Liquefaction Features from a Subduction Zone Earthquake: Preserved Examples from the 1964 Alaska Earthquake

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WASHINGTON DIVISION OF
GEOLOGY AND EARTH RESOURCES

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In cooperation with the
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Front Cover—Aerial view of Twentymile River north toward the Chugach Mountains. Twentymile Glacier is visible at the base of the mountains. This area subsided about 6 ft during the March 1964 earthquake and was inundated by spring tides. Rapid deposition of the Placer River Silt blanketed the lower reaches of the (now) grassy upland surface. This silt layer preserved numerous clastic dikes that are now being exposed by stream-bank erosion.

Back Cover *(Top)*—A forest killed by inundation with salt water when tectonic subsidence lowered the ground surface to within reach of spring tides at Girdwood, near the head of Turnagain Arm.

Back Cover *(Bottom)*—A drowned forest on the Copalis River in coastal southern Washington. This forest died about 300 years ago. It is inferred that it was killed by the same mechanism as the forest in the photo above. Photo by B. F. Atwater.

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Brian F. Atwater, U.S. Geological Survey: back cover (bottom)

Preface

Randall Updike, U.S. Geological Survey, suggested that a joint project among several states would be an effective way for the USGS to support regional efforts in earthquake-hazard reduction. He encouraged those of us in the Pacific Northwest states, including Alaska, to work together on an aspect of the paleoseismology of subduction zone earthquakes—a threat shared by all three states. This led us to propose an analogue study to apply lessons from the 1964 Alaskan earthquake to the Cascadia Subduction Zone.

The work described in this report results from cooperative agreements between the U.S. Geological Survey and the state geological surveys of Alaska (Alaska Division of Geological and Geophysical Surveys), Oregon (Oregon Department of Geology and Mineral Industries), and Washington (Washington Division of Geology and Earth Resources).

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ABSTRACT

The M_w 9.2 1964 Alaska earthquake caused widespread damage from ground failures in southern Alaska. We investigated earthquake-induced ground failures along the Knik and Matanuska Rivers and associated tidal channels at the head of Knik Arm, Portage Creek and Twentymile and Placer Rivers at the head of Turnagain Arm, and the Copper River delta, and at a site in the Kenai Lowland north of Sterling.

Along the Knik and Matanuska Rivers, ground cracks are open to 1.3 m depth and 3.7 m width but show no evidence of sand injection. Our excavations suggest that these cracks healed by filling from above and were loci of minor or no sand extrusion.

By contrast, we observed 150 clastic dikes and sills in the Portage and Twentymile River area that we attribute to liquefaction during the 1964 earthquake. This area is on the axis of maximum coseismic subsidence, which resulted in deposition of as much as 2 m of intertidal silt. Lateral migration of stream channels has exhumed many clastic dikes, most of which intersect the pre-earthquake surface through breaks in the 1964 soil and are probably associated with ground cracks mapped soon after the earthquake.

Clastic dikes we observed range in width from 0.5 cm to 1.9 m. Dikes are predominantly medium to coarse sand, but 27 dikes contain appreciable pebble-size gravel, and three are dominantly gravel. The coarsest dike analyzed has a mean grain diameter of 4.0 mm and a gravel content of 78 percent. Dikes of gravel or gravelly coarse sand are moderately sorted, typically fine upward, and contain generally less than 5 percent silt. Gravel in some of the coarsest dikes is clast supported, suggesting that the gravel liquefied. In other dikes, gravel is matrix supported in sand, indicating passive upward movement of gravel in a slurry of liquefied sand.

We found sand boils at 26 sites. Extruded sand ranges in thickness from 1 or 2 grains to 6 cm and rests on 1 to 2 cm of silt overlying the 1964 soil. Sand in the upper portion of many dikes was removed to as much as 92 cm below the 1964 soil and replaced with silt, probably by post-earthquake tidal flooding and deposition of silt.

Borehole data suggest that sand and gravel at least as deep as 30 m liquefied in the Portage area. Furthermore, source beds as shallow as 30 cm provided sand and gravel for dikes that erupted to the surface, even though the source beds initially must have been above the water table. These beds apparently liquefied after ground water rose in the soil column. Present methods of assessing earthquake-induced liquefaction susceptibility may underestimate the true liquefaction potential for earthquakes of long duration.

About 2 m of coseismic uplift occurred in the Copper River delta. Liquefaction-induced ground cracks and sand extrusions were reported as common, but we were unable to find evidence of liquefaction in the banks of sloughs.

In the Kenai Lowland, we trenched a wide ground crack through which a large sand boil was extruded. We did not reach a source for the sand, which vented through at least 4 m of lodgment till exposed in our trench.

Our observations lead to three conclusions useful for paleoseismology studies:

- Preservation of clastic dikes is strongly influenced by depositional environments. Regional tectonic uplift exposed the loose sediments created by liquefaction and slumping to erosion, thereby limiting preservation. In contrast, preservation of liquefaction features along tidal margins was strongly enhanced by subsidence followed by rapid deposition of a protective blanket of intertidal silt. Channel migration after streams returned to grade exposes (and erodes) clastic dikes in stream banks.
- Tidal erosion of clastic dikes resulting from coseismic subsidence can obscure the contact relations necessary to constrain the age of dike emplacement. The color (due to oxidation state) of post-earthquake silt filling eroded dikes is distinct from that of pre-earthquake silt, but the distinction will become less recognizable with age.
- Thickness distribution of preserved dikes is strongly skewed toward narrow dikes. This is likely a function of initial distribution, greater erodibility of wide dikes, and the tendency of wide dikes to trigger localized slumping, which conceals them. Therefore, if maximum dike width is used to estimate paleoearthquake magnitude, the frequency distribution of observed dike widths should be evaluated to help verify the likely local maximum dike width.

INTRODUCTION

The M_w 9.2 (Kanamori, 1977) 1964 Alaska earthquake was the second largest earthquake in the instrumental record. Three to four minutes of moderate to severe shaking associated with the earthquake resulted in losses to public and private property estimated at $311 million in 1964 dollars (Hansen and others, 1966). The transportation system in southern Alaska was severely damaged. A total of 141 highway bridges were damaged; 92 of them were severely damaged or destroyed (Kachadoorian, 1968). Damage to the southern 150 mi of The Alaska Railroad was also extensive. More than 110 culverts and 125 bridges were damaged or destroyed (McCulloch and Bonilla, 1970). Much of the railroad and highway damage was the result of liquefaction-induced ground failure in the form of "landspreading" (McCulloch and Bonilla, 1970). Bartlett and Youd (1992) termed these ground failures lateral spreads, following a suggestion by Youd (1973) to use the term "lateral spreading landslide", as defined by Varnes (1958), to include landspreading. That convention will be followed herein.

Damage to bridges was especially heavy in three areas: the Knik and Matanuska Rivers and associated tidal channels at the head of the Knik Arm of Cook Inlet; the drainages in the Portage area (Twentymile and Placer Rivers and Portage Creek) at the head of the Turnagain Arm of Cook Inlet; and the Copper River Highway near Cordova (Fig. 1).

Other evidence of earthquake-induced ground failure was also reported over much of the southern Alaska mainland, such as on the Copper River delta near Cordova (Reimnitz and Marshall, 1965) and in the Cook Inlet area (Foster and Karlstrom, 1967).

PURPOSE

The 1964 Alaska earthquake is commonly used as an analogue for the study of subduction zone earthquakes elsewhere. For instance, in this earthquake (Plafker, 1969), as in the 1960 Chilean earthquake (Plafker and Savage, 1970), vertical tectonic deformation occurred over large areas (Fig. 2). Where subsidence occurred near shorelines, some forests were killed by saltwater inundation. Such ghost forests (see back cover) are among the most striking effects of coseismic subsidence preserved in the paleoseismic record. These effects have been used, in conjunction with other evidence, to infer the prehistoric occurrence of great subduction zone earthquakes on the Cascadia subduction zone off the coast of the Pacific Northwest (Atwater, 1987; Atwater and others, 1995) and in the region of the 1964 Alaska earthquake (Combellick, 1993).

Our purpose in this study was to examine some of the geologic effects of earthquake-induced liquefaction during the 1964 Alaska earthquake as an analogue for recognizing and interpreting evidence of prehistoric earthquakes in the Pacific Northwest (for instance, Atwater, 1994) and other subduction areas. In particular, we sought to: (1) document these effects as an aid to their recognition in the geologic record, (2) gain a qualitative understanding of the likelihood of finding these effects while searching for evidence of prehistoric earthquakes, and (3) determine the effects of coseismic uplift and subsidence on the preservation of liquefaction features.

We focused our field work on four areas: (1) the Knik and Matanuska Rivers and associated tidal channels at the head of the Knik Arm of Cook Inlet, (2) the drainages in the Portage area (Twentymile and Placer Rivers and Portage Creek) at the head of the Turnagain Arm of Cook Inlet, (3) the Copper River delta, and (4) a network of large ground fractures in the Kenai Lowland north of Sterling (Fig. 1). At the first three of these sites, ground failures attributed to liquefaction were numerous. In the Kenai Lowland, ground cracking was accompanied

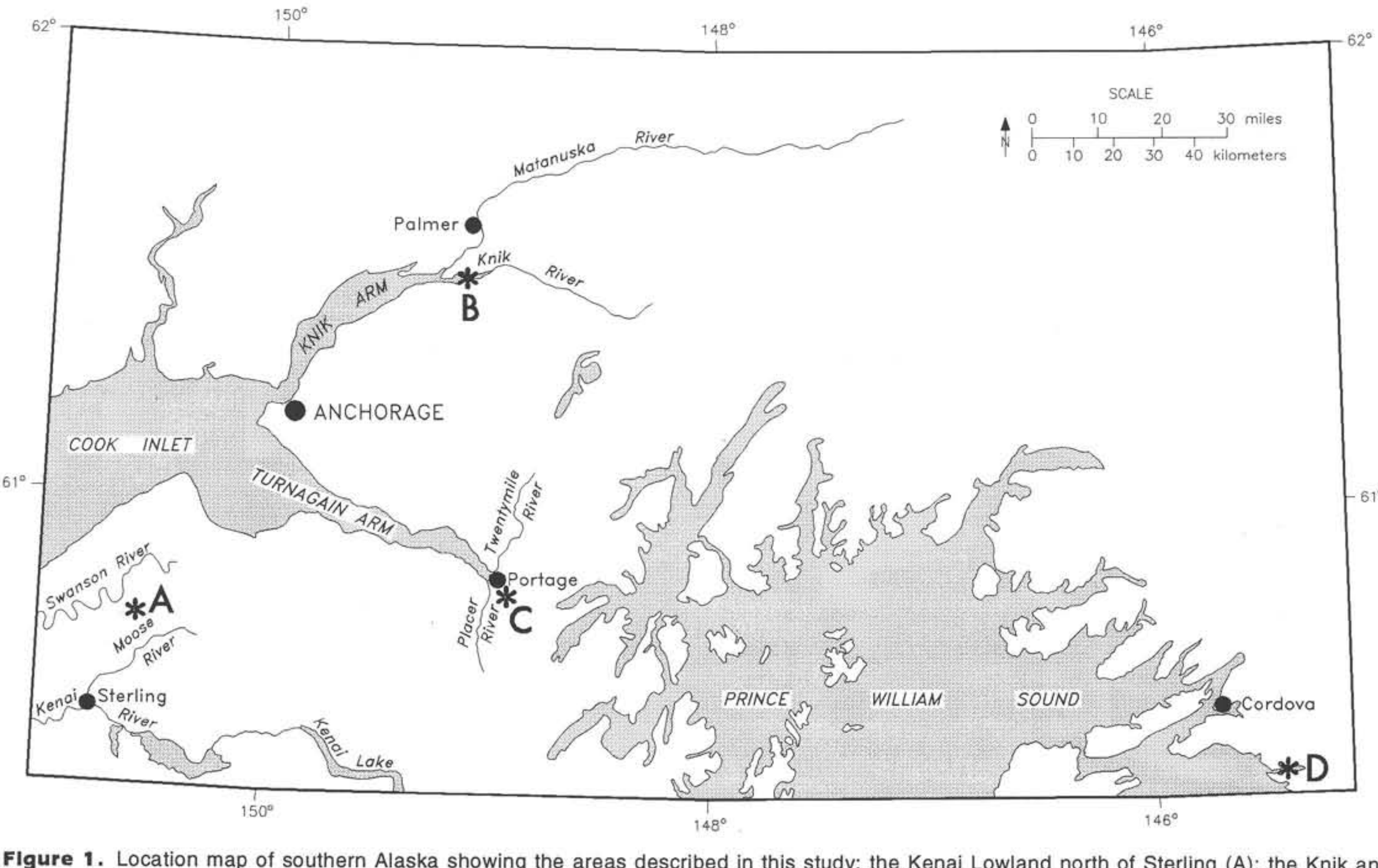

Figure 1. Location map of southern Alaska showing the areas described in this study: the Kenai Lowland north of Sterling (A); the Knik and Matanuska Rivers area south and east of Palmer (B); the Portage and Twentymile River area near Portage at the head of Turnagain Arm (C); and the Copper River delta southeast of Cordova (D).

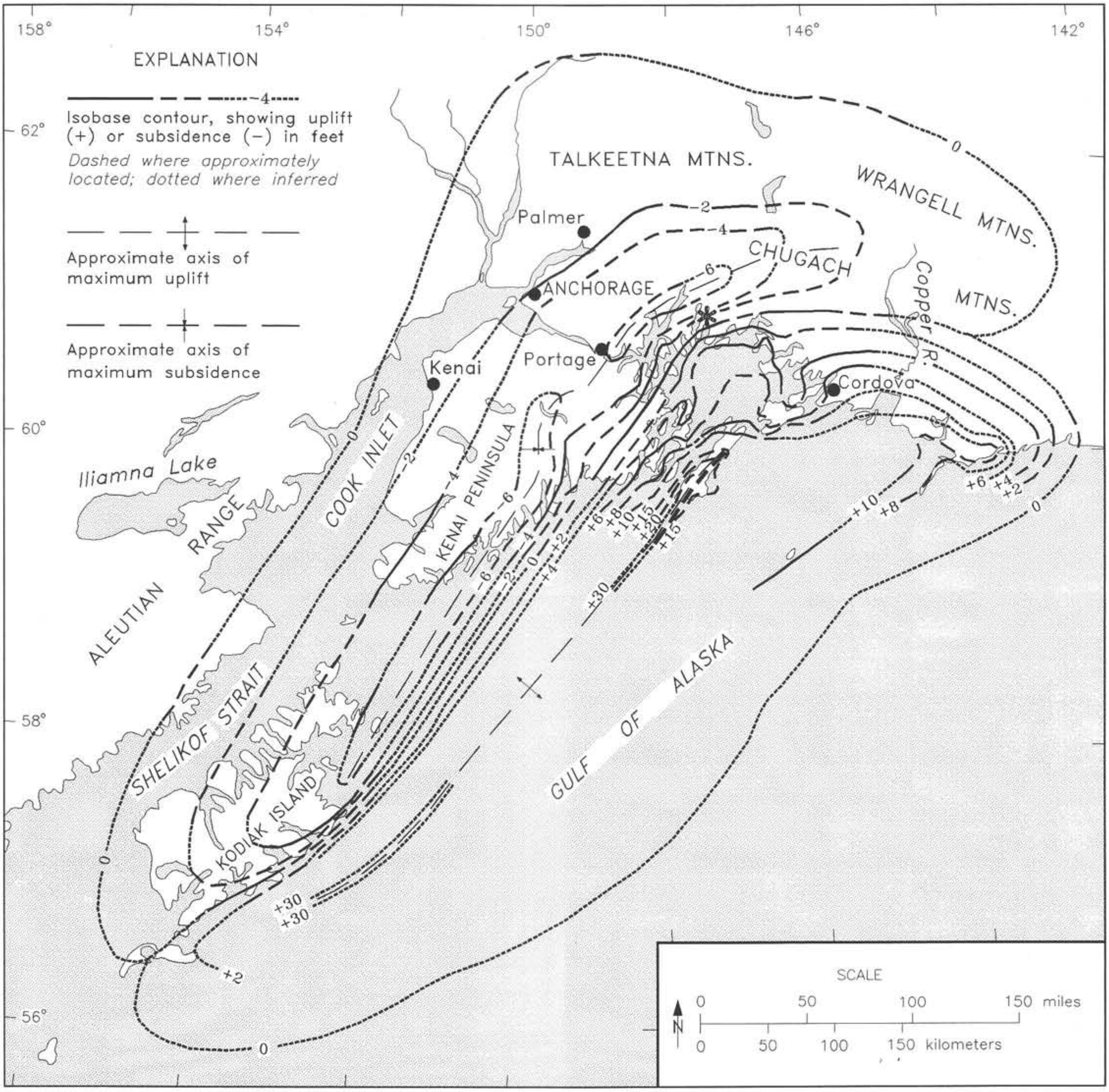

Figure 2. Map of vertical tectonic deformation (uplift and subsidence, in feet) caused by the 1964 Alaska earthquake. Additional subsidence due to compaction is locally important but is not included in this figure. ✱, epicenter. Modified from Plafker (1969).

by extrusion of sand but was not attributed to liquefaction (Foster and Karlstrom, 1967).

Locations of the effects of earthquake-induced ground failures were well documented in the Knik and Matanuska Rivers area, Portage and Twentymile River area, and in the Kenai Lowland (McCulloch and Bonilla, 1970; Foster and Karlstrom, 1967). Reimnitz and Marshall (1965) and Reimnitz (1972) described (but did not map) liquefaction-induced ground cracks and sand extrusions in the Copper River delta, and Kachadoorian (1968) reported blankets of sand ejecta along the Copper River Highway. However, we were unable to find evidence of liquefaction features in the Copper River delta.

METHODS OF INVESTIGATION

We traversed all channels of the lower Knik and Matanuska Rivers (Figs. 3, 4) and all of the drainages in the Portage area (see Figs. 8, 9, 10) using Zodiacs™ powered by outboard motors. In the Copper River delta, we examined more than 40 km of stream bank exposure (see Fig. 7) in the same manner. In all of these areas, we worked only at low tide, which proved to be essential for finding sand dikes in the Portage area where high tides completely inundate the buried 1964 soil and all liquefaction features on, within, or beneath it. Navigation was accomplished by a combination of modern topographic maps (scale 1:25,000), aerial photographs, and a hand-held Global Positioning System (GPS) receiver.

In the Knik and Matanuska Rivers area near Palmer, where there was less than 0.6 m (2 ft; see Fig. 2) of coseismic subsidence and less alluviation since the 1964 earthquake, we investigated several dozen interconnected ground cracks that we inferred to be the result of the earthquake. Many of these cracks appear to correlate with cracks mapped by McCulloch and Bonilla (1970) (Fig. 3). They are open to depths of as much as 1.3 m and have widths up to 3.7 m. Locally, they serve as tidal channels. We hand-trenched large cracks at two localities.

In the Portage area, the 1964 surface (represented by a peaty soil) has been buried by as much as 2 m of intertidal silt (the Placer River Silt) (Ovenshine and others, 1976). We examined those areas where streams have migrated since 1964. Our examination of the stream banks at low tide in these areas showed many breaks in the 1964 soil. Virtually every break was underlain by a clastic dike. We excavated most dikes by hand down to water level and measured and photographed them. Several dikes and source beds were sampled for grain-size analysis.

In the Kenai lowlands north of Sterling (see Figs. 60, 61), sand erupted from a series of interconnected open fractures that opened during the 1964 earthquake (Foster and Karlstrom, 1967). We used a backhoe to excavate one of the fractures, which we then described, measured, sampled, and photographed.

The basic data recorded at each site are shown in Table 1. Photographs of individual sites appear in the approximate order

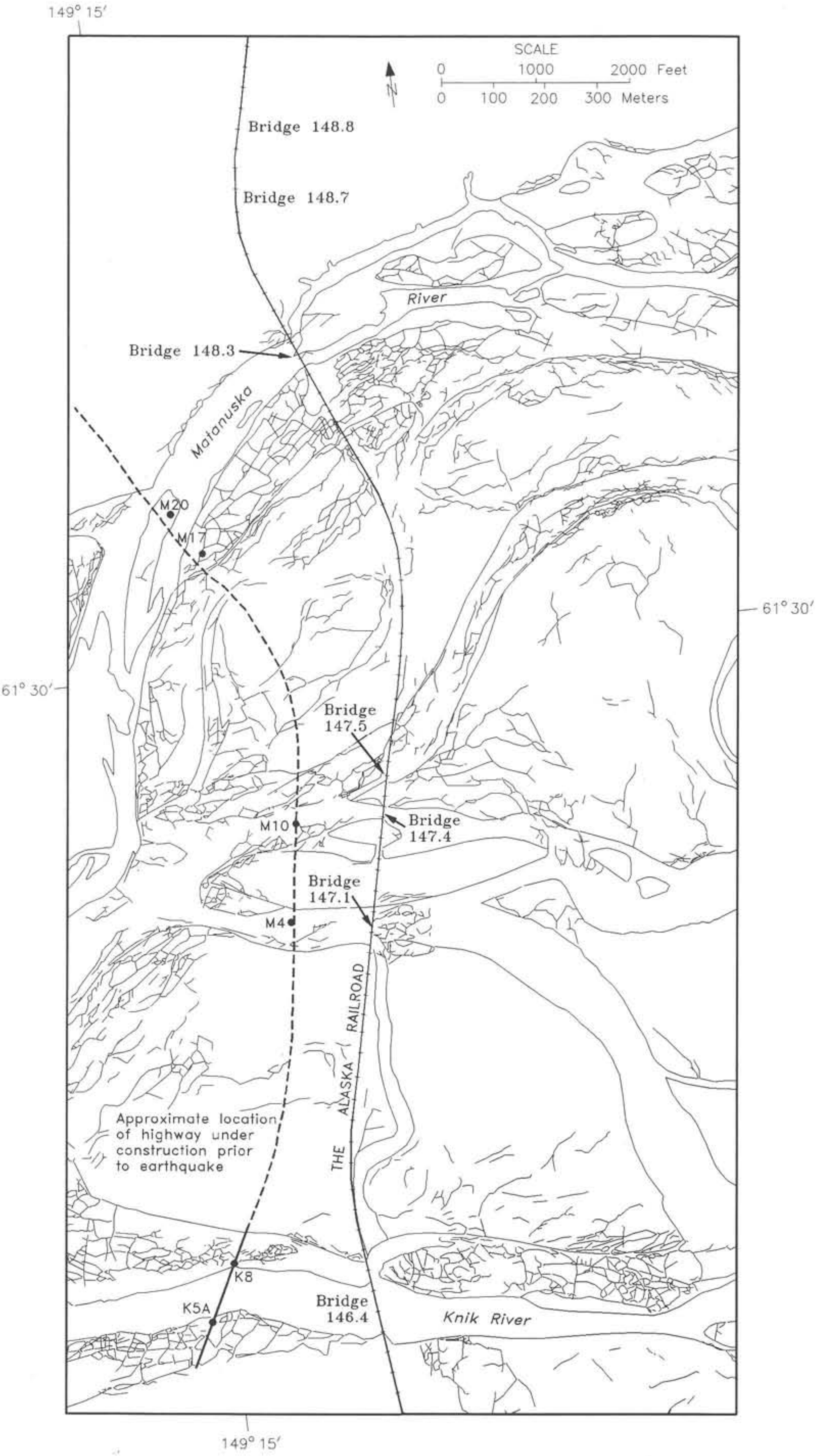

Figure 3. Map of earthquake-induced ground cracks along The Alaska Railroad in the Knik and Matanuska Rivers area. Redrawn from McCulloch and Bonilla (1970).

of entries in Table 1, which is the order in which we examined features. The photo scales are marked in both inches and centimeters.

LOCATION (GLOBAL POSITIONING SYSTEM)

We used a Trimble Pathfinder Global Positioning System™ (GPS) receiver to determine site locations accurately, usually recording 60 satellite fixes over a 2- to 3-minute period at sites listed in Table 2. We also recorded the site locations on 1:12,000-scale vertical aerial photographs. Along exposures where we observed many liquefaction features, we recorded GPS positions for the ends of the exposures and for selected intermediate sites. Between these fixes, we measured the distances of numbered sites by tape measure. These locations are given in Table 1.

GPS data were digitally logged in the receiver unit and later downloaded to a computer for differential correction. We obtained commercial GPS base-station data for a survey marker in southeast Anchorage, 50–60 km from the Knik River and Portage study areas. Trimble processing software allowed us to use the base-station data to differentially correct all individual fixes. We then determined the average of the corrected fixes for each location. With differential correction, the standard deviation of fixes at most locations ranged from 1 to 6 m in both north–south and east–west directions (Table 2).

Using a Geographic Information System (GIS), we plotted all corrected GPS locations on digitized 1:25,000-scale USGS topographic maps. Figures 4, 9, and 10 show these locations for the Knik River and Portage and Twentymile River study areas.

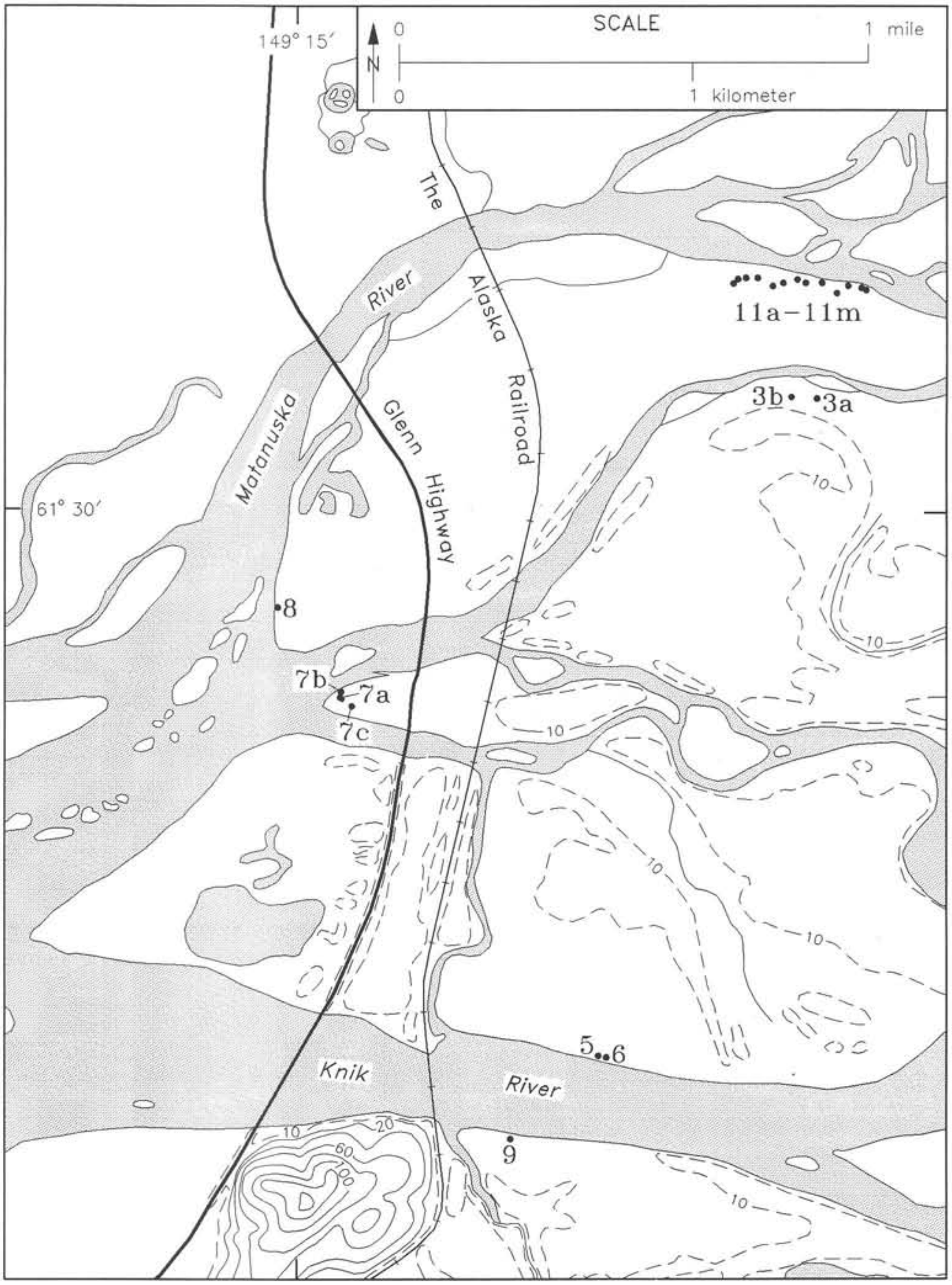

Figure 4. Map of GPS locations of sites along the lower Knik and Matanuska Rivers. The base is from U.S. Geological Survey 1:25,000-scale topographic maps for Anchorage B-6 NW, B-7 NE, C-6 SW, and C-7 SE quadrangles, revised 1992 and 1993.

RESULTS

Knik and Matanuska Rivers Area

In the Knik and Matanuska Rivers area, we investigated several dozen interconnected ground cracks inferred to have been caused by the 1964 earthquake. Many cracks are open to as much as 1.3 m depth and 3.7 m width. The cracks are U-shaped and appear to have been extensively modified by running water. Our excavations did not expose any clear-cut evidence of sand extrusion, although there was evidence of contorted bedding and extension (Figs. 5, 6). We infer that ground cracks below the present surface expressions opened and closed with little or no extrusion of sand.

A sample of peat exposed in the west side of the trench at site 11 (Fig. 6) was sent to Beta Analytic Inc. of Miami, Florida, for radiocarbon dating. The laboratory reported that the carbon contained in the sample was 126.6 ± 0.7% of the modern reference standard, indicating a post-A.D. 1950 age. Comparison of the ^{14}C content with curves representing modern atomic bomb effects (Taylor, 1987) indicates a date of approximately A.D. 1961, consistent with burial of the 1964 soil. Contamination of an older peat layer by modern material, however, cannot be completely ruled out. If this is the 1964 surface, then the thickness of silt overlying the peat suggests

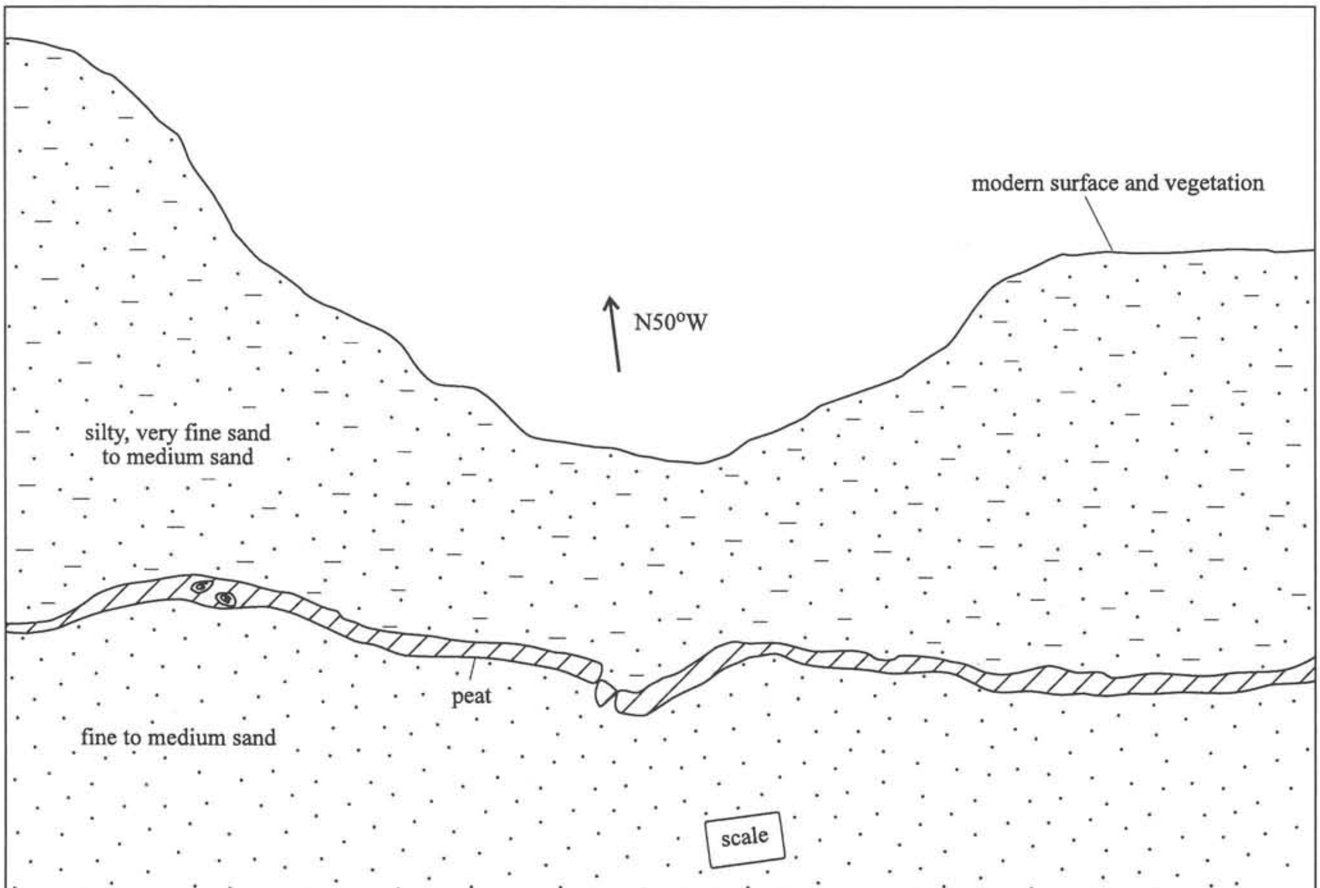

Figure 5. Photo and drawing of excavation of ground crack at **site 6** along the Knik River. We found no evidence of extruded sand although the peaty soil 30 cm below the bottom of the ground crack shows evidence of having been pulled apart and then compressed. The scale bar here and in the rest of the figures is marked in inches and centimeters.

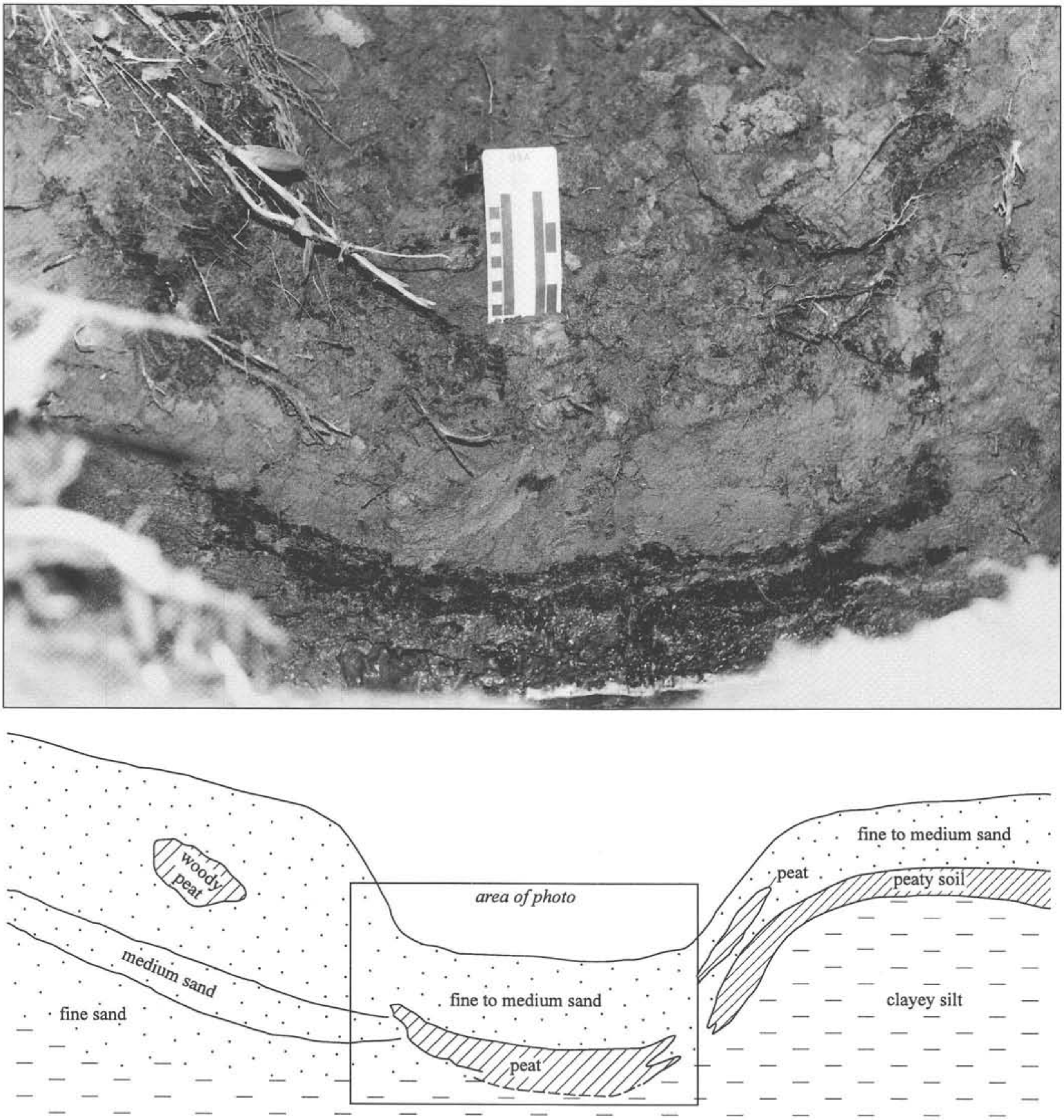

Figure 6. Photo and drawing of excavation of crack at **site 11m** along the Matanuska River. We found no evidence of extruded sand here; the ground crack here is above a graben that shows evidence of extension. The peaty soil at the bottom is apparently the 1964 soil (Beta #83165; corrected age = A.D. 1961), suggesting an accumulation of 42 cm of silt between 1964 and 1994.

about 40 cm of post-earthquake alluviation at this site. Tectonic subsidence here was 0.6 m (2 ft) or less (Fig. 2).

Copper River Delta

Reimnitz and Marshall (1965) reported abundant earthquake-induced liquefaction features in the marshes of the Copper River delta. They reported that slump cracks—cracks following the slough banks, bordered by slumps with as much as 6 ft of subsidence and 3 ft of horizontal displacement toward the channels—were very common. Reimnitz (1972) noted that cracks in the marsh were frequently filled with sediment.

We traversed about 40 km of slough in the marshes of the Copper River delta without finding any evidence of liquefaction in the predominantly well exposed banks. Stream bank exposures commonly contained a fibrous peat (in places with rooted stumps) overlain by organic-rich clayey silt grading upward to the modern soil. In two separate continuous exposures of 100 m in Alaganik Slough, we found no clastic dikes nor any breaks in the peat. In Pete Dahl Slough, we found layers

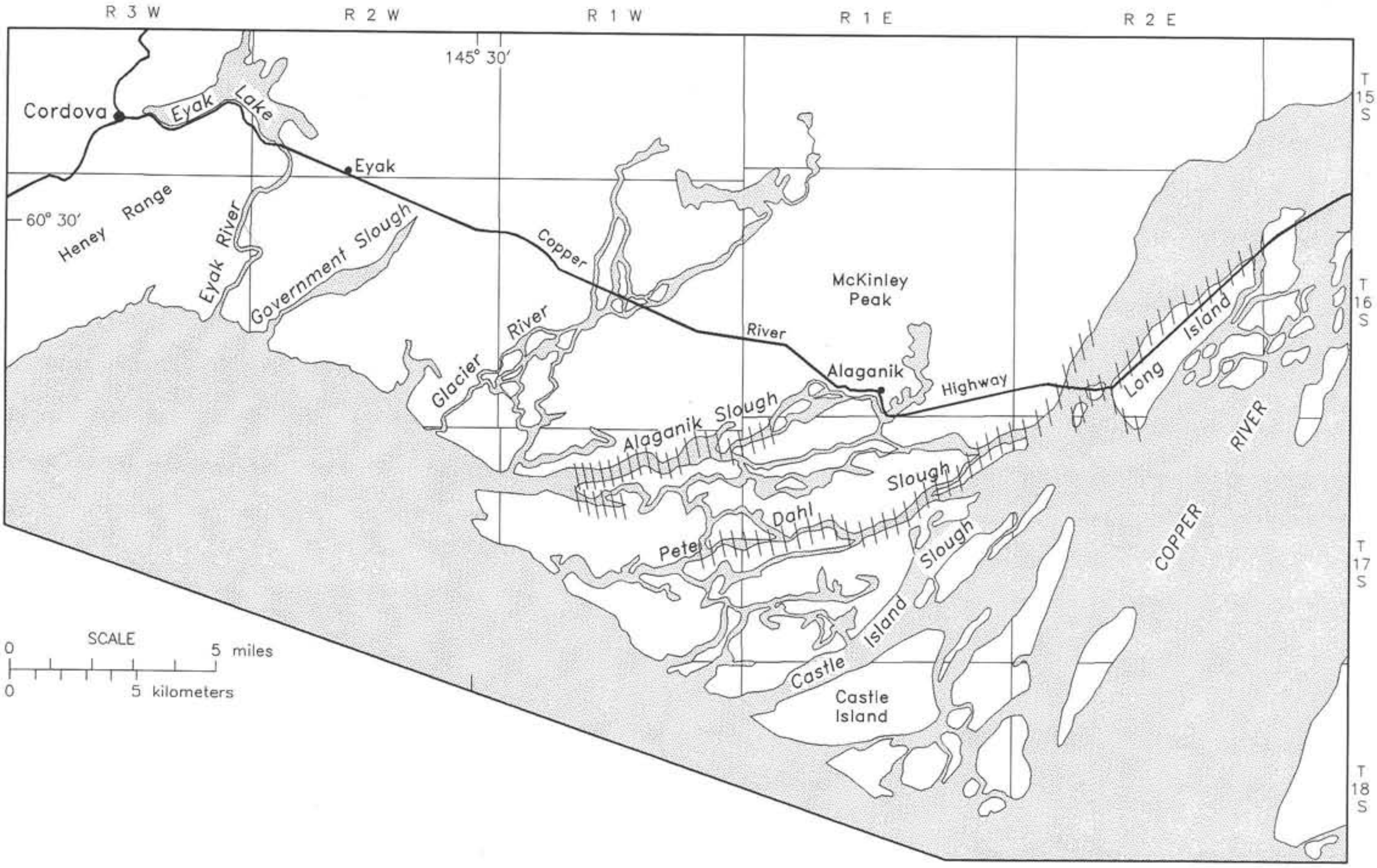

Figure 7. Location map of the Copper River delta showing reaches of stream bank traversed (highlighted).

of fine to coarse sand interbedded with the peat, but we found no breaks in the peat. The exposure in Pete Dahl Slough was capped by windblown sand.

