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Relationship Between Fault Zone Architecture and Groundwater Compartmentalization in the East Tintic Mining District, Utah

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RELATIONSHIP BETWEEN FAULT ZONE ARCHITECTURE

AND GROUNDWATER COMPARTMENTALIZATION

IN THE EAST TINTIC MINING DISTRICT, UTAH

by

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GRADUATE COMMITTEE APPROVAL

of a dissertation submitted by

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This dissertation has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the dissertation of Sandra M. Hamaker in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

RELATIONSHIP BETWEEN FAULT ZONE ARCHITECTURE AND GROUNDWATER COMPARTMENTALIZATION IN THE EAST TINTIC MINING DISTRICT, UTAH

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The Eureka Lilly fault zone provides an impermeable barrier for groundwater flow in the East Tintic mining district. The fault zone separates two distinct groundwaters that have different temperatures, compositions, and potentiometric surfaces. The damage zone of the fault is an extensive network of interconnected open fractures and fault intersections that provide conduits for groundwater flow in otherwise impermeable units. The fault-core breccia has been re-cemented and mineralized, which eliminates porosity in the rock by

creating a thick impermeable zone, which has compartmentalized groundwaters across the fault zone. The compartmentalization of groundwater shows that fault zone variability (from strain partitioning and multiple deformation episodes) make traditional basin flow concepts inaccurate and difficult to apply in this area.

ACKNOWLEDGMENTS

I would like to thank Ray Irwin, Paul Spor and the staff of Chief Consolidated Mines (Tintic Utah Metals LLC) for opening their offices to me and giving me unlimited access to their records and data. Their assistance and input has made this project possible.

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Thanks to my parents and family have been supportive and encouraging every step of the way (even the small steps). Thanks for your constant support and for teaching me by example the value of education and hard-work. Lastly, thanks to Eric, who is the reason that this was started in the beginning, and who sacrificed whatever was needed so that I could complete this in the end.

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INTRODUCTION

Groundwater flow in unconsolidated sediments is traditionally described as following a potentiometric surface, a description which is difficult to apply to massive consolidated rock units where there is little primary porosity to enable fluid flow. Instead, fracture networks serve as the primary conduits for fluids (Davis, 1969). For example, geothermal groundwater moving up through cemented limestone units can have a different and independent flow regime than a shallow, valley-fill sedimentary aquifer (Bense, 2003).

The East Tintic mining district of Utah provides a unique opportunity to study the complex interaction of groundwater movement through fracture networks associated with fault zones, because of both surface and subsurface control. The fault structure and limited hydraulic connectivity in this area challenge traditional ideas on fluid-fault interactions, such as inter-basin flow (Maxey, 1968; Mifflin, 1968, Eakin 1966). By utilizing mine data and observations from the surface and subsurface, a detailed description of the groundwater and fracture relationship can be shown.

A greater understanding of the relationship between groundwater and fault zones impacts many fundamental problems relating to the extraction and containment of fluids in rocks. Water is a resource that is becoming increasingly more valuable. Thus, by utilizing water more effectively, there are economical, sociological and technological benefits. The East Tintic Mining District provides a unique opportunity to investigate how fault architecture controls groundwater movement.

Previous investigations of this problem are summarized by recent work by Caine and Forster (1999), who found that the damage and core zones of faults can both enhance and retard fluid flow. Whether the fault core will act as a conduit, barrier, or a combined conduit-barrier system is controlled by the relative percentage of fault core and damage zone structures, fracture permeability and the inherent variability in grain scale of the rock units (Caine et al, 1996). The purpose of this investigation is to examine an extensively documented fault zone and groundwater interaction. In this district, rock units have almost no porosity, so groundwater flow is limited by the architecture of the associated fault zones and fracture networks. This provides an opportunity to understanding how compartmentalization of groundwater occurs in fracture dominated flow regimes. Unpublished data from mine reports documenting subsurface relations between water levels across faults, and field studies of surface fault architecture and water chemistry provide a way of demonstrating how the architecture of the Eureka Lilly fault zone compartmentalizes groundwater from different sources in East Tintic Mining District.

GEOLOGIC SETTING

The East Tintic Mining District is located in the East Tintic Mountains, which is a horst in the eastern Basin and Range province of central Utah (Figure 1). Prior to block faulting by Basin and Range extension, it formed part of the Sevier fold and thrust belt (Armstrong 1968, Morris and Mogensen, 1978) and volcanic arc associated with subduction along the western edge of North America.

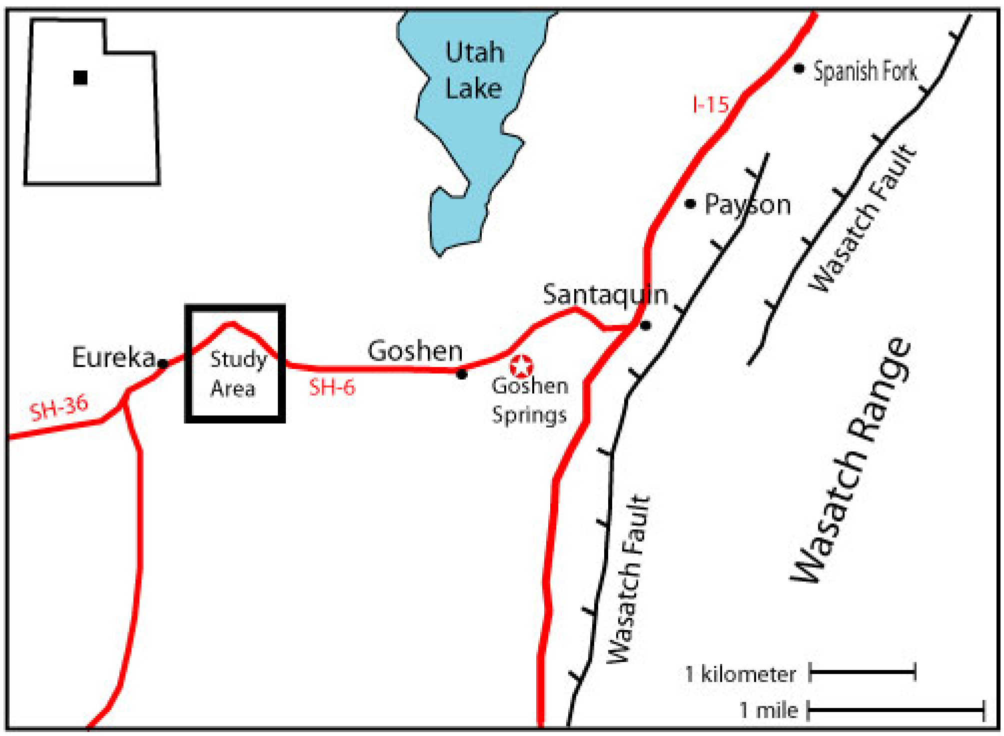

Figure 2. Index Map of East Tintic mining district, with location of study area, major highways and Wasatch fault.

Geological studies have been undertaken in the East Tintic region primarily to determine the economic potential for silver, zinc and lead mining and to further understand the nature of these volcanic deposits. The ore bodies are concealed by thick Tertiary lava flows and are mostly hosted in the Cambrian sedimentary units (Figure 2). These units are multiply deformed by Sevier folding and thrusting, and again by Tertiary extension and magmatism. The structure consists of overlapping thrust sheets, which repeat a sequence comprised of folded Cambrian to Mississippian sedimentary rocks, which are unconformably overlain by Tertiary volcanic rocks (Figure 3). These units were later extended and cut by normal faults. Some thrust faults were reactivated as normal faults or cut by extensional structures (Lovering and Morris, 1979). The multiple phases of deformation have created an abundance of extensional and shear fractures, and fault intersections that can potentially influence the flow of groundwater.

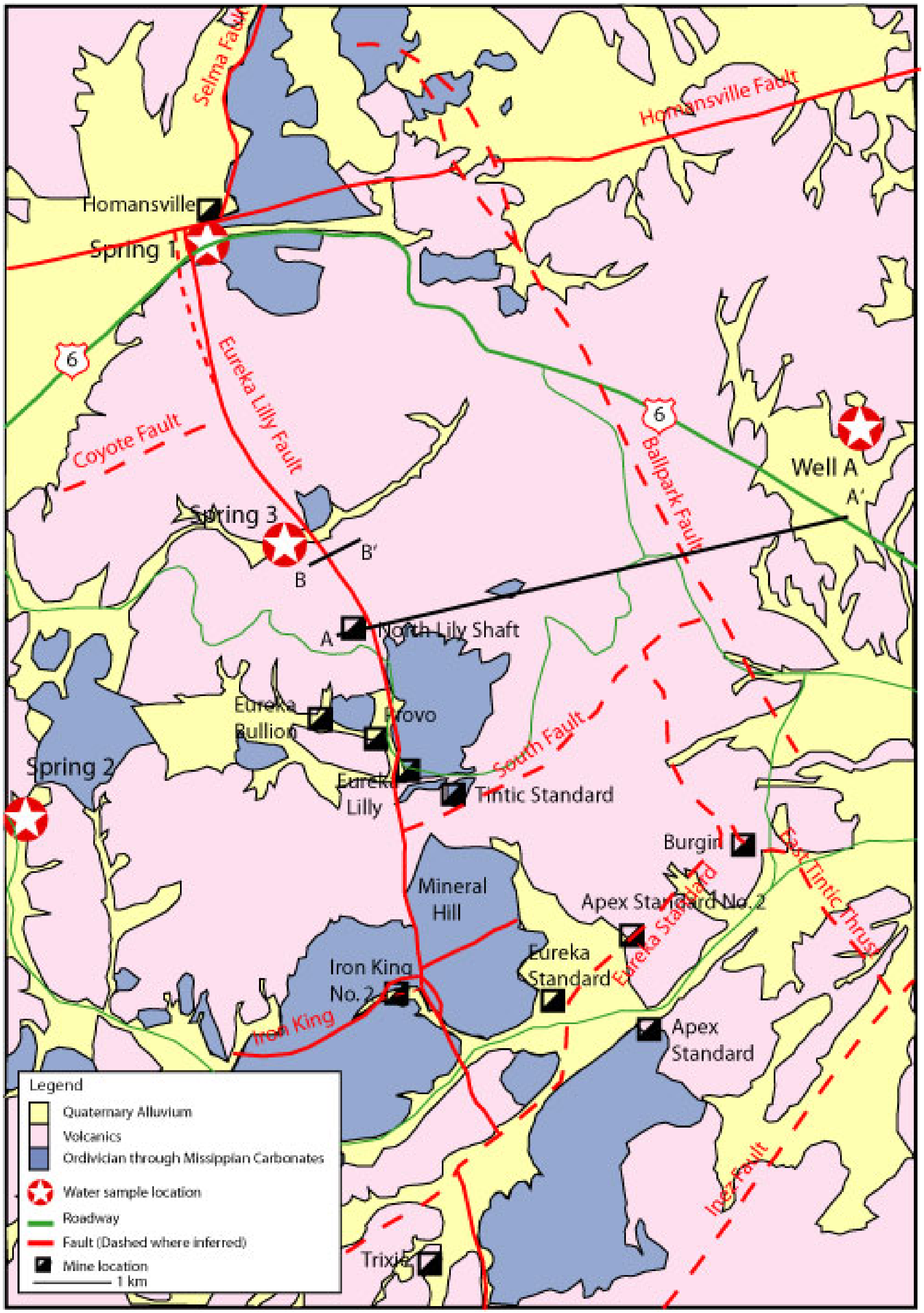

Figure 2. Major geologic features of East Tintic mining district (adapted from Morris and Lovering, 1961; Lovering and Morris, 1979).

