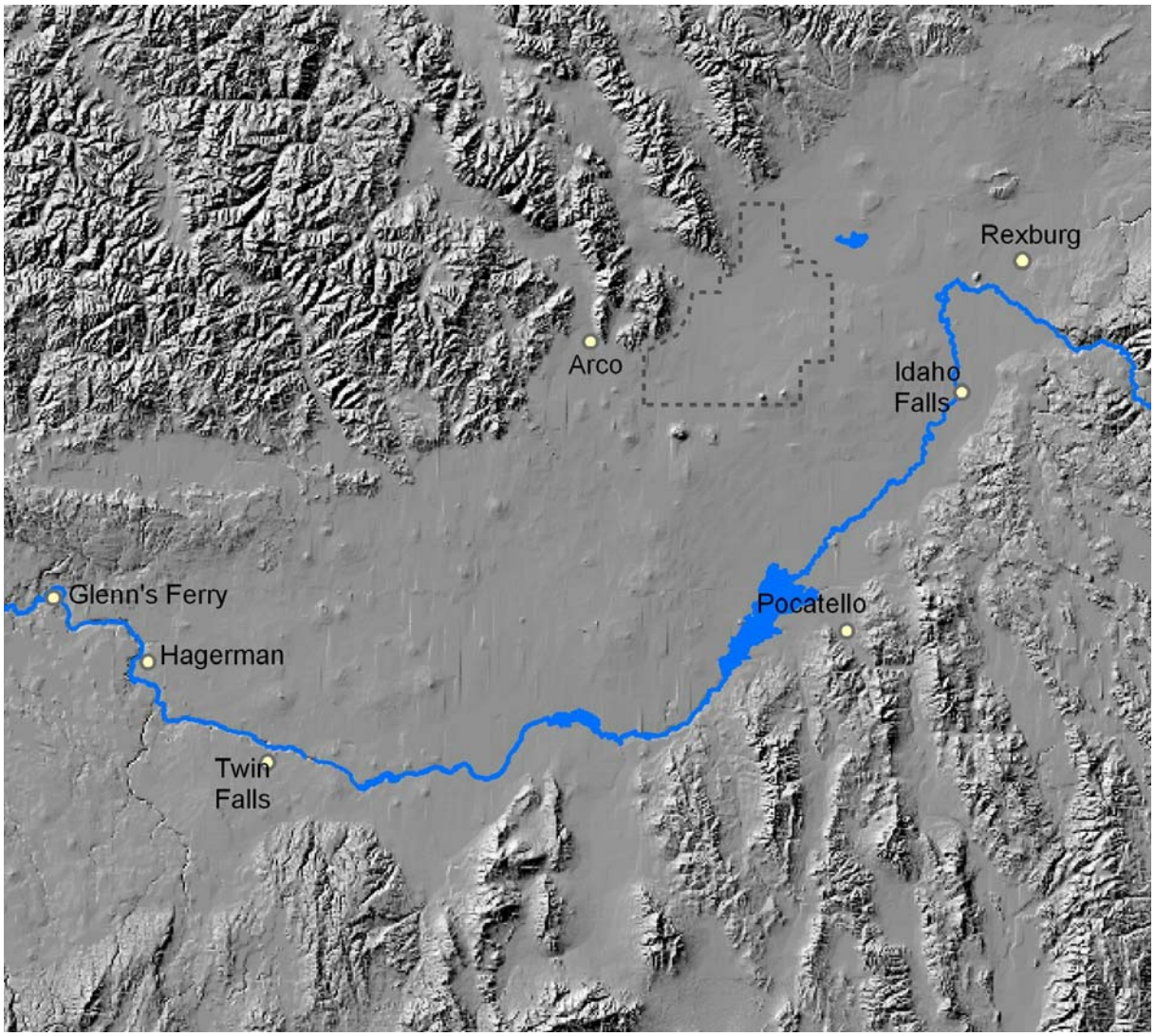
Inland Northwest Research Alliance
Subsurface Science Graduate Program

Subsurface Architecture Field Trip
March 12-14, 2008



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Subsurface Science Graduate Program
Subsurface Architecture Field Trip
March 12-14, 2008

Geology, Hydrogeology, and Subsurface Science on the Eastern and Central Snake River Plain

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Purpose and Objectives:

This field trip is designed to acquaint INRA students with the surface and subsurface geology of the Snake River Plain, including parts of the INL. The unifying theme of the trip is spatial scaling of natural heterogeneities in sedimentary and volcanic systems. Over the course of two days, students will examine salient aspects of the hydrogeology of this aquifer system via analogs represented in landscape and outcrop exposures, and from borehole core and geophysical logs.

Emphasis will be placed on specific topics and features covered in the various INRA Course Modules. An introductory session the evening prior to the trip (Day 1) will illustrate the regional physical character of the Snake River Plain system to provide a geohydrological context for the INL and the Thousand Springs in that system. At selected stops, instructors and guest lecturers will describe important outcrop features and instrumentation / measurement approaches and provide you with illustrative handout materials. You will be given assignments at key field stops requiring you to observe, document, and draw interpretations from the sediment, soil, and rock exposures visited on the Plain and along the Snake River. These will be discussed and amplified in a round-robin discussion to be held at the end of Day 2. Additional assignments will be made during Day 3 and discussed during a wrap-up evaluation prior to returning to Pocatello.

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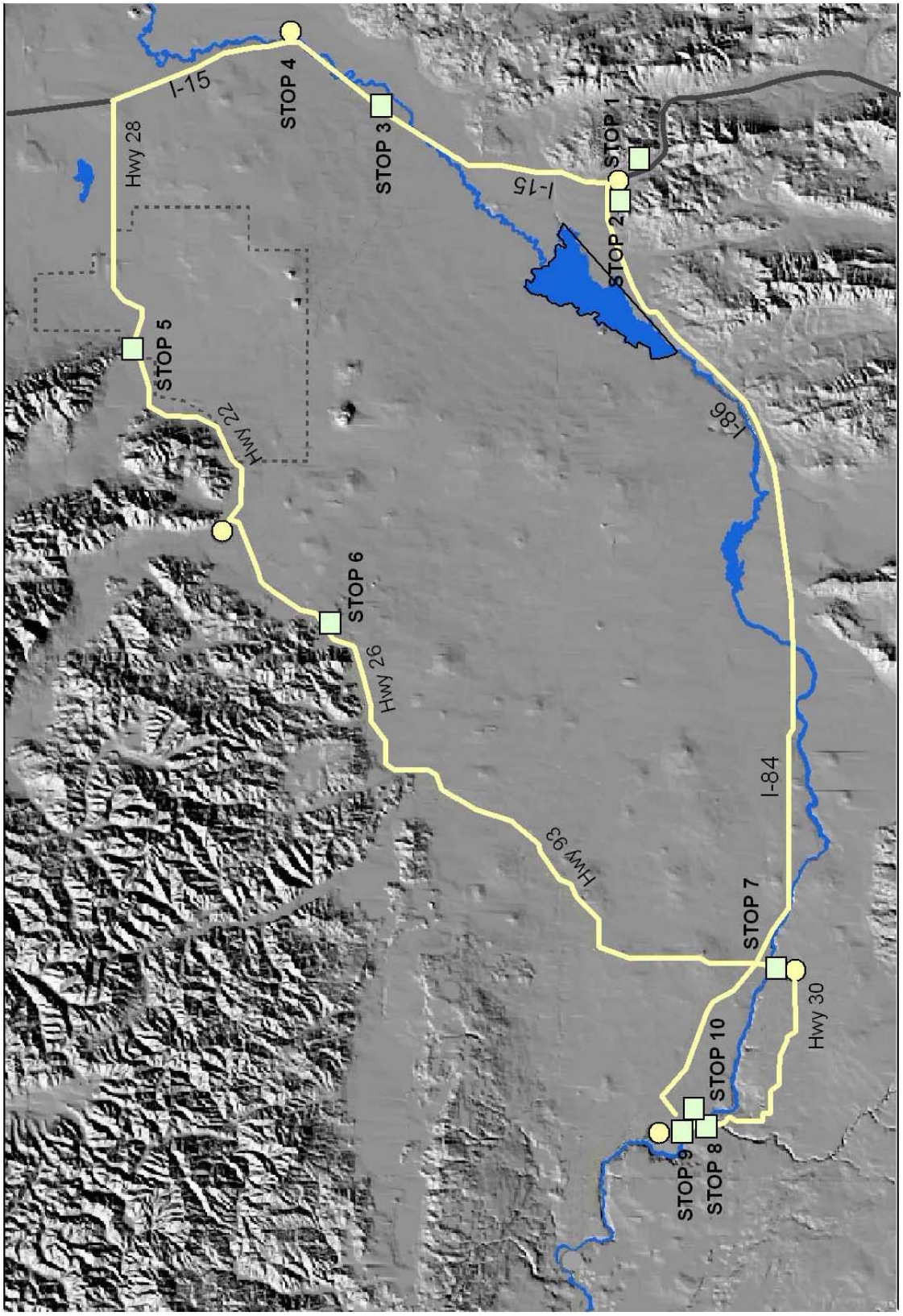
INRA Field Trip Participants

Name	Affiliation
Alicia Arrigoni	University of Montana
Seyoum Gebremariam	Washington State University
Emily Hinz	Boise State University
Dumindu Jayasekera	Utah State University
Kelsey Jencso	Montana State University
Andrew Lamb	Boise State University
Jessica Mitchell	Idaho State University
Elizabeth Powers	University of Idaho
Doc Richardson	University of Montana
Neelanga Weragala	Utah State University
Graham Woolley	University of Montana

