10. Evaluating and Communicating Geological and Geotechnical Information for Use in Risk Assessments

Purpose/Objective

This chapter along with the associated collection of example drawings (*Geologic Example Drawings.pptx*) provides guidance to enhance the communication of geologic conditions and environment, construction methods, foundation treatment and foundation/structure performance over time in order to reduce uncertainty and improve estimates of foundation performance for dam safety. The important task of evaluating, summarizing and portrayal of this information is outlined. The effective communication of this geological and geotechnical information is essential for estimating risk, and has always been an important aspect for all dam/levee designs as well as safety programs, independent of risk analysis. Because of their unique importance, separate specific discussions are included to address geomorphology, karst foundations and mining and fluid withdrawal near structures.

For many dam projects, the volume of available data can be substantial. The process of sorting through this information, pulling out the most applicable photographs and data then assimilating it into a useful and concise format is extremely important for understanding the foundation characteristics and how they relate to the potential failure modes. For some projects, the amount of available data is extremely limited. In these cases, it is even more important to use the data available to make reasonable interpretations of the geological environment by drawing on past experience. Regardless, the role of an experienced engineering geologist to provide a scientific perspective and insightful approach to communicating geologic environments is crucial. Without a complete effort to analyze the data and understand the conditions of the dam foundation, the ability to evaluate performance and accurately estimate the likelihood of various event nodes can be severely limited. Summarizing this information on detailed plan, profile and cross sectional drawings is essential for the risk analysis and also to communicate foundation conditions to reviewers and decision makers. The importance of this communication is reflected in the fact that many dam failures and incidents have been attributed to the foundation of the structure or the interaction at the dam/foundation interface. Some of the most catastrophic failures were thought to have occurred due to a severe incompatibility between the foundation and the dam. In some cases, the foundation was not able to withstand the demands brought on by the presence of the structure and the reservoir. In other cases, failure occurred due to geologic factors (sometimes in combination with seepage and/or loading from the reservoir) that resulted in conditions not adequately addressed by the details of the dam.

Philosophy and Iterative Approach

The effort spent reviewing, evaluating, understanding and portraying subsurface information is highly variable and often determined by the scope and/or stage in the dam safety process. The dam safety process ranges from initial screening level efforts and Potential Failure Mode Analysis (PFMA) to detailed risk analysis studies that are part of an Issue Evaluation Study or Modification Report. An iterative approach to the foundation evaluations and analyses is often required as the details of the dam/levee are added and both are evaluated in light of the details of the engineering geology and the structure. However, this important effort should be conducted in the earliest phases of the particular stage of the process. All subsequent phases of work will be drawing upon the engineering geology information gathered and communicated to the team. In fact, if due diligence is conducted at the earliest phases to establish the foundation baseline conditions, wasted time could be avoided at later phases.
A complete and thorough study on a large project could take a team many months and the need for this detailed level of effort must be justified and weighed against many considerations, including resource requirements on other projects that may be a higher priority. Additionally, for initial evaluations the failure modes may not have been discussed or clearly defined, so it may be necessary to review and search for additional information as the team becomes more focused on specific failure modes.

The appropriate level of effort for the development of subsurface data must be determined by the team responsible for using the information (and an experienced advisor(s), as needed) based on the amount of information, the details of the failure modes of concern, and the scope of the evaluation. Some of the data needs described in this chapter may be developed in a second phase of study once the team understands the level of uncertainty associated with the evaluations. This team should include a geotechnical engineer working closely with the engineering geologist to develop an appropriate scope of work once there is a general understanding of the type and volume of data available.

The collaboration between the engineering geologist and geotechnical engineer is essential for developing interpretations based on the understanding of depositional environments, particularly when data are sparse and limited. This is an opportunity for the geologist to learn more about material properties and other considerations that influence seepage and piping initiation, progression and continuation and to apply knowledge of sedimentation and stratigraphy to help estimate continuity and predict behavior. The knowledge gained is often more important than the products developed and this process can significantly influence the risk estimates. For this reason, delegating or contracting the data review and development to individuals not involved in the risk analysis misses a very important learning opportunity.

A specific list of the primary questions or most important parameters is a very useful method to guide data collection, evaluation and reporting. Prior to sorting through all the information and pulling out the essential data it is important to formulate the key questions associated with the specific potential failure modes that will be evaluated. This list should be produced and prioritized by one or more individuals with the experience to recognize the importance of various data sets in the context of evaluating dam or levee and foundation performance and estimating risk. An event tree is an excellent guide for determining what data are most important. Sorting through the available information to determine its relative importance to dam or levee safety requires significant experience and should be assigned accordingly. Care should be taken to reference the source documents for all essential extracted information to assist in building the dam or levee safety case and assuring interpretations and conclusions have clear links to supporting data.

Plan maps, cross sections, profiles, tables, graphs and photos are the primary products most useful to help summarize a large amount of foundation data. In some cases much of the required subsurface information may already exist on plan and profile drawings and photographs which are adequate for the early meetings in the assessment process. Usually there is initial work required months in advance to organize the data for ready access to conduct the risk analysis and discuss potential failure modes.

The engineering geologist and geotechnical engineer should be prepared to make a presentation to the risk analysis team in order to explain the most important aspects of the embankment and foundation that can be tied to potential failure modes. The foundation plan and profile drawings along with historical photographs should be a key aspect of this presentation.

Data Evaluation and Summary Process

The process of identifying, evaluating, understanding, portraying and communicating the most important dam foundation information is critical for improving the project team's foundation knowledge, reducing uncertainty in risk estimates and enabling better communications with a broader audience (including reviewers and decision-makers). The foundation information in most cases must be portrayed in concert with the dam/levee information to develop and understanding of the potential interaction between them and important properties and boundaries of each that is needed. The geologic/engineering drawings developed during this process are important products for understanding and communicating foundation conditions. Sometimes these drawings are hand-drawn or observations made on as-built drawings. Data availability is more important than final drafted CADD drawings, especially during the initial analysis. The primary goal of the data evaluation and summary process is to maximize the understanding of those parameters most important for evaluating potential failure modes and estimating future performance. The process is also essential to help identify key data gaps. The ability to capture this information succinctly in a set of foundation drawings can save many hours during the risk analysis by eliminating the need to continually search through multiple reports, borehole logs, and unorganized data and documents.

It is not practical to develop a list of foundation and embankment data requirements that is applicable to all dams and levees or all potential failure modes. Every dam or levee and foundation has unique characteristics. Therefore, the most effective way to communicate foundation data must be customized for each project, and must be related directly to failure modes of concern. Examples of various types of foundation drawings are included in the PowerPoint file "Geologic Drawing Examples.pptx intended to be used along with this chapter.

Foundation (and dam) Data Requirements for Failure Modes Associated with Embankment Dam Foundation Seepage

The possibility of foundation seepage leading to internal erosion will be at least initially considered on nearly every embankment dam or levee. A partial list of issues associated with potential failure modes is provided in Chapter 1. The following general list of potential seepage-related failure modes is provided to help focus the data collection, evaluation and communication process on appropriate meaningful questions and parameters:

Examples of Potential Seepage-Related Failure Modes

- Erosion of the sandy or silty foundation soils exiting downstream or possibly exiting into coarse natural deposits or coarse fill material such as berms, or into open discontinuities within bedrock etc. Piping progresses from downstream to upstream.
- Erosion of embankment material into coarser gravely foundation deposits or into open discontinuities in a bedrock foundation. Piping progresses upstream or may stope upwards.
- Scour of embankment material at the foundation contact due to seepage occurring in coarse gravel deposits or within open discontinuities in a bedrock foundation. Erosion may progress along a continuous feature, or stope upwards. Seasonal reservoir loading fluctuations may influence progression.
- Scour of finer natural silt and fine sand materials in the foundation that are adjacent to highly permeable gravel materials capable of higher velocity flow.
- Scour, erosion, or stoping within the embankment and/or surficial deposits associated with concentrated foundation seepage in karstic foundations or highly permeable gravel layers or channels.
- Seepage and erosion beneath structures (outlet works, spillway walls, etc) exiting downstream into a broken drain , the ground surface or into coarser materials or open discontinuities in bedrock.

The investigation and assessment of these (and many other) potential seepage-related failure modes leads to the development of important questions that will help guide the collection, evaluation and presentation of subsurface data. Much of this information can and should be portrayed on a set of drawings with associated figures, plots and photographs. Some of the important data associated with these potential seepage and piping failure modes include:

- Geologic descriptions of foundation soil properties and geomorphology
    - Geologic descriptions of foundation materials from borehole or test pit logs
    - Location of all exploratory holes shown on plan map and sections
    - Geologic descriptions of materials exposed on the surface nearby
    - Drillers notes related to material properties or behavior
    - Interpretation of range of expected material properties based on understanding of depositional environment and local geomorphology (particularly highly permeable or highly erosive material, geometry, and internal variability)
    - Interpretation of range of expected continuity of various materials based on depositional history and available data (including erosive materials,

roof-forming cohesive materials, and highly permeable coarser gravel units, etc.)

- Descriptions and properties of bedrock associated with seepage and piping
    - Orientation of discontinuities (joints, shears, bedding, faults)
    - Width of discontinuities (openness)
    - Spacing of discontinuities
    - Infilling characteristics of discontinuities (extent, physical properties)
    - Continuity of open joints, shears, bedding, faults, etc
    - Photographs of rock exposures, including construction records, cutoff trench, representative exposures in the area, etc.
    - Geologic descriptions of rock units, material types, etc.
- Material properties and descriptions of the embankment and/or foundation soils, including
    - Gradations (graphs of all available lab results in dam and foundation)
    - USCS classifications with plus 3 inch fraction included
    - Plasticity
    - Density (Construction control data including percent compaction, moisture content, etc.)
    - Permeability and water loss zones from borehole drilling records
    - Artesian pressures and confining layers
    - Penetration data (SPT, CPT, Vane Shear, Becker Penetration Tests – drilling methods can influence results significantly)
    - Cementation
    - Dispersion potential
    - Descriptions, sketches and photos of in-situ soil materials to help understand issues such as:
        - point to point contact of gravel (e.g., matrix vs. clast support, likelihood of open-framework gravels)
        - gravel floating in a sand matrix
        - thin layering of different materials that may have been averaged by sampling
        - influence of gravel on SPT or other penetration testing
        - depositional environment providing clues to estimate continuity
    - Geologic records from surrounding area providing insight into possible conditions in dam foundation (quarries, borrow excavations, road cuts, water well logs, regional mapping, foundation investigations for other structures, etc).
    - Available published soils maps and reports from USGS and NRCS
    - Surface and borehole geophysical logging, when applicable
- Design and Construction Records related to seepage interception and control (original construction and subsequent modifications)
    - Design Memorandums (written descriptions of original design considerations and intent, etc.) Especially related to seepage analysis, filter design, stability analyses, etc.)

- As-built drawing showing location of all seepage control features (original and all subsequent additions or changes). This includes:
  - Toe drains
  - Downstream seepage control berms and/or filters
  - Embankment filters and drains
  - Upstream seepage control blankets
  - Cutoff trench dimensions, location and conditions
  - Outlet works and spillway
- Material descriptions, foundation maps and records from construction and foundation reports
- Photographs of embankment material placement or borrow areas
- Photographs of foundation soils or bedrock exposed during construction records, including overhangs and steep bedrock exposures
- Photographs of foundation treatment (or lack of), especially the treatment of open discontinuities in bedrock
- Chronologic summary of seepage evaluation and modifications made throughout history of project
- Location of all known seepage areas or springs pre-dating construction
- Written descriptions of subsequent design considerations and changes/improvements performed to mitigate seepage concerns
- Grouting records showing location of all grout holes, water tests, grout takes, grout mix, pressures, grout hole communication, refusal criteria and observations of grout travel and break-outs

- Instrumentation data needed for risk analysis
  - Location of all embedded instruments shown on geologic sections
  - Time series plots of piezometer response to reservoir fluctuations for the complete project history
  - Correlation plots of pool elevation verses piezometric response
  - Projections of piezometer responses to reservoir/pool levels above historic maximum
  - Written evaluation of piezometer data as related to dam or levee performance history and changes over the life of the instruments
  - Maximum piezometer readings plotted on geologic sections
  - Measured and predicted (where appropriate) piezometric pressure gradients along potential seepage paths (depicted on geologic sections)
  - Surface and internal deformation data that could be related to seepage and erosion problems
  - Location of all known surfacing seepage locations downstream
  - Sand boil and other sediment accumulation locations
  - Hydrographs of all measured seepage and leakage flow data
  - Correlation plots of pool elevation versus seepage and leakage response
  - Weir flow data tied to reservoir levels

- Consultant observations made throughout the history of the project
    - Note any recommendations for remedial actions
    - Document associated actions taken as a result of consultant review
    - Document dam or levee performance following remedial actions
    - Evaluate and utilize previous seepage analyses, including flow nets and stability calculations and confirm conclusions when compared to more recent data

Drawings necessary to summarize and communicate foundation and embankment material properties and behavior

The partial list of useful data provided above can serve as a starting point for evaluation of failure modes or risk estimates, but it is necessary to assimilate and summarize the most important information or it is nearly impossible to use and communicate it effectively. A set of non-exaggerated, detailed, full sized drawings combining geological, geotechnical, and instrumentation data is essential. In most cases it is possible to incorporate nearly all significant information onto the geologic/engineering cross sections to serve as the database for evaluating potential failure modes.

Developing detailed cross sections to depict geology, material properties and instrumentation response

There is no single "correct" way to develop geologic cross sections (or profiles) and display data. Such guidance would stifle the imagination of those responsible who should be continually striving to improve the management and communication of this information and make it site-specific. Sometimes it makes most sense to draft these sections using CADD software. Sometimes hand-drawn cross sections are the quickest and most effective, or annotations made on existing sections. Automated input of borehole data onto geologic sections may save time initially in some CADD systems, though these computer-generated cross sections always require additional thought, interpretation, geologic evaluation, and work to assure the appropriate meaningful data are displayed legibly.

Cross sections and sometimes profiles are important to develop at the location of potential foundation problems and where piezometer and observation well data may provide a better interpretation of seepage conditions. The team should discuss the location and data requirements of cross sections or profiles most important to pending discussions. The three-dimensionality of the geology/structure geometry cannot always be adequately communicated with one cross section. Often several sections along with a detailed plan map may be required. A cross section along the outlet works is generally needed, particularly for conduits through the embankments where seepage erosion will be evaluated. At a minimum, a typical section is required that shows the foundation interpretation along with embankment zoning and design features.

Regardless of the method and approach to developing the cross sections, there are some guiding principles that should be followed and some basic data requirements, including:

- Non-exaggerated scales (this is necessary to see true thicknesses, slopes, and gradients)
- Full sized drawings NOT drafted to use half size (in order to plot very detailed information on the vertical scale such as gradations, soil classification, uniformity coefficients, etc)
- Scales generally between 1’ = 20’ and 1” = 40’ to fit borehole information
- Location of the top and bottom of piezometer influence zones and all other significant instrumentation
- Piezometer readings tied to specific reservoir elevations (maximum historic for example)
- Phreatic surface from available piezometers and predicted phreatic surface for higher reservoir levels up to the top of dam
- Separation of factual data from interpretations (use solid, dashed, and dotted lines along with question marks to help portray relative uncertainty and include notes).
- Interpretations of vertical and horizontal continuity of important foundation layers, lenses or units (carefully show what is known and unknown). Where interpretations are made, include reasoning and logic as notes on the section so confidence and uncertainty can be communicated. In sedimentary rock, a straight line interpretation of the top of bedrock often misses a common occurrence of cliffs and benches.
- Unified Soil Classification System symbols for all borehole sampling, including plus 3 inch material by volume (sorting out differences between field and lab classifications)
- Percent fines, sand and gravel when evaluating potential seepage and piping flow paths and susceptibility to erosion in granular materials
- Avoid the use of computer generated symbols that force continual reference to a legend to understand (rely more on USCS classifications and gradations)
- Assure all computer-generated soils data are legible (this requires manual drafting in most cases)
- Distances and directions of drill holes when projected onto cross sections
- Labels for the location of every other intersecting cross section. (This is generally shown as a short vertical line near the top of the drawing).
- Dam stationing for all profiles near centerline
- Embankment zone design features (cutoffs, grout curtain, found. treatment) and appurtenant structures (outlet works, spillway, etc.)
- All seepage control features and associated “plumbing” (toe drains, berms, upstream blankets, cutoff trench, drainage blankets, rock drains, relief wells, etc)
- Continuity of foundation soil units of concern
- Continuity of rock lithology or discontinuity features important to foundation performance

Developing detailed plan maps

In order to adequately evaluate dam performance and estimate risks associated with various potential failure modes, it is essential to clearly understand the location of all design and construction elements and everything associated with monitoring the structure, particularly the exploration and instrumentation. The plan map serves this purpose and as the key drawing to show the locations of all cross sections. This requires a plan map drawn at a scale sufficient to portray the necessary details of all important information.

The level of detail required and the amount of significant information varies between dam projects and is generally influenced by the number of explorations , the amount of construction related features (grout curtains, key walls, special treatment zones, dental concreted and slush grouted bedrock contacts, fillet walls, etc), and the complexity of the seepage control features (drains, berms, blankets, filters and associated "plumbing"). Dams with a large amount of data may require a layering approach when developing the plan map in order to toggle on and off various data sets, depending on the specific needs of the analysis. Various CADD systems have been used to successfully develop these types of plan maps which can be saved as working PDF documents for easy distribution and use. This is a powerful way to share an enormous amount of data. Sometimes more than one plan map is required, for example when a top of rock contour map is used to portray rock properties and discontinuity information, or when ground water contours are needed in combination with piezometers, observation wells, relief wells and other data useful for evaluating seepage.

For initial failure mode evaluations existing plan maps may be adequate. However, it is often necessary to update the map(s) by adding more recent explorations, instrumentation and noted design changes or additions. The need to improve and update the plan map should be assessed several months prior to the risk assessment meeting, along with updating the as-built sections and profiles. These maps should be updated as part of any dam safety program, independent of risk analysis.

Basic information displayed on the plan map often includes the following:

- Topography of the dam and surrounding area (updated as needed to represent current conditions)
- Inspection trenches, cutoff trenches, grout lines, concrete bulkheads, concrete fillets, special treatment zones. (note these features typically shown as dashed/hidden lines on the plan view showing the dam.)
- Outline of the dam with dam stationing
- Location of all cross sections and profiles being used with the current plan map
- Location of the outlet works, spillway and stilling basin
- All seepage control features including drains, drainage blankets, stability berms, relief wells, water conveyance pipes, filters, etc. (not used to seeing chimney filters on plan views)
- All exploration holes drilled at the site, including post-construction drilling, test pits, trenches
- Location of all instruments, including piezometers, weirs, inclinometers, surface deformation points, crack monitoring gages, (identify active piezometers)
- Geologic contacts, especially the limits of materials influencing potential failure modes
- Faults and Shear zones as mapped in the foundation or nearby
- Pre-existing springs prior to dam/reservoir and current springs differentiated
- Abandoned gas/oil/water wells, farm ponds (springs), sinkholes, caves, etc
- Outline of original river channel prior to diversion or construction and during construction if within the footprint.
- Location of other features (e.g., gravel pits, borrow pits and other excavations, utilities, etc)
- Location of important photographs
- Location and types of distress features

- Any deviations from original design due to difficulties encountered during construction.
- Haul road locations (over-consolidation of embankment soils (?), or potential for impacts on chimney filters from vehicular traffic, resulting sharp changes in soil properties)

Possible sources of geologic mapping, soils information and ground images to supplement project records during the initial data collection phase (see resource list at end of this chapter)

- USGS geologic maps and EROS Data Center for imagery
- BLM maps and aerial photographs
- Natural Resources Conservation Service (NRCS) soils mapping
- State Geological Surveys (often linked to aerial photographs and local and regional soil and rock mapping)
- Terraserver
- Google Earth

In addition, aerial photographs obtained prior to project construction can show geomorphic structures and other features important to the analysis.

Analysis and use of construction photographs and field records

Construction photographs have proven to be some of the most important records for documenting and understanding the dam embankment placement and the foundation conditions. All photographs, including historic aerial photographs should be considered extremely valuable. Every effort should be made to locate, review, sort and annotate existing photos from all available records, especially the construction documents. Existing photographic prints should be carefully scanned at very high resolution to preserve digital files along with the originals. It is most useful to "re-publish" the most important photographs within current documents to help support the dam safety case and efficiently communicate conditions. In addition, field records from construction (inspector's notebooks, Project Engineer's log book, construction payment modifications, etc) can be extremely valuable. Sometimes it is possible to contact and interview individuals present during construction.

Examples of some types of information obtained from evaluation of photographs:

- The type, degree and quality of foundation treatment
  - Slush grouting
  - Dental grouting
  - Clean up details, equipment, technique, areas cleaned
  - Treatment of faulted, sheared and fractured rock
- The shape and configuration of bedrock or soil surfaces
  - Overhangs in bedrock
  - Steep bedrock areas left in place
  - Cutoff trench shape, extent, steepness, conditions, etc
  - Location of construction roads that may influence embankment performance (cracking at steep road cuts remaining in foundation)
- The details of rock discontinuities
  - Orientation
  - Aperture of open joints and bedding planes, etc.

    - Material properties of infilling material
    - Details of backslope of cutoff trench
- Embankment placement details
    - Thickness of lifts
    - Compaction effort and type of equipment
    - Compaction problems adjacent to outlet works and other structures
    - Filters and drain locations, properties and placement
    - Temporal discontinuities during placement and treatment of surface when construction is re-initiated.
- Seepage areas downstream
    - Location and extent of seepage problem areas
    - Seepage changes over time
    - Flood fighting efforts; sand bags, dikes, berms, filters, etc
    - Relief well flow
    - Sediment transport into downstream seepage areas
- Conditions of materials sampled during explorations
    - Undisturbed soil or rock samples in sample barrels
    - Soil or rock samples in core boxes
    - Test pit and trench wall exposures showing materials and depositional environment, stratigraphy, continuity, range of variation, etc.
    - Spoil piles from excavations depicting material types, oversize, etc
    - Amount of oversize (plus 3 inch) material that may not be represented by laboratory testing
    - Cementation or apparent cohesion in exposed soil slopes
- Locations of older stream channels and soil deposits of interest
    - Aerial photographs taken early in the project showing old stream channels that may influence foundation seepage
    - Old channels that may have been backfilled during construction
    - Extent and size of boulder, cobble and gravel materials exposed during construction
    - Evidence that foundation soils contain lenses that are too coarse to be sampled accurately in drill hole information; especially gradation data. Historic channels migration over time
    - Photographs of test pit walls can reveal more than a gradation analysis of samples.
- Details of Construction
    - Sequencing of fill placement and diversion if applicable
    - Methods, equipment, and techniques used
    - Locations of temporary construction features such as haul roads, borrow pit type and location
    - Record of flood damage
    - Erosion features that formed on temporary foundation and embankment slopes
    - Point of completion at which a work suspense occurred
    - Construction or design details that may not be adequately documented

Geomorphology for dam and levee foundation evaluations

Geomorphology is the scientific study of the formation, alteration, and configuration of landforms, including the depositional and erosional processes active during their formation. Through these studies geologists are able to understand more about the physical environment during deposition and subsequent modifications that may have occurred through erosion or other processes. For most embankment dams and levees founded on soil, a detailed understanding of the geologic depositional environment is essential to augment exploration and performance data and help interpret material property variations and continuity. In most cases, drill hole data alone are insufficient.

An experienced geologist with a geomorphology background can be very important to help educate and lead the risk estimating team to reasonable assumptions and estimates about these conditions at a particular site. This is particularly critical in many of the Holocene alluvial foundations (especially glacial outwash) when sampling is limited, but the continuity of potentially erosive or permeable materials needs to be estimated for the risk analysis. This expertise is also essential for identifying landslides in and around the dam and reservoir using aerial photographs. For most levee investigations, geomorphic mapping of the exposed soils (especially channel fill deposits) should be an essential initial component to help guide subsequent studies. The geologic maps are most useful in combination with performance data including mapped locations and of previous seepage locations and associated documentation. The extent of the geologic mapping efforts vary widely and often include an initial evaluation of the areal distribution of the Holocene environments of deposition determined from high altitude aerial photography. Older aerial photographs are often more useful since ground disturbance from development can obscure some of the natural features. However, modern aerial Light Detection and Ranging (LiDAR) surveys provide geomorphologists with a new tool for "stripping" vegetation and visualizing the ground surface morphology. In either case, the initial geomorphic studies are often reconnaissance in nature, often with minimal or no field checking and few additional drill holes or test pits to provide quality control. Existing exploration information should first be used to cross check these maps. The accuracy of individual contacts can be affected by the scale of the map and limitations in the source data.

The mapping can often be supplemented with pertinent surface and subsurface data from geological publications, bulletins, reports and boring data from a variety of Federal and State agencies, including Departments of Transportation, the State Geological Surveys, USGS, and several private engineering firms. More detailed subsurface information, generally the logs of specific borings drilled on or near the structure, can be used to construct cross sections and to further refine the surface interpretations.

Each depositional environment can be identified by a unique color and/or pattern on the developed maps. Thin deposits on the surface such as alluvial fans/colluvial aprons and natural levees can be shown as a dashed or dotted overprint in order that the underlying deposits can also be identified. The remaining depositional environments can be identified by a color pattern. Major swales in point bar environments can be identified and mapped to show the trends of the meanders, or on alluvial fans analyses of slopes can aid in identifying the sequence of deposition. Similarly, in a flood plain, terraces of multiple ages may represent different periods of cut and fill during the stream's evolution. Understanding the timing of deposition is important and how such features project under earthen embankments. The basic geomorphic model can be vital for developing a better understanding of potential seepage and piping failure modes. Many failure modes are sensitive to the extent of features both in section and in plan view.

Unfortunately, drilling and sampling which are among the most limited methods for evaluating and understanding stratigraphy and continuity in complex alluvial deposits are often the primary tools used for investigating dam and levee foundations. Depositional units in these environments are often characterized by very rapid and complex changes over short distances, both vertical and lateral. The combination of a wide spacing between drill holes, very small sample size (diameter of borehole over space between borings), sample disturbance, mixing, poor recovery of gravel and larger sizes, and the difficulty viewing sedimentary structures in recovered samples often results in overly simplified and incomplete geologic models that do not reflect the natural variability. Data more useful for understanding continuity and developing a subsurface model include:

- Test pits
- Trenches
- Nearby exposures including road cuts, quarries, borrow pits, exposed foundations
- Aerial photographs (from the earliest available to the most recent in 5-10 year increments if available)
- Topographic Maps (7-1/2 USGS topographic quadrangles)
- Regional maps of surficial geology or soil (USGS, NRCS)
- Academic reports, theses and guidebooks from conference field trips
- Photographs and maps of original foundation excavations (cutoff trench, outlet works, and other structure foundation exposures)
- LiDAR imagery that allows the geologist to “remove” vegetation and better evaluate surface morphology and infer geologic conditions
- Examination of old aerial photos to determine potential impact associated with recent land use such as sand and gravel pits, mining, and dump sites.

The purpose of these geomorphic investigations is generally to (a) determine the areal distribution and physical characteristics of the various surficial deposits, (b) reconstruct the general geologic history of the area, (c) conduct subsurface stratigraphic correlation of various geologic environments of deposition as an aid in determining foundation and underseepage conditions, (d) provide a scientific basis for supporting estimates of material properties and continuity for a risk assessment, (e) help in the identification of other landforms important to dam safety, such as paleo-landslides.

Even with limited exposures and sparse sampling it is often necessary to make “reasonable” best estimates of material properties and continuity based on knowledge of local geomorphology. A qualified geologist (experienced and trained in soils analysis) can assess the surface morphology and evaluate the environment(s) responsible in the development of surface features. Then, using principals of sedimentology and stratigraphy a geomorphologist can link processes from modern analogs and infer the nature of the deposits in the subsurface. Naturally, the degree of uncertainty in these estimates is important to consider, discuss and document.

The existing exposures should be mapped, logged and sampled if possible and used by the geologist along with boring logs and all other available records to develop a subsurface stratigraphic model.

The following incomplete list is an example of some geologic environments (depositional models) that might be considered when developing interpretations of subsurface soil conditions when, for example, fine sand or silt is known to exist in some samples and continuity must be estimated based a geomorphic model;

Materials sampled in the foundation may be representative of:

- Limited, isolated lenses perhaps as small local streams or older meander belts
- channel fill sediments left by point bars in slowly moving streams on inside bends and thus with limited continuity
- Overbank deposits draped on the floodplain during floods, possibly continuous
- Continuous but sometimes narrow stream channel fill that could extend upstream to downstream possibly in sinuous form
- Continuous, laterally extensive layers of sandy material from a lacustrine environment (beach or deltaic deposits) or a broad outwash plane downstream of a retreating glacier or distal deposits within an alluvial fan
- Abandoned channels and swales partially or completely backfilled that can act to focus seepage (channel-fill deposits)
- Abandoned terrace deposits along the active channel or valley
- Windblown silt deposits expected to form continuous layers
- Natural levees or low ridges that flank river channels and influence subsequent deposition during flooding (crevasse splay deposits, etc.)
- Backswamp deposits of fine-grained sediments deposited in broad shallow basins during river flood stages
- Dune or beach sand deposits in an aggrading delta environment
- Fault zones with abrupt changes in material juxtapositions at depth
- Various combinations of several deposition environments that need to be considered as a system, with possible material continuity/connections independent of depositional or geologic continuity
- Rapidly changing depositional settings where fine sands can be overlain by silty or clayey deposits capable of forming a roof
- Erratic ice or water-laid deposits containing layers or lenses of very fine sands or rock flour in direct contact with coarse grained and very pervious deposits.
- Drowned valley deposits.

The character and evolution of floodplain deposits can provide essential clues useful for interpreting material properties and continuity. This is especially true for foundations where sampling is limited. Floodplains are formed by a complex interaction of processes governed by stream power and the character of the sediment as well as natural dams formed by ice or landslides and more recent man-made dams. The deposition can range from coarse-grained high energy confined environments to unconfined fine-grained low energy environments, each with unique geomorphological features. Understanding and defining the range of expected environments for a particular site helps form the basis of important interpretations and judgment that are not possible using the physical sample data alone.

For dams the upstream to downstream continuity of deposits is the primary concern. For example; what is the likelihood that a sandy or gravelly channel deposit exist in the foundation that extends from upstream to downstream or that a series of interconnected similar deposits exist? How does particle size change along this pathway and is the pathway straight or sinuous? For levees, the lateral continuity of deposits extending from the waterside to the landside of the levee is the primary concern. For example, does an old meander channel extend below the levee from the riverside to the landside of the embankment? Are there pinchouts in the old buried channels where porewater pressure could be elevated? Where are the surficial low permeability deposits thin? Some type of geologic model is required to understand the existing conditions and subsequently estimate these probabilities.

In many geologic environments the likelihood of any particular material being laterally continuous is dependent on many variables (e.g., distance from primary sediment source(s), nature of sediment available for transport, depositional setting in the channel, etc.). For this reason, large dams with large footprints often have lower probabilities of material continuity than small dams. Conversely, the foundation of small dikes and levees in the same geologic setting are often more likely to have lateral continuity and spatially small features have a higher likelihood of being able to cross the entire feature and create a vulnerability that could lead to failure.

In some areas geomorphic principals are also critical for the evaluation of seismic and hydrologic hazards. Paleoseismic investigations include trenching (and logging), surface mapping and landform evaluations (from aerial photographs, topographic maps and LiDAR imagery) to map surface lineaments indicative of possible faulting. Geomorphic surface mapping may be required to establish relative or absolute age control on displaced features to determine when displacement last occurred.

Conversely, in a strictly stratigraphic sense, just being able to map the different landforms allows the geomorphologist to predict subsurface stratigraphic relationships through an understanding of erosional and deposition processes, and through developing an understanding of the sequence of events responsible for landform development. Borehole logging and stratigraphic interpretations may also be complicated by bed offsets that cannot be resolved without knowing that a fault is present. This may be critical in defining the hydrostratigraphic framework controlling seepage. Geomorphic mapping plays a critical role in identifying such structures.

Geomorphic mapping and principals have proven to be an important method for understanding the occurrence or non-occurrence of past or ancient flood events (paleoflood), particularly in the western United States. The climate data typically used in predictive models are mostly derived from 50-to 100-year long river gage and precipitation records. These records are too short to include the infrequently occurring extreme events. Desserts are one of the ideal locations for the preservation of evidence of catastrophic floods since rivers flow infrequently, human impact is low, and vegetation is sparse. Radiocarbon dating of organic matter (small particles of charcoal, seeds and other organics) permits estimates of flood frequency extending over thousands of years. These data can be very important for informing the estimates of flood recurrence probabilities by including flood events as old as 10,000 years in the records. The application geomorphology techniques to ancient flood deposits can provide a record of extreme rainfalls enabling a better understanding of the nature of past climate variability, the timing of extreme floods and their effect on the landscape. These techniques moved beyond the research stage in the early 1970's and can allow us to improve the hydrologic models used to estimate recurrence relationships of large floods, essential for dam and levee safety studies.

Influence of Human Activity on Levee Foundations

Since many flood walls and levees are constructed around major urban centers or along stretches of highly prized agricultural lands, human activity has sometimes influenced the foundation materials. In an urban environment, the structure alignment will most likely be well within the limits of the old urban area which once extended to the river's edge. Prior to levee construction, the original foundation materials could have been modified in order to maximize the area adjacent to the river. In agricultural areas, farmers may have influenced the river courses by constructing smaller soil berms to increase crop production. As a result, a more detailed examination of the human impacts on the foundation and adjacent materials may be required.

Suspected modifications to the natural foundation should to be investigated; changes mapped and overlaid; and potential impacts to foundation or embankment material properties communicated.

Through the life of the current levee, multiple processes may have influenced the foundation, levee embankment, or borrow areas. The effects might include changes to the natural fluvial deposition rates or processes. In some cases rock diversion dam, dikes, jetties, and river bank armoring may have been constructed to force river flow towards the major urban center to help maintain wharf or ferry service centers. These structures and the resulting changes to the natural system could be important to understand.

Areas within the levee footprint may have been filled in with a variety of natural or man-made waste materials which could impact the behavior of the foundation. These man-made alterations would most likely be prevalent in the areas of heaviest urban development for docks, ports, wharfs, railroad lines, rail-yards and the railroad beds themselves.

Valuable records from the county courthouse or local sanitation districts may include historical mapping, land owner plots, historical photographs, aerial photography, or land surveys. Overlaying this information with other data can be useful, including the location of borings, relief wells, closures, penetrations, seepage, and slope instability.

Evaluation of seepage and piping in karst terrain

Embankment dams constructed on untreated karst foundations have significant and somewhat unique risks for seepage and piping problems. This terrain, formed by dissolution of carbonate rocks (primarily limestones and dolomites) and evaporite rocks (primarily gypsum and salt), features sinkholes, breccias, subsidence problems, dry valleys, sinking streams, caves, springs and rock pavements. While there is extensive discussion in the geological literature on the nature of cave and karst development (phreatic, vadose and local water table controlled), all authors agree that karst development occurs through the action of water. The acidity of past groundwater played an important role controlling solutioning rates. Most of the groundwater during the development of karst is believed to have been mildly acidic. The carbonic acid that causes these features is formed as rain passes through the atmosphere picking up CO_2. Over geologic time, karst terrain forms an interconnected network of solution features.

As Waltham and Fooks state in their 2005 Paper, *Engineering classification of karst ground conditions*, "All voids in a block of karstic limestone are interconnected because they were formed by through drainage…"[1] (note that the "voids" can become filled will soils and collapse breccias and then are not "voids" until removed.)

Further complicating the matter is the fact that karst features are opportunistic. They develop along cracks, crevices, joints and bedding planes; wherever it is easiest for water to get access. This development can be structurally controlled. Where joint sets or faults are present at the site, there is likely further solution widening along these features. Thus, valley stress relief joints as well as other local jointing patterns can control the karst development of an area. As many dams are located in valleys where stress relief fracturing of the rock could be expected, the likelihood of an upstream to downstream seepage path can be quite high. Additionally, at changes in lithology, particularly when a more resistant bed is encountered, dissolution at the contact will concentrate. This can result in more horizontal cave and karst development.

The epikarst area (at and near the top of rock) is usually more weathered that the underlying karst system, allowing easy access to the overlying soils. This presents particular dam safety problems as sinkholes can form above an untreated earth embankment foundation and seepage pathways can exist at the soil/rock contact.

A more extreme karst terrain can be found in evaporite deposits (ie., gypsum, salt) which generally forms in more arid regions or where the evaporite rocks are buried and protected from rainfall. Where they are exposed at the surface in more humid areas, like the Eastern United States, these deposits dissolve quickly. In some cases, these deposits are removed nearly in their entirety and replaced by breccias that later became cemented and form higher quality rock.

Pre-existing solution channels in gypsum can enlarge quickly, particularly when impounding a reservoir. The proposed Upper Mangum Dam in Oklahoma was abandoned before construction due to gypsum deposits and the catastrophic failure of the Quail Creek Dike in Utah in 1989 was due in part to a gypsum unit located beneath the earth fill.

In addition, there are areas of "pseudokarst" where formation of caves and openings in the rock was not formed by solutioning of the rock, but was formed by other means such as lava tubes, sea caves and ice caves.

Because karst development is dependent upon the particulars of local and regional geology, the risks presented by different sites can vary. Some sites, such as Wolf Creek Dam, KY have large cave openings beneath the dam; others may present a more vertical karst development along joint features as with Center Hill Dam, TN. Where the limestone rock is inclined, bedding features may become particularly important. All have interconnected networks and paths, but the size and nature of these openings will be different depending upon the local and regional geological conditions. The risks can also

[1] *Waltham, A.C. and Fooks, P.G. "Engineering classification of karst ground conditions" published in Speleogenesis and Evolution of Karst Aquifers, republished from Quarterly Journal of Engineering Geology and Hydrogeology, 2003, vol. 36, pp 101-118.*

vary due to differences and extent of rock or soil breccias within and the existence of soil deposits over karst deposits.

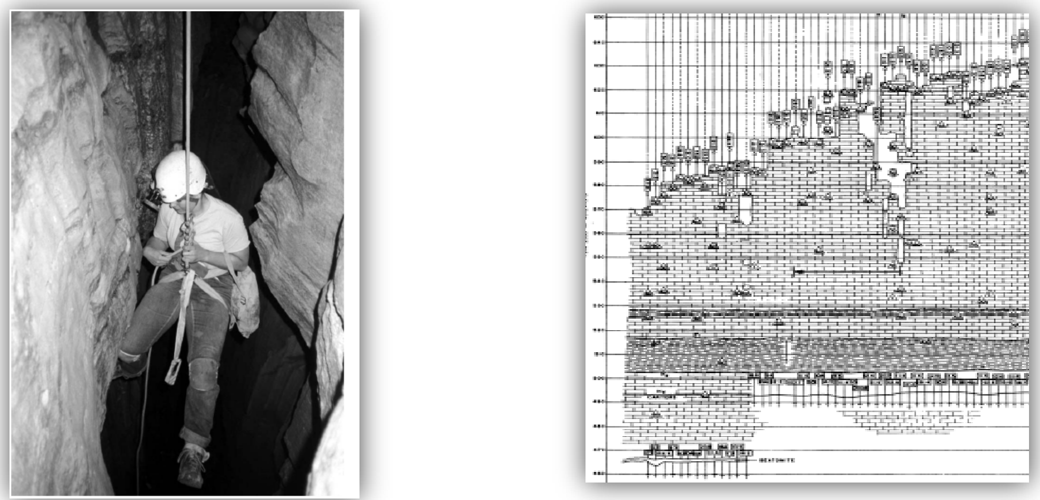
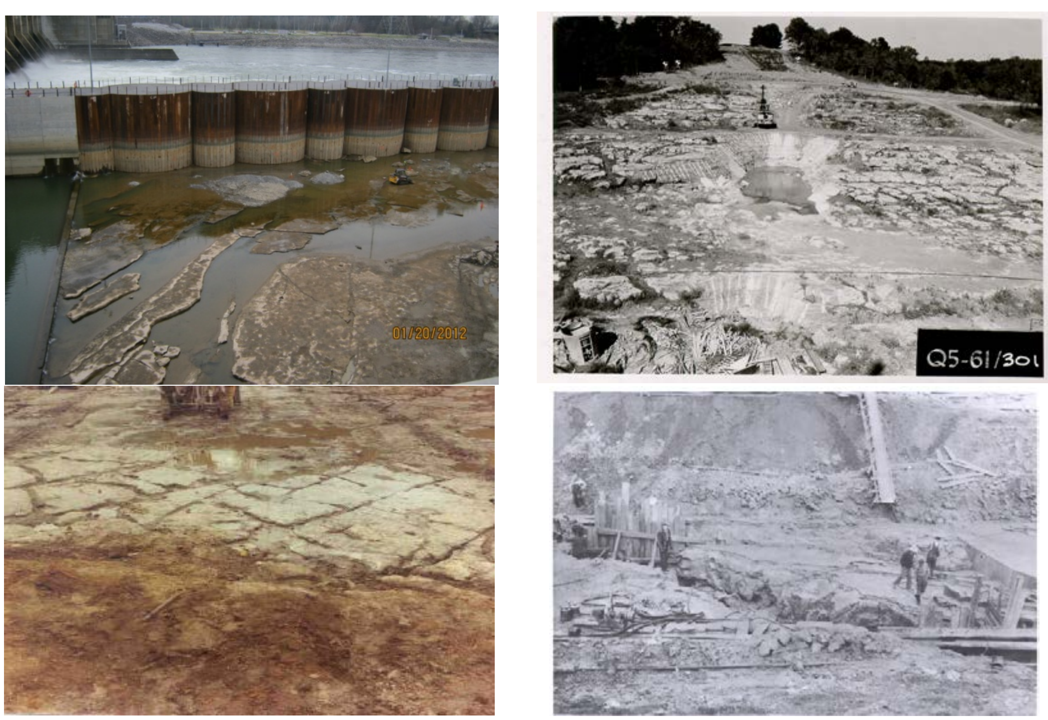


Figure 1. *Above*: Photograph of vertical development of "Plateau Margin" Karst in Tennessee[2]. *Right:* Geological Section from 1980s Center Hill Grouting program showing similar vertical development in the rocks underlying Center Hill Dam.[3]



[2] *Crawford, N.C. "Karst landform development along the Cumberland Plateau Escarpment of Tennessee" in* *<u>Groundwater as a Geomorphic Agent</u>, Lefleur, R.G. (ed) Bosten, Allen and Unwin, Inc. pp. 294-338, 1984.*

[3] *USACE, Center Hill Dam - Major Rehabilitation Evaluation Report Supplement, Appendix G, 2012.*

Figure 2. Photos of epikarst areas exposed by construction projects. (from upper left moving clockwise) **a.)** Epikarst Area in the Tennessee River at the new Chickamauga Lock, Chattanooga TN. **b.)** Rock foundation exposed underneath J. Percy Priest Dam, TN. **c.)** Beech Creek Limestone pavement below Patoka Lake Dam, Indiana. **d.**) Solution widened joint exposed in the cutoff trench during construction of Clearwater Dam, Missouri.

Even after extensive site investigations, it may be very difficult to quantify the extent of solutioning and the quantity of potential seepage. Joint patterns may inform the geologist of a likely seepage direction, but unless the dam foundation was completely cleaned and treated, it is impossible to accurately locate all potential karst openings which may contact the embankment.

To further complicate the issue, ancient karst development (paleo karst) at greater depth can be buried by younger sediments and preserved. This paleokarst development, which is well documented in many parts of the country, may have a completely different morphology than the currently active system.

The amount of soil infilling inside these openings can be highly variable and it is far more erodible than the surrounding rock. Sticky clay, often found on the sides of solution-widened joints and described as “cave-mud”, is extremely difficult to displace by pressure grouting and veins of grout can be formed within the soil breccias that are not removed.

Figure 3. Karst Foundation in limestone with inclined bedding beneath Haig Mill Dam, Georgia

Where there is sufficient water flow in these openings, this soil can erode over time. A grouting operation may fill openings in the rock, but it often will not eliminate all possible seepage paths and may require future grouting. As the infill material erodes over time, new grouting programs in the same location may take increasing quantities of grout to reach closure. Water may continue to erode the soil unless the karst opening is completely filled with grout, which can rarely be guaranteed.

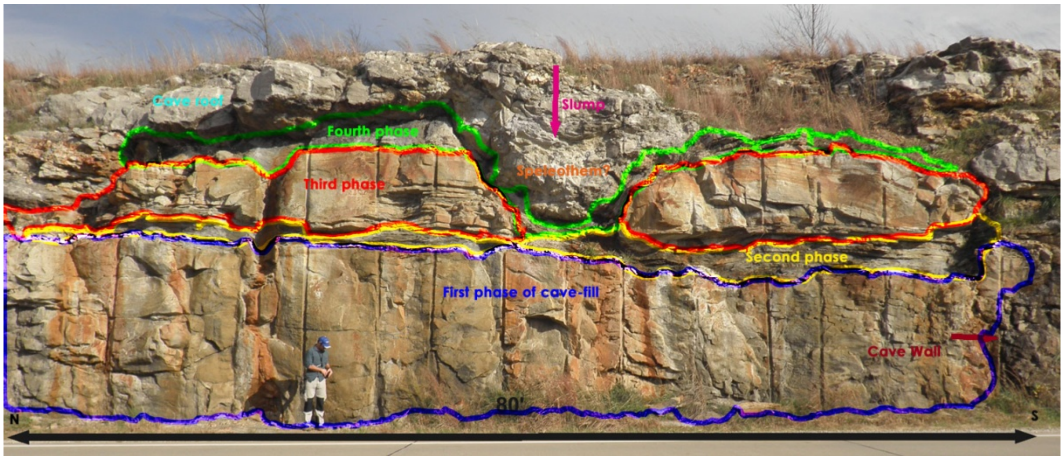


Figure 4. Missouri paleokarst exposed on Highway 39, Dade County, MO (from http://mississippian-cave-fill.blogspot.com/)

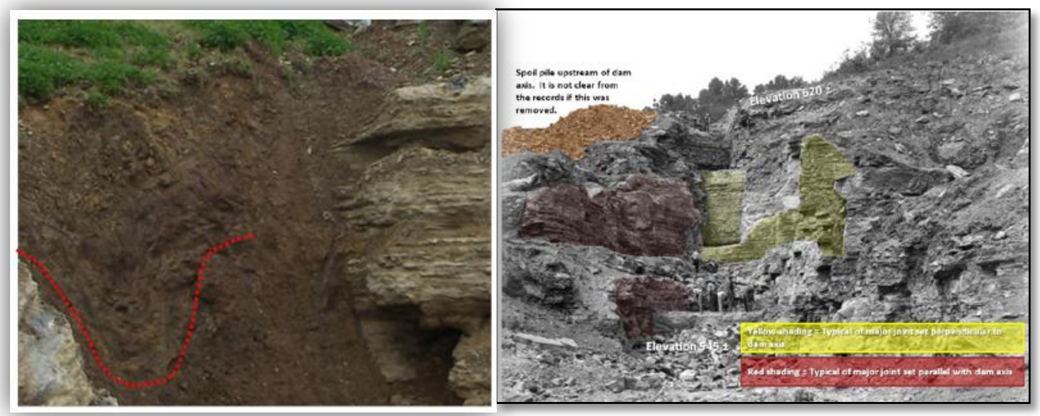
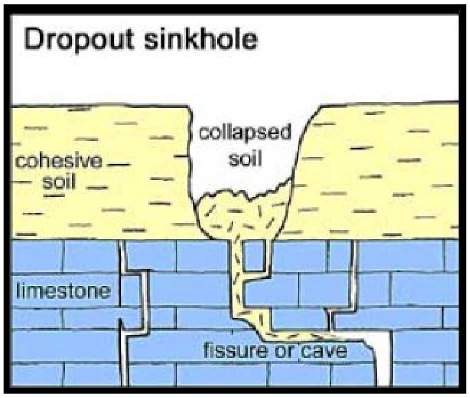


Figure 5. *Left:* Migration of soil into a karst feature at the left rim area of Center Hill dam. *Right:* Joint faces exposed in the core trench during construction of Center Hill Dam.

quantified.