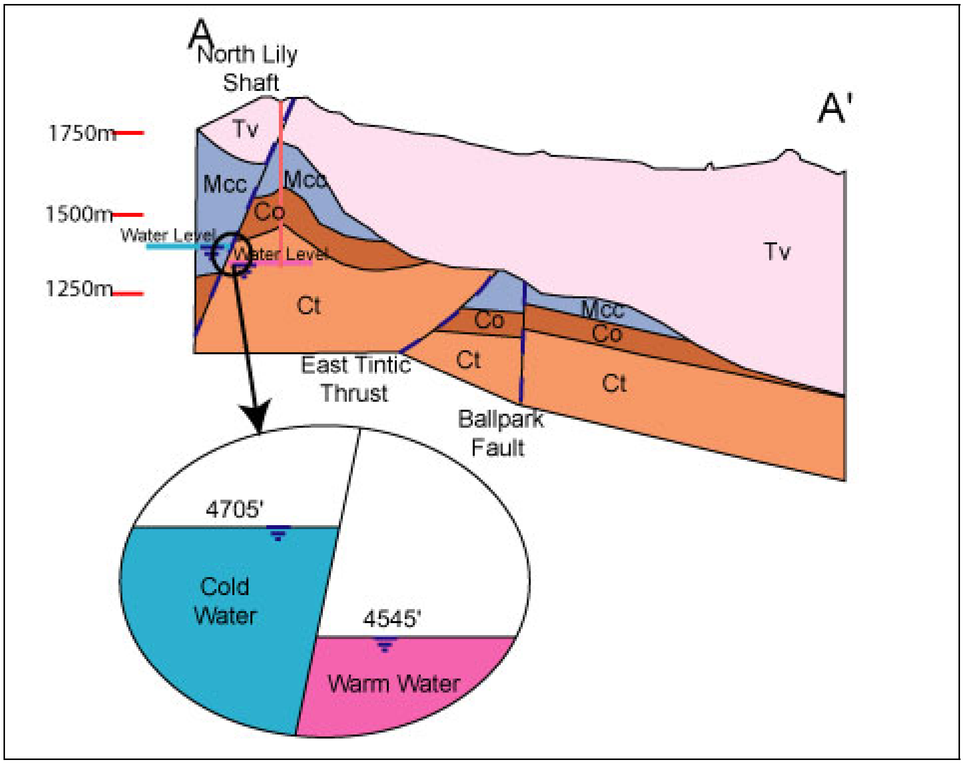

Figure 3. Cross-section through the East Tintic Mining District (see Figure 2 for location) showing extensional deformational overprint of Sevier thrust sheets, and Tertiary volcanic cap. Note the different water levels across the Eureka Lily Fault (blue is cold water and pink is warm water).

STRATIGRAPHY

Most of the mine workings are in the Cambrian Tintic Quartzite, which is overlain by the Ophir Formation and Cambrian to Mississippian carbonate units. The Tintic Quartzite is 700-975 meters thick in the East Tintic Mountains, and is an important host rock for pyritic copper-fold veins and other ore bodies. Its stratigraphic position indicates an early Cambrian age, although there is no fossil evidence to support this assumption (Morris and Lovering, 1979). The Tintic Quartzite is a medium grained sedimentary quartzite with predominately silica cement and very low porosity, which makes it brittle and more fracture-prone near faults (Lovering and Morris, 1961). The contact between the Tintic Quartzite and the overlying Ophir Formation is gradational, but in most places, the base of the Ophir is marked by a bed of dark-brown to greenish-gray laminated shale.

The Ophir Formation is 83-131 meters thick, consisting principally of shale intercalated with sandstone and rare limestone of middle Cambrian age. In the East Tintic district the Ophir consists of upper and lower shale members and a middle limestone member. The stratigraphic position of the Ophir Formation above the relatively non-reactive Tintic Quartzite promotes its alteration. It is commonly the first unit affected by hydrothermal solutions (Morris and Lovering, 1961).

Cambrian, Ordovician and Mississippian carbonates are the most dominant rock type in the East Tintic Mountains and they are the primary host of most ore mineralization. The Cambrian through Ordovician units accumulated on an Atlantic-style passive margin, whereas Mississippian carbonates accumulated in intra-cratonic basins (Gutschick and Sandberg, 1983).

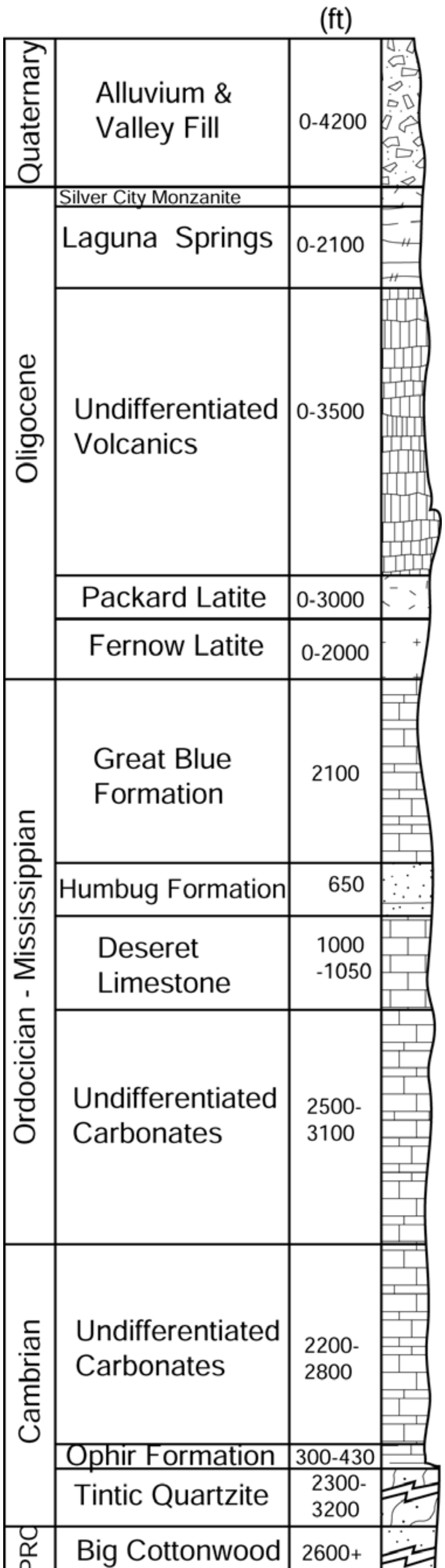

Figure 4. Generalized stratigraphy of the East Tintic Mining District (adapted from Hintze, 1988).

Mississippian carbonates include the Deseret Limestone (about 304 meters thick), the Humbug Formation (205 meters thick) and the Great Blue Formation (762 meters thick).

A major angular unconformity separates the Cambrian to Mississippian units from the overlying Cenozoic volcanic rocks. The volcanic rocks in the East Tintic Mountains are remnants of a large composite volcano of Oligocene age located slightly northeast of the area (Morris and Lovering, 1961; Keith et al, 1991). The eruptive center is characterized by multiple intrusions of monzonite stocks, plugs and dikes. There are three major Oligocene extrusive volcanic successions in the East Tintic Mountains:

1. The Packard Quartz Latite (oldest) is composed of a basal quartz latite tuff, a widely distributed porphyritic unit and an upper vitrophyre.
2. The Laguna Springs and Tintic Mountain Volcanic Group Latite, which are intermediate aged units of latite tuffs, flows, agglomerates and volcanic gravels.
3. Late basalt flows (youngest), which are located mostly in the northeastern part of the East Tintic Mountains. These consist of flows of fine to medium grained, porphyritic basalts.

East Tintic intrusive rocks are primarily quartz monzonite, monzonite lamprophyre, andesite and diabase (Morris and Lovering, 1961).

STRUCTURE

Deformational Events

The Paleozoic units were first deformed by extension during the opening of Mississippian intra-cratonic basins (Gutschick and Sandberg, 1983). During the Mesozoic Sevier Orogeny, these units were deformed by thrust faults and folds propagating from west to east, which formed a series of overturned, asymmetric folds throughout the area (Shepard, 1966). At around 15 Ma, normal faults formed as a result of Basin and Range extension and reactivated some of the Sevier faults, some of which remain active in this region (Lovering and Morris, 1979).

Faults

Faults in the East Tintic Mining District, according to Lovering and Morris (1979) can be broadly categorized as:

a. Contractional faults formed during fold-thrust deformation associated with the Mesozoic Sevier orogeny
b. Extensional faults formed after contraction, but before volcanic activity commenced
c. Syn-volcanic mineralized normal faults and fractures of smaller magnitude

d. Late Basin and Range normal faults formed in late Oligocene or early Miocene time, some of which cut Pleistocene and Holocene deposits. Movement of these faults produced the elongated modern north-trending mountain ranges.

The East Tintic Mining District is generally bounded on three sides by major faults: the Homansville to the north, the Eureka Lilly to the west and the Inez to the south (Figure 2). The Eureka Thrust underlies the entire district. The purpose of this study is to test how these brittle structures may influence groundwater movement, although the focus here is the Eureka Lilly fault zone.

The Eureka Lilly fault was identified and described by Morris and Lovering (1979). It strikes northward through the central portion of the East Tintic district (Figure 2). Although it originated as a thrust fault during the Sevier orogeny, it has been reactivated at least twice, once between the time the volcanic rocks were deposited and ore mineralization, and again during Basin and Range extension. Displacement along the fault varies from 152 meters, near the Eureka Lilly shaft, to 182 meters near the Homansville fault.

The Homansville fault is a steeply dipping (≈80°N) normal fault trending east to northeast (Morris and Lovering, 1979; Figure 2). Further east it is buried by the lavas and has a throw of about 914 meters.

The Selma fault is a normal fault extending from the Homansville area northward. It is mentioned here because of its proximity and close relationship to the Eureka Lilly. The Selma Fault was formed during Basin and Range extension. During these tectonic events, the East Tintic mountains block was broken into two blocks by the Selma faults, which in part followed the pre-existing plane of the Eureka Lilly fault (Lovering and Morris, 1979).

METHODS

FIELD METHODS

Splits of water for cation and anion analysis were filtered in the field with a 0.45 μm filter. Cation splits were acidified with 5-6 drops of 7 N of trace-metal grade nitric acid in ~50 ml of filtered water. Temperature, pH, and conductivity were determined in the field using a VWR Scientific (model 2000) pH meter and YSI 30/10 conductivity meter. 50 mL amber vials with polyseal caps were collected for isotopic analysis.

ANALYTICAL METHODS

Anion concentrations were determined at Brigham Young University (BYU) using a Dionex 4100 ion chromatograph. Cation abundances were measured with a Perkin Elmer 5100C Atomic Absorption Spectrometer. Stable isotope ratios, were measured at BYU with a Finnigan Deltaplus isotope ratio mass spectrometer.

FAULT ANALYSIS

Descriptions of both the surface and subsurface expression of fault architecture are rare. Data from mines bridge this gap and help evaluate the lateral continuity of fault architecture and how it controls groundwater flow. In the East Tintic Mining District most faults intersected in the subsurface are blanketed by volcanic rocks and not exposed at the surface. However, there are some surface exposures of the Eureka Lilly Fault, which is also intersected by mine shafts in the subsurface.

SURFACE EXPOSURES OF THE EUREKA LILLY FAULT

The surface trace of the Eureka Lilly fault was examined in two places at the surface at a road cut exposure on highway 6 and where it surfaces briefly above the volcanic units near Mineral Hill. Additional observations were made of an exposure of a fault (location, and orientation indicated this is likely associated with the Eureka Lilly fault system) near the Apex mine.

The Eureka Lilly Fault zone is a multiply deformed structure composed of repetitions of overprinted fault core and damage zones from repeated slip events with different motions. The core zones of faults in the region are commonly impermeable areas of re-cemented silica and calcite and are highly altered breccia with some clay-rich gouge (Figure 5 and 6). This breccia zone demonstrates the additional strength (displayed by its resistance to erosion) when fractures are cemented. This effectively fuses the cracks and heals the fault core, which creates a barrier for fluid flow.

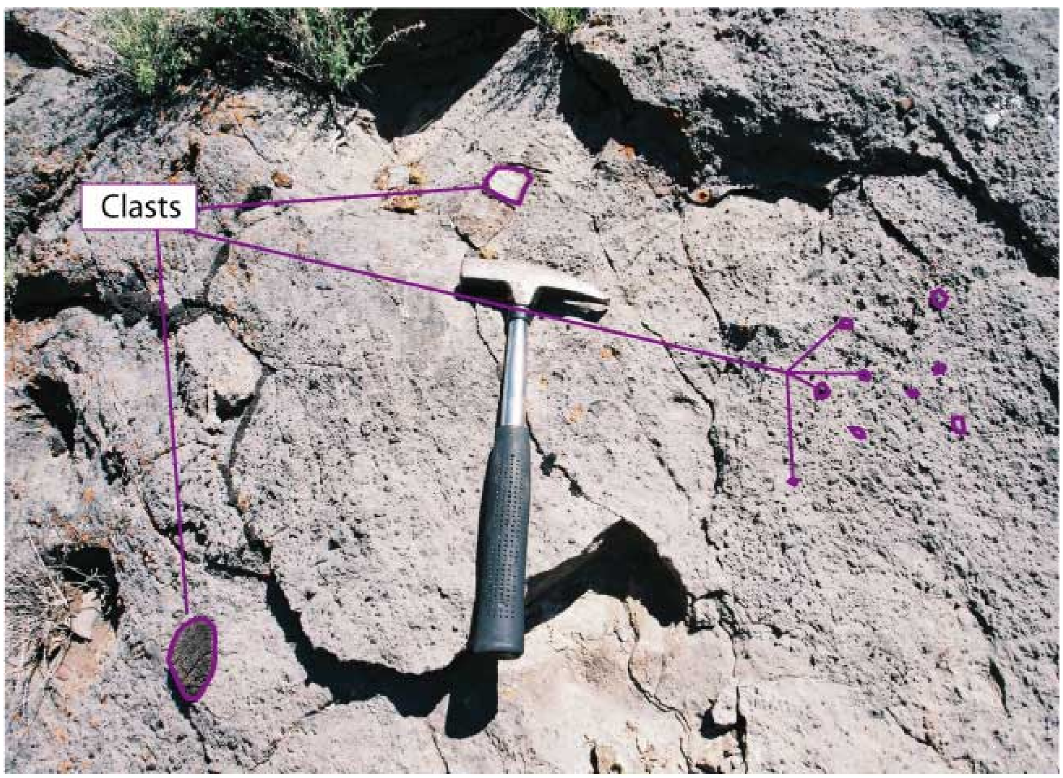

Figure 5. Breccia zone near the Apex mine. These rocks are the erosional remnants of the core zone of an unnamed fault associated with the Eureka Lilly fault. Clasts range in size from 0.5cm to 15cm and are encased in a mostly recemented carbonate matrix.

