IMAGE: *courtesy of Newmont Mining Corp.*

MINING AND EXPLORATION HYDROLOGY

121st Annual Meeting

American Exploration and Mining Association

November 30 – December 4, 2015

Spokane Convention Center, Spokane, WA USA

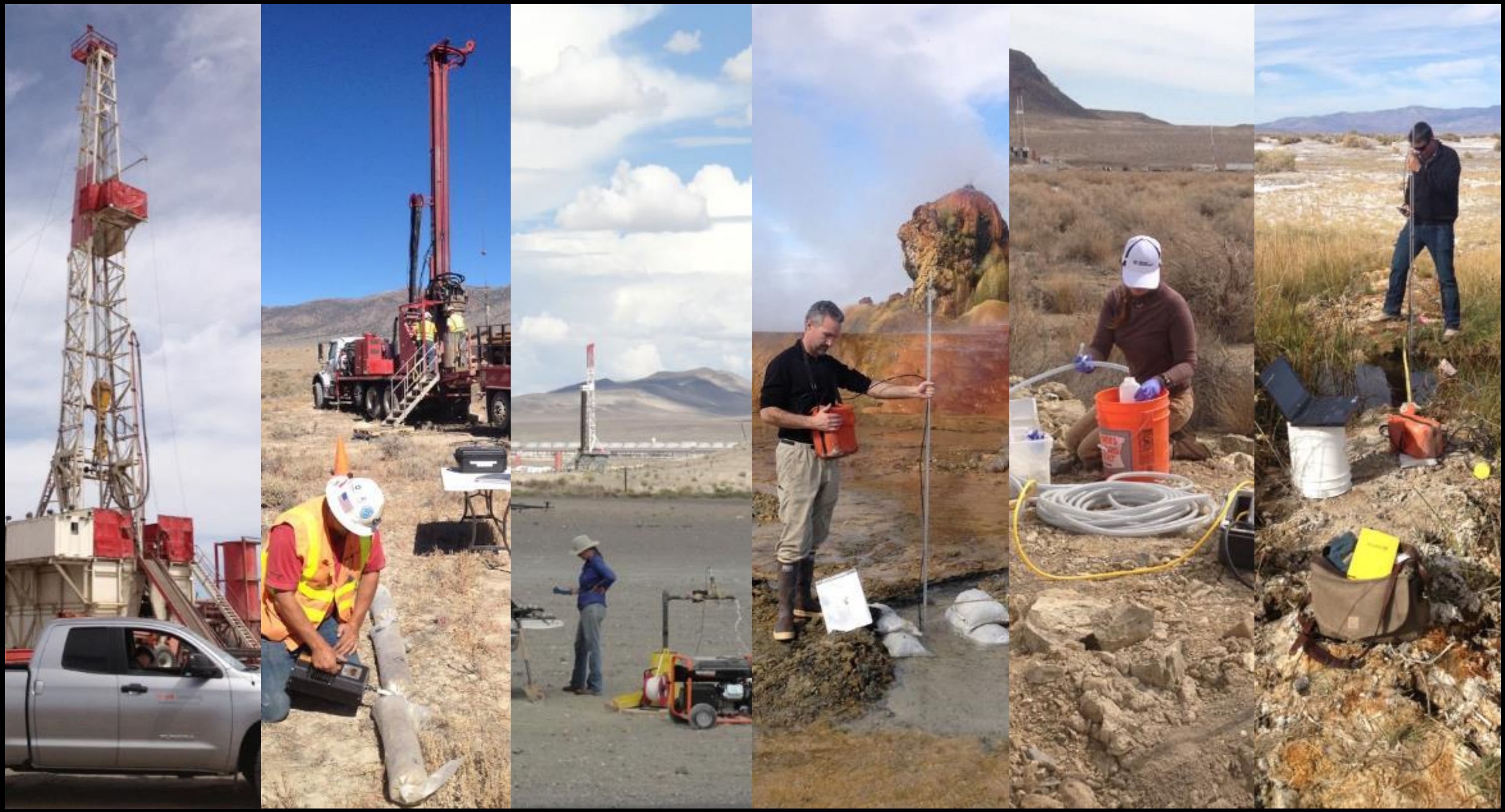
Mike Hardy, PE, PG, WRS

LUMOS & ASSOCIATES

Ron Parratt, Jr

Schlumberger WATER SERVICES

INTEGRATED APPROACH TO WATER RESOURCE CHARACTERIZATION FOR MINERAL EXPLORATION PROJECTS



Presented by:
Tim Donahoe, PLS, WRS, CEM
Senior Consultant

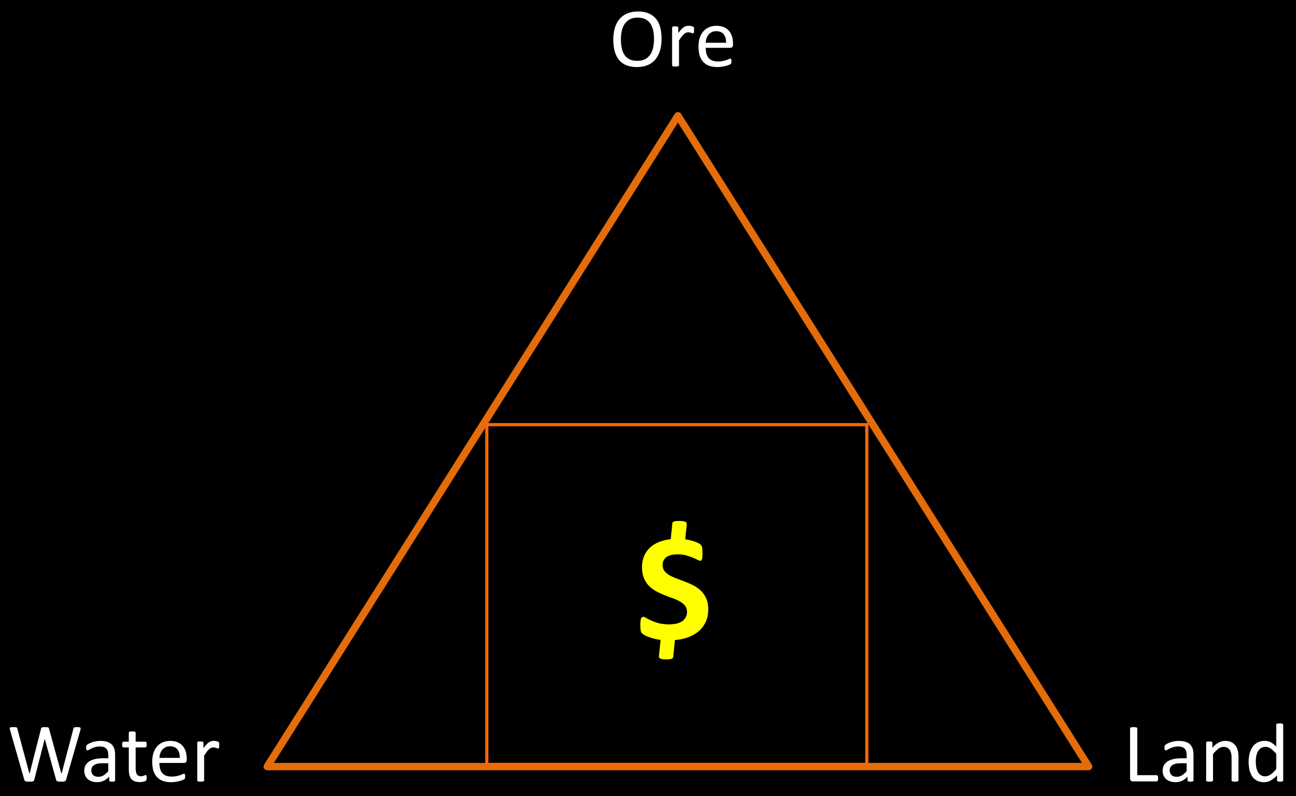
srk consulting

THE MINING SEQUENCE

Early exploration...

Advanced exploration…

Essential Natural Resources for a Mine



Mine Development

- **Increasingly complex process**
  - Changing federal, state and local environmental regulations
- **Mine development/operation projects carry potential long-term environmental liabilities**
- **Every aspect of the mine development process must be considered in tandem**
- **Plan and design for closure**
  - Requires comprehensive characterization and <u>representative</u> data sets
    - Hydrological characterization
    - Geochemical characterization
    - Geotechnical characterization

WATER
"It's the ~~economy~~ stupid!"

Characterization/Baseline Studies for NEPA

- Jurisdictional Determinations for Waters of the U.S.
- Noxious Weeds, Invasive and Non-Native Species
- Cultural and Native American Resources/Values
- Surface Water and Groundwater Resources
- Minerals and Paleontological Resources
- Threatened and Endangered Species
- Social and Economic Values
- Wastes, Hazardous or Solid
- Human Health and Safety
- Land Use Authorization
- Special Status Species
- Grazing Management
- Climate/meteorology
- Visual Resources
- Migratory Birds
- Wilderness
- Air Quality
- Recreation
- Vegetation
- Soils

Long-lead items

Water Resource Characterization

Past experience has shown that:

from Nevada BLM, 2008 – Water Resource Data and Analysis Guide for Mining Activities; IM-NV-2008-032

- The development of water resource data is an extensive, costly and <u>most</u> time consuming endeavor
- To optimize the water resource characterization program, mining companies should be advised to collect characterization and baseline water resources data during exploration activities
- Data collection methods must be accepted/defensible with BLM, EPA and NDEP

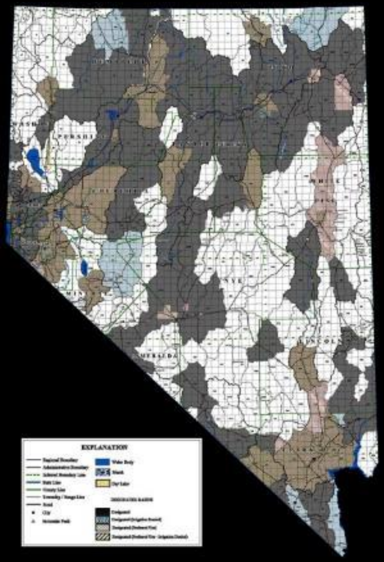
* Data collection methods and water resource monitoring, management and mitigation (3M) plans must also be acceptable/defensible with NDWR, local government, and stakeholders per NRS 533.353

Program Design

- **Designed to *piggy-back* with advanced exploration stage of mine development process**
  - Reduce costs associated with hydrogeological, geochemical and geotechnical characterization programs
  - Streamline the planning, design and permitting phases of the mine development process
- **Must follow current federal, state and local statutes, codes, regulations, ordinances and policies**
- **Utilize accepted/defensible data collection, data management and analytical methods**
  - Only collect data sets that are necessary to support mine development (exploration, planning, design, permitting) mining operations, and mine closure
  - Optimize collection and quality of data required for permitting and compliance
- **Utilize state of the art software to process representative data sets**

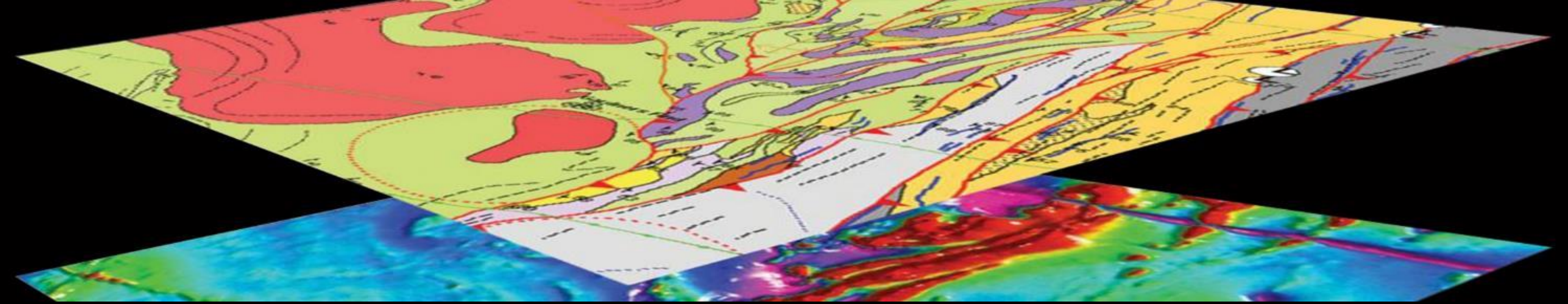
WATER RIGHTS: *where hydrologic science meets water law*

- Mine water demand vs. availability
- Dewatering (consumptive vs. non-consumptive)



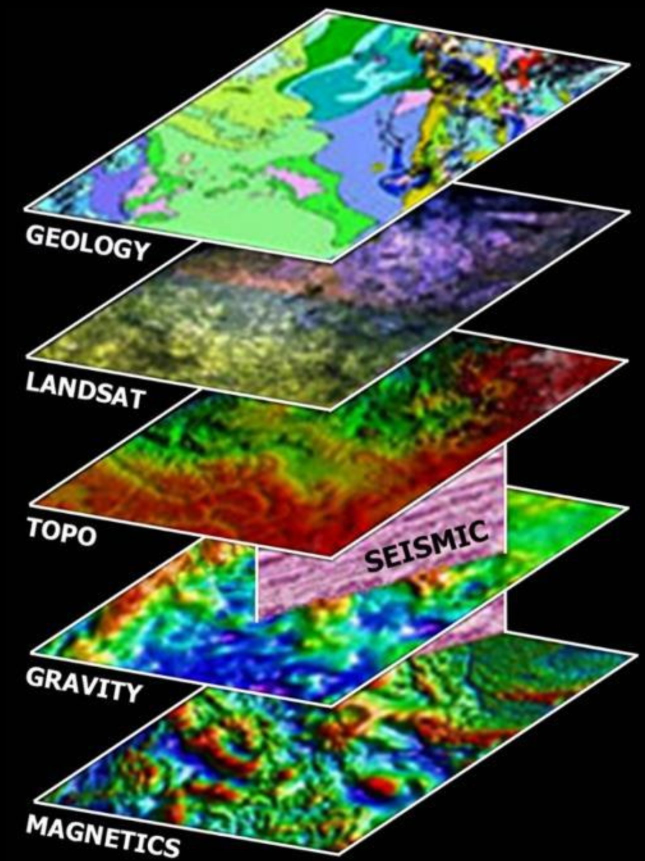
NDWR, 2015

- Unappropriated water available?
  - Hydrographic Area (Basin) status
  - Perennial yield vs. committed water rights
  - Basin study vs. purchase/lease of existing rights
  - Water rights database
  - Pumpage inventories
  - Crop inventories



BASIN-SCALE CHARACTERIZATION

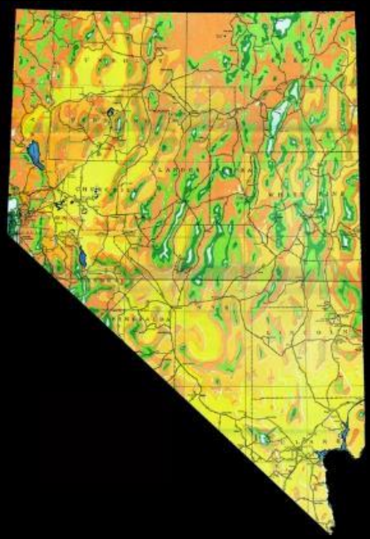
- Climate
- Land cover
  - LandSAT
- Geology
  - Geophysics
- Hydrology
- Hydrogeology



Precipitation

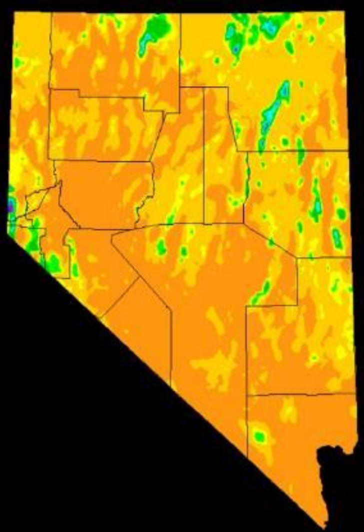
- Models are sensitive to simulated precipitation distribution (spatial and temporal)
  - Multiple data sets and robust period of record often necessary

