarly retain only remnants of the pre-1964 soil.

Sediments burying the forest layer are primarily cobbles, 5 to 20 cm in diameter, and less-abundant pebbles, both of sedimentary lithology. Most clasts are subrounded, evidencing abrasion in a beach environment. Occasional subangular and angular clasts of granite, up to small boulder in size, represent deposition of colluvium from the adjacent hillslope. Offlapping, subparallel beds and lenses of gravel and cobbles dip at angles of 5 to 25° towards the tidal pond. The probable depositional environment of the 2 m of sediments burying the forest bed was a high-energy beach similar to the presently active, cobble barrier beach 200 m to the seaward.

Timing and Apparent Magnitude of the Subsidence Event at Verdant Cove

Bark fragments or the outermost 2 cm of wood from the buried stumps were radiocarbon dated to estimate the time of tree death. Dates range from 780 ± 60 to 940 ± 80 ^{14}C BP (Fig. 6, Table 1), but are statistically identical at the 95% confidence level using a χ^2 test ($0.90 > P > 0.75$) (Ward and Wilson 1978, Stuiver and Reimer 1993). These trees died, simultaneously from the perspective of radiocarbon dating, ca. 860 ± 50 ^{14}C BP, the pooled mean age of the 6 samples. Within the 95% confidence interval determined by 2σ error estimates and using a laboratory error multiplier (Stuiver and Pearson, 1993; Stuiver and Reimer, 1993) equal to 2, the mean estimated time of tree death in the buried forest is 740 AD with a 2σ -age range of 570-960 AD.

Following tree death, the forest layer was buried by nearly 2 m of beach sediment within 1 or 2 centuries, as indicated by dates of 600 ± 60 and 690 ± 60 ^{14}C BP on peat and a log intercalated with peat in remnant soil patches on the south shore of the tidal pond (Fig.

6, Table 1). Rapid burial of the forest by beach sediments also is indicated by the preservation of the tree-trunk cast in the burying gravels.

Leveling with a transit and stadia rod showed that the lowest root crowns of trees dying ca. 860 ^{14}C BP near the tidal pond are now 180 ± 10 cm below the lowest root crowns of trees killed by the 1964 earthquake (Fig. 7). The lowest tree killed by the 1964 earthquake on the shore of the tidal pond is 100 ± 10 cm below the lowest tree still alive on the pond shore today.

Uplift Prior to the 1964 Earthquake

Conifer trees killed following subsidence during the 1964 earthquake stand on the present beach of the Verdant Cove spit. The root crowns of these trees outline the pre-1964 earthquake topography and show that trees were growing on the seaward side of the storm berm that enclosed the then tree-covered Elymus surface (Fig. 8). Some of the dead trees on the seaward face of the Elymus-surface storm berm were salvage-logged after the 1964 earthquake. Ring counts of 32 of these cut stumps reveal that the oldest trees germinated before 1815 A.D. (Fig. 9), indicating that the storm berm enclosing the Elymus surface was abandoned by the sea before this date. These counts probably underestimate tree ages by up to several decades, since the cross sections are 1 to 2 m above root crown. We assume the trees died within the year following the earthquake.

Discussion

Geomorphic History of the Verdant Cove Spit

The present plan form of the spit, the stratigraphy on the shore of the tidal pond, and the occurrence of rapid subsidence ca. 860 ^{14}C BP suggest the following history of spit development and relative sea level (RSL) change. A spit of unknown size existed prior to ca. 860 ^{14}C BP, providing the paleosurface where the buried forest grew. Following spit subsidence, the sea reworked sediments shoreward and buried the forest before 690 ± 60 ^{14}C BP. The highest spit gravels deposited against the hillside inland of the tidal pond are 3.5 m above the buried forest layer (Fig. 4). Even assuming these unweathered and apparently wave-worn gravels were deposited after the ca. 860 ^{14}C BP subsidence event, this 3.5 m elevational difference is only a maximum-limiting estimate of the magnitude of subsidence. While living, the buried forest probably was protected from high wave energies by an intervening paleo-spit, which also may have buffered it from the full tidal range. The extent that tidal range is buffered in the tidal pond today is evident by comparing the magnitude of coseismic subsidence in 1964 AD estimated around the tidal pond by leveling, 100 ± 10 cm (Fig. 7), to the magnitude of coseismic subsidence estimated by tide observations in the open cove, 140 cm (Hicks 1972). Comparison of the elevations of trees killed after the 1964 AD earthquake and those dying ca. 860 ^{14}C BP suggests the ancient forest subsided at least 180 cm below its contemporary sea level (Fig. 7). The burial of the ca. 860 ^{14}C BP forest under 3.5 m of high-energy beach sediments is consistent with a RSL rise of > 1 m but < 3.5 m.

The innermost ridge on the Tsuga surface was abandoned by the sea before 690 ± 60 ^{14}C BP (Table 1, Fig. 6), the age of the oldest terrestrial organics on the inland margin of the tidal pond. A date of 570 ± 50 ^{14}C BP on archaeological charcoal at the southern end of the

Elymus surface (Table 1, Fig. 3) indicates the present spit prograded rapidly in the several hundred years after ca. 860 ^{14}C BP.

The highest spit gravels inland of the tidal pond (Fig. 6) are 1.8 m below the crest of the highest, outermost beach ridge on the Tsuga surface (Fig. 4). This difference, together with the trend for the Tsuga ridges to increase in crest altitude towards the sea, might suggest that RSL was rising during deposition of the Tsuga surface after ca. 860 ^{14}C BP. However, we think it more likely this upward trend in beach-ridge altitude was caused by increasing wave energy as the spit prograded outward. Rapid spit progradation is typically a response to falling sea level, especially in a setting where sediment supply is limited (Elliot 1978; Davis and Clifton 1987; Walker and Plint 1992). We suggest that RSL was falling, or less likely, was stationary, during the rapid progradation phase of the spit.

The switch from a shore-parallel to a shore-normal orientation of beach ridges between the Tsuga and Elymus surfaces may have occurred at a geomorphic threshold determined by wave-approach angles in Verdant Cove. As the spit grew outwards, predominant wave direction would have shifted from westerly to more northerly as wave refraction around the headland decreased (Fig. 3). The deposition of shore-normal ridges accompanied development of a lone, shore-parallel barrier beach flanking them to the seaward. Alternately, the switch in beach-ridge plan between the Tsuga and Elymus surfaces could have resulted from a fall in RSL. Sudden progradation could have occurred in response to falling sea level, allowing construction of the Elymus surface with its small, perpendicular ridges flanked by a large barrier beach.

At two locations we attempted to dig through the modern storm berm to locate the top of the pre-1964 storm berm. Both pits caved in at depths of 1 m, before reaching the root

crowns of trees once growing on the crest of the 1963 storm berm. The storm berm flanking the Elymus surface stood at the same position before the 1964 earthquake, but was > 1m lower than the present berm crest and >0.5-1m lower than the crest of the outermost Tsuga beach ridge (Fig. 4). This decrease in crest altitude between the Tsuga and Elymus surfaces is consistent with a fall in RSL between the time that the oldest Tsuga ridge and the youngest part of the Elymus surface were deposited. The establishment of trees on the shoreface of the barrier beach flanking the Elymus surface also is consistent with a fall in RSL. Sometime before 1800 AD, the flanking barrier beach was abandoned by the sea, allowing conifer trees to colonize its crest and seaward flank (Fig. 9).

Following 1.4 m of subsidence during the 1964 earthquake, salt water invaded the rooting zone of trees growing on the Elymus surface, killing them and creating today's ghost forest there. Most trees on the Tsuga surface were rooted high enough to avoid death. The pre-1964 barrier beach flanking the Elymus surface currently is being moved onshore and made higher in response to subsidence in 1964.