Dam foundations with a highly permeable, open or partially open solution 3D networks capable of transporting high volumes of soil can progress more rapidly to failure. Substantial erosion of joint fill material can progress with no visible signs of distress, reducing the opportunity for detection and intervention. The surface area of the void feature that is in direct contact with the embankment can have a direct influence on erosion rates and the probability that erosion leads to failure. Features that are continuous at the foundation contact are more critical than smaller voids that isolate leakage within the bedrock.

Existing exploration technologies (drilling, sampling, geophysics) are often insufficient to accurately quantify the rate of sediment removal or identify active sinkhole development. Compacted clay embankments overlying sinkholes will tend to form arches which can be stable, sometimes for many years, before they suddenly collapse.



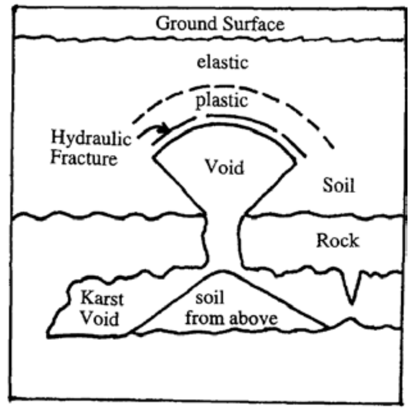


Figure 6. Diagrams of Sinkhole Development in soil. *Left:* Dropout (also known as cover-collapse) type sinkhole from Waltham and Fooks[4], *Right:* Sinkhole formation in cohesive soils from Tharp[5]

Where water has direct access to the underlying karst opening, enlargement of the sinkhole can be quite rapid. These types of sinkhole failures can be induced or accelerated by man-made activities that include increasing drainage flows, drilling, and reservoir loading. Declines in groundwater levels due to drought or pumping can also accelerate sinkhole progression.

In addition to the typical drill hole logs and permeability testing, the type of information that has proven useful for evaluating karst foundations includes:

- Detailed photographs of exposed bedrock in the foundation during construction:
    - Location and size of open or solutioned joints and cavities that are exposed to the overlying foundation and/or embankment structure
    - Details of infilling material – nature, type, classification and how open are the features where infilling is exposed. Does the infilling appear to be weathered in-place residual material or is it transported material?
    - Higher velocities flows are much more likely where gravel deposits are found instead of clay infilling.
    - Continuity of solution features – how likely are these features to provide an upstream/downstream connection?
    - Orientation and character of controlling geologic structure including joint faces which may be visible during construction (How are the features open to the overlying soils? Are they open "windows" with particular apertures or are they "slot like" with pinnacles and vertical fissures?)
    - Amount of weathering on exposed solution features in the rock. Are the walls smooth which may indicate higher velocity water flow? Are the walls fluted which indicate smaller scale turbulent water flow which may be a little more restricted? Are there cave deposits such as flowstone visible?

[4] *See Waltham and Fooks, Footnote 1.*

[5] *Tharp, T.M., "Cover-Collapse Sinkhole Formation and Soil Plasticity" in Sinkholes and Karst 2003, ASCE, pp 110-123, 2003.*

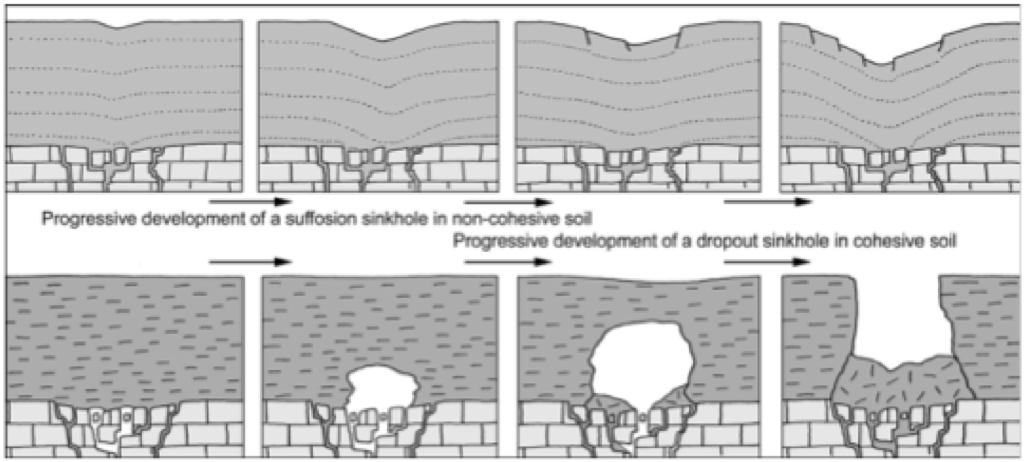


Figure 7. Development of typical sinkholes in non-cohesive soils and in cohesive soils. The non-cohesive soils produce a more slowly developing subsidence. The cohesive soils, with the ability to bridge over the developing void in the soil, can collapse suddenly.[6]

- Construction foundation reports and design data:
  - Descriptions of foundation treatment – was the entire foundation cleaned? Was the rock foundation treated or did the designers depend on a small core trench leaving most of the foundation untreated resulting in high gradients into open unfiltered features?
    - Grouting quantities, large takes, interconnections – is there a particular pattern to the interconnections noted during grouting programs? Are there areas with very high takes only under gravity grouting such as large takes for casing grout?
    - Slush grouting or dental concrete location and extent – were all exposed features cleaned and treated with dental concrete or did construction only clean out and fill certain features? Were features cleaned across the entire foundation?
    - Bulkheads at large openings – were caves exposed in the foundation or in the core trench?
  - Records of exploration borehole fluid losses, voids, etc. – for certain types of drilling the only record of karst features exposed in the subsurface may be tool drops and fluid losses.
  - Drawings, sketches or sections showing solution features
- Piezometer Data: Careful, detailed evaluation of piezometer response data can be particularly difficult in karst terrain . Piezometers will respond differently depending upon whether they are located in the dam embankment; in a completely open karst drainage path; in a partially blocked drainage path; or in a completely blocked karst opening. If the context of the instrument is not known, then its behavior is difficult to understand. Essential points for evaluating instrumentation include:
  - Evaluation of headwater and tailwater influence on piezometers indicating permeable connectivity. The head difference and reaction time is important to understand.

[6] *Ibid 6.*

    - Sudden increases or decreases in water levels indicating shifting drainage and flow conditions. These can sometimes be correlated with high headwater events or construction-induced changes.
    - Long term changes in the instrument response, or tighter correlation with headwater and/or tailwater over time. Subtle decrease in water levels may indicate that flow paths are opening and providing more drainage.
    - Increasing gradients are more important to look for than simply changes in water levels
    - Determination if gradients are into or out of the bedrock and if gradients fluctuate seasonally between these conditions.
    - An appreciation for the sampling interval of the instrument. Piezometers only read monthly often provide very little useful data in karst. In special cases such as nearby construction, daily readings are more helpful. Karst foundations are often very reactive to drilling, water pressure testing or grouting and can react instantaneously to these operations. Automated piezometers recording at 15 minute intervals are far more useful in these situations.
- Review of published information on regional karst development and review of exposed rock in the vicinity of the project.
- Review of existing geophysical investigations
    - DC resistivity methods have been useful in defining contrasts between limestone and water or air filled voids. Resistivity can be analyzed in 2D, but the 3D tomographic methods may also be of use in locating potential voids. These investigations are most effective when combined with targeted drilling or where previous boreholes help inform the geological model.
    - Ground penetrating radar is effective where the overlying soils are not clay
    - Self potential difference models have been useful to show seepage paths, especially in combination with resistivity or with ground penetrating radar.
    - Downhole geophysics, testing and photography can also add to the understanding of the rock underneath the dam:
        - Gamma-gamma methods can identify clay layers
        - Cross-hole P and S wave velocity measurements can be used where tightly spaced boreholes are available.
        - Borehole image logs: the Optical and Acoustical Televiewer (OTV/ATV) provides static pictures of the borehole circumference with depth.
        - CCTV cameras can be used to explore large openings or assess flow rates where water is filling a hole. They can be useful in large openings, particularly if a light source can be introduced in a separate drill hole
    - Microgravity surveys can also provide data because the negative anomalies produced by this method represent “missing mass: which can be interpreted as either an air filled, or water filled void.
    - Permanently installed electrical resistivity grids for real time monitoring to assess changes with time (DC resistivity and self potential

Drilling in Karst

In solutioned foundations the interpretation of conditions between boreholes is extremely challenging. The perils of this process are easily seen when looking at rock cuts in karst (figure 8). Even in relatively simple cases, vertical boreholes are commonly insufficient to describe the existing conditions and inclined boreholes are preferred.

Projections made between drill holes require an appreciation of the uncertainties and an understanding of the nature of the karst system. Interpretation should be carefully informed by:

- Anticipated depth to rock.
- Extent of the karst development in the area – can large openings be expected or is the karst development small and perhaps primarily along bedding? Is there significant vertical karst development? Are there numerous mapped sinkholes in the area? Are there numerous springs in the area?
- Structural controls presented by area jointing, faulting and bedding patterns. Intersections of joints or fractures in the rock are likely to be more eroded and widened by previous solutioning.

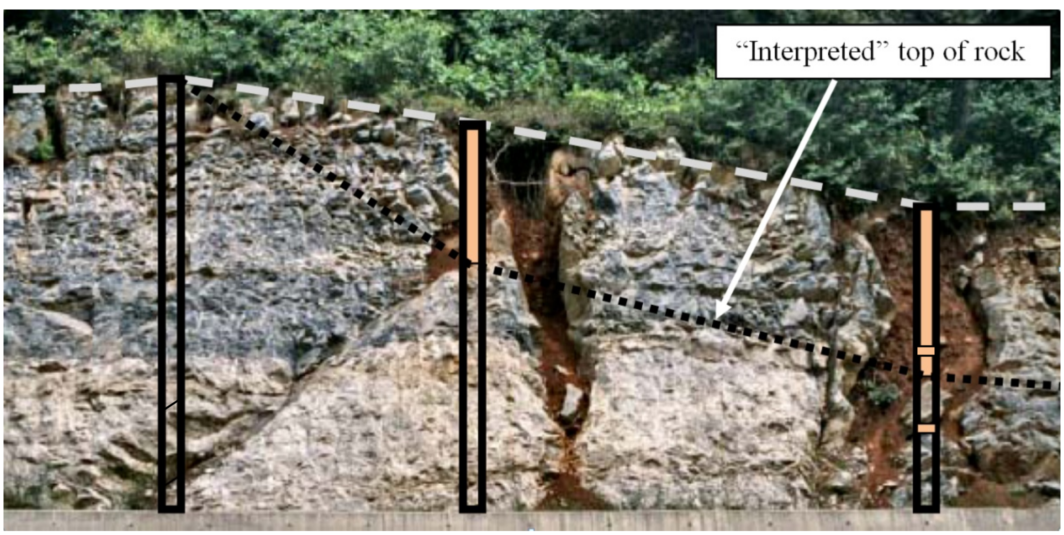


Figure 8. The perils of "connecting the dots" between drill holes in karst terrain. This photograph, taken from Waltham and Fooks[7], has regularly spaced boreholes. The vertical development of karst shown in this rock cut means that simply drawing a line between adjacent boreholes can produce a substantially incorrect interpretation.

[7] Ibid, Footnote 1

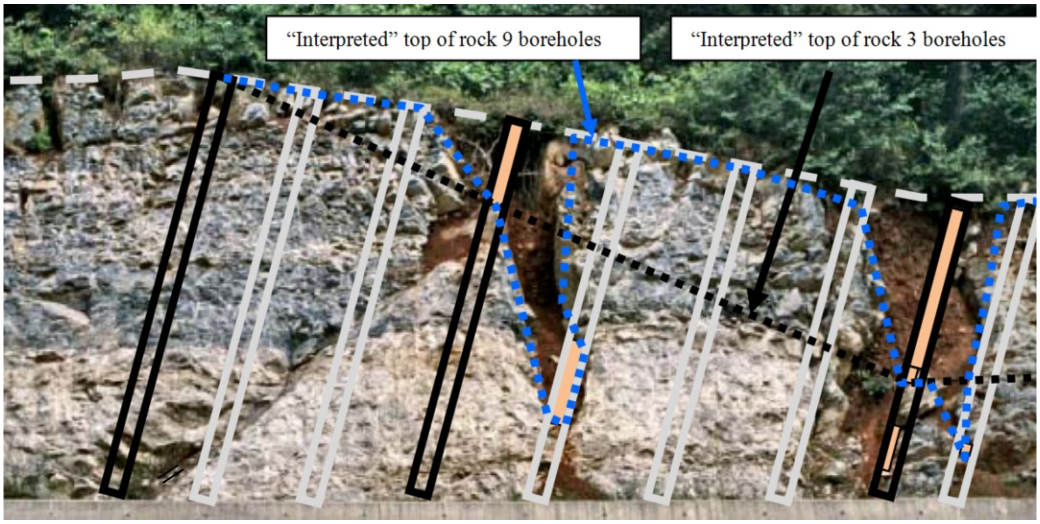


Figure 9. Drilling “interpretation” based on inclined boreholes for the same number of boreholes and interpretation based on 3 times the number of initial inclined boreholes. Inclining the holes, and adding additional holes greatly improves accuracy in interpretation with boreholes alone.

- Anticipated depth of the epikarst zone – this can vary both regionally and locally depending upon the topography, waters’ access and changes in lithology.
- Changes in rock lithology which can change the pattern of the karst development. When less soluble rock is encountered, karst development tends to continue and enlarge along the bedding contact, even if overlying development is more vertical.

Supplementing a drilling investigation with geophysics, area geological mapping and a firm grasp of the geological context of the site will improve the geological interpretation and produce a more reliable understanding of potential failure modes essential for estimating dam safety risks. Computer modeling can be instrumental for sorting and displaying large amounts of data in three dimensions. This is especially true for projects with previous remedial work including grouting or cutoff wall construction since the volume of available information can be overwhelming to sort, plot and understand. The advancement of GIS capabilities, CADD modeling and relational databases to store large volumes of data give the modern geologist or engineer more ready access to enormous amounts of information. Evaluating large projects requires integrating all of this data into a usable and understandable form.

Individual risk estimates associated with karst solutioning can be highly variable, especially when data are poorly organized and the foundation is not understood Estimates can become subjective and based more on the “gut instinct” of estimators rather than on carefully evaluated data.

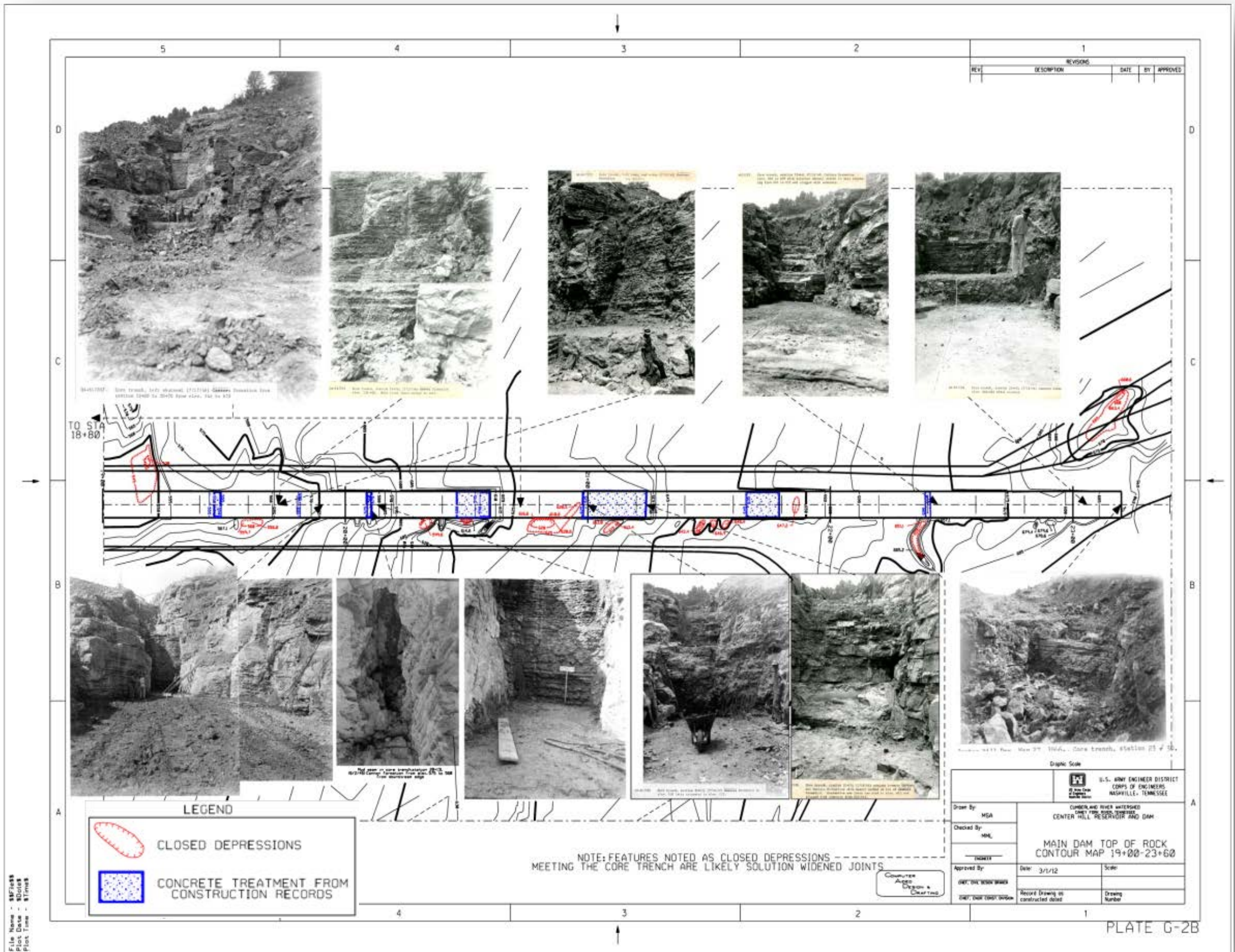


Figure 10. Example Plan View of a section of the Center Hill Dam Core Trench showing top of rock contours, areas of dental concrete treatment and construction photographs

If all the geologic clues are not assimilated and presented in a form for the team to understand, there may be no common basis for estimates and uncertainty will be so large that the value of the risk estimates may be limited.

This evaluation can benefit greatly from the input of geologists with experience in karst evaluations working to develop a geologic model that represents the best estimate of subsurface conditions based on available supporting data. It is only after such a complete and detailed evaluation that the need for (and type of) additional investigations and studies can be properly assessed.

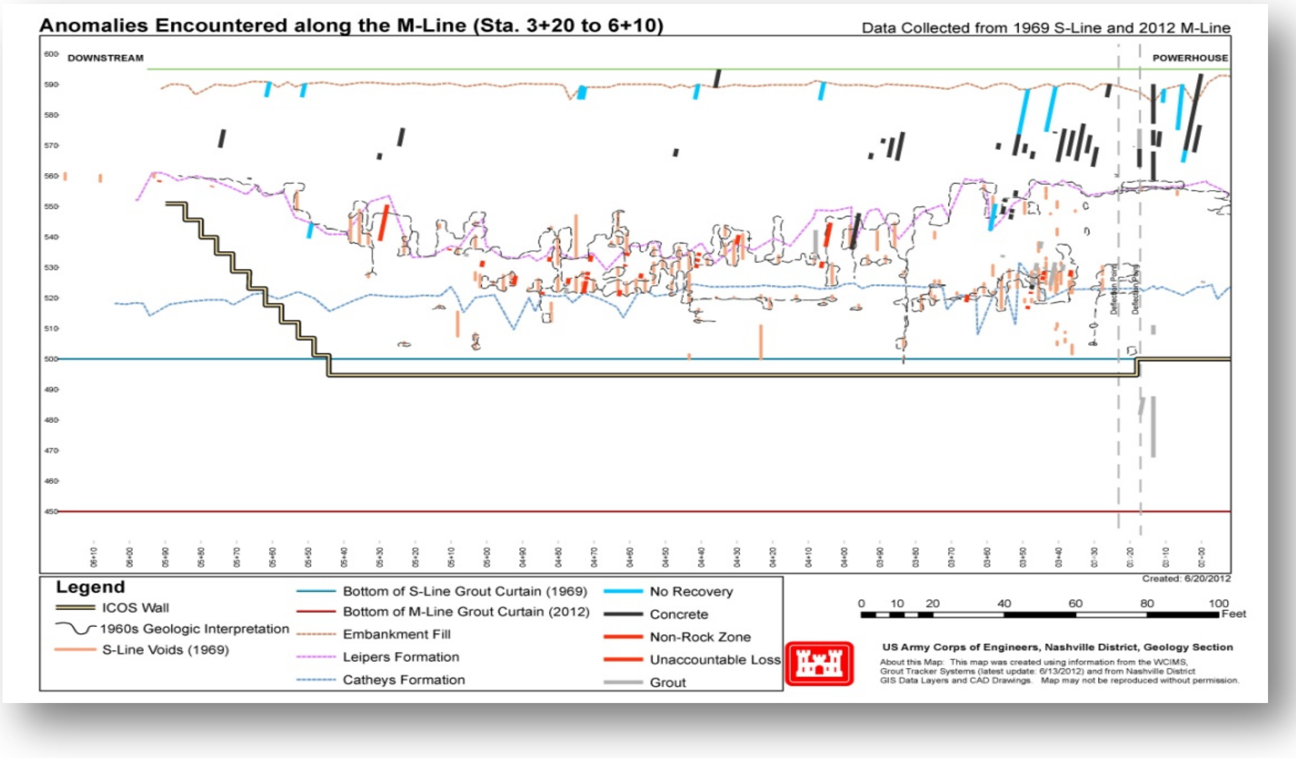


Figure 11. Example Geological Section produced with GIS along a section of the Switchyard Wall at Wolf Creek Dam summarizing the interpreted top of rock profiles, non-rock intervals and other anomalies from the 1969 and 2012 drilling programs. This section was used, along with the next figure to provide an interpretation of the subsurface response to the 2012 grouting program.

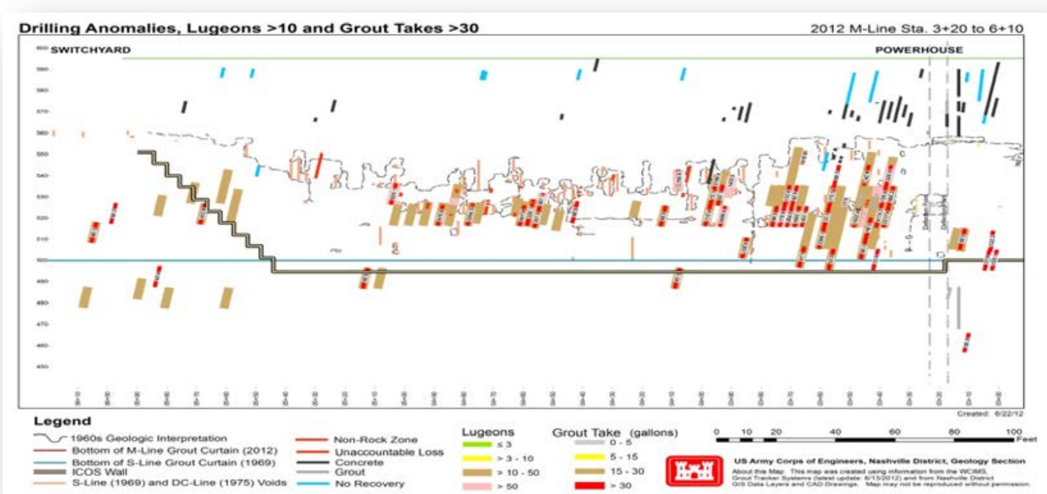


Figure 12. Example Geological Section produced with GIS along a section of the Switchyard Wall at Wolf Creek summarizing areas of large lugeon values during water pressure testing and high grout takes during pressure grouting. Note the correspondence between the interpreted geological section, non-rock intervals from drilling and the higher lugeons and grout takes.

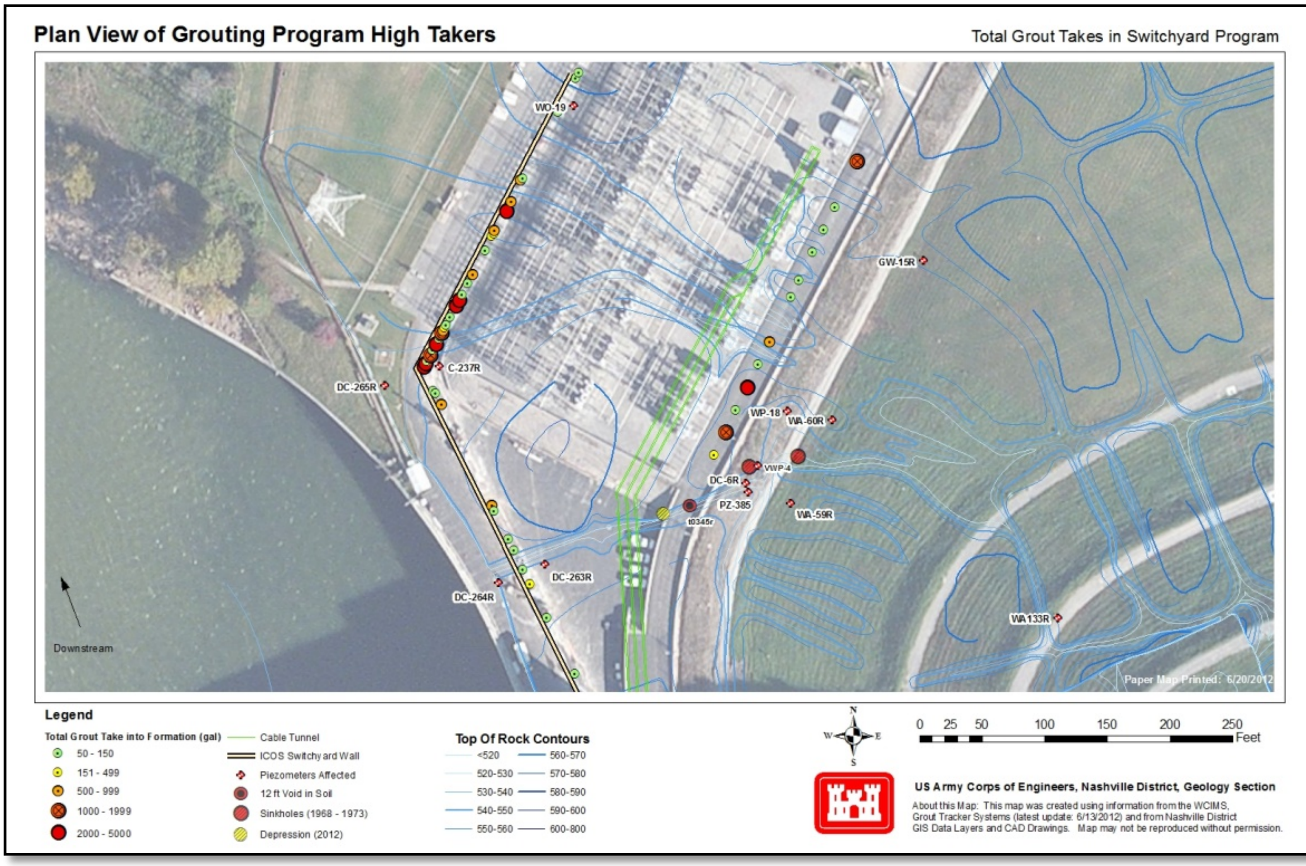


Figure 13. Example Plan View Map produced with GIS at Wolf Creek dam showing grouting results, interpreted top of rock map, pertinent features and key piezometers.

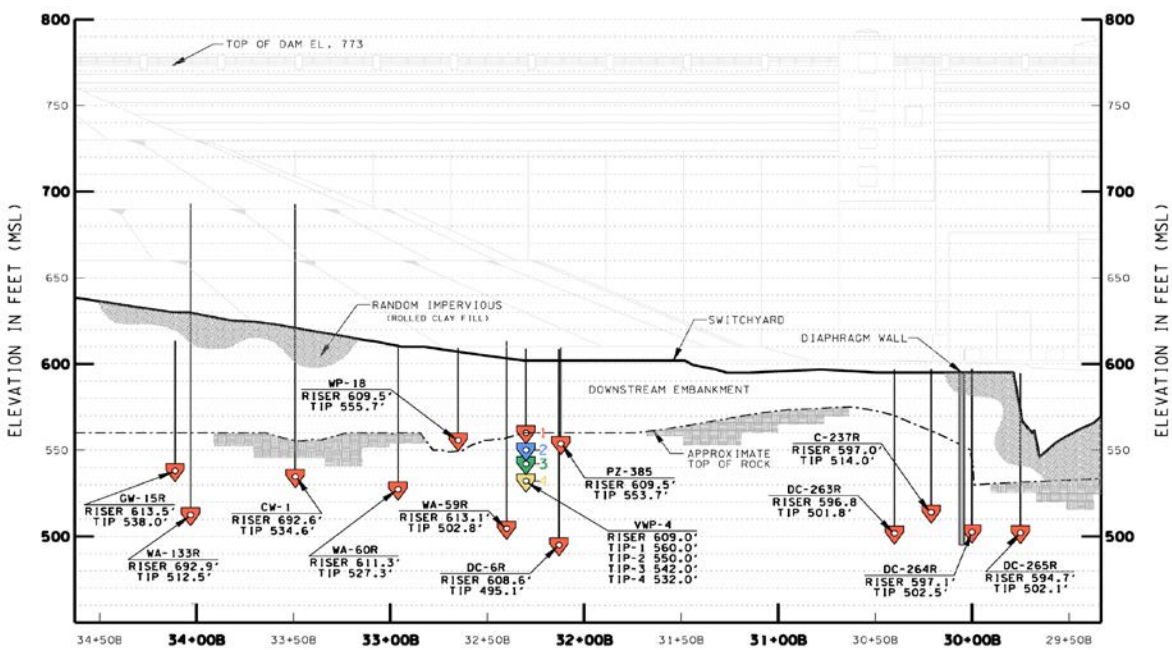


Figure 14. Example Geologic Section at Wolf Creek Dam Switchyard produced with CADD projecting the locations of pertinent piezometers and their sensing elevations relative to the switchyard wall.

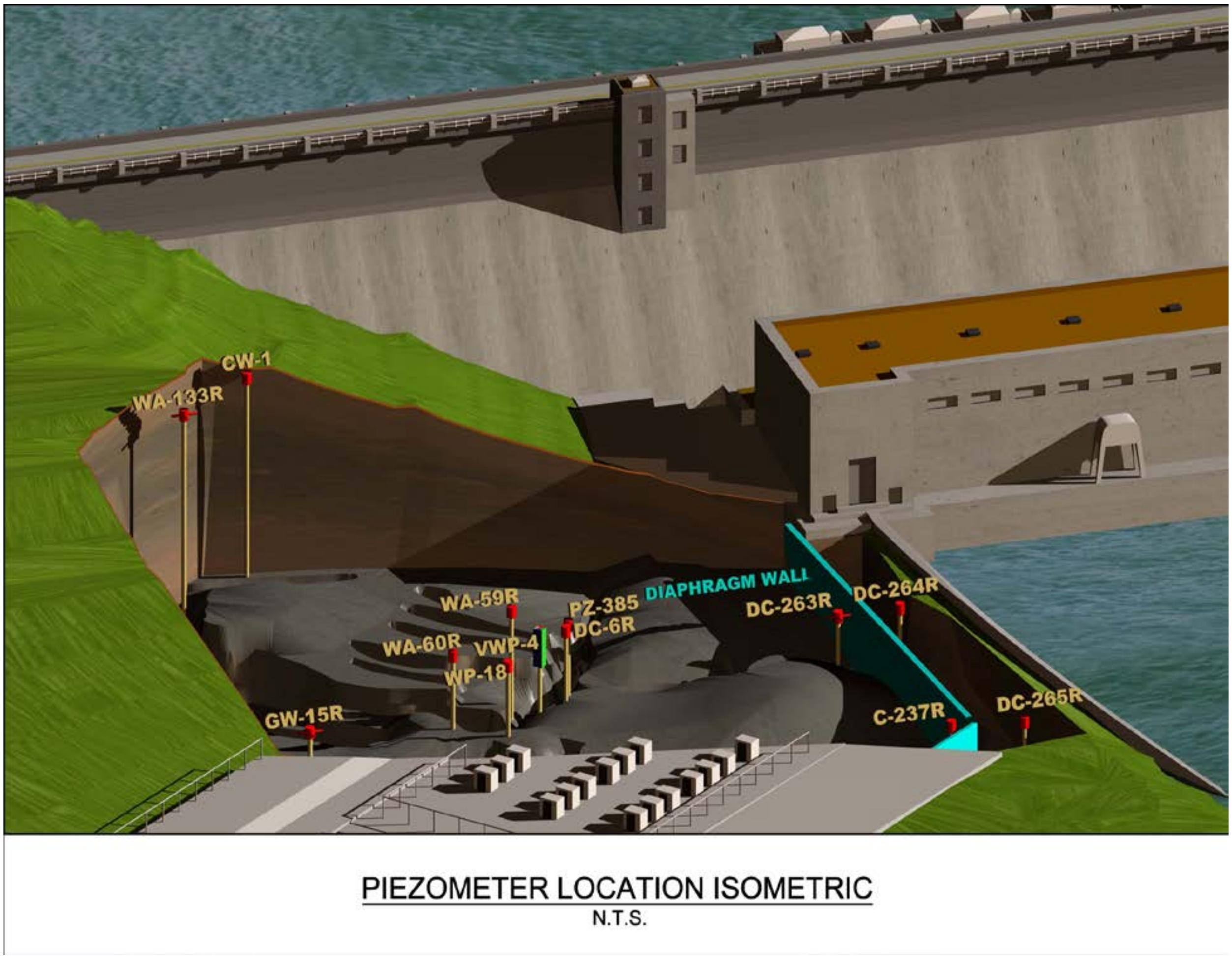


Figure 15. Example Isometric View of Wolf Creek Switchyard produced with CADD showing top of rock, switchyard features and relevant piezometers for evaluating the 2011-2012 Switchyard Grouting Program.

Mineral Extraction Failure Modes

Mineral extraction for the purpose of this document refers to the removal of solids, fluids or gas from the ground beneath or in the area of a levee, dam or reservoir. Examples include:

- Natural gas and oil production
- subsurface and surface mining (for coal, salts, sulfides and minerals such as copper, iron ore, aluminum, etc.)
- Blasting
- Hydraulic fracturing for well production
- Saline pumping, including injection of waste brines
- Groundwater pumping
- Sand and gravel pits
- Coal bed methane extraction
- Geothermal energy
- Carbon sequestration
- Minerals related infrastructure, such as pipelines and compressor stations

These extraction activities can act to exacerbate failure modes already considered and/or result in additional unique failure modes. This list is by no means exhaustive, so it is important to evaluate any minerals related activities that occur in close proximity to a project. It is also expected that mining technologies will continue to evolve over time and may facilitate the development of resources that are currently considered to be undevelopable. As a result, minerals extraction may continue to present new and different performance considerations that our dams and levees were not designed to accommodate. For example, recent improvements in the technologies associated with horizontal drilling and hydraulic fracturing have dramatically increased drilling and production of oil and gas in previously unexploitable shale deposits. Referred to as “unconventional” extraction since it relies on increasing the permeability of the formation via hydraulic fracturing to extract the gas or oil found within the target geologic unit, unconventional extraction has become commonplace in many areas of the United States. Because unconventional shale deposits underlie hundreds of dams and thousands of miles of levees, we must consider the impacts of each part of the process (drilling, hydrofracturing, extraction and injection) on the integrity and performance of critical infrastructure.

Whenever mineral extraction related activities occur in the vicinity of the embankment, appurtenances or reservoir, associated potential failure modes must be considered and evaluated. The failure of Baldwin Hills Dam in 1963 was suspected to be a result of differential movement along an existing fault due to subsidence associated with oil extraction. Evaluations of potential failure modes in the case of mineral extraction are very site-specific and should be based on details of the mining activities and known or estimated geologic conditions beneath the dam and reservoir. Some sources of information useful for evaluating the effects of mineral extraction include records from State and County regulatory agencies, the USGS, the EPA, industry and academic literature. Company data may include such things as 3-D seismic surveys and interpretations, micro-seismic data, core borings, well construction information, drilling details, mine layout and sequencing, waste disposal practices, aerial photographs, and permit application submittals, etc.

Because evaluation of mining processes and their effects is not a traditional area of dam safety expertise, it may be necessary to obtain outside experts to help determine potential failure modes associated with these activities, and to develop reasonable estimates for likelihood of occurrence. When seeking such expertise, it is important to avoid sources with close ties to the industry to help avoid potential conflicts of interest and the appearance of bias in the study findings.

The different methods used for various types of mining will produce varying impacts at the surface and in the underlying strata. For example, subsidence resulting from the room and pillar method of mining produces surface characteristics and collapse mechanisms that are quite different from the subsidence associated with longwall mining or the extraction of gas, oil or water.

Minerals related activities may exacerbate failure modes already considered and/or result in additional unique failure modes, including:

- Subsidence leading to embankment of foundation cracking
- Subsidence leading to differential settlement or tilting
- Subsidence leading to loss of freeboard

- Mine collapse that stopes to the surface
- Movement along pre-existing faults or shears in the foundation
- Differential settlement leading to cracking along the interface between the embankment rigid concrete structures (spillways and outlet works)
- Induced seismic activity that may contribute to liquefaction or stability problems
- Differential movements leading to displacement of the conduit allowing uncontrolled erosion of the embankment into tor along the conduit
- Loss of reservoir water into mines with possible downstream flooding
- Fluid pressures associated with well blowout or uncontrolled hydrofracturing may contribute to erosion of the embankment of foundation

Considerations when evaluating the potential impact of mineral extraction on dam or levee safety include:

- Depth and lateral distance of all activities from dam, levee, or reservoir
- Size of subsurface mine excavations (low roof versus high roof workings)
- Location and magnitude of deformation, both local and wide-spread
- Engineering properties of the target formation (Young's modulus, Poisson's ratio, etc.)
- Influence of local geologic structure (faults, shears, jointing, etc.)
- Influence of local geologic stratigraphy (different lithologies, thickness of units, and rock strengths)
- Possible long-term influence associated with gas, oil or fluid withdrawal
- Location and characteristics of pipelines, compressors and other infrastructure needed to transport the product.

Other Minerals Related Impacts

In addition to dam or levee safety issues, there are numerous environmental issues associated with mineral extraction that can have significant impact on authorized project purposes. While these are not likely to contribute to failure, environmental concerns would likely impact water supply, water quality, low-flow augmentation, fish and wildlife protection, natural resource management and protection, navigation, and recreation warrant evaluation.

Important Reading for Engineering Geologists

Terzaghi, K.v., "Engineering Geology on the Job and in the Classroom", Harvard Soil Mechanics Series No. 62, Vol 48, April 1961, p. 97-139

Terzaghi, K.v., "Past and Future of Applied Soil Mechanics", Harvard Soil Mechanics Series No. 62, Vol 48, April 1961, p. 97-139

Terzaghi, K.v., Effects of Minor Details on the Safety of Dams, Am. Inst. of Min. and Metal. Engrs., Technical Publication No. 215, Feb. 1929

Deere, Don U., "Engineering Geologist's Responsibilities in Dam Safety Studies", ASCE publication Foundation for Dams, Asilomar Conference Grounds, Pacific G rove California, March 17-21, 1974.

Burwell, Edward B., Roberts, George D., The Geologist in the Engineering Organization",   Application of Geology to Engineering Practice, the Berkey Volume, Geological Society of America, 1950.

Geologic Resources for Dam and Levee Geology Drawings

Woerner, E.G., Dunbar, J.B., Villanueva, E., and Smith, M. (2003), "Geologic Investigation of the Middle Mississippi River" (ERDC/GSL TR-03-7); United States Army Corps of Engineers, Engineering Research and Development Center, Geotechnical and Structures Laboratory

Glynn, M.E and Kuszmaul, J. (2004). "Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model" (ERDC/GSL TR-04-12) *Technologies and Operational Innovations for Urban Watershed Networks Research Program*, United States Army Corps of Engineers, Engineering Research and Development Center, Geotechnical and Structures Laboratory   http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA428221 *IMPORTANT NOTE: Glynn (2004) has been superseded by a revision in 2010. The model equation had a TYPO error*.