Field Trip Route



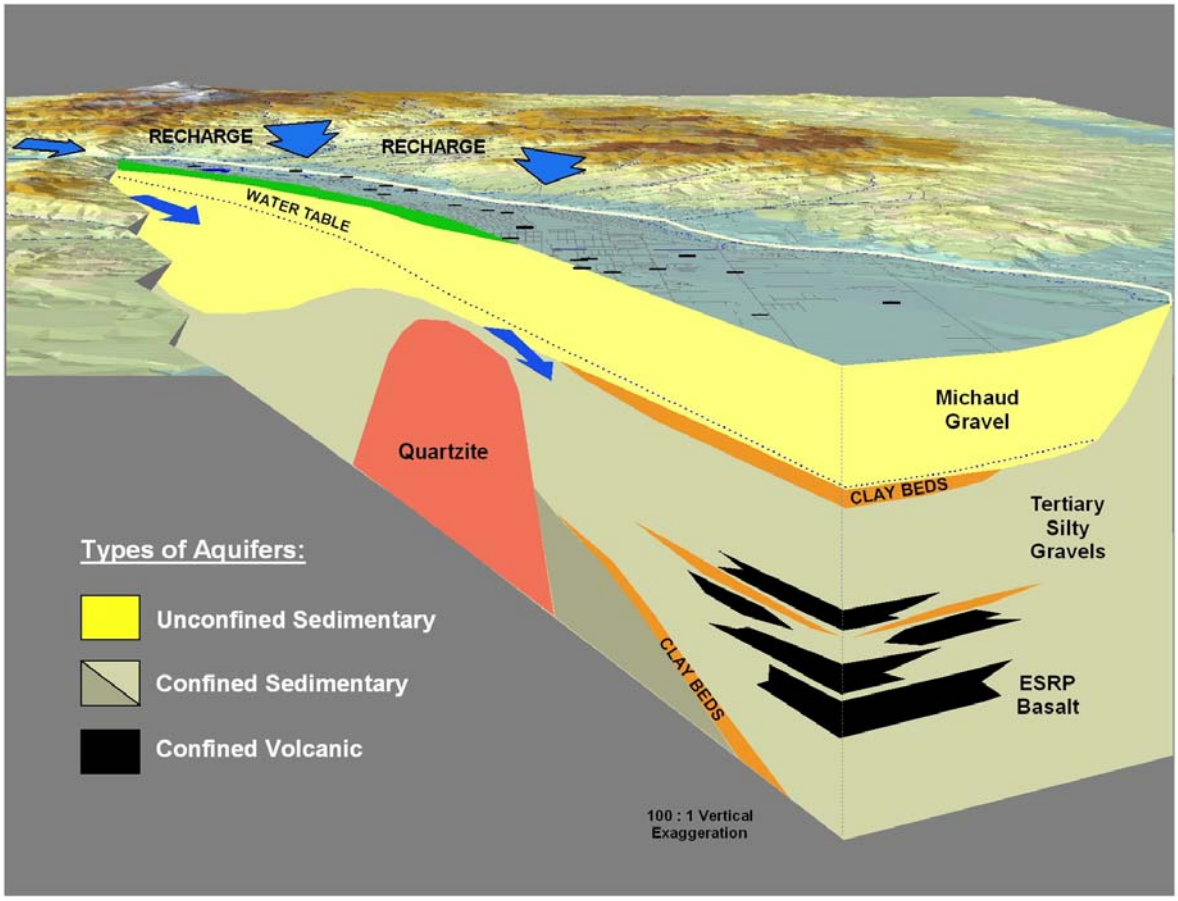
Field Trip Schedule

EVENT	TIME	DESTINATION	OBJECTIVE
Day 1, March 12			
Dinner	6:00 - 7:00pm	Red Lion Inn	Icebreaker
Presentations, discussion	7:30 - 9:30 pm		Trip overview
Day 2, March 13			
Leave, drive to STOP (1)	7:45 - 8:00 am	Red Hill quartzite	Heterogeneity
STOP (1)	8:00 - 9:00 am		and fluid flow
Drive to STOP (2)	9:00 - 9:15 am	Michaud gravel pit	Overview of Bonneville
STOP (2)	9:15 - 10:15 am		flood gravel deposits
Drive to STOP (3)	10:15 - 10:45 am	Hell's Half Acre	Features of basalt lava,
STOP (3)	10:45 - 12:00 pm	rest stop	scales of heterogeneity
Drive to STOP (4)	12:00 - 12:30 pm	University Place	Carbon sequestration,
STOP (4) / lunch	12:30 - 4:00 pm		INL core, environmental geophysical monitoring
Drive to STOP (5)	4:00 - 5:00 pm	Howe Point overlook	Overview of volcanic
STOP (5)	5:00 - 6:00 pm		features on ESRP
Drive to Pickles Cafe	6:00 - 6:30 pm	Arco, Idaho	Overview and evening
Dinner	6:30 - 8:00 pm		discussion
Overnight lodging in Arco			
Day 3, March 14			
Breakfast at Pickles Cafe	On your own time		
Check out, load up vans	8:00 - 8:10 am		
Drive to STOP (6)	8:10 - 8:40 am	Craters of the Moon	Young ("active") volcanic
STOP (6)	8:40 - 10:00 am	overlook area	field; dikes, fissures, mega-scale heterogeneity
Drive to STOP (7)	10:00 - 12:00 pm	Perrine Bridge	Basalt features, water-rock
STOP (7) / lunch	12:00 - 2:00 pm	Twin Falls overlook area	interaction, interbeds
Drive to STOP (8)	2:00 - 3:00 pm	Silgars Hot Springs	Hagerman Valley geology
STOP (8)	3:00 - 3:30 pm		overview of 1000 Springs
Drive to STOP (9)	3:30 - 3:45 pm	Vader Grade pull off	Glenns Ferry Fm, effect of
STOP (9)	3:45 - 4:15 pm		meso-scale heterogeneity
Drive to STOP (10)	4:15 - 4:30 pm	Thousand Springs	ESRP aquifer discharge
STOP (10)	4:30 - 5:00 pm		zone; discussion/synthesis
Drive to Twin Falls	5:00 - 5:30 pm	Garibaldi's Restaurant	Trip wrap-up discussion
Dinner & wrap-up	5:30 - 8:00 pm		and take-home points
Drive to Pocatello	8:00 -10:00 pm	ISU	Lodging in student dorms

Intermountain Bedrock and Alluvial Aquifers

- the lower Porneuf River valley has a number of different fractured and porous intergranular aquifers, from extremely low-permeability fractured crystalline bedrock to some of the most highly permeable flood gravels in the West
- porosities ranging from < 1% to 30% and permeabilities, from 10^{-6} to 10^{3} meters/day
- flow can be almost stagnant in clay-rich colluvial deposits to extremely high (10 meters/day) in well-sorted Lake Bonneville flood gravels
- fault-controlled, intra- and trans-basin flow can be important in some basins

The lower Portneuf River aquifer

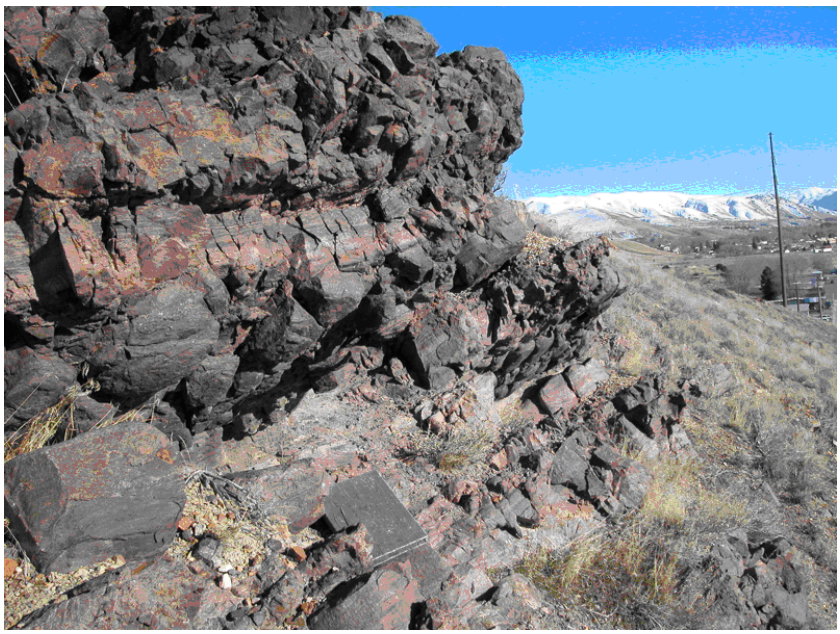


Stop 1: Bedrock Fracture Zone at Red Hill

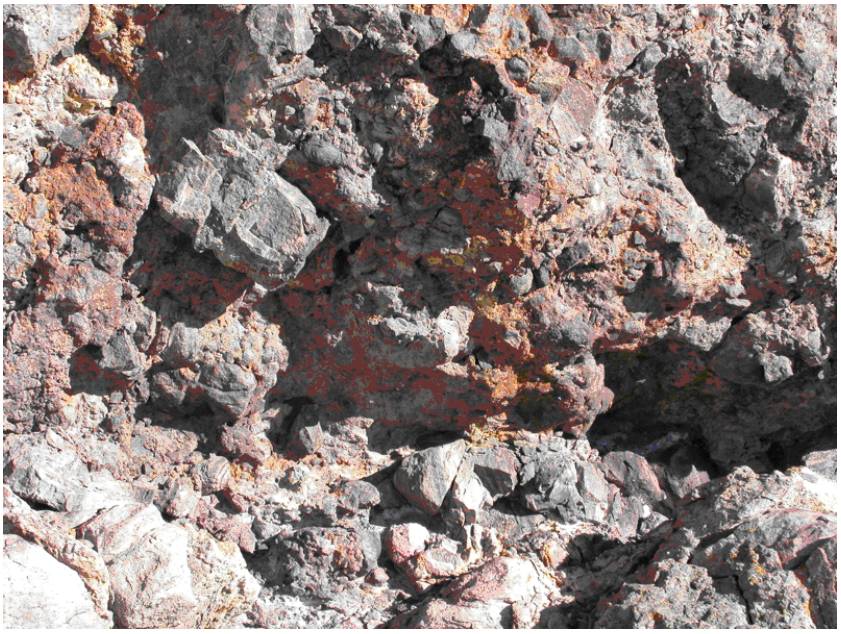
Objectives:

- observe outcrop-scale textures in quartzite bedrock
- associate textures with formational or deformational processes
- identify potential groundwater flow paths

Quartzite outcrop.