The Hardman Map



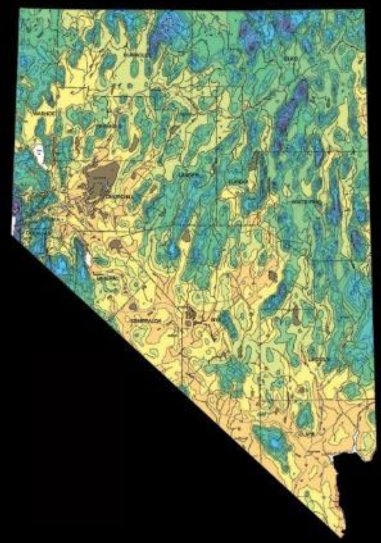
Hardman, 1965

PRISM



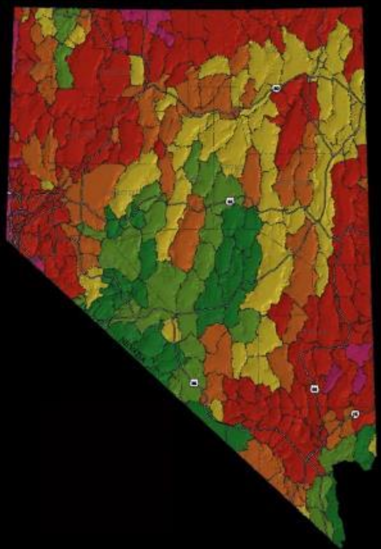
Daly, 1997

PRISM



Prism Climate Group, 1998

RPD: PRISM - Hardman



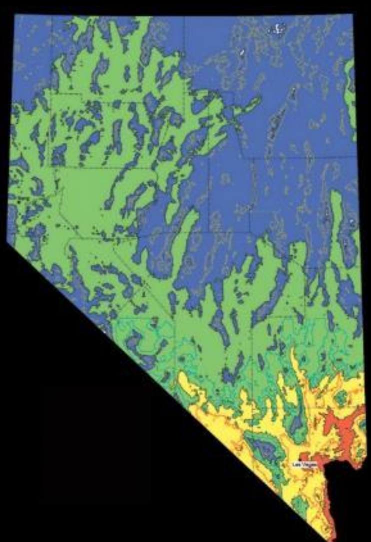
Jeton et al., 2005

http://www.gettyimages.com/detail/photo/desiccation-cracks-on-alien-landscape-high-res-stock-photography/135623034

Evaporation/Evapotranspiration (ET)

- Models are sensitive to simulated ET distribution (spatial and temporal)
  - Multiple data sets and robust period of record often necessary

Potential ET

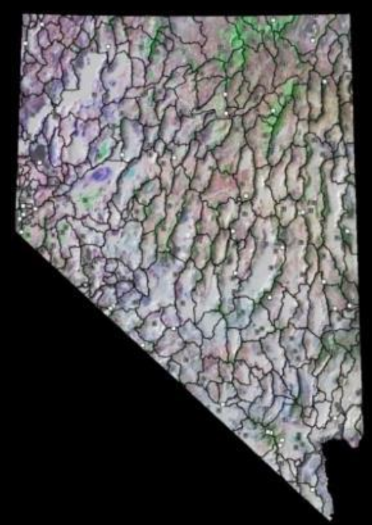


Shevenell, 1996

NIWR

Huntington, 2010

Station Locations

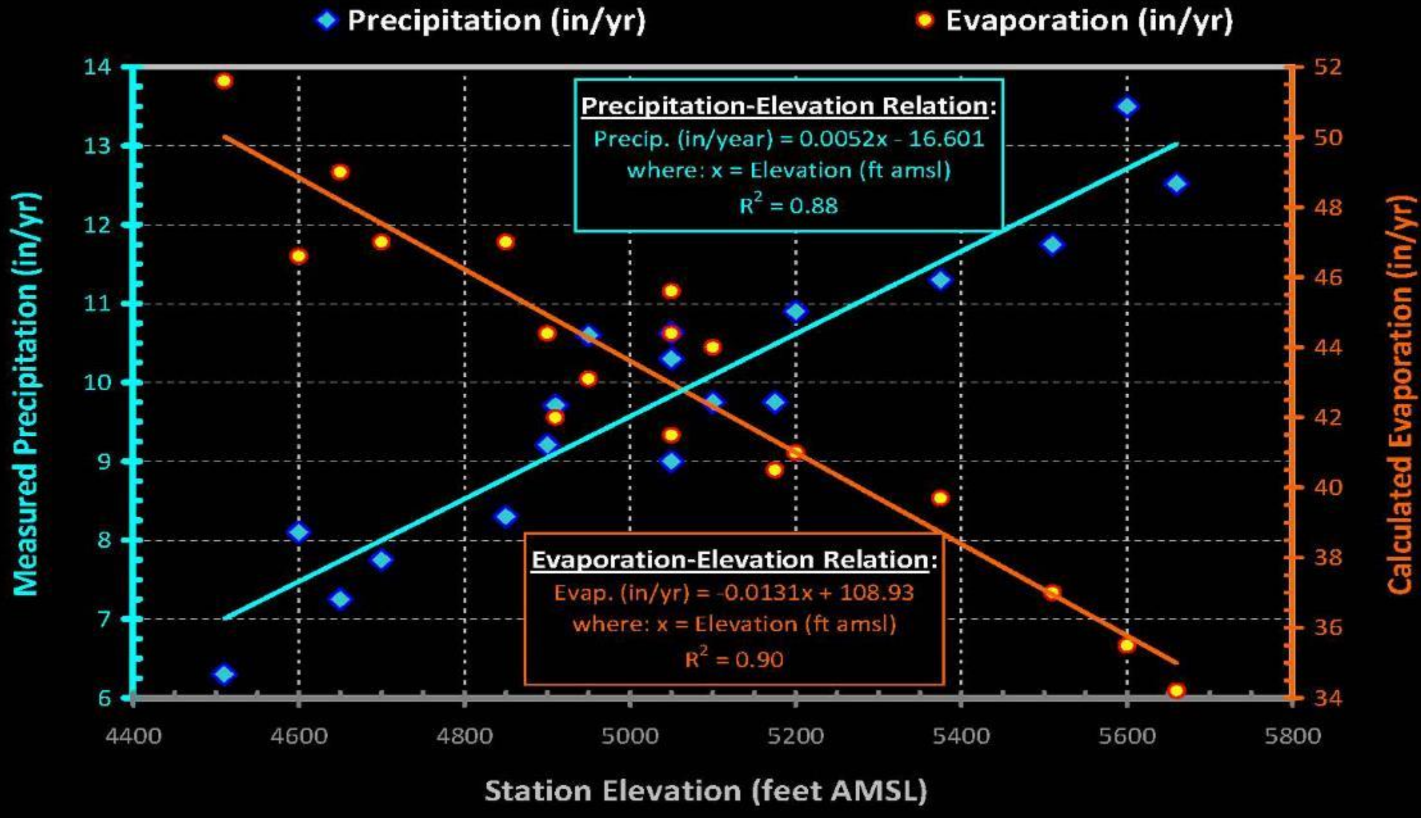


Huntington, 2010

https://commons.wikimedia.org/wiki/File:Weather_station_on_Mount_Vesuvius_(2437693238).jpg

Precipitation and Evaporation

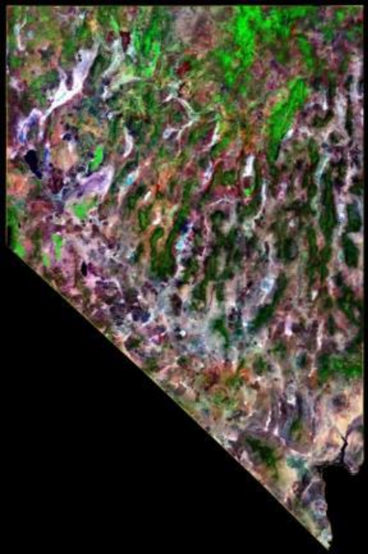
- Statistical relationships in terms of elevation



Land Cover

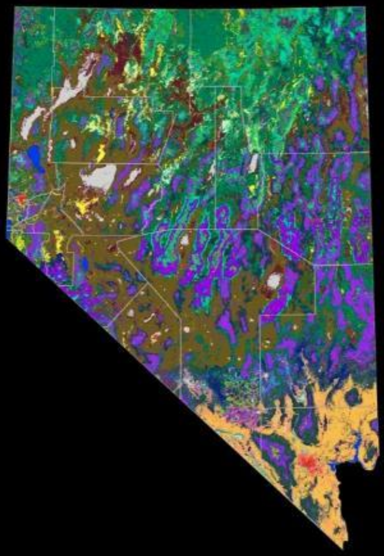
- Satellite imagery – thematic mapping
- Aerial imagery – color infrared (CIR)

Landsat TM



Landsat TM, 2005

Land Cover



SWReGAP, 2008

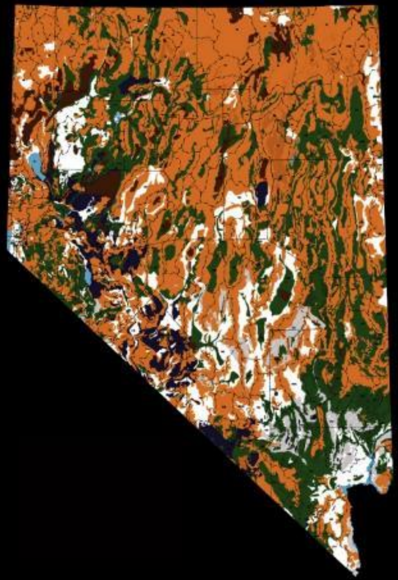
Patua Spring Complex

USDA NAIP, 2013

Soil/Sediment

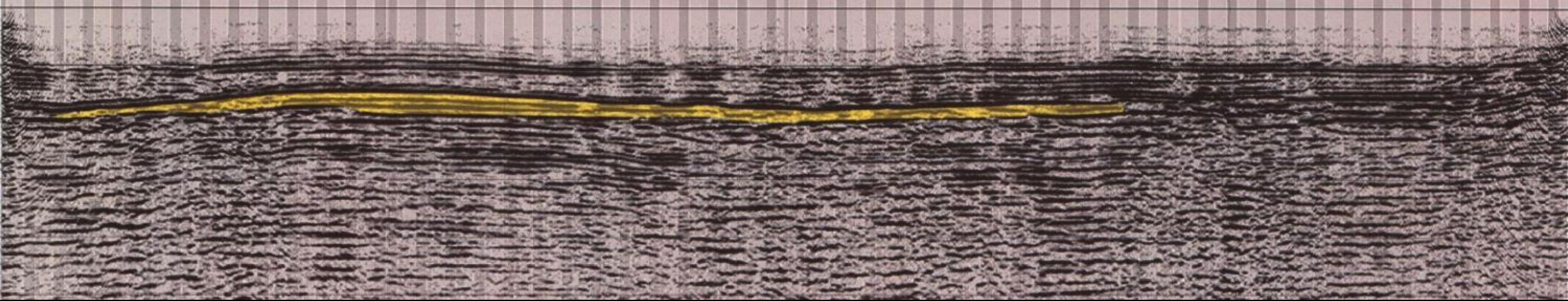
- Permeability
- Vadose zone hydrology / soil moisture balance

Soil Permeability



Maurer et al., 2004

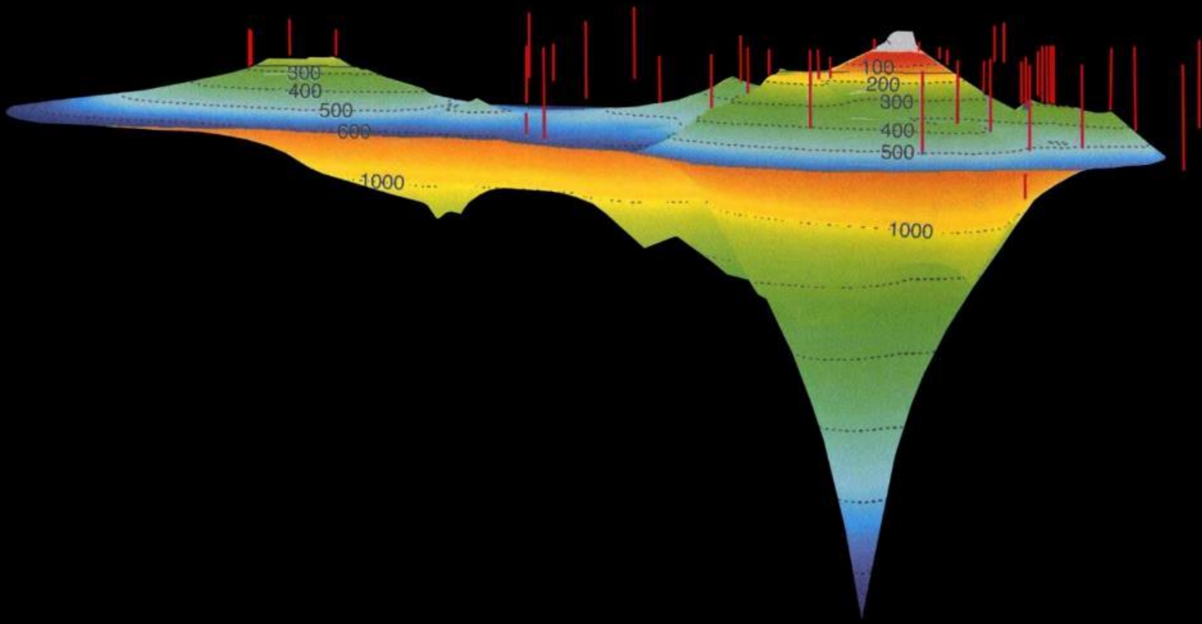
Double Ring Infiltrometer



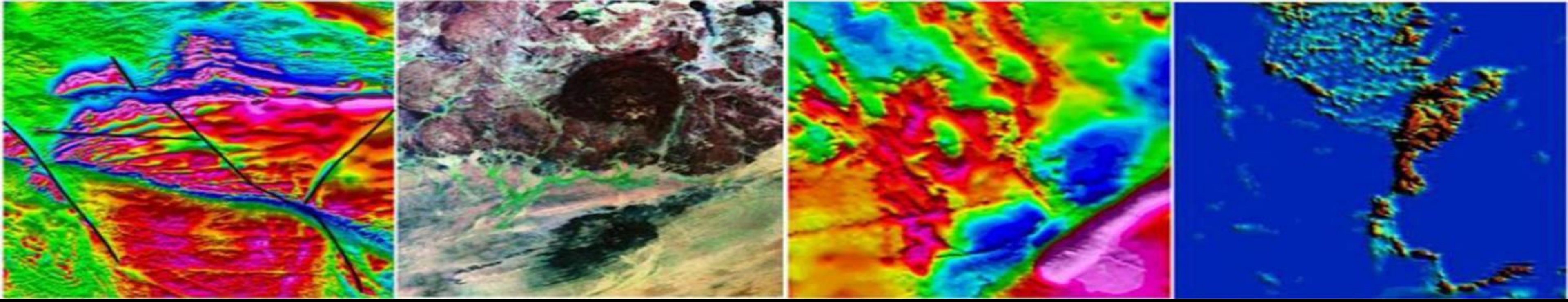
Maurer and Welch, 2001

Seismic Surveys

- Passive, low impact, non-invasive
- Based on material densities and gravitational effects