Kolb, C. R. (1975). "Geologic control of sand boils along Mississippi River levees," Technical Report S-75-22, United States Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA014274

Shaffner, P.T., "Geologic Data and Risk Assessment; Improving Geologic Thinking and Products" United States Society on Dams, 21st Century Dam Design – Advances and Adaptations, 31st Annual USSD Conference, San Diego0, CA, April 2011
http://ussdams.com/proceedings/2011Proc/545-570.pdf

National Geology and Mapping Resources

http://nationalmap.gov - USGS National Map Viewer and Download Platform

http://ngmdb.usgs.gov/ - USGS National Geologic Map Database

http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm - Soil Surveys

http://earthquake.usgs.gov/ - USGS Earthquake resources

http://lmvmapping.erdc.usace.army.mil/ - ERDC Geology maps of Mississippi

https://corpsmap.usace.army.mil/ - Corps maps program

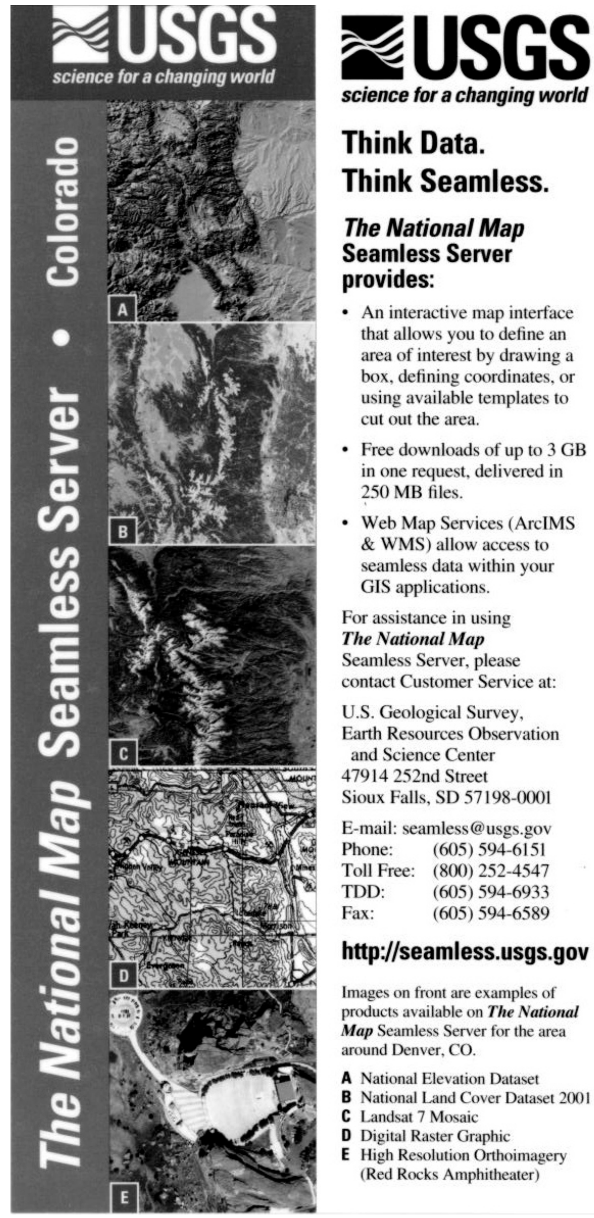
http://www.cflhd.gov/resources/agm/ - Geophysics resource, Federal Highway Administration

http://msrmaps.com/ - USGS air photos and maps – free

http://www.esri.com/data/free-data - ESRI links to free GIS web based data http://www.stategeologists.org/ - Association of American State Geologists – links to all state geological surveys web pages

http://www.techtransfer.osmre.gov/NTTMainSite/Initiatives/NMMR/nmmr.shtm - National Mine Map repository includes abandoned and active mines

http://www.usbr.gov/library/ - USBR Library page has many useful links inside and outside of USBR



USACE Geologic Data Collection

Subsurface Drawing and Data Requirements for PFMA, Risk Analysis, Modification Reports, Issue Evaluations, etc; Geology, Geotechnical Engineering and Instrumentation. USACE LINK (Technical Excellence Network) for Geology: https://ten.usace.army.mil/Files/4/5/5/9/Drawing%20and%20Data%20Requirments%20for%20PFMA%20and%20Risk%20Analysis%20(5)%20(8).pdf -

Additional references and information provided for USACE employees under "General Information" USACE Link: https://ten.usace.army.mil/TechExNet.aspx?p=s&a=CoPs;104 -

Technical Excellence Network site for Geotechnical Engineering, USACE link: https://ten.usace.army.mil/TechExNet.aspx?p=s&a=COPS;8 -

RADSII Risk Management Center Resources and Information; example drawings provided under "Geotech and Geology"; USACE link: https://radsii.usace.army.mil/RMCResources.aspx -

RADSII project data, etc.; USACE Link: https://radsii.usace.army.mil/Login.aspx

https://kme.usace.army.mil/Centers/IWR/RMC/default.aspx - RMC – sharepoint

Levee Tools and Data

lmvmapping.erdc.usace.army.mil - Geomorphic Maps: Lower and Middle Mississippi Valley Engineering Geology Mapping Program, Technical Reports, US Army Corps of Engineers, Engineering Research and Development Center,

http://nld.usace.army.mil/egis/f?p=471:1:3936126924813426 – National Levee Database http://maps.crrel.usace.army.mil:7778/lstp/f?p=480:1 – Levee Screening Tool

http://maps.crrel.usace.army.mil:7778/apex/cm2.cm2.map?map=UOC – CorpsMap

http://www.fema.gov/plan/prevent/fhm/lv_lamp.shtm - FEM

Bureau of Reclamation Publications

Engineering Geology Field Manual (pdf) vol 1 and 2:
http://www.usbr.gov/pmts/geology/geoman.html

Earth Manual part 1 (*Earth Manual* comprehensively covers the engineering of earthen structures. Extensive bibliographies supplement each chapter. An exhaustive index references and cross-references hundreds of terms):
http://www.usbr.gov/pmts/materials_lab/pubs/earth.pdf

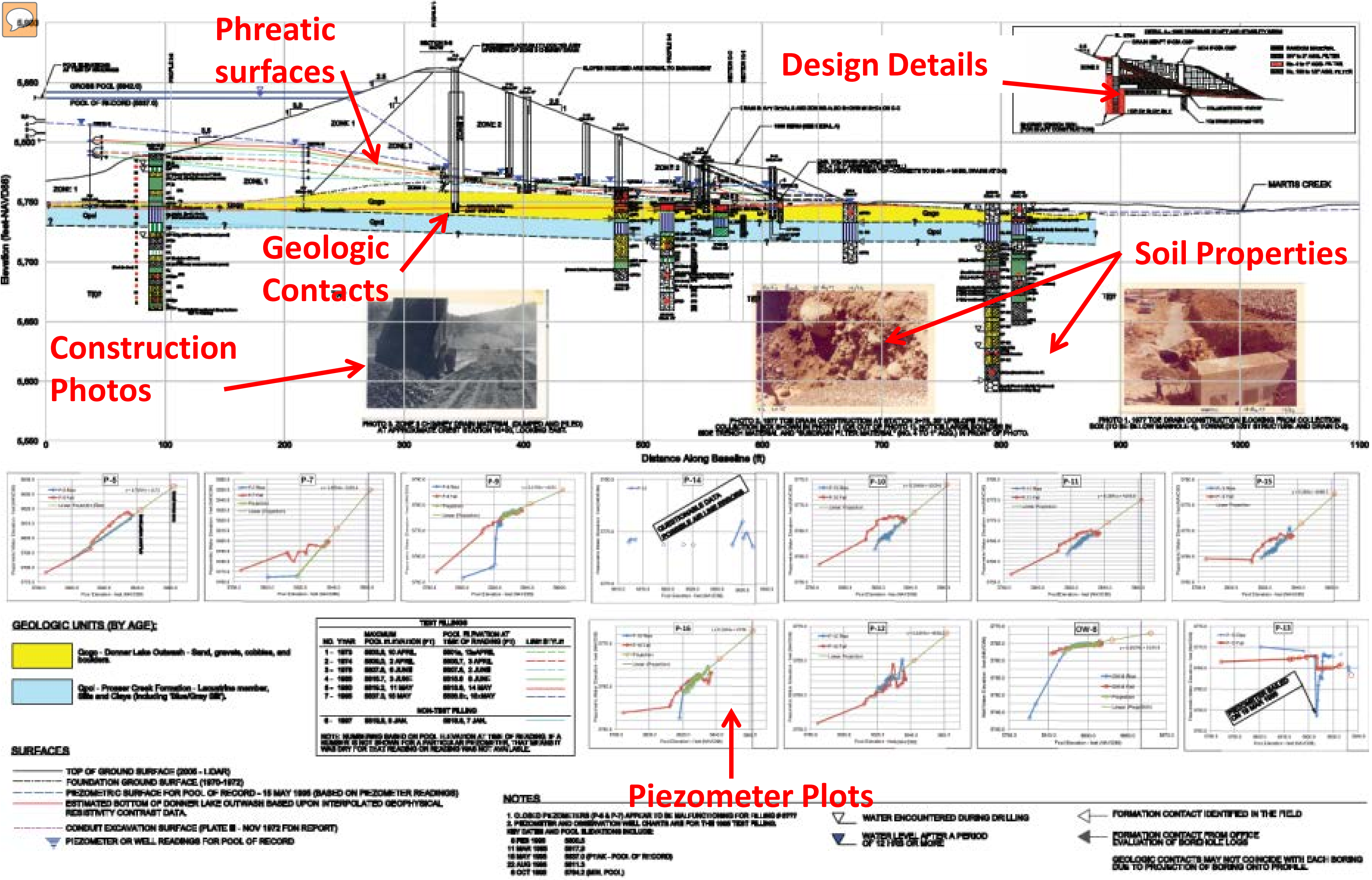
Examples of Geologic Sections displaying Dam Foundation Data

This collection of example drawings is intended to be used along with Chapter 10 of the Best Practices manual “Engineering and Geology”. The examples come from the Bureau of Reclamation, the US Corps of Engineers and private industry.

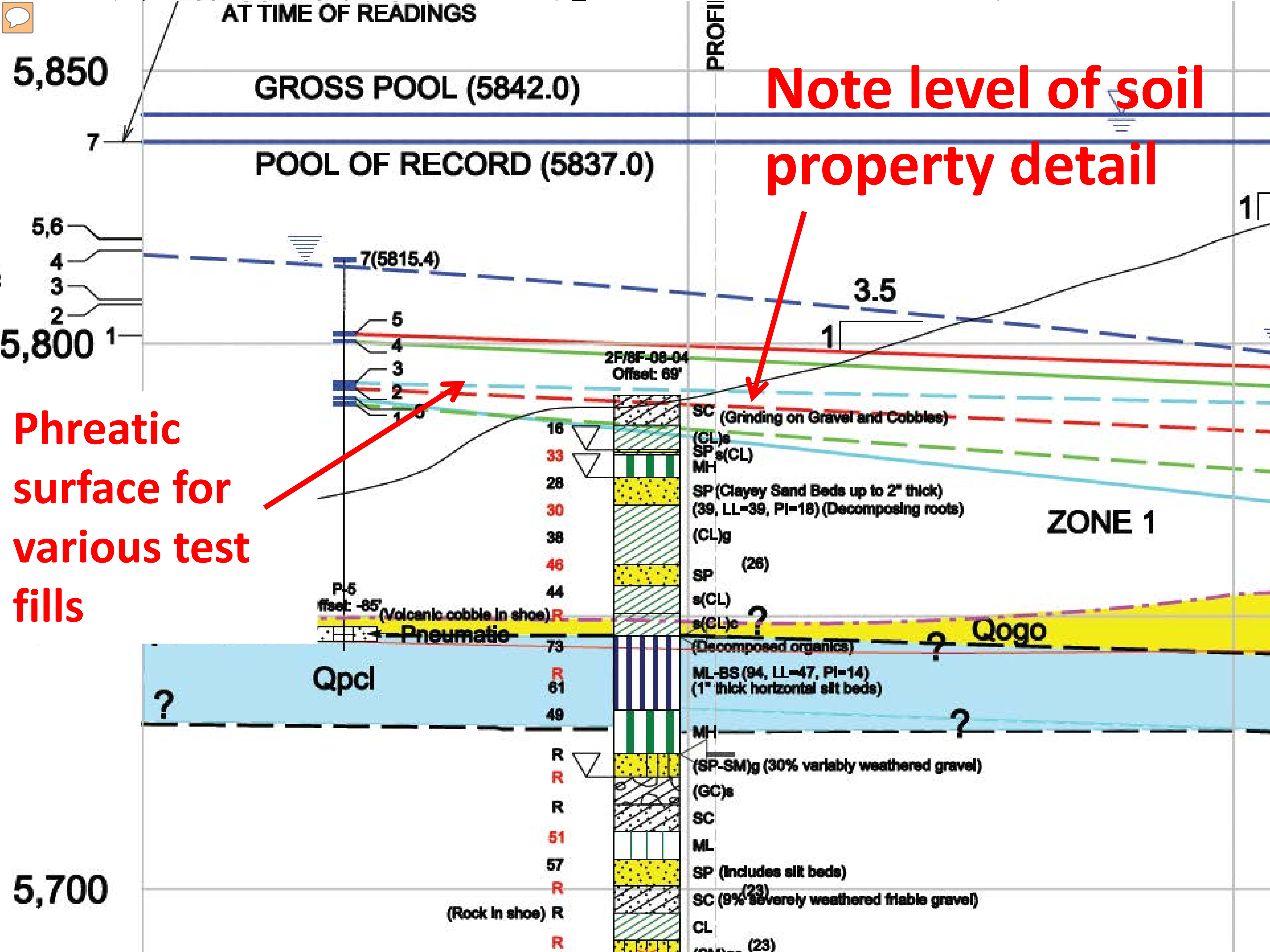
Most of the examples provided in this powerpoint file are taken from full sized drawings developed to be used with no reduction. It is difficult to legibly display on a powerpoint slide the detailed engineering properties that are easily read on the full sized drawings. The advantage of non-exaggerated full size drawings is that a scale of 1”=20” or 30” can be used to display the detailed engineering properties essential to evaluation the dam and foundation.

Where time permitted, portions of the cross sections were enlarged for display in this presentation to show the viewer the details visible on the full sized drawings. For Corps of Engineers employees, additional full sized PDF drawing examples are available here:
https://radsii.usace.army.mil/RMCResources.aspx
(Corps of Engineers Risk Management Center Resources, RADSII directory; see “Geotech and Geology” link).

Martis Creek Dam



Martis Creek Dam Foundation Drawings: Ken Pattermann and Thom Davidson and "the team"


Note level of soil property detail
Phreatic surface for various test fills
AT TIME OF READINGS
5,850
GROSS POOL (5842.0)
7
POOL OF RECORD (5837.0)
PROFI
5,6
4
3
2
1
5,800
7(5815.4)
5
4
3
2
1
3.5
1
1
2F/SF-08-04
Offset: 69'
SC (Grinding on Gravel and Cobbles)
(CL)s
SP s(CL)
MH
SP (Clayey Sand Beds up to 2" thick)
(39, LL=39, PI=18) (Decomposing roots)
(CL)g
SP (26)
s(CL)
s(CL)c ?
(Decomposed organics)
ML-BS (94, LL=47, PI=14)
(1" thick horizontal silt beds)
MH
(SP-SM)g (30% variably weathered gravel)
(GC)s
SC
ML
SP (Includes silt beds)
SC (9% severely weathered friable gravel)
(23)
CL
(23)
16
33
28
30
38
46
44
R
73
R
61
49
R
R
R
51
57
R
R
R
(Rock in shoe)
P-5
Offset: -85'
(Volcanic cobble in shoe)
Pneumatic
ZONE 1
Qogo
Qpcl
?
?
?
5,700

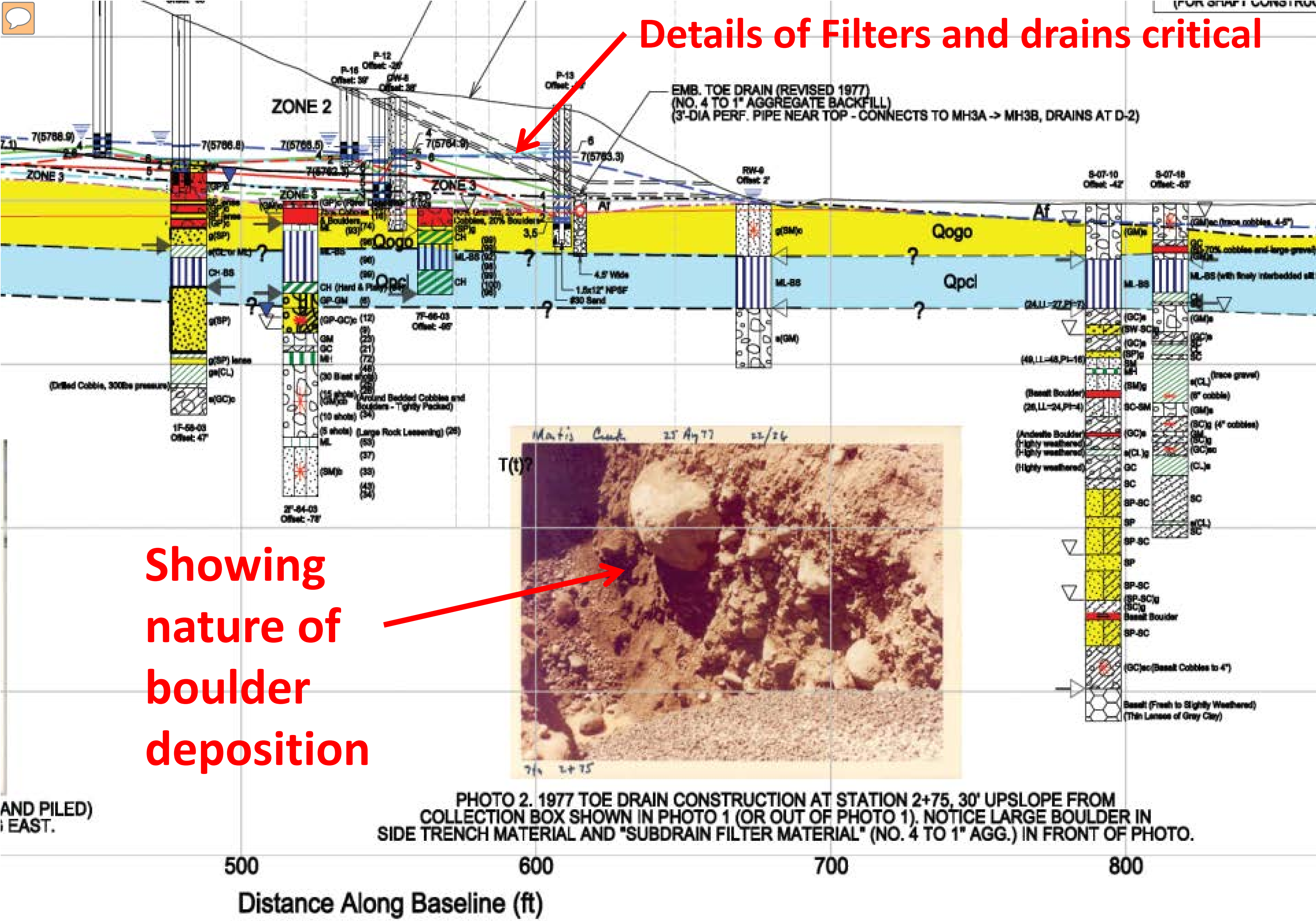
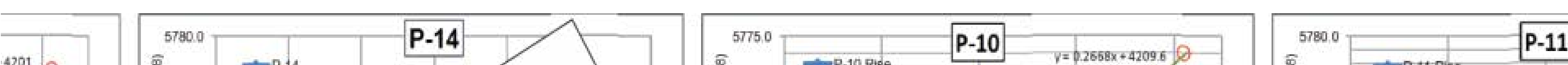
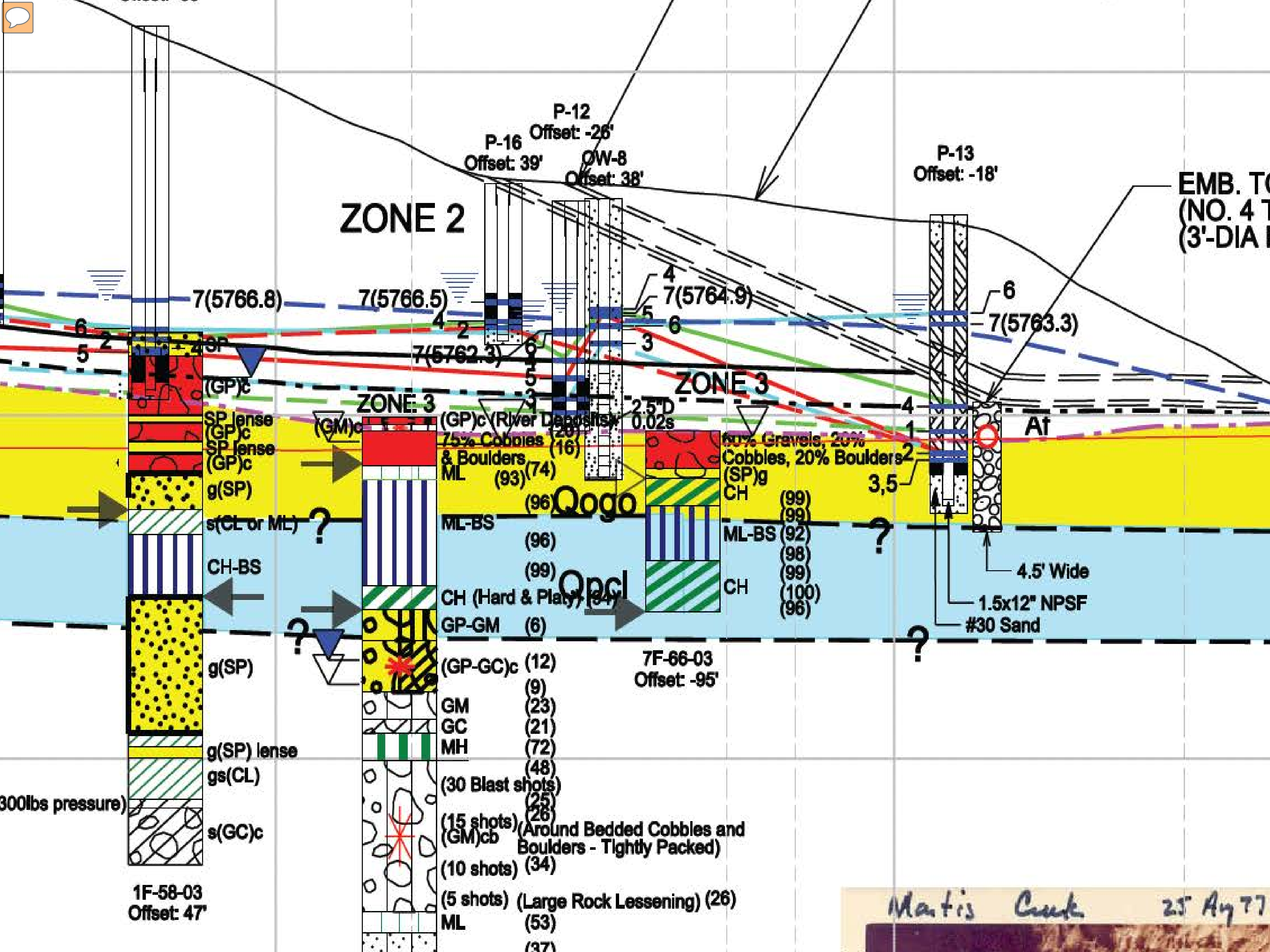
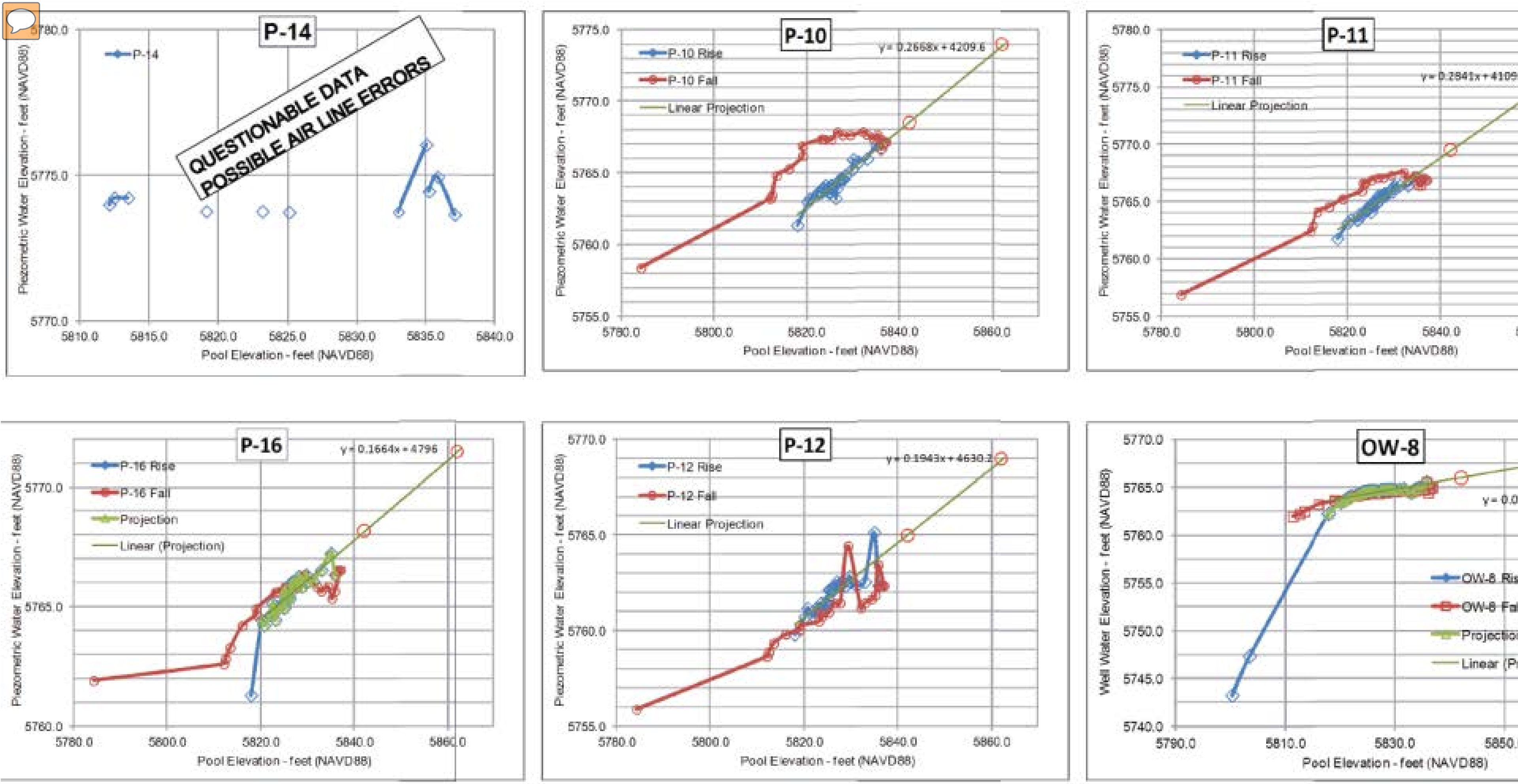


PHOTO 2. 1977 TOE DRAIN CONSTRUCTION AT STATION 2+75, 30' UPSLOPE FROM COLLECTION BOX SHOWN IN PHOTO 1 (OR OUT OF PHOTO 1). NOTICE LARGE BOULDER IN SIDE TRENCH MATERIAL AND "SUBDRAIN FILTER MATERIAL" (NO. 4 TO 1" AGG.) IN FRONT OF PHOTO.

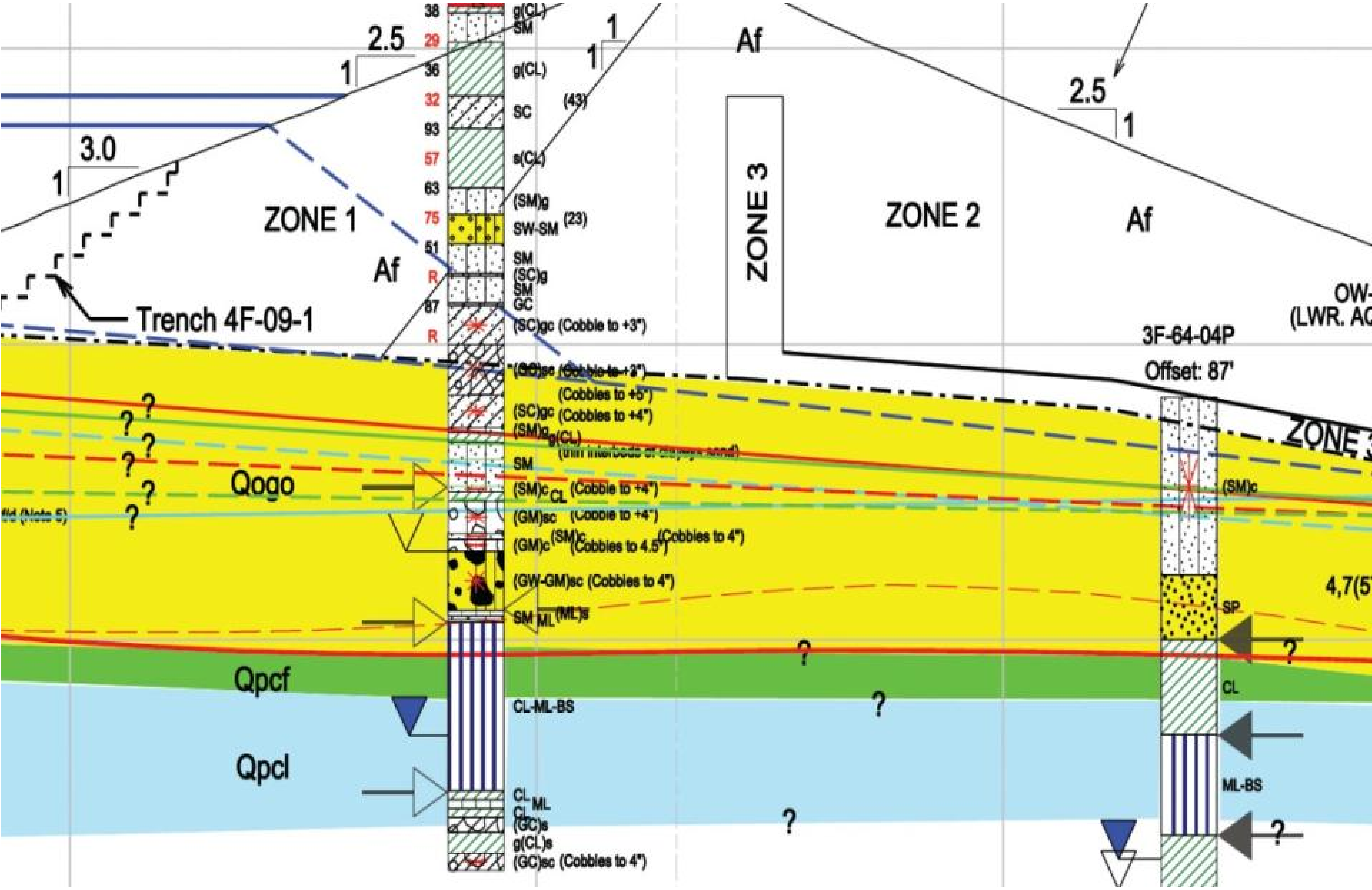




ZONE 2
ZONE 3
ZONE 3
P-16
Offset: 39'
P-12
Offset: -26'
OW-8
Offset: 38'
P-13
Offset: -18'
EMB. T
(NO. 4 T
(3'-DIA
7(5766.8)
7(5766.5)
7(5764.9)
7(5763.3)
7(5762.3)
SP
(GP)c
SP lense
(GP)c
SP lense
(GP)c
g(SP)
s(CL or ML)
CH-BS
g(SP)
g(SP) lense
gs(CL)
300lbs pressure)
s(GC)c
1F-58-03
Offset: 47'
(GM)c
(GP)c (River Deposits)
75% Cobbles
& Boulders
ML
ML-BS
CH (Hard & Platy)
GP-GM
(GP-GC)c
GM
GC
MH
(30 Blast shots)
(15 shots)
(GM)cb
(Around Bedded Cobbles and
Boulders - Tightly Packed)
(10 shots)
(5 shots)
(Large Rock Lessening)
ML
(20)
(16)
(74)
(93)
(96)
(96)
(99)
(84)
(6)
(12)
(9)
(23)
(21)
(72)
(48)
(25)
(26)
(34)
(26)
(53)
(37)
2.5"D
0.02s
Qogo
Qpcl
60% Gravels, 20%
Cobbles, 20% Boulders
(SP)g
CH
ML-BS
CH
(99)
(99)
(92)
(98)
(99)
(100)
(96)
7F-66-03
Offset: -95'
Af
4.5' Wide
1.5x12" NPSF
#30 Sand
3,5
Martis Creek
25 Aug 77

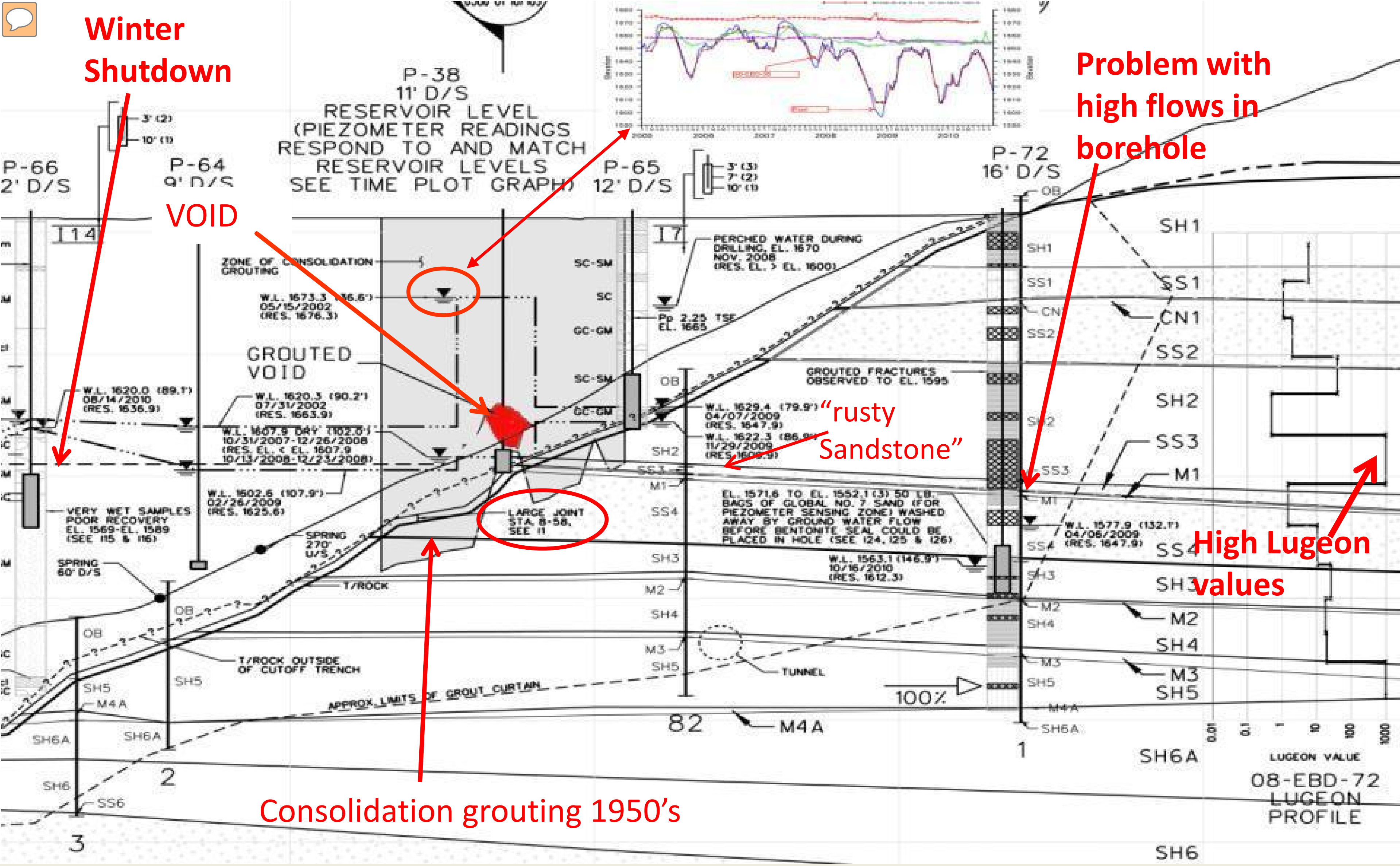


Instrumentation Data analyzed by Mike Snyder (NAB)



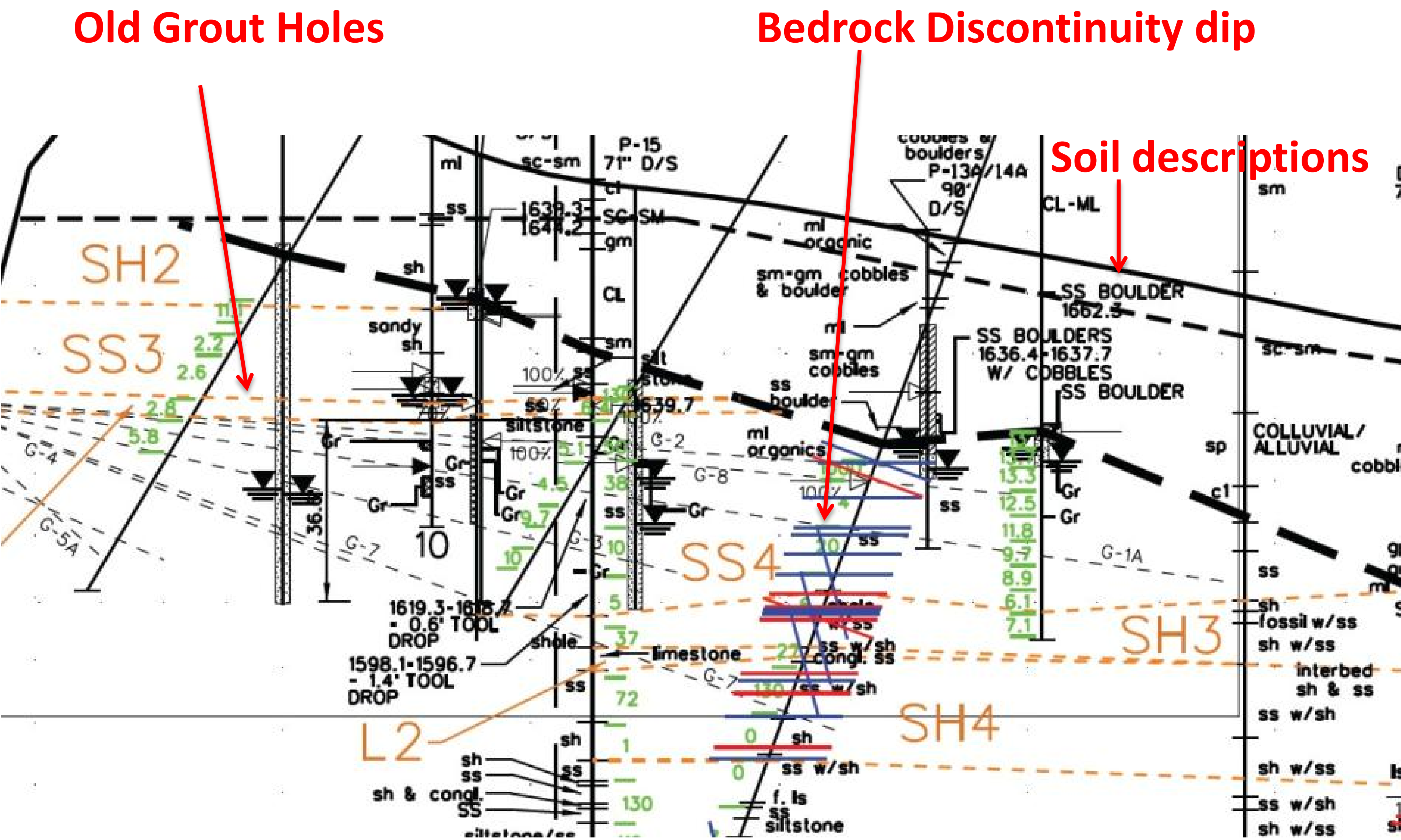
2.5
1
3.0
1
1
1
ZONE 1
Af
Trench 4F-09-1
Af
ZONE 3
ZONE 2
Af
2.5
1
3F-64-04P
Offset: 87'
OW-
(LWR. AC
ZONE 3
Qogo
Qpcf
Qpcl
g(CL)
SM
g(CL)
SC
(43)
s(CL)
(SM)g
SW-SM (23)
SM
(SC)g
SM
GC
(SC)gc (Cobble to +3")
(Cobbles to +5")
(SC)gc (Cobbles to +4")
(SM)g g(CL)
SM
(SM)c CL (Cobble to +4")
(GM)sc
(GM)c (SM)c (Cobbles to 4.5") (Cobbles to 4")
(GW-GM)sc (Cobbles to 4")
SM ML (ML)s
CL-ML-BS
CL ML
CL
(GC)s
g(CL)s
(GC)sc (Cobbles to 4")
(SM)c
SP
CL
ML-BS
4,7(5
38
29
36
32
93
57
63
75
51
R
87
R

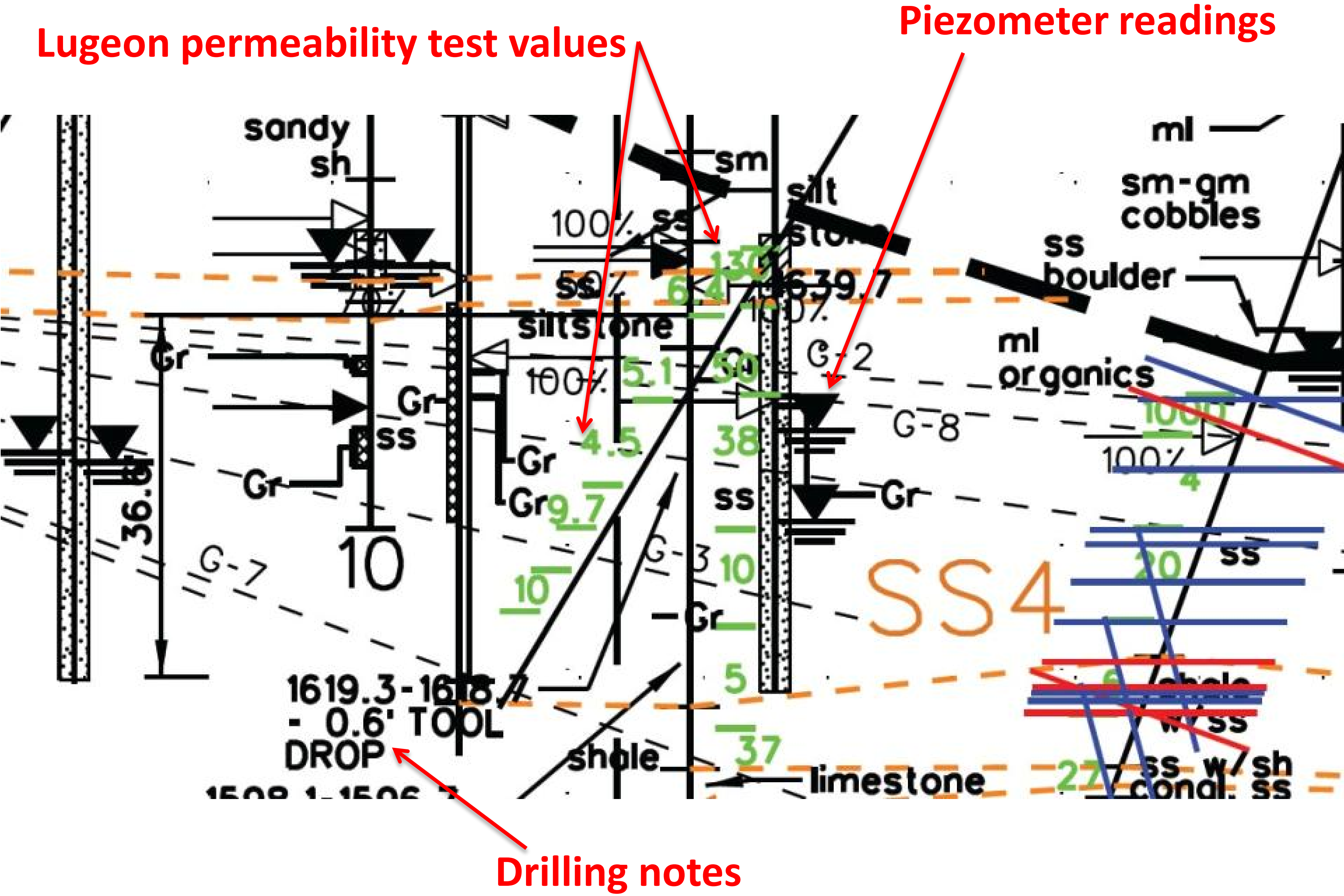
East Branch Dam

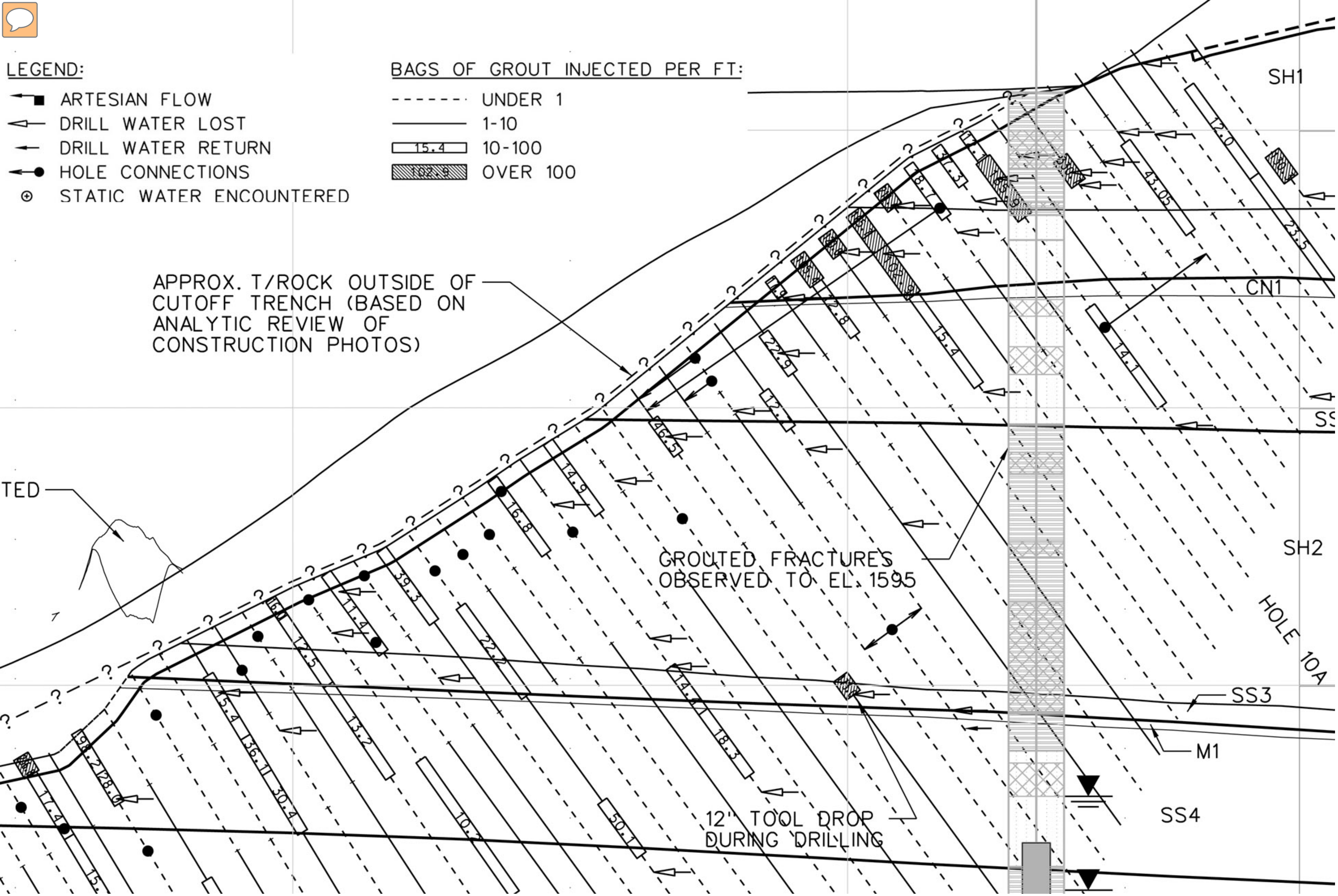


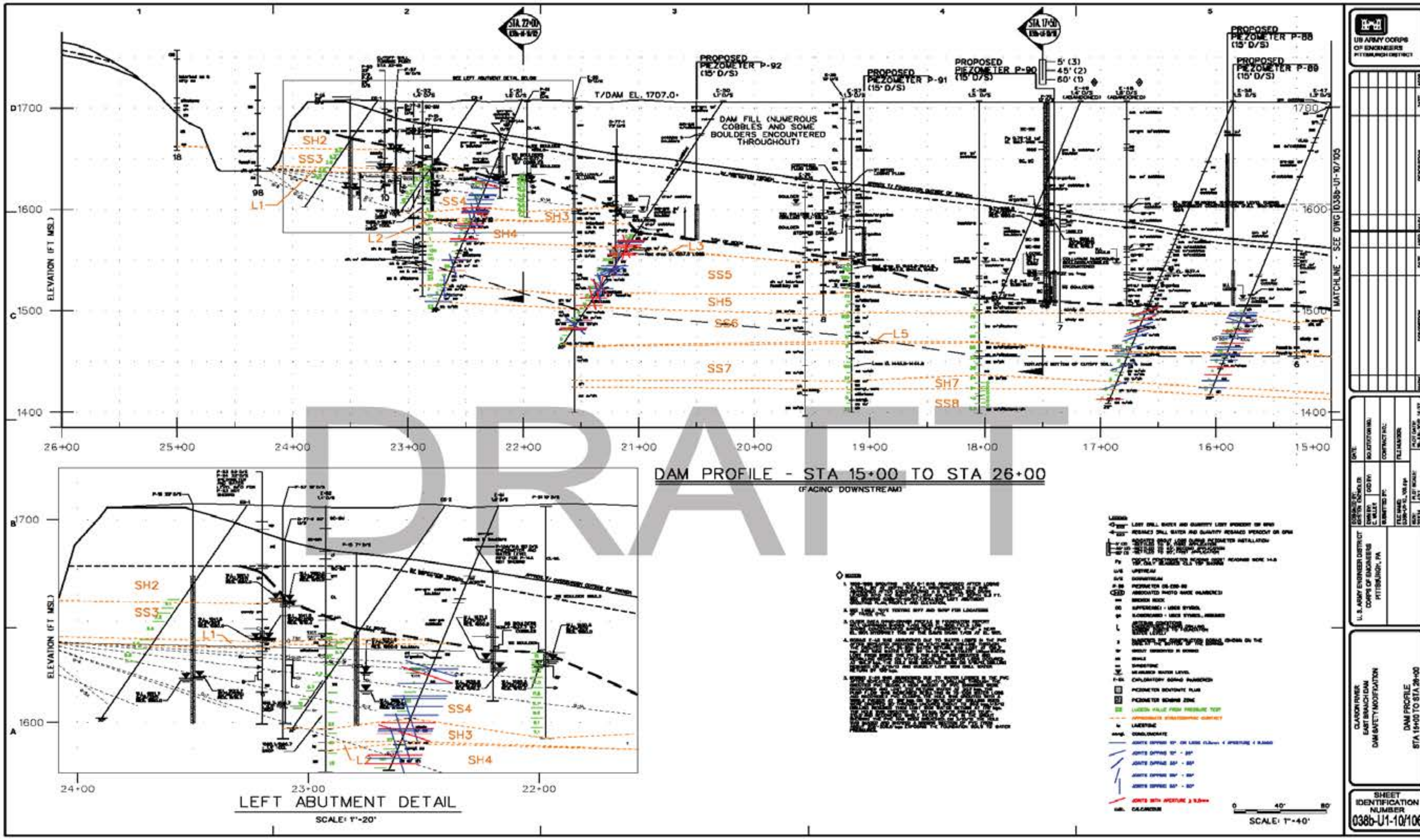
Geology, geotechnical engineering and instrumentation need to be integrated to focus on the same questions tied to failure modes