Portage and Twentymile River Area

In the Portage and Twentymile River area, we found abundant features caused by liquefaction—too many for uniformly detailed description and measurement in the limited time available. All told, we found 150 clastic dikes and sills in this area.

In the Portage area (Figs. 22, 25 (bottom), 26, 54), the submerged surface and its vegetation (1964 peat) were buried by as much as 2 m of intertidal deposits (Placer River Silt) within a decade of the earthquake (Ovenshine and others, 1976). Lateral migration of stream channels has exposed many breaks in the 1964 peat (Figs. 49, 54, 56, 58) that we infer to be associated with the ground cracks mapped by McCulloch and Bonilla (1970) shortly after the earthquake. In contrast to the Knik and Matanuska Rivers area, ground cracks are sharp-walled and typically narrow (mostly 2 to 7 cm, ranging up to 42 cm), and nearly every ground crack investigated could be traced downward to a clastic dike.

We found sand boils at 26 sites. Extruded sand is generally limited to 1- to 2-grain thickness but reached a maximum of 6 cm. Sand boils rest on 1 to 2 cm of silt containing vertically oriented rootlets overlying the peat (Figs. 17, 21, 29, 50, 55). This silt is probably analogous to the layer of windblown silt trapped at the base of the plants on the modern marsh surface.

In at least 50 cases, dikes terminated at depths as much as 92 cm below cracks in the 1964 soil surface, and the cracks were filled with unoxidized, massive silt up to the 1964 surface (Figs. 12, 13, 15, 16, 18, 21, 33, 34, 55). In at least 17 cases, the margins of the ground crack above these silt-filled dike throats are mantled with extruded sand, suggesting that these dikes erupted to the surface. We infer that the loosely packed, noncohesive sand and gravel of the dikes were sluiced out of the narrow channels of the ground cracks by currents from spring tides, which inundated this area after approximately 2 m of coseismic subsidence. On several occasions, we witnessed incoming tides sluicing out dikes we had excavated (note, for instance, Fig. 17, site 20). On one occasion, we left a trenching tool, folded into an 'L' position, standing with handle up at one of our excavations when the tidal bore in Turnagain Arm reached the site. When we retrieved the trenching tool the next day, 5 cm of silt had been deposited on the blade. A similar process probably eroded many dikes during the rising tide from the spring tides about two weeks after the earthquake, then deposited cohesive, less erodible silt during stillstand, thus protecting the dikes from further erosion. Eventually, the cracks were filled by the more cohesive Placer River Silt deposited by the glacial-flour-rich Placer and Twentymile Rivers, Portage Creek, and Turnagain Arm (Bartsch-Winkler and others, 1983). This contact is well defined by the color contrast between the pale blue-gray post-1964 silt and the buff-to-pale yellowish-orange pre-1964 silt.

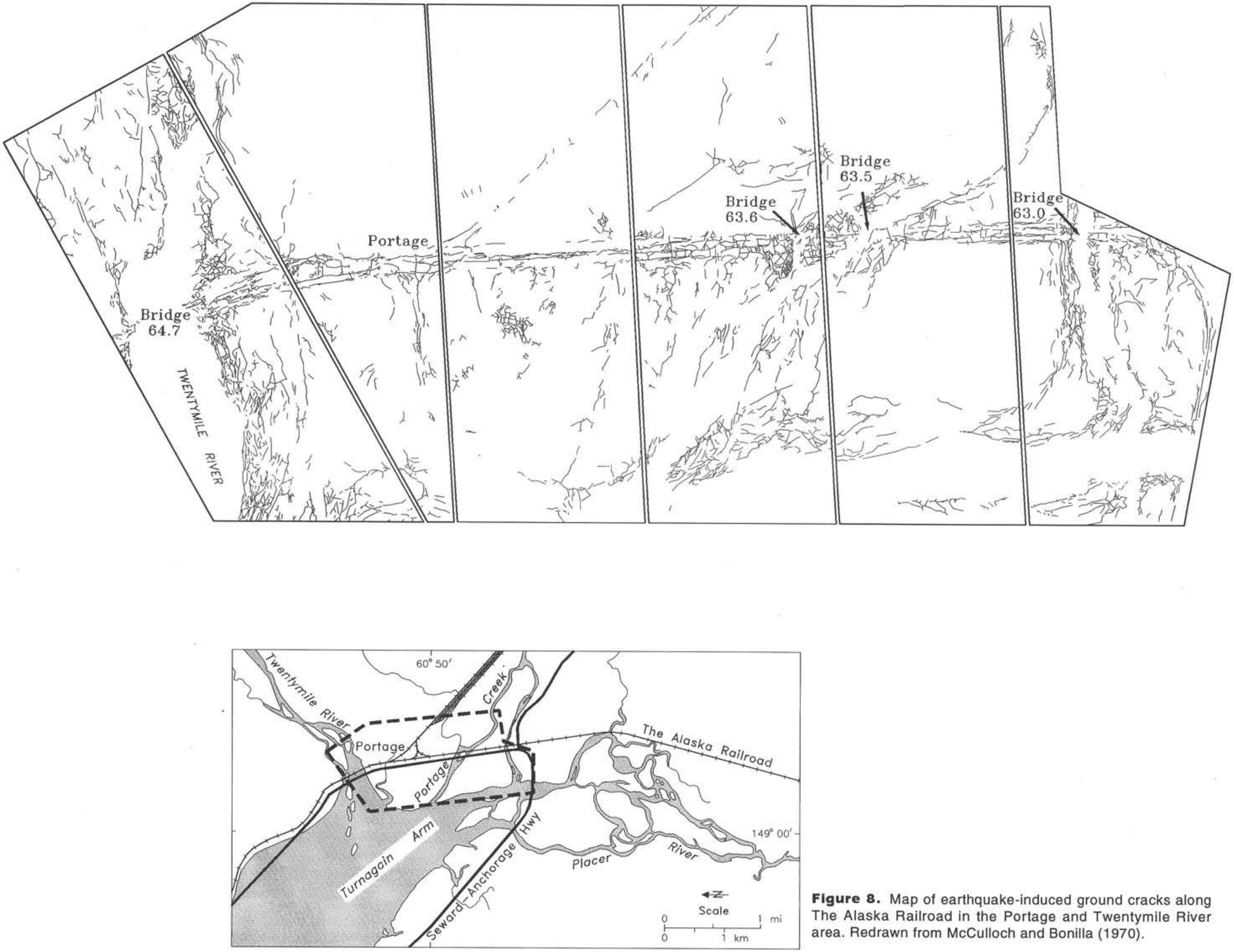

Figure 8. Map of earthquake-induced ground cracks along The Alaska Railroad in the Portage and Twentymile River area. Redrawn from McCulloch and Bonilla (1970).

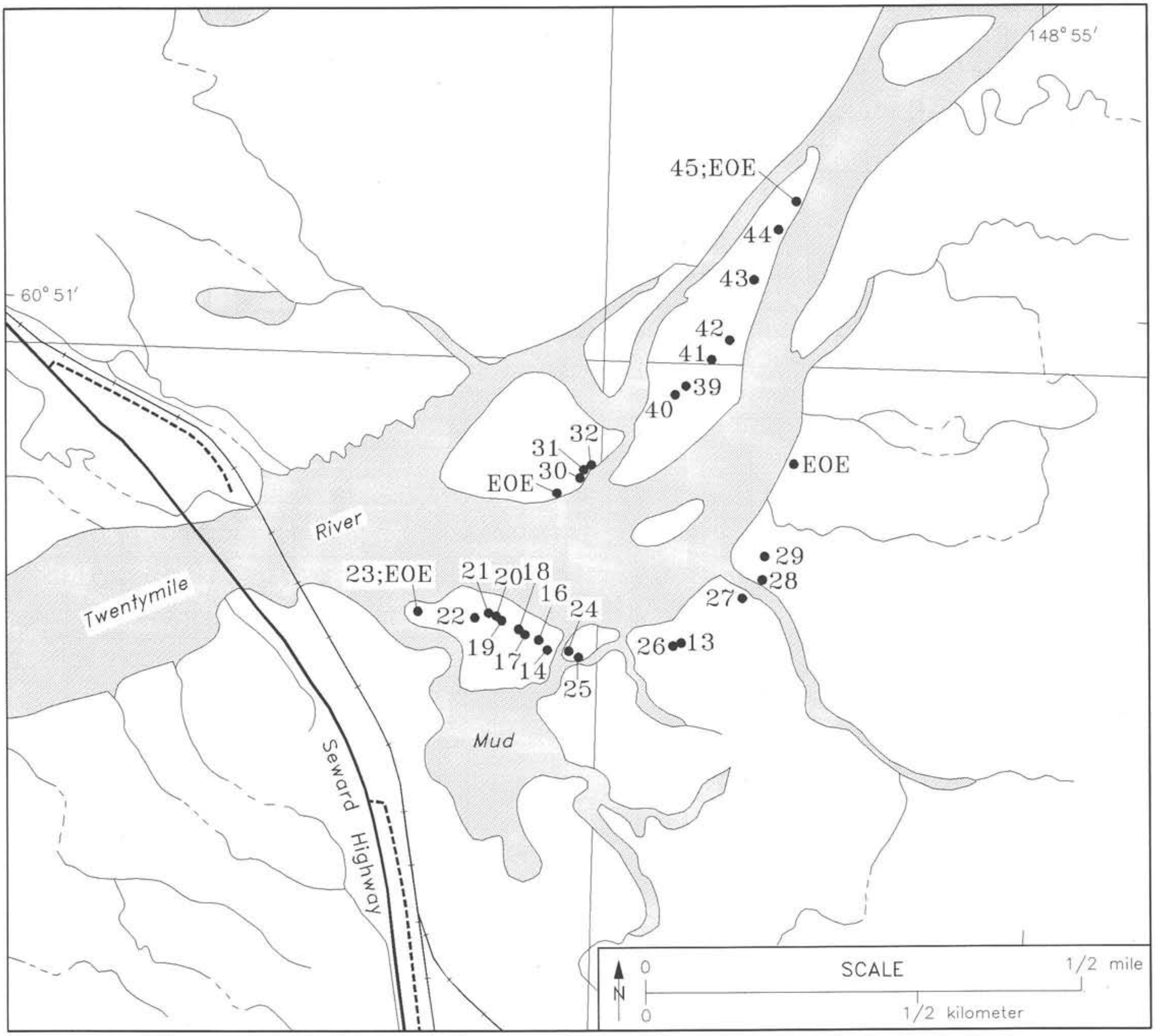

Figure 9. Map of GPS locations of sites along lower Twentymile River at Portage. Base is from U.S. Geological Survey 1:25,000-scale topographic map for Seward (D-6) SE quadrangle, provisional edition, 1984, enlarged to 1:12,500 scale. EOE, end of exposure.

In other cases, dikes may not have filled ground cracks all the way to the surface. In the Copper River delta, for instance, Reimnitz and Marshall (1965) reported that some ground cracks were only partially filled with sediments. Many dikes we examined are not associated with extruded sand. Aerial photography flown along The Alaska Railroad in the Portage area about two weeks after the earthquake (McCulloch and Bonilla, 1970) clearly shows cracks in the snow-covered frozen ground, but very little extruded sand is visible. This suggests that (1) extrusions of sand from ground cracks were rare, (2) extrusions of sand were generally smaller than the resolution of the aerial photography (probably about 1 m), (3) sand boils were eroded before the photography was flown, or (4) some combination of the above.

Some dikes we observed were tabular, but many dikes were very irregular, changing appearance significantly as we excavated. Figure 14, for instance, shows a shore-parallel dike that bifurcates into shore-normal dikes, probably defining the margins of lateral-spread blocks. Parts of this dike system are tabular, but areas of the dike near these bifurcations are highly irregular. Because sediment-laden water forming a clastic dike follows a pressure gradient, these orthogonal corners where the gradient drops off in several directions at once and where stresses are omnidirectional (McCulloch and Bonilla, 1970) are places where complex dikes form. Also, because they follow pressure gradients, dikes can be injected downward as well as laterally or upward. The dike at site 80e (Fig. 57) apparently filled a relatively large (6 cm) crack upward and

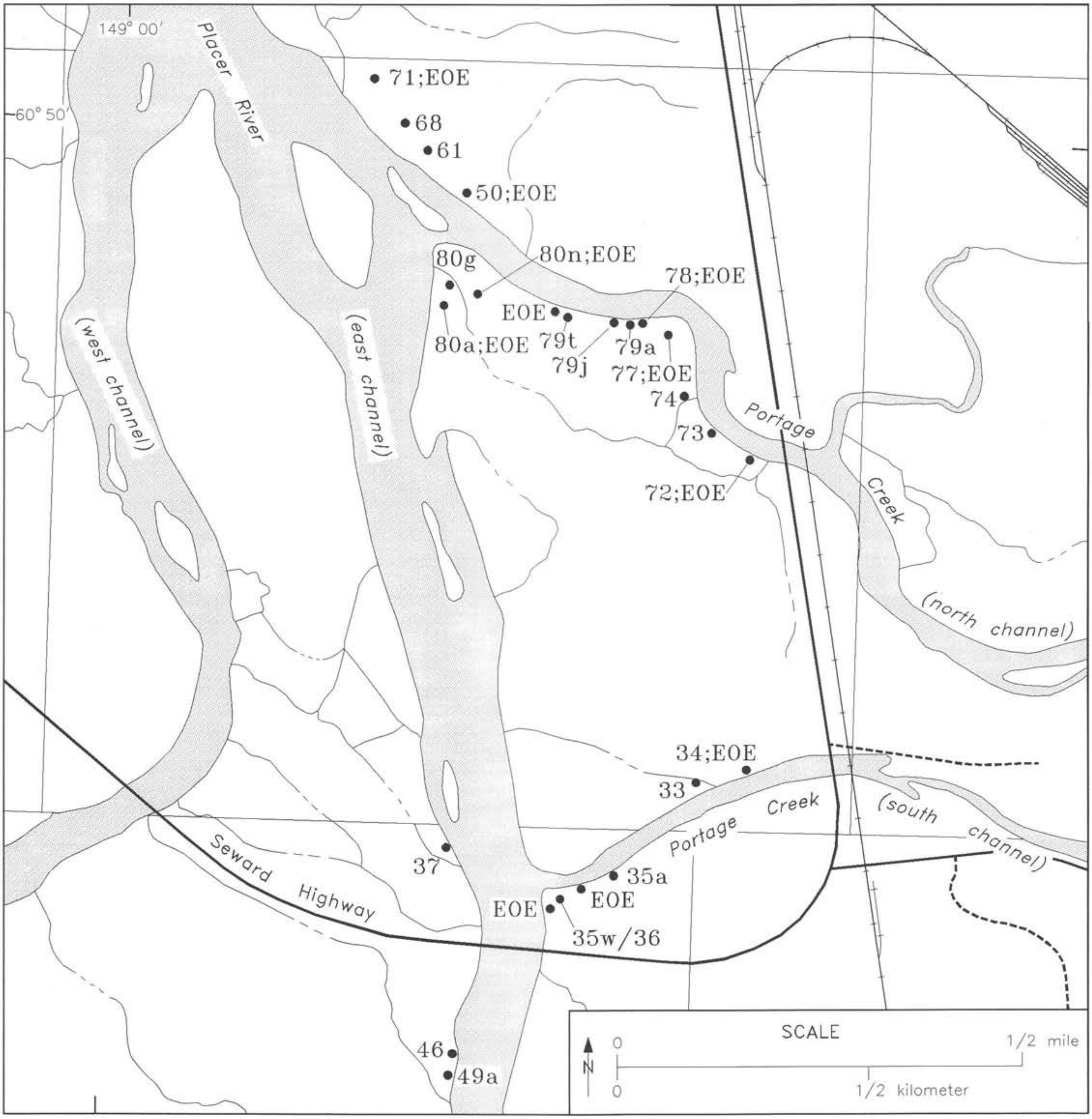

Figure 10. Map of GPS locations of sites along the north and south channels of Portage Creek and the east channel of Placer River. Base is from U.S. Geological Survey 1:25,000-scale topographic map for Seward (D-6) SE quadrangle, provisional edition, 1984, enlarged to 1:12,500 scale. EOE, end of exposure.

shoreward and then sent tendrils downward into smaller cracks developing in the laterally spreading block.

Average depth to the top of the source bed from the pre-earthquake ground surface, where measurable, is 64 cm. Intertidal silt is the capping layer at all locations. Source beds are as shallow as 30 cm but are commonly deeper than the approximately 2 m of stream bank exposed at low tide. Because exposed source beds extend below water level, their bases were not observed. Liquefaction analysis by Bartlett and Youd (1992) using data from 14 boreholes in the Portage and Twentymile River area (McCulloch and Bonilla, 1970; Combellick, unpublished data) shows that, on average, the upper 11 m of sediments is liquefiable. In one borehole, 20 m of the upper 23 m is liquefiable. The depth of liquefaction is consistent with the observation by McCulloch and Bonilla (1970) that the piles commonly were not tilted when bridges were compressed, suggesting that lateral displacements in foundation soils were constant with depth, at least to the base of the piles.

The dikes and sills contain predominantly dark gray to black medium to coarse sand and gravel as large as coarse pebble size; 27 contain appreciable pebble-size gravel and three are dominantly gravel (that is, median diameter 2.0 mm). Gravel in some of the coarsest dikes is clast supported (Figs. 23, 44), suggesting either that the gravel liquefied or that the matrix was winnowed out. In other dikes, gravel is matrix supported in sand, indicating passive upward movement of gravel in a rapidly moving slurry of liquefied sand. Dikes of gravel or gravelly coarse sand are moderately sorted, typically fine upward, and contain generally less than 5 percent silt.

The width of dikes is highly variable, ranging from 0.5 to 194 cm over a small area (Table 1). We plotted the maximum width of individual dikes against frequency of occurrence in the Portage and Twentymile River area (Fig. 59). The narrowest dikes are by far the most abundant; of 144 we measured in the Portage and Twentymile River area, 52 (36%) are 5 cm wide or narrower. Only eight of them (5.6%) are wider than 30 cm.

A few dikes contain inclusions. Figure 32 shows a dike at site 37b with inclusions of the silt that is interbedded with the top of the source bed. This dike carried blocks of laminated silt that capped the liquefied layer upward into the crack in the 1964 soil. Laminae in the silt, which can be correlated from one block to another, remained horizontal, showing that there was no rotation about axes in the horizontal plane and suggesting that this dike intruded the soil by laminar flow. Figure 33 shows a dike of predominantly medium to coarse sand at site 39 that carried an isolated metamorphic rock pebble (3.8 cm x 4.8 cm x 5.9 cm) at least 50 cm above its source bed.

Although some dikes terminated in sills, we found only two intrusions that we positively identified predominantly as sills (at sites 22 and 33, Figs. 19, 26). Bedded sands and gravels commonly have distorted contacts with the overlying silt that probably acted as slide planes during lateral spreading. We identified horizontal sand bodies as sills on the basis of pinchouts, apophyses, inclusions, and minor cross-cutting relationships.

Spring tides in this area presently reach the 1964 surface. Because this area subsided about 2 m, many of these source beds must have been significantly above tidewater at the time of the earthquake. Sites 37a and 37b (Figs. 31, 32), in particular, are located on the bank of a small low-relief island in the inactive flood plain of Placer River; the top of the source bed for liquefaction is 42 cm below the 1964 surface and initially must have been above the water table.

Kenai Peninsula

We trenched a ground crack near Silver Lake (Fig. 60) that we infer to be one of the large cracks in the upper right corner of figure 4 of Foster and Karlstrom (1967), reproduced here as Figure 61. This modified ground crack measured 2.2 m deep and 1.3 m wide at the base, widening to 2.1 m at the surface. Extruded sand about 40 cm thick fills the axis of the ground crack and mantles the ground surface on the north side of the crack. It is absent on the slope to the south of the ground crack, suggesting that the crack opened after the extrusion process had begun. When the crack opened, the south margin must have been vertical or nearly vertical; when it pulled away, the vegetative mat with its overlying sand dropped into the crack, leaving a mantle in the axis and on the north slope, but not on the south slope.

The large ground cracks (Fig. 61) are approximately orthogonal to the free face of the nearby lake and are at a high angle to the minor cracks. Only the smallest cracks are parallel to the free face, suggesting that displacement may not be due to liquefaction-induced lateral spreading.

The ground crack we trenched developed in a compact diamicton, which we interpret to be lodgment till of the late-Wisconsin Moosehorn advance (Reger and Pinney, in press). Near the top of the excavation, the clastic dike that fed the sand blow that covered the area is broken up into a complex set of dikes that resembles a positive flower structure. At depth only a single vertical dike, about 2 cm wide, appeared in the trench (Figs. 62–66). The host sediment intruded by this dike is compact diamicton to a depth of 4 m. The source bed is at an unknown depth below the base of our excavation.

Textural Analysis

We took 18 samples for sieve analysis (Table 3; Appendix Figs. A1–A12); we used sieves at 0.5-ϕ ($-\log_2 x$, where x = grain diameter) intervals between -2.0 ϕ (4 mm) and 4.0 ϕ (.064 mm). For gravel coarser than -2.0 ϕ, we used 3-ϕ (8 mm) and 4-ϕ (16 mm) sieves. Grain-size parameters were calculated using moment statistics (McBride, 1971). We selected samples to document unusually coarse features, to correlate source material with dikes and document changes during extrusion, and to correlate dikes to extruded sand.

Among 13 dike samples analyzed in the laboratory, the coarsest has a mean grain diameter of 4.0 mm and a gravel content of 78 percent (Site 49b, Table 3; Fig. A11). The dominant material in two dikes (sites 40a and 42; Figs. A8, A9) is clearly the finer (sand) mode of a bimodally distributed source bed of gravelly sand, suggesting that gravel in the source bed rode passively into the dike with the mobilized sand.

The dike at site 43 (Fig. 36) has a textural oxidation state and induration contrast along a sharp internal margin, which we interpret to be a dike intruded by another dike during the same lateral spreading event. Figure A10 clearly shows that the outer part of this dike complex, while texturally similar, is much richer in silt and clay than the inner part. Alternatively, this could be the result of infiltration of fines into the outer part of a single dike during the waning stages of dike injection.

The grain-size analyses of the two samples taken from the backhoe pit (locality 2 of Foster and Karlstrom, 1967) in the Kenai Lowland (Fig. A12) show an obvious match between the surface sand sheet and the rather small dike that appears to have fed it.

DISCUSSION

Creation and Preservation of Liquefaction Features

It is significant that the area for which we found the most evidence of liquefaction was the Portage and Twentymile River area. This area is about 85 km west of the initial epicenter, which is near the initiation of greatest moment release (Christensen and Beck, 1994) and about 30 km perpendicular distance from the closest part of the rupture surface (Zhao and others, 1995). The Portage and Twentymile River area is located on the axis of maximum coseismic subsidence. In the Copper River delta, about 150 km southeast of the initial epicenter, tectonic uplift averaged about 2 m and was locally as much as 3.5 m (Reimnitz and Marshall, 1965, and Fig. 2), shifting the pre-earthquake shoreline about 10 km seaward. This increased the gradient of distributary channels, causing them to decrease sedimentation in the upper delta and flush sediment down the tidal channels. Slumped sediments bordering the slump cracks and the noncohesive sand ridges within the cracks (Reimnitz and Marshall, 1965; Reimnitz, 1972) likely were eroded where they were near slough banks. Also, sand deposits on the marsh surface are extensively reworked by wind, and reworked sand boils would not be readily distinguishable from other windblown sand.

These negative results in an area where liquefaction features are known to have been abundant suggest that a lack of evidence of earthquake-induced liquefaction in susceptible sediments does not rule out liquefaction.

The Knik and Matanuska Rivers area also showed no evidence of sand extrusion. We know of no reports of vented sand there, although the damage to bridges implies lateral spreading (McCulloch and Bonilla, 1970; Bartlett and Youd, 1992). Liquefaction susceptibility analysis by Bartlett and Youd (1992) shows that fairly coarse, liquefiable sand and gravel was present all the way to the surface in some boreholes. We speculate that the lack of a capping layer may have permitted venting of excess pore pressure without localized extrusion or that mobilized sand and gravel never reached the surface.

Because of subsidence and rapid burial by Placer River Silt, many liquefaction features were preserved in the stratigraphic record in the Portage and Twentymile River area. Similar features were presumably eroded on the Copper River delta. Once streams in the Portage area came to grade and began eroding into their banks, clastic dikes became exposed in vertical cuts that were covered while Placer River Silt was being deposited. In other words, many of the clastic dikes that we observed would likely not have been exposed before streams in the Portage and Twentymile River area achieved grade and likely will be lost to erosion within a few decades of channel migration.

Another consequence of subsidence in the Portage and Twentymile River area is that loose, noncohesive sediments deposited by extrusion due to earthquake-induced liquefaction were exposed to erosion and reworking by tidal currents to depths as much as 92 cm below the 1964 soil surface. Reworking significantly obscured the contact relationships necessary to constrain the age of dike injection. The color (due to oxidation state) of post-1964 silt is distinct from that of pre-1964 silt, but this distinction will become less recognizable with age. In older dikes in other areas, x-radiography of acetate peels may reveal cross-cutting relationships that are not discernible to the naked eye.

The distribution of dike widths that we observed is significant for paleoseismologic studies relying on maximum dike width to estimate earthquake magnitude (Obermeier and others, 1993; Obermeier, 1995a, 1995b). Our observations suggest that the greatest dike widths for an area have a small probability of being sampled. Our maximum dike width exceeded the dike width at the 90th percentile by an order of magnitude. Although the relationship between ground-shaking intensity, liquefaction susceptibility, and lateral spread potential (and therefore dike width) is well established, the low probability of observing the maximum dike width suggests that dike width is not a robust estimator of earthquake magnitude. Using the frequency distribution of a large number of dike widths (Fig. 59) would help determine whether the largest dikes in an area had been sampled.

Liquefaction of Layers Initially above Water Table

Several possible mechanisms may account for liquefaction of sand and gravel that were initially above the water table:

(1) These beds may have liquefied after shaking-induced compaction forced water upward in the soil column, saturating sediments that were previously in the vadose zone, and then liquefying them. (Strong ground shaking in this earthquake continued for several minutes and may have remained strong for long enough to cause secondary liquefaction.)

(2) Tectonic and compaction-related subsidence may have dropped these beds below water level, and diffusion may have proceeded rapidly enough to saturate them while ground shaking was still strong enough to induce liquefaction.

(3) Liquefaction at depth may have resulted in sufficient overpressure to expel sand-bearing water by stoping through unsaturated, noncohesive sediments, venting through cracks generated by processes other than liquefaction.

(4) Water perched within locally unfrozen layers may have permitted saturated sediments close to the surface to liquefy.

The clastic dike at site 37b (Fig. 32) suggests that, at least on this reach of Placer River, sand extrusion proceeded by laminar rather than turbulent flow. This suggests a gradual dissipation of pore pressures. If water vented from a significant depth, the large pore pressure would likely cause the venting sandy water to reach a velocity high enough to induce turbulence, rendering mechanism 3 unlikely. The apparent continuity of the dike with the sand and gravel immediately underlying the silt bed also argues against mechanism 3. Mechanism 4 is also unlikely. Because the ground was insulated by about 0.5 m of snow, the depth of the frozen layer likely did not exceed 1 m (H. R. Livingston, Alaska Department of Transportation and Public Facilities, oral commun., 1995). Therefore the total volume of a potential perched layer would be small relative to the volume of sand expelled at sites 37a and 37b; this would result in discernible collapse of the overlying soil column. The absence of distortion of the top contacts at sites 37a and 37b argues against this mechanism.

We are unable to choose between mechanisms 1 and 2 because we have no data about the potential rates of groundwater rise due to increased pore-water pressure or the rate of subsidence coupled with the rate of diffusion of pore water into unsaturated sediments. In either case, it seems likely that liquefaction occurred in sediments initially above the water table that became saturated as a result of earthquake shaking.

Apparent Liquefaction in the Kenai Lowland

The apparent liquefaction in the Kenai Lowland remains difficult to interpret. The lodgment till through which sand vented is apparently too dense to liquefy, yet a very large sand boil was extruded through it via a very narrow conduit. Our excavation did not reach a layer that could have been a source for the vented sand, which must have been very incompressible to remain loose enough to vent sand even though it had been overridden by as much as 300 m of ice (Reger and Pinney, in press). Accordingly, we are unable to determine if liquefaction occurred in a sand layer beneath the lodgment till or if the sand was merely carried along passively by venting water from squeezing an aquifer. Such a process occurred during the 1983 Borah Peak earthquake in Idaho (Wood and others, 1985; Waag and Lane, 1985) and may have occurred along the Copalis River in southern coastal Washington between about 900 and 1,300 years ago (Atwater, 1992).

CONCLUSIONS

Our observations of areas affected by earthquake-induced liquefaction from the 1964 Alaska earthquake lead to three generalizations useful to paleoseismology studies:

(1) Preservation of clastic dikes is strongly influenced by depositional environments. In the Copper River delta, regional tectonic uplift exposed the loose sediments created by liquefaction and slumping to erosion. This erosion was enhanced by increased stream competence caused by locally higher stream gradients. Liquefaction features, though well documented shortly after the 1964 earthquake, are not readily observable in stream banks 30 years after the earthquake. In the Portage and Twentymile River area, preservation was strongly enhanced by subsidence followed by rapid deposition of a protective blanket of intertidal silt. Subsequent erosion due to channel migration after streams returned to grade exposed outcrops of clastic dikes in stream banks. Continued channel migration, however, is currently destroying these exposures and creating new ones farther from the 1964 channels.

(2) Subsidence in the Portage and Twentymile River area brought upland surfaces within reach of spring tides. Loose, noncohesive sediments, which were deposited by liquefaction-induced extrusion and were exposed to erosion and reworking by tidal currents, were removed to depths as much as 92 cm below the 1964 surface. Because dikes commonly do not intrude the youngest sediments, the contact relationships necessary to constrain the age of dike injection are significantly obscured. In these 30-year-old deposits, the color (due to oxidation state) of post-earthquake silt is distinct from that of pre-earthquake silt, but the distinction will become less recognizable with age. In older dikes, x-radiography of acetate peels may reveal cross-cutting relationships that are not discernible to the naked eye.

(3) The distribution of dike widths is strongly skewed toward narrow dikes. This probably reflects the initial distribution, because ground cracks filled with vented sand tend to shatter into numerous small cracks at the corners of lateral spread blocks. Additionally, lateral spreading of any given distance can be accommodated by either a large number of small cracks or a small number of large cracks. Erosion is less likely to occur in narrow dikes where friction from the dike wall impedes water flow, thus biasing the distribution of preserved dikes toward narrow dikes. Larger dikes are also more likely to trigger localized slumping, making it less likely that they will be exposed. In short, all factors mitigate against the generation, preservation, and exposure of large dikes. The likelihood of random samples of our database encountering the largest dikes is small. This bias is likely to increase with age, making maximum dike width a difficult parameter to measure and therefore not robust as a paleoseismic estimator of ground-shaking intensity. Earthquake magnitude may be underestimated if based on maximum observed dike width.

Additionally, the observation that liquefaction may occur in sediments that are not saturated before an earthquake suggests that present methods of assessing earthquake-induced liquefaction susceptibility may underestimate the true liquefaction potential.

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Table 1. Descriptive data for sites in the Knik River, Portage, Kenai Lowland, and Copper River areas Location scaled from map. [1] Measured from pre-earthquake surface to top of source bed. [2] Grain-size analysis available (table 3). *GPS location available (Table 2). Abbreviations: C, coarse; M, medium; F, fine; V, very; P, pebbly; S, sandy; G, gravelly; —, not measured

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
1	Possible surface cracks	Middle Knik River channel, ~100 m east of railroad bridge 147.1	—	—	—	—	—	—	Submerged under 30.8-ft high tide	—
2	Northernmost Knik River channel, south bank, ~150 m upstream from railroad bridge 147.5	Possible surface cracks	—	—	—	—	—	—	No evidence of surface cracks	—
3a	Matanuska River, south channel; east end of ground crack*	Surface crack	N82W	290	—	—	—	—	Length 93.6 m, max. 1 m deep	—
3b	Matanuska River, south channel; west end of ground crack*	Surface crack	N82W	290	—	—	—	—	Length 93.6 m, max. 1 m deep	—
4	Middle Knik River channel, north bank, ~1/2 km upstream from bridge 147.1	Exposure, no dikes or cracks	—	—	—	—	—	—	Exposure ~60 m long	—
5	Southern Knik River channel, ~0.8 km upstream from railroad bridge 146.4*	Surface crack, bank exposure	parallel to bank	—	—	—	—	—	Healed crack up to 1 m deep	—
6	Southern Knik River channel, ~20 m east of site 5*	Surface crack	—	110	—	—	—	—	1-m-deep crack parallel to shore; 2 cracks intersecting shoreline 10 m apart	5
7a	Near mouth of Matanuska River*	Crack network	various	—	—	—	—	—	—	—
7b	Near mouth of Matanuska River, west end of ground crack*	Surface crack	variable	50	—	—	—	—	54 cm max. depth	—
7c	Near mouth of Matanuska River, east end of ground crack*	Surface crack	variable	50	—	—	—	—	54 cm max. depth	—
8	Near mouth of Matanuska River, across channel north from site 7*	Crack network	various	180	—	—	—	—	1 m max. depth	—
9	Southern Knik River channel, south bank, ~200 m upstream from railroad bridge 146.4*	Surface crack	11	250	—	—	—	—	Total length 26 m; max. 1.3 m deep	—
10	Palmer Slough, ~3 km west of Glenn Highway*	Exposure, no dikes or cracks	—	—	—	—	—	—	No ground cracks or dikes along entire slough	—
11a	Matanuska River, ~30 m south of south bank, west end of ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11b	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11c	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11d	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11e	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11f	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11g	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11h	Matanuska River, ~30 m south of south bank, 5 m SE of test trench (Walsh site I)*	Long shore-parallel crack	N88W	370	—	—	—	—	Trench is across subsidiary crack	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
11i	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11j	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11k	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11l	Matanuska River, ~30 m south of south bank, along ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	—	—
11m	Matanuska River, ~30 m south of south bank, east end of ground crack*	Long shore-parallel crack	N88W	370	—	—	—	—	Point of max. depth, 1 m	6
12	South bank of Matanuska River, 0.8 km upstream from railroad bridge 148.3	Inactive interdistributary bar; no visible dikes or cracks in an area of extensive mapped cracks in 1964	—	—	—	—	—	—	Surface cracks, if any, probably filled with modern tidal sediment	—
13	SE bank of Twentymile River, ~3/4 km upstream from bridge*	Sand sill	—	12	PM–VC sand	—	—	—	Sill is 90 cm below 1964 peat; discontinuous. Total exposed length is 5.45 m	11
14	SE bank of Twentymile River, ~1/2 km upstream from bridge*	3 dikes, 1 break in peat	—	23	S pebble gravel	—	—	—	Dikes merge upward to 33-cm break in 1964 peat; left and right dikes are sand, middle dike is pebble gravel; dikes replaced with silt from 45 to 83 cm below 1964 surface	12
15	Hunter Flats	None observed	—	—	—	—	—	—	Found no evidence of ground cracks shown in McCulloch and Bonilla (1970), plate 2	—
16a	SE bank of Twentymile River, ~20 m downstream from site 14*	First of two intersecting dikes	N60E	29	M–C sand	—	—	—	Dikes merge upward to single 42-cm break in 1964 peat; outer 5 mm of dike margins strongly oxidized	13
16b	SE bank of Twentymile River, ~20 m downstream from site site 14*	Second of two intersecting dikes	N80W	—	M–C sand	—	—	—	Dikes merge upward to single 42-cm break in 1964 peat; outer 5 mm of dike margins strongly oxidized	13
17	SE bank of Twentymile River, 24.5 m downstream from site 16; east end of 20-m-long shore parallel dike*	Shore-parallel dike	N70W	34	M–C sand	—	—	—	Texture highly variable, sand to pebble gravel; trend is also variable (strike is average)	14
18a	SE bank of Twentymile River, a few meters downstream from site 17*	Dike 1 of 2	N30E	—	M sand	—	—	—	Minor erupted sand adjacent to break in peat; dike replaced with silt to 45 cm below 1964 surface; top 10 cm of sand reworked and cross-bedded	15
18b	SE bank of Twentymile River, a few meters downstream from site 17*	Dike 2 of 2	N50E	—	M sand	—	—	—	Minor erupted sand adjacent to break in peat; dike replaced with silt to 40 cm below 1964 surface; peat offset 8 cm at dike, up on right (SW) side	15
19a	SE bank of Twentymile River, ~40 m downstream from site 18*	Dike 1 of 2	NS	5	VF sand	—	—	—	Dikes 2.3 m apart	16
19b	SE bank of Twentymile River, ~40 m downstream from site 18*	Dike 2 of 2	N35E	4	Silt	—	—	—	Dikes 2.3 m apart	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
20	SE bank of Twentymile River, 5.4 m downstream from site 19*	Dike	N35E	5.5	F–M sand	—	—	—	Upper 36 cm filled with silt; erupted sand 5 cm thick overlies a 2-cm-thick layer of light-gray silt on top of peat	17
21a	SE bank of Twentymile River, 5.3 m downstream from site 20*	Dike 1 of 2	N60E	5	C sand	—	—	—	Dikes are 1.5 m apart; upper 43 cm replaced with silt	—
21b	SE bank of Twentymile River, 5.3 m downstream from site 20*	Dike 2 of 2	N60E	16	F–M sand	—	—	—	Dikes are 1.5 m apart; upper 40 cm replaced with silt; upper 24 cm of sand dike reworked and cross-bedded; break in peat is 35 cm wide	18
22	SE bank of Twentymile River, ~30 mi downstream from site 21*	Sill	—	20	PM–C sand	—	—	—	Possible minor erupted sand on indistinct 1964 surface	19
23	SE bank of Twentymile River, dike at westernmost end of exposure*	Dike	N52E	10	PM–C sand	—	—	—	Dike is sinuous; strike is average of range N40E–N65E; replaced with silt to 15 cm below 1964 surface	—
24	SE bank of Twentymile River, between sites 13 and 14*	Dike	N75E	3	Silt	—	—	—	Dike replaced with silt to 53 cm below 1964 surface; 2 dikes merge upward at 32 cm depth	20
25	SE bank of Twentymile River, between sites 13 and 14*	Dike	N10W	10	M–C sand	—	—	—	Discontinuous; 7-cm break in peat, filled with silt; patchy extruded sand above peat	21
26	SE bank of Twentymile River, between sites 13 and 14*	Dike	EW	5	Silt–VF sand	—	—	—	Tapers downward from 5.0 to 0.5 cm, terminates 1.1 m below 1964 surface; may be filled from above	—
27	SE bank of Twentymile River, NE of site 13*	Dike	N40W	6	Silt–VF sand	—	—	—	Dike eroded out to 50-cm depth; 1-cm break in 1964 peat; some extruded VF sand up to 10 cm thick, tapers out 30 cm each side of dike; very slight textural difference between extruded sand and overlying silt	—
28	SE bank of Twentymile River, NE of site 13*	Dike	N70W	6	Silt–VF sand	80	4	Silt–VF sand	Silt–VF-sand extrusion extends up to 70 cm laterally, max. 4 cm thick; dike traced to apparent source bed of silt to VF sand; source bed thins to 1.5 cm for a lateral distance of 25 cm at intersection with dike	22
29	Easternmost dike along SE bank of Twentymile River*	Dike	N40E	2	Silt–VF sand	—	—	—	Faint; no apparent break in 1964 peat	—
30	Southernmost dike on NW bank of Twentymile River*	Dike	N80E	9	M–C sand	—	—	—	Forms multiple sills below peat; rounded pebbles to 5 x 3 x 2.5 cm; coarse sand above peat possibly erupted from this dike	23

