

# **HYDROGEOLOGY OF CONFINED, IDAHO GROUP-HOSTED AQUIFERS AND OVERLYING GRAVELS NEAR GREENLEAF, CANYON COUNTY, IDAHO**

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## **INTRODUCTION**

Greenleaf, an incorporated community of over 800 residents, lies in the interior of the western Snake River Plain, in Canyon County, Idaho (Figure 1). The town derives domestic water from two wells that penetrate confined aquifers in the upper part of the Neogene Idaho Group. This report summarizes results of a study to assist Greenleaf in expanding its water supply with additional ground water. It was completed by the Idaho Water Resources Research Institute's (IWRRI) Technical Assistance for Rural Ground-Water Development in Idaho project

Figure 1 near here

## **STATEMENT OF PROBLEM**

Several factors impact some uses of ground water in the Greenleaf area. These include elevated concentrations of arsenic, fluoride, manganese, iron, organically derived gas, and elevated temperature. The IWRRI project team was initially asked to study the issue of smelly water at Greenleaf because the community planned to drill a new well in the fall of 2003. Understanding the concentration and distribution of arsenic and other dissolved constituents in ground water is important in locating and constructing a new well of the city. We undertook this study to provide the city with technical information that will enhance the possibility of a successful drilling program.

## **OBJECTIVES**

This study was undertaken for several reasons:

- To define the source aquifers from which Greenleaf draws water,
- To analyze the stratigraphy that hosts confined aquifers in the Greenleaf area,
- To study the distribution of naturally occurring constituents such as organically derived gases, arsenic, and other metals,
- To locate potentially clean aquifers,
- To understand potential geometries and flow paths of thermal water and its impact on ground water.

## **GROUND WATER DEVELOPMENT CONCEPTS**

Ground water occurs and moves through interconnected fractures and intergranular pore space in an aquifer. It moves under the force of gravity in an aquifer from higher elevation recharge areas to lower elevation discharge areas. Most recharge results from infiltration of precipitation, though some occurs from streams and lakes at elevations higher than the water table. Typical discharge areas include springs, streams and lakes. Ground water moves slowly, generally less than 10 feet per day.

Subsurface geology provides strong controls on water movement within an aquifer. Therefore, an understanding of the subsurface distribution of unlithified sediment, lithified rock, faults, and their physical properties generally leads to a commensurate understanding of ground water flow systems.

Mapping surface rock outcrops and reviewing logs of material penetrated by wells helps interpret these features.

The basis for proper ground water development requires characterizing natural ground water discharge from springs and seeps, knowing the discharge of interconnected streams, and understanding the quantity and location of annual aquifer recharge. Sustainable well development requires less ground water use than aquifer recharge because removal of water results in water level decline with an associated reduction in natural discharge. Additionally, municipal water supplies need a recharge zone protected from contamination because contaminants can mix with ground water and degrade the municipal supply.

## **GEOLOGY**

### **REGIONAL GEOLOGY**

Greenleaf lies near the center of the western Snake River Plain (WSRP), an intracontinental rift basin formed in Neogene time. Numerous geological studies have been completed, including those of Wood and Clemens, 2003; Wood, 1994; Othberg 1994; Kirkham, 1935; Newton and Corcoran, 1963, Wood and Anderson, 1981; Malde and Powers, 1962, and Malde and Powers, 1972. Fine-grained siliciclastic sediments of the Idaho group fill the basin and reach a thickness of over 6500 feet. Several deep gas and hydrothermal exploration wells in the WSRP show that Miocene basalt underlies a several thousand-foot-thick section of lacustrine Idaho group strata. Dissected gravels remaining from extinct river systems lie disconformably above the Idaho Group sediments and cap terraces throughout the WSRP. Othberg (1994) correlates similar gravels immediately south of

Greenleaf with the Ten Mile Gravel sequence. These gravels directly underlie a thin mantle of surficial sediment throughout much of the area.

The WSRP has been recognized as an area with elevated subsurface temperature. Contoured measurements by Brott and Blackwell (1976) show elevated heat flow along both the northeast and southwest margins of the basin (Figure 2).

Figure 2 near here

### **PROJECT AREA GEOLOGY**

Knowledge of the area geology is based mostly on well log information and results from geophysical studies. Wood (1994) used high-resolution seismic data to identify a lacustrine delta within Idaho Group strata between Greenleaf and Caldwell. The top of the deltaic sequence lies at a depth of about 1000 feet below ground surface. The delta prograded from southeast to northwest into an 800-foot-deep lake basin (Figure 3; Wood, 1994). Water-wells in the Greenleaf area generally do not exceed 1000 feet of depth, so the upper surface of the deltaic sequence represents the bottom of the section discussed herein.

Figure 3 near here

The top 1000 feet of strata, above the deltaic sequence, consists primarily of unlithified clay and silt beds with local interlayers of fine to medium-grained sand and pea gravel. We studied lithologic logs from 69 drill holes in T4N R4W (IDWR records repository) in order to define the subsurface distribution of strata in the Idaho Group. Of the drill holes studied 24 are located on the active flood plain of the Boise River; the remaining holes lie on the Greenleaf bench to the

south. These sediments probably accumulated in environments representing ephemeral lakes, meandering rivers and on flood plains.