Microscale textures.



Exercise 1.1:

a) sketch and label a range of textures in these outcrops that are expressed by stratification, color, grain size, fractures such as joints and faults, and possible compositional contrasts.

b) which of these textures reflect processes associated with deposition of the original sandstone, and how do you know? What evidence is there that the remaining textures reflect deformational processes after the rock was formed?

c) what evidence can you find that groundwater once flowed through some or all of these outcrops? Describe the spatial arrangement of porosity at the time water passed through. Does the rock have the same porosity today?

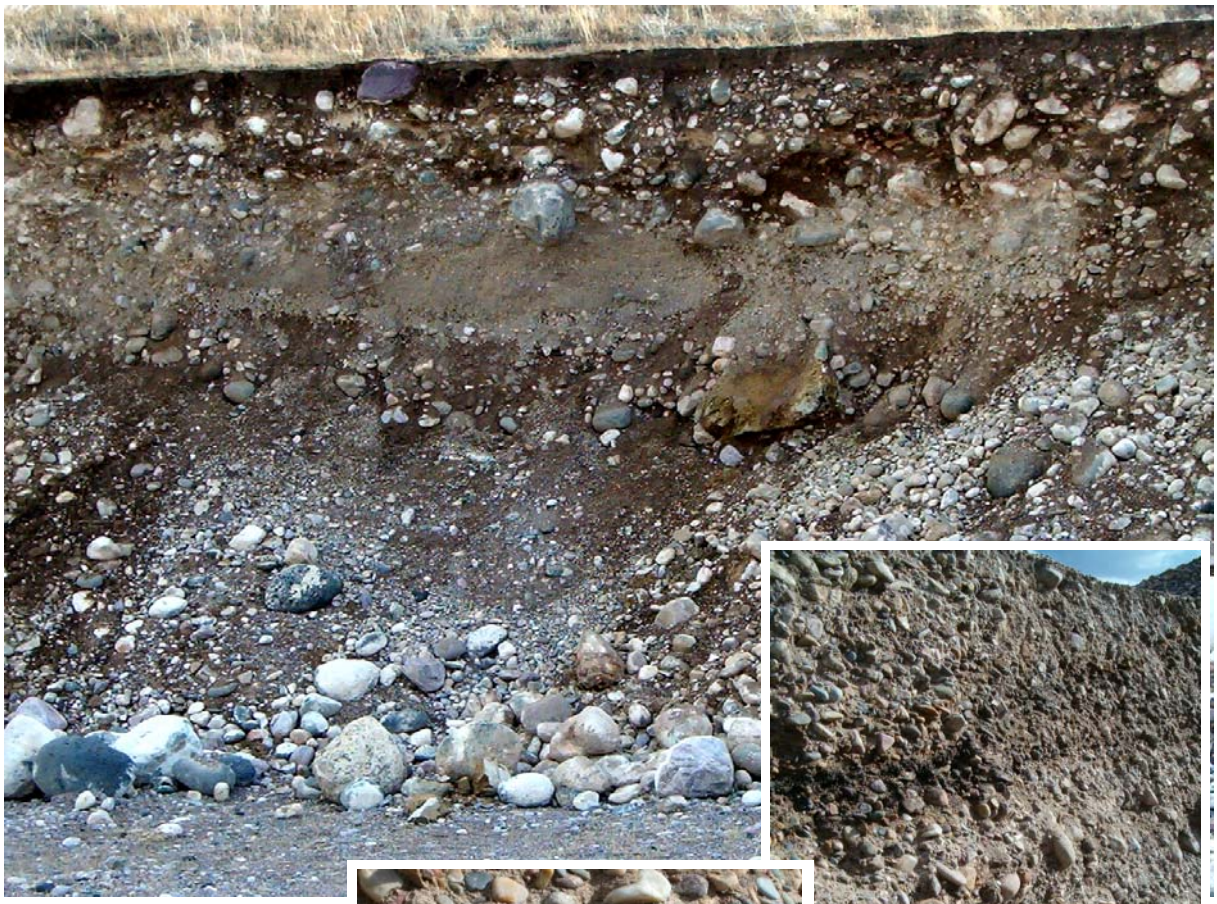
Notes

Stop 2: Postglacial Flood Gravels on the Michaud Flats

Objectives:

- identify features of highly permeable gravel/sand deposits that affect flow and transport
- discuss scale-dependent issues that affect testing, sampling, and instrumentation

*Micro- and mesoscale heterogeneity in flood and fluvial gravel*s



Flood gravels (above)

Fluvial gravels (insets)

Exercise 2.1:

a) identify microscale features that affect hydrologic properties in this aquifer material

b) how would flow and transport behavior be affected in a such an aquifer (e.g., what effects on hydraulic gradient, flow velocity, dispersivity)?

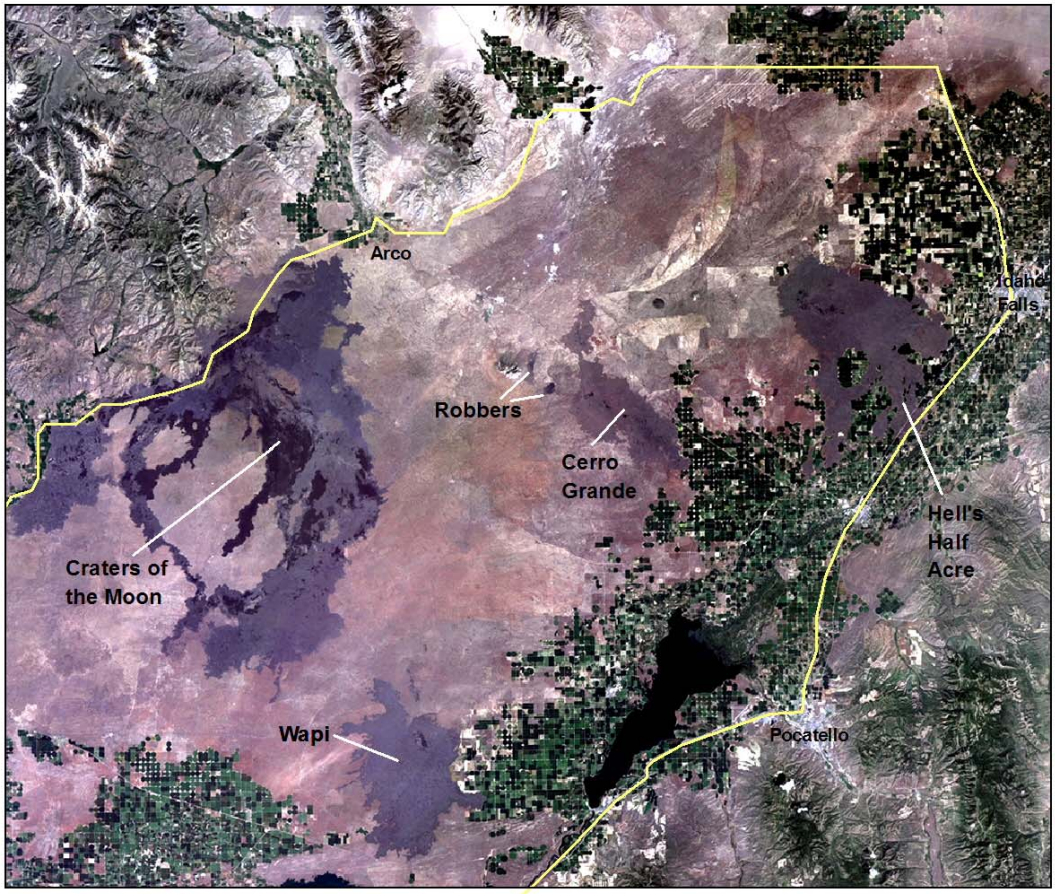
c) what kinds of instrumentation issues would you have to face in making hydraulic tests and chemical measurement in such an aquifer?

The Eastern Snake River Plain Aquifer:

- one of the most prolific aquifers in North America; water storage equivalent to Lake Erie (480 km^3)
- more first-magnitude springs (>10 m^3/sec) than any region in the U.S.
- depth to ground water varies from less than 10 to >200 meters
- very permeable, fast flowing (1 to >10 meters/day; mean residence time ca. 200 years)

- hosted in layered olivine tholeiite basalt and intercalated silt, sand, and gravel beds with minor occurrences of volcanic rocks of higher silica content (e.g., rhyolitic)
- sedimentary interbeds are exposed only in the Snake River canyon (Twin Falls)
- the layered basalts are derived from low shield volcanoes (lava fields) , 95% of which are emplaced as inflated pahoehoe and whose morphology and permeability exert the dominant controls on aquifer porosity, permeability, and contaminant transport
- Holocene lava fields (ca. 2000 - 15000 years old) and surficial sediments are analogs from which subsurface architecture and aquifer heterogeneity can be inferred

Holocene lava fields on the eastern Snake River Plain.



Stop 3: Hell's Half Acre Interstate Rest Area

Objectives:

- observe mesoscale architecture and features relevant to ESRP aquifer
- identify microscale features of basalt relevant to permeability
- discuss aspects of basalt morphology and scale-dependent permeability
- discuss preferential flow concepts and predictive transport modeling

Cross-section of an inflated lava flow lobe.

Cross-section of a flow lobe's upper collonade showing subhorizontal jointing.

Exercise 3.1: Sketch the hydrologically-relevant features of these outcrops, keying on

a) types and spatial arrangement of porosity within the rock;
b) where contaminants would tend to accumulate and how they would migrate;
c) types of porosity that may develop between older and younger lava flows; and
d) locations of the highest relative permeability (connected porosity) following burial by later basalts.

Aerial view of inflated and partially buried inflated flow units (Junipers for scale).

Exercise 3.2:

a) Aerial views reveal important physical and morphological relationships that constrain conceptual models of the subsurface. What types of morphologic features are evident in this photo that might affect aquifer porosity and permeability?

b) Where would permeability tend to remain highest after burial by successive basalt flows? after burial with sediment?

c) What are the implications for how water and contaminants would move in such an aquifer?

