Final Technical Report
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Shear Wave Velocity, Geology and Geotechnical Data of Earth Materials in the Central U.S. Urban Hazard Mapping Areas

External Grant Award Number 06-HQ-GR-0192

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Abstract

This project collected shear wave velocity measurements of nonlithified and bedrock geologic materials, lithologic descriptions and geotechnical properties for the cooperative earthquake hazard mapping in the St. Louis Urban Hazard Mapping area and the Tri-State (Evansville) Urban Hazard Mapping area of Indiana, Kentucky and Illinois. This produced a relationship between lithologies and seismic wave velocities for use in production of soil profile type derivative maps – soil site class maps. This was performed by collecting existing shear wave velocity, coordinating with USGS Golden office on their measuring of in situ shear wave velocities in materials and areas where no or few values exist, and relating lithologic and geotechnical data to collected shear wave velocity values. The data have been entered into an electronic database at the Illinois State Geological Survey. A comparison was also made between the shear wave velocity values gathered by different measuring techniques and the variations in estimating the soil profile type. The collection of new geologic data also provided information to develop a better understanding of the sediment relationships in the greater Evansville, Indiana area. Several paleoseimic features were also investigated in this area.

Introduction

The Illinois, Indiana, Kentucky and Missouri Geological Surveys collected shear wave velocity measurements of nonlithified and bedrock geologic materials, lithologic descriptions and geotechnical properties for the cooperative earthquake hazard mapping in the St. Louis Urban Hazard Mapping area and the Tri-State (Evansville) Urban Hazard Mapping area of Indiana, Kentucky and Illinois. This work was performed in cooperation of the two working groups in each region including the U.S. Geological Survey who has liaisons in each group and who also mapped surficial materials in the Evansville area. The work of the State Surveys produced a relationship between lithologies and seismic wave velocities for use in production of soil profile type derivative maps – soil site class maps. This was performed by collecting existing shear wave velocity, coordinating with U.S. Geological Survey's Golden office on their measuring of in situ shear wave velocities in materials and areas where no or few values exist, and relating lithologic and geotechnical data to the shear wave velocity values. The data was entered into an electronic database at the Illinois State Geological Survey. Also a comparison was made of shear wave velocity values generated by different measuring techniques at one site and the variations in estimating the soil profile type. The collection of data also provided enough information to develop a better understanding of the sediment relationships in the greater Evansville, Indiana area. A paleoseismic fault and liquefaction features in the area were also investigated. A report on each state survey's work is described below.

Investigations undertaken

Illinois State Geological Survey

Shear wave values Shear wave velocity data was compiled from ISGS downhole and reflection/refraction measurements, U.S. Geological Survey and consulting firms seismic cone penetrometer tests, Indiana Geological Survey downhole tests, and crosshole and downhole measurements found in publications for power plants, locks and dams, enrichment facilities and other research projects. Locations for the measurements are shown in Figure 1. The database has all the measurements identified with formation names, depth, latitude-longitude, type of measurement and citation source, if it is from a published report. This data allowed for an analysis of variation of velocity values with depth for each formation and materials, resulting in assigning average velocities with depth for most of the units in the study area in Illinois and Indiana (table 1). Thick residuum soils in non-glaciated areas of St. Louis do not have downhole or seismic cone shear wave velocity values because of the difficulty of drilling or pushing a cone through the chert rich residuum.

Comparison of measuring methods - The Survey coordinated with the University of Missouri – Rolla staff in assisting to pick locations in Illinois for their MASW shear wave velocity measurements. Some of their measurement sites are also sites where the Illinois State Geological Survey (ISGS) performed downhole shear wave velocity measurements within cased boreholes. This allowed comparison between these two techniques at the same site (Figure 2 & 3). This site is in the America Bottoms in the St. Louis Urban Hazard Mapping area where there is 100+ feet of sand with some gravel resting over Mississippian limestone. The ISGS

coordinated with the U.S. Geological Survey's Earth Hazard Program staff to have their shear wave measurement techniques (refraction/reflection) performed at the same site (Williams et al., 2007). This allowed for a comparison between 3 different shear wave velocity measurement techniques at a fairly simple geologic site. A comparison between the downhole and MASW methods show a 35% difference in values (Figure 3). The average shear wave velocities calculated for the column of material for these two measuring techniques shows about a 15% difference. Hunter et al. (2002) did similar comparisons between measuring methods performed in Canada and found similar amounts of variation between methods and Williams et al. (2003) found <15% difference between refraction/reflection and downhole values in four out of six sites and 21% and 48% difference in the other two sites in Washington State and California.

The previous comparisons were made at the same locations and geologic setting. Other comparisons were made between the downhole data and seismic cone penetrometer tests (SCPT) in the American Bottoms, which were not performed at the same exact sites. The SCPT shows larger variations in shear wave velocity with depth (Figure 4). Greater variations probably occurs because measurements are taken at intervals of only several feet and the seismic cone may be sitting in direct contact with material in a layer of sediment with varying properties instead of averaging velocities over greater distances for measurement taken from within a cased borehole.

Shear wave velocity per formation – Relationships of shear wave velocities with depth were investigated for each formation. Also the consistency of relationship per formation was investigated. Each formation represents different material types and ages.

One of the largest continuous bodies of nonlithified materials in the Central U.S. is the sands with some gravel that fills the Mississippi River valley. The younger, upper sand in the valley is the Cahokia Formation (less than about 6,000 years old). The Cahokia rests in/on the older, 12,000 to 45,000 year old, Henry Formation (Figure 5), which is also sand with some gravel. Both are very similar lithologies and have similar relationships of shear wave velocity values with depth (Figure 6). The relationship of shear wave velocity with depth for the wind blown silts of the Peoria and Roxana Formations is shown in Figure 7. These deposits are thickest along the eastern side of the major river systems from which they were blown (Figure 8). Relationships were also developed for lacustrine (lake) deposits of the Equality Formation (Figure 9).

The consistency of the shear wave with depth relationship for a widely distributed fairly uniform formation is shown by the Cahokia Formation, which is found up and down the Mississippi River valley (Figure 10). Downhole shear wave velocity measurements have been made near in the Cahokia near St. Louis and Risco, Missouri and Marked Tree, Arkansas. This covers a distance of over 280 miles along the Mississippi River valley. Other formations such as the Equality formation are large individual lakes found along drainage ways that emptied into the major rivers of the Central U.S. These lakes formed when large amount of sediment was carried down the major rivers at the time of the glacier retreat and melting. The sediments filled the valleys major river valleys, damming up the drainage ways flowing into them, creating large extensive lakes. These lake sediments contain datable materials from about 21,000 to 44,000 year before present (Curry and Grimley, 2006). They are shown in Figure 8 as the areas of no

loess (0 thickness) extending as much as 60 miles upstream from the confluences with the Mississippi, Ohio and Wabash Rivers in Southern Illinois and Indiana. These lakes accumulated clays, silts and some sand. The small variation of shear wave velocity differences between these different materials is shown in Figure 11. The small variations are probably caused by these lithologies not existing as thick layers of separate, pure material but the layers have all the material types present with different material types being dominant in different layers. Another lake type deposit in the area can be found on the American Bottoms as the materials infilling the old abandoned courses of the Mississippi River, oxbow lakes (Figure 5). Before investigating these deposits, it was believed that they were very clay rich and would then amplify earthquake ground motion much more than the sands. Drilling shows that these deposits are dominated by silt and have shear wave velocities similar to the surround sands. Figure 6 compares the shear wave velocity of the sands and the silt dominated infill deposits (Cahokia silty-clay on graph). These shear wave velocity values indicate that the infilled areas will amplify earthquake ground motions similar to the surrounding sands.

Reference profiles A shear wave velocity reference profile for the American Bottoms can have the stepped increases in the shear wave velocity divided up many different ways since the various materials seem to have similar velocity that are depth dependent. One profile, Figure 12 divides the shear wave velocity into 5 meter thick layers.

Soil site class map

Introduction - The Illinois State Geological Survey (ISGS) produced a new soil site map for the southern most 34 counties of Illinois. This was accomplished by assigning shear wave velocity values to the various layers (units) in the upper 30 meters of soil/bedrock materials. The shear wave velocity database cited above was used with a combination of maps showing depth to bedrock and a state-wide map of layers of materials (stack unit map) for the upper 15 meters.

The soil site class map was produced using “local” site conditions in order to be used for amplification of ground shaking in the HAZUS earthquake loss estimation program. The general process to produce soil site class maps is outlined in the Building Seismic Safety Council (2004) and the International Code Council (2003). The classification is based on the average shear wave velocity of the upper 30 meters of the “local” site geology.

Stack unit map - The stack-unit map of Berg and Kempton (1988) was used to indicate what layers of units, in increments, are stacked over each other in the study area, down to a depth of 15 meters. This map is a set of polygons with each polygon coded for the stack of layers found at a location and for some polygons it also indicates deposits deeper than 15 meters. This allowed an extrapolation to 30 meters based on some of the polygon information and also on the general setting of where the polygon is located in the geologic landscape. Also a state-wide depth to bedrock map was used as additional guidance. An example of part of the stack-unit map is shown in Figure 13.

Procedure - Both the Building Seismic Safety Council (2004) and the International Code Council (2003) disregard soil materials less than 3 meters in thickness between bedrock and the footings of structures. Based on this practice, areas of the stack-unit map with less than 6 meters (smallest increment on stack unit map) of soil over bedrock did not include this thin soil in the

calculation. This thin layer is not included in the calculation of the average shear wave velocity of the stack of materials and for the designation of soil type F for thin potentially liquefiable materials over non-liquefiable materials. These areas that have thin materials over bedrock and thin potentially liquefiable materials over non-liquefiable materials which are being disregarded are shown in Figure 14. The largest, continuous thin soil area is the Shawnee National Forest area, which runs east-west across the width of the southern part of the state.

Bedrock is not included in the averaging of the shear wave velocity in the upper 30 meters except for locations were bedrock is shale. Shale has a low shear wave velocity of about 1,500 m/sec even when not weathered. Since the shale bedrock has a weathering profile and a low shear wave velocity value less than 600 m/sec, it is included in the average shear wave velocity values when present in the upper 30 meters of the "soil" profile.

A spreadsheet was produced (Table 2) assigning thicknesses and average shear wave velocity values for each layer of each stack of units represented by the codes for each polygon. The average shear wave velocity was calculated using the procedures specified in the Building Seismic Safety Council (2004) and International Code Council (2002) which is the sum of the thickness of all layers divided by the sum of each individual layer thickness divided by its shear wave velocity. The map was produced using the Building Seismic Safety Council (2004) and International Code Council (2002) procedures to first designating any soil which is vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays and collapsible weakly cemented soils. Soil Class F also has peat or highly organic clays greater than 3 meters (10 feet) thick, very highly plasticity (PI > 75) clays greater than 7.6 meters (25 feet) thick, and very thick soft/medium stiff clays greater than 36.6 meters (120 feet) thick. Following classification of these types of soils as F, the rest of the soils are classified using their average shear wave velocity for the stack of materials in the upper 30 meters (Figure 15). This soil site classification is shown in the last column in Table 2. Figure 16 shows a comparison of the 1999 Soil Site Class Map and the 2007 map produced using the procedures outline in this paper. The difference between the maps is mostly in response to more shear wave velocity information and the use of new data showing changes in shear wave velocity with depth.

Indiana Geological Survey

Introduction The Indiana Geological Survey (IGS), in collaboration with the Kentucky Geological Survey, has continued its study of the Quaternary stratigraphy of the Bluegrass Creek and Pigeon Creek drainage basins as part of a seismic risk investigation in the greater Evansville area, Indiana. The goal of this project is to generate the information essential to adequately define the three-dimensional distribution and thickness of seismically sensitive sediments such as wet sands and thick, soft clays. Such information is essential to evaluate tributary valley-fill models, and to provide the data needed to map lithologies and associated shaking potential and liquefaction susceptibilities here and in similar tributary basins of the Ohio, Wabash, and Mississippi rivers

An important source of data was added in 2006 with the acquisition with the return of a radiocarbon date from wood material collected from a trench adjacent to core site 04-1095 (

(Figures 17 and 18). Additionally, geoprobe cores were collected adjacent to previous years coring sites for additional OSL dating by the USGS lab in Lakewood, Colorado. This data, in combination with a core holes and gamma-logs collected in 2004, north of Pigeon Creek (04-1095) and 2005 (06-1001), on the north side of Evansville (Figures 17 and 18) and the approximately 4.5-miles of seismic lines acquired in 2004 in three segments, County Line Road north of Pigeon Creek, Burkhardt Road south of Pigeon Creek, and Kimber Lane north of Highway 66 plus pre-existing IGS gamma-ray logs and cuttings descriptions have resulted in the establishment of a detailed Quaternary stratigraphy for the greater Evansville area.

Methodology The wood fragment collect at 14ft depth returned a radiocarbon date of approximately 20,800. This 'older' date at such a shallow depth resulted in a reevaluation of the core and seismic data, as well as dozens of gamma-ray logs and drill cuttings currently archived in the IGS files and a reinterpretation of the depositional history. From this database, 7 lines of cross section have been constructed (Figure 18) to facilitate facies reconstructions and to resolve depositional sequences.