The well logs define the distribution of oxidized sediments, which is important when making stratigraphic correlations between drill holes. The contours in Figure 4 show the depth and shape of the base of surface oxidation; the relevance of this is discussed below.

Figure 4 near here

### **STRATIGRAPHY**

Bed forms such as large-scale climbing dunes, displayed in exposures of strata on the escarpment north of Greenleaf, show that the top part of the Idaho Group section was eroded and redeposited by wind prior to deposition of the overlying Ten Mile gravels (Figure 5). This photograph shows that the lower boundary of oxidation occurs at the interface between lacustrine beds and unconformably overlying eolian beds. Erosion and redeposition by wind may have caused the upper surface of the Idaho Group to oxidize previous to deposition of the Ten Mile gravels. If so, the contours on the base of oxidized material, shown in Figure 4, may indicate the distribution of windblown sediments. A number of drill holes in the southern part of the township contain similar oxidized beds up to 60 feet thick below and within the gravel sequence. Mapping by Othberg (1994) correlates strata exposed at surface with slack-water deposits from the Bonneville flood. The presence of eolian beds within and below the Ten Mile gravels, however, suggests that the Bonneville flood probably did not deposit some of these strata.

Figure 5 near here

We studied the lithologies of the upper 1000 feet of the Idaho Group in water-well logs and attempted to define the distribution of correlative strata between holes. This analysis resulted in defining four intervals of coarser clastic sediments within the generally clay-rich sequence, which appear to correlate throughout township 4N 4W (Plate 1). We have labeled these clastic sequences, from top down, A1, A2, A3, and A4. There are a number of assumptions that underlie our correlations:

Sedimentary strata exposed along the Greenleaf bench show an undeformed flat-lying section (Figure 5). Seismic data analyzed by Wood (1994, his Figure 7) show that the beds to a depth of at least 2500 feet in adjacent areas are also flat lying. Our correlations, therefore, assume that the beds cut by drill holes that we studied are also flat lying. Therefore strata at similar elevations correlate temporally.

We recognize that strata deposited on flood plains and by rivers show facies transitions depending on lateral variations in depositional environments. For instance, coarse gravel may represent the axis of a river channel in the stratigraphic section while temporally correlative strata accumulated on the flood plain would form sand-rich silt deposits. Even further from the river channel silt-rich clay would represent the correlative section, and thence to clay beds. Where evidence permits we have accommodated such facies variations in our correlations.

Sandy and gravelly sediments universally transmit higher volumes of ground water than clay beds. We assume that the

coarser grained clastic sequences defined herein transmit significantly more water than the confining sub- and superjacent clay beds.

#### A4 Clastic Sequence

The A4 clastic sequence lies at an average elevation of 1880-1900 feet above mean sea level (MSL). Only seven drillholes penetrate these strata, so due to limited data A4 is poorly understood (Table 1). Primary lithologies include pebble-gravel beds and black sand intervals. The Dean Fry well in Section 22 (Plate 1) cuts the A4 aquifer between 1938 and 1885 feet elevation, and then penetrates deeper pea gravel beds at 1770-1785 feet elevation. A proposed well at Greenleaf in section 21 would need to penetrate  $\pm 640$  feet of section to fully cut these coarser clastic strata.

#### A3 Clastic Sequence

At least 17 wells intersect strata of the A3 clastic sequence, which lies at an average elevation of 2120 feet above mean sea level (Table 1). Most holes that cut this sequence indicate that it is composed of fine- to medium-grained sand beds, though the Johnson well in section 2 bottomed in a 16-foot-thick section of pebble gravel. The entire sequence occurs well below the deepest level of surface oxidation.

#### A2 Clastic Sequence

A2 is intersected by 30 drill holes and has an average elevation of 2290 feet above MSL (Table 1). It lies entirely below the level of surface oxidation and is confined by clay-rich lacustrine strata. It is generally composed of fine- to medium-grained black sand beds concentrated within the

generally clay-rich section. This is the highest of the confined Idaho Group aquifers in the Greenleaf area.

### A1 Clastic Sequence

The A1 section consists of river gravels that lie unconformably on the Idaho Group and underlie much of the present erosional surface on the Greenleaf bench. The gravels that occur in most of the drill holes on the bench probably correlate with the Ten Mile Gravel of Othberg (1994). It is generally not possible with logs of holes on the flood plain of the Boise River to distinguish gravels deposited by the present Boise River from those deposited by ancestral streams. The elevation of the A1 sequence ranges from its base on the Boise River flood plain at  $\pm 2240$  feet to its top on the Greenleaf bench of  $\pm 2550$  feet. It has a maximum thickness of about 60 feet.

The Boise River probably deposited the surficial gravels in holes nearest the river. Logs from other holes further from the river but still on the flood plain indicate the presence of a down-faulted section of the Ten Mile gravels. This interpretation is based on the presence of oxidized sediments below, within, and above the gravel section that are lithologically similar to strata exposed along the upper edge of the Greenleaf bench (Figure 5) and in holes on top of the bench (Plate 1).

### **STRUCTURE**

Regional deep-seated structural fabrics form during major tectonic events and then often get inherited during later tectonism. Some of these deep-seated and long-lived zones of crustal weakness may provide the structural architecture of the western Snake River Plain and may also control hydrothermal

fluid circulation, which generally occurs along vertically transmissive zones. The following paragraphs discuss the history and orientations of some important structural grains that occur in rocks adjacent to and perhaps beneath the Snake River Plain, in the northern Basin and Range province. The purpose of this discussion is to provide geometric context to geochemical and geothermal patterns that are present at Greenleaf, and in the western Snake River Plain.

