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Issues in Using Liquefaction Features for Paleoseismic Analysis

Stephen F. Obermeier
U.S. Geological Survey
Reston, Virginia 20192

Eric C. Pond
Western Technologies, Inc.
Albuquerque, New Mexico 87113

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Stephen F. Obermeier
U.S. Geological Survey
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Western Technologies, Inc.
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ABSTRACT

Three questions always arise when using liquefaction features for paleoseismic analysis: What was the strength of shaking? Where was the source region? And what was the magnitude? Credible answers to these questions have been provided by liquefaction studies in the eastern and central U.S. In addition, paleoliquefaction studies have been used in many areas to show a lack of strong shaking through much of Holocene time.

A high level of confidence in interpretations depends on widespread availability of exposures containing sediments susceptible to liquefaction. Throughout large parts of the U.S. there are sufficient exposures to permit detection of effects of shaking from any nearby $M > 7$ earthquakes (say, centered within 30 to 50 km) that have struck. In many field settings the record of paleoliquefaction encompasses much of Holocene time.

A high level of confidence in interpretations also requires an in-depth appreciation of the processes involved in liquefaction-induced ground failure, as well as an appreciation of the strengths and shortcomings of the geotechnical procedures for analysis. Geotechnical analysis of the strength of prehistoric shaking often requires recognition of the mechanism of liquefaction-induced ground failure at a site. Liquefaction-induced ground failure almost always involves at least one of three mechanisms: hydraulic fracturing, lateral spreading, or surface oscillations. Conditions favorable for formation of liquefaction features can depend strongly on the local field setting and involves factors such as properties and thicknesses of sediments, depth to the water table, and proximity to a stream bank; conditions that are most favorable differ for each mechanism of ground failure. The strength of shaking can also have a major role in determining which of the mechanisms is operative at a site.

Three geotechnical methods are available for analysis of paleoliquefaction effects at individual sites. The Seed et al. method generally can establish only a lower bound value of acceleration. The two other methods, recently developed, permit making estimates of upper bound and actual accelerations. One, by Ishihara, is for sites of hydraulic fracturing and can be used to establish an upper bound estimate. The other, an energy-based solution by Pond, is primarily applicable at sites of lateral spreading and provides an estimate of actual acceleration values. Both the

Ishihara and the Pond method have great usefulness for paleoseismic analysis.

Back-calculated accelerations using the procedures above can be used to make an estimate of prehistoric magnitude. Also, in some tectonic situations the farthest extent of liquefaction from the energy source region can be used to estimate the magnitude. The confidence in interpretation of paleomagnitude is highest whenever different procedures yield the same value.

Despite several notable and very successful paleoliquefaction studies in the past 15 years or so, misconceptions abound concerning what can be derived from a paleoliquefaction study. Much more can be deduced than is generally recognized. But, correct interpretation of a paleoliquefaction study requires major input from expertise ranging from geologic to geotechnical. A comprehensive study requires input from all these disciplines even while searching for liquefaction features in the field. Successful studies that have incorporated a wide range of expertise have been relatively common in the eastern and central U.S. A similar co-operative approach could probably bracket the strength of shaking from subduction earthquakes in the Pacific Northwest of the U.S.

INTRODUCTION

This paper focuses on issues that relate to conducting field searches for paleoliquefaction features and interpreting the findings of those searches. The use of paleoliquefaction features for analysis of prehistoric seismicity is a new and rapidly expanding tool. Only within the past 15 years has the method of systematically searching for paleoliquefaction features over large geographic areas been used to detect and interpret the paleoseismic record. These areas include the southeastern, central, and northwestern U.S., where the physical settings and seismotectonic situations differ greatly from one another. Yet despite being used successfully in such diverse settings, the potential power of a paleoliquefaction study is not appreciated by many. Another compelling reason for this paper is that new geotechnical procedures for analyzing paleoliquefaction data have evolved greatly during the past few years, and the capabilities of these procedures are little known by many in the geologic and geotechnical communities.

Three questions often arise concerning interpretations of paleoliquefaction features, irrespective of seismotectonic setting or site specific conditions. One question is whether paleoliquefaction features can be used to interpret the source region of strongest shaking of the paleo-earthquake. A second is whether an absence of paleoliquefaction features indicates an absence of strong paleoseismic shaking. A third is whether effects of liquefaction can be used to interpret the strength of prehistoric shaking.

Before addressing these questions, though, a brief discussion of the process of liquefaction is necessary, especially as the process relates to the manifestations of liquefaction in most field areas. This short summary is restricted to liquefaction-induced features that characteristically form in a clay- or silt-rich host that lies above a sand-rich deposit that liquefied. A typical field setting is a river valley on the modern flood plain or on a terrace that is only a few meters higher. The top of the host can be above or below the level of the water table. For such a setting the observed features are most often steeply dipping, tabular, clastic dikes, whose typical morphology in sectional view is illustrated in Figure 1. Features that are much more irregular than those shown in Figure 1 commonly abound where liquefaction has been especially severe. Intrusions that are more horizontally inclined, such as the sills depicted in Figure 2, are also present in many field settings.

Discussion will not include soft-sediment deformations that involve plastic deformation of muds and freshly deposited cohesionless sediments, such as load casts, ball and pillows, convolute bedding, etc. Such features are not within the class of "liquefaction-induced features" that we consider in this paper because of the secondary role of elevated pore-water pressure that is probably typically involved in their formation. Furthermore, not only is a seismic origin often difficult to verify for plastically deformed soft-sediments, but they commonly form at such low levels of seismic shaking as to not be relevant to seismic hazards (e.g., Sims, 1973).

Conversely, the origin of clastic dikes can usually be determined rather easily. And, features of seismic-liquefaction origin typically require much stronger shaking for their formation than do plastically deformed soft-sediments, and thus are much more relevant for assessment of seismic hazards. The minimum earthquake magnitude to form liquefaction features in most field settings is about moment magnitude M 5.5 (Ambraseys, 1988), which is about the same as the threshold for damage to man-made structures. (In this article the earthquake magnitude (M) is always moment magnitude.) The minimum value of peak accelerations required for formation of liquefaction features decreases with increasing magnitude, with reported values as low as 0.025 g for M 8.25 and 0.12 g for M 5.5 (Carter and Seed, 1988); the vibration frequencies of interest are less than a few tens of Hz.

Collection of liquefaction data for the analyses that we describe below requires searching over a large area, at least tens of kilometers in radius. Many kilometers of exposures must be examined at scattered locales. In most places the only practical method of doing this is to search banks of ditches or streams.

In this manuscript we do not attempt a comprehensive technical discussion of many issues, nor do we give more than a cursory list of references. Rather, we generally direct the reader to articles that contain comprehensive references. Expanded discussions of much of the material in this paper are in articles by Obermeier (1996a, 1997) and by Pond (1996). The section that immediately follows is basically an excerpt from articles by Obermeier, which are largely compendia that focus on the role of liquefaction in paleoseismic interpretations, and the interested reader should consult them for details and for more complete references.

THE PROCESS OF LIQUEFACTION AND ITS MANIFESTATIONS

The Basic Process

Liquefaction is the transformation of a saturated granular material from a solid state to a liquefied state as a consequence of increased pore-water pressure (Youd, 1973; Seed and Idriss, 1982). Liquefaction is caused by the application of shear stresses, which causes a breakdown of the soil skeleton and a buildup of interstitial pore-water pressure. The process typically occurs in sediments that are cohesionless or nearly so. The liquefied mixture of sand and water acts as a viscous liquid with a greatly reduced shear strength.

The shear stresses that cause seismically induced liquefaction are primarily due to cyclic shear waves propagating upward through the soil column, although waves travelling along the ground surface are important locally. Sediment on level ground undergoes loading as illustrated in Figure 3, with the shear stresses being somewhat random but nonetheless cyclic. Cohesionless sediments that are packed loosely enough tend to become more compact when sheared. Rapid cyclic shearing can cause the pore-water pressure to increase, often suddenly to the static confining pressure, which can lead to large strains and flowage of water and suspended sediment. The changes in the packing of sediment grains caused by liquefaction are illustrated in Figure 4. A large change in pore-water pressure commonly happens during the transition from the initial packing (Fig. 4A) to that illustrated for the liquefied state (Fig. 4B). The pore-water pressure in Figure 4B must carry the weight of all overlying sediment and water. In many field situations this pressure changes by a factor of severalfold within a few seconds. This large change commonly provides sufficient pressure to easily hydrofracture a finer grained cap lying directly above the level of the liquefied zone.

Figure 4C illustrates the next phase of the process. Slight densification occurs throughout much of the column of liquefied sediment during dissipation of excess pore-water pressure. Large quantities of water can be expelled. The water flows upward, carrying along sediment. (This process whereby flowing water transports sediment is referred to as "fluidization" by geologists (Lowe, 1975)). The flowing water causes sediment to be carried grain-by-grain or dragged along by other grains. It is this process of fluidization that leaves behind the sediment that fills clastic dikes and sills that are observed in paleoliquefaction studies.

Liquefaction can occur during a few cycles of shaking or may require many cycles. For a very loose packing of sediment grains, the breakdown of grain structure can be very abrupt and liquefaction can be virtually instantaneous (e.g., Fig. 2.26 in National Research Council, 1985). Such loose packings are relatively common in delta and wind dune deposits, as well as in very young (< 500 yrs) river channel deposits (Youd and Perkins, 1978). For older river deposits, the buildup of pore-water pressure is a more gradual process and requires many cycles of shearing. Indeed, some fluvial sands have initial packings that are so dense that any pore-pressure increase is either small or insignificant, and liquefaction never occurs (Seed et al., 1983). Thus, a broad range of susceptibility to liquefaction may be encountered in the field. These levels of susceptibility must be kept in mind whenever interpreting the results of a field search, as discussed below.

The relative state of packing of sand deposits (called the "relative density" by geotechnical engineers) and susceptibility to liquefaction are related to Standard Penetration Test blow counts. The relative density of a sand deposit is simply a measure of how densely the sand grains are packed, in comparison to the loosest and densest possible states (Terzaghi and Peck, 1967).

Relative density ranges from very loose to very dense, depending on arrangement of grains. Correlations with Standard Penetration Test blow counts used in this article are listed in Table 1. For practical purposes, sediments having blow counts much in excess of about 30 generally are not very prone to liquefaction or may not liquefy, especially at depth where overburden stresses are high.

Table 1. Relative density of sand as related to Standard Penetration Test blow counts (from Terzaghi and Peck, 1967).

No. of blows (N)	Relative density or compactness
0-4	Very loose
4-10	Loose
10-30	Medium or moderate
30-50	Dense
>50	Very dense

Conditions Favorable for Formation of Liquefaction Features

Liquefaction can occur yet leave behind no clearcut signatures within the bed that liquefied. Indeed, in nearly all paleoliquefaction studies the occurrence of liquefaction is indicated by out-of-place cohesionless sediment cutting through a finer-grained host, forming clastic dikes such as are shown in Figure 2. Clastic dikes form most readily where a thick, sand-rich deposit is capped by a low-permeability deposit, and the water table is very high. Grain sizes that are generally the most prone to liquefy and fluidize range from silty sand to gravelly sand. Thicknesses of a meter or so of liquefied sediment are generally needed to form recognizable clastic dikes, although liquefaction-induced landslides (lateral spreads) can develop on a single stratum only centimeters in thickness, if it is of great lateral extent (Obermeier, 1996a).