Figure 6. Linear trace of resistant breccia zone near Apex mine protruding from erosional surface.

Damage zones are located adjacent to the cores, and consist of abundant open fractures that show extensive connectivity and localization for fluid flow through otherwise impermeable units. The lateral extent of the core and damage is zone is thought to be largely dependant upon the rock type and the amount of displacement (Caine et al, 1996). However, although the Eureka Lilly fault shows much more damage and alteration in the shale and limestone units and less fractures in quartzite units, the entire mining district is highly fractured by multiple brittle deformational events, and may be considered a damage zone. Fault intersections in particular have high fracture densities.

The surface expression of the Eureka Lilly fault was mapped through a stream channel west of Mineral Hill (Figure 2). Evidences of the fault include an abrupt change in the dip of bedding planes (35˚S to 30˚W) and rock type (limestone to dolomite) on either side of the valley (from E to W), respectively. A resistant breccia zone crops out parallel to the stream channel, which is about 30 meters across and follows the damage zone of the fault. The damage zone dissipates into mostly intact outcrops around 50-60 meters away from the brecciated core zone of the fault.

The geomorphology of local drainage systems is highly controlled by fault architecture. Surface water flows through and erodes open fractures in the exposed damage zone, preferentially eroding it to form valleys. Valley margins show where the damage zone transitions into less fractured country rock and where there are fewer fractures. What remains are damage zone controlled stream valleys with scattered outcrops of resistant breccia from the core zone and occasional bluffs of limestone and dolomite country rock.

The surface trace of the fault is also delineated by the many mine adits and tunnels used to extract ore concentrated along the fault. The fault controlled the flow of hot mineralizing fluids during Tertiary magmatic activity in the region (Lovering and Morris, 1979), essentially these deposits assisted in sealing he core zone and parts of the damage zone to form the hydraulic barriers observed in this study.

Road cuts on Highway 6 expose a cross-section through the Eureka Lilly Fault Zone near its intersection with the Homansville Fault. It strikes 342˚ and dips ~90˚, juxtaposing Cambrian limestone in the footwall with Tertiary volcanic rocks. The Eureka Lilly Fault has a displacement of about 250 meters in this area (Lovering and Morris, 1979).

The fault core generally consists of breccia encased in gouge with a gradual shift from limestone to volcanic-rich clasts extending from the footwall into the hanging wall (Figure 7). It has a maximum width of 3 to 3.5 meters, but the ratio of gouge to breccia varies. Core zone development may have been minimized by the high contrast in brittle strength between limestone and quartzite units of the footwall and much weaker tuffs on the hangingwall. A large limestone block detached from the footwall was found within the core zone encased in gouge. Fault striations at the top of the block are near vertical and at the bottom they rake 70˚ north.

Figure 8 (see Figure 7 for location) shows the oxidation alteration resulting from fluid flow through the core zone gouge. Veining indicates that formerly open fracture zones have now been sealed by clay minerals and calcite.

Figure 9 shows a small excavation across the fault core. The entire zone consists of breccia encased in gouge with a gradual shift from limestone to volcanic rich clasts extending from the footwall into the hanging wall.

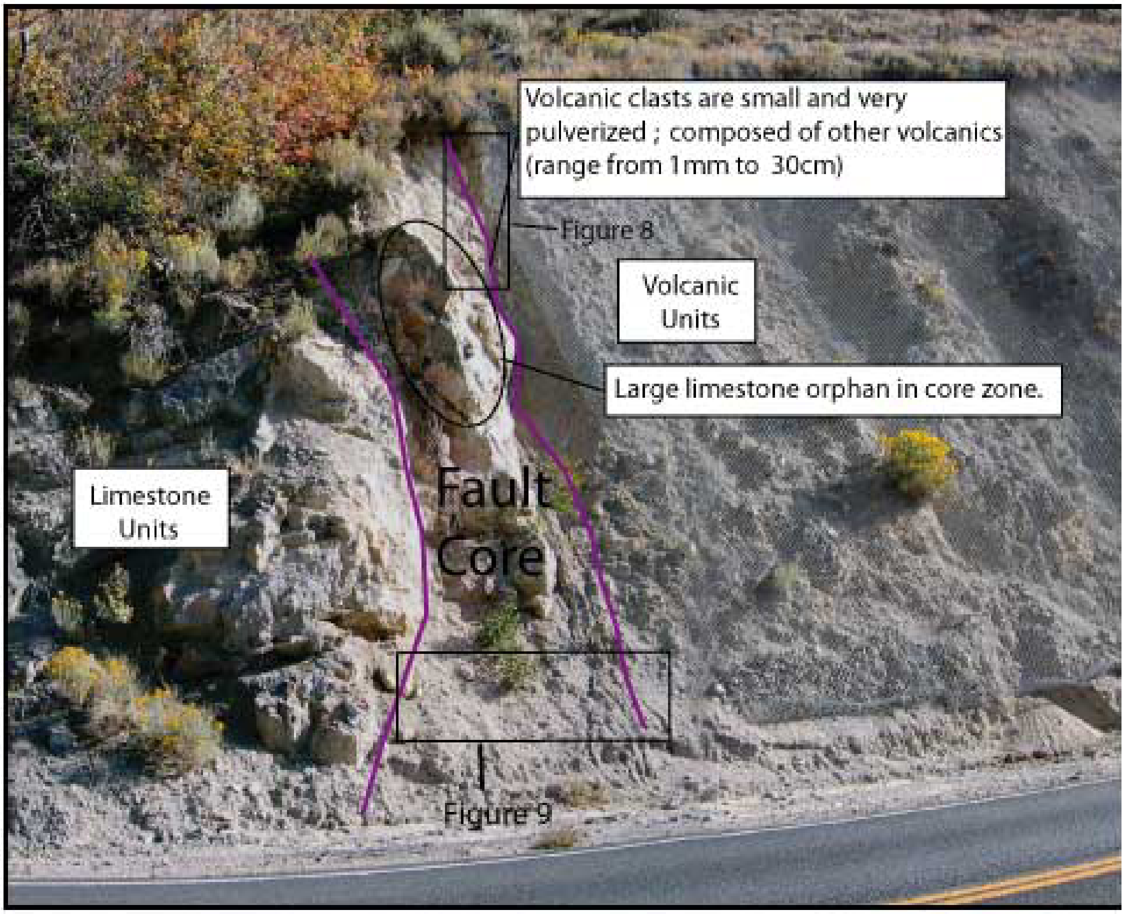

Figure 7. Eureka Lilly fault core. Cambrian limestone of the footwall is juxtaposed with tuffaceous volcanic units of the hanging wall (mostly covered by the chain-link fencing).

Figure 8. Detail of Eureka Lilly fault Gauge, showing alteration due to fluid flow along slip surface and clay-rich gouge.

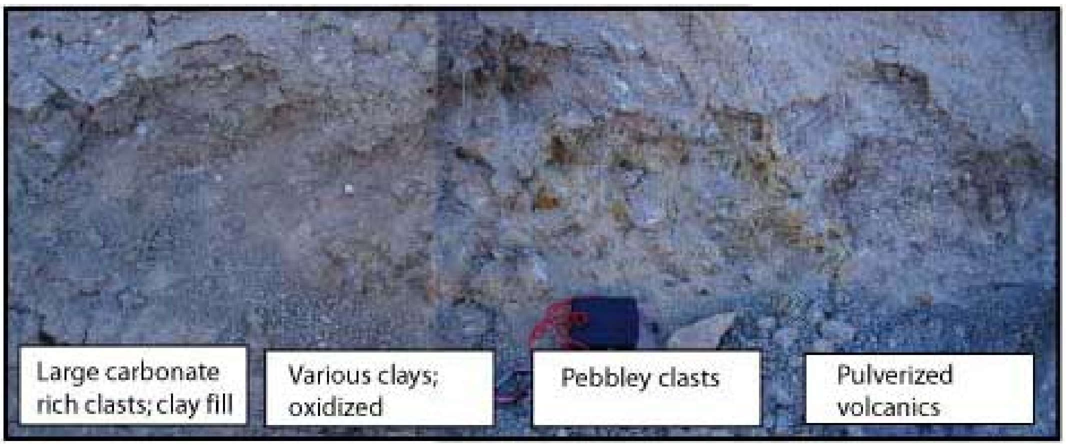

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Figure 9. Excavation of fault breccia and gouge

The damage zone is adjacent to the core zone and consists of a high density of interconnected extensional and shear fractures. It expressed differently in the limestone and volcanic units. In the limestone footwall damage zone, the rock is more fractured (Figure 14), which creates zones of multiple reactivated slip surfaces and zones of only slight fracturing. Closer to the fault core the limestone is locally shattered to the extent that no unfractured rock is found (Figure 10).

Figure 10. Intensely fractured limestone adjacent to core zone.

The damage zone also consists of faults associated with the main slip surface found in the core zone. Just 2.5 to 3 meters from the fault core is a large fault/fracture zone, filled by thin films of gouge (Figure 11). Slip is mostly localized along discrete shear fractures in the damage zone within the limestone footwall.

Figure 11. Localized shear along conjugate fracture set in limestone footwall. The blocks between fractures are broken into gouge in many places. The gouge zone here is about 150cm across at the bottom and decreases to 30cm near the top.

Figure 12. Low angle normal fault offsetting contractional structures in damage zone.

There are also many areas where damage zone fractures have slipped, such as low-angle normal faults that may have been thrust faults (Figure 12). Further away from the fault core, fewer shear fractures are found, but the rock is still highly fractured and intensely shattered in some localized zones where shear was arrested. Alteration zones associated with many of these fractures demonstrate how hot fluids have moved along fractures in the damage zone.

In many areas, it is clear that the orientation of the rock face greatly influence the measurement of fracture density. For example, in Figure 13, large faces have relatively few fractures, whereas the nearly orthogonal faces are highly fractured. This is likely a result of the stress shadow effect of the large systematic fractures. Other fracture zones similar to that shown in Figure 13 were difficult to determine exact shear relationships, as there were few marker beds.

Figure 13. Fractures are most prevalent on the perpendicular faces, whereas those facing parallel are less broken up.

The hanging wall of the fault at the surface is composed of successions of welded and unwelded tuff. The tightly welded areas are fractured and have many normal faults. Strain is more distributed in poorly welded tuffs, and few, if any, outcrop scale fractures are distinguishable (Figure 14). Poorly welded rock near the core zone is pulverized into gouge. Faults seen in the volcanic units are at least 100 meters from the fault core, which may indicate that the entire zone is extremely altered and crushed from movement.

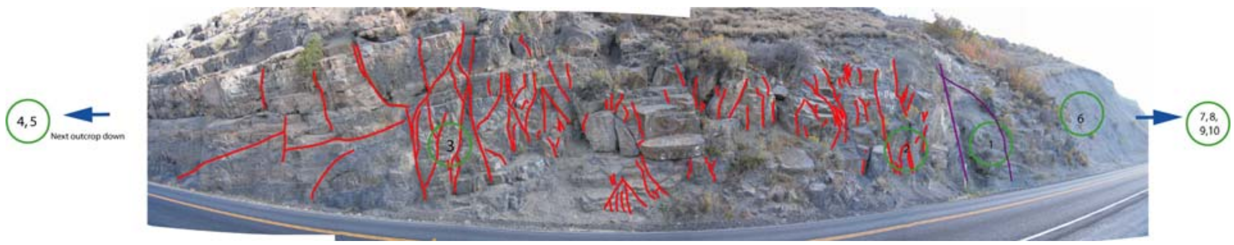

Figure 14. Photo of major fractures in limestone and dolomite footwall. Circles are locations of fracture density measurements; fractures indicated by red lines.

