Hydrostratigraphic Modeling Investigation Methodology

Data collection

While there has not been a great deal of study regarding the large-scale hydrogeology of Shasta Valley and the surround basin, there have been a few key studies, mostly by the United States Geological Survey and the State of California, that have studied the basin's geology and how it directly relates to the groundwater system throughout the Valley. Usage of this information was key to constructing the 3-D geological model of Shasta Valley and the surrounding basin.

-DWR OSWCR database

The California Department of Water Resources' (CDWR) Online System for Well Completion Reports (OSWCR) database (https://data.ca.gov/dataset/well-completion-reports) contains records of all of the legally drilled and completed (as well as abandoned or destroyed) groundwater wells in the basin. The OSWCR database contains details relating to precise (or general) location, date of operations, notes on events encountered during drilling and completion operations, drillers' lithologic logs, completion design (usually including screened zone(s) information and total complete depth), any available aquifer performance tests, geophysical borehole logs, planned well use type, and other information. However, the OSWCR database is known to contain many errors and inconsistencies in potentially any of the fields in the database that require additional review by the user to verify the usage of these records. This specifically applies to the inconsistent, and many times inaccurate, interpretation of lithology encountered during drilling operations. Additionally, as the majority of well completion reports have been spatially registered to the center of the Public Land Survey System section (one square mile or ~2.6 square kilometers), the user of the records usually needs to more precisely locate the well. The OSWCR database is the only known source of information regarding lithology in the basin.

-USGS GW & Geology Features of Shasta Valley

Mack (1960) contributed what is considered to be the most comprehensive hydrogeologic investigation of the Valley as the Valley's hydrogeology was not studied prior to the 1950's and study at a similar scale to Mack (1960) has essentially not taken place since. Mack (1960) investigated the thickness and extent of water-bearing geologic zones, hydrogeologic properties of the aquifer materials, groundwater flow, water chemistry analyses, hydrographs, water well records, aquifer pumping rates, and broad groundwater storage estimate of the Valley. The report contains a number of geologic cross sections through the Valley based on limited drillers' lithologic logs available at the time. All of the available information included in this study are incorporated directly into the geological model.

Blodgett and others (1985) provide a follow-on study to Mack (1960) but mainly investigated the updated information regarding groundwater hydrographs and water quality of more springs at higher elevation on Mount Shasta. The data presented in this report are useful for understanding potential changes over time to water quality signatures that would infer geologic control on the groundwater system and particularly for an updated mapping of the springs, which imply geological contrasts useful for knowledge in constructing the geological model.

-Holliday Thesis on Yellow Butte Fault geology

Holliday (1982) investigated the Paleozoic and Mesozoic geology in the southeast area of the Valley. This study was mainly restricted to the Haystack and Yellow Buttes and the Yellow Butte Fault zone that surrounds the horst features. A number of cross sections were developed for this area and integrated in the construction of the geologic model for the subset area of covered by this study.

-USGS Mt. Shasta Debris Avalanche geologic analysis

Crandell and others (1984) and Crandell (1989) reinterpreted the central volcanic deposits of the Valley as a very large, catastrophic debris avalanche originating of the collapse of Ancestral Mount Shasta, which altered the surface and groundwater hydrology of the Valley. One the most pertinent aspects of the studies is that they define the extent and thickness of the debris avalanche deposit, which impacts the flow of groundwater across the Valley.

-CGS surface geologic map

Wagner and Saucedo (1987) represents the most recent and detailed surface geologic map of the entire basin. The publication also includes two thick, large-scale E-W cross sections across the basin. The cross sections are to the north and south of the basin boundary but nonetheless provide a geologic framework for the deep-seated basement rock underlying the basin.

-DWR Draft Report – data needs assessment

Ward and Eaves (2011) compiled and reinterpreted the vast majority of the data resources found in published reports from the United States Geological Survey and the State of California (particularly mapping publications available from the California Geologic Survey (in cooperation with the United States Geological Survey) as well as in unpublished data from California Department of Water Resources. This includes updated drilling logs and cross sections. The study integrates all of the available information to provides updated estimates to the extents and thicknesses of aquifer zones and to cross sections across the Valley, some coincide with previously published cross sections of Mack (1960). Additionally, Ward and Eaves (2011) provided digitization into GIS shapefile format of the published surface geology polygons of Wagner and Saucedo (1987). This shapefile was directly used in the construction of the geologic model with the surface geology as a hard constraint for the geologic boundaries of the formations and a guide to interpreting drilling logs located within each surface geologic polygon.

-Other USGS reports defining Paleozoic plutonic/metamorphic & Mesozoic sedimentary geology

Irwin (1972, 1994) provide deep study of the Paleozoic geology of the plutonic and metamorphic rocks that make up the Klamath Mountains, which also largely underlie the sedimentary and volcanic rocks of the Valley. These studies are helpful for guiding the estimation of basement rock in the geologic model either explicitly where encountered in the drilling logs or implicitly based on structural geologic trends.

DWR WCR Location Process

California Department of Water resources has about 3,400 Well Completion Reports (WCRs) in its database (CA OSWCR) listed for the Shasta Valley hydrologic basin (eight-digit Hydrologic Unit Code 18010207). These WCRs contain the pertinent hydrogeologic information needed to assist in constructing a geologic model for groundwater investigation purposes. However, many of the WCRs are not precisely located enough standards of constructing an appropriate resolved geologic model.

-Recently drilled and logged WCRs with precise locations

While roughly half of the WCRs are listed as being within 50 feet (15.24 m) of their noted coordinate location, the rest are located to the center of the township and range section (an area of one square mile). The WCRs listed as being within 50 feet (15.24 m) are considered to be precise enough for purposes of constructing this geologic model and were included in the model construction.

-WCR Logs with imprecise locations but have addresses and/or detailed site maps

The other roughly half of the WCRs available for the basin are not precisely located well enough for purposes of constructing the geologic model and needed to be located more precisely for inclusion in the model. However, a subset of the WCRs with imprecise locations do have an included map or physical address detailing the location of the well within the township and range section. WCRs with this mapped or addressed location information were included in the model. We used Google Earth Pro (Alphabet, Inc.) to more precisely locate wells given the address and/or detailed map. We located the well visually in available satellite imagery by either directly locating it, if outside, or indirectly in a likely external shed or enclosure, or at the residence listed at the address if unable to locate the well outside the dwelling. In some cases, Siskiyou County was able to provide septic tank records that map groundwater wells at least 100 feet (30.48 m) away from the septic tank (California state regulation).

-WCR Logs with imprecise locations and no addresses or detailed site maps but list APN record

While some WCRs did not have a precise location, address, or map included, some did have an attached Assessor Parcel Number (APN) recorded in the report. We used the APN as a final locating method for those records not containing the other well location information. We assumed that if an APNs area is relatively small, then its centroid location would not be very far from the actual well's location. In these instances, we utilized the APN's centroid as an approximate location for the well location.

Drilling Log Interpretation Procedure and 3-D Geologic modeling

Once located more precisely, we could utilize the resulting subset of precisely located WCR lithologic logs to construct a representative subsurface geologic model with a focus on hydrogeologic properties and matched to mapped surface geologic units. Initially, we chose to model lithological descriptions as specified simplified bins but realized that the scale of the basin and large distances between some of the wells were too great to adequately model with a discrete, computerized geologic model. Instead, we then chose to model the interpreted geological formation that the lithology of the well most closely represented, based on mapped surface geological units (which contain descriptions of the various lithologies present in various formations) of the area in which the wells were located and the projected depths of those units based on the lithologic logs and published cross sections of the basin.

-Standardization of WCR lithologies to set of classification bins

Driller's lithologic logs recorded in WCRs are consistently reported as the lithologic type observed (e.g. gravel, clayey sand, basalt etc.), however in many cases the drillers are not trained geologists or experienced in the locality-specific geology of the basin area to be able to accurately assess the lithology of recovered drilling samples. In some cases, there is enough detail and context in the logs to discern what basic lithologic type of sediment or rock is being described. We reclassified the observed lithology with depth for each WCR included in the model. We settled on 19 classification bins that fit all of the drilling log descriptions of sediments and rocks encountered. The table below lists the specific classification bins we chose to use to reclassify the driller descriptions. While in the end these classification bins were not modeled directly, they were saved in the database to help guide the interpretation of the lithologic descriptions into the most likely geologic units to which they belong.

alluvium
boulders
clay
cobble

conglomerate
fractured metamorphic rock
fractured mudrock
fractured plutonic rock
fractured sandstone
fractured volcanic rock
gravel
metamorphic rock
mudrock
plutonic rock
sand
sandstone
silt
volcanic rock
volcanic sediment

-Interpretation of lithological classifications to geologic surface formations

The binned lithologic classifications are not classified as a geologic unit or formation (e.g. Hornbrook Formation). While a more accurate, high-resolution hydrogeologic model would keep track of these lithologic classification types, which are needed for fine-scale understanding of how groundwater flows preferentially through the basin, it is too much to discretize for a discrete computerized geologic model at the scale of this basin (approximately 800 square miles or ~2,000 square kilometers). Instead, we chose to follow the approach used in published cross sections of the Valley and converted lithologic types to their likely geologic formation, using the mapped surface geologic units (shown in first table below) as a guiding template for the geologic interpretation.

Table of Geologic units identified present in Shasta Valley River basin WCRs analyzed

Cbg- Bragdon Formation - Basement
Dc- Copley Greenstone - Basement
Dkn- Kennett Formation - Basement
Dsg- Gazelle Formation - Basement
Kh- Hornbrook Formation
Mzd- Plutonic Dioritic rocks - Basement
MzPz ms- metasedimentary rocks - Basement
MzPz mv- metavolcanic rocks - Basement
MzPz mvs- metavolcanoclastic sedimentary rocks - Basement
MzPz s- Stuart Fork Formation - Basement
MzPz- Undifferentiated - Basement
Oam- Antelope Mountian Quartzite - Basement
Op- Trinity peridotite - Basement
Ogb- Gabboric and dioritic rocks - Basement

Pv- Pliocene Volcanic rocks
Pza- Abrams Mica Schist - Basement
Q- Alluvium
Qg- Glacial deposits
Qv- Pleistocene Volcanic rocks
Qvs- Volcanic rocks of Shasta Valley
Smc- Moffett Creek Formation - Basement
SOd- Duzel Formation - Basement
Tv- Western Cascade Volcanics

Table of Finalized hydrostratigraphic units included in hydrogeologic model

Basement - Basement rock group
Kh- Hornbrook Formation
Pv- Pliocene Volcanic rocks
Q- Alluvium
Qg- Glacial deposits
Qv- Pleistocene Volcanic rocks
Qvs- Volcanic rocks of Shasta Valley
Tv- Western Cascade Volcanics

The approach we took to convert the lithologic classification bins to geologic formations using geologic interpretation was as follows: 1.) map the lithologic classification bin in a 3-D geologic modeling software; we used the Leapfrog software package (Seequent Ltd.) 2.) import various georeferenced geologic mapping products (most in GIS shapefile format) in the model space to assist in our interpretation of the geology 3.) interpret the upper-most lithology in the log to that which matches the surface geologic unit it falls within 4.) find lithologic contacts that most certainly represent changes in geologic unit and utilize published geologic mapping products as a guide as to what unit is encountered 5.) continue Step 4 from top down, going from areas where geologic unit contacts are better known (e.g. published in cross sections georeferenced in 3-D space in the model framework) to areas where they are not as well-known.

After initially converting the lithologic classifications to interpreted geologic units for each of the logs, we then used those logs as input in the geologic model to build contact surfaces. Leapfrog uses an in-house, proprietary method for constructing geologic models which they call “Implicit Modeling” using the FastRBF™ algorithm, which is a type of radial basis function (RBF) that Seequent has developed for Leapfrog. The method honors the data it is given (i.e. surface geology polygon and digitized borehole geology data) and additionally honors the geologic type and timing of the deposit to create geologic contact surfaces. These surfaces can then be used to construct 3-D geologic unit volumes. Once we constructed the initial geologic contact surfaces, we were able to refine the logs to better represent the geologic contact surfaces as close as feasibly possible to what we interpret as geologic reality. We were additionally able to incorporate structural geologic controls on the geologic surface constructions in the software based on published literature to guide the surfaces to what we interpret as the most realistic trends of the geologic surfaces. After several iterations of interpretation of log descriptions and creating geologic surfaces, we arrived at the most probable structural interpretation of the geology of the basin given all of the available data. We then used the surfaces to construct the final resulting geologic model.

Visual Accompanying Addendum Material to the 3-D Geologic Interpretation and Modeling Procedure

The attached addendum presentation adds visualizations to this modeling methodology to better illustrate the steps taken to develop the Shasta Valley Geological Model building process and verification. It is attached after the reference section of this technical memorandum. It highlights the process described above visually to help clarify the detailed modeling process.

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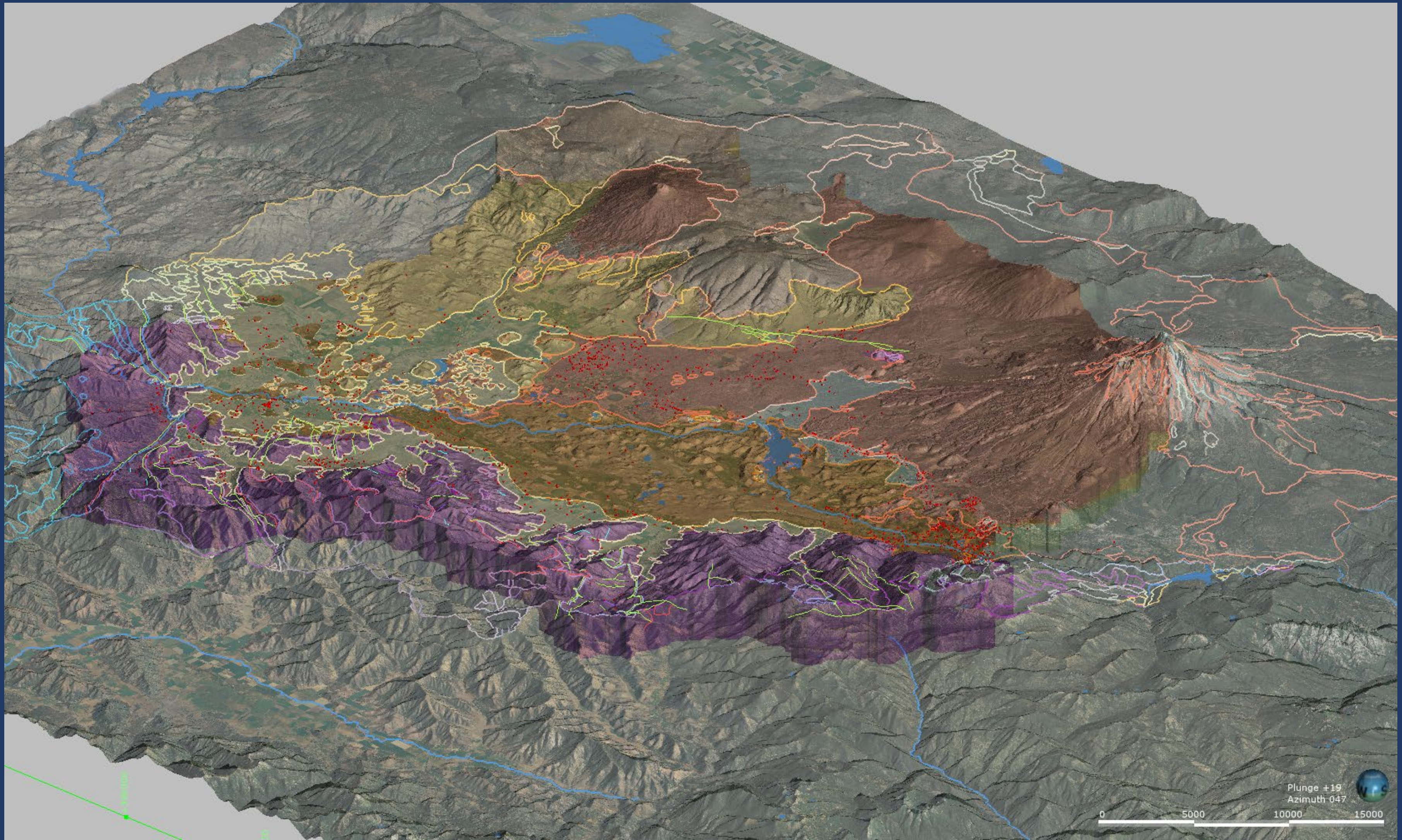
3-D Geological & Geophysical Mapping/Modeling

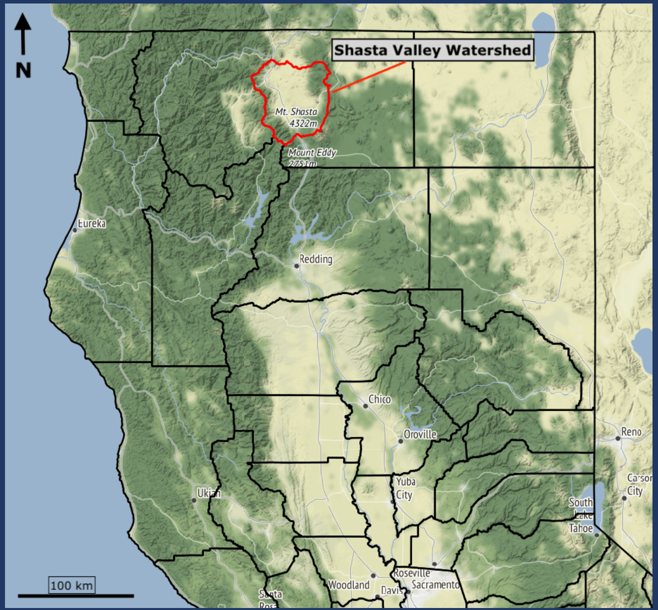
Joint research (UC Davis) & consulting (LWA) project:

- Shasta Valley Groundwater Basin 3-D geological model



Shasta Valley Groundwater Basin 3-D geological model

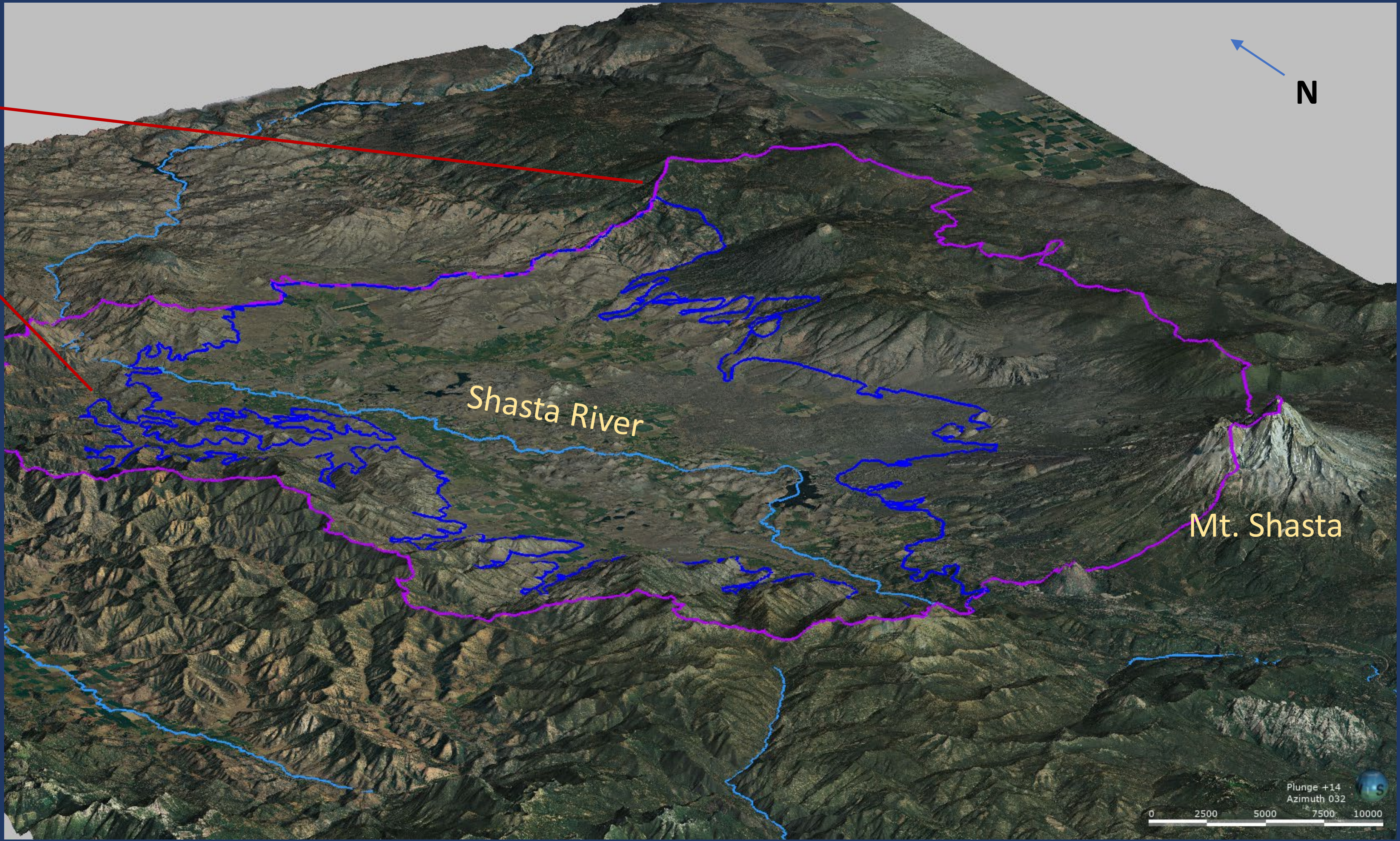
Shasta Valley

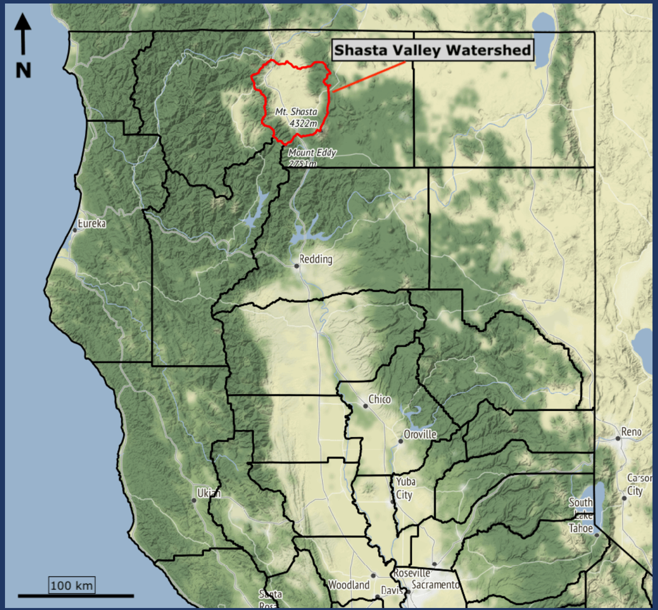


Shasta Valley Groundwater Basin 3-D geological model

Shasta Valley

- ~800 mi^2 watershed
- ~350 mi^2 Bulletin 118 groundwater basin

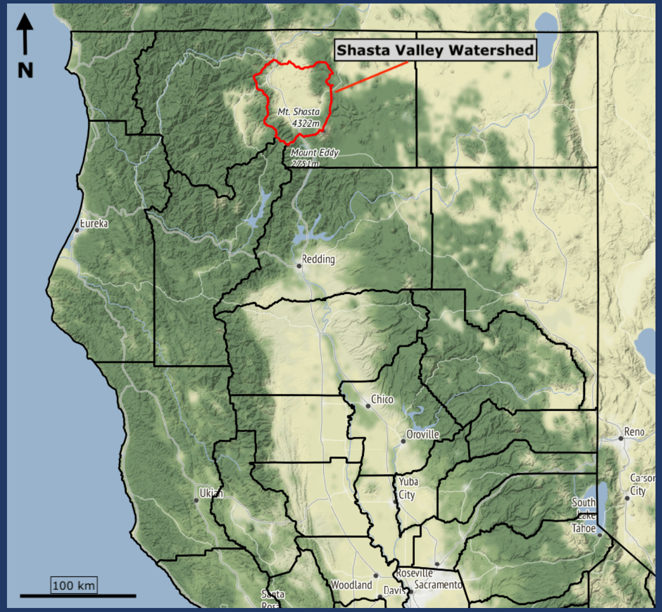


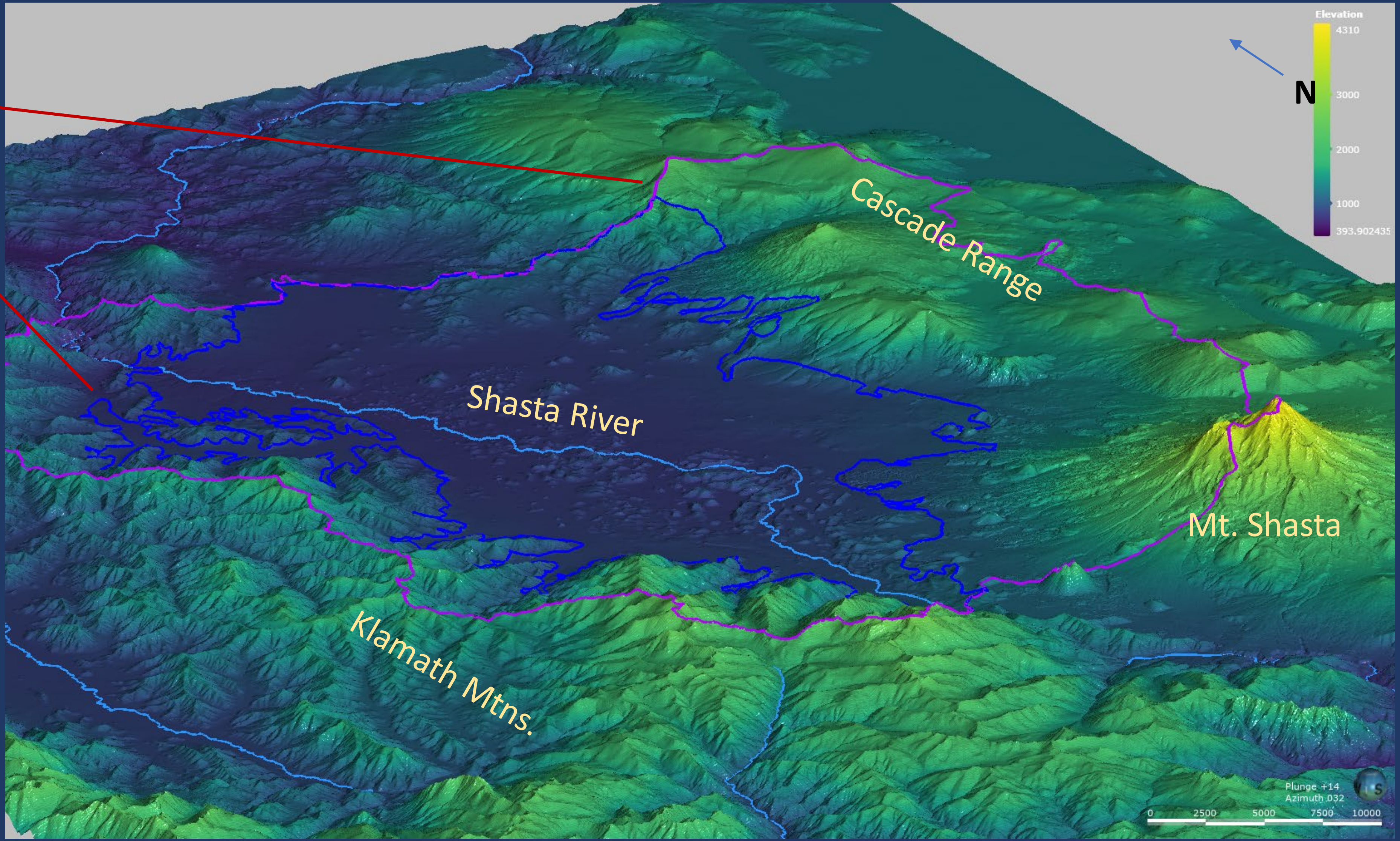


Shasta Valley Groundwater Basin 3-D geological model

Shasta Valley

- ~800 mi^2 watershed
- ~350 mi^2 Bulletin 118 groundwater basin
- ~2k-14k ft amsl elevation range
- North-dipping valley floor

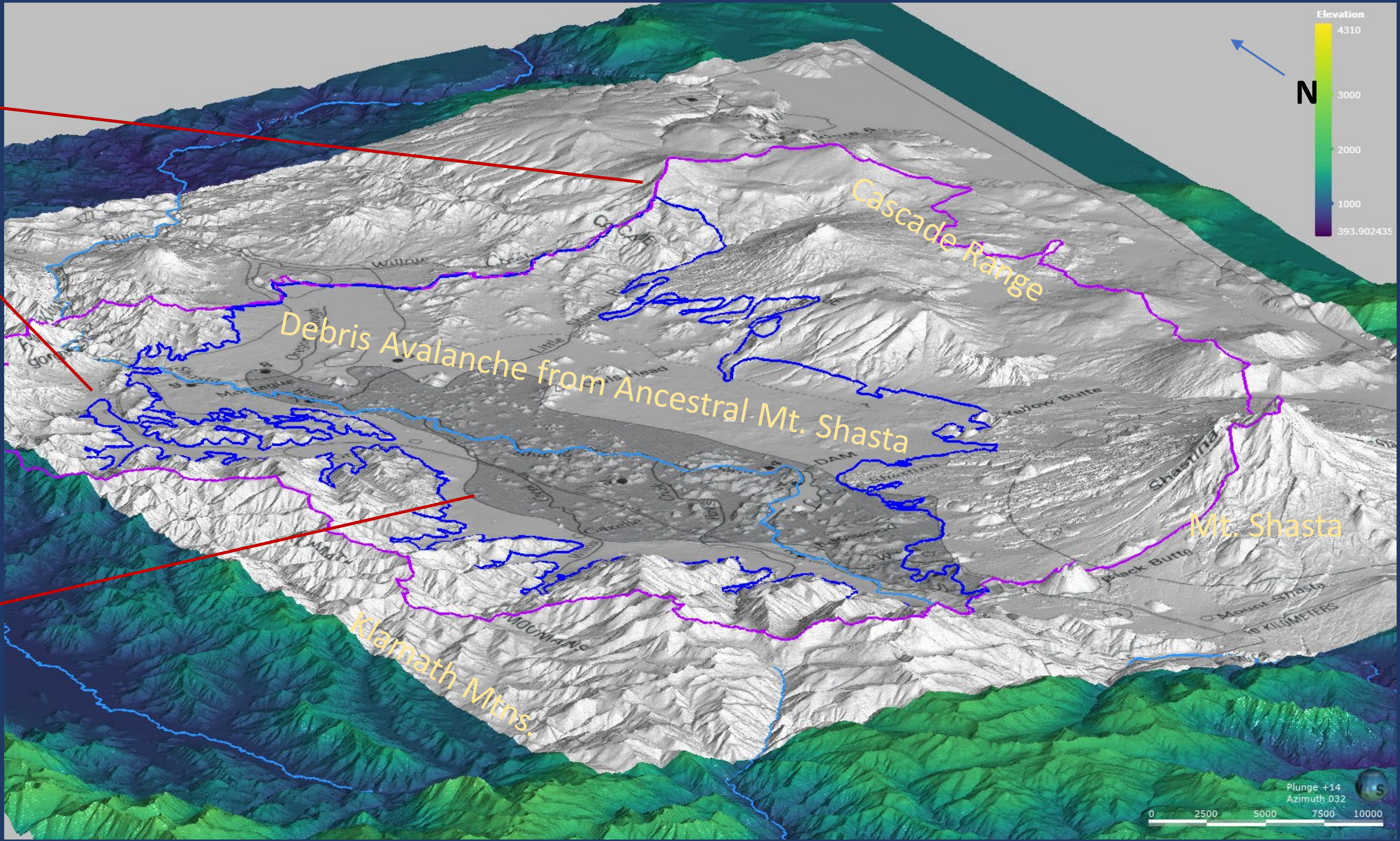




Shasta Valley Groundwater Basin 3-D geological model

Shasta Valley

- ~800 mi^2 watershed
- ~350 mi^2 Bulletin 118 groundwater basin
- ~2k-14k ft amsl elevation range
- North-dipping valley floor
- Large Q-aged debris avalanche covers much of the valley

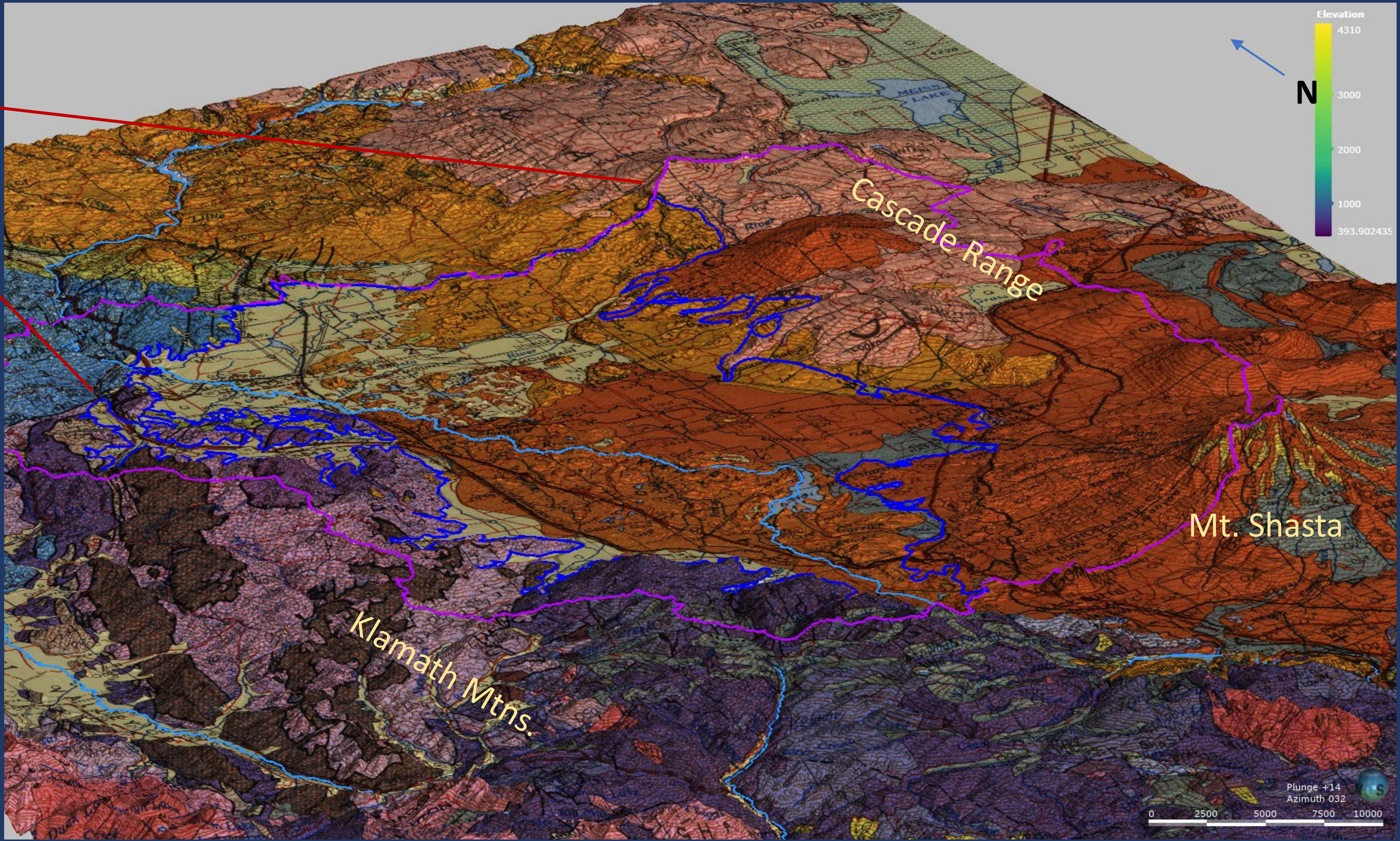


Draped map on topography from Crandell et al. (1989)

Shasta Valley Groundwater Basin 3-D geological model

Shasta Valley

- ~800 mi^2 watershed
- ~350 mi^2 Bulletin 118 groundwater basin
- ~2k-14k ft amsl elevation range
- North-dipping valley floor
- Large Q-aged debris avalanche covers much of the valley
- Complex geology



Draped map on topography from CGS (1987)