Dikes readily cut entirely through caps having thicknesses of a meter or so, and can cut through much greater thicknesses where shaking and liquefaction have been severe (Ishihara, 1985; Obermeier, 1989). Field observations show that clastic dikes readily form in caps having consistencies ranging from very soft (soft enough to force the thumb into the host) to stiff (requiring effort to crush a piece of soil between the thumb and finger). (See Terzaghi and Peck (1967, p. 30) for relations between consistency and compressive strength of clay). Dikes have been observed to have formed in hard, silt and clay-rich glacial tills (too strong to be crushed between the fingers). The most likely sites where dikes may form in hard deposits are those most conducive to formation of dikes, such as at lateral spreading sites on slopes where seismic shaking has been very strong.

Liquefaction occurs at shallow depth, commonly from several tens of centimeters to several tens of meters (e.g., Seed, 1979). A typical depth is two to ten meters. Greater depths generally require exceptionally severe shaking. Liquefaction is unlikely at the greater depths because the increasing overburden pressure increases the shear resistance of cohesionless sediment beyond the shear stress induced by seismic shaking.

Effects of liquefaction are most pronounced where the water table lies within a few meters or less of the surface. Where the water table is five meters or more in depth, the effects of liquefaction are always much suppressed. A change in water table depth from the surface to a depth of 10 m can change the ability to liquefy from high to nil, respectively (e.g., see Table 4-1 in National Research Council, 1985).

Mechanisms That Form Liquefaction Features

Dikes in a fine-grained cap are induced chiefly by three ground-failure mechanisms: hydraulic fracturing, lateral spreading, or surface oscillations. These three can operate independently or can reinforce one another.

The various ground failure-mechanisms

Hydraulic fracturing of the cap is driven by high pore-water pressure in the liquefied sediment. Hydraulic fracturing typically causes tabular dikes to form, mainly parallel to one another but also in an irregular, crazing pattern in plan and sectional views where liquefaction has been severe. Dikes from this mechanism are typically quite narrow, ranging from a few millimeters to less that 10 cm wide.

Lateral spreads reflect movement downslope or toward a topographic declivity such as a stream bank. The effects are manifest primarily as tabular clastic dikes, which have a strong tendency to parallel the declivity or downslope contours. These dikes are the result of fluidized sand and water flowing into breaks through the cap that were opened by gravity or directly by shaking. Dikes associated with lateral spreading are commonly quite wide. Dikes can be as much as 0.5 to 0.7 m in width even where shaking has been only moderately strong (say, 1/4 g). Widths of as much as a few to several meters are not unusual where shaking has been very strong.

Surface oscillations cause tabular clastic dikes to originate in response to the fine-grained cap being strongly shaken back and forth above liquefied sediment. Dike widths from this mechanism are typically less than 15 cm except where surface oscillations have been extremely severe. The dikes strongly tend to parallel one another with a spacing of tens to hundreds of meters apart. Shaking in the cap can originate by either surface waves (Youd, 1984) or body waves (Pease and O'Rourke,1995).

The three mechanisms noted above generally are dominant in producing the larger dikes, especially tabular dikes visible at the ground surface. However, liquefaction can also leave behind small tubular clastic dikes in a fine-grained cap. Small tubular dikes as much as a few cm in diameter commonly develop where venting has taken place through an extremely soft cap (Obermeier, 1996a). Also, small tubular dikes can develop in pre-existing holes left behind by decayed roots and in holes excavated by creatures such as crabs or crawfish (Audemard and de Santis, 1991).

Factors controlling mechanism of ground failure

Different levels of shaking are required to form dikes visible at the ground surface for each of the mechanisms of lateral spreading, surface oscillations, and hydraulic fracturing. For cohesionless deposits that are very loose to moderate in relative density (Table 1), lateral spreads form most easily and also form the farthest from the meizoseismal region (providing a stream bank is nearby). Dikes from surface oscillations (Youd, 1984) can also develop considerably beyond the meizoseismal zone, especially where conditions are favorable for developing surface oscillations from surface waves (e.g., broad valleys, alluvium at least tens of meters in thickness, flat-lying bedrock). In most field situations with moderate liquefaction susceptibility, hydraulic fracturing causes only small, scattered dikes to form beyond the meizoseismal zone, even for earthquakes in excess of $M \sim 7$.

Field relations commonly show the relative influence of lateral spreading and hydraulic fracturing in formation of dikes. Figure 5 shows relations that are observed commonly, and illustrates formation of dikes above liquefied sands of moderate compactness. Relations in the figure are for sites where liquefaction has not been very severe and the influence of hydraulic fracturing not very strong. Farther from the meizoseismal zone, the influence of hydraulic fracturing is generally negligible and relations shown in Figure 5B are observed.

The thickness of cap that is penetrated by hydraulic fracturing depends strongly on the thickness of sand that liquefies, as shown in Figure 6. The penetrated thickness is also strongly dependent on the severity of ground shaking (i.e., peak surface acceleration). Relations in Figure 6, first hypothesized by Ishihara (1985), appear to be valid for earthquakes of $M \sim 7.5$ and stronger in that the procedure predicts where surface effects will both occur and will not occur (e.g., see Youd and Garris, 1995). Youd and Garris also found that dikes caused by hydraulic fracturing commonly have heights that are much less than for lateral spreading and for surface oscillations. The maximum thickness of cap that has been observed to have been ruptured by hydraulic fracturing is about 8 m (Fig. 6). No data are available concerning strengths of caps that can be ruptured by hydraulic fracturing, but unreported data by Obermeier show that this mode commonly occurs in caps having a wide range of consistencies, varying from soft to firm. (It should be noted that Youd and Garris (1995) state only that the relations in Figure 6 are not valid for lateral spreading or surface oscillations; by the process of elimination, we attribute the mechanism to be chiefly hydraulic fracturing.)

The maximum thickness of ruptured cap from lateral spreading is commonly much greater than from hydraulic fracturing (Youd and Garris, 1995, Fig. 3). The maximum that has ever been documented is about 16 m (T.L. Youd, Brigham Young Univ., 1997, oral commun.). In many field settings the maximum thickness is probably controlled by the maximum depth of liquefaction; this is so because of the relatively low strength of the cap in relation to the stresses imposed on the cap by gravity and seismic shaking. Caps composed of silt and clay sediments that are of Holocene and late Pleistocene ages typically are so unlithified that they have low tensile strengths, and so they are quite susceptible to being pulled apart by lateral spreading. Dikes probably caused by lateral spreading have been observed by Obermeier in the central

U.S., even where clay-rich caps have been compacted to a hard consistency by glacial loading, although the level of shaking required for formation of the dikes was likely very high.

The formation of lateral spreads is not nearly as dependent on thickness of the liquefied zone as is hydraulic fracturing. Lateral spreads have been observed to have formed on liquefied sand strata only a few centimeters in thickness (J.R. Keaton, SHB AGRA, Inc., Salt lake City, Utah, written commun., 1993). Lateral continuity of the liquefied bed is especially important for lateral spreading.

Not only is the thickness of cap ruptured by surface oscillations commonly greater than from hydraulic fracturing (Youd and Garris, 1995), but effects of surface oscillations tend to extend much further from the meizoseismal zone. In general, though, breakage of the cap by surface oscillations is quite localized away from the meizoseismal zone, even for a very large earthquake.

No data are available concerning the role of thickness of liquefied sediment on development of surface oscillations, although we suspect that at least a meter or more suffices near the meizoseismal region of a very large earthquake. This tentative suggestion is based on our field observations in the Wabash Valley of Indiana-Illinois. Preliminary data by Obermeier also indicate that parallel joints in the cap can develop from seismic shaking, even where no liquefaction has occurred, providing that shaking has been strong enough. (Joints from other mechanisms such as weathering and desiccation are not parallel to one another, as are those of seismic origin.)

In the previous section it was noted that formation of liquefaction effects depends on depth to the water table. The influence of water-table depth on formation of liquefaction features seems to be very dependent on the mechanism that is primarily responsible in breaking apart the cap. Unpublished data by Obermeier indicate strongly that breakage by hydraulic fracturing is much more sensitive to depth of the water table than is lateral spreading. No data are available for surface oscillations.

Field Examples of Various Manifestations of Liquefaction

Evidence of the three dominant liquefaction-related ground failure mechanisms is apparent in aerial photographs of the meizoseismal zone of the great 1811-12 New Madrid earthquakes. Within a time span of only three months, numerous strong earthquakes struck along a 125-km-long fault zone. Two were probably of at least M 8 (Johnston and Schweig, 1996). The earthquakes were centered beneath a huge region of liquefiable deposits, and tremendous liquefaction occurred. Sand that vented to the surface formed a veneer more than 0.5 to 1 m in thickness over hundreds of square kilometers. More than 1 percent of the ground surface was covered by vented sand over thousands of square kilometers (Obermeier, 1989). The meizoseismal zone of the 1811-12 earthquakes is one of the best in the world to see effects of liquefaction in sectional view, which is the view that is most useful for paleoliquefaction studies.

Figures 7A and 7B are aerial photographs from the meizoseismal zone of the 1811-12 earthquakes. These photographs illustrate effects of lateral spreading, hydraulic fracturing, and probably surface oscillations. Fissuring and venting took place in braid-bar deposits of latest Pleistocene age and in Holocene point-bar deposits. The ground surface is quite flat, overall, except at stream banks that typically are only several meters high. The light-colored portions of the photos show sand vented to the surface. The dark background is the dark-colored, clay-rich cap onto which the sand vented. The light-colored linear features are long fissures through which sand vented, and the light-colored spots are individual sites of venting. Venting was through dikes, as illustrated in Figure 1.

Note the abundance of linear fissures that are more or less parallel to one another in the upper right side of the photo of Figure 7A. These fissures are of lateral spreading origin, and they have formed near a break in slope. Individual sand blows, which are particularly well expressed in the upper left part of the photo, formed by hydraulic fracturing. The development of lateral spreads and individual sand blows is typical of that throughout the meizoseismal region, in that the dikes from lateral spreading commonly extend a large distance (even more than a kilometer) from any breaks in slope, and the isolated sand blows have developed throughout the area, independent of proximity to a stream bank.

The fissures in the central part of Figure 7B probably formed chiefly from surface oscillations. This origin is interpreted because the fissures are more or less parallel to one another, and they have developed on very flat lying ground that seems too far from any banks to be associated with lateral spreading.

There is a widespread perception that wide dikes that form by lateral spreading are restricted to being very near stream banks. However, in the meizoseismal region of the New Madrid 1811-12 earthquakes, dikes from lateral spreading as much as 0.5 m in width are plentiful even hundreds of meters from any significant slopes. In another example, in the Wabash Valley of Indiana-Illinois, within the meizoseismal zone of a prehistoric $M \sim 7.5$ earthquake, dikes up to 0.5 m in width probably formed hundreds of meters from any stream banks when the earthquake struck (Munson and Munson, 1996; Pond, 1996; Obermeier, 1997).

In both the New Madrid and Wabash regions, liquefaction susceptibility is not exceptionally high (Obermeier, 1989; Pond, 1996) and is probably typical of medium-grained fluvial deposits. Data from a worldwide compilation of historical earthquakes by Bartlett and Youd (1992) clearly show that horizontal movements of a few to several meters commonly extend hundreds of meters back from stream banks, especially where seismic shaking has been very strong. Wide dikes should also be expected for these conditions, far from the banks.

WHERE WAS THE SOURCE REGION?

Verification of a seismic origin to suspected liquefaction features typically involves demonstrating that (1) details of individual clastic dikes conform with those of known seismic origin, (2) both the pattern and location of dikes in plan view conform with a seismic origin, on a scale of tens to thousands of meters, (3) the size of dikes on regional scale identifies a central "core" region of widest dikes, which conforms with severity of effects expected in the energy source region (the meizoseismal zone), and (4) other possible causes for the dikes, such as artesian conditions and landsliding, are not plausible (Obermeier, 1996a, 1997). The purpose of the following discussion is how to identify the core region.