In conclusion, we infer that the subsidence event ca. 860 ^{14}C BP in Verdant Cove was 1-3.5 m in magnitude. RSL fell or remained constant, during construction of the Tsuga-surface portion of the spit complex, which occurred rapidly during the several hundred years following ca. 860 ^{14}C BP. RSL fell during construction of the Elymus-surface portion of the spit. A scenario of sudden coseismic subsidence followed by gradual interseismic uplift conforms with the earthquake deformation cycle suggested both theoretically and by paleoseismic reconstructions for the rupture zones of great subduction zone earthquakes (Thatcher 1984; Darienzo and Peterson 1990; Savage and Plafker 1991; Darienzo et al. 1994).

Alternate Hypotheses for the Cause of the ca. 860 ^{14}C BP Subsidence Event at Verdant Cove

Glacial isostasy, changes in global ocean volume, mass movement, and/or interseismic subsidence are possible alternate causes of forest drowning on the Verdant Cove spit ca. 860 ^{14}C BP. Glaciers in the Kenai Mountains fluctuated repeatedly during the last 4000 years (Wiles and Calkin 1994). However, it is unlikely that isostatic depression during a glacial advance drowned the forest at Verdant Cove, since at 800-900 ^{14}C BP glacier termini in the Kenai Mountains were in retracted positions (Wiles and Calkin 1994). Maximum isostatic depression probably occurred after maximum ice loads were reached between 1400 and 1900 AD.

Gradual, interseismic vertical displacements can result in subsidence or uplift of similar magnitudes to coseismic displacements (Savage and Plafker 1991; Atwater et al. 1992). Interseismic submergence of 2 to 7 mm a^{-1} , over a span of at least 800 years, occurred over much of the region affected both by coseismic uplift and subsidence during the 1964 Alaska earthquake (Plafker 1969; Plafker et al. 1992). Global sea level has risen by 1-3 mm a^{-1} over the last century (National Research Council 1990; Emery and Aubrey 1991). Isostatic adjustments following removal of Pleistocene ice sheets and refilling of the world's ocean basins may be causing 0.5 ± 0.5 mm a^{-1} of ongoing sea level rise in south-coastal Alaska (Peltier and Tushingham 1989).

However, the rate of RSL change evidenced by the buried forest at Verdant Cove is not compatible with gradual subsidence caused by interseismic subsidence and/or eustatic sea-level rise. The species composition of the buried forest, identified from microscopic wood structure (U.S. Forest Service, Forest Products Laboratory, written communication, 1994), holds clues about the rate of subsidence. Two of the 6 trees in the buried forest are hemlocks. Both

mountain and western hemlock live in the area today, although only mountain hemlock grows on the spit. Both species of hemlock are sensitive to salt-water exposure. They grow in sites protected from salt-water spray and from root inundation by brackish water. If the now-buried forest had subsided gradually, we would not expect to find salt-sensitive trees growing in it. The ages of bark and outermost wood from these two hemlocks are indistinguishable in state of preservation and ^{14}C age from the adjacent spruce trees. Gradual submergence also is contradicted by the nature of the sediments burying the forest layer. The deposition of cobbles over the ca. 860 ^{14}C BP forest was not interrupted by other forest layers or soils, suggesting that burial was rapid and occurred on a high-energy shore face, not in a protected, shoreface-distal setting implied by the forest layer itself. A sudden switch between depositional regimes suggests a sudden change in RSL, not a gradual one. Regarding events after ca. 860 ^{14}C BP, a gradual fall in sea level, rather than the gradual rise expected from eustatic sea-level rise or interseismic subsidence, is suggested by the rapid progradation of the spit.

Another alternative is that the buried forest on the Verdant Cove spit was drowned by nonseismic slumping of the spit itself. This seems unlikely, given the continually water saturated, coarse particle composition of the spit, a situation not conducive to fluctuations in effective pore pressure. No slumpage scarps are visible in the regular microtopography of the beach ridges

The buried forest could have been drowned by a sudden lateral shift in the position of a barrier beach located to its seaward. This seems unlikely, since the spit in Verdant Cove occupies the most protected corner of an otherwise deep embayment at the extreme

downdrift end of a sediment-transfer cell driven by regional swell direction. There is little place for barrier beaches on the spit to shift laterally, even if regional swell direction changed.

Regional Correlations, Extent, and Age Estimate for an Earthquake

Rapid subsidence of 1 to 3.5 m in Verdant Cove shortly after 860 ^{14}C BP correlates with other dates on the penultimate earthquake in south-central Alaska (Fig. 10). Conifer-tree establishment and terrestrial-peat accumulation began on a coseismically uplifted portion of the Copper River delta sometime between 850 and 710 ^{14}C yr B.P. (Reimnick 1972; Plafker 1990; Plafker et al. 1992) (Table 1). Coseismic uplift probably occurred shortly before these dates. Interseismic subsidence and perhaps sediment compaction caused the subsequent death and burial of this terrestrial vegetation before 500 ^{14}C BP (Fig. 11). Uplift of 1-3 m occurred on the Copper River delta during the 1964 earthquake (Plafker 1969).

Near the town of Girdwood in the Turnagain Arm of upper Cook Inlet (Fig. 10), an earthquake caused the subsidence below high-tide range of conifer trees rooted in terrestrial peats sometime between 800 and 900 ^{14}C BP (Combellick 1993). This buried forest layer probably corresponds to one dated by Karlstrom (1964) to 700 ± 250 ^{14}C BP (Table 1). Subsidence of 1.7 m occurred in upper Turnagain Arm during the 1964 earthquake (Plafker 1969).

In other intertidal sections in upper Cook Inlet (Fig. 10), also within the region of coseismic subsidence in 1964, Combellick (1991, 1993) ^{14}C -dated one or more subsidence events between 500 and 1100 BP. However, evidence for these subsidence events does not come from in situ, buried forests but from cores that show poor inter-core correlations in both

stratigraphy and ^{14}C ages, suggesting they are unsuitable for reconstructing a reliable history of seismic events (Combellick 1991). Similarly, Bartsch-Winkler and Schmoll (1992) conclude that dating reversals in stratigraphic sections and the lack of stratigraphic continuity between sections render their dates on buried peat horizons imprecise in regards to the timing of subsidence events in upper Cook Inlet. Under the influence of an 11 m tidal range and rapid sediment input from the surrounding high mountains (Bartsch-Winkler et al. 1983; Bartsch-Winkler and Ovenshine 1984), tidal channels in upper Cook Inlet are constantly eroding marshes, burying marsh peats in the overbank sediments, and depositing layers of detrital wood and peat.

No record for an earthquake between 1300 BP and 1964 AD exists on Middleton Island where a flight of uplifted marine terraces records coseismic uplift during 5, pre-1964 earthquakes over the last 5100 years (Plafker et al. 1992). It is possible that a terrace was uplifted coseismically ca. 800 ^{14}C BP on Middleton Island but later was destroyed by marine erosion (Plafker et al., 1992). Alternately, the extents of previous earthquakes within the rupture zone of the 1964 earthquake have varied. The heights of coseismically-formed terrace risers on Middleton Island vary by two to three times, suggesting significant variations in coseismic and/or interseismic movements over the last 5000 years.

