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GEOLOGICAL SURVEY

Field studies of earthquake-induced, liquefaction-flowage features in the Charleston, South Carolina, area: preliminary report

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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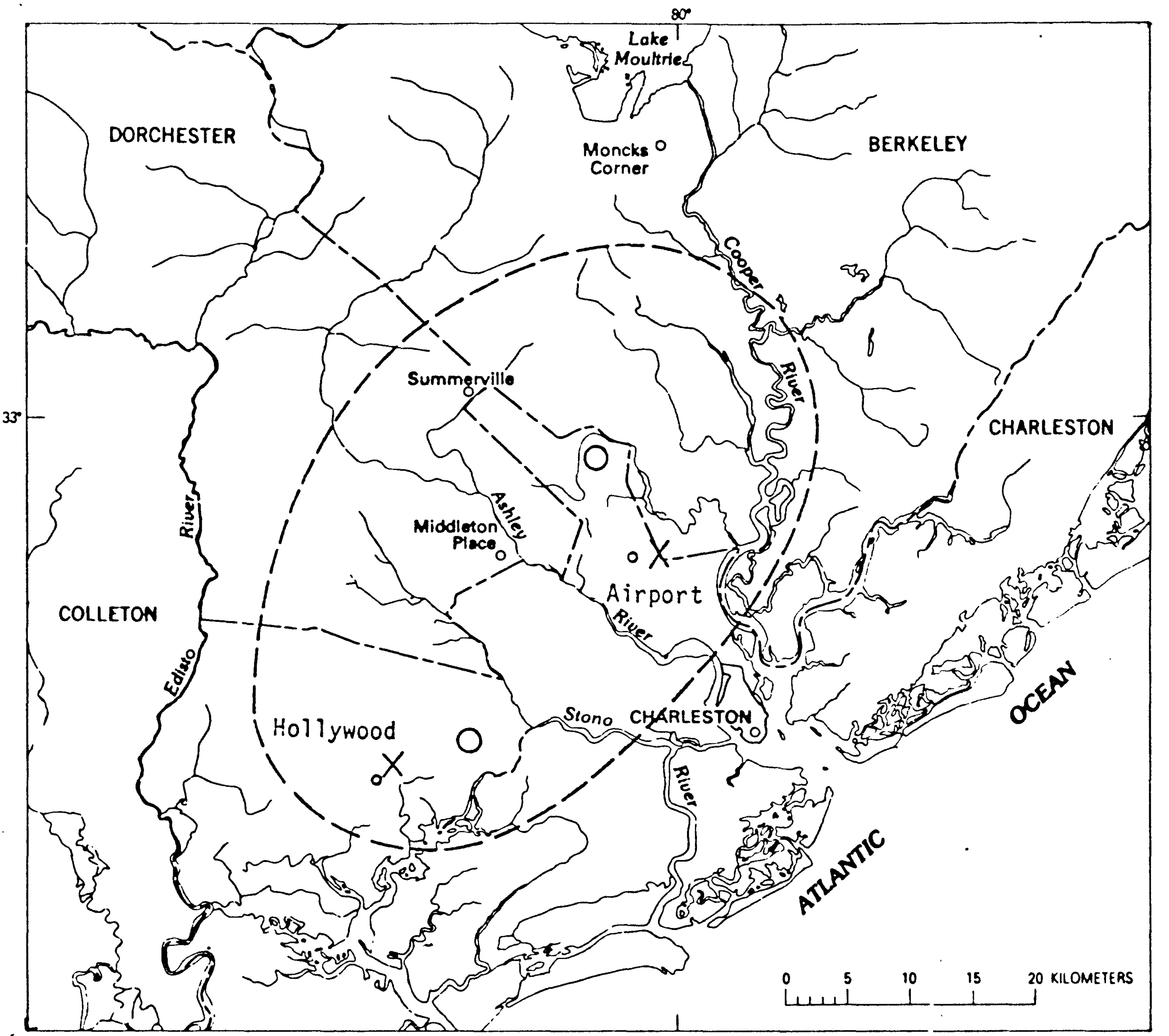
Introduction

Extensive geologic, geophysical, and seismologic studies have been conducted during the past decade in the Charleston, South Carolina, region by the U.S. Geological Survey, the University of South Carolina, and other institutions (see, for example, Rankin, 1977; Gohn, 1983; Hays and Gori, 1983). Many of these studies were designed to determine whether large earthquakes similar to the 1886 Charleston event (Modified Mercalli intensity IX-X; Bollinger, 1977) might occur in other parts of the southeastern United States or whether that event is uniquely related to special tectonic conditions in the vicinity of Charleston. To date, no unequivocal association has been demonstrated between the historic and continuing modern seismicity at Charleston and any particular structure or set of structures. The causative mechanism of the Charleston seismicity therefore remains uncertain although numerous seismotectonic hypotheses have been proposed (see the chapters in Hays and Gori, 1983, p. 84-168). This lack of clear association of the 1886 earthquake with geologic structure has made it difficult to understand where and how often future large earthquakes might take place in the Southeast (Pomeroy, 1983; Brocoum and others, 1983).

One geologic method of assessing the spatial and temporal distribution of past moderate and large earthquakes in the Southeast is a field study of liquefaction-induced flow features (sand blows) produced in near-surface sediments by earthquake shaking (Cox and Talwani, 1983a; Gohn and others, 1983; Seeber and Armbruster, 1983; McKeown, 1983; McWhorter, 1983). For example, near Charleston, numerous sand-blow craters were produced in 1886 during the MM IX-X event (Dutton, 1889) over an area of more than 700 sq km in Charleston, Berkeley, and Dorchester Counties (see fig. 1 for county locations). In addition, 1886 sand blows were reported up to about 100 km from Charleston (Seeber and Armbruster, 1981, 1983). Therefore, if late Quaternary earthquakes as large or larger than the 1886 event had occurred near Charleston, it seems likely that widespread geologic evidence of prehistoric liquefaction [1/] should be present.

A field study designed to uncover evidence of prehistoric earthquake-induced, liquefaction-related, ground-failure features near Charleston was initiated by the writers in the winter of 1983-84 following a reconnaissance field survey by University of South Carolina and USGS geologists in 1982 and 1983 (Cox and Talwani, 1983a; Gohn and others, 1983). The principal result of the reconnaissance survey was the excavation and study of a documented 1886 sand blow by Cox and Talwani (1983b, 1984). The present study focused on Charleston County; in particular, sites that had relatively young sediments (Holocene and late Pleistocene) were examined because they would have been

[1/] Liquefaction is defined as "the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-water pressures" (Youd, 1973). In the liquefied state, the material basically behaves as a fluid mass (that is, the material flows as a fluidized mass). The increased pore pressure is understood as being caused either directly or indirectly by earthquake shaking (that is, either during or immediately after the earthquake).



EXPLANATION

○ Centers of highest intensity of 1886 earthquake (Dutton, 1889)

— — Approximate boundary of 1886 meizoseismal zone

X Sites with liquefaction-induced flowage features, this study

Figure 1.--Map of the greater Charleston, South Carolina, area that shows the meizoseismal area of the 1886 Charleston earthquake and the location of study sites in Charleston County.

most prone to liquefaction during the past few tens of thousands of years and would have most relevance to questions of modern seismicity.

This article describes preliminary results of the field study during which the following features were discovered: pre-1886, earthquake-induced sand blows at a site in southern Charleston County; at the same site, sand blows that possibly resulted from the 1886 earthquake; in central Charleston County, a sand blow that possibly resulted from the 1886 earthquake; and, at several sites, probable and possible earthquake-induced liquefaction features of unknown age.

Geologic setting.--The study area (fig. 1) is located within the Atlantic Coastal Plain. The sedimentary section in the area is approximately one kilometer thick and consists primarily of Upper Cretaceous and Tertiary deposits (Sanders and others, 1982; Ward and others, 1979; Weems and others, 1982; Gohn and others, 1977). Mantling these older beds are several sequences of Pleistocene shoreline deposits that are highly variable with regard to their thicknesses and lithologies (McCartan and others, 1984). Virtually all natural and man-made exposures reveal only Pleistocene and Holocene sediments. Estuarine, tidal-marsh, and fresh-water swamp deposits of Holocene age are widespread in this low-lying coastal area, but they are almost always inaccessible for studies of liquefaction features, which typically require trenches or other exposures above the water table.

Most of the liquefaction-induced features described in this paper occur in beach or nearshore-marine sands of map unit Q_3 or the older part of unit Q_2 of McCartan and others (1984) or in Pleistocene fresh-water swamp deposits. On the basis of weathering characteristics of the sediments, biostratigraphic data, and uranium-series ages of corals, McCartan and others (1984) estimate that Q_3 sediments were deposited about $2x10^5$ YBP and that the older Q_2 sediments were deposited about $1.2x10^5$ YBP.

Characteristics of documented 1886 sand blows

In preparation for the field study, existing descriptions of the 1886 sand blows were analyzed to provide a comparative basis for the recognition of any newly discovered sand blows. The most extensive documentations of 1886 sand-blow craters are in the reports by Dutton (1889) and Cox and Talwani (1983b, 1984) and old photographs from the Charleston Museum. Dutton's report shows the regional distribution of 1886 sand blows, and the photographs show the morphology of the craters and the nature of the sediments in and around them.

Figure 2 shows a pen sketch, made from one of the museum photographs, of a large 1886 crater and the ejected material around its rim (photograph also reproduced as pl. XXI in Dutton, 1889; and as the frontispiece in Gohn, 1983). The crater is typical of many seen in the old photographs and is about 0.5 to 1.5 m deep. This crater is slightly larger, however, than most of the photographed craters, and it contains within it, at its right side, another crater and its surrounding rim of sand (a sand volcano). The long axis of the large crater is at least 8 m in length at the ground surface. Photographs of other craters show that their rims are commonly 3 to 6 m in diameter or longest dimension where irregular.

