FAULT-RELATED GROUND-WATER COMPARTMENTALIZATION IN THE EAST TINTIC MINING DISTRICT, UTAH

by

Sandra Hamaker[1] and Ron Harris[1]

ABSTRACT

Polyphase deformation and magmatism in the East Tintic mining district of central Utah formed highly permeable damage-zone conduits for water circulation and mineralization, yet clay-rich and re-cemented fault core zones form impermeable barriers that compartmentalize and isolate local ground-water systems at scales of a few kilometers. The effects of the Eureka Lilly fault, a major structure in the area, are most pronounced. It separates two distinct ground waters with a vertical separation of 50 m that have different temperatures and compositions, indicating little to no communication across the fault. Damage zones parallel to the fault form very permeable networks of interconnected and open fractures that discharge 11,000 to 34,000 L/min in otherwise impermeable units. Fracture density measurements show that the damage zone is discontinuous with localized fracture networks separated by mostly coherent blocks.

Three distinct types of ground water are found near the Eureka Lilly fault: (1) strongly thermal (>54°C), Na^+- and Cl^--rich ground water with high total dissolved solids (TDS) at <1385 m elevation in the footwall of the fault; (2) modestly thermal (<27°C), Mg^{2+}- and SO_4^{2-}-rich ground water with intermediate TDS at >1434 m elevation in the hanging wall of the fault; and (3) cold, low-TDS, shallow ground water that extends only 100 m below the surface, leaving a >243 m dry zone between it and waters 1 and 2. These observations bring into question simple basin-flow models involving ground water moving easily through bedrock and across faults between basins.

INTRODUCTION

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

Because of having both surface and subsurface control, the East Tintic mining district of Utah provides a unique opportunity to study complex interactions of ground-water movement through fracture networks associated with fault zones. The fault structure and limited hydraulic connectivity in this area challenge traditional ideas on fluid-fault interactions, such as interbasin flow (Eakin, 1966; Maxey, 1968; Mifflin, 1968). Subsurface observations provided by mining data and drilling allow us to test if, and how, fault architecture influences ground-water flow systems.

A greater understanding of the relationship between ground water and fault zones impacts many fundamental problems relating to the extraction and containment of fluids in rocks. Caine and Forster (1999), who found that the damage and core zones of faults both enhance and retard fluid flow, summarized previous investigations of this problem. Whether the fault core will act as a conduit, a 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 and others, 1996; Gudmundsson and others, 2001).

The purpose of this investigation is to examine an extensively documented, mostly blind fault zone, and the ground-water systems it partitions. In the East Tintic mining district, rock units have almost no porosity, so ground-water flow is limited to fracture networks associated with multiple phases of deformation. This geological setting provides an opportunity to understand how local compartmentalization of ground water occurs in fracture-dominated flow regimes. Unpublished data from mine reports documenting subsurface relations between water levels across faults, field studies of surface-fault architecture, and water chemistry provide a way of demonstrating how the architecture of the Eureka Lilly fault zone compartmentalizes ground water from different sources in the East Tintic mining district.

[1]*Department of Geological Sciences, Brigham Young University, Provo, UT 84602 smconrad@hotmail.com ron_harris@byu.edu*

GEOLOGIC SETTING

The East Tintic mining district is located in the East Tintic Mountains, a horst block in the eastern Basin and Range Province of central Utah (figure 1). Prior to block faulting by basin-and-range extension, the area was part of the Sevier fold and thrust belt (Armstrong, 1968; Morris and Mogensen, 1978), and of the Tertiary volcanic arc associated with subduction along the western edge of North America.

Detailed geological studies in the East Tintic area were conducted primarily to determine the economic potential for silver, zinc, and lead mining, and to further understand the nature of these volcanic deposits (Lindgren and others, 1919; Bush and others, 1960; see also Moore and others, this volume). Most ore bodies are blind (concealed by thick Tertiary volcanic rocks) and are predominantly hosted in Cambrian sedimentary units (figure 2). These and other Paleozoic units were deformed multiple times by Sevier folding and thrusting, and again by Tertiary extension and magmatism. The structure consists of overlapping thrust sheets that repeat a sedimentary succession comprising folded Cambrian to Mississippian clastic and carbonate units unconformably overlain by Tertiary volcanic rocks (figures 3 and 4). All of these units were later deformed by extension and offset by normal faults. Multiple phases of deformation have produced a dense array of extensional and shear fractures in Paleozoic units that enhance the flow of ground water in otherwise mostly impermeable bedrock (Wallace and Morris, 1986), and also formed impermeable fault-core zones that compartmentalize the ground water.