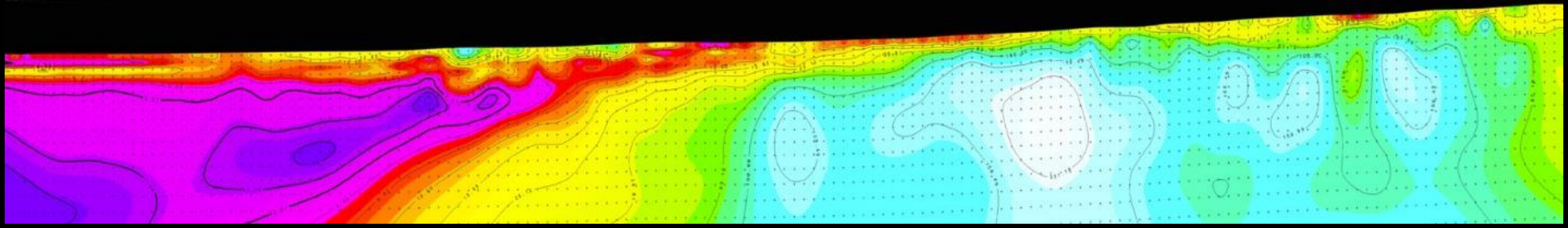


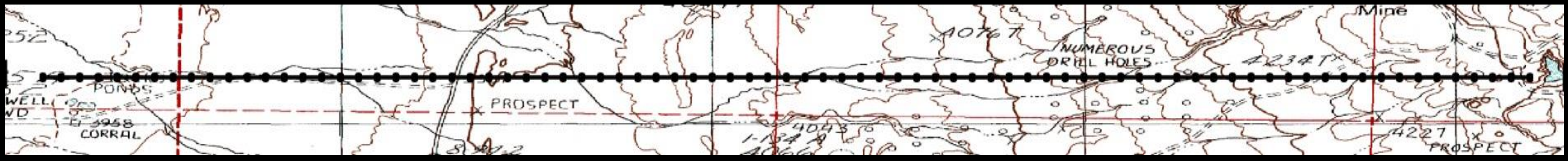
Modified from Maurer and Welch, 2001

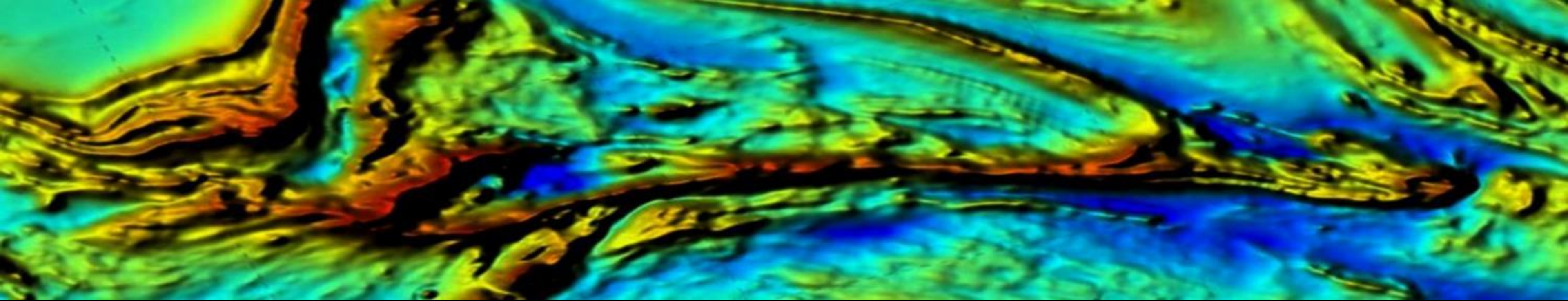


CSEM/CSAMT Surveys

- CSEM (Controlled-source Electromagnetics)
- CSAMT (Controlled-source Audio-Frequency Magnetotellurics)
- Data utilized to define geologic structures, lithology, water table trends and fluid salinity



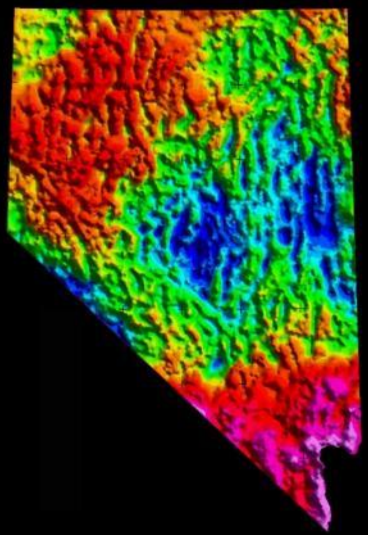




Gravity and Magnetic Surveys

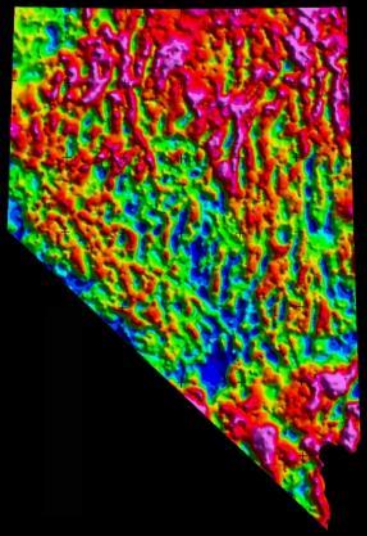
- Data utilized to delineate subsurface geology, magnetic rocks, sedimentary basin depth, basement topography, and buried faults or contacts that can affect fluid flow

Bouguer Gravity Map



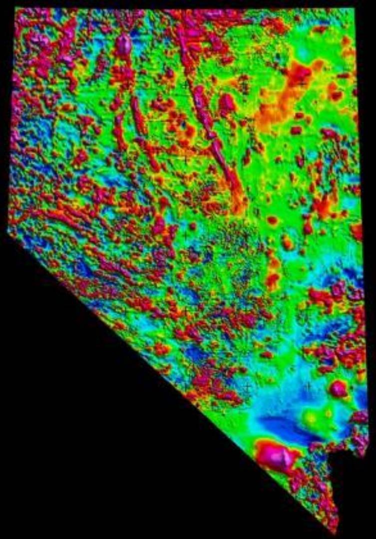
Kucks, et al., 2006

Isostatic Gravity Map



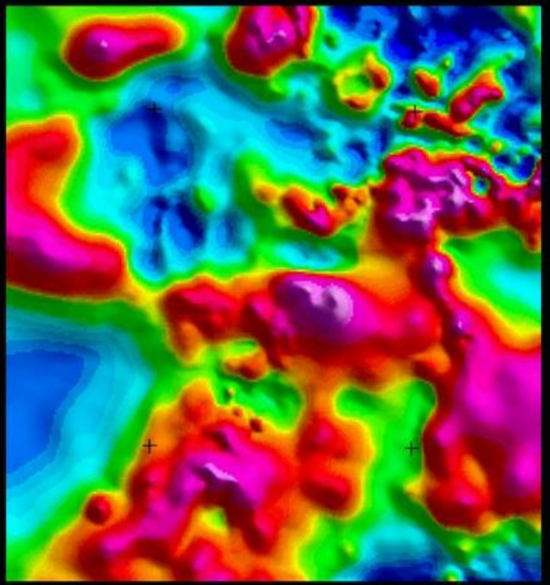
Kucks, et al., 2006

Magnetic Anomaly Map



Kucks, et al., 2006

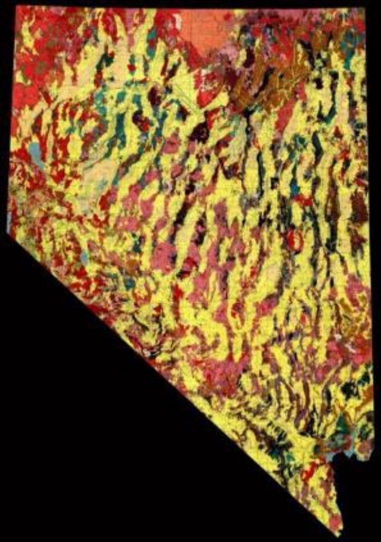
Comstock Magnetic Anomaly Map



Geology

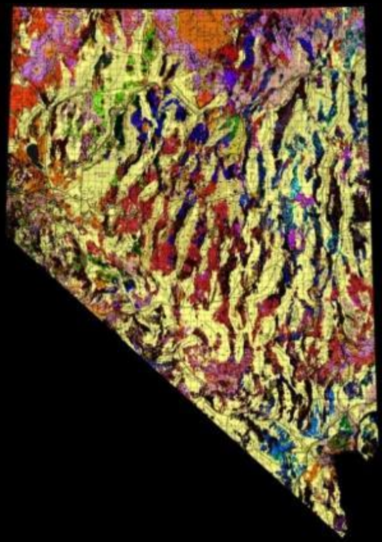
- Geology
- Hydrogeology

Geologic Map



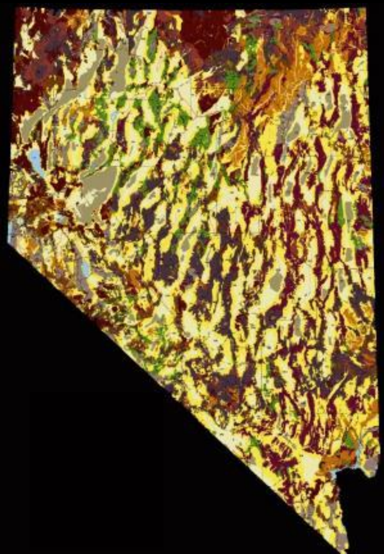
Carlson, 1978

Geologic Terrane Map

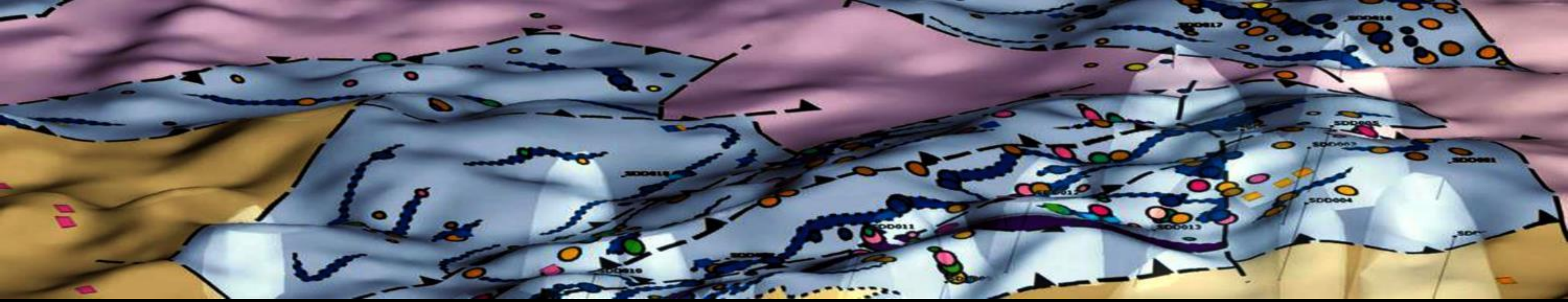


Crafford, 2010

Hydrogeologic Unit Map

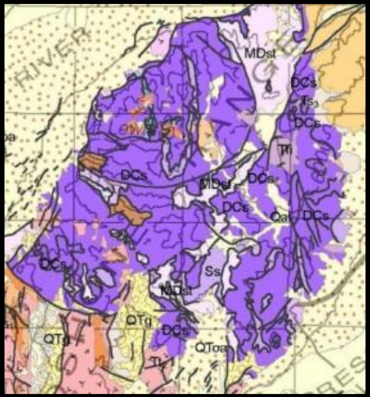


Maurer et al., 2004

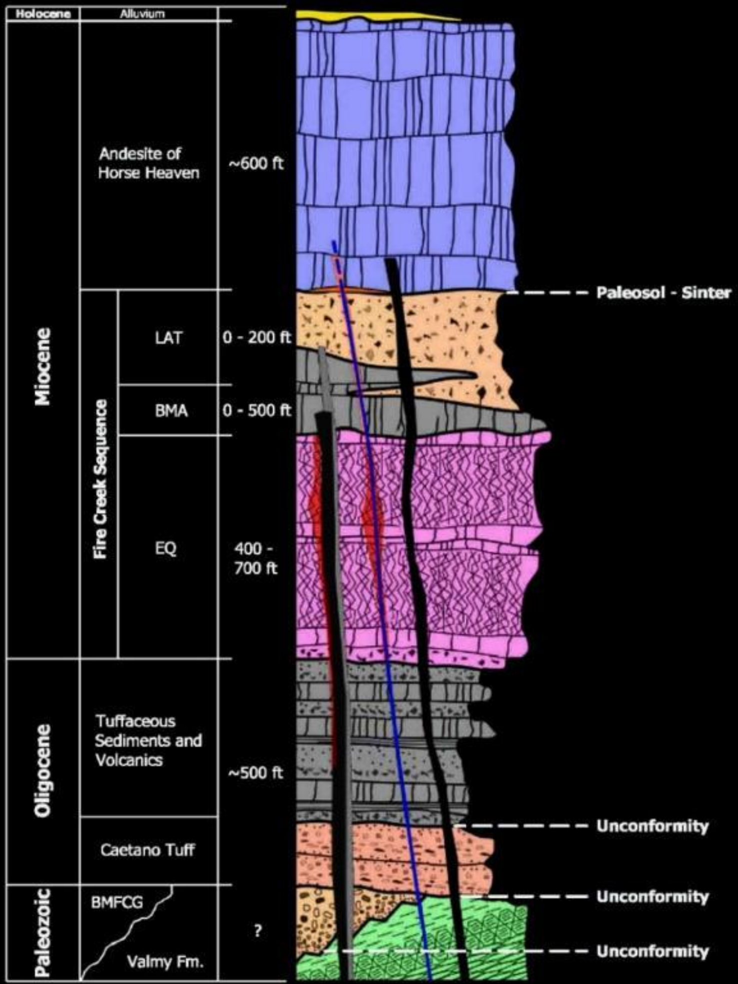


Geology

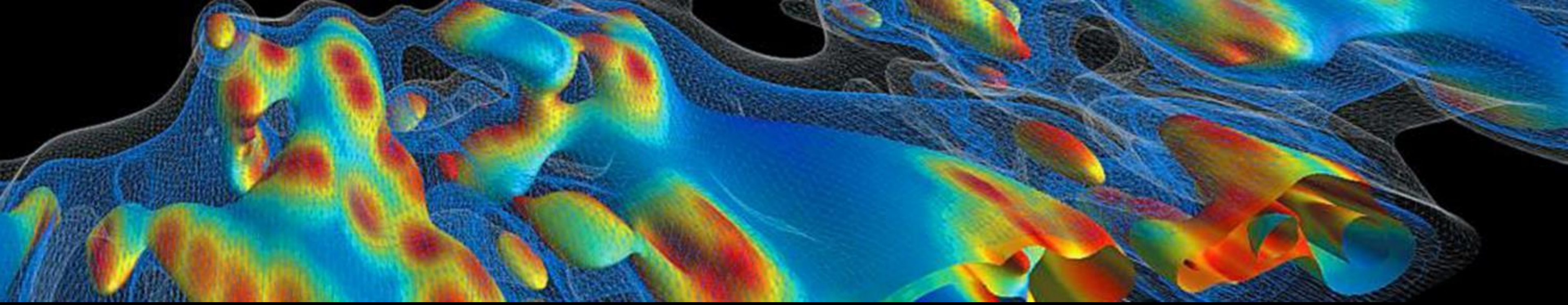
- Site-specific
- Stratigraphic correlation
- Structural controls
  - Mineralization
  - Groundwater flow



Crafford, 2010

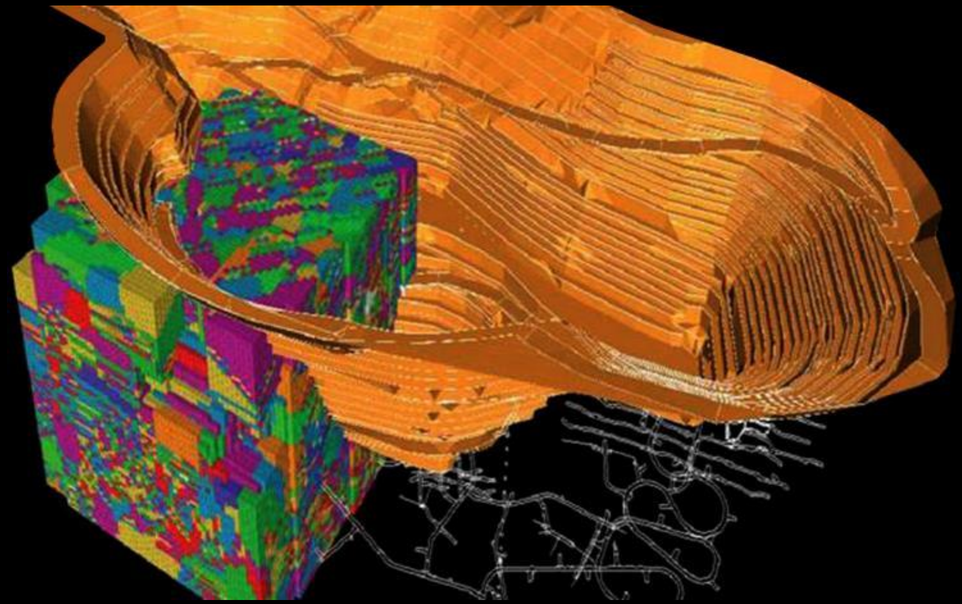


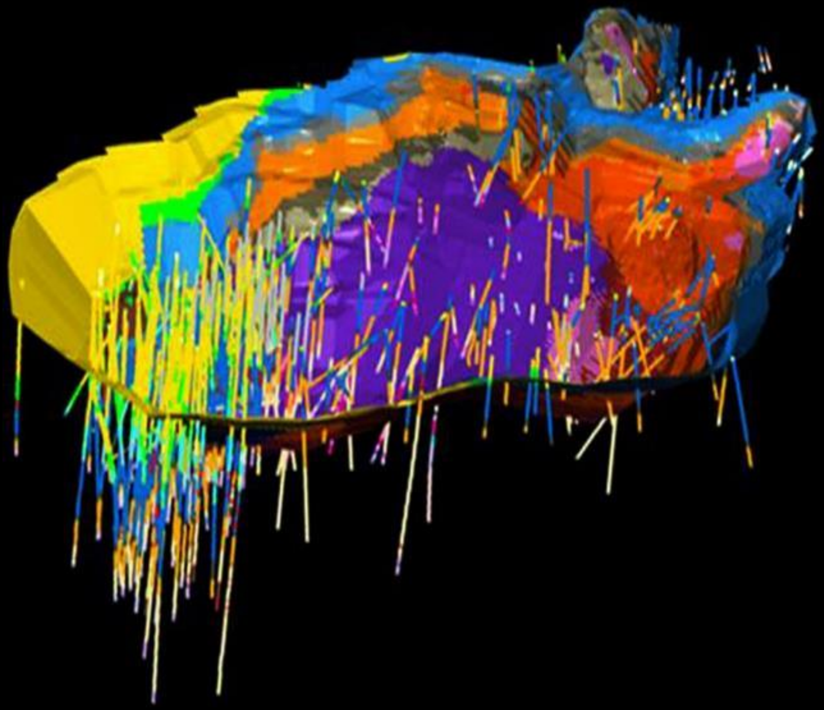
Modified from Practical Mining LLC, 2014