Shasta Valley Groundwater Basin 3-D geological model

Data available

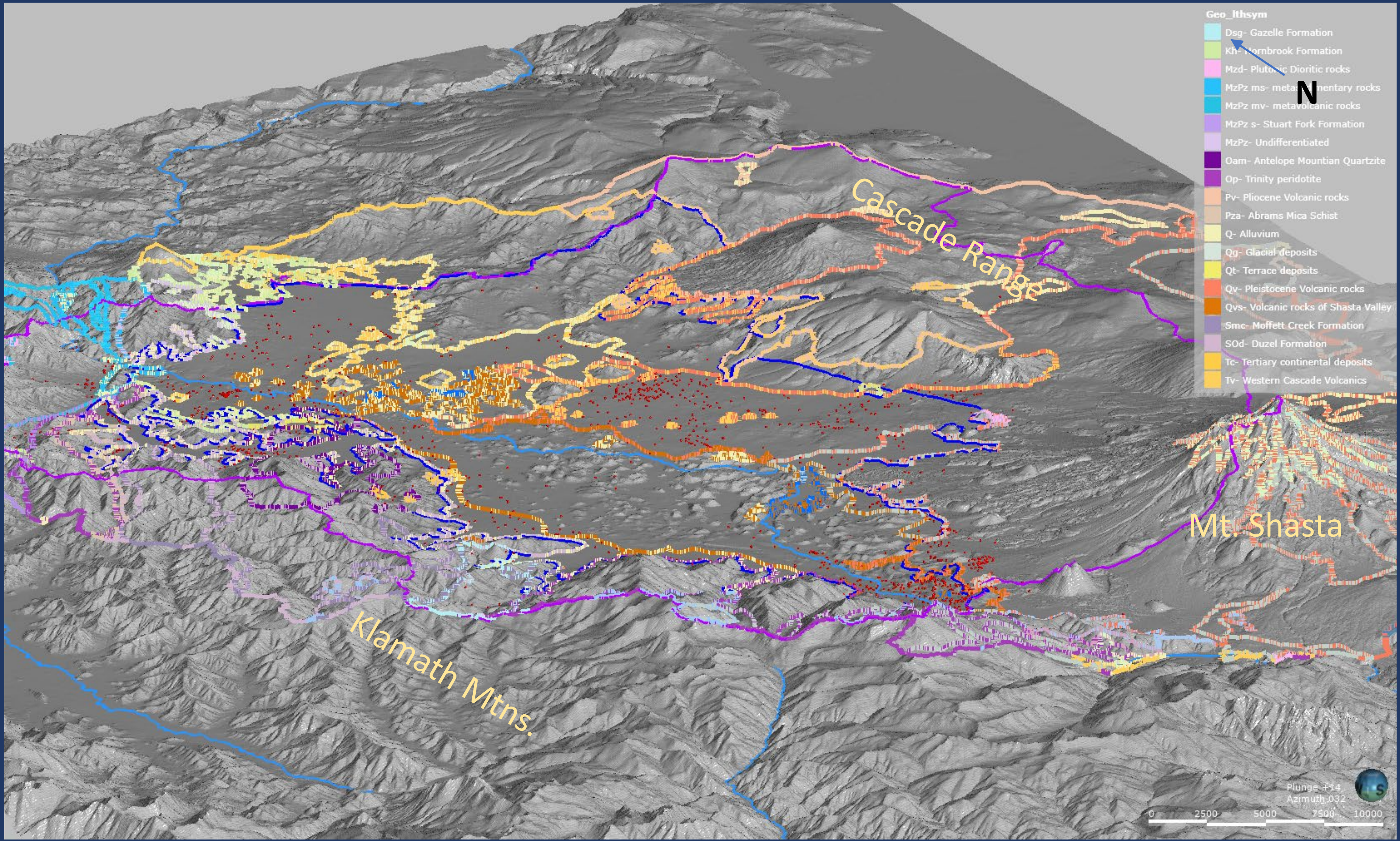
- Digitized surface geologic maps

Draped map on topography from CGS (1987), digitized by DWR-NRO (2011)

Shasta Valley Groundwater Basin 3-D geological model

Data available

- Digitized surface geologic maps
- ~3,400 total WCRs

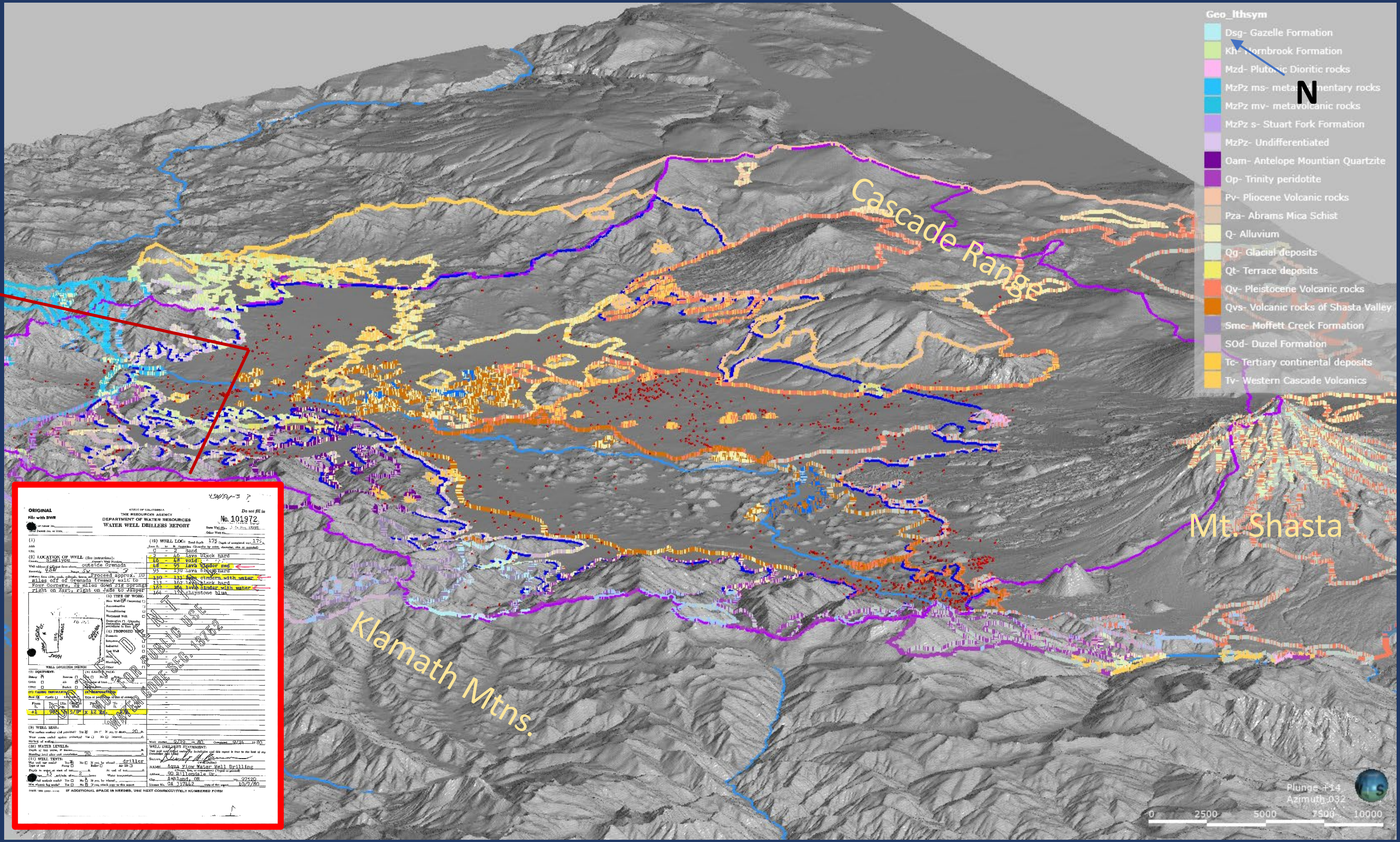


Draped map on topography from CGS (1987), digitized by DWR-NRO (2011)

Shasta Valley Groundwater Basin 3-D geological model

Data available

- Digitized surface geologic maps
- ~3,400 total WCRs
- 1,300+ WCRs precisely <u>located</u> and <u>digitized</u>

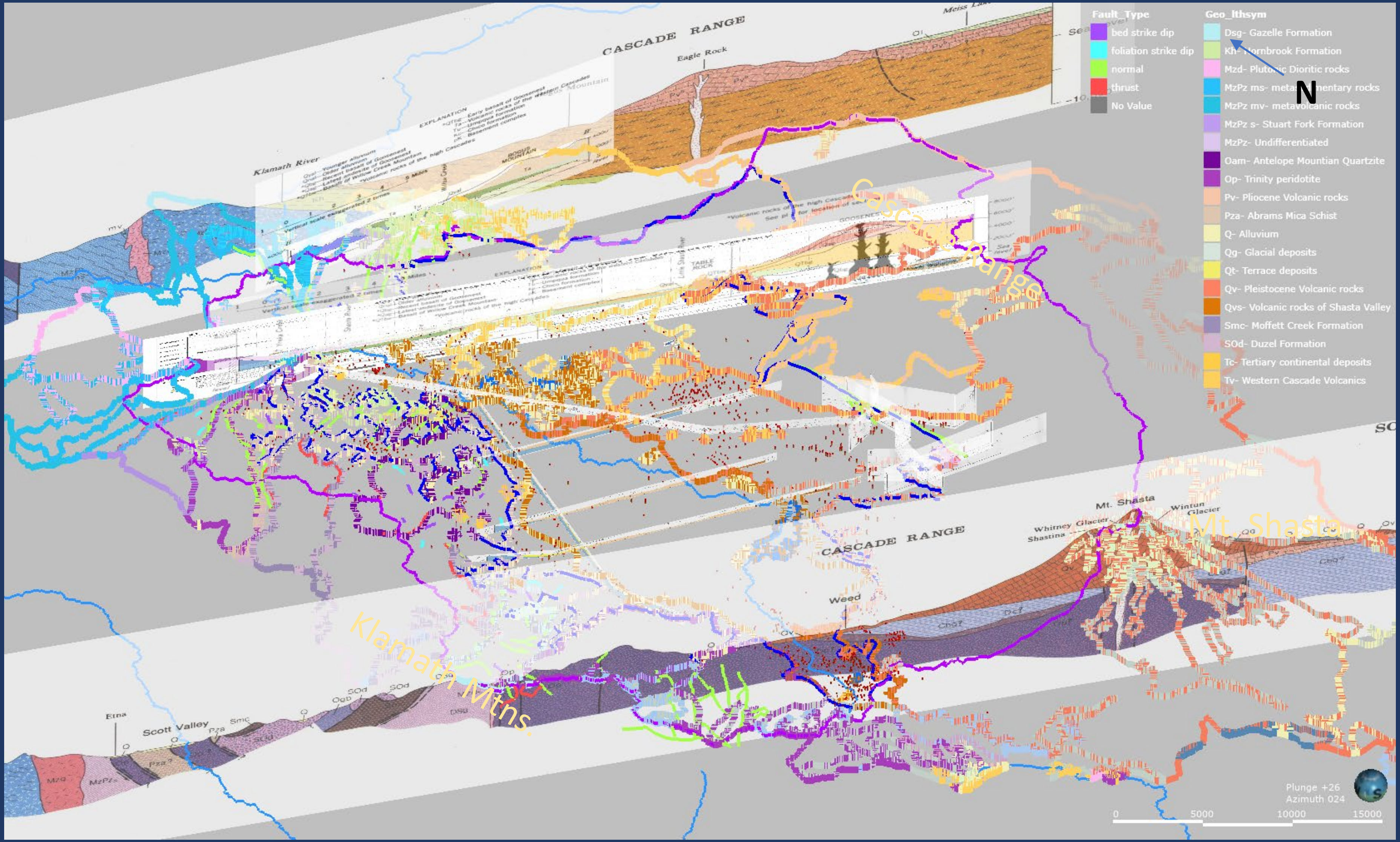


Draped map on topography from CGS (1987), digitized by DWR-NRO (2011)

Shasta Valley Groundwater Basin 3-D geological model

Data available

- Digitized surface geologic maps
- ~3,400 total WCRs
- 1,300+ WCRs precisely <u>located</u> and <u>digitized</u>
- Cross sections available, but based on limited drilling data
- USGS geologic formation descriptions (included with other surface maps)
- Geophysical data (*not shown*)

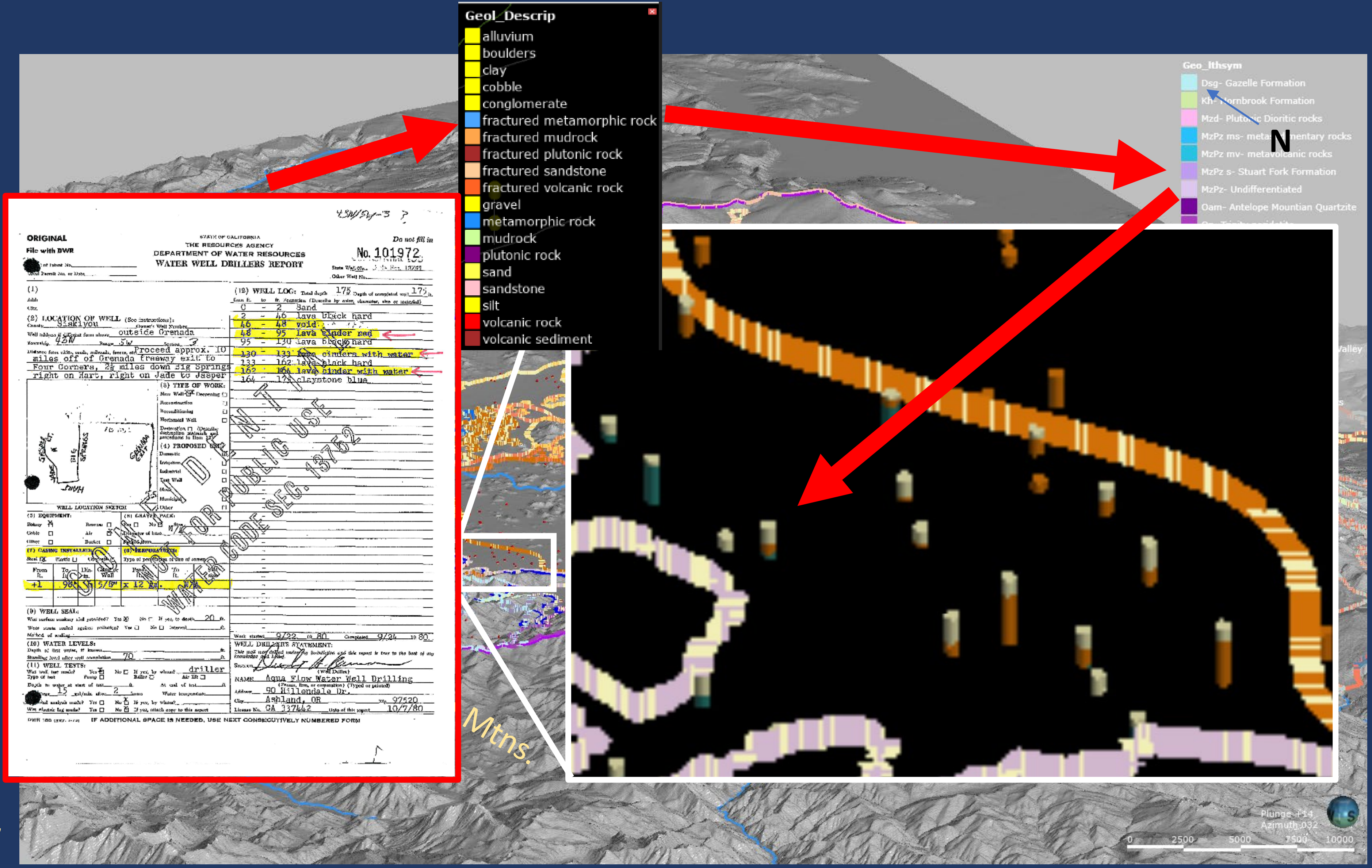


Cross sections from Mack (1960), Holliday (1983), CGS (1987), & DWR-NRO (2011)

Shasta Valley Groundwater Basin 3-D geological model

Methods

- Convert WCR lithology into geologic units using mapped surface geology
- Start at the top lithology and work down depth
- Geologically complex area yields driller terms that vary enough for geologist to ID stratigraphic changes (e.g. alluvium-volc.-meta)
- USGS descriptions of geologic Fms are key

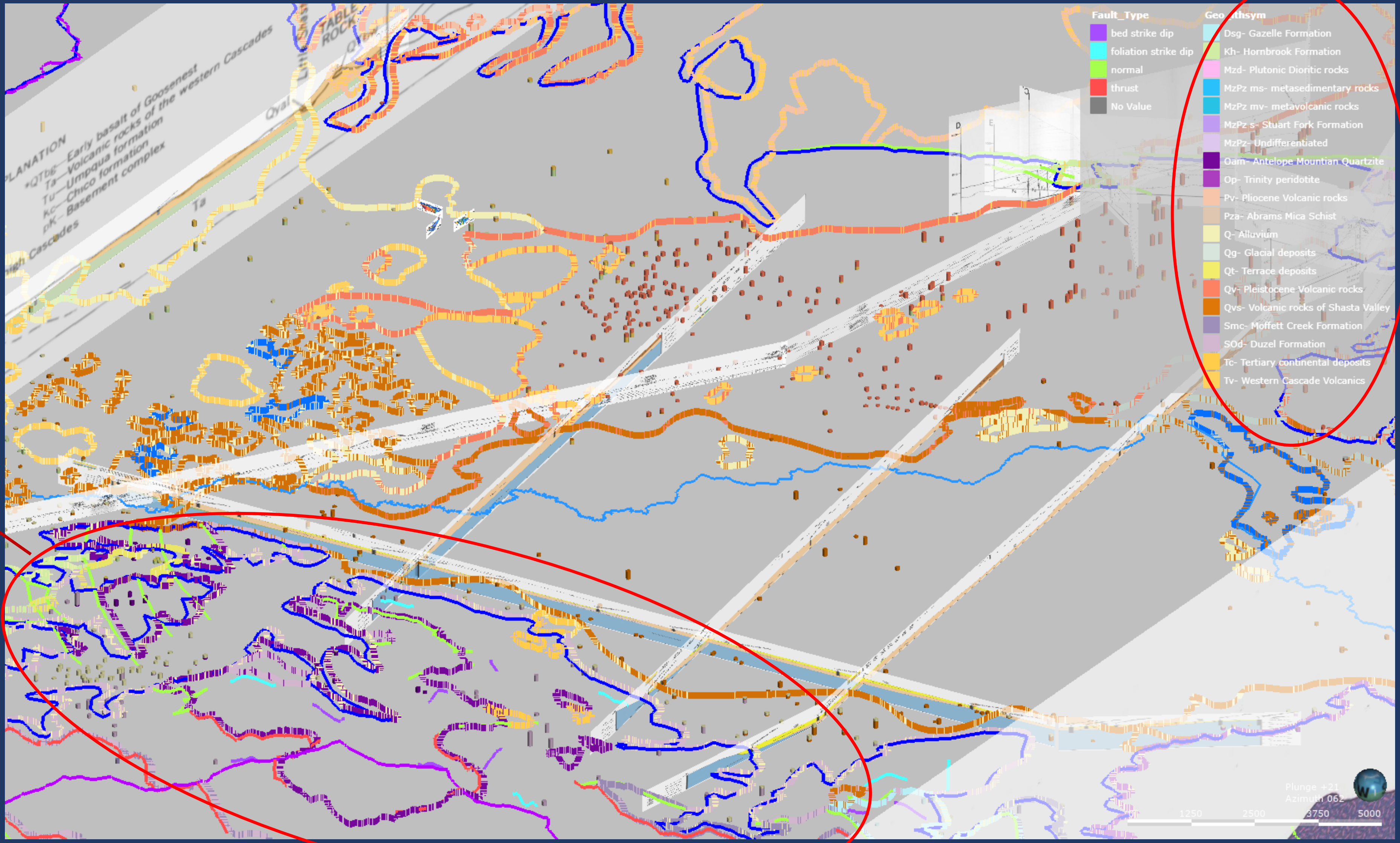


Utilized Leapfrog modeling software for model construction and figures

Shasta Valley Groundwater Basin 3-D geological model

Methods

- Fit-for-purpose geological modeling mentality
- Purpose is ultimately for groundwater modeling grids
- Lump metamorphic basement units into grouped basement unit