East Branch Dam

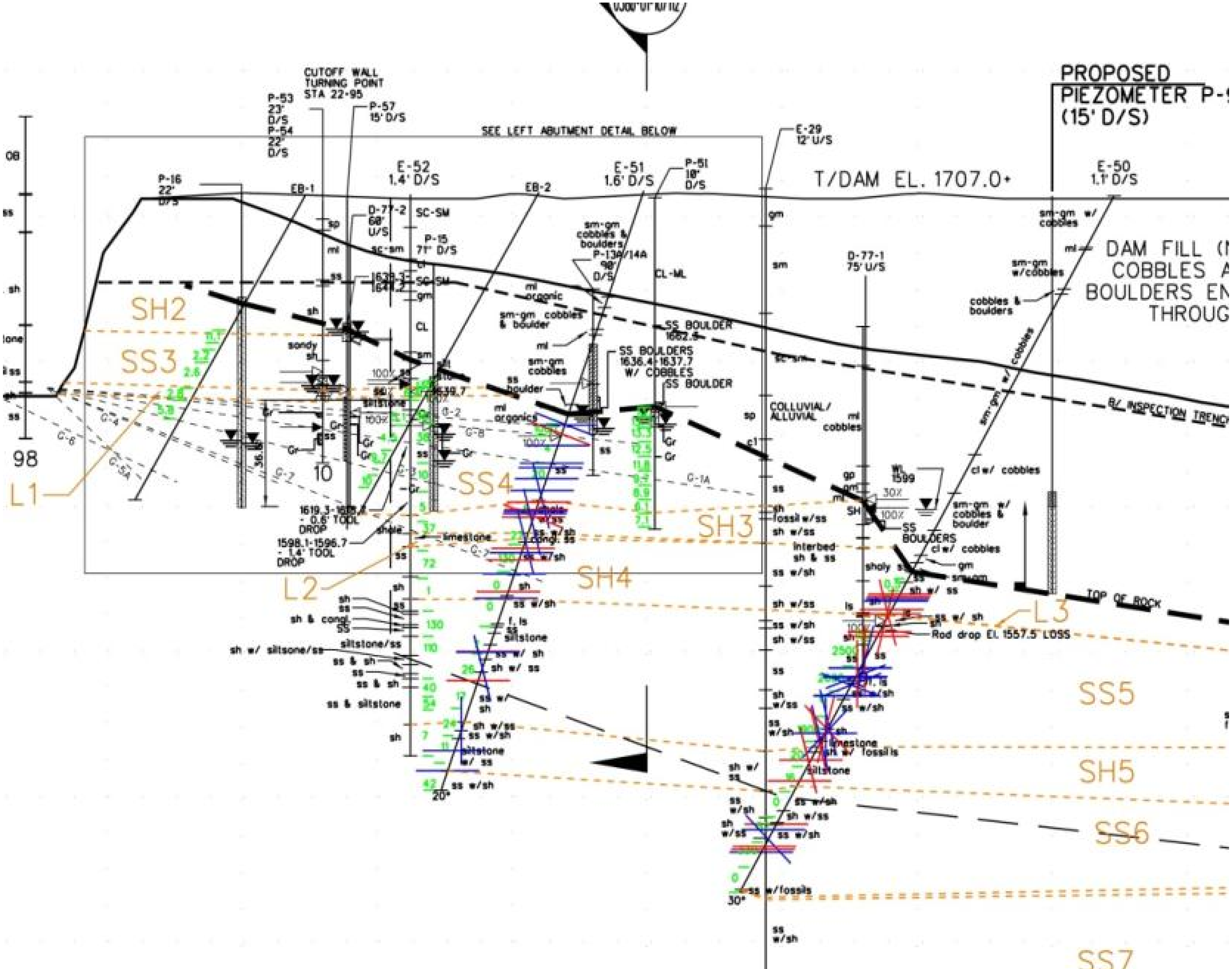

Old Grout Holes
Bedrock Discontinuity dip
Soil descriptions
SH2
SS3
SS4
SH3
SH4
L2
P-15
71" D/S
P-13A/14A
90'
D/S
SS BOULDER
1662.5
SS BOULDERS
1636.4-1637.7
W/ COBBLES
SS BOULDER
COLLUVIAL/
ALLUVIAL
1619.3-1618.7
- 0.6' TOOL
DROP
1598.1-1596.7
- 1.4' TOOL
DROP
limestone
G-4
G-5A
G-7
G-2
G-8
G-3
G-1A
sandy
sh
siltstone
ml
organic
sm-gm cobbles
& boulder
CL-ML
fossil w/ss
interbed
sh & ss
ss w/sh
sh w/ss

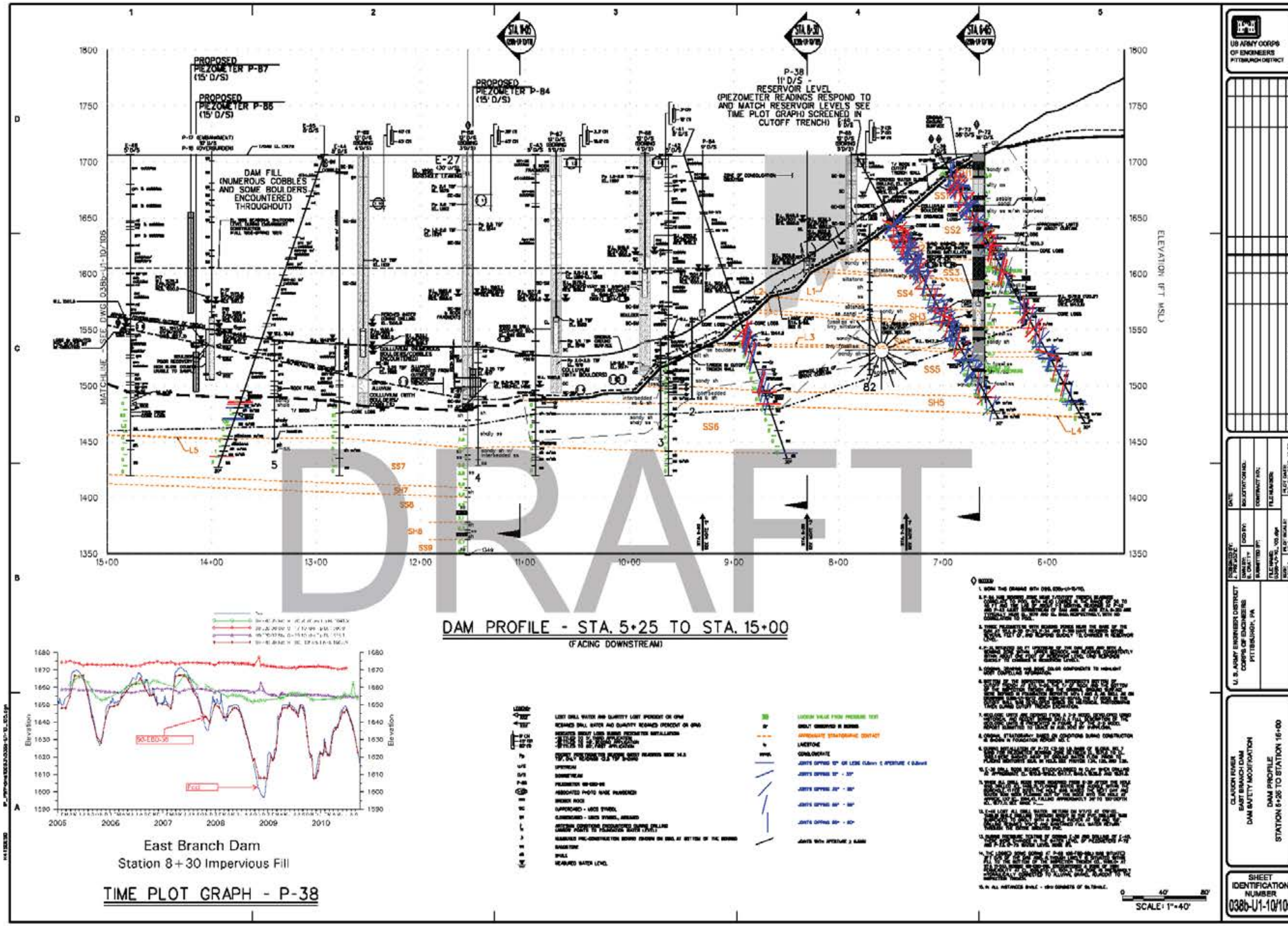

Lugeon permeability test values
Piezometer readings
Drilling notes
sandy sh
sm
silt stone
ml
sm-gm cobbles
ss boulder
100% ss
50%
siltstone
1639.7
100%
G-2
G-8
ml organics
100%
Gr
ss
10
G-7
G-3
SS4
1619.3-1618.7
- 0.6' TOOL DROP
shale
limestone
ss w/sh
congl. ss


LEGEND:
ARTESIAN FLOW
DRILL WATER LOST
DRILL WATER RETURN
HOLE CONNECTIONS
STATIC WATER ENCOUNTERED
BAGS OF GROUT INJECTED PER FT:
UNDER 1
1-10
15.4
10-100
102.9
OVER 100
APPROX. T/ROCK OUTSIDE OF CUTOFF TRENCH (BASED ON ANALYTIC REVIEW OF CONSTRUCTION PHOTOS)
TED
GROUTED FRACTURES OBSERVED TO EL. 1595
12" TOOL DROP DURING DRILLING
SH1
CN1
SH2
HOLE 10A
SS3
M1
SS4
12.0
43.05
23.5
14.1
15.4
272.9
17.8
46.5
14.9
16.8
39.3
11.4
17.5
22.2
13.2
36.1
30.4
18.3
50.1
17.4

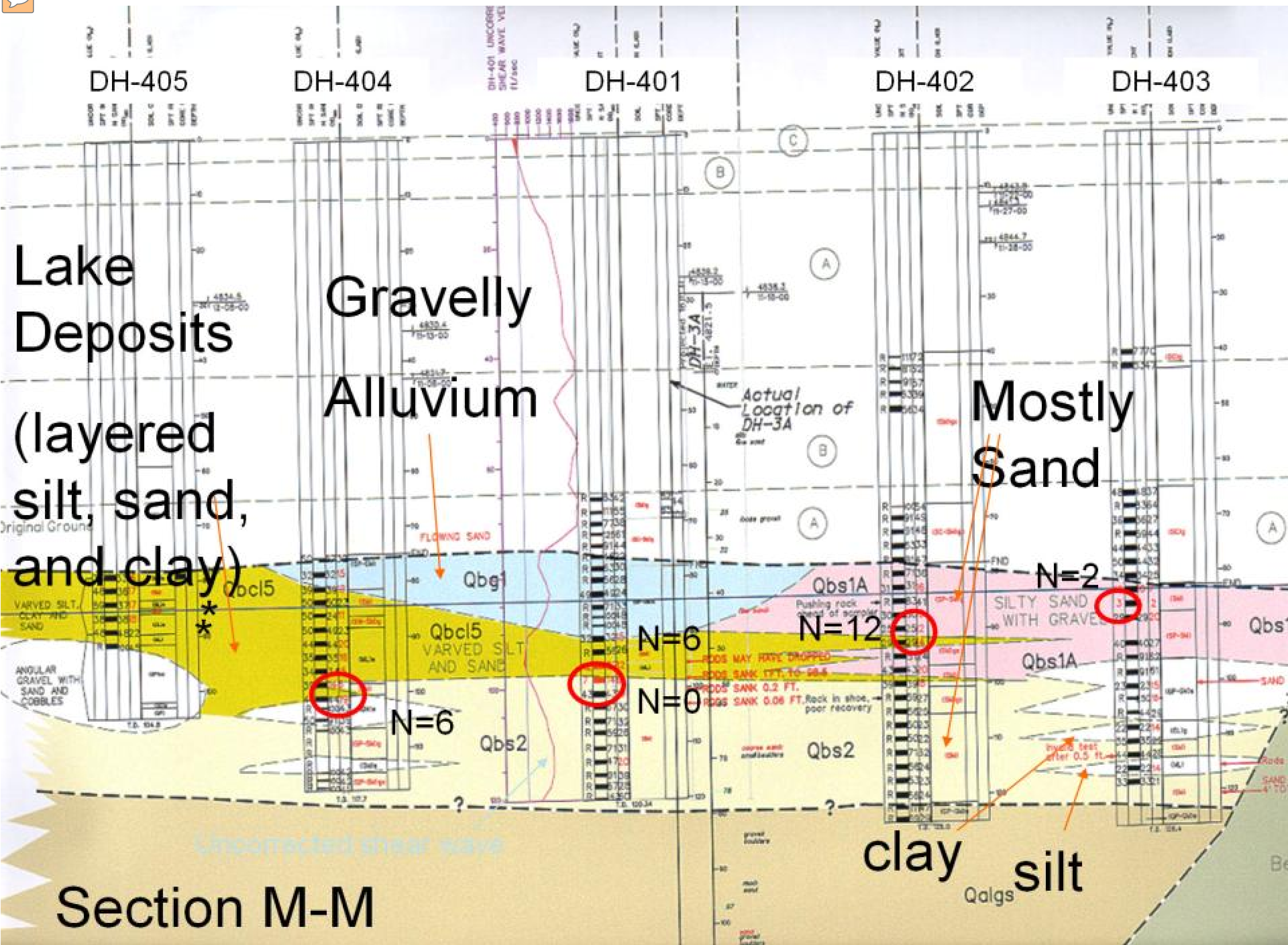


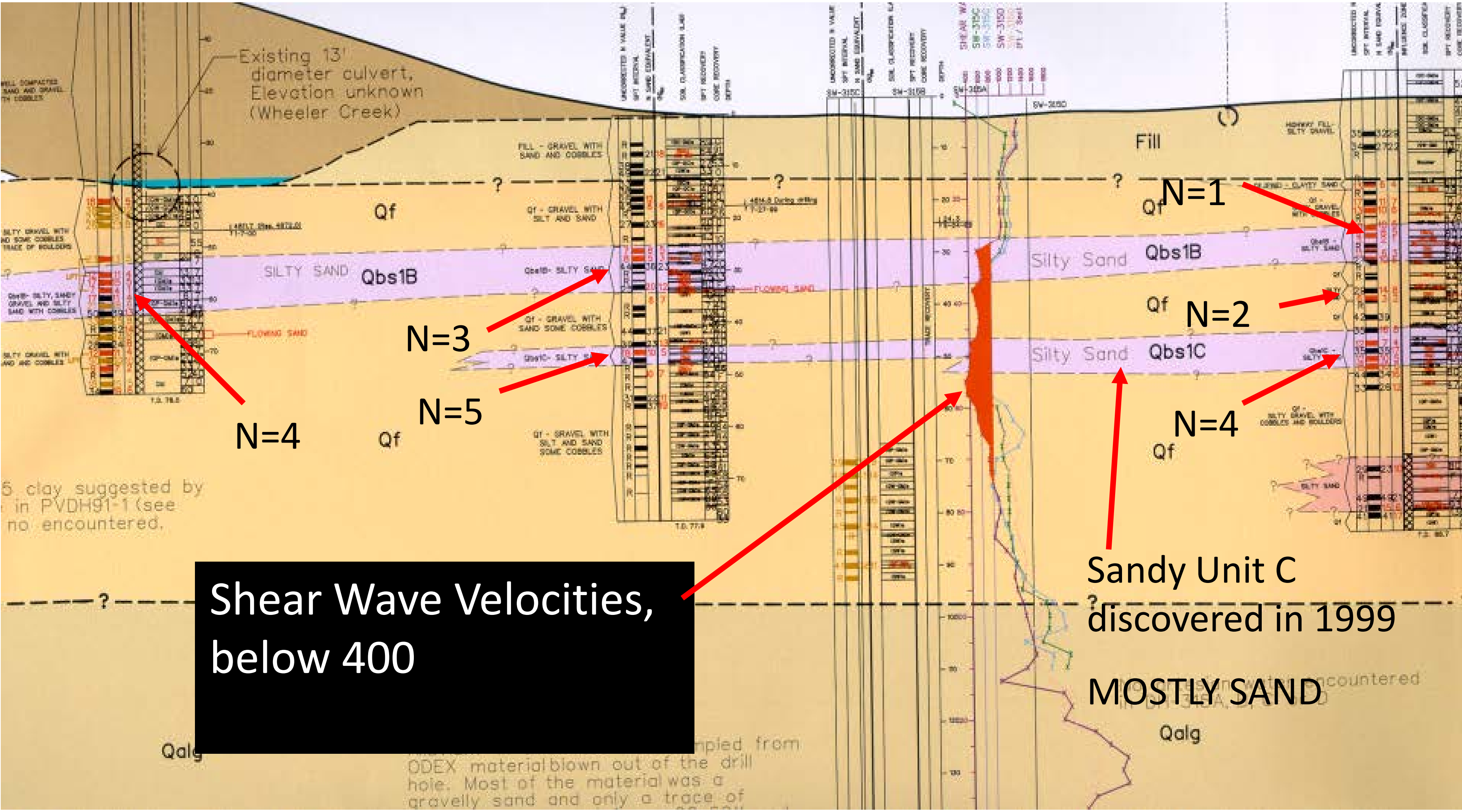
DAM PROFILE - STA 15+00 TO STA 26+00
(FACING DOWNSTREAM)
LEFT ABUTMENT DETAIL
SCALE: 1"=20'
SCALE: 1"=40'
T/DAM EL. 1707.0±
DAM FILL (NUMEROUS COBBLES AND SOME BOULDERS ENCOUNTERED THROUGHOUT)
PROPOSED PIEZOMETER P-92 (15' D/S)
PROPOSED PIEZOMETER P-91 (15' D/S)
PROPOSED PIEZOMETER P-90 (15' D/S)
PROPOSED PIEZOMETER P-88 (15' D/S)
PROPOSED PIEZOMETER P-89 (15' D/S)
5' (3)
45' (2)
60' (1)
STA. 22+00
STA. 17+50
ELEVATION (FT MSL)
1700
1600
1500
1400
26+00
25+00
24+00
23+00
22+00
21+00
20+00
19+00
18+00
17+00
16+00
15+00
SH2
SS3
SS4
SH3
SH4
SS5
SH5
SS6
SS7
SH7
SS8
L1
L2
L3
L5
MATCHLINE - SEE DWG 038b-U1-10/105
DRAFT
US ARMY CORPS OF ENGINEERS PITTSBURGH DISTRICT
U.S. ARMY ENGINEER DISTRICT CORPS OF ENGINEERS PITTSBURGH, PA
CLARION RIVER EAST BRANCH DAM DAM SAFETY MODIFICATION
DAM PROFILE STA 15+00 TO STA 26+00
SHEET IDENTIFICATION NUMBER
038b-U1-10/106

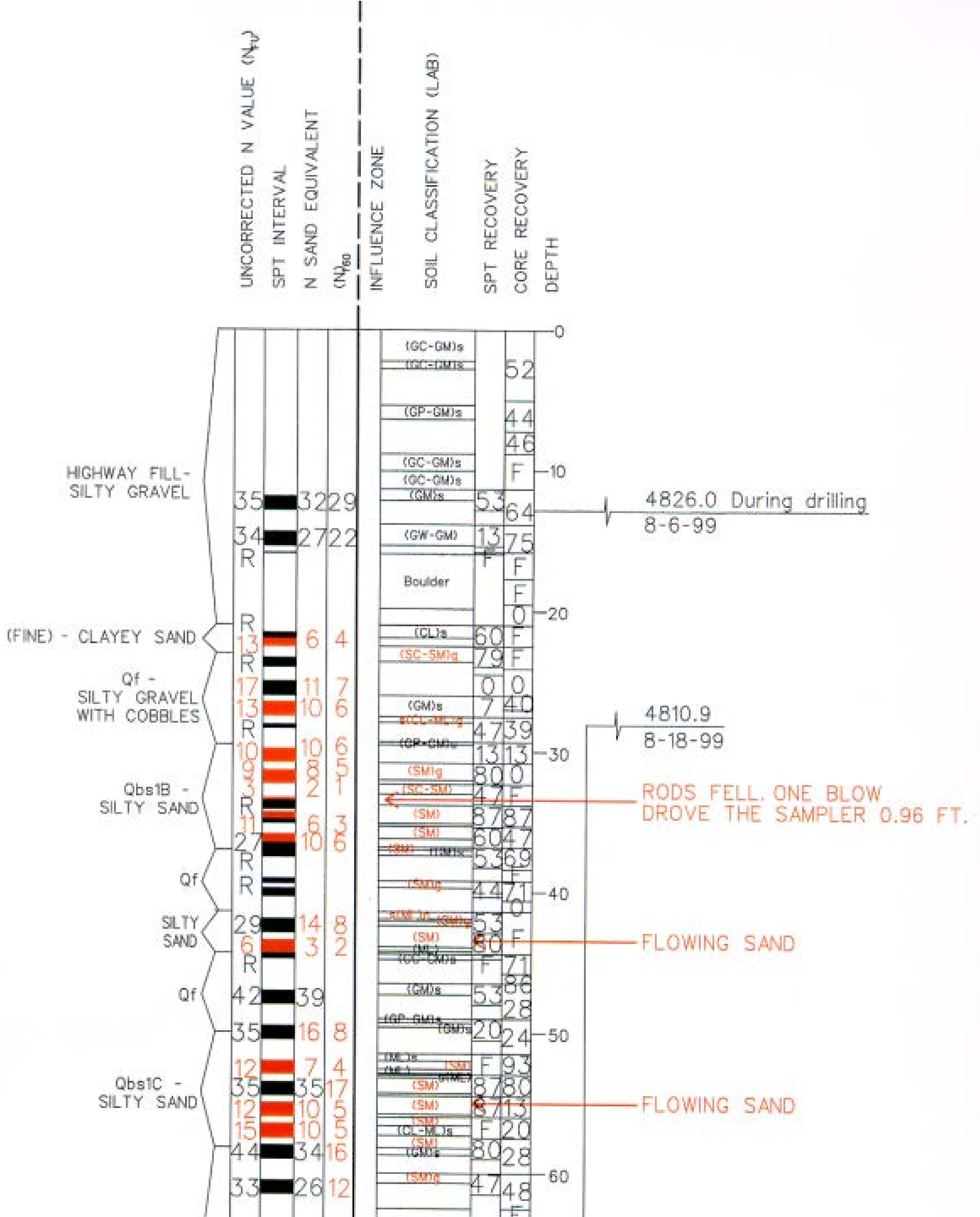

PROPOSED
PIEZOMETER P-
(15' D/S)
T/DAM EL. 1707.0+
SEE LEFT ABUTMENT DETAIL BELOW
CUTOFF WALL
TURNING POINT
STA 22+95
P-53
23'
D/S
P-54
22'
D/S
P-57
15' D/S
P-16
22'
D/S
EB-1
EB-2
E-52
1.4' D/S
E-51
1.6' D/S
P-51
10'
D/S
E-29
12' U/S
E-50
1.1' D/S
D-77-2
60'
U/S
P-15
71' D/S
D-77-1
75' U/S
P-13A/14A
90'
D/S
DAM FILL
COBBLES
BOULDERS
THROUG
SS BOULDER
1662.5
SS BOULDERS
1636.4-1637.7
W/ COBBLES
SS BOULDER
COLLUVIAL/
ALLUVIAL
B/ INSPECTION TRENC
TOP OF ROCK
1619.3-1618.4
- 0.6' TOOL
DROP
1598.1-1596.7
- 1.4' TOOL
DROP
Rod drop EL 1557.5' LOSS
SH2
SS3
SS4
SH3
SH4
SS5
SH5
SS6
SS7
L1
L2
L3
20°
30°


DRAFT
PROPOSED PIEZOMETER P-87 (15' D/S)
PROPOSED PIEZOMETER P-88 (15' D/S)
PROPOSED PIEZOMETER P-84 (15' D/S)
DAM FILL (NUMEROUS COBBLES AND SOME BOULDERS ENCOUNTERED THROUGHOUT)
P-38 11' D/S - RESERVOIR LEVEL (PIEZOMETER READINGS RESPOND TO AND MATCH RESERVOIR LEVELS SEE TIME PLOT GRAPH) SCREENED IN CUTOFF TRENCH)
E-27
MATCHLINE - SEE DWG 038b-U1-10/106
ELEVATION (FT MSL)
DAM PROFILE - STA. 5+25 TO STA. 15+00
(FACING DOWNSTREAM)
East Branch Dam
Station 8+30 Impervious Fill
TIME PLOT GRAPH - P-38
US ARMY CORPS OF ENGINEERS PITTSBURGH DISTRICT
U. S. ARMY ENGINEER DISTRICT CORPS OF ENGINEERS PITTSBURGH, PA
CLARION RIVER EAST BRANCH DAM DAM SAFETY MODIFICATION
DAM PROFILE STATION 5+25 TO STATION 15+00
SHEET IDENTIFICATION NUMBER
038b-U1-10/105
SCALE: 1"=40'

Pineview Dam


DH-405
DH-404
DH-401
DH-402
DH-403
Lake Deposits
(layered silt, sand, and clay)
Gravelly Alluvium
Mostly Sand
Actual Location of DH-3A
Qbcl5
VARVED SILT, CLAY AND SAND
ANGULAR GRAVEL WITH SAND AND COBBLES
Qbg1
Qbcl5
VARVED SILT AND SAND
Qbs1A
SILTY SAND WITH GRAVEL
Qbs1A
Qbs2
Qbs2
FLOWING SAND
RODS MAY HAVE DROPPED
RODS SANK 0.2 FT.
Rock in shoe, poor recovery
N=6
N=6
N=0
N=12
N=2
clay
silt
Qalgs
Section M-M

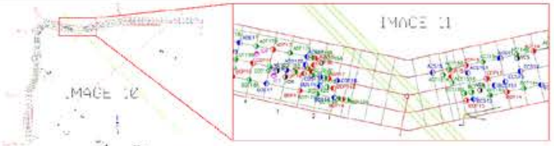

Existing 13' diameter culvert, Elevation unknown (Wheeler Creek)
Fill
Qf
SILTY SAND Qbs1B
Silty Sand Qbs1B
Silty Sand Qbs1C
FLOWING SAND
N=1
N=2
N=3
N=4
N=5
N=4
Qalg
Shear Wave Velocities, below 400
Sandy Unit C discovered in 1999
MOSTLY SAND



All clues of weaker material shown in red

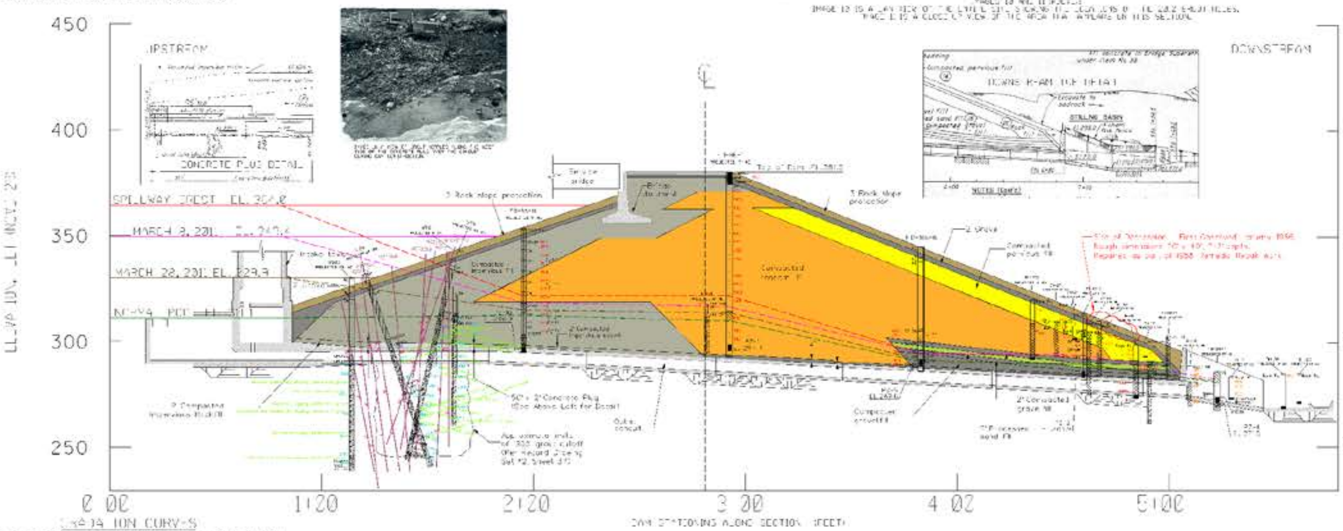
- sandy materials,
- low blow counts,
- flowing sand,
- rods dropping (etc)

Hop Brook Dam



Joint Set	Strike (Azimuth)	Dip (degrees)	Description
1	[illegible]	90	[illegible]
2	[illegible]	[illegible]	[illegible]
3	[illegible]	90	[illegible]
4	[illegible]	[illegible]	[illegible]
3	[illegible]	90	[illegible]
4	272	[illegible]	Tight, planar, widely spaced
5	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]

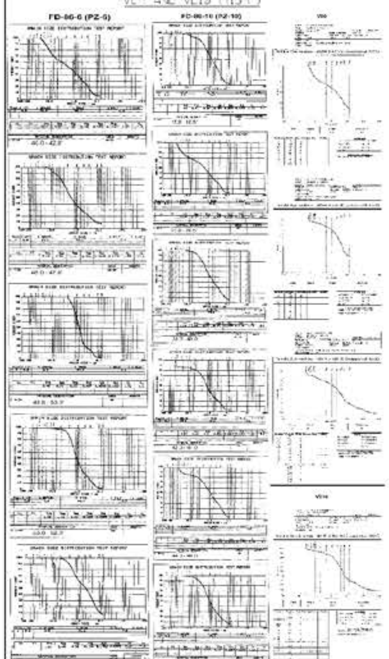
JOINT SETS AT HOP BROOK DAM:



GRADATION CURVES

FD-86-6/PZ-6 (LEFT), FD-86-10/PZ-10 (CENTER), VD11 AND VD13 (RIGHT)

SEC. 0010 CROSS SECTION AT CONDUIT STA 4+60 (FE)



STANDARD SPECIFICATIONS FOR EMBANKMENT MATERIALS

IMPERVIOUS FILL

	SIEVE	% PASS
WELL GRADED	3"	100
30% PASS #4 SHALL ALSO PASS #200	4	90-100
	200	27-30

RANDOM FILL

	SIEVE	% PASS
20% PASS #4 SHALL ALSO PASS #200	3"	100
OPTION: SCREENINGS FROM ROCK PROCESSING CAN BE PLACED IN RDM ZONE US OF CL	4	95-100
IMP FILL CAN BE USED AS RDM FILL AFTER RDM EXHAUSTED AND SUFF IMP FILL REMAINS	200	10-20

PERVIOUS FILL

	SIEVE	% PASS
WELL GRADED SAND OR GRAVELLY SAND		
<50% LARGER THAN 3"	3"	51-100
25% PASS 3" SHALL ALSO PASS #4	4	12-25
10% PASS #4 SHALL ALSO RETAIN ON #40	40	10-22
<10% PASS #4 SHALL PASS #200	200	1-2
<3% PASSING #4 SHALL PASS 0.01MM	0.01	0.7

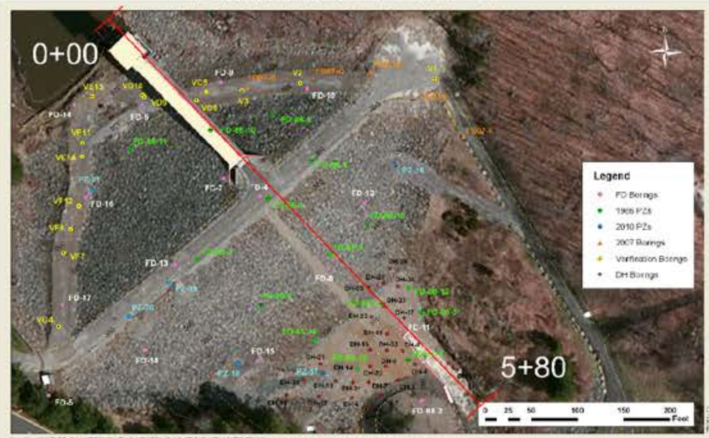
GRAVEL FILL

	SIEVE	% PASS
WELL GRADED GRAVELLY SAND OR SANDY GRAVEL		
<60% LT THAN 3"	3"	61-100
MATERIAL PASS 3", >25% BUT <60% SHALL PASS #4	4	12-50
10% PASS #4 SHALL ALSO RETAIN ON #40	40	10-54
<10% PASS #4 SHALL PASS #200	200	1-4
<3% PASSING #4 SHALL PASS 0.01MM	0.01	0.7

PROCESSED SAND FILL

SIEVE	% PASS
3/8"	100
4	95-100
16	45-80
30	20-55
50	10-30
100	2-10

PLAN VIEW OF SECTION AT CONDUIT (FE)

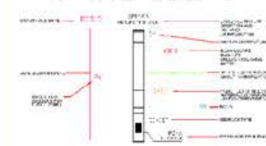


Hop Brook Dam - Boring Locations

LEGEND FOR POOL ELEVATIONS:

SYMBOL / INDICATOR	
PMF	
SPILLWAY CREST EL 364	
POOL MARCH 9, 2011 EL 349.4	
MARCH 28, 2011 EL 329.97	
NORMAL POOL	

LEGEND FOR BOREHOLES



LEGEND FOR SOILS AND CONTACTS

PIEZOMETER RESPONSES TO POOL LEVELS

POOL LEVEL	FD86 10/PZ 10	FD86 1/PZ 1	FD86 6/PZ 6	FD86 2/PZ 2	FD86 4/PZ 4
Spillway Crest, El. 364	323.7	311.7	294.1	292.7356	N/A
March 9, 2011, El. 349.4	315.48	315.11	294.57	290.56	291.88
March 28, 2011, El. 329.97	316.65	315.63	291.02	289.35	283.09
February 16, 2011, El. 313.1	312.26	309.55	290.35	289.25	283.4

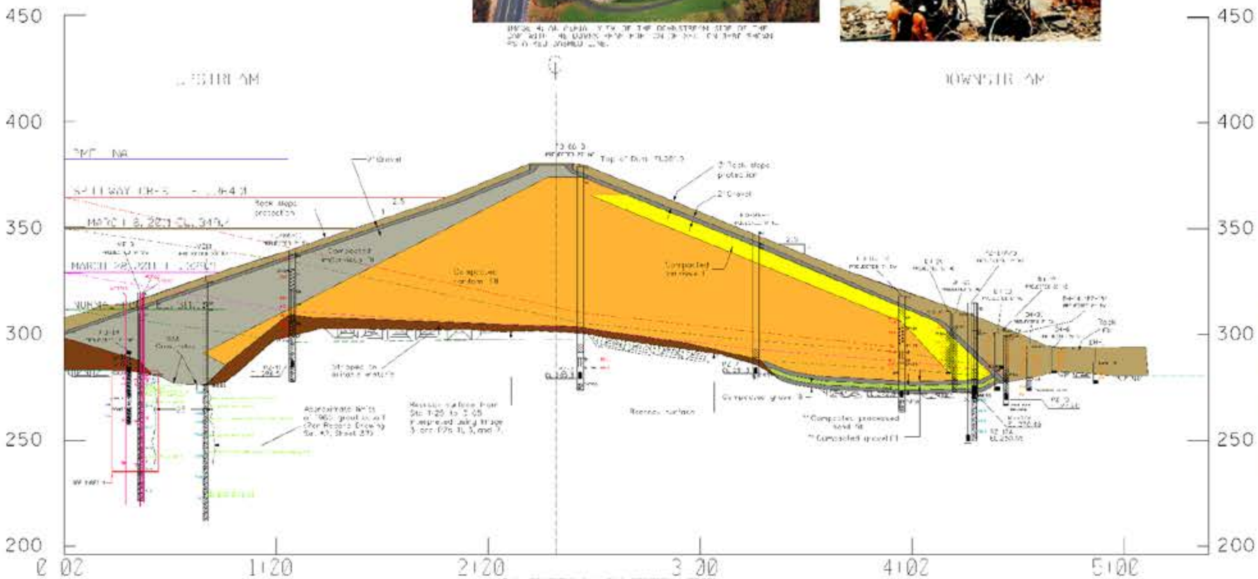
CONDUIT SECTION

DEPARTMENT OF THE ARMY

HOP BROOK DAM

JOINT SETS AT HOP BROOK DAM:

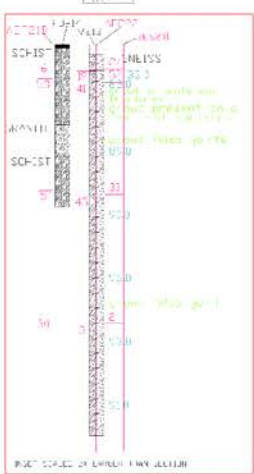
Joint Set	Strike (Azimuth)	Dip (degrees)	Description
1	55	90	Planar tight, widely spaced, locally continuous
2	50	45	Planar, tight, 5-10' spacing, rough to stepped
3	30	90	Planar tight, widely spaced, locally continuous
4	20	15	Planar, rough, tight to locally open (1 inch), seeps observed outlet works
5	85	90	Curviplanar, close to widely spaced, tight to 1/16" app.
6	277	42	Tight, planar, widely spaced
7	330	55	Foliation joint, tight, slickensided, moderately spaced
8	120	50	Planar to curviplanar, tight to slightly open (1/4" locally)

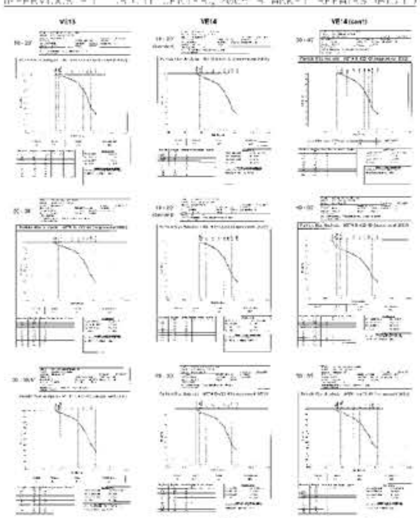


GEOLOGIC CROSS SECTION AT OLD RIVER CHANNEL (STA 3+80)

GRADATION CURVES

INSET





PLAN VIEW OF OLD RIVER CHANNEL SECTION AT 3+80

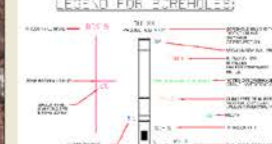
Hop Brook Dam - Boring Locations

PIEZOMETER RESPONSES TO POOL LEVELS							
POOL LEVEL	PZ-11	PZ-9	PZ-7	PZ-14	PZ-17A	PZ-17B	PZ-15
PMF	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SPILLWAY CREST	N/A	309.5	N/A	295.8	N/A	N/A	N/A
MARCH 8, 2011	333.6	304.7	297.2	291.8	284.3	289.6	284.31
MARCH 28, 2011	320.3	302.9	293.2	287.4	284.2	285.9	280.88
NORMAL POOL	296.5	298.0	287.9	285.7	281.2	282.3	277.85

LEGEND FOR POOL ELEVATIONS:
SYMBOL / LINE COLOR
DASHED LINE = PZ RESPONSE

PMF N/A
SPILLWAY CREST
HIGH POOL MARCH 8, 2011 EL. 349.42
MARCH 28, 2011 EL. 329.97
NORMAL POOL

LEGEND FOR BOREHOLES:



LEGEND FOR SOILS AND CONTACTS:

SECTION AT 3+80

DEPARTMENT OF THE ARMY

HOP BROOK DAM
GEOLOGIC CROSS SECTION
STA 3+80

JOINT SETS AT HOP BROOK DAM:

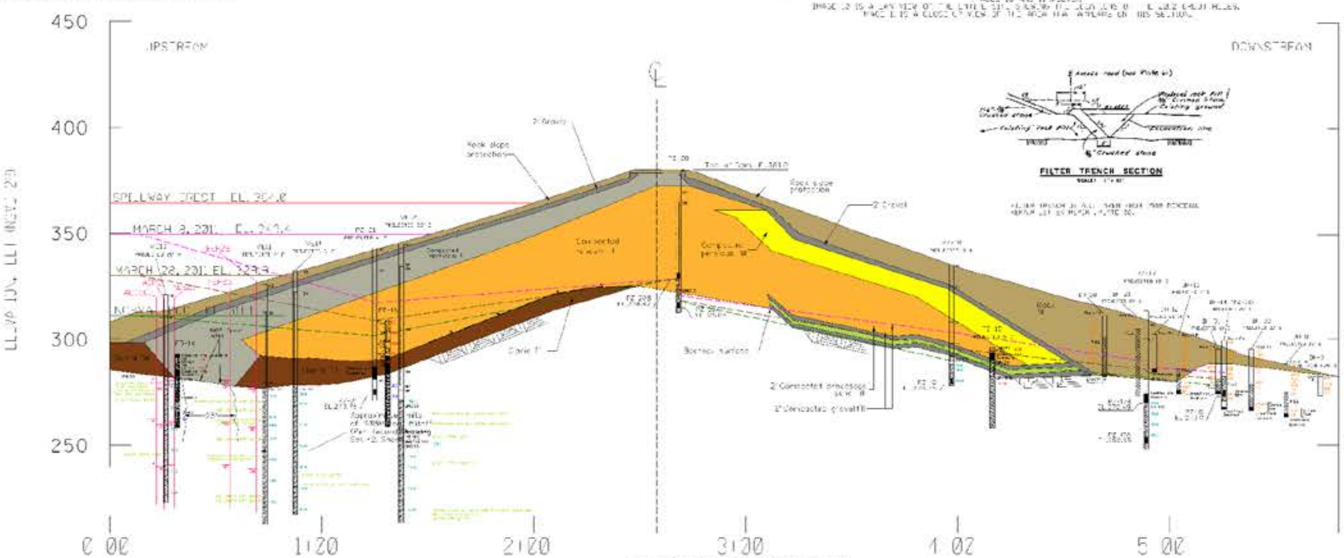
Joint Set	Strike (Azimuth)	Dip (degrees)	Description
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

IMAGE 6

IMAGE 7

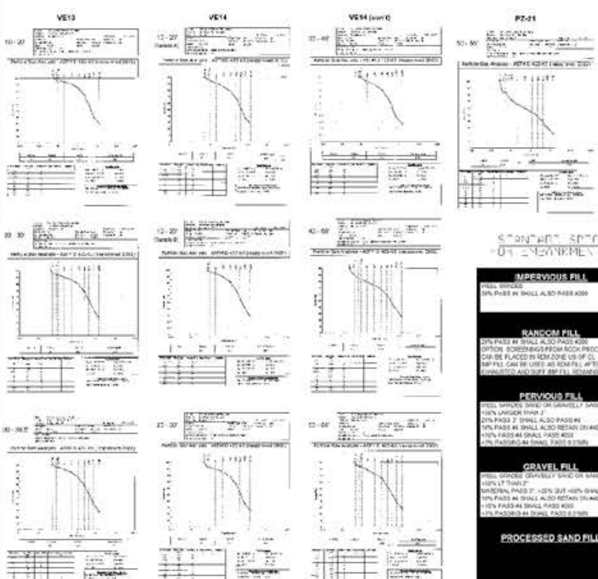
IMAGE 8

IMAGE 9



GEOLOGIC CROSS SECTION AT RIGHT ABUTMENT

GRADATION CURVES



STANDARD SPECIFICATIONS FOR EMBANKMENT MATERIALS

IMPERVIOUS FILL

	SIEVE	% PASS
WELL GRADED		
50% PASS #4 SHALL ALSO PASS #200	[illegible]	100
	4	[illegible]
	200	[illegible]

RANDOM FILL

	SIEVE	% PASS
20% PASS #4 SHALL ALSO PASS #200		
OPTION: SCREENINGS FROM ROCK PROCESSING	[illegible]	100
CAN BE PLACED IN RDM ZONE US OF CL	4	[illegible]
IMP FILL CAN BE USED AS RDM FILL AFTER RDM	200	[illegible]
EXHAUSTED AND SUFF IMP FILL REMAINS		

PERVIOUS FILL

	SIEVE	% PASS
WELL GRADED SAND OR GRAVELLY SAND		
[illegible] LARGER THAN 2"	2"	[illegible]
20% PASS 2" SHALL ALSO PASS #4	4	[illegible]
50% PASS #4 SHALL ALSO RETAIN ON #40	40	[illegible]
[illegible] PASS #4 SHALL PASS #200	200	[illegible]
[illegible] PASSING #4 SHALL PASS 0.02MM	[illegible]	[illegible]