Notes

Notes

Stop 4: Carbon Sequestration Geochemistry, INL Core, and Environmental Geochemistry

Objectives:

a) presentation on carbon sequestration in mafic rocks
b) examine and discuss examples of core from INL bore holes
c) presentation on environmental geophysical monitoring techniques

4.a. Carbon sequestration potential of basins in southern Idaho

Travis L. McLing, Idaho National Laboratory, Idaho Falls, ID 83415

Carbon sequestration is one approach to stabilize or reduce the levels of potentially climate-changing greenhouse gasses in the earth atmosphere. Geologic sequestration is the storage or entombment of carbon dioxide in naturally occurring subsurface geologic formations. Because approximately one third of the carbon dioxide emitted annually in the United States is from point sources, source capture coupled with geologic entombment has high potential to limit emissions. Geologic sequestration of CO_2 occurs via three interrelated processes. Hydrodynamic trapping dominates in short time frames where a distinct supercritical CO_2 rich fluid fills pore space within subsurface media. In the medium-term, solubility trapping becomes important in which the supercritical CO_2 dissolves into subsurface fluids (e.g., formation waters). Mineral trapping can become the dominate sequestration process at longer time-scales where CO_2 reacts with subsurface media to form solid-phase carbonates. The permanence of sequestration by the three trapping processes is the inverse of their trapping time scale. Mineralization trapping offers the most permanent sequestration, hydrodynamic trapping the least. In an ideal sequestration site CO_2 would be permanently stored utilizing multiple trapping mechanisms.

The Idaho National Laboratory and our partners, participate in the U.S. Department of Energy's Carbon Sequestration Partnership program, and are charged to determine the potential of northern Rocky Mountain and Great Plain geologic formations for long-term carbon sequestration. Of particular interest to the Northwest are the mafic volcanic rock and volcanic bounded basins of southern Idaho because they serve as an example of the inherent potential for permanent mineral trapping of large amounts of CO_2 in the abundant basalts of the northwestern U.S. Carbon dioxide injected into the subsurface dissolves in pore-water to form carbonic acid that is neutralized by the weathering of host-rock minerals to produce carbonate and bicarbonate ions (alkalinity) and/or mineral carbonates. For example, the weathering of the calcic component of plagioclase feldspar (a common basalt mineral phase) to calcite and a clay mineral can be written as

$$CaAl_2Si_2O_8 + 2H_2O + CO_2 \quad CaCO_3 + Al_2Si_2O_5(OH)_4$$

The thermodynamics for this reaction indicate that for any CO_2 pressure important for sequestration, the reaction will proceed as written, entombing the introduced CO_2 as solid calcium carbonate. Mineralization potential will be highest in rocks with abundant Ca-, Mg-, and Fe-silicates such as basalt and lowest in rocks poor in these phases (e.g., sandstone). The time frame and extent of mineralization for a given subsurface environment (and hence its mineralization potential) are functions of the weathering rates and the abundance of silicate phases. We are conducting a preliminary assessment of the CO_2 sequestration potential of volcanic rocks and volcanic hosted basins in southern Idaho using The Geochemist's Workbench computer code and a generalized mineral dissolution rate law that we have developed. Simulation results suggest that more that 20 kg carbon m^{-3} of rock can be sequestered in typical basalt. Furthermore, mineral trapping becomes the dominant form of sequestration after approximately 300 years. In addition to considering direct trapping in basalts, we are also considering the potential of basalt as an impermeable cap rock. The simulations indicate that mineralization processes can result in a significant decrease in porosity (and by inference permeability), suggesting that the cap rock seal may become more robust with time in some subsurface environments. Overall, our preliminary assessments based on mineral reactivity indicate that mafic volcanic rocks and volcanic bounded sedimentary basins of southern Idaho and Eastern Washington have significant potential for the permanent sequestration of CO_2.

Notes

4.b. Micro-scale heterogeneity and characteristics of basalt and sedimentary interbed cores

Textures and features of basalt core: Inflated pahoehoe lava flow, top to bottom

Contact between fine-grained sedimentary interbed and fractured, vesicular basalt

Micro-scale heterogeneity involving transitions from highly permeable fractured basalt to low-permeability massive basalt and impermeable sedimentary materials exerts fundamental controls on the direction and rate of ground-water flow. It is even more important to understanding the transport of reactive solutes. Local variations in mineralogy, texture and surface area exert considerable control on chemical reactivity, on microbiologically mediated transformations, and on absorption, precipitation, and diffusion-limited reactions. The local direction of movement of dissolved and colloidal material is controlled by the overall flow field in response to micro-scale heterogenities, but the rate of movement, especially for reactive species, is determined by surface area, mineralogy and the nature of water-rock interaction at the micro-scale.

4.c. Environmental Geophysical Monitoring Techniques

Gail Heath, Idaho National Laboratory, Idaho Falls, ID 83415

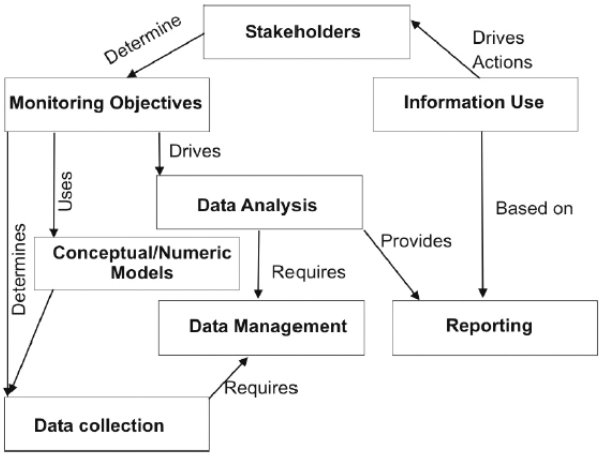
Autonomous monitoring of fluid movement using 3-D electrical resistivity tomography

The electrical resistivity tomography method (ERT) is seeing increasing use in long-term monitoring. Applications might include monitoring of advanced remediation methods, vadose zone fluid-flow monitoring, and monitoring below-ground tanks at the Hanford reservation. For this method to be cost effective, future systems will need to be highly automated. This paper compares different strategies for collecting three-dimensional (3-D) data sets. We discuss the critical design aspects of the system and the importance of using integrated hardware for data collection, and software for data interpretation. An autonomous acquisition system was used to monitor a field experiment at the Idaho National Engineering and Environmental Laboratory. The system was successful at collecting data that were used to monitor infiltration of water into interbedded sediment and basalt layers. The results showed the advantages of autonomous systems for collecting data, and the need for robust operating systems designed specifically for autonomous operation.

Spatial focusing of electrical resistivity surveys considering geologic and hydrologic layering

Electrical resistivity tomography ERT has shown great promise for monitoring transient hydrologic processes. One advantage of ERT under those conditions is the ability of a user to tailor the spatial sensitivity of an ERT survey through selection of electrode locations and electrode combinations. Recent research has shown that quadripoles can be selected in a manner that improves the independent inversion of ERT data. Our ultimate interest lies in using ERT data along with measurements from other sensors, which typically can provide high-quality data from shallow regions of the subsurface, in a joint inversion. As a result, we do not consider the selection of quadripoles specifically for inde-pendent ERT inversion. Rather, we present an approach to focusthe spatial sensitivity of ERT surveys in specific subsurface regions with the assumption that those data, when interpreted along with other measurements that are sensitive to those regions, will lead to more complete hydrologic characterization. Because we are interested in monitoring rapid processes, our approach is designed to efficiently identify optimal quadripoles. This is achieved by separating the optimization from the inversion grid, significantly reducing computational effort. We extend our previous work to consider the use of both surface and borehole ERT electrodes and to consider the impacts of horizontally layered electrical conductivity conditions. Results confirm the ability of the method to focus survey sensitivity while showing the importance of incorporation of prior knowledge of the subsurface electric conductivity structure in designing optimal ERT surveys.

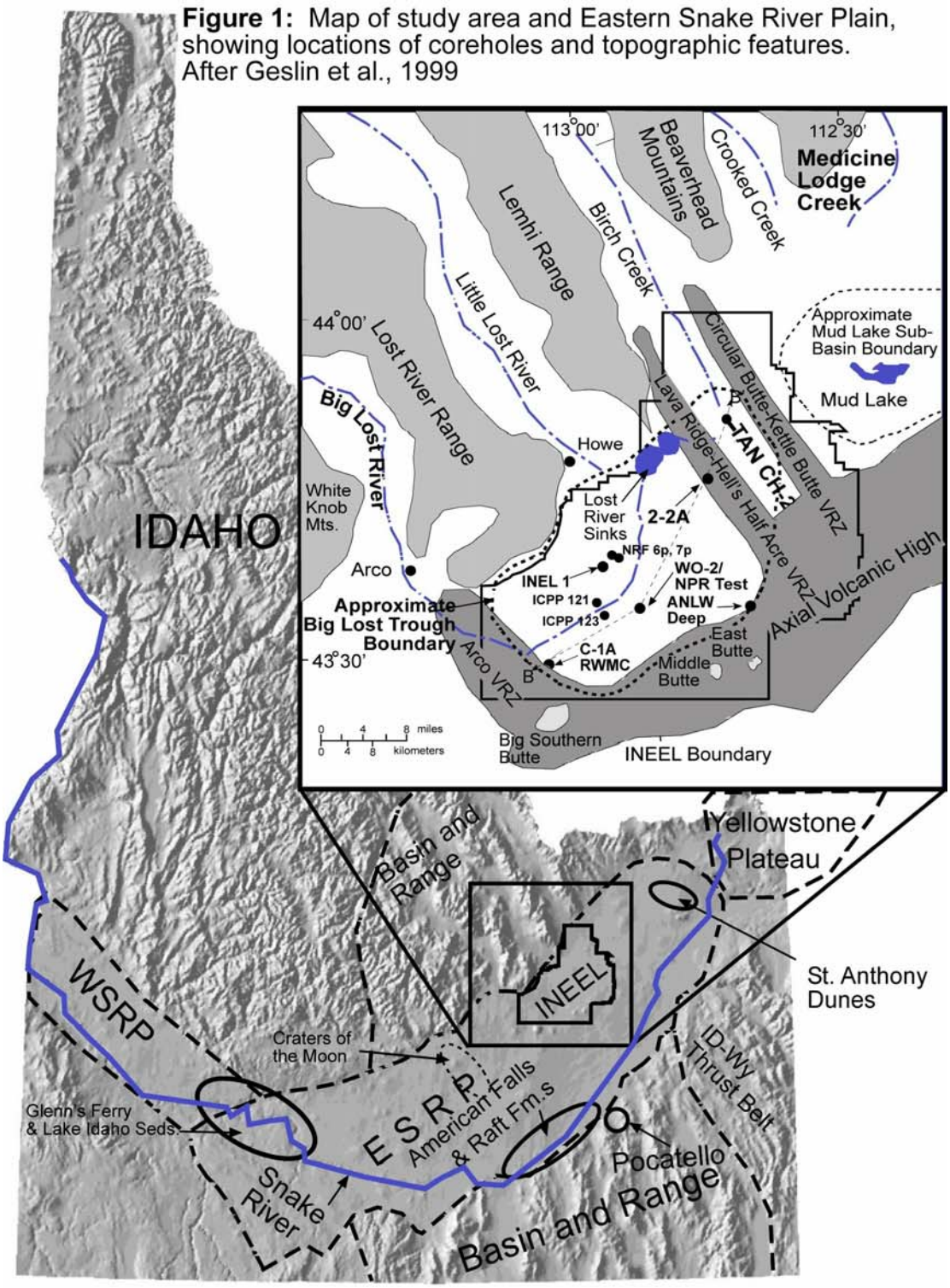
A structured approach to the use of near-surface geophysics in long-term monitoring