Geological Modeling

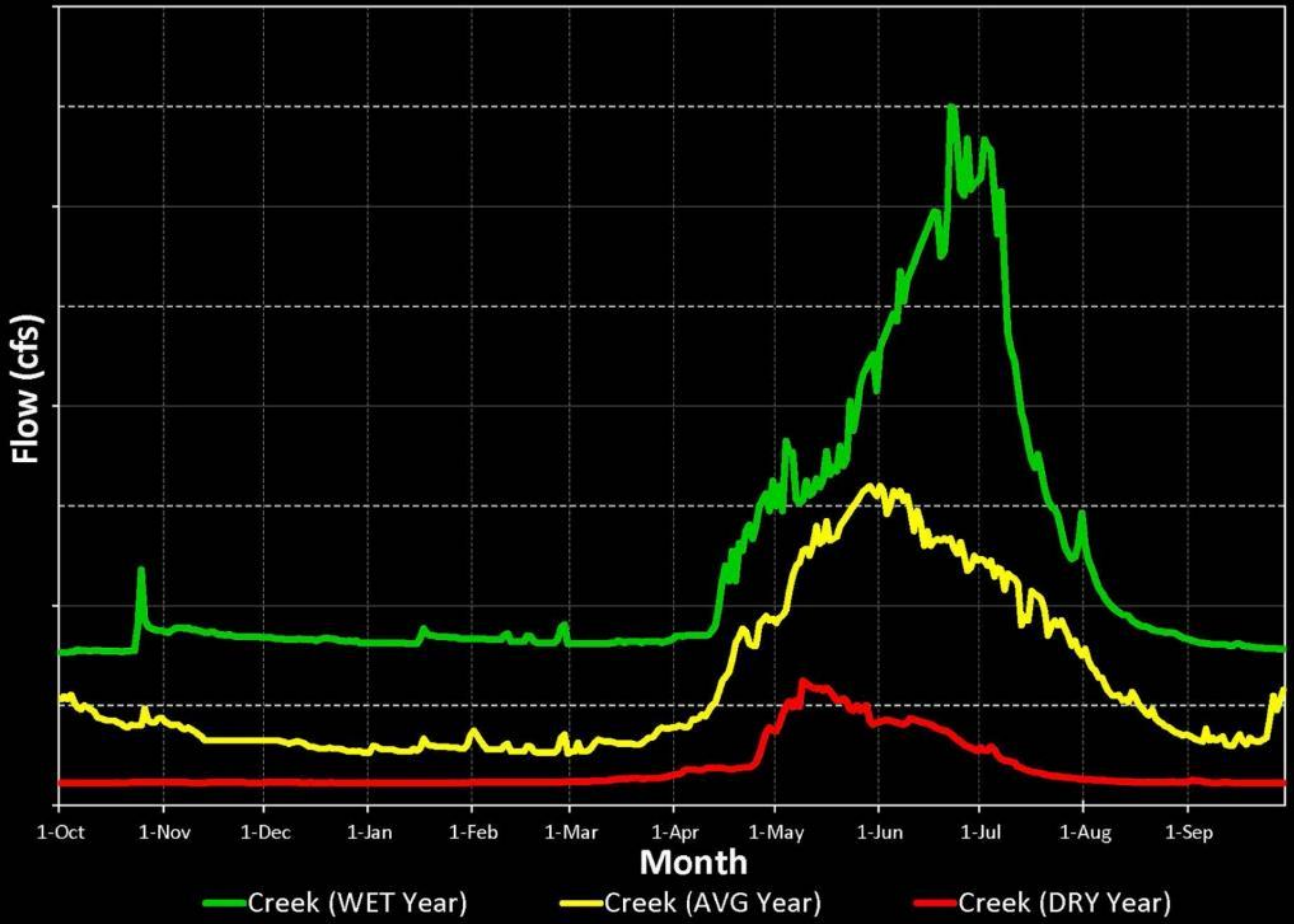
- 3D visualization of geologic units, structures, and other multi-element data sets





SURFACE WATER HYDROLOGY

- Flow/stage
  - Peak flow
  - Average flow
  - Base flow



Weirs

- Simple design and installation
- Low cost (<$500 fabrication)
- Raises head
- Requires freeboard and still pool
- Not self-cleaning
- Less accurate than a flume
- Work in Waterway Permit not required

Flumes

- More involved installation
- Higher cost (≥$2,000 fabrication)
- Moving flow
- Minimal raise in head
- Self-cleaning
- Submerged flow (certain types)
- Work in Waterway Permit often required

Velocity – Area

- Inexpensive and reliable method
- Most practical for large streams
- Used extensively
- Velocity measurement
  - Float
  - Current meter
  - Slope method

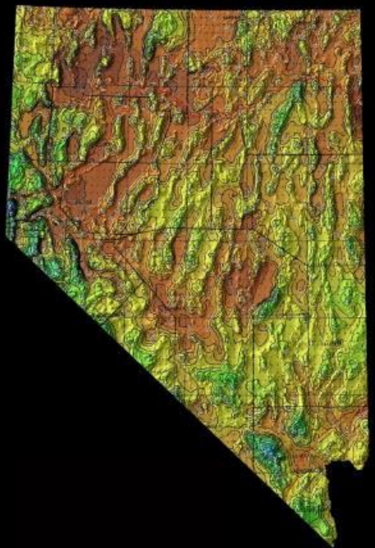
Bucket Testing

- Inexpensive and accepted method
- Size of container dictates range of flows
- Used extensively

Surface Water Models: Tools for Hydrogeology

- Precipitation statistics
- Spatial distribution of runoff and pit inflows

100-Yr Isopluvial Map

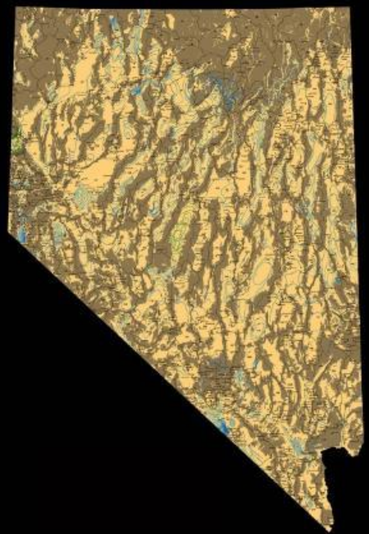


NOAA, 2015

Potentiometric Surface

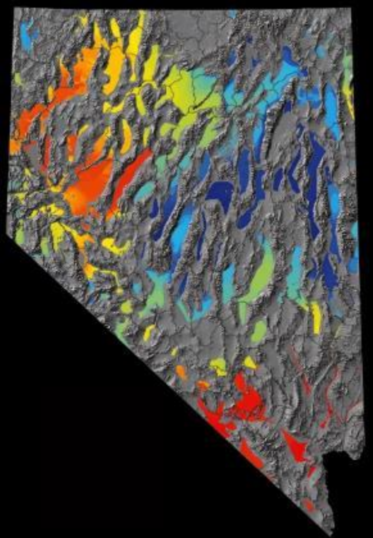
- Water level surface contours
- Hydraulic gradients and flow directions

Groundwater Contours



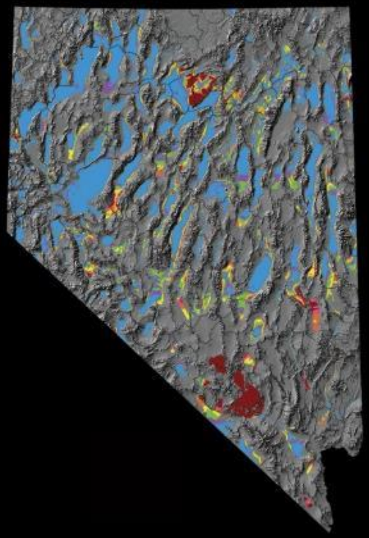
Lopes, et al., 2006

Groundwater Elevations

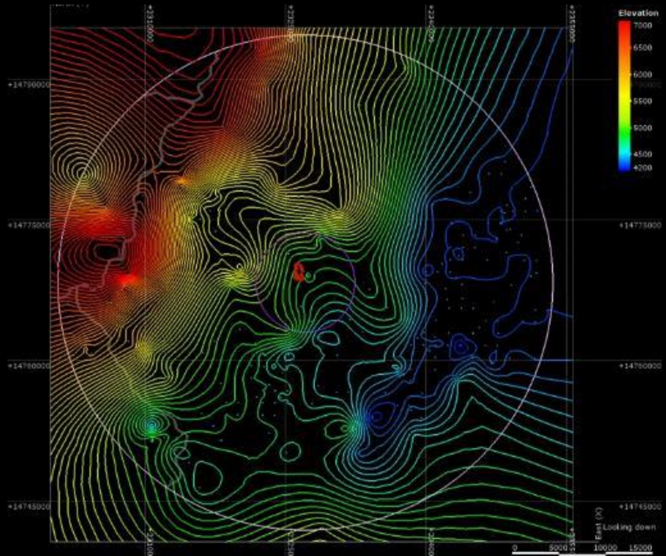


Lopes, et al., 2006

Depths to Water



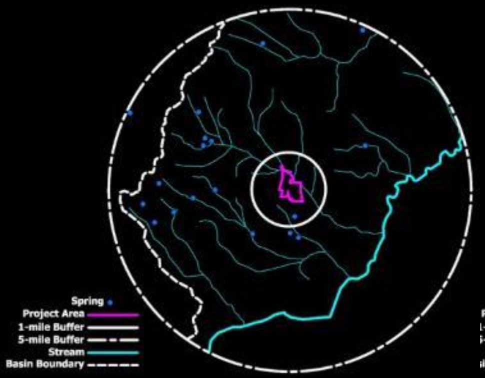
Lopes, et al., 2006



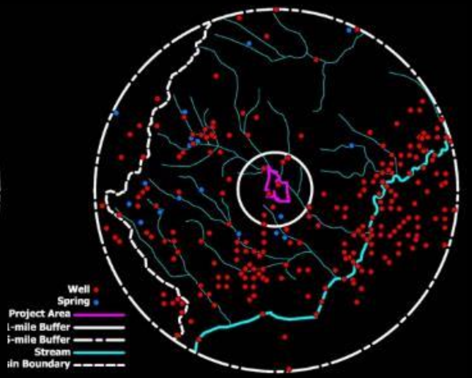
Potentiometric Surface

- Combined data sets
  - Surface water rights/resources inventory/characterization
    * Stage/flow of seeps, springs, streams, lakes and ponds
  - Groundwater rights/resources inventory/characterization
    * Well logs, underground water rights and water levels