#### Regional northwesterly structural fabrics

A number of structural fabrics occur in rocks of the northern Great Basin. Sedimentological features that form when strata originally accumulate dates the earliest known movement on the structures. Proterozoic and/or lower Paleozoic ages of earliest movement are not uncommon for many of these regional zones.

North central Nevada's Carlin Trend forms the largest accumulation of gold deposits in North America (Teal and Wright, 2000), and is one of the world's largest gold-producing districts. The approximately 36 mile-long axis of the district trends  $\pm$  North  $40^\circ$  West, parallel to the margins of the WSRP. The Carlin district hosts a number of northwesterly faults that form a broad zone of crustal weakness with sustained high heat flow (Teal and Wright, 2000). Similarly oriented structures occur throughout the northern Great Basin. The distribution of sedimentary facies across these structures and intrusions along them show that these zones have been active since at least lower Paleozoic time.

Mapping by Otto (in press and unpublished mapping) defines a North 60 to 70 West-trending structural zone that controlled lower, middle and upper Paleozoic sedimentary facies along a

zone that traverses over 150 miles through north central Nevada. Many of the large gold-producing mines in northern Nevada display structures that parallel this fabric and control the grade distribution of Tertiary-age ore, suggesting that this structural orientation was intermittently active throughout Phanerozoic time. Similar North 70 West-trending structural zones occur throughout the interior northwest. Some of these include the Lemhi Pass fault zone near Salmon (Staatz, 1979) the Volcano Valley fault system in central Montana (Cominco, unpublished mapping) and the Coeur d' Alene mining district (Hobbs and others, 1965). The Volcano Valley fault zone shows movement as early as middle Proterozoic time.

#### Regional northeasterly structural fabrics

An extensive array of northeast-trending shear zones suture Archean cratonic rocks together to form the Precambrian North American shield. O'Neill (1985; 1990) suggests that the northeasterly trending Great Falls Tectonic Zone in southern Saskatchewan and central Montana represents a Proterozoic-age suture zone between an early Proterozoic terrain and Archean metamorphic rocks. The Great Falls tectonic zone passes southwesterly into Idaho near Salmon, and continues southwesterly as the Trans-Challis fault zone to the northeast margin of the Snake River Plain near Middleton, an overall strike length of nearly 600 miles. The structure shows recurrent movement from middle Proterozoic to Holocene time (O'Neill, 1990). Along its path the tectonic zone controls the distribution of numerous important mining districts, including Butte in Montana, and in Idaho, the Salmon, Leesburg, Blackbird, Casto, Yankee Fork, Stanley, Boise Basin, and the Pearl-Horseshoe Bend gold belt. These historic districts

produced gold, silver, cobalt, copper, and fluorite. Abundant arsenic-bearing minerals occur in each of these districts (Otto, unpublished mapping).

The Trans-Challis fault zone has not been identified to the southwest beyond the northern margin of the WSRP. It is unlikely, however, that a tectonic zone of this extent would end abruptly. Indirect evidence suggests that the zone does continue beneath the plain and has simply been buried by younger strata. This evidence includes the location of a lacustrine delta defined by Wood (1994), by the distribution of regional heat flow (Figure 2; Blackwell, 2003), by a peculiar morphology of the Boise River Valley at Caldwell (Figure 6), and from northeasterly trending structural geometries in the Greenleaf area.

Figures 5 and 6 near here

The delta described by Wood (1994) formed at the southwest end of a Pliocene lake where it prograded northwesterly across an 800-foot deep basin margin over a relatively short horizontal distance. If the margin of this lake were not fault controlled it is unlikely that the lake would deepen so abruptly in this clay-rich environment. Additional structural geometries near Greenleaf suggest that northeasterly trending faults pass beneath this area. These features include apparent stratigraphic offset in the Ten Mile Gravels along a northeasterly trend (Plate 1), occurrences of hydrothermally altered strata in wells (Plate 1), and anomalously high temperatures in selected wells (Figure 4; Plate 1). These features describe a northeasterly orientation that parallels the projection of the Trans-Challis fault zone.

These three primary structural fabrics occur in the western Snake River Plain (Wood and Clemens, 2003; Blackwell, 2003). The North 40 West-trending fabric forms the exterior basin margins that Wood and Clemens (2003) ascribes to a zone of preexisting lithospheric weakness. This zone parallels the lower Paleozoic Carlin-Trend fabric in Nevada, indicating a long-lived ancestry. Wood and Clemens (2003) discuss a North 70 West-trending zone that localizes mafic volcanic vents in the interior of the western Snake River Plain. This zone also parallels the long-lived structural fabric that occurs throughout the northwestern United States. Heat flow data, discussed below, define a prominent northeasterly pattern within the basin that lies parallel to the Trans-Challis fault zone. Though parallelism is not proof of complicity it is certainly prima facie evidence worthy of further study.