Dating of the ca. 860 ^{14}C BP earthquake can be refined by using ^{14}C ages on wood from the Copper River delta, the Girdwood area of Turnagain Arm, and Verdant Cove (Fig. 11). Dates from the buried forest at Verdant Cove suggest the earthquake occurred sometime between 690 and 790 cal BP. Although there is no statistically significant difference between the ^{14}C ages of drowned, *in situ* stumps at Girdwood and Verdant Cove ($0.99 > \chi^2 P > 0.98$), the calibrated, calendric ages of stumps from Girdwood (Combellick 1993) are slightly

older, between 760 and 810 cal BP (Fig. 11). The overlap between the Girdwood and Verdant Cove samples at the 1σ confidence interval is between 760 and 790 cal BP, suggesting the earthquake occurred shortly after or within this time interval. For comparison with these maximum-limiting dates, minimum-limiting dates come from stumps that were drowned on the Copper River delta by submergence following tree establishment on surfaces uplifted coseismically (Reimnick 1972; Plafker 1990; Plafker et al. 1992). Wood dates from the Copper River delta suggest the earthquake preceded 700 cal BP, a date consistent with the age of terrestrial peat deposited above the beach sediments burying stumps at the tidal pond in Verdant Cove (Fig. 11). We conclude that the earthquake occurred between 700 and 800 cal BP.

Interestingly, tsunami deposits dating between 500-800 cal BP occur on western Vancouver Island, together with deposits left by a tsunami generated by the 1964 Alaska earthquake (Clague and Bobrowsky 1994). These authors suggest the penultimate great earthquake in southern Alaska was one possible cause of the 500-800 year old tsunami on Vancouver Island.

Was the 700-800 cal BP seismic event in southern Alaska a great earthquake (moment magnitude > 8)? Based on the geographical separation of sites preserving stratigraphic evidence for sudden uplift or subsidence about this time, it probably was (Combellick, 1993). The 700-800 cal BP earthquake occurred over an area at least 300 km long (Copper River delta to Aialik Bay) by 150 km wide (a line to upper Cook Inlet normal to the previous one) (Fig. 10). A length of coseismic deformation of at least 300 km places the 700-800 cal BP event within the observed length ranges of great earthquakes worldwide (West and McCrumb 1988) and of great

earthquakes occurring historically along the Aleutian Arc (Nishenko and Jacob 1990; Taber et al. 1991).

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TABLE 1
Radiocarbon Dates Relating to the Penultimate Earthquake in South-central Alaska

Sample	Laboratory number	Dated material	$\delta^{13}\text{C}$ per mil	^{13}C -adjusted radiocarbon age (^{14}C yr B.P.) ^a	1σ Calibrated age range (cal yr before A.D. 1950) ^b	2σ Calibrated age range (cal yr before A.D. 1950) ^c	Relation of date to earthquake
Verdant Cove Spit : Tidal Pond							
Deep-out	Beta-74353	<u>Picea</u> , outermost 2 cm of wood on stump	-26.6	780±60	570 - 790	530 - 950	F ^d
B50	Beta-65022	"	-27.3	810±50	660 - 800	560 - 930	F
West Outer	Beta-65024	"	-28.8	940±80	670 - 1050	560 - 1180	F
Outer Middle	Beta-67121	"	-28.9	890±70	670 - 950	560 - 1160	F
West Pit #2	Beta-67123	<u>Tsuga</u> , bark on root	-28.6	920±50	690 - 950	560 - 1070	F
West Pit #3	Beta-67124	<u>Tsuga</u> , outermost 2 cm of wood on stump	-28.9	900±50	690 - 930	660 - 1050	F
Salt Pond #1	Beta-67122	2 cm-diameter conifer branch at base of peat layer at pond margin	-26.9	330±60	0 - 510	0 - 540	P ^e
On Bench	Beta-77858	peat with wood fragments under tan tephra	-27.4	690 ± 60	540 - 730	510 - 880	P
Under Tree	Beta-65023	rotten wood under <u>Picea</u> tree dying after 1964 AD earthquake	-27.2	600±60	510 - 660	330 - 740	P
Verdant Cove spit : <u>Elymus</u> Surface							
KEJF-93-11	Beta-67277	archaeological charcoal	—	550±50	510 - 650	330 - 670	P

Copper River Delta (Reimnitz 1972)					
LJ-GAP 32	tree buried by intertidal mud, 5.1 m below 1963 sea level	—	700 ± 50	560 - 690	520 - 790 P
LJ - 939	tree buried by intertidal mud 4.8 m below 1963 sea level	—	725 ± 30	650 - 690	555 - 740 P
LJ - 938	tree buried by intertidal mud 5.1 m below 1963 sea level	—	700 ± 30	560 - 670	540 - 730 P
LJ-GAP 33	tree buried by intertidal muds, 4.8 m below 1963 sea level	—	860 ± 50	670 - 920	570 - 960 P
Copper River Delta (Plafker 1992, Plafker et al. 1992)					
88APR11g	W-6097 ^f sedge peat buried by intertidal muds	—	960 ± 60	730 - 970	660 - 1170 P
88APR11h	W-6098 ^f peat buried by intertidal muds	—	830 ± 60	660 - 910	550 - 960 P
Upper Cook Inlet, Girdwood (Karlstrom 1964, Plafker 1969)					
W - 175	tree buried by intertidal muds 0.8 m below pre-1964 earthquake surface	—	700 ± 250	0 - 1170	0 - 1590 F

^a Laboratory-reported error terms are 1 σ with a laboratory-cited error multiplier = 1.

^b Determined by the CALIB program of Stuiver and Reimer (1993). The range represents the 68% confidence interval based on the 1 σ error limits of the radiocarbon age. For calculation of calibrated ages, laboratory error multiplier = 2.

^c Determined by the CALIB program of Stuiver and Reimer (1993). The range represents the 95% confidence interval based on the 2 σ error limits of the radiocarbon age. For calculation of calibrated ages, laboratory error multiplier = 2.

^d Earthquake followed this date

^e Earthquake preceded this date.

^f Plafker et al. (1992) calibrated these dates, along with a third date of 350 ± 60 ¹⁴C yr B.P. (W-6102), to calendar years and interpolated to estimate a coseismic uplift event at 780 ± 115 cal yr B.P. However the calibrated ages presented for these dates in Plafker et al. (1992) Table 28.1 are widely different from the ages recalculated using the 1993 version of CALIB (Stuiver and Reimer 1993) and are disregarded here.

FIGURE CAPTIONS

Fig. 1. South-central Alaska showing the northeastern portion of the rupture zone of the 1964 Alaska earthquake. Contours (meters) connect areas of similar vertical displacement in 1964. "PWS" is Prince William Sound and "AFG" is Afognak Island. Redrawn from Plafker (1969).

Fig. 2. Location of Verdant Cove on the eastern side of the Harris Peninsula. The Verdant Cove spit is one of only a few unconsolidated coastal landforms on the intricate, glacially-scoured bedrock coastline of the southeastern Kenai Peninsula.

Fig. 3. Plan view of the Verdant Cove spit showing the two groups of beach ridges distinguished by their orientation and vegetation. A - A' is the leveling transect shown in Figure 4. Drawn from a 1:10,000-scale enlargement of a vertical, color-infrared photograph taken in 1978.

Fig. 4. Leveling transect across the Verdant Cove spit. The datum is an arbitrary tide height. An autolevel and stadia rod were used to complete a leveling circuit with a closing error of 6 cm.

Fig. 5. The tidal pond near the inland margin of the Verdant Cove spit showing locations of three of the six stumps (arrows) in the ca. 860 ¹⁴C BP buried forest layer. The tidal pond rises and falls with the tide in the nearby cove, sea water passing freely through the cobbles of the intervening spit.

Fig. 6. Cross section through the inland margin of the tidal pond on the Verdant Cove spit. Buried stumps along the pond margin were located by digging during low tides. A trench dug perpendicular to the pond bank uncovered another stump 6 m inland at the same level as the others.