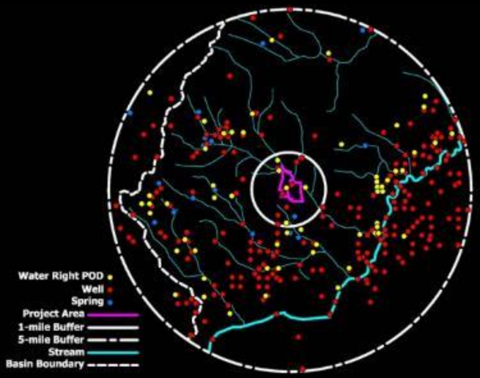
Surface water resources



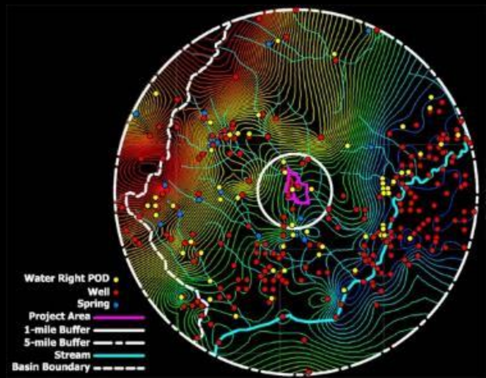
Wells / piezometers

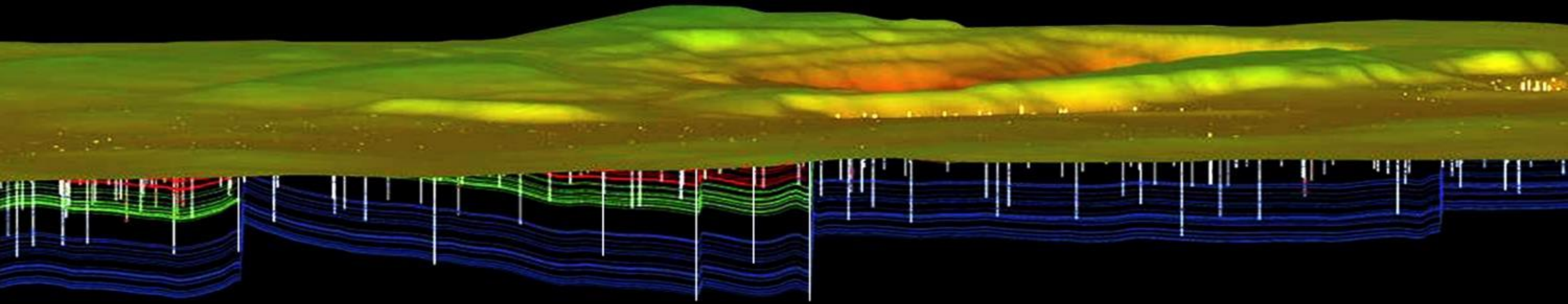


Water rights



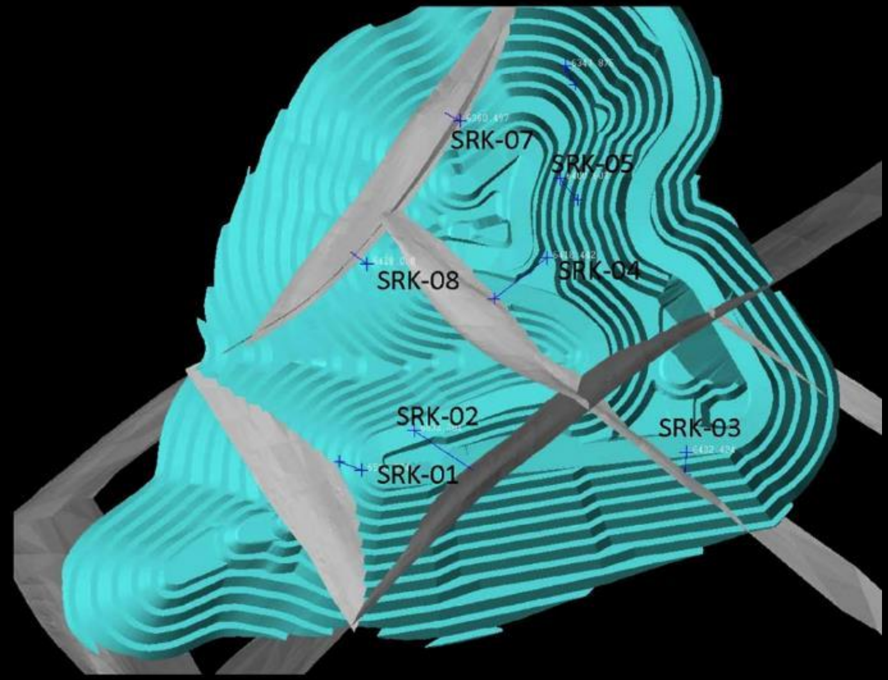
Potentiometric surface

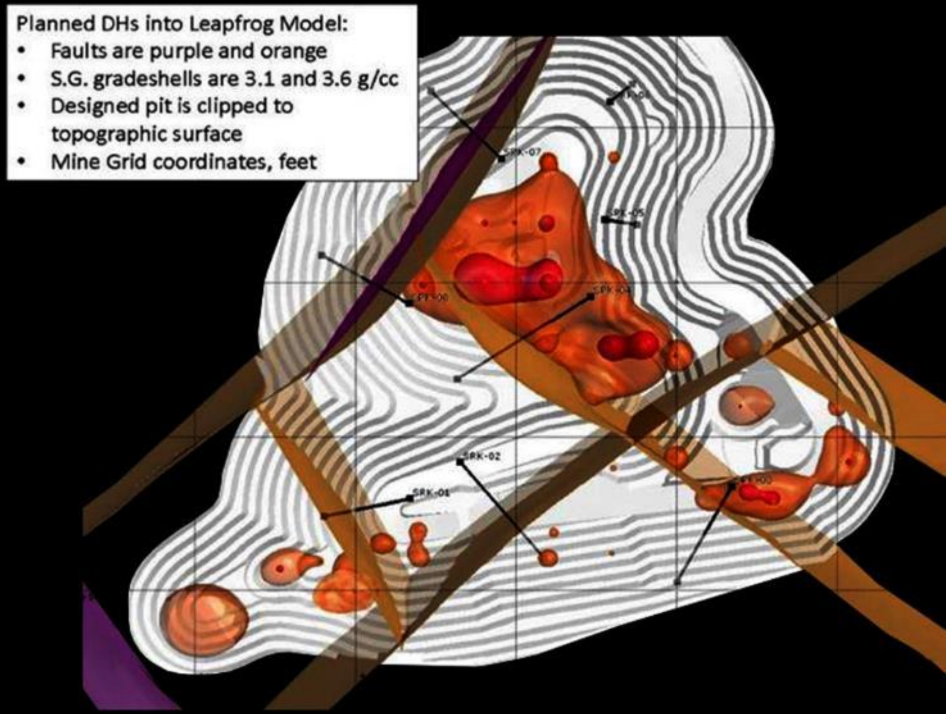


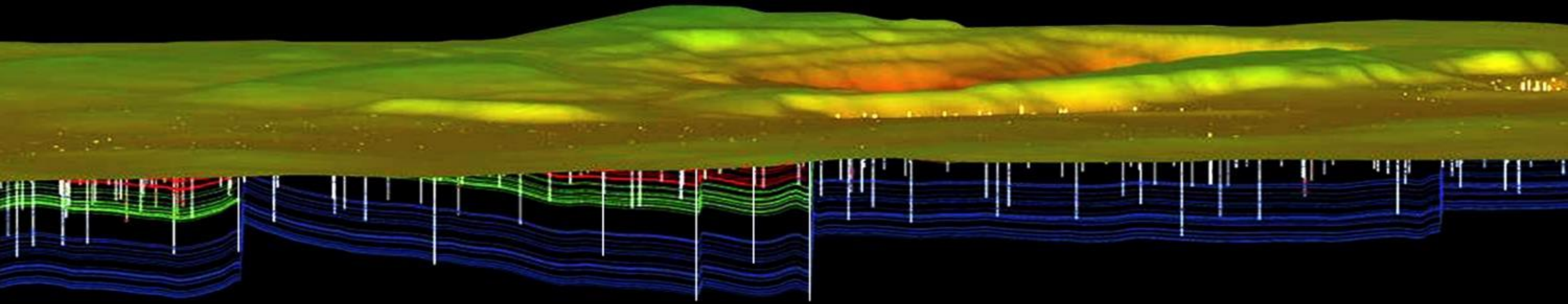


Geologic Models: Tools for Hydrogeology

- Targeting geologic units and structures for hydraulic testing from exploration coreholes

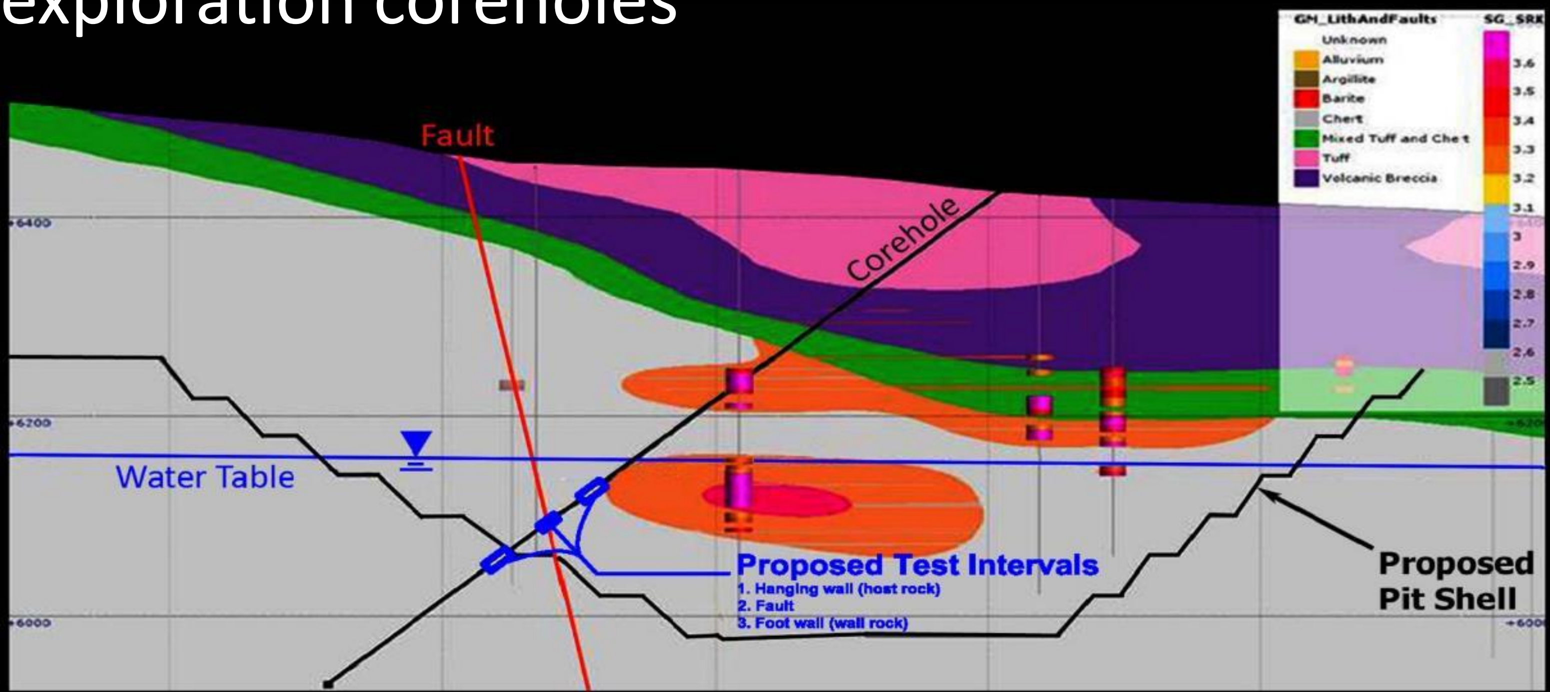




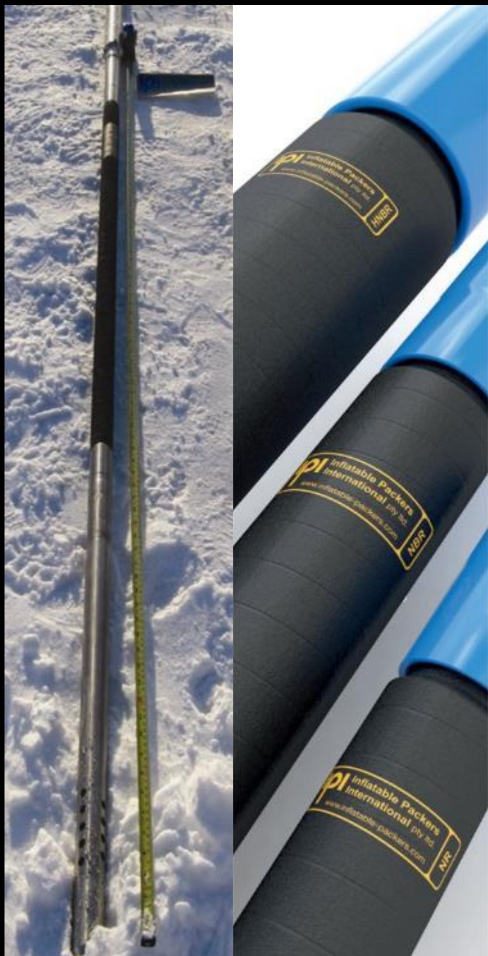


Geologic Models: Tools for Hydrogeology

- Targeting geologic units and structures for packer isolated hydraulic testing from exploration coreholes



Hydraulic Packers

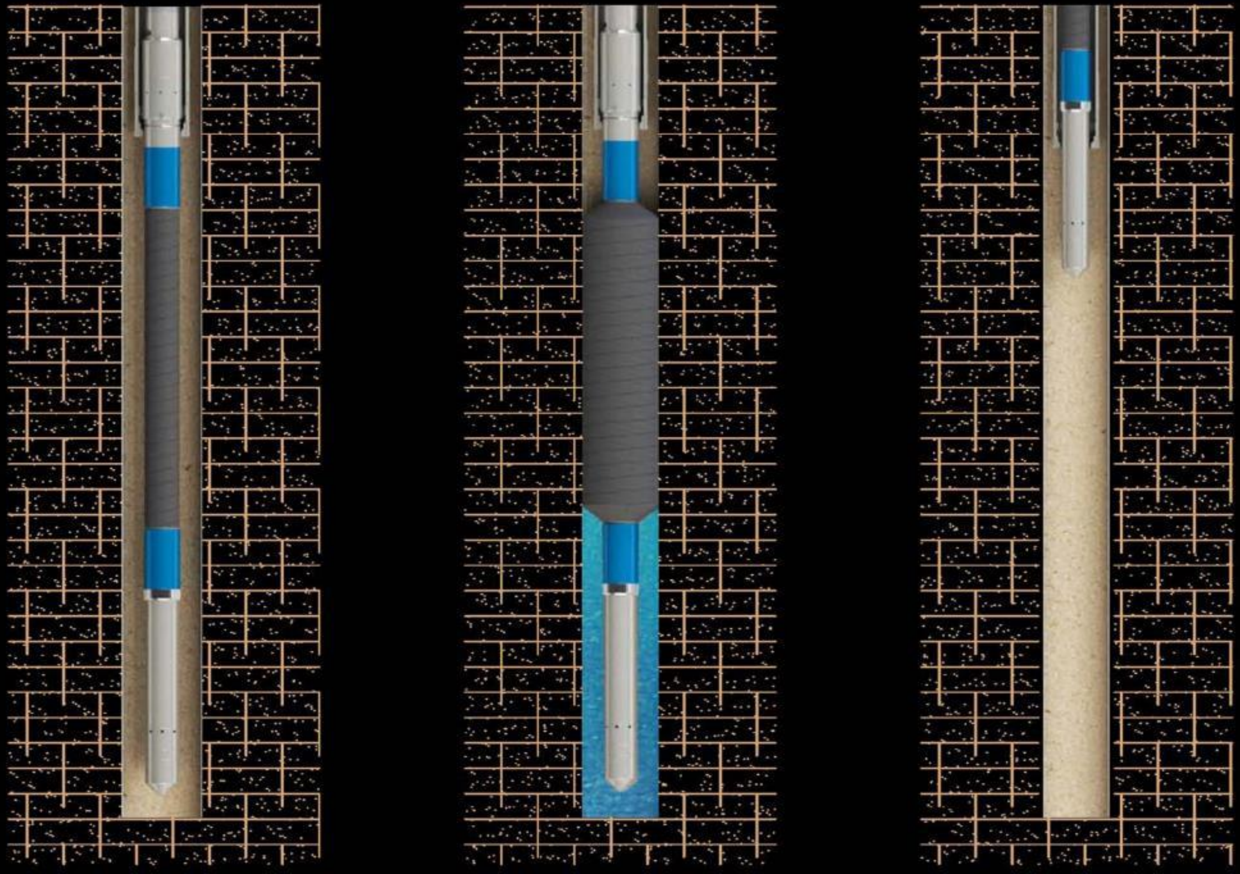


Images courtesy of Inflatable Packers International

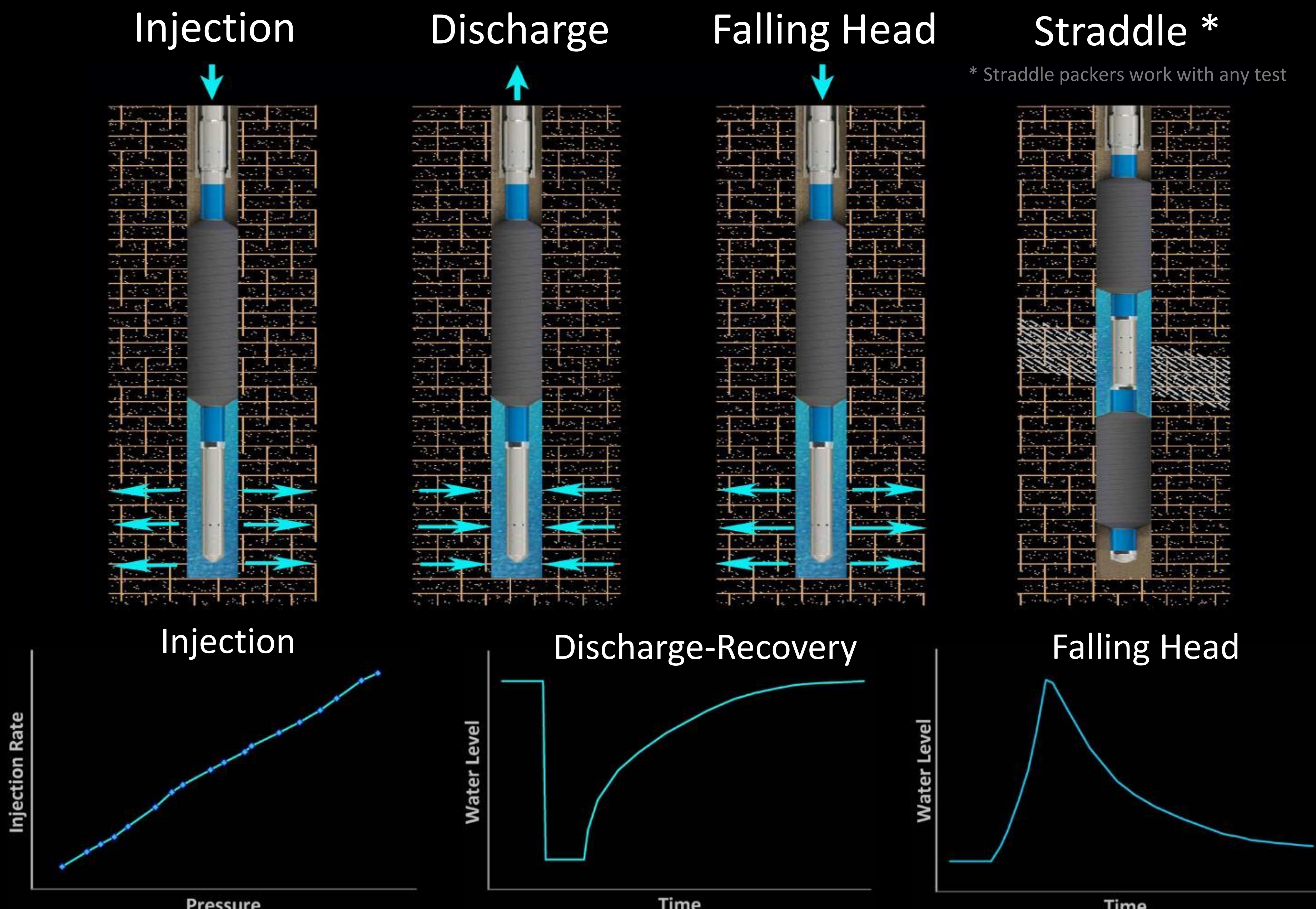
- Hydraulic testing
- Monitoring
- Aquifer storage and recovery (ASR)
- Solution (ISR) mining
- Rock stress mechanics
- Hydraulic fracturing