Although no measurements were made on the orientation of fractures, as can be seen in Figure 14, most of these are vertical (or near vertical). According to Gudmundsson et at (2001), vertical fractures in rigid host rocks can yield nearly six times as much water as horizontal fractures of equal dimension. This may be a large factor on the amount of water that is seen in the subsurface. Certainly this vertical framework is permitting large volumes of water to consistently (even during pumping) to be moved along this damage zone.

Fracture Density Analysis

To measure fracture density, a circle was marked off on the outcrop and the lengths of all fractures inside the circle were measured. The purpose of the analysis was to quantify fracture density by measuring fractures at various distances from the fault core. It was hoped that this would shed further light on the localization of strain in the damage zone (Table 1, Figure 15). Although fracture lengths in all of these locations range from microscopic to regional scale, measurements were only made of those at least 3-5 cm in length.

Table 2. Summary of Fracture Density data (see Appendix for complete data set).

	Units	Location									
		5	**4**	**3**	**2**	**1**	**6**	**9**	**8**	**7**	**10**
Sum of fracture lengths	(cm)	582	438	815	383	955	208	184	555	572	255
Sum of fracture lengths/area	(cm/cm^2)	0.10	0.07	0.13	0.06	0.16	0.03	0.03	0.09	0.09	0.04
# of measurements		30	15	45	19	42	12	6	26	23	13
average length	(cm)	19.4	29.2	18.1	20.2	22.7	17.3	30.7	21.3	24.9	19.6

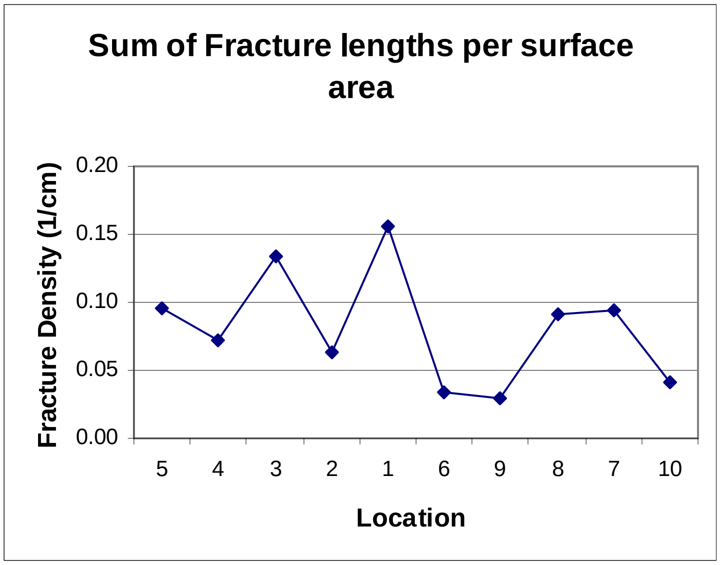

Figure 15. Sum of Fracture lengths per surface area across fault zone.

In the limestone units, there is a clear correlation between fracture density and distance from the core zone (Table 1, Figure 14). Spikes in the data are found at the intersections of shear zones. Types of shear fractures also vary with distance from the core zone. Dominantly extensional faults near the core zone in the footwall limestone block change to mostly thrusting further out. The extensional faults are pervasive and overprint the entire area, whereas thrust faults are very localized.

Fracture densities in the limestone footwall (locations 1 through 5) demonstrate strain is very localized. Some measurements were intentionally taken to show end-members, of pulverized units versus largely coherent regions, with a few large-scale fractures. The high degree of clustering of fractures indicates localization of strain along pre-existing fractures in the limestone footwall. There are few, if any, low-strength units interbedded with the carbonate.

The volcanic rocks of the hanging wall consist of layers with very different physical properties. Welded tuffs behave more strong and brittle similar to the limestone, whereas non-welded tuffs behave weakly like mudstone. The weaker non-welded units responded to stress by distributing it throughout the entire unit. Closer to the fault zone, the volcanic unit is less welded, with few well-developed fractures. Further from the fault core, fracture systems are seen in zones where the tuff is strongly welded. Locally, small-scale faults offset ash flows.

The lateral extent of the damage zone in volcanic rock is difficult to precisely define, and it is likely that it extends beyond the outcrops provided by the road-cut. Across the entire section investigated, there are significant fracture zones with correlating synthetic and antithetic faults. The extent of the damage zone and the corresponding fracture network allow it to potentially hold large amounts of groundwater within low porosity rocks. The extent of intersecting shear fractures provides many connected conduits for enhancing permeability in otherwise very impermeable rocks. In an area like the East Tintic mining district, where faults are overprinted and reactivated several times, damage zones begin to coalesce providing an interconnected network capable of storing and moving large amounts of groundwater.

The Eureka Lilly fault zone exposure at the road-cut is very close to the intersection with the Homansville fault. It is likely that this fault intersection could contribute to the degree of rock pulverization and brecciation observed, as well as overprinted fracture networks in the associated damage zones. This fracture overprint may lengthen, widen and open pre-existing fractures.

SUBSURFACE EXPOSURE

Examination of the Eureka Lilly fault system in subsurface mine shafts and exploration drilling logs provides further insights into lateral variations in fault architecture, and most importantly, how these discontinuities influence the flow of groundwater.

Most of the understanding of the subsurface of the Eureka Lilly fault zone is achieved through analysis of a few locations where the cores of faults associated with the Eureka Lilly fault zone are exposed in mine shafts, drill core, and well logs. There are currently no available shafts that provide access to the Eureka Lilly fault zone, although there have been several in the past including the Homansville, North Lily, Eureka Lilly, Iron King No. 2, Trixie and South Standard shafts. For a short time, there was access to an associated fault in the Trixie mine.

Anaconda Exploration

In 1973 and 1974, Anaconda Company began an exploration program in the North Lily area with three bore holes. These were intended to locate mineralized limestone that may be in the footwall of the East Tintic thrust fault. The holes did not encounter any silver-lead-zinc ore, but they do shed light on the geologic structure in the vicinity of the [1]North Lily Mine. The first hole, TUL-1, encountered a thrust fault at about 762 meters below the surface that is interpreted as the East Tintic Thrust. At about 427 meters, the hole passes through a normal fault, which they named the North Lily fault and interpreted as a normal fault that parallels the Eureka Lilly fault, and is likely a synthetic fault strand of the Eureka Lilly fault zone.

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[1] To maintain consistency with East Tintic mine records, there are 3 spellings of Lilly in this area: Eureka Lilly, North Lily and Water Lillie.

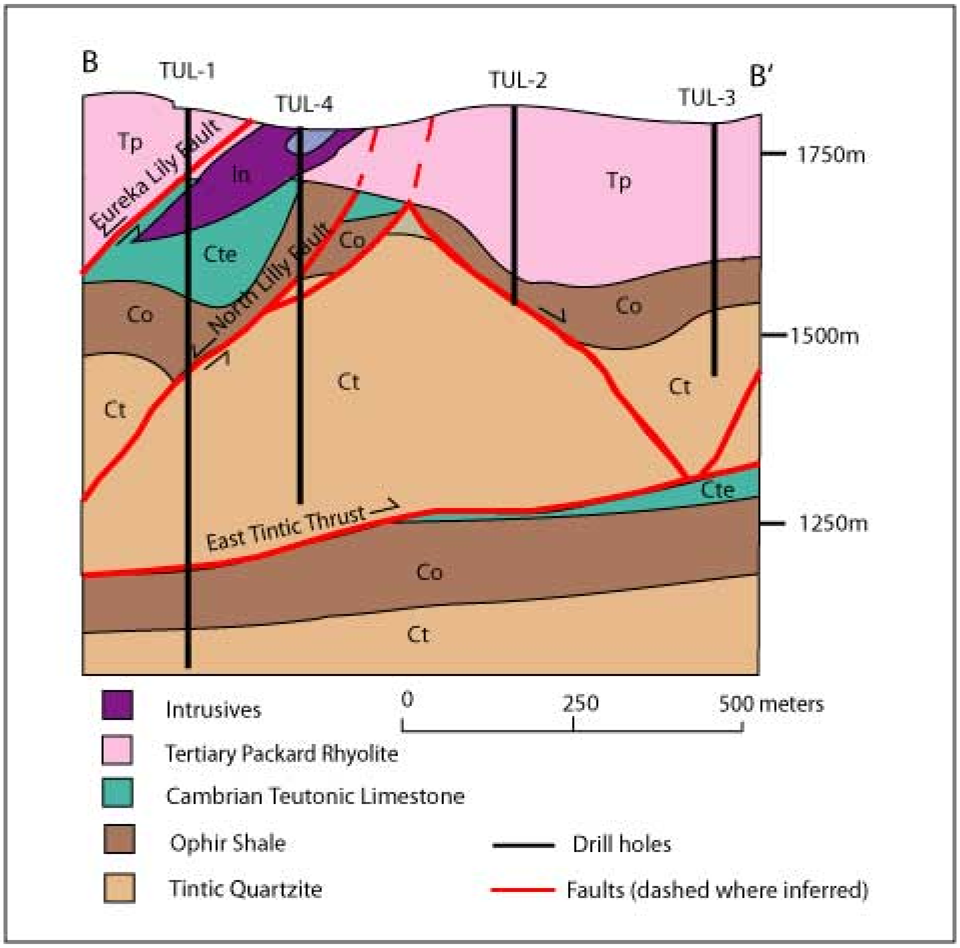

Figure 16. Structural model resulting from exploratory drilling. The clay-rich Ophir formation forms the basal detachment of the East Tintic Thrust. Normal faults terminated into this detachment and may be reactivated thrust faults. Varying thickness of volcanic cap indicates the pre-volcanic topography (See Figure 2 for line of section).

The structural model resulting from this drilling program (Figure 16) provided a more detailed interpretation of the East Tintic thrust zone (Anaconda, 1975). The Eureka Lilly fault clearly offsets the Cambrian Tintic Quartzite in the subsurface, and there is also evidence that it cut the Tertiary Packard Latite in the mine area. In spite of the projection of the Eureka Lilly fault to the north of this location, which shows it clearly offsetting the Tertiary rocks, Anaconda concluded that the Eureka Lilly fault in the Tintic Standard and North Lily mines is pre-Packard Latite in age. They also suggested that the Eureka Lilly fault may be two entirely different but parallel faults. The evidence in these holes is likely not conclusive on the age of fault slip, although it does show cross-cutting relationships are commonly ambiguous. These data also show how the hanging wall of the East Tintic thrust has been damaged extensively by subsequent normal faults.

Mine Descriptions

North Lily – The Eureka Lilly Fault Zone is southwest of the main ore deposit, striking 323° in the area north of the North Lily shaft and turning to 350° south of the shaft. The ore mineralization is essentially in faults on the footwall of the Eureka Lilly fault that may relate not only to the Eureka Lilly fault zones but to the Tintic Standard Thrust, which is intersected by the mine shaft (Figure 17). This also shows that extension in this area is both pre- and post- Packard latite (Lovering and Morris, 1979).

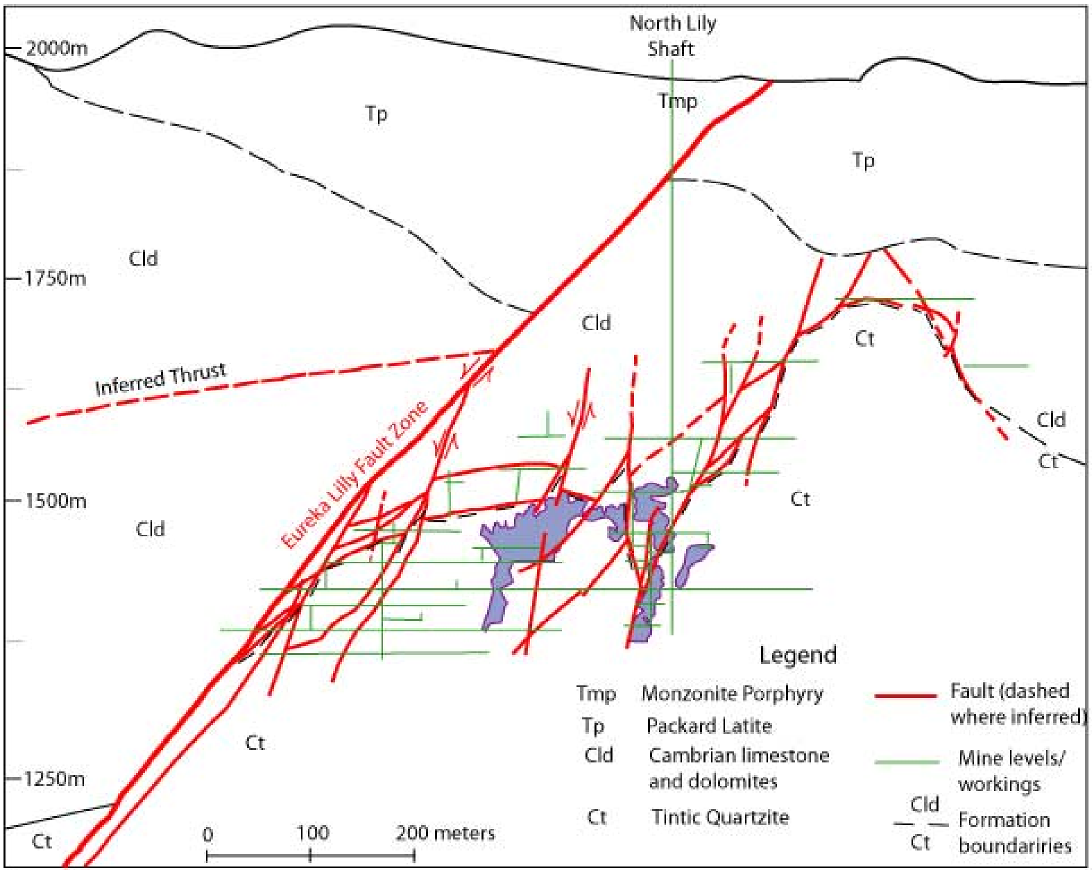

Figure 17. Simplified cross-section of North Lily Shaft, showing relationship to Eureka Lilly Fault and mineralization (adapted from Lovering and Morris, 1965).