We have used two methods to estimate the source region (presumed to be the locale of strongest bedrock shaking) in the Wabash Valley. Both methods have widespread applicability for paleoseismic studies. One involves a direct measurement of dikes, and the other involves back-calculating the strength of shaking. Both require collecting data over a large region in order to see a clearcut trend in the data. In practical terms, for a M 6-7 earthquake, data must be collected over an area of several to many tens of kilometers in radius. Preferably, data are collected from the region of distal effects of liquefaction, where dikes are small (narrow) and infrequent, to much closer to the source region where dikes are much larger (wider) and plentiful.

Dike width serves as a superior parameter to estimate the location of the source region (Obermeier, 1996a). This width generally reflects the amount of lateral spreading except where dikes are relatively small (say, less than 10 cm). Conceptual verification for using dike width is provided from a study of historical earthquakes by Bartlett and Youd (1992). Dike width works well because the amount of lateral spreading is largely independent of thickness and strength of the cap, at least for sediments typical of Holocene and late Pleistocene ages. Either maximum dike width or the sum of dike widths at a site seems to work equally well for estimating the source location (Munson et al., 1995). Valid interpretations based on the width of dikes obviously requires that bank erosion not have been so severe as to have destroyed dikes from lateral spreading. Problems of interpretation due to erosion are generally not serious in the meizoseismal zone of a very large-magnitude earthquake because of the tendency for large lateral spreads to develop quite far from the stream banks.

Data from historical earthquakes in the Wabash Valley region, in the forms of Modified Mercalli Intensities and instrumentally-located epicenters (Rhea and Wheeler, 1996), suggest that using liquefaction effects to locate the source region of prehistoric earthquakes is generally accurate within a few tens of kilometers (Obermeier, 1997). The uncertainty in location probably increases with increasing magnitude because of the tendency for the epicenter of larger earthquakes to be farther removed from the area of strongest shaking (e.g., Youd, 1991). Still, effects of liquefaction can be used to reasonably estimate the region of strongest bedrock shaking (Pond, 1996).

Other parameters such as density of dikes per unit length and density per unit of area have been used by other researchers in their attempts to locate the region of strongest shaking. There are numerous practical problems in trying to interpret the data from such an approach, however, because dike density is controlled by different factors for each of the mechanisms of lateral spreading, surface oscillations, and hydraulic fracturing. In many field situations it is impossible to determine which mechanism(s) controlled the density of dikes. Interpretations can be questionable without such a differentiation.

Back-calculation of the strength of shaking at widespread sites can sometimes be used to locate the source region, wherever dike-width data are too sparse to locate the region. Verification of the back-calculation procedure has been done by comparing this interpretation with that of the dike-width method that was discussed above, and both yielded the same result (Pond, 1996). (Discussion of the method for back-calculating the strength of shaking is in a section below.)

A question that is often asked is whether paleoliquefaction features resulted from a single large earthquake or from a series of small earthquakes that were closely spaced in time. The answer to the question is generally best resolved by analysis of the regional pattern of dike widths. The attenuation pattern of dike widths around a core region should be examined in orthogonal coordinates (preferably along the fault axis and perpendicular to the axis). A monotonic decrease in orthogonal directions around the core indicates a single large earthquake. In the Wabash Valley this approach was verified by geotechnical calculations of the prehistoric strength of shaking, for four prehistoric earthquakes (Pond, 1996). The use of dike widths alone to resolve the issue of number of events requires that the liquefaction susceptibility be reasonably uniform on a regional basis, and also that the amplification of bedrock motions be similar on a regional basis. Where these conditions are not met, calculations of bedrock motions can sometimes resolve the issue (Pond, 1996).

For the question of a single or multiple earthquakes, the methods described above usually work best for very large earthquakes because of the tendency for the regional pattern of liquefaction effects to become more conspicuous with increasing magnitude. For example, the regional pattern of dike widths may be able to resolve whether liquefaction features that were recently discovered within the meizoseismal region of the great 1811-12 New Madrid earthquakes, yet predating the 1811-12 earthquakes, were from a single great earthquake or from numerous smaller events (Tuttle and Schweig, 1996). The New Madrid region seems suitable for this type of analysis because the liquefaction susceptibility is remarkably uniform over a huge area, the causative fault system for major earthquakes is likely known, and the regional pattern and extent of liquefaction from the 1811-12 earthquakes are already known or probably can be determined, even at the extremities. The pattern and extent of liquefaction from the 1811-12 earthquakes provides calibration for other earthquakes.

DID STRONG SHAKING OCCUR WITHOUT LEAVING EVIDENCE BEHIND?

Many geologists have the perception that liquefaction can occur in a region, but leave behind no evidence to be discovered in a search for effects of the liquefaction. The answer to that perception is yes - and no. It depends on the severity of liquefaction. Effects should be easy to discover where liquefaction has been severe throughout a region. Below we consider some of the major factors that determine the severity of liquefaction.

Effects of Strength of Shaking and Liquefaction Susceptibility

The discussion below is largely in terms of occurrence and severity of liquefaction effects, as the effects relate to Modified Mercalli Intensity (MMI). This approach is used because MMI correlates with both severity of liquefaction and destruction to man-made facilities (Wood and Neumann, 1931). MMI also correlates with peak surface acceleration (Krinitzsky and Chang, 1988). Seed et al. (1985) reported similar correlations that have been developed in China for M ~ 7.5 earthquakes. The Chinese correlations (below) appear to emphasize higher magnitudes of earthquakes than do those of Krinitzsky and Chang (below), whose relations are for a much wider range of magnitudes. Relations below by Krinitzsky and Chang (1988, Fig. 7) are for sites at the "far field," which are removed from the region of strongest shaking.

Table 2. Correlations between Modified Mercalli Intensity (MMI) and peak surface acceleration.

MMI	Peak Surface Acceleration	
	Chinese	Krinitzsky and Chang
VII	~ 0.1 g	~0.13 g
VIII	~ 0.2 g	~0.2 g
IX	~ 0.35 g	no data

Throughout the meizoseismal region of a very strong earthquake, in which the MMI value is IX or higher, liquefaction features should abound even where the liquefaction susceptibility is only moderate (as defined below). Any reasonable effort to locate numerous liquefaction features should be successful. At least some wide dikes and many small dikes should be discovered.

For moderate liquefaction susceptibility in regions of MMI VII-VIII, small liquefaction features may be very sparse but still should be numerous enough that some would be discovered during the examination of tens of kilometers of stream banks.

Moderate liquefaction susceptibility implies moderate relative density (Table 1) as well as a water table within several meters of the surface and a cap thickness less than 8 or 9 meters. Moderate liquefaction susceptibility is about the norm for deposits of latest Pleistocene and Holocene ages that have been laid down by moderate- and large-sized streams in the central and eastern U.S. (We have insufficient data to comment about the western U.S.) This level of susceptibility applies to streams of both glaciofluvial braid-bar and Holocene point-bar origins. A lower limit of moderate susceptibility requires a bed of silty sand, sand, or gravelly sand (generally less that about 40 percent gravel) that is at least a few to several meters thick; the bed should preferably be capped by at least a half a meter or more of finer sediment of lower permeability. In addition, the base of the cap must lie beneath the water table at the time of the earthquake.

Still, it is not unusual that source beds much thinner than a few meters produce liquefaction features. Where shaking is quite strong (say, in excess of 0.2 g), a sand thickness of only 1 m or less can suffice to develop dikes in response to hydraulic fracturing. Even a thickness of 0.3 m can suffice for this level of shaking (e.g., Youd and Garris (1995)). Such a thickness of liquefiable sand is commonly found at the top of glaciofluvial gravel and cobble beds. For this field setting, and with a water table depth of less than about two meters, dikes have been found to develop within the meizoseismal zone of a M ~ 7 earthquake, at least in the central U.S. (e.g., Pond, 1996).

Effect of Grain Size

Even though sand containing little or no fines is the grain size that is highly prone to liquefy and form dikes, sandy gravel with as much as 60 percent gravel and perhaps even more can liquefy readily and form large dikes in response to shaking, providing the shaking is strong enough. Still, extreme levels of shaking do not seem to be required in many field situations. Both historic examples (Andrus, 1994) and prehistoric examples (Pond, 1996) have been reported recently. Magnitudes of M ~ 7-7.5 and shaking levels of 0.4 g or lower were thought to have been involved in the examples cited above.

Clean silt will also liquefy and fluidize to form dikes, sometimes extensively (Youd et al., 1989). "Dirty" sands containing as much as 35 percent fines (silt and clay) will also liquefy, but it is unclear whether a large amount of fines requires much stronger shaking than if none were present. Seed et al. (1985) have advocated that an increasing fines content increases the level of shaking required for development of liquefaction features. In some (many?) cases, alternatively, sand with a silt content as high as 30 percent may even be more susceptible than clean sand (T.L. Youd, written commun, 1997). Clearly more research is needed to determine the role of fines content on liquefaction susceptibility.

Still, it has been the experience of Obermeier that dikes and liquefaction-induced features that have developed from liquefaction of very dirty sand (say, > 20-30 percent fines) are only rarely observed in paleoliquefaction searches, even where shaking has been very strong; liquefaction features with smaller amounts of silt are commonplace.

There seem to be two possibilities that explain this discrepancy between the engineering studies and the paleoliquefaction searches, for sand with the higher fines content. One is that the engineering studies misidentified the source beds that liquefied and the other is that the paleoliquefaction searches failed to find the liquefaction features. Engineering studies typically identify source beds by using penetration data in combination with sampling of sediment by driving a tube into the ground. Locating the source bed with this procedure can sometimes be very difficult and controversial.

Paleoliquefaction searches, on the other hand, often permit direct observation of possible source beds. Dirty sands typically lie directly beneath a fine-grained cap. These dirty sands are commonly 0.3 to 0.6 meters in thickness, and they represent part of the fining-upward sequence that is normally present beneath channel-fill and overbank deposits. Paleoliquefaction searches are normally done by examination of stream banks in vertical section, when stream levels are very low. Often any possible source beds are observed during this time of low water, and so liquefaction features should be especially conspicuous. The failure of paleoliquefaction searches to locate the effects of liquefaction from dirty sands can be explained at some places by the lack of a large difference in grain sizes between the host sediment cut by any dikes and the material in the dike. This lack of an obvious grain size difference is especially a problem in trying to detect the effects of many older paleo-earthquakes, in which pedological processes have deeply weathered and obscured effects of liquefaction.

Still, though, the overall lack of liquefaction effects from dirty sands that have been found during paleoliquefaction searches seems somewhat inexplicable. But, experience shows that an absence of dikes and other effects in a cap above a potential source zone of dirty sand (say, more than about 20 percent fines) should not be interpreted to mean an absence of strong shaking since the deposits were laid down.

Effect of Depth to Water Table

Where the water table is more than four or five meters deep, it appears that effects of liquefaction become much suppressed and can be scarce even where shaking is quite strong. For example, lateral spreads can have dikes as much as 0.7 m in width yet the effects of hydraulic fracturing can be so sparse as to require kilometers of exposures for their discovery.

It is commonly observed that dikes from lateral spreading are the only ones observed in an exposure, as illustrated in Figure 5B, even where dikes are as much as 0.3 m wide and the water table was within 2 m of the surface at the time of the earthquake. Levels of shaking for this situation probably can be as high as about 1/4 g, in field settings where the source sands are fluvial in origin, medium sized, and moderately compact.

HOW STRONG WAS THE PALEO-EARTHQUAKE?

Much progress has been made the past few years in development of techniques for back-calculating the strength of shaking and magnitude of paleo-earthquakes. The techniques vary widely in their basic approaches, which provides the opportunity for independent assessments.