Stratigraphy Our studies have established that the valley-fill materials for the incised tributary valleys in the greater Evansville area can be broken down into five intervals. In ascending order they are: 1) a lower pedogenically modified interval that rests directly on the basal Quaternary/Pennsylvanian unconformity and that is composed of a variety of lithologies ranging from coarse-grained sands to muds; 2) a fluvial deltaic/marginal lacustrine/lacustrine facies of mostly silt and clays with interfingering fine-grained sands derived primarily from Pennsylvanian bedrock; 3) an intermediate fluvial/floodplain succession with well developed paleosols with an intervening lacustrine/marginal lacustrine facies formed in mostly fine-grained facies; 4) an upper fluvial deltaic/marginal lacustrine/lacustrine facies composed mostly of silt and clay with interfingering very fine-grained sands and coarse silts primarily derived from reworked loess; and 5) an upper loess and pedogenic facies composed of silt and clay formed under largely subaerial conditions. Units 3 and 4 have been sampled for radiocarbon age determination.

The five intervals are best defined within the paleovalley tributaries to the ancestral Ohio River. The facies tend to become sandier towards the Ohio River (Figure 19). The Ohio River paleovalley fills are principally composed of sands and some gravels representing stacked channels of the Quaternary Ohio River. Finer-grained facies near the base of the Ohio River paleovalley fills (Figure 19) imply a possible change in fluvial styles from high-sinuosity (meandering?) near the base to mud-poor, sand-dominated braided channel-fill in the intermediate and upper portions.

The radiocarbon date leads to the interpretation that the valley-fill stratigraphy is one similar to those of the Great Missoula floods, although on a much smaller scale. This is to say the valley experience multiple flood events, cutting and filling each time.

Future Research Plans The IGS intends to correlate the IGS data to the USGS cone penetrometer data and ultimately to the shear wave data generated by the USGS.

Indiana staff are currently evaluating depositional models and comparing data to Kentucky Geological Survey data obtained by Ron Counts and William Andrews for the Ohio River valley.

Kentucky Geological Survey

Introduction The Kentucky Geological Survey (KGS) received funding over the past three years (2005, 2006, and 2007) to characterize nonlithified sediments that are relevant to the Tri-State (Evansville) Urban Hazard Mapping study area. The majority of urban development occurs within the tributary valleys of the Ohio River, and current depositional models often fail to accurately characterize the types of sediments in these areas and/or their distribution. This project focused on understanding the nature, variability, and the three dimensional architecture of fill sequences in Ohio River valley and its tributaries, and was done in-part as a collaborative effort with the Indiana Geological Survey (IGS).

Methods Funding from this project provided 9 surface-to-bedrock cores, which were drilled and logged by the Illinois State Geological Survey (ISGS), and partially funded the collection of nearly 2 kilometers of seismic data, also collected and processed by the ISGS. These data, combined with additional shallow coring, field mapping, and numerous outcrop studies helped established a stratigraphic framework for Quaternary deposits in this region. This framework, in turn, has lead to the identification of several elements pertinent to a seismic hazard assessment, which include: 1) the presence of paleoseismic features in the region (but outside the project area) that were previously unrecognized, 2) a zone of thixotropic silt that is pervasive in the region, and 3) complex facies relationships and sedimentary sequences in the study area that can only be recognized by the examination of cores.

Results

Paleoseismicity Recent fieldwork has uncovered a number of paleoseismic features and potential paleoseismic indicators in the greater Evansville area, although none are published in previous research (e.g. Obermeier et al., 1993, Munson and Munson, 1996; Obermeier, 1998**)**.

Clastic Dikes - A clastic dike was discovered between Henderson, KY and Owensboro, KY, 21 river miles from the confluence of the Green and Ohio Rivers, where the Green River is inset within Ohio River outwash (Figure 20). The dike is weakly cemented, 4 cm -7 cm wide, and is composed of sandy gravel that was injected into clayey-silt floodplain deposits of the Green River. Coarser gravel up to 1 cm in diameter dominates the lower portion of the dike, and the upper section is dominated by fine sandy gravel (Figure 21). Whether this represents a fining upward sequence from a single event or was the result of multiple seismic events was not apparent.

The dike originates in a sandy gravel deposit, penetrates a gray clay bed, and extends upward through silt deposits of the Green River floodplain where it terminates ~3 meters from the floodplain surface. Several small pebbles can be found in a discolored zone directly above the main gravel mass within 1 m of the floodplain surface (Figure 22), but it is not clear if the dike penetrated a former land surface. Field evidence indicates that a ~5.5M earthquake was responsible for the clastic dike (Counts et al., 2007).

Additional fieldwork was conducted along the Green River searching for other liquefaction features, and two poorly preserved clastic dikes were located ~100 m downstream from the initial clastic dike along the same stretch of riverbank (Figure 23). Both were derived from the same source bed. Many sand beds are present at higher elevations on this reach of the Green River, but they only contained very minor deformation features. This may indicate that the water table was depressed at the time of liquefaction.

Wood was abundant in the clay bed that was penetrated by the clastic dike. A large piece was collected for isotopic analysis, which produced an age of 9850 ± 70 radiocarbon years. This age represents a maximum age for the earthquake that produced the dike, and considering that nearly 3 meters of sediment accumulated above the clay bed before the dike was created, it is likely that the earthquake occurred in the early- to mid-Holocene.

Minor paleoseismic indicators - A number of minor paleoseismic features were identified along the Green River (Figure 24) and are likely associated with the earthquake that produced the clastic dike. Similarly, a trench near the Vanderburgh-Warrick County line contained a domed, volcano-shaped structure in laminated silts and clays that appears to be the result of seismic activity (Figure 24). Alternatively, this feature could be a dewatering structure associated with sediment loading.

Potential Seismogenic Fault - An anomalous lineation, approximately 20 km west of the Urban Hazard Mapping study area, was identified in 2006 (Figure 25). Geomorphic indicators and preliminary seismic reflection data suggest it is a fault scarp, not a terrace, and is likely part of the Wabash Valley Seismic Zone. This feature is currently the subject of an active research project, and no additional data are available at this time.

Densification of sand - An excavation at Angel Mounds in Evansville, IN uncovered a disturbed cultural layer that was unlike any that archaeologists on-site and archaeologists from Indiana University had ever seen (Figure 26a). Immediately beneath the cultural layer was a ~1.5 m thick silty sand deposit that contained vertical, dike-like features (Figure 26b), and beneath the silty sand deposit was at least 2 m of well sorted medium-grained sand. One plausible explanation for the observed deformation is the densification of sand due to paleoseismicity. Radiocarbon and luminescence dating techniques indicate the cultural layer formed at ~1400 A.D (Monaghan, personal communication). Oddly, there was a large earthquake on the Reelfoot fault in the New Madrid Seismic Zone around 1450 A.D. ± 150 yrs (Kelson et al., 1996) and also on the Blytheville fault (Tuttle et al., 2002). Additional work is needed to determine whether these are coincidental or related events.

Thixotropic Sediments Many of the cores drilled in the study area have intervals that exhibit thixotropic properties. These materials are firm and retain their shape until they are shaken, after which they liquefy (Figure 27). The thixotropic intervals range from 10 cm to 3 m thick and appear to be composed primarily of silt-sized particles. The reason for the thixotropicity of these intervals is unknown but thought to be a function of grain size, water content, mineralogy, or some specific combination of these properties. Short videos of how cores and sediment taken from within the study area react to shaking can be viewed at http://www.youtube.com/jokulhlaups.

Complex sedimentary architecture

Stratigraphic Framework - Sediments in the project area can be broadly grouped into four genetic categories: 1) modern alluvium, late Pleistocene outwash, lacustrine silts and clays, and windblown silt (Figure 28). The stratigraphy within the main valley of the Ohio River is relatively simple and consists of glacial outwash overlain by modern alluvium. Thick loess mantles the upland regions and a thin cover overlies most of the valley.

The stratigraphy of the tributary valleys is much more complex and can be any combination of outwash, silt, clay, and alluvium, representing interfingering deposits of fluvial, lacustrine, and deltaic processes (Figure 28). Detailed descriptions of cores at the IGS have identified five major depositional intervals in the tributary valleys that include a broad variety of sediment grain sizes ranging from gravels to clay.

Tributary Valley Fills - The majority of the outwash in the main valley is Wisconsinan. Only a small volume of older outwash underlies the Wisconsinan outwash because most of it was removed by erosion during the last interglacial interval. The erosive abilities of streams in the tributary valleys were significantly lower than the Ohio River, and core data indicate they contain: 1) clays that are pre-Wisconsinan, 2) sands, gravels, and paleosols from the last interglacial, and 3) lacustrine/deltaic clays and silts from the last glacial cycle. Wood collected 14 feet below the surface in a tributary valley on the northeast side of Evansville produced an age of 20,800 ± 220 radiocarbon years, suggesting that at least some of the tributary valleys contain fill sequences that are significantly older than the last glacial period. This is relevant to seismic studies because pre-Wisconsinan deposits, especially clays, are extremely dense compared to younger clays. Therefore, although a stratigraphic column might show a vertical sequence that is mostly clay, the older clay could have higher shear wave velocities.

Future Research Cores collected during this project period were described in the field, but many are still in storage and awaiting grain size and mineralogical (XRD) analyses. In August of 2007, five cores were taken to the Limnological Research Center (LRC) at the University of Minnesota for processing, where a suite of geophysical measurements were performed on them, they were split, imaged, described in detail, and samples were collected for age dating. Results from the LRC have not yet been received. The remaining four cores will be taken to the LRC in the spring of 2008 for analyses.

Generalized cross sections shown on geologic maps are not likely to capture the complexities of the tributary valley fills. The best method to characterize the fills is through drilling, but drilling is expensive and time consuming. One promising alternative to drilling is seismic reflection, and in the few seismic lines the KGS has acquired, the data are outstanding (Figure 29). The KGS plans to continue mapping efforts in the region, combining drilling with other geophysical methods to better characterize the tributary valleys, and ultimately develop a new tributary valley fill model that fits observations from core and seismic data.

Luminescence samples were collected from the Green River clastic dike in an attempt to bracket the timing of the earthquake responsible for its formation. These samples are awaiting analysis at the USGS luminescence lab in Lakewood, CO.

Coordination with USGS

The Central U.S. Earthquake Consortium State Geologists have coordinated with the Earth Hazards Program in selection of some sites for shear wave velocity measurements. This allows for a comparison with a third different measuring technique at the same location (Williams et al., 2007).

Summary

The Central U.S. Earthquake Consortium (CUSEC) State Geologists are continuing to gather shear wave velocity and borehole lithologic information in the areas of St. Louis Urban Hazard Mapping and the Tri-State (Evansville) Urban Hazard Mapping area of Indiana, Kentucky and Illinois. Shear wave velocity data is also being collected throughout the states which have similar geologic materials to the Urban Hazard Mapping areas. The added data provides an understanding of the variations in shear wave velocity spatially and especially with depth and for weathered profiles. A comparison between different shear wave velocity measuring techniques of MASW and downhole for the same site in Illinois showed a 35% difference between techniques and a difference of 15% between averages for the entire borehole (column). An electronic database of downhole and crosshole values with their locations and lithologic context is maintained at the Illinois State Geological Survey. The Illinois State Geological Survey used the new shear wave velocity values with depth and existing 3 dimensional maps of nonlithified materials to bedrock to produce a new Soil Site Class map for the 34 southern most counties. The new shear wave values with depth greatly changed the site class map in comparison to the one produced in 1999 which only used one average shear wave velocity value for the entire thickness of a lithology.

The Indiana and Kentucky Geological Surveys used new borehole information and dating of materials to develop a better 3 dimensional understanding of the lacustrine sediments deposited along the valleys leading into the Ohio River and the relationship of these lacustrine sediments with the Ohio River sediments where they meet. This also includes a better understanding of the history of the sediments in the Ohio River valley. The Kentucky Geological Survey staff also found paleoliquefaction features along the Green River which are yet to be dated. They also found faulted river sediments which appear to be related to the Wabash Valley Seismic Zone.