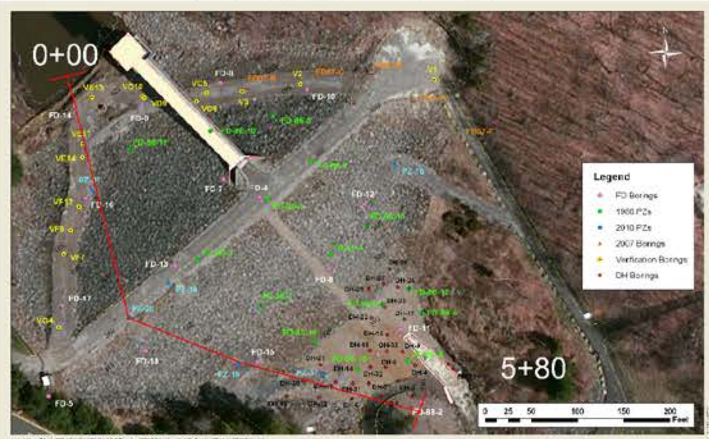
GRAVEL FILL

	SIEVE	% PASS
WELL GRADED GRAVELLY SAND OR SANDY GRAVEL		
[illegible] LT THAN 2"	2"	[illegible]
MATERIAL PASS 2", [illegible] SHALL PASS #4	4	[illegible]
50% PASS #4 SHALL ALSO RETAIN ON #40	40	[illegible]
[illegible] PASS #4 SHALL PASS #200	200	[illegible]
[illegible] PASSING #4 SHALL PASS 0.02MM	[illegible]	[illegible]

PROCESSED SAND FILL

SIEVE	% PASS
3/8"	100
4	[illegible]
16	[illegible]
30	[illegible]
50	[illegible]
100	[illegible]

PLAN VIEW OF RIGHT ABUTMENT SECTION



Hop Brook Dam - Boring Locations

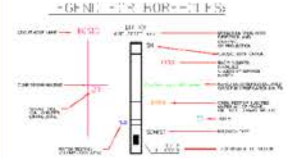
PIEZOMETER RESPONSES TO POOL LEVELS

POOL LEVEL	PZ-21	PZ-20A	PZ-20B	PZ-18	PZ-17A	PZ-17B	PZ-15
PMF	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SPILLWAY CREST	N/A	N/A	N/A	[illegible]	N/A	N/A	N/A
MARCH 9, 2011	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MARCH 28, 2011	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
NORMAL POOL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LEGEND FOR POOL ELEVATIONS:
SYMBOL = LINE COLOR
DASHED LINE = PZ RESPONSE

PMF N/A
SPILLWAY CREST EL. 364
HIGH POOL MARCH 9, 2011 EL. 345.42
MARCH 28, 2011 EL. 329.97
NORMAL POOL EL. 301.7

LEGEND FOR BOREHOLES



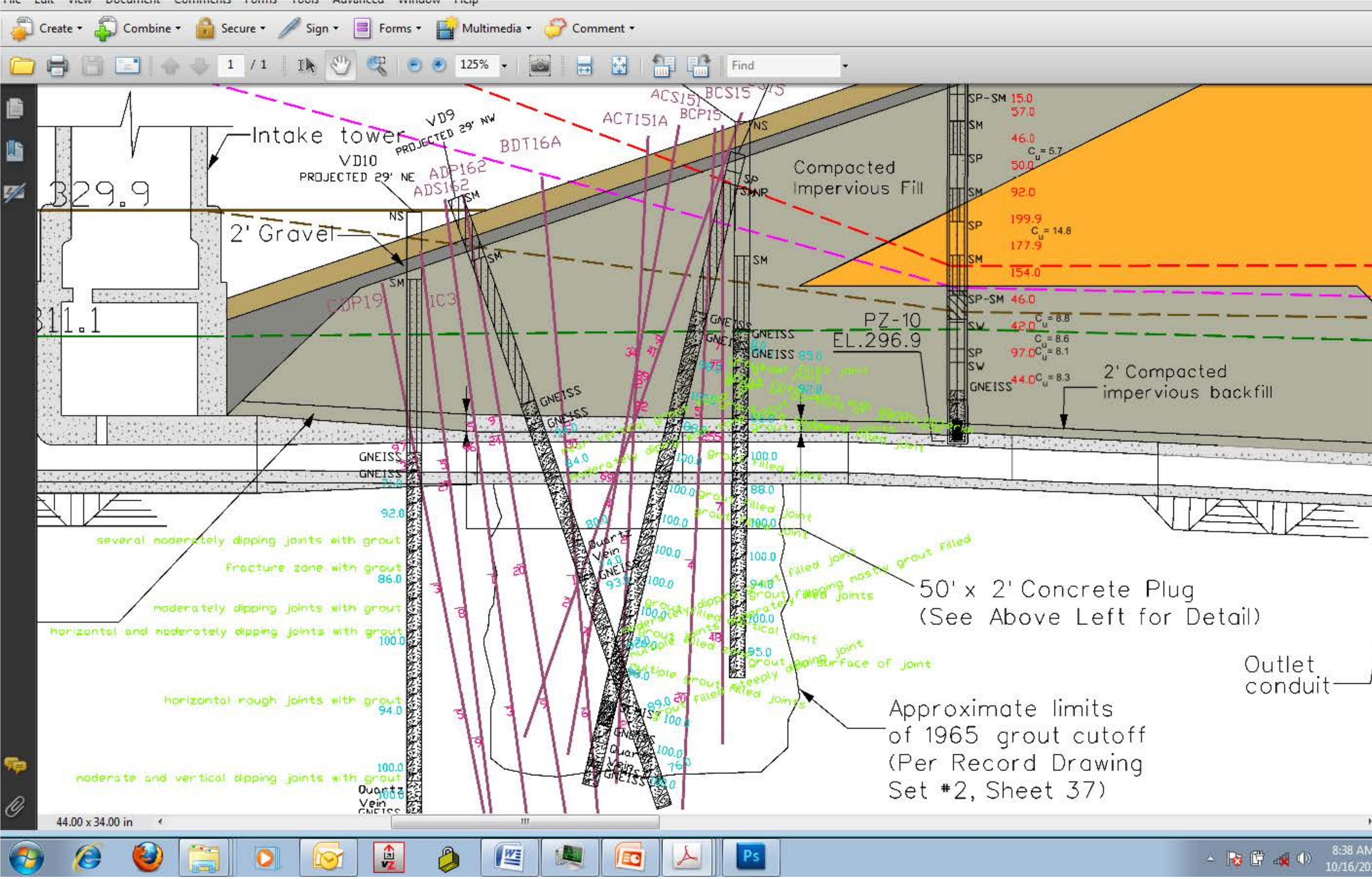
LEGEND FOR SOILS AND CONTACTS:

RIGHT ABUTMENT SECTION

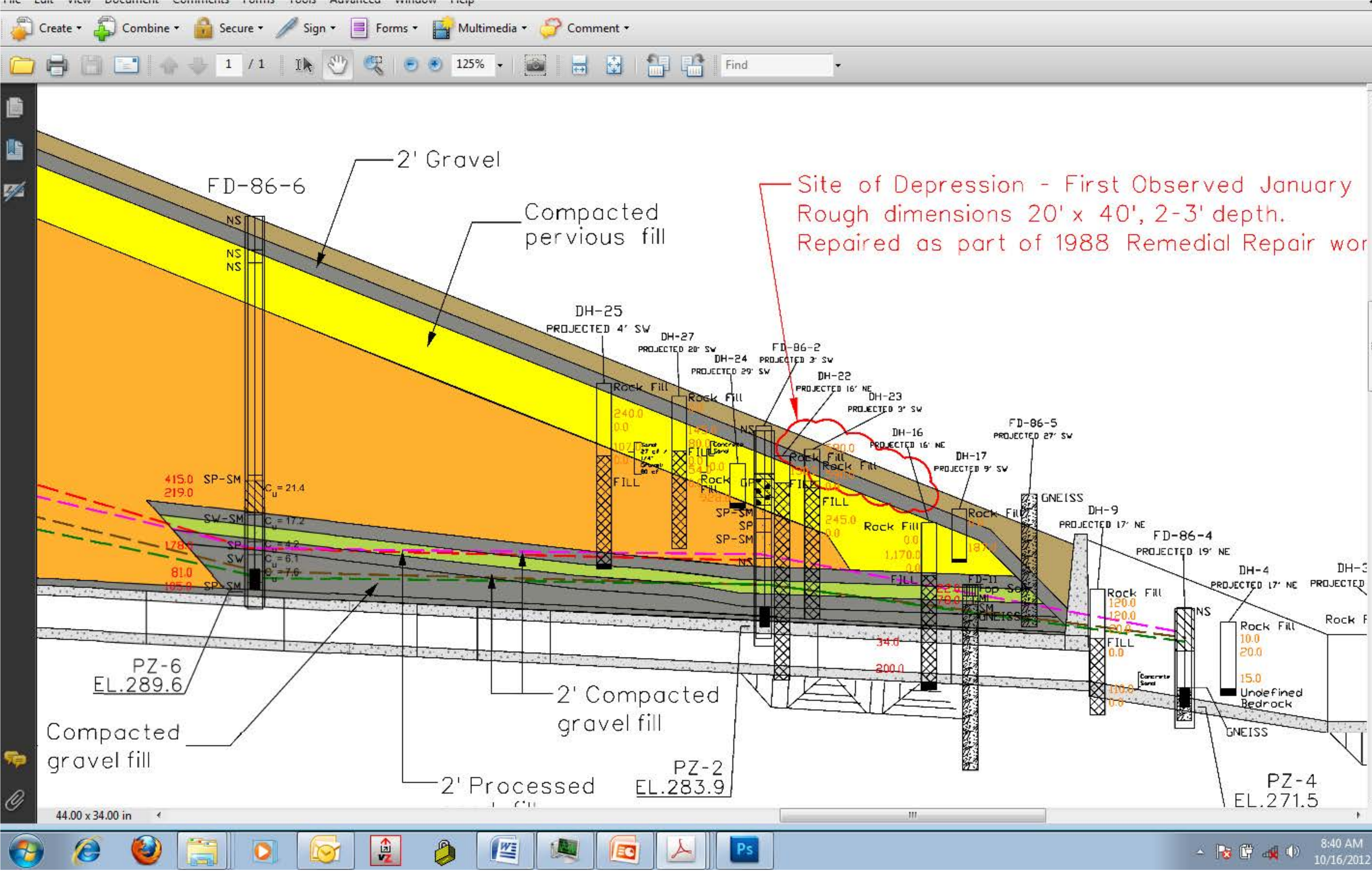
NOTE:
ELEVATIONS SHOWN
REFERENCE NGVD 29

DEPARTMENT OF THE ARMY

HOP BROOK DAM
GEOLOGIC CROSS SECTION
RIGHT ABUTMENT SECTION



Hop Brook Dam



2' Gravel
FD-86-6
Compacted pervious fill
Site of Depression - First Observed January
Rough dimensions 20' x 40', 2-3' depth.
Repaired as part of 1988 Remedial Repair wor
DH-25
PROJECTED 4' SW
DH-27
PROJECTED 20' SW
DH-24
PROJECTED 29' SW
FD-86-2
PROJECTED 3' SW
DH-22
PROJECTED 16' NE
DH-23
PROJECTED 3' SW
DH-16
PROJECTED 16' NE
DH-17
PROJECTED 9' SW
FD-86-5
PROJECTED 27' SW
DH-9
PROJECTED 17' NE
FD-86-4
PROJECTED 19' NE
DH-4
PROJECTED 17' NE
Rock Fill
FILL
GNEISS
Undefined Bedrock
PZ-6
EL.289.6
Compacted gravel fill
2' Processed
2' Compacted gravel fill
PZ-2
EL.283.9
PZ-4
EL.271.5
44.00 x 34.00 in
8:40 AM
10/16/2012

Create ▾ Combine ▾ Secure ▾ Sign ▾ Forms ▾ Multimedia ▾ Comment ▾

1 / 1 50% Find

GIC CROSS SE ION CONDU S 4 30 (FF)

ICATIONS
MATERIALS

	SIEVE	% PASS
	3"	100
	4	90-100
	200	27-30

	SIEVE	% PASS
SING	3"	100
	4	95-100
RDM	200	19-20

	SIEVE	% PASS
	3"	51-100
	4	12-25
	40	10-22
	200	1-2
	0.01	0.7

GRAVEL	SIEVE	% PASS
	3"	51-100
PASS #4	4	12-60
	40	10-54
	200	1-6
	0.01	0.7

PLAN VIEW OF SECTION AT CONDUIT - FF

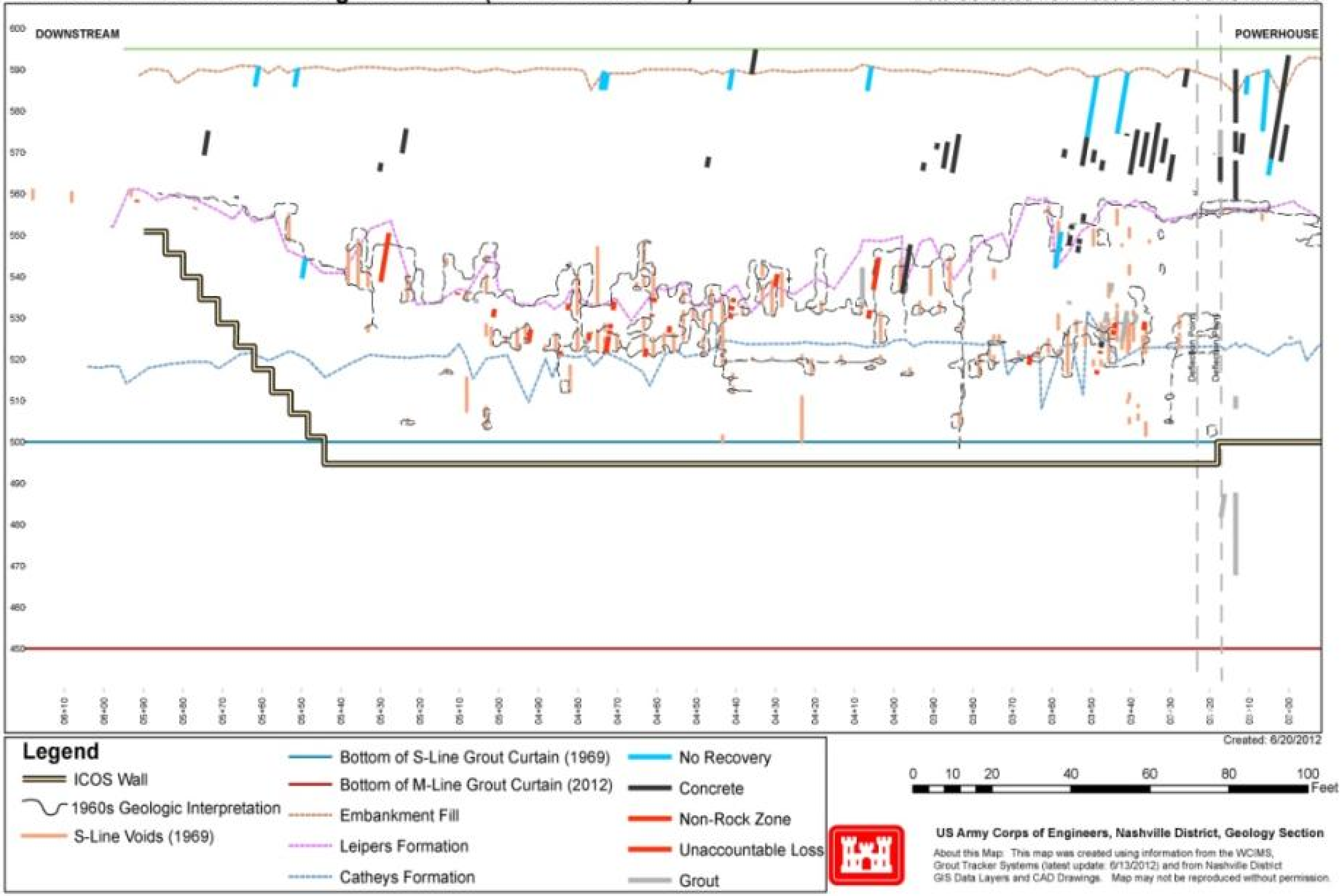
Hop Brook Dam - Boring Locations

44.00 x 34.00 in

Wolf Creek Dam

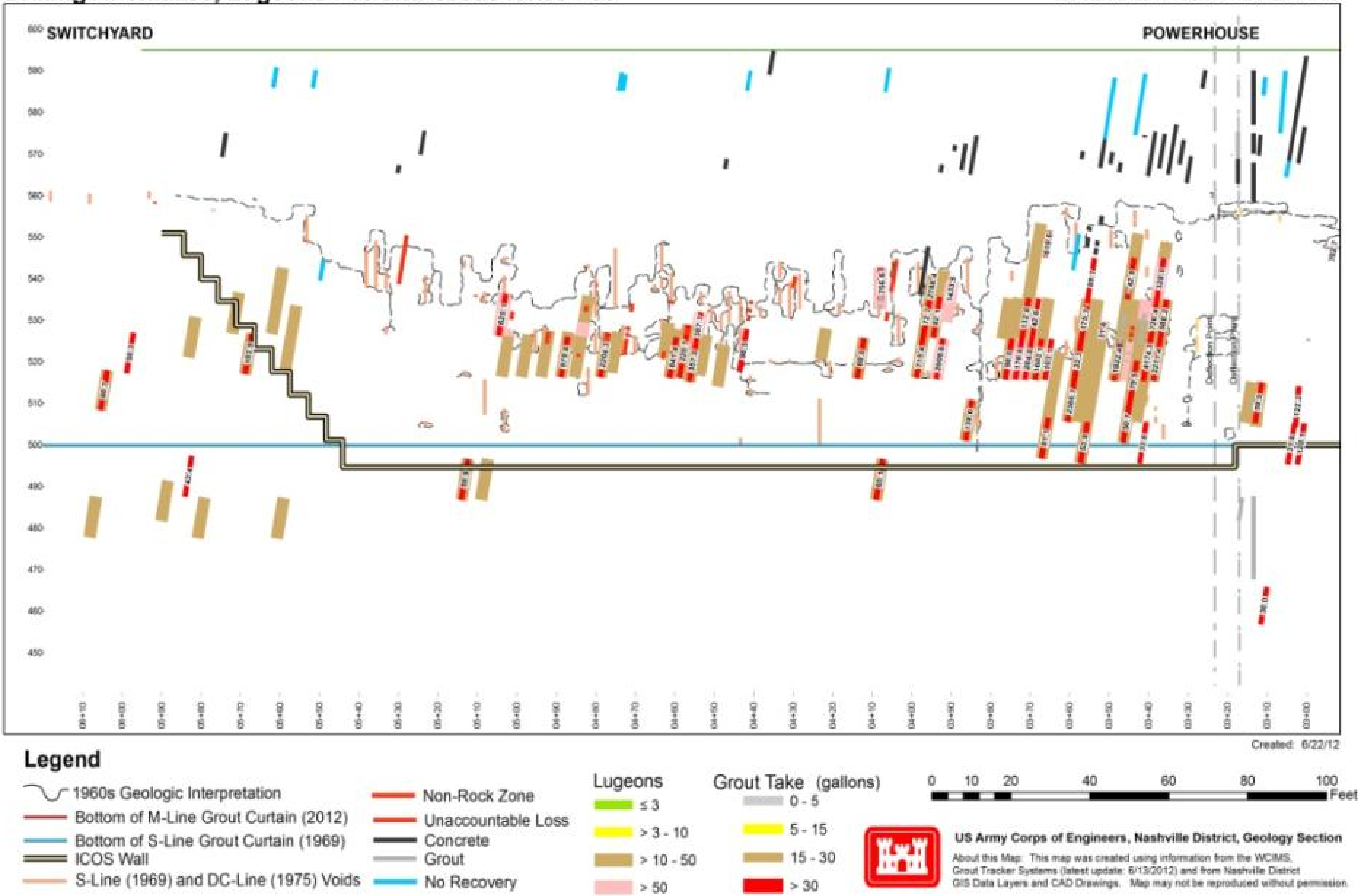
Anomalies Encountered along the M-Line (Sta. 3+20 to 6+10)

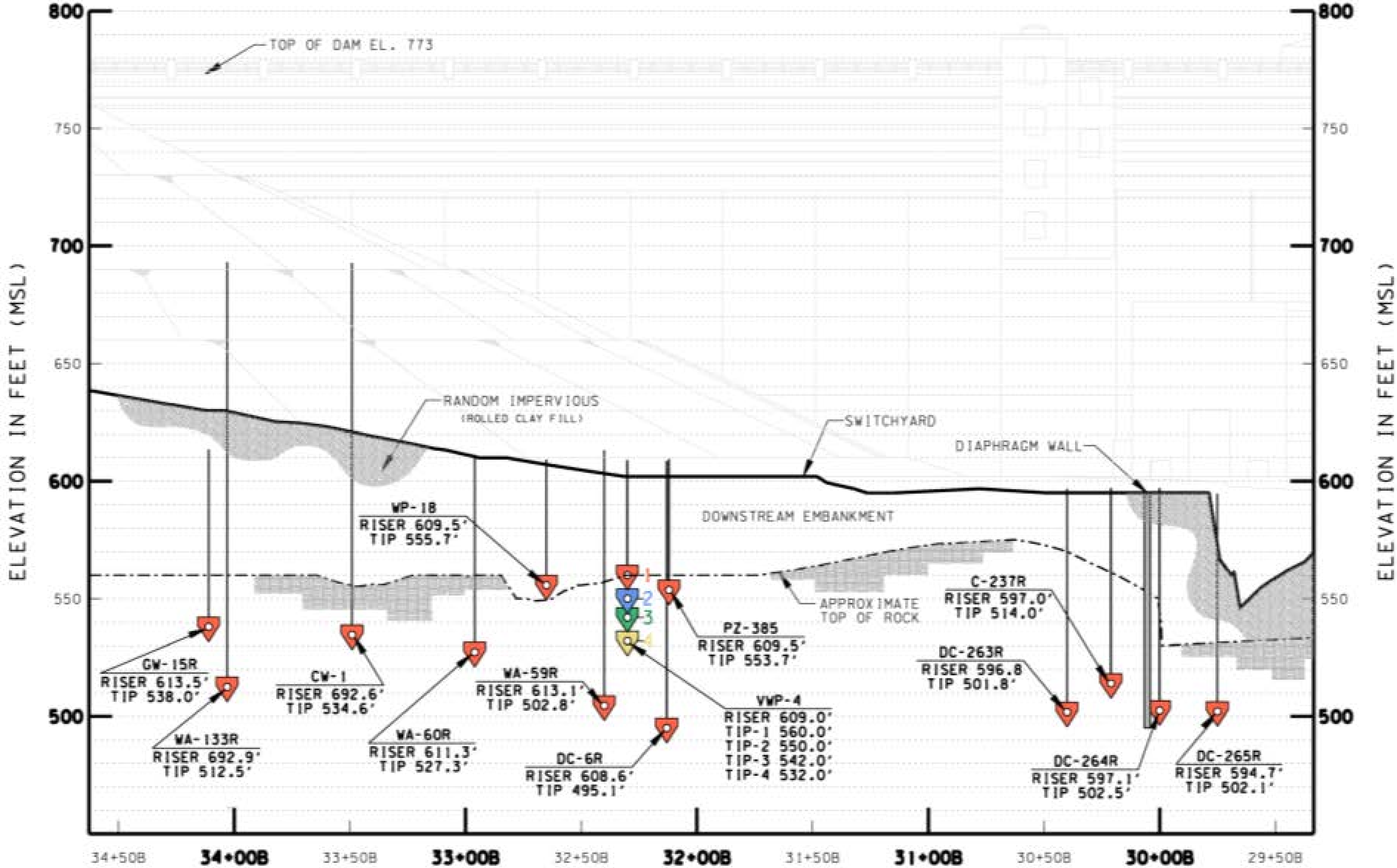
Data Collected from 1969 S-Line and 2012 M-Line



Drilling Anomalies, Lugeons >10 and Grout Takes >30

2012 M-Line Sta. 3+20 to 6+10




800
750
700
650
600
550
500
ELEVATION IN FEET (MSL)
TOP OF DAM EL. 773
RANDOM IMPERVIOUS
(ROLLED CLAY FILL)
SWITCHYARD
DIAPHRAGM WALL
DOWNSTREAM EMBANKMENT
APPROXIMATE TOP OF ROCK
WP-18 RISER 609.5' TIP 555.7'
GW-15R RISER 613.5' TIP 538.0'
WA-133R RISER 692.9' TIP 512.5'
CW-1 RISER 692.6' TIP 534.6'
WA-60R RISER 611.3' TIP 527.3'
WA-59R RISER 613.1' TIP 502.8'
DC-6R RISER 608.6' TIP 495.1'
PZ-385 RISER 609.5' TIP 553.7'
VWP-4 RISER 609.0' TIP-1 560.0' TIP-2 550.0' TIP-3 542.0' TIP-4 532.0'
C-237R RISER 597.0' TIP 514.0'
DC-263R RISER 596.8 TIP 501.8'
DC-264R RISER 597.1' TIP 502.5'
DC-265R RISER 594.7' TIP 502.1'
1
2
3
4
34+50B
34+00B
33+50B
33+00B
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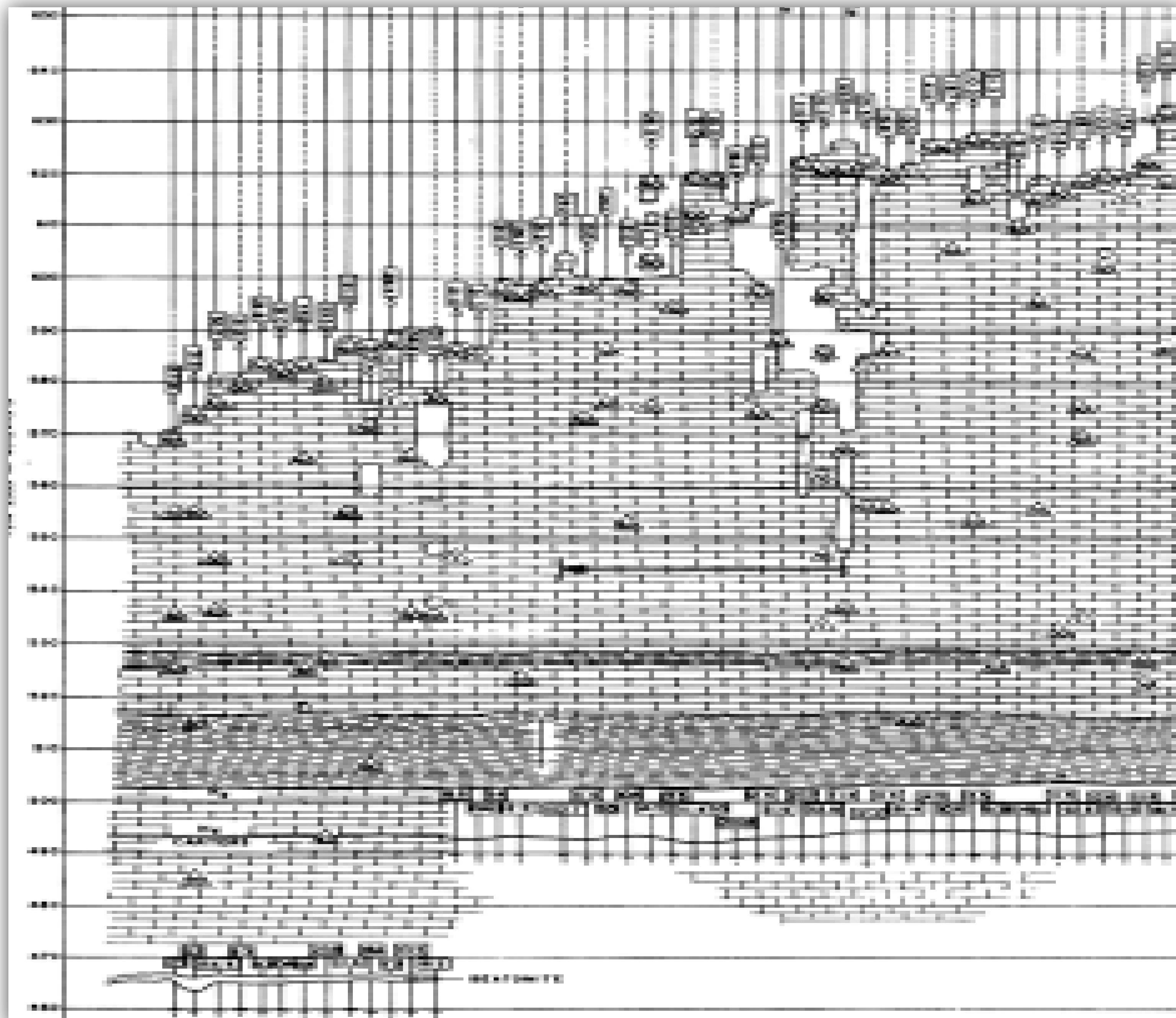
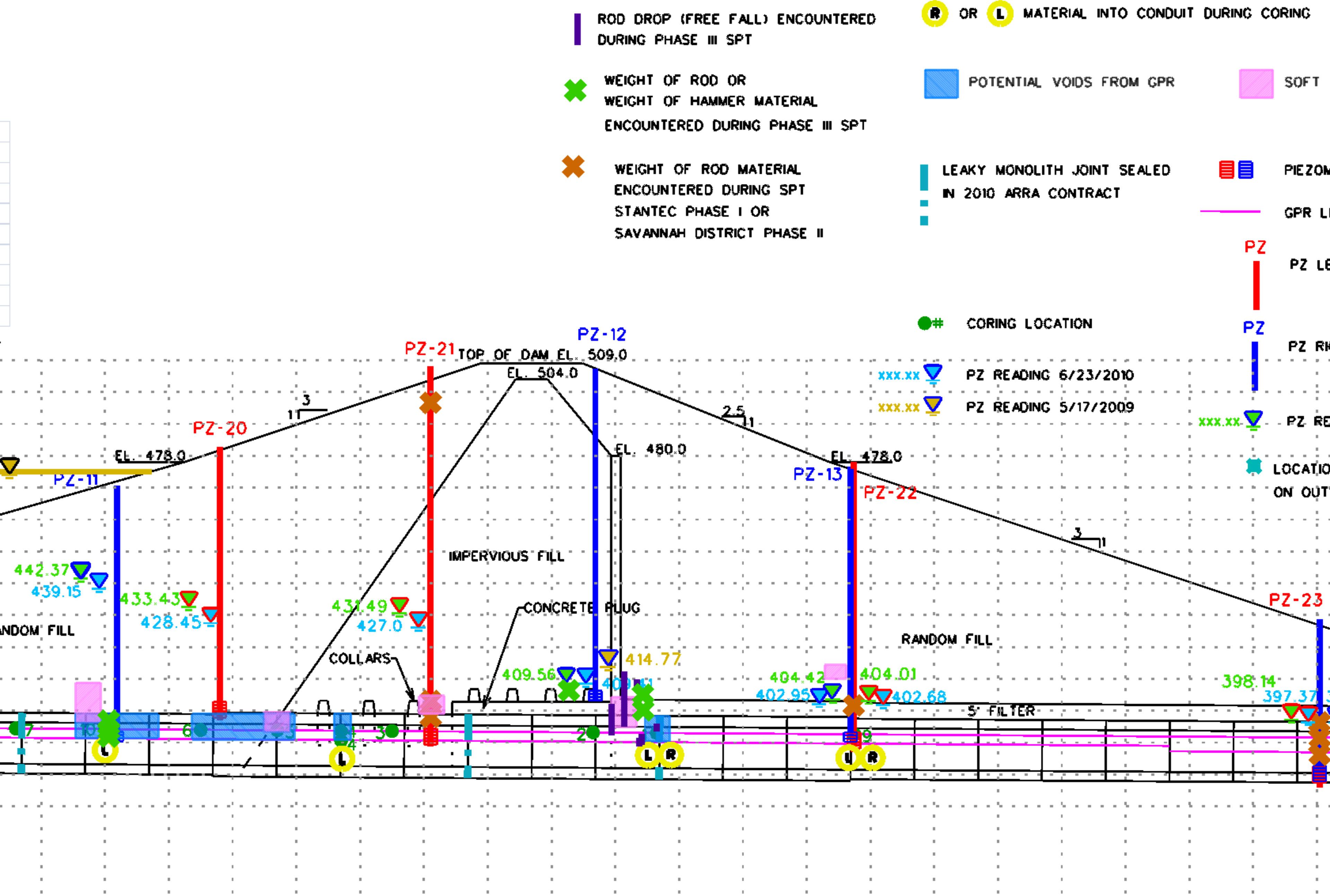
31+00B
30+50B
30+00B
29+50B

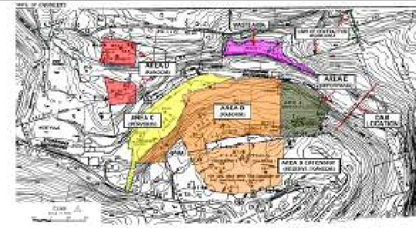


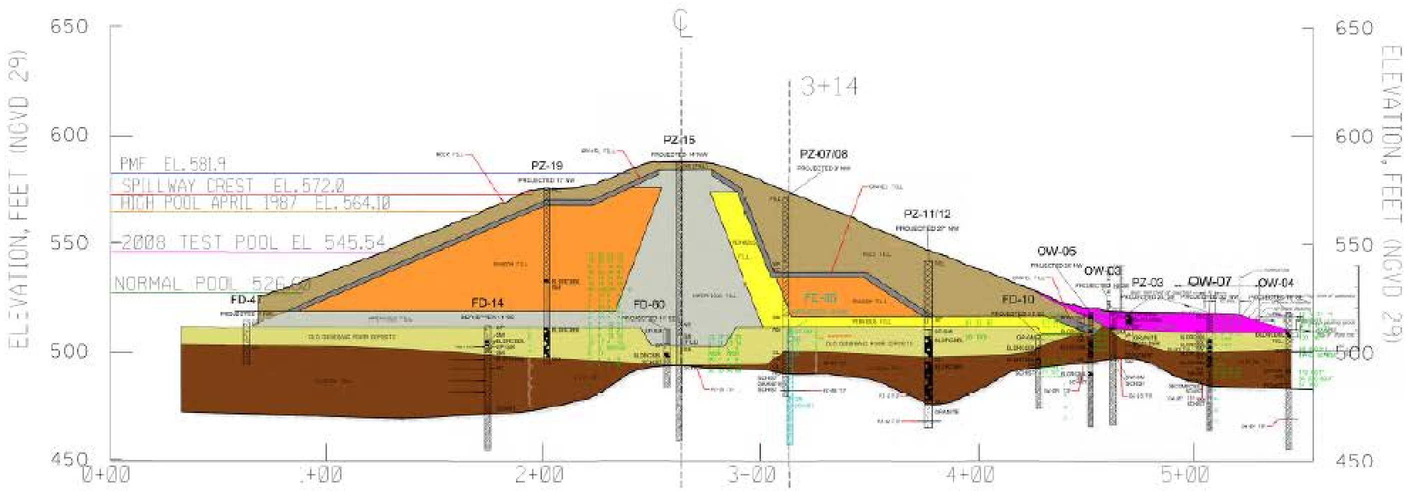
PINE CREEK

CONDUIT INVESTIGATION AND PZ LOCATIONS



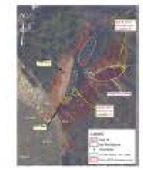
Westville Dam





DAM STATIONING ALONG SECTION (FEET)

GEOLOGIC CROSS SECTION AT STA 5+20

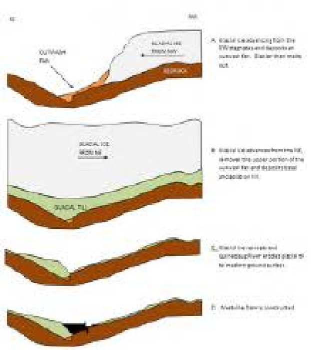


LEGEND FOR POOL ELEVATIONS

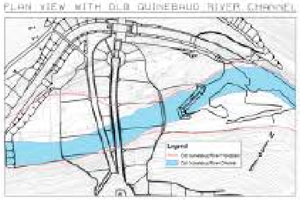
SYMBOL / LINE COLOR
DASHED LINE = PZ RESPONSE

PMF EL. 581.9
SPILLWAY CREST EL. 572.0
HIGH POOL APRIL 1987 EL. 564.10
TEST POOL EL. 545.54
NORMAL POOL EL. 526.60

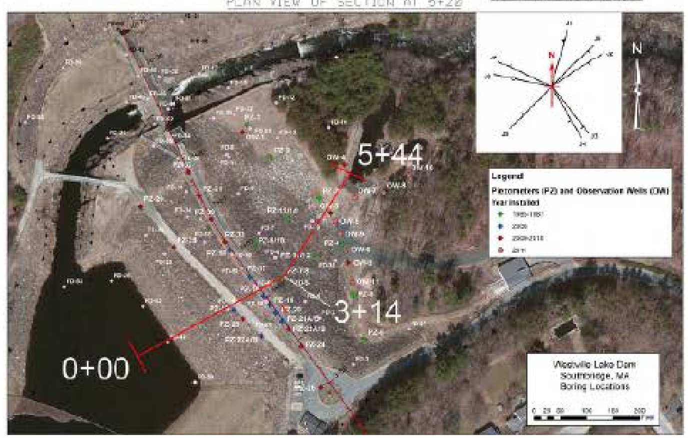
GEOLOGIC DEPOSITIONAL SEQUENCE



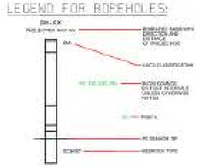
PLAN VIEW WITH OLD QUINEBAUG RIVER CHANNEL



PLAN VIEW OF SECTION AT 5+20



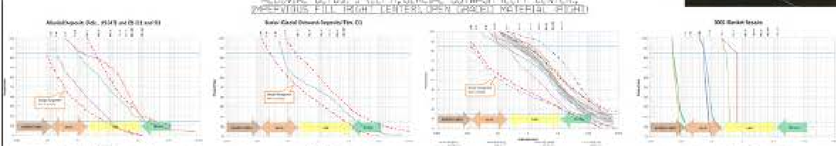
LEGEND FOR BOREHOLES:



LEGEND FOR SOILS AND CONTACTS:

GRADATION CURVES

ALLUVIAL DEPOSITS (LEFT), GLACIAL OUTWASH (LEFT CENTER), IMPERVIOUS FILL (RIGHT CENTER), OPEN GRADED MATERIAL (RIGHT)



PIEZOMETER RESPONSES TO POOL LEVELS:

Pool Level	PZ-9	PZ-10A	PZ-10B	PZ-6A	PZ-6B
PMF	564.0	DRY	DRY	426.3	434.9
Spillway Crest	560	DRY	DRY	425.1	433.5
August 2011	501.1	DRY	DRY	423.3	427.7
Winter Pool	445.5	DRY	DRY	422.5	424.9

SECTION AT 5+20

SCALE 1"=20'

NOTE:
ELEVATIONS SHOWN
REFERENCE NGVD 29

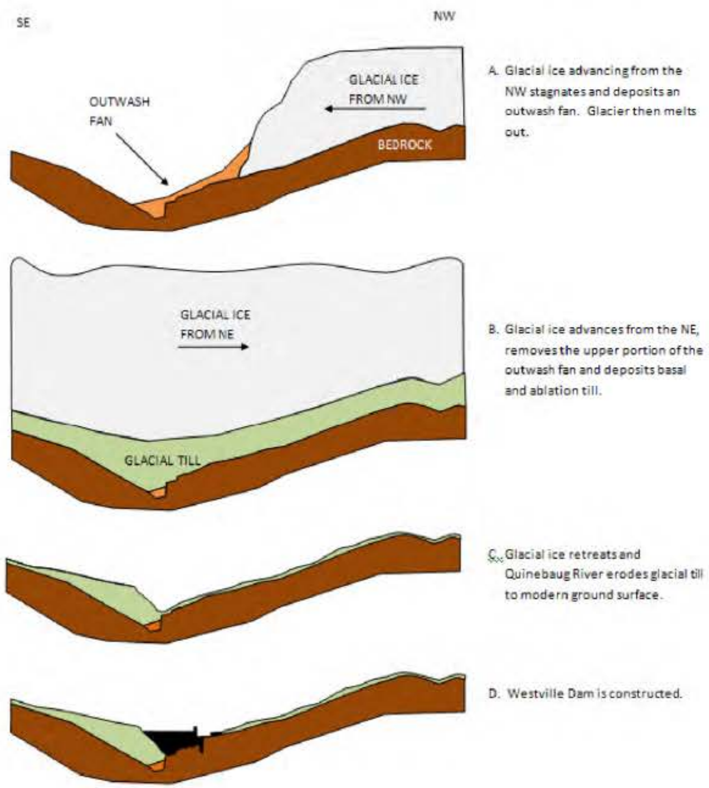
DEPARTMENT OF THE ARMY

WESTVILLE LAKE DAM
GEOLOGIC CROSS SECTION
STA 5+20

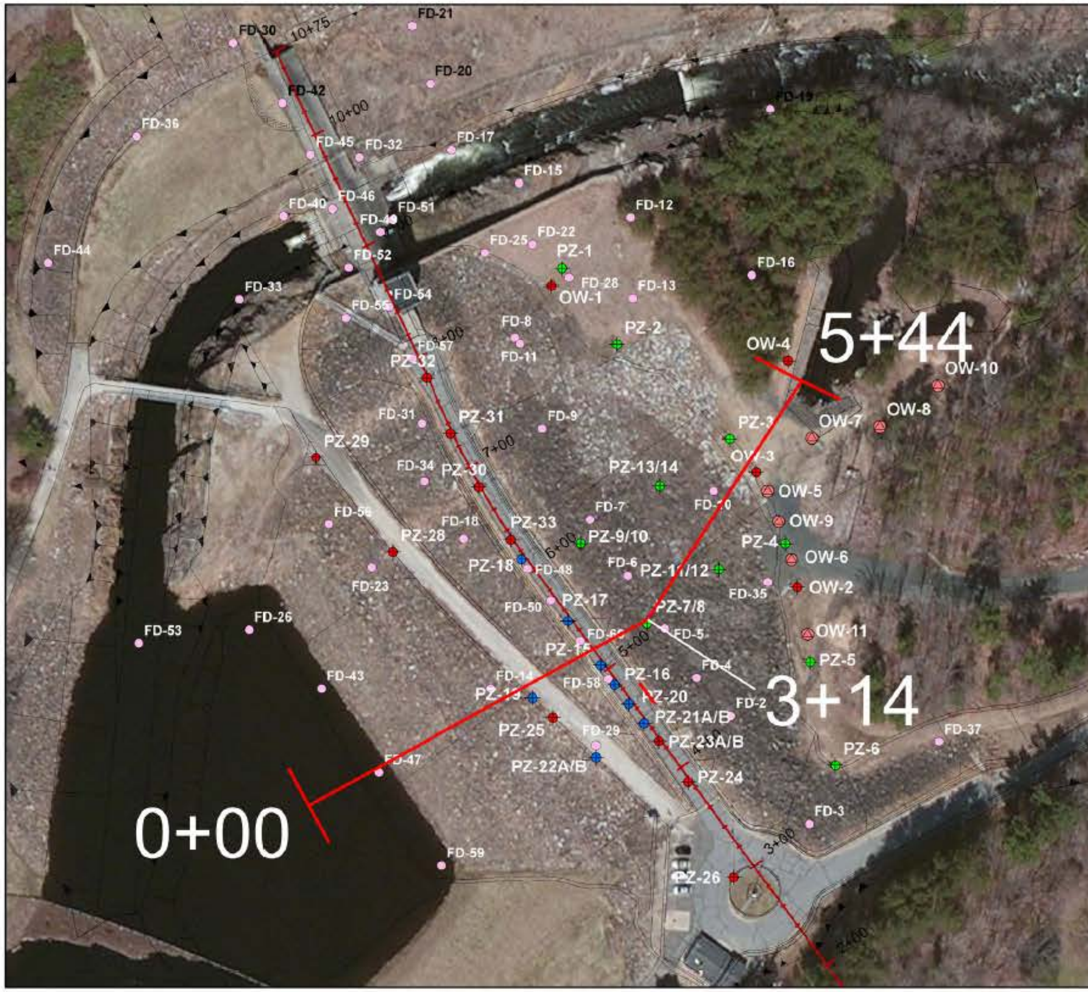
SCALE AS SHOWN

GEOLOGIC CROSS SECTION AT STA 5+20

GEOLOGIC DEPOSITIONAL SEQUENCE

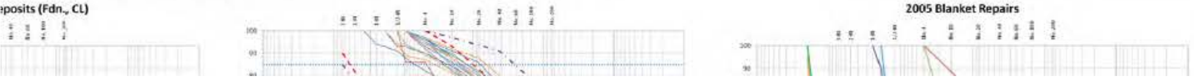


PLAN VIEW OF SECTION AT 5+20



GRADATION CURVES

...POSITS (LEFT), GLACIAL OUTWASH (LEFT CENTER), ...LL (RIGHT CENTER), OPEN GRADED MATERIAL (RIGHT)



PIEZOMETER RESPONSES TO PO

IMAGE 4: A VIEW OF THE RIGHT ABUTMENT IN AUGUST 1961.
NOTE THE STEP IN THE GLACIAL TILL MATERIAL.

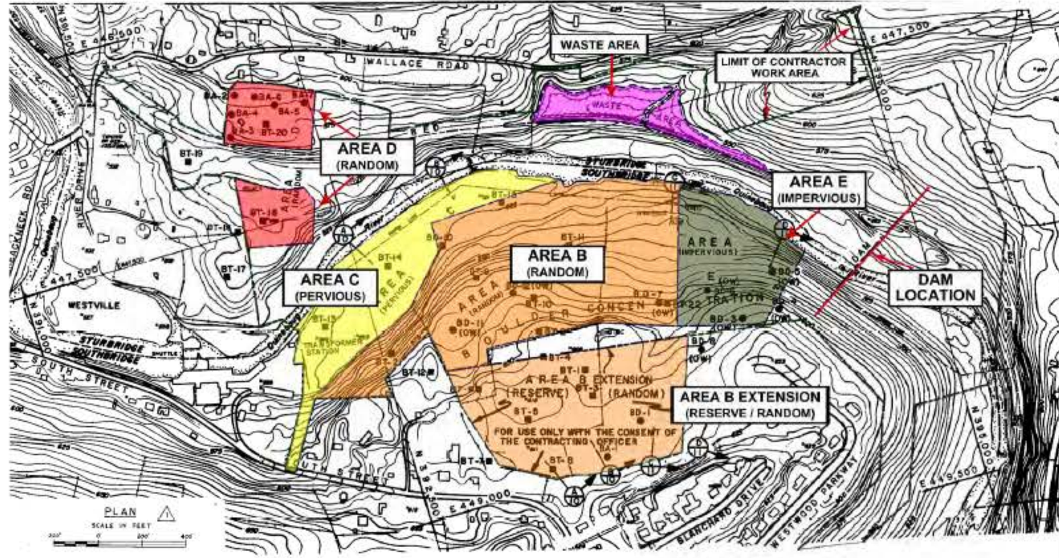


IMAGE 5: A PLAN VIEW OF THE BORROW AREAS FOR DAM CONSTRUCTION. EACH BORROW AREA IS LABELED WITH A LETTER AND THE TYPE OF MATERIAL THAT WAS EXCAVATED FROM THE BORROW AREAS IS NOTED.