Fig. 7. Differences in elevation between the lowest root crowns of living trees, all Sitka spruce, the root crowns of conifer trees dying as a result of the 1964 earthquake, and the root crowns of

the 6 buried stumps (4 Sitka spruce, 2 hemlock).

Fig. 8. Conifer trees killed by subsidence during the 1964 Alaska earthquake on the Verdant Cove spit. The elevation and orientation of the root masses record the outline of the pre-1964 beach.

Fig. 9. Ages of conifer snags on the shoreface of the storm berm that flanks the *Elymus* surface on the Verdant Cove spit. These trees were logged after their death caused by subsidence in the 1964 earthquake.

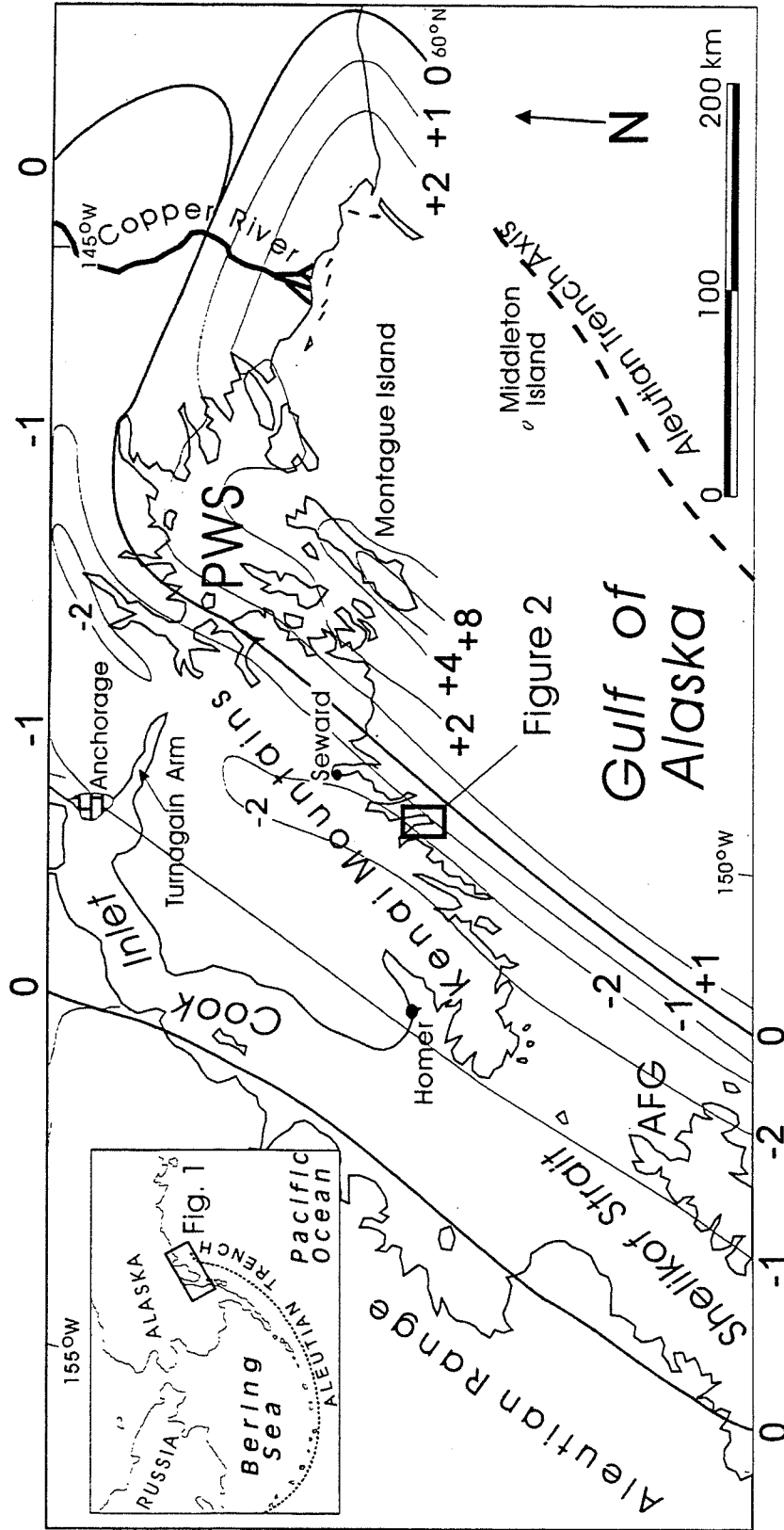
Fig. 10. Distribution of sites with evidence for coseismic sea-level change 700–800 years ago in south-central Alaska. Questions marks indicate sites where ages come from ^{14}C dates on submerged peats not associated with drowned forest beds in the geomorphically complex setting of macrotidal upper Cook Inlet (Bartsch-Winkler and Schmoll 1992; Combellick 1993).

Superimposed are contours of equal vertical displacement (meters) during the 1964 Alaska earthquake (Plafker 1969).

Fig. 11. Plot of calibrated ^{14}C ages from Table 1 and from Combellick (1993, Figure 4) comparing maximum- and minimum-limiting ages for the penultimate great earthquake in south-central Alaska. Radiocarbon ages are calibrated using the method and curves of Stuiver and Reimer (1993). See the text for our rationale about excluding peat dates from upper Cook Inlet. Horizontal bars show calibrated age ranges based on 1σ and 2σ error estimates corresponding to 68% and 95% confidence limits. In the case of the maximum-limiting dates from Girdwood and Verdant Cove, boxes enclose the minimum overlap between 1σ age ranges. Only dates on wood or bark from rooted stumps, not on peat, constrain these boxes. Drawing these boxes assumes that the ^{14}C dates are from tree tissues killed by coseismic subsidence and that the range of

possible dates is due to uncertainties in the radiometric analyses and in ^{14}C calibration to calendar years. Wood and peat from the Copper River delta and near the tidal pond in Verdant Cove provide minimum-limiting dates. The minimum-limiting age box encloses the minimum overlap between 1σ age ranges of wood samples from the Copper River delta.