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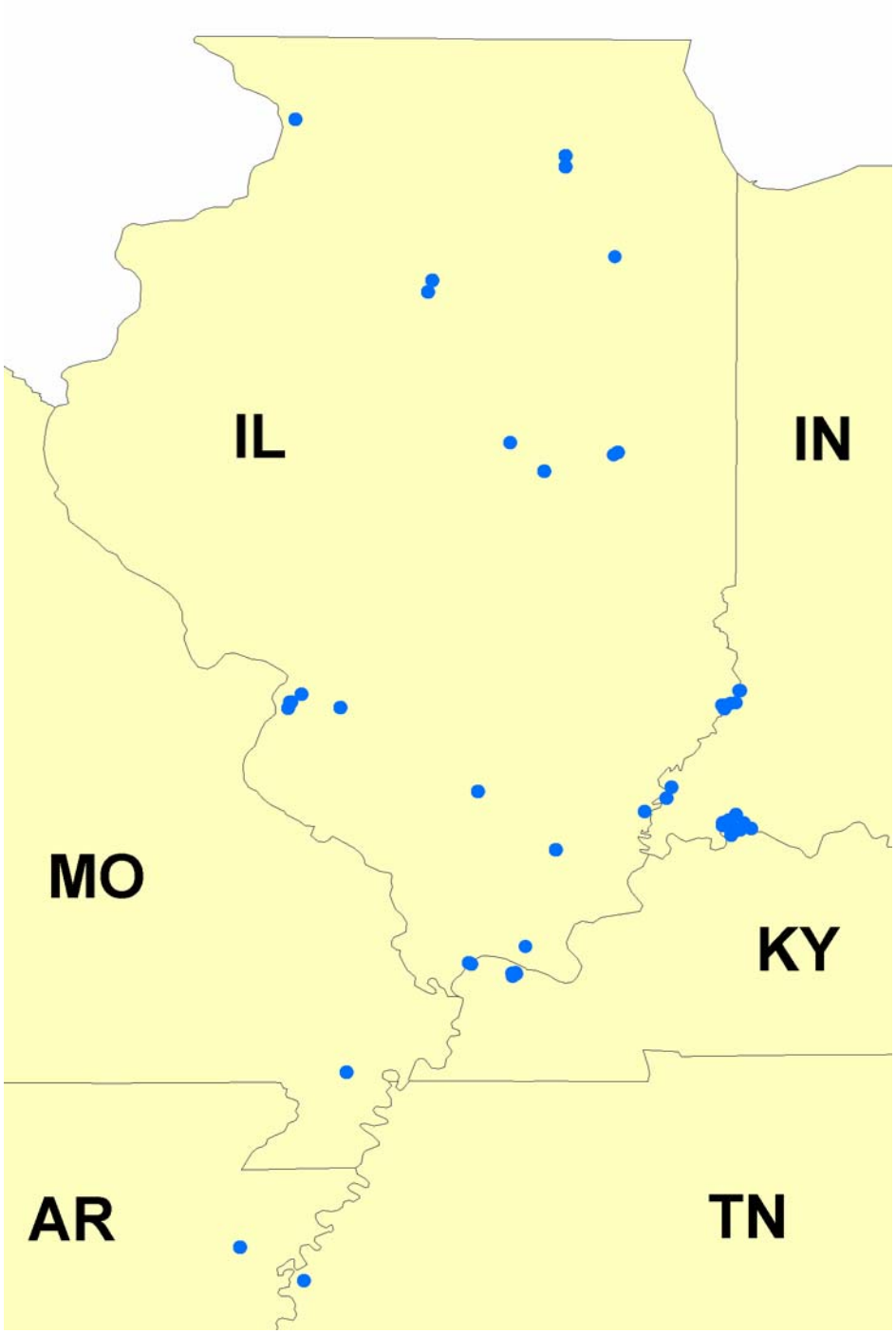

Figure 1. Location of shear wave velocity measurements in database.

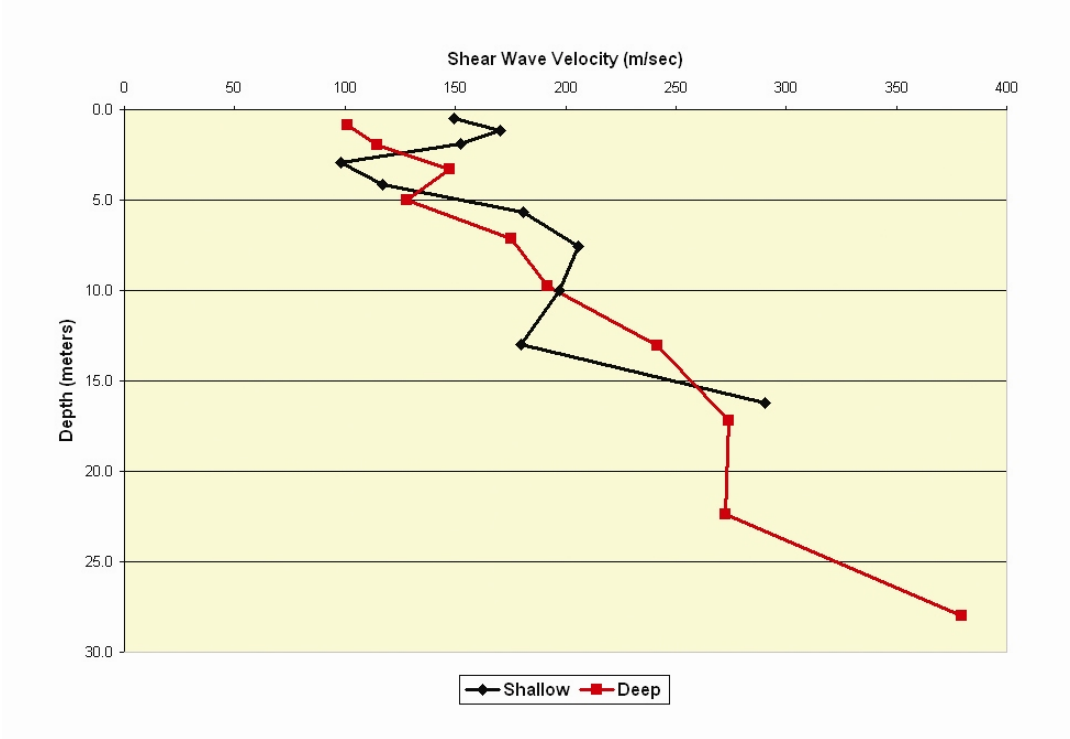

Figure 2. Comparison of the same MASW measurements processed for two different depths (University of Missouri-Rolla, David Hoffman).

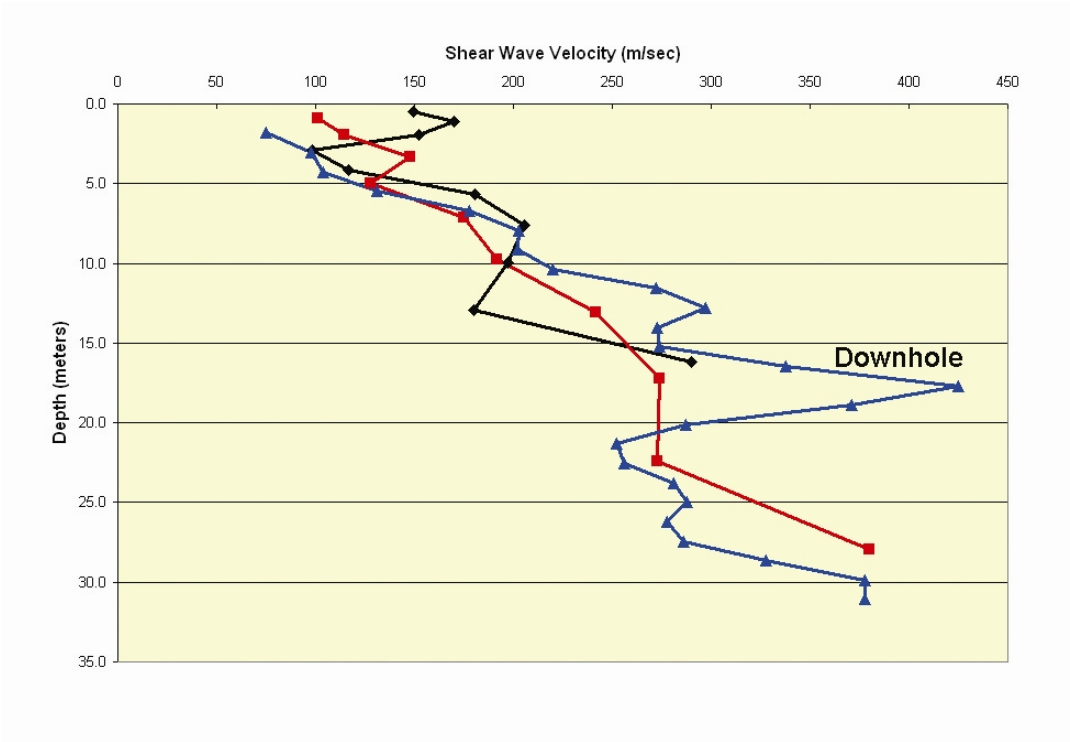

Figure 3. Comparison of Downhole shear wave velocity measurements to the MASW analysis shown in Figure 2 – both measurements taken at the same site.

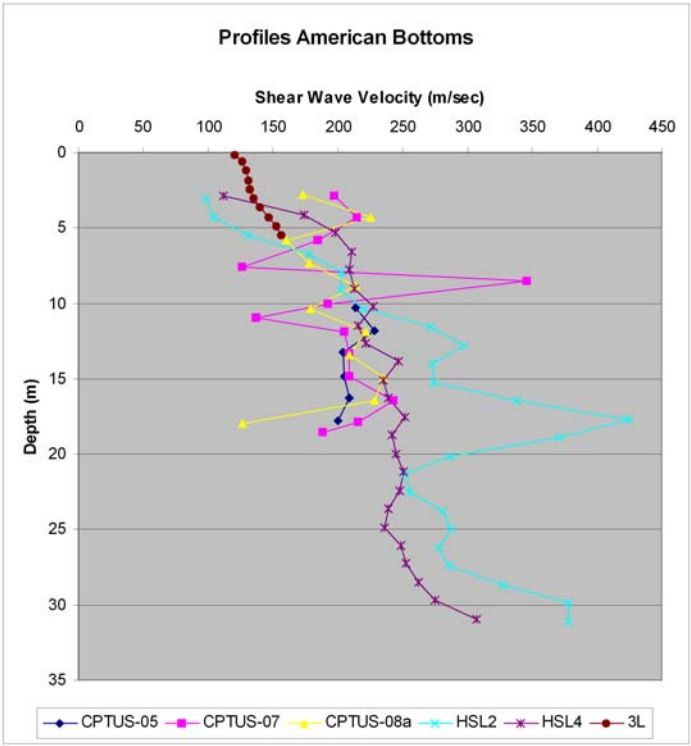

Figure 4. Comparison of downhole and CPT seismic cone shear (CPTUS curves) wave velocity measurements in the American Bottoms. This includes the Cahokia and Henry Formations of sand and the Cahokia formation silty materials that infill the old river channels (3L curve).

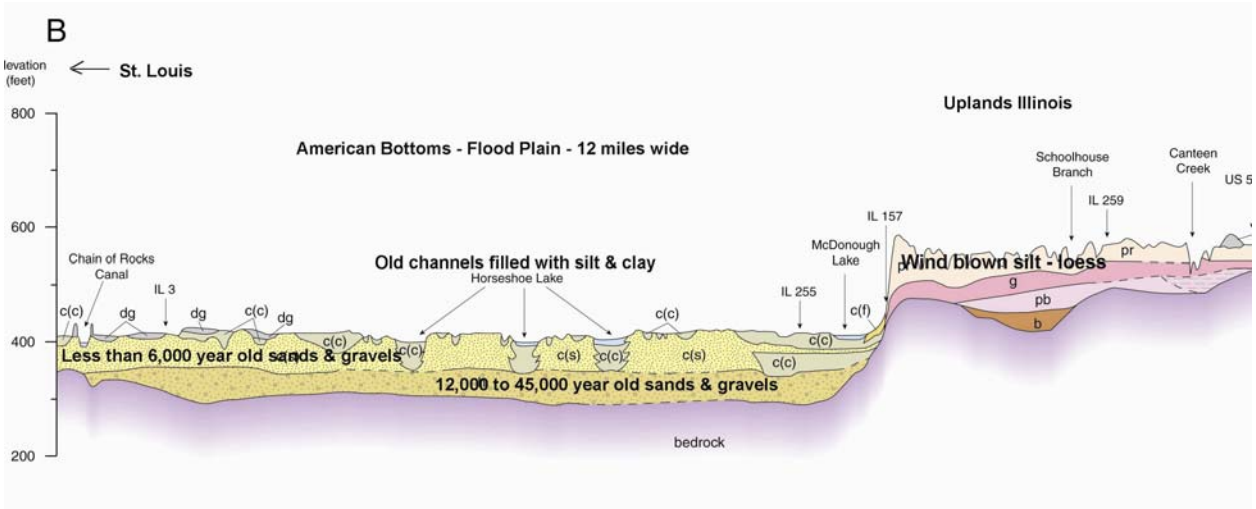

Figure 5. East-West cross section showing materials in the Mississippi River valley.

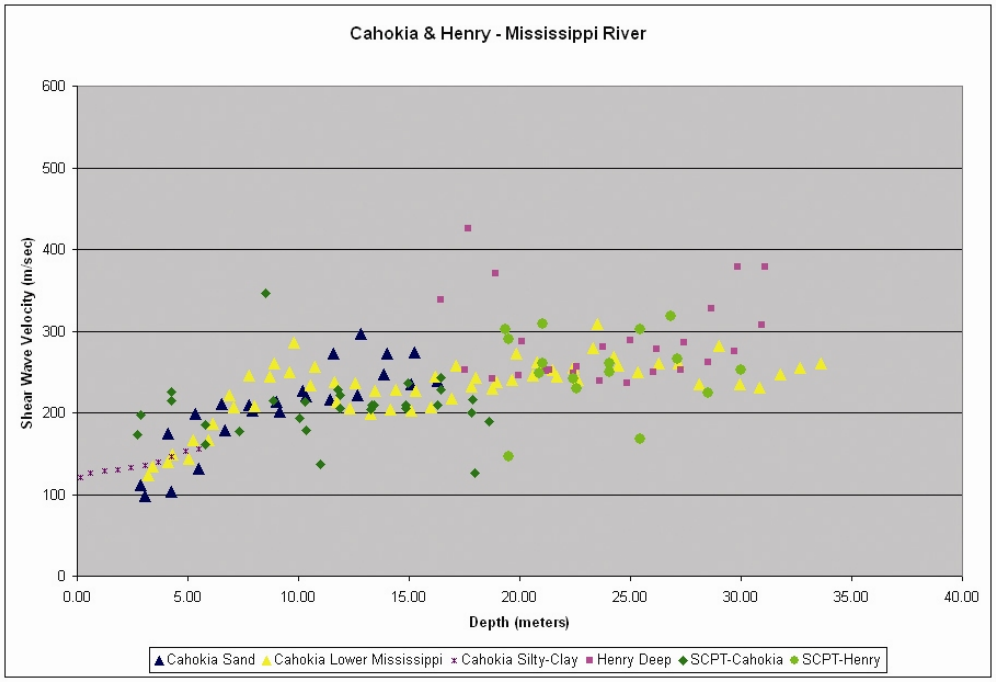

Figure 6. Downhole and SCPT shear wave velocity measurements with depth for the Cahokia and Henry Formations of sand with some gravel.