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
31a	NW bank of Twentymile River, ~15 m NE of site 30*	Dike	EW	64	M–C sand	—	—	—	Dike replaced with silt to 41 cm below 1964 surface; 34-cm break in peat	24
31b	NW bank of Twentymile River, 3.8 m upstream (NE) of site 31a	Dike	N75W	7	Sand	—	—	—	Dike replaced with silt to 22 cm below 1964 surface; 5-cm break in peat	—
32	NW bank of Twentymile River, 5.5 m NE of site 31*	Dike	EW	9	Pebbly sand	—	—	—	Extruded sand observed near dike but connection to dike not visible; sparse pebbles to 1.8 x 1.3 x 1.0 cm in extruded sand	25
33a	North bank of Portage Creek (south channel), west end of exposure*	Sill	—	—	Sand	—	—	—	Sill below peat, traced for 6.8 m (washed out sand indicates total extent of 27 m to west); sand boil on top of peat	26
33b	North bank of Portage Creek (south channel), west end of exposure*	Dike 1 of 2	N50W	25	M–C sand	35	—	—	Feeds sill(?)	26D
33c	North bank of Portage Creek (south channel), 1 m west of site 33a	Dike 2 of 2	EW	9	—	—	—	—	Replaced with silt to 19 cm below 1964 surface	—
34	North bank of Portage Creek (south channel), east end of exposure; site 34 is between here and site 33a*	Dike	N45W	7	Sand	—	—	—	Replaced with silt to 35 cm below peat surface; sand boil to 2.5 cm thick extends 80 cm right of break in peat, 45 cm left, and overlies 2–3-cm-thick silt layer on top of peat	27
35a	South bank of Portage Creek (south channel); east end of series of dikes*	Dike	N80W	10	M–PVC sand	—	—	—	Break in peat not evident; dike terminates in sill below 1964 peat	—
35b	South bank of Portage Creek (south channel), 17–24 cm west of site 35a	Dike	N80W	13	VF–PVC sand	—	—	—	Coalesces with 35a 72 cm below 1964 surface to form dike 35 cm wide	—
35c	South bank of Portage Creek (south channel), 9.0 m west of site 35a	Dike	N60W	14	M–C sand	—	—	—	Feeds sill below 1964 peat; minor eruption through break in peat; 18-cm-thick cross-bedded zone at top of sand dike	—
35d	South bank of Portage Creek (south channel), 10.4–16.3 m west of site 35a	Dike	N60E	20	Sand	—	—	—	Sinuous, shore-parallel dike; minor erupted sand at upstream (NE) end	—
35e	South bank of Portage Creek (south channel), 16.6 m west of site 35a	Dike	N70W	13	M–C sand	—	—	—	1964 peat absent here	—
35f	South bank of Portage Creek (south channel), 17.5 m west of site 35a	Dike	N45W	12	VC sand w/ granules	—	—	—	1964 peat absent here	—
35g	South bank of Portage Creek (south channel), 17.5 m west of site 35a	Dike	N75W	50	M–C sand	—	—	—	Replaced with silt to 14 cm below 1964 surface	—
35h	South bank of Portage Creek (south channel), 21.3 m west of site 35a	Dike	N35E	5	C sand –S gravel	—	—	—	Pebbles to 3.2 x 1.3 x 2.8 cm; dike pinches out 17 cm below 1964 surface	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
35i	South bank of Portage Creek (south channel), 20.5–23.0 m west of site 35a	Shore-parallel dike	N55E	16	M–VC sand	—	—	—	Pinches out laterally both ends	—
35j	South bank of Portage Creek (south channel), 23.4 m west of site 35a	Dike	N60W–N40W	12	M sand	—	—	—	Replaced with silt to 33 cm below 1964 surface; 12-cm break in peat	—
35k	South bank of Portage Creek (south channel), 28.7 m west of site 35a	Dike	N5E	2.5	M–C sand	—	—	—	Pinches out upward 6 cm below top of 1964 peat; no break in peat	—
35l	South bank of Portage Creek (south channel), 28.9–31.6 m west of site 35a	Large dike complex	various	194	M–C sand	150	—	G sand	Minor pebbles to 3.0 x 2.3 x 1.7 cm; dikes widen at base, possibly at top of source bed ~1.5 m below 1964 surface; 1-cm dike erupted through both peat and minor sand	28
35m	South bank of Portage Creek (south channel), 31.6–34.5 m west of site 35a	Shore-parallel dike	N60W–N50E	13	Sand	—	—	—	Joins with complex at 35l and tributary dikes at 35n; dike replaced with silt to 47 cm below 1964 surface	—
35n	South bank of Portage Creek (south channel), 33.4 m west of site 35a	Two small dikes	N35W	4	Sand	—	—	—	5 cm apart; replaced with silt to 43 cm below 1964 surface; trace of sand silled into 1964 peat	—
35o	South bank of Portage Creek (south channel), 35.2 m west of site 35a	Dike	N45W	21	M–C sand	—	—	—	20-cm break in peat but no erupted sand; dike eroded out to 35 cm below 1964 surface	—
35p	South bank of Portage Creek (south channel), 36.6 m west of site 35a	Dike	N35W	1	F sand	—	—	—	No break in 1964 peat	—
35q	South bank of Portage Creek (south channel), 37.0 m west of site 35a	Dike	N35W	1	F sand	—	—	—	No break in 1964 peat	—
35r	South bank of Portage Creek (south channel), 37.2 m west of site 35a	Sand boil	—	6.5	Sand	—	—	—	20 cm wide; source not evident; no break in peat	—
35s	South bank of Portage Creek (south channel), 39.5 m west of site 35a	Dike	N40W	1	M–C sand	—	—	—	Pinches out upward near base of 1964 peat	—
35t	South bank of Portage Creek (south channel), 41.6 m west of site 35a	Dike	N55W	6	C sand with minor granules	—	—	—	Terminates in sill 44 cm below 1964 surface; sill is 20 cm thick, extends 1.8 m west	—
35u	South bank of Portage Creek (south channel), 43.4 m west of site 35a	Dike	—	1	Sand	—	—	—	—	—
35v	South bank of Portage Creek (south channel), 43.7 m west of site 35a	Dike	—	1	Sand	—	—	—	32 cm west of 35u	—
35w/36	South bank of Portage Creek (south channel), 49.4 m west of site 35a*	Dike and sand boil	N15W	7	F–M sand	—	—	—	Dike continuous through 1964 peat; sand boil on top of peat, max. 4 cm thick, merges right with boil at site 35x; sand boil overlies 2-cm-thick layer of silt with rootlets on top of 1964 peat	29

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
35x	South bank of Portage Creek (south channel), 49.9 m west of site 35a	Dike and sand boil	N55W	8	Sand	—	—	—	Dike continuous through 1964 peat; sand boil on top of peat merges left with boil at site 35w/36	—
35y	South bank of Portage Creek (south channel), 51.1 m west of site 35a	Dike and sand boil	N60W	2	M sand	—	—	—	Replaced with silt to 4 cm below 1964 surface; sand boil 4 cm max. thick, extends 6 cm upstream, 9 cm downstream; 2-cm break in peat	—
35z	South bank of Portage Creek (south channel), 57.3 m west of site 35a	Dike	NS	5	M–C sand	—	—	—	Replaced with silt to 14 cm below 1964 surface; no extruded sand; 2-cm break in peat	—
35aa	South bank of Portage Creek (south channel), 59.4 m west of site 35a	Dike	N10W	12	M sand	—	—	—	Replaced with silt to 41 cm below 1964 surface; no extruded sand; 2-cm break in peat	—
35ab	South bank of Portage Creek (south channel), 62.0 m west of site 35a	Dike	N10W	2	M sand	—	—	—	Relationship to 1964 surface obscured by slump	—
35ac	South bank of Portage Creek (south channel), 62.7 m west of site 35a	Dike	N25W	7	M sand	—	—	—	Relationship to 1964 surface obscured by slump	—
35ad	South bank of Portage Creek (south channel), 62.7 m west of site 35a	Anastomosing dike	N60W	11	M sand	—	—	—	Replaced with silt from 30 to 45 cm below 1964 surface; anastomoses to 3 dikes	30
37a	West bank, Placer River (east channel), opposite confluence with Portage Creek (S channel)*	Dike 1 of 2	—	—	M sand	42	—	P gravel	Dike extends from source to break in 1964 peat; fines upward	31
37b	West bank, Placer River (east channel), opposite confluence with Portage Creek (S channel), ~3 m N of site 37a*	Dike 2 of 2	N85E	25	M sand	53	—	GC sand	Dike continuous through 1964 peat; no boil, but silled into peat. Dike contains nonrotated fragments of silt bed that overlie source	32
38	Flood plain east of Portage railroad terminal	Linear trough	N45W	—	—	—	—	—	Trough ~0.5 km long and up to 1.4 m deep; 1964 peat exposed at 1.0 m depth in silt; no extruded sand; may not be ground crack	—
39	West bank, Twentymile River, ~1 km upstream from railroad bridge*	Dike	N5W	52	M–C sand	90	11	M–C sand*	Replaced with silt to 38 cm below 1964 surface; rounded pebble 3.8 x 4.8 x 5.9 cm in middle of dike; no extruded sand	33
40a	West bank, Twentymile River, ~20 m SW of site 39*	Dike, merges with 40b	N20E	26	M sand	106	—	GC sand to F sand*	Replaced with silt or VF sand to 55 cm below 1964 surface; no extruded sand	34
40b	West bank, Twentymile River, ~20 m SW of site 39*	Dike, merges with 40a	N20E	11	M sand	106	—	GC sand to F sand	Merges upward with 40a 55 cm below 1964 surface	34
41	West bank, Twentymile River, NE of site 39*	Dike	N30W	1	Sand	66	12	G sand	Small pod of erupted sand adjacent to break in 1964 peat	35

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
42	West bank, Twentymile River, NE of site 39*	Dike	N50E	146	PM–C sand	50	—	Gravel*	Replaced with silt to 33 cm below 1964 surface; source bed not exposed in excavation but crops out at water level nearby	37
43	West bank, Twentymile River, NE of site 39*	Dike	N55E	29	Sand	—	—	—	Dike shows two stages of extrusion	36
44	West bank, Twentymile River, NE of site 39*	Dike	N25W	4	—	—	—	—	Dike terminates 63 cm below 1964 surface; crosses G sand layer 6 cm thick at 50 cm depth	—
45	West bank, Twentymile River, NE of site 39; upstream limit of observed dikes*	Dike	N30W	2	—	—	—	—	Pinches out 48 cm below 1964 surface; extruded M sand 5 cm thick	38
46	West bank, Placer River (east channel); dike at north end of exposure, ~200 m south of bridge*	Dike	N65W	16	M–C sand	180	—	Gravel	Irregular silt body replaces upper 15 cm of dike; 37-cm break in peat; peat offset 20 cm across break; at least three phases of injection are indicated by different grain sizes	39, 40, 41
47	West bank, Placer River (east channel), 7.2 m south of site 46	Dike	N65W	15	—	—	—	—	Top of dike concealed by stump	42
48	West bank, Placer River (east channel), 25.1 m south of site 46	Dike	N40W	—	—	—	—	—	Dike not traceable to 1964 peat	—
49a	West bank, Placer River (east channel), 38.2 m south of site 46; south end of exposure*	Dike 1 of 2	N40W	7	—	—	—	—	—	44, 45
49b	West bank, Placer River (east channel), 38.2 m south of site 46; south end of exposure	Dike 2 of 2	N75E	25	GC sand	—	—	—	Dike not traceable to 1964 peat, except there is a break in peat above the dike; dike replaced to 25 cm below 1964 surface; upper 25 cm of remaining dike is cross-bedded F sand and silt	—
50	North bank, Portage Creek (north channel) near mouth, SE end of exposure*	Dike	EW	13	Silt	45	20	M–C sand	13-cm-wide silt block collapsed into crack	—
51	North bank, Portage Creek (north channel), 11.5 m NW of site 50	Dike	N20E	6	Sand	45	18	M–C sand	Two dikes coalesce upward below single break in 1964 peat; no extrusion; upper 25 cm of dike is interbedded VF–C sand	—
52	North bank, Portage Creek (north channel), 21.4 m NW of site 50	Dike	EW	14	Sand	54	11	M–C sand	Erupted sand overlies thin silt layer with rootlets on 1964 surface	46, 47
53	North bank, Portage Creek (north channel), 39.0 m NW of site 50	Dike	N60E	5	Sand	62	4	M–C sand	—	—
54	North bank, Portage Creek (north channel), 45.6 m NW of site 50	Dike	N45E	12	Sand	95	—	M–C sand	—	—
55	North bank, Portage Creek (north channel), 60.9 m NW of site 50	Dike	N75W	12	Sand	—	—	—	—	43

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
56	North bank, Portage Creek (north channel), 64.3 m NW of site 50	Dike	EW	3.5	Sand	47	7	M–C sand	—	—
57	North bank, Portage Creek (north channel), 68.9 m NW of site 50	Dike	N5W	20	Sand	—	—	—	Sinuous shore-parallel dike extends to 3 m NW of site 59; shore strikes N40W; dike feeds subsidiary dikes at sites 56–59; crosses sand bed in section	48
58	North bank, Portage Creek (north channel), 74.2 m NW of site 50	Dike	N75W	29	Sand	52	70	M–C sand	West end of dike at site 57; replaced with silt to 40 cm below 1964 surface	49
59	North bank, Portage Creek (north channel), 79.5 m NW of site 50	Dike	NS	5	Sand	56	5	M–C sand	Erupted sand on 1964 surface, max. 4 cm thick	50
60a	North bank, Portage Creek (north channel), 89.4 m NW of site 50	Dike 1 of 2	N65W	12	Sand	—	—	—	Dike strike is average of variable trend W–N40W; erupted sand on 1964 surface	51
60b	North bank, Portage Creek (north channel), 89.4 m NW of site 50	Dike 2 of 2	N50E	3	Sand	—	—	—	Erupted sand on 1964 surface; dike pinches out downward at 30 cm below 1964 surface	51
61	North bank, Portage Creek (north channel), 113.9 m NW of site 50*	Dike	N30E	2.5	Sand	—	—	—	Erupted sand on 1964 surface; dike pinches out downward at 30 cm below 1964 surface	52
62	North bank, Portage Creek (north channel), 126.9 m NW of site 50	Dike	N90E	10	Sand	95	20	P sand	Sand boil max. 0.5 cm thick, discontinuous to 35 cm wide, not connected to dike; dike is gravel in lower 8 cm, fines upward to F–M sand; margins oxidized	53
63	North bank, Portage Creek (north channel), 132.6 m NW of site 50	Dike	N40E	1.5	F sand	—	—	—	Pinches out downward at 50 cm below 1964 surface	—
64	North bank, Portage Creek (north channel), 146.6 m NW of site 50	Dike	N80E	0.5	F–M sand	—	—	—	Pinches out downward at 45 cm below 1964 surface; dike dips 55°N	—
65	North bank, Portage Creek (north channel), 153.1 m NW of site 50	Dike	N30E	3	VF sand	—	—	—	F–M sand extruded as sand boil 2 cm thick; boil contains pebbles to 2.1 x 1.2 x 1.0 cm; dike absent at 70 cm below 1964 surface	—
66	North bank, Portage Creek (north channel), 162.1 m NW of site 50	Dike	N85W	5	M–C sand	92	20	P gravel	Dike fines upward; oxidized margins stand in relief	54
67	North bank, Portage Creek (north channel), 169.5 m NW of site 50	Dike	N73E	8	F–M sand	90	20	G sand	Replaced with silt to 45 cm below 1964 surface	—
68	North bank, Portage Creek (north channel), 193.8 m NW of site 50*	Dike	N45E	4	M sand	—	—	—	Pinches out downward at 42 cm below 1964 surface	—
69	North bank, Portage Creek (north channel), 234.1 m NW of site 50	None	—	—	—	—	—	—	Deformed sand layer mistaken for dike	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
70	North bank, Portage Creek (north channel), 274.5 m NW of site 50	Dike	EW	19	M sand	—	—	—	Contains pebbles to 2.4 x 2.3 x 1.0 cm; filled with modern peat to 45 cm below 1964 surface; dike turns to other strikes, N10E, N40W, N35W	—
71	North bank, Portage Creek (north channel), NW end of exposure, 301.7 m NW of site 50*	Dike	N80E	5	Sand	—	—	—	Pinches out downward 25 cm below 1964 surface; replaced with silt to 7 cm below 1964 surface; small sand blow, max. 1 cm thick	—
72	South bank of Portage Creek (north channel); SE end of exposure, next to bridge. No dikes.*	None	—	—	—	—	—	—	Beginning of exposure extending downstream (NW) from bridge; 1964 peat rests on pebbly coarse sand	—
73	South bank of Portage Creek (north channel), ~100 m NW of site 72*	Dike	—	2	Silt	—	—	—	Possible extruded pebbles to 6.8 x 4.0 x 3.8 cm on top of 1964 peat 50 cm either side of dike. Source of dike unknown; may be filled from above	—
74	South bank of Portage Creek (north channel), ~250 m NW of site 72*	Dike	N15E	7	G M–C sand	60	—	G sand	Replaced with silt to 30 cm below 1964 surface; pods of erupted sand and pebbles in and onto 1964 peat. Sill 6 cm thick extends W unknown distance	55
75	South bank of Portage Creek (north channel), ~15 m NW of site 74	Dike	N40E	2	CP sand	93	—	G sand	Pinches out downward 45 cm below 1964 surface; not traced to source. May be filled from above	—
76	South bank of Portage Creek (north channel), ~40 m NW of site 74	Dike	N75E	4.5	Sand	125	—	—	Dike washed out to 40 cm below 1964 surface	—
77	South bank of Portage Creek (north channel), dike at NW end of exposure, ~300 m NW of site 72*	Dike	N85E	2.5	F sand	30	5	F–M sand	Dike discontinuous. Source bed underlain by P–C sand of unknown thickness	—
78	South bank of Portage Creek (north channel), ~70 m west of site 77; east end of exposure (no dikes)*	Vertical crack in peat	EW	5	—	—	—	—	Clastic dike not visible below break in peat	—
79a	South bank of Portage Creek (north channel), beginning of series of clastic dikes, ~20 m west of site 78*	Dike	N50W	3	C sand	40	4	M sand	Dike terminates downward at M sand layer, but it is not clear that the layer is the source of the dike sand; source is coarser than dike	—
79b	South bank of Portage Creek (north channel), 0.8 m W of site 79a	Dike	N35E	9.5	PVC sand	40	4	M sand	Dike terminates downward at M sand layer, but it is not clear that the layer is the source of the dike sand; source is coarser than dike	—
79c	South bank of Portage Creek (north channel), 2.0 m W of site 79a	Dike	N35W	8	C sand	—	—	—	Pinches out downward at 35 cm below 1964 surface	—
79d	South bank of Portage Creek (north channel), 3.6 m W of site 79a	Dike	N25E	10	M–C sand	—	—	—	Pinches out downward at 39 cm below 1964 surface	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
79e	South bank of Portage Creek (north channel), 5.5 m W of site 79a	Dike	N10W	1.5	F sand	—	—	—	Not visible below 20 cm below 1964 surface	—
79f	South bank of Portage Creek (north channel), 7.7 m W of site 79a	Dike	N60W	12	PM–C sand	—	—	—	Pinches out downward at 32 cm below 1964 surface	—
79g	South bank of Portage Creek (north channel), 9.2 m W of site 79a	Dike	N60W	74	M sand	50	—	—	Minor erupted sand	58
79h	South bank of Portage Creek (north channel), 13.2 m W of site 79a	Dike	N65E	12.5	GC sand	—	—	—	Single break in peat at confluence of two dikes; strike and width measured at peat break. Dike contains pebbles to 2 cm	58
79i	South bank of Portage Creek (north channel), 16.0 m W of site 79a	Dike	N5W	16.5	GC sand	—	—	—	Pinches out downward at 48 cm below 1964 surface	—
79j	South bank of Portage Creek (north channel), 25 m W of site 79a*	Dike	N20W	18	F–M sand	—	—	—	Pinches out downward at 34 cm below 1964 peat	—
79k	South bank of Portage Creek (north channel), 50 m W of site 79a	Dike	N50E	16	F sand	—	—	—	Top of dike replaced with silt to 30 cm below 1964 surface	—
79l	South bank of Portage Creek (north channel), 61 m W of site 79a	Dike	N65E	9	Silt	92	25	G sand	No sand; entire dike replaced with silt	—
79m	South bank of Portage Creek (north channel), 68 m W of site 79a	Dike	N30W	2.5	F sand	90	30	G sand	Top of dike replaced with silt to 29 cm below 1964 surface	—
79n	South bank of Portage Creek (north channel), 74 m W of site 79a	Dike	N55W	12	GC sand	94	30	GC sand	Dike traced to source bed; top of dike replaced with silt to 35 cm below 1964 surface. Dike contains pebbles to 1.5 cm	—
79o	South bank of Portage Creek (north channel), 79 m W of site 79a	Dike	N45W	19	GC sand	100	30	GC sand	Dike traced to source bed; top of dike replaced with silt to 26 cm below 1964 surface. Dike contains pebbles to 0.5 cm	—
79p	South bank of Portage Creek (north channel), 94 m W of site 79a	Dike	N60E	20	F–C sand	125	10	GC sand	Top of dike replaced with silt to 35 cm below 1964 surface. Dike fines upward from F to C sand.	—
79q	South bank of Portage Creek (north channel), 110 m W of site 79a	Dike	N70E	13.5	F sand	117	10	GC sand	Top of dike replaced with silt to 14 cm below 1964 peat	—
79r	South bank of Portage Creek (north channel), 112 m W of site 79a	Dike	N70E	10	GVC sand	110	—	—	Top of dike replaced with silt to 22 cm below 1964 peat	—
79s	South bank of Portage Creek (north channel), 116 m W of site 79a	Dike	N15W	5.5	M–C sand	110	—	—	Top of dike replaced with silt to 28 cm below 1964 peat	—
79t	South bank of Portage Creek (north channel), 132 m west of site 79a*	Dike	N80E	7.5	F sand	90	—	—	Dike discontinuous; top replaced with silt to 10 cm below 1964 surface	—
79u	South bank of Portage Creek (north channel), 138 m west of site 79a	Dike	N40W	11	F–C sand	90	—	—	Top of dike replaced with silt to 19 cm below 1964 peat	—
79v	South bank of Portage Creek (north channel), 144 m west of site 79a	Dike	N85E	8	F–M sand	100	—	—	Top of dike replaced with silt to 9 cm below 1964 peat; minor erupted sand	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
79w	South bank of Portage Creek (north channel), 146 m west of site 79a	Dike	EW	8	M–C sand	100	—	—	Top of dike replaced with silt to 10 cm below 1964 peat	—
79x	South bank of Portage Creek (north channel), 149 m west of site 79a	Dike 1 of 2	EW	14.5	GC sand	60	10	GC sand	1964 peat eroded away	—
79y	South bank of Portage Creek (north channel), 149 m west of site 79a	Dike 2 of 2	N20W	1.8	C sand	60	10	GC sand	1964 peat eroded away	—
79z	South bank of Portage Creek (north channel), 151 m west of site 79a	Dike	N20W	5	F–VC sand	75	10	GC sand	Dikes fines upward from very coarse to fine sand	—
79aa	South bank of Portage Creek (north channel), 152–155 m west of site 79a	Dike	N85W	10	GC sand	80	—	—	Sinuous, shore-parallel dike. Pebbles to 1 cm	—
79ab	South bank of Portage Creek (north channel), 158–163 m west of site 79a	Dike	N80W	11	GVC sand	80	—	—	Shore parallel. Tapers west to 2.5 cm width	—
80a-1	West-facing bank at mouth of Portage Creek (north channel), south end of exposure*	Dike 1 of 3	N5E	13	Granule gravel	65	—	P sand	3 dikes coalesce; upward fining	56
80a-2	Same site as site 80a-1*	Dike 2 of 3	N30W	12	Granule gravel	65	—	P sand	3 dikes coalesce; upward fining	56
80a-3	Same site as site 80a-1*	Dike 3 of 3	N80W–N45W	6	Granule gravel	65	—	P sand	3 dikes coalesce; upward fining	56
80b	West-facing bank at mouth of Portage Creek (north channel), 6.1 m north of site 80a	Dike	N60W	1	C sand	—	—	—	Erupts to surface but no sand remaining on top of 1964 peat	—
80c	West-facing bank at mouth of Portage Creek (north channel), 8.7 m N of site 80a	Dike	N45W	6	GC sand	—	—	—	Peat top is 60 cm above erupted sand for at least 1.1 m along dike	—
80d	West-facing bank at mouth of Portage Creek (north channel), 14.95 m north of site 80a	Dike	N60W	4	C sand	66	—	—	Minor erupted sand, 3 cm thick	—
80e-1	West-facing bank at mouth of Portage Creek (north channel), 19.4 m north of site 80a	Dike 1 of 4	N70W	2	—	95	—	—	Joins 80e-4 at right angle	57
80e-2	West-facing bank at mouth of Portage Creek (north channel), 21.0 m north of site 80a	Dike 2 of 4	N70W?	2	—	95	—	—	Parallel to 80e-1; joins 80e-4 at right angle; pinches out downward	57
80e-3	West-facing bank at mouth of Portage Creek (north channel), 21.0 m north of site 80a	Dike 3 of 4	N70W?	1	—	95	—	—	Parallel to 80e-1; joins 80e-4 at right angle; pinches out downward	57
80e-4	West-facing bank at mouth of Portage Creek (north channel), 21.0 m north of site 80a	Dike 4 of 4	N20E	16	VF–M sand	95	—	—	Shore parallel; variable texture, VF–M sand; some erupted sand on top of 1964 peat; pinches out downward	57
80f	West-facing bank at mouth of Portage Creek (north channel), 33.7 m north of site 80a	Dike	N35W	36	P sand	92	—	—	No visible erupted sand	—
80g	Northwest-facing bank at mouth of Portage Creek (north channel), 41.3 m north of site 80a*	Dike	N60W	—	MP gravel	90	—	CP gravel	Pebble clasts to 4.2 x 2.3 x 1.5 cm near base of dike; fines upward	—

Site no.	Location notes	Described feature	Strike (°)	Max. width or thickness (cm)	Visual texture	Source depth (cm)	Source thickness	Source texture	Additional information	Figure no.
80h-1	North-facing bank at mouth of Portage Creek (north channel), 5.2 m east of site 80g	Dike 1 of 4	N20W	1	F–M sand	—	—	—	Pinches out downward at 50 cm below 1964 surface; erupts to surface	—
80h-2	North-facing bank at mouth of Portage Creek (north channel), 7.15 m east of site 80g	Dike 2 of 4	N15W	4	C sand	—	—	—	Erupts to surface; trend changes to N50E at bank	—
80h-3	North-facing bank at mouth of Portage Creek (north channel), 8.15 m east of site 80g	Dike 3 of 4	N30E	2.5	C sand	—	—	—	Bifurcates 44 cm below 1964 surface (each 2 cm thick); one branch pinches out upward 25 cm below 1964 surface; second replaced with silt to 32 cm below 1964 surface	—
80h-4	North-facing bank at mouth of Portage Creek (north channel), 9.65 m east of site 80g	Dike 4 of 4	N75E	2	M–C sand	—	—	—	Dike pinches out downward at 40 cm below 1964 surface	—
80i	North-facing bank at mouth of Portage Creek (north channel), 16.7 m east of site 80g	Dike	N80W	5	M–C sand	70	—	—	Small sand boil 4 cm thick, 8 cm across	—
80j	North-facing bank at mouth of Portage Creek (north channel), 21.0 m east of site 80g	Dike	N50E	10	C sand	—	—	—	Sand boil 6 cm thick, 36 cm wide	—
80k	North-facing bank at mouth of Portage Creek (north channel), 45.0 m east of site 80g	Dike	N20E	1	F–M sand	—	—	—	Dike pinches out downward at 30 cm below 1964 surface; sand boil 2.5 cm thick, 6 cm wide	—
80l	North-facing bank at mouth of Portage Creek (north channel), 50.0 m east of site 80g	Dike	N40E	12	FPG–C sand	70	—	—	Dike fines upward; replaced with silt to 23 cm below 1964 surface; sand boil 4 cm thick, 32 cm wide	—
80m	North-facing bank at mouth of Portage Creek (north channel), 54.4 m east of site 80g	Dike	N45E	6	C sand to gravel	70	—	—	Replaced by silt to 33 cm below 1964 surface; no extruded sand visible	—
80n	North-facing bank at mouth of Portage Creek (north channel), 56.5 m east of site 80g; east end of exposure*	Dike	N60E	13	F gravel to VC sand	—	—	—	Fines upward; extruded sand 2 grains thick, 6 cm wide	—
Locality 2	Foster and Karlstrom (1967), Kenai Lowland*	Sand dike	N85W	7	F sand	390	—	F sand	Dike in backhoe pit; source bed not found, but 'source' sample taken from feeder dike at base of pit	62–66
CR1	Copper River delta, north bank of Alaganik Slough*	Stratigraphic section; no dikes	—	—	—	—	—	—	Peat layer 30 cm thick, top 2.5 m below surface; could be 700-yr-old peat of Reimnitz (1972)	—
CR2	Copper River delta, north bank of Alaganik Slough southwest of CR1 on same bank*	Stratigraphic section; no dikes	—	—	—	—	—	—	Peat layer 30 cm thick, top 2.5 m below surface; could be Reimnitz' 700-yr-old peat	—
CR3	Copper River delta, south bank of Pete Dahl Slough*	Stratigraphic section; no dikes	—	—	—	—	—	—	Layered F–M sand with peat; no clastic dikes or cracks	—

Table 2. Global Positioning System (GPS) locations for observational sites in the Knik River, Portage, Kenai Lowland, and Copper River delta areas. [1] Location scaled from map. [2] GPS data not differentially corrected; base-station data not available

Site no.	Location notes	GPS ID	Latitude	Corrected Longitude	GPS fixes	Std. dev. (m) N–S	Std. dev. (m) E–W
1	Middle Knik River channel, ~100 m east of railroad bridge 147.1	—	61°29′29.8″N[1]	149°14′12.7″W[1]	—	—	—
2	Northernmost Knik River channel, south bank, ~150 m upstream from railroad bridge 147.5	—	61°29′50.1″N	149°14′02.9″W[1]	—	—	—
3a	Matanuska River, south channel; east end of ground crack	E080921A	61°30′13.56″N	149°13′00.09″W	61	5.8	4.2
3b	Matanuska River, south channel; west end of ground crack	E080922A	61°30′13.96″N	149°13′06.11″W	60	5.6	2.8
4	Middle Knik River channel, north bank, ~1/2 km upstream from bridge 147.1	—	61°29′37.3″N[1]	149°13′41.5″W[1]	—	—	—
5	Southern Knik River channel, ~0.8 km upstream from railroad bridge 146.4	E081001A	61°28′56.40″N	149°13′51.72″W	61	1.6	1.9
6	Southern Knik River channel, ~20 m east of site 5	E081002A	61°28′55.84″N	149°13′49.62″W	36	1.9	0.6
7a	Near mouth of Matanuska River	E081019A	61°29′38.80″N	149°14′50.37″W	60	1.9	1.0
7b	Near mouth of Matanuska River, west end of ground crack	E081019B	61°29′39.64″N	149°14′50.64″W	60	1.5	0.8
7c	Near mouth of Matanuska River, east end of ground crack	E081020A	61°29′37.32″N	149°14′47.26″W	60	1.9	0.7
8	Near mouth of Matanuska River, across channel north from 7	E081022A	61°29′49.00″N	149°15′05.26″W	60	3.0	2.6
9	Southern Knik River channel, south bank, ~200 m upstream from railroad bridge 146.4	E081101A	61°28′46.98″N	149°14′11.04″W	60	2.9	5.3
10	Palmer Slough, ~3 km west of Glenn Highway	E081220A	61°30′50.77″N	149°17′30.99″W	200	1.3	1.2
11a	Matanuska River, ~30 m south of south bank, west end of ground crack	E081321A	61°30′27.07″N	149°13′19.02″W	60	7.7	4.7
11b	Matanuska River, ~30 m south of south bank, along ground crack	E081321B	61°30′27.52″N	149°13′18.00″W	90	6.3	5.4
11c	Matanuska River, ~30 m south of south bank, along ground crack	E081321C	61°30′27.59″N	149°13′15.93″W	60	10.8	5.2
11d	Matanuska River, ~30 m south of south bank, along ground crack	E081321D	61°30′27.45″N	149°13′15.79″W	60	7.8	5.4
11e	Matanuska River, ~30 m south of south bank, along ground crack	E081322A	61°30′27.42″N	149°13′13.26″W	60	8.1	5.5
11f	Matanuska River, ~30 m south of south bank, along ground crack	E081322B	61°30′26.79″N	149°13′10.11″W	60	7.9	3.0
11g	Matanuska River, ~30 m south of south bank, along ground crack	E081322D	61°30′27.08″N	149°13′07.36″W	60	9.7	5.8
11h	Matanuska River, ~30 m south of south bank, 5 m SE of test trench (Walsh site I)	E081322E	61°30′27.36″N	149°13′04.40″W	60	3.8	3.4
11i	Matanuska River, ~30 m south of south bank, along ground crack	E081323A	61°30′27.06″N	149°13′02.31″W	60	7.2	6.7
11j	Matanuska River, ~30 m south of south bank, along ground crack	E081323B	61°30′27.19″N	149°12′59.16″W	60	8.6	4.2
11k	Matanuska River, ~30 m south of south bank, along ground crack	E081323C	61°30′26.04″N	149°12′55.70″W	61	13.0	3.2
11l	Matanuska River, ~30 m south of south bank, along ground crack	E081323D	61°30′26.59″N	149°12′52.55″W	60	18.0	3.8

Site no.	Location notes	GPS ID	Latitude	Corrected Longitude	GPS fixes	Std. dev. (m) N–S	Std. dev. (m) E–W
11m	Matanuska River, ~30 m south of south bank, east end of ground crack	E081400A	61°30′26.44″N	149°12′48.91″W	60	3.4	2.3
13	SE bank of Twentymile River, ~3/4 km upstream from bridge	E081522A	60°50′39.11″N	148°58′12.64″W	85	1.8	1.0
14	SE bank of Twentymile River, ~1/2 km upstream from bridge	E081521A	60°50′38.74″N	148°58′29.29″W	112	2.2	1.3
15	Hunter Flats	—	60°33′14.5″N[2]	149°13′24.0″W[2]	—	—	—
16a	SE bank of Twentymile River, ~20 m downstream from site 14	E081701A	60°50′39.27″N	148°58′30.36″W	60	1.0	0.5
16b	SE bank of Twentymile River, ~20 m downstream from site 14	E081701A	60°50′39.27″N	148°58′30.36″W	60	1.0	0.5
17	SE bank of Twentymile River, 24.5 m downstream from site 16; east end of 20-m-long shore parallel dike	E081701B	60°50′39.65″N	148°58′31.84″W	60	1.2	1.7
18a	SE bank of Twentymile River, a few meters downstream from site 17	E081722B	60°50′39.78″N	148°58′32.46″W	60	1.0	1.1
18b	SE bank of Twentymile River, a few meters downstream from site 17	E081722B	60°50′39.78″N	148°58′32.46″W	60	1.0	1.1
19a	SE bank of Twentymile River, ~40 m downstream from site 18	E081723A	60°50′40.32″N	148°58′34.76″W	60	1.0	0.9
19b	SE bank of Twentymile River, ~40 m downstream from site 18	E081723A	60°50′40.32″N	148°58′34.76″W	60	1.0	0.9
20	SE bank of Twentymile River, 5.4 m downstream from site 19	E081800A	60°50′40.39″N	148°58′35.34″W	70	1.3	0.8
21a	SE bank of Twentymile River, 5.3 m downstream from site 20	E081801A	60°50′40.52″N	148°58′35.71″W	60	2.7	1.1
21b	SE bank of Twentymile River, 5.3 m downstream from site 20	E081801A	60°50′40.52″N	148°58′35.71″W	60	2.7	1.1
22	SE bank of Twentymile River, ~30 m downstream from site 21	E081819A	60°50′40.51″N	148°58′37.60″W	60	0.7	1.1
23	SE bank of Twentymile River, dike at westernmost end of exposure	E081600B	60°50′40.72″N	148°58′45.09″W	32	1.0	1.2
24	SE bank of Twentymile River, between sites 13 and 14	E081718A	60°50′37.99″N	148°58′25.70″W	60	2.5	1.9
25	SE bank of Twentymile River, between sites 13 and 14	E081718D	60°50′37.77″N	148°58′24.61″W	60	3.3	1.3
26	SE bank of Twentymile River, between sites 13 and 14	E081719A	60°50′38.95″N	148°58′13.31″W	60	2.8	0.7
27	SE bank of Twentymile River, NE of site 13	E081719B	60°50′42.28″N	148°58′05.25″W	65	1.2	0.9
28	SE bank of Twentymile River, NE of site 13	E081720A	60°50′43.33″N	148°58′03.10″W	60	1.8	1.7
29	Easternmost dike along SE bank of Twentymile River	E081720B	60°50′44.60″N	148°58′02.66″W	62	0.8	0.9
30	Southernmost dike on NW bank of Twentymile River	E081822A	60°50′49.21″N	148°58′25.18″W	60	0.5	0.5
31a	NW bank of Twentymile River, ~15 m NE of site 30	E081823A	60°50′49.67″N	148°58′24.57″W	70	2.8	1.5
32	NW bank of Twentymile River, 5.5 m NE of site 31	E081900A	60°50′49.81″N	148°58′24.15″W	61	2.4	0.7
33a	North bank of Portage Creek (south channel), west end of exposure	E081921A	60°49′16.03″N	148°58′42.36″W	68	3.2	2.6

Site no.	Location notes	GPS ID	Latitude	Corrected Longitude	GPS fixes	Std. dev. (m) N–S	Std. dev. (m) E–W
34	North bank of Portage Creek (south channel), near west end of exposure	E081921A	60°49′16.03″N	148°58′42.36″W	68	3.2	2.6
33b	North bank of Portage Creek (south channel), east end of exposure; site 34 is between here and site 33a	E081921B	60°49′16.92″N	148°58′36.01″W	60	1.5	0.8
35a	South bank of Portage Creek (south channel); east end of series of dikes	E081918A	60°49′09.60″N	148°58′53.05″W	60	1.2	0.5
35w/36	South bank of Portage Creek (south channel), 49.4 m west of site 35a	E081922C	60°49′08.01″N	148°59′00.08″W	60	2.5	1.1
37a	West bank, Placer River (east channel), opposite confluence with Portage Creek (S channel)	E082019A	60°49′10.80″N	148°59′14.19″W	63	2.1	2.6
37b	West bank, Placer River (east channel), opposite confluence with Portage Creek (S channel), ~3 m N of 37a	E082019A	60°49′10.80″N	148°59′14.19″W	63	2.1	2.6
39	West bank, Twentymile River, ~1 km upstream from RR bridge	E090101A	60°50′55.46″N	148°58′12.84″W	60	2.1	1.0
40a, 40b	West bank, Twentymile River, ~20 m SW of site 39	E090101B	60°50′54.93″N	148°58′14.15″W	60	1.6	1.3
41	West bank, Twentymile River, NE of site 39	E090200A	60°50′57.10″N	148°58′09.42″W	60	1.0	1.0
42	West bank, Twentymile River, NE of site 39	E090200B	60°50′58.47″N	148°58′07.57″W	60	1.1	0.9
43	West bank, Twentymile River, NE of site 39	E090201A	60°51′02.38″N	148°58′04.67″W	60	0.9	1.3
44	West bank, Twentymile River, NE of site 39	E090201B	60°51′05.33″N	148°58′01.85″W	6	0.8	0.7
45	West bank, Twentymile River, NE of site 39; upstream limit of observed dikes	E090201C	60°51′06.96″N	148°58′00.09″W	60	1.7	1.3
46	West bank, Placer River (east channel); dike at north end of exposure, ~200 m south of bridge	E082023A	60°48′56.80″N	148°59′13.31″W	68	4.2	1.6
49a	West bank, Placer River (east channel), 38.2 m south of site 46; south end of exposure	E090218B	60°48′55.46″N	148°59′13.65″W	60	1.1	0.7
50	North bank, Portage Creek (north channel) near mouth, SE end of exposure	E090220A	60°49′55.95″N	148°59′15.03″W	116	1.6	1.4
61	North bank, Portage Creek (north channel), 113.9 m NW of site 50	E090322A	60°49′58.55″N	148°59′20.34″W	60	2.0	2.5
68	North bank, Portage Creek (north channel), 193.8 m NW of site 50	E090323A	60°50′00.56″N	148°59′23.52″W	84	0.9	1.6
71	North bank, Portage Creek (north channel), NW end of exposure, 301.7 m NW of site 50	E090400A	60°50′03.36″N	148°59′27.52″W	60	1.4	1.1
72	South bank of Portage Creek (north channel); SE end of exposure, next to bridge. No dikes.	E090417A	60°49′38.44″N	148°58′36.43″W	60	6.3	1.9
73	South bank of Portage Creek (north channel), ~100 m NW of site 72	E090418A	60°49′40.42″N	148°58′41.75″W	60	1.2	1.2
74	South bank of Portage Creek (north channel), ~250 m NW of site 72	E090419A	60°49′42.55″N	148°58′45.44″W	60	1.9	2.0
77	South bank of Portage Creek (north channel), dike at NW end of exposure, ~300 m NW of site 72	E090420A	60°49′46.86″N	148°58′47.85″W	60	1.0	1.3
78	South bank of Portage Creek (north channel), ~70 m west of site 77; east end of exposure (no dikes)	E090421A	60°49′47.75″N	148°58′51.95″W	62	1.2	0.9

Site no.	Location notes	GPS ID	Latitude	Corrected Longitude	GPS fixes	Std. dev. (m) N–S	Std. dev. (m) E–W
79a	South bank of Portage Creek (north channel), beginning of series of clastic dikes, ~20 m west of site 78	E090421B	60°49′47.52″N	148°58′53.17″W	60	2.9	1.6
79j	South bank of Portage Creek (north channel), 25 m W of site 79a	E090422A	60°49′47.68″N	148°58′54.85″W	60	1.0	0.7
79t	South bank of Portage Creek (north channel), 132 m west of site 79a	E090423B	60°49′47.89″N	148°59′01.11″W	60	0.9	0.7
80a-1 80a-2 80a-3	West-facing bank at mouth of Portage Creek (north channel), south end of exposure	E090502B	60°49′48.29″N	148°59′17.47″W	60	1.1	0.8
80g	Northwest-facing bank at mouth of Portage Creek (north channel), 41.3 m north of site 80a	E090502C	60°49′49.64″N	148°59′16.84″W	60	1.1	1.0
80n	North-facing bank at mouth of Portage Creek (north channel), 56.5 m east of site 80g; east end of exposure	E090502D	60°49′49.19″N	148°59′13.28″W	60	1.4	1.2
Locality 2	Foster and Karlstrom (1967)	E090723A	60°38′59.73″N	150°49′06.87″W	70	3.1	2.3
CR1	Copper River delta, north bank of Alaganik Slough	E082819A	60°25′40.72″N[2]	145°18′21.53″W[2]	60	33.2	13.6
CR2	Copper River delta, north bank of Alaganik Slough southwest of CR1 on same bank	E082820A	60°25′36.93″N[2]	145°18′42.43″W[2]	60	14.7	12.7
CR3	Copper River delta, south bank of Pete Dahl Slough	E082921A	60°25′10.59″N[2]	145°08′42.77″W[2]	63	15.5	4.5

Table 3. Grain-size data for source beds and clastic intrusions at Portage resulting from liquefaction during the 1964 great Alaska earthquake ($M_w = 9.2$) and for a dike and sand blow in the Kenai Lowland (Locality 2). Size ranges (grain diameter: gravel, >2.0 mm; sand, 0.625–2.0 mm; silt/clay, <0.625 mm. Graphs of these data are shown in the Appendix

Site no.	Feature	Mean diameter (mm)	Standard deviation(ϕ)	Skewness(ϕ)	Percent gravel	Percent sand	Percent silt/clay
13	Sill	0.81	1.8	1.0	20.8	67.5	11.7
14	Dike	2.46	2.0	1.3	66.8	27.7	5.5
16b	Dike	1.41	1.7	0.6	41.9	54.9	3.2
17	Dike	2.83	2.0	1.0	67.9	29.9	2.2
17	Dike	0.44	1.1	0.8	0.8	93.5	5.7
30	Dike	0.76	1.9	-0.3	19.3	74.5	6.2
37b	Dike	1.00	1.4	0.0	21.3	77.0	1.7
39	Dike	0.31	0.7	1.8	0.1	96.2	3.7
39	Source bed	0.35	1.0	1.1	0.6	92.9	6.5
40a	Dike	0.35	0.7	1.5	0.0	97.3	2.7
40a	Source bed	2.64	2.3	0.4	56.5	40.7	2.8
42	Dike	0.44	0.7	0.8	0.3	98.4	1.3
42	Source bed	1.74	2.1	-0.1	44.8	54.1	1.1
43	Dike, 1st stage	0.38	1.7	0.6	3.5	74.2	22.3
43	Dike, 2nd stage	0.54	1.1	1.4	1.9	92.5	5.6
49b	Dike	4.00	2.0	1.6	78.1	17.9	4.0
Locality 2	Extruded sand	0.22	1.1	-0.1	0.8	90.8	8.4
Locality 2	Dike at base of pit	0.20	1.0	0.1	0.3	92.4	7.3