650

600

550

ELEVATION, FEET (

OW-05

BELOW: A PLAN VIEW OF ICE MELT AND SEEPAGE AREAS IN THE TOE POND. THERE HAVE BEEN SEVERAL RECORDED SEEPAGE EVENTS IN THIS AREA OVER THE LAST 25 YEARS, INCLUNDING A 4' DIAMETER BOIL DURING THE 1998 POOL OF EL. 553.

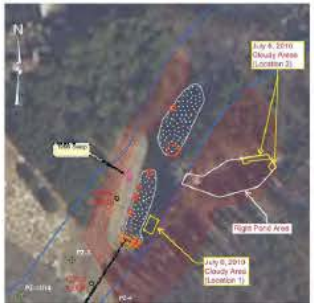
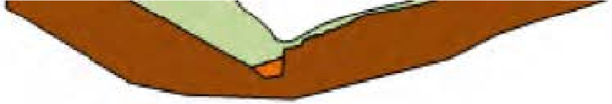
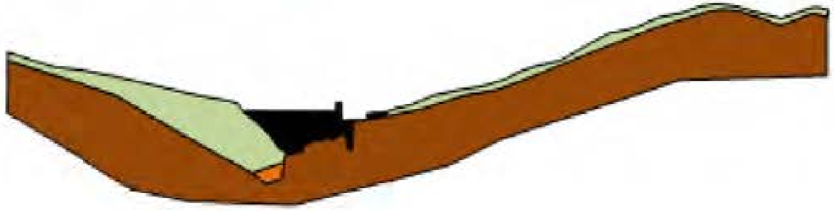


IMAGE 8 (ABOVE): VIEW FROM STA 4+95 LOOKING TOWARDS RIGHT ABUTMENT.



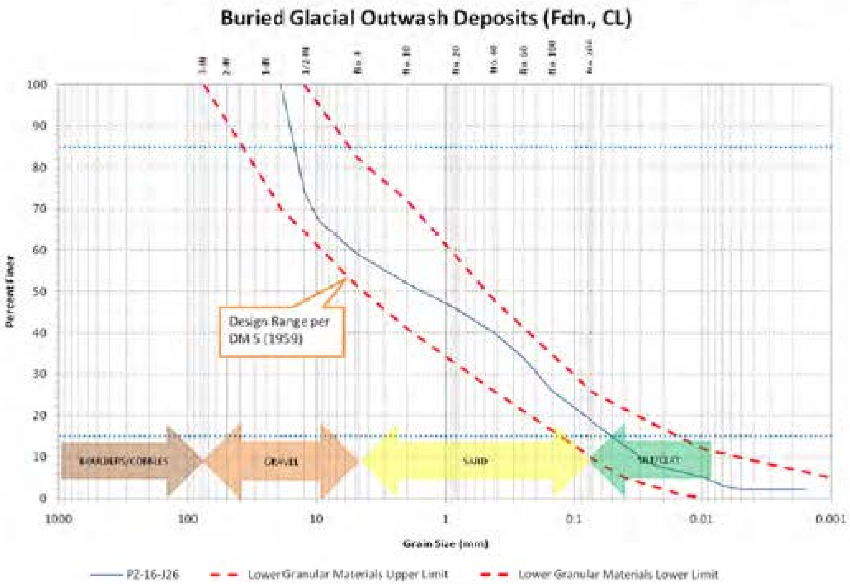
to modern ground surface.

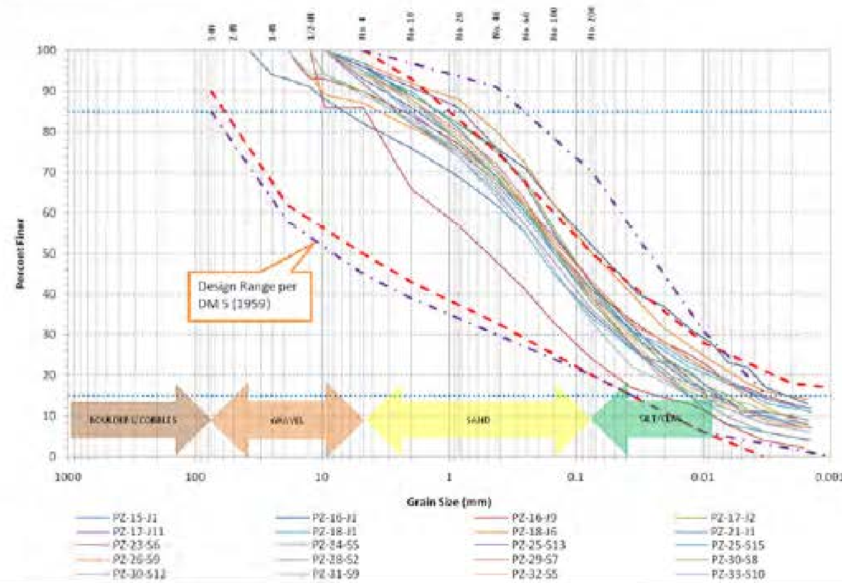


D. Westville Dam is constructed.

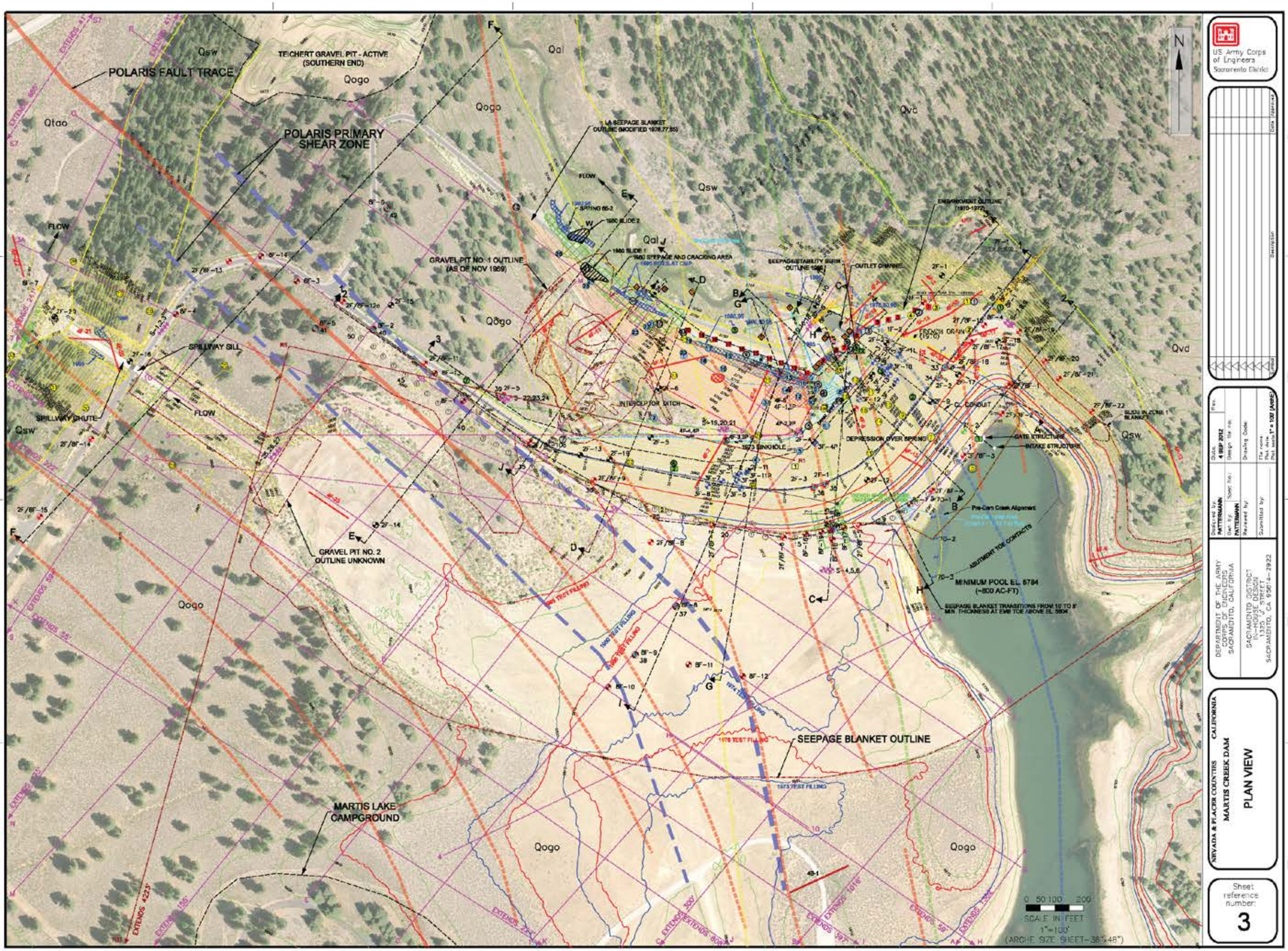
GRADATION CURVES

ALLUVIAL DEPOSITS (LEFT), GLACIAL OUTWASH (LEFT CENTER), IMPERVIOUS FILL (RIGHT CENTER), OPEN GRADED MATERIAL (RIGHT)





Examples of Plan Maps

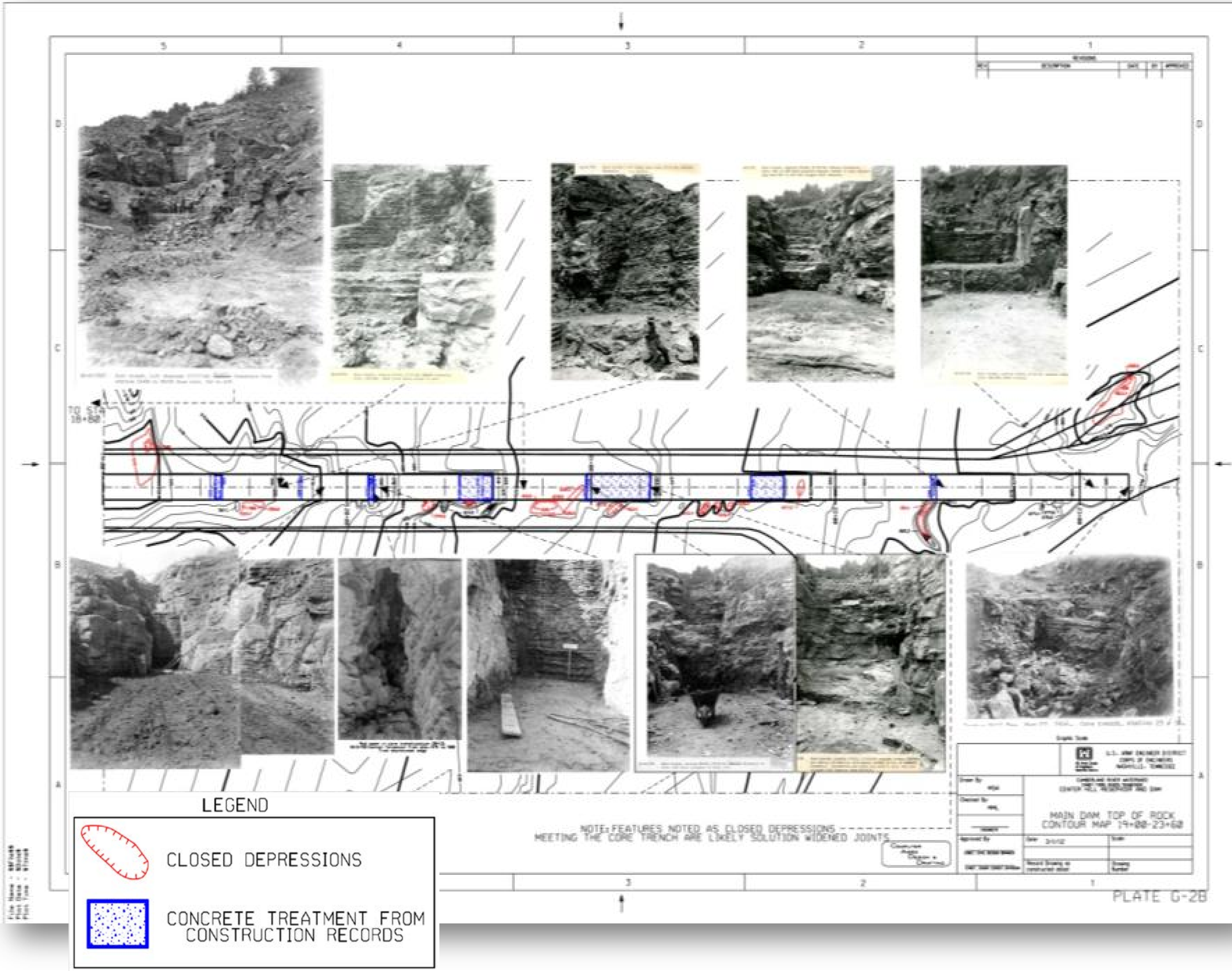

POLARIS FAULT TRACE
POLARIS PRIMARY SHEAR ZONE
TEICHERT GRAVEL PIT - ACTIVE (SOUTHERN END)
Qsw
Qogo
Qtao
Qal
Qvc
Qvd
FLOW
SPILLWAY SILL
SPILLWAY CHUTE
GRAVEL PIT NO. 1 OUTLINE (AS OF NOV 1969)
GRAVEL PIT NO. 2 OUTLINE UNKNOWN
INTERCEPTOR DITCH
1973 SINKHOLE
OUTLET CHANNEL
EMBANKMENT OUTLINE (1970-1972)
FRENCH DRAIN
CL CONDUIT
DEPRESSION OVER SPRING
GATE STRUCTURE
INTAKE STRUCTURE
Pre-Dam Creek Alignment
ABUTMENT TOE CONTACTS
MINIMUM POOL EL 5784 (~800 AC-FT)
SEEPAGE BLANKET OUTLINE
MARTIS LAKE CAMPGROUND
N
0 50 100 200
SCALE IN FEET
1"=100'
(ARCH E SIZE SHEET=36"x48")
US Army Corps of Engineers Sacramento District
DEPARTMENT OF THE ARMY CORPS OF ENGINEERS SACRAMENTO, CALIFORNIA
SACRAMENTO DISTRICT IN-HOUSE DESIGN 1325 'J' STREET SACRAMENTO, CA 95814-2922
NEVADA & PLACER COUNTIES CALIFORNIA
MARTIS CREEK DAM
PLAN VIEW
Sheet reference number:
3
1
2
3
4
5
A
B
C
D

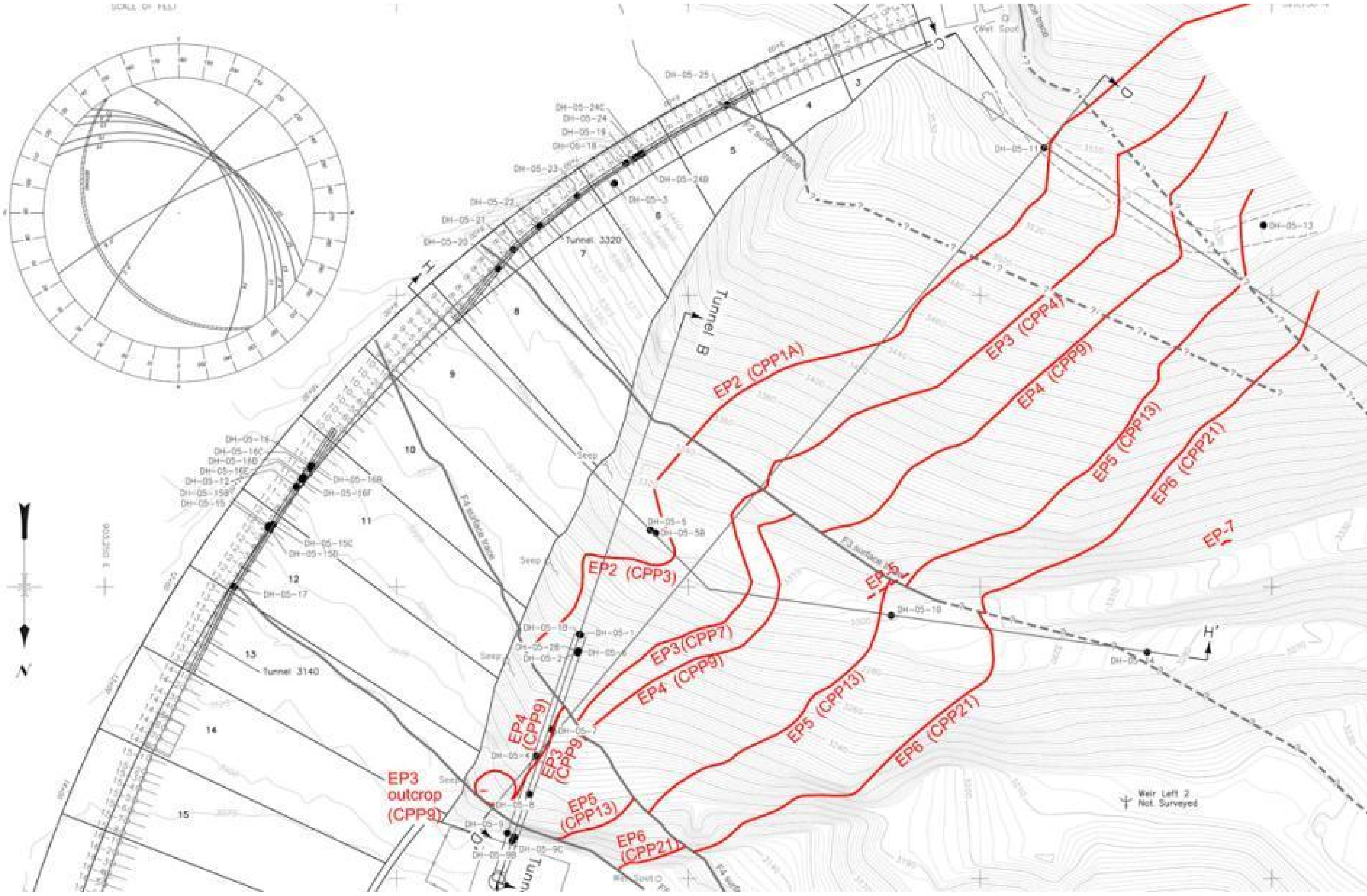
Plan View of Grouting Program High Takers

Total Grout Takes in Switchyard Program

US Army Corps of Engineers, Nashville District, Geology Section

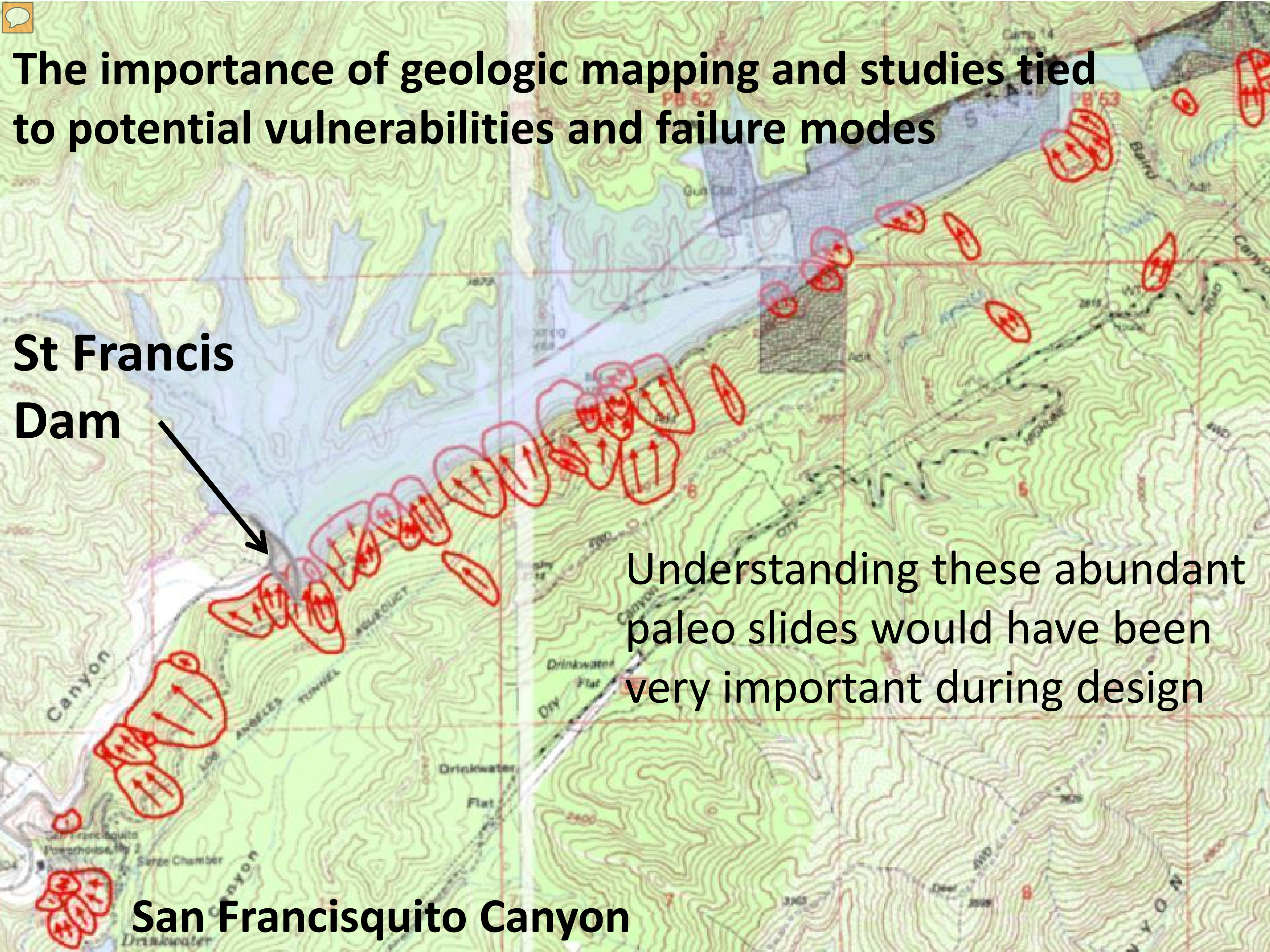
About this Map: This map was created using information from the WCIMS, Grout Tracker Systems (latest update: 6/13/2012) and from Nashville District GIS Data Layers and CAD Drawings. Map may not be reproduced without permission.

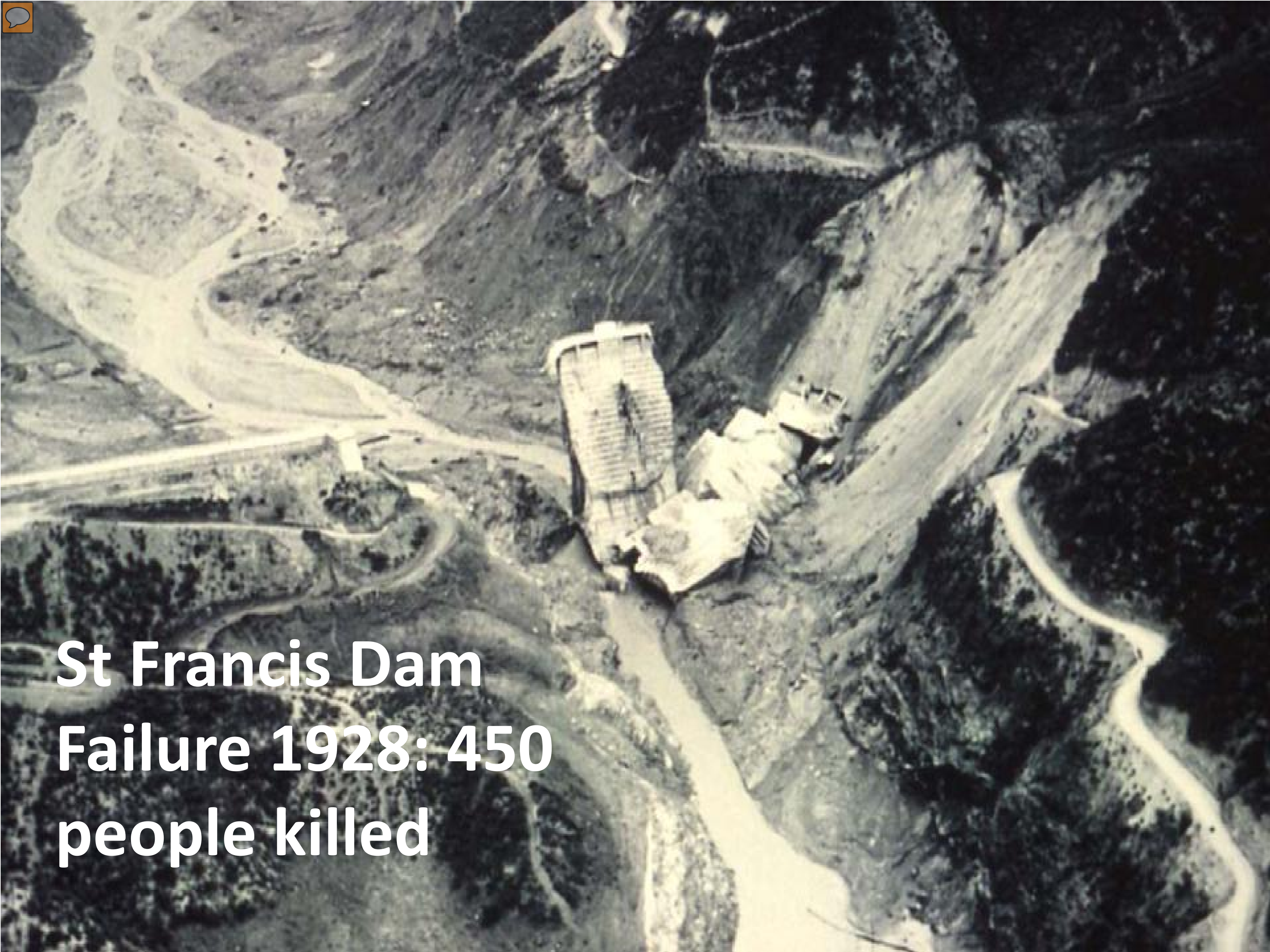

LEGEND
CLOSED DEPRESSIONS
CONCRETE TREATMENT FROM CONSTRUCTION RECORDS
NOTE: FEATURES NOTED AS CLOSED DEPRESSIONS MEETING THE CORE TRENCH ARE LIKELY SOLUTION WIDENED JOINTS
MAIN DAM TOP OF ROCK CONTOUR MAP 19+00-23+60
PLATE G-2B

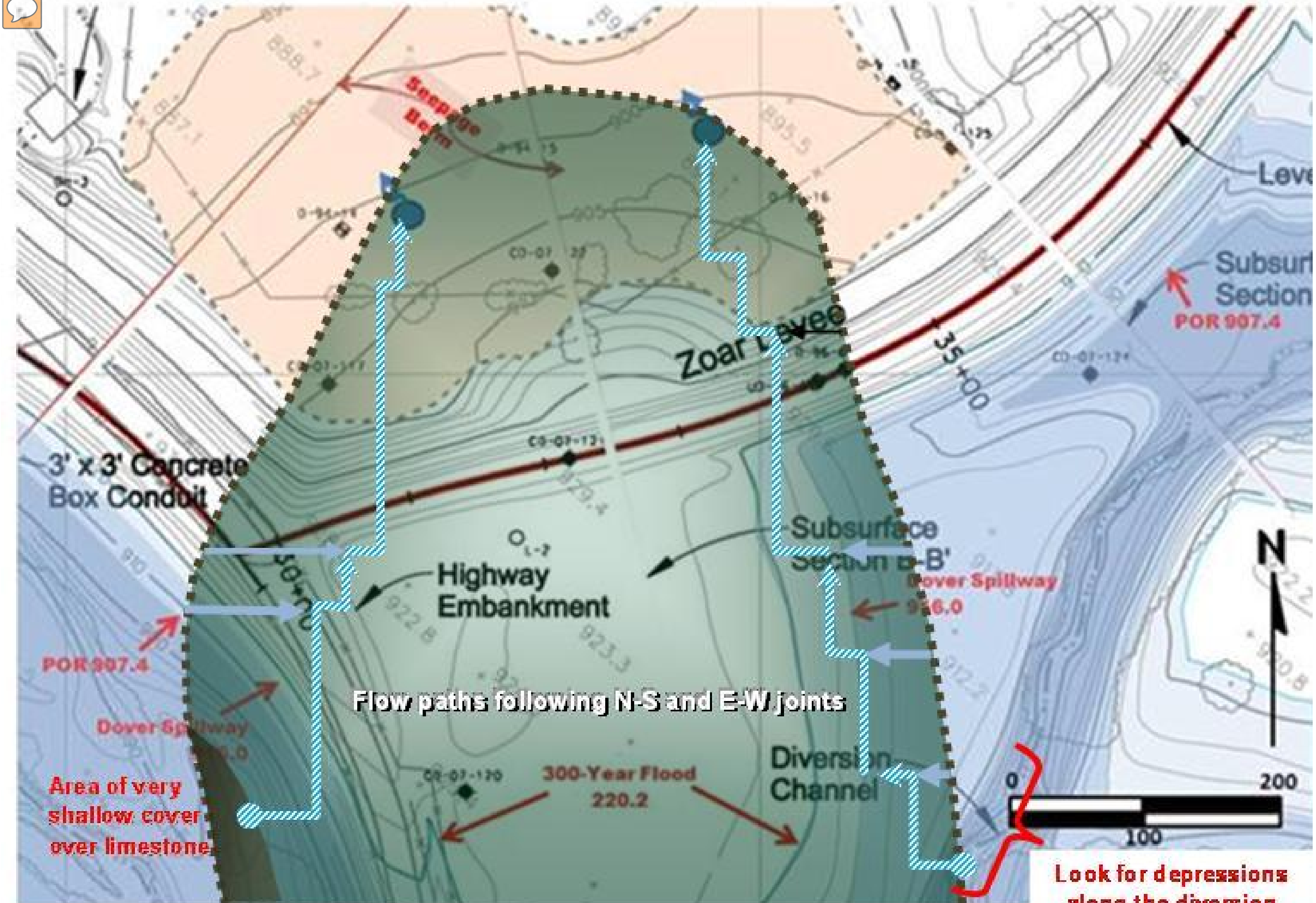


EP2 (CPP1A)
EP3 (CPP4)
EP4 (CPP9)
EP5 (CPP13)
EP6 (CPP21)
EP-7
EP2 (CPP3)
EP3(CPP7)
EP4 (CPP9)
EP5 (CPP13)
EP6 (CPP21)
EP4 (CPP9)
EP3 (CPP9)
EP3 outcrop (CPP9)
EP5 (CPP13)
EP6 (CPP21)
Tunnel 3320
Tunnel 3140
Tunnel B
Weir Left 2 Not Surveyed

The importance of geologic mapping and studies tied to potential vulnerabilities and failure modes




St Francis Dam
Failure 1928: 450
people killed



Approximate extent of limestone in the Rock Knoll with associated geology and hypothetical flow paths.

Examples of Levee Geomorphic Mapping

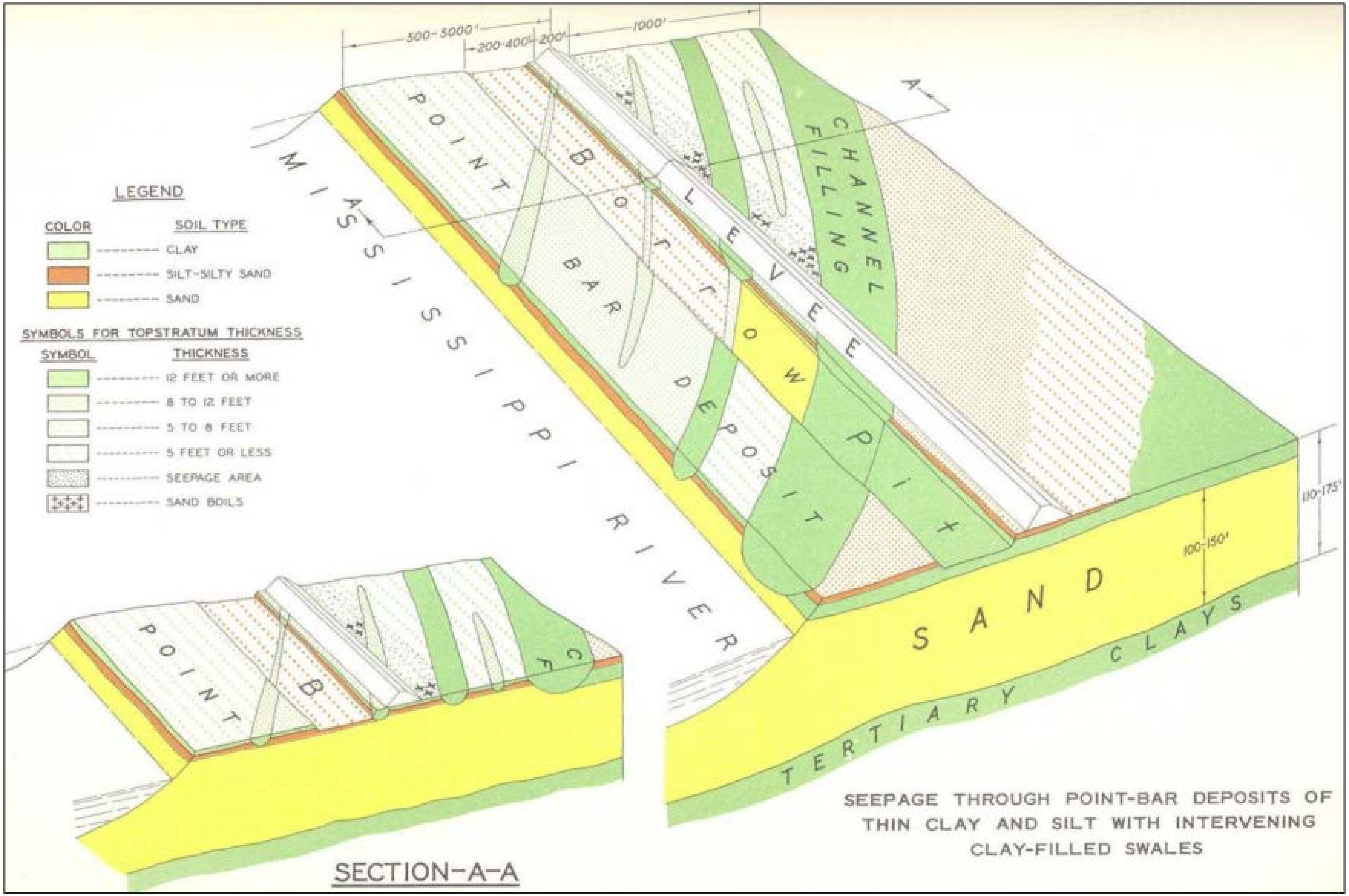
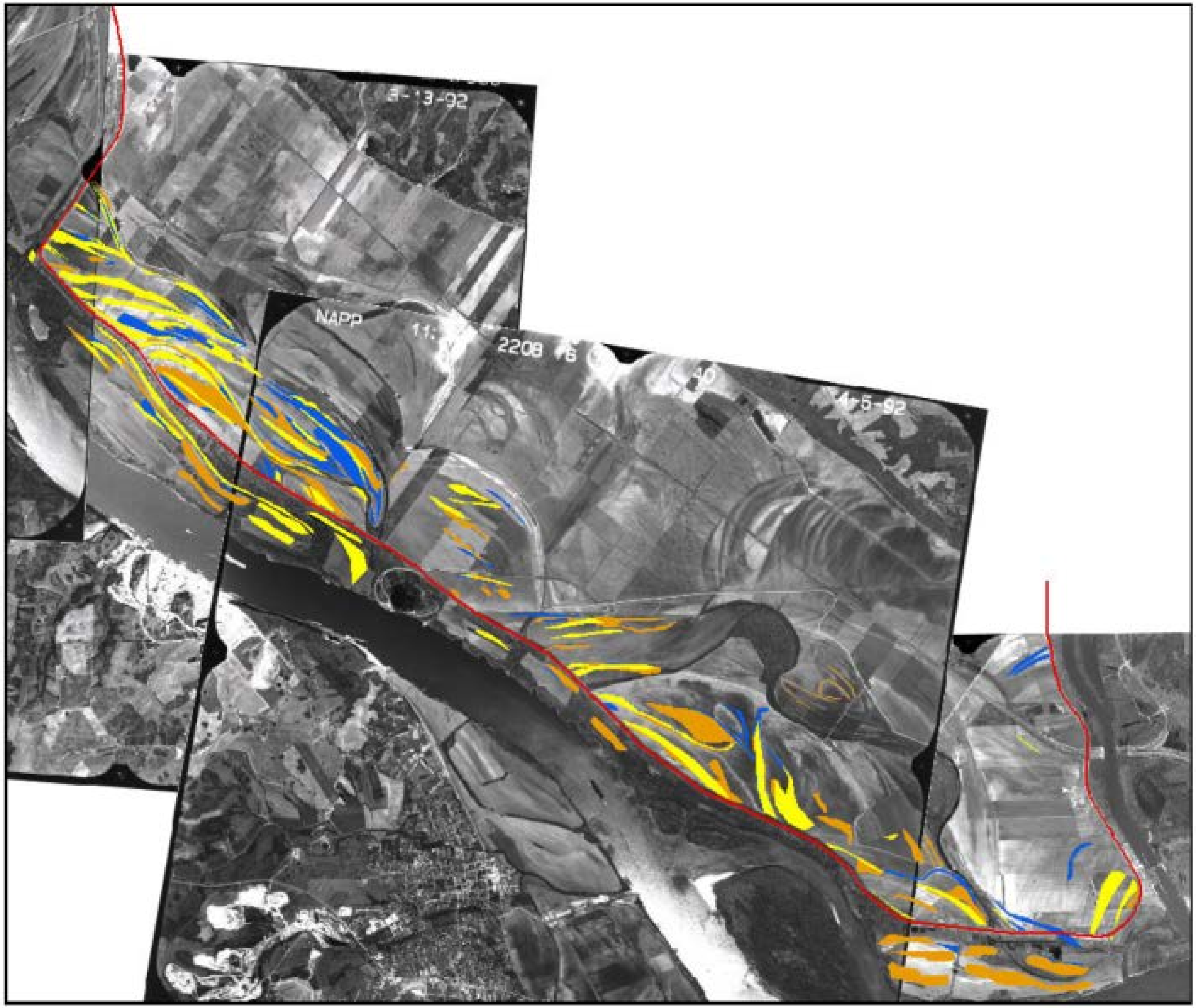


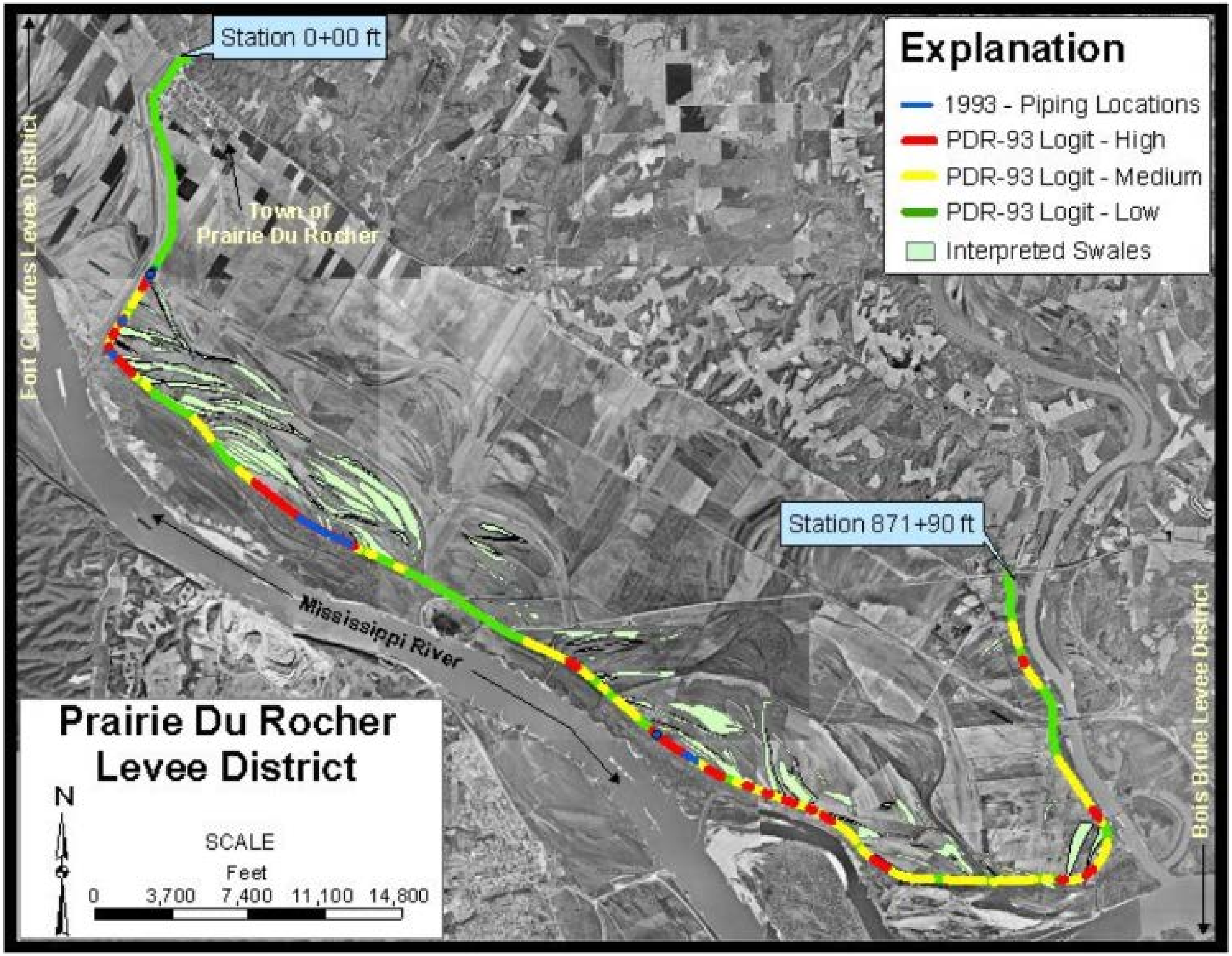
Figure 4. Influence of surface geology and levee orientation on seepage (USACE 1956a)

From Glynn, M.E. and Kuszmaul, J., 2004. Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model. ERDC/GSL TR-04-12



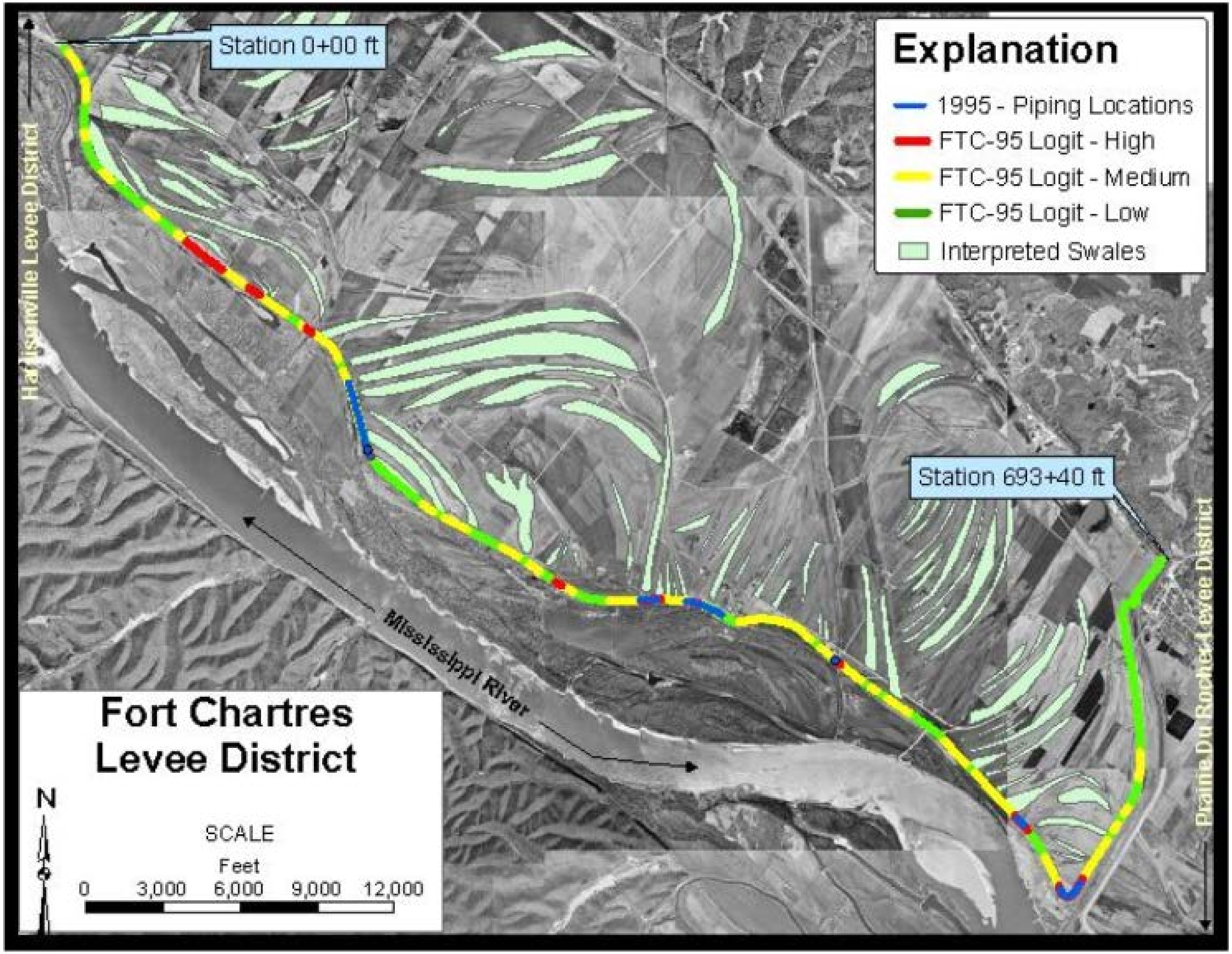
Detailed mapping of smaller swales, Prairie Du Rocher, IL. Colors denote swales visible in 1992, 1994, and 1996 aerial photos