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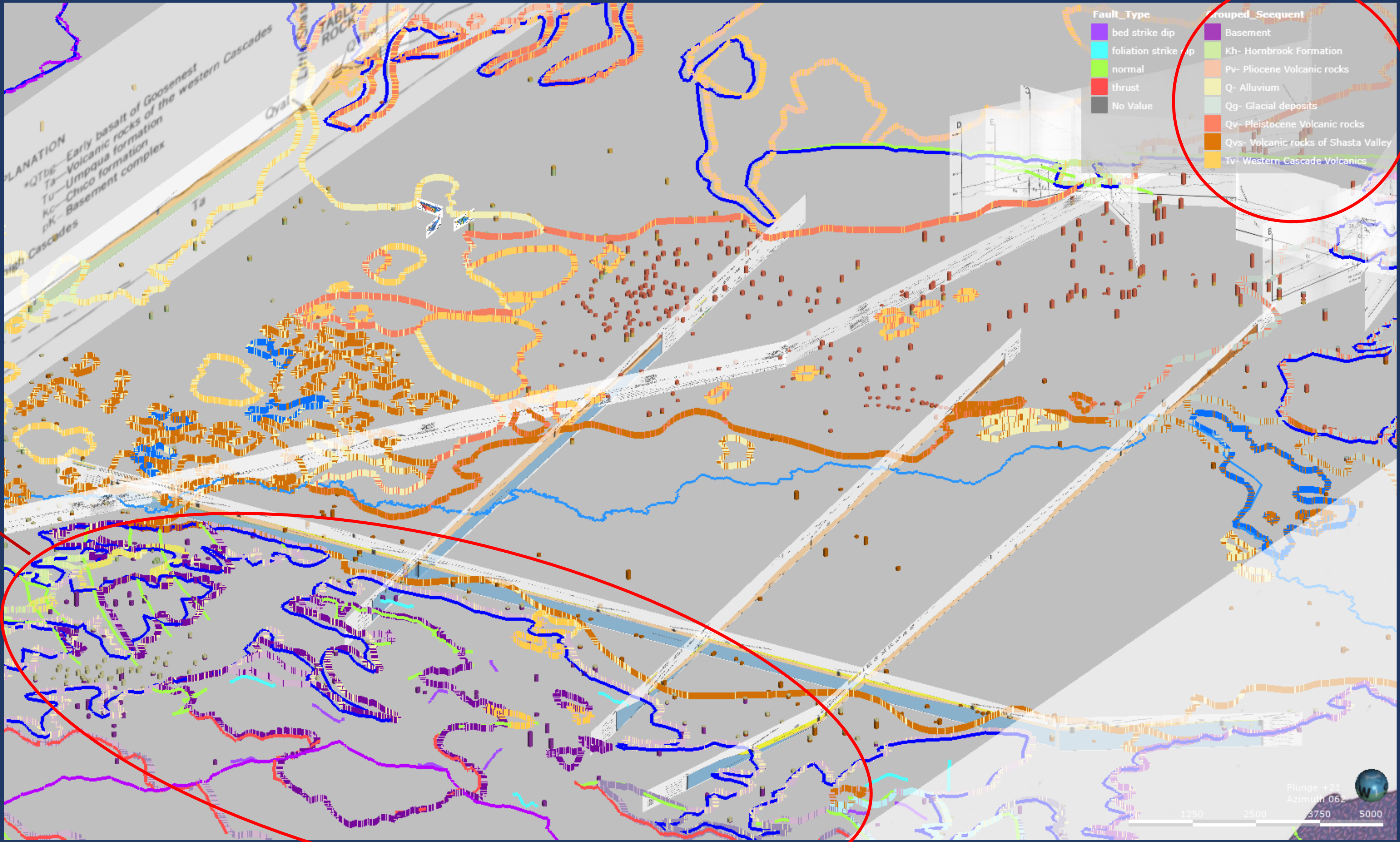

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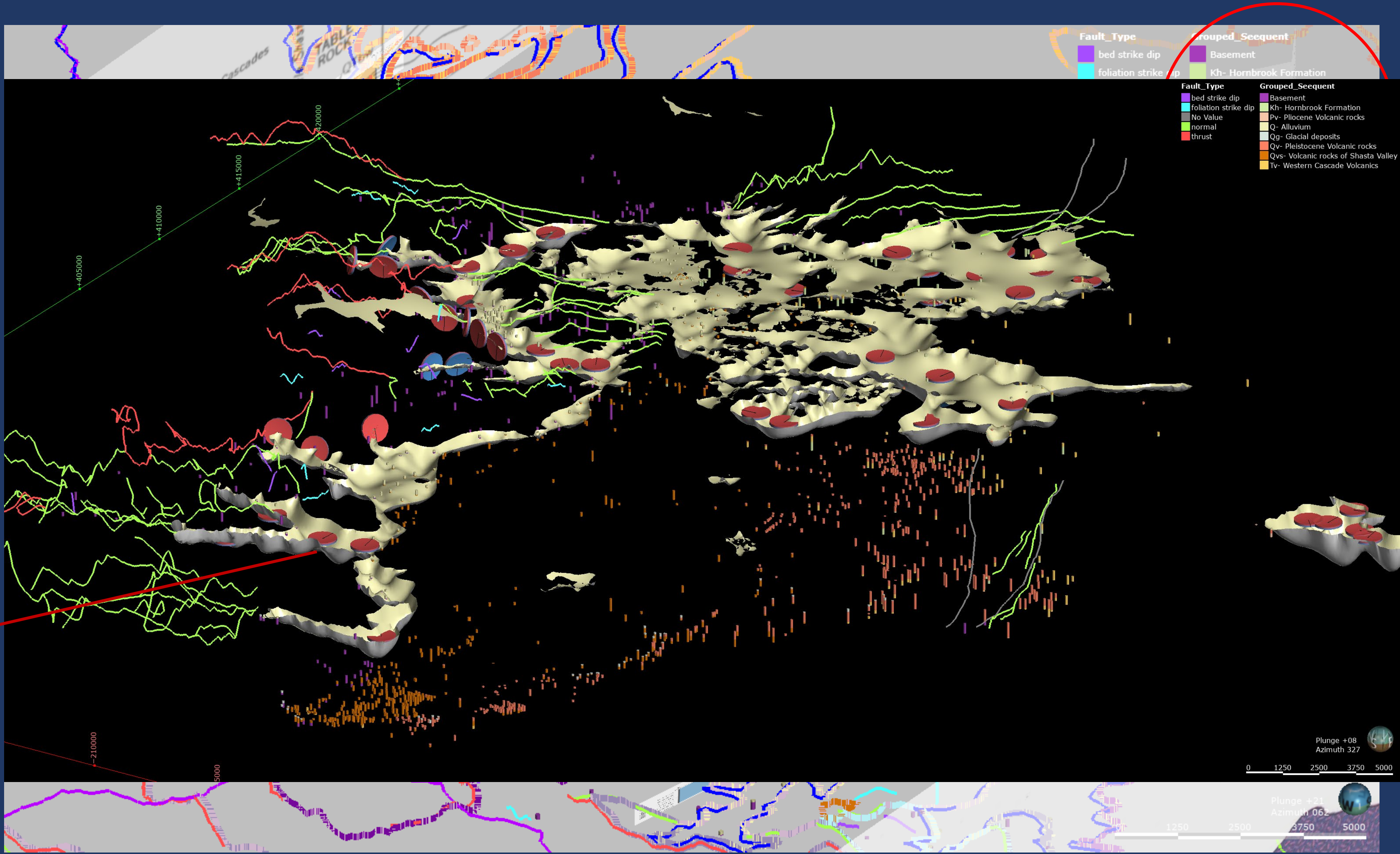
Shasta Valley Groundwater Basin 3-D geological model

Methods

- Fit-for-purpose geological modeling mentality
- Purpose is ultimately for groundwater modeling grids
- Lump metamorphic basement units into grouped basement unit
- Use structural data and cross sections to guide creation of contact surfaces



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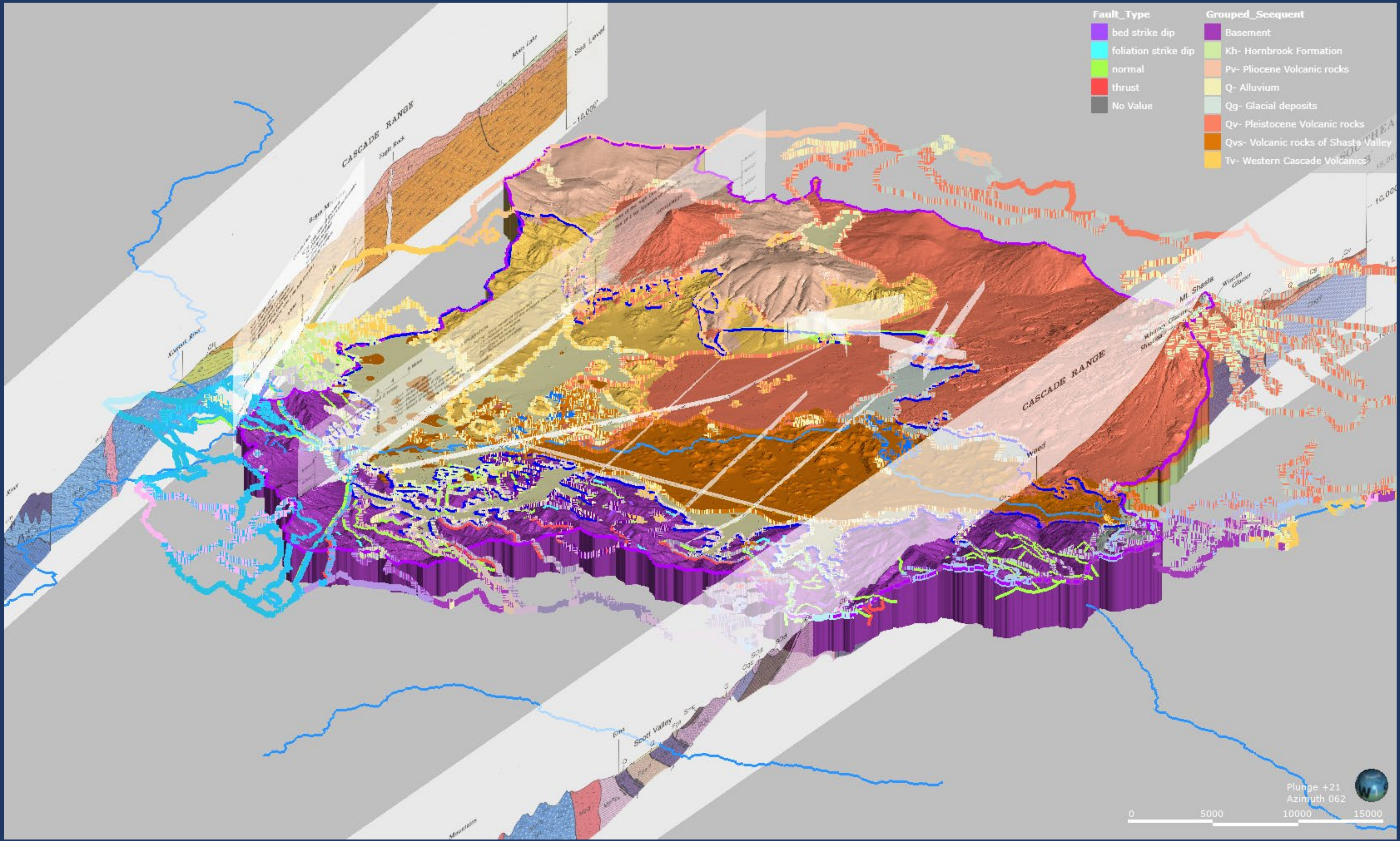
Shasta Valley Groundwater Basin 3-D geological model

Methods

- Fit-for-purpose geological modeling mentality
- Purpose is ultimately for groundwater modeling grids
- Lump metamorphic basement units into grouped basement unit
- Use structural data and cross sections to guide creation of contact surfaces
- Create block model



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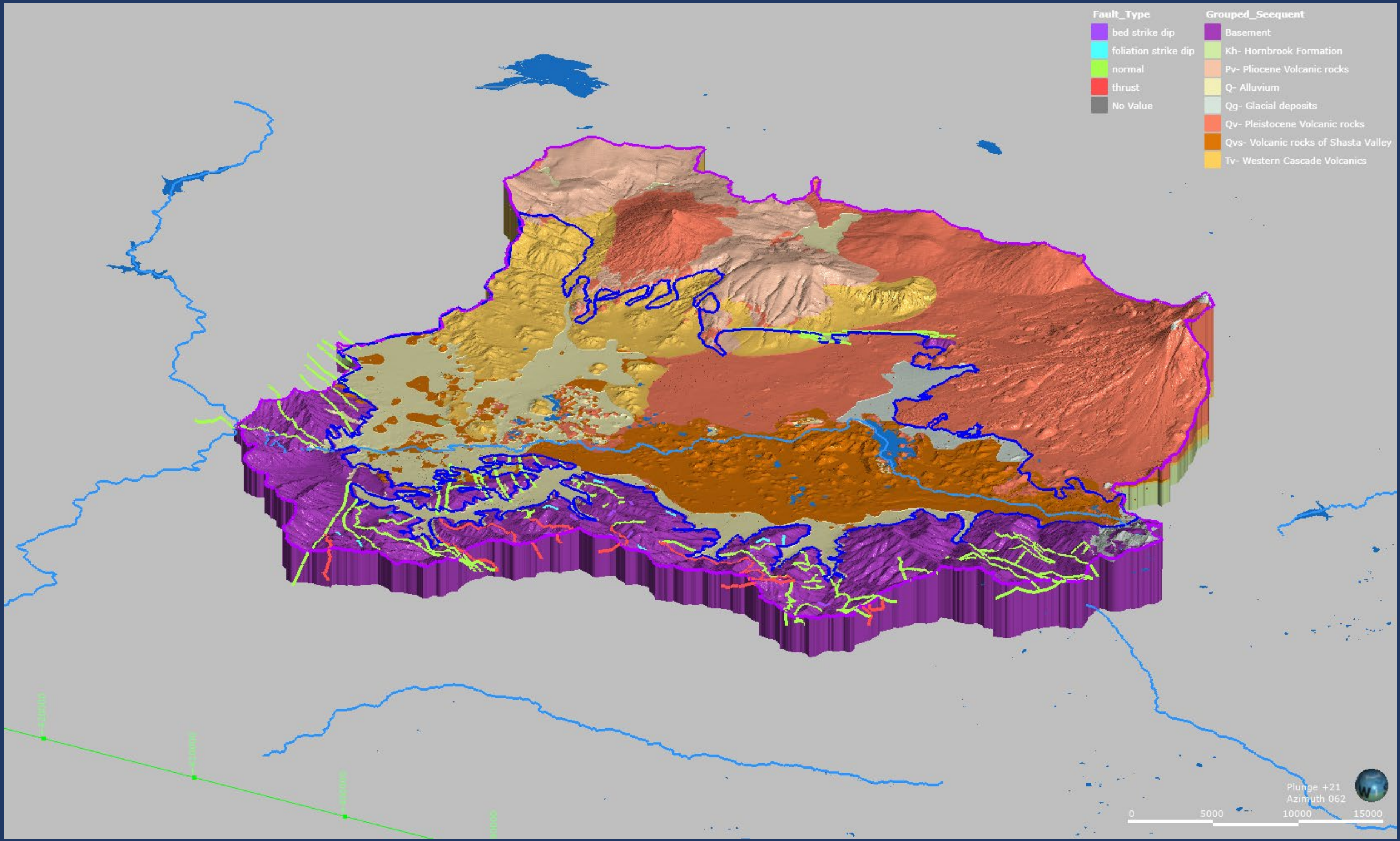
Shasta Valley Groundwater Basin 3-D geological model

Methods

- Fit-for-purpose geological modeling mentality
- Purpose is ultimately for groundwater modeling grids
- Lump metamorphic basement units into grouped basement unit
- Use structural data and cross sections to guide creation of contact surfaces
- Create block model
- Iterate until fit for use

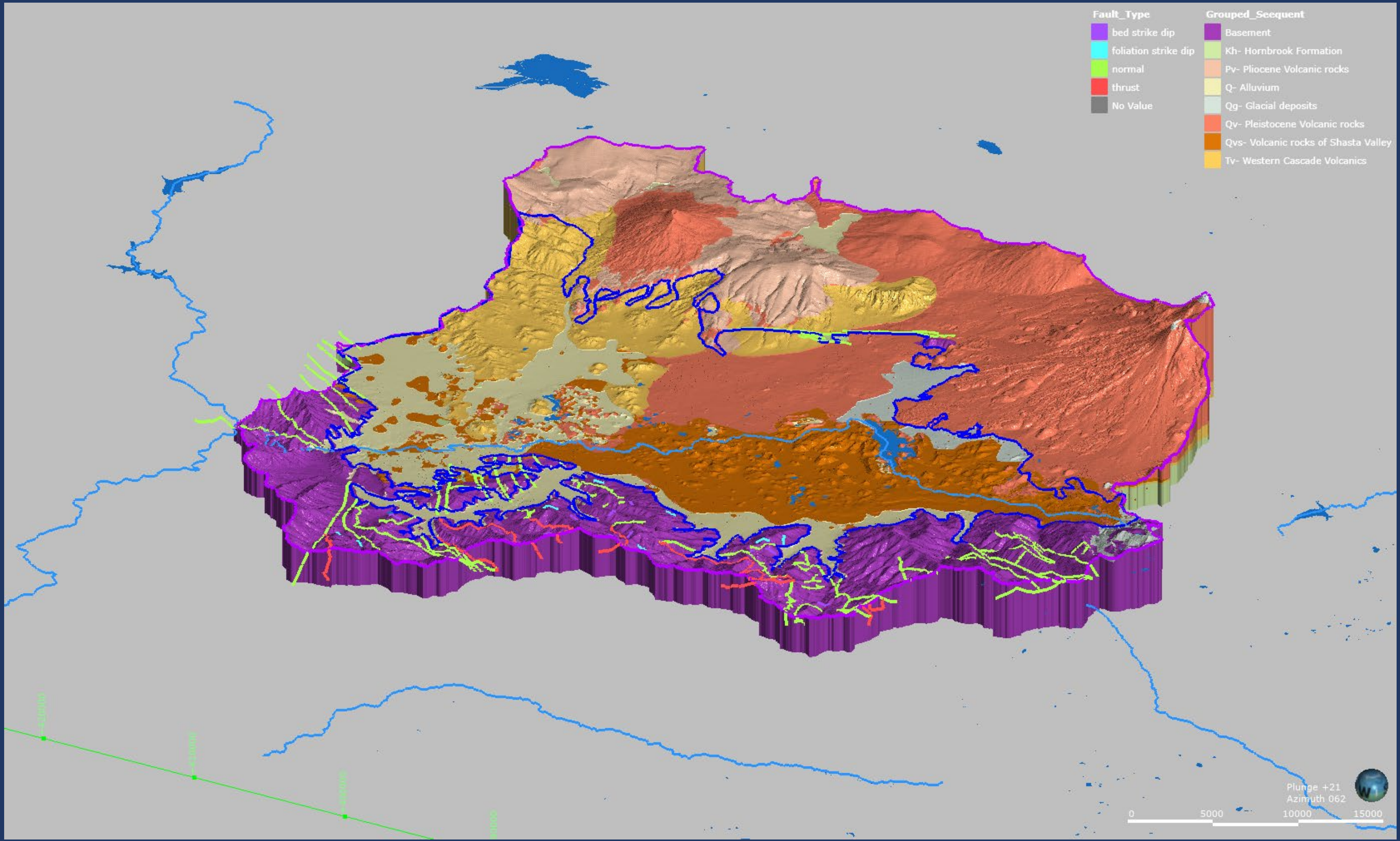


Utilized Leapfrog modeling software for model construction and figures

Shasta Valley Groundwater Basin 3-D geological model

Results

- Fit-for-purpose for groundwater modeling
- Focus is on the valley floor where drilling data inform the model the most and groundwater resources are most relevant
- Limited data in upland recharge areas