Four methods are available. One method uses the radius of liquefaction to estimate magnitude (magnitude-bound method), a second uses peak accelerations (Seed et al. method), a third uses an energy approach (Pond method), and a fourth uses dike height (Ishihara method). Selection of appropriate method(s) depends on the types of liquefaction data available.

The confidence in interpretations is highest where different methods yield the same values of prehistoric magnitude. Even in this case though, there can be uncertainty because some of methods may depend similarly on the seismic parameters of stress drop and focal depth (Obermeier, 1997). The Pond method can likely circumvent much of this problem, however, as we discuss below.

Magnitude-Bound Method

The magnitude-bound method uses the radius from the presumed source region to the most distal effects of liquefaction to estimate the magnitude. This method is based on the premise that within a specific seismotectonic setting, parameters such as stress drop and focal depth are reasonably constant through time, and their effects can be reasonably approximated. Data from historical earthquakes within the region preferably are available to calibrate the influence of these effects.

Figure 8 shows the bound that has been developed from data from numerous earthquakes worldwide, using epicentral distance. (Data shown in Figure 8 are from Ambraseys (1988), although data from another source (Keefer, 1984) yields a bound that is virtually identical.) Data points in the figure are almost exclusively from sites of venting of sand or lateral spreading. Sites of soft-sediment deformations such as ball-and-pillows, load casts, or convoluted bedding have not been included as data points.

Use of the magnitude-bound method for paleoseismic analysis requires large numbers of exposures in the vicinity of the distal effects in order to have high confidence that the radius to the distal effects is approximately correct. Figure 8 also shows the bound that has been developed specifically for the Wabash Valley region of Indiana-Illinois and is based on liquefaction effects from historical earthquakes thought to be representative of the region. The curve for the Wabash Valley region is properly thought of as showing the maximum distance from the zone of strongest energy release - which is undoubtedly a more fundamental and proper parameter for paleoseismic analysis than epicentral distance, because the epicenter of many larger earthquakes is far removed from the zone of strongest energy release (e.g., Bartlett and Youd, 1992).

The curve in Figure 8 for the Wabash Valley region has been used to estimate the magnitude of many prehistoric earthquakes there (Munson and Munson, 1996; Pond, 1996; Obermeier et al., 1993; Obermeier, 1997). Assessments of those paleomagnitudes using the energy-based method of Pond (discussed below) have yielded essentially the same values as the magnitude-bound method (Pond, 1996).

The magnitude-bound method appears to work well for estimating paleomagnitudes in the Wabash region for a variety of reasons, including the manner in which historical observations were used. The bound for the Wabash region was defined chiefly by data points from three historical earthquakes, of M ~ 8.3, 6.9, and 5.5 (see Obermeier et al. (1993) and Pond (1996)). Use of data from the M ~ 8.3 earthquake (one of the 1811-12 New Madrid events) is illustrative. The data points for the M ~ 8.3 earthquake represent where liquefaction effects were widely scattered yet sufficiently commonplace to have been noticed by people living in a sparsely settled area. The effects of liquefaction probably went further yet. More distal features almost certainly developed in geologically very young islands in the major rivers and in point bar deposits bordering the rivers. In a similar vein, the data point for the M ~ 5.5 earthquake was from an observation on a broad terrace, which is not the type of field setting that is most conducive to development of liquefaction features (i.e., lateral spreading along stream banks). Why, then, would the types of observations above be expected to yield a reasonable limit of liquefaction for the magnitude-bound method, in the Wabash region?

The answer is that the bound in the Wabash region probably reasonably approximates the distance at which liquefaction features from a prehistoric earthquake can be relocated in a paleoliquefaction search. This has been borne out by the results of extensive searching for liquefaction features caused by the 1811-12 earthquakes. These searches were conducted beyond the epicentral region of the 1811-12 earthquakes to the northeast (in the vicinity of the Ohio and Wabash Valleys) as well as to the northwest (in the vicinity of the Mississippi Valley, near St. Louis, Missouri). The paleoliquefaction searches discovered only scattered, small dikes that could have been caused by the 1811-12 earthquakes, in the vicinity of the historical observations of scattered liquefaction from the 1811-12 earthquakes. This finding was the case both in the vicinity of the Ohio and Wabash Valleys as well as in the vicinity of the Mississippi Valley (see Obermeier (1997) and McNulty and Obermeier (1997)). No dikes were found beyond the limits of the historical observations in 1811-12.

A similar finding has taken place in South Carolina. A $M \sim 7.5$ earthquake struck near Charleston in 1886. Newspaper accounts reported ground failure from liquefaction as far as 100 km south of Charleston. Searches made 100 years later located liquefaction features that could be reasonably associated with the earthquake in 1886, at distances of up to 100 km south of Charleston (Obermeier et al., 1993, p. 21-22).

In summary, the results of paleoliquefaction searches make it appear that historic observations of liquefaction can sometimes be used to define the limit of liquefaction for the magnitude-bound method. However, confidence in interpretations using the magnitude-bound method also requires knowledge of the approximate depth of the water table at the time of the earthquake. For clean sands, medium grained and coarser, this depth can probably be estimated by observing the highest level of the base of dikes at widespread sites. For the field situation where the water table is much below the base of the fine-grained cap, the high permeability typically found with these clean sands would probably permit the excess pore-water pressures caused by liquefaction to bleed off along the base of the cap, thereby precluding development of liquefaction-induced ground failure.

The magnitude-bound method probably has worked well in the Wabash Valley region because of rather special field settings. Many streams in the region are very underfit, in that they occupy valleys that formed when great quantities of sediment were being debouched during melting of the glaciers. These valleys are kilometers across and at many places contain tens of meters of sand and gravel capped by a thin silt layer. Radiocarbon data show that the depth to the water table in many of these valleys has rarely been greater than 2 to 3 m throughout the Holocene (Obermeier, 1997). Thus, the ability to form liquefaction features has remained relatively constant through Holocene time in many of these underfit valleys.

Seed et al. Method

The Seed et al. method (1983, 1985) is a stress-based (acceleration) geotechnical procedure for estimating the strength of cohesionless sediment that is required to prevent liquefaction during an earthquake. The strength is evaluated in terms of the parameter $(N_1)_{60}$, which is the Standard Penetration Test blow count value (N) normalized to account for depth of the sediment and depth of the water table. Figure 9 shows the bound for M 7.5 earthquakes as given by Seed et al. (1985), which relates the $(N_1)_{60}$ value to the seismic cyclic stress; the bound is intended to delineate where liquefaction is likely from where it is unlikely. The bound of Figure 9 was developed from field observation of liquefaction behavior from many earthquakes worldwide, supplemented with laboratory data. The field observations were from sites where liquefaction-induced ground failure was evident at the ground surface as manifest by lateral spreads, sand blows from hydraulic fracturing, and possibly other mechanisms. The bound of Seed et al. in Figure 9 has been thought until recently to represent a logistic probability of about 20 percent for occurrence of liquefaction. Very recent analysis shows, however, that the bound represents a probability of about 20 to 50 percent, with the lower probability being associated with the higher values of $(N_1)_{60}$ (Youd and Noble, in press, 1998). (Youd and Noble have also revised the bound of the Seed et al. method for magnitudes other that M 7.5.)

No distinction of the mechanism of ground failure is made in Figure 9. For other than exceptionally strong earthquakes with very strong shaking, though, the boundary likely represents the threshold for lateral spreads, at least for $(N_1)_{60}$ values up to about 15 to 20. The failure mechanism can differ at higher values because liquefied ground becomes increasingly stiff as $(N_1)_{60}$ increases, and the stiffness makes lateral spreading increasingly difficult and less probable in comparison to other mechanisms of ground failure (p. 1440-1441 in Seed et al., 1985; Bartlett and Youd, 1992).

To reiterate, at low to moderate $(N_1)_{60}$ values, the Seed et al. bound approximates conditions for threshold development of lateral spreading. Even for these $(N_1)_{60}$ values, the bound probably closely approximates the threshold for marginal ground failure from the other mechanisms in many field settings. This is so because lateral displacement on level ground requires that the sediment beneath the laterally moving blocks be liquefied completely or nearly so; and, if there is complete liquefaction (complete liquefaction is defined as the state where the pore-water pressure equals the total static pressure of overlying sediment and water), the pore pressure increase is likely to be high enough to hydrofracture through a thin cap (order of a meter or so?). Complete liquefaction (rather than partial liquefaction) is highly probable in the field at low to moderate values of $(N_1)_{60}$ (e.g., Fig. 8 in Seed et al., 1985; Castro, 1987); thus, for these values of $(N_1)_{60}$, the bound of the Seed et al. procedure is probably nearly synonymous for either lateral spreading or hydraulic fracturing through a thin cap.

As noted previously, for higher values of $(N_1)_{60}$ lateral ground motions are much more restricted, and "sand boils" (i.e., hydraulic fracturing) can be the mechanism of ground failure that develops most easily (Seed et al., 1985). As a consequence we suspect that throughout the range of $(N_1)_{60}$ values the threshold acceleration varies similarly for the various mechanisms of ground failure, at least for a thin cap.

It is often observed in paleoliquefaction searches that small dikes penetrate only a small fraction of the height of a thick fine-grained cap (see Fig. 1B). Even for this situation the Seed et al. bound can almost certainly establish the lower limit of the strength of shaking that was required to form the small dikes. The logic for this conclusion is that the bound for the Seed et al. method was developed from surface observations of liquefaction where dikes had penetrated all the way to the surface, irrespective of thickness of the cap; and, development of liquefaction beneath a cap having a thickness in excess of several meters, where a higher overburden pressure suppresses liquefaction, almost certainly requires stronger shaking than beneath a thin cap.

Field observations show that the bound in Figure 9 separating sites where liquefaction occurred from sites of no effects is remarkably well defined (e.g., Liao, 1996), considering the practical difficulty in locating the source bed that liquefied in many field situations . Still, identification of the source bed is difficult to virtually impossible in many field settings. Figure 2 shows such an example, where a sill extends horizontally a long distance before venting to the surface. Here the sill runs beneath a mat of roots or peat. Similarly, as indicated in Figure 10, fluidized sediment can travel horizontally many meters beneath a sloping cap before venting, especially where channel-fill deposits are inset deeply into overbank deposits. Therefore, the possible role of the geologic setting on surface manifestations of liquefaction must be carefully evaluated when trying to establish the source bed that liquefied (e.g., Obermeier, 1996b).

Because the bound in Figure 9 represents sites where effects of liquefaction are minimal at the ground surface, paleoliquefaction sites that are appropriate for estimating actual strengths of shaking are limited. Back-calculation at a site of severe liquefaction may reflect only a lower bound of shaking, and this lower bound can be much lower than what actually happened.

Even at sites of marginal liquefaction, a practical problem in using the Seed et al. method to back-calculate accelerations is caused by the variability of blow counts of most natural sediments. Only the loosest sediment can confidently be assumed to have liquefied. As a result the Seed et al. method can yield only a lower bound of prehistoric accelerations and magnitudes in most field situations. However, the Seed et al. method can be used in combination with other procedures to make a best estimate of accelerations and magnitude (such combinations are discussed in sections that follow).

There is some question whether the Seed et al. method is applicable to earthquakes that are unusual in parameters such as stress drop and focal depth; for example, a very high stress drop will induce very strong peak accelerations (Hanks and Johnston, 1992), which in turn might cause liquefaction to be exceptionally severe. However, the study of a historical earthquake (M 5.9 Saguenay earthquake, in 1988), which had a very high stress drop and a very deep focal depth, indicates that the method of Seed et al. correctly predicted the observed liquefaction evidence (Tuttle et al., 1990).

Other inherent shortcomings in the Seed et al. method for evaluating liquefaction potential have been discussed by Law et al. (1990), who suggest that energy is a more fundamental and accurate parameter for evaluating whether liquefaction should occur. Specific deficiencies of the Seed et al. method are that (1) the peak acceleration in one direction does not always reflect the amount of energy acting on a point, and (2) the peak horizontal acceleration does not reflect what is happening in all vibration frequencies.