#### Structural control of regional heat flow

Contoured heat flow data indicate that the WSRP shows anomalous heat along both of its northwesterly trending margins (Brott and Blackwell, 1976). We contoured more recent and comprehensive heat-flow data acquired from Blackwell's web site (2003) and recognize that in addition to heat flow along the basin margins there are northwesterly and northeasterly trending zones within the basin interior that show steep thermal gradients (Figure 2). One such zone follows a trend that extends southwesterly from the last known location of the Trans-Challis fault zone, southwesterly through the Caldwell-Greenleaf area and into Owyhee County. Additionally, we recognized a steep North 40° West trending thermal gradient that underlies Caldwell and Nampa. It parallels the basin margins, but is located well within it's interior. These two zones and

other similar zones to the southwest form a rectilinear pattern, (Figure 2).

According to Blackwell (1983) geothermal systems in the northern Basin and Range province appear to be related to deep fluid circulation in active tectonic settings rather than to young silicic volcanic rocks. The rectilinear pattern defined by heat flow in the WSRP suggests such a deep-seated structural control. Kiilsgaard (1990) recognized that many hydrothermal veins within the northeast-trending Trans-Challis fault system occur along steep northwesterly structures within the overall northeast trend. He suggests that the veins formed by hydrothermal fluid circulation through dilated zones that were caused by differential slip along the two fault systems. A similar structural mechanism may explain the orientation and focus of heat flow in the western Snake River Plain where deeply buried northeasterly trending faults intersect and dilate the northwesterly faults, or vice versa.

#### Greenleaf area structure

The northwesterly trending Greenleaf bench is strikingly linear, and lies along the North 40 West thermal gradient discussed above. Either of two mechanisms may explain this linearity; rapid vertical erosion by streams, faulting, or a combination of both. Meandering rivers of low gradient generally do not form linear features over long distances. The sinuous meanders of the Boise River today are probably a good proxy for what this stream has looked like for much of Quaternary time. Faults that cut unlithified sediments are extremely difficult to identify because of a lack of exposure, and because first-hand evidence such as shattered rock is generally not present at the visible level of exposure. At

Greenleaf this is particularly acute because the internal stratigraphy of the Idaho Group has not been defined, and offset sedimentary beds have not been recognized by prior work. Information from driller's logs is useful but may not be highly reliable.

The gravels of the A1 sequence discussed above may represent such an offset across the Greenleaf bench. Wood (1994) identified a fault adjacent to the study area at 1000 feet depth that parallels the bench. His analysis using seismic data demonstrates that faults with this orientation occur in the area, and therefore show viability of this interpretation. If correct, this suggests that the Greenleaf bench may be a stream-modified fault scarp, and the lower Boise Valley may lie within an internal sub-graben. Heat flow contours (Figure 2) nicely define the regional geometry of this potential graben.

Contoured bottom-hole temperatures (from IDWR well logs) in the Greenleaf area show a northeast and northwest rectilinear geometry similar to that defined by the contoured regional heat flow data from Blackwell (2003; Figure 4). The Norm Batt well in Section 32 and the Dean Fry well in Section 22 (Plate 1) strongly influence these contours because their bottom-hole temperatures far exceed the regional geothermal gradient (Figure 7). The depth of these wells and the bottom-hole temperatures suggest that geothermal water discharges into A4 clastic strata. Close observation of the Ten Mile Gravels on the Greenleaf bench across this northeasterly trending thermal gradient shows a 30- to 50-foot drop in elevation from southeast to northwest in some wells. These two observations suggest the possible presence of a northeasterly trending structure (Plate 1).

Figure 7 near here

## **HYDROGEOLOGY**

### **REGIONAL HYDROGEOLOGY**

Ground water in the western Snake River Plain flows generally from east to west (Hutchings and Petrich, 2002). Hutchings and Petrich (2002) go on to suggest that the northeastern margin of the western Snake River basin, adjacent to the Boise foothills, provides recharge to confined aquifers in lower Treasure Valley. They further conclude that the residence time of water in distal reaches of these deep aquifers ranges from 20,000 to 40,000 years.

Sediments of the Idaho Group host several stacked confined aquifers. Surficial sediments of the Ten Mile Gravel sequence occur intermittently throughout the region and host the uppermost, unconfined aquifer at Greenleaf. Aquifers in the Idaho Group consist of stacked, flat-lying, sand and pea-gravel layers interbedded with lacustrine clay.

Several wells in the Boise River flood plain have flowing artesian heads. This shows that the deeper aquifers generally have an upward hydraulic gradient. Those on the floodplain discharge water into the river system, a conclusion also reached by Hutchings and Petrich (2002). Wells on the Greenleaf bench have artesian heads that lie above the confined aquifers but below the surface gravels. There is therefore a downward hydraulic gradient from the shallow unconfined aquifer on the Greenleaf bench to the uppermost confined aquifer.

## **PROJECT AREA HYDROGEOLOGY**

We studied strata down to about 1000 feet below ground surface using logs from drill holes (IDWR records repository). The coarser clastic sequences described above define three stacked aquifers confined by clay beds of the Idaho Group, and an unconfined surficial gravel aquifer. Bottom hole temperature measurements in some of the deeper wells show that geothermal water influences these aquifers, so is also a source of recharge. Primary recharge to the unconfined gravel aquifer is probably from canal leakage and irrigation.