Schematic of monitoring system design. All elements are constrained by initial and O&M budgets

Notes

Stop 5: Howe Point Overlook - Volcanic and Morphologic Features of the ESRP



Howe Point Overlook (cont'd)

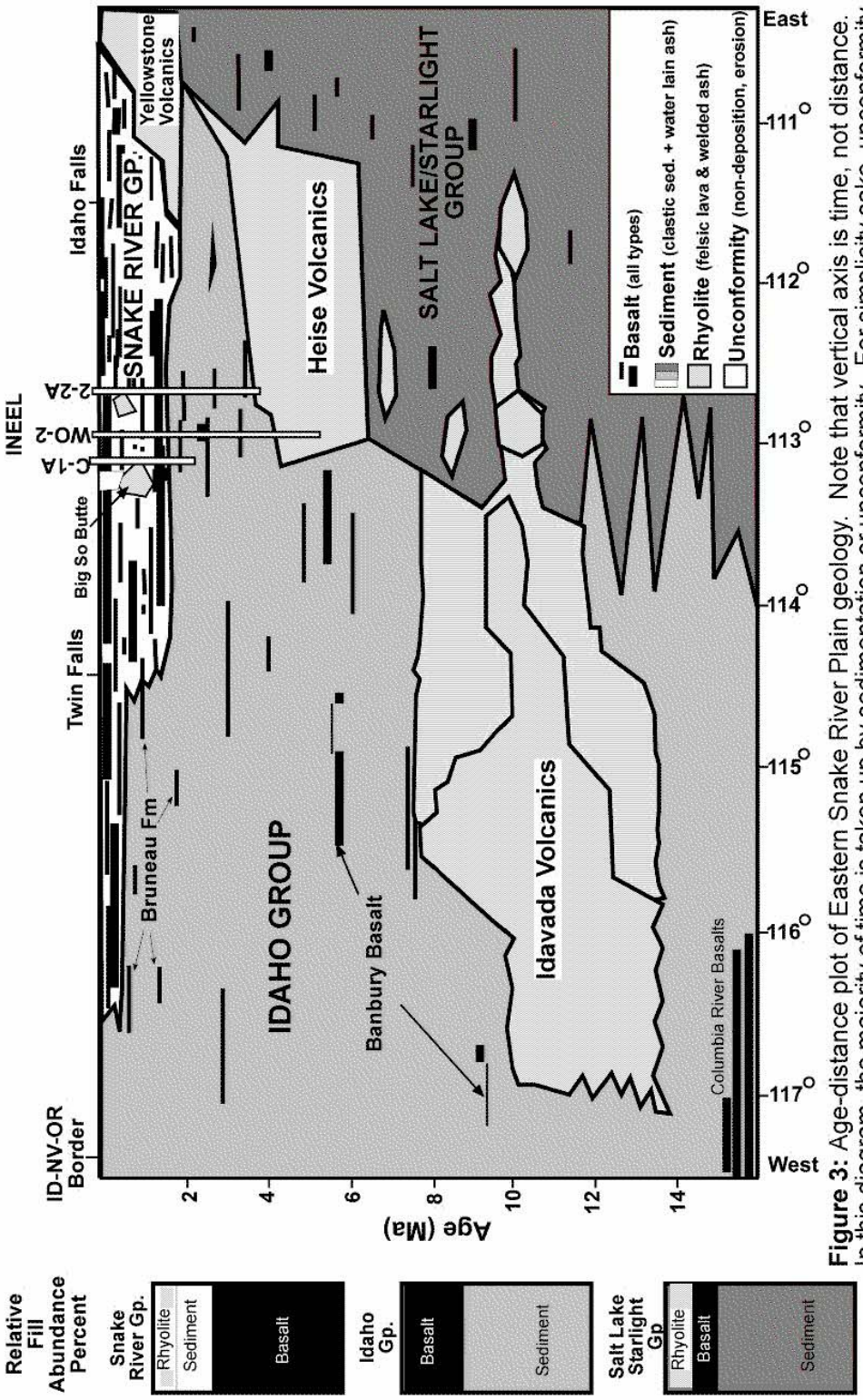
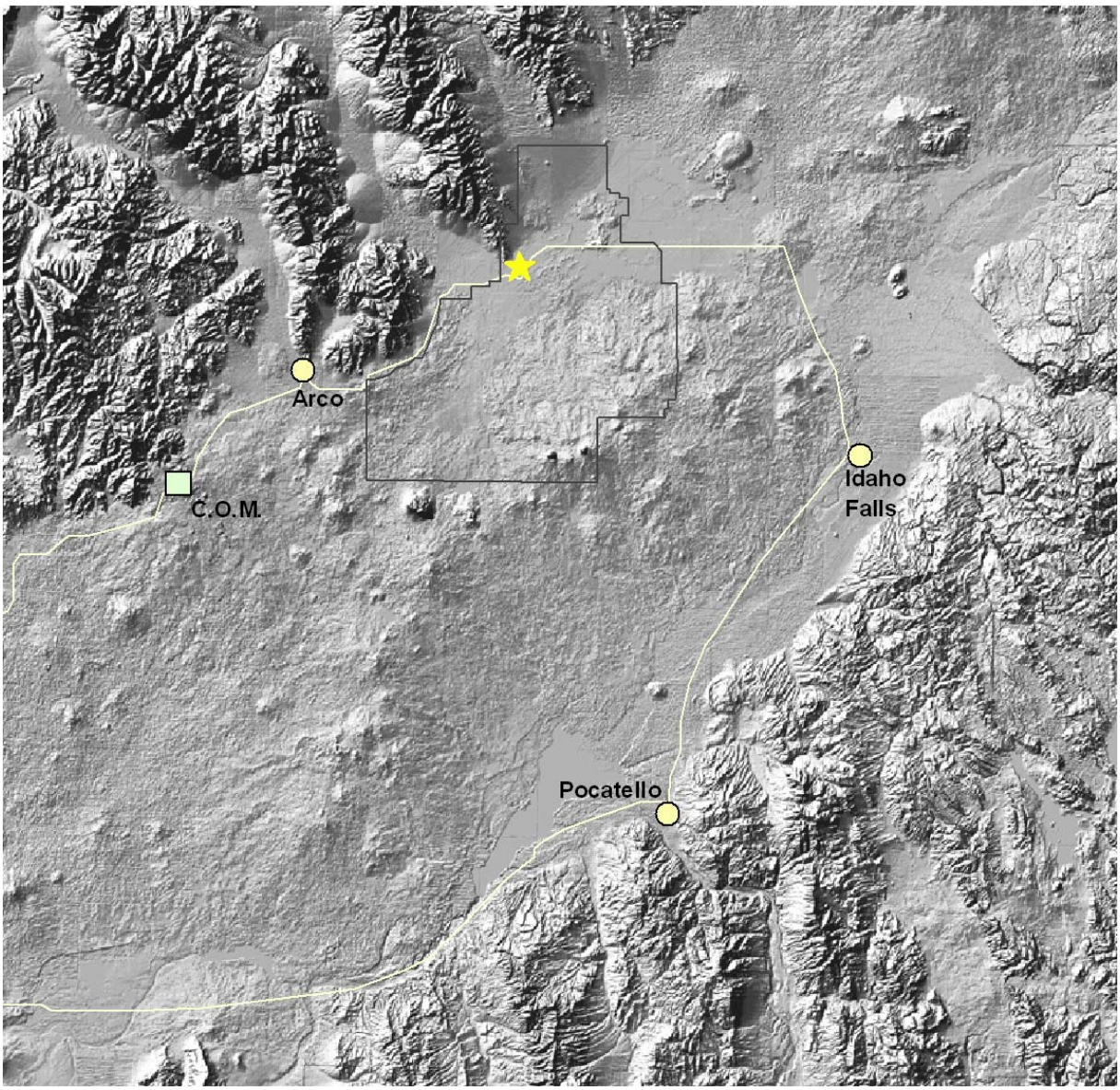


Figure 3: Age-distance plot of Eastern Snake River Plain geology. Note that vertical axis is time, not distance. In this diagram, the majority of time is taken up by sedimentation or unconformity. For simplicity sake, unconformity from within rhyolites, basalts and sediments are not shown explicitly. Relative fill abundance shows the approximate relative amounts of fill-volume percent (vertical axis = lithology) of various stratigraphic groups.