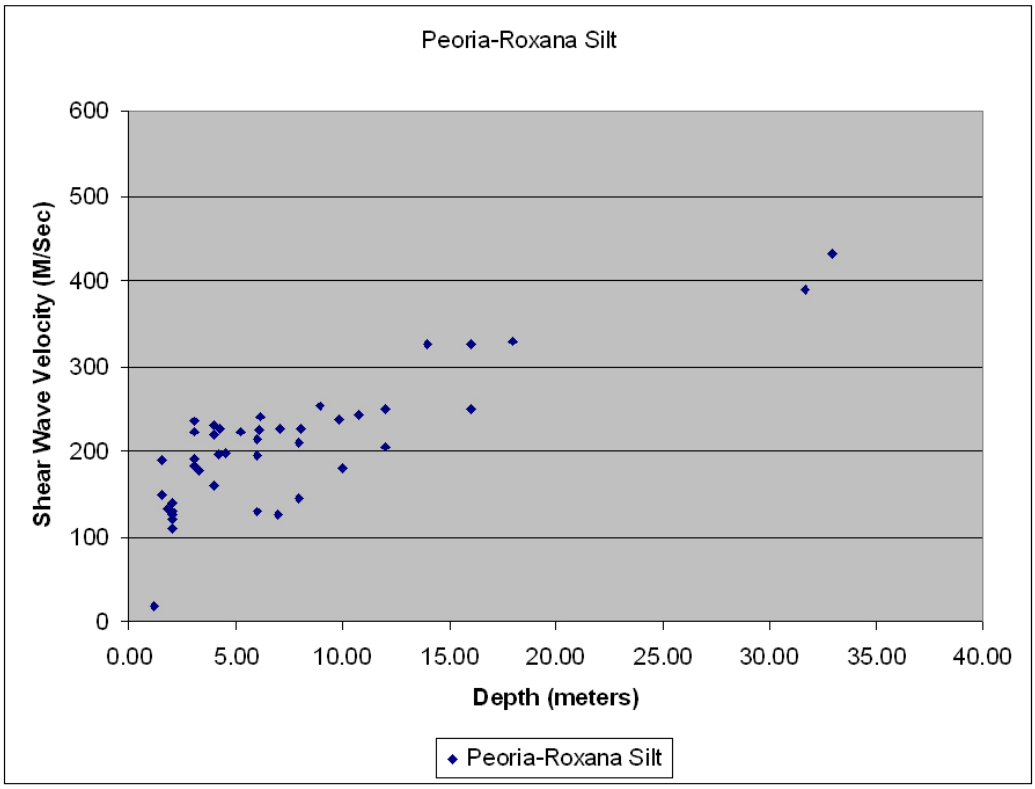

Figure 7. Downhole shear wave velocity measurements with depth for the wind blown silts – Peoria and Roxana Formations.

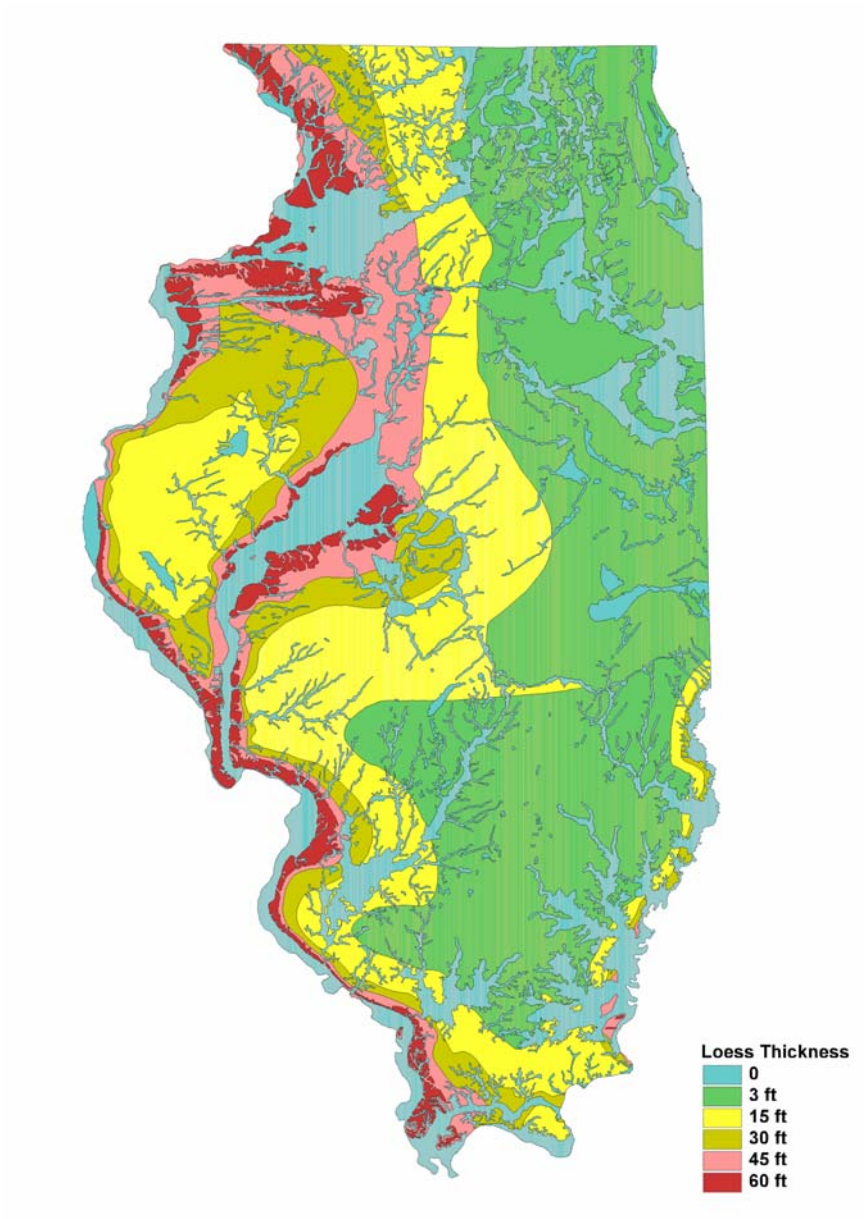

Figure 8. Diagram showing thickness of loess, wind blown silts of the Peoria and Roxana Formations. These silts were blown out of the valleys of the major river systems.

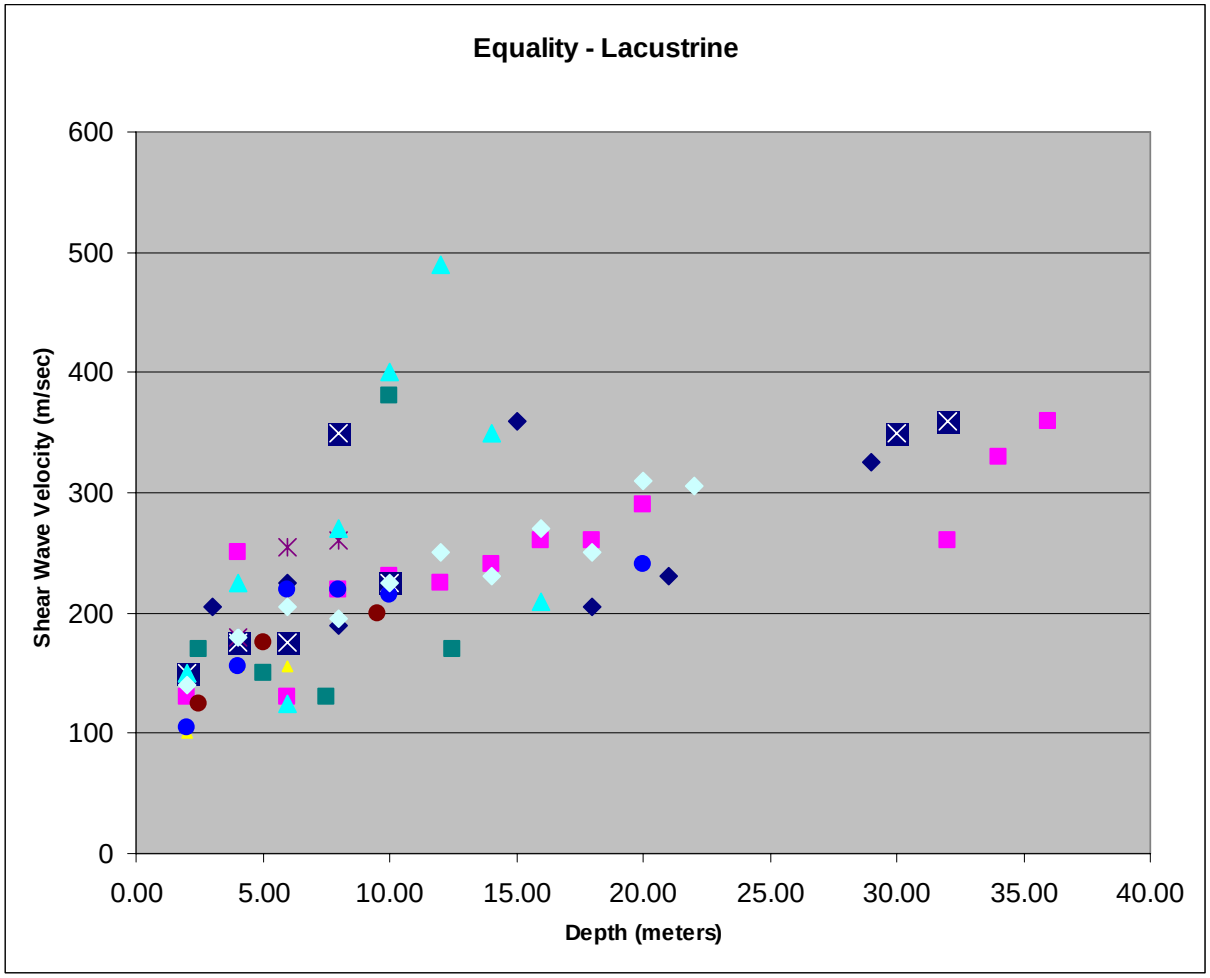

Figure 9. Downhole shear wave velocity measurements with depth for lacustrine (lake) sediments of the Equality Formation. Data only shown to depth of 40 meters for comparison with data in figures 6 & 7.

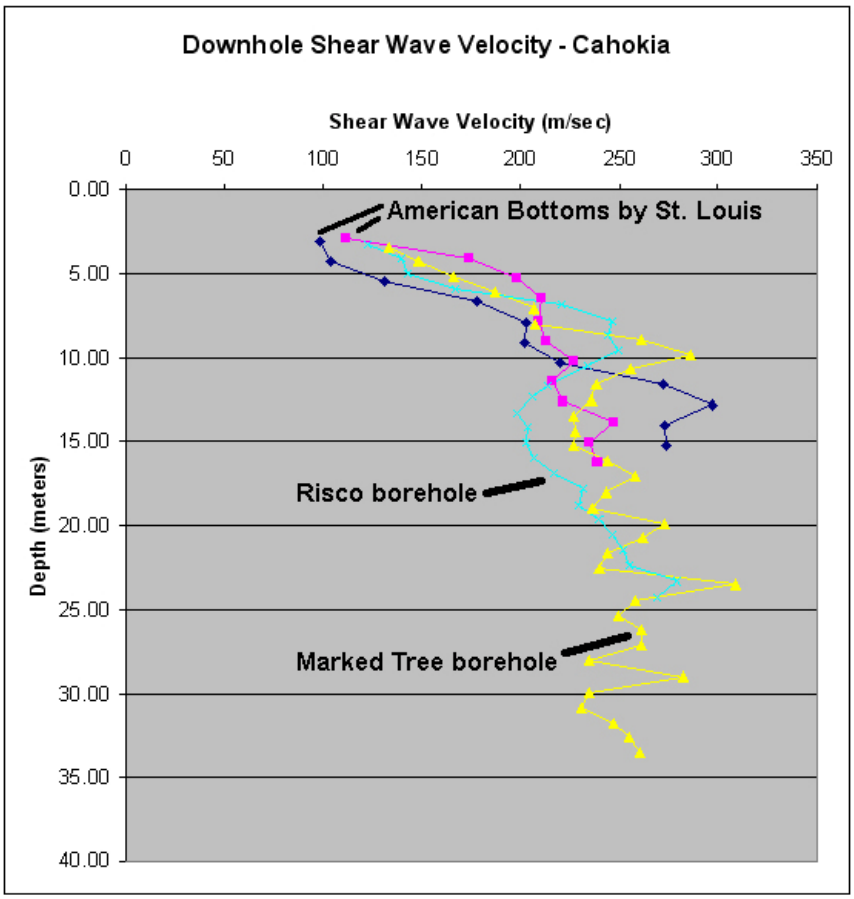

Figure 10. Consistency of materials and shear wave velocities of the Cahokia (recent) sediments in the Mississippi River valley as shown by downhole shear wave measurements in the widely spaced boreholes from near St. Louis, to the bootheel of Missouri (Risco) and Arkansas (Marked Tree), covering a distance of about 450 valley kilometers.