Shasta Valley Groundwater Basin 3-D geological model

Results

- Fit-for-purpose for groundwater modeling
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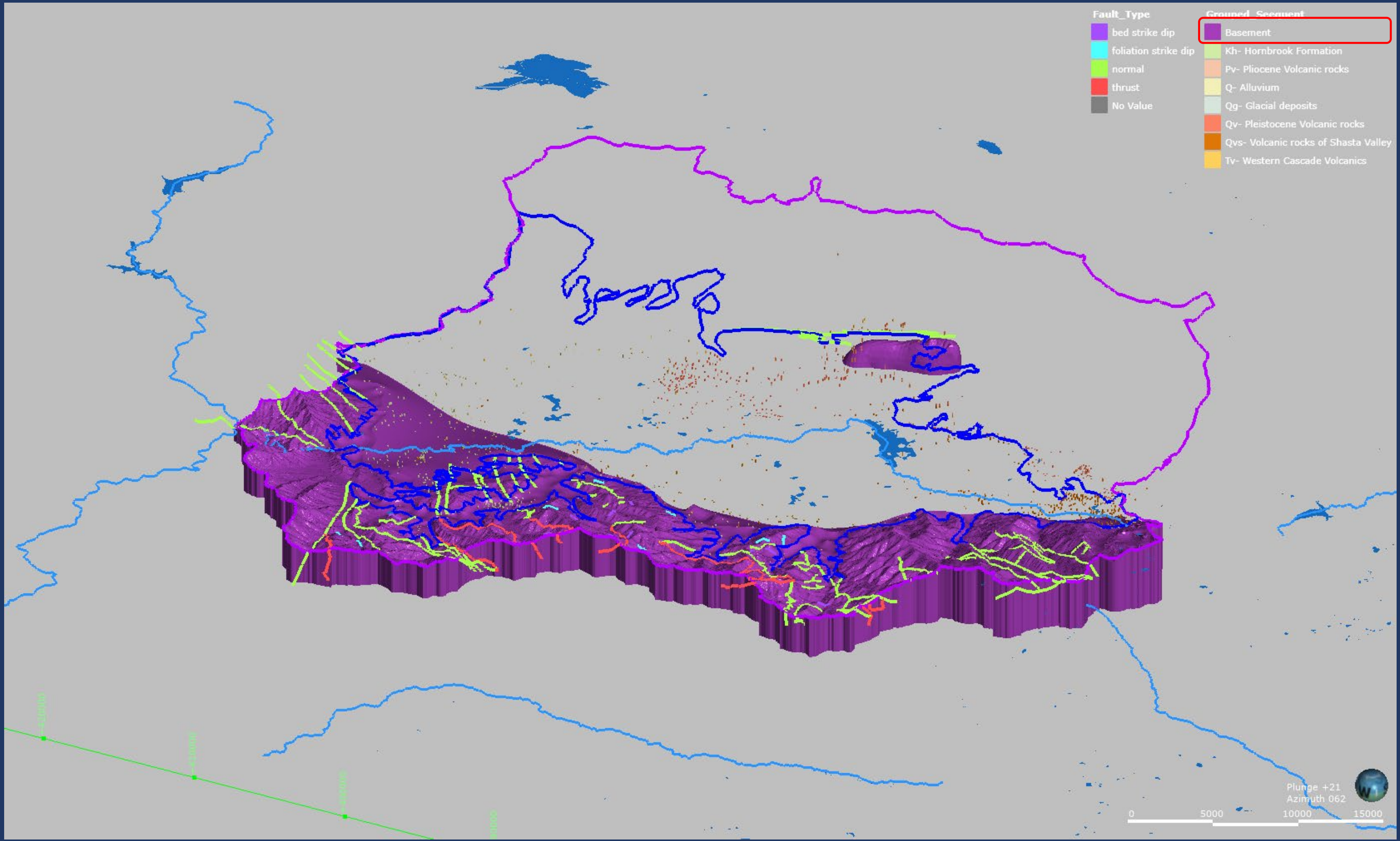
- Limited data in upland recharge areas
- Basement- *Paleozoic*



Shasta Valley Groundwater Basin 3-D geological model

Results

- Fit-for-purpose for groundwater modeling
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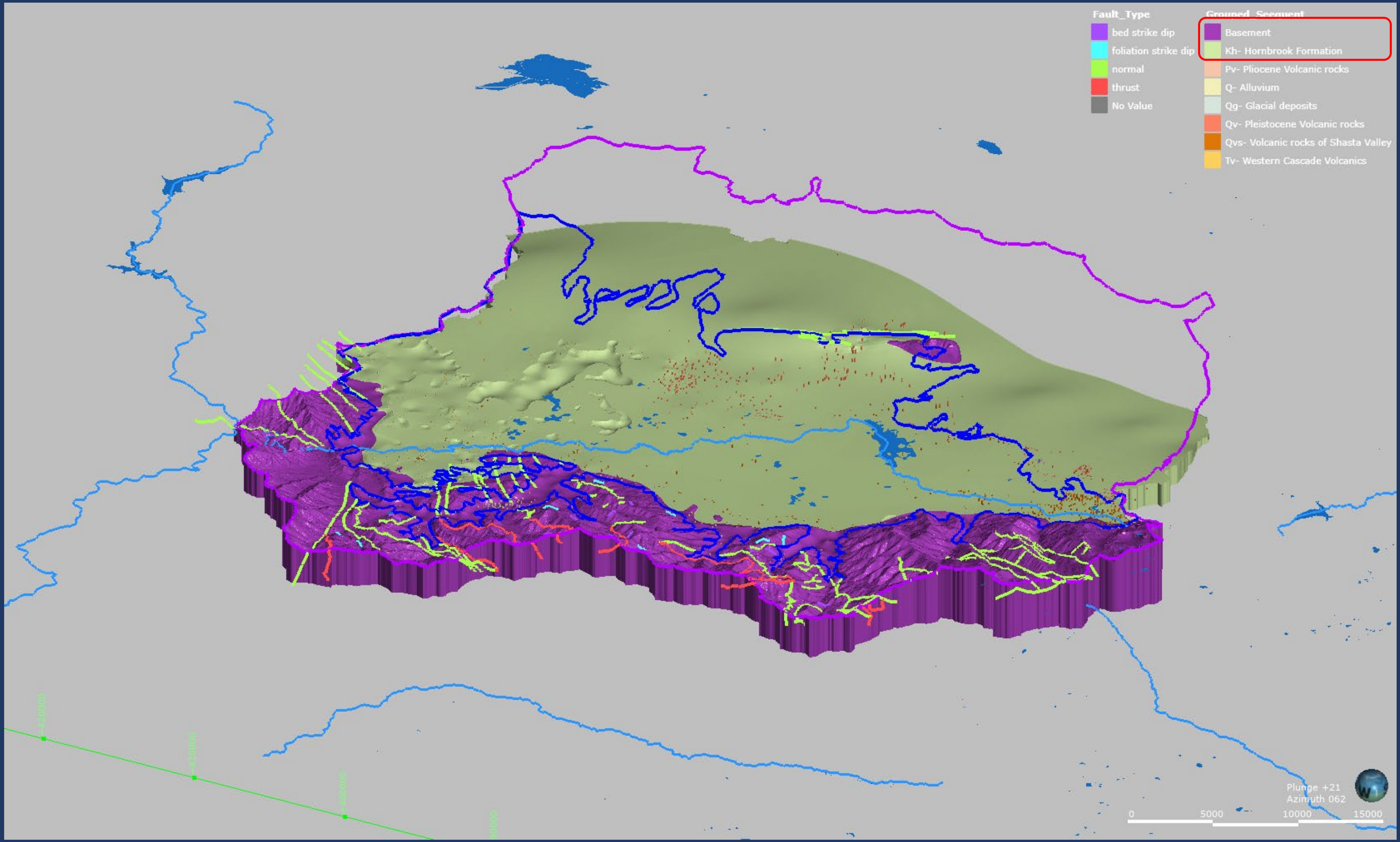

Shasta Valley Groundwater Basin 3-D geological model

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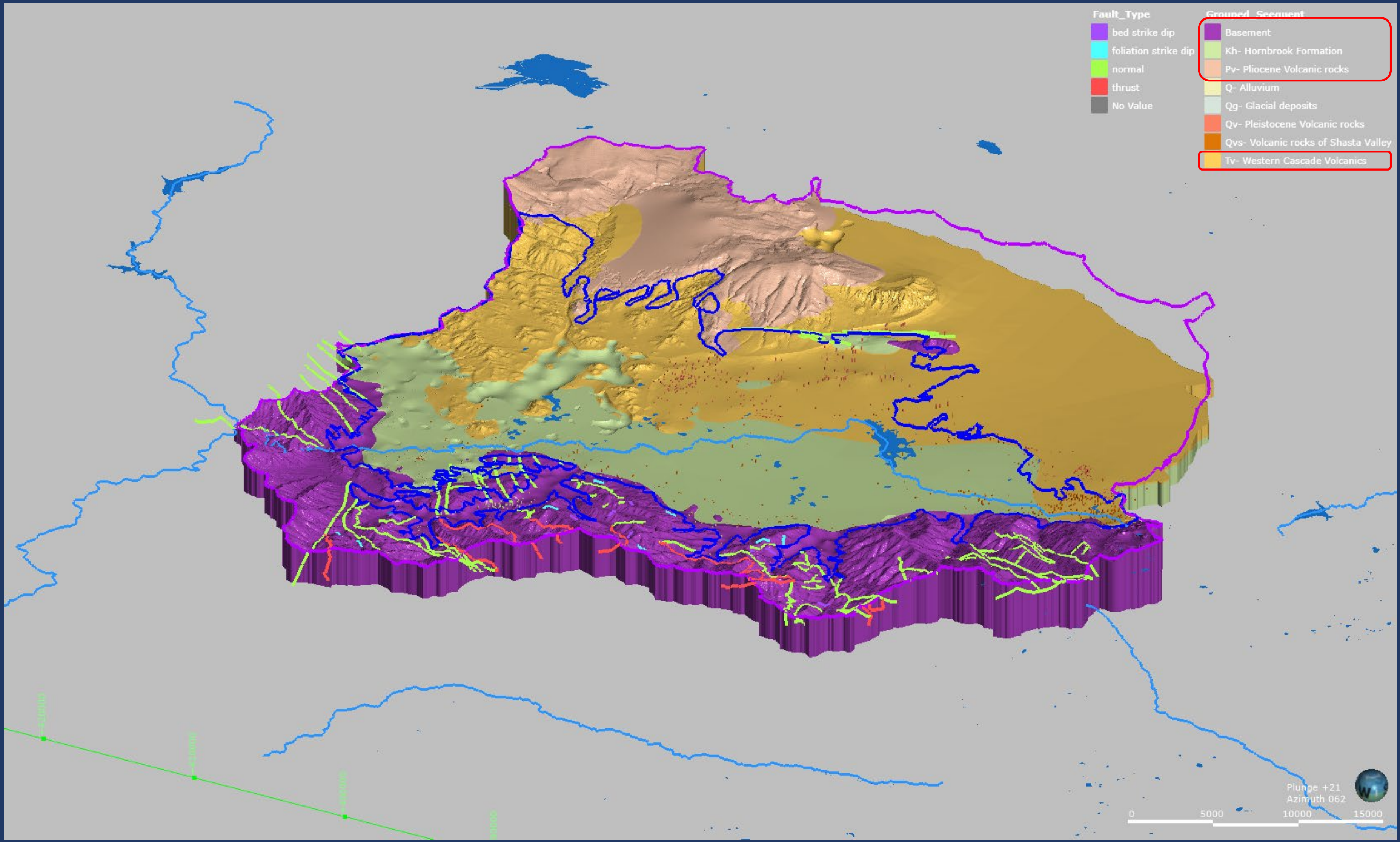
- Cenozoic



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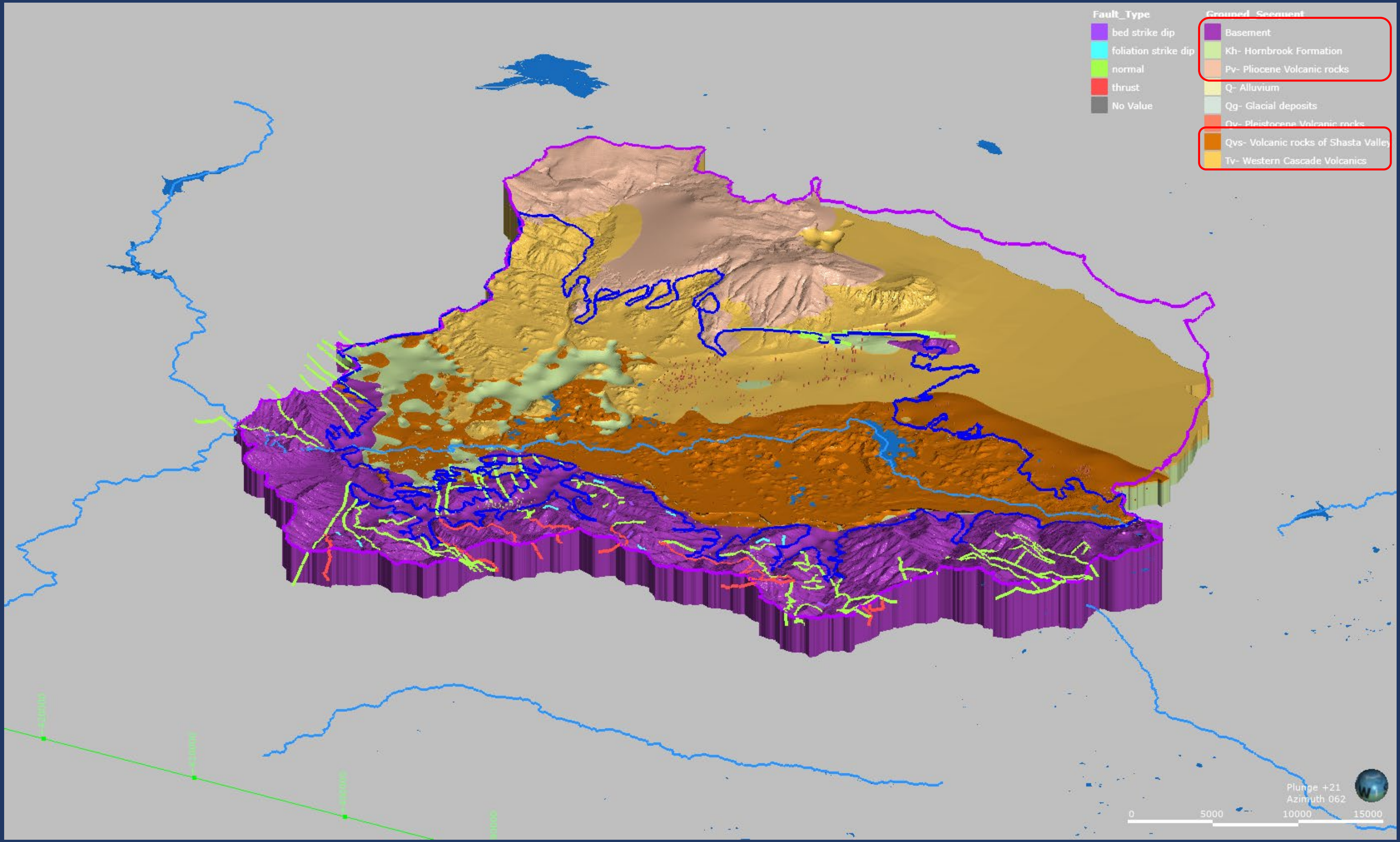

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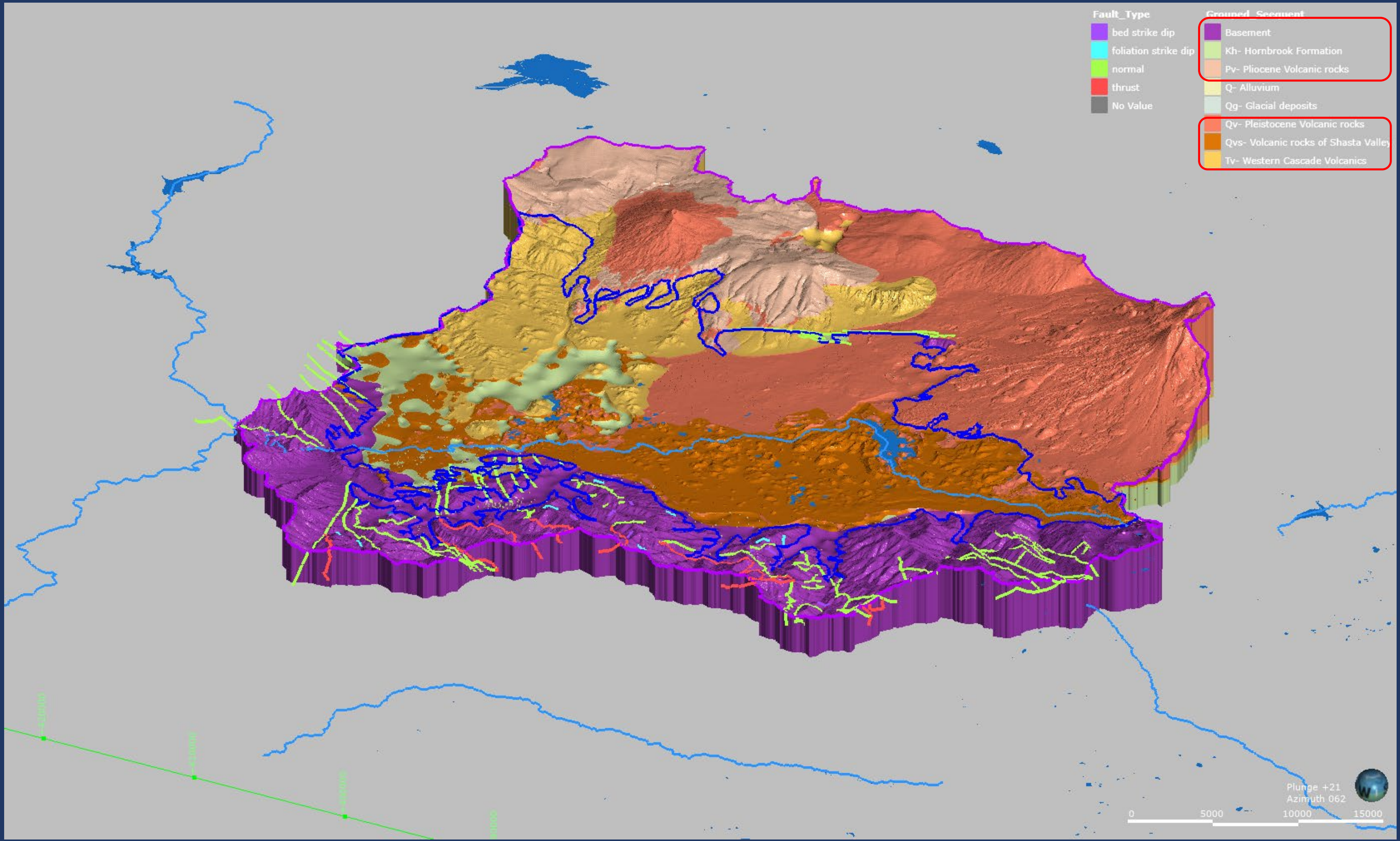