Fig. 1



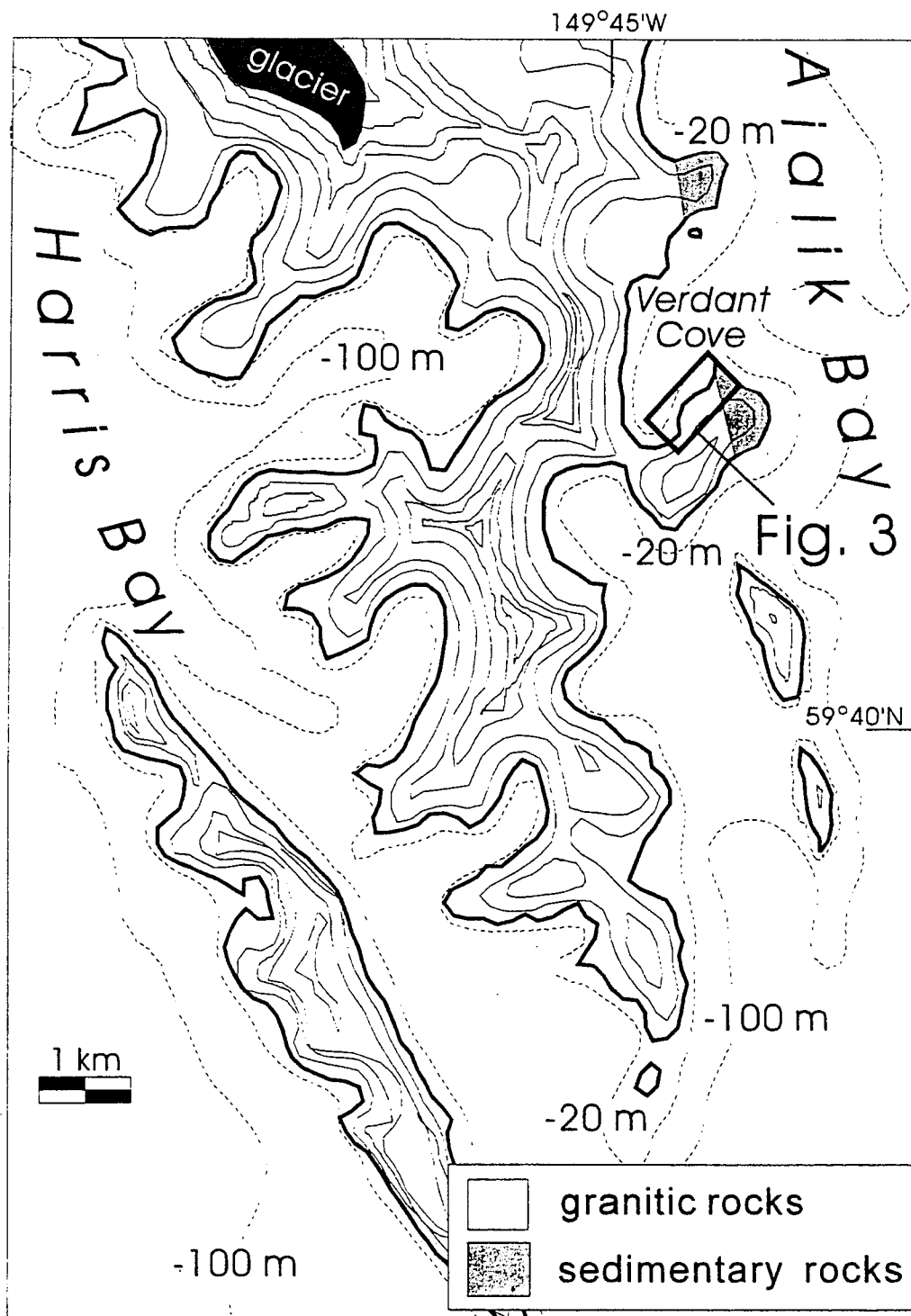


Fig. 3

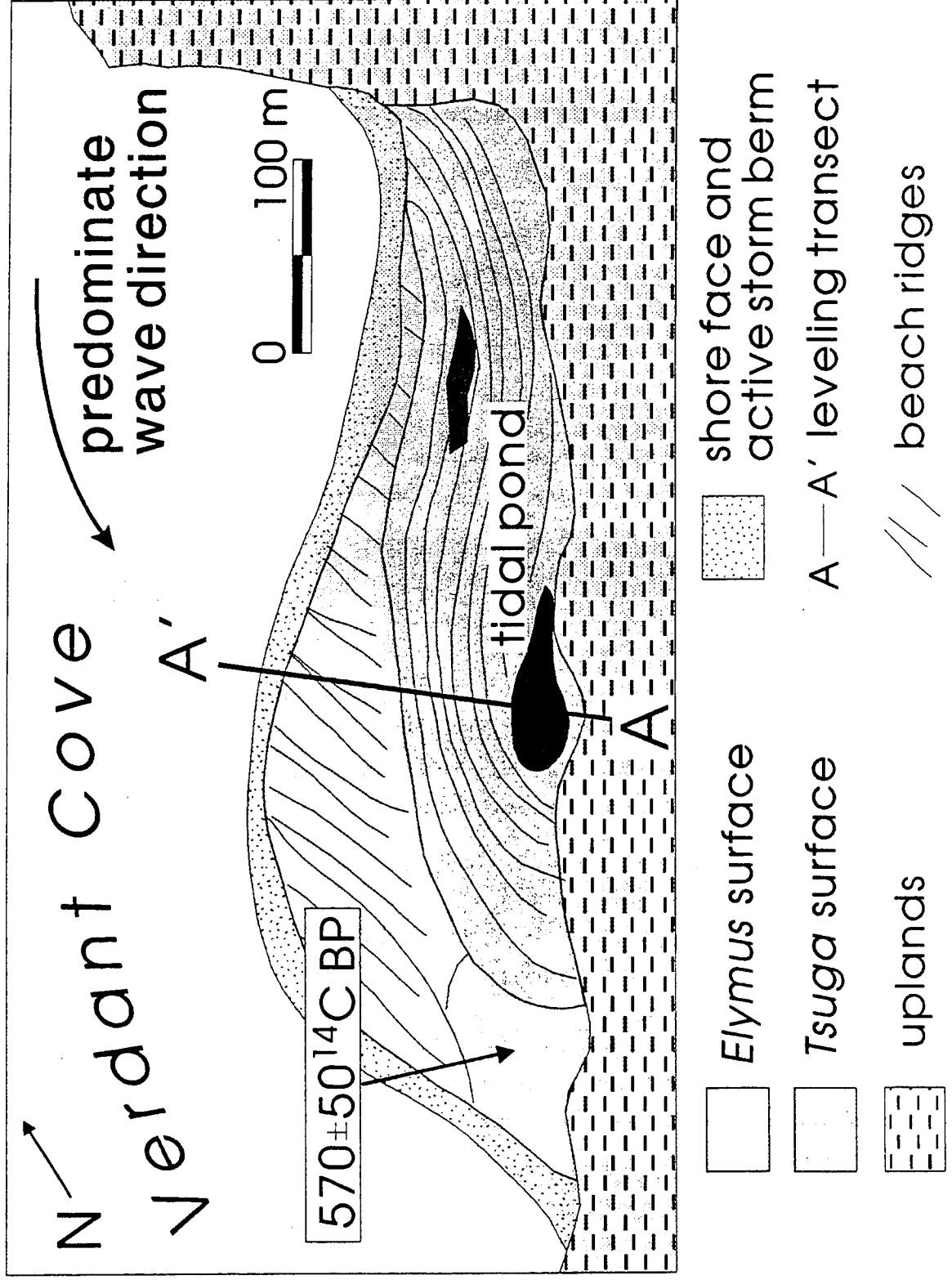