### Thermal Ground water flow system

IDWR ground water monitoring wells in the western Snake River Plain show regionally elevated temperatures in deep ground water (Figure 7). The average geothermal gradient for the area based on these data is 29° F per 1000 feet of depth. The nearby Swan Falls meteorological station records a 50-plus-year annual average temperature of 55°F (WRCC, 2003). Assuming that this average annual surface air temperature applies to Greenleaf, ambient shallow ground water should have a similar temperature. The A4 aquifer, at a depth of ±500 feet, should therefore have a predicted temperature of ±70°F and A3 should be ±64°F. Several of the wells in the Greenleaf area that tap A3 and A4 demonstrate these general temperatures. For instance the Greenleaf Harmony well that produces water from the A3 level has a temperature of 64°F. A few wells, however, show significantly elevated temperatures; the 541-foot-deep Norm Batt well in section 32 has a bottom hole temperature of 98°F, and the 642-foot-deep Dean Fry well in section 22 is 83°F (Plate 1). These elevated temperatures demonstrate local discharge of

thermal water into the A4 ground water system, and their locations suggest that they discharge from a northeasterly structure. The temperature of ground water in the surficial A1 gravels is apparently not affected by geothermal activity.

#### Ground water flow system in unconsolidated sediment

The A1 gravel sequence hosts the uppermost aquifer in the Greenleaf area. This aquifer is likely recharged by infiltration from canal leakage, agricultural irrigation, and annual precipitation. Recharge cannot come from the Boise River because these gravels lie well above river level and are physically disconnected from it. Chemical analyses, discussed below, suggest that water from this aquifer does not mix with the underlying confined aquifers.

Thickness of the aquifer is highly variable. The gravel occurs at or near land surface; some of the section has either been entirely removed by erosion or was never deposited while the gravel in other areas is nearly 60 feet thick. Exposures of the gravel and well log data indicate that the gravel is entirely oxidized.

#### Ground water flow systems in confined aquifers of the Idaho Group

The A2, A3 and A4 clastic sequences host aquifers confined by intervening accumulations of clay-rich lacustrine sediment. Flowing artesian wells in the Boise River flood plain, particularly in wells close to the river, suggest that these aquifers discharge to the river. This indicates that recharge must occur from higher elevations outside of the Greenleaf area. Likely sources include the Boise front (Hutchings and Petrich, 2002), the Owyhee Mountains, and up gradient stretches

of the Snake River Plain. An exposure of these strata (Figure 5) and well logs show that these aquifers occur in reduced strata.

#### Analysis of well development

Two wells supply water to Greenleaf, the Friends well and the Harmony well (Plate 1, Table 2, Figures 13 and 14). The Friends well is 285 feet deep and is screened intermittently from 209 to 275 feet. The drillers log (Figure 13) indicates that a pump test of this well when drilled produced 125 gpm from 172 feet. The Harmony well is 303 feet deep and is screened intermittently from 245 to 290 feet. The drillers log (Figure 14) indicates that a pump test of this well when drilled produced 120 gpm; depth of the test was not provided.

Both of the community wells produce water from a confined aquifer in the Idaho Group, and our work shows a stratigraphic correlation to the A3 level. Only one additional well, the Bill Lane well in SE Section 16 produces water from the A3 level in this area. The nearest others lie greater than one mile away (Plate 1). Our stratigraphic correlations show that the A3 sequence is distributed throughout most of T4N R4W.

#### Water Chemistry

Chemical analyses from Greenleaf area ground water indicate elevated concentrations of arsenic, manganese, fluoride, and iron (IDWR Ground water monitoring data; Table 2). Arsenic is concentrated well above the EPA year-2006 MCL of 10  $\mu$ l in A1 and A2 but occurs only in trace amounts in A3 and A4 (Figure 8). Fluoride conversely is more concentrated in A3 and A4 but less so in A1 or A2 (Figure 9). The concentrations of fluoride are generally less than the EPA MCL of 4 mg/l but above the

suggested MCL of 2 mg/l. The Dean Fry well in section 22 (Plate 1) derives water exclusively from the A4 aquifer so is perhaps a good indicator of water chemistry at this level. Table 2 shows that this water is relatively clean and free of arsenic but elevated in fluorine, manganese, and iron.

Past work indicates a perception that water quality deteriorates with distance from the Boise River (Appendix C in Keller, 2002). Our stratigraphic correlations and geochemical data from individual aquifers suggest a closer spatial association of these elements with specific aquifers, and therefore with depth rather than planimetric distribution (Figures 7 and 8).

Figures 8 and 9 near here

We studied the possibility that low levels of arsenic in reduced water of A3 and A4 could have been added to and concentrated in the oxidized A1 aquifer by irrigation returns from deep wells. This is apparently not the case because the ground water in the A1 gravel does not mix with the three lower aquifers. This conclusion is based on ternary plots showing the systems As-Ca-Cl and As-Ca-Na (Figure 10). Chlorine and sodium are significant components of minerals formed by evaporation so if arsenic is being enriched by irrigation returns we would also expect chlorine and sodium to be enriched, but their concentrations actually decrease as arsenic increases.