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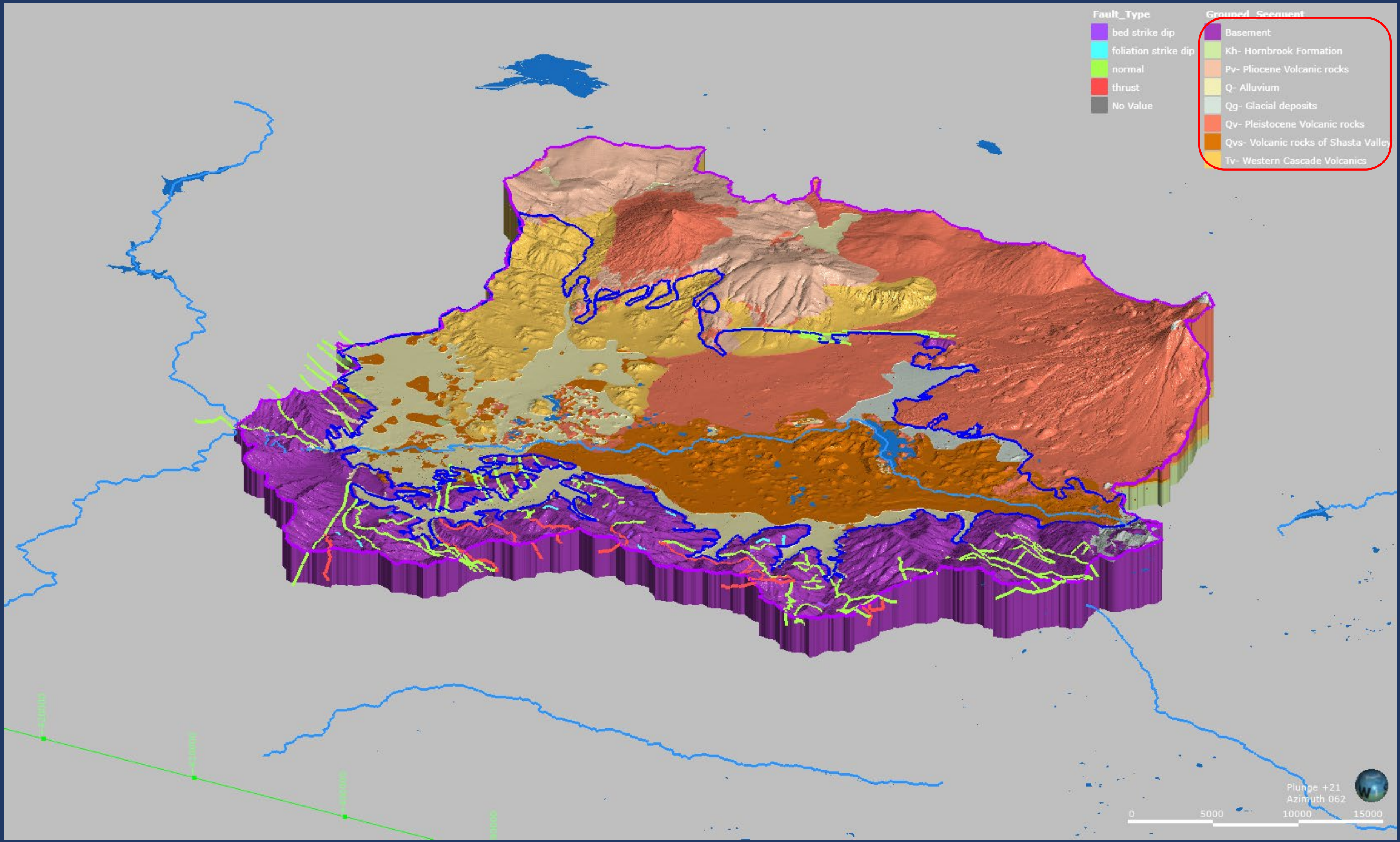
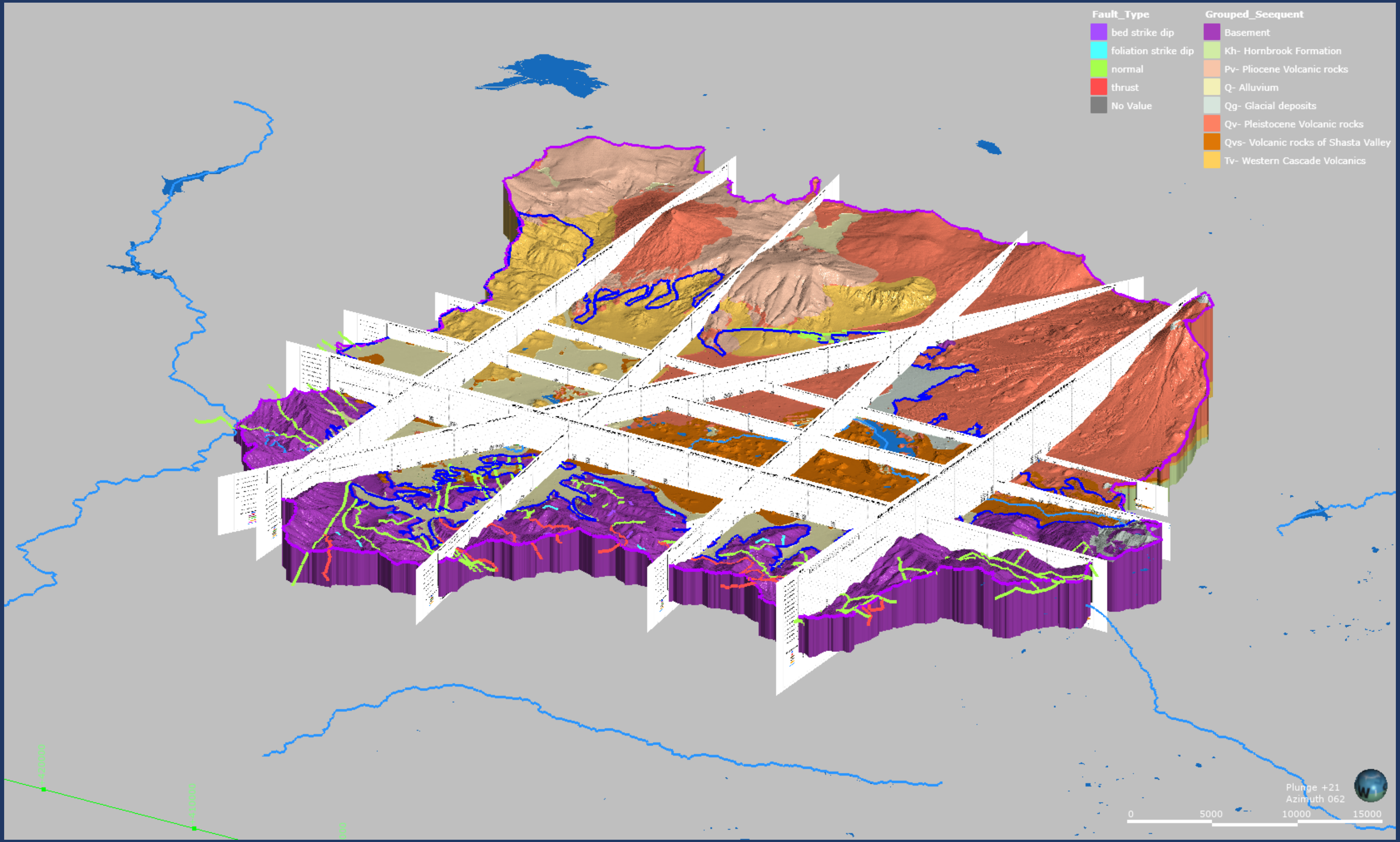
- Mesozoic
- Cenozoic



Shasta Valley Groundwater Basin 3-D geological model

Products

- Cross sections required by SGMA for GSP



Shasta Valley Groundwater Basin 3-D geological model

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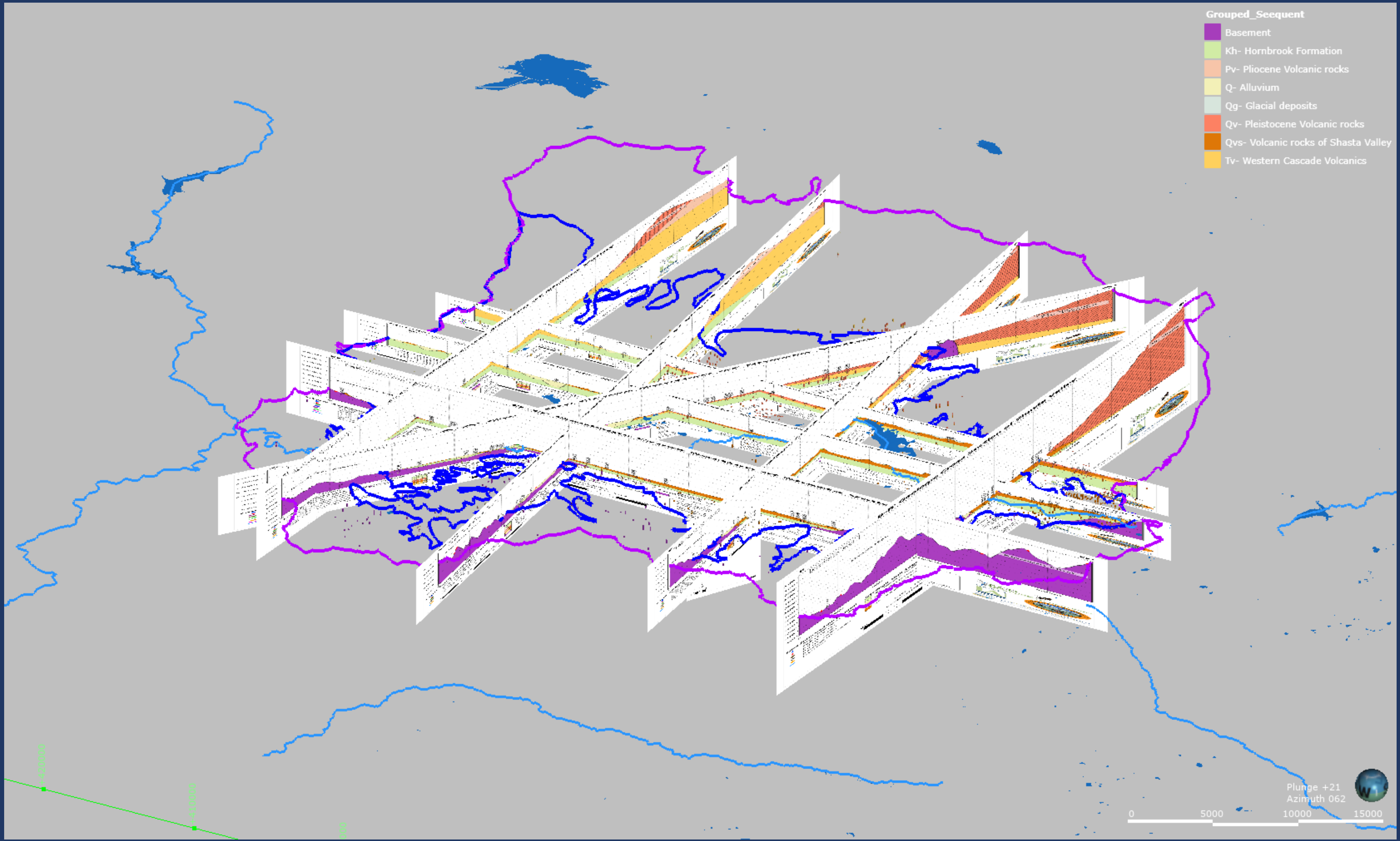

Shasta Valley Groundwater Basin 3-D geological model

Products

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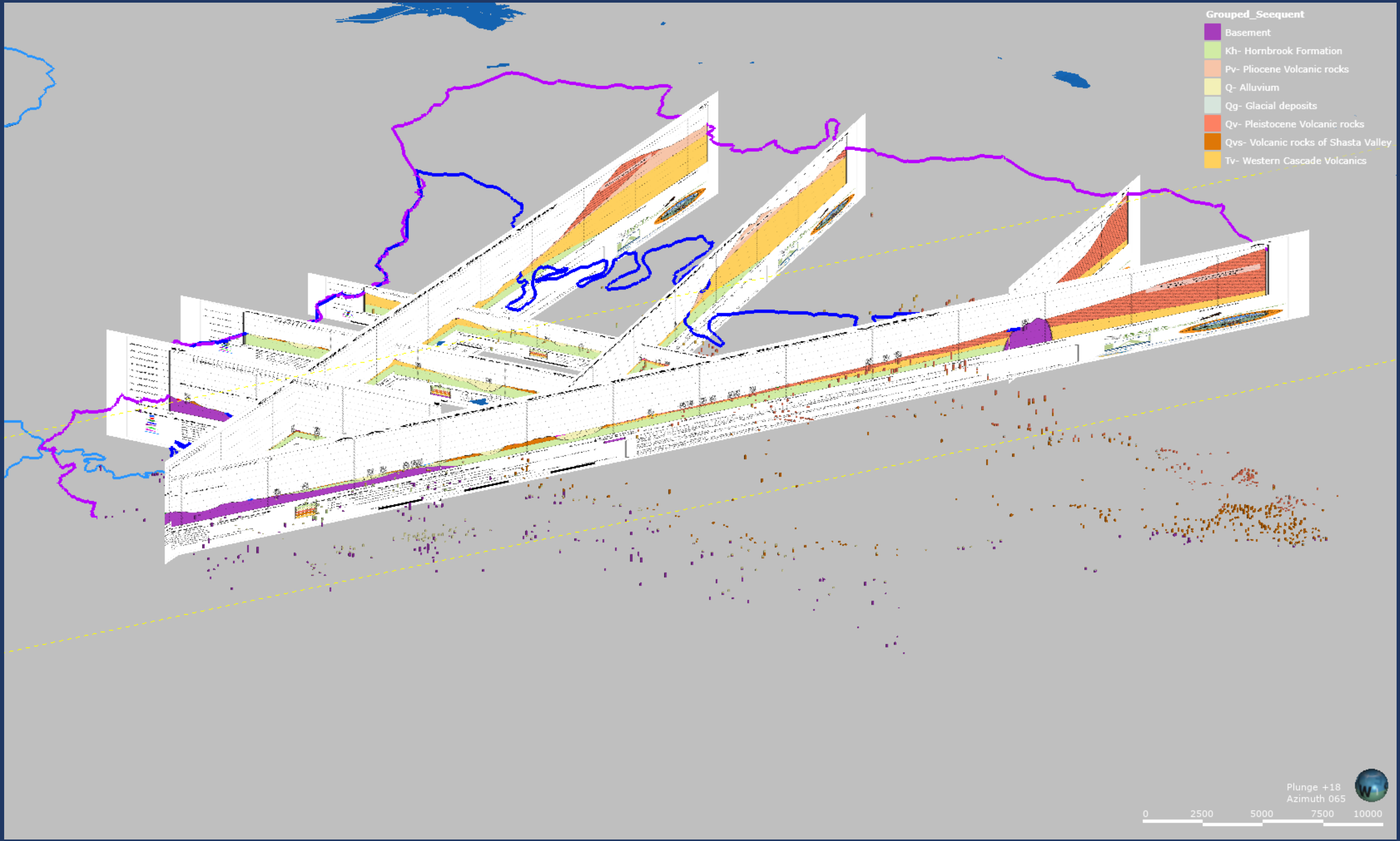
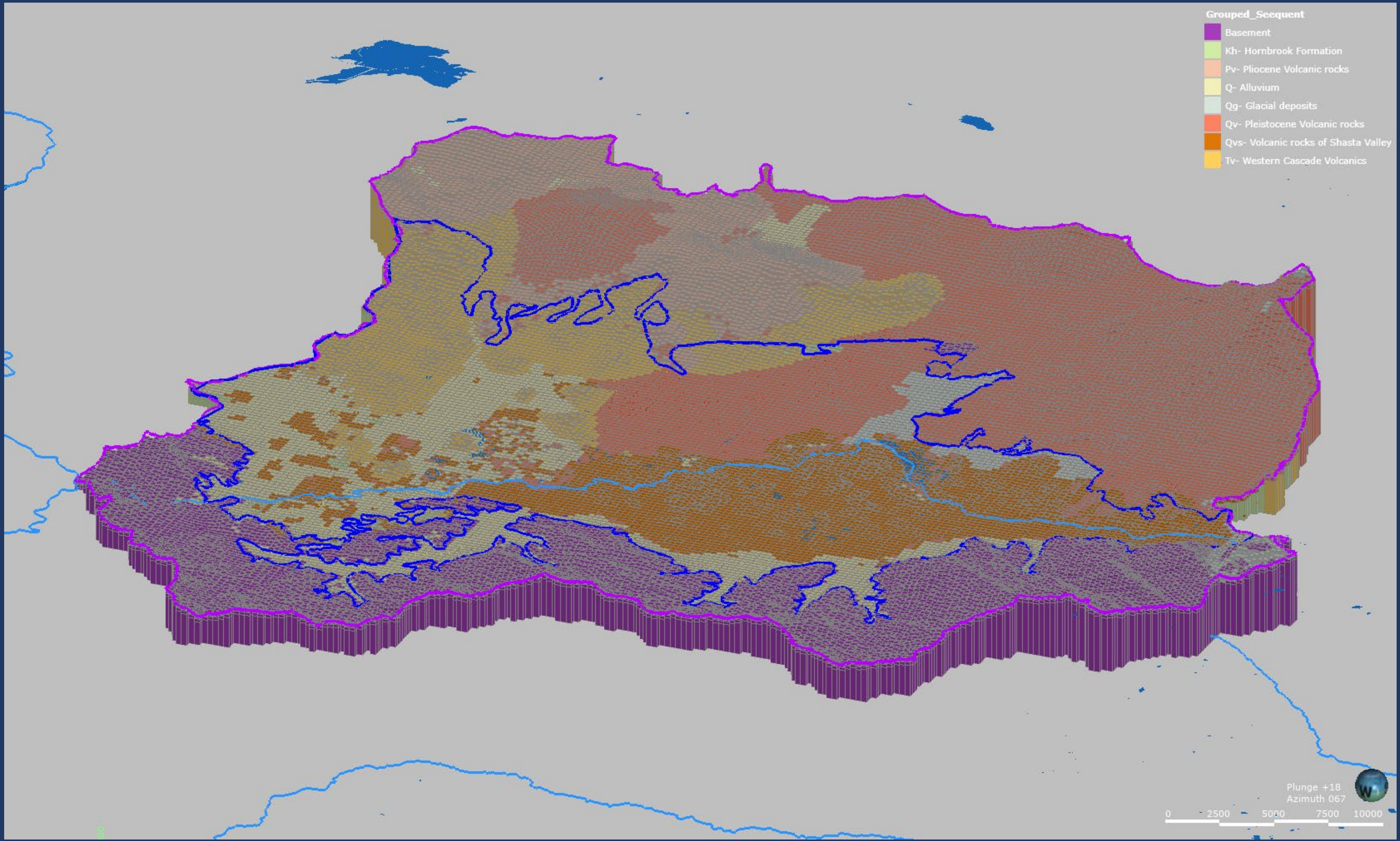