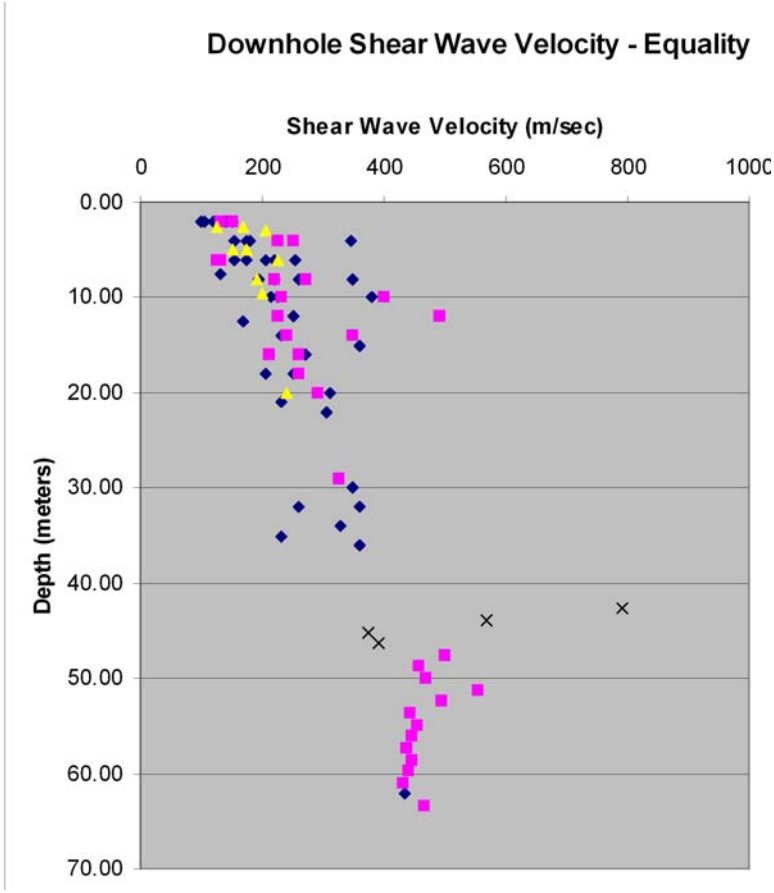

Figure 11. Variation in shear wave velocity with depth for the various lithologies associated with the lake deposits (lacustrine) of the Equality Formation.

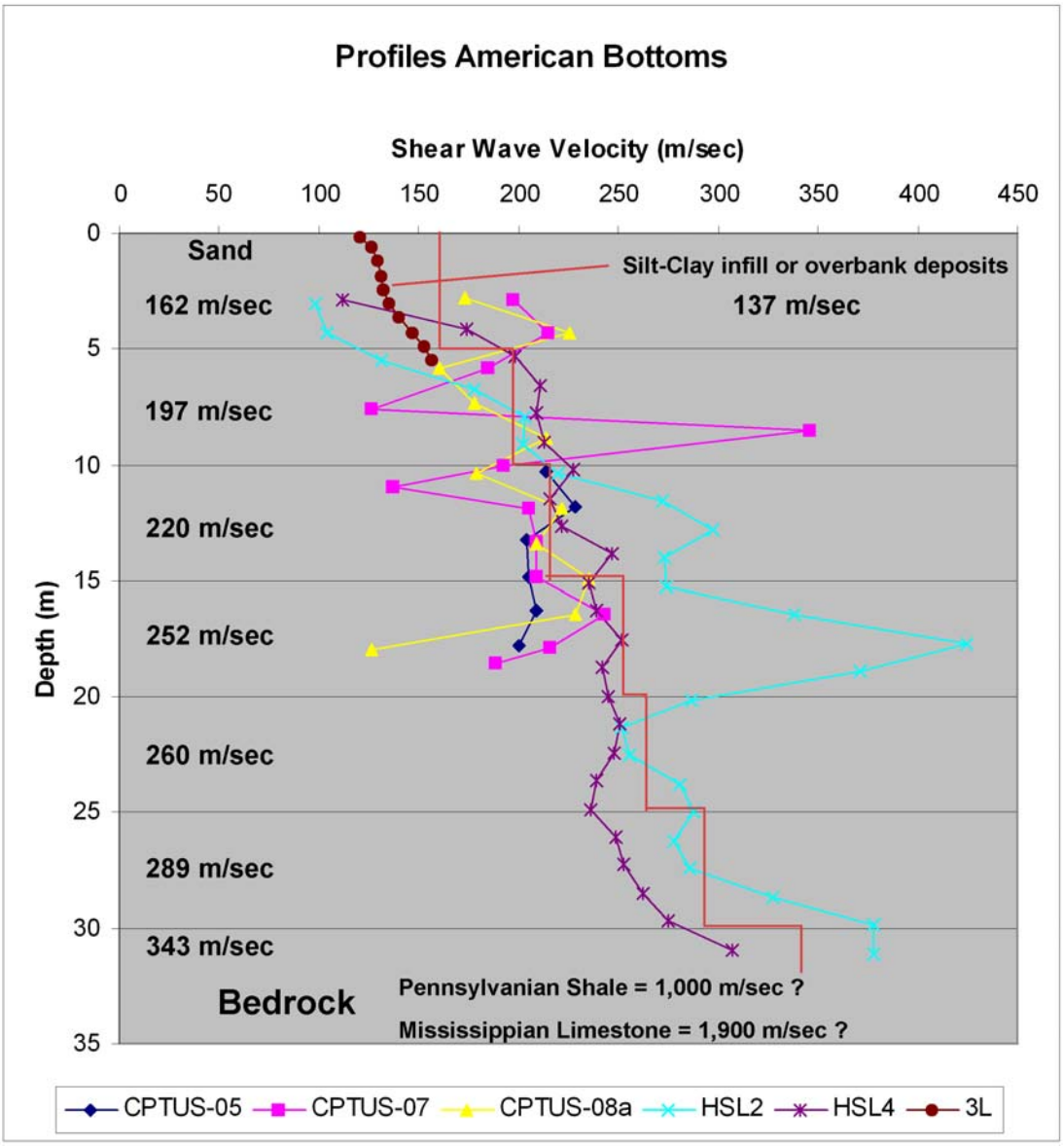

Figure 12. Shear wave velocity reference profile for American Bottoms near St. Louis.

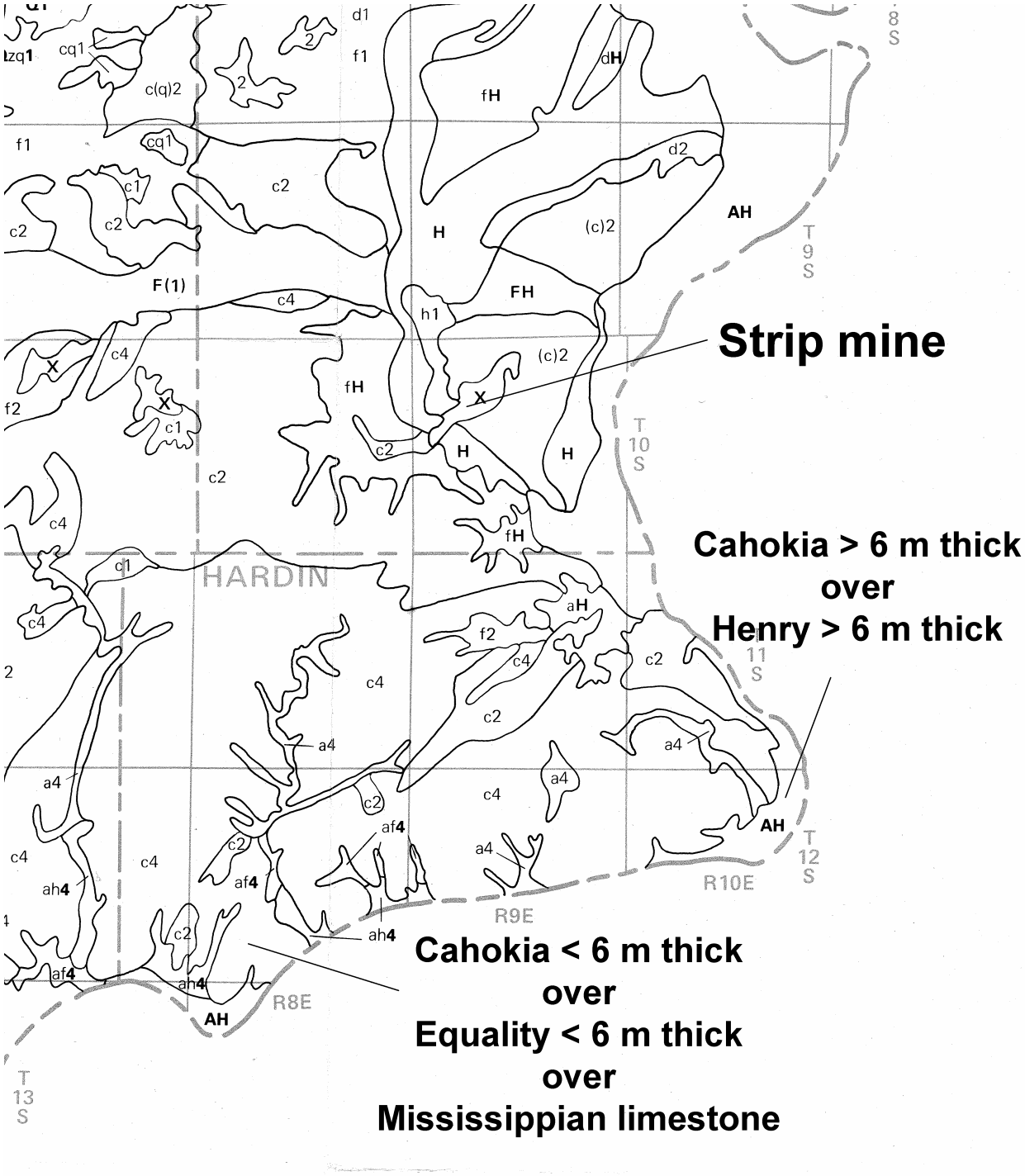

Figure 13. Part of the stack-unit map showing some examples of explained code.

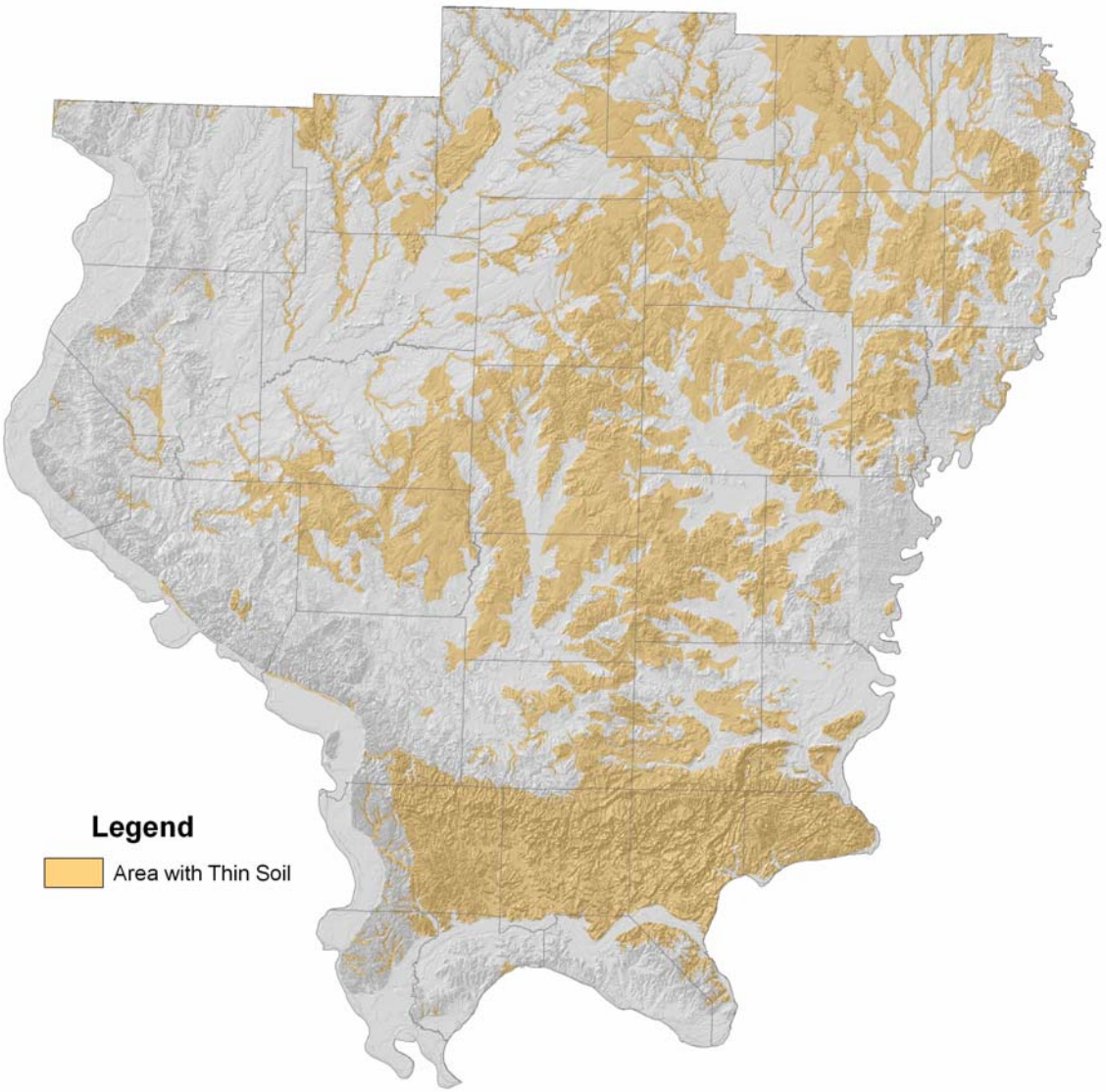

Figure 14. Map showing areas where thin soils over bedrock or thin potentially liquefiable materials over non-liquefiable materials were not included in calculation for production of maps.