Figure 10 near here

Many of the wells in the area, including those used by Greenleaf contain offensive concentrations of organically derived methane (?) gas. Driller's logs indicate the local presence of organic matter such as woody material throughout

the section drilled. For instance the George Wright well in section 4 contains tree bark at 382 feet depth, just above the A4 clastic section. The gas is probably generated by the deterioration of organic matter in an oxygen-deficient environment. If the process is taken to completion the gas would cease to concentrate and would eventually dissipate. The fact that it is still concentrated suggests that the process is progressing very slowly in an oxygen-starved environment. The presence of gas-laden water may also indicate low rates of ground water flow in the deeper, confined aquifers. The 20,000- to 40,000-year residence time derived by Hutchings and Petrich (2002) supports this interpretation.

## **DISCUSSION OF RESULTS**

This study identifies and correlates four coarser grained clastic sequences that host aquifers in the Greenleaf area. The shallowest, A1, consists of unconfined gravels that cap the Greenleaf terrace. The others, A2, A3, and A4, occur within and are confined by clay beds of the Idaho Group. Our correlations suggest that the confined aquifers extend laterally at least as far as the boundaries of our study area, T4N R4W.

Chemical data that specifically fingerprints water chemistry of each aquifer are limited because of two factors; many of the wells mix water from multiple aquifers, and not many wells penetrate the deeper aquifers. This study utilizes, to the best of our knowledge, chemical analyses that represent each of the aquifers.

All wells for which we have definitive analyses show that arsenic concentrations above the new 10 µg/l MCL are restricted

to the A1 and A2 aquifers. Arsenic concentrations in these upper two aquifers have no known or obvious present-day source.

Geothermal water can contain a wide spectrum of dissolved constituents, from very clean to strongly metal laden. The elements found in Greenleaf area water commonly occur dissolved in geothermal waters Krauskopf, 1979; Deer Howie and Zussman, 1962), indicating this as a potential source. Available chemistry, however, shows an inverse correlation of arsenic with temperature, suggesting that the geothermal fluids that presently discharge into A3 and A4 do not contribute the increased arsenic concentration.

Geothermal water may have contributed these constituents in the geologic past when the hydrothermal system was hotter and with a higher hydraulic head than today's. Numerous fossil hydrothermal systems along both margins of the western Snake River Plain show that hydrothermal activity was stronger and more prevalent in the past (Otto, unpublished mapping). The hydrothermal alteration in these fossil systems affects Idaho Group sediments so is younger than them, and many of these relict systems contain elevated concentrations of arsenic, mercury and gold.

Elevated water temperature provides enhanced ion solubility and fluid buoyancy, and periods of wetter climate probably add more recharge to the regional hydrothermal system. During wetter climates, such as in the Pleistocene, thermal fluids may have discharged at higher elevations than what they are capable of reaching today, perhaps into A1 and A2. Strata in A1 and A2 have locally been hydrothermally altered, which provides evidence of past thermal fluid flow absent from these strata today. Two things may have happened as the system cooled and

the climate became drier; elevations of hydrothermal discharge probably decreased, and the concentration of metals dissolved in the fluids decreased.

Extremely long residence times of aquifer water calculated by Hutchings and Petrich (2002) and excessive concentrations of gas indicate that water in the deeper aquifers travels slowly, and may have first entered the system during the wetter climate of Pleistocene time. If so, water in the deeper aquifers may not be replenished as rapidly as it is being pumped. Regional continuity of the deeper clastic aquifers suggests that they may have a great deal of storage, however, at some future time the water in these deeper aquifers may become depleted. A lack of historic water-level data from deeper aquifers precludes an accurate analysis of this possibility.

An analysis of regional structures shows three important fabrics in rocks north and south of the western Snake River Plain. These structural patterns may also occur in older rocks that underlie the WSRP at depth and influence the tectonic style in rocks of Snake River Plain age. The Greenleaf area lies at the intersection of the (projected) regional northeasterly trending Trans-Challis structure and a northwesterly Snake-River-basin-parallel fabric defined by heat flow. Interference patterns created by the interaction of these fault systems may have created the deep-seated plumbing necessary to support a regional hydrothermal system. Normal faulting along the northeasterly trending Trans-Challis structure may also have controlled the locations of the lake margins and delta described by Wood (1994).

## **CONCLUSIONS AND RECOMMENDATIONS**

Deeper aquifers have less arsenic than shallow ones in the Greenleaf area. Wells drilled to these lower levels will likely contain less arsenic than shallower wells, but will probably contain elevated levels of fluorine, iron and manganese. Water from wells drilled into the lower aquifers probably will be at higher temperature, and they will likely contain elevated levels of dissolved gas. The A4-hosted aquifer has documented water temperatures of up to 98 degrees. The aquifer hosted by the A3 clastic sequence may hold the best attributes for production: there are no known arsenic concentrations above the year-2006 MCL of 10  $\mu\text{g}/\text{l}$ , and temperatures are somewhat cooler than A4. Fluoride, iron, manganese, and dissolved gas, however, may be a problem. Some of the wells in the study area have concentrations of Fluoride greater than 2 mg/l, the suggested EPA SMCL (Table 2). Both of the Greenleaf wells currently produce from the A3 zone, so they should expect similar characteristics from this zone to what is known of the present community water supply.

Our analysis of the wells in T4N R4W shows that most draw water from the A1 gravels, and progressively fewer draw from the deeper aquifers. Given the generally low recharge and flow rates indicated by Hutchings and Petrich (2002) wells drilled into the lower aquifers may have gradual water-level decline. We suggest that accurate static water levels for the confined A4, A3, and A2 aquifers be routinely monitored.