Shasta Valley Groundwater Basin 3-D geological model

Products

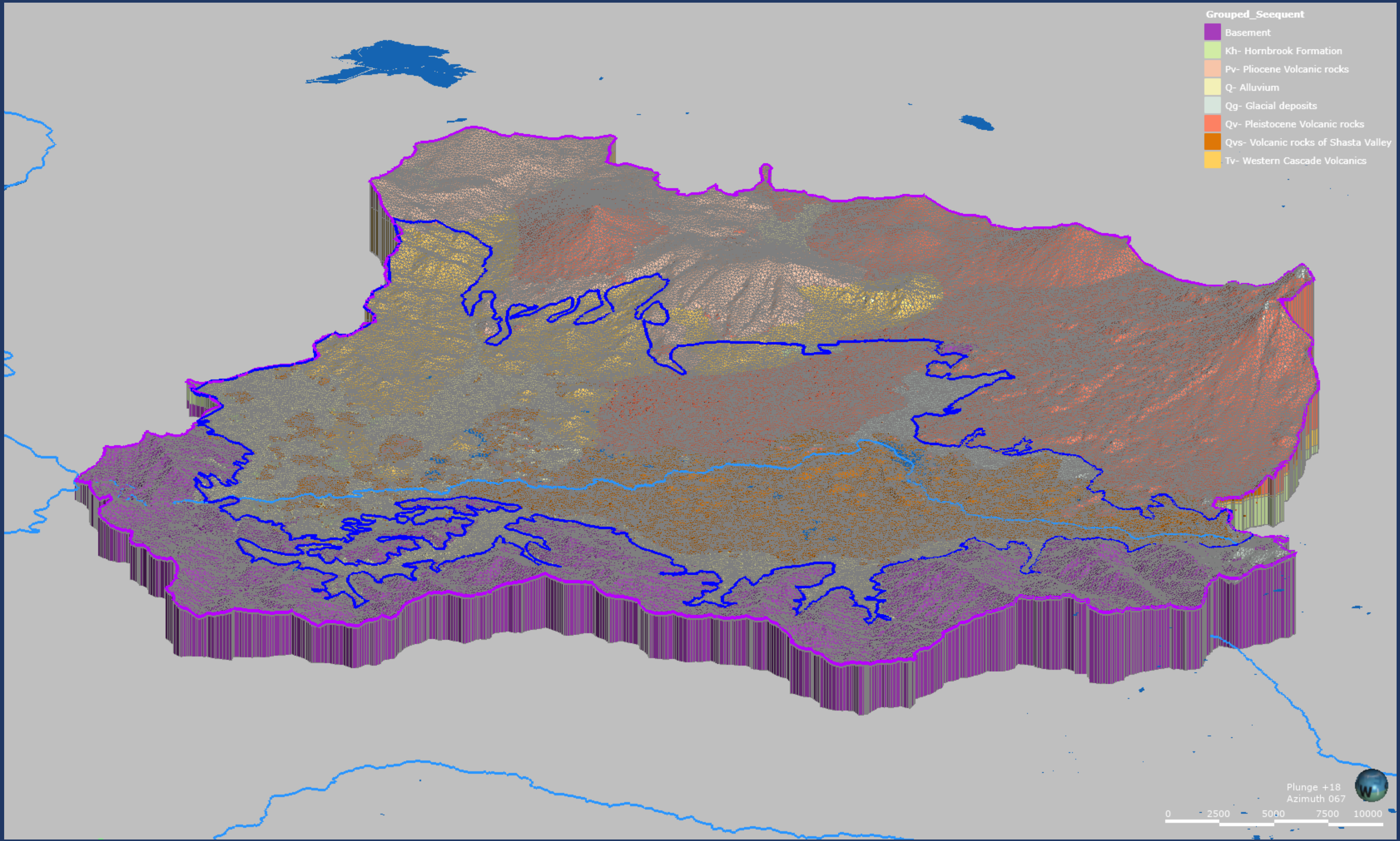
- Cross sections required by SGMA for GSP
- Groundwater modeling grids
  - MODFLOW



Shasta Valley Groundwater Basin 3-D geological model

Products

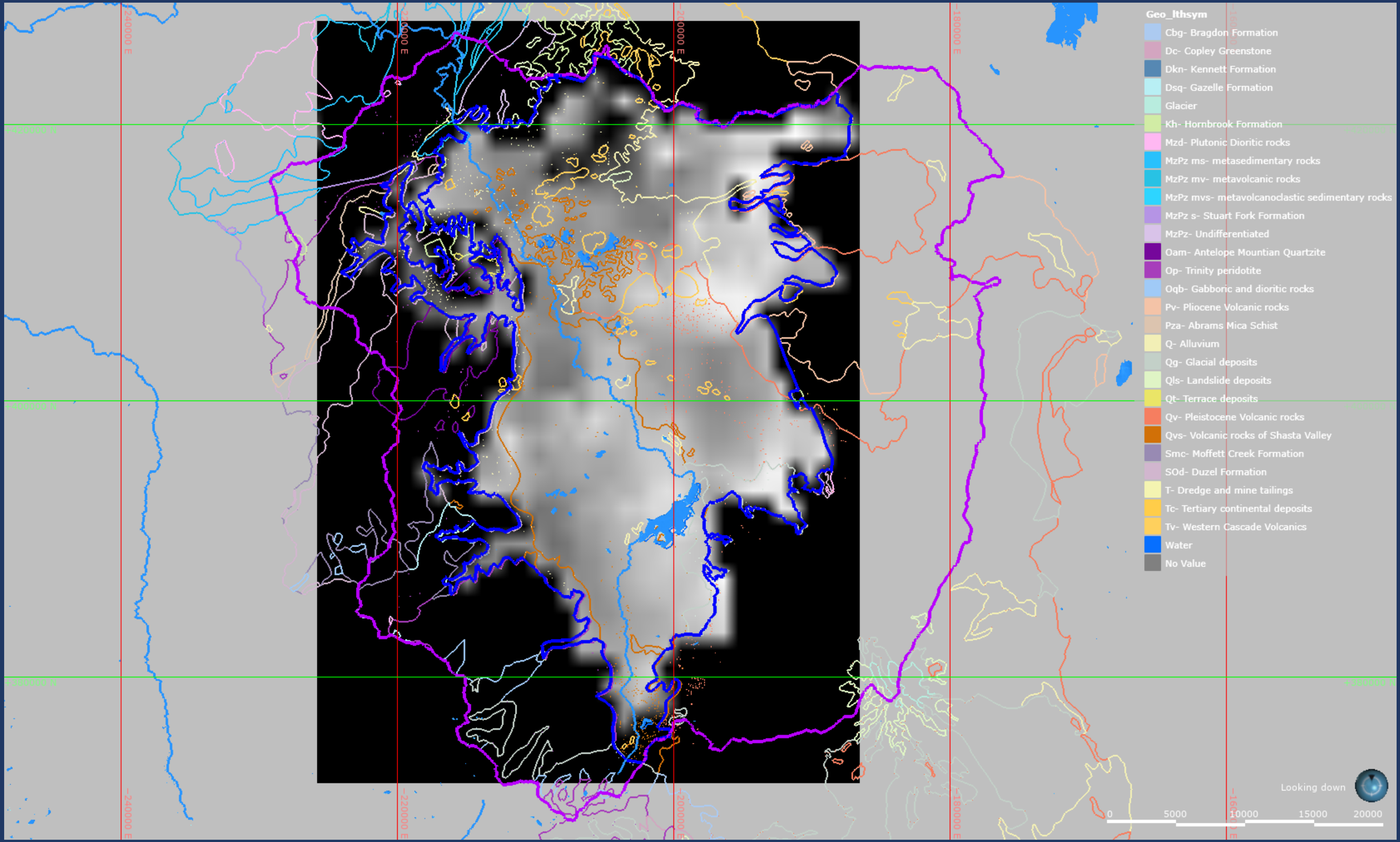
- Cross sections required by SGMA for GSP
- Groundwater modeling grids
  - MODFLOW
  - FEFLOW



Shasta Valley Groundwater Basin 3-D geological model

Products

- Cross sections required by SGMA for GSP
- Groundwater modeling grids
  - MODFLOW
  - FEFLOW
- Comparison with InSAR subsidence data



Shasta Valley Groundwater Basin 3-D geological model

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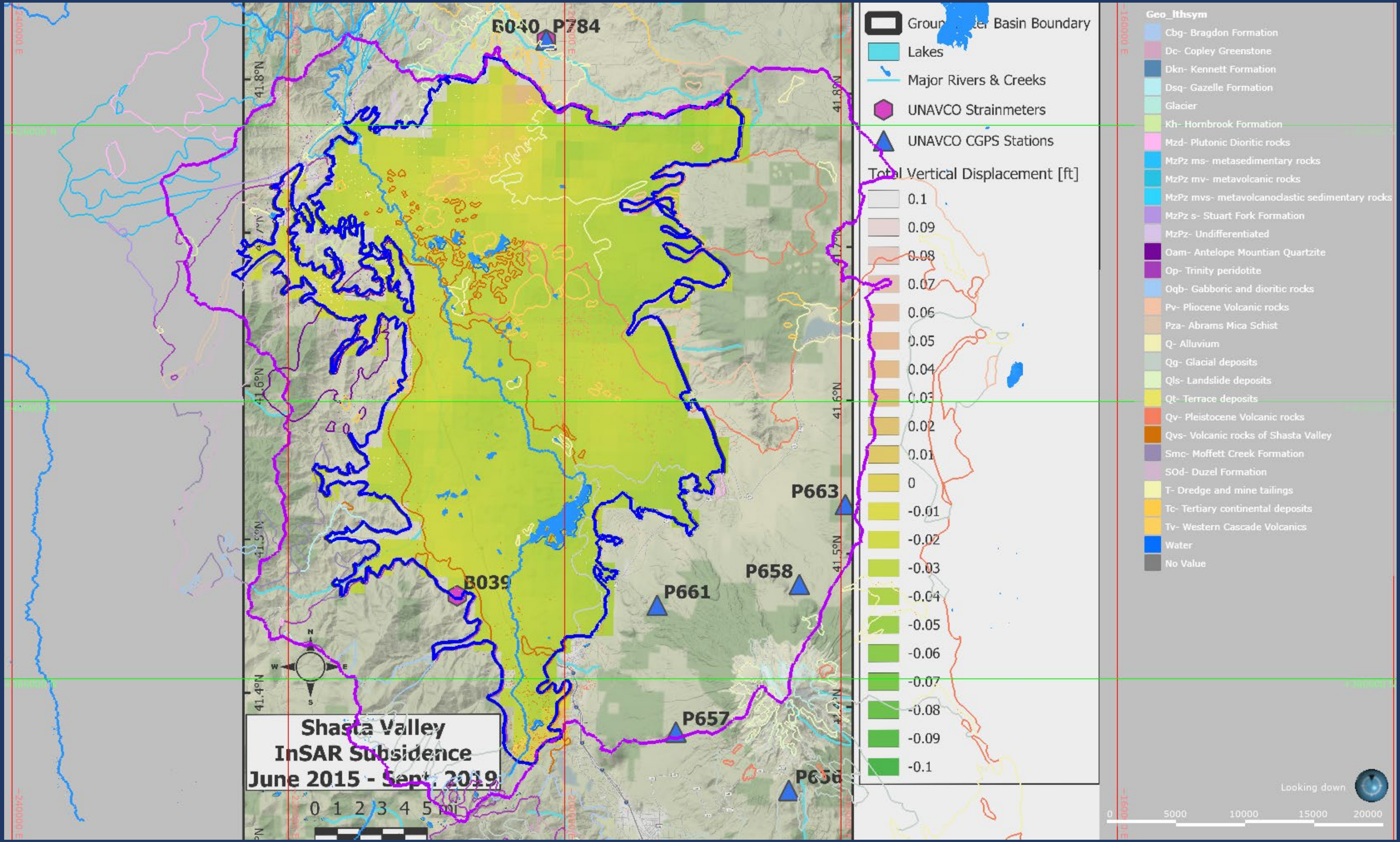
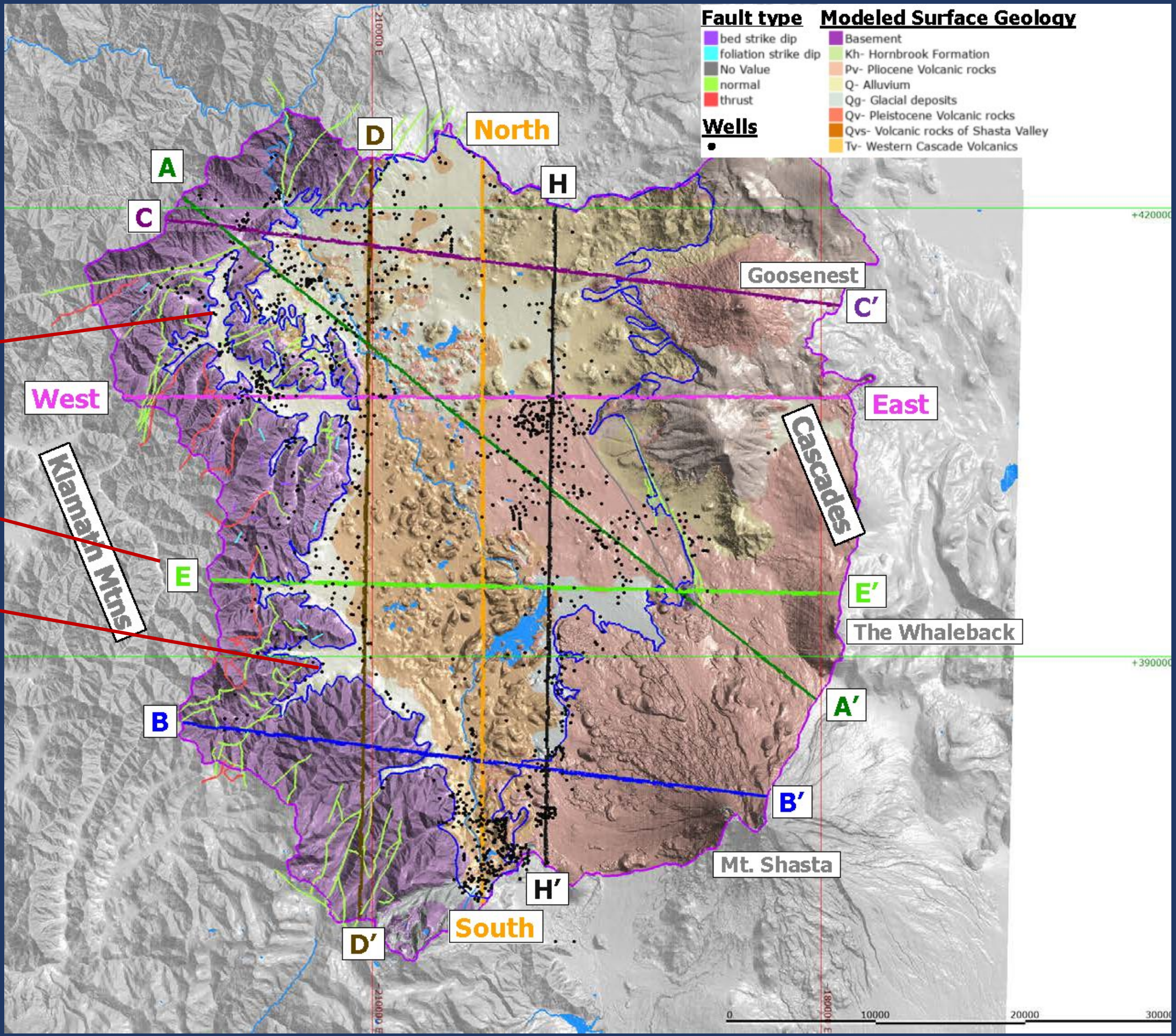


Shasta Valley Groundwater Basin 3-D geological model

Uncertainties

- Uncertainty is generally expected to be greatest in areas furthest from data points, including:
  - WCRs
  - Published x-secs
  - Digitized geologic surface map contacts



Shasta Valley Groundwater Basin 3-D geological model

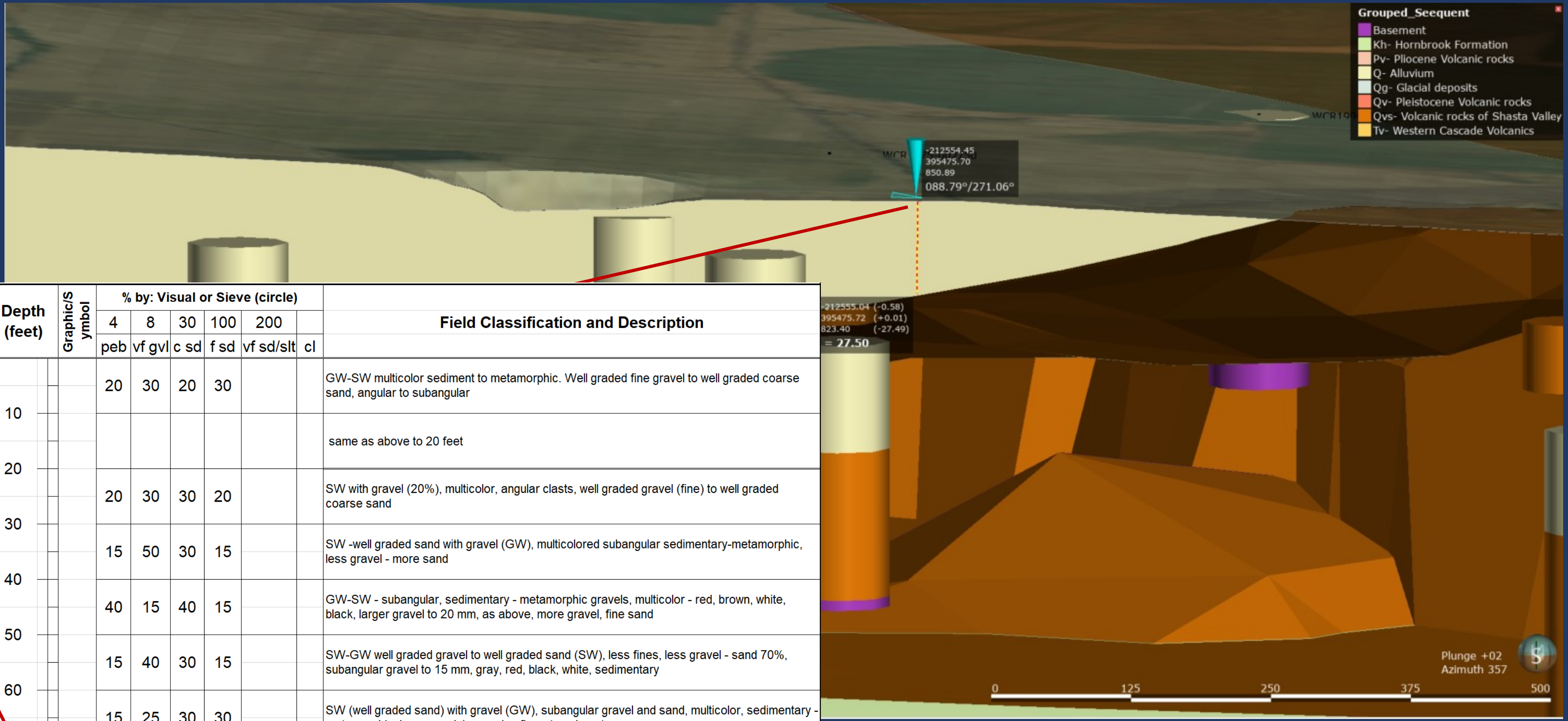
Uncertainties

- DWR TSS monitoring well drilled after model completion
- Qa to Qvs transition modeled at ~90' bgs at proposed well location