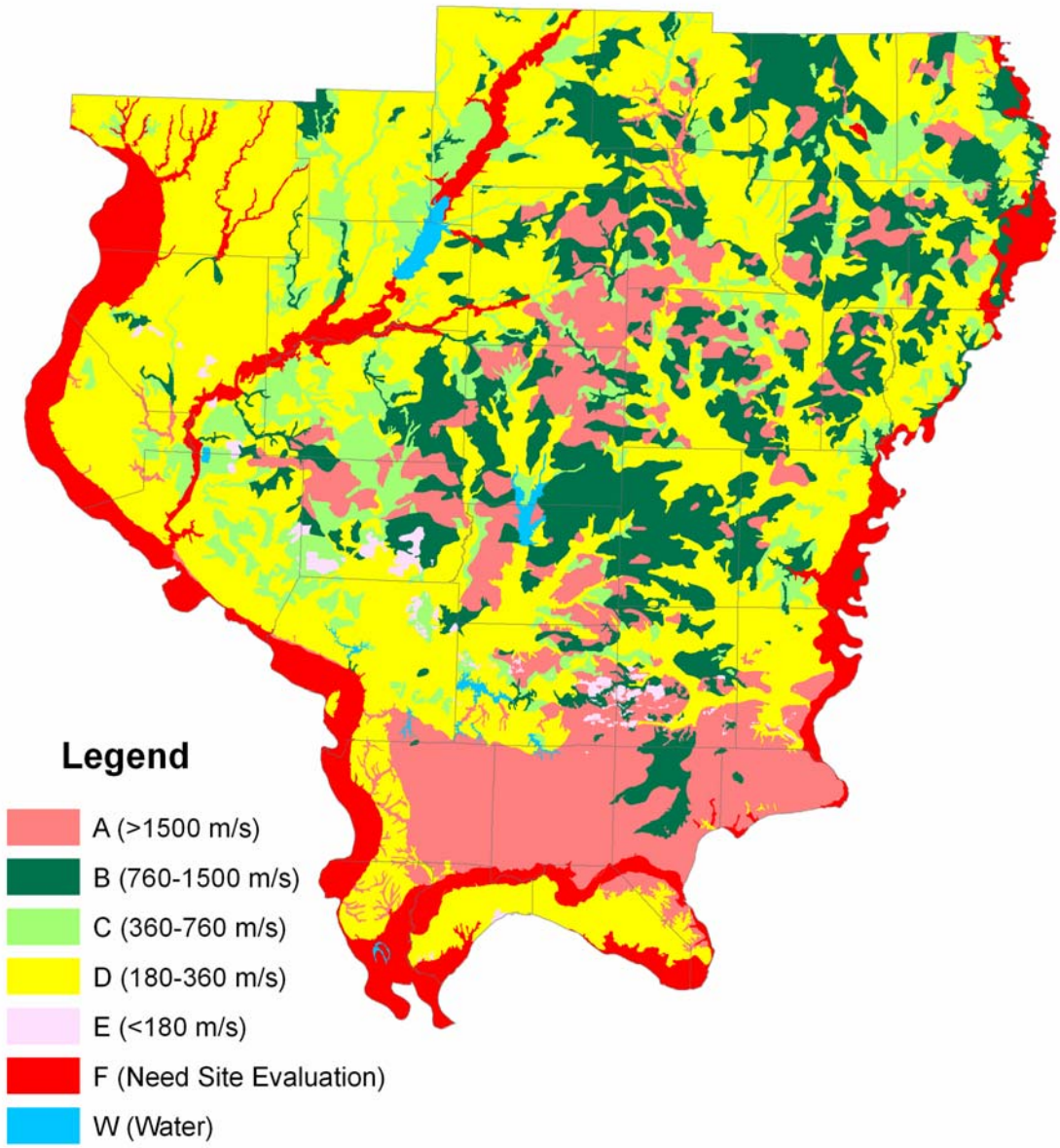

Figure 15. Soil site class map produced following NEHRP and Code provisions. Thin soil layers over bedrock and thin potentially liquefiable materials over non-liquefiable materials were not included for classification.

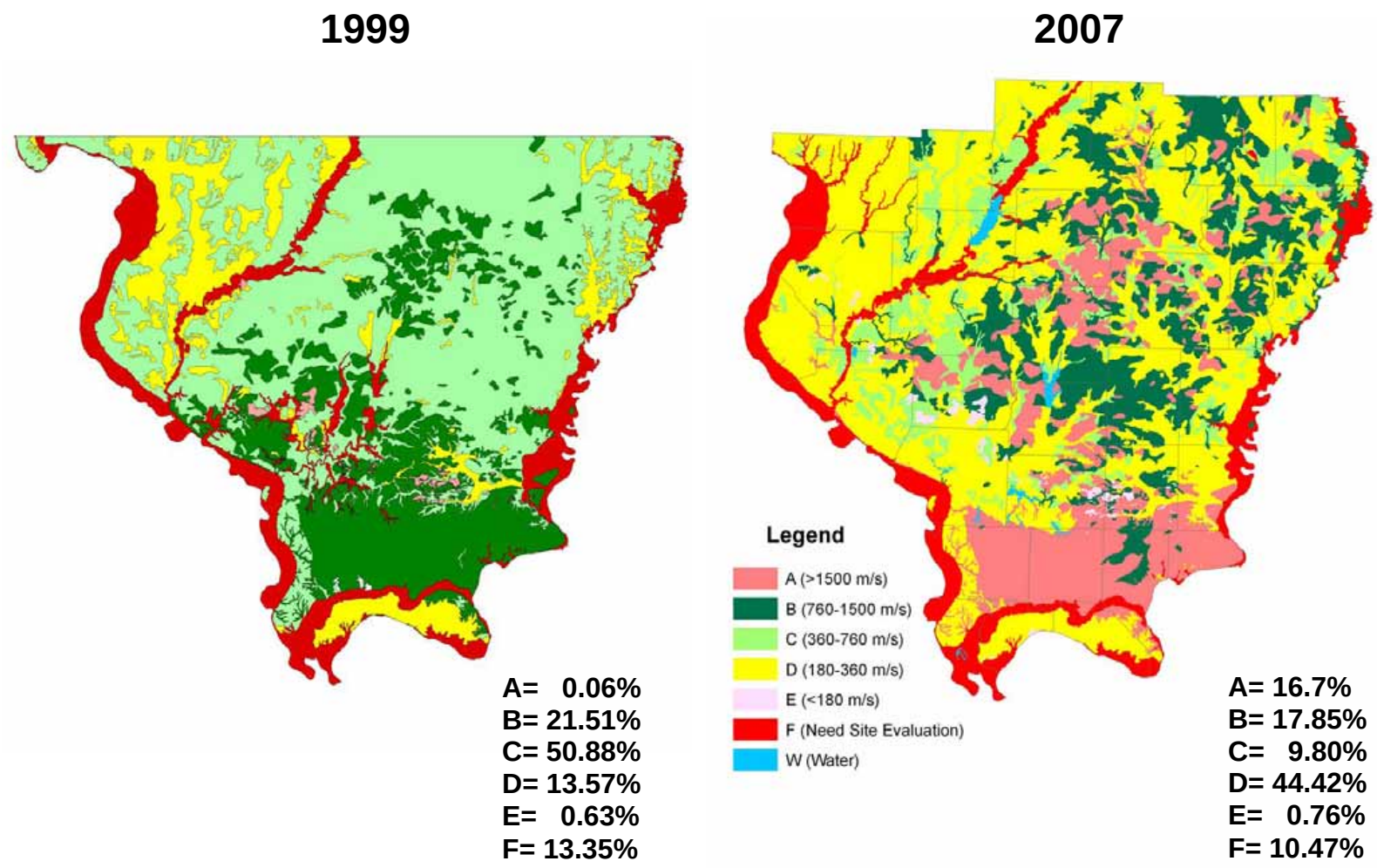

Figure 16. Comparison of 1999 Soil site class map and 2007 Soil Site Class Map based on shear wave velocity of the upper 30 meters of materials.

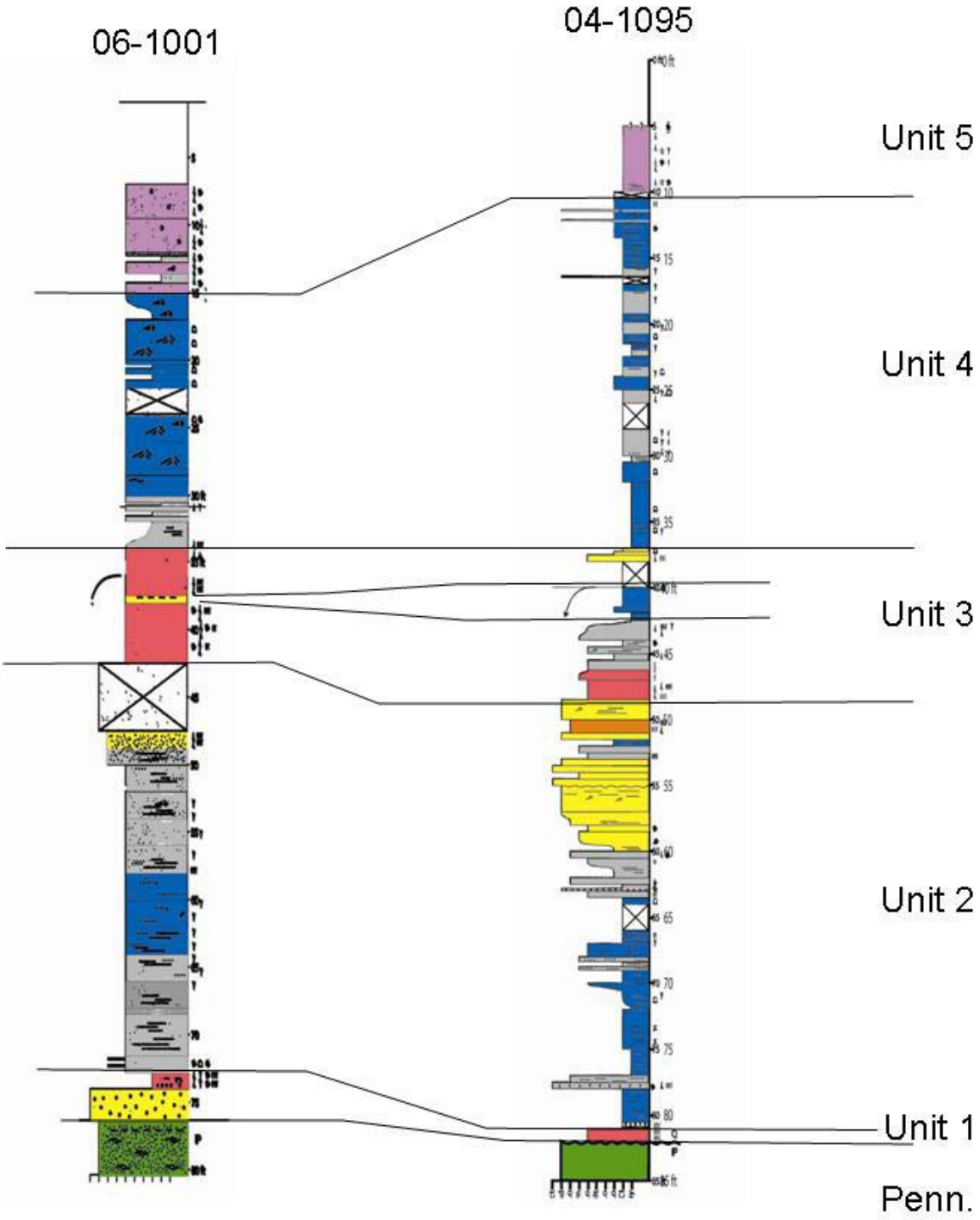

Figure 17. Graphic log of two core holes from Evansville study area. Yellow – fluvial, fluvial/deltaic deposits; grey – marginal lacustrine; blue – lacustrine; red – pedogenically modified floodplain; purple – loess deposits; green – Pennsylvanian bedrock.