There are several maps of subsurface mining operations (Chief, 2000), which provide further insight into the detailed structure of the Eureka Lilly fault zone. In one map of the Coyote area of the North Lily Mine, the Eureka Lilly fault is represented as a series of parallel structures about 90 meters apart. It also indicates that the Eureka Lilly fault zone is a total of about 150 meters across in this section (Figure 18).

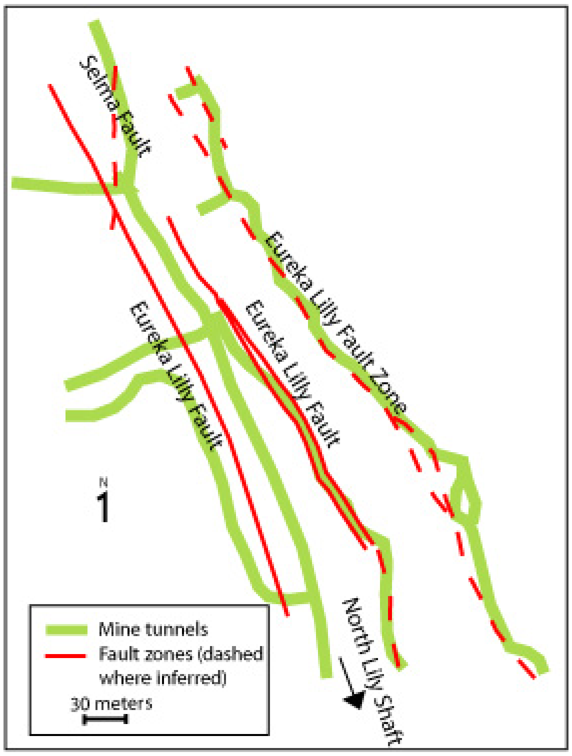

Figure 18. Map of Coyote area of North Lily shaft. The Eureka Lilly fault zone is characterized by multiple strands in this area.

Eureka Lilly - In this area the Eureka Lilly Fault has placed latite against Cambrian age sedimentary rocks. The Eureka Lilly fault zone trends northerly and dips 50˚ W. The total throw is estimated at 180 to 210 meters in the vicinity of the shaft. Younger fractures associated with the Eureka Lilly Fault zone cut the folded and faulted sedimentary rocks and overlying volcanic rocks. Commonly, these fractures are associated with pebble dikes and monzonite porphyry dikes. (Lovering and Morris, 1965)

Iron King No. 2 - This mine was established to explore mineralization along the Eureka Lilly Fault about 213 meters below the surface near the intersection with the Iron King Fault (Figure 19). The rocks above the Eureka Lilly fault zone are in the footwall of the Iron King fault and range from the Cambrian Bluebird Dolomite to the Cambrian Teutonic Limestone. The rocks below this level are chiefly Tintic Quartzite, with a thin interval of the basal part of the Ophir Formation. Most of the mine workings explored the mineralized Eureka Lilly fault zone north of its intersection with the Iron King fault (Figure 19). The water level in this mine is at 1390 meters elevation.

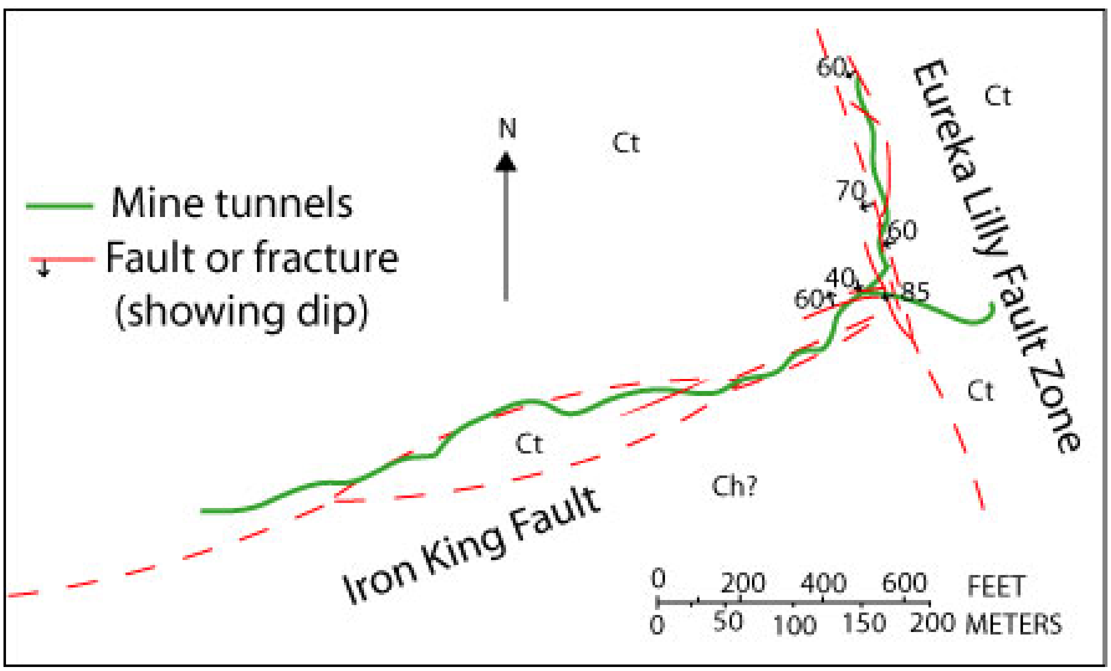

Figure 19. Plan view structure and mine map of geologic relationship between Iron King Fault and Eureka Lilly Fault zone, with additional clarification of cross sectional relationships (after Lovering and Morris, 1965).

Trixie - During excavation in the Trixie mine in an unnamed fault near the Eureka Lilly fault zone, an attempt was made to explore their intersection as potential location of concentrated ore mineralization. However, this was abandoned when miners were unable to drill through the densely brecciated core zone of the projected Eureka Lilly fault zone as exploratory drilling was only able to penetrate 2 to 3 meters into the breccia, preventing any further measurements of its thickness and extent. In the tunnel approaching this termination/intersection several parallel smaller scale faults were observed that all have small amounts of mineralization along their slip surfaces. Each of these deposits was mined into for about 3 to 5 m. The small faults that parallel the Eureka Lilly fault zone are spaced at about 5 to 7 m intervals adjacent to the brecciated core zone.

Porosity and Permeability measurements

Rock samples were collected from a drill core near the Trixie mine for measurement of porosity and permeability. Samples A through E were taken from the same vertical core at increments across the Trixie fault in well log ET-162. Samples A and B were taken from the hanging wall of the fault; Sample C is from the Core zone; Sample D from an Tintic Quartzite in the footwall and sample E from an associated breccia zone in the footwall. Sample SH was taken from a hand sample collected of the breccia zone of the fault core shown in Figure 6.

Measurements of porosity (Table 2) show that the quartzite unit is very tight with very low pore volume. Groundwater would be unable to flow through the matrix of the Tintic Quartzite, so fluid flow must be through connected systems of open fractures, which are found primarily in fault damage zones. Measurements of the brecciated limestone units indicate it can have significant porosity and permeability. As fault cores evolve, the clay units along the slip surface will seal the fault zone, which decreases the permeability. As shown in the sample of the fault core breccia zone (SH), as fluids move along the fault, precipitation can close fractures and seal the core zone, significantly decreasing porosity and permeability. Sample SH still has some significant porosity, which could be a result of some weakness enhanced by surface erosion processes. It also indicates that these brecciated core zones are significantly more impermeable as a result of the clay-rich alteration, not just the inherent impermeability of the rock.

Table 2. Porosity and Permeability Measurements; ρ,grain is porosity of individual grains, ρ,rock is the rock porosity.

sample	Description	Porosity	ρ,grain (g/cm^3)	ρ,rock (g/cm^3)	Permeability (mD)
A	Tintic Quartzite – slightly altered (iron rich veining)	6.0	2.63	2.48	negligible (0)
B	Tintic Quartzite	0.6	2.61	2.59	negligible (0)
C	Brecciated limestone	24.2	2.87	2.17	3.7
D	Tintic Quartzite	0.9	2.64	2.61	0.0
E	Brecciated limestone	25.2	2.88	2.16	16.3
SH	Breccia zone	9.2	2.79	2.53	4.2

SUMMARY OF EUREKA LILLY FAULT ZONE ARCHITECTURE

Deformation involves multiple phases of fracturing and shear, often along reactivated fault planes. The deformation resulted in the formation of thick (hundreds of meters) damage zones with well-connected fracture networks. These fractures open flow paths for groundwater through otherwise impermeable rock.

Mineral rich waters flowed through the fault core zone and left rich ore deposits that reduced permeability and in some cases sealed the core. The fault core was already partially sealed by clay units within the limestones, smearing long the slip surface, creating a barrier to fluid movement.

The Eureka Lilly fault is structurally varied. Surface exposures show areas where it is a narrow, single strand with a wide extensive damage zone. Other areas show much more complexity with associated slip surfaces and gouge zones laterally in the damage zone that take up some of the fault strain. These associated fractures extend out well past the traditional core zone of a fault. Fractures can be enlarged by carbonate dissolution of the limestone units.

The Tintic Quartzite is one of the best prospective aquifers due to its high fracture density, stratigraphic location (overlain by units of lower hydraulic conductivity) and relationship with major faults in the area (Hurlow, 1999).

HYDROLOGIC ANALYSIS

GROUNDWATER SYSTEMS

There are three distinct groundwaters found in this region: a deep warm geothermal water system is encountered in the footwall of the Eureka Lilly fault; a deep cooler water system is found in the hanging wall of the Eureka Lilly Fault Zone and a shallow groundwater system in the surface volcanic rocks.

The only published study of groundwater in the Tintic Mining District was conducted by Lovering and Morris (1965), who focused on the thermal system. They found a correlation between anomalous temperatures, geologic structure and certain formations. High temperature water is generally restricted to the area east of the Eureka Lilly fault (Figure 2 and 3). Lovering and Morris determined that the warmer water flows dominantly through fractures in

Paleozoic rocks, specifically the Tintic Quartzite. Geothermic groundwaters are found at fault intersections, such as the South and Eureka Standard Fault with the East Tintic thrust.

Lovering and Morris (1964) proposed that the damage zone of the East Tintic thrust fault acts as a conduit for rising hot water. Thermal gradient measurements indicate that water generally moves upward and toward the east or northeast through the damage zone. Water temperatures range between 40°C and 49°C, with increasing temperatures towards the west. Water chemistry data led Lovering and Morris (1961) to conclude the saline groundwater is of magmatic origin, although it could also be deeply circulating geothermal water. However, no water source or method for the required deep circulation predicted by the Lovering model is suggested.

Hydrologic studies of other thermal water systems and surface waters near the East Tintic Mining District, such as Goshen Valley, Lincoln Point and Goshen Bay, provide additional information on regional groundwater characteristics and hydrochemical data (Baskin et al., 1994; Brooks and Stolp, 1995; Cordova, 1970; and Dustin and La Vere, 1980). Cole (1983) conducted a study of the hydrogeochemistry of geothermal waters along normal faults in Utah and determined that waters with temperatures greater than 40°C are enriched in $Na^+ + K^+$ and SO_4^{2-}+Cl^-. On the other hand, higher concentrations of

HCO_3^- + CO_3^- and Ca^{2+} + Mg^{2+}, similar to local groundwaters, characterize lower temperature springs. The deeper waters found adjacent to the Eureka Lilly fault zone correlate with these observations, although the higher Mg^{2+} found in the North Lily does not correlate.