## **ACKNOWLEDGEMENTS**

The authors are alone responsible for the interpretations expressed in this document. These do not necessarily reflect those of the University of Idaho and IWRRI, the U.S.

Environmental Protection Agency, or any other institution. Rather, they are observations shaped by our experiences in the field, study of the scientific and technical literature, and understanding of input provided by colleagues and from representatives of Franklin.

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Table 1: Depth intervals where drillholes penetrate the clastic sequences used in the correlation of Idaho Group stratigraphy in T4N R4W (see plate 1).

Drillhole Name	Collar elevation	A1 depth interval		A2 depth interval		A3 depth interval		A4 depth interval	
		From	To	From	To	From	To	From	To
04N04W01SESE	2319	4	14						
04N04W02NWNE	2318	0	30			204	220		
04N04W03NENE	2300	5	27						
04N04W04SESW	2290	4	29						
04N04W04SESW2	2288	3	14			70	180		
04N04W05NENE	2280	2	36			162	174		
04N04W05NWSW	2280	0	40						
04N04W06SWSW	2384	4	13	83	136				
04N04W07SWNW2	2410	21	40	129	180	295	335		
04N04W07SWNW1	2410	19	34						
04N04W08NWNW	2280	0	21			156	180		
04N04W08NENE	2289	2	20						
04N04W10SENE	2300	4	33			145	182	482	500
04N04W11NWNE	2304	7	45						
04N04W12NESW	2316	1	28						
04N04W13NENW	2320	3	34						
04N04W14SENE	2316	3	30						
04N04W15NENE	2301	1	28						
04N04W15NWSE	2302	3	28						
04N04W16SWNW	2380	9	20						
04N04W16SWSE	2352	16	35			184	282		
04N04W17NENW	2400	10	20	140	171				
04N04W17NWSE	2400	6	15	150	172				
04N04W18SWSW	2420	19	30	66	119	318	330	533	553
04N04W18SWSE	2423	21	32			331	343		
04N04W19SWNW	2420	3	38	47	96				
04N04W20NESW	2421	6	33	120	188	240	322		
04N04W21NENW1	2406	23	33	155	175	207	275		
04N04W21NESW	2423	16	36						
04N04W21NENW2	2409	24	40						
04N04W21NESW	2386	7	9	79	115				
04N04W21SWSE	2435	14	31	176	177				
04N04W21SESE	2403	10	34	125	130				
04N04W22NENW	2322	10	40						
04N04W22SESW	2413	18	43			227	276	475	524
04N04W22NESW	2349	10	45						
04N04W23SWSW	2340	8	45	49	56				

Drillhole Name	Collar elevation	A1 depth interval	A2 depth interval	A3 depth interval	A4 depth interval				
04N04W23SWSE	2343	30	38	42	81				
04N04W23SESE	2346	10	25	55	65				
04N04W24SWSE	2350	10	39	59	60				
04N04W25SENE	2382	10	49						
04N04W25SWSW	2421	10	45						
04N04W26NESE	2430	18	43	144	150				
04N04W26SESW	2486	4	20	185	245				
04N04W26NESW	2430	5	16						
04N04W27SESE	2466	18	72	130	150				
04N04W27NENW	2421	26	50	122	162				
04N04W27NWNW	2433	24	44	165	175				
04N04W28SESE	2486	35	50						
04N04W28NENW	2461	15	59	178	191				
04N04W28NWNW	2470	15	57						
04N04W29SENE	2466	10	44	160	183				
04N04W29NWSE	2482	20	30	168	181	298	383	529	543
04N04W29SWNW	2475	20	45						
04N04W30NWNW2	2480	6	44						
04N04W30NWNW1	2473	19	37						
04N04W30SWSE	2484	30	45						
04N04W31SENW	2490	22	28						
04N04W32NWNW	2490	14	39	225	243	379	423	538	541
04N04W32NWSW	2558	4	28	294	298				
04N04W32SESE	2561								
04N04W33SESW2	2530	60	90	204	214				
04N04W33SESW1	2530	34	37						
04N04W33NENW	2540	14	78						
04N04W34NWNW	2461	14	50	155	200				
04N04W35SWSW	2531	5	27						
04N04W36SWNW	2493	3	35	192	223	350	404		
04N04W36NENW	2485	5	27	172	219	365	432	506	518
04N04W36NWSE	2490	6	24	188	190	367	407	525	562
Total wells in interval		68		30		17		7	