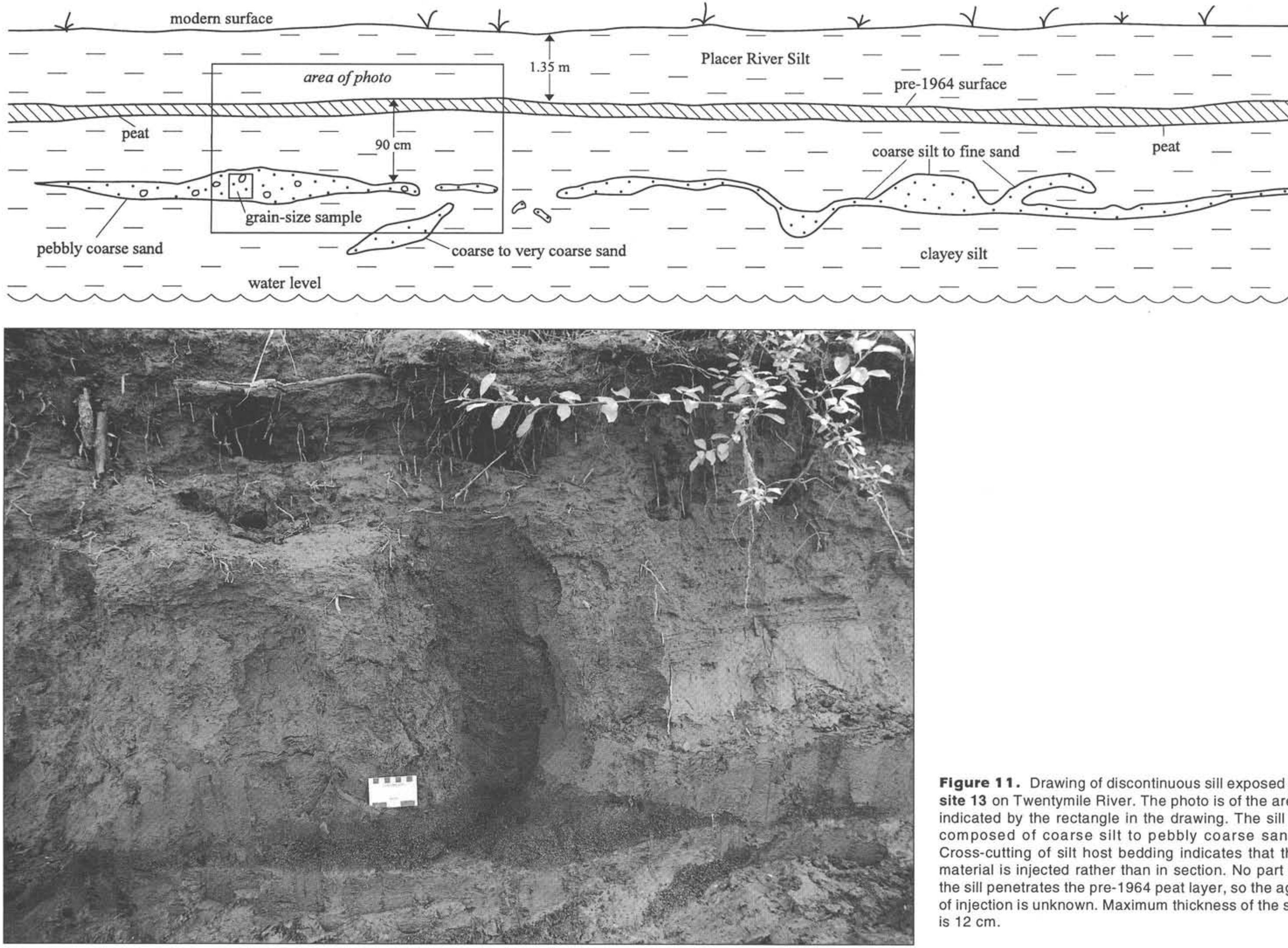
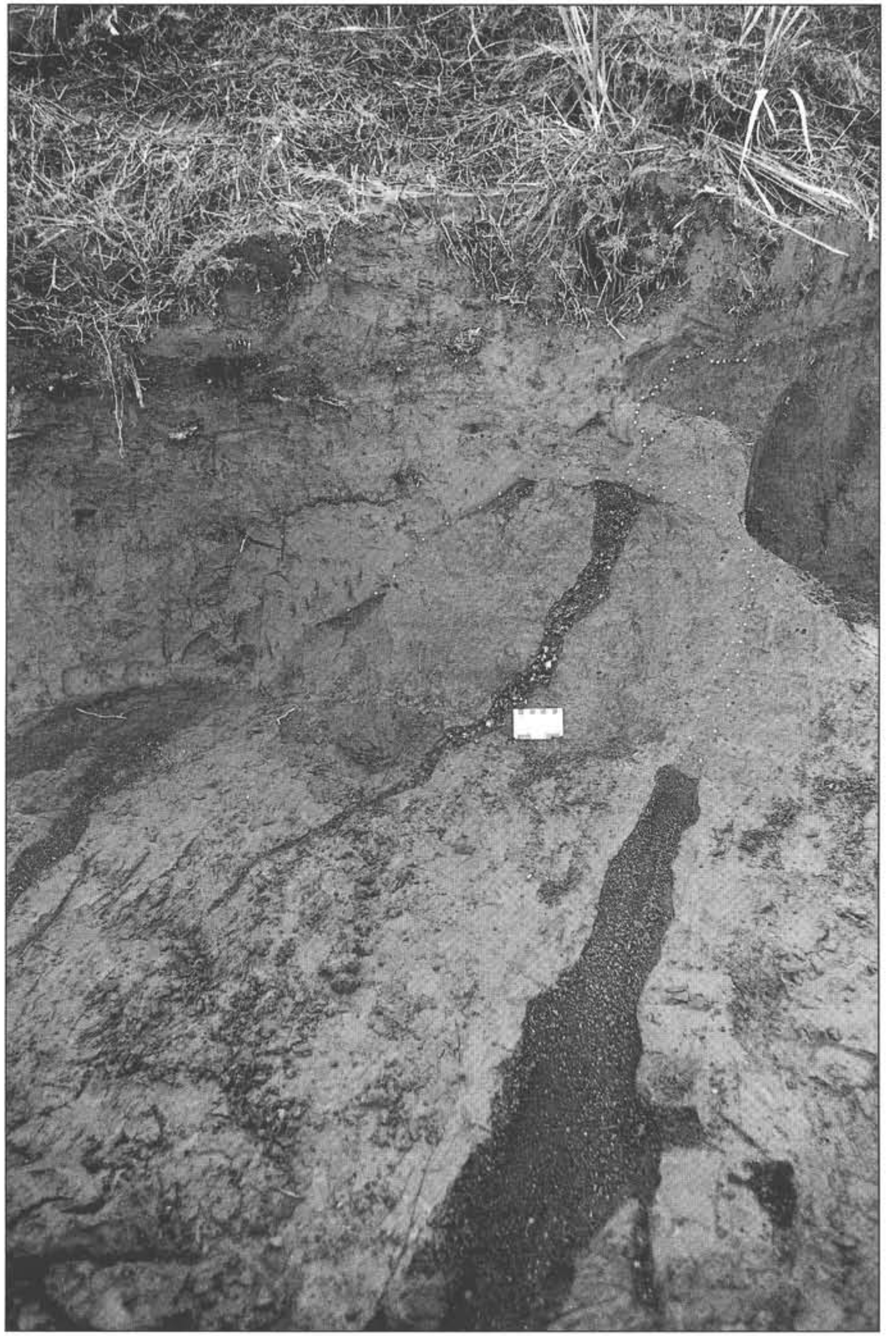


Figure 11. Drawing of discontinuous sill exposed at **site 13** on Twentymile River. The photo is of the area indicated by the rectangle in the drawing. The sill is composed of coarse silt to pebbly coarse sand. Cross-cutting of silt host bedding indicates that the material is injected rather than in section. No part of the sill penetrates the pre-1964 peat layer, so the age of injection is unknown. Maximum thickness of the sill is 12 cm.



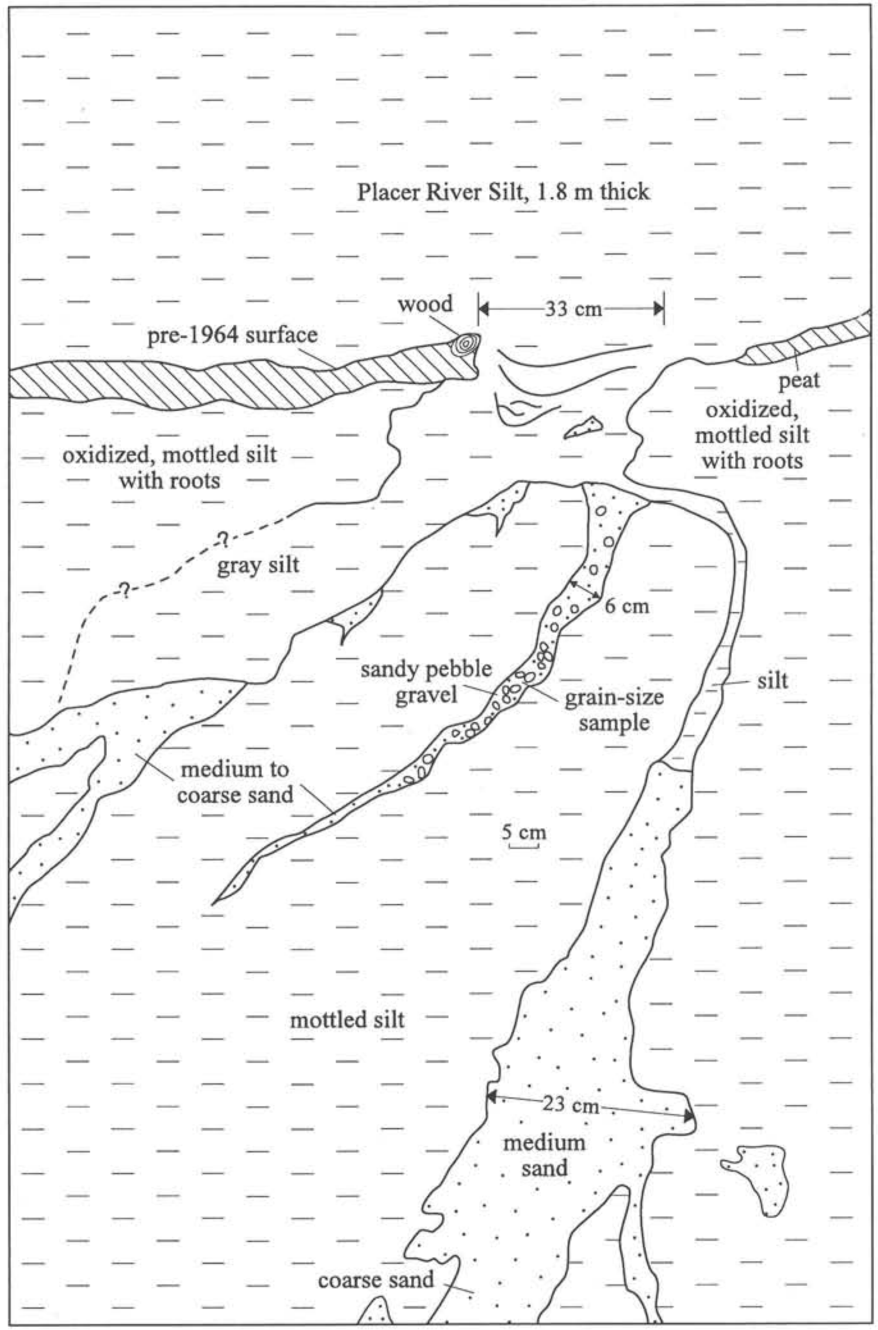


Figure 12. Photo and drawing of dikes at **site 14** on Twentymile River. Three dikes of medium sand to sandy pebble gravel merge upward to connect at a single 33-cm-wide break in the pre-1964 peat layer. The upper parts of the dikes have been truncated and replaced by silt infilling from above, probably as a result of reworking by tidal flooding after the earthquake. Silt replacement extends to a maximum of 83 cm below the top of the pre-1964 surface.

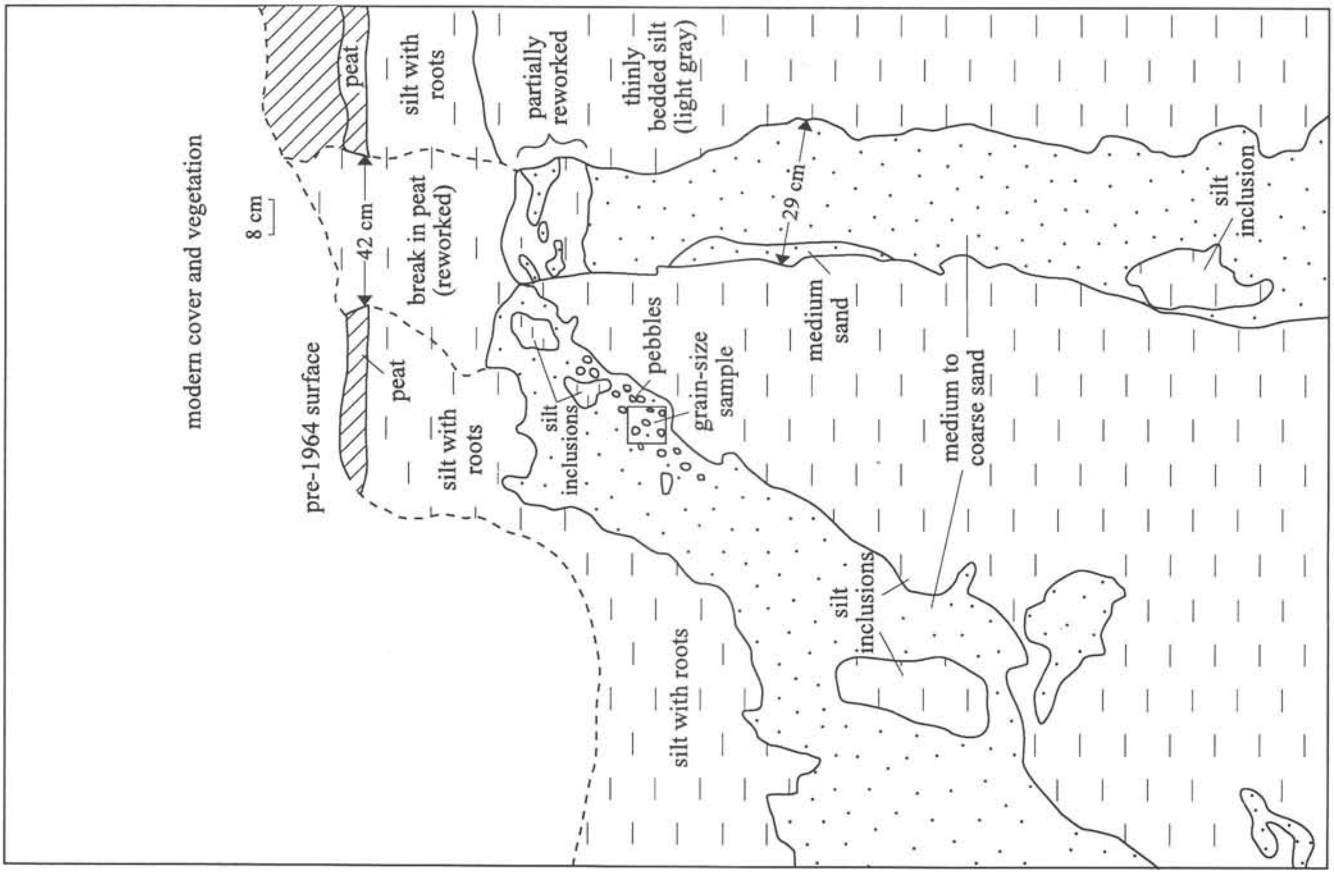


Figure 13. Photo and drawing of dikes at **site 16** on Twentymile River. Two dikes of medium to coarse sand merge upward to connect at a single 42-cm-wide break in the pre-1964 peat layer. Dikes are locally gravelly, with pebbles ranging in size to as much as 2 cm diameter. Dike margins have oxidized crusts up to 3 cm thick. The upper parts of both dikes are reworked and replaced with silt from above.

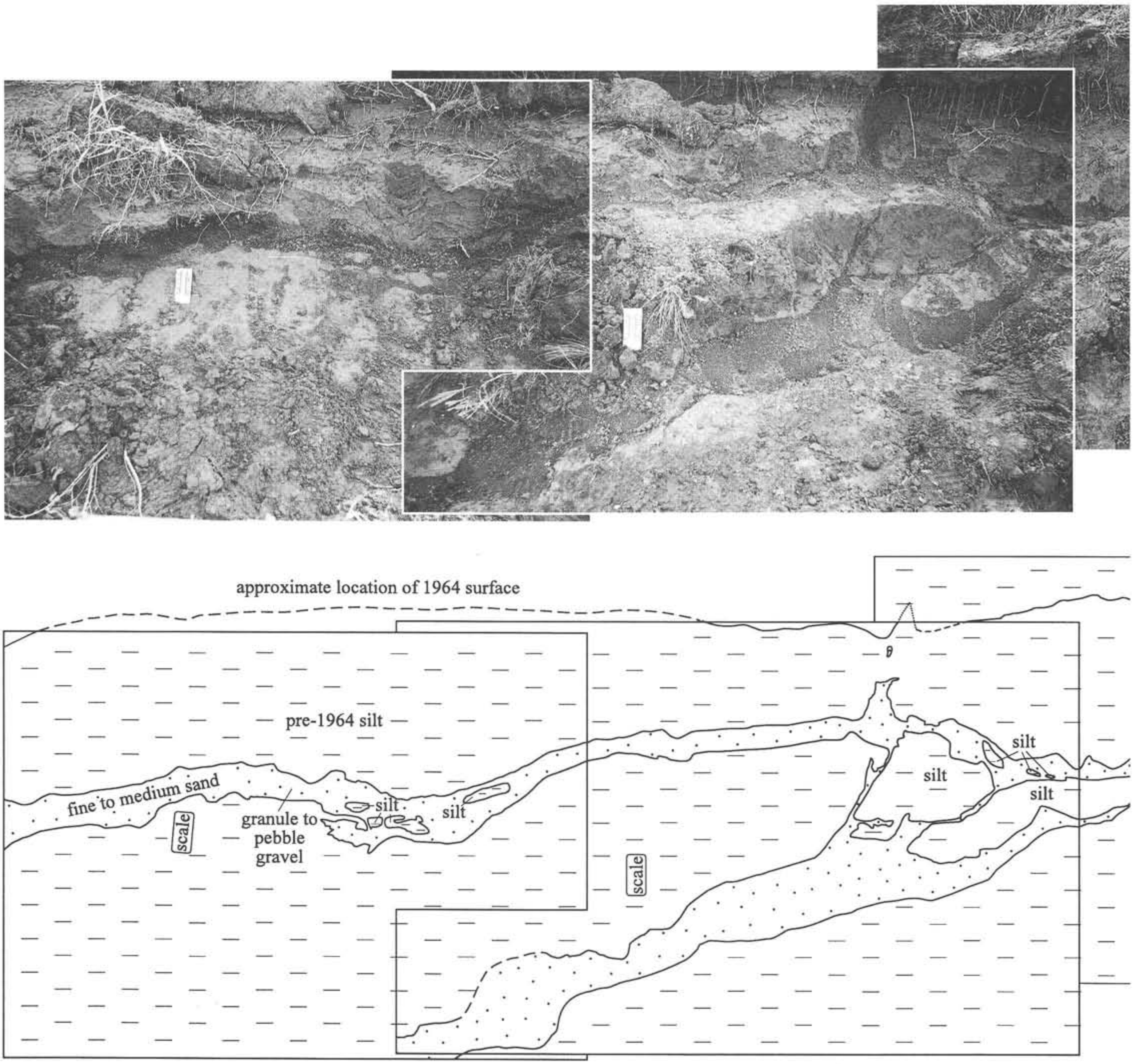
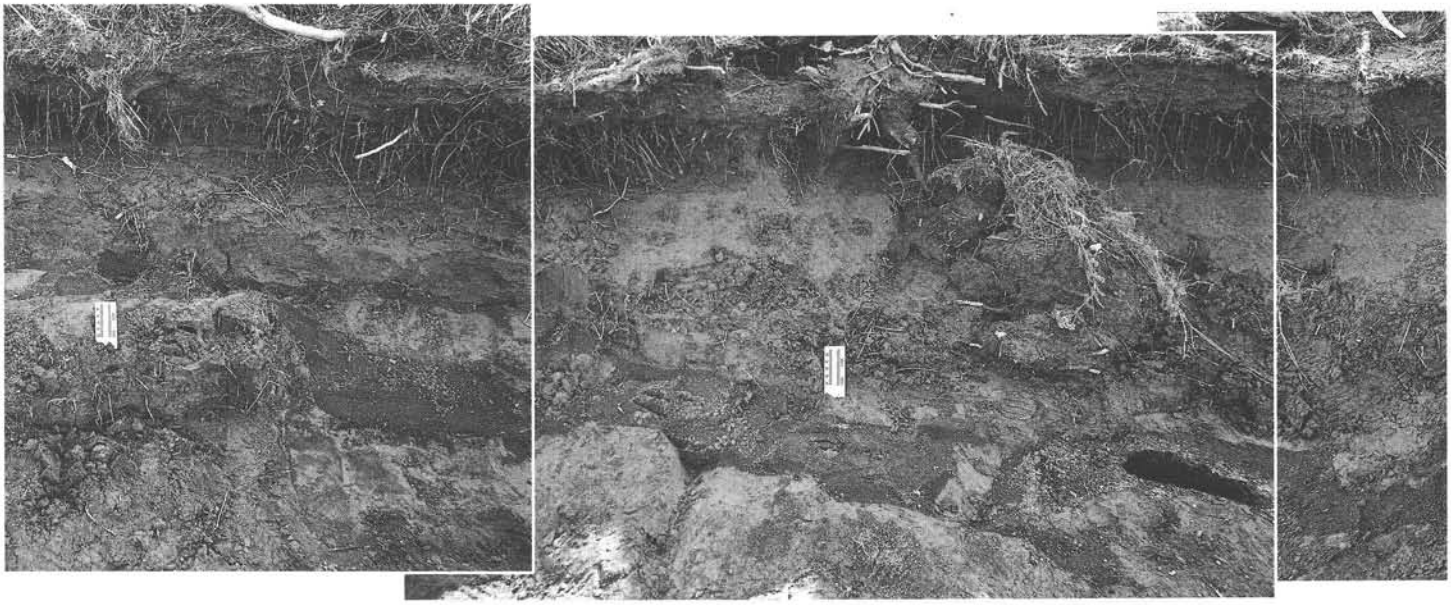


Figure 14. Photo and drawing of complex dike at **site 17** on Twentymile River. This dike extends parallel to shore for 17.5 m and has three branches that are normal to shore, apparently bounding two landslide blocks caused by lateral spreading.



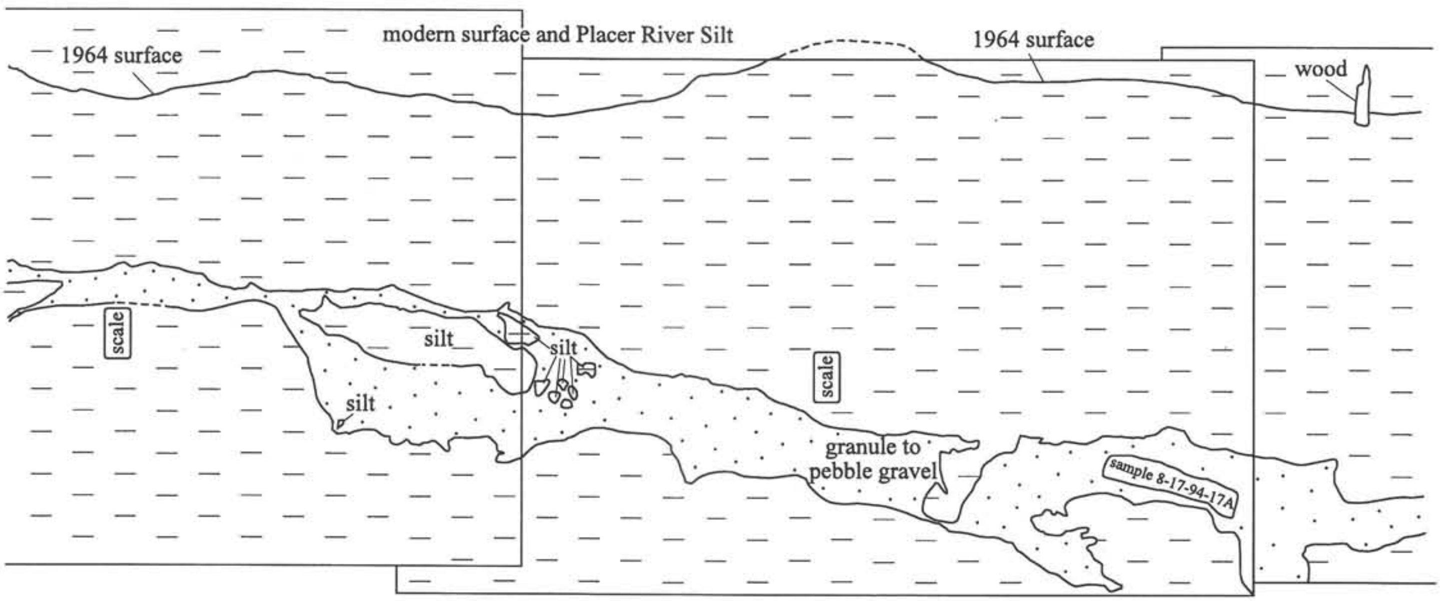


Figure 14. *(continued)* Photo and drawing of complex dike at **site 17**. Analysis of sample given in Appendix figure A4.

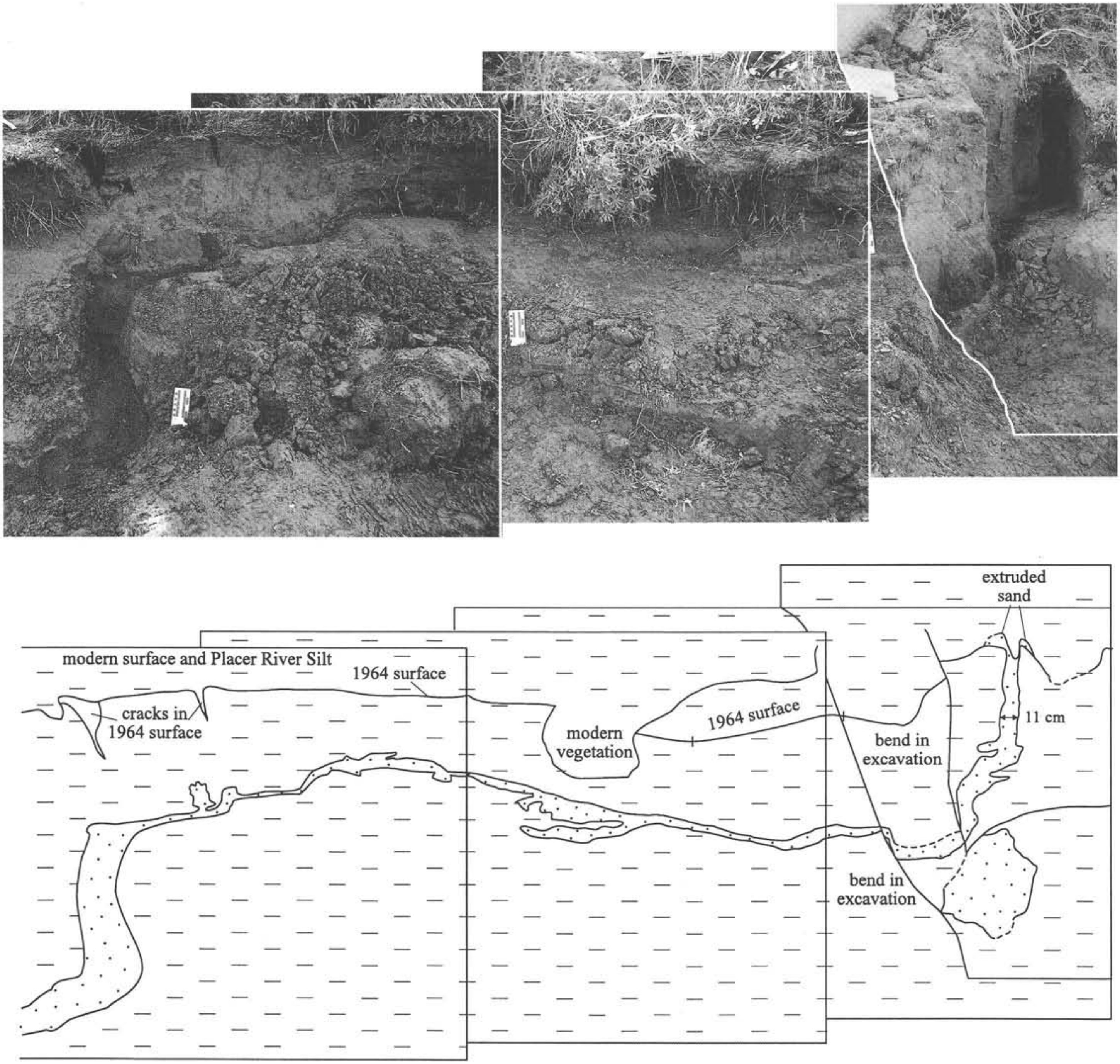


Figure 14. *(continued)* Photo and drawing of complex dike at **site 17**.

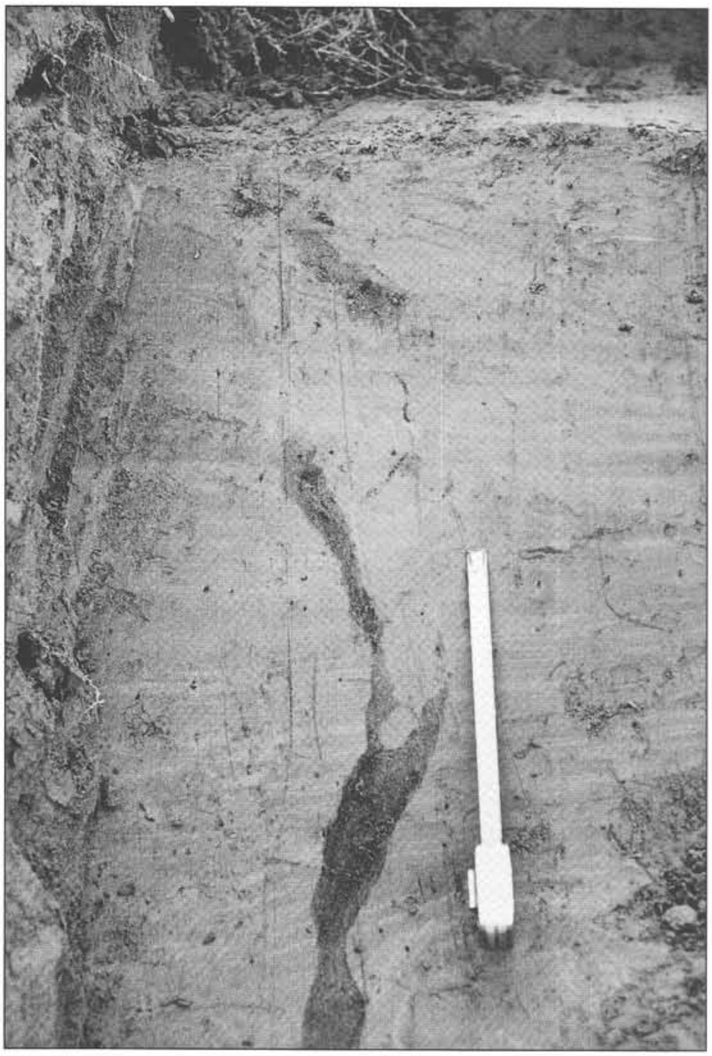


Figure 15. *(above)* Photo of two large sand dikes at **site 18** on Twentymile River. Dikes consist of dark gray medium sand and terminate 40–45 cm below the top of the pre-1964 peat layer. The peat layer is delimited by two horizontal rows of white pins. The upper parts of the dikes are replaced with silt from above, probably as a result of tidal reworking after the earthquake. Both dikes show cross-bedding in silt near the sand–silt contacts, indicating reworking of the sand into the lower portion of the silt. Replacement silt in the dike on the left truncates a sand sill that was likely injected from the dike. A thin layer of medium sand overlying the peat layer near the left dike is probably a remnant of a sand boil associated with the dikes.

Figure 16. *(left)* Photo of thin (3–5 cm) dike at **site 19** on Twentymile River that bifurcates 70 cm below 1964 peat (not shown in photograph). Dike is composed predominantly of medium lithic sand with minor granule-bearing sand. Thin (1–2 mm) sand stringers define the right margin of the dike above where it bifurcates. The area between the limbs is filled with very fine, light-gray sand that is coarser than the silt intruded or the overlying Placer River Silt.

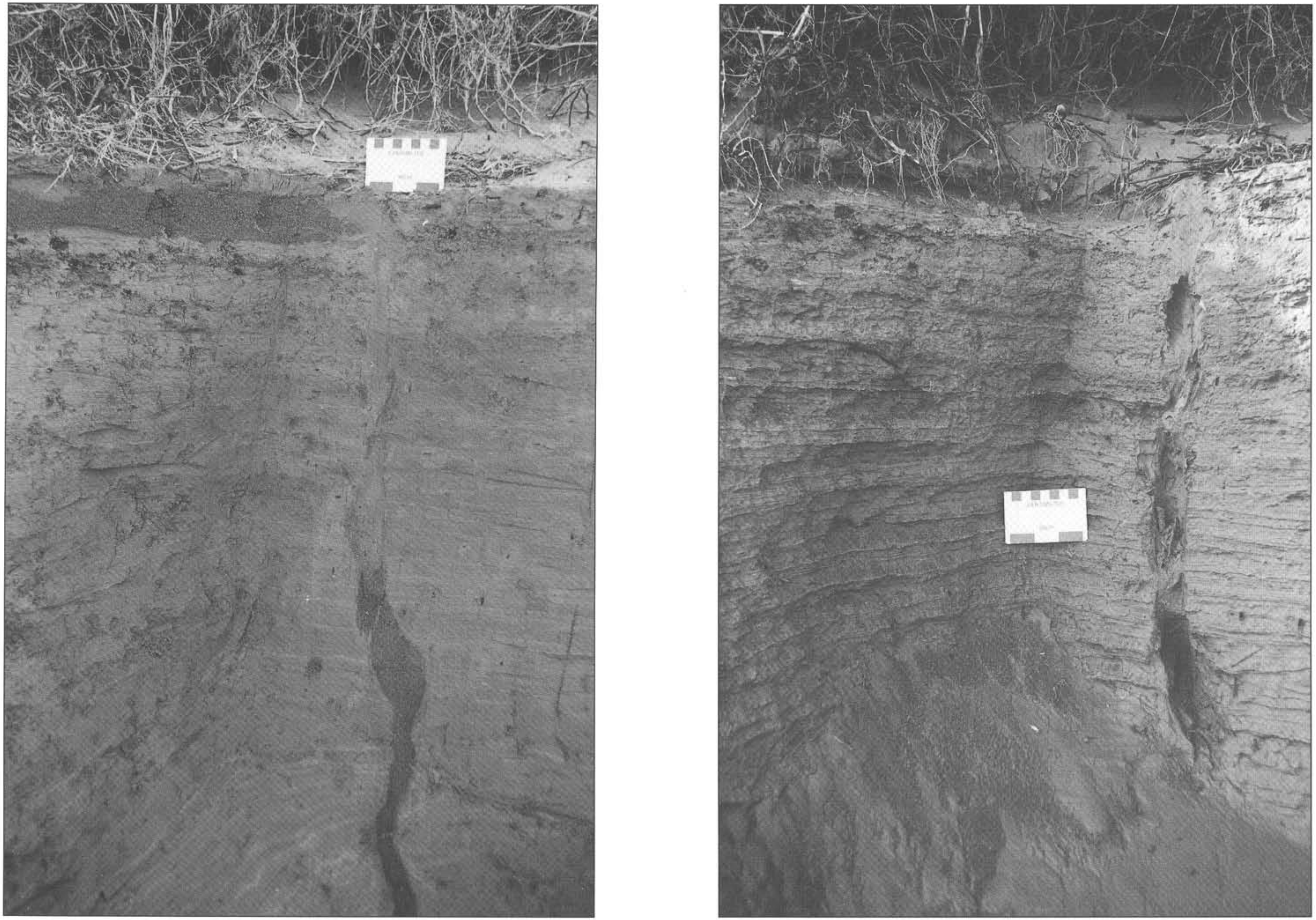


Figure 17. Photos of sand dike and boil at **site 20** on Twentymile River before and after etching by high tide. The left photo shows the remainder of a partially eroded sand boil, 5 cm thick, extending to the left of the dike. This sand boil overlies 2 cm of silt, which in turn overlies a thin (1 cm) peat that marks the pre-1964 surface. The upper part of dike is replaced with silt to 36 cm below the pre-1964 surface. The right photo shows that the sand erodes much more rapidly than silt during tidal flooding.

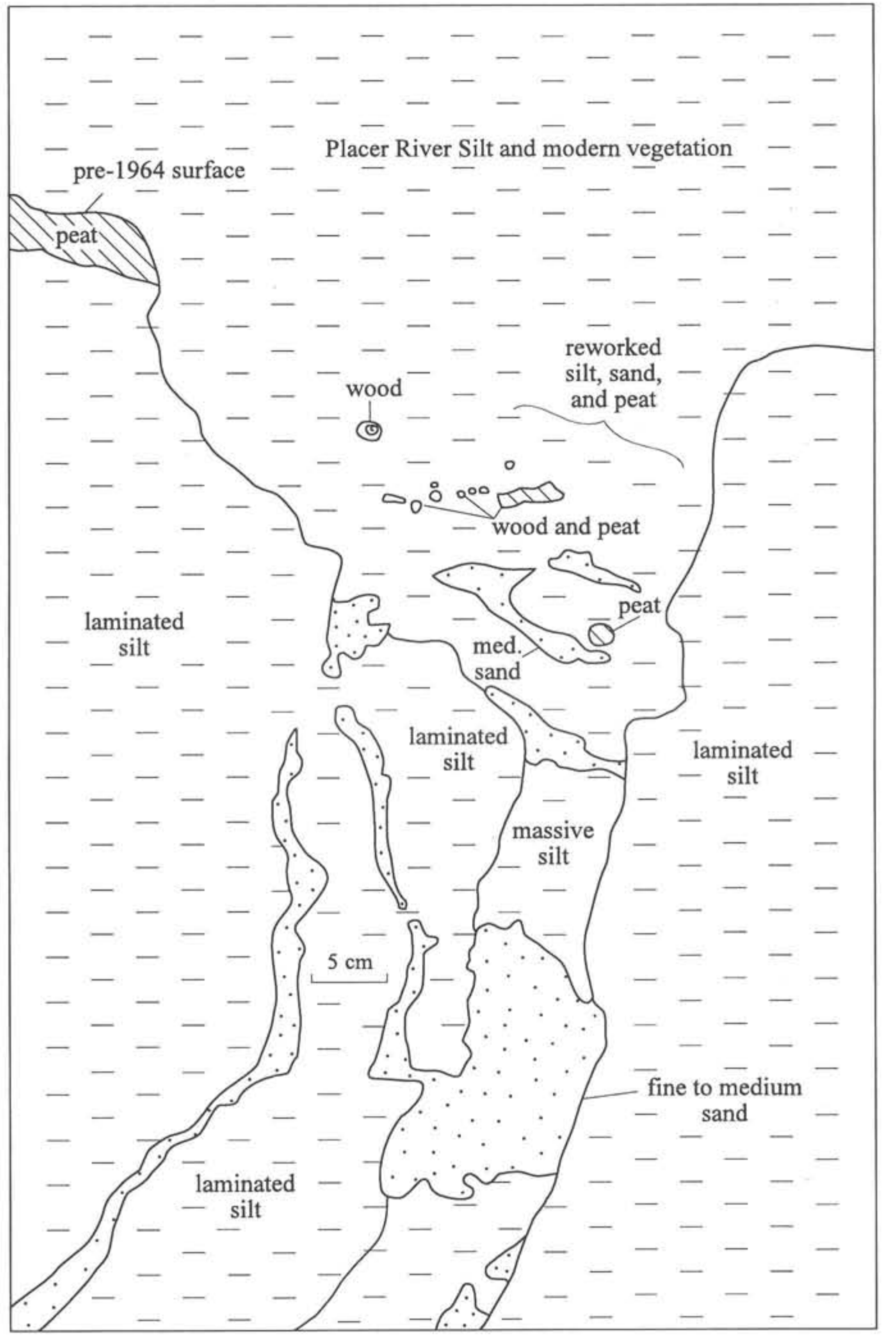


Figure 18. Photo and drawing of discontinuous, anastomosing dikes at **site 21** on Twentymile River. Silt replaces the upper 40 cm of the thicker dike on the right and truncates the thinner dike on the left. Reworked peat and dike sand appear in the replacement silt, which was probably emplaced during tidal flooding after the earthquake. Host silt is laminated. The break in the pre-1964 surface (top of peat layer) is 35 cm wide.