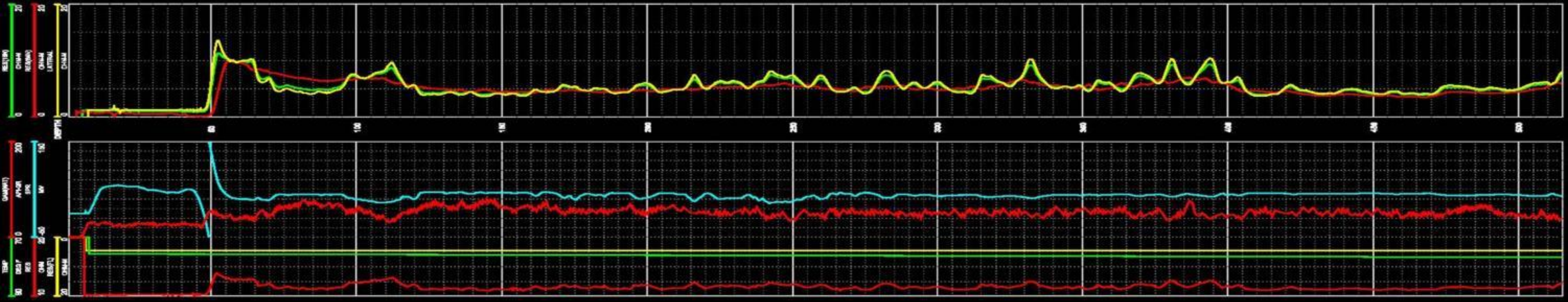
Packer Deployment/Retrieval

- 1. Deploy to target depth
- 2. Inflation/testing
- 3. Deflation/retrieval via rig wireline



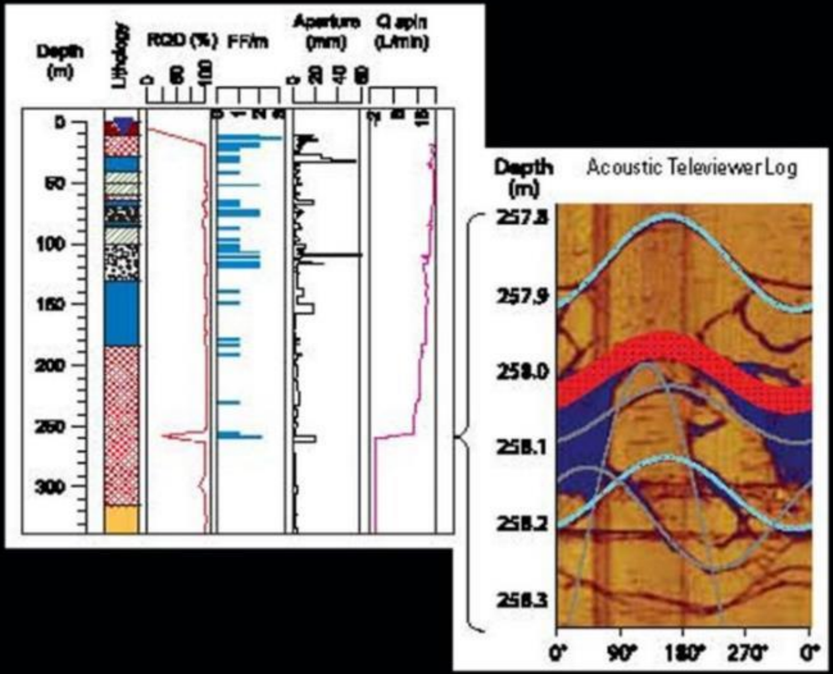
Types of Packer Tests

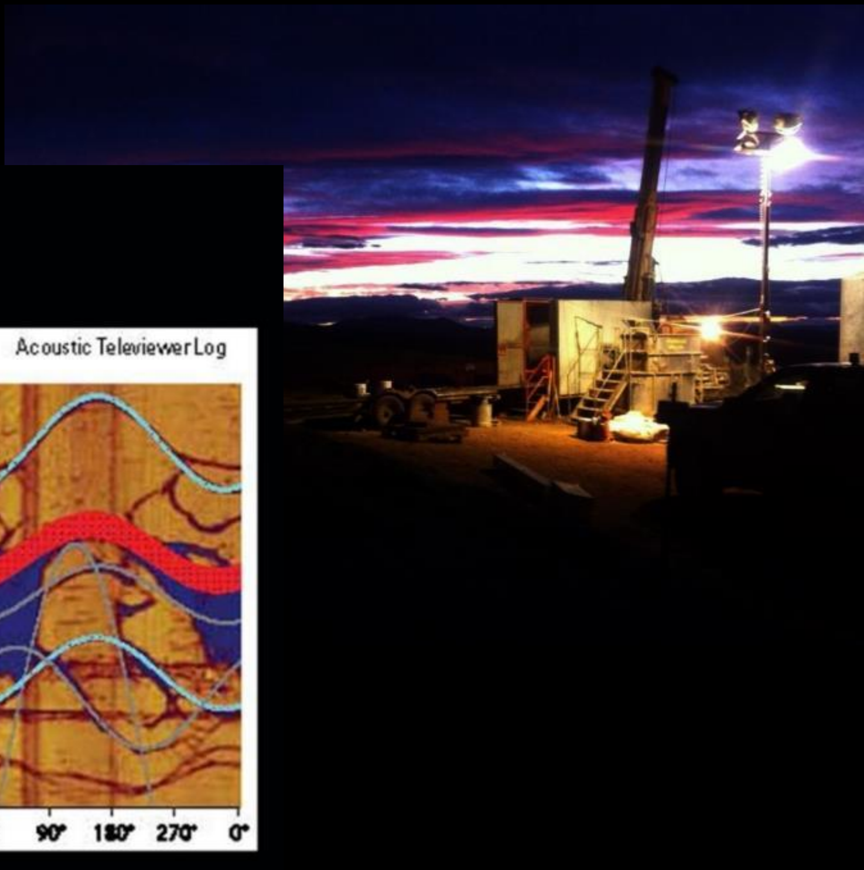




Down-hole Geophysical Surveys

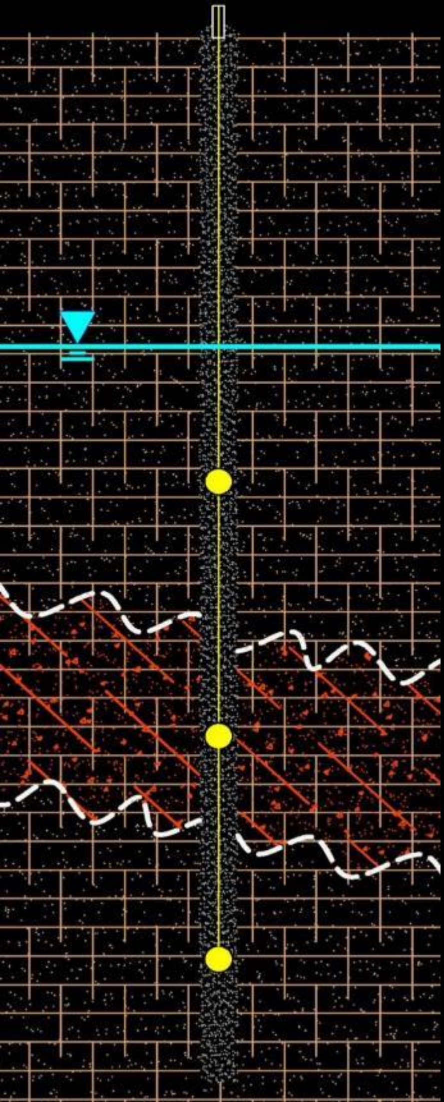
- Orientation/deflection
- E-log
- Spinner
- AT





Instrumentation Boreholes

- Vibrating Wire Piezometer (VWP)
  - Water level monitoring
  - Stability/deformation monitoring
  - Licensed well driller <u>not</u> required



WELL DRILLING AND CONSTRUCTION

- Licensed well driller required
- Waiver required to:
  - Drill monitoring wells
- Water right permit required to:
  - Drill production well in designated basin, or
  - To use water from the well if in non-designated basin

Monitoring Wells

- Generally located upgradient and downgradient from process facilities
- Nested completions to assess vertical gradients

Air Lifting

- Common well development method
- **The "Poor Man's Pumping Test"**
- Limited by:
  - Line submergence (≥60% ideal)
  - Pressure
  - Volumetric displacement rate

Initial air lift

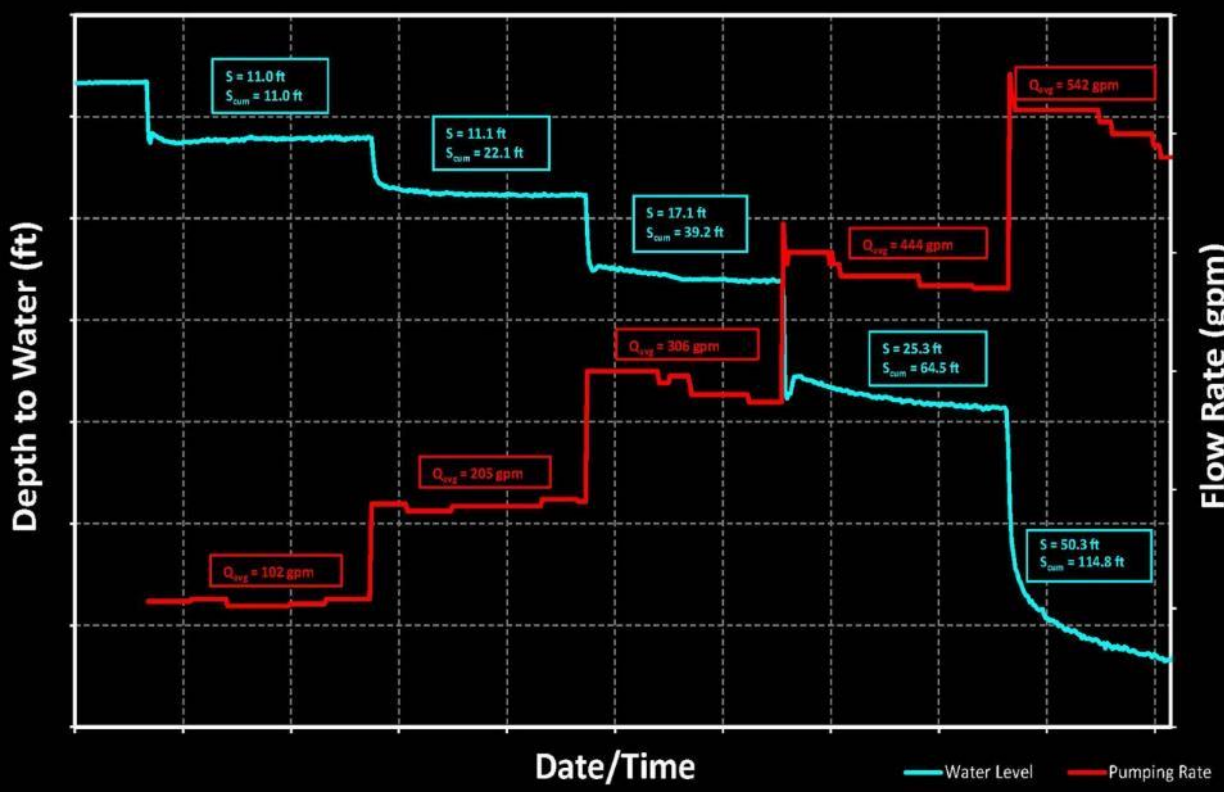
Subsequent air lift

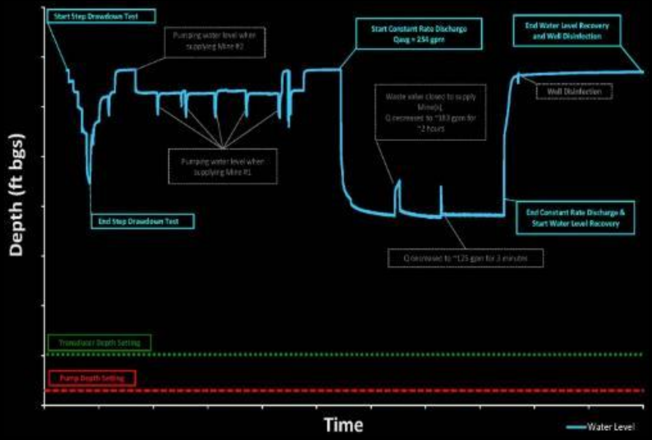
Slug and Injection Tests

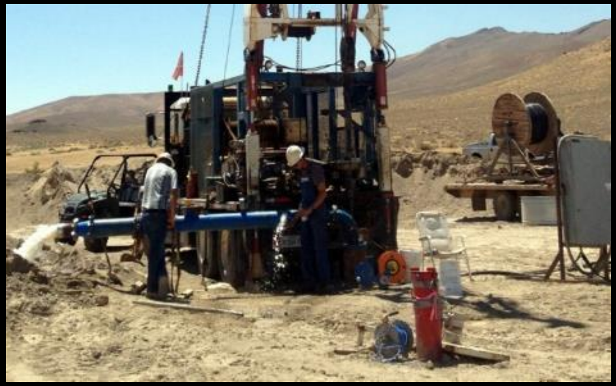
- Small-scale test methods
  - Low permeability/yield
  - Shorter duration
- Large-scale test methods
  - Higher permeability/yield
  - Longer duration
- Large-scale behavior can be underestimated with small-scale tests
- Tests performed from piezometers or monitoring wells
  - Can alter ambient groundwater chemistry and cause future water quality samples to be unrepresentative