From Glynn, M.E. and Kuszmaul, J., 2004. Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model. ERDC/GSL TR-04-12



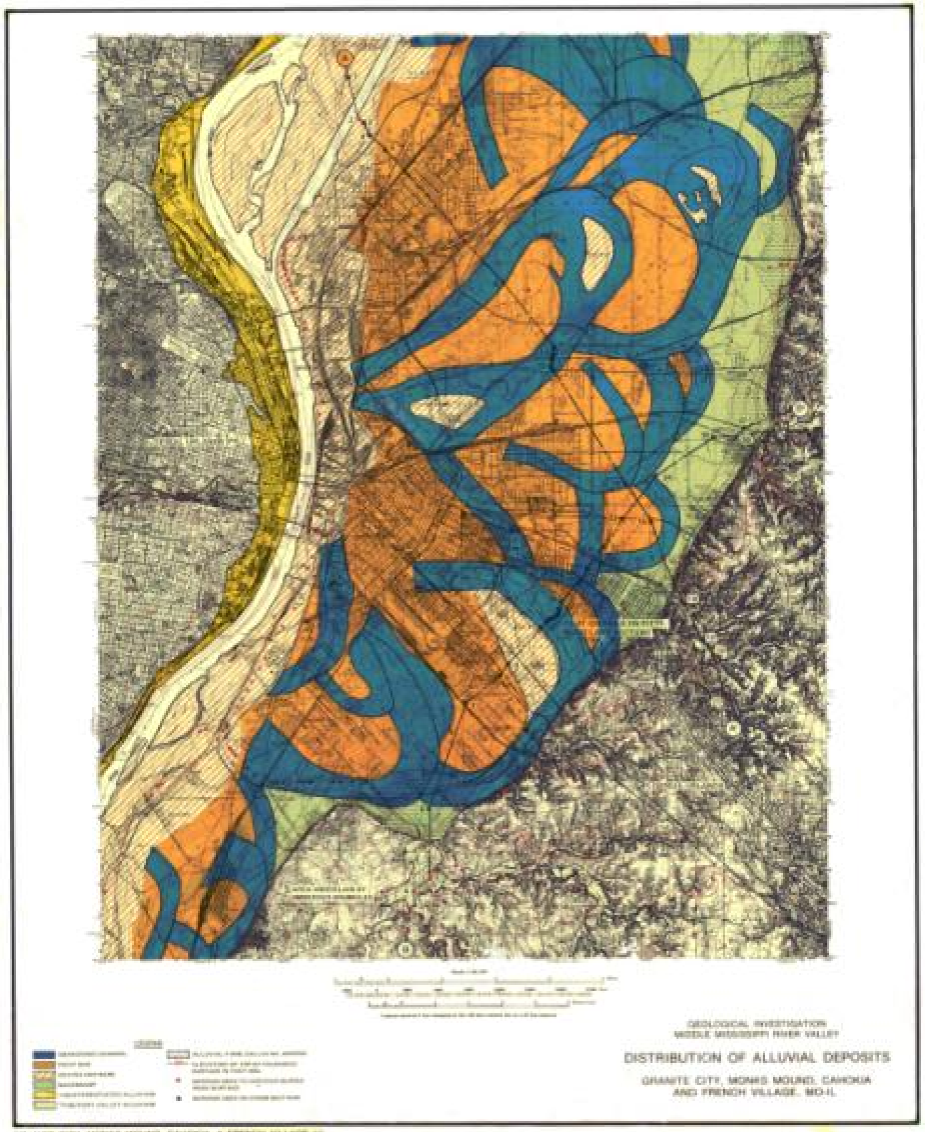
Coded levee reaches in relation to the location of piping in 1993 and identified swales for the Prairie Du Rocher levee district

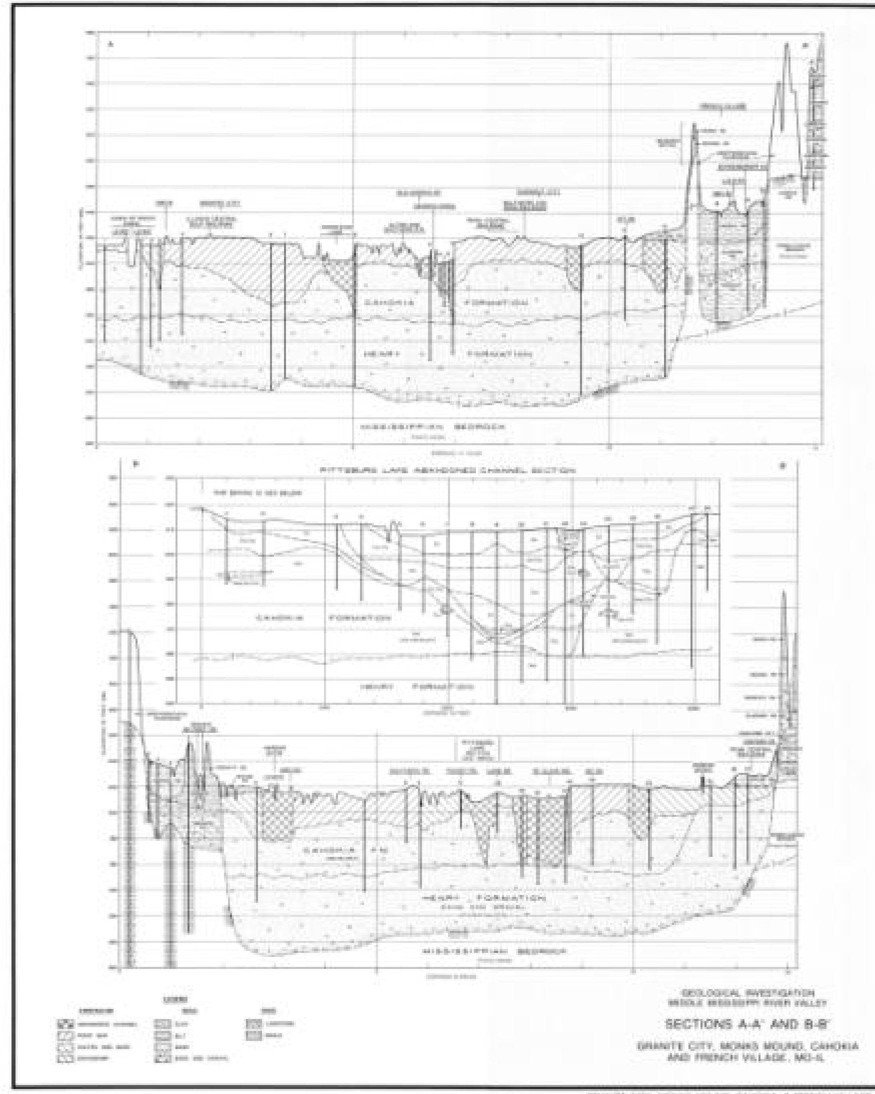
From Glynn, M.E. and Kuszmaul, J., 2004. Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model. ERDC/GSL TR-04-12



Coded levee reaches in relation to the location of piping in 1995 and identified swales for the Fort Chartres District

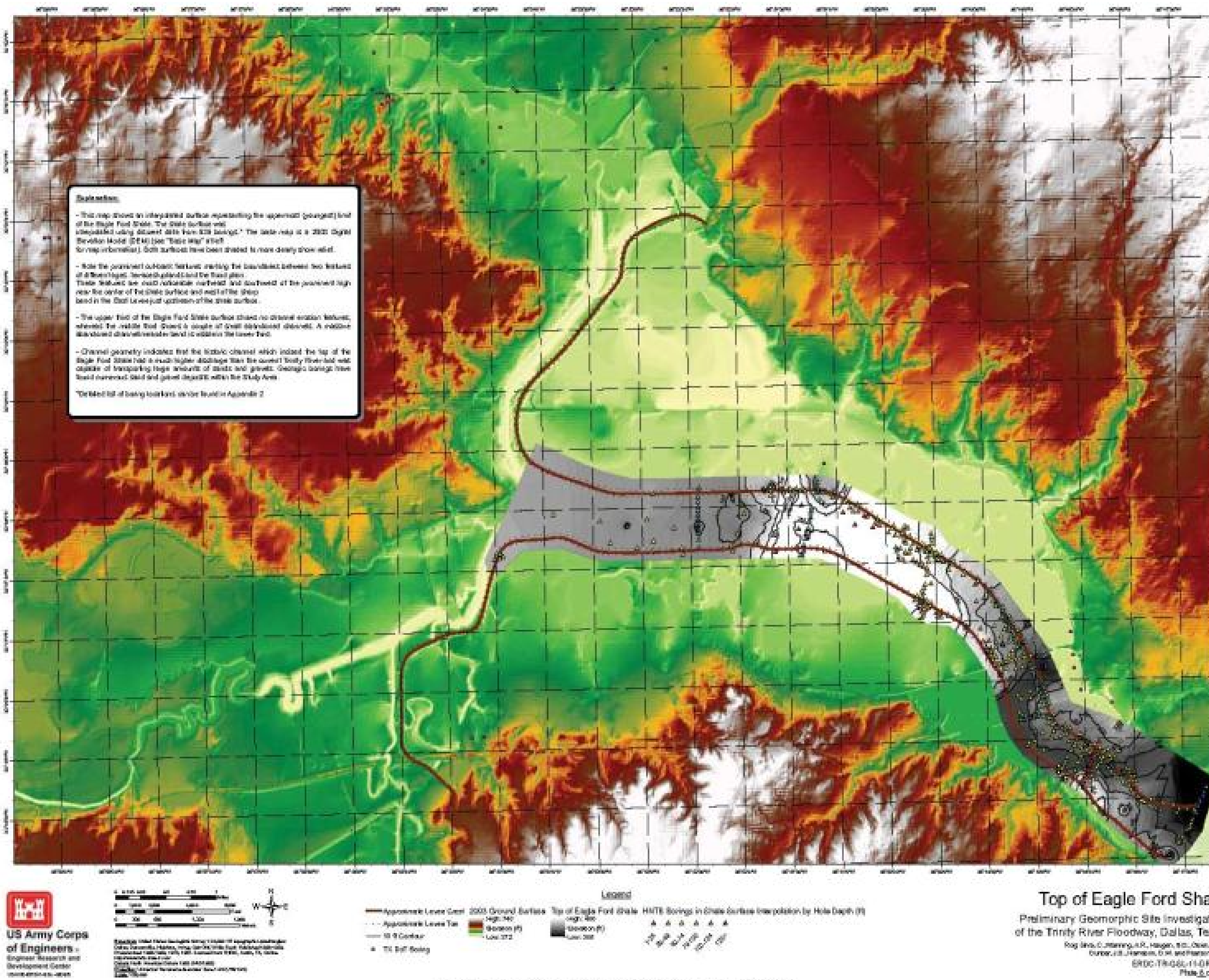
From Glynn, M.E. and Kuszmaul, J., 2004. Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model. ERDC/GSL TR-04-12





From Woerner, E.G., Dunbar, J.B., Villanueva, E., Smith, L.M., 2003, Geologic Investigation of the Middle Mississippi River, ERDC/GSL TR-03-7

Binding Edge

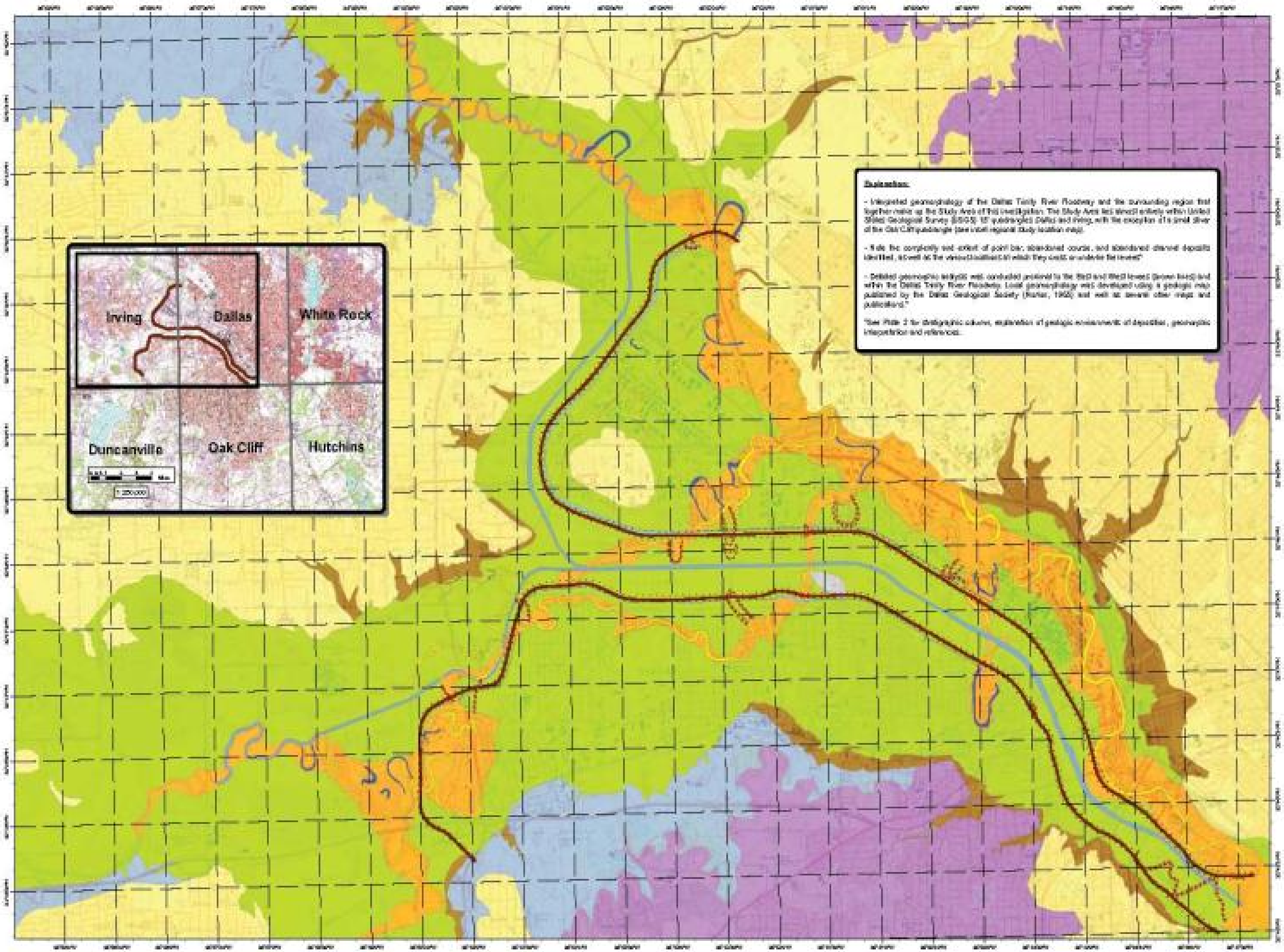


Top of Eagle Ford Shale

Preliminary Geomorphic Site Investigation of the Trinity River Floodway, Dallas, Texas

This study is based on available data provided by Trinity River Project contractors as of March 1, 2010

Binding Edge



US Army Corps of Engineers

Legend

Point Bar	Quaternary Terrace	Abandoned Channel	Scaled Channel
Crevasse Splay	Middle Austin Chalk	Abandoned Course	Approximate Levee Crest
Flood Basin	Lower Austin Chalk	Active Channel	Approximate Levee Toe
Undifferentiated Alluvium	Eagle Ford Shale	Pump Station Channel	

Surface Geology and Alluvial Deposits

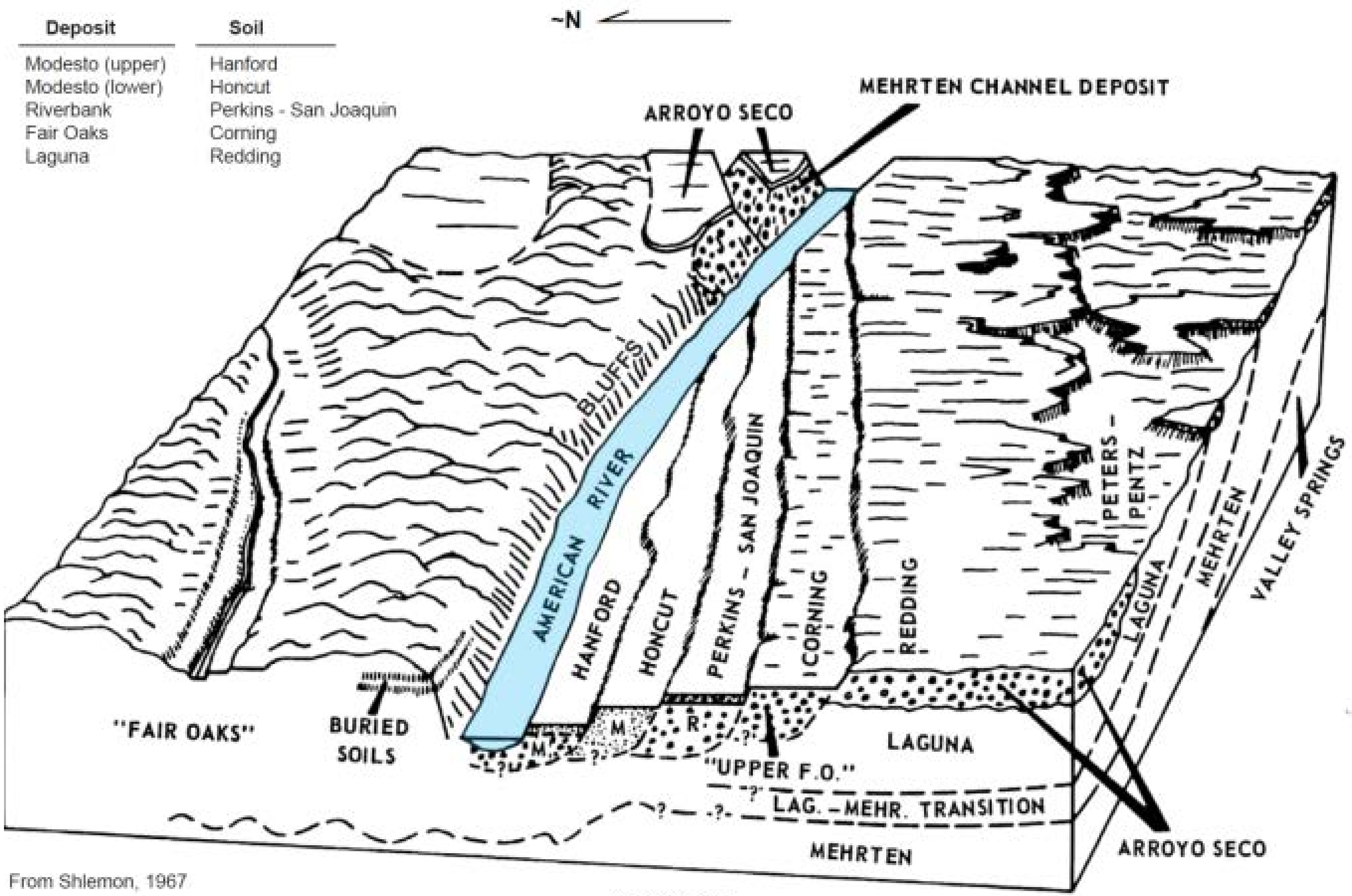
Preliminary Geomorphic Site Investigation of the Trinity River Floodway, Dallas, Texas

ERDC-TR-GSL-11-DRAFT

Plate 1 of 65

This study is based on available data provided by Trinity River Project contractors as of March 1, 2010

Deposit	Soil
Modesto (upper)	Hanford
Modesto (lower)	Honcut
Riverbank	Perkins - San Joaquin
Fair Oaks	Corning
Laguna	Redding



From Shlemon, 1967

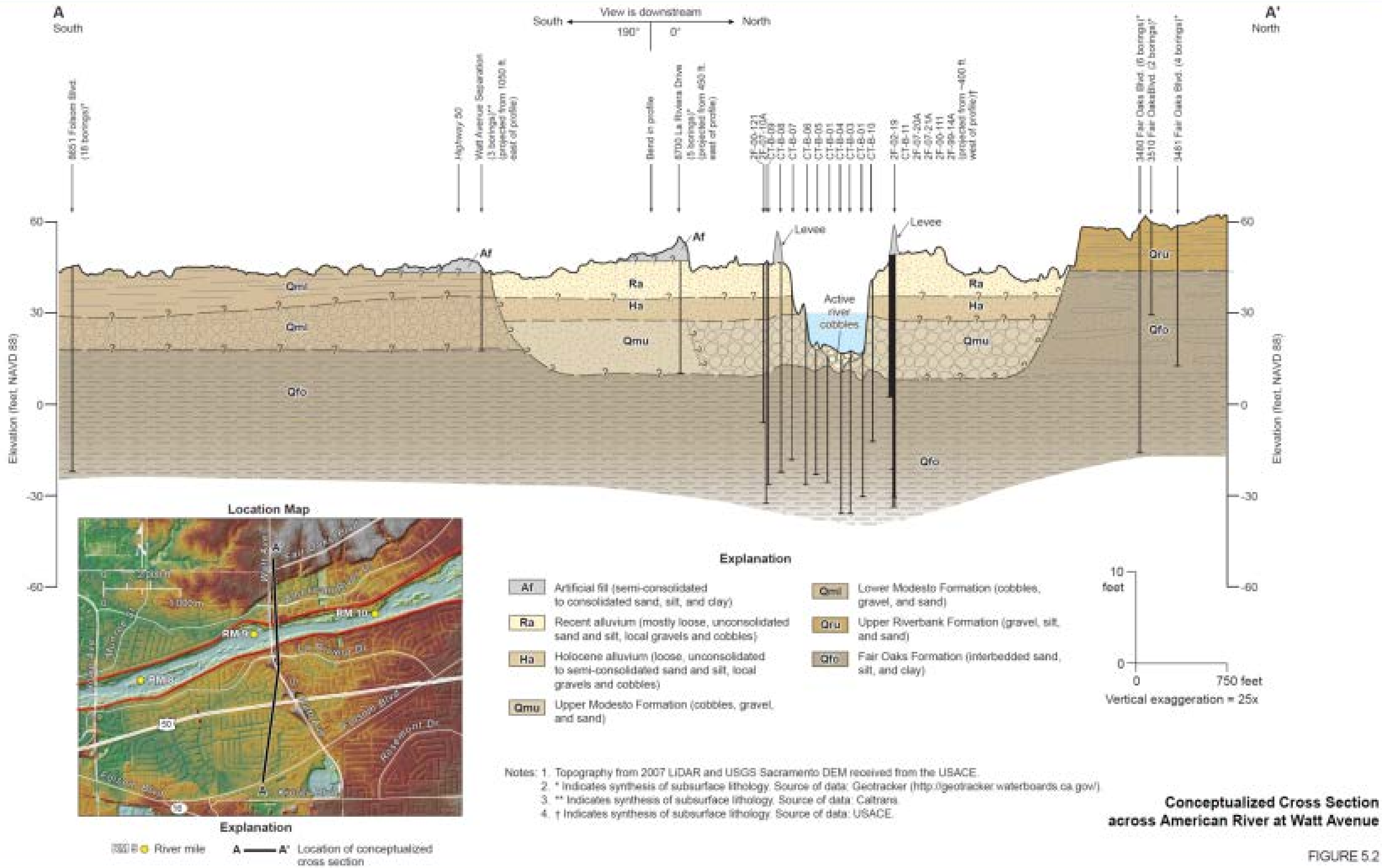
Abbreviations:

M = Modesto Formation
R = Riverbank Formation
"Upper F.O." = Upper Fair Oaks Formation

Landscape Evolution Model: Soils and Geologic Unit Associations

This is modified out of Roy Shlemon's dissertation. The model shows the river geomorphology and associated stratigraphy.

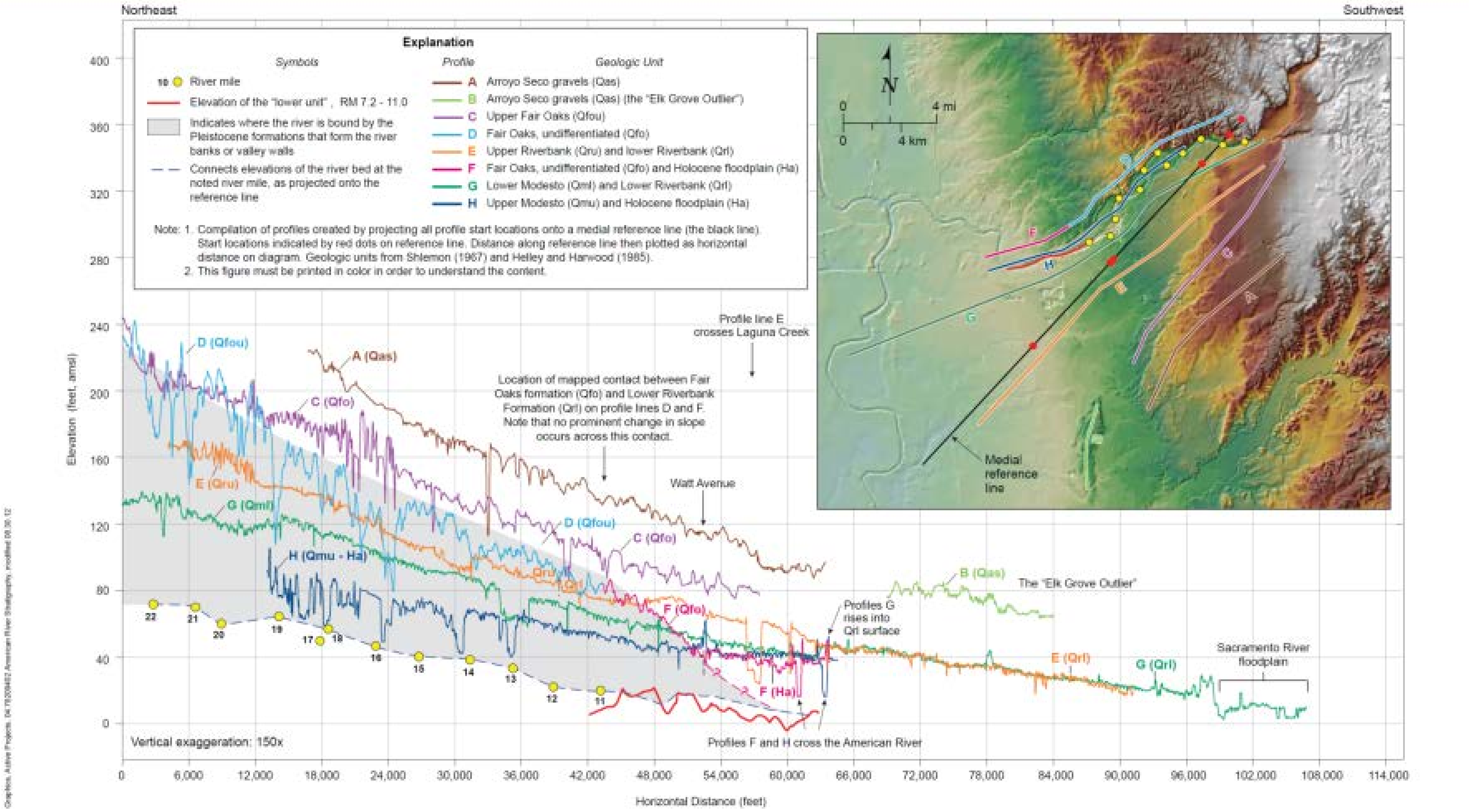
Shlemon, R.J., 1967, Landform-Soil Relationships in northern Sacramento County, California, [Ph.D. thesis]: Berkeley, University of California, 335 p., 1 plate.



Notes: 1. Topography from 2007 LiDAR and USGS Sacramento DEM received from the USACE.
2. * Indicates synthesis of subsurface lithology. Source of data: Geotracker (http://geotracker.waterboards.ca.gov/)
3. ** Indicates synthesis of subsurface lithology. Source of data: Caltrans.
4. † Indicates synthesis of subsurface lithology. Source of data: USACE.

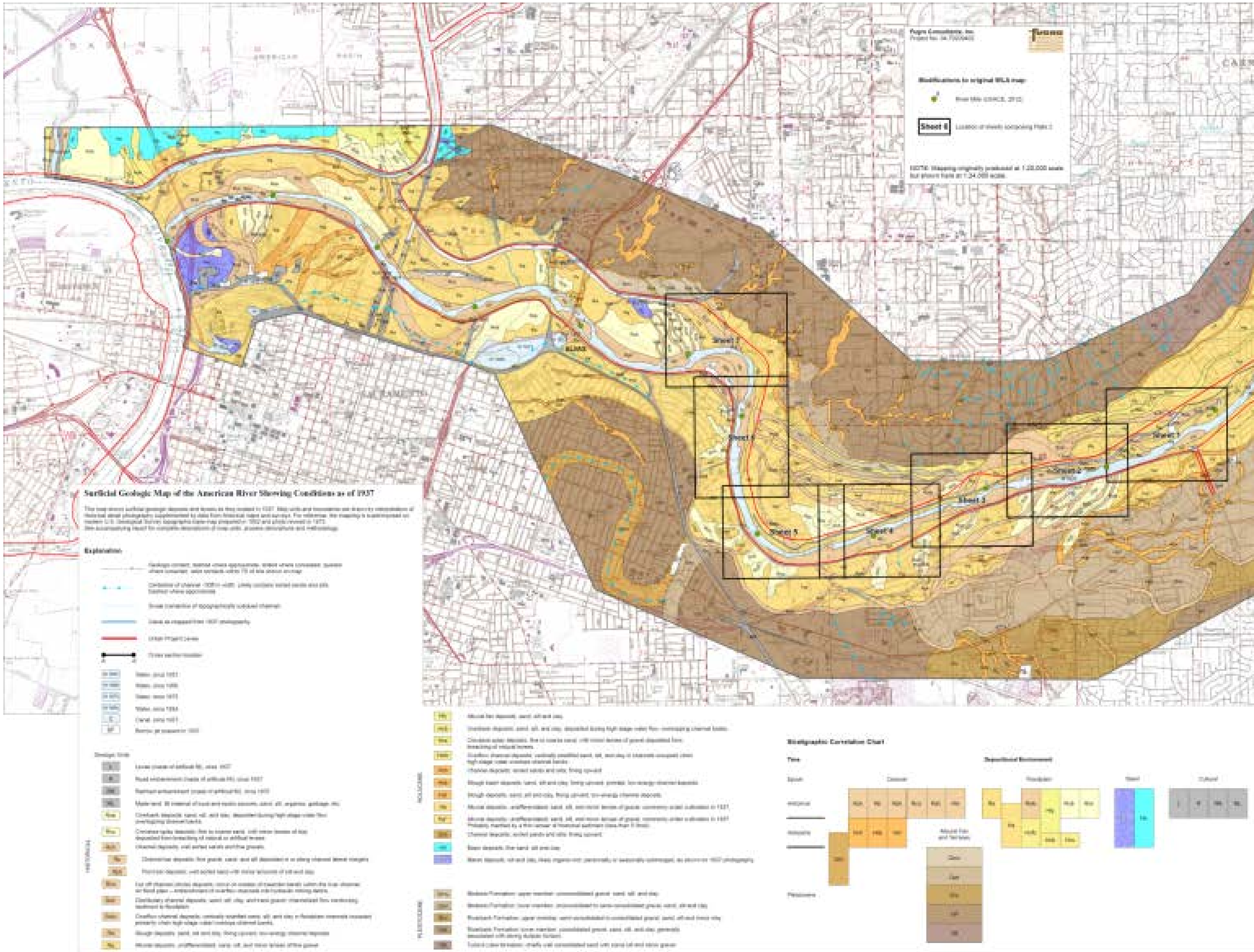
Conceptualized Cross Section across American River at Watt Avenue

FIGURE 5.2



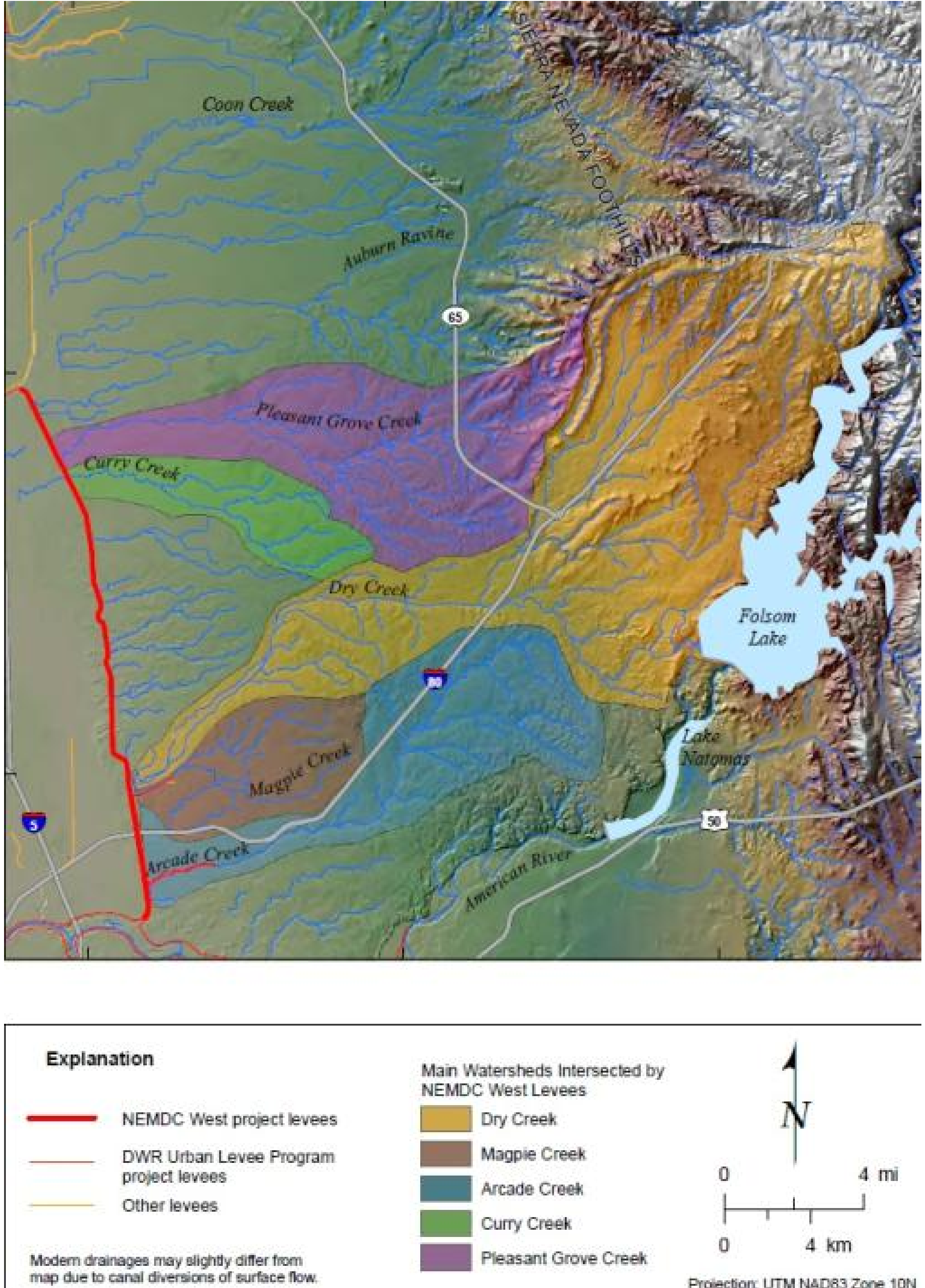
Regional Topographic Profiles

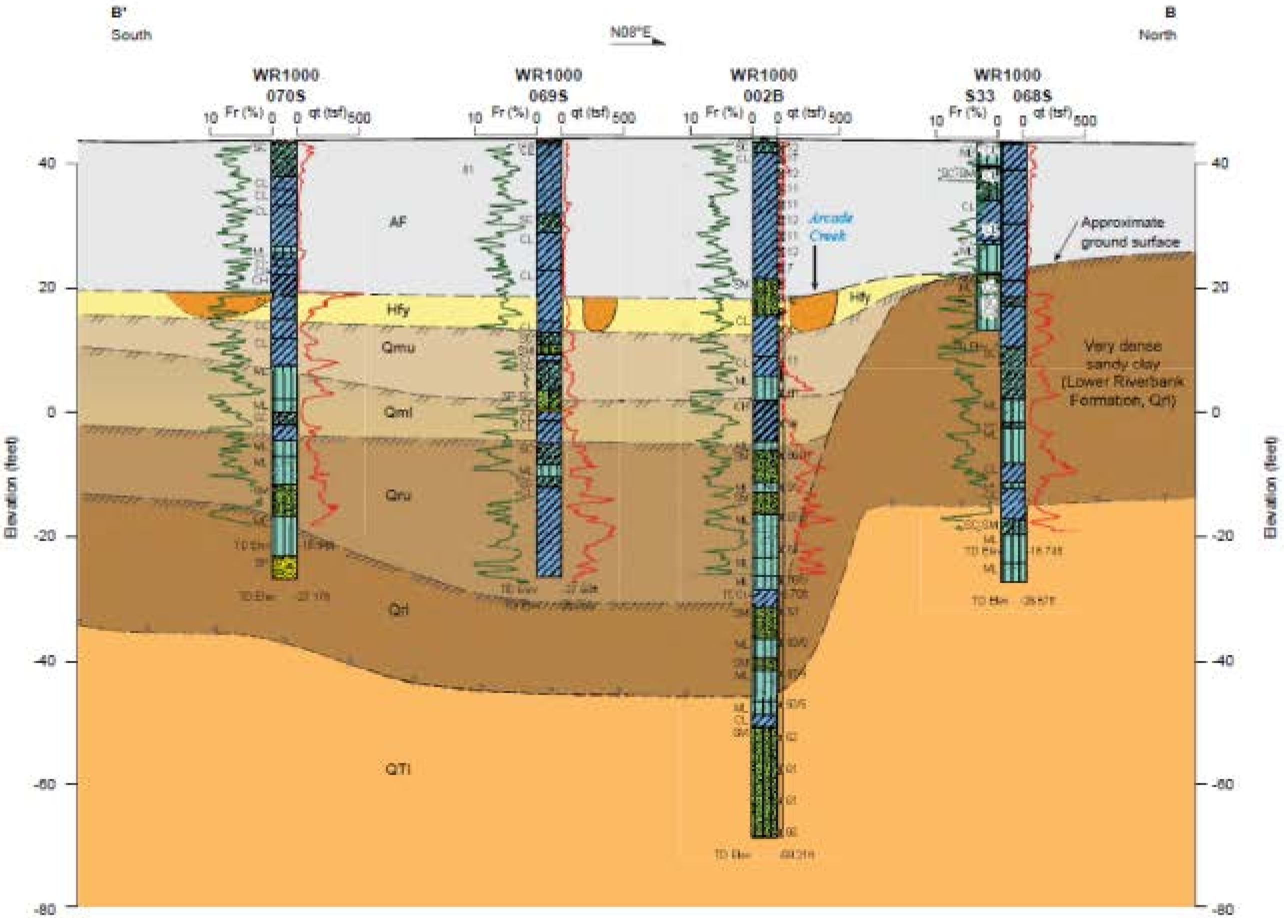
FIGURE 6.1



Lower American River Stratigraphic and Geomorphic Mapping Report
American River Common Features, Sacramento County, CA

Plate 3: Lower American River Geologic Mapping of WLA (2008) Showing Conditions as of 1937


Coon Creek
SIERRA NEVADA FOOTHILLS
Auburn Ravine
65
Pleasant Grove Creek
Curry Creek
Dry Creek
Folsom Lake
80
Lake Natomas
Magpie Creek
5
50
Arcade Creek
American River
Explanation
NEMDC West project levees
DWR Urban Levee Program project levees
Other levees
Modern drainages may slightly differ from map due to canal diversions of surface flow.
Main Watersheds Intersected by NEMDC West Levees
Dry Creek
Magpie Creek
Arcade Creek
Curry Creek
Pleasant Grove Creek
N
0
4 mi
0
4 km
Projection: UTM NAD83 Zone 10N



Explanation

Unit Descriptions

- AF — Levee fill
- Hfy — Loose clayey sand (alluvial fan deposits)
- Qmu — Medium dense sandy clay (Upper Modesto Formation
- Qml — Dense sandy clay (Lower Modesto Formation)
- Qru — Dense sandy clay (Upper Riverbank Formation)
- Qrl — Very dense sandy clay (Lower Riverbank Formation)
- QTl — Turlock Lake Formation?

Symbols

- Channel deposits
- Moderate paleosol (hardpan)
- Strong paleosol (hardpan)

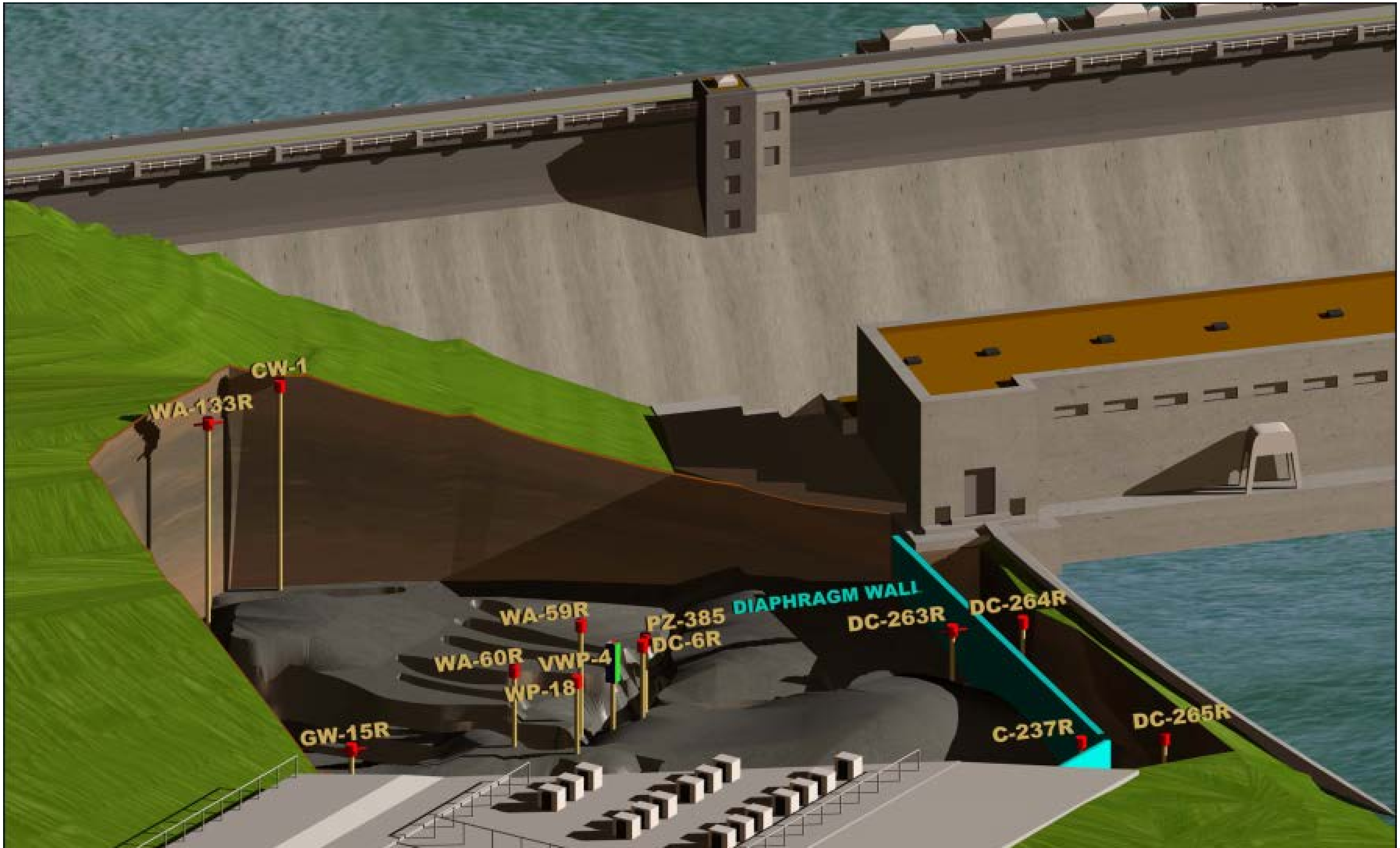
Notes:
1. Conceptual diagram looking toward the west.
2. Surficial geologic units and contacts from this study.
3. Borehole locations and graphic logs from NEMDC West MSGDR ; other boreholes not included on this figure.
4. Drilling method indicated as last letter in borehole name; B= rotary wash with SPT, S = vibrasonic.
5. See Plate 1 for location of diagram.