Klauk and Davis (1984) and Cordova (1970) identify groundwater of moderate salinity in Goshen Valley. Many of the Goshen groundwaters are chemically similar to water encountered in the Burgin mine as well as thermal groundwater discharging at Lincoln Point in Utah Lake (Klauk and Davis, 1984). Previous groundwater sampling in Goshen Valley indicated that this chemical and thermal similarity is naturally occurring rather than being influenced by mine-water discharge (Hood, 1975; Dames and Moore, 1985).

GENERAL DESCRIPTIONS

A hot saline groundwater is found in deep areas east of the Eureka Lily fault, affecting the North Lily, Tintic Standard, Eureka Lilly, Eureka Standard, Apex Standard and Burgin mines. According to Kennecott, this water was pumped from the Burgin mine at rates from 3000 to 9000 gpm for 13 years (data in Appendix 1) without apparent decrease in volumes, water temperature or salinity (Groundwater Aspects of Burgin Miner Project: East Tintic Mining District Utah County UT, 1994). This represents a total quantity of discharged water of 54.7 x 10^9 gallons. Pumped water from the Burgin mine was discharged at the surface to a natural ephemeral stream channel and allowed to flow downstream to a series of disposal ponds constructed on an alluvial fan about 3.5 miles downstream. Discharge from ponds was though evaporation and seepage (Earthfax, 1990).

Originally, the early mine geologists thought that the high temperatures encountered with the groundwater were a result of exothermic oxidation of sulfides associated with the ore deposits (Lovering and Morris, 1965). Subsequent exploration showed there was little correlation between mineralization and higher wallrock temperatures (Lovering and Morris, 1979). Then underground geothermal waters were invoked as an explanation. This idea was supported by an increase in the TDS with depth, an indication of the water being closer to the hot spring source (believed to be below the East Tintic thrust). Additionally, they pointed to similarities in the chemistry between the water from the Burgin mine and several other highly saline surface hot springs in Utah. These hot springs (including Cooper, Roosevelt, Crystal, Utah, El Monte, Hooper, Joseph, Red Hill, Abraham and Becks Hot springs) are characterized by high chloride, low to moderate sulfate, and low to moderate bicarbonate, which correlate well with the Burgin waters (Cole, 1982). These are all distinctly different than the fresh, shallow groundwater found near Eureka and used for the city's water supply (Lovering and Morris, 1965). Lovering and Morris (1965) also concluded that the thermal water rises along a north-trending fracture zone in the footwall of the East Tintic thrust and spreads northeastward or southwestward along northeast trending fractures in its hanging wall.

According to a study conducted by SSI, a local mining operator, there is a relative "hot spot" near the Apex Standard No. 2 shaft due to geothermal groundwater associated with Oligocene volcanism. They believe that this source contributes about 200 gpm. Since the pumping rates from the Burgin mine show the water influx to be at least 6000 gpm, this indicates that most of the water in the system is groundwater. Groundwater flow is generally towards the east-northeast throughout the region (ESA Consultants, 1984). Oligocene magma would no longer contribute significant heat, so instead deep circulating geothermal waters could contribute this heat.

To the west of the Eureka Lilly Fault the water level is at about 1434 meters, which slopes up towards the southwest (Figure 20). On the East of the Eureka Lilly Fault Zone, the water table is at 1385 meters (in the North Lily mine, sloping to the Burgin mine to the SE (1382 meters) and to the Water Lillie mine in the north (1371 meters)). Regionally the water level is controlled by the height of Utah Lake, about 16 km to the northeast of the mining district, at an elevation of 1367 meters.

Table 3. Burgin mine water characteristics from 1962 to 1981. Values in ppm (Sunshine Mining Company, 1988)

Parameter	Low	High	Average
Water Temperature (°C)	130	150	140
Conductivity (μmhos/cm)	10000	10500	10400
pH	6.5	7.5	7
Total Dissolved Solids	6800	7600	7000
Total Suspended Solids	50	700 (up to 5%)	500
Alkalinity (as CaCO3)	100	600	525
Arsenic	0.001	0.5	0.03
Bicarbonate	500	650	600
Boron	3	7	4.5
Calcium	150	400	325
Carbonate	0.2	0.40	0.3
Chloride	2500	4500	3800
Copper	0.01	0.05	0.03
Fluoride	1	4	2
Hardness (as CaCO3)	750	2200	1100
Iron (total Fe)	1	10	8
Iron (filtered)	0.15	1.0	0.5
Lead	0	0.3	0.01
Magnesium	50	100	70
Manganese	1	40	15
Potassium	50	250	150
Silica	20	150	70
Sodium	700	2500	2200
Sulfate	300	1500	400
Zinc	0.05	10	0.3
Carbon Dioxide	100	500	300

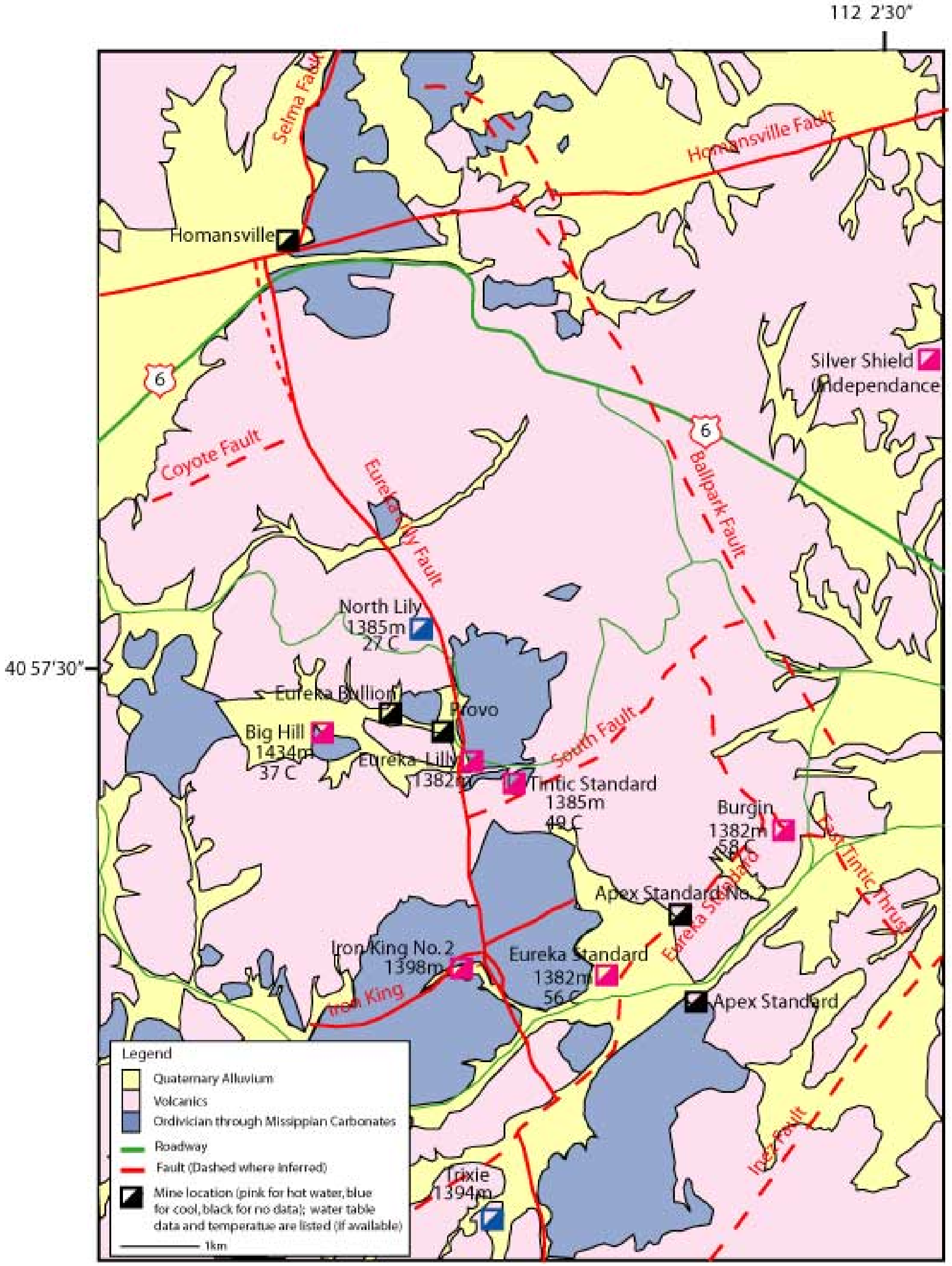

Figure 20. Topographic map showing locations of mines and groundwater information. There is a general correlation that locations on the East side of the Eureka Lilly fault have a cooler groundwater table elevation of 1434meters, whereas locations on the West side of the fault have hot saline groundwater at elevations between 1382 and 1398 meters.

SPECIFIC MINES

Many of the mines (Figure 20) in the East Tintic District intersect groundwater, providing small "windows" into the groundwater at different locations.

Eureka Standard

The groundwater is intersected in the Eureka Standard mine at an elevation of 1381 meters. This water is similar in many aspects to the groundwater in the Burgin mine, containing more than 5500 ppm solids and reaching temperatures as high as 56˚C and possibly higher (Lovering and Morris, 1965). The precipitated salts from the groundwater are more than 50% NaCl; others include $CaSO_4$, $CaCO_3$, MgCl and KCl. This is consistent with Cole's survey (1983) of the hydrochemistry of warm springs associated with normal faults in Utah. The large volume of groundwater, along with its high temperature and corrosive nature prevented any deeper development of the mine.

Burgin

In the Burgin Mine, wall-rock temperatures vary widely from 35˚C in the broken carbonate rocks to 58˚C in or near exposures of Tintic Quartzite in the NW of mine (Lovering and Morris, 1965). These temperatures are nearly 20˚C higher than would be expected at this depth from the geothermal gradient

(Western Regional Climate Center, 2005). As the mine developed below the water table, water temperatures increased with depth, reaching an average of 64˚C at the [2]1300 level.

Mine waters were high in dissolved materials, chiefly NaCl, but also including K^+ and Ca^{2+}, SO_4^{2-} and HCO_3^- and other constituents. Continued monitoring of the combined mine discharge waters indicates and average content of 3500 ppm chloride. Samples collected on the 1200 level of the mine contained about 4500 ppm chloride with a temperature of 69˚C in the west part of the mine. In contrast, in the East part of the mine, there was only 2200 ppm chloride and a temperature of 35˚C. This suggests a local source of thermal brine inflow at depth in an undetermined area to the west of the Burgin mine being diluted with water that is both cooler and with a lower TDS content.

Eureka Lilly

The Eureka Lilly mine extensively mined the Eureka Lilly fault zone, but never reached the water table depth. The water table in this mine is at 1382 meters (from exploration logs) and it is described as a hot saline "Burgin-like" water (Lovering and Morris, 1979).

Tintic Standard No. 1 and 2

The water table is at an elevation of 1382 meters, about 6m below the 1450

[2] Mine levels refer to the distance (in feet) below the surface of a particular mine tunnel

level. The average wall-rock temperature at this elevation is 120˚F (48.8˚C). The waters are slightly to moderately saline. During the 1940's, the No. 2 shaft was deepened to the 1570 level and ore was mined below the water table, resulting in a considerable volume of water being pumped to the surface. Although no records were found of chemical analysis for the water, it is described as being similar to the saline thermal water present in the Burgin mine (Lovering and Morris, 1979).

<u>Iron King No. 2</u>

The water table in the No. 2 shaft stands at an elevation of 1398 meters, about 5ft below the 1450 level. This is the same warm groundwater found in other East Tintic mines.

<u>Independence or Silver Shield Shaft</u>

Temperature data indicates that the mine was very hot in areas where it was not ventilated, indicating that the East Tintic thermal area extends northward at least as far as the Independence Shaft (Lovering and Morris, 1979).

<u>Trixie</u>

The water table in the Trixie mine stands at 1394 meters below the surface. There is also a small perched water table in the lavas in the upper part of the shaft. The water in this mine is fresh and maintains a constant temperature of about 24˚C at the 750 level (Irwin, 2001).

Big Hill

Strong inflows of water first appeared at 1434 meters in this mine. This halted any subsequent development (Lovering and Morris, 1979).

Apex

The wallrock temperatures exceeded 57˚C at the 1100 ft level and were 51˚C at the 900 level (elevation of about 1493 meters). Groundwater was never actually encountered in this mine (Lovering and Morris, 1979).

North Standard mine

This mine was mined down to the 1400 level. Although the water table was not reached, reports indicate that it was exceptionally hot and gassy, especially in the deeper levels (Lovering and Morris, 1979).