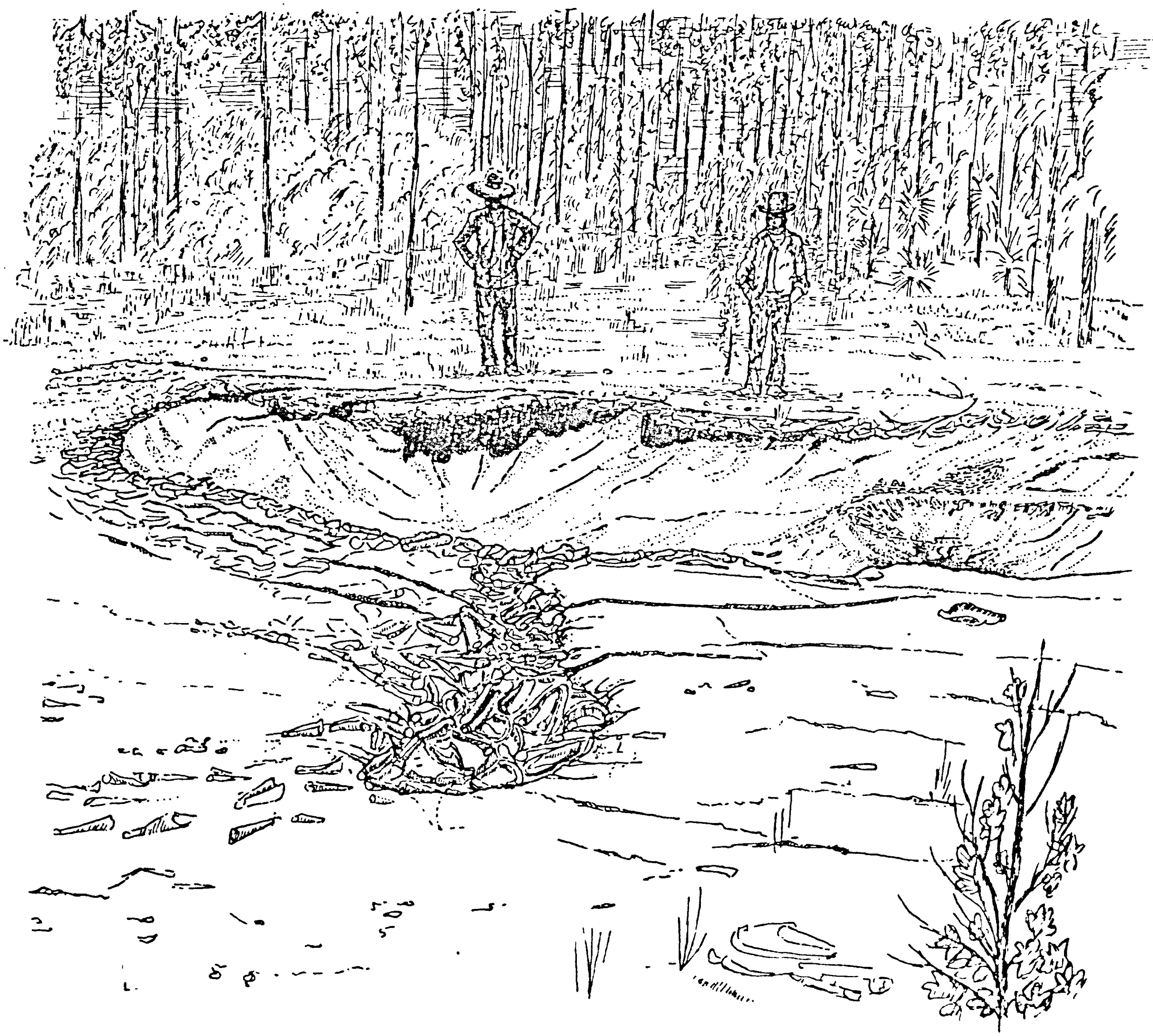


Figure 2.--Sketch from a photograph of an 1886 sand blow on Ten Mile Hill near the present Charleston airport. Note the sand within the crater, the blanket of ejected sand around the crater, and the constructional sand volcano at the right.

Figure 2 shows that both the large and small craters contain sand, and that the larger sand blow is bowl-shaped in vertical cross section and elliptical in plan view. A blanket of ejected white sand extends a few tens of meters in all directions. There is a thin veneer of curled, dried mud in the foreground and near the rim of the small crater that overlies the ejected sand.

The sequential development of 1886 sand blows of the kind represented in figure 2 can be interpretated from the photographs and descriptions in Dutton (1889). Four stages in the development of an individual sand blow are recognized: an initial explosive phase, a subsequent flowage phase, a collapse phase, and a final period of infilling of the crater. All four phases produce a recognizable geologic record.

Prior to the explosion, cyclic seismic loading produces physical changes in a water-saturated subsurface sand bed. Pore-water pressure increases and shear strength is lost in the sand body, and it is transformed from the solid state to a liquefied state (Youd, 1973). The liquefied mass then flows to the surface with sufficient force to "explode" and at least partially excavate a crater (for example, the large crater in figure 2). The force of the sand expulsion is recorded by ejection-flowage blankets that are tens of meters across. Dutton (1889) recorded areas of many acres that were covered with ejected sand (probably coalesced from numerous vents) to depths of 0.7 m or more in 1886, and he also noted that ejected sand was found covering tree limbs at heights of 6 m above the ground. Ground fracturing apparently accompanied or preceded the sand movement because dry fractures connecting craters were common in 1886 (Dutton, 1889). These fractures also result from earthquake shaking and are typical of large earthquakes that produce liquefaction (for example, see Tuthill and Laird, 1966; Foster and Karlstrom, 1967). The geologic record of this explosive phase is the excavated crater and part of the ejection blanket. Clasts of excavated solum might be expected within the ejection blanket.

Flow from the crater apparently continues for some time after the initial explosion (probably minutes to hours) and adds additional sand to the ejection blanket (flowage phase). Judging from its unaltered constructional geometry and its location within the larger crater, the sand volcano in figure 2 brought sand to the surface following expulsion of sand from the larger crater. (There is a possibility that the sand volcano was produced by an aftershock.) Another photographed 1886 sand blow (not figured herein) has a distinct outflow channel that extends from the rim of its vent and cuts across and is incised into the ejection blanket. In the geologic record, the flowage phase is represented by part of the ejection blanket, sand volcanoes, and possibly by subsurface conduits ("dikes") that fed such late constructional features as the sand volcano.

The nature of material transport changes as the pore water pressure decreases. Shortly after the explosive phase, pore water pressures are so high that many large clasts are carried along in the fluidized mass. Then, as the pore water pressure decreases, the large and (or) dense clasts are either "frozen" at an equilibrium position within the crater or else settle into the fluidized mixture. Small and (or) light clasts may continue to be transported upward. This phase of fluidized transport thus grades into the collapse phase. Upward transport of even fine-grained material eventually stops as the pore water pressure decreases; thereafter, only collapse deformations take place. Collapse deformation apparently involves a reversal (downward) of sediment movement in the crater, and overall reduction in the voids between clasts, sand, and silt (that is, compaction). This downward movement, following the excavating effect of the initial blast, typically results in craters that are not full to their rims following the liquefaction-flow event (see fig. 2 and examples in Dutton, 1889). Collapse due to gravity, decreased pore pressure, and subsurface volume loss caused by sand expulsion beneath and beyond the crater margin, probably contribute to this phase in a complex manner. The geologic record of this collapse phase may be represented by coarse-tail grading of sediments in the crater caused by sinking of large soil clasts, downward flow structures, and perhaps local small-scale dewatering structures in the crater sand. In addition sand caught in the bottom of the crater's bowl (for example, the sand visible within the large crater in fig. 2) may contain vegetation, large clasts of soil material or disaggregated soil material that would distinguish this sand from underlying sand that had not reached the surface. Gravitational faults also may develop.

Following the collapse phase, filling of the partially empty crater probably continues for weeks to months. Sediment is undoubtedly added to the crater floor by collapse of the rim, sediment washovers during rainstorms, and eolian processes.

At least one 1886 sand blow has been restudied in recent years. Cox and Talwani (1983b, 1984) excavated and described an 1886 sand blow that consisted of a sand-filled fissure and a thin ejection blanket. The subaerial blanket of ejected sand covers about 180 m^2 and consists of well-sorted, fine quartz. The sand-filled fissure is about 3.7 m long and up to 0.6 m wide and contains the same white sand. Clasts of the surrounding solum were present in the fissure sand. The source of the liquefied sand was encountered between depths of 2.1 m and 5 m in auger holes (Cox and Talwani, 1984).

Results of new field study

Location

Numerous sand blows occur in a drainage ditch in southern Charleston County within the region reported by Dutton (1889) to contain sand blows caused by the 1886 earthquake. This ditch is located in the Wadmalaw, S.C., 7.5-minute quadrangle (U.S. Geological Survey, 1960, revised 1971) near the town of Hollywood (fig. 1). The ditch is located about 0.4 km north of highway 162 and is roughly parallel to that road within and east of the Hollywood boundary line. Dozens of filled sand-blow craters and related structures are scattered over a distance of about 3 km in the 2.5-m-deep ditch.

Typical soil profile

An understanding of undisturbed soil profiles in the Hollywood ditch is necessary because differences in the development of the profile occur where sand blows cut the solum. That is, older soils are disrupted by sand blows, and younger soils are developed on the sand-blow sands. The relative ages of the liquefaction features can therefore be derived from their relationship to the soils.

Most of the soils exposed in the Hollywood ditch are spodosols that were assigned to the St. Johns Series in the Soil Survey of Charleston County (Miller, 1971). These soils probably would now be assigned to the Baratari or Leon Series (H. Markewich, pers. commun., 1984). Below a thin (less than 5 cm) organic surface layer, A, E, Bh, and C horizons are present in the exposed profiles. All of these horizons consist of fine to medium sand. The A horizon is 0 to 15 cm thick, black, and friable. It contains abundant organic matter and roots. Numerous white quartz grains cause a salt and pepper appearance. The E horizon is 0 to 15 cm thick and is much lighter-colored (generally medium gray, N5) and has a more pronounced salt and pepper appearance than the A horizon. The E horizon has clear upper and lower boundaries and consists of noncoherent, loose to friable material. In engineering terms, the E horizon consists of very loose material[2/]. The Bh horizon is brownish black (5YR 2/1), massive, dense, and cemented with humate. Cementation has made the Bh horizon compact to extremely compact[2/], and at some places it can be excavated only by chopping with hand shovels. Thickness of the Bh horizon ranges from about 0.5 to 1.0 m. A B-C transition horizon occurs locally below the Bh horizon. It is light to medium gray (N5-N7) or pale reddish brown (10R 5/4), friable, structureless, and compact to very compact[2/]; thickness varies from 0 to 15 cm. Where present, the B-C horizon has a clear or gradual boundary with the underlying C horizon, which is much lighter colored. The C horizon is typically yellowish gray (5Y 8/1) and locally highly mottled with light brownish-gray (5YR 6/1) coloring. C horizon material is structureless, friable, and compact[2/]. The C horizon generally extends down to 175 cm or more beneath the ground surface. Locally a layer of pale-brown (5YR 5/2), clayey sand (0-50 cm thick) occurs within the C horizon. This clayey layer is tentatively interpreted as a clay pan although its origin remains uncertain.

Possible 1886 sand blows

Three liquefaction-related features in the ditch represent a geologically recent earthquake that may be the 1886 event. Two of these features, identified herein as features I and II, consist of thin, sand-filled fissures that cut across the modern solum at moderately steep angles. Feature III is a complex array of large sand-filled sills.

Feature I.--As shown in figure 3, fissure I occurs almost entirely within the C horizon of the soil profile and below a 1.5 to 2.0-m-thick Bh horizon.

[2/] The descriptions of soil horizons given herein conform to the standard nomenclature of soil scientists except for "compactness". This word is used in the geotechnical engineering sense, and is intended as a semi-quantitative term to represent the relative state of packing, because it is a measure of the susceptibility to liquefaction during earthquake shaking. Compactness is described in the following terms, ranging from states that are extremely susceptible to nearly unsusceptible to liquefaction during shaking: very loose; loose; moderately compact; very compact; and extremely compact. Cohesionless soils that are very compact and extremely compact can be liquefied after shaking, if the pore water pressures generated during shaking move upward with sufficient force.

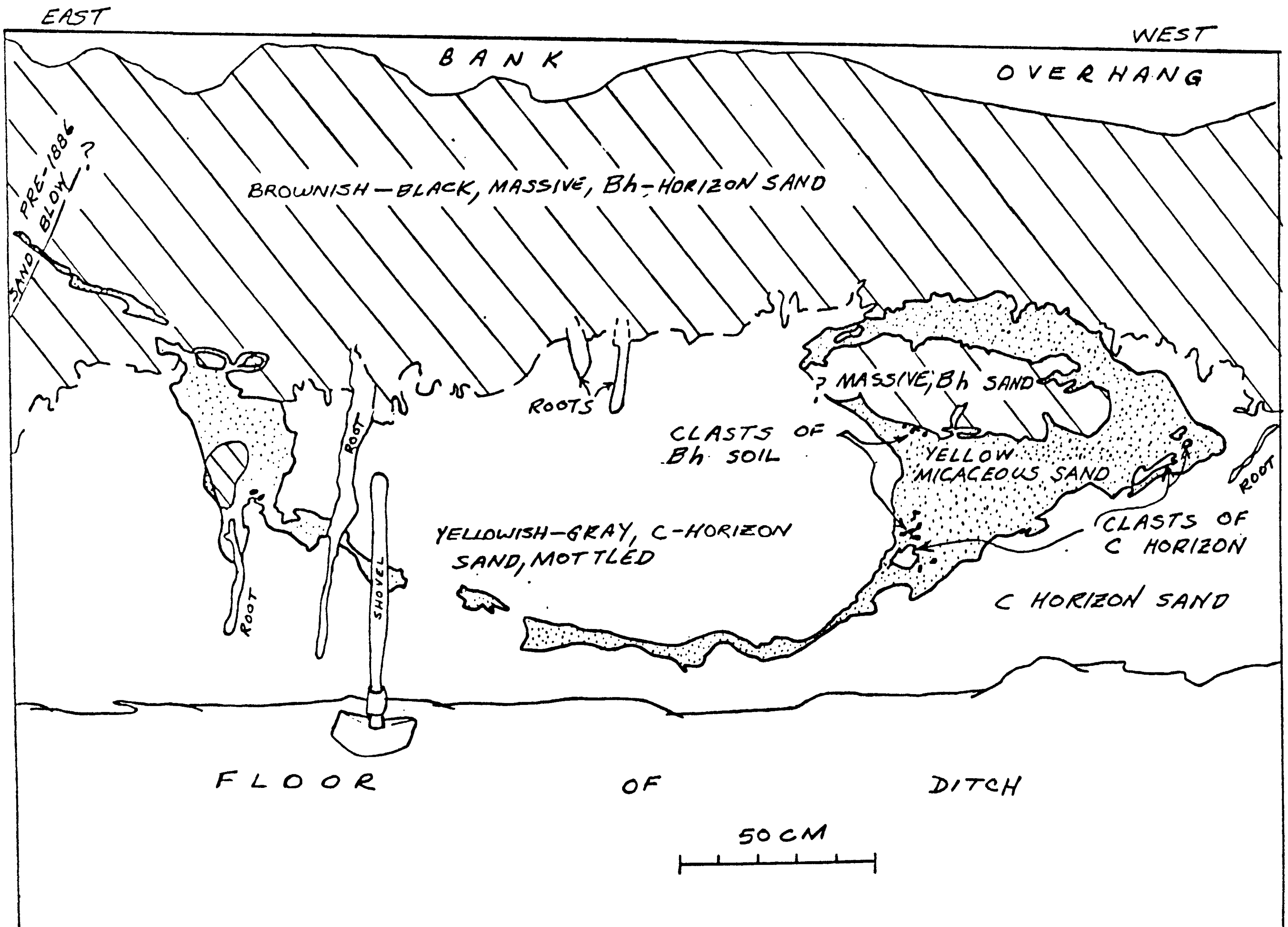


Figure 3.--Sketch from a photograph of fissure I in the Hollywood ditch. **Note that** the fissure (dot pattern) contains down-dropped blocks of Bh **material and** that the fissure cuts an older (pre-1886) sand blow at the **eastern end of** the exposure.

Along most of its length, the width of fissure I varies from 7 cm to less than 1 cm, and it is locally absent (in the plane of the outcrop) for distances up to 10 cm. The fissure expands just below the Bh horizon to widths of 0.3 m on the eastern end and 1.0 m on the western end. Above the bulbous part of the fissure at its eastern end, a thin extension of the fissure continues discontinuously upward for about 0.6 m. This extension crosses into the Bh horizon and into the interior of an older sand blow (cross-cutting relationships are discussed below). A second thin fissure filled with yellow sand could be seen in the floor of the ditch at the water line. However, this second fissure could not be traced physically into fissure I nor could it be traced downward. The relationship of this fissure to fissure I, and the geologic significance of this fissure, remain unexplored.

A 0.3-m-deep hole dug horizontally into the outcrop across the center of fissure I shows that it is a three-dimensional, dike-like body that dips down into the outcrop (south) at a moderate angle. The parabolic shape of the fissure in the vertical face of the outcrop and the dip of the fissure suggest that its overall shape approximates a half-cylinder or half cone whose long axis plunges to the south.

Distinct lithologic differences between the fissure sand and the surrounding sands are obvious in the field. The fissure sand is a yellowish-gray color that is lighter and has a slightly higher chroma than the yellowish-gray color of the C horizon or the brownish-black color of the Bh horizon. In addition, the fissure sand contains a visibly greater and coarser grained fraction of detrital white mica than any other unit in the exposure.

Coherent clasts of B-horizon sand are present within the fissure sand but are absent in the C-horizon sand except for one small cluster near the bulbous western terminus of the fissure. Clasts within the fissure sand are typically subrounded, irregular to nearly spherical in outline, and typically 0.5 to 3 cm in longest dimension. Clast-clast boundaries are rare, and most clasts appear to "float" in the fissure sand. A single large clast occurs in each of the expanded terminal sections of the fissure.

Fissure I resembles a small sand fissure produced during the October 15, 1979, Imperial Valley, California, earthquake that was studied by Muir and Scott (1982). In the California example, a dike-like fissure of sand originated in a liquefied bed located just below the water table (about 2 m below ground surface) and traveled to the surface, where it produced a small sand cone. The California fissure was 1.5- to 2-cm wide. Flow laminations caused by segregation of heavy minerals in the California fissure were not observed in fissure I (or II), perhaps because the heavy minerals were removed in the weathering zone prior to mobilization.

Feature II.--Fissure II was found about 20 m west of fissure I (fig. 4). It is similar in shape and size to fissure I but lacks the bulbous terminations. Feature II consists of a 1- to 4-cm wide, locally discontinuous fissure that is filled with micaceous, yellowish sand identical to the sand in I (fig. 4). Thin, 1-cm-long veinlets of fissure sand project into the surrounding material along the entire length of the fissure. Fissure II appears as an asymmetrically curved feature whose eastern limb has an apparent

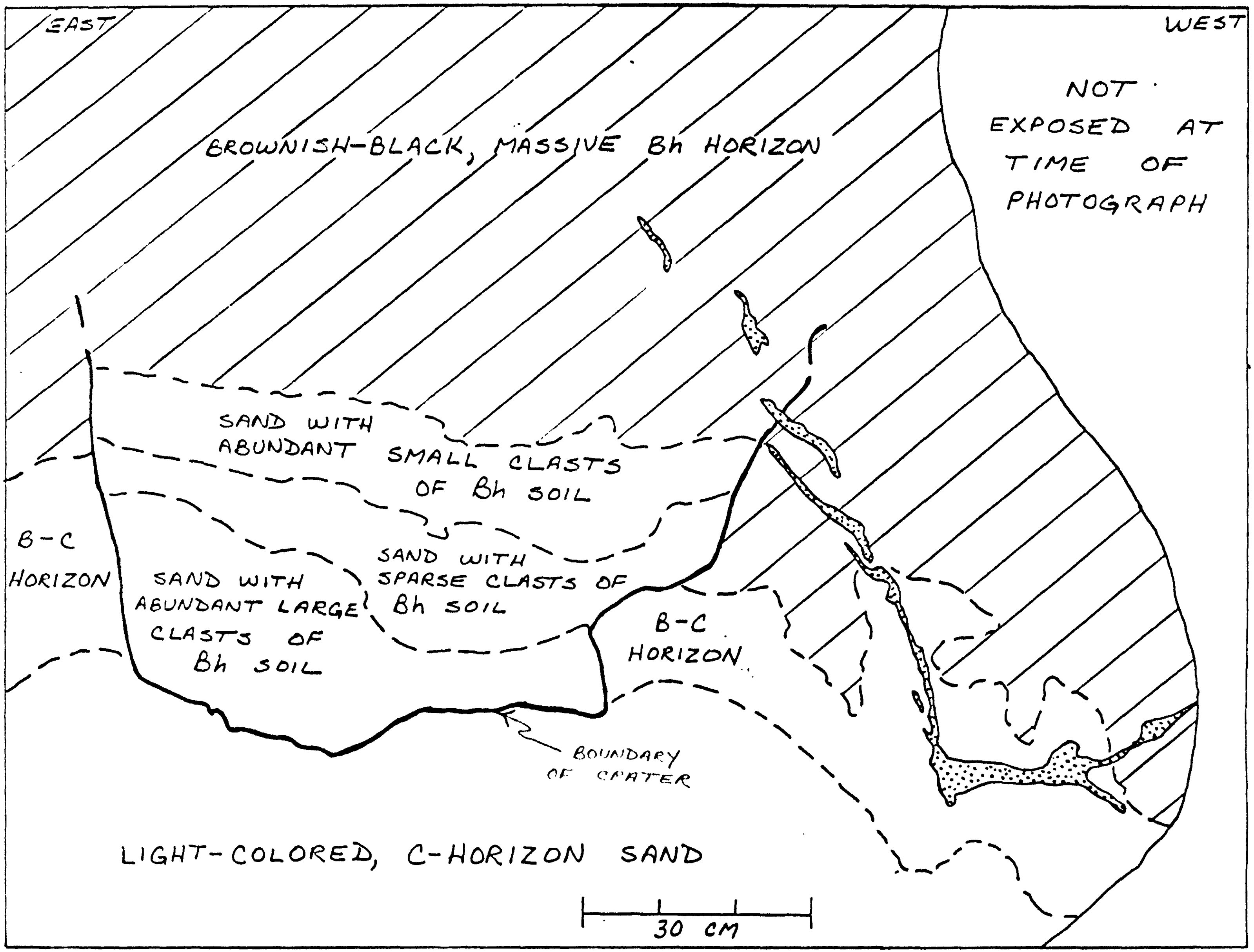


Figure 4.--Sketch from a photograph that shows part of fissure II (dot pattern) and its cross-cutting relationship to an older, filled, sand-blow crater.

western dip of 70 degrees and whose western limb has a 20-degree apparent dip to the east. The dip of the western limb in a small horizontal excavation suggested that fissure II has a half-cone or possibly half-cylinder shape (axis plunging moderately south) similar to the shape of fissure I. The exposed length of the eastern limb is about 1.0 m, whereas the exposed western limb is about 2.0 m. As seen in this outcrop (fig. 4), fissure II is located entirely within the Bh horizon except for its lowermost part. The eastern limb of fissure II cuts across the edge of an older sand-blow crater and extends 35 cm into the older feature.

Feature III.--In a north-south oriented section of the Hollywood ditch, there are numerous (at least 10) sill-like intrusions (hereafter referred to as "sills") of loose to friable, well-sorted, white, fine- to medium-grained, quartz sand. A larger, vertically elongate (cylindrical?) body of white sand occurs with the sills. Minor reverse faulting along the edge of the larger sand body truncates soil horizons and at least one sill. The sills and associated features constitute composite feature III, which we interpret as the result of very forceful intrusion of fluidized sand in the recent past.

Figure 5 is a sketch showing field relations of one sill. The sills are up to 7 m long and are generally about 15 cm thick. They were observed to extend at least 2 m laterally in the horizontal plane. The sills generally have an envelope or rind of black humate-rich sand that is typically about 5 to 10 cm thick. Most of the sills turn up at their northern ends and connect with a surficial sheet of white sand that is about 15 to 20 cm in thickness. The veneer is thickest where intersected by the sills and probably consists of sand ejected from the sills. Slight organic staining of the upper 10 cm of the sand sheet is present.

At most places the sills cut through moderately compact B-horizon sands. Most of the B horizon can be easily excavated by hand shovels; however, the uppermost part is much stronger and brittle, and excavation by hand tools in the uppermost 1 m of the weathered zone must be done more by chopping and chipping than shoveling.

Locally, where the sills are very thick, they extend about 2 m beneath the surface and have a lower contact with a black, humate-rich sand stratum of unknown thickness. At a few places, the sills appear to cut into the black sand for 10 to 20 cm, but the sills cannot be traced deeper because the color contrast becomes weaker with depth. It appears, however, that the source stratum for the sand in the sills is beneath the black sand.

Age of features I, II, and III.--A relatively young age is inferred for fissures I and II because the sands in these fissures do not show evidence of any humate accumulation although they cut a dense, humate-rich B horizon. Similarly, the limited alteration (solum development) of the ejected sand and the sand in the sills in feature III also suggests a relatively young age for that feature. In contrast, the thicknesses and high humate contents of the black rinds around the sills possibly suggest an older age although the origin of the rinds is not presently understood.

It is possible that features I, II, and III were produced during the 1886 Charleston earthquake because they are the geologically youngest liquefaction-related phenomena that we have observed. Because the 1886

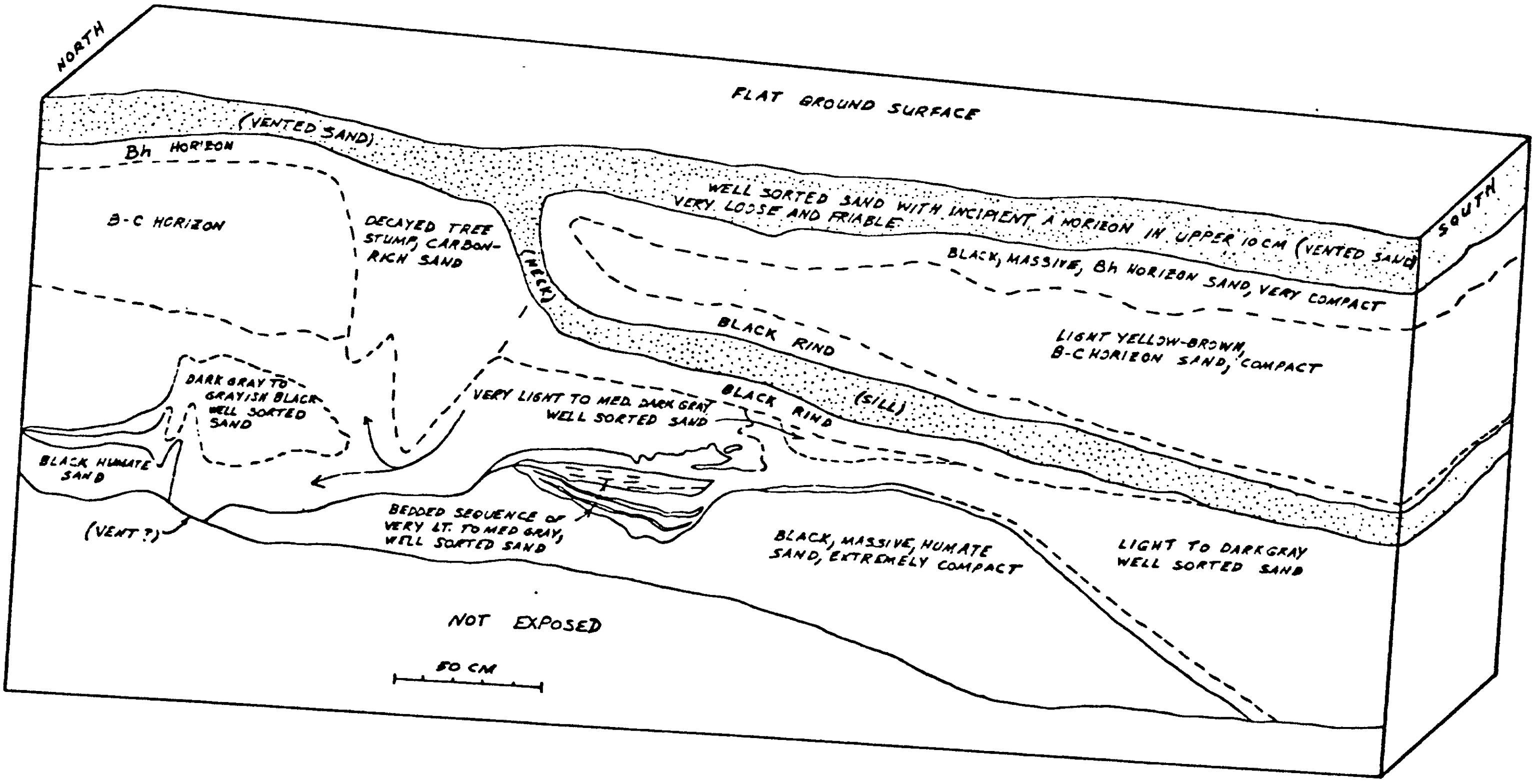


Figure 5.--Block diagram drawn from several photographs that shows one of the several sand-filled sills of feature III. Note that the sill reaches the surficial sand layer, which probably represents sand ejected from this and neighboring sills. The black rind around the sill is a humate-stained sand.

earthquake is known to have produced sand blows in the area, correlating these features with the 1886 event would be a conservative approach to determining the number of large earthquakes that have struck the Charleston area. However, the geologic record of an earthquake that was a few hundred years older than the 1886 event probably could not be distinguished from that of an 1886 sand blow unless good samples of material for C-14 dating were fortuitously associated with the deposit. Therefore, features I, II, and III could conceivably represent an earthquake that occurred shortly before the development of a written history for the greater Charleston area.

Pre-1886 sand blows

Description.--Bowl-shaped features that we interpret to represent filled sand-blow craters similar to those produced by the 1886 earthquake are abundant in the Hollywood ditch. A physically similar feature was found in a field near the Charleston Airport (fig. 1). In some places, lateral excavations and horizontal auger holes were made into the ditch wall to ascertain the third dimension of the craters.

Four typical filled craters are described below. Features IV and V have the overall shape and internal character that is most generally present in these features. Features VI and VII occur in the same exposure and probably represent two earthquakes.

Figure 6 shows a thick Bh horizon cut by an irregularly bowl-shaped crater, feature IV, that contains structureless and bedded sequences of light- to dark-gray sand and clasts of Bh material. Within the filled crater, the Bh horizon and underlying B-C transition horizon are 40 cm thinner than to either side. Beneath the Bh and B-C horizons developed on the sand blow, there is a structureless very-light-gray, fine to medium sand with only slight humate staining. This sand overlies a sequence of thin, light- and dark-colored layers of fine to medium sand. The coloration in the dark beds is probably imparted from humate. In the bedded sequence, there is no evidence of humate staining of the light-colored sands except at their lateral extremities near the contact with the undisturbed Bh horizon. The lowermost stratum of the bedded sequence sharply overlies a sand layer containing many small clasts of Bh material, wood and plant fragments, and some clasts of light-colored sand. This zone of many clasts grades down into a sand with sparse, scattered clasts. This sand in turn grades down into a basal sand with densely packed small and large clasts of Bh material. At and below the thinly bedded sequence, the sides of the sand blow are sharply defined as a color boundary and by the restriction of Bh clasts to the sand within the crater. The sands are moderately compact in both the clast-bearing zones and the C horizon, and very compact to extremely compact in the very dark Bh horizon. The auger hole above the bedded sequence (fig. 6) showed that the crater extended about 1 m into the ditch wall; that is, undisturbed Bh soil was encountered about 1 meter behind the face of the outcrop.

Sand blow V (fig. 7) is quite similar to IV; except that, in V, the lowermost zone of sand containing Bh clasts has two branches that extend down into the C horizon. The Bh horizon in the central part of figure 7 is light-colored compared to the similar horizon in figure 6. Outside the sand blow, the Bh is darker and thicker (100 to 125 cm) than within the crater. Much as

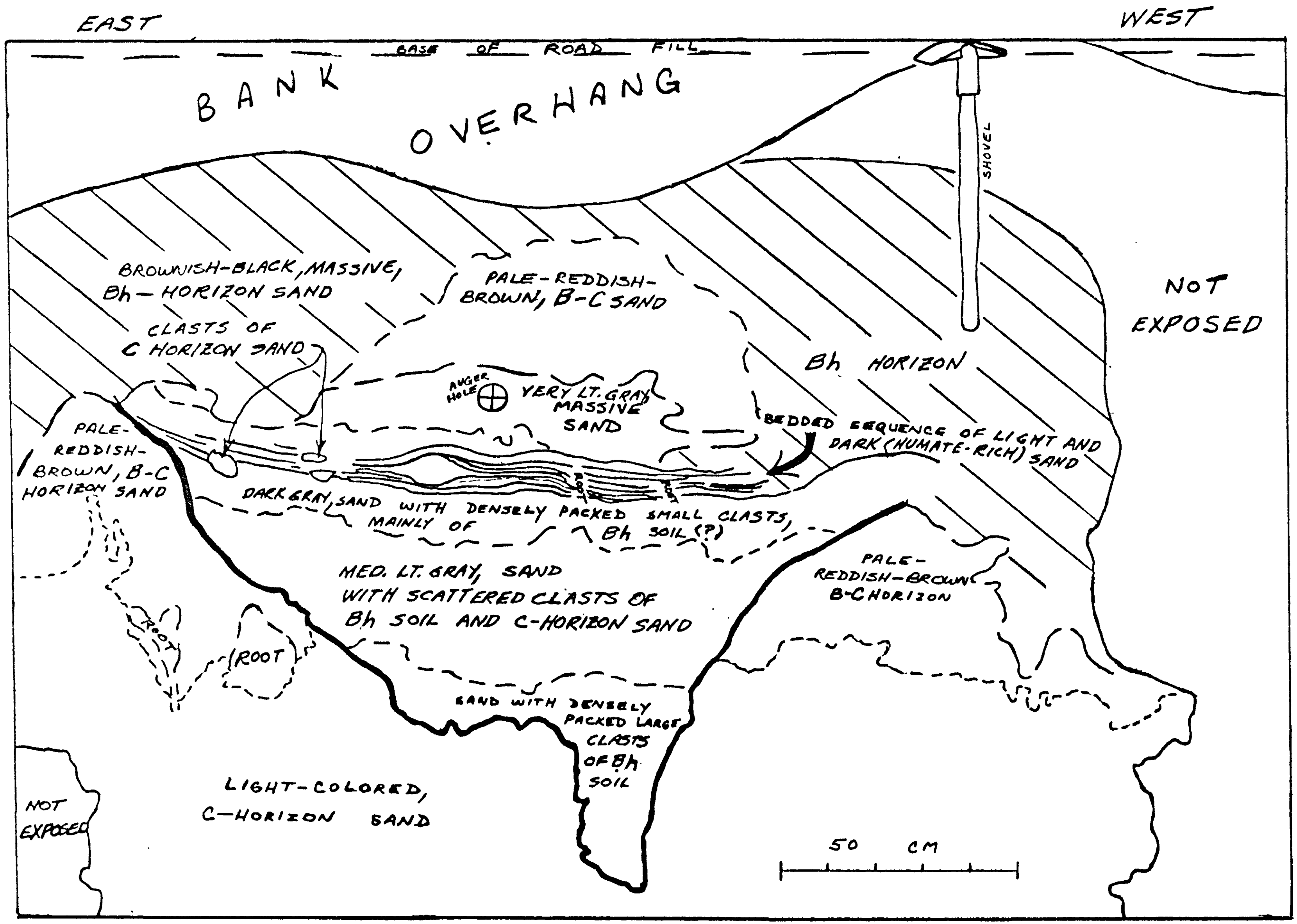


Figure 6.--Sketch from a photograph of sand blow crater IV. The irregularly shaped crater contains several layers of sand containing varying amounts of clasts of Bh material. Note that the Bh and B-C horizons developed on the crater sands are thinner than those developed in the adjacent undisturbed areas.

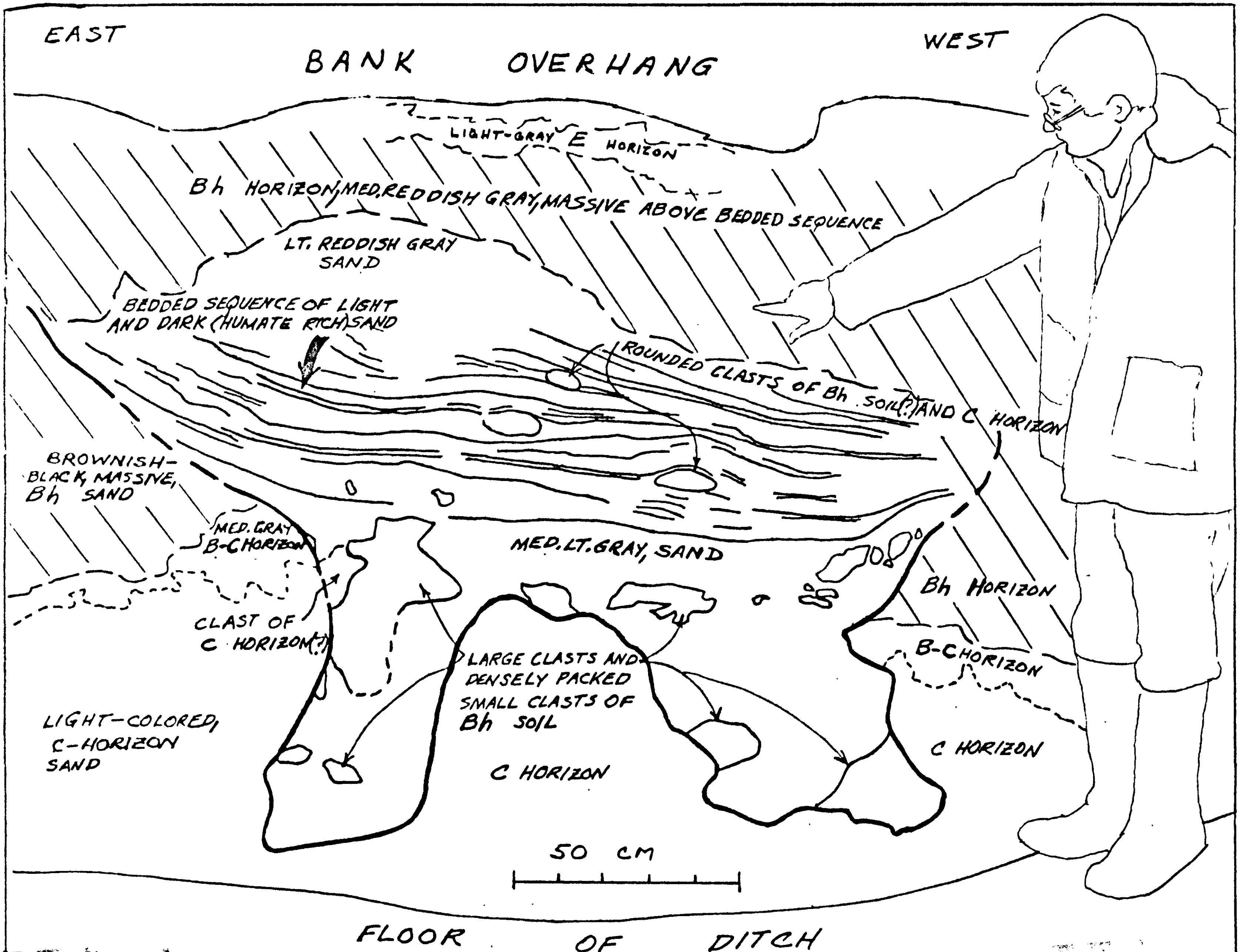


Figure 7.--Sketch from a photograph of sand blow crater V. Note the differences in thickness and organization of the various sand layers within the crater as compared to those in crater IV.

in figure 6, there is limited evidence of staining of light-colored layers in the bedded sequence and almost none in the underlying sand-clast zones.

Figure 8 shows a thick, dark Bh horizon cut by a complex succession of bedded and nonbedded sands in features VI and VII. Feature VI (fig. 8a) is similar to IV and V. Downward below a Bh horizon, feature VI consists of a thinly bedded sequence, a sand with densely packed clasts of B-horizon material and wood, a sand with sparse clasts, and a basal sand with densely packed large clasts of Bh material. The upper part of VI is cut by several small, vertical faults.

Sand blow VII (fig. 8b) cuts across all of the layers in VI and is clearly younger than VI. Crater VII consists of a vertical sand-filled tube that is crowded with clasts of Bh material in its lower part and contains scattered clasts in its upper part. At about the middle of the outcrop, the tube flares outward abruptly, and a thinly bedded sequence is discernible below the Bh horizon. The sands in VI and VII and the C horizon are moderately compact, whereas the very dark horizon Bh is very compact to extremely compact.

Origin.--The features in figures 6, 7, and 8 are interpreted as filled sand-blow craters that followed a sequential development similar to that of the 1886 crater-type sand blows (fig. 2). The following phases are recognized: excavation of an initial large hole in the ground by an explosive expulsion of sand, humate-rich soil, and water; possible continued expulsion of sand following the explosion; a churning about of sand, soil clasts, and water in the bowl and throat of the exploded hole with settling of larger particles as the upward flow diminished; after the flowage had stopped, a slow filling of the upper part of the crater over many weeks or months.

The holes produced by the initial explosive phase are represented by the bowl-shaped outlines of the now-filled craters. Faulting in sand blow VI (fig. 8) may have been caused during the later explosion of crater VII. It is likely that ejection blankets were formed around these features during and after the explosion, but they cannot be recognized at present. The ejected material probably constitutes the upper part of the outcrop where its identity is masked by the subsequent development of the A and B horizons.

The sand, soil clasts, and wood below the bedded sequence in each crater were trapped at the bottom of the crater during the loss of pore pressure. The clasts in this zone were segregated (coarse-tail grading) in the churning fluidized mixture as the largest sized (or most dense) particles settled fastest in the fluid and the smaller sized (or least dense) particles were carried upward by upward-flowing water. The largest clasts, some up to 20 cm across, are almost invariably at the base of this zone. Another example of the eluviation of finer sediment from a sand blow and concentration of coarse material within its crater is probably represented by a large fissure eruption described by Coulter and Migliaccio (1966, p. C23-25; May 27, 1964, Alaska earthquake).

Just above the basal zone of large clasts, there are only a few clasts of soil larger than 1 to 2 cm scattered in a mixture of sand and some very small clasts (1 to 5 mm) of soil. Above this zone, and just beneath the bedded sequence of light-and dark-colored sand, there is a dark sand with

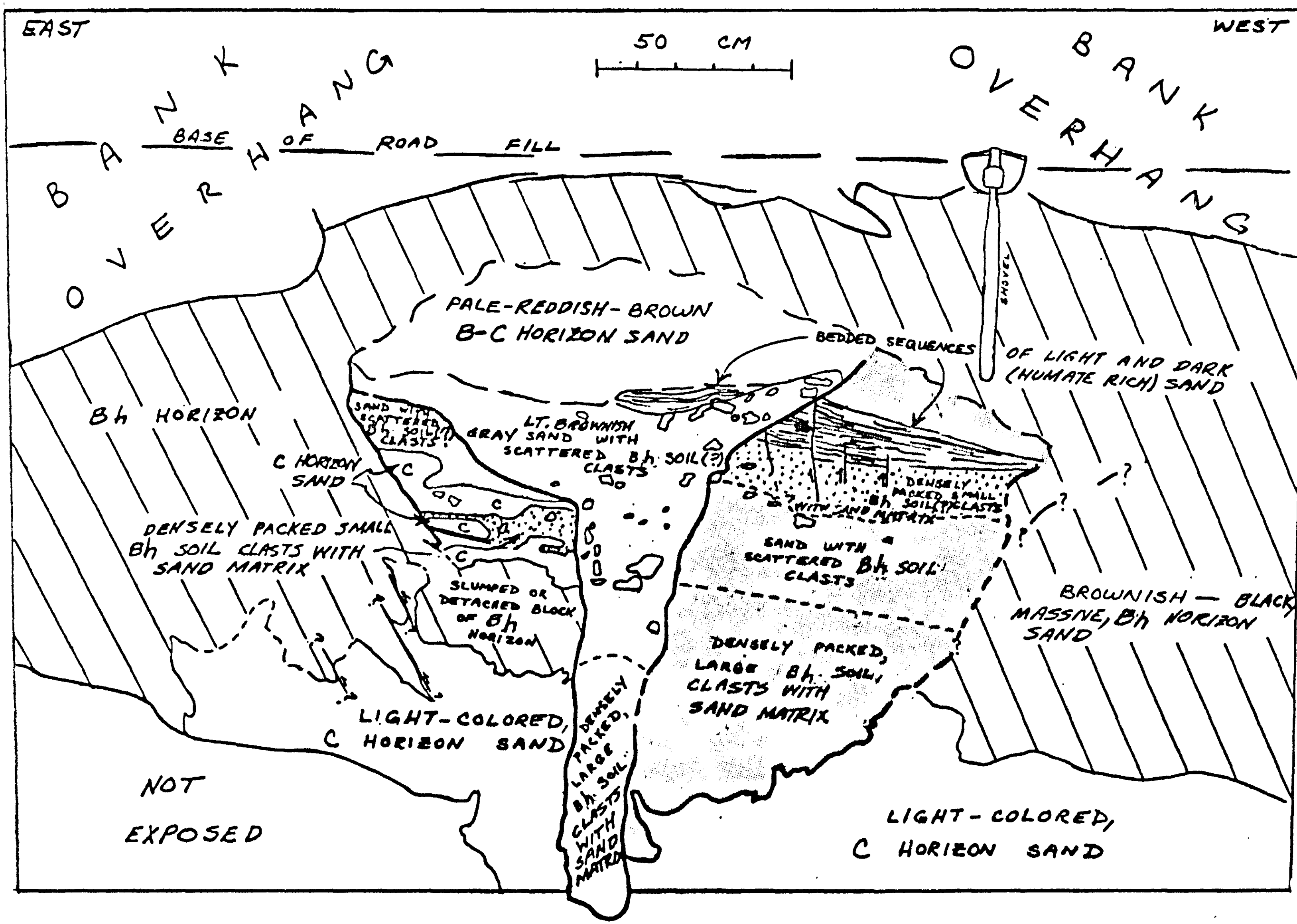


Figure 8.--Sketch from a photograph of sand-blow craters VI and VII. **Crater** VI is shaded in figure 8a, and crater VII is shaded in figure **8b. Note** that VII cuts across all of the visible layers in VI. The Bh **horizon is** much thicker in the undisturbed areas than in the crater sands.

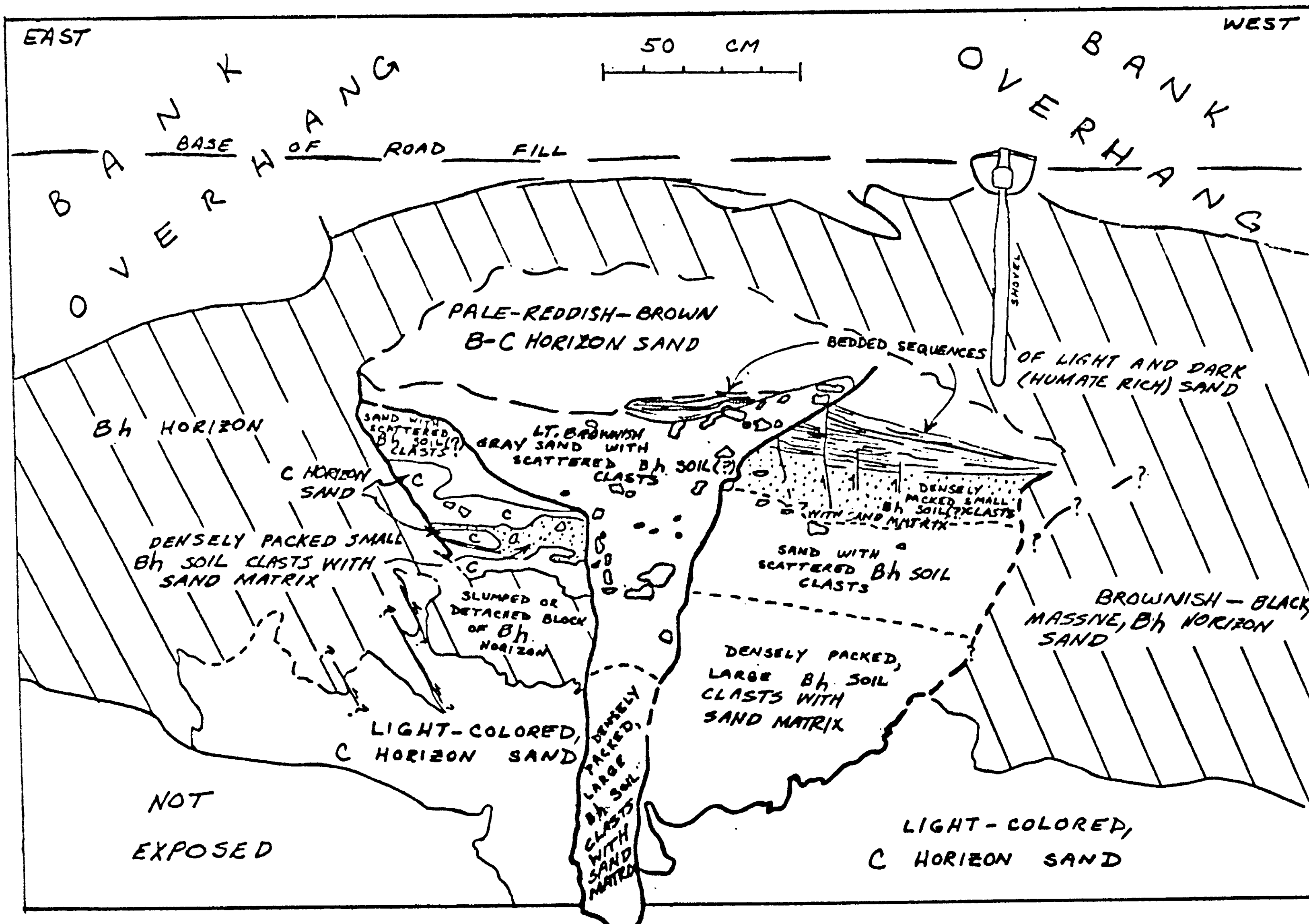

EAST
WEST
50 CM
BANK OVERHANG
BANK OVERHANG
BASE OF ROAD FILL
SHOVEL
PALE-REDDISH-BROWN B-C HORIZON SAND
BEDDED SEQUENCES OF LIGHT AND DARK (HUMATE RICH) SAND
Bh HORIZON
SAND WITH SCATTERED Bh SOIL(?) CLASTS
LT. BROWNISH GRAY SAND WITH SCATTERED Bh SOIL(?) CLASTS
C HORIZON SAND
DENSELY PACKED SMALL Bh SOIL CLASTS WITH SAND MATRIX
SLUMPED OR DETACHED BLOCK OF Bh HORIZON
DENSELY PACKED SMALL Bh SOIL(?) CLASTS WITH SAND MATRIX
SAND WITH SCATTERED Bh SOIL CLASTS
BROWNISH-BLACK MASSIVE, Bh HORIZON SAND
DENSELY PACKED, LARGE Bh SOIL CLASTS WITH SAND MATRIX
DENSELY PACKED, LARGE Bh SOIL CLASTS WITH SAND MATRIX
LIGHT-COLORED, C HORIZON SAND
NOT EXPOSED
LIGHT-COLORED, C HORIZON SAND

Fig 8b

abundant small clasts of Bh material and wood. The clasts in this zone are believed to have been carried to the surface of the churning mixture because of their relatively low density.

The bedded sequence is interpreted to represent slow filling of the crater (such as the crater in figure 2), following the liquefaction-flow event. Sediments of the individual layers were probably washed in during rains or slumped from the craters' rims. Cross-bedded units were not seen in these filled craters although the bedding is locally inclined and nearly parallel to the crater wall along the margins of the craters (figs. 6, 7). Structureless sand above the bedded sequence may represent deposition into a dry crater, whereas the bedded sequence may represent deposition into standing water in the crater shortly after the eruption.

Although injection of fluidized sands into the craters must have occurred, a geologic record of the intrusion is rarely observed. As the pore pressure is dissipated and upward flow ceases at the end of the eruption, structures produced by the downward settling of sand and soil clasts replace structures formed during upward flow. However, several lines of evidence suggest that the source bed (liquefied zone) for the mobilized sand is the C horizon seen at the bottom of the ditch. In one filled crater (similar to IV), C-horizon sand can be traced from the C horizon as stringers extending into and through the basal zone of large clasts within the crater. In another example, a large coherent block of Bh and B-C material (about one m^2 as seen on the ditch wall) had foundered into the liquefied C horizon directly below a filled crater. There are fewer clasts of soil material within this crater than are typically present, and C-horizon sand can be readily traced up into the crater. Therefore, the liquefied source bed for the sand found in the craters is the sandy C horizon located immediately below the confining, dense solum at depths of 1.5 to 3 m or more below the ground surface. This is in the depth range of the source beds reported by Cox and Talwani (1984) for their excavated 1886 sand blow, by Muir and Scott (1982) for the Imperial Valley sand blow described above, and by Coulter and Migliaccio (1966) for the fissure-type eruption produced during the May 27, 1964, Alaska earthquake. In these cases, depth to the top of the water table at the time of the earthquake appears to define the minimum depth of liquefaction.

In summary, it is concluded that craters IV, V, VI, and VII have characteristics that are consistent with those described in historical accounts of 1886 sand blows and that are consistent with inferred mechanical and physical processes associated with formation and filling of a sand-blow crater. We have named these earthquake-induced, liquefaction-flowage features as <u>explosion-collapse craters</u> on the basis of their genetic history. Probable examples of other explosion-collapse craters have been described from several historic earthquakes, for example, 1886 Charleston (fig. 2, this report; Dutton, 1889), and March 27, 1964, Alaska (Foster and Karlstrom, 1967; Tuthill and Laird, 1966, fig. 11). Possible older examples have been reported from trenches across the San Andreas fault, California, by Sieh (1978) and Meisling (1979). The California examples differ from the Charleston examples in not containing large clasts of the host sediment. This difference may result from a difference in the cohesion of the materials surrounding the sand blows in the two areas.

Age.--A prehistoric age for the explosion-collapse craters in the Hollywood ditch (craters IV through VII and similar craters) is inferred from the fact that sand-filled fissures I and II cut across two craters of this type. A prehistoric age for the older craters is therefore established because fissures I and II represent the 1886 earthquake or a geologically recent, prehistoric earthquake and because no other historic earthquakes capable of producing liquefaction are known from the Charleston area.

Differences in the relative development of the soil horizons in the craters, as compared to those developed on undisturbed sediments, also provide a basis for assuming a prehistoric age for the set of explosion-collapse craters in the Hollywood ditch. Relatively little is known about the rate at which spodosols develop; however, Pye (1983) suggests that spodosols can develop in humid climates in a few tens of thousands of years and perhaps in only a few thousands of years. All of the Hollywood craters contain clasts of Bh material, which indicates that significant soil formation had occurred between deposition of the Pleistocene sediments and the earthquake that produced the craters. The fact that no humate has accumulated in fissures I and II suggests that they are no more than a few hundreds of years old. In contrast, the Bh horizons developed on the crater sands are one-half to one-third the thickness of Bh horizons in the adjacent undisturbed areas (figs. 6, 7, 8). It would appear likely, therefore, that the earthquake that produced the explosion-collapse craters occurred well after the deposition of the Pleistocene sediments but considerably before the earthquake that produced fissures I and II. The Pleistocene sediments that enclose the sand blows have been assigned an age of about $2x10^5$ years (McCartan and others, 1984). However, uncertainties in this stratigraphic assignment and in the total range of the mollusk *Anadara braziliana*, which occurs in the sediments along the Hollywood ditch allow for a possible younger age of about $1.2x10^5$ years.

Sand blow VII cuts across all of the internal layers of crater VI (fig. 8) and is obviously younger than VI. However, the Bh horizon developed on VII is nearly as thick as the equivalent horizon developed on VI, and it is possible that crater VII was produced only a few months to a few tens of years after crater VI. This close temporal association allows for the possiblity that crater VII represents a major aftershock of the earthquake that produced crater VI.

Possible earthquake-related features

A wide variety of disrupted sedimentary fabrics and soil horizons were seen during the field study. Many of these features are attributed to primary depositional processes such as bioturbation and local erosion (cut and fill) or to later surficial processes such as root mottling. However, the origin of some of these features remains equivocal, and one type is described in this section because of its widespread distribution in the Hollywood ditch. These poorly understood structures are herein called pillar structures.

Pillar structures are abundant in many parts of the Hollywood ditch where they occur sporadically over a distance of at least 3 km. The structures are developed in a layer that is almost everywhere a pale-brown, clayey sand (fig. 9). The top of the layer is typically 1 to 2 m beneath the ground surface, and it is typically 0.3 to 0.5 m in thickness. A light-colored,

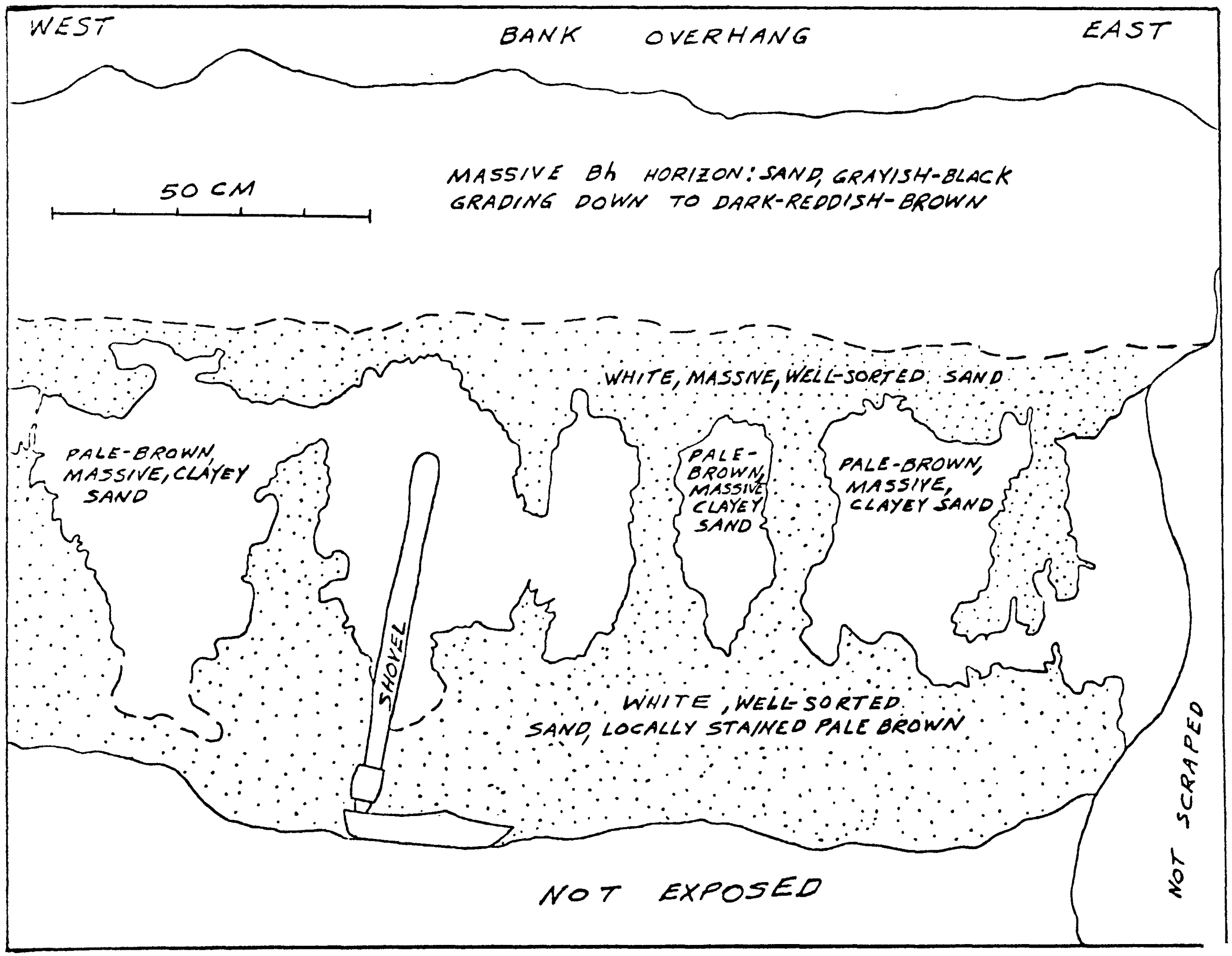


Figure 9.--Sketch from a photograph of pillar structure in the Hollywood ditch. A probable clay pan is disrupted by continuous and discontinuous sand pillars that connect over- and underlying sand bodies.

well-sorted, fine to medium quartz sand cuts vertically across the clay layer at many places and therefore creates pillars or balls of the brown clayey sand encased in pillars of light-colored sand. The sand pillars are typically about 5 to 10 cm wide but may be as wide as 30 cm. They are spaced locally at irregular or at regular intervals. The sand also overlies and underlies the clayey sand at most localities. At some places, the sand appears to extend down into the clayey sand, and at others it extends upward. The contact of the sand and the brown clayey sand is typically sharp with regard to texture and color.

The clayey sand layer is tentatively interpreted as a claypan within an enclosing C-horizon (light-colored, well-sorted) sand. This interpretation is suggested by the widespread distribution of the layer, its position below the solum, and by the fact that the clay fraction of the layer is greatest near its top and decreases downward (a pattern of development common in claypans and fragipans).

Some aspects of the morphology of these pillar structures support a fluidization origin that was perhaps caused by earthquake-induced liquefaction. Oriented fragments of brown plastic clay in the sand pillars suggest intrusion of the sand while in the fluidized state by hydraulic pressures originating at greater depth. The rather elevated topographic setting of the region where the ditch is located, and the nearly level attitude of underlying impermeable strata, suggest that ground-water springs probably were not the cause of the pillar structure.

Arguments against a liquefaction-related origin include the apparent downward penetration of the sand into the brown sandy clay, the close spacing of the sand pillars, and the uniformity of the tops of the clayey sand balls. Figure 9 illustrates that the sand does not always appear to cut through the brown clayey sand, but may penetrate downward for about 10 to 20 cm at some places. Not enough excavations have been made, however, to fully describe the morphology.

The locally developed close spacing of the pillars is troublesome for an earthquake origin because fractures in fine-grained cappings over earthquake-liquefied sand are typically spaced erratically, and quite far apart (many tens to hundreds of meters). Desiccation or frost action may have affected this spacing in some manner. The tops of the clay balls are typically at about the same elevation (at a given outcrop) or are enveloped by a gently undulating surface. If very forceful fluidization had occurred, an irregular displacement of the clay balls would be expected. In summary, it is clear that more field work is needed to attribute a specific origin to the pillar features.

Implications of field study

The evidence for pre-1886 earthquakes near Charleston significantly lengthens the known seismic record of that area beyond the historic record. Craters IV, V, VI, and VII represent one or more earthquakes that occurred several thousands to several tens of thousands of years before 1886 although accurate appraisal of their ages awaits the results of C-14 age determinations. Fissures I and II may also represent a prehistoric earthquake, or they may have formed in 1886. This lengthened seismic history of the Charleston area affects our understanding of southeastern seismicity in two ways: it establishes that more than one moderate-to-large earthquake has occurred near Charleston and permits calculation of the average recurrence interval for these earthquakes; it provides part of the data base that is necessary for evaluation of the seismotectonic uniqueness of the Charleston area.

Recurrence intervals.--For the Charleston area, preliminary average recurrence intervals for earthquakes capable of producing liquefaction--flowage features (generally cited as earthquakes of magnitude 5.5 or greater) can be calculated from the present data. A reliable estimate of the age of the oldest event is not yet available; therefore, the age of the Pleistocene sediments that contain the sand blows is used for this prelimary calculation. However, because uncertainties exist in the age of the Pleistocene sediments (2.0×10^5 yrs or 1.2×10^5 yrs) and in the number of prehistoric events represented by the sand blows, maximum and minimum recurrence intervals are calculated. A maximum average recurrence interval based on the present data is derived if fissures I and II are correlated with the 1886 earthquake and if crater VII is assumed to represent an aftershock of the event that produced crater VI (and the other explosion-collapse craters) and hence is excluded as a nonrandom event. Using these correlations and the maximum age of the sediments, the average recurrence interval is 1×10^5 years (2×10^5 yrs/2 events). A minimum average recurrence interval of 3×10^4 years (1.2×10^5 yrs/4 events) is derived if crater VII does not represent an aftershock, if fissures I and II do not represent the 1886 earthquake, and if the minimum age of the sediments is used. These preliminary average recurrence intervals could change significantly if C-14 ages indicate: that the oldest known event is significantly younger than 10^5 years, and(or) that the numerous explosion-collapse craters in the Hollywood ditch represent more than one or two events.

Uniqueness of Charleston seismicity.--Ten years ago, when comparatively little was known about the seismicity at Charleston, there was a clear tendency to view the 1886 earthquake as the product of a local, unique seismotectonic setting. Following a decade of extensive work on the seismicity of the Charleston area and the entire Southeast, the opinions of many workers have changed to where the Charleston area is no longer considered tectonically unique in the Southeast and hence probably not seismotectonically unique (Pomeroy, 1983; Wentworth, 1983). This opinion has emerged even though an undisputed causative mechanism for the Charleston seismicity has not been found.

Taken in a narrow context, the findings of the present study tend to support the older concept of a unique seismotectonic setting at Charleston. That is, the evidence for several moderate-to-large earthquakes near Charleston contrasts strongly with the absence of evidence for any similar earthquakes elsewhere in the Southeast. However, we strongly suggest that this conclusion cannot be accepted at the present time because of our inadequate knowledge of the prehistoric seismic record in other parts of the Southeast. Extensive searches for paleoliquefaction-flowage features have not been conducted in other parts of the Atlantic Coastal Plain, and our understanding of Southeastern seismicity could change depending upon the findings of such studies. For example, discovery of prehistoric liquefaction-flowage features in the northern New Jersey Coastal Plain near the Ramapo [illegible] and in the Virginia Coastal Plain within the Central Virginia seismic zone would suggest a similarity of these historically active seismic zones to the Charleston area. Further, discovery of geologic field evidence for major prehistoric seismicity in a historically aseismic area such as eastern North Carolina would significantly alter our concept of seismicity in the Southeast. We emphasize, therefore, that it would be prudent to await the results of field searches for liquefaction-induced features conducted throughout the Atlantic Coastal Plain before a "final" assessment of the seismotectonic uniqueness of the Charleston area is attempted on the basis of combined historic and prehistoric seismic records.

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