J.J. Blair, 2002, ISU M.S. Thesis

Howe Point Overlook (cont'd)



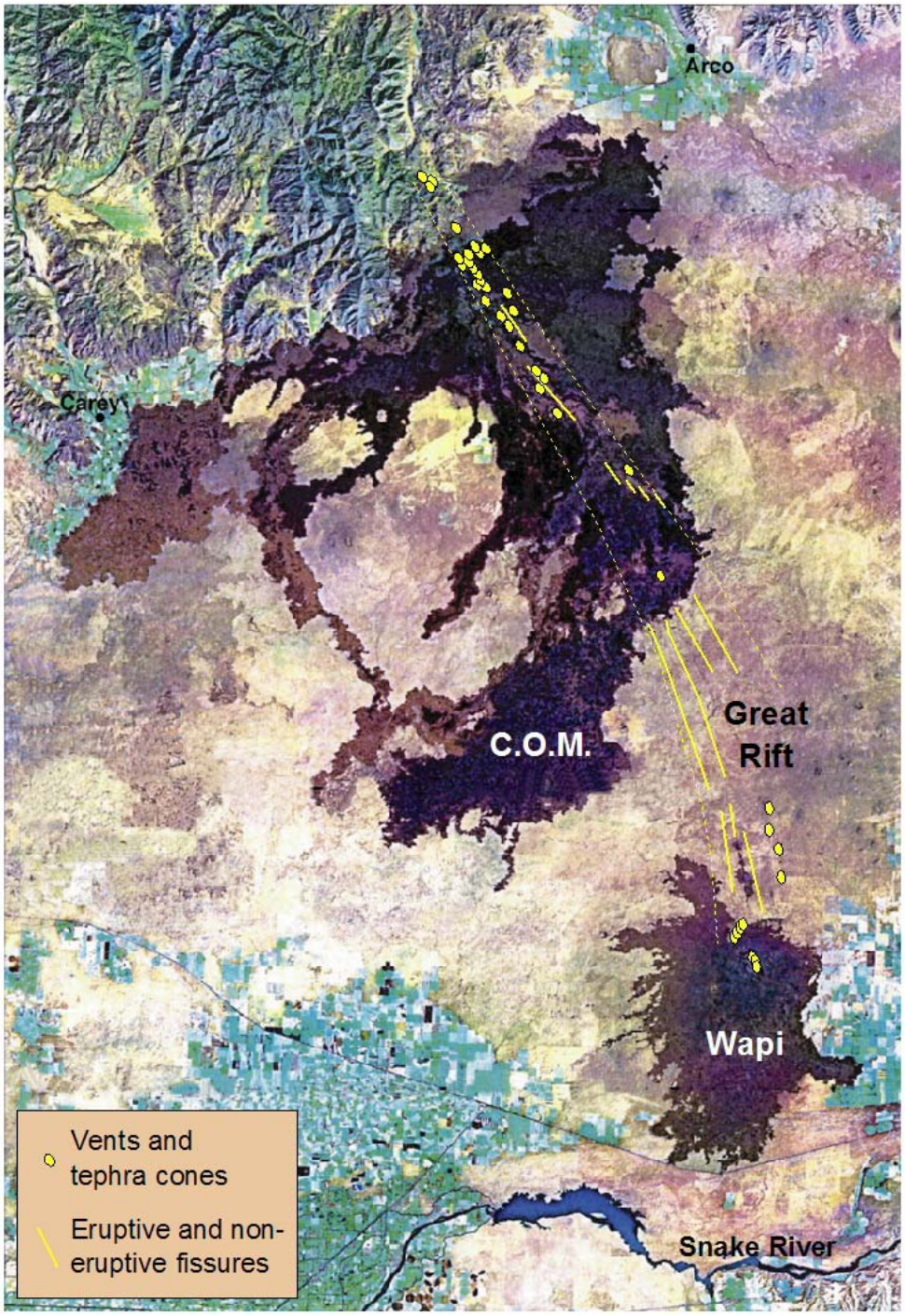
Greatly exaggerated vertical relief reveals characteristic "plains-style" volcanic architecture of the eastern Snake River Plain, comprising hundreds of coalesced shield volcanoes that control fluvial drainage and sediment deposition on the margins of the Plain. Location of the field trip stop is indicated by the star.

Stop 6: Craters of the Moon Overlook

Objectives:

- compare and contrast a polygenetic Holocene eruptive center with Hell's Half Acre
- consider the role of large-scale heterogeneity (dikes, fissures) on groundwater flow

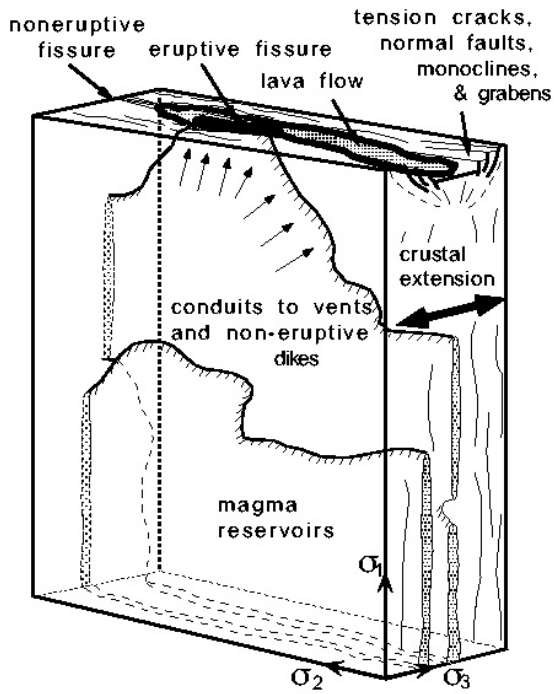
The Great Rift and major volcanic features.



Cinder cones and rafted blocks.

Non-eruptive fissure at King's Bowl.

Conceptual model of dike intrusion and fissure geometry in a rift zone.

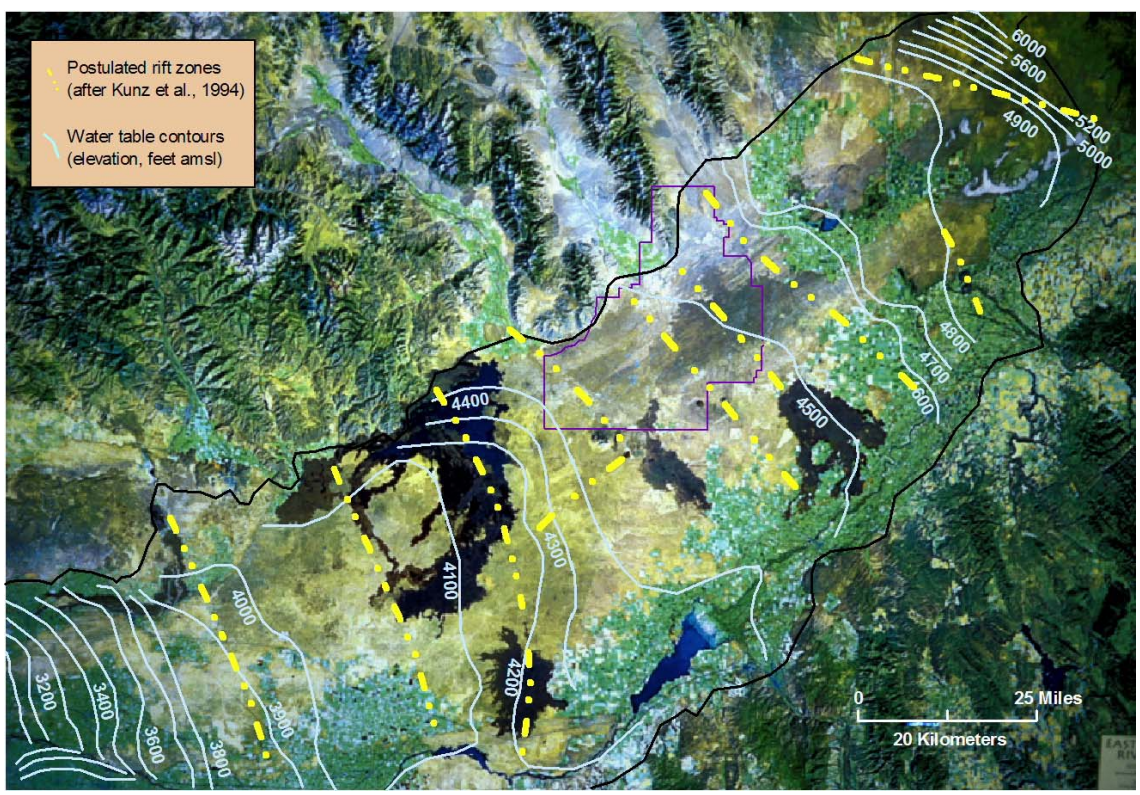


Crustal extension along the axis of the eastern Snake Plain may be the cause of the fissuring observed in major rift zones on the Plain.

Fissuring caused by extension would create natural pathways for the rise of shallow crustal magma and control the formation and geometry of dikes and dike swarms in the subsurface.

Compared to the layered stratigraphy produced by coalesced shield volcanoes and their sub-horizontally oriented preferential pathways, such dike swarms could impart very different hydraulic characteristics to the aquifer in the vicinity of a rift zone. The question is whether the overall effect would be to impede ground-water flow on a regional scale or whether such dike-induced heterogeneity would be offset by higher permeability near-vent facies in the rift.

Relationship of major rift zones (yellow) and water table gradients on the ESRP.