North Lily

The Groundwater table stands at an elevation of 1385 meters in the North Lilly shaft. This is close to its elevation throughout the footwall block of the Eureka Lilly fault. In the hanging-wall block the water table apparently rises sharply, having been cut at an elevation of 1434 meters in the nearby Big Hill shaft (Lovering and Morris, 1979). This water is relatively cool (27°C) in contrast to that of the Burgin Mine (about 49°C). Note that this is still higher than the mean annual temperature and the geothermal gradient for this depth (assuming 2.5 °C per 100m depth, at the depth of 535 meters, this would give us a temperature of 21.5 °C) (Western Regional Climate Center, 2005), indicating that it is still a thermal groundwater .

WATER SAMPLING

Water was sampled from five locations in the study area (see Figure 2, Table 4). Goshen springs are located outside of Figure 2, just south and east of the town of Goshen (shown in Figure 1). These were the only sites that had any water flowing during the summer of 2002. Water sample 2842 was from a standing 2.1 meter well. Water in this well was covered in a brownish slime. To prepare the well, and attempt to get an accurate sample, the well was purged prior to sampling.

Table 4. Field measurements for sampled waters

Sample Location	pH	Conductivity (µS)	Temperature (˚C)	Lab Number
Well A	7.21	845	17.5	2842
Spring 1 – Homansville site (just N of SH6)	8.28	351.3	20.3	2774
Spring 2 (just W of Burriston Pass)	6.87	278	10.4	2775
Spring 3 – Hannibal Spring	7.78	714	11.8	2843
Goshen Warm Springs	7.75	1907	7.75	2846

Water from near the Homansville site was taken from a source where it discharges and flows into a marshy spring area. Spring 2 flows from a small mine adit. Water flowing into the standing water was sampled. Spring 3 emanates at the bottom of a very large hill where water discharges from a plastic pipe in the hillside. Goshen warm springs was sampled where water flows into a pond, although it was not possible to sample directly at the discharge location.

Stable Isotopes

The isotopic content of precipitation is influenced by altitude, distance inland from the ocean, season, latitude and temperature, with the ^{2}H and ^{18}O content of precipitation decreasing with altitude, latitude, and inland from the coast (Clark and Fritz, 1997). The mean $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios of precipitation define the meteoric water line (Craig, 1961). Evaporation and geothermal rock interaction will result in isotopic ratios that will not fall on the Meteoric Water Line (Figure 21).

The samples (Table 5) show δD values that vary from -112 to -121 ‰, whereas $\delta^{18}O$ values range from -13.5 to -14.9 ‰.

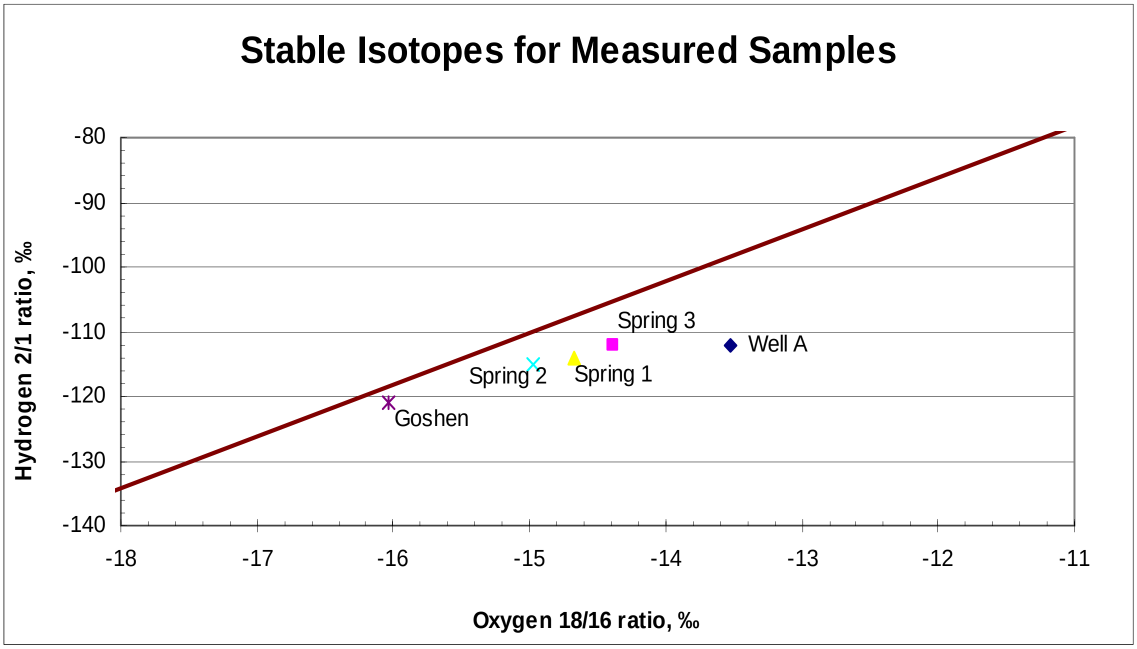

Figure 21. Graph showing water isotopes in comparison to the Meteoric Water Line.

Table 5. Oxygen and Hydrogen isotope ratios determined for sampled waters.

	18/16O	3/2H
WELL A	-13.53	-112.1
Spring 3	-14.39	-112.1
Spring 1	-14.67	-114.0
Spring 2	-14.97	-115.1
GOSHEN	-16.03	-120.9

The sample from Well A is the most enriched in ^{18}O compared to the other samples, due to slight evaporation. The Goshen spring samples are comparatively depleted in ^{18}O and ^{2}H. It would be fair to assume that the Goshen spring sample is from a groundwater that has a significantly different source. This is of course substantiated by its location much closer to Utah Lake and the range front faults than the other samples. These faults likely provide a conduit for a deeper geothermal water to reach the surface.

Both the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios compared to the Meteoric Water Line indicate the water for the 3 springs may have all undergone slight evaporation, although this may also just be the effective precipitation in this region (Figure 21).

Water Chemistry

Table 6 shows the results of the chemical analysis performed on the sampled waters. The waters appear to be Ca-Na, HCO_3-SO_4 rich. Goshen Warm springs is the most saline of the samples and is likely the result of water moving up one of the Wasatch Mountain range front faults mapped adjacent to the spring. The Goshen sample also is most similar to the trend of the Burgin water – perhaps it represents a dilution of a similar or common source. There is a correlation between Na^{+} and Cl^{-} in all of the samples, so it perhaps the water flows through a halite unit in the subsurface. Ca^{2+} and Mg^{2+} correlate with the HCO_3^{-} concentrations, except at Spring 3, where SO_4^{2-} is much higher in concentration. This could mean that Spring 3 is flowing through perhaps less carbonate-rich rocks than the other samples resulting in less dissolved carbonate in the water. In all cases, the error seems to be low indicating that all major ions were accounted for in the testing.

Table 6. Cation and Anion measurements from sampled waters

Location	Ca	Mg	Na	K	Fe	Total Cations
			meq/L			
Spring 1	3.63	1.34	2.86	0.12	0.01	7.96
Spring 2	3.11	0.89	1.55	0.05	0.01	5.61
Spring3	4.88	1.71	2.44	0.06	0.01	9.1
Well A	5.28	0.58	2.98	0.06	0.01	8.91
Goshen	3.68	2.77	11.87	0.73	0.01	19.06

Location	HCO3	F	Cl	NO3	Br	HPO4	SO4	Total Anions	% error
			meq/L						
Spring 1	4.11	0	2.66	0	0	0	1.41	8.18	-1.4
Spring 2	2.95	0.01	1.01	0	0	0	2.02	5.99	-3.3
Spring3	3.4	0	1.5	0	0	0	4.6	9.5	-2.2
Well A	6.44	0	2.51	0	0	0	0.8	9.75	-4.5
Goshen	5.17	0.07	12.94	0.02	0	0	1.93	20.13	-2.7

Clearly, the Burgin water has more Cl^-, HCO_3^-, Na^+ and SO_4^{2-} than the sampled waters (Figure 22). This is expected, as the sampled waters are from surface springs and runoff, whereas the Burgin mine water is from much deeper in the subsurface and is consistently described as saline. None of the waters sampled are from the same source as the Burgin water.

In the conceptual model proposed in this thesis, hot, saline groundwater is found only on the east (footwall) side of the fault. This would indicate that the source is somewhere below the East Tintic thrust, or is feeding into the East Tintic thrust fault. Since the water found on the hanging wall (west) side of the fault appears to be different in temperature, elevation and chemical characteristics, it would appear the water is from a different source. The Eureka

Lilly Fault is the only major structure in the area and thus appears to be the barrier between these two waters. There is no obvious mixing zone between these two waters.

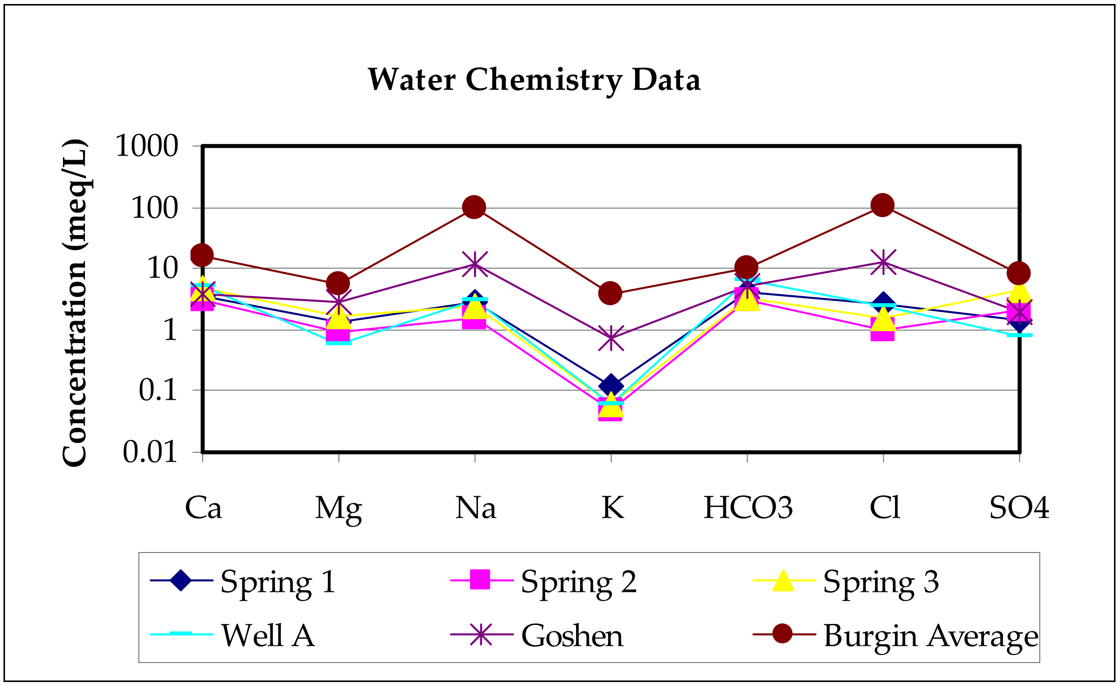

Figure 22. Water Chemistry by location shows that the Burgin water is much higher in Na, HCO_3, Cl^- and SO_4^{2-} ions than the surface samples.

SUMMARY

There are three separate groundwaters in this area:

1. Strongly thermal, high-TDS Na^+-Cl^- rich groundwater: This is characterized by temperatures of at least 54°C and an elevation of 1385 meters. It is extremely high in sodium and chloride and found only in the footwall of the Eureka Lilly fault.

2. Modestly thermal, intermediate TDS Mg^{2+}-SO_4^{2-} rich groundwater: This water is found on the hanging wall of the Eureka Lilly fault and has temperatures of 27 °C and elevations of 1434 meters (significantly higher than on the footwall).

3. Cold, low TDS shallow groundwater: these waters experience shallow circulation through the volcanic rocks and limestones.

DISCUSSION

Lateral Variation along fault

The expression of the Eureka Lilly Fault varies laterally across this district. In the north, at the roadcut site, it is a narrow brecciated fault core, with a wide extensive damage zone. The damage zone in the limestone units extends laterally overlapping small scale thrust and normal faults, with discreet zones where the rock has been shattered by slip events. In the hanging wall, the tuff unit is pulverized in the unwelded units, whereas in welded units, we see the same normal fault pattern. In contrast near Mineral Hill, the fault briefly surfaces in a canyon where it shows very little brecciation, and no evidence of a thick core zone. Instead we see a narrow damage zone that is extremely fractured and has been largely eroded, with damage zone fractures apparent in the remaining valley walls. In the subsurface, mines describe much more extensive zones of brecciation and altered rock, in zones 50 meters wide. They also commonly show several strands of overlapping and sinusoidal in faults.

These structural variations act to further compartmentalize water, as these differentiate how the fault architecture limits or enhances groundwater flow. As demonstrated by Gudmundsson (2001), the breccia zone associated with the fault core is normally the greatest barrier to groundwater flow. This is supported by the compartmentalization shows along the Eureka Lilly fault in this area.