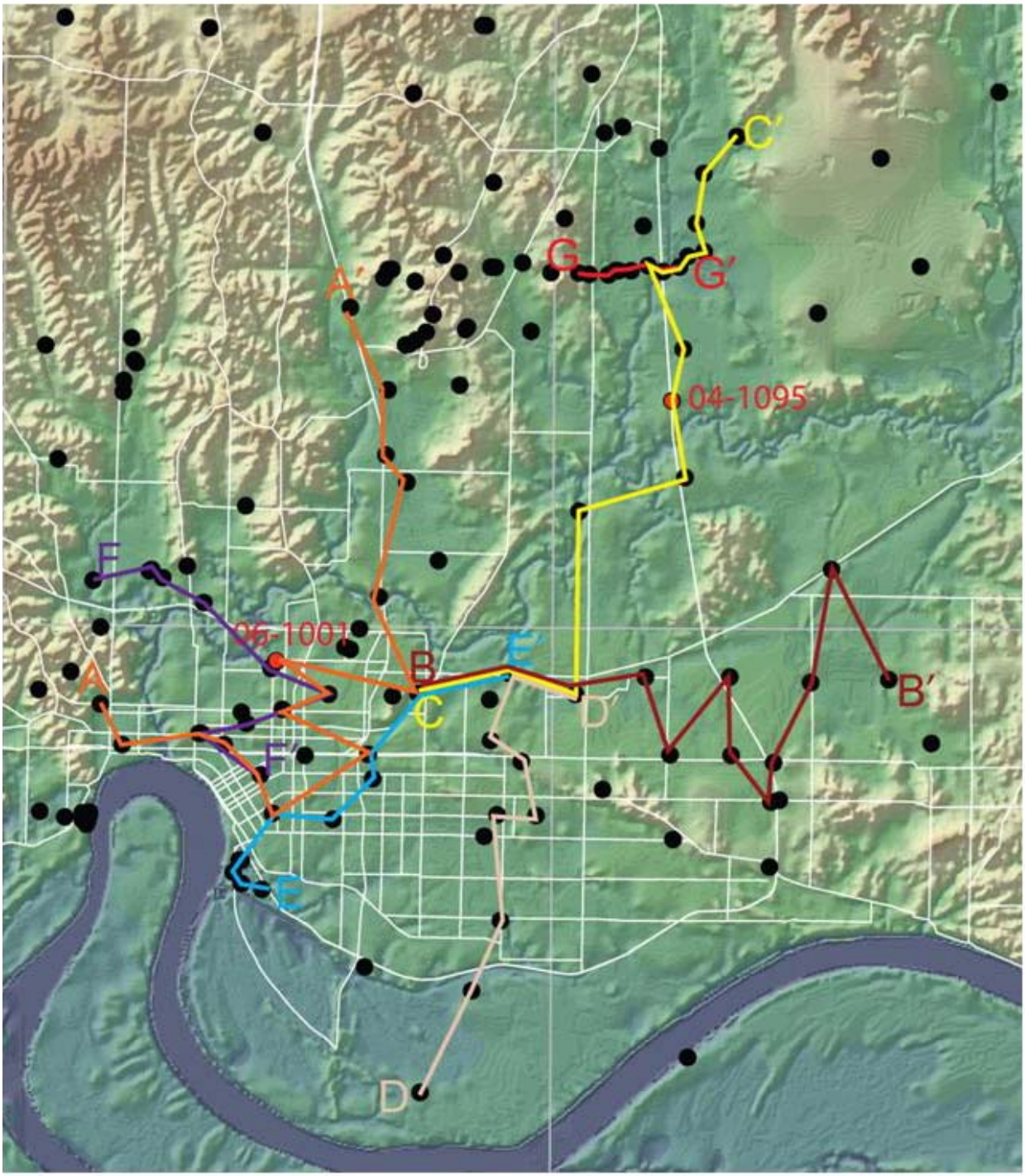

Figure 18. Map showing location of IGS gamma-ray logs used for this study (black dots) and core hole locations (red dots) and lines of cross sections constructed for this study.

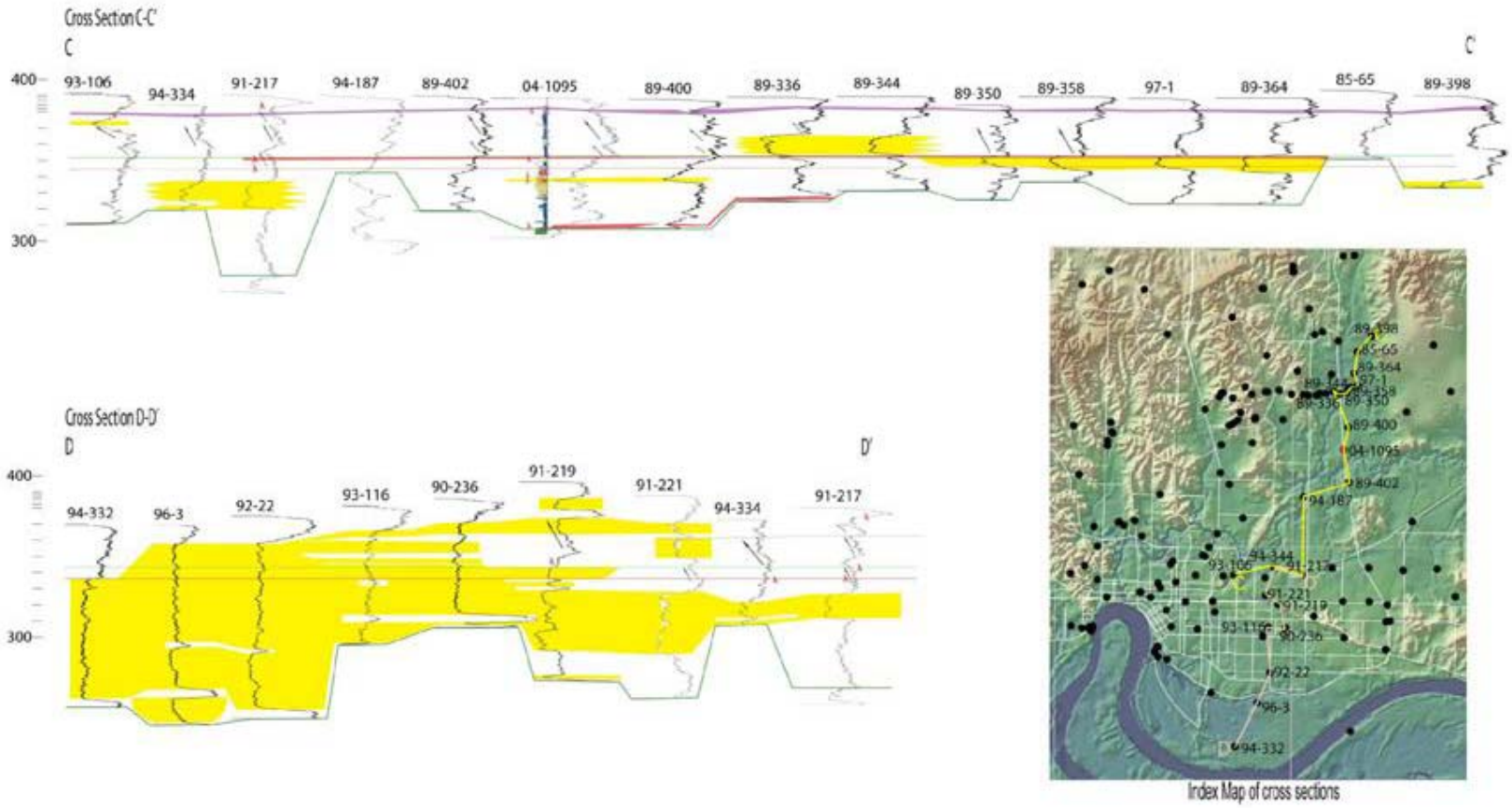

Figure 19. Two lines of cross section showing distribution of sand (yellow) up the Bluegrass Creek drainage from the Ohio River.

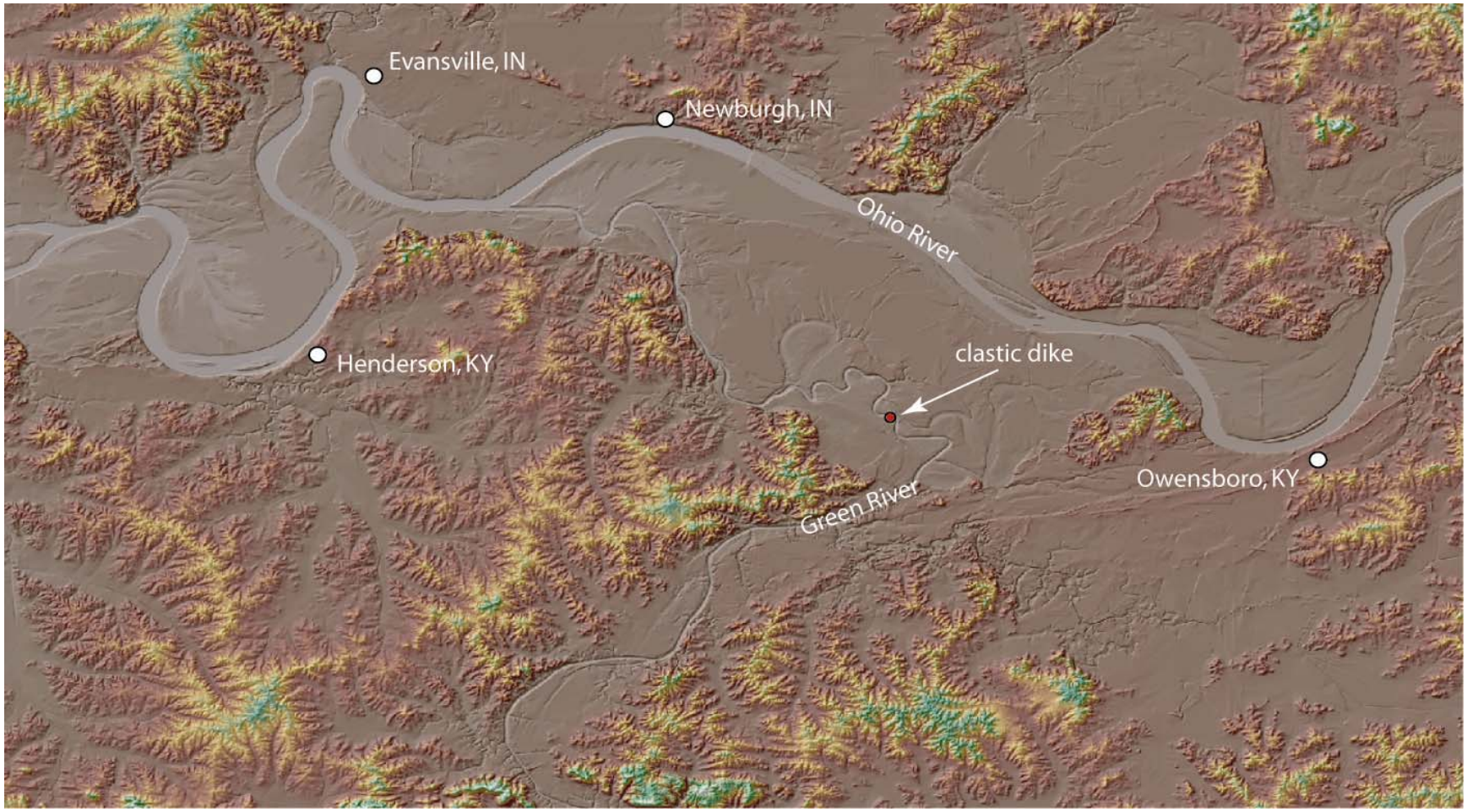

Figure 20. Shaded digital elevation model of the lower Ohio River Valley showing the location of clastic dikes found along the Green River in 2006.

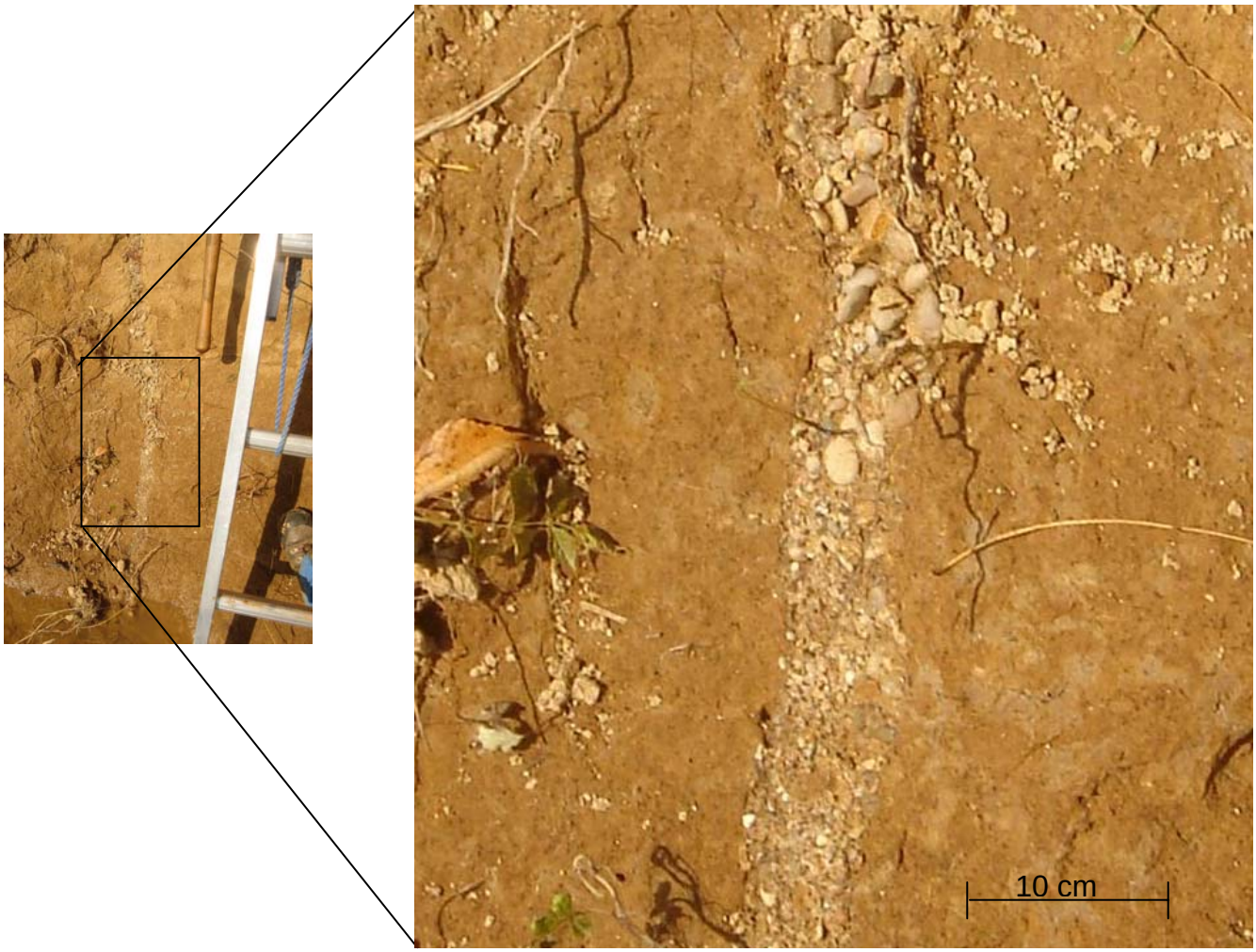

Figure 21. The Green River clastic dike located on Figure 20 has two distinctive grain sizes. This may be the result of sorting in the original source bed or could represent liquefaction from multiple seismic events.