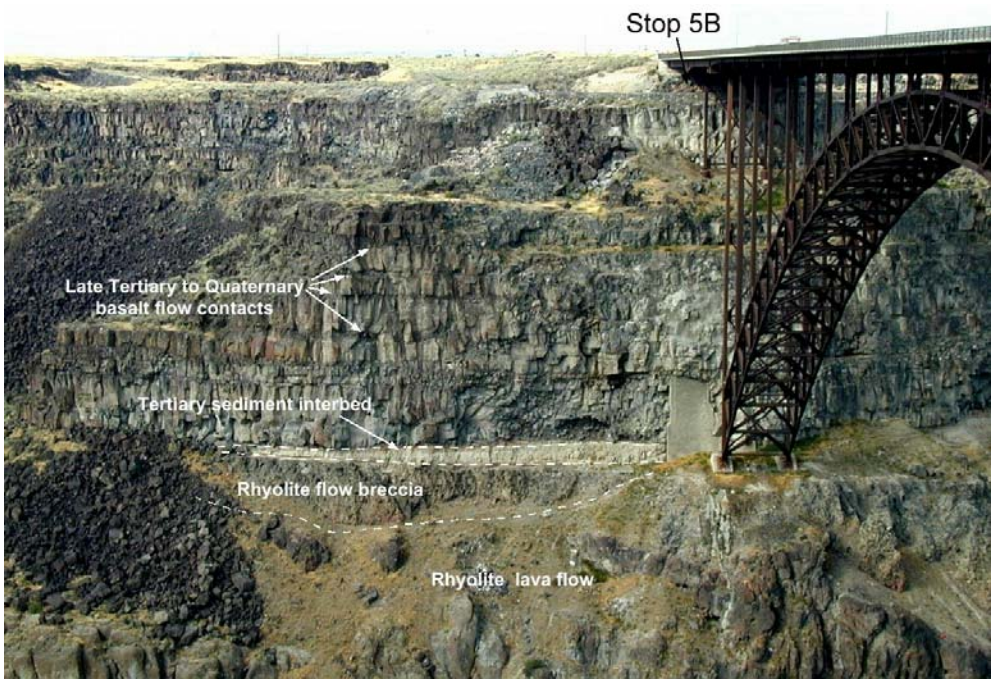
Notes

Stop 7: Snake River Canyon at Twin Falls

Objectives:

- observe large-scale stratigraphic and structural features of the ESRP aquifer
- relate stratigraphic features to the hydrogeology of the aquifer
- observe water-affected basalts ('WABs'), discuss aspects of aquifer hydrogeochemistry, WABs, and water-rock interaction
- discuss 3D and scale-dependent features of these rocks

Views of layered basalt / sedimentary interbed stratigraphy

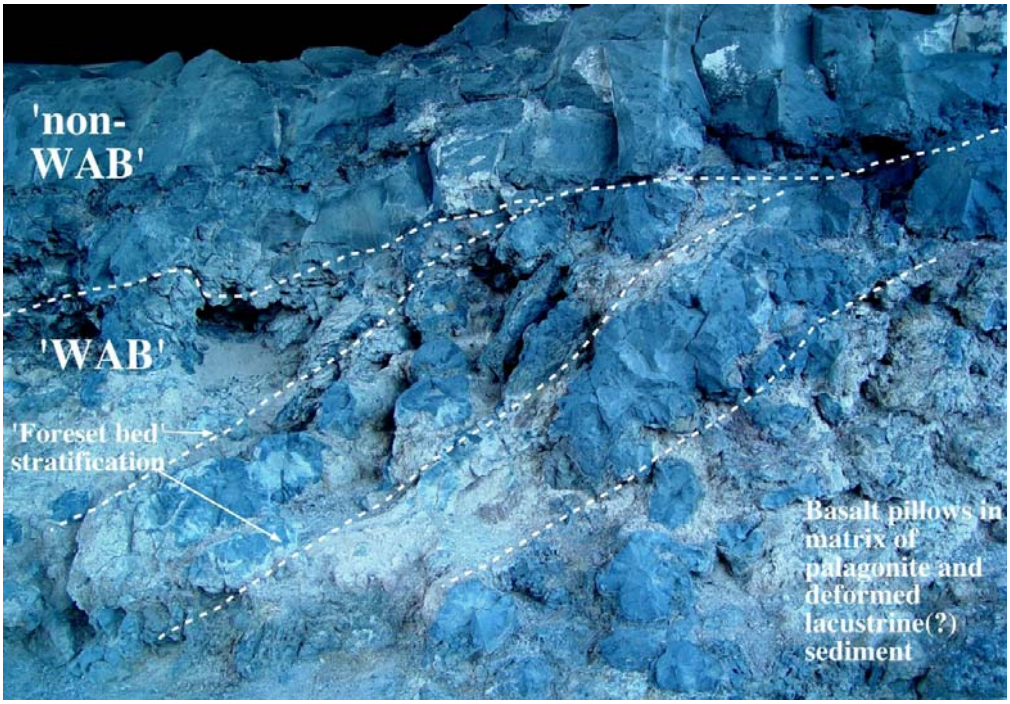


Exercise 7.1

a) Describe features of the aquifer framework at this scale that were not apparent at Stop .3

b) This outcrop face is an excellent analog for the ESRP aquifer. Describe the kinds of problems faced in measuring and predicting ground water and contaminant movement in such an aquifer.

Outcrop of water-affected basalt.



Exercise 7.2

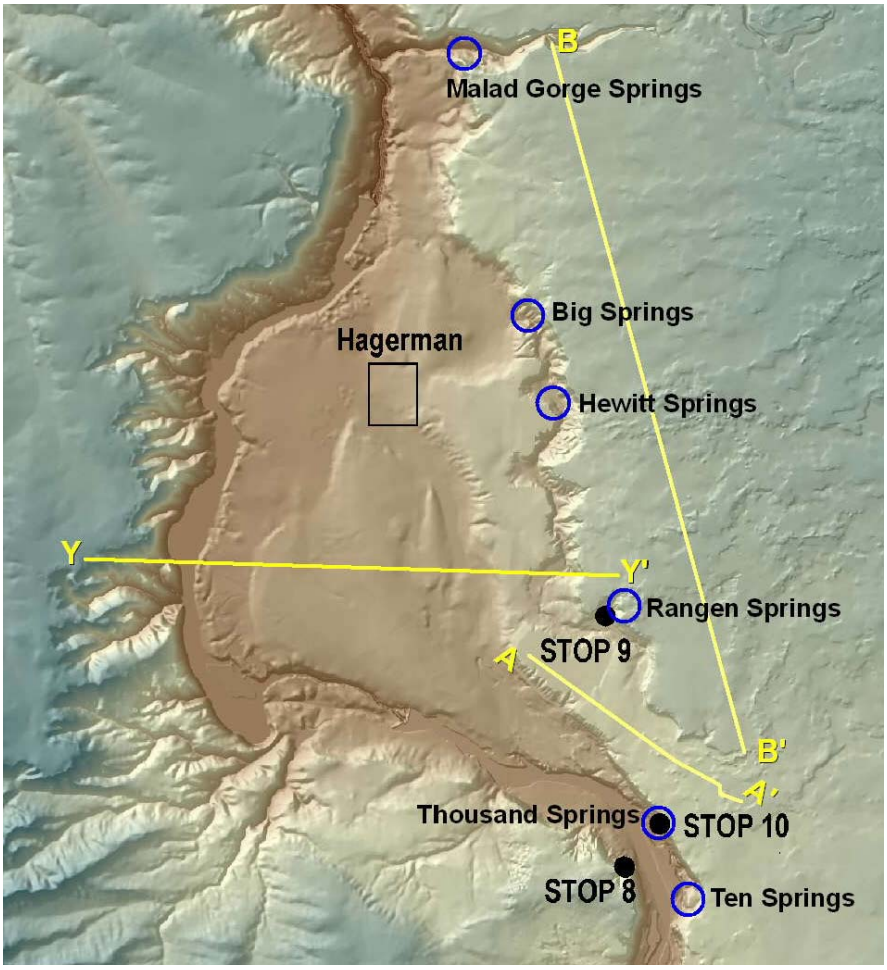
Rock alteration can significantly affect the hydraulic and geochemical properties of the original rock. Based on your observations at this location, describe how alteration occurring during interaction with water-rich sediment could change the geochemistry of typical ESRP basalts and their hydrogeochemical impact on ground water flowing through them.

Stop 8: Sligar Hot Springs Rest Area Across the Snake River from Thousand Springs

Objectives:

- obtain an overview of the Thousand Springs ground-water discharge system in the context of the Hagerman valley's geology and structure
- formulate hypotheses about the mechanisms controlling spring discharge in this and other spring complexes in the Hagerman valley

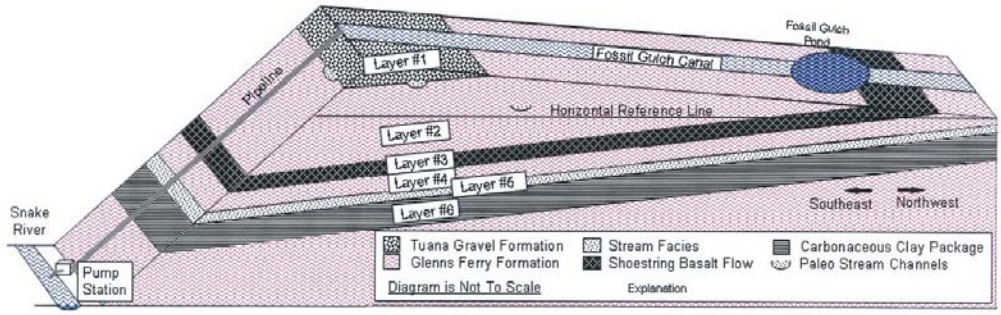
Shaded relief map of the Hagerman valley showing some of the spring locations



Background:

The Hagerman valley is an approximately six square mile expanse of Snake River flood plain bounded by steep canyon walls on the west and basalt cliffs on the east. The valley is bounded by very different geology on the east and west sides of the Snake River. The fine-grained sediments of the Glenn's Ferry Formation dominate the stratigraphy on the west side of the valley, acting as impediments to ground water flow, with intercalated basalt lavas and buried fluvial channel facies acting as hosts for preferential ground water flow within the low-permeability sediments of the Glenn's Ferry Formation.