Fig. 4

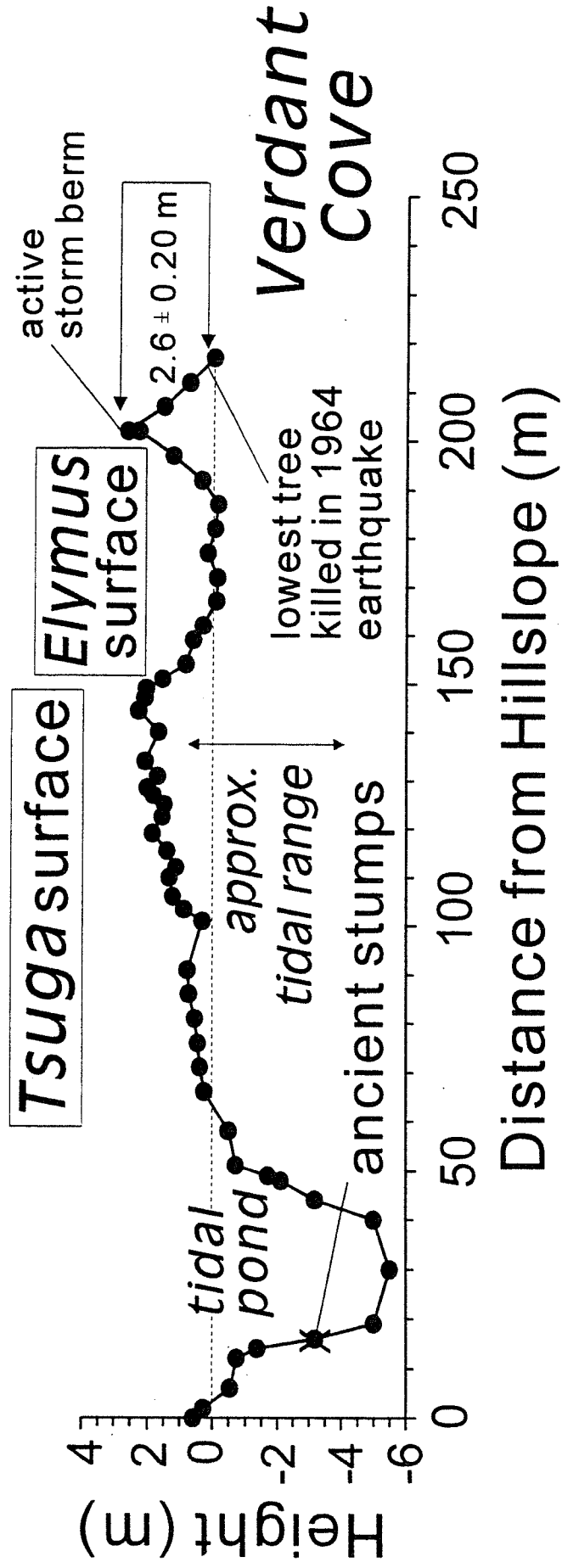


Fig. 5

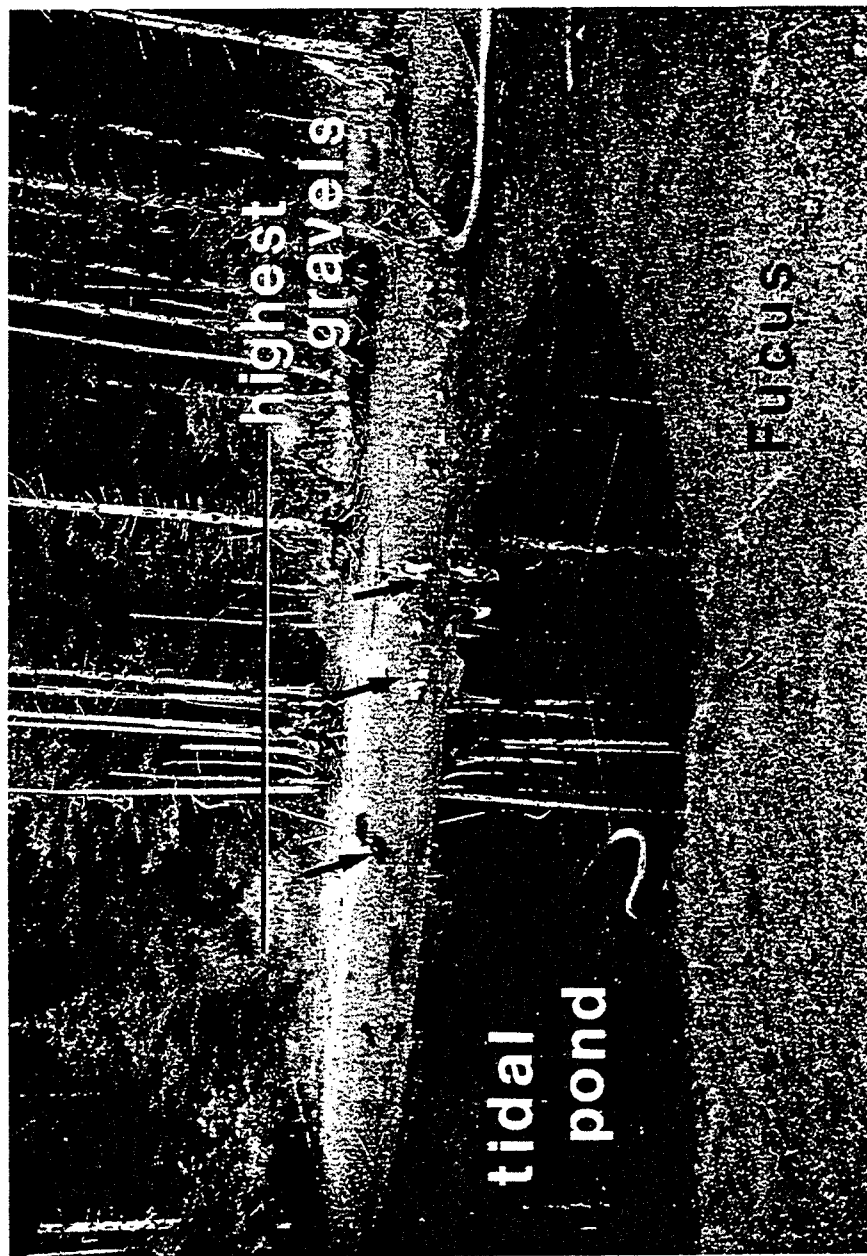