Pumping Tests

- Step drawdown

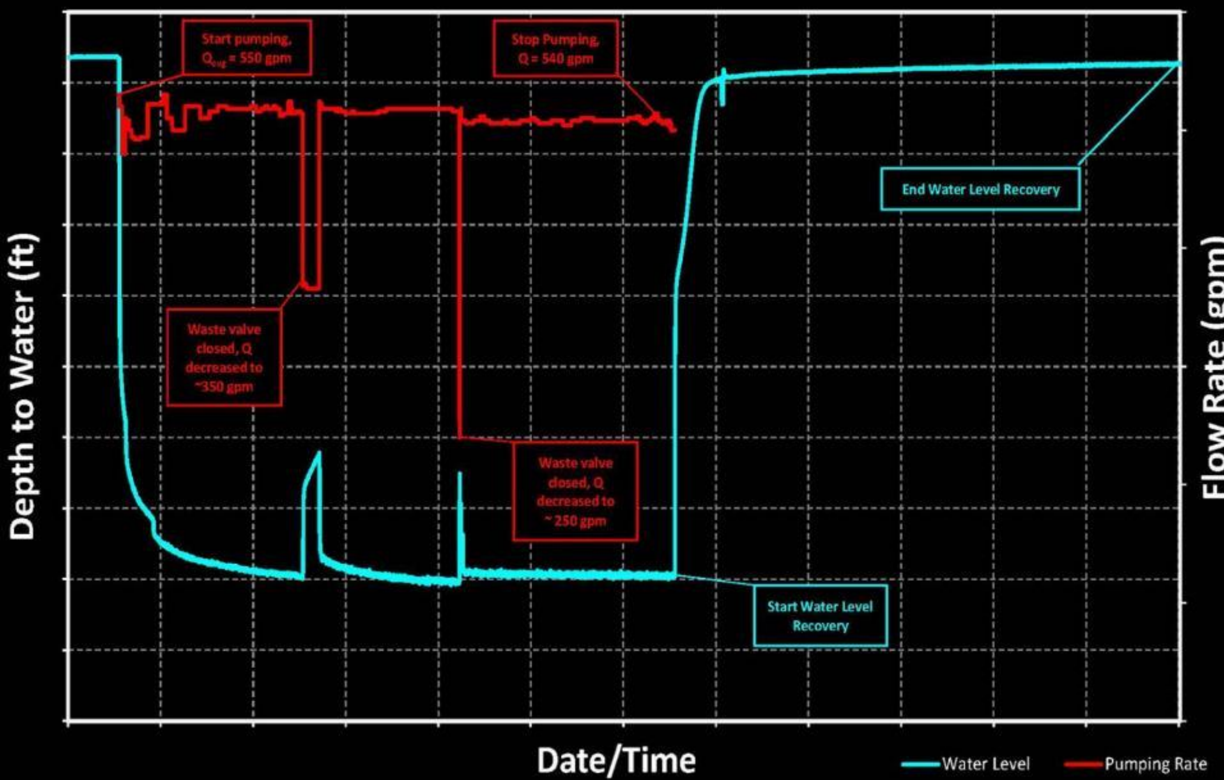


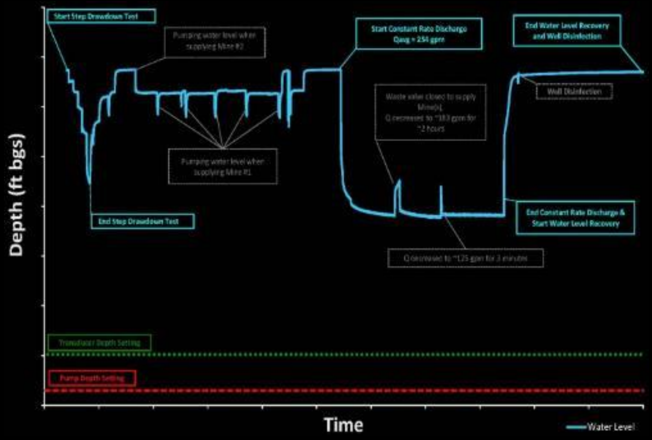




Pumping Tests

- Constant rate discharge





Well Purging and Sampling

- 3-well Volume
- Low-flow
- Minimum Purge
  - HydraSleeve™
  - Passive Diffusion Bag Sampler (PDBS)
  - Polysulfone Membrane Sampler (PSMS)
  - Regenerated Cellulose Sampler (RCS)
  - Rigid Porous Polyethylene Sampler (RPPS)

3-well Volume Purging and Sampling

- Cost limitations
- Water management and disposal
- Time limitations

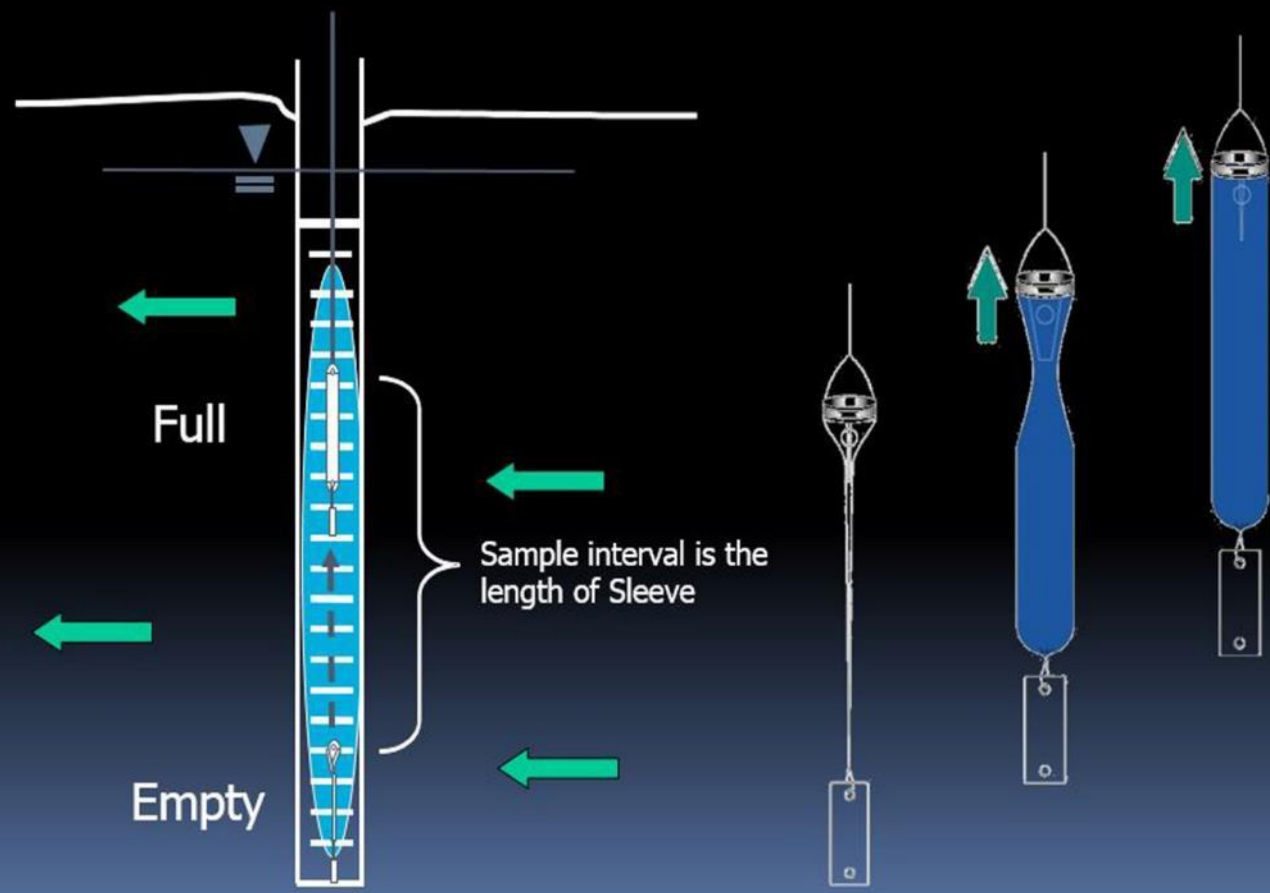
Low-flow Purging and Sampling

- Water management and disposal
- Cost limitations
- Depth limitations
- Time limitations

HydraSleeve

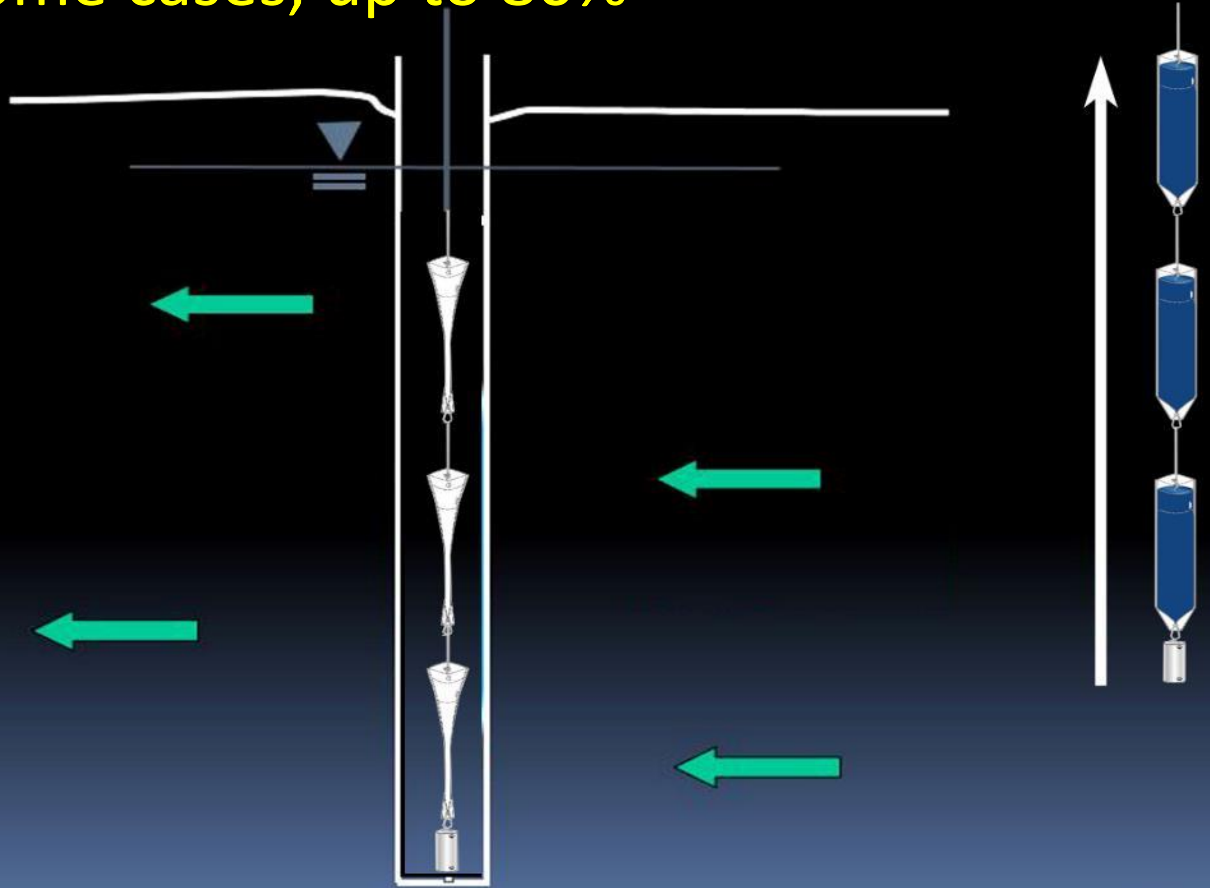
- Discrete depth interval, no-purge groundwater sampler
- Independently tested to provide comparable results
- Simple and repeatable (3-steps)

1. Deploy
2. Retrieve
3. Discharge



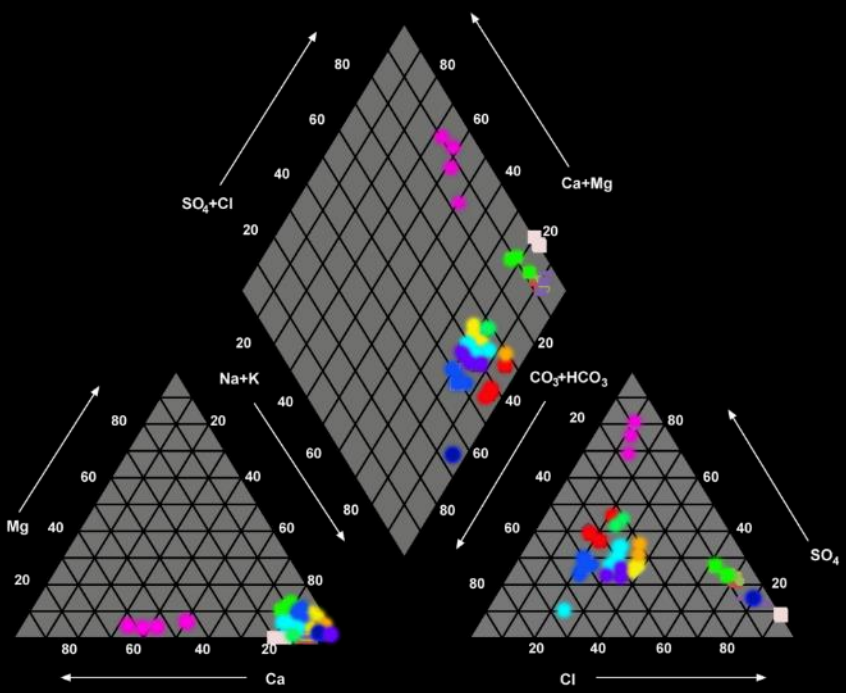
HydraSleeve

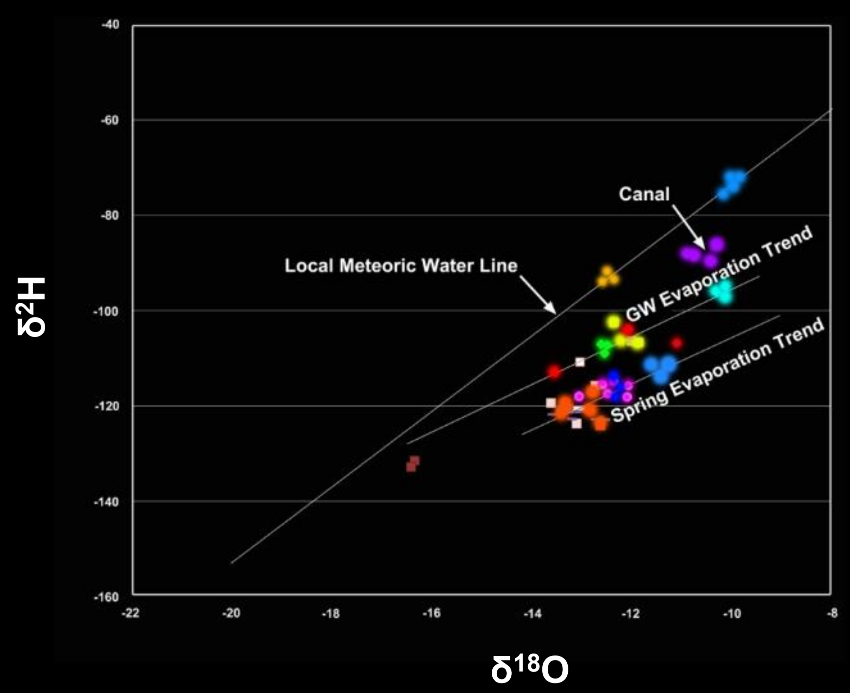
- Facilitates simultaneous collection from discrete intervals
- Most cost effective groundwater sampling method
- Can reduce field labor, sampling and equipment costs by ≥50% and, in some cases, up to 80%