Figure 22. The main gravel mass of the Green River clastic dike terminates ~3 m below the floodplain, but pebbles are present in a discolored zone above the dike to within 1 m of the surface.

Figure 23. Eroded clastic dikes on the Green River that cut through the same clay bed as the dike shown in Figure 22.

Figure 24. Photos A, B, and C are minor deformation features found along the Green River in the same region as the clastic dikes. Photo D is a dewatering feature that was exposed in a trench on the northeast side of Evansville, IN.

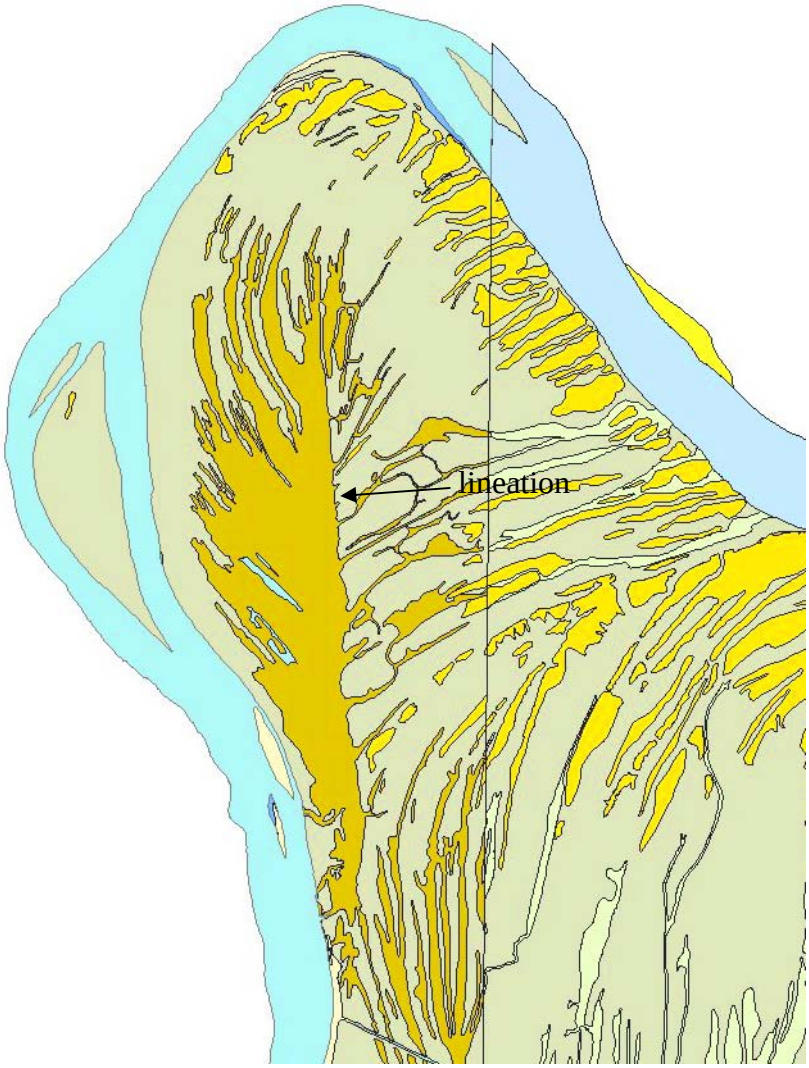

Figure 25. Anomalous lineation ~20 km west of the Urban Hazard Mapping project area.

Figure 26. Photo A: A disturbed cultural horizon at Angel Mounds in Evansville, IN was enigmatic to the archaeologists from Indiana University who uncovered it. Photo B: silty sand layer beneath the cultural horizon contains discolored zones. One hypothesis to explain the features in both photos is the densification of the underlying sand due to an earthquake.

Figure 27. Thixotropic sediments from cores liquefy when they are shaken. These materials appear to be widespread in the study area.

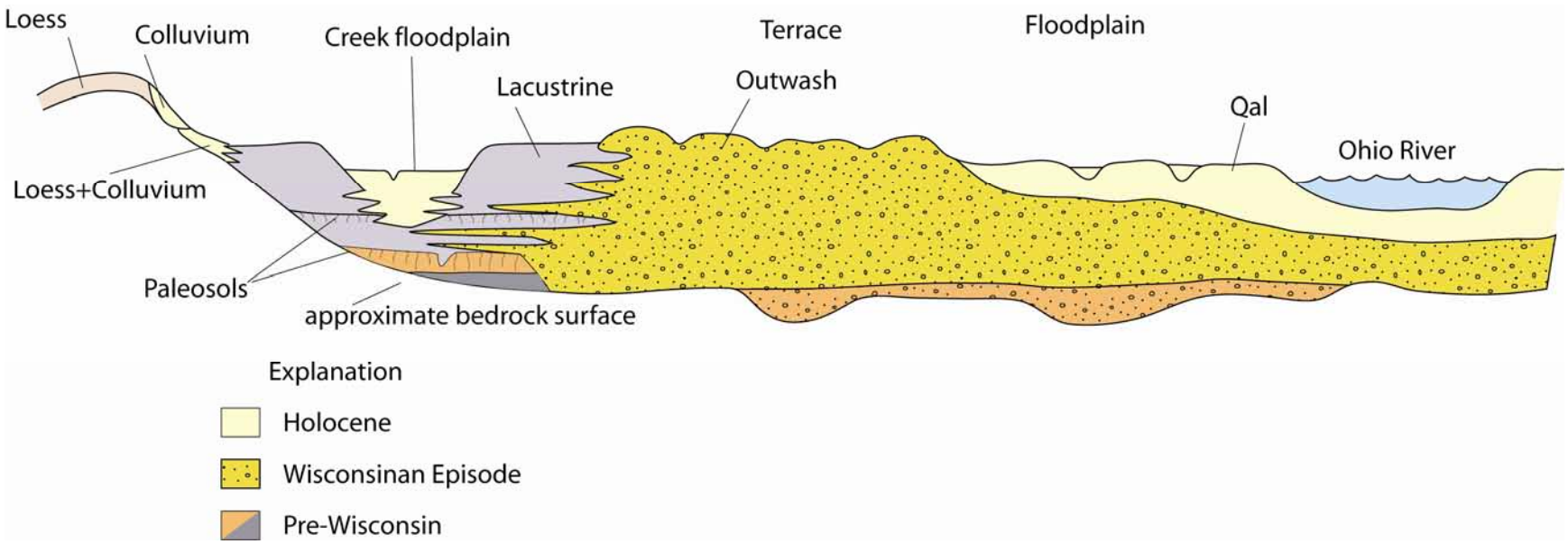

Figure 28. Conceptual cross-section showing the spatial relationships of map units and their ages. The upper few meters of the outwash terrace were reworked during the Holocene, which is not depicted (modified from Moore et al., 2007)

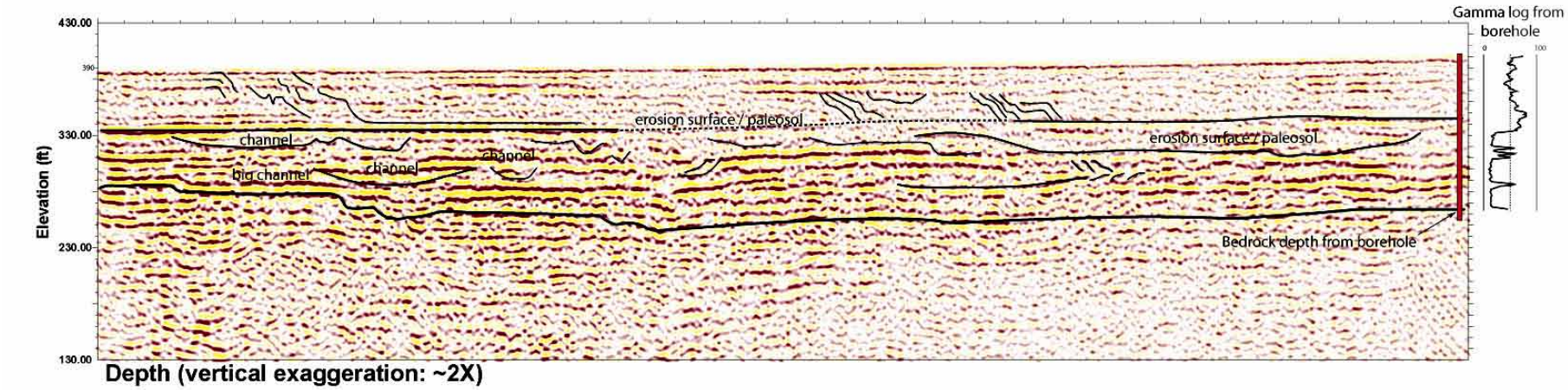

Figure 29. High-resolution seismic reflection profile along Clay Cemetery Road in the Wilson Quadrangle, KY. Reflection data, a gamma log from a borehole, and the core description were all consistent, revealing a high-energy, coarse-grained sedimentary sequence overlain by a lower energy, finer grained sedimentary sequence. Total length of reflection data shown is 1.2 km.

Table 1. Average shear wave velocity values assign to units in the study area. For most units average values were also assigned by depth or thickness.

Map Units	Unit Name	Average Shear Wave Velocity (m/sec)								
		Average	< 6 meters	6 to 15 m	>15 to 30 m	0 to 15 m	6 to 30 m	0 to 30 m		
A	Cahokia alluvium				248	206				
a	Cahokia alluvium		144	228	248					
C	Peoria/Roxana Silt (loess)				240	190				
c	Peoria/Roxana Silt (loess)		170	214	240					
d	Parkland sand	246							Indiana - eolian sand	
F	Equality Carmi Mbr - silt & clay			262	275	212	267			
f	Equality Carmi Mbr - silt & clay		172	262	275					
H	Henry - sands & gravel			286	294	246	294			
h	Henry - sands & gravel		167	286	294					
I	Wedron silt-clay till			322	588	325	430			
O	Pearl Frm	482								
o	Pearl Frm	482								
P	Glasford silty-clay till			243		250	243			
p	Glasford silty-clay till		243	243						
Q	Glasford loam-sand till			243		250	243			
z	Glasford sand btw 6-15 m			223	306	223	288			
q	Glasford loam-sand till		243	243						
r	Sand & gravel w/in Glasford			223	306	223	288			
V	Mounds gravel	593								
v	Mounds gravel	593								
W	Cretaceous silts, sands, etc.	120							Paducah values	
X	Surface mines/man-made land	180							Estimate	
		Thickness in upper -		10 m		15 m	24 m	30 m		
1	Penn mainly shales	1500		597		597	967	1137		
2	Penn mainly sandstones	2000								
3	Miss mainly shales			597		597	967	1137		
4	Miss mainly limestones	2900								
5	Silurian/Devonian dolomite	2800								
6	Ordovician shale - Maquoketa			597		597	967	1137		

Table 2. Example of part of spreadsheet used to calculate average shear wave velocity per polygon of stacked units from the Berg and Kempton (1988) stack-unit map of geologic materials in Illinois.

Stack	Material	Unit Thickness (m)	Unit Shear Wave Velocity m/sec	Calculated V30 m/sec	Soil Profile NEHRP & By Code
(a*)1*	Cahokia alluvium	5	144*	967	B
	Penn mainly shales		967		
(a*)2*	Cahokia alluvium	5	144*	2000	A
	Penn mainly sandstones		2000		
(a*)F 4	Cahokia alluvium	5	144	262	D
	Equality Carmi Mbr - silt & clay	9	262		
	Miss mainly limestones		2900		
(a*)f* q* 1	Cahokia alluvium	4	144	335	D
	Equality Carmi Mbr - silt & clay	4	262		
	Glasford loam-sand till	4	243		
	Penn mainly shales	18	597		
(a*)H	Cahokia alluvium	5	144	233	F
	Henry - sands & gravel	15	294		
(a*)H (v*)	Cahokia alluvium	5	144	316	F
	Henry - sands & gravel	10	286		
	Mounds gravel	15	593		
(C) 2	Peoria/Roxana Silt (loess)	10	190	190	D
	Penn mainly sandstones		2000		
(C) 2 4	Peoria/Roxana Silt (loess)	10	190	190	D
	Penn mainly sandstones		2000		
	Miss mainly limestones		2900		
(C) 4	Peoria/Roxana Silt (loess)	10	190	190	D
	Miss mainly limestones		2900		
(C) 5	Peoria/Roxana Silt (loess)	10	190	190	D
	Silurian/Devonian dolomite		2800		

* Shaded cell indicating thin soil over bedrock that was disregarded in calculating the average shear wave velocity and designation of soil type F.