In addition, the peak horizontal acceleration may relate poorly to shear strain, which is the physical mechanism that breaks down grain-to-grain contacts and leads to liquefaction. A poor correspondence between shear strain and acceleration may be important where surface shaking is dominated by the combination of very low vibration frequencies, large shear strains, and low accelerations. Use of the Seed et al. method for this scenario would probably lead to an over-estimate of the peak acceleration. This situation could possibly occur where very thick (order of a kilometer), unlithified sediments dampen out high frequency vibrations as they pass upward (Chapman et al. 1990). Many coastal areas of the U.S. are underlain by unlithified Tertiary sands and clays that are extraordinarily thick and thus may be prone to this problem.

Energy-Stress Method

This method relies on a direct relationship between energy dissipation and buildup of pore-water pressure during undrained cyclic loading of saturated sands (Nemat-Nasser and Shokooh, 1979; Davis and Berrill, 1982; Simcock et al., 1983; Liang et al., 1995).

Berrill and Davis (1982) were the first to develop an energy model for predicting liquefaction at sites in the field. The model was later modified by Berrill and Davis (1985) and then by Law et al. (1990). By using an empirical approach to predict the seismic energy arriving at a site, they developed a description of the parameters affecting liquefaction susceptibility within a soil deposit as a function of the value of $(N_1)_{60}$ of the soil. Pond (1996) has since developed a similar approach for paleoseismic analysis, but using different characterizations of the energy arriving at a site and of the liquefaction susceptibility at a site. In Pond's method, the database of Liao and Whitman (1986) forms the basis for relating occurrences of liquefaction to $(N_1)_{60}$ of the soil and the level of seismic energy. For paleoseismic analysis, the average value of $(N_1)_{60}$ is used. (The basis for using this average value is not intuitively obvious. The logic and technical backup are explained in Pond (1996; p. 241-250) and Pond (1998).

Paleoseismic analysis using Pond's method is an iterative process. First it is necessary to assume an earthquake magnitude and energy source location. From these an estimate can be made of the level of seismic energy that arrived at sites of liquefaction ranging between the energy source, where liquefaction effects can be severe, to the extremities of liquefaction where only small features are present. The liquefied portion at a site is taken as that portion of the soil profile for which the average of the measured $(N_1)_{60}$ values equals the predicted value, with the predicted value being based on the estimate of seismic energy at the site. Next, the Seed et al. method (Fig. 9) is used to determine the threshold acceleration at increments through the liquefied portion of the soil profile. The peak acceleration is estimated to be the average of the threshold accelerations throughout the liquefied portion. Many iterations of the procedure described above, using energy levels from variously assumed paleomagnitudes and epicentral distances, may be required before the back-calculated accelerations agree well with predictions using seismological relations. The best estimate of magnitude is where agreement between the two methods for prediction is best for all paleoliquefaction sites between the epicentral region and the distal sites of liquefaction.

Pond's method has the attribute of providing an estimate of the actual value of peak acceleration at a site. The method was developed for sites of lateral spreading, which are the most common sites discovered in many paleoliquefaction searches. However, the method is probably also applicable to sites of hydraulic fracturing where the fine-grained cap is relatively thin (i.e., on the order of a meter or so). A further attribute is that the method probably applies to sites where lateral spreading has been severe, in addition to sites of only marginal lateral spreading, even for source beds of moderately dense and more compact sediments.

Pond (1996) has applied his method to well-documented cases of liquefaction as well as cases of non-liquefaction from recent earthquakes. Eleven sites from four separate earthquakes were investigated. Seven sites were at locales of liquefaction, and four were at sites of no reported liquefaction. Pond's method correctly predicted all. Back-calculated accelerations using Pond's method agreed very well with values observed in the field, and agreed reasonably well with estimates based on empirical attenuations.

Accelerations that are determined using Pond's method are probably best thought of as being probabilistic values, because the (probabilistic) Seed et al. method is used for calculations. Curves of the Seed et al. method for different probabilities (e.g., Youd and Noble, in press, 1998) permit making respective adjustments in the back-calculated accelerations. But, the specific tie-in of the probability between the Seed et al. method and Pond's method is yet to be studied.

The database for relating seismic energy at a site to the average value of $(N_1)_{60}$ is relatively robust (Pond, 1998). This robustness makes Pond's method especially suitable for analysis of liquefaction effects from paleo-earthquakes because unknown seismic parameters can be modelled to determine appropriate energy values. Stress drop can be varied and other parameters such as focal depth can be changed. By means of a parametric study, the Pond method can be used to determine the most likely strength of shaking and magnitude of a paleo-earthquake.

Ishihara Method

The premise of the Ishihara method (1985) is that the maximum height of dikes is controlled by two factors: the thickness of liquefied sediment and the peak acceleration (Fig. 6). The Ishihara method was originally developed using data from only a few earthquakes whose magnitudes were on the order of $M \sim 7.5$. Using worldwide data, the method has been shown to not be violated for a much wider range of earthquake magnitudes (M 5.3 to 8), but only for the mechanism of hydraulic fracturing (Youd and Garris, 1995). Data in the Youd and Garris report also show that for earthquake magnitudes greater than about M 7.5, the method generally predicts where surface effects of liquefaction occur as well as do not occur, although insufficient data are available for rigorous evaluation of all the curves in Figure 6. The Ishihara method seems to be valid for a wide range of cap properties.

The Ishihara method seems to have great potential for paleoseismic analysis. The method is ideally suited for using measurements of dike height and cap thickness, which are so readily observable in paleoliquefaction searches of stream banks. Where the dike height approaches the cap thickness, the Ishihara method can provide an upper bound estimate of the peak acceleration. This upper bound is ensured irrespective of whether or not the dike was induced by hydraulic fracturing because of the finding by Youd and Garris (1995) that the threshold acceleration for hydraulic fracturing is higher than for other mechanisms.

To best use the Ishihara method for a paleoseismic analysis requires locating sites of hydraulic fracturing where the maximum dike heights approach or barely equal the cap thickness. Sites are needed at widely scattered locales ranging from the epicentral region to the more distal effects of liquefaction. Finally, a parametric study needs to be used to find the best-fitting solution for variously assumed magnitudes.

Why the Ishihara method seems to work is unclear, but below we explain our state of understanding. The height that a dike intrudes into the cap is controlled partly by the pore pressure change in the water upon liquefaction. As the thickness of cap increases, the depth to the top of a potentially liquefiable sand increases, causing the effective confining stress at the top of the sand bed to also increase (Fig. 11). This higher confining stress requires a higher shear stress (acceleration) to induce liquefaction and also induces a greater pore pressure change upon liquefaction; the greater increase in pore pressure, in turn, can hydraulically fracture a greater cap thickness.

Other factors also are clearly involved in determining the height of dikes. Figure 6 shows that for a fixed thickness of liquefied sediment, the height of dikes also depends on the peak acceleration. Why peak acceleration is so important may relate to a number of factors, yet unverified. Most likely possibilities include that (1) a higher acceleration is more likely to cause breakage of the cap, irrespective of hydraulic fracturing, (2) a higher acceleration is more likely to be associated with a longer duration of strong shaking, and (3) a higher acceleration is likely to induce a greater thickness of liquefied sediment, providing more water for hydraulic fracturing; this third point may apply especially to more compact sediments that require many cycles of shearing to be liquefied completely.

Field situations where there is a concentration of flow beneath the cap may be suspect for the Ishihara method. A likely field situation for concentration is illustrated in Figure 10. The figure illustrates that upon liquefaction, there is a tendency for water and suspended sediment to be forced upward along the relatively steeply dipping basal portion of the fine-grained channel-fill. The surface evidence of liquefaction thereby occurs where the channel-fill comes in contact with the thinner overbank deposit.

The Ishihara method may also be invalid where the pore pressure change in a body of sand is extremely abrupt during shaking, as for very loose sand. In very loose sand, both the initial pore-water pressure buildup and complete liquefaction are virtually synonymous. In contrast, in moderately compact sands the rate of pore-water pressure buildup can be much more gradual. More data need to be collected in order to critique this factor more completely.

To summarize, the Ishihara method is thought to be applicable where the cap thickness is reasonably uniform (or at least does not slope much along the base), and where the source sand is moderately compact. Fortunately, many fluvial deposits meet these requirements.

CONCLUDING COMMENT

Liquefaction features have been used extensively during the past fifteen years to interpret of Holocene seismicity, especially in the eastern and central U.S. Findings from paleoliquefaction studies will undoubtedly continue to be relied on heavily in these parts of the U.S., in part because of the overall lack of exposures that might reveal faults. The studies in the eastern and central U.S. have typically involved close co-operation among geologists, archeologists, soil scientists, and geotechnical engineers, both during the field study and while making interpretations, and these combined efforts have proven extremely successful (e.g., see Martin and Clough, 1994; Munson et al., 1995; Obermeier et al., 1993; Obermeier, 1997; Pond, 1996). Knowledge is becoming widespread of the success of using these various skills in combined efforts.

The use of liquefaction features for paleoseismic analysis has not met with widespread acceptance in some areas, especially in the western U.S. A large part of this lack of acceptance is likely due to the lack of co-operative studies between individuals having a wide range of expertise. Whereas searching for liquefaction features and interpreting their origin is relatively straightforward, using liquefaction effects for interpretations of strength of prehistoric shaking is quite another matter. A strong background in geotechnical engineering is required for assessing the strength of shaking. Furthermore, a sound knowledge is required of the processes controlling liquefaction and its field manifestations. These critical skills have not been utilized in most western studies.

An area where extensive paleoliquefaction studies have the potential to be especially beneficial is in the Pacific Northwest of the U.S. Although it is clear that great subduction earthquakes strike there periodically, we believe that the strength of shaking from these earthquakes is not yet reasonably bounded. Results of preliminary paleoliquefaction studies indicate that peak onshore accelerations from a subduction earthquake about 300 years ago were not especially strong (Obermeier, 1995; Obermeier and Dickenson, 1997). Results of geophysical modelling using seismic parameters from California earthquakes, in contrast, indicate the possibility of very high onshore accelerations for the subduction earthquake of about 300 years ago (Wong and Silva, 1996). We believe that a paleoseismic study involving extensive geotechnical input could resolve the issue of the actual strength of shaking 300 years ago.

The newly-developed techniques for analysis of paleoliquefaction features, which we have discussed in this article, can be used in the Pacific Northwest (or anywhere else for that matter) because they can be used in conjunction with parametric modelling of factors such as stress drop and hypocentral depth. Ground motions predicted from the modelling can be compared with values that have been back-calculated from analysis of paleoliquefaction features, to select the most likely strength of prehistoric shaking.