Aquifer definition

In rocks with low porosity and permeability groundwater can be held only in the secondary porosity provided by fracture networks and dissolution associated with fault zones. In this way, groundwater cannot be described in terms of an elevation or stratigraphic units, as traditional aquifers are, but instead by the relationship with the fault (and the nature of the fault architecture). Groundwater held only in damage zones will be compartmentalized by the lateral extent of the fault zone.

Fault intersections

Intersections significantly increase the number and the width of fractures, enabling more groundwater flow. The extensive faulting found in the East Tintic district results in overprinted fracture networks that extend laterally from major faults. In this area fault intersections are so extensive massive blocks of unfractured country rock can't be found. Instead overprinting damage zones extend fracture networks, and thus the capacity to hold and transmit groundwater, in large three dimensional zones dependant only on fault architecture. If these conduits later become cemented, then compartmentalization of groundwater increases.

Groundwater flow regime

Groundwater flow through fracture networks is fundamentally different than flow in shallow, unconsolidated sediments. In shallow, unconsolidated units groundwater can flow through a porous matrix. However in consolidated rocks with little to no permeability, this does not occur. Even in units with high porosity, only fractures will provide enough permeability to allow groundwater flow. Fracture networks associated with faults are not laterally continuous, uniform, or dependant on stratigraphy and may both enhance and retard groundwater flow depending on the geologic history of the region.   When the rock matrix is impermeable, flow through the fractured rock is mostly controlled by a combination of conductivity of individual fractures and fracture zones (Odling, 1997).

In the East Tintic mining district the core zones of faults were initially very effective conduits for advection of hot mineralizing fluids. Cementation associated with mineralization changed the once permeable core zones into highly effective barriers to groundwater transmission.

According to Caine and Forster (1999) computer models show increasing fracture aperture by only one order of magnitude can change the porosity by one to five orders of magnitude and similar variance in permeability. In this way, the key may not only be the number of fractures but the aperture that is vital to large water storativity. Fault intersections will create overprinted fracture zones, resulting in grater aperture in damage zone fractures (Evans, et al, 1997).

Pumping of Burgin Mine

When the Burgin was pumped for several years, there was no change in temperature, chemical composition or discharge rate. This indicates that the fracture network that held this groundwater was very effective at transmitting fluids, but not in communication with the cooler, lower Na-Cl groundwater on the hanging wall of the Eureka Lilly fault. Even within the same fault zone, fracture networks can compartmentalize groundwaters.

Caine model of fault architecture

The conceptual models proposed by Caine and Forster (1999) may apply to areas without a structural inheritance, but must be modified to apply to the East Tintic mining district. The Eureka fault zone has characteristics of a distributed deformation zone, where strain is partitioned to pre-existing fractures and localized along these zones. In contrast to their model, where a fault progresses from a single strand to a distributed damage zone to either a localized or composite deformation zone, the Eureka Lilly fault cannot simply be characterized by one of these. The Eureka Lilly fault zone has a varied history and nature due to small and regional scale faults that create a non-uniform damage zone adjacent to multiple intertwined fault cores.

Fault controlled groundwater and interbasin flow

The non-uniform nature of faults adds perturbations of fracture permeability in the groundwater systems. Even for major faults, the extent of the damage zone is limited by the nature of the rock type and the amount of localized strain. These limitations would prevent fault controlled groundwaters from contributing to inter-basin flow. There are a multitude of factors that compartmentalize groundwater flow, even within a single fault, that such large scale connectivity in areas like the Basin and Range seems highly unlikely.

Related Studies

Lachmar et al (2002) did a study looking at the effect of fractures, faults and structural geology on the aquifer characteristics of the Snyderville Basin near Park City. They were able to conclude that fractures enhanced the permeability of the anticline zone and that clay gouge decreased permeability perpendicular to the faults. Although they noted that the damage zone enhanced fluid flow in the area, they cautioned utilizing it exclusively did to the limited size (and thus water potential).

In the East Tintic Mining district, we see that the fault damage zones and fracture networks are so large and interconnected, that it allows an extremely large groundwater system to be held in a system almost entirely controlled by secondary (fracture) permeability. This shows that fracture zones, under the right conditions can be contributors to large volumes of groundwater and can provide a reliable source.

CONCLUSIONS

1. The faults here have controlled water circulation patterns throughout the Tertiary Period. Currently the fault core zones form an impermeable barrier caused by the breccia recementation and gouge development. The damage zone of the fault holds groundwater in open fractures and transmits water by interconnected fracture flow. These fractures are gradually being filled in by mineral precipitation.
2. Groundwater in the hanging wall and footwall of the Eureka Lilly fault and surface water are unconnected and compartmentalized, as shown by the following differences in water on either side of the fault zone:
   - elevation of water levels
   - temperature
   - composition
   - isotopic chemistry
3. The heterogeneity in the fault core and damage zone indicates that models for groundwater flow across any fault zone must be investigated individually in order to draw any conclusions.
4. Significant lateral variations of fault geometry, slip, architecture and fluid transmissivity are observed along even single strands of the Eureka Lily Fault zone.

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APPENDIX A: MINE PUMPING DATA

Year	Deep wells		Production Shaft No. 2	1200 level	1300 level	TOTAL
	1050 level	1200 level				
1965	2000	0	1300	0	0	3300
1966	2000	1250	50	900	0	4200
1967	2000	0	1200	900	300	4400
1968	1825	750	600	1000	275	4450
1969	2615	1450	0	970	165	5200
1970	2400	1285	45	1000	2200	6930
1971	3370	665	250	645	3520	8450
1972	2065	230	675	575	5305	8850
1973	1800	0	670	500	6030	9000

(Source: Kennecott Annual Reports 1967-1975 and Hall, 1975.)

APPENDIX B: COMPILED TINTIC WATER CHEMISTRY DATA

Location	Burgin No. 2	Burgin No. 2 (1350 Drift)	Burgin No. 1	Burgin No. 2
Date Collected	21-Dec-71	21-Dec-71	5-Jan-72	27-Dec-71
LAB #	72-c8244	72-c8243	72-c8242	72-c8241
TDS (ppm)	6219	7765	7182	7617
Chlorides - Cl (ppm)	2926	3783	3391	3462
NaCl (ppm)	4828	6241	5595	5712
Flourides - F (ppm)	0.5	1.5	1.5	1.5
Nitrates (ppm)	0.055	0.06	0.5	0.2
pH	7.9	7.6	7.7	7.6
Silica (SiO2)				
Calcium				
Mg				
Na+K				
Cl				
SO4				
Alkalinity as CaCO3				
Hardness as CaCO3				
As				
Fe				
Mn				
Pb				
F				
Zn				
Temp (C)				
Temp (F)	126	140		
Conductivity(milliohms/cm)				
Source	A	A	A	A

Location	Tailings Inflow	Burgin Tailings	Burgin settling pond	Burgin No. 1
Date Collected	27-Dec-71	27-Dec-71	27-Dec-71	5-Feb-75
LAB #	72-c8239	72-c8240	72-c8238	75-c0237
TDS (ppm)	8915	7995	7234	6607
Chlorides - Cl (ppm)	3676	3284	3676	3128
NaCl (ppm)	6065	5418	6065	5161
Flourides - F (ppm)	1.5	2	1.5	1
Nitrates (ppm)	none	2.1	70.00%	6.6
pH	8.9	7.9	8.1	7
Silica (SiO2)				
Calcium				
Mg				
Na+K				
Cl				
SO4				
Alkalinity as CaCO3				
Hardness as CaCO3				
As				
Fe				
Mn				
Pb				
F				
Zn				
Temp (C)				
Temp (F)				
Conductivity(milliohms/cm)				
Source	A	A	C	A

Location	Burgin No. 2	Tailings Inflow	Tailings Overflow	Dispersion Pond Inflow
Date Collected	5-Feb-75	5-Feb-75	5-Feb-75	5-Feb-75
LAB #	75-c0238	75-c0241	75-c0242	75-c0240
TDS (ppm)	7147	8541	8522	7046
Chlorides - Cl (ppm)	3452	3308	3380	3524
NaCl (ppm)	5696	5458	5577	5814
Flourides - F (ppm)	1	3	3	1.2
Nitrates (ppm)	3	3	4.8	7.7
pH	7.2	7.5	7.3	7.7
Silica (SiO2)				
Calcium				
Mg				
Na+K				
Cl				
SO4				
Alkalinity as CaCO3				
Hardness as CaCO3				
As				
Fe				
Mn				
Pb				
F				
Zn				
Temp (C)				
Temp (F)				
Conductivity(milliohms/cm)				
Source	A	A	A	A

Location	Dispersion Pond No. 4	Settlement Pond No. 5	Settlement Pond Inflow	Burgin No. 2
Date Collected	5-Feb-75	15-Jul-76	15-Jul-76	15-Jul-76
LAB #	75-c0239	76-c9667	76-c9666	76-c9669
TDS (ppm)	7086	7187	6906	6916
Chlorides - Cl (ppm)	3524	3608	3472	3326
NaCl (ppm)	5814	5954	5730	5488
Flourides - F (ppm)	0.8	1.5	1.7	1.5
Nitrates (ppm)	7.5	0.44	0.4	0.3
pH	7.8	8.2	7.8	7.5
Silica (SiO2)				
Calcium				
Mg				
Na+K				
Cl				
SO4				
Alkalinity as CaCO3				
Hardness as CaCO3				
As				
Fe				
Mn				
Pb				
F				
Zn				
Temp (C)				
Temp (F)				
Conductivity(milliohms/cm)				
Source	A	A	A	A

Location	Burgin No. 1	Burgin No. 2	Burgin discharge	Burgin
Date Collected	15-Jul-76	22-Nov-67	15-Aug-74	1963
LAB #	76-c9668	68-c802	74-1821	
TDS (ppm)	7313	7052	6860	6375
Chlorides - Cl (ppm)	3472	3340		2328.9
NaCl (ppm)	5730			
Flourides - F (ppm)	1.8	1.6		2.2
Nitrates (ppm)	0.1	0.7		1.1
pH	7.7	7.2	6.6	6.55
Silica (SiO2)		41.4	40	77.8
Calcium		325.2	200	318
Mg		58.2	68	119
Na+K		2090.9	2345	1441
Cl		3340	3475	2328.9
SO4		363.4	278	942
Alkalinity as CaCO3		500	120	313
Hardness as CaCO3		1051.6	780	1282
As		0.32	0.25	0.123
Fe		0.4	0.62	7.05
Mn		1	0.07	47.9
Pb		0.25	0.11	0.03
F		1.6	0.95	2.2
Zn		0.04	0.05	0.22
Temp (C)				
Temp (F)				
Conductivity(milliohms/cm)			11400	
Source	A	A	B	C

Location	Burgin	Burgin	Burgin	Burgin No. 2
Date Collected	1965	1969	1970	30-Dec-75
LAB #				0732-75
TDS (ppm)	8518	6131	7204	
Chlorides - Cl (ppm)	3500	3845	3565	
NaCl (ppm)				
Flourides - F (ppm)	1	2.2	1.85	
Nitrates (ppm)		0.8	0.6	
pH	7.2	7.7	7	8.35
Silica (SiO2)	68.6	102	35	
Calcium	320	173	329	240
Mg	60	73	66	74
Na+K	2214	2368	1985	2065
Cl	3500	3845	3565	3265
SO4	350	401	400	468
Alkalinity as CaCO3	565	520	510	
Hardness as CaCO3	1050	733	120	
As	0.35	0.42	0.33	
Fe	1.5	0.15	4	
Mn	0.8	0.8	0.11	
Pb	0.02	0.3	0.06	
F	1	2.2	1.85	
Zn	0.03	0.3	0.51	
Temp (C)				42
Temp (F)				
Conductivity(milliohms/cm)				12500
Source	C	C	C	D

Location	Burgin No. 3
Date Collected	27-Jul-76
LAB #	0469-76
TDS (ppm)	
Chlorides - Cl (ppm)	
NaCl (ppm)	
Flourides - F (ppm)	
Nitrates (ppm)	
pH	8
Silica (SiO2)	57
Calcium	330
Mg	60
Na+K	2320
Cl	3700
SO4	430
Alkalinity as CaCO3	
Hardness as CaCO3	
As	
Fe	
Mn	
Pb	
F	
Zn	
Temp (C)	58
Temp (F)	
Conductivity(milliohms/cm)	13600
Source	D

Sources for Data:

A Department of Agriculture, office of state chemist for Kennecott Copper Corp (Unpublished)

B State of Utah Department of Social Services Division of Health for Kennecott Mining (Unpublished)

C Kennecott Mine data (Unpublished)

D Analysed by Amtech for Phillips Petroleum Company (Unpublished)