WATER QUALITY / AQUEOUS GEOCHEMISTRY

- Piper plot / trilinear diagram
- Evaporative trends / isotopes





Conceptual Modeling – General Approach

Exploration Drilling and Geological Modeling

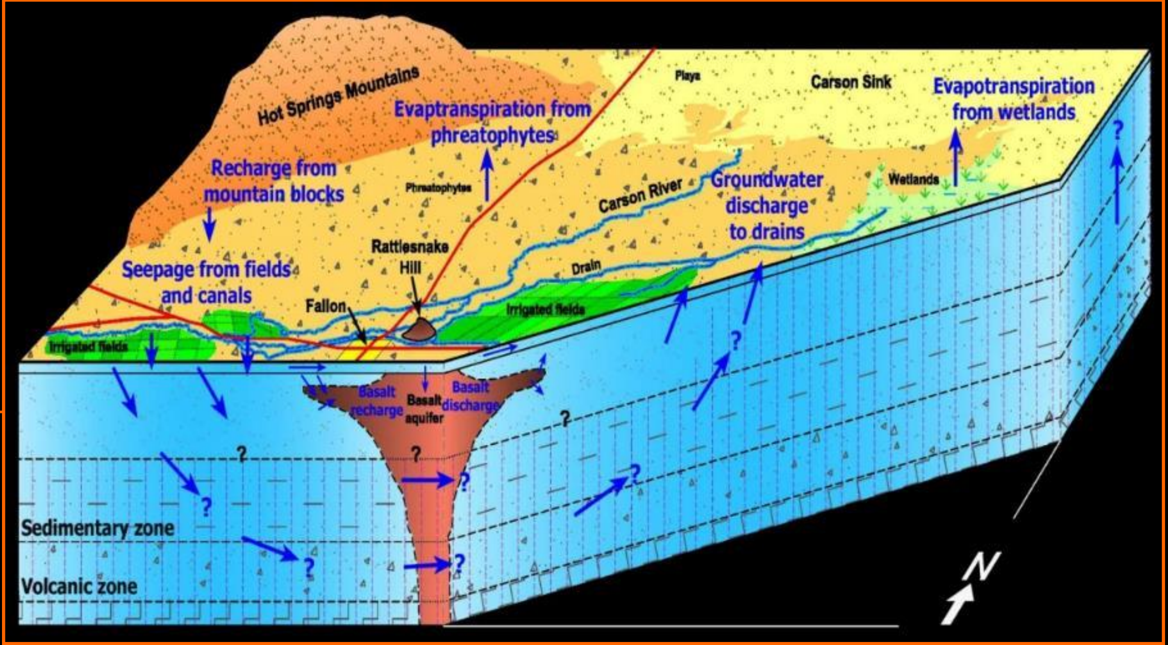
Hydrological Characterization

Geochemical Characterization

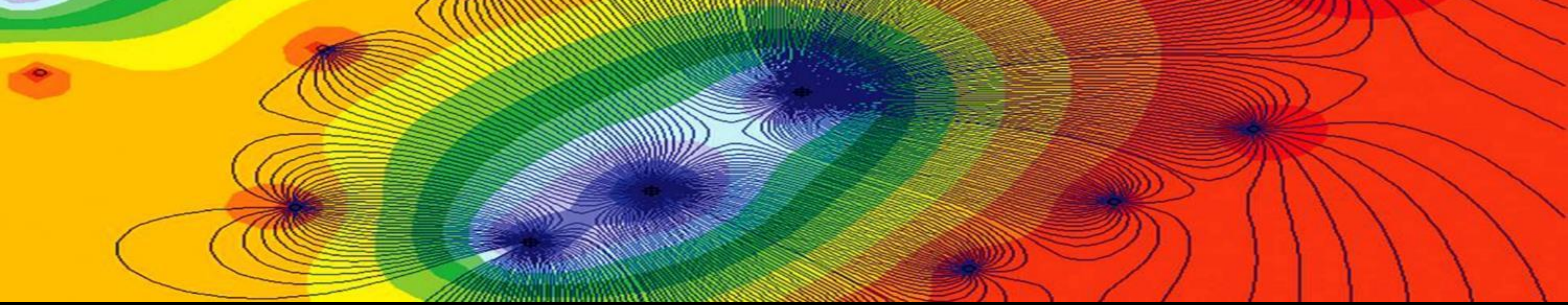
Geotechnical Characterization

Surface Water Modeling

Conceptual Hydrogeological Modeling

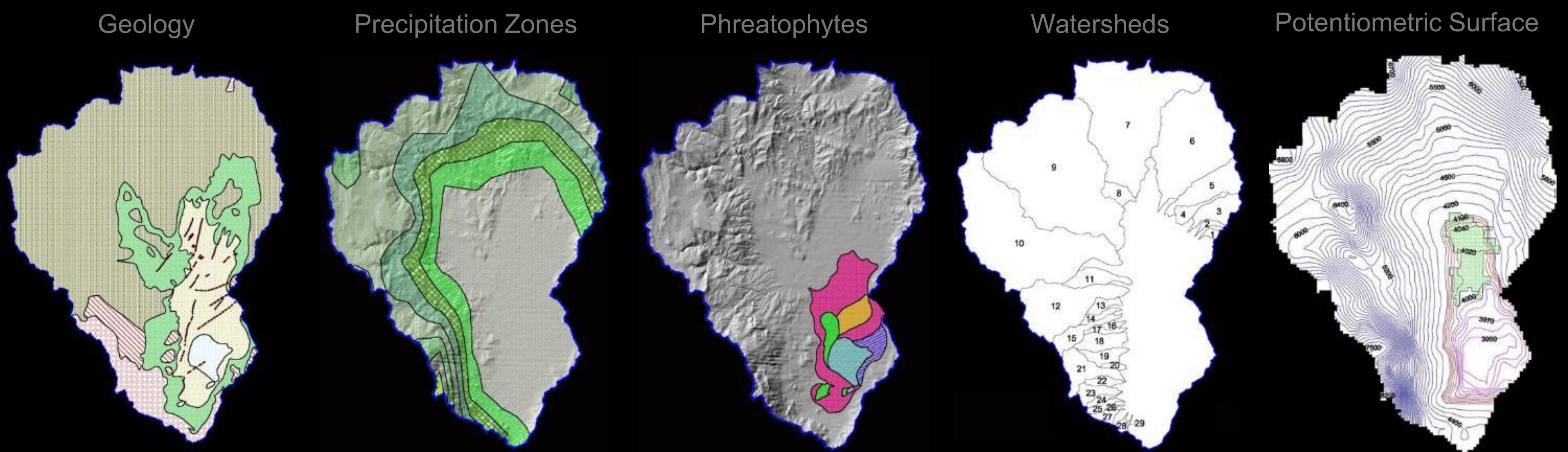


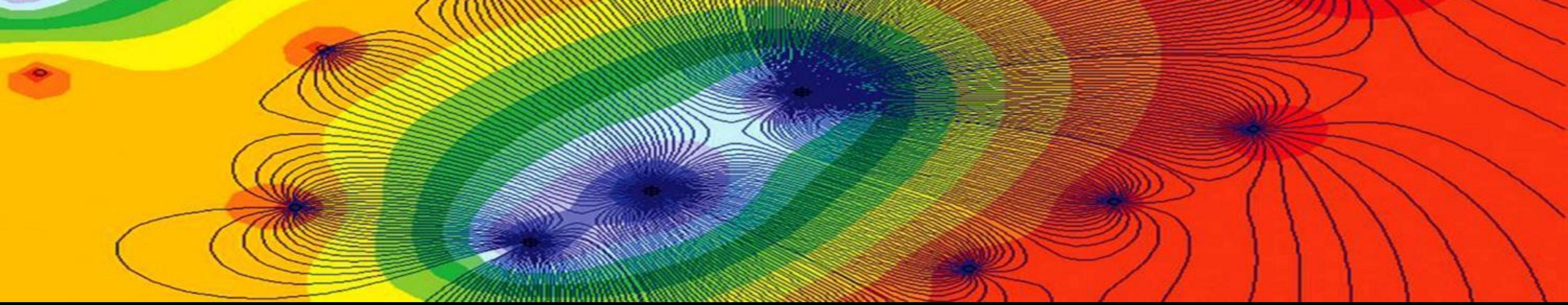
Maurer and Welch, 2001



Conceptual Hydrogeologic Model

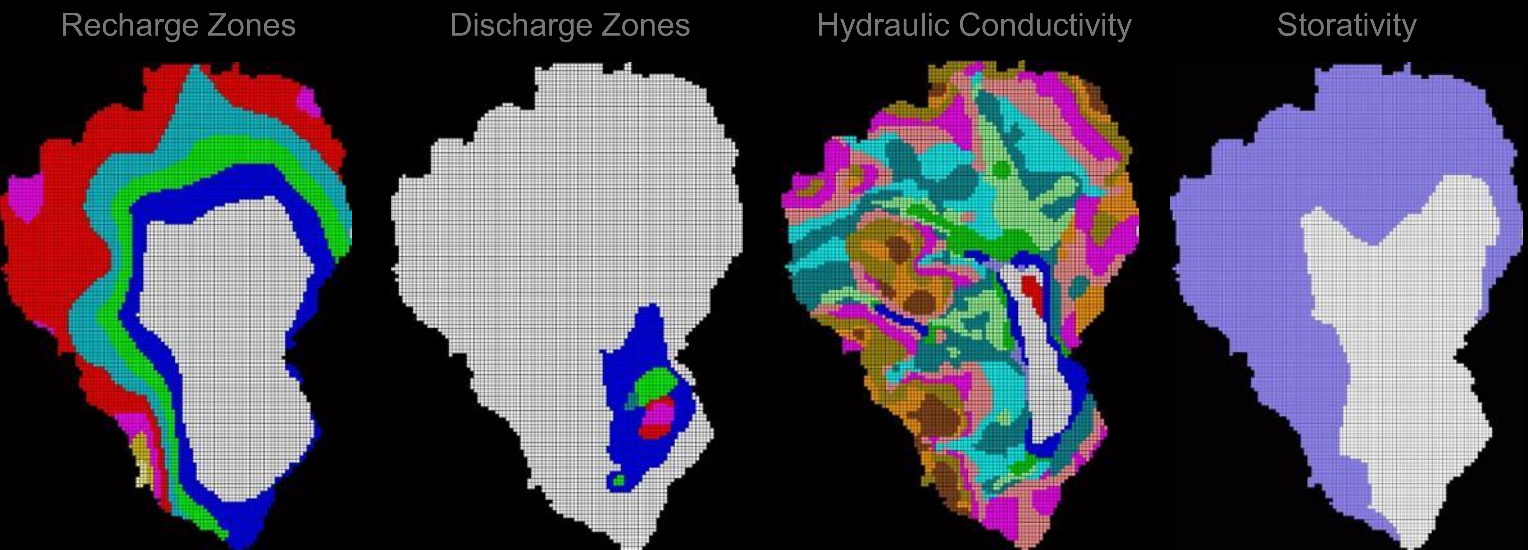
- Selected components





Conceptual Hydrogeologic Model

- Selected components



Groundwater Modeling – General Approach

Conceptual Hydrogeologic Model

Numerical Model Construction and Calibration

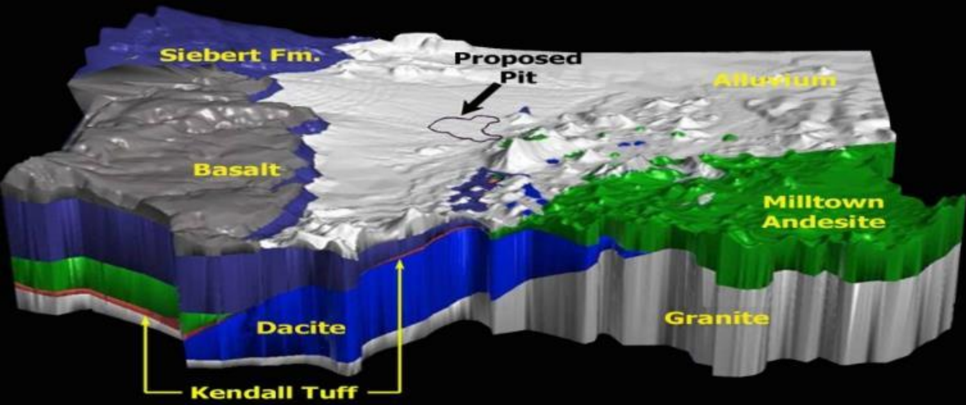
Incorporate Current Mining Plan

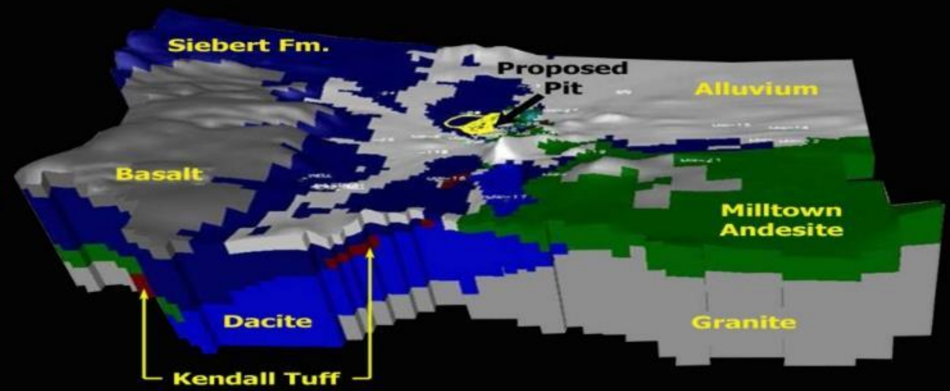
Predict Inflows and Determine Mine Water Demand

Develop Dewatering Plan and Water Supply Plan

Dewatering Simulation and Impact Prediction

Conduct Sensitivity/Uncertainty Analyses

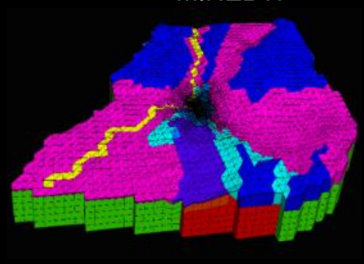




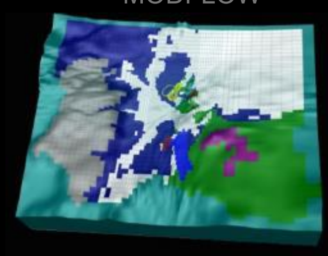
Groundwater Models as Tools

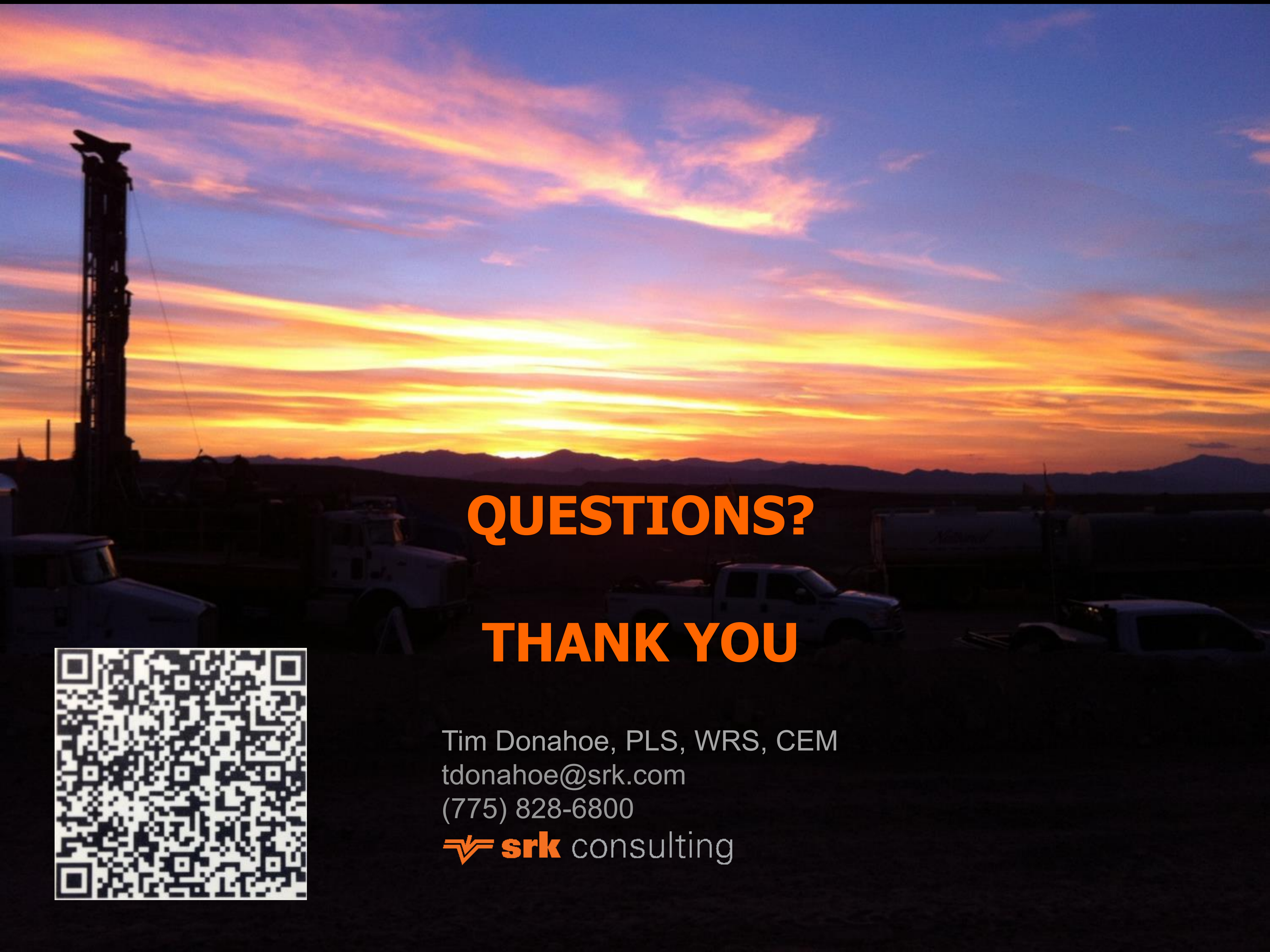
- Planning, design, permitting, operations, reclamation and closure
- Prediction of pre-mining, operations/closure and post-mining conditions
  - Infilling rates for open pits and underground workings
  - Draindown from HL, TS, and WRS facilities and soil covers
- Optimization
  - Dewatering systems/programs, and
  - Mine water supply systems/programs
- Prediction of pore pressures
  - Slope stability (open pit), and
  - Roof stability (underground)
- Prediction of cumulative impacts to water resources
  - Dewatering, water supply and water disposal programs
  - Infiltration from HL, TS, and WRS facilities

MINEDW



MODFLOW




QUESTIONS?
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