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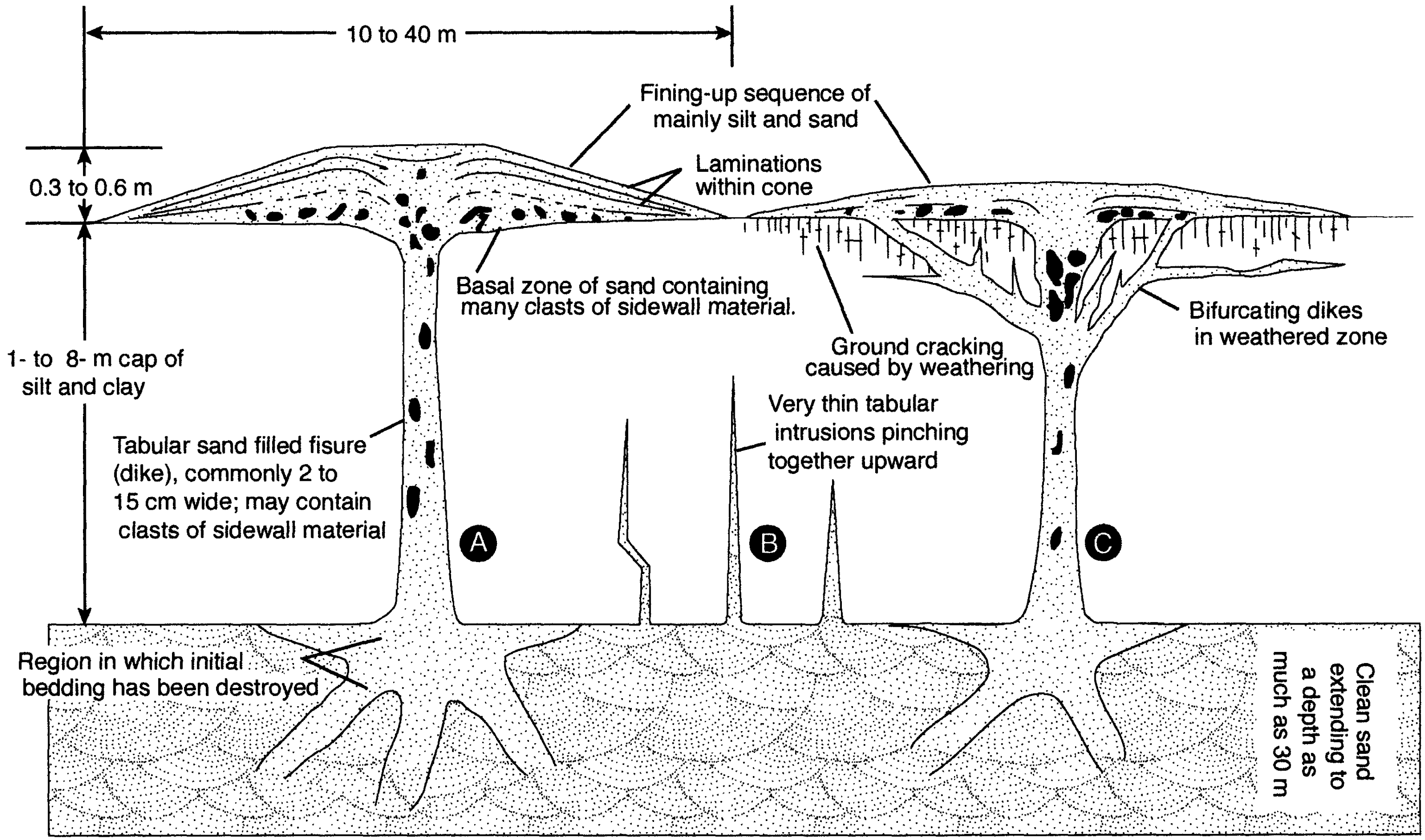

Figure 1. Schematic vertical section showing idealized dikes cutting through silt and clay strata. All dikes are tabular in plan view. Sketches are based mainly from field observations in the meizoseismal zone of the 1811-12 New Madrid earthquakes, from the Wabash Valley of Indiana-Illinois, and from islands in the lower Columbia River of Oregon-Washington (Obermeier, 1996a). All dikes are tabular in plan view, regardless of whether they vent to the surface or pinch together. A. Stratigraphy of dike with sediment vented to the surface. B. Dikes that pinch together as they ascend. C. Dike characteristics often associated with fractured zone of weathering that develops in highly plastic clays.

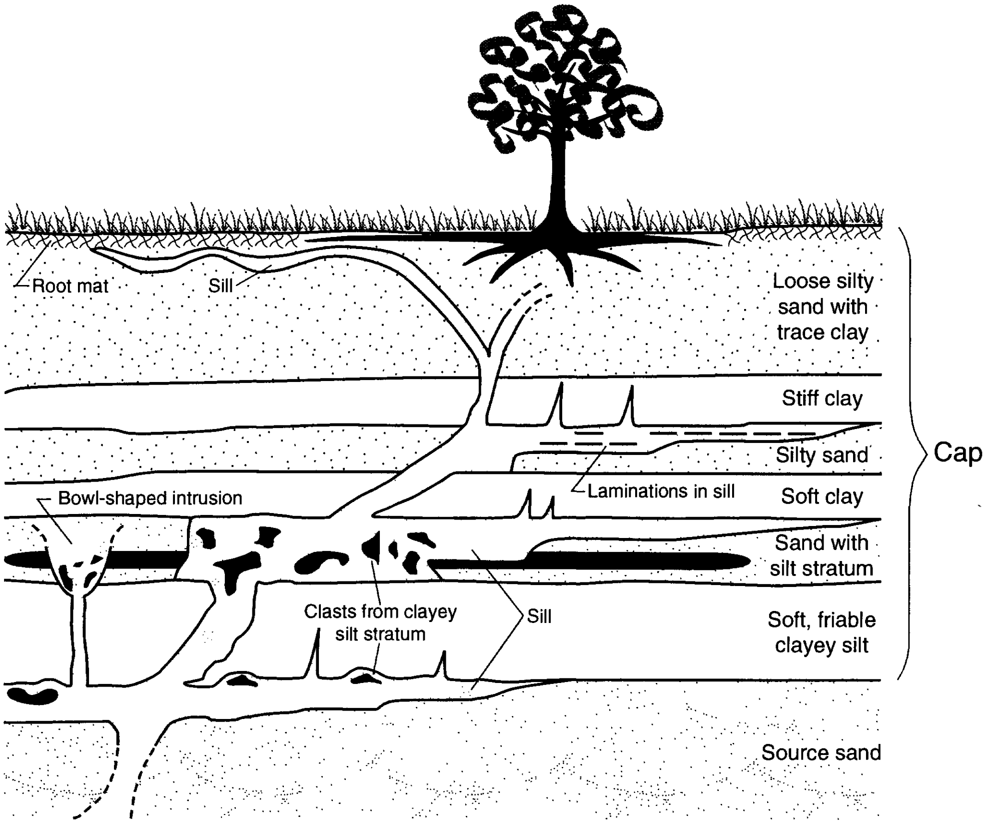

Figure 2. Schematic vertical section showing where sills have been observed to form preferentially. Length of sketch represents 10-100 m. Height represents 3-5 m. Such severe sill development is typically accompanied by venting of sand to the surface.

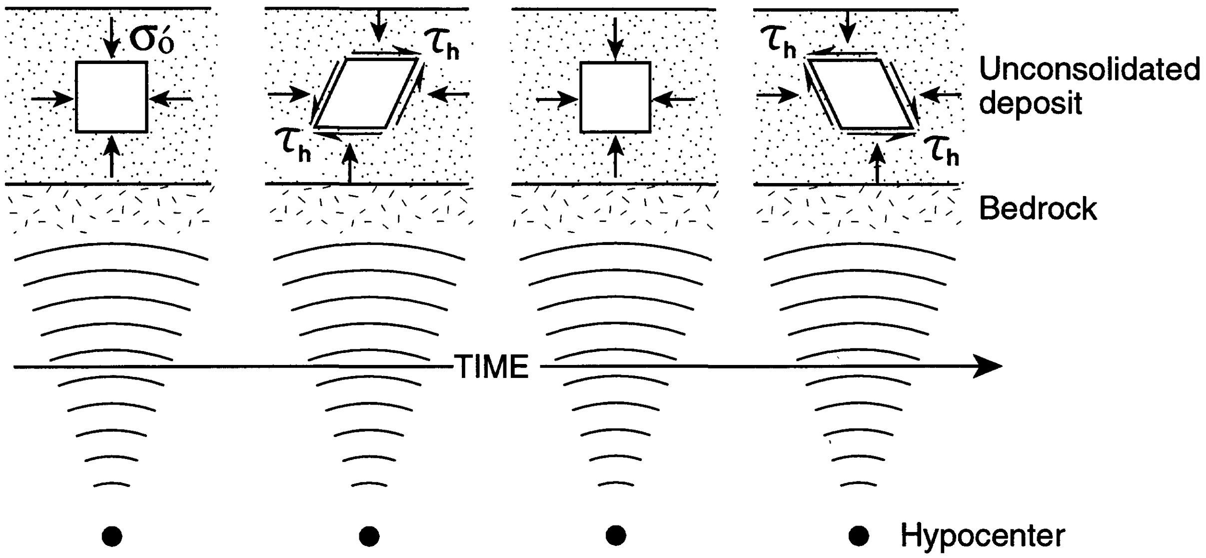

Figure 3. Schematic vertical section showing idealized field loading conditions changing with time as energy propagates upward from hypocenter. Stresses shown represent preliquefaction cyclic loading conditions. σ_0', initial vertical effective overburden stress; τ_h, earthquake-induced horizontal cyclic shear stress.

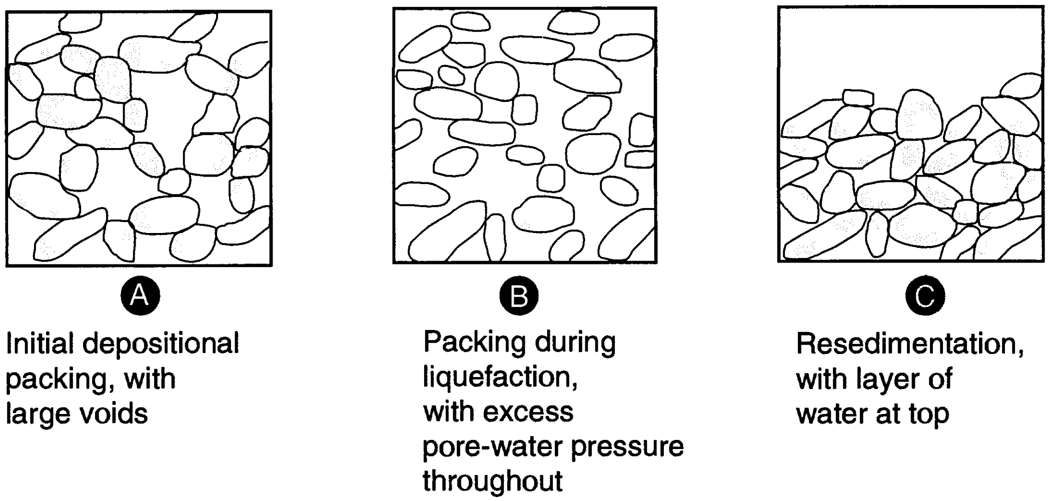

Figure 4. Changes in packing of sediment grains caused by liquefaction.