Fig. 6

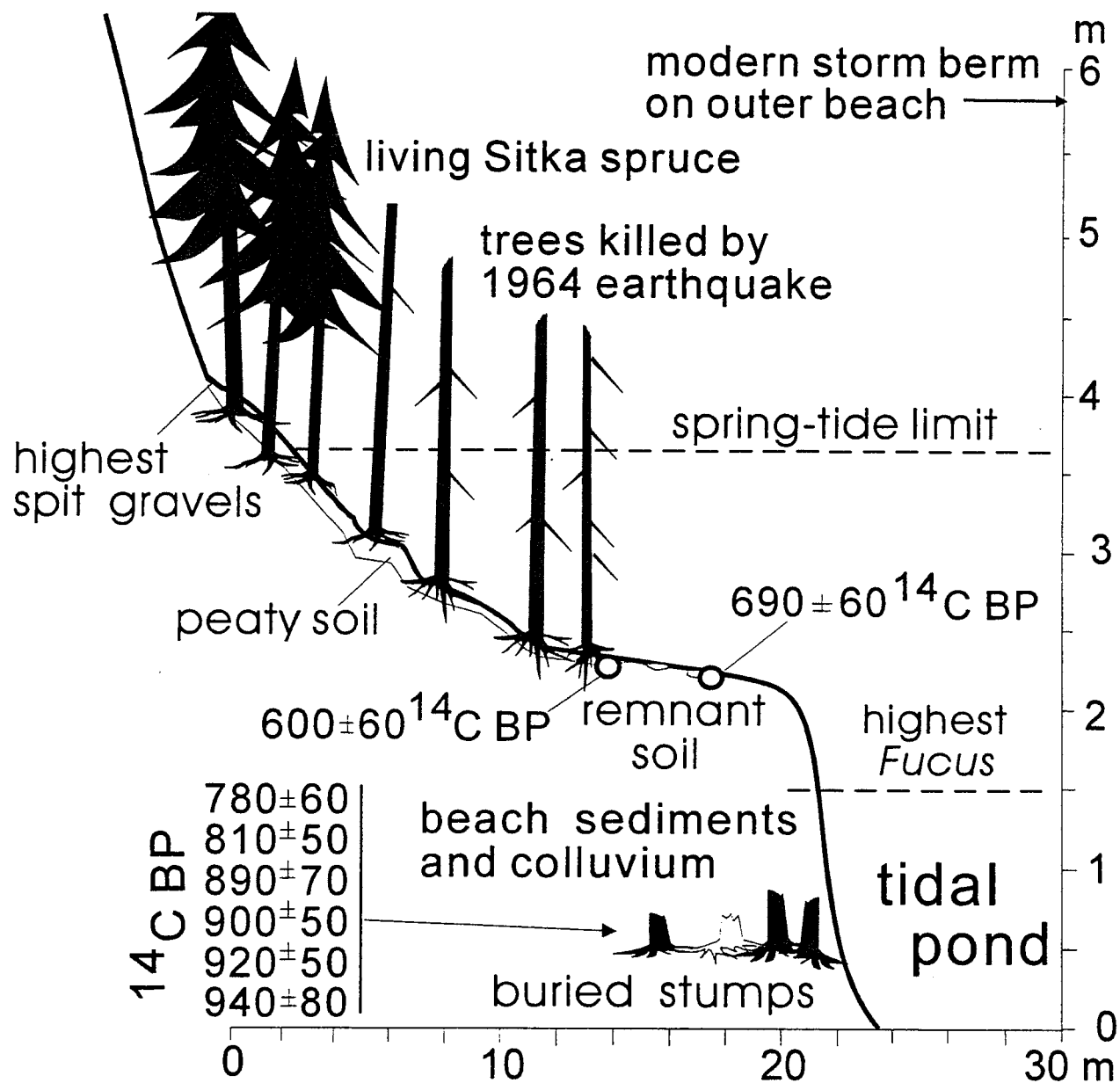
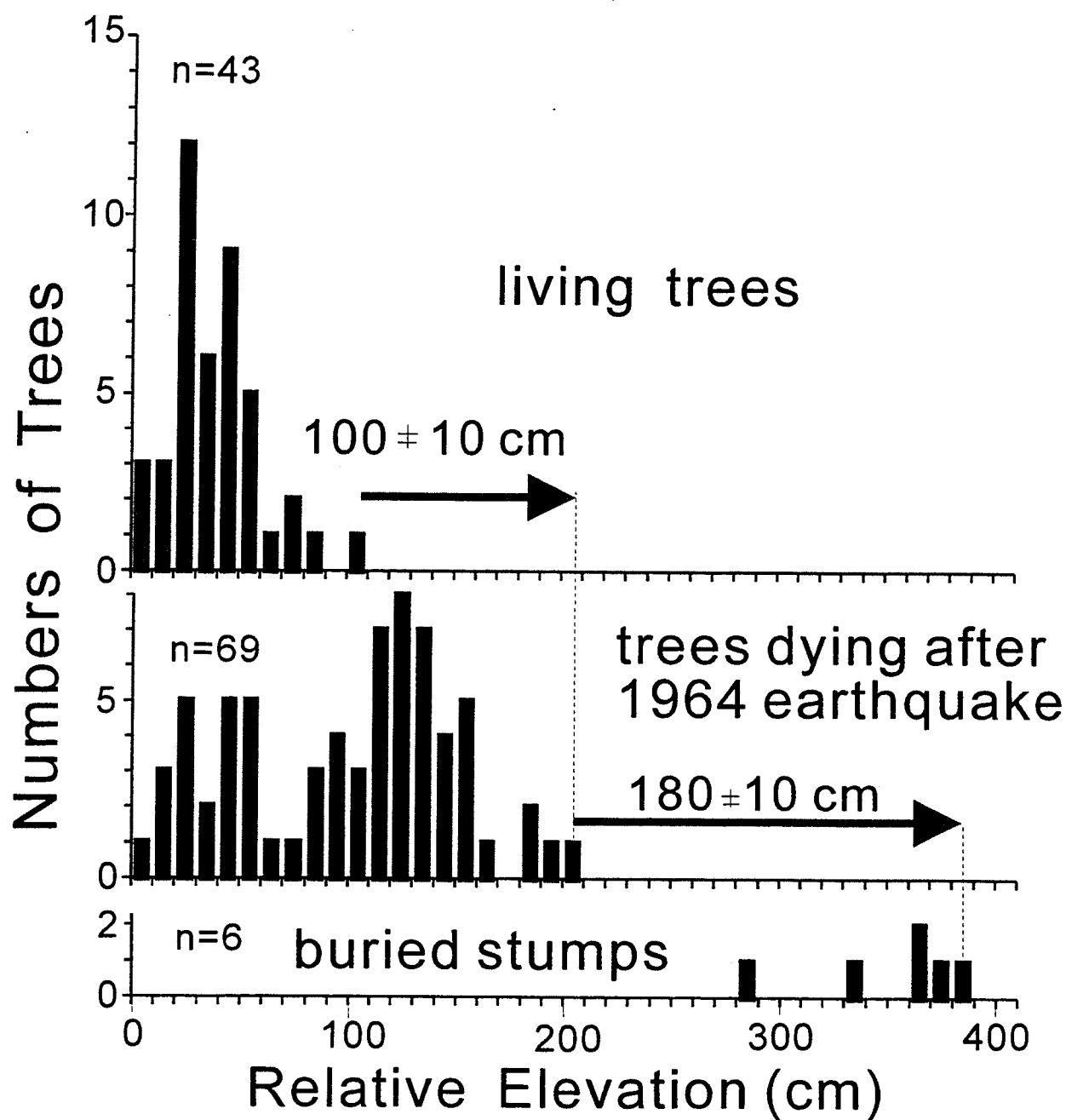