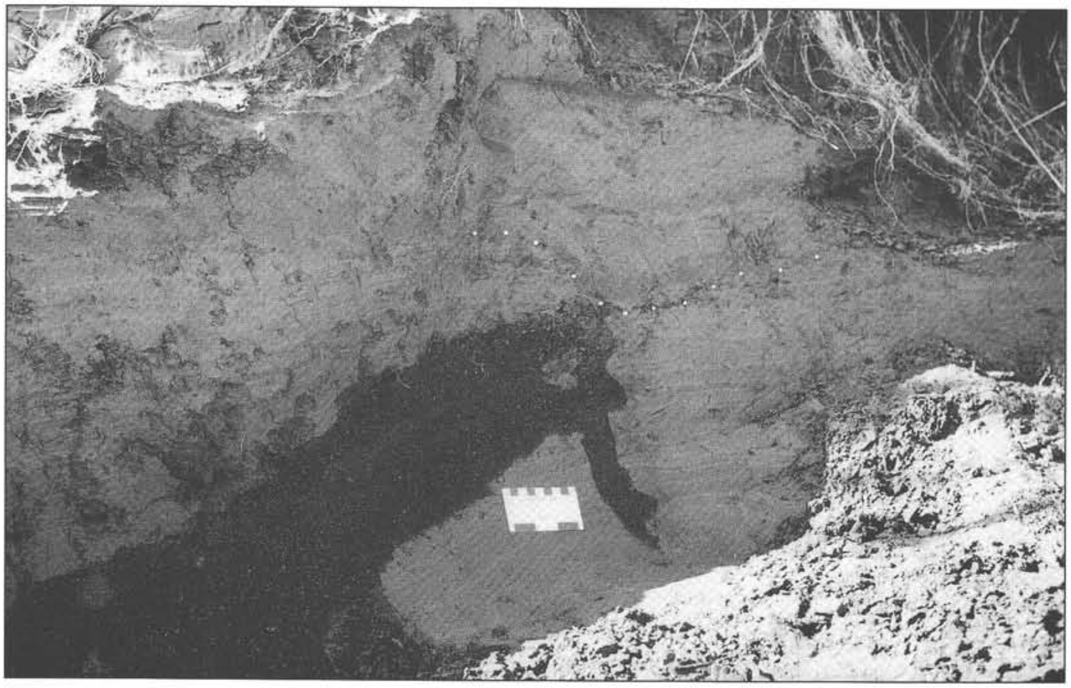


Figure 19. Photo of dike/sill 20 cm thick at **site 22** on Twentymile River. It is composed of pebbly medium to coarse lithic sand. Largest clast is 3 x 2 x 0.4 cm. Pins mark the position of poorly expressed 1964 peat surface. A thin sand stringer over the peat surface may be extruded sand. The source is shown at base of the photo. The vertical distance from the source to the peat is approximately 42 cm.

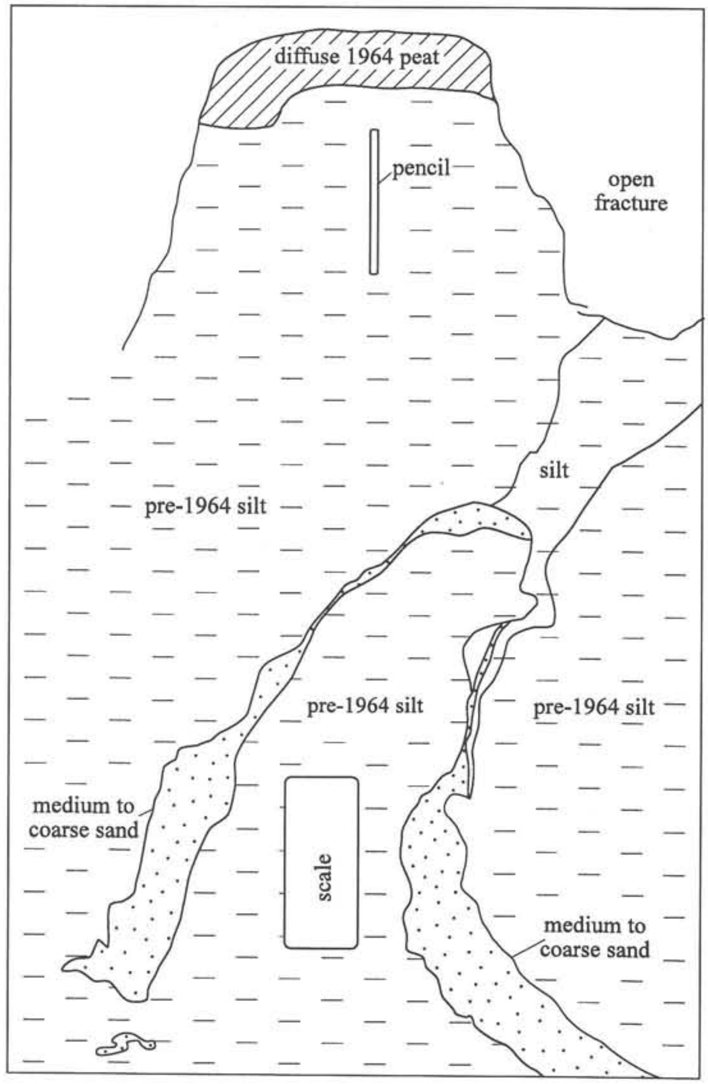


Figure 20. Two dikes at **site 24** that coalesce 32 cm below base of the 1964 peat. The top of the pencil marks the base of the 1964 surface. Dikes are 5 cm *(left)* and 6 cm *(right)* wide and pinch out approximately 50 cm below the 1964 surface. Both dikes are composed of medium to coarse sand. The upper 20 cm of the dike has been replaced by Placer River Silt. There is 20 cm of open fracture between the top of the dike and the 1964 surface. There is no evidence of erupted sand.

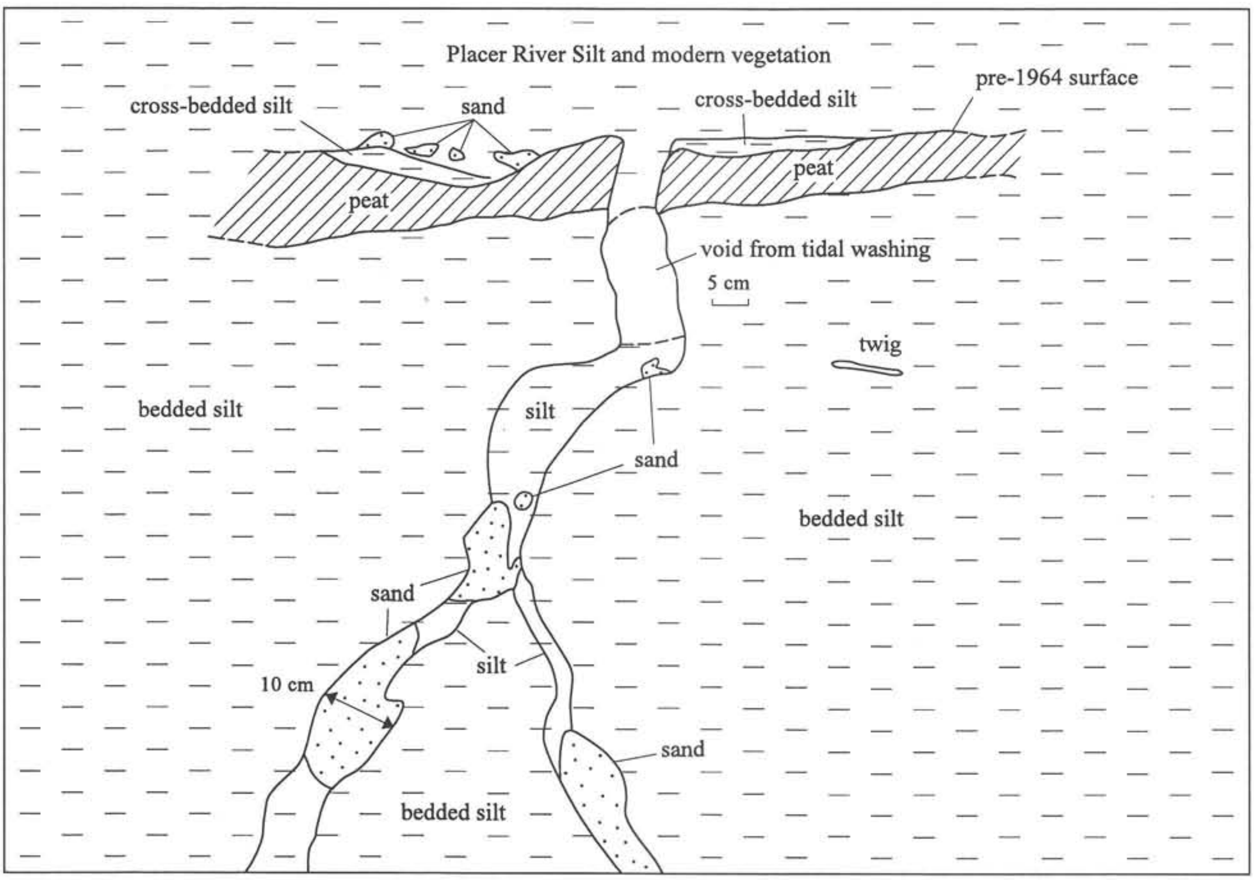
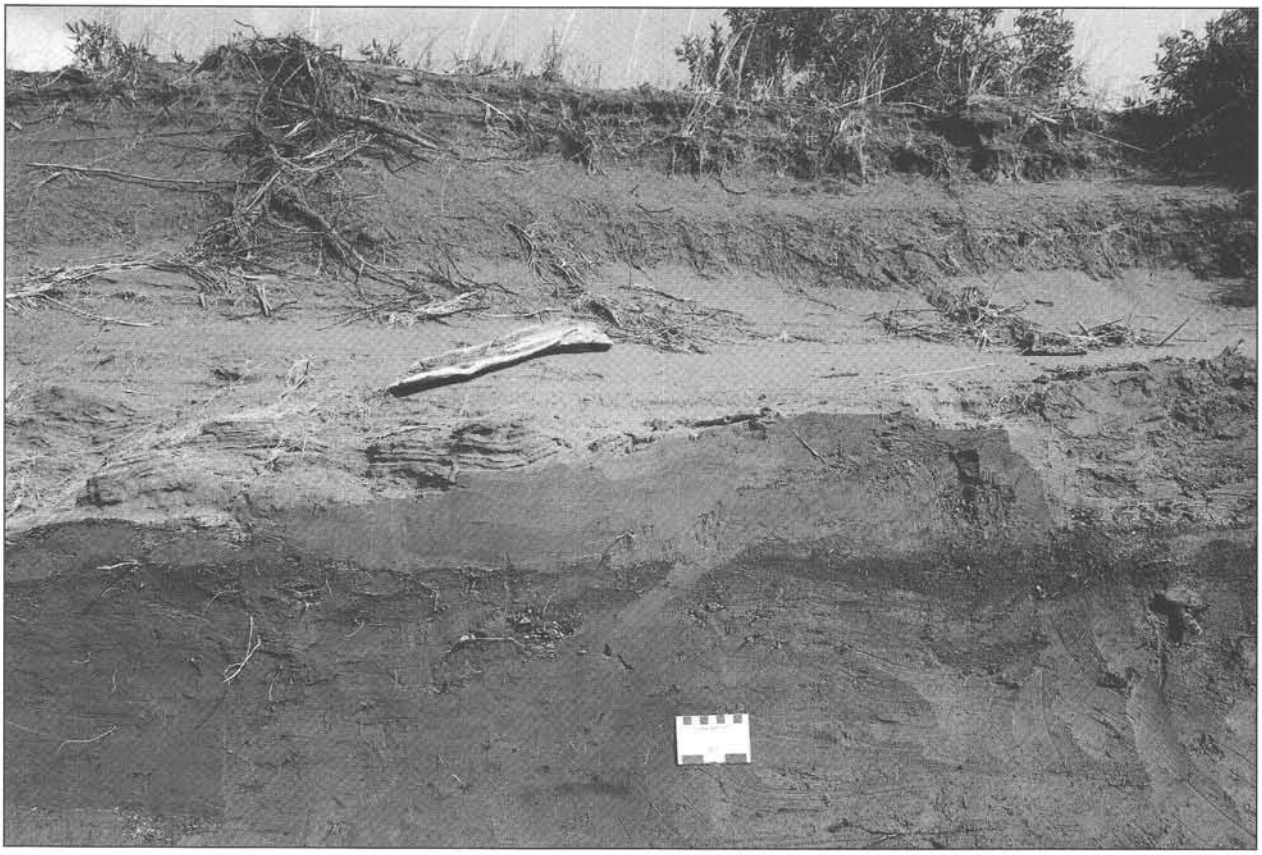


Figure 21. Photo and drawing of discontinuous, coalescing dikes at **site 25** on Twentymile River. White pins mark the boundaries of the dike above the junction and the pre-1964 surface above the peat layer. Silt from above replaces the dike sand down to the junction at a depth of about 40 cm below the pre-1964 surface. Small sand pods above the pre-1964 surface left of the dike are probably remnants of a sand boil that emanated from this dike. The large void in the upper part of the dike is from recent tidal erosion.



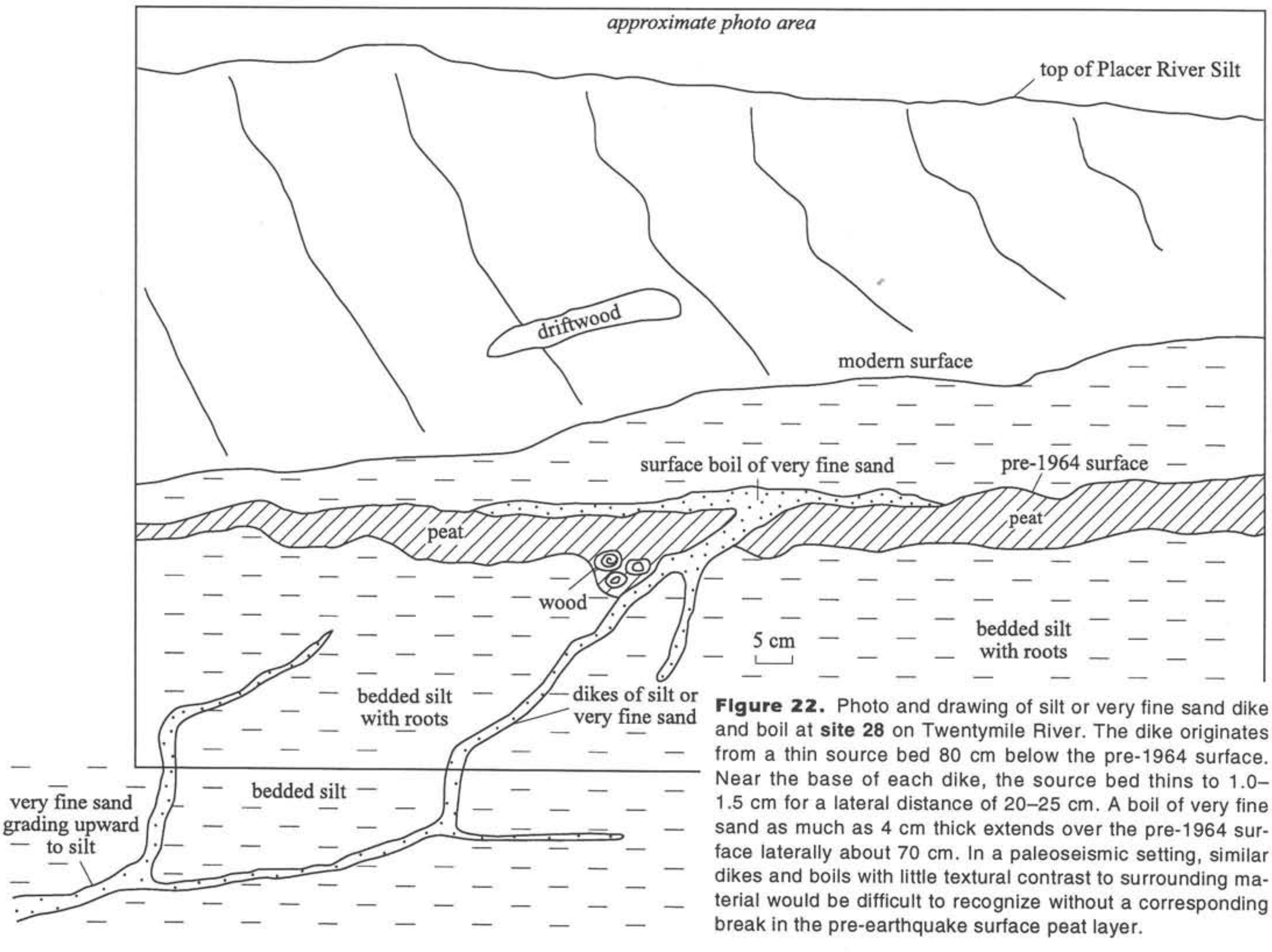


Figure 22. Photo and drawing of silt or very fine sand dike and boil at **site 28** on Twentymile River. The dike originates from a thin source bed 80 cm below the pre-1964 surface. Near the base of each dike, the source bed thins to 1.0–1.5 cm for a lateral distance of 20–25 cm. A boil of very fine sand as much as 4 cm thick extends over the pre-1964 surface laterally about 70 cm. In a paleoseismic setting, similar dikes and boils with little textural contrast to surrounding material would be difficult to recognize without a corresponding break in the pre-earthquake surface peat layer.

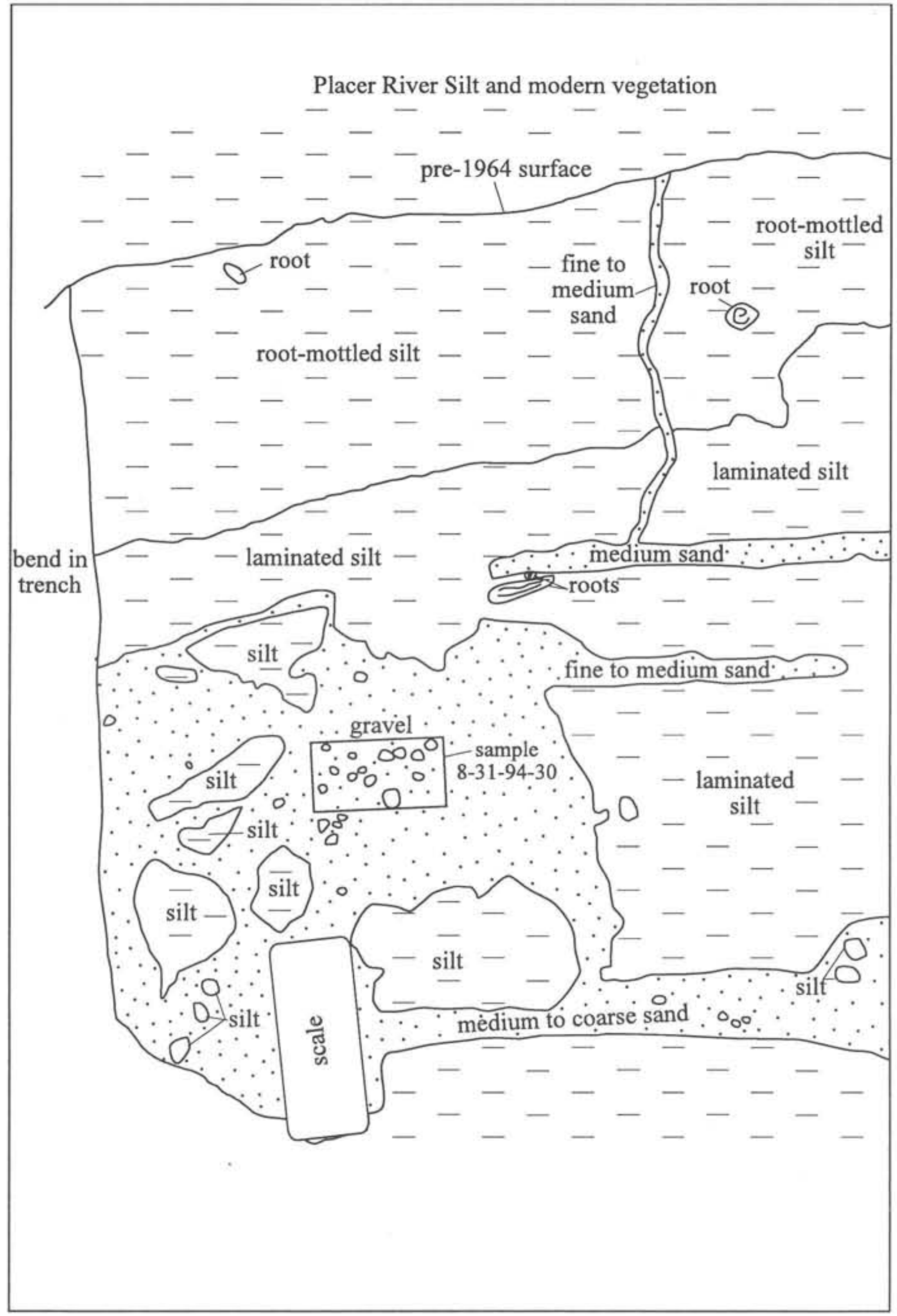


Figure 23. Photo and drawing of dike and sill complex at **site 30** on Twentymile River. This intrusion ranges from fine sand to pebbly coarse sand; it was briefly examined earlier as the tide was rising and appeared to be dominantly gravel. An apophysis of this dike penetrates the 1964 surface, but there is no evidence of a sand blow. The analysis of the indicated sample is given in Appendix figure A5.

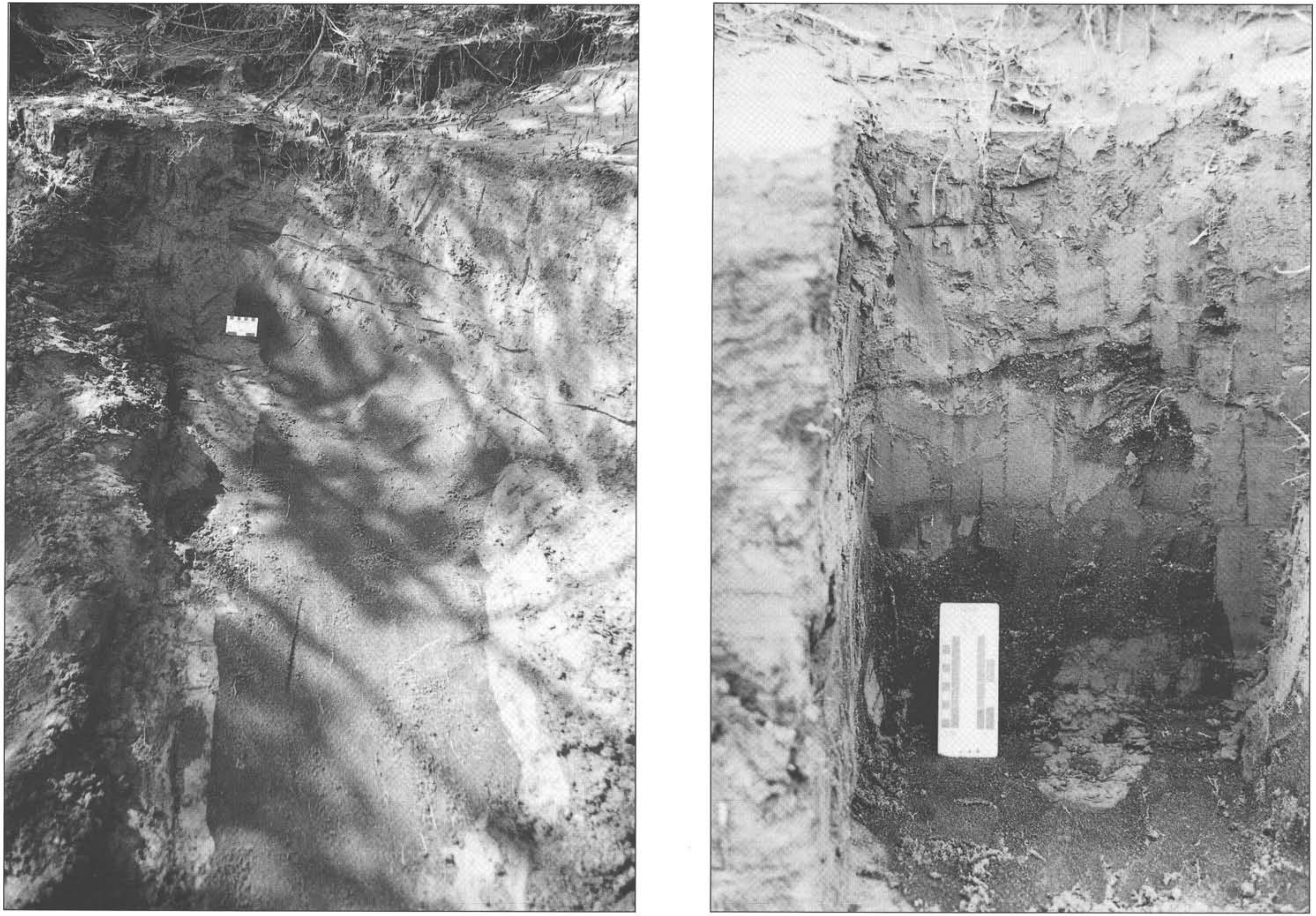


Figure 24. Photos of a large sand dike at **site 31** on Twentymile River. The dike *(left)* is composed of dark-gray, medium to coarse sand with minor pebbles to 1.5 x 2 x 3.5 cm. A relatively resistant pre-1964 peat layer forms a bench near the top of both photos and has a 34-cm-wide break above the dike. Sand similar to the dike sand appears on the pre-1964 surface nearby but cannot be traced to the dike. Sand in the upper portion of the dike is replaced with cross-bedded silt and sand to a depth of 41 cm below the pre-1964 surface. Detail photo *(right)* shows a silt inclusion suspended in the upper part of the sand dike, probably dislodged from the dike wall.

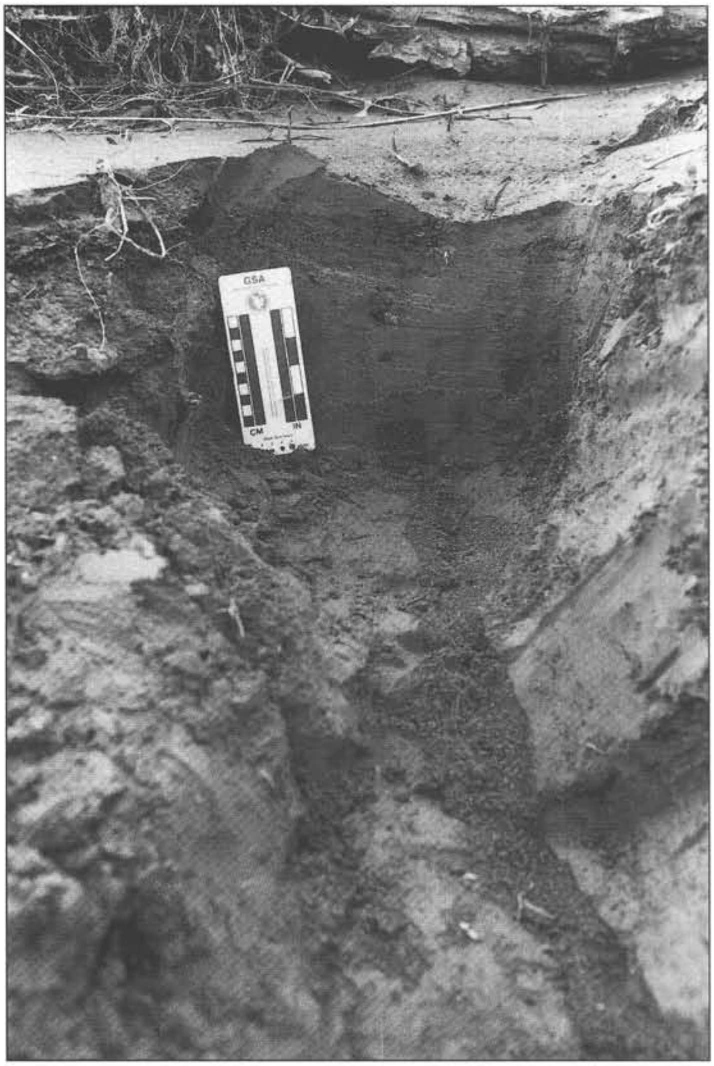
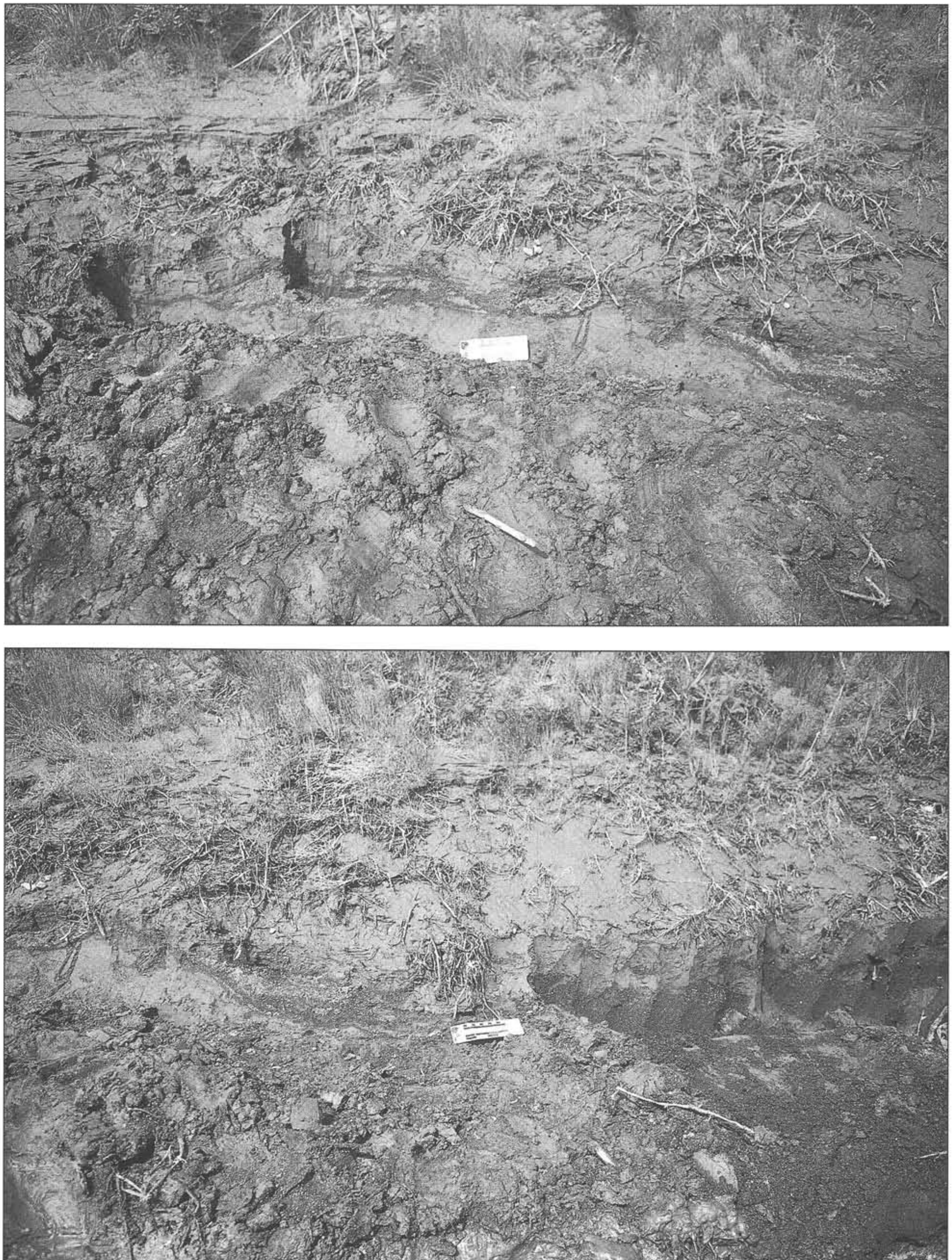


Figure 25. Photo *(left)* of a clastic dike at **site 32** on Twentymile River. This dike is truncated and filled with silt to 19 cm below the 1964 surface. No sand extrusion is visible directly above this dike, but there is a sheet of sand 2 m across preserved atop the 1964 surface about a meter to the west of this dike. A large slump obscured the pre-1964 exposure.

Photo *(below)* of a buried forest along Twentymile River, taken from site 32. The trees are rooted in a soil that is buried by about 2 m of Placer River Silt. The roots have been exposed by bank erosion since deposition of the Placer River Silt.



A

B

Figure 26. Photos of a 6.8-m-long sill of medium to coarse sand at **site 33** on Portage Creek. The west end of this sill dipped to beneath water level; black sand from beneath the 1964 surface was actively eroding from the bank for another 28 m and may have been a continuation of this sill.

C

D

Figure 26. *(continued)* Photos of a 6.8-m-long sill of medium to coarse sand at **site 33** on Portage Creek. The 1964 surface is marked by the pallet and hewn wood and other debris. Near the eastern end of this exposure (shown in the lower photo) the sill is underlain by a 25-cm-wide dike that can only be traced down to water level.

Figure 27. Photo of a dike at **site 34** on Portage Creek. It is filled with medium sand and terminates in a sand blow 128 cm in diameter and 1.5–2.5 cm thick. The upper 10 cm of the dike is an open fracture (partially obscured by scale). Beneath the scale is 12 cm of wavy- to lenticular-bedded sand and silt resting on 11 cm of silt. Between the 1964 surface and the extruded sand is a 2–3-cm layer of silt containing vertically oriented rootlets.

Figure 28. Photo of complex sand intrusion at **site 35l** on Portage Creek. The dikes widen downward to as much as 1.5 m, probably near the source bed. The source bed appears to be slightly below low-tide level, about 1.5 m below the pre-1964 surface. The intrusion consists of medium to coarse sand with minor pebbles to 1.7 x 2.3 x 3.0 cm. A 1-cm-wide dike intruded the pre-1964 peat layer and erupted minor sand on the pre-1964 surface. Two wider dikes are associated with breaks in the pre-1964 peat but are replaced with silt to depths of 22 and 46 cm below the pre-1964 surface.

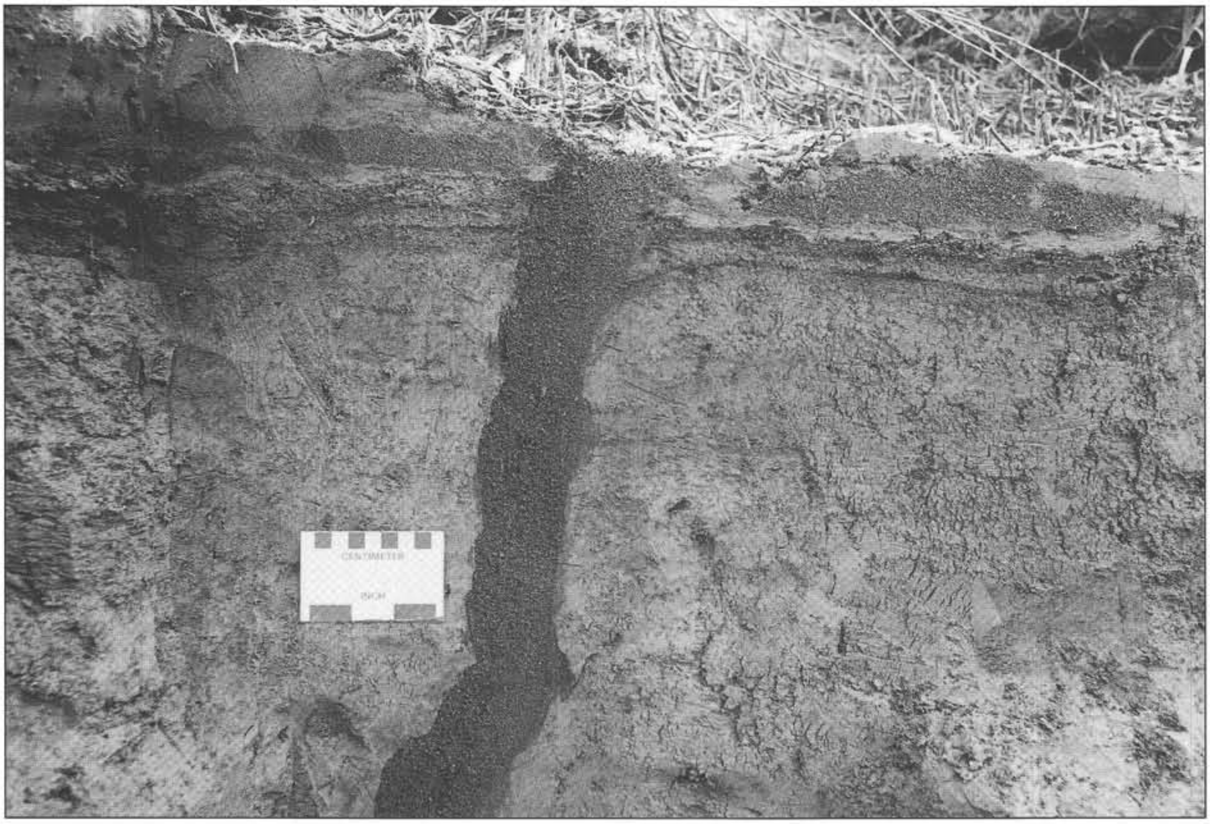
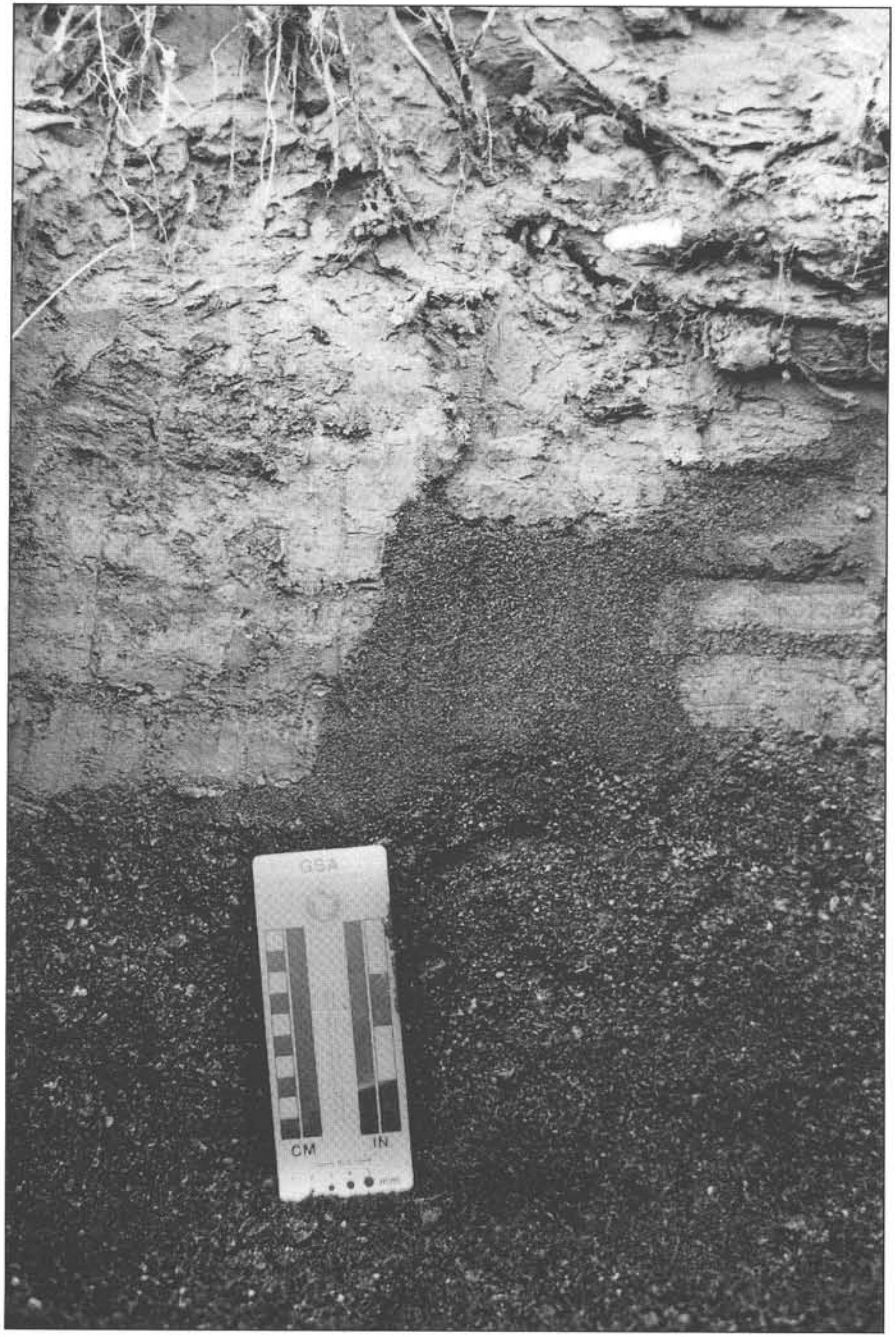


Figure 29. *(above)* Photo of a sand dike and boil at **site 35w/36** on Portage Creek. The dike is continuous through a 7-cm break in the pre-1964 peat layer, which appears here as two dark, thin seams below the sand boil. The peat layer is offset about 2 cm by the dike. Dike margins are locally oxidized to bright reddish brown. Both the dike and sand boil are composed of clean, fine to medium sand. The sand boil, maximum 4 cm thick, overlies 2–3 cm of silt lying on top of the pre-1964 peat layer and extends 33 cm to the left. To the right, the sand boil merges with another sand boil emanating from a dike 50 cm away.

Figure 30. *(left)* Photo of anastomosing dike of medium sand at **site 35ad** on Portage Creek. The tops of the branches are replaced with silt from 30-45 cm below the 1964 surface.