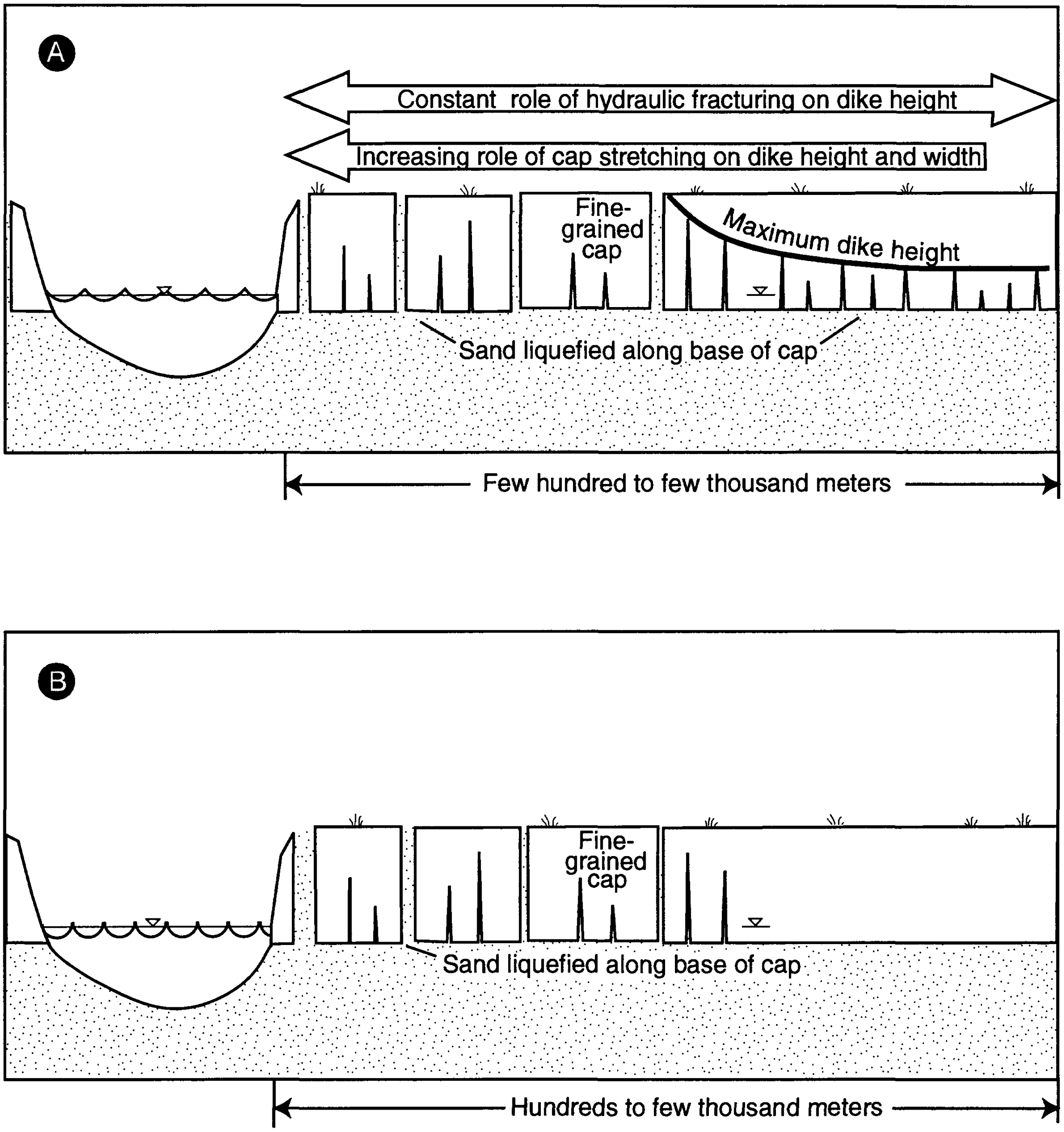

Figure 5. A. Vertical section near a stream bank showing relative roles of lateral spreading and hydraulic fracturing. Note that the height of dikes from hydraulic fracturing approaches a constant maximum value far from the stream bank. B. Vertical section showing the restricted locale of dikes that is often observed where liquefaction has not been severe.

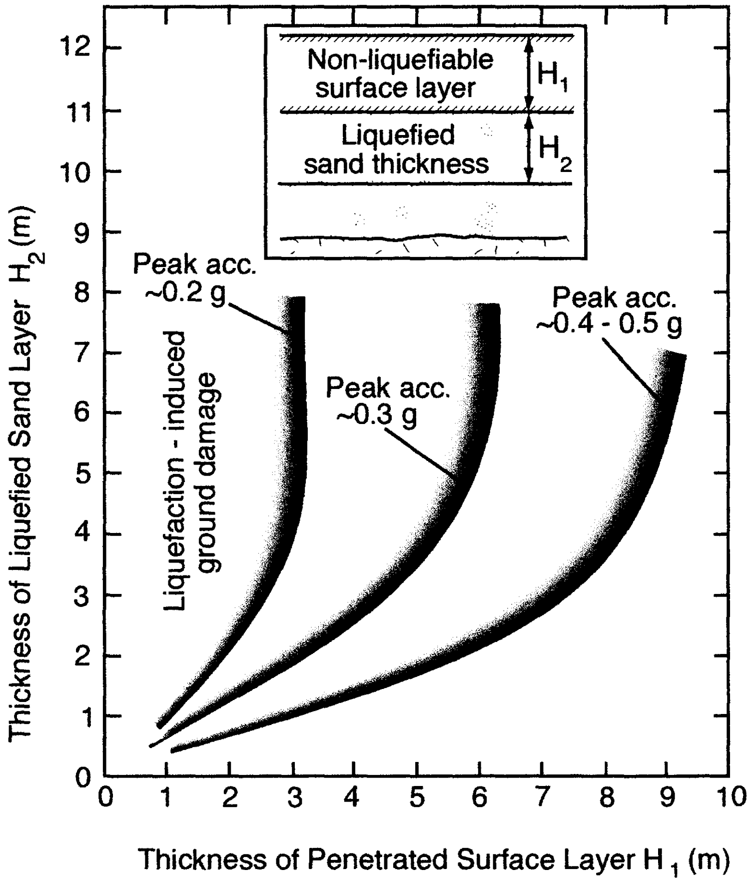

Figure 6. Thickness of cap penetrated by hydraulic fracturing, as related to thickness of liquefied sand and peak surface accelerations. Modified from Ishihara (1985).

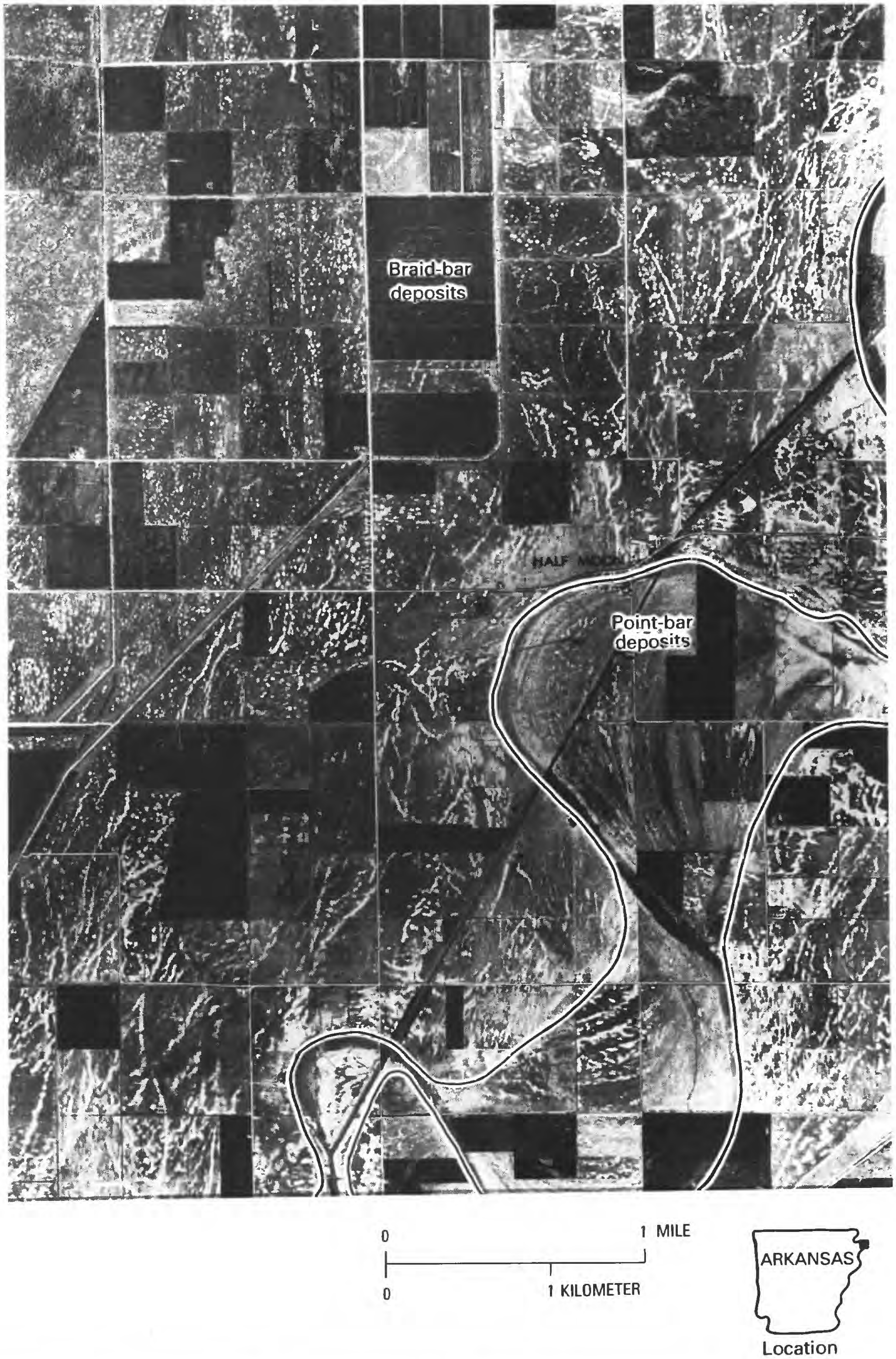

Figure 7. A. Aerial photograph showing effects of severe liquefaction in the meizoseismal zone of the great 1811-12 New Madrid earthquakes. White linear features show sand that has vented through breaks in the cap caused by lateral spreading. Note the concentration of linear breaks in proximity to stream banks. Isolated white spots show sand that has vented through breaks in the cap caused by hydraulic fracturing.

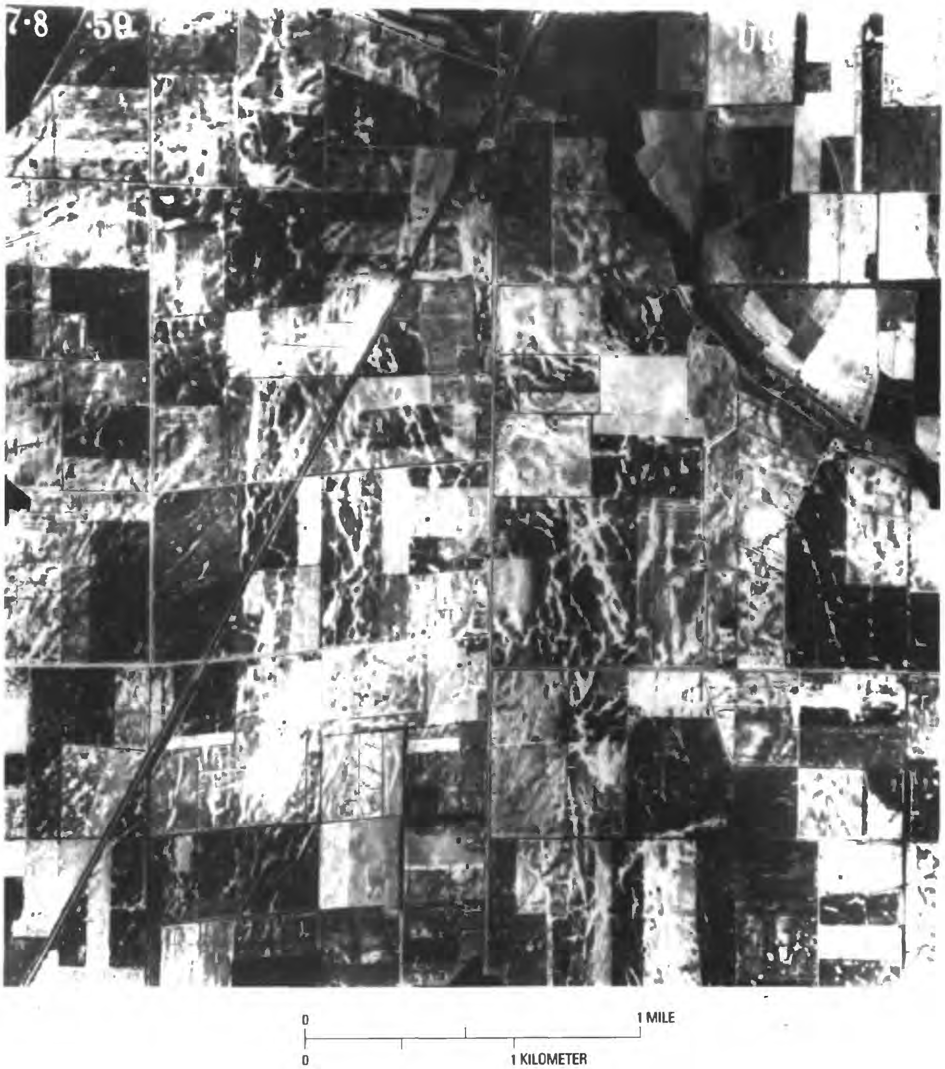

Figure 7. B. Aerial photograph showing where linear fracturing of the cap and venting have occurred, probably chiefly in response to surface oscillations. Note the absence of stream banks in proximity to the large, linear fissures in the central part of the photo. Surface oscillations often cause dikes and joints to form parallel to one another in a fine-grained cap. The strike of the breaks in the cap caused by surface oscillations is often independent of properties of the cap, such as thickness.