Fig. 7



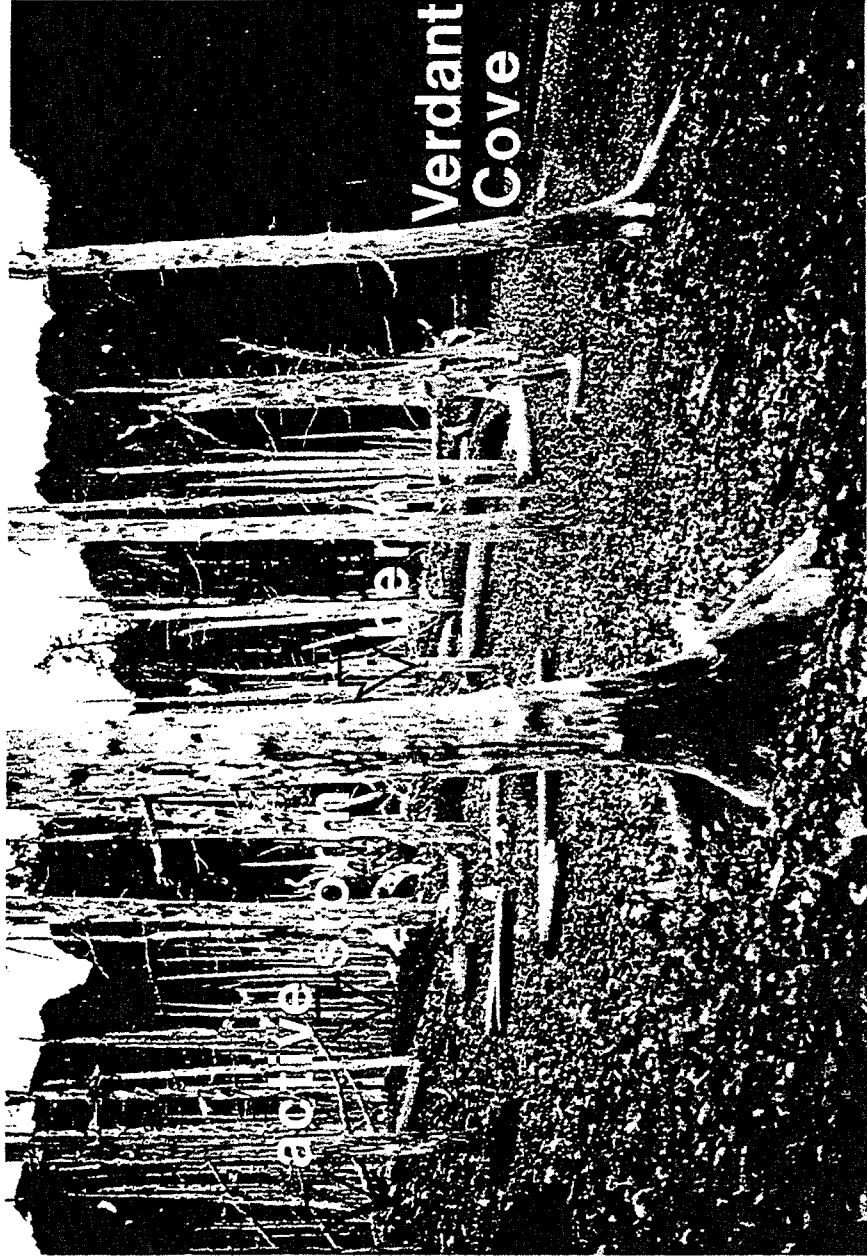


Fig. 9

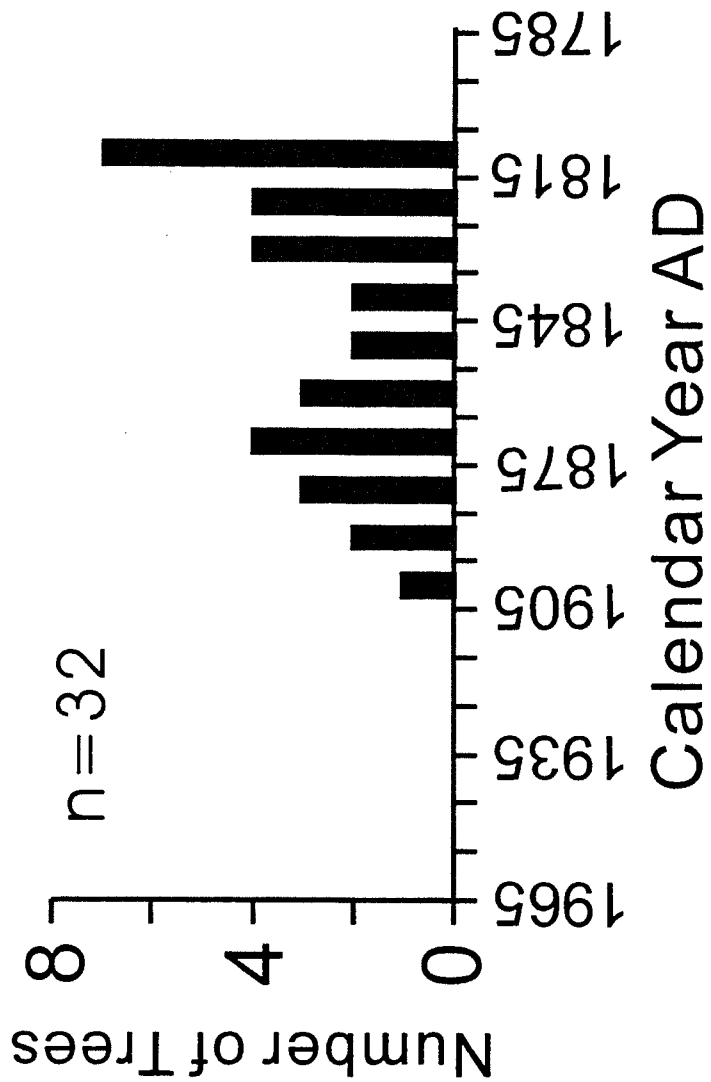


Fig. 10

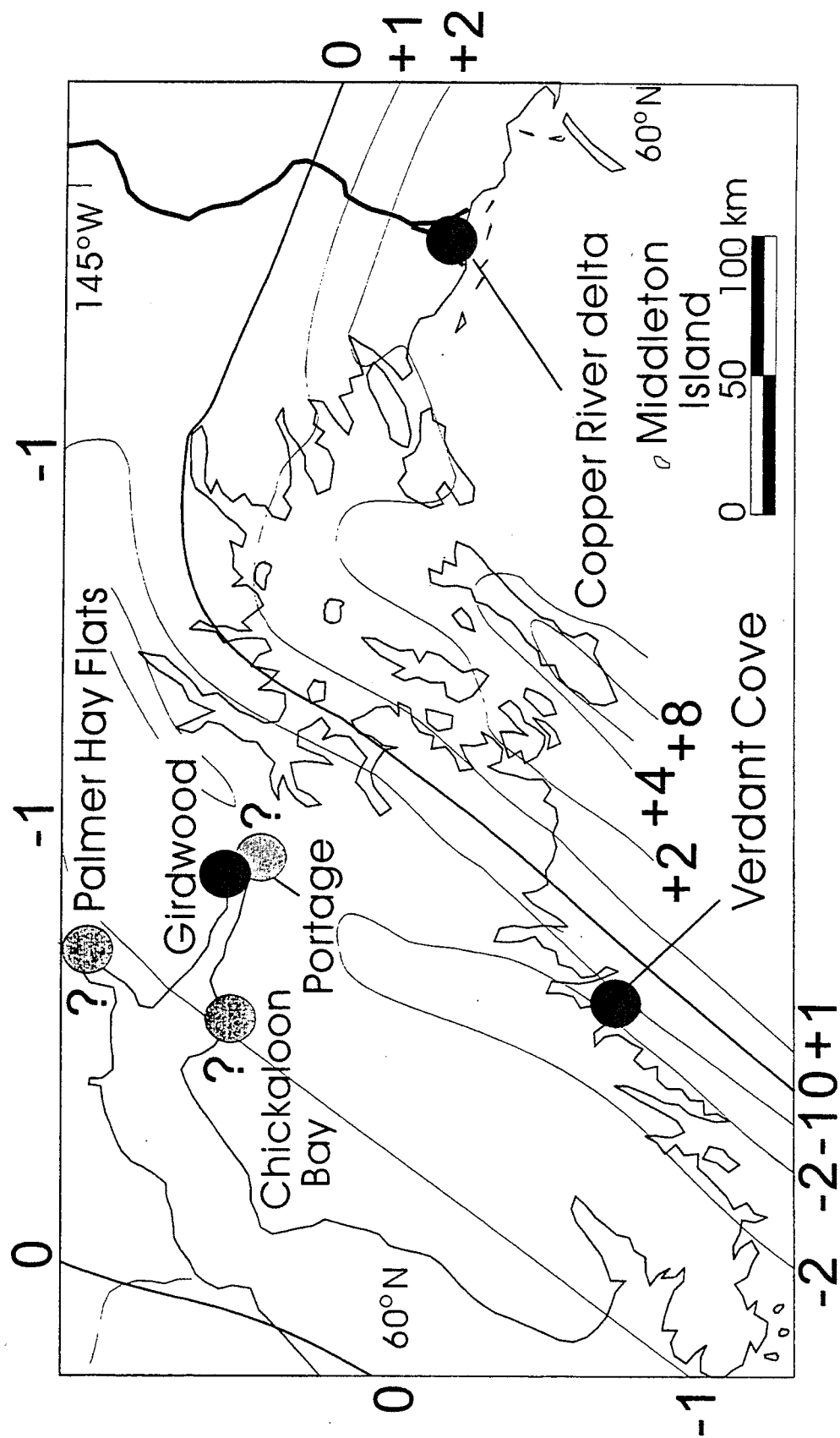


Fig. 11