Stratigraphy

The oldest exposed unit in the East Tintic mining district is the Cambrian Tintic Quartzite (figure 2), which is a medium-grained sedimentary quartzite with predominantly silica cement and no effective porosity (table 1).

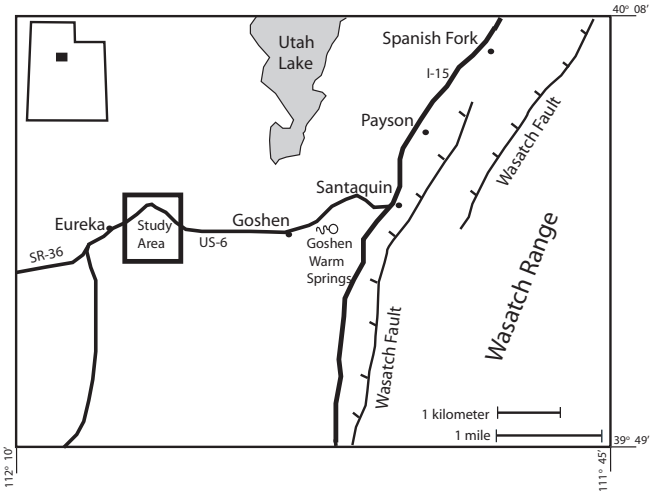

Figure 1. East Tintic mining district, with location of study area, major highways, and major fault zones.

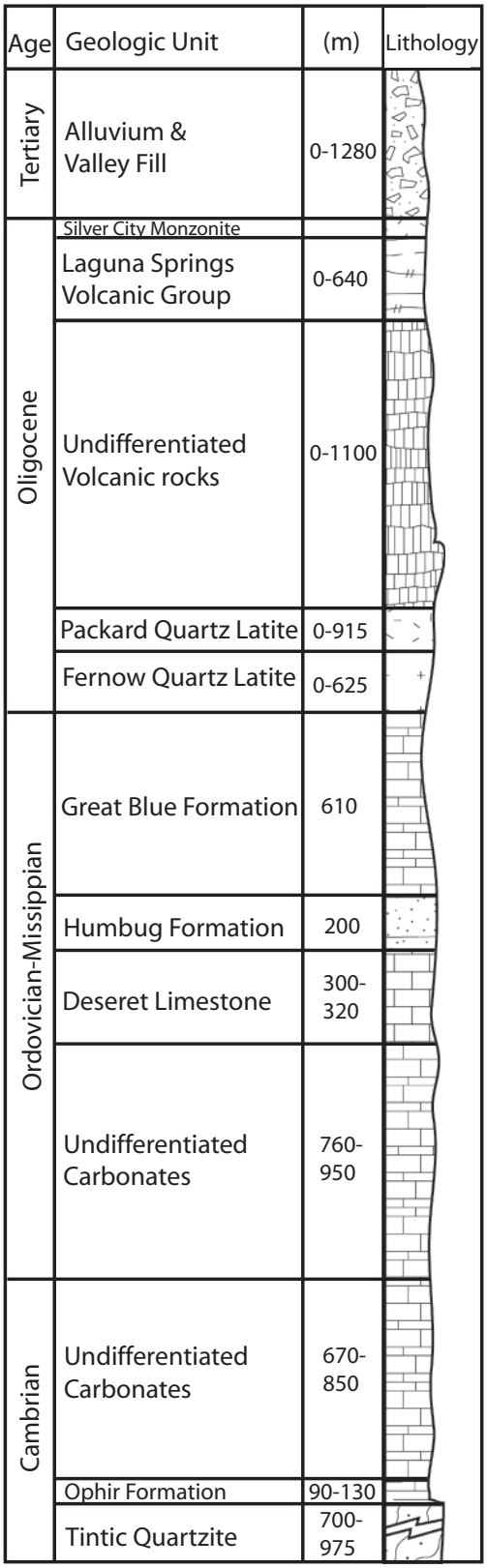

Figure 2. Generalized stratigraphy of the East Tintic mining district. Adapted from Morris and Lovering (1961) and Hintze (1988).