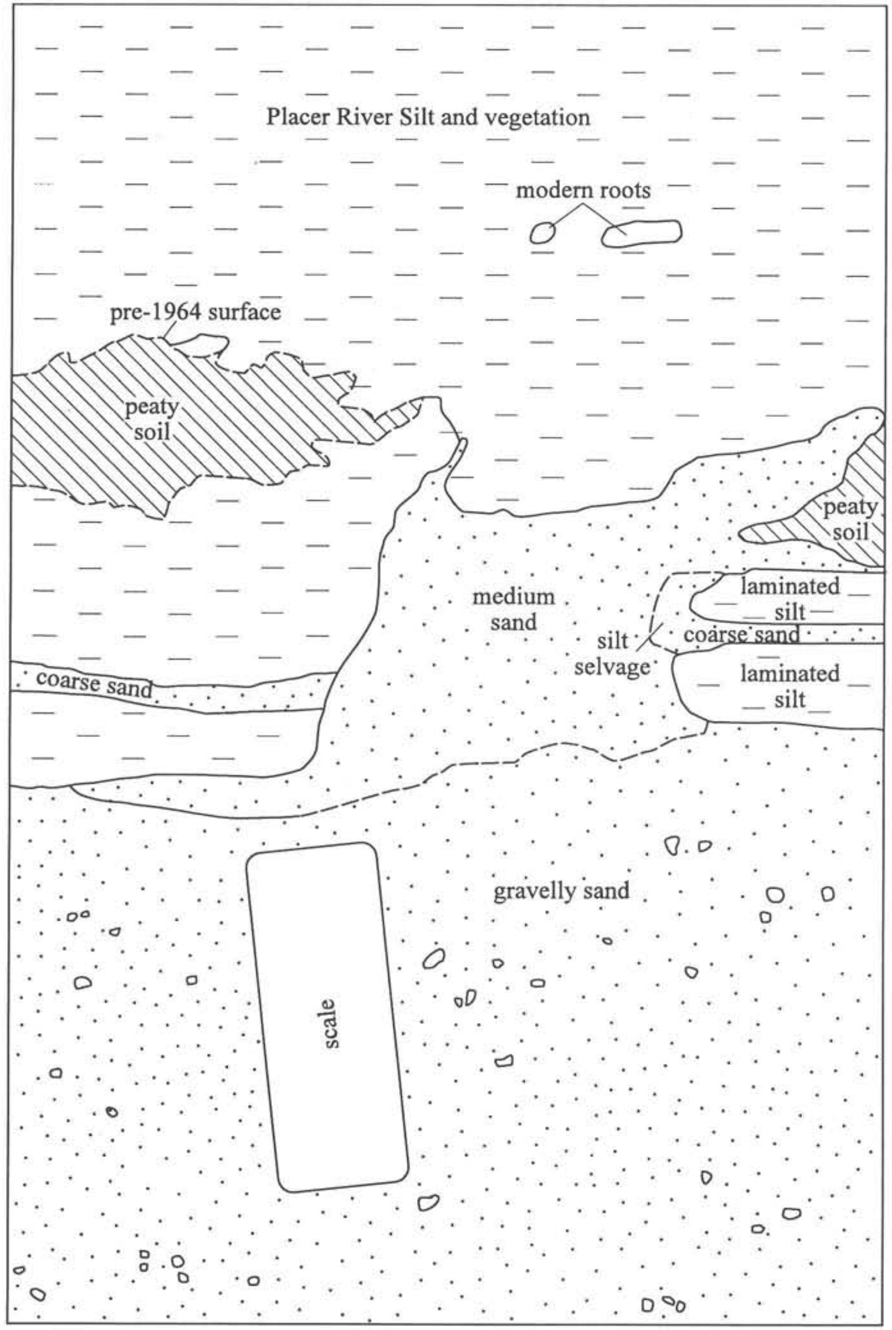


Figure 31. Photo and drawing of a clastic dike at **site 37a** on Placer River. The top of the source bed is only 42 cm below the 1964 surface. Note the sill of medium sand immediately above the scale and the abundance of centimeter-size gravel.

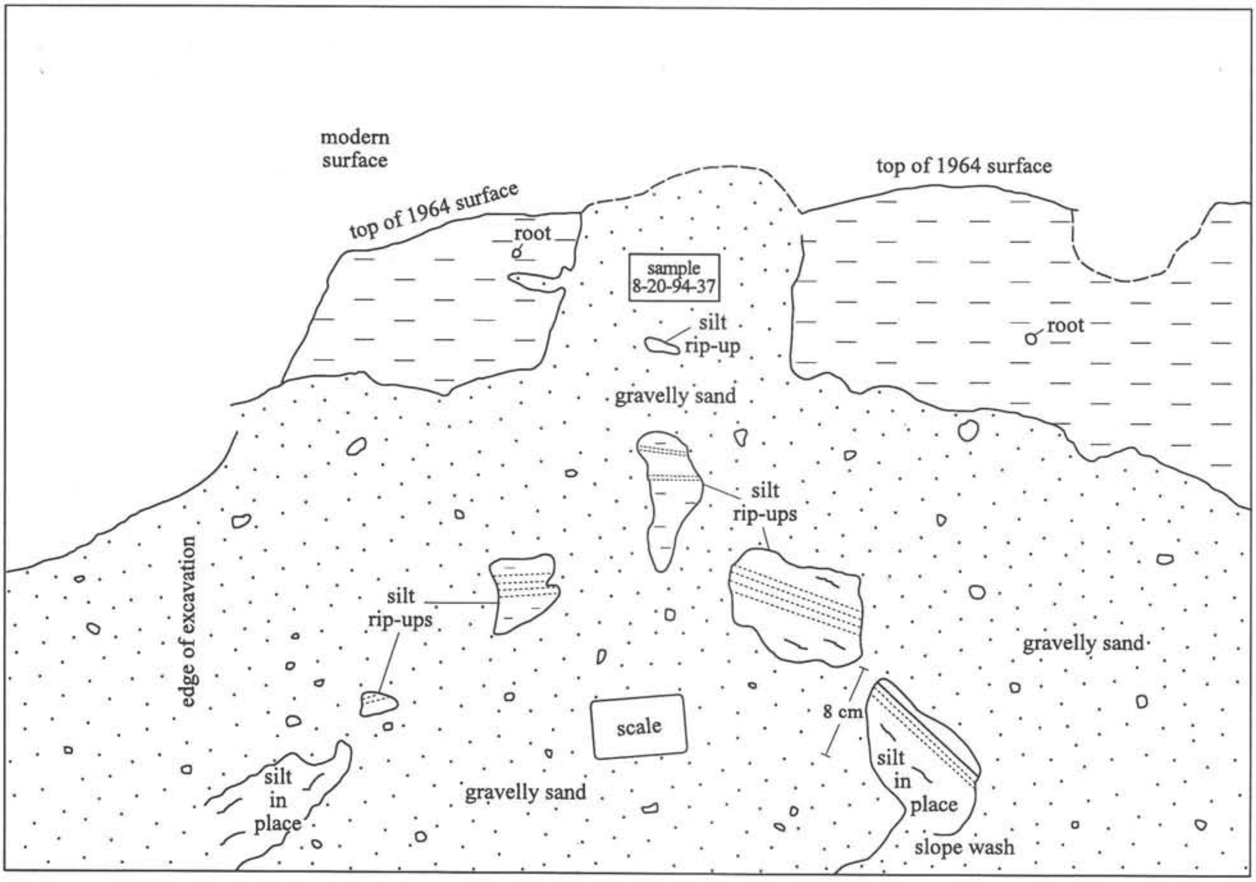


Figure 32. Photo and drawing of a clastic dike with inclusions of silt at **site 37b** on Placer River. The laminated silt in the lower right and lower left corners are in place. The ripped-up blocks of silt in the center indicate relative displacements that are larger in the center of the dike than on its margins, suggesting that during emplacement, the dike had enough shear strength to undergo frictional resistance at the margins. Also note that the blocks are not rotated, which suggests laminar flow. Analysis of the indicated sample is given in Appendix figure A6.

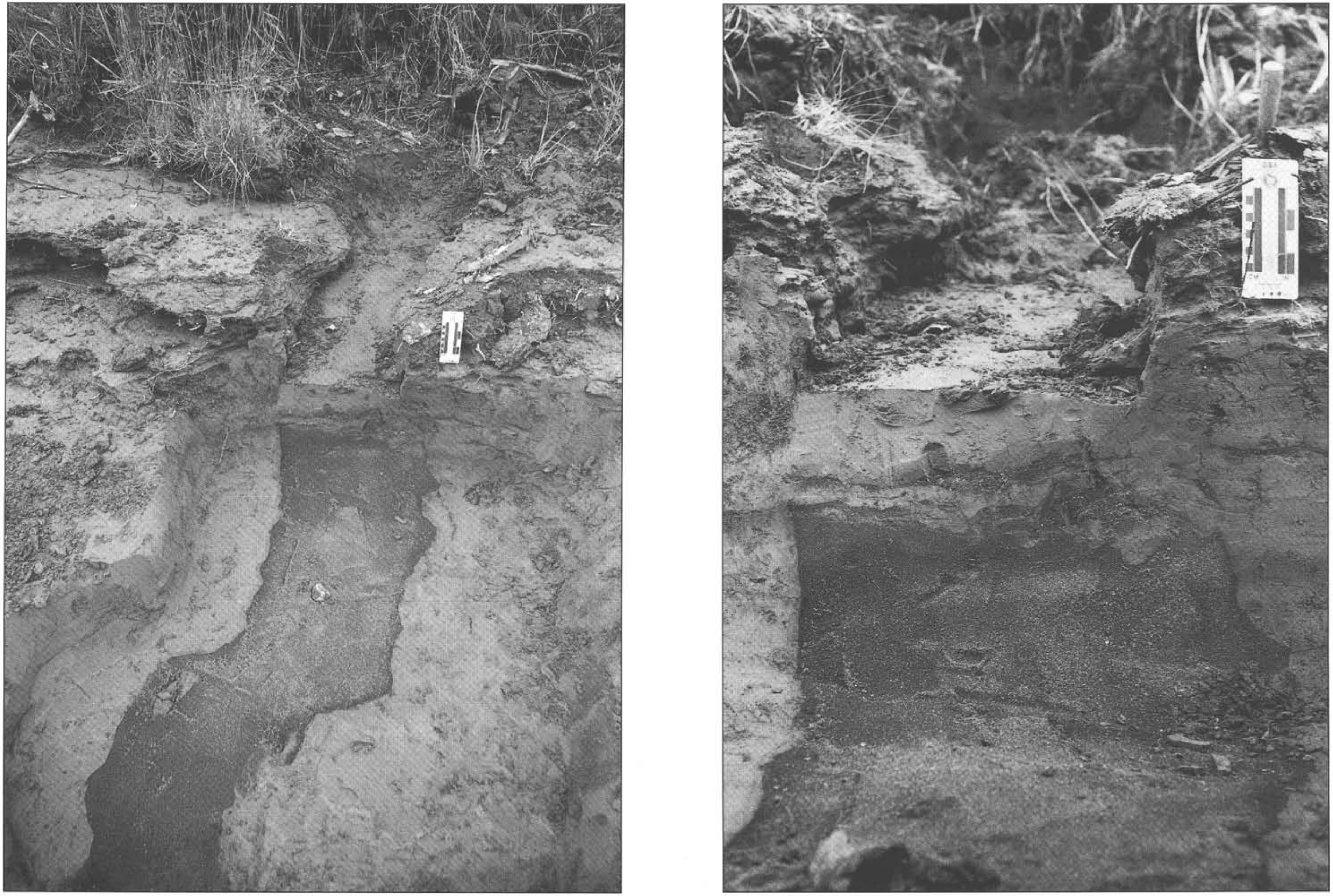


Figure 33. Photos of a large dike of medium to coarse sand at **site 39**. Maximum width is 52 cm. The host material is mottled gray silt. The pre-1964 peat layer forms a resistant bench and has a 40-cm-wide break in line with the dike. A single subrounded pebble, 3.8 x 4.8 x 5.9 cm, is suspended in the sand near the center of the dike, about 50 cm below the pre-1964 surface. Near the left margin of the dike (lower left center) is a silt inclusion suspended in the sand dike, probably dislodged from the dike wall. The sand-source layer is 90 cm below the 1964 surface and is 6-11 cm thick. The upper portion of the dike is replaced with silt and reworked sand to a depth of 38 cm below the pre-1964 surface. The detail photo (right) shows reworked and crudely bedded sand and silt in this upper portion, where replacement silt has been partially removed by erosion in the break in peat. No erupted sand remains on the pre-1964 surface at this location. erupted sand remains on the pre-1964 surface at this location.

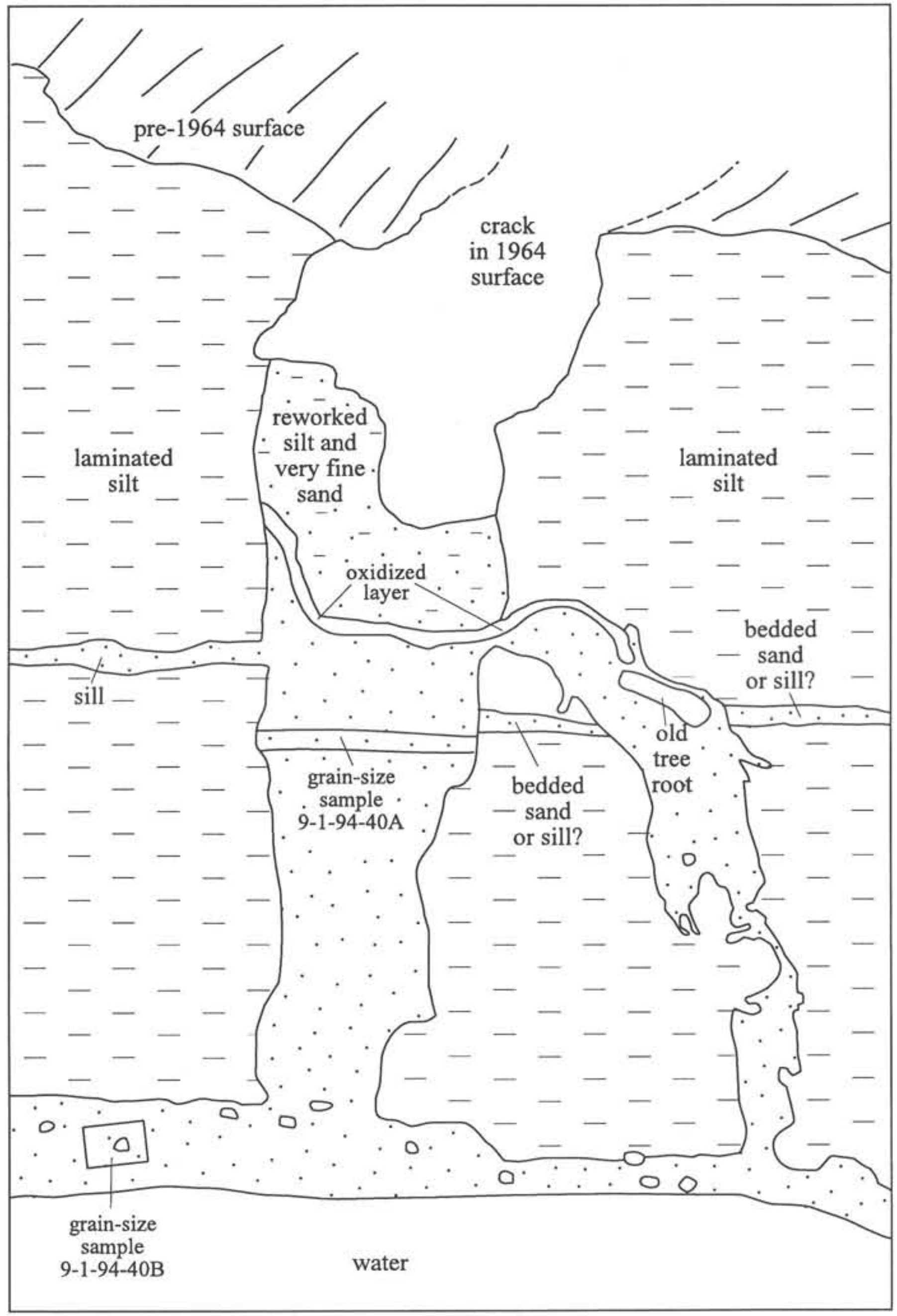



Figure 34. Photo and drawing of clastic dike at **site 40** on Twentymile River. It shows a truncated top infilled with silt and some of the complex branching that was common in the larger dikes. Compare grain-size analyses in Appendix figure A8.

Figure 35. Photo of a narrow (1 cm) dike at **site 41** on Twentymile River. This dike appears to have left a sand blow, but the dike could not be traced all the way to the sand resting on the 1964 surface.

Figure 36. Photo of a complex dike at **site 43** on Twentymile River. This dike has two different textures separated by a sharp (but faint in this photo) contact. This suggests either two dikes, one intruding the other, or infiltration of silt into the margins of the dike during the waning stages of emplacement.

Figure 37. *(left)* Photo of a clastic dike at **site 42** along Twentymile River. The dike at the bottom of this photo is 1.5 m wide.

(below) A closeup of the top of the dike, which has narrowed to 52 cm.

Figure 38. Photo of a thin (maximum 2 cm) sand dike at **site 45** on Twentymile River. The scale rests on the pre-1964 surface, which is at the top of a thin, indistinct peaty silt layer. The dike tapers downward and disappears 48 cm below the 1964 surface. This dike may be either a tapering apophysis of a larger dike behind the bank or a surface crack that was filled from above. A 5-cm-thick sand layer overlying the pre-1964 peat (behind the scale) may be the source of the dike fill. The host material is bedded silt with abundant roots.

Figure 39. Photo of a large complex dike at **site 46** on Placer River. The vertical distance from source bed to the break in the 1964 peat surface is 1.8 m. Maximum dike thickness is 23 cm; the break in well-developed 1964 peat surface is 39 cm wide. The base of peat surface is offset 20 cm across dike (down to the left of the photo). Three distinct phases of injection are represented—very fine sand, medium sand, and granule-bearing coarse sand. The upper part of the source bed is visible just above the pool of water at the base of the photograph. It consists of pebbly to granule-bearing coarse sand. The upper 10–20 cm of the dike has been replaced by Placer River Silt.

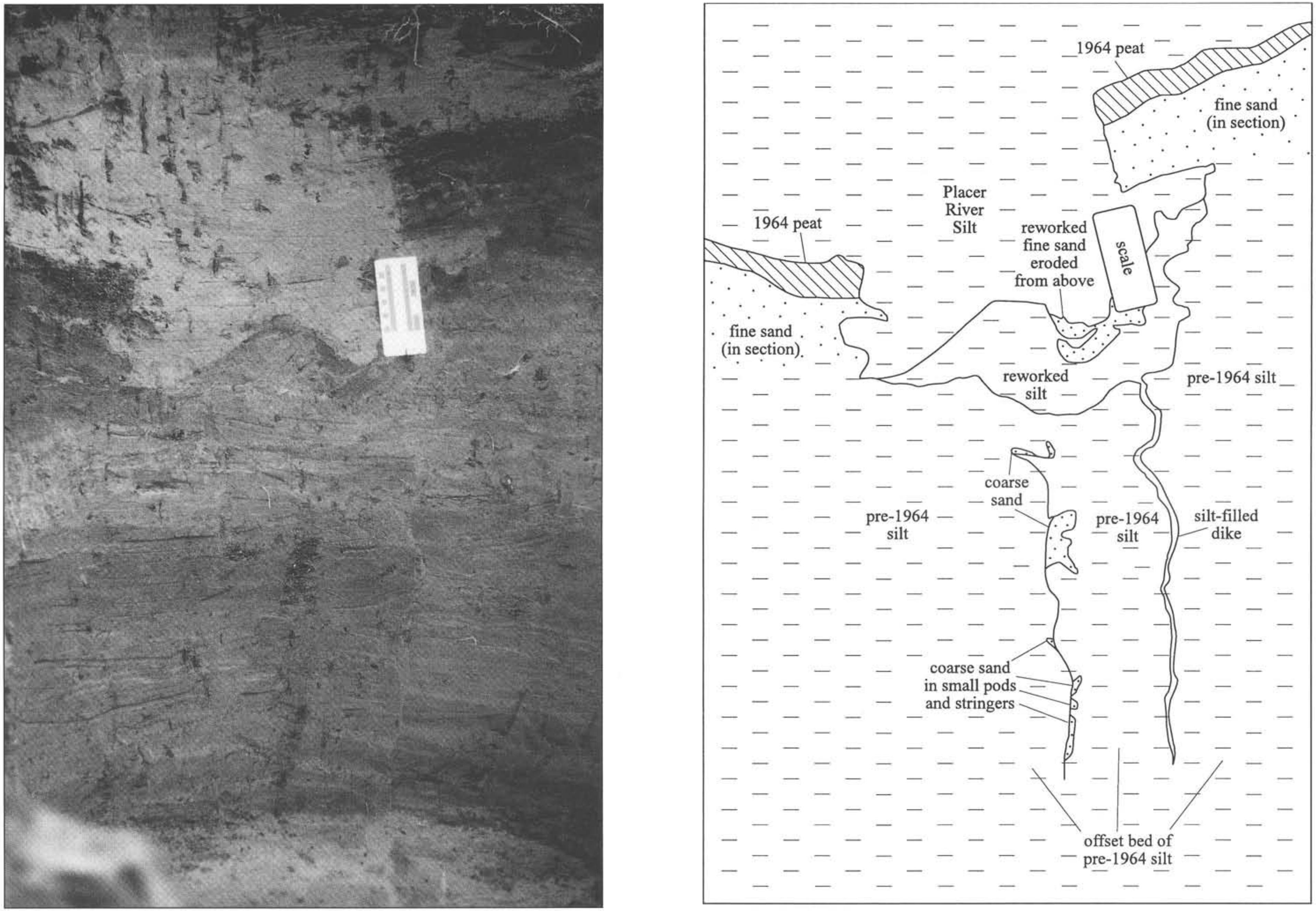
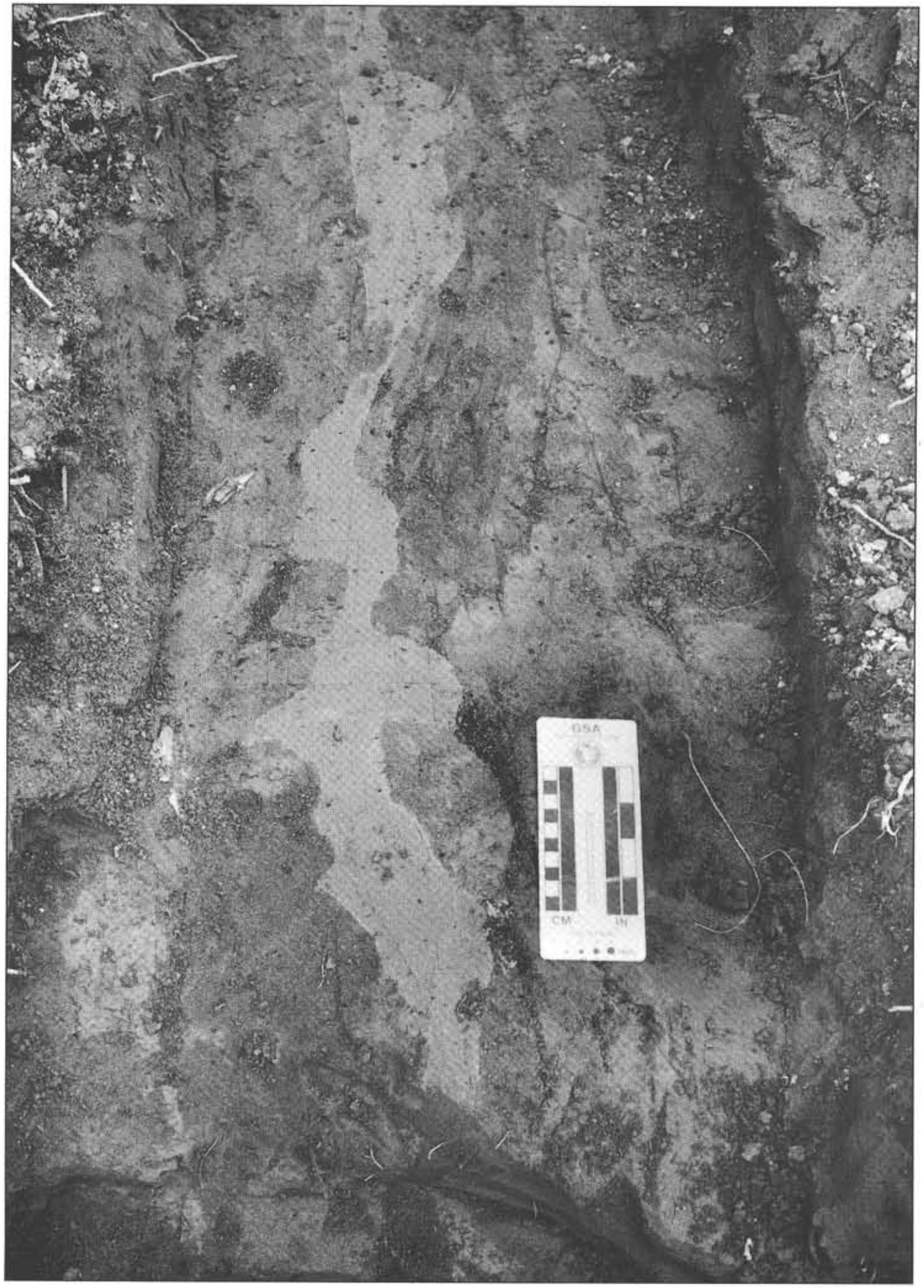


Figure 40. Photo and drawing showing details of the top of the dike at **site 46** on Placer River. The 1964 peat surface (represented by the dark upper 4 cm of the layer above the scale) is well developed. The remainder of the dark layer is *in-situ* fine sand. The break in 1964 surface is 39 cm wide; the 1964 surface is offset 20 cm (down to the left of photograph). A dike on the left is composed of thin discontinuous stringers of coarse sand (see line drawing, right). The upper 10–20 cm of dike is replaced by Placer River Silt. There is a 25–30 cm zone of reworked material (interbedded fine sand and silt) below the replacement Placer River Silt.



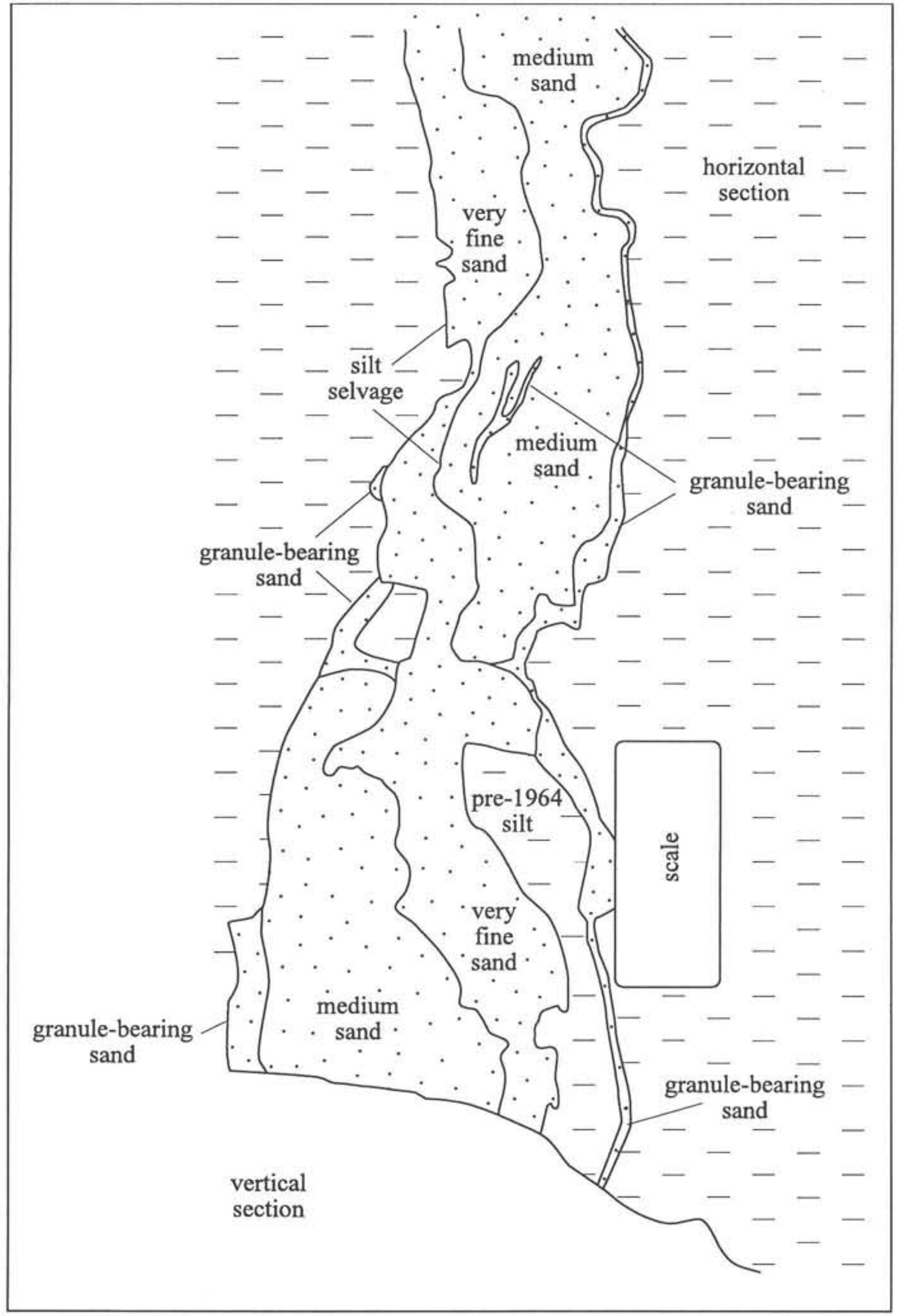


Figure 41. Photo and drawing showing details of three phases of injection at the approximate midpoint of **site 46**. The first phase is represented by stringers of granule-bearing to coarse sand at the dike margins. Second phase is represented by medium sand. The final phase of injection, represented by very fine sand, cuts across all other contacts. A thin (1 mm) silt selvage, common in many dikes in this area, is also present at the margins of this final phase.

Figure 42. Photo of a dike composed of granule-bearing sand at **site 47** on Placer River. The lower 5 cm is pebbly (maximum clast size 1.5 x 1.0 x 0.5 cm). Maximum width 15 cm. The top of the dike is buried beneath slump block (not shown).

Figure 43. Photo of a medium to coarse sand dike at **site 55** on Portage Creek. The dike ranges in thickness from 7 to 13 cm.

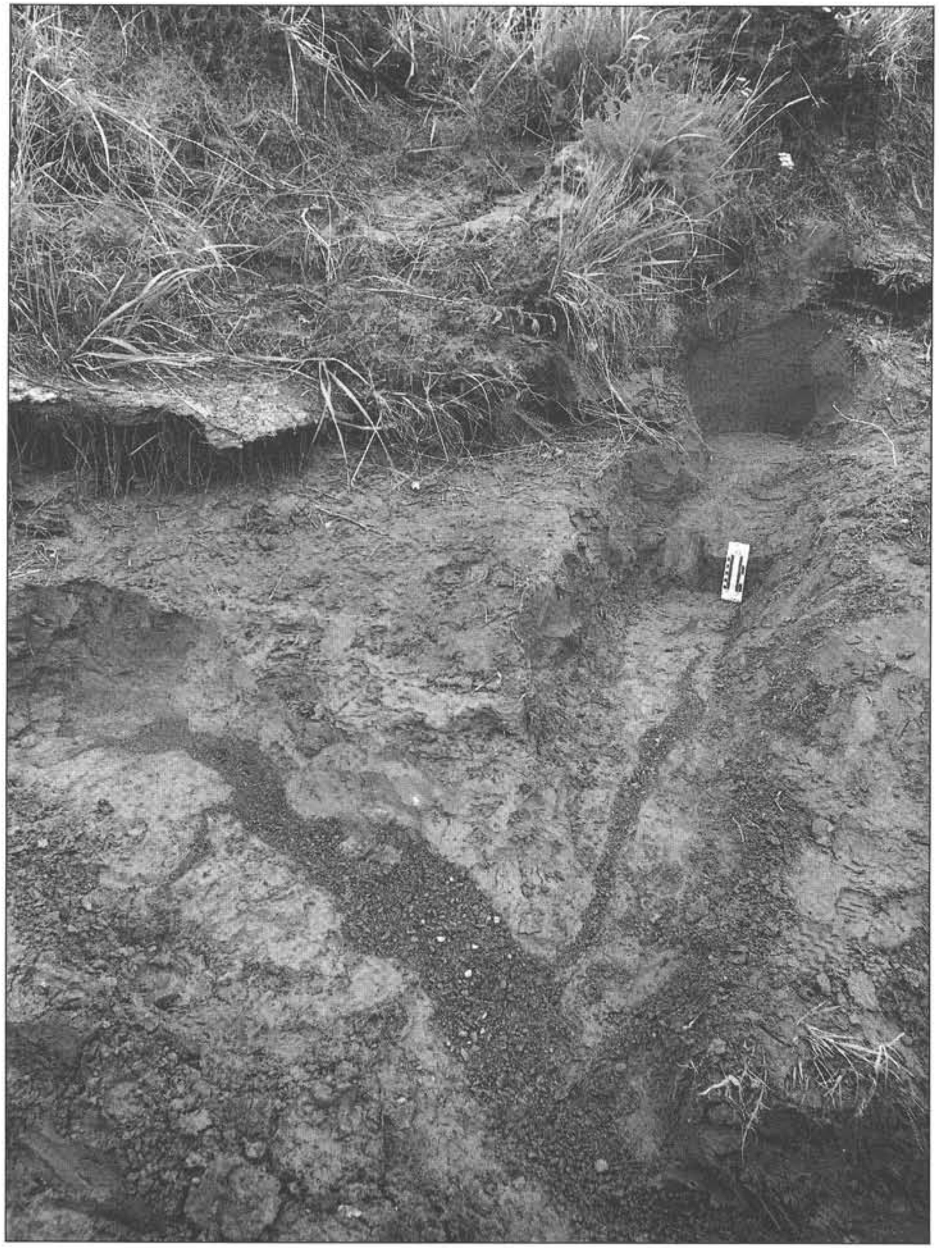


Figure 44. Photo of the lower part of a dike at **site 49** on Placer River. The dike is composed of pebbly granule-bearing sand. Maximum clast size 3.5 x 2.3 x 1.8 cm; maximum width 21 cm. A sample (the coarsest of all our samples; Table 3) was taken immediately left of the bifurcation. The branch trending toward the scale is 3 cm wide and fines upward from pebbly sand to granule-bearing sand at the apex. A second upward fining en echelon dike starts just below the scale. The two dikes probably connect laterally. The area above the scale is shown in Figure 45.

Figure 45. Photo showing detail of the top of the dike at **site 49**. The dike fines upward over a vertical distance of 22 cm from granule-bearing sand (base of branch in Figure 44), through medium sand, fine sand, and very fine sand. At the top of the dike is a cusp-shaped reworked zone consisting of 50 cm of interbedded fine sand and silt. There is a break in the 1964 peat surface, but there is no obvious extruded sand.

Figure 46. *(left)* Photo of a dike pair at **site 52** on Portage Creek. Both are composed primarily of granule-bearing to coarse sand. The left dike is 14 cm wide and contains a few scattered entrained pebbles 35–40 cm below 1964 peat surface (maximum clast size 1.0 x 0.6 x 0.2 cm). Right dike is 2 cm wide. The top of this dike is shown in more detail in Figure 47.

Figure 47. *(below)* Photo of the termination of the larger dike at **site 52** shown in Figure 46. The reworked zone left of the scale is interbedded sand and silt. The 1964 peat surface is the diffuse dark band just above the scale. Above the 1964 surface is a 1–2 cm silt layer containing vertically oriented rootlets. Above the silt layer is a 4-cm layer of extruded sand.

Figure 48. Photo of a shore-parallel sand dike and layer at **site 57** on Portage Creek. This dike has a maximum width of 20 cm and a corresponding break in the pre-1964 peat layer and surface, which form the upper bench in this photo. The dike feeds subsidiary dikes at sites 56–59 and cuts across a 7-cm-thick sand layer in section about 40 cm below the pre-1964 surface. The upper portion of the dike has been replaced with silt to about 30 cm below the pre-1964 surface, but this silt has been largely removed by modern tidal erosion. Host material is layered silt.

Figure 49. View east along the north bank of Portage Creek (north channel), showing a shore-parallel dike emerging from the bank at left at **site 58**. This is the same dike as shown in Figure 48 at site 57. Maximum dike width here is 29 cm.

Figure 50. Photo of a clastic dike terminating in a sand blow at **site 59** on Portage Creek. Note the layer of silt on the 1964 surface beneath and atop the sand blow. This is located only a few meters from the dike and sand blow in Figure 49.

Figure 51. Photo of two dikes of medium to coarse sand at **site 60** on Portage Creek. The dikes feed a sand-filled depression that may have been part of a sand boil before it was truncated by erosion. The pre-1964 surface and peat layer are not visible here and were probably removed by erosion.

Figure 52. Photos of a thin (maximum 2.5 cm) sand dike at **site 61** on Portage Creek. At the unconformity between older laminated silt and modern massive silt, a sand layer as much as 2.5 cm thick extends laterally about 40 cm to the left. This sand layer may be either a remnant of a sand boil or dike sand that has been reworked during tidal erosion. The sand dike tapers downward and disappears 30 cm below the unconformity. *(left)* This photo including the lower part of the section shows a possible source layer, but no visible connection to the dike.

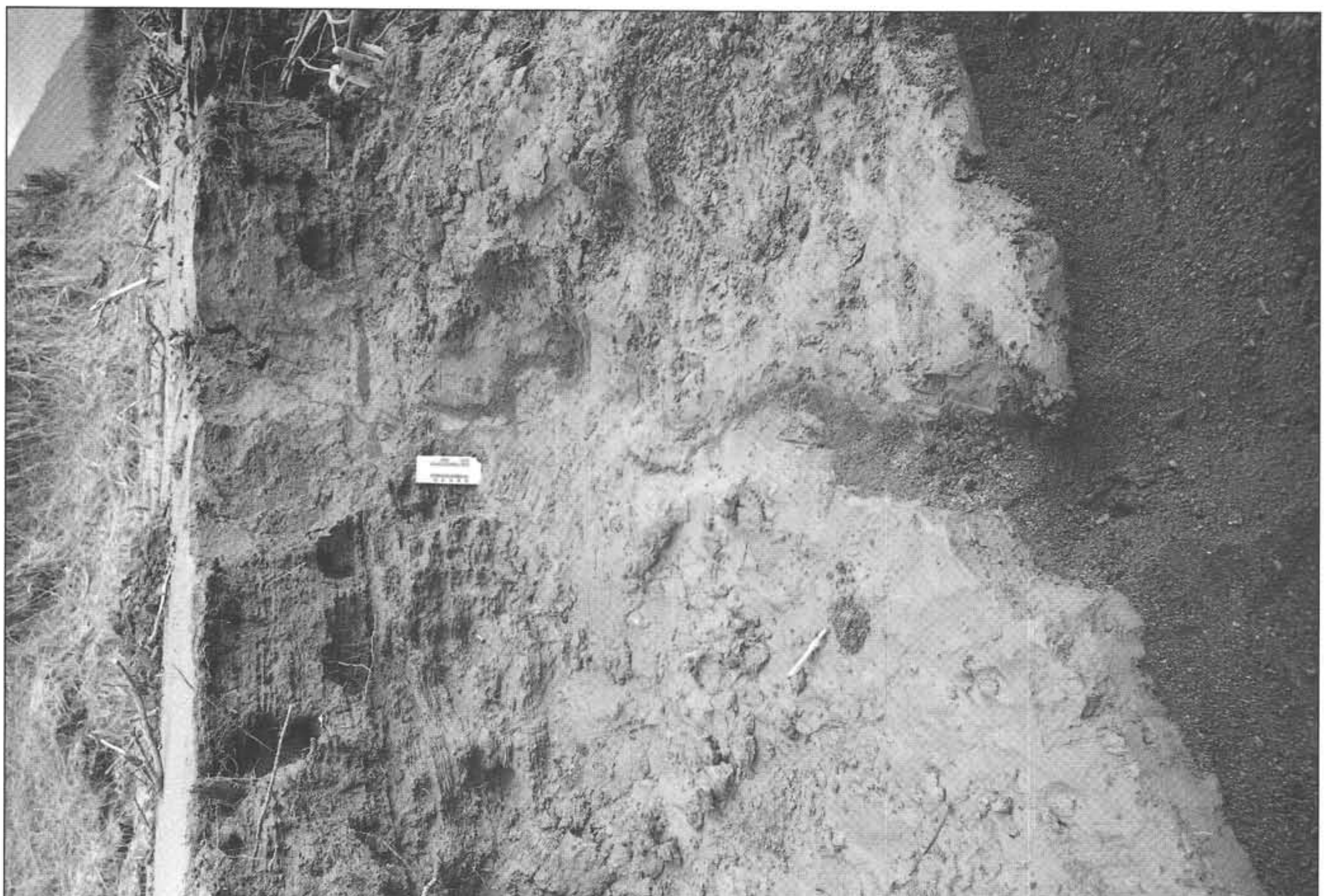


Figure 53. Photo of dike at **site 62** on Portage Creek at its confluence with Placer River. The source of this dike is 95 cm below the top of the 1964 surface. Its maximum width is 10 cm.