10 ft
0
0 250 ft
25x vertical exaggeration

Conceptual Subsurface Diagram across the NEMDC West Levee at Arcade Creek

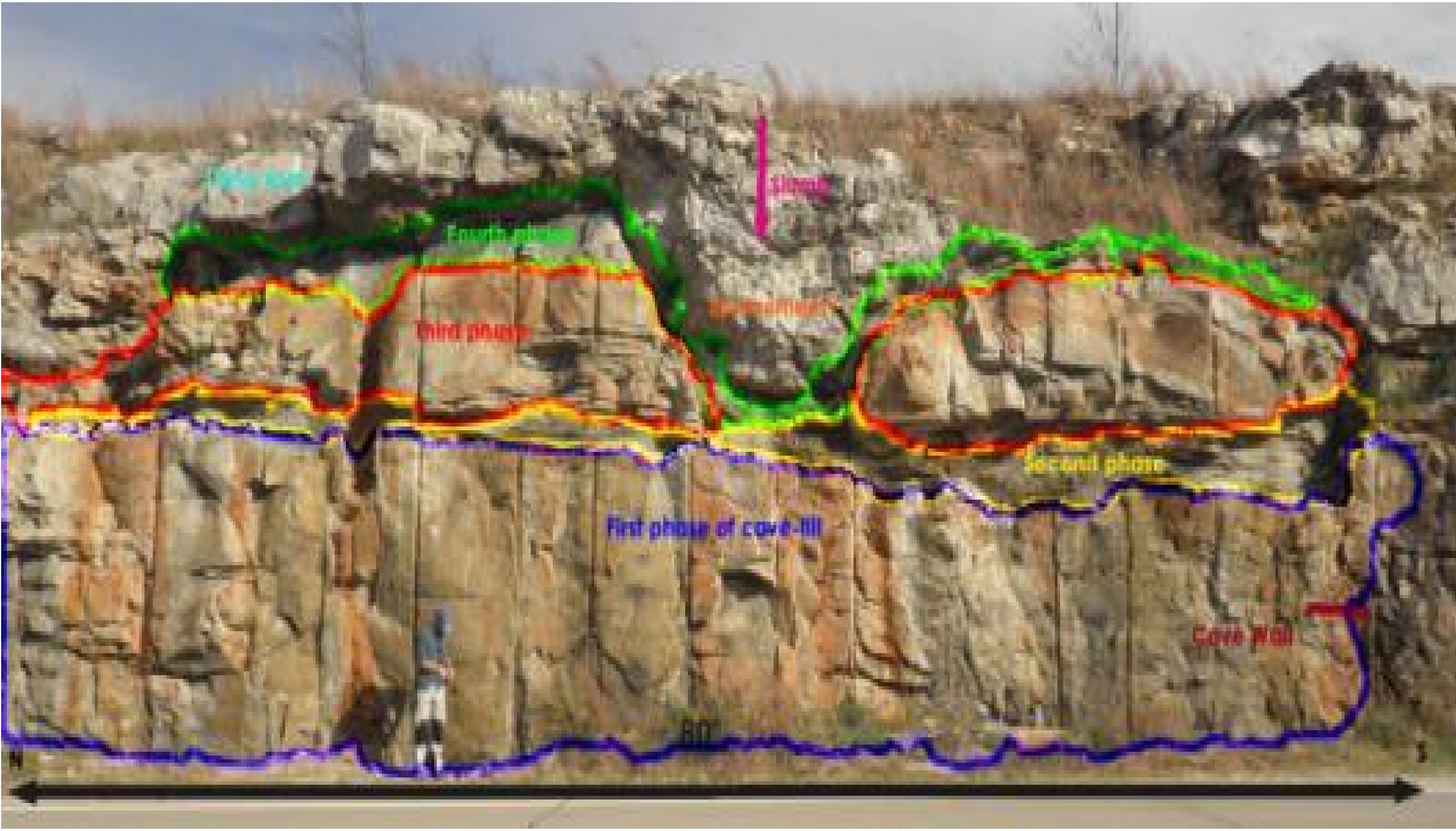
FIGURE 5

Examples of mapping on photographs and geologic models



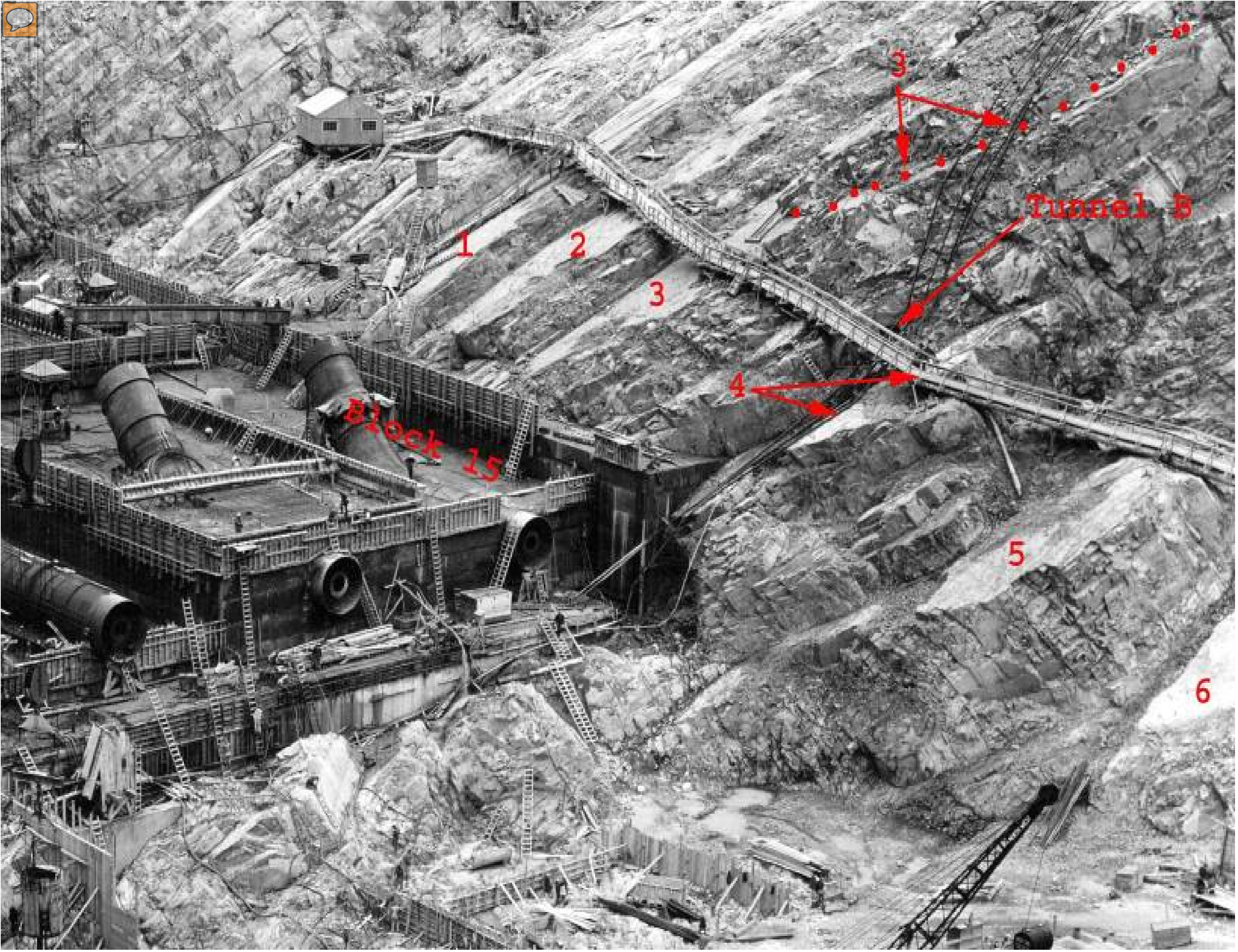
PIEZOMETER LOCATION ISOMETRIC

N.T.S.

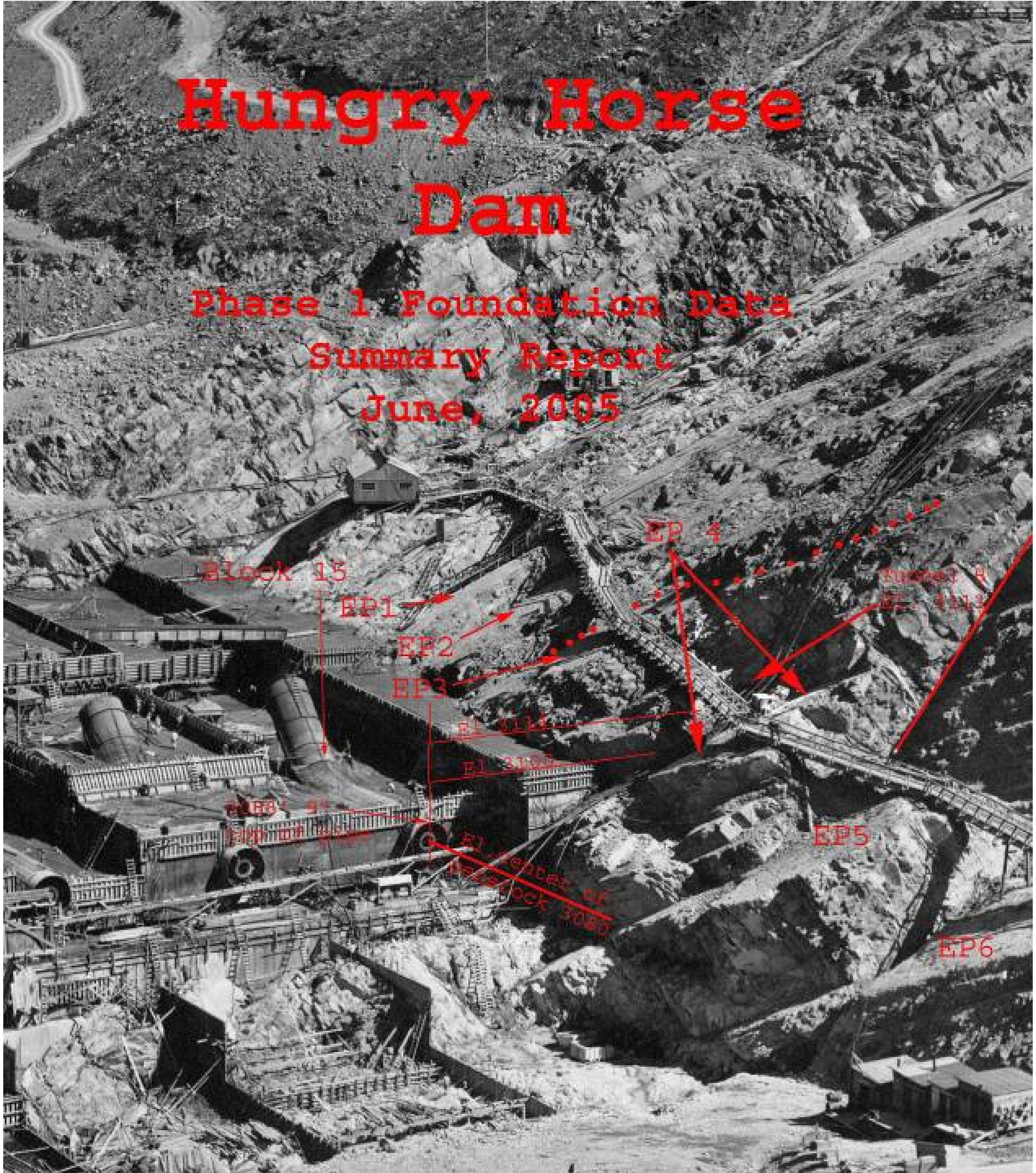


Fourth phase
Third phase
Second phase
First phase of cave-III
Cave wall


Spoil pile upstream of dam axis. It is not clear from the records if this was removed.
Elevation 620 ±
Elevation 545 ±
Yellow shading = Typical of major joint set perpendicular to dam axis
Red shading = Typical of major joint set parallel with dam axis



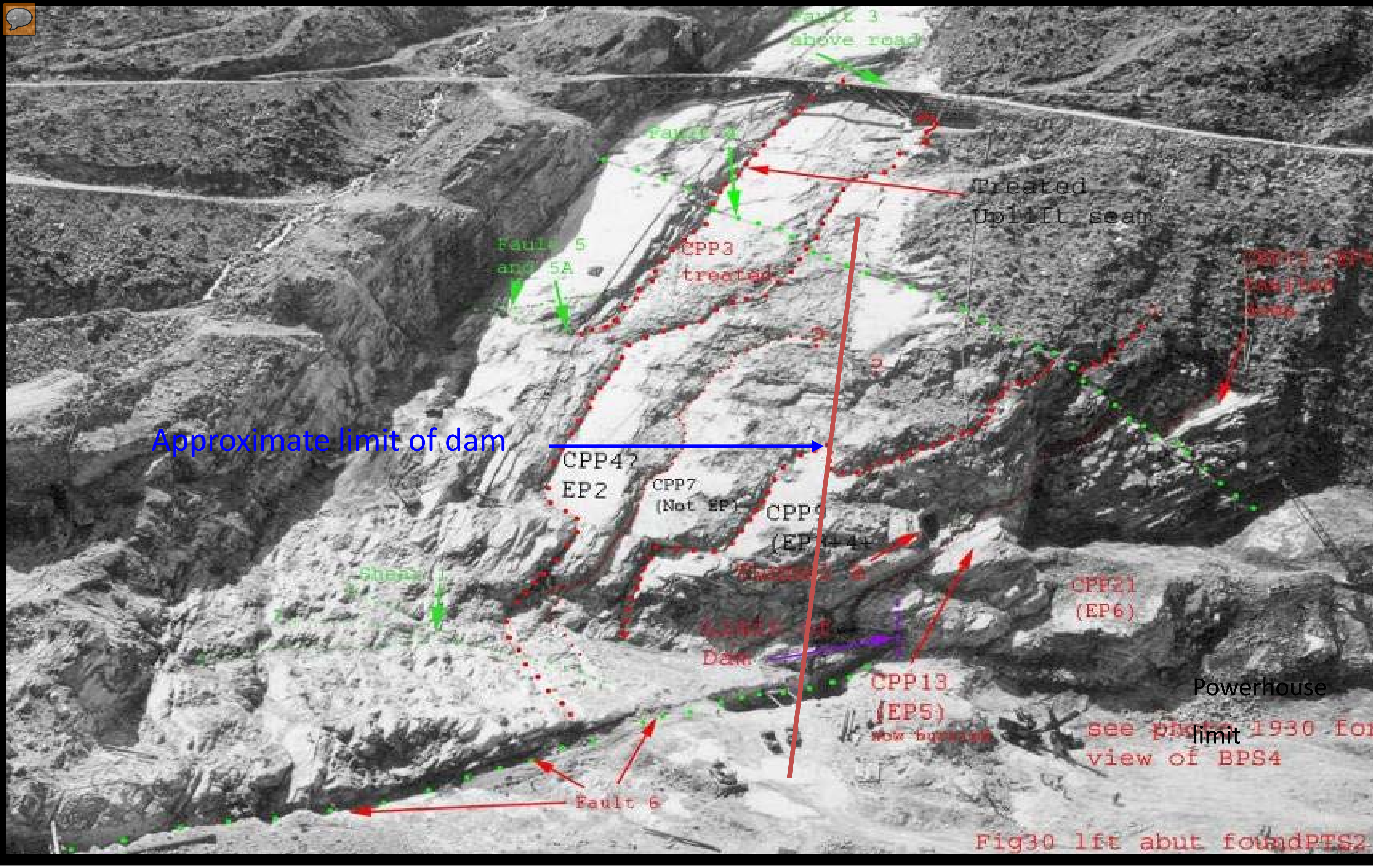
Photographs are a critical part of the geology package



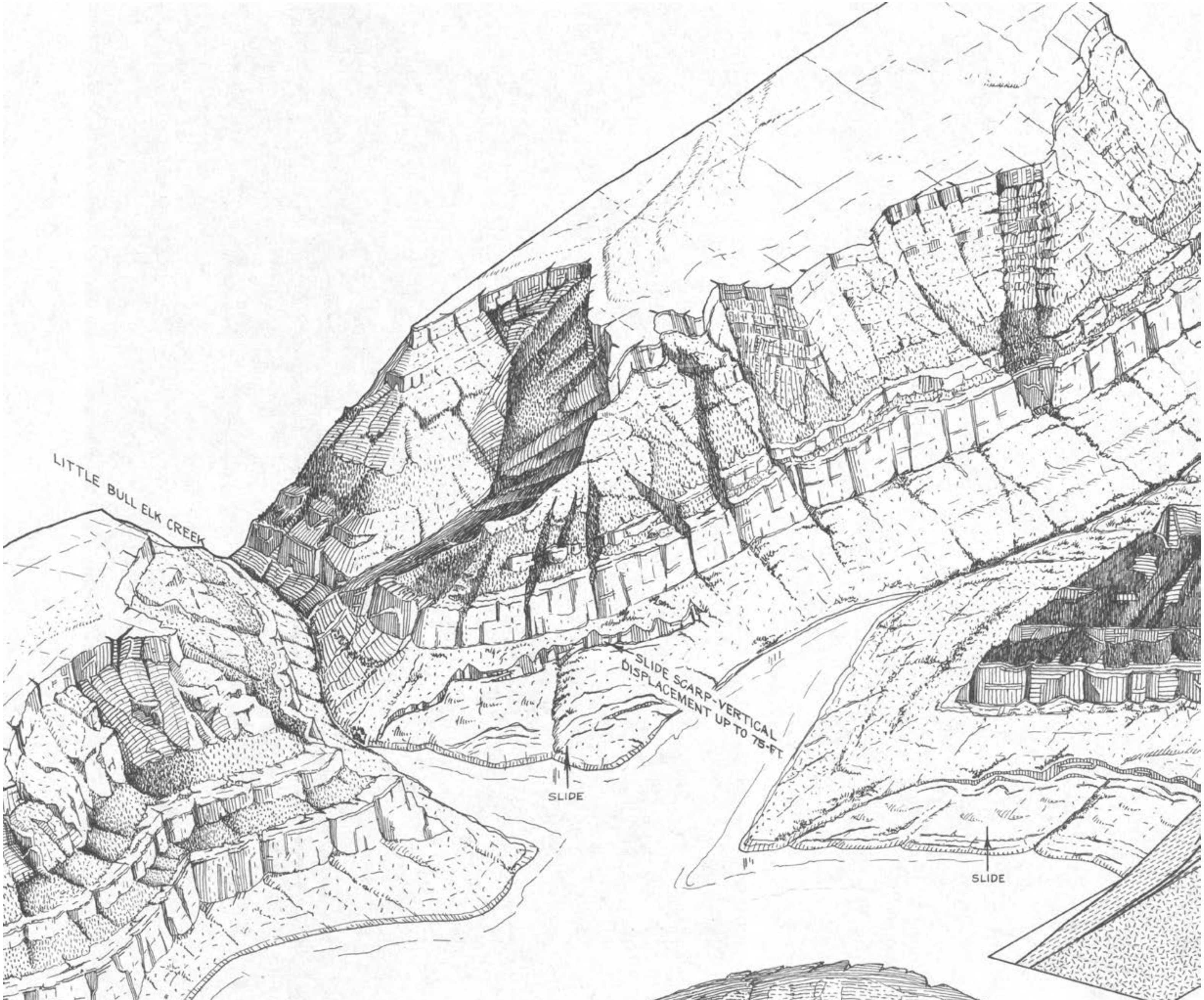
Identifying "discontinuities"

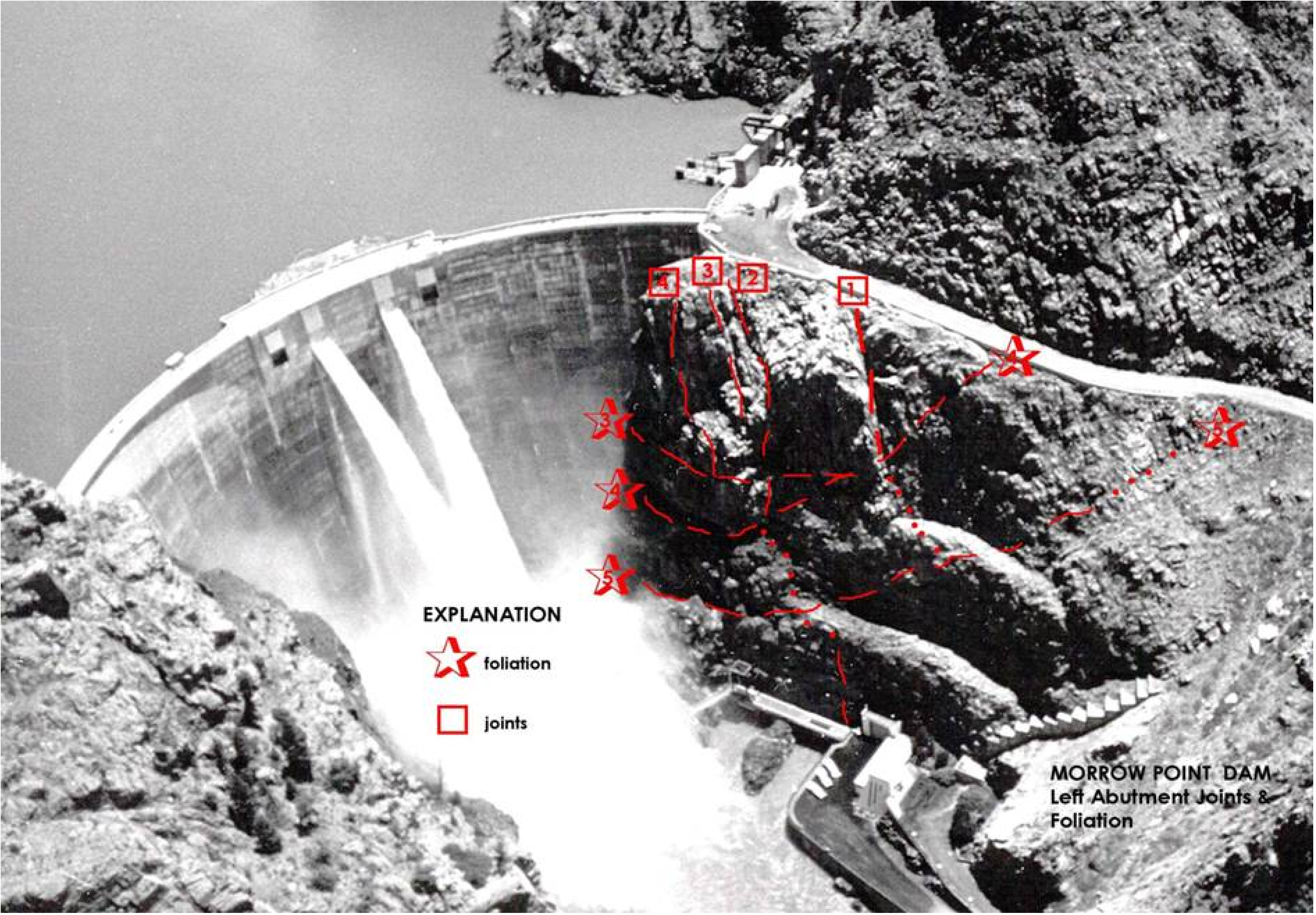
Defining potential foundation blocks

Using old construction photographs to reconstruct the foundation geology

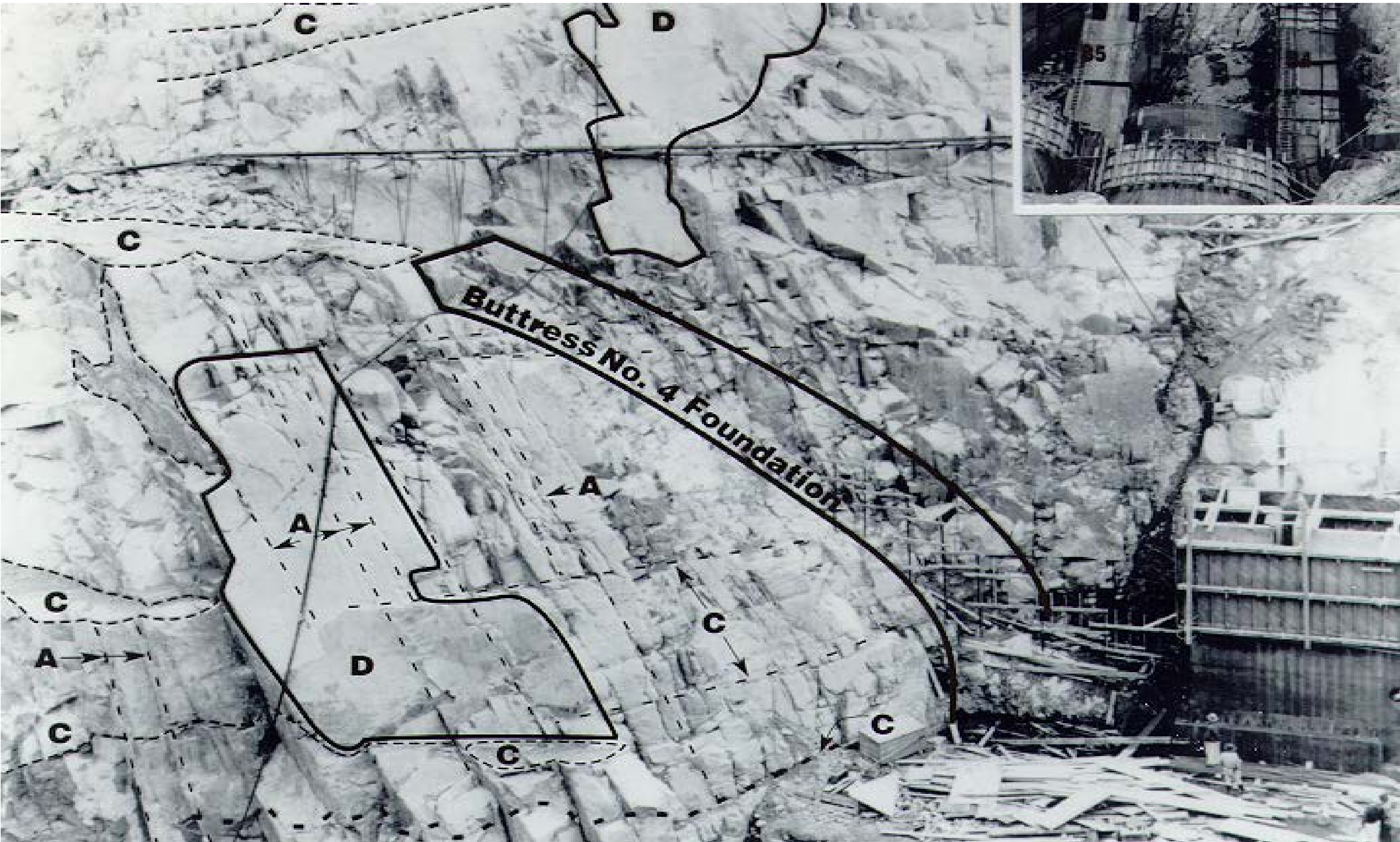


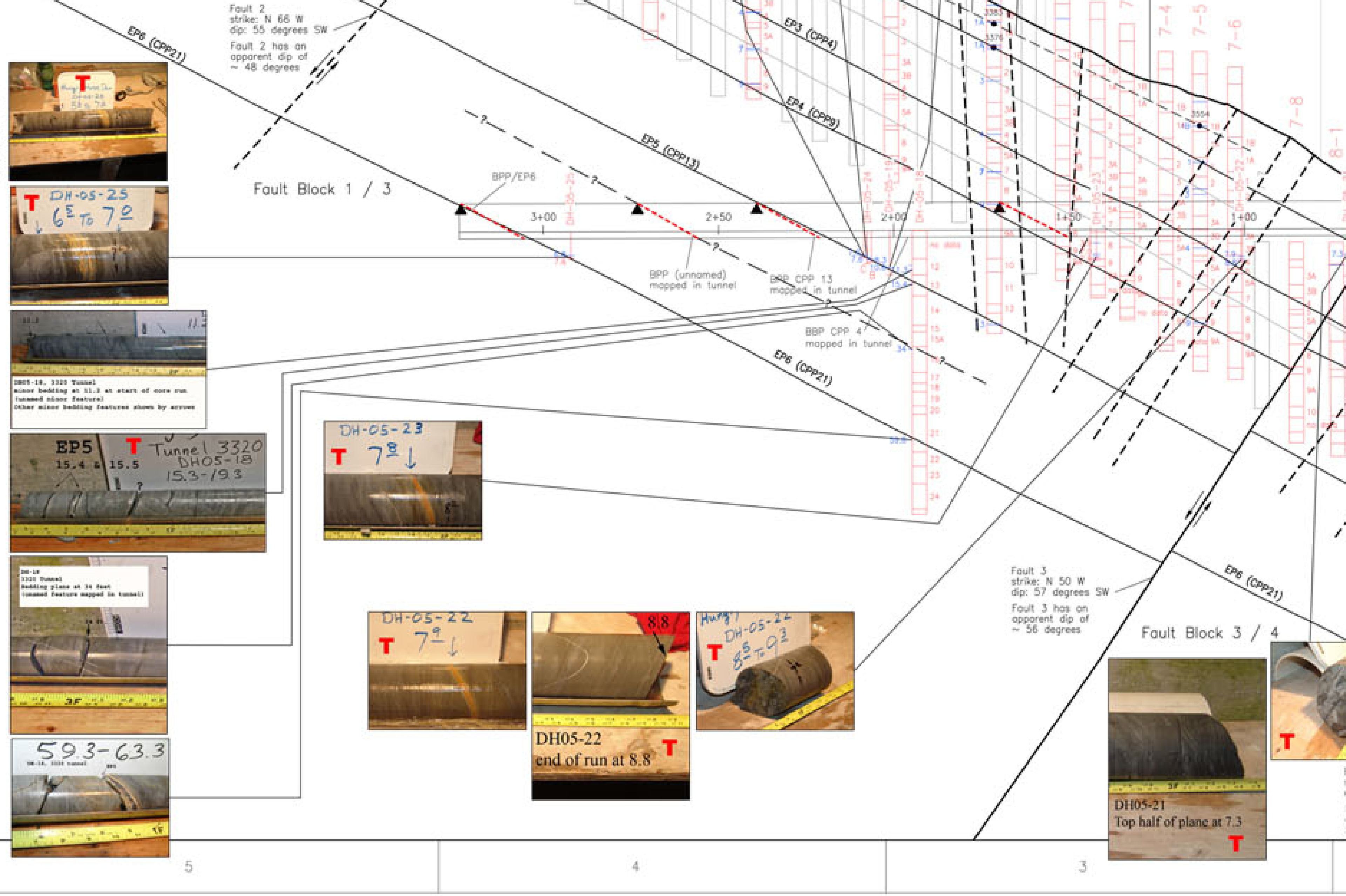
Photographs can be worth hundreds of thousands of dollars


LITTLE BULL ELK CREEK
SLIDE SCARP-VERTICAL DISPLACEMENT UP TO 75-FT.
SLIDE
SLIDE

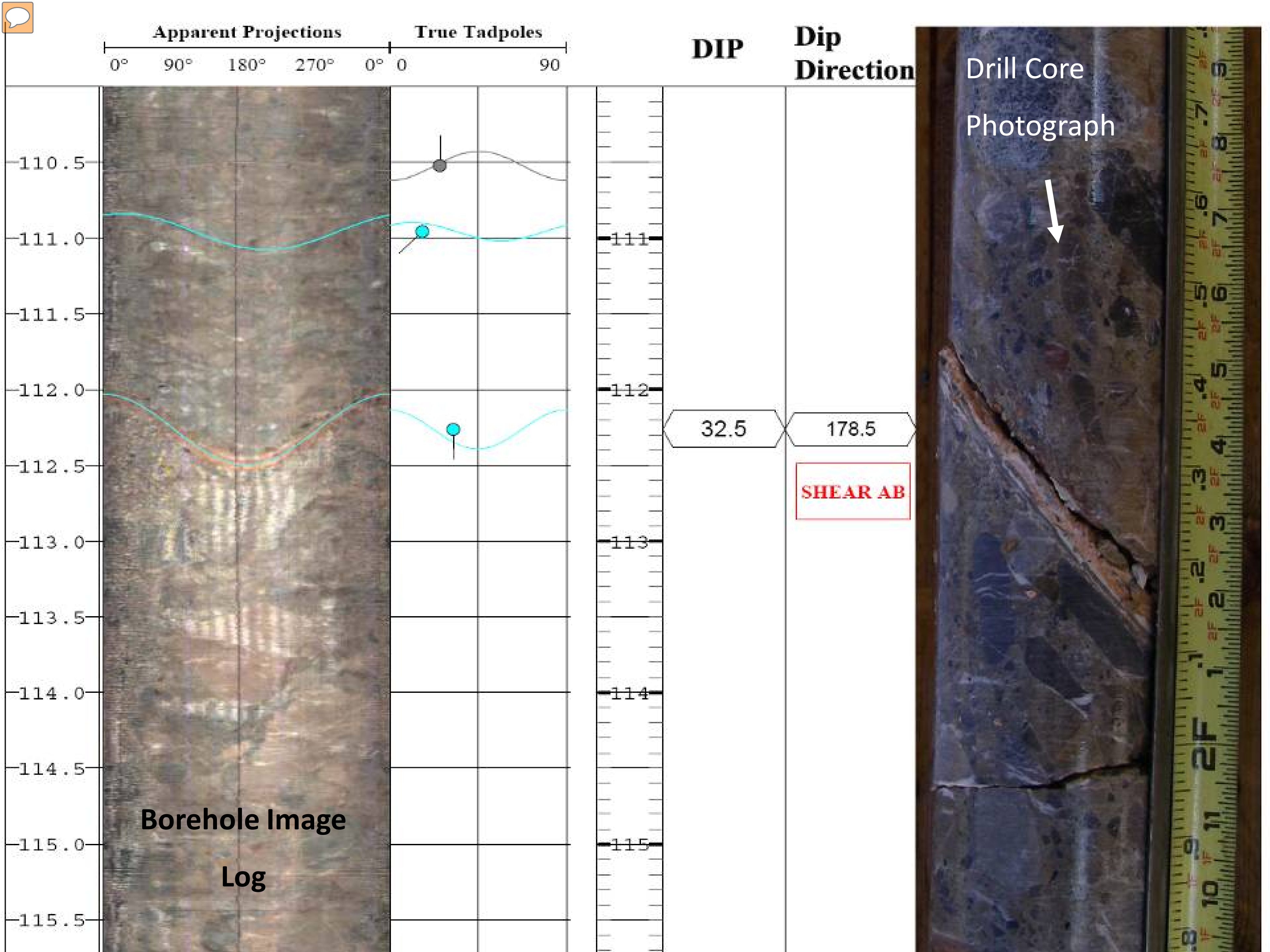

4
3
2
1
4
3
5
4
5
EXPLANATION
foliation
joints
MORROW POINT DAM
Left Abutment Joints &
Foliation

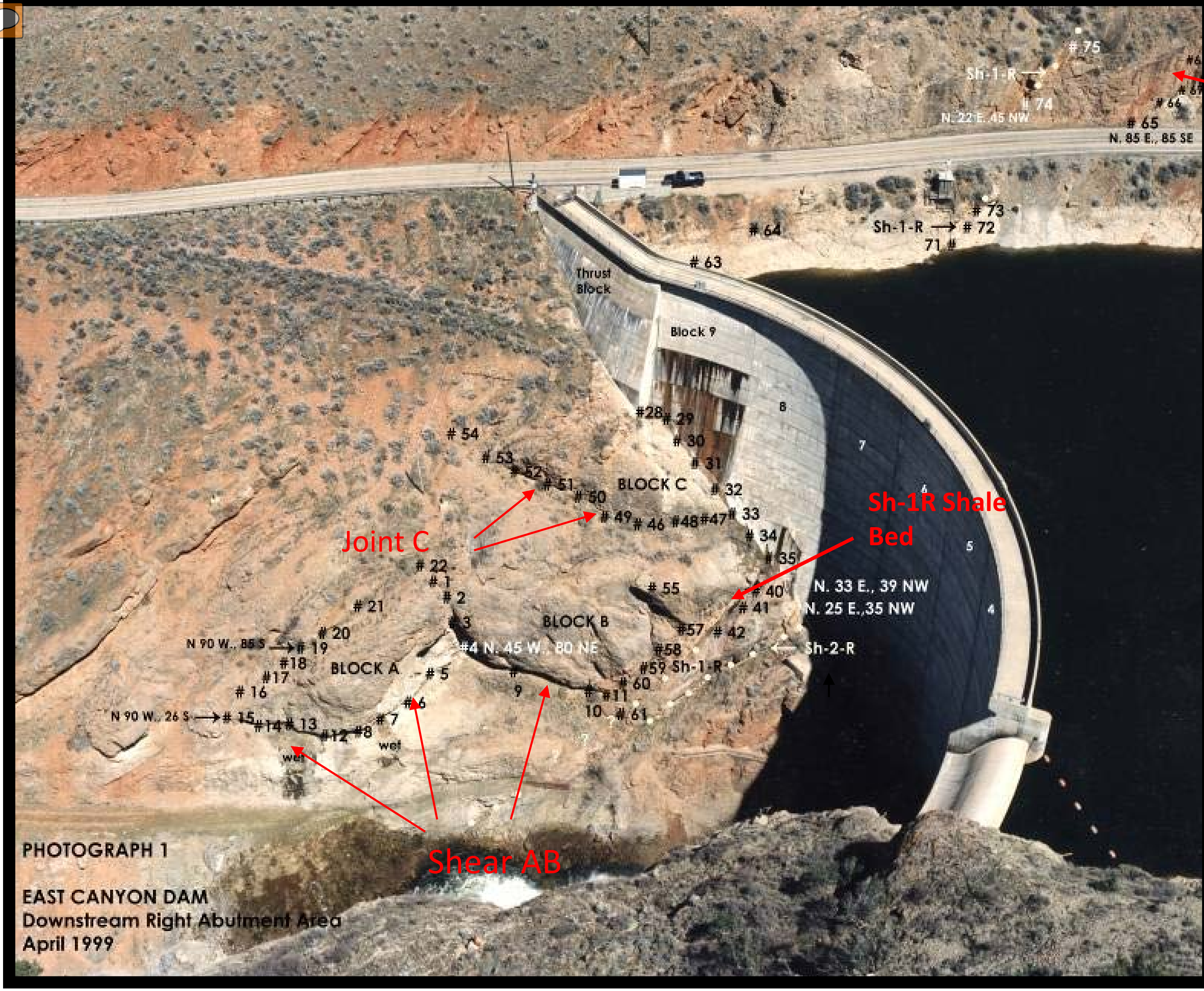
Bartlett Dam: Modern mapping on old photographs: Geology was not really understood at the time of construction



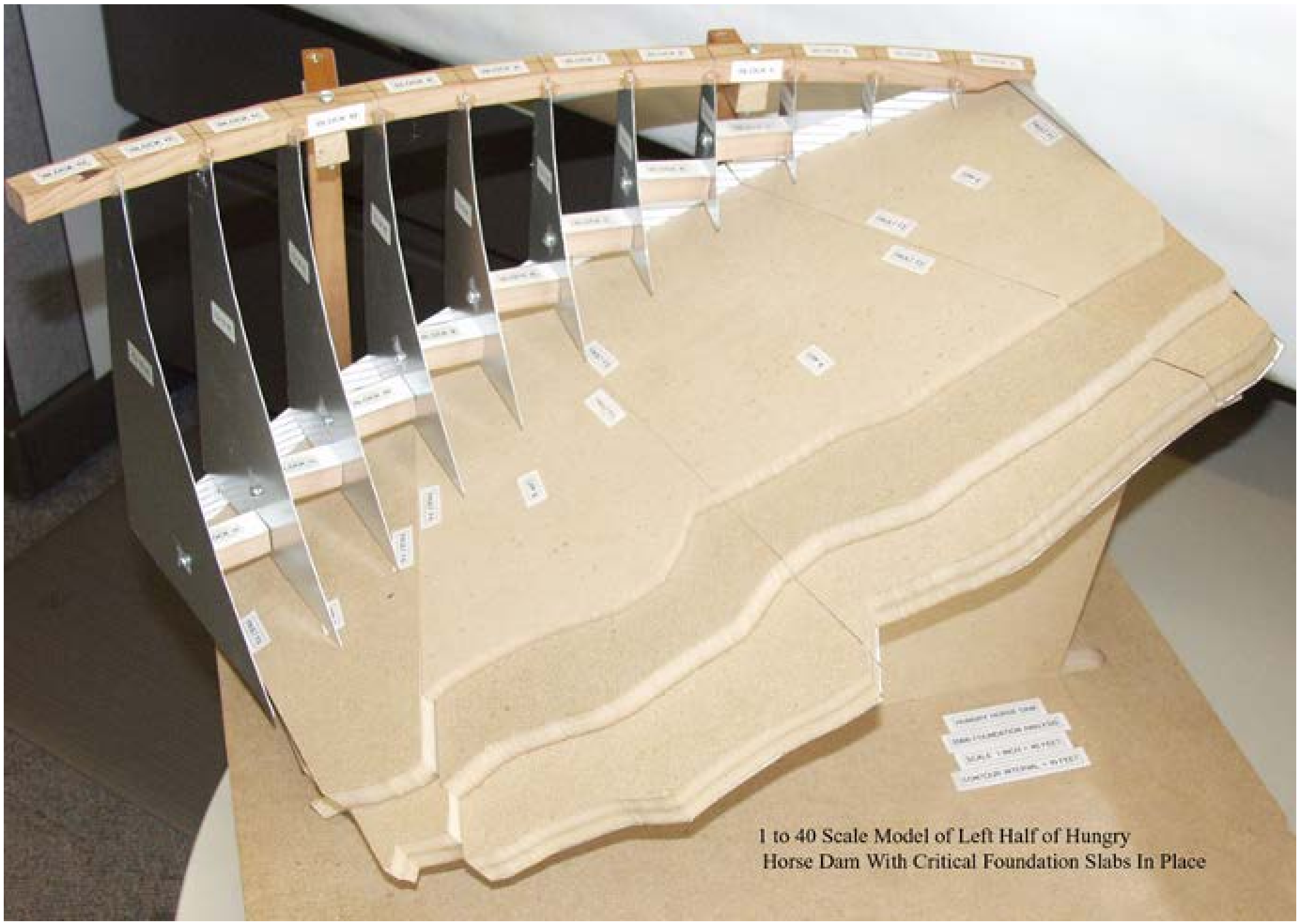


Fault 2
strike: N 66 W
dip: 55 degrees SW
Fault 2 has an apparent dip of ~ 48 degrees
EP6 (CPP21)
EP3 (CPP4)
EP4 (CPP9)
EP5 (CPP13)
Fault Block 1 / 3
BPP/EP6
3+00
2+50
2+00
1+50
1+00
BPP (unnamed) mapped in tunnel
BBP CPP 13 mapped in tunnel
BBP CPP 4 mapped in tunnel
DH-05-25 6.5 To 7.0
DH05-18, 3320 Tunnel
minor bedding at 11.2 at start of core run (unnamed minor feature)
Other minor bedding features shown by arrows
EP5
15.4 & 15.5
Tunnel 3320
DH05-18
15.3-19.3
DH-05-23 7.8
DH-18
3320 Tunnel
Bedding plane at 34 feet (unnamed feature mapped in tunnel)
59.3-63.3
DH-05-22 7.9
DH05-22
end of run at 8.8
DH-05-22 8.5 To 9.3
Fault 3
strike: N 50 W
dip: 57 degrees SW
Fault 3 has an apparent dip of ~ 56 degrees
Fault Block 3 / 4
DH05-21
Top half of plane at 7.3
5
4
3

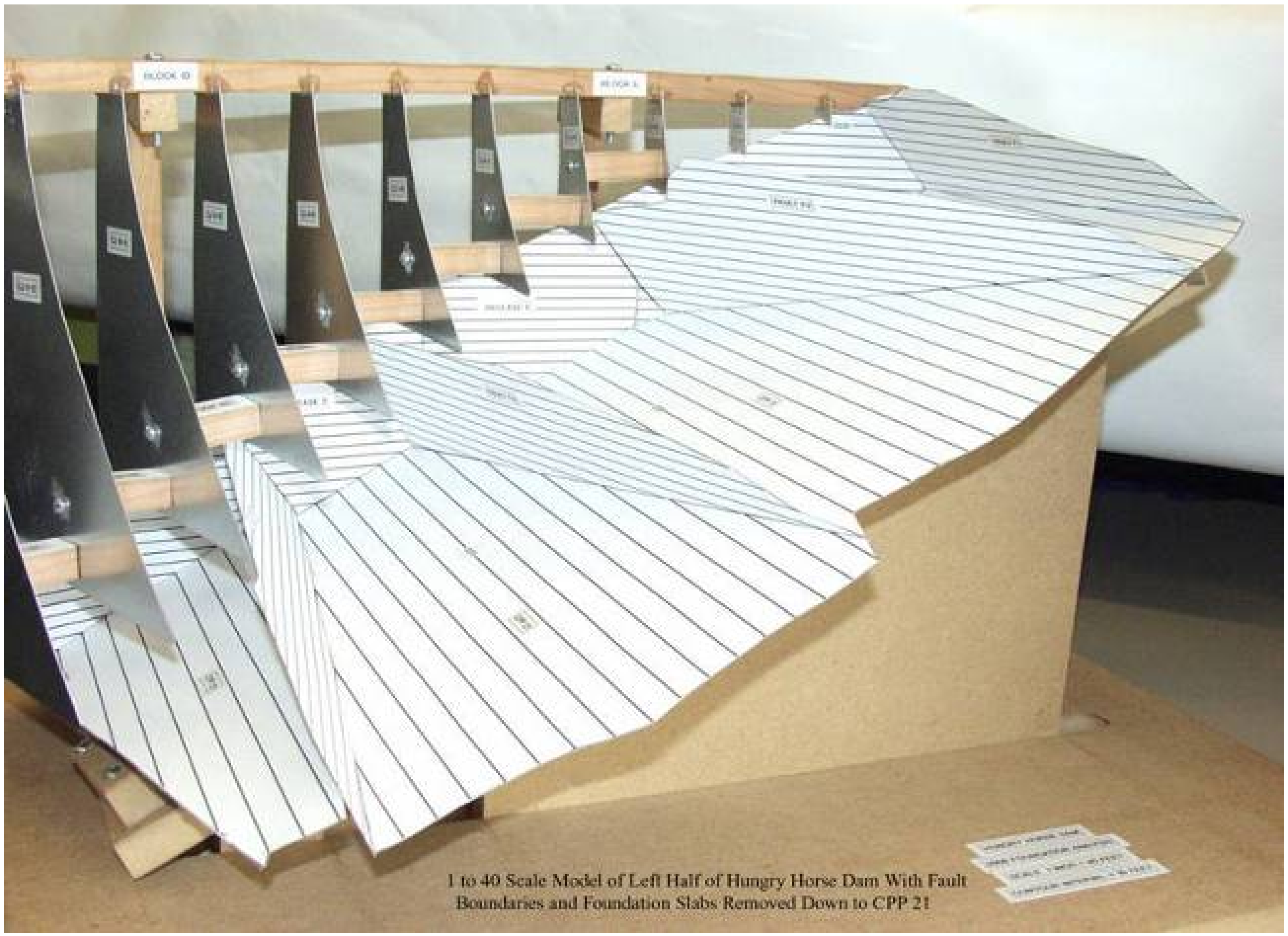

Apparent Projections
0° 90° 180° 270° 0°
True Tadpoles
0 90
DIP
Dip Direction
Drill Core Photograph
110.5
111.0
111.5
112.0
112.5
113.0
113.5
114.0
114.5
115.0
115.5
111
112
113
114
115
32.5
178.5
SHEAR AB
Borehole Image Log



RJ 3 side joint



1 to 40 Scale Model of Left Half of Hungry Horse Dam With Critical Foundation Slabs In Place



1 to 40 Scale Model of Left Half of Hungry Horse Dam With Fault Boundaries and Foundation Slabs Removed Down to CPP 21