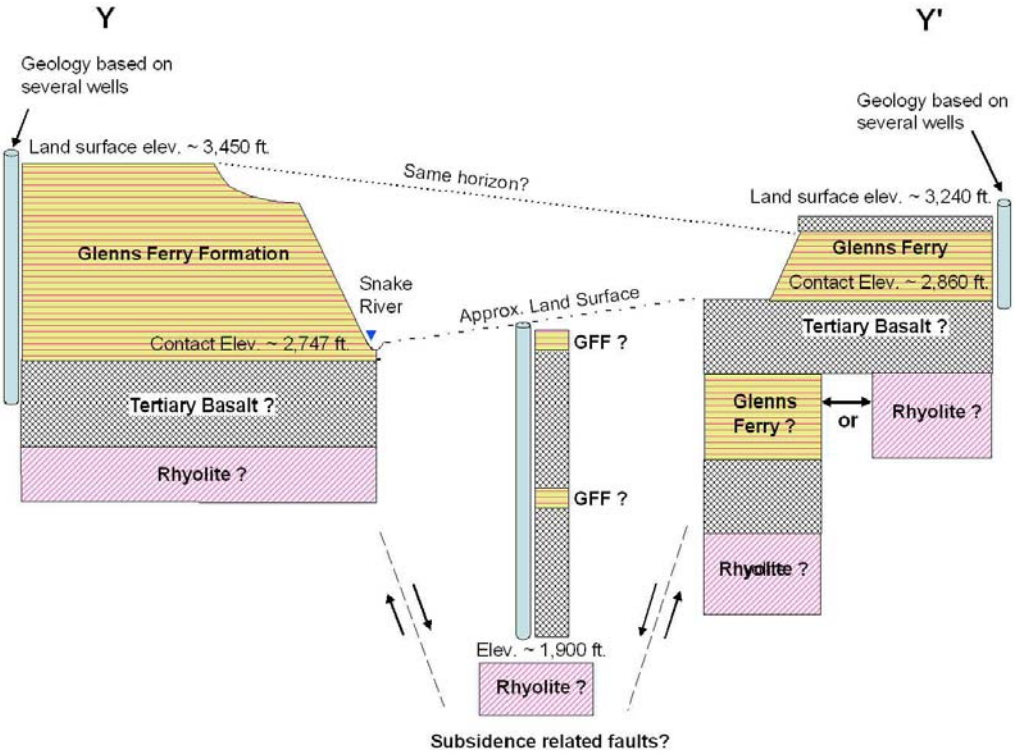
Conceptual hydrogeologic model, south side of Snake River (view looking south).



(after Neal Farmer, 1998, Univ. Idaho M.S. thesis)

In addition to the impacts of outcrop- and larger-scale heterogeneity seen in the basalt-dominated ESRP aquifer, ground water flow is controlled by even larger-scale heterogeneity, such as where the fine-grained, low permeability Glenn's Ferry sediments interfinger with the highly permeable basalts on the east side of the Hagerman valley (see cross-section Y-Y', below).

Conceptual geologic cross-section Y-Y' through the Hagerman valley.



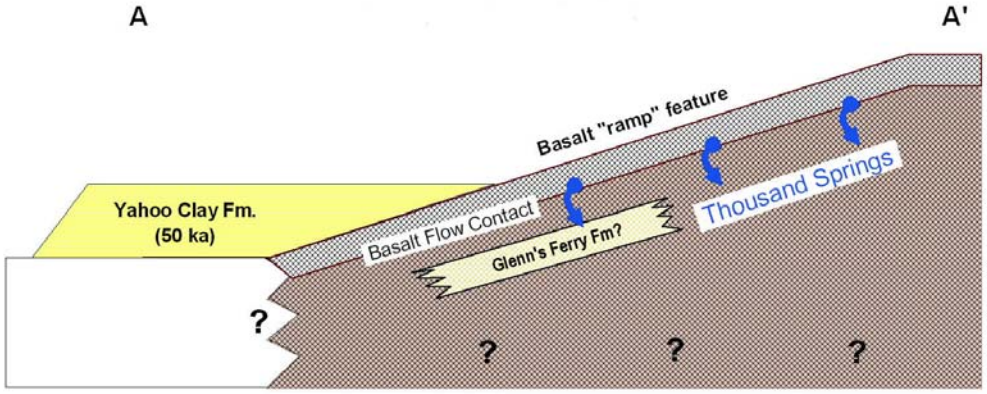
(courtesy of Neal Farmer, IDWR)

Snake River canyon rim looking east, showing some of Thousand Springs discharge from the upper contact of a northwest-dipping basalt lava flow group.

(courtesy of Neal Farmer, IDWR)

As well as being a zone of lithologic and stratigraphic change, the Snake River has downcut and exposed the ESRP ground-water flow system in the Hagerman valley, creating some of the largest natural springs in the U.S. (collectively known as the Thousand Springs area, but comprising many individual spring complexes such as Ten Springs, Thousand Springs, Malad Gorge Springs, etc.). The valley is a topographic depression displaying tantalizing clues that suggest the valley may be structurally controlled or possibly the geomorphic expression of the interplay between weathering, fluvial erosion and volcanism.

Conceptual cross-section A-A', through the northwest-dipping basalt "ramp"



(courtesy of Neal Farmer, IDWR)

Notes

Stop 9: Glenn's Ferry Outcrop at Vader Grade Pull Out

Objectives:

- compare and contrast the nature of geologic heterogeneity here with what you have observed in the basalt-dominated eastern Snake Plain aquifer
- consider scale-dependent features of basalt and sedimentary heterogeneity that control ground water motion through the aquifer where it interfingers with sediments of the Glenn's Ferry Formation.

View of Glenn's Ferry Fm. at two spatial scales: Basalt overlying fine-grained sediments at Vader Grade (foreground), and steep cliffs across the Hagerman valley (background).

(courtesy of Neal Farmer, IDWR)

The Glenn's Ferry sediments impart a striking hydraulic contrast to the basalts' high permeability and, like almost all sedimentary interbeds intercalated within the aquifer's basaltic stratigraphy, have a marked effect on ground-water flow rate, direction and, when water levels are low, spring discharge.

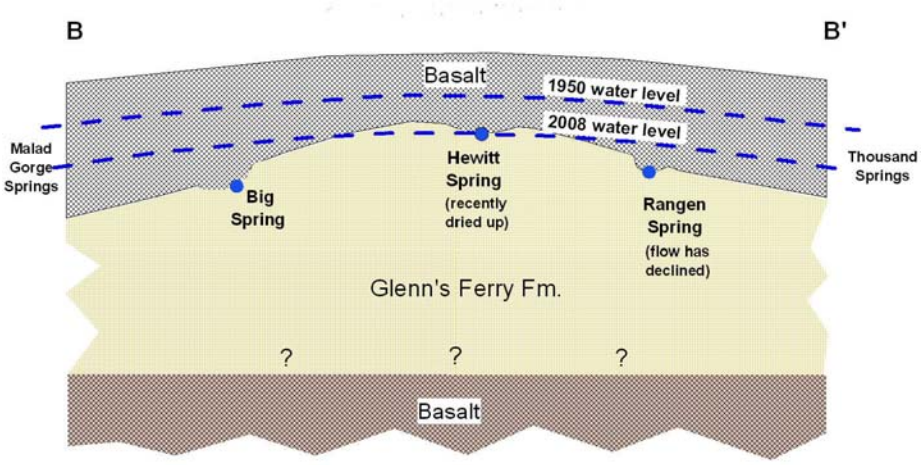
Because Glenn's Ferry sediments were deposited in a lake environment, they tend to be fine-grained, low permeability, and have high reactive surface area compared to the basalts. In areas where basalt erupted onto these wet lakeshore sediments, "water-affected basalts" were formed at the base of lava flows (e.g., as at Perrine Bridge).

Basalt lava flow overlying "WAB" pillows and Glenn's Ferry sediments at Veenstra Dairy

(courtesy of Neal Farmer, IDWR)

Of particular interest to ground-water users and managers is the decreasing flow that has characterized the springs in Hagerman valley, where ground-water discharge has decreased by more than 40% since 1950 as aquifer water levels have dropped. Glenn's Ferry sediment within the basalt aquifer may have much to do with this (N. Farmer, pers. comm., 2008). Well logs in and around the Hagerman valley reveal that the Glenn's Ferry Formation on the east side of the valley has a bowed upper surface, either a paleo-topographic or a structural (anticlinal) feature, that may affect the local water table and may also explain why the highest elevation springs have experienced the greatest decline in discharge.

Conceptual cross-section B-B', showing how some springs are more susceptible to drought.



(courtesy of Neal Farmer, IDWR)

Notes

Stop 10: Thousand Springs

Objectives:

- observe outcrop-scale hydrogeologic features that characterize the ESRP aquifer
- relate mesoscale hydrogeology to the larger stratigraphic context of regional flow
- wrap up field observations and discuss implications

View of basalt outcrop, showing locus of ground water discharge relative to lava flow lobes.

Exercise 10.1

a) describe the rock textures and structures that you observe at this outcrop
b) sketch geologic features of the outcrop, particularly
    - lava flow lobes' shape and lateral continuity, and the contacts between flows
    - fractures, vesicle-rich zones, and rubble zones
    - locations of ground-water discharge relative to these features

Notes

Wrap-Up Discussion Points:

a) Compare your observations of micro- and mesoscale features that control gound-water flow, as seen at Stops 3 and 7-10.

b) How would you conceptualize and describe the nature of ground water flow in the ESRP aquifer?

c) How would you conceptualize and describe the nature of ground water flow in the west (sediment-dominated) side of the canyon.

c) How would the migration of dissolved contaminants differ during transport on the east and west sides of the Hagerman Valley?

c) How similar or different would your instrumentation have to be in these two different aquifers, in order to:
   - accurately determine hydraulic properties of the aquifer
   - determine ground-water flow rate and direction among wells 20 m apart
   - characterize water quality and rate of contaminant movement
   - monitor, model, and predict transport?