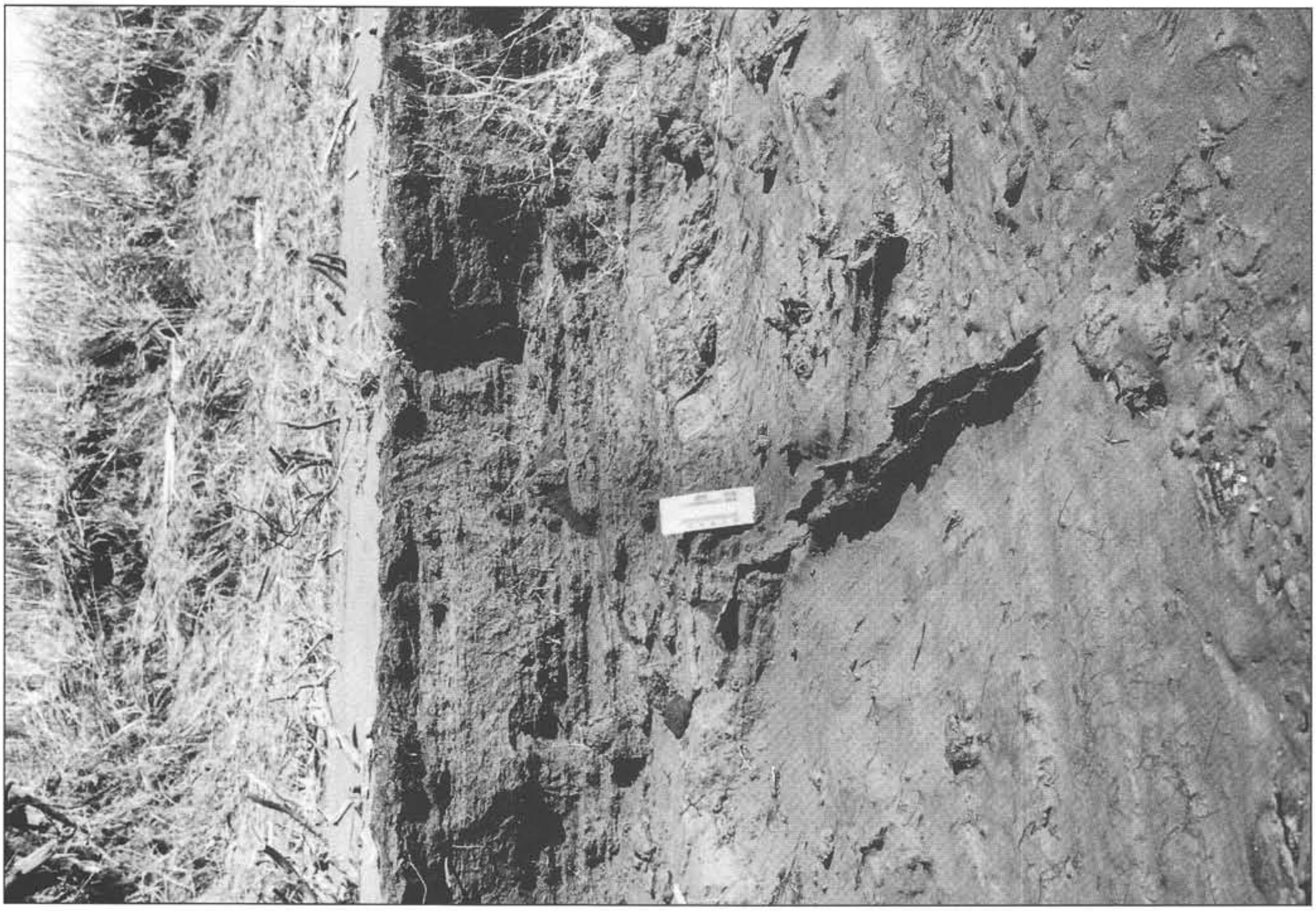


Figure 54. Photo of a dike at **site 66** at the confluence of Placer River and Portage Creek. The margins of the dike are precipitated rust-colored carbonate, probably deposited by seepage of ground water when the tide receded.

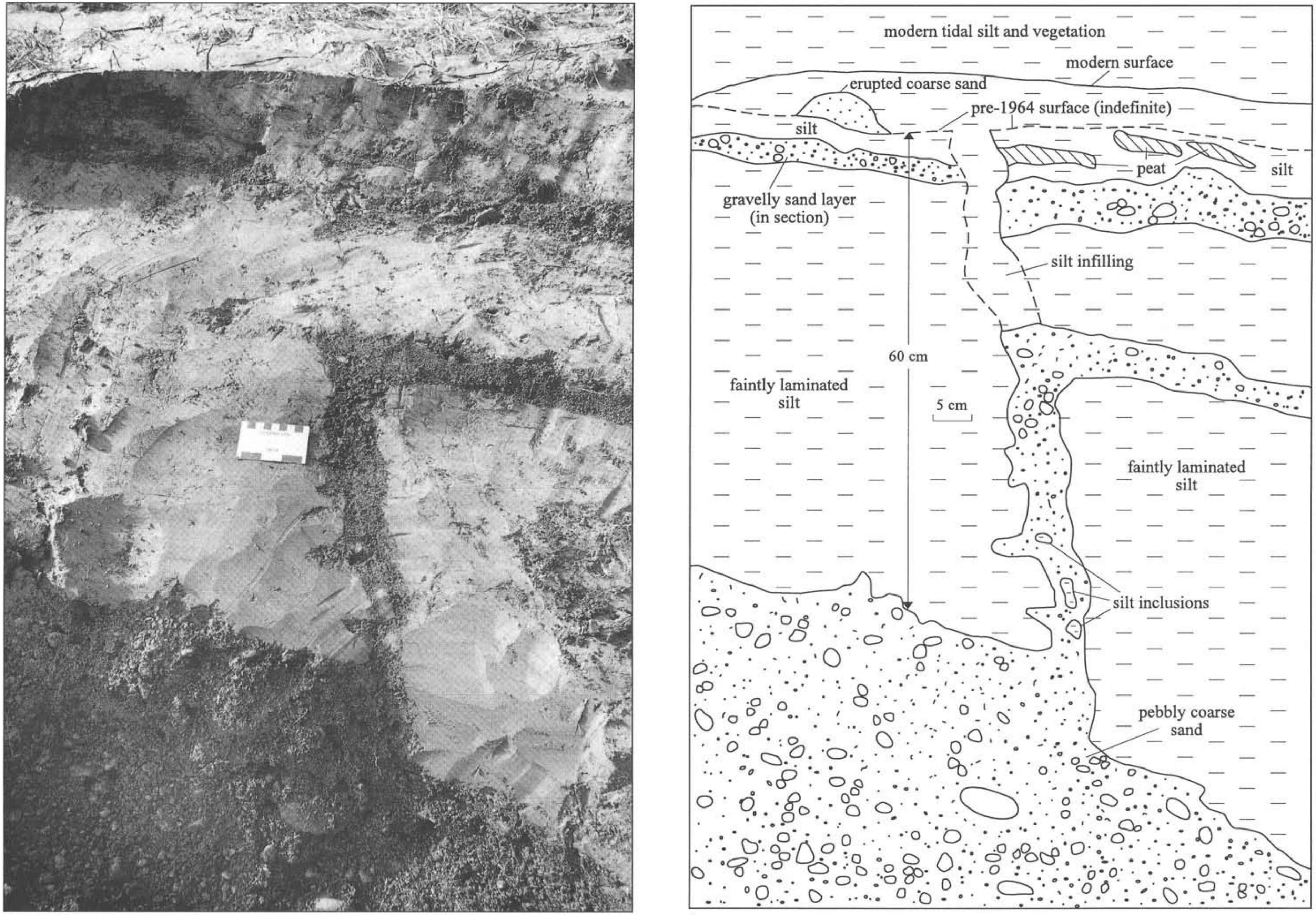


Figure 55. Photo and drawing of a gravelly medium to coarse sand dike and sill at **site 74** on Portage Creek. The portion of this dike above the sill has been replaced with silt from above, probably as a result of tidal reworking following the 1964 earthquake. The replacement silt fills a break in a gravelly sand layer near the top of the section and in a discontinuous layer of peat above this layer. A lens of sand above the discontinuous peat layer may be a remnant of a sand boil emanating from the dike. The silt filling at the top of this dike is barely distinguishable from the surrounding faintly laminated silt. A thick bed of gravelly coarse sand (bottom) is the apparent source for this dike. The top of this bed is about 60 cm below the pre-1964 surface.

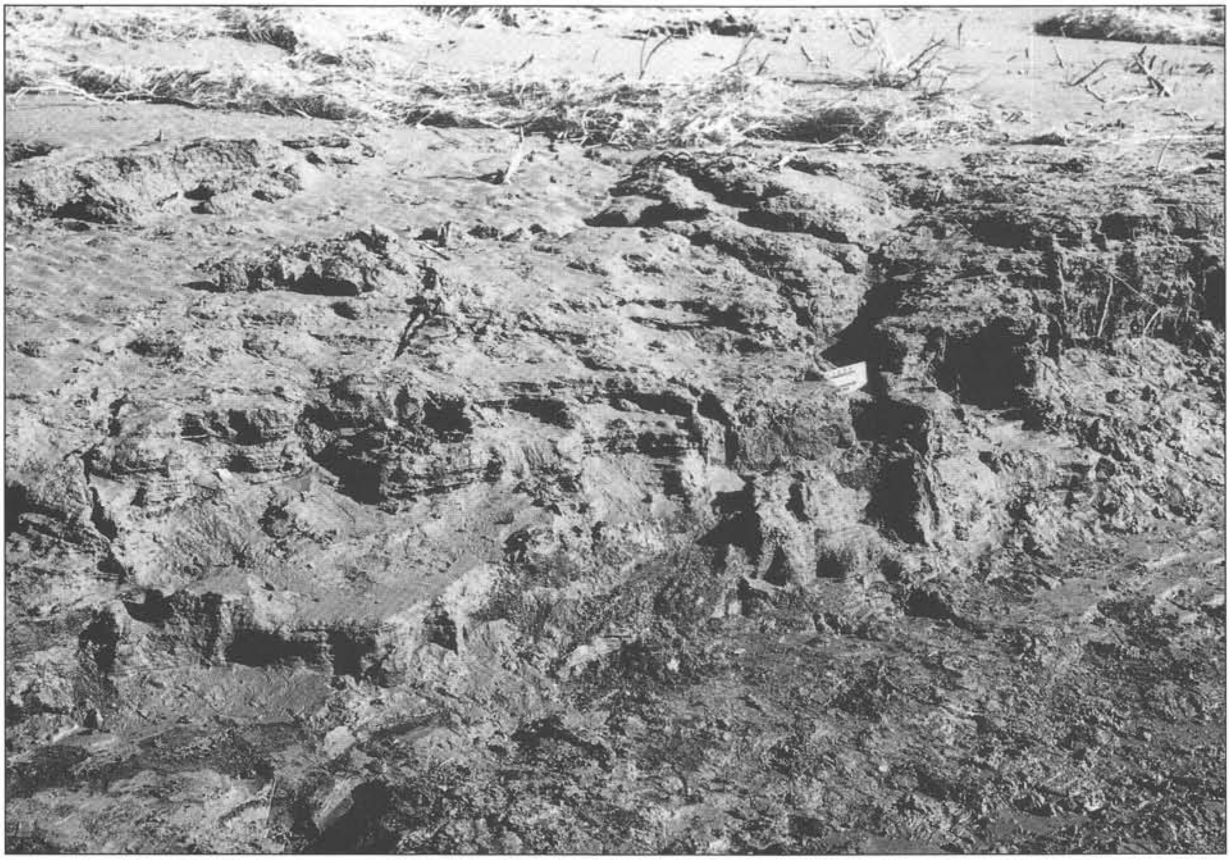
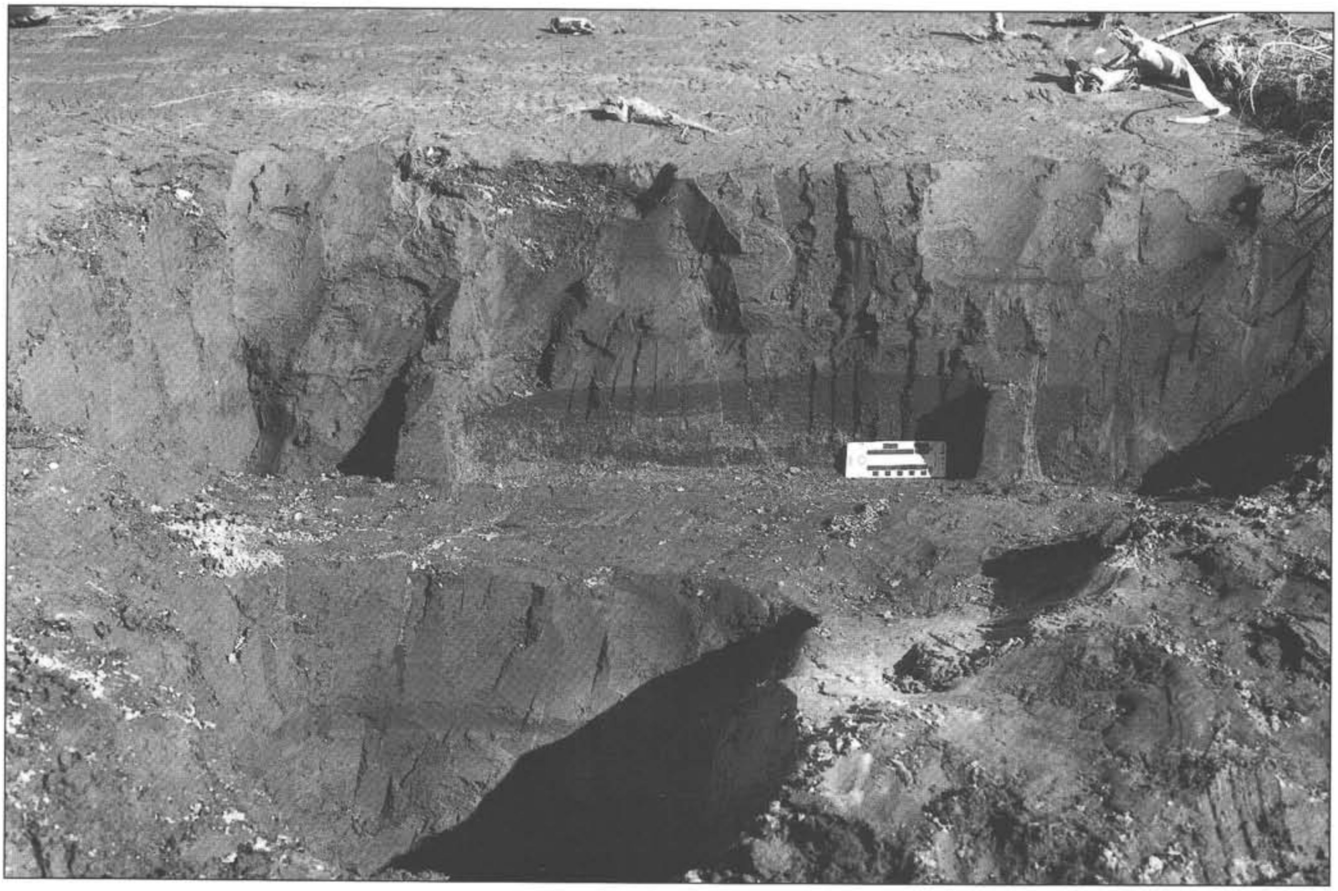


Figure 56. Wide-angle photo *(above)* and closeup *(left)* of a natural exposure of a clastic dike with oxidized rims at **site 80a** on Portage Creek. The source bed, which is 65 cm below the 1964 surface, is composed of pebbly coarse sand. The dike fines upward from granule gravel at the base to medium sand at the surface. The dike is 13 cm wide at its base, bifurcating 20 cm upward into 12- and 6-cm-wide dikes.



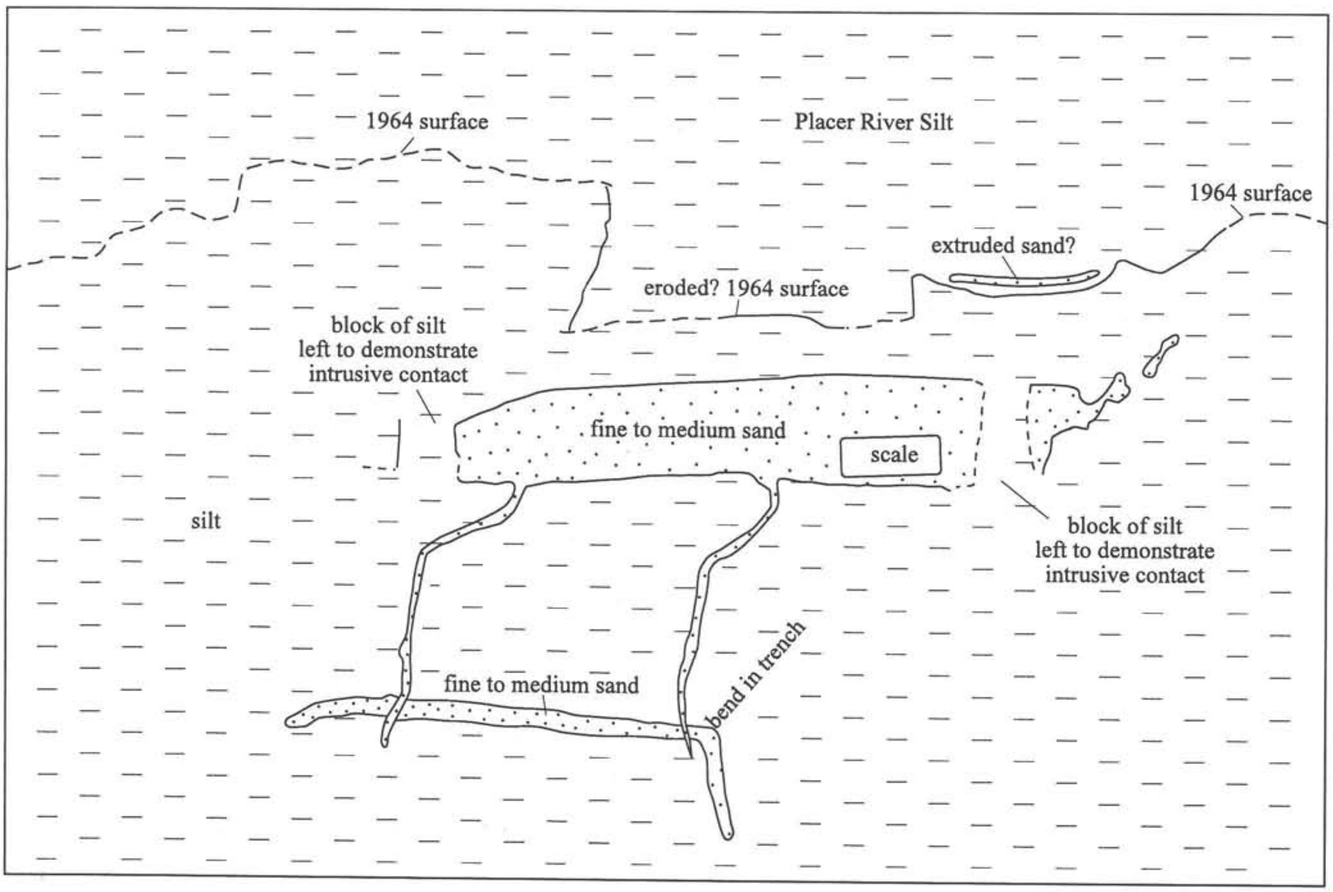


Figure 57. Photo and drawing of a dike at **site 80e** on Portage Creek. This dike was apparently injected downward as well as upward, with apophyses extending downward and truncating in silt.

Figure 58. View southeast along the south bank of Portage Creek (north channel), showing sand dikes intersecting the bank at **sites 79g-h**. A large dike at the center is nearly shore-parallel and has a maximum measured thickness of 74 cm. All the dikes are associated with breaks in the pre-1964 surface and peat layer, within which the upper part of the dike has been replaced with silt. Minor thin sand above the pre-1964 surface may be remnants of sand boils erupted from these dikes. Exhumed bushes at the break in slope are rooted in the peat layer that was buried as a result of submergence during the 1964 earthquake. The overlying Placer River Silt is about 2 m thick.

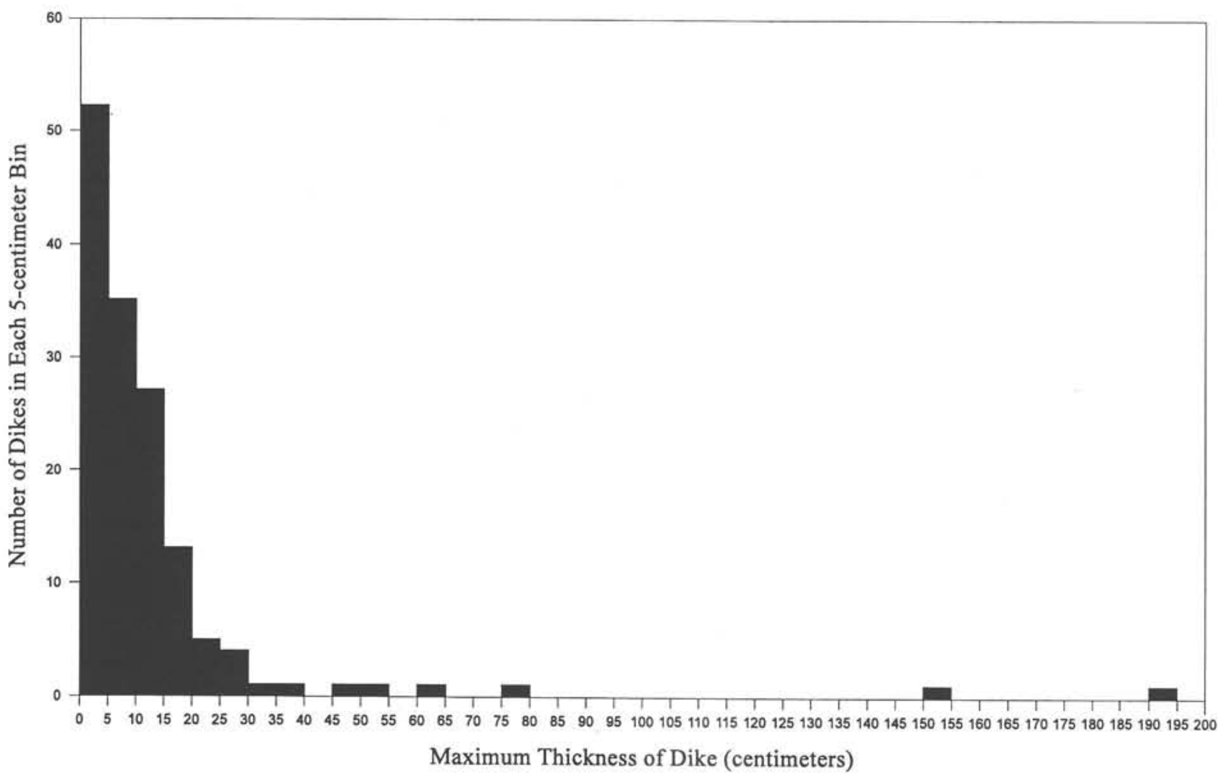


Figure 59. Histogram of frequency of occurrence versus dike widths in 5-cm increments for the Portage and Twentymile River area.

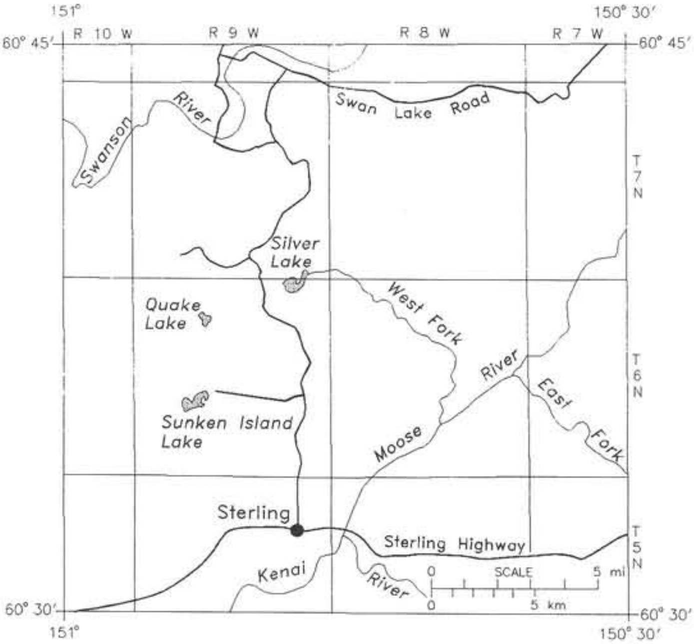
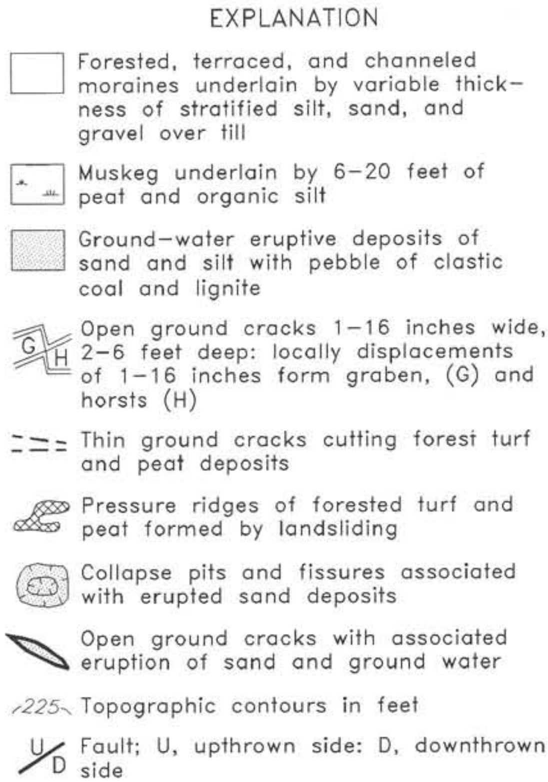


Figure 60. Location map of part of the Kenai Lowland. Figure 61 shows the area near Silver Lake investigated in this study.



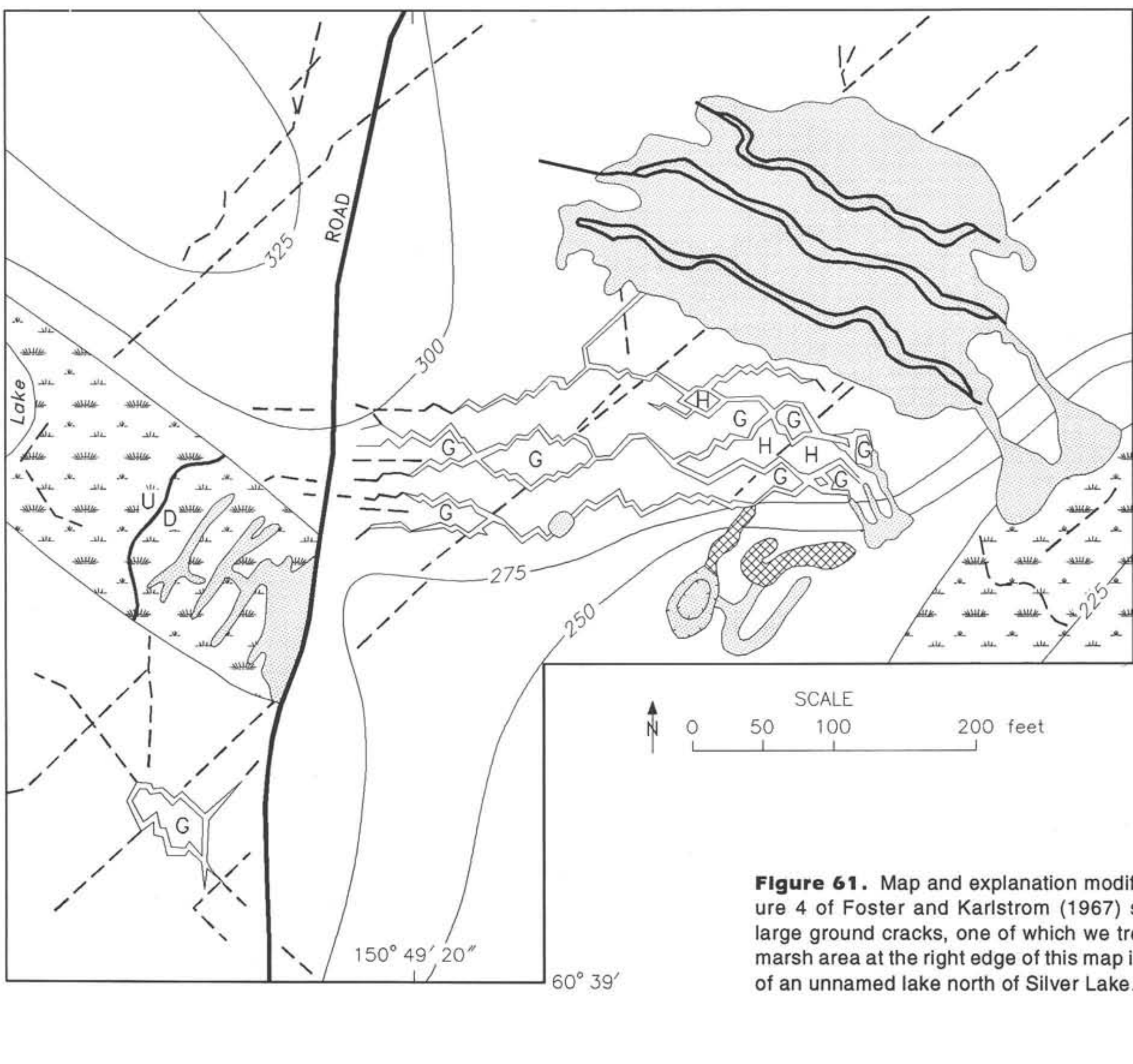


Figure 61. Map and explanation modified from figure 4 of Foster and Karlstrom (1967) showing the large ground cracks, one of which we trenched. The marsh area at the right edge of this map is the margin of an unnamed lake north of Silver Lake.

Figure 62. *(above)* Photo of the southwest corner of the pit at the Foster and Karlstrom site. The pit is in a well-indurated boulder till. At the top right of the photograph is the open ground crack, ~1 m deep and 1.5 m wide. The light-colored layer beneath the vegetative cover and above the geologist's back is extruded sand. It can be traced downward via a sloping dike to the pod (light-colored bed) to the right of the geologist. A thin dike can be traced vertically from this "reservoir" to the bottom of the pit. The geologist is standing in the area shown in Figure 63.

Figure 63. *(left)* Detail of the left side of the previous photo. Beneath the vegetative cover at top left of this photograph is a light-colored extruded sand. This sand can be traced downward via a sloping, pinching and swelling dike to the pod of light-colored sand above the shovel handle. A vertical dike can be traced downward from this pod to the floor of the pit. The hole to the right of and below the shovel represents a portion of the dike that was propped open by a clast from the boulder till after the extrusion process was complete.

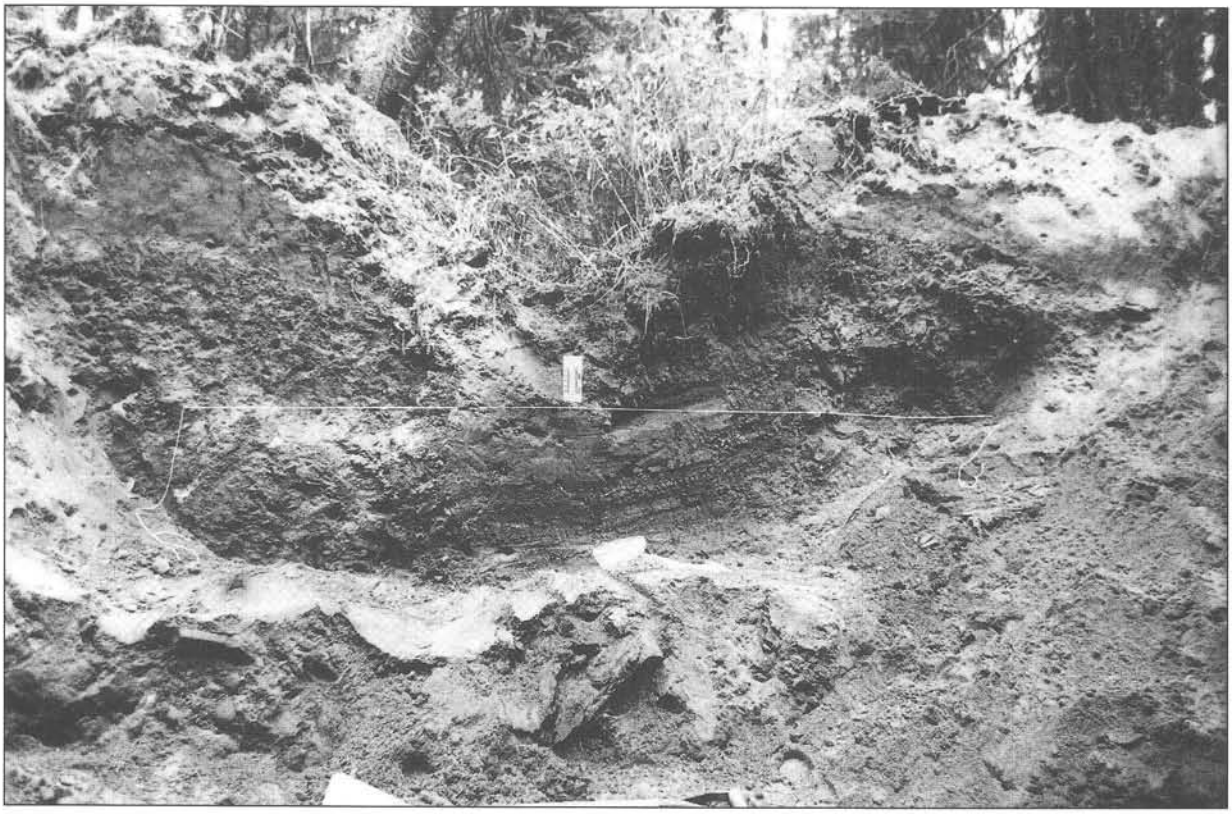


Figure 64. Photo of the east side of the pit at the Foster and Karlstrom site. Above the scale is the open ground crack, ~1 m deep and 1.5 m wide. After sand extrusion, the soil column collapsed into the crack. The vertical distance from the base of the peat on the south (right) side of the fracture and the base of the peat in the crack is 82 cm. The base of the 1964 peat surface is the dark layer at the top of the scale. Extruded sand mantles the north (left) slope of the crack to a depth of 10–14 cm and is 15 cm thick in the axis of the crack. Extruded sand is absent from the south slope of the crack. Figure 65 shows the area immediately to the left of the scale.

Figure 66. *(above)* Photo of the bottom of the pit at the Foster and Karlstrom site showing the faint trace of the feeder dike crossing the pit.

Figure 65. *(left)* Detail of previous photo, showing a thin (7 cm maximum width) sand dike slightly left of center and right of the scale. The dike can be traced to a break in the 1964 peat surface. It appears to be the feeder for extruded sand (the light-gray material beneath the vegetative cover at top right). The dike can be traced across the floor of the pit to the feeder dike on the west side described in the previous two figures.

REFERENCES CITED

Atwater, B. F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: Science, v. 236, no. 4804, p. 942-944.

Atwater, B. F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington: Journal of Geophysical Research, v. 97, no. B2, p. 1901-1919.

Atwater, B. F., compiler, 1994, Geology of Holocene liquefaction features along the lower Columbia River at Marsh, Brush, Price, Hunting, and Wallace islands, Oregon and Washington: U.S. Geological Survey Open-File Report 94-209, 64 p.

Atwater, B. F.; Nelson, A. R.; Clague, J. J.; Carver, G. A.; Yamaguchi, D. K.; [and 11 others], 1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone: Earthquake Spectra, v. 11, no. 1, p. 1-18.

Bartlett, S. F; Youd, T. L., 1992, Case histories of lateral spreads caused by the 1964 Alaska earthquake. *In* O'Rourke, T. D.; Hamada, M., editors, Case studies of liquefaction and lifeline performance during past earthquakes; v. 2, United States case studies: National Center for Earthquake Engineering Research, Technical Report NCEER-92-0002, p. 1-127.

Bartsch-Winkler, S. R.; Ovenshine, A. T.; Kachadoorian, Reuben, 1983, Holocene history of the estuarine area surrounding Portage, Alaska, as recorded in a 93-m core: Canadian Journal of Earth Sciences, v. 20, no. 5, p. 802-820.

Combellick, R. A., 1993, The penultimate great earthquake in southcentral Alaska—Evidence from a buried forest near Girdwood. *In* Solie, D. N.; Tannian, Fran, editors, Short notes on Alaskan geology 1993: Alaska Division of Geological and Geophysical Surveys Professional Report 113, p. 7-15.

Christensen, D. H.; Beck, S. L., 1994, The rupture process and tectonic implications of the great 1964 Prince William Sound earthquake: Pure and Applied Geophysics, v. 142, no. 1, p. 29-53.

Foster, H. L.; Karlstrom, T. N. V., 1967, Ground breakage and associated effects in the Cook Inlet area, Alaska, resulting from the March 27, 1964 earthquake: U.S. Geological Survey Professional Paper 543-F, 28 p.

Hansen, W. R.; Eckel, E. B.; Schaem, W. E.; Lyle, R. E.; Warren, George; Chance, Genie, 1966, The Alaska earthquake March 27, 1964—Field investigations and reconstruction effort: U.S. Geological Survey Professional Paper 541, 111 p.

Kachadoorian, Reuben, 1968, Effects of the earthquake of March 27, 1964, on the Alaska highway system: U.S. Geological Survey Professional Paper 545-C, 66 p.

Kanamori, Hiroo, 1977, The energy release in great earthquakes: Journal of Geophysical Research, v. 82, no. 20, p. 2981-2987.

McBride, E. F., 1971, Mathematical treatment of size distribution data. *In* Carver, R. E., editor, Procedures in sedimentary petrology: Wiley-Interscience, p. 109-127.

McCulloch, D. S.; Bonilla, M. G., 1970, Effects of the earthquake of March 27, 1964, on the Alaska Railroad: U.S. Geological Survey Professional Paper 545-D, 161 p.

Obermeier, S. F., 1995a, Preliminary estimates of the strength of prehistoric shaking in the Columbia River valley and the southern half of coastal Washington, with emphasis for a Cascadia subduction zone earthquake about 300 years ago: U.S. Geological Survey Open-File Report 94-589, 46 p.

Obermeier, S. F., 1995b, Using liquefaction-induced features for paleoseismic analysis. Part A. *In* Obermeier, S. F.; Jibson, R. W., Using ground-failure features for paleoseismic analysis: U.S. Geological Survey Open-File Report 94-663, p. 1-56.

Obermeier, S. F.; Martin, J. R.; Frankel, A. D.; Youd, T. L.; Munson, P. J.; Munson, C. A.; Pond, E. C., 1993, Liquefaction evidence for one or more strong Holocene earthquakes in the Wabash Valley of southern Indiana and Illinois, with a preliminary estimate of magnitude: U.S. Geological Survey Professional Paper 1536, 27 p.

Ovenshine, A. T.; Lawson, D. E.; Bartsch-Winkler, S. R., 1976, The Placer River Silt—An intertidal deposit caused by the 1964 Alaska earthquake: U.S. Geological Survey Journal of Research, v. 4, no. 2, p. 151-162.

Plafker, George, 1969, Tectonics of the March 27, 1964, Alaska earthquake: U.S. Geological Survey Professional Paper 543-I, 74 p.

Plafker, George; Savage, J. C., 1970, Mechanism of the Chilean earthquakes of May 21 and 22, 1960: Geological Society of America Bulletin, v. 81, no. 4, p. 1001-1030.

Reger, R. D.; Pinney, D. S., in press, Late Wisconsin glaciation of the Cook Inlet region with emphasis on Kenai Lowland and implications for early peopling. *In* Davis, N. Y.; Davis, W. E., editors, The anthropology of Cook Inlet—Proceedings from a symposium: Cook Inlet Historical Society, Anchorage.

Reimnitz, Erk, 1972, Effects in the Copper River Delta. *In* Committee on the Alaska earthquake of the Division of Earth Sciences, National Research Council, The great Alaska earthquake of 1964—Oceanography and coastal engineering: National Academy of Sciences, p. 290-302.

Reimnitz, Erk; Marshall, N. F., 1965, Effects of the Alaska earthquake and tsunami on recent deltaic sediments: Journal of Geophysical Research, v. 70, no. 10, p. 2363-2376.

Taylor, R. E., 1987, Radiocarbon dating; An archeological perspective: Academic Press, 212 p.

Varnes, D. J., 1958, Landslide types and processes. *Chapter 3 in* Eckel, E. B., editor, Landslides and engineering practice: Highway Research Board Special Report 29, National Academy of Sciences—National Research Council Publication 544, p. 20-47.

Waag, C. J; Lane, T. G., 1985, Structural control of groundwater eruptions and sediment boil formation in the Chilly Buttes area. *In* The Borah Peak, Idaho, earthquake of October 28, 1983: Earthquake Spectra, v. 2, no. 1, p. 151-168.

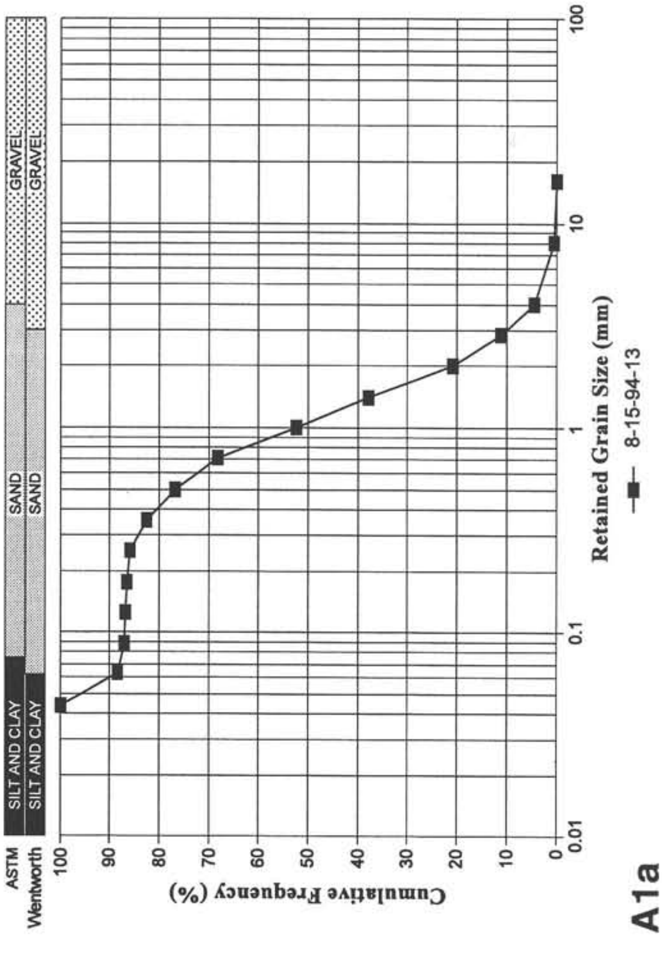
Wood, S. H.; Wurts, Caroline; Lane, Ted; Ballenger, Nick; Shaleen, Mary; Totorica, Dolores, 1985, Hydrologic effects. *In* The Borah Peak, Idaho, earthquake of October 28, 1983: Earthquake Spectra, v. 2, no. 1, p. 127-150.

Youd, T. ., 1973, Liquefaction, flow, and associated ground failure: U.S. Geological Survey Circular 688, 12 p.

Zhao, Dapeng; Christensen, Douglas; Pulpan, Hans, 1995, Tomographic imaging of the Alaska subduction zone: Journal of Geophysical Research, v. 100, no. B4, p. 6487-6504. ■

Appendix

We sieved 18 samples at ½ ϕ ($-\log_2 x$, where x = grain diameter) intervals. The results are plotted in figures A1 through A12; the summary statistics are presented in Table 3. The sample number is the date sampled followed by the site number and a letter when more than one sample was taken from the same site. Samples from the same site are plotted together to demonstrate similarities or changes from source to dike, within dikes, or from dike to sand blow. Each grain-size analysis is plotted both by cumulative and relative frequency. All material passing the 4 ϕ (0.064 mm) sieve was arbitrarily plotted at 4.5 ϕ (0.044 mm).