Shasta Valley Groundwater Basin 3-D geological model

Uncertainties

- DWR TSS monitoring well drilled after model completion
- Qa to Qvs transition modeled at ~90’ bgs at proposed well location
- Drilling data showed this to be close at ~100’ bgs

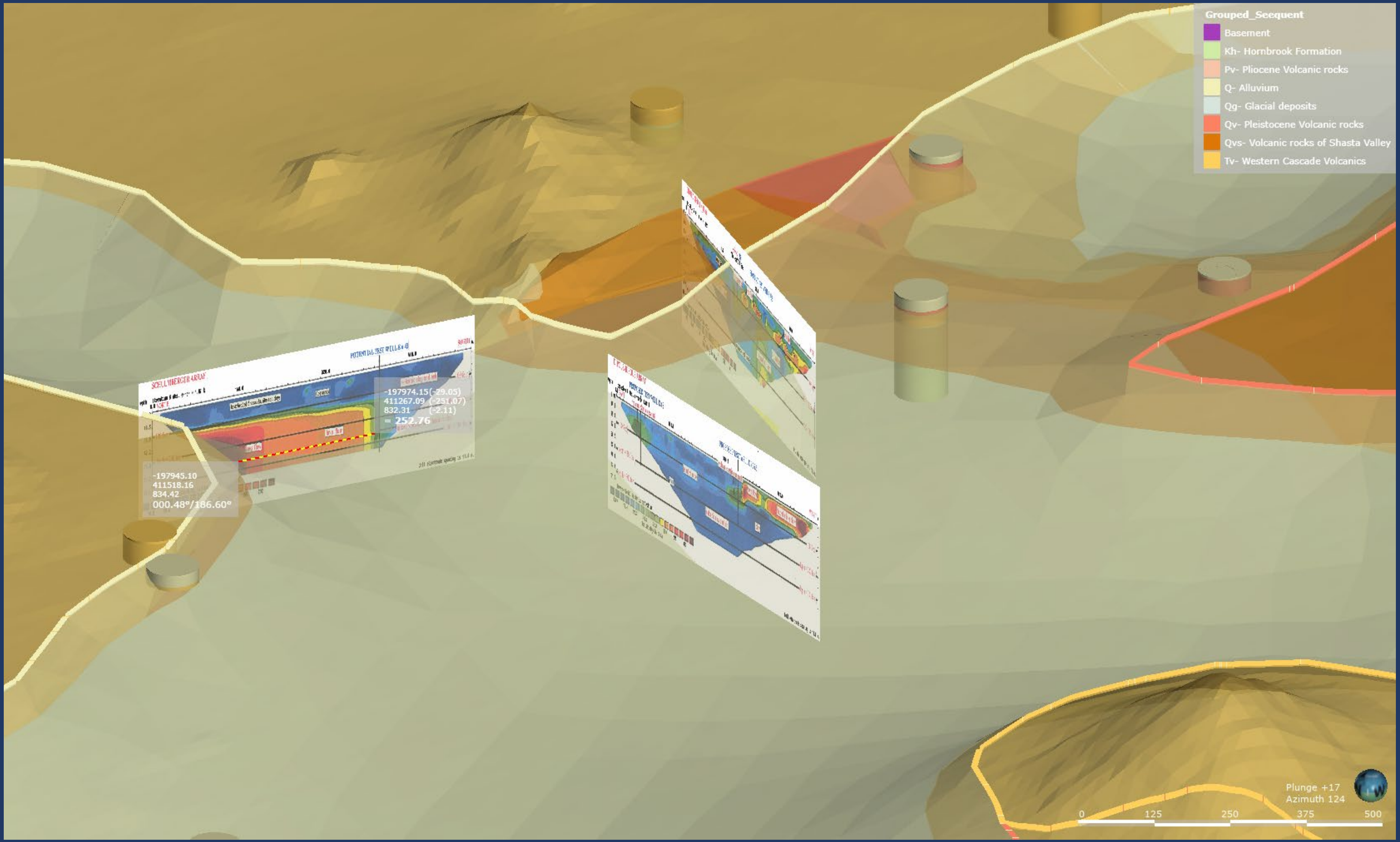


Depth (feet)	Graphic/Symbol	% by: Visual or Sieve (circle) 4 peb	8 vf gvl	30 c sd	100 f sd	200 vf sd/slt	cl	Field Classification and Description
		20	30	20	30			GW-SW multicolor sediment to metamorphic. Well graded fine gravel to well graded coarse sand, angular to subangular
10								same as above to 20 feet
20		20	30	30	20			SW with gravel (20%), multicolor, angular clasts, well graded gravel (fine) to well graded coarse sand
30		15	50	30	15			SW -well graded sand with gravel (GW), multicolored subangular sedimentary-metamorphic, less gravel - more sand
40		40	15	40	15			GW-SW - subangular, sedimentary - metamorphic gravels, multicolor - red, brown, white, black, larger gravel to 20 mm, as above, more gravel, fine sand
50		15	40	30	15			SW-GW well graded gravel to well graded sand (SW), less fines, less gravel - sand 70%, subangular gravel to 15 mm, gray, red, black, white, sedimentary
60		15	25	30	30			SW (well graded sand) with gravel (GW), subangular gravel and sand, multicolor, sedimentary - metamorphic, less gravel, increasing fines (as above)
70		10	35	35	20			SW (with fines) to SM, little gravel, primarily coarse to medium sand, red, gray, white grains, subangular, well graded sand to silty sand, more fines than gravel, gravel same description as above to 15 mm
80		15	30	40	15			SW, coarse to medium sand, as above, brown, gray, red, white, gravel to 1/2 inch
90		15	35	30	20			SW, well graded sand increasing silt content, subangular gravel, GW, multicolor as above, gravel to 1/2 inch
100		5	5	5	85			ML-CL, gravelly, sandy, silty clay, medium plasticity, light gray, can see grains

Shasta Valley Groundwater Basin 3-D geological model

Uncertainties

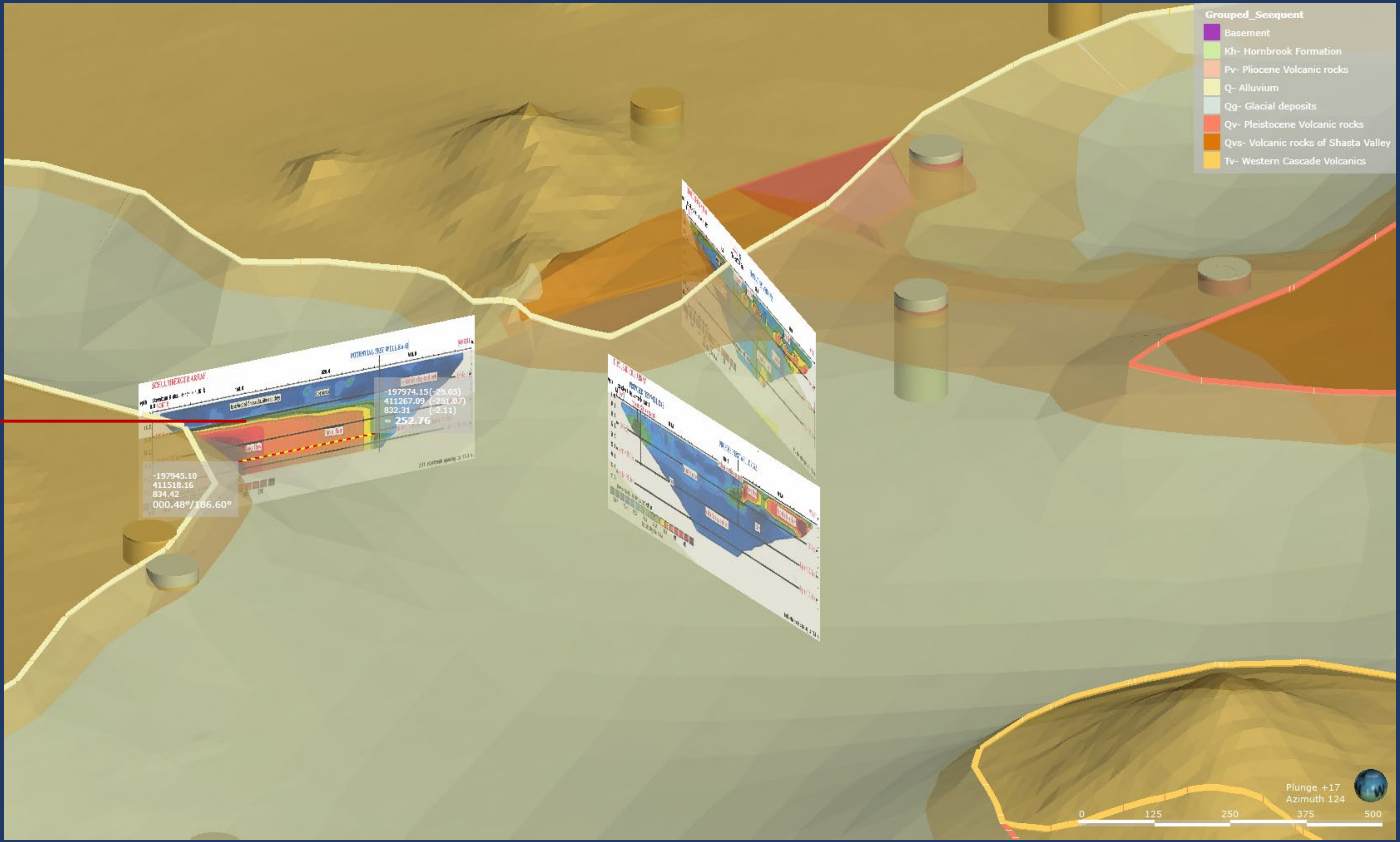
- Old geophysical survey results for farm-property scale provided after modeling completed



Shasta Valley Groundwater Basin 3-D geological model

Uncertainties

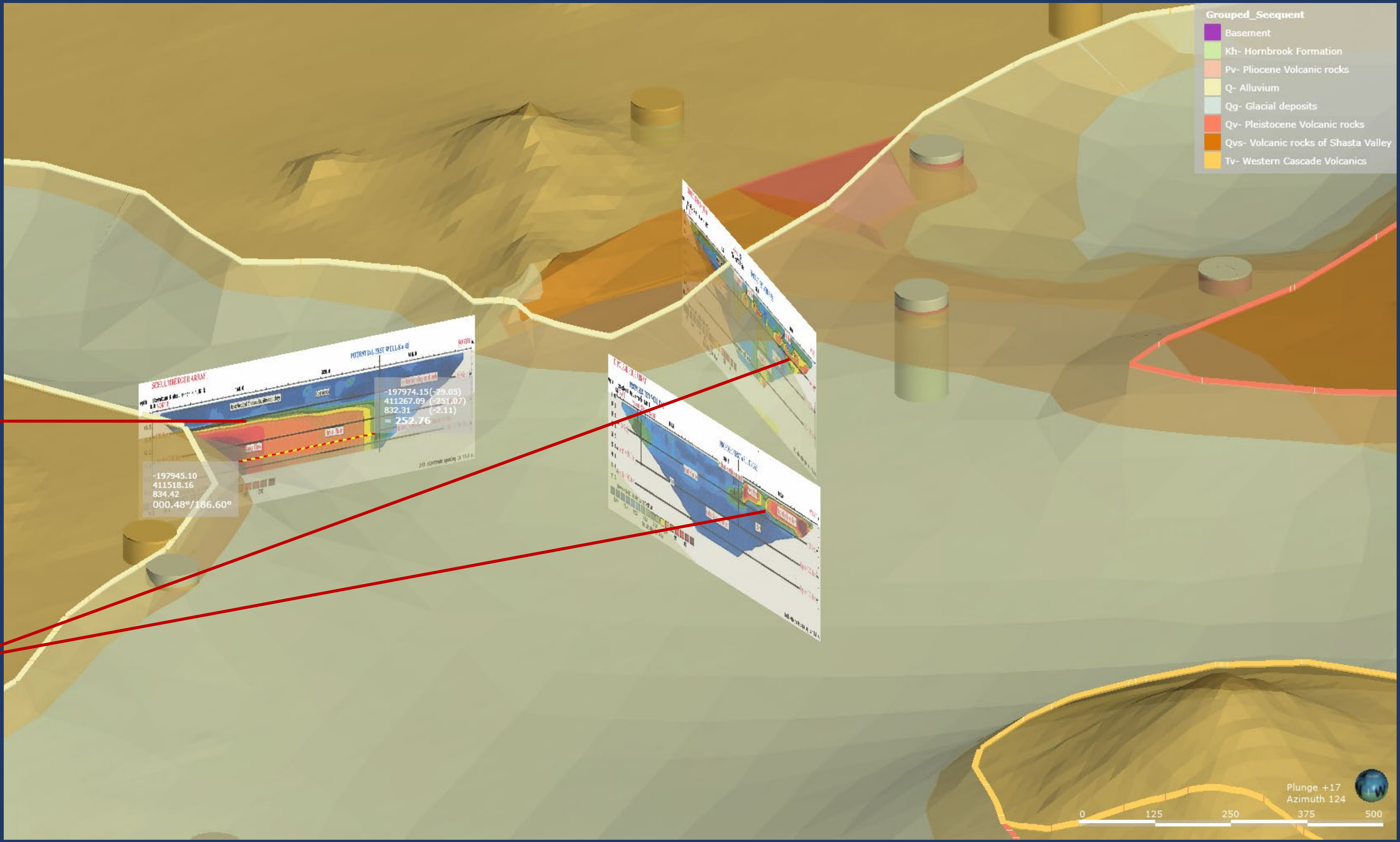
- Old geophysical survey results for farm-property scale provided after modeling completed
- Some larger modeled volcanic structures are close to geophysical feature geometries



Shasta Valley Groundwater Basin 3-D geological model

Uncertainties

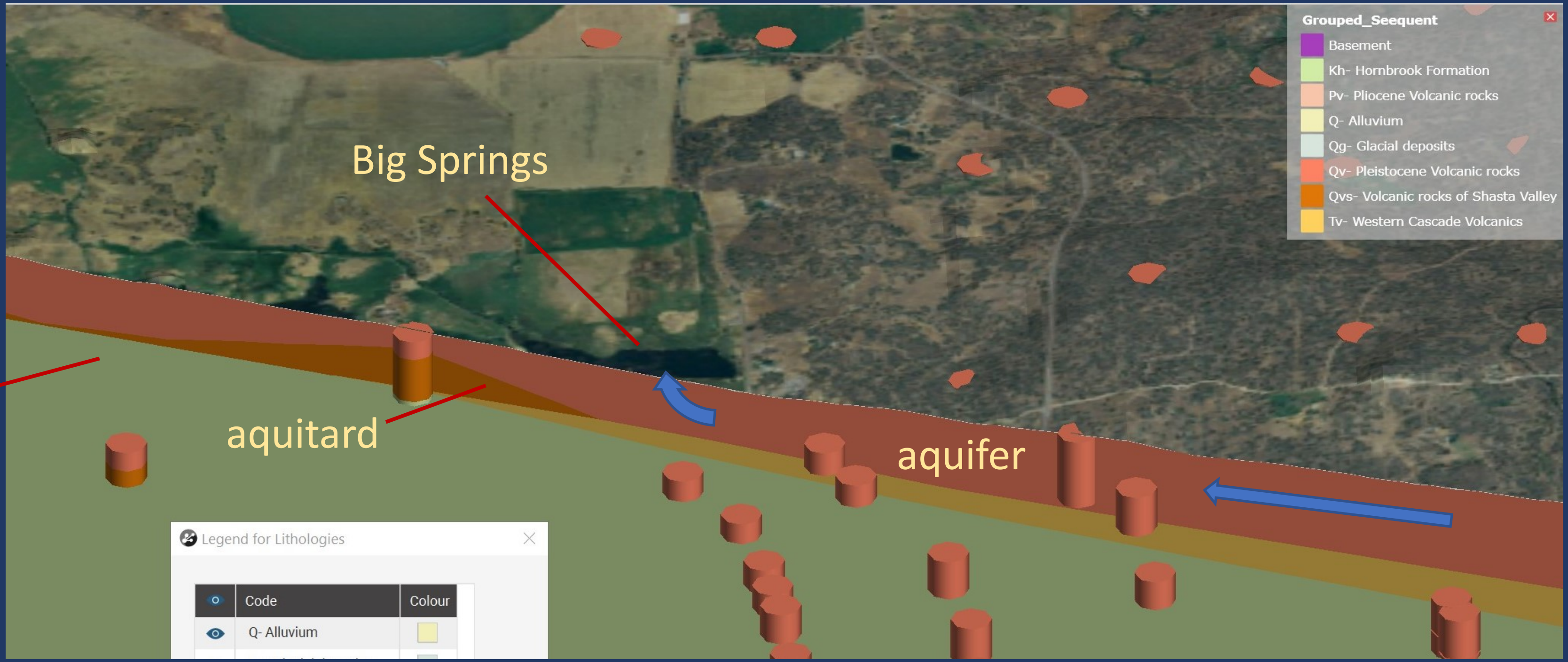
- Old geophysical survey results for farm-property scale provided after modeling completed
- Some larger modeled volcanic structures are close to geophysical feature geometries
- Small-scale volcanic features and contacts are not able to be accurately modeled



Shasta Valley Groundwater Basin 3-D geological model

Limitations/Utility

- Geological model is useful for using for groundwater investigations at basin- to field-scale (larger Ag fields)
- May be useful as a starting point for managed recharge operations and integrated surface water/groundwater studies



Shasta Valley Groundwater Basin 3-D geological model

Limitations/Utility

- Geological model is useful for using for groundwater investigations at basin- to field-scale (larger Ag fields)
- May be useful as a starting point for managed recharge operations and integrated surface water/groundwater studies
- 3-D WCR database alone is a major effort for future management & planning purposes