**Table 2**  
**Water Quality Analyses From**  
**Selected Wells in T4N R4W**

Source			Dixon New Irrigation Well	Dixon Old Irrigation Well	Greenleaf Harmony Main Well	Greenleaf Friends Well	Dean Fry Well	Doug Cheney Well	Al Winslow Well	Bill Lane Well	Dixon Old Domestic (Mikes Metal Fab)	Dean Oliver 15DBB1	21CAA2 (Rafael Pedraza)	28ACB2 (Alva Tish?)	Keith Schweikhart 33CDC3	Greg Gencall 33CDC2	Dallas Holton? 15CDDD1	15CDDD2 (Ed Griffiths?)	16DDDD1	17ADC1	George Wright 4CDC1	32DBB1	30BBB2
<b>Map No. (04N 04W)</b>			210CD1	210CD2	21ACA1	21BAA1	22CDD1	22ACB1	22BBD1	16DCC1	21DCD3	15DBB1	21CAA2	28ACB2	33CDC3	33CDC2	15CDDD1	15CDDD2	16DDDD1	17ADC1	04CDC1	32DBB1	30BBB2
<b>Producing Interval</b>			175-236	23-60	182-222	209-275	642	120-125	150-162	298-310	176-177	134-176	35-36	54-57	270	72	125	30	95	142	420	165	71
<b>Static Water Level</b>			23	14	75	81	62	1	8	-5	45		23	32	85						-2		
<b>Date</b>	<b>M C L</b>	<b>S M C L</b>	4/25/2003	4/25/2003	4/25/2003	4/25/2003	4/30/2003	4/30/2003	4/30/2003	4/30/2003	7/30/1992	6/16/1999	7/18/2002	9/3/1993	8/11/1999	7/10/1992	9/4/1997	10/8/1997	9/8/1997	9/22/1997	7/12/2000	9/9/1975	8/11/1999
<b>Aquifer</b>			A2	A1	A3	A3	A4	A3	A3	A3	A2	A3	A1	A1	A2	A1	A2	A1		A2	A4		A1
<b>Collar elevation</b>			2440	2475	2430	2406	2413	2350	2335	2352	2435	2302	2423	2470	2530	2530	2315				2288		
<b>Flow rate</b>			0	15	0	125	50	0	100	30	150	0	13	20	18		10				18		
<b>Log Availability</b>			Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	No	No
arsenic	0.010*		<b>0.017</b>	<b>0.070</b>	0.007	0.006	<0.003	<0.003	0.006	<0.003	<b>0.012</b>	<0.001	<b>0.027</b>	<b>0.025</b>	<b>0.042</b>	<b>0.018</b>	0.002	<b>0.056</b>			0.001		<b>0.019</b>
ammonia			0.58	<0.04	0.72	0.79	129	0.65	0.94	147	0.62	0.754	<0.04	0.03	0.385	0.02		<0.015	0.522	197	192		<0.02
bicarbonate			241	233	168	162	193	128	126	139	302	160	383	264									
calcium			88.3	39.6	68.8	59.7	13	16.6	26.2	18.4	71	14	42.4	35	102	50					15.9	32	54
chloride		250	22	18	30	27	7	6	7	28	7.6	9.64	7.5	114	27						5.7	23	11
fluoride	4	2	0.58	1.11	0.5	0.57	<b>2.2</b>	129	0.66	0.83	0.6	15	0.7	0.6	0.5						2	0.5	0.6
hardness			102	132	191	170	34.1	42.5	69.7	49.7	213	37	240	186								170	
iron		0.3	<b>1.24</b>	<0.05	<0.05	0.060	<b>0.700</b>	0.220	0.250	<b>0.360</b>	0.210	0.032	0.015	<0.003	0.231	<0.003	0.05				0.07	<0.01	<0.01
magnesium			9.72	9.14	8.14	6.91	0.75	102	2.12	162	8.9	0.79	33.7	24	22.7	33					165	21	34.5
manganese		0.05	<b>0.396</b>	<0.005	<b>0.326</b>	<b>0.254</b>	<b>0.090</b>	0.034	<b>0.091</b>	<b>0.087</b>	<b>0.390</b>	0.043	<0.002	<0.001	0.85	<0.001	<b>0.066</b>				<b>0.100</b>		0.002
nitrate	10		<0.20	6.66	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.05	<0.05	7.1	7.1	<0.05	9.9	<0.05	4.35	<0.05	0.067	<0.05	2	<b>12.1</b>
potassium			8.9	7.4	8.3	8.8	8	4.4	5.3	7.8	8.1	5.3	2.83	2.4	10.9	2					7.1	1	3.5
sodium			68.3	96.4	39.5	40.7	77.1	45.8	38.5	42.5	71	44	79.2	46	44.8	44					53.7	33	55.3
sulfate		250	123	55	74	63	<1	4	21	3	100	0.45	61	38	157	88					<0.03	46	71
TDS		500	<b>512</b>	396	370	318	238	146	158	154	<b>506</b>	219	<b>515</b>	375								298	
All results in mg/L																							
<b>Field Parameters</b>																							
Temp. (C)			17.8	13.4	17.8	14.9**	17.9**	15.7	14.8	14.9	18.1	15.8	14.7	15.8	18.4	15.7	17.4	14.2	15.7	17.6	20.4	16.5	14.6
Temp (F)			64.0	56.1	64.0	58.8	64.2	60.3	58.6	58.8	64.6	60.4	58.5	60.4	65.1	60.3	63.3	57.6	60.3	63.7	68.7	61.7	58.3
SC umhos/cm			666	573	512	478	377	274	302	290	726	270	764	554	846	700	277	849	301	937	357	451	737
pH		6.5-8.5	7.8	7.7	7.6	7.6	7.9	8.1	8.1	8.0	7.7	<b>8.7</b>	7.8	8.0	7.4	7.9	8	7.4	8	7.5	7.7	8	7.7
values shown in bold type exceed primary or secondary standard																							
*future standard; current standard is 0.050																							
**Stabilized temperature may be higher; well probably not pumped long enough prior to sampling																							
Data courtesy of Scanlan Engineering																							