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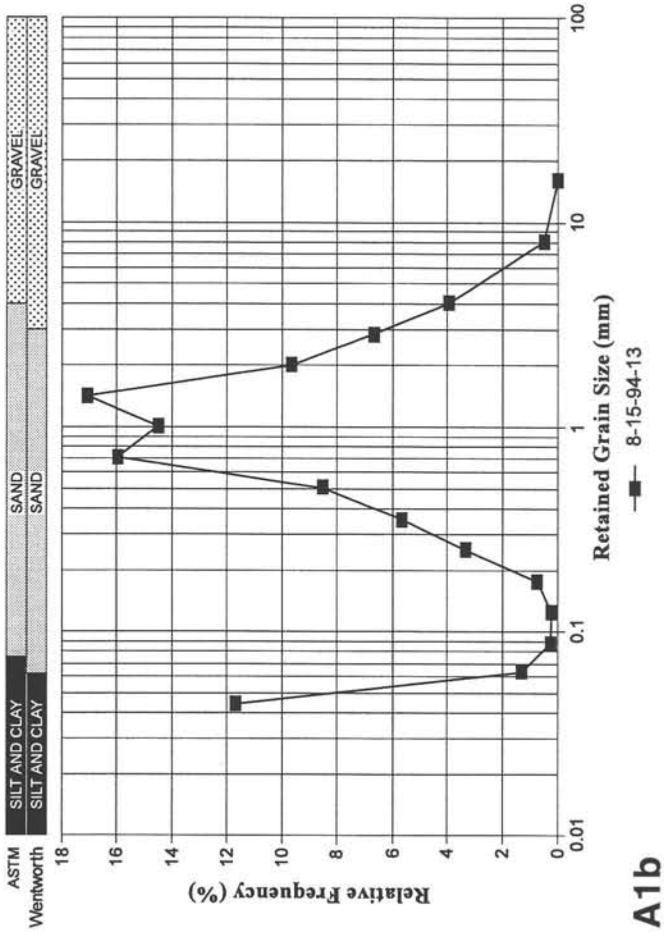

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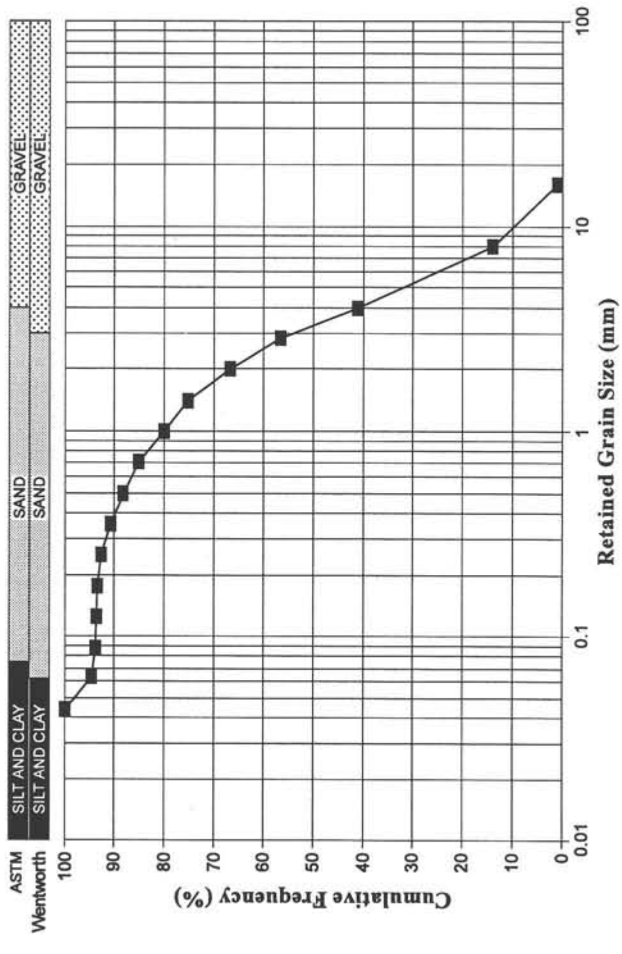

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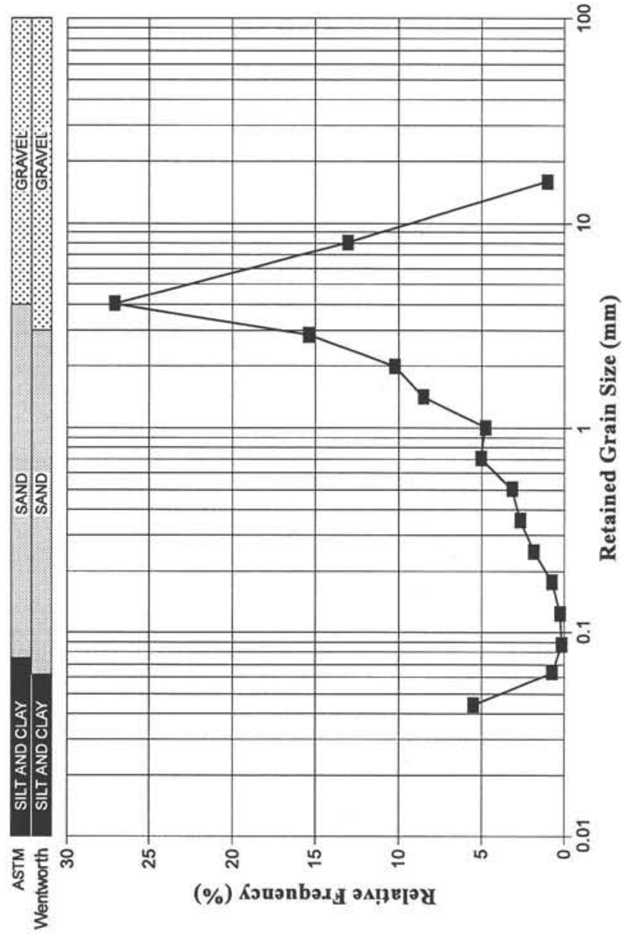

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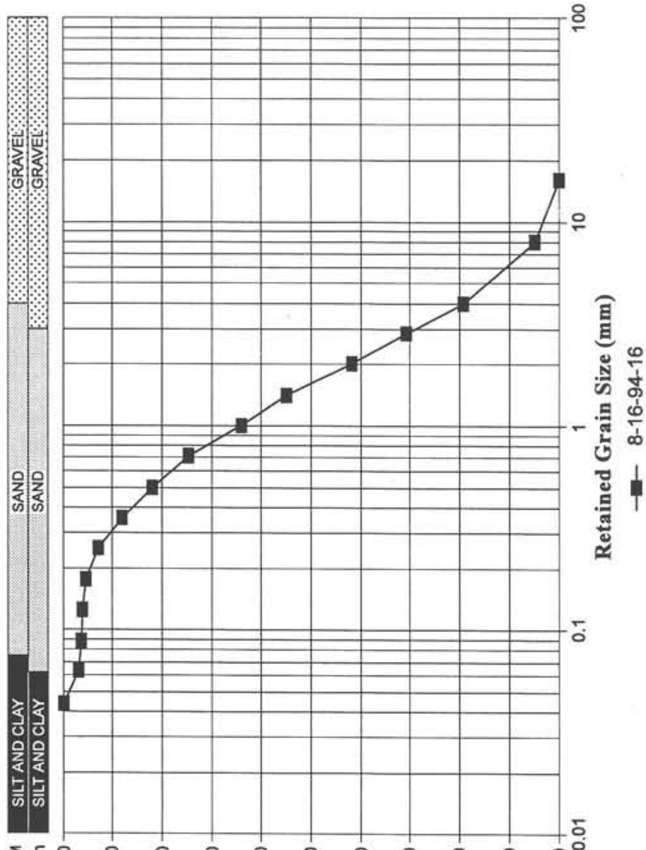

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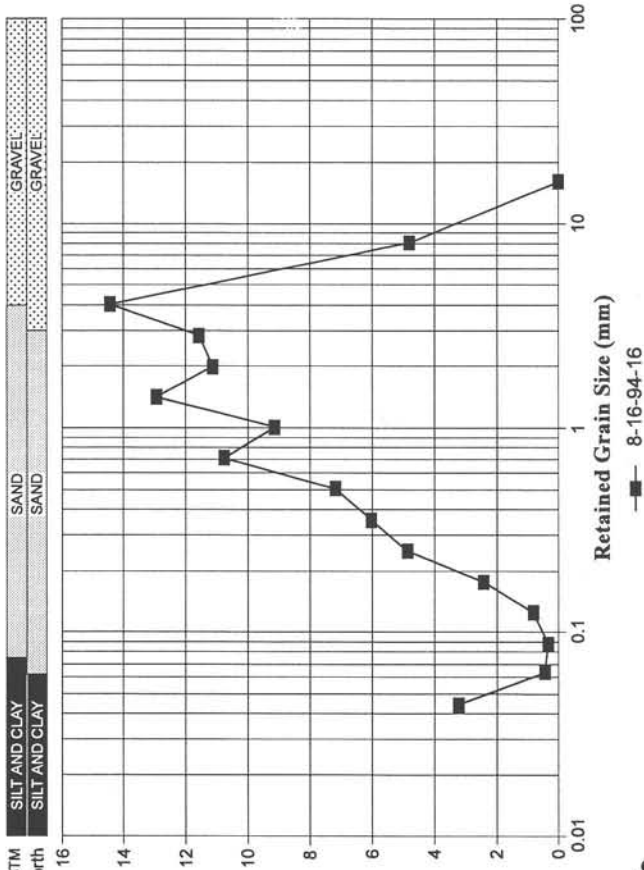

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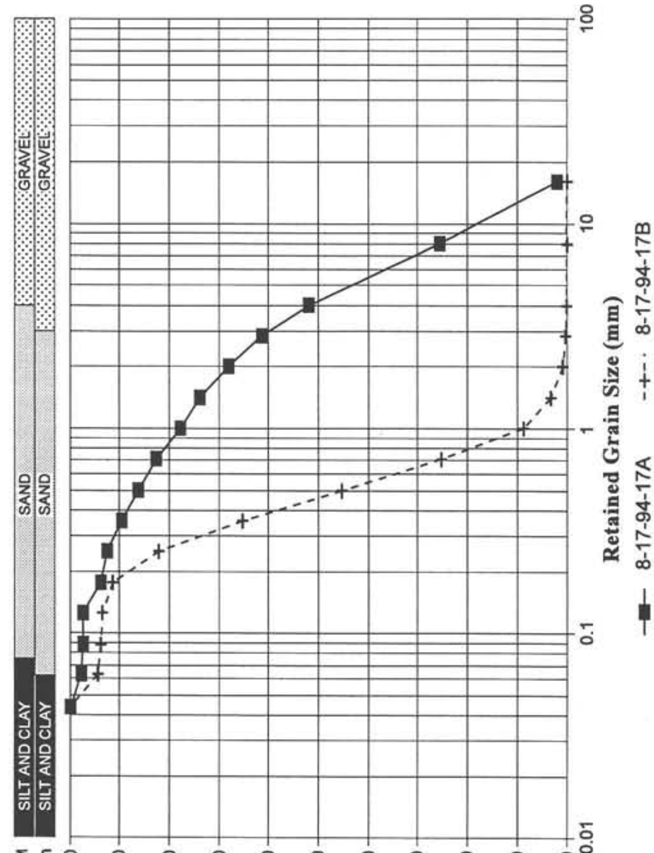

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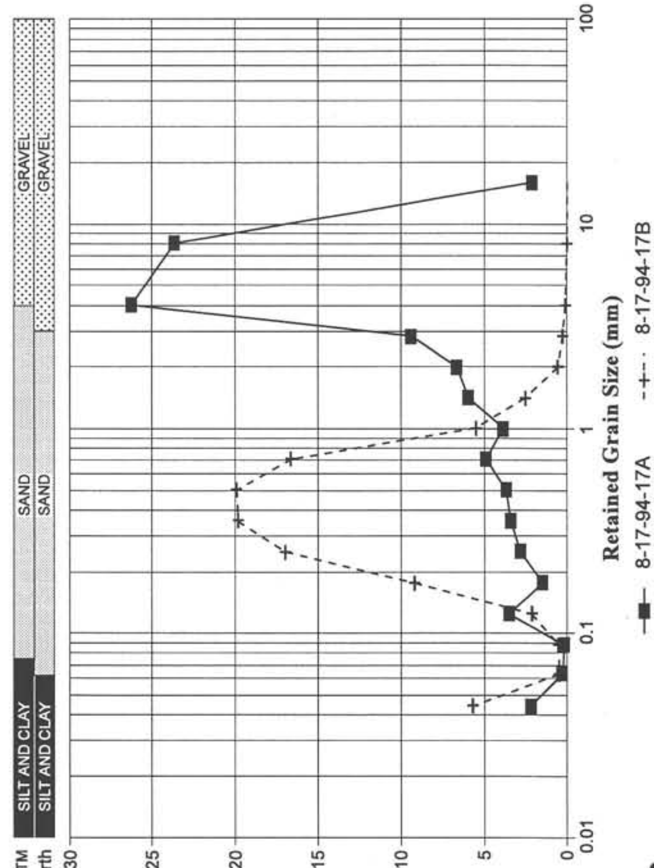

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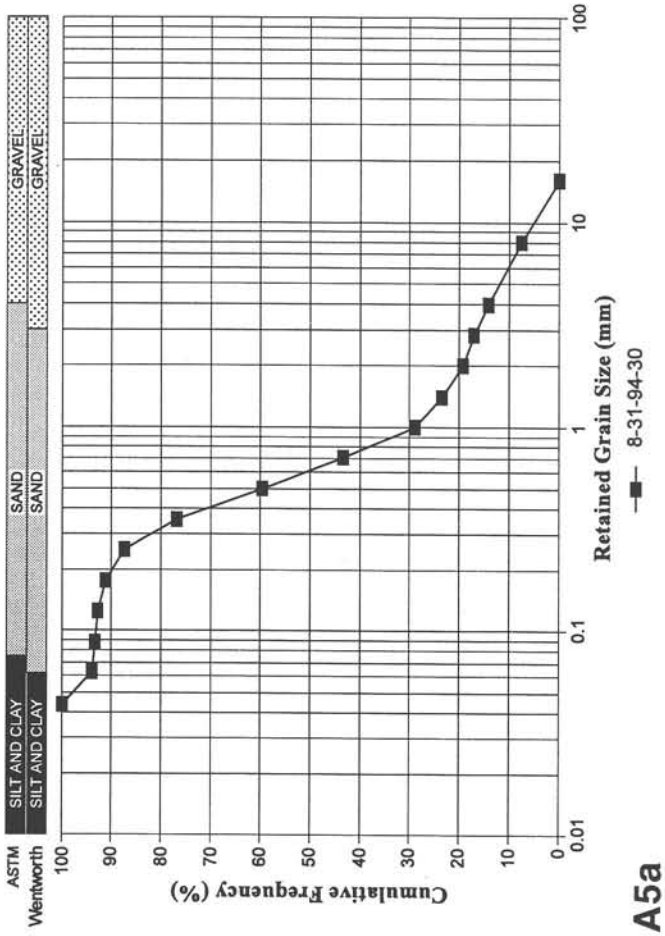

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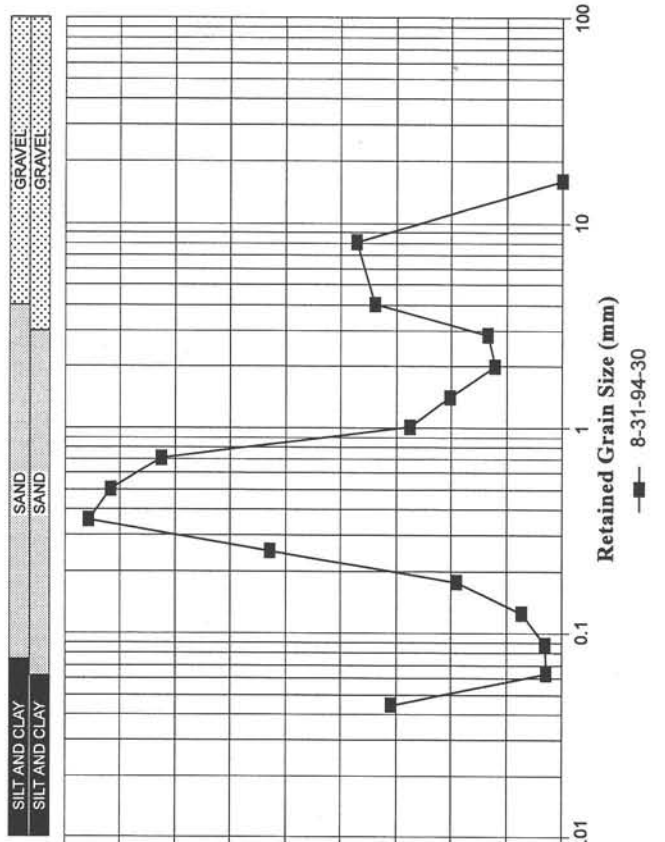

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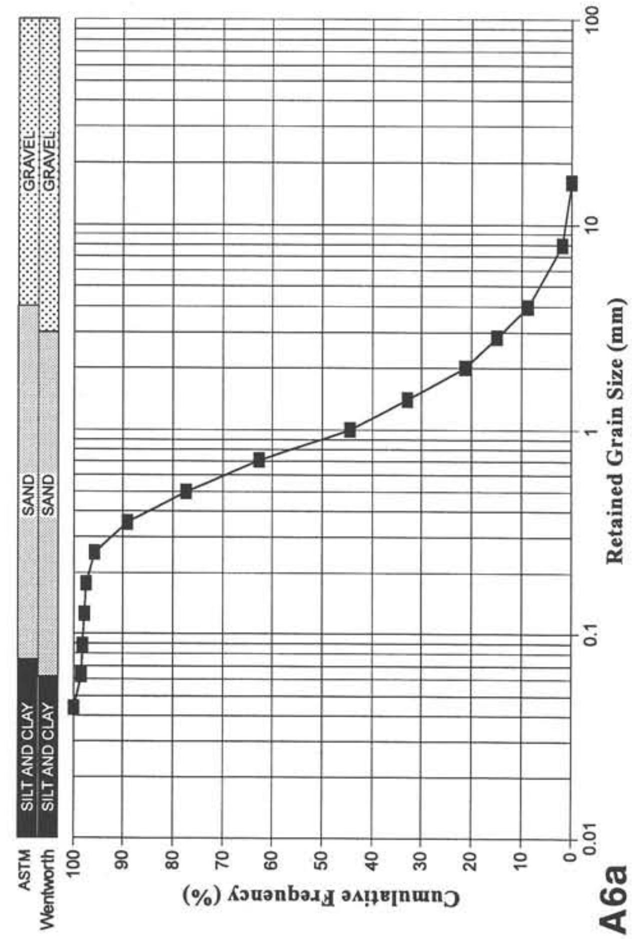

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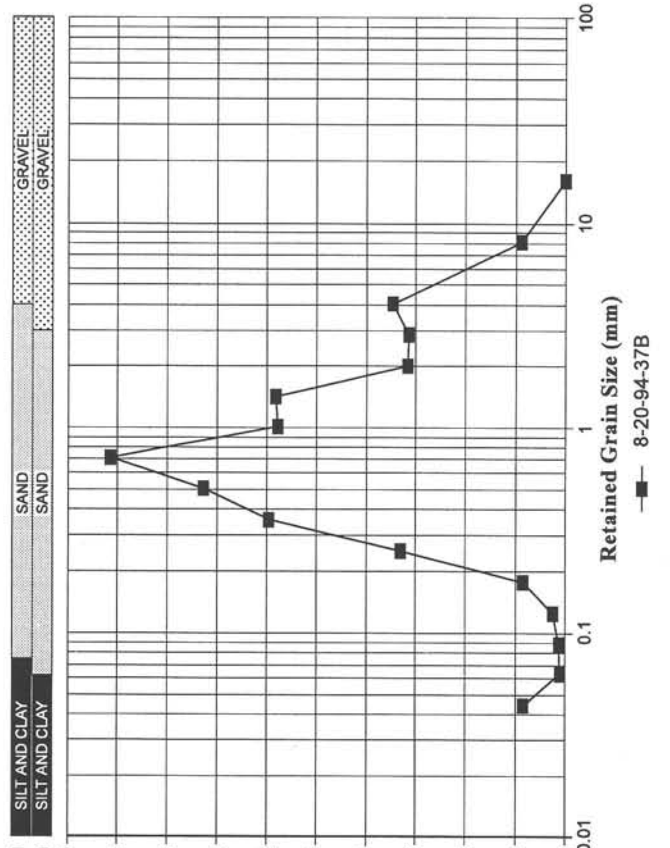

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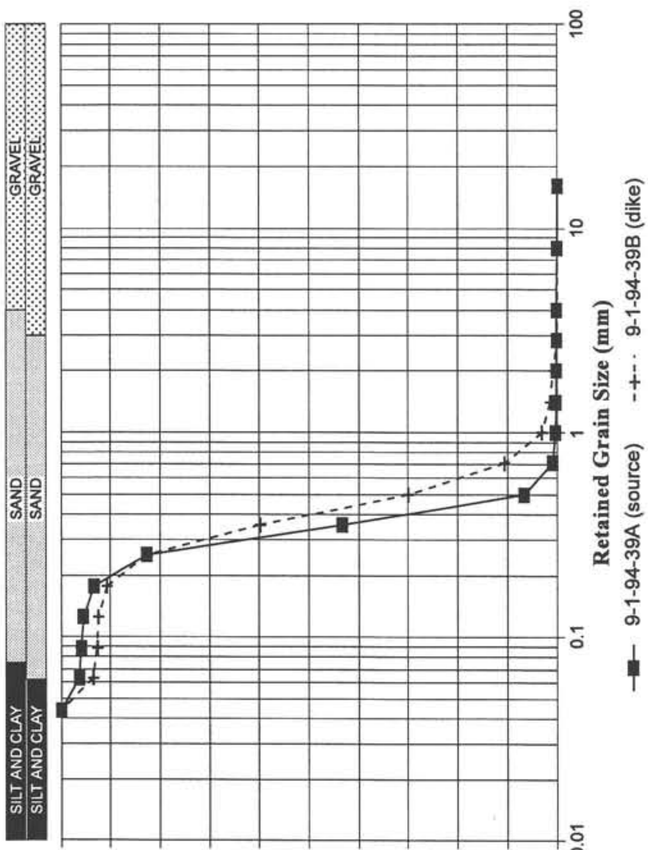

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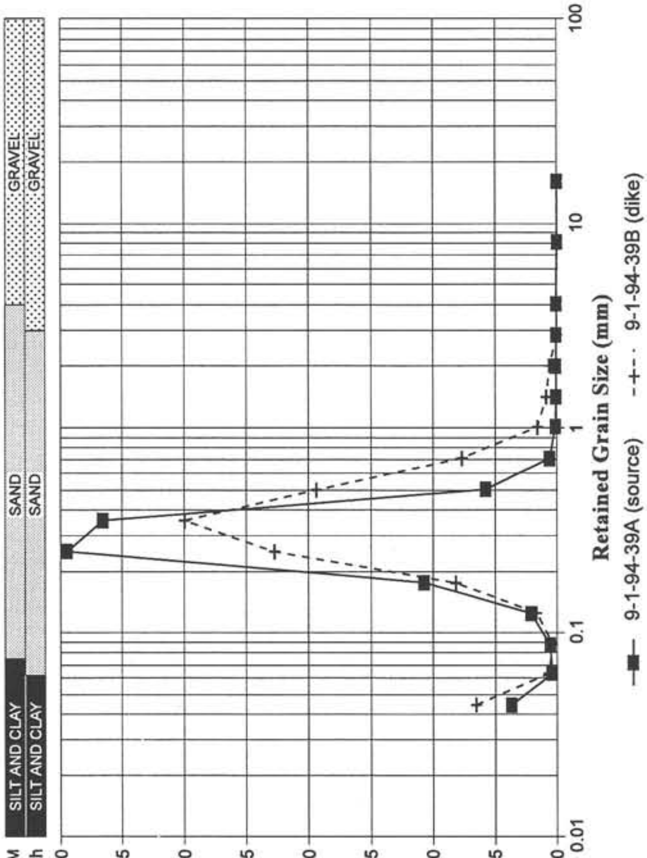

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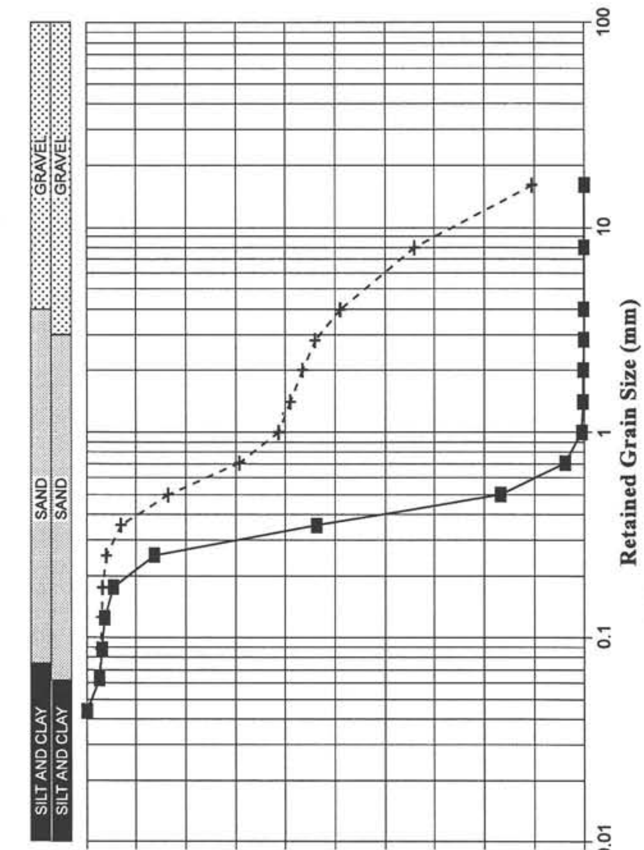

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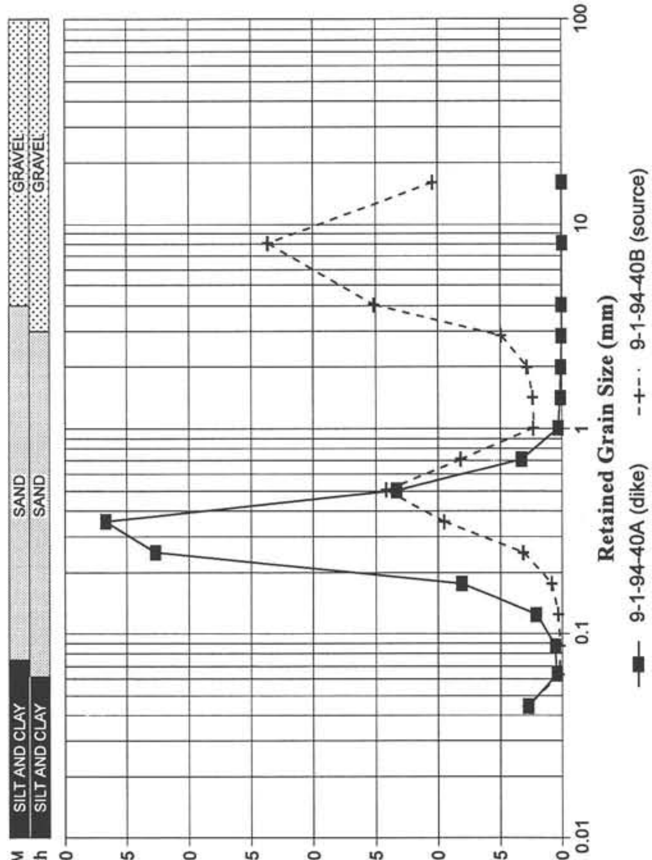

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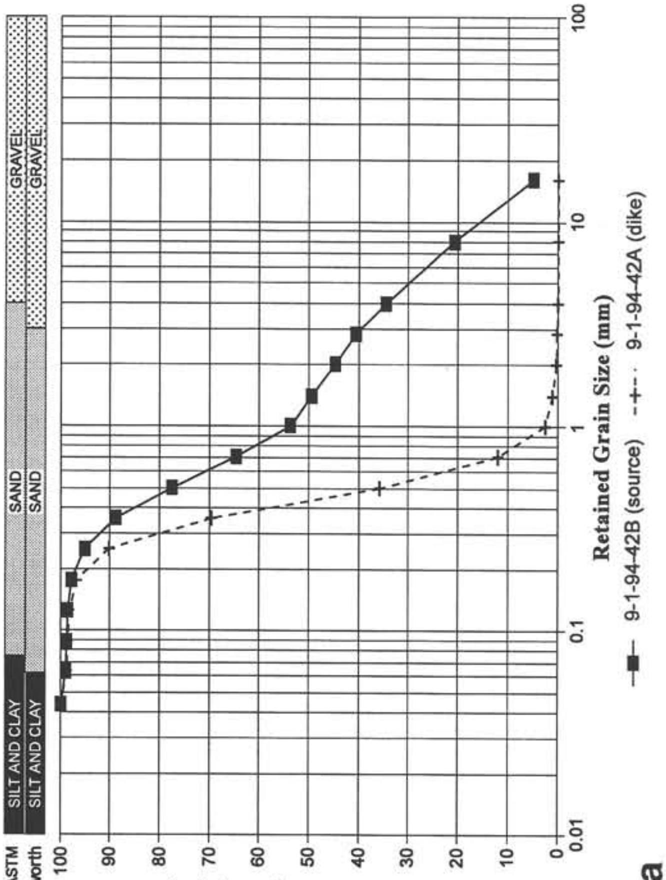

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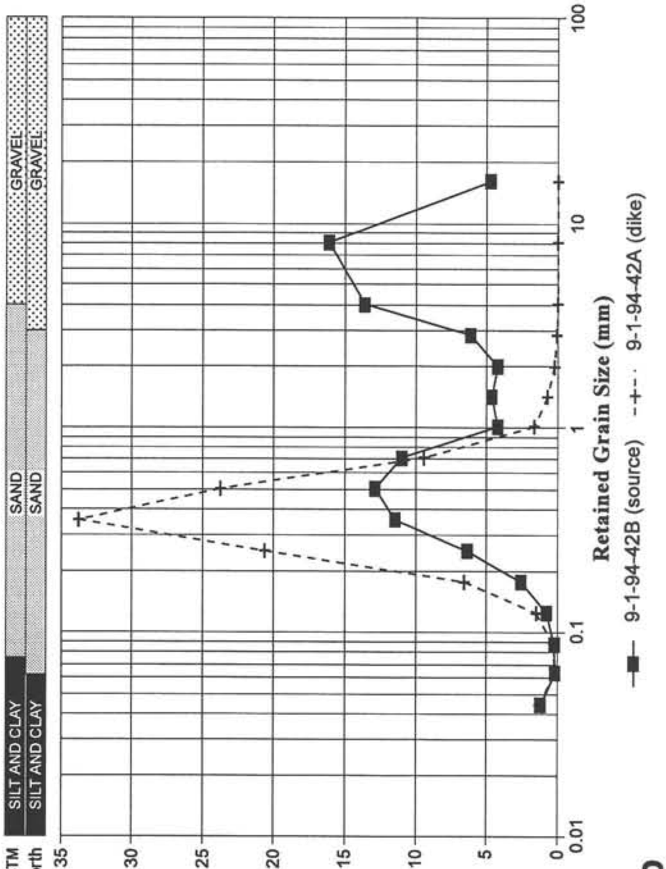

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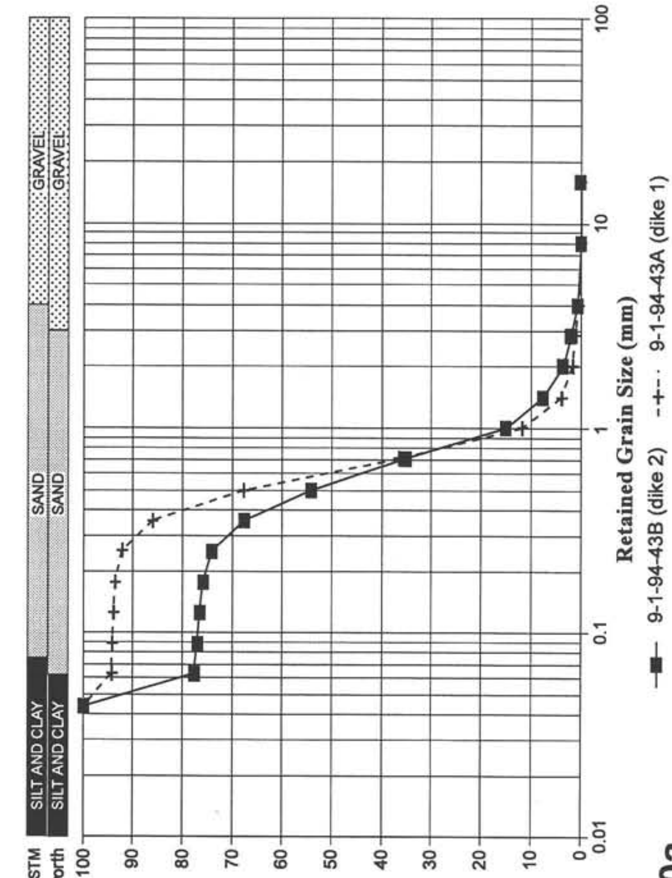

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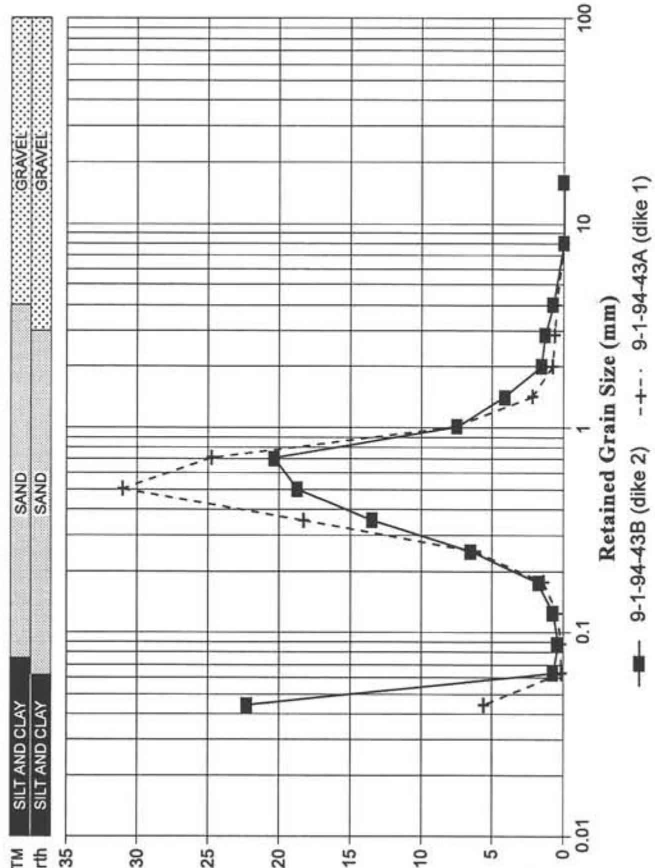

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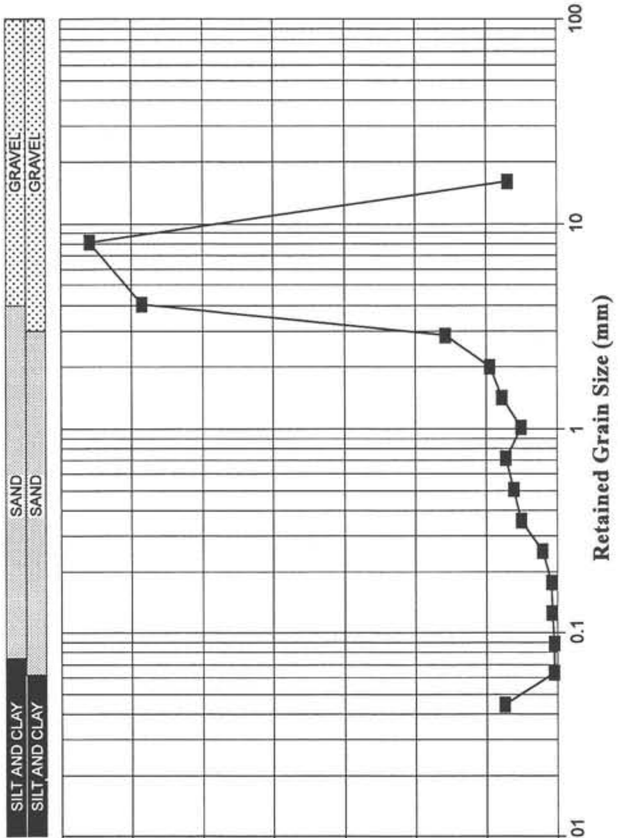

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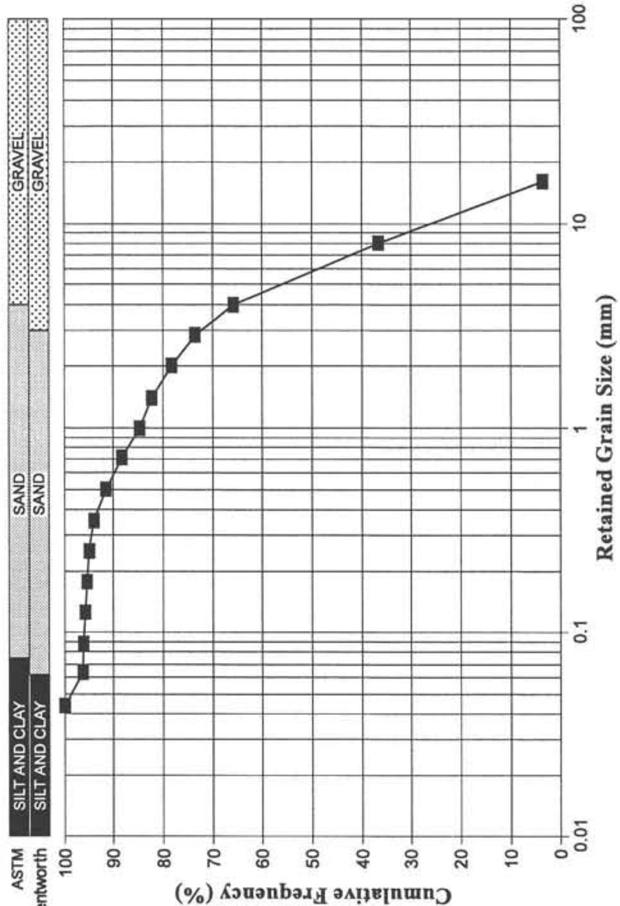

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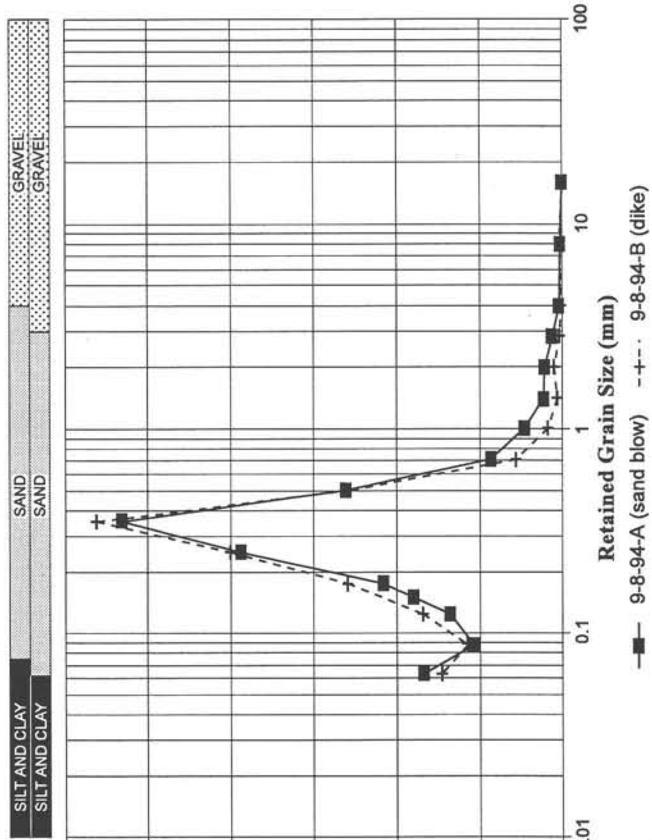

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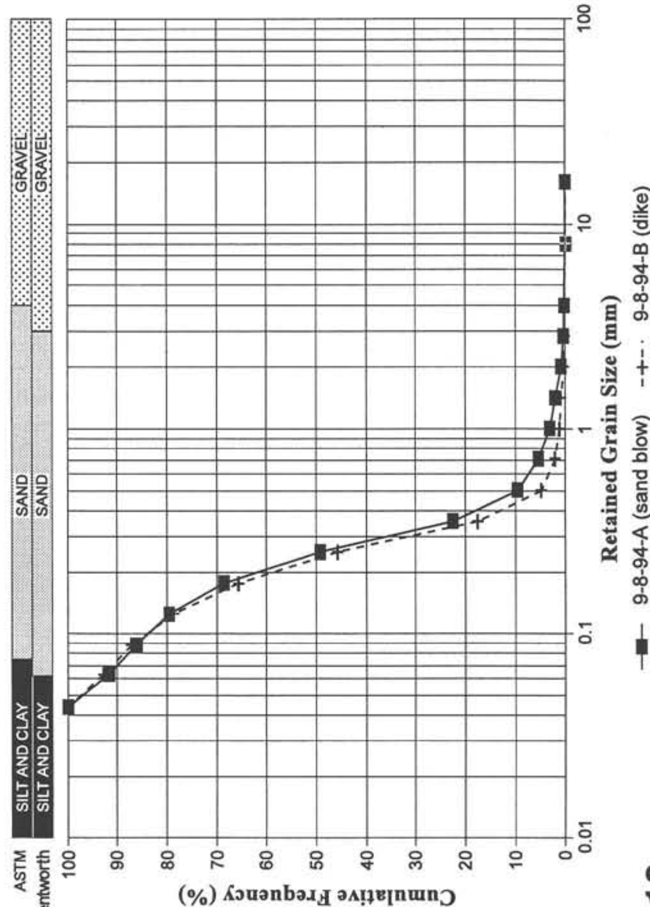

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