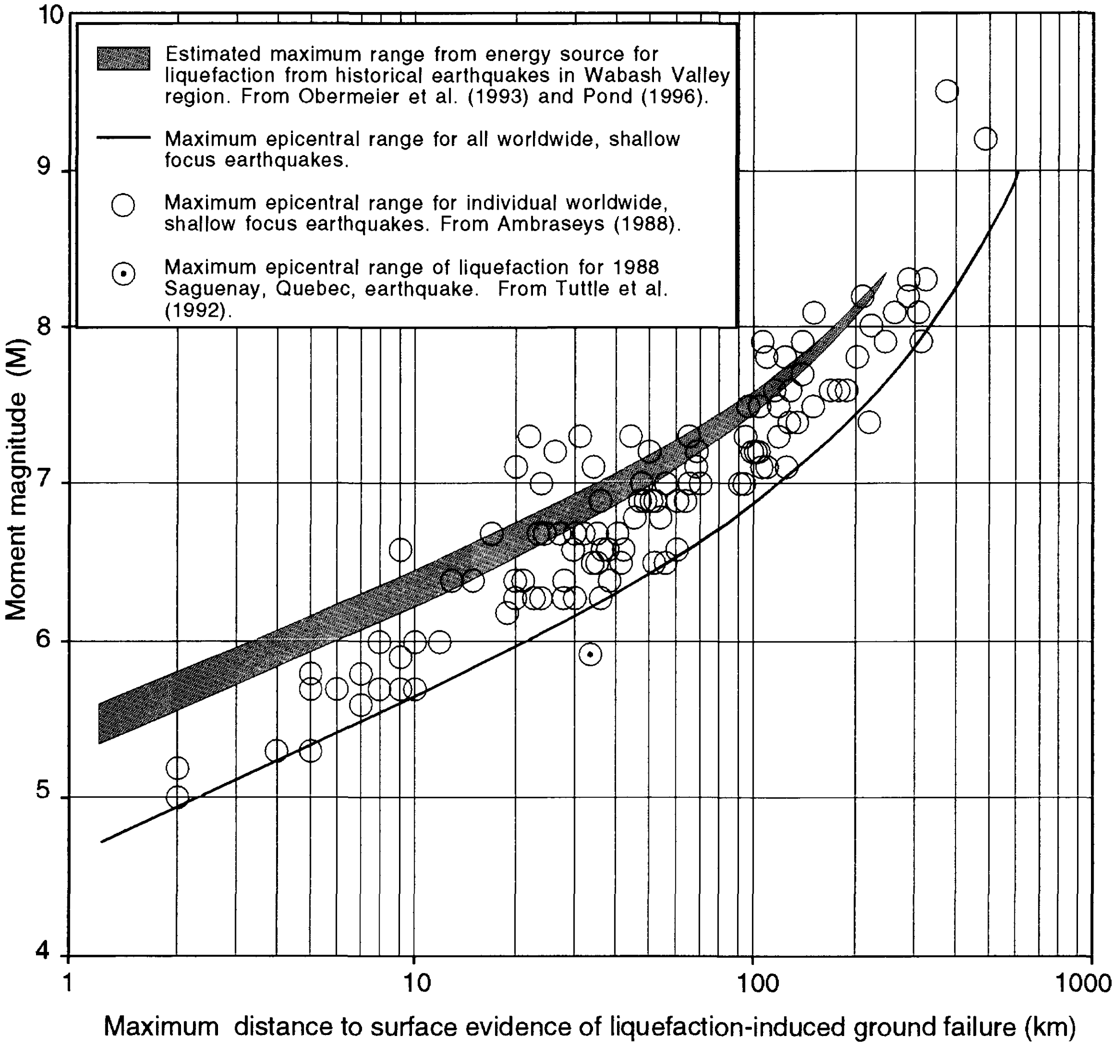

Figure 8. Moment magnitude versus maximum distance to surface evidence of liquefaction effects. Solid line (from Ambraseys (1988) and Keefer (1984)) shows bound for maximum epicental distance of worldwide, shallow focus earthquakes (<50 km). Darkened band shows maximum distance from energy source, for historical earthquakes in the Wabash Valley area. From Obermeier et al. (1993) and Pond (1996).

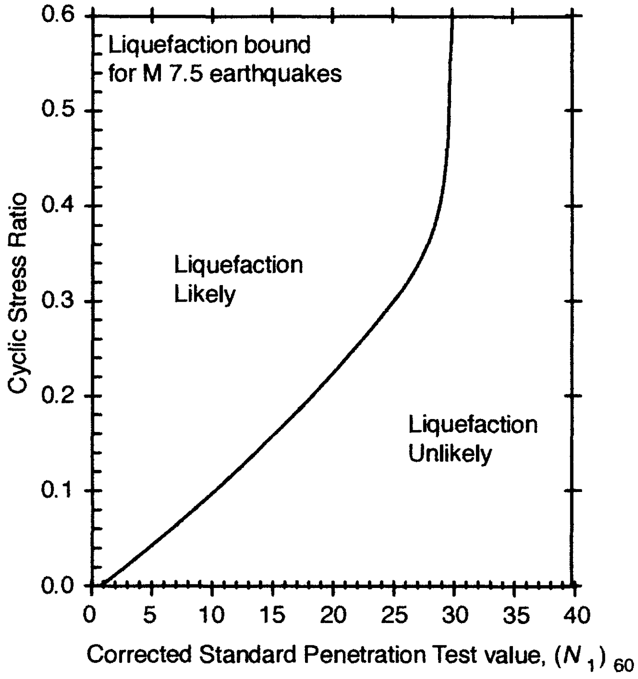

Figure 9. Seed et al. method (1983, 1985) showing curve used to evaluate the potential occurrence of liquefaction with accompanying venting of sand or appreciable ground cracks at a site on level ground, during a M 7.5 earthquake. Curve is for clean sand deposits. Points above and to the left of the curve show conditions having high potential for liquefaction.

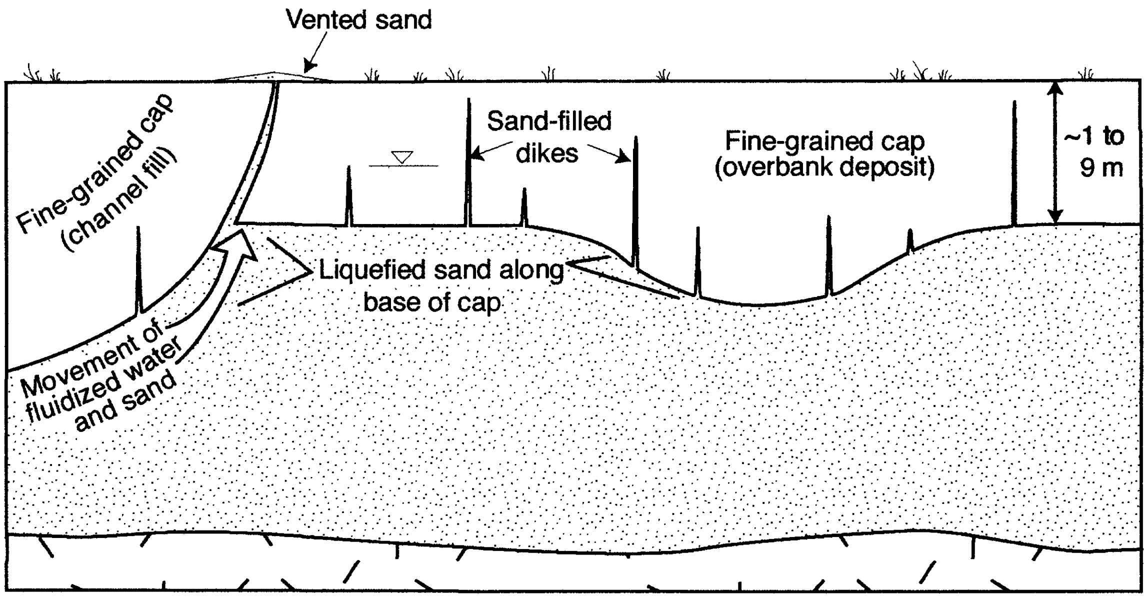

Figure 10. Vertical section showing field situation where venting occurs preferentially. Modified from Fiegel and Kutter (1994), Obermeier (1996b), and Tuttle and Barstow (1996).

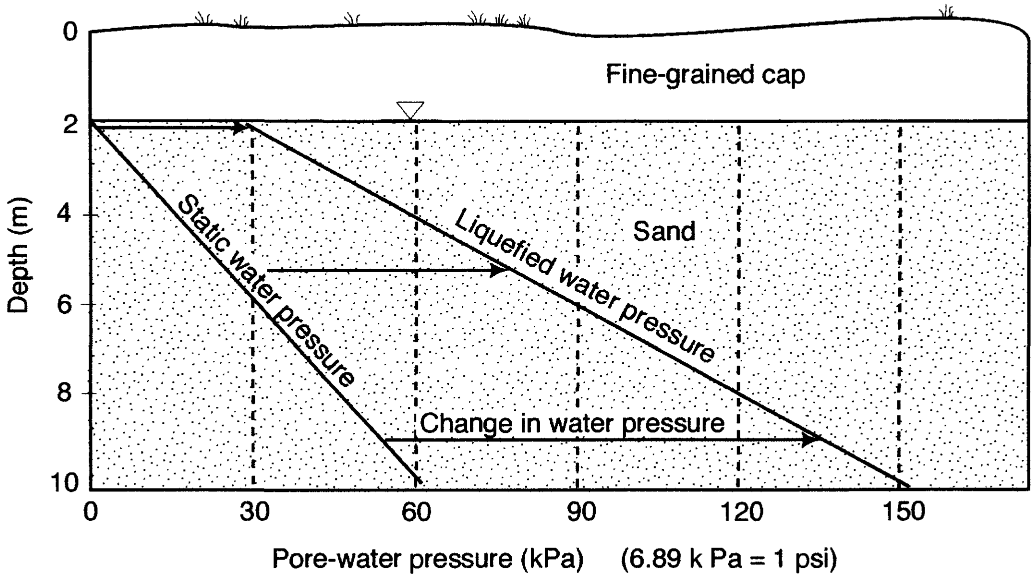

Figure 11. Vertical section with an example of a typical field setting, showing the strong influence of depth on change in pore-water pressure due to liquefaction. Water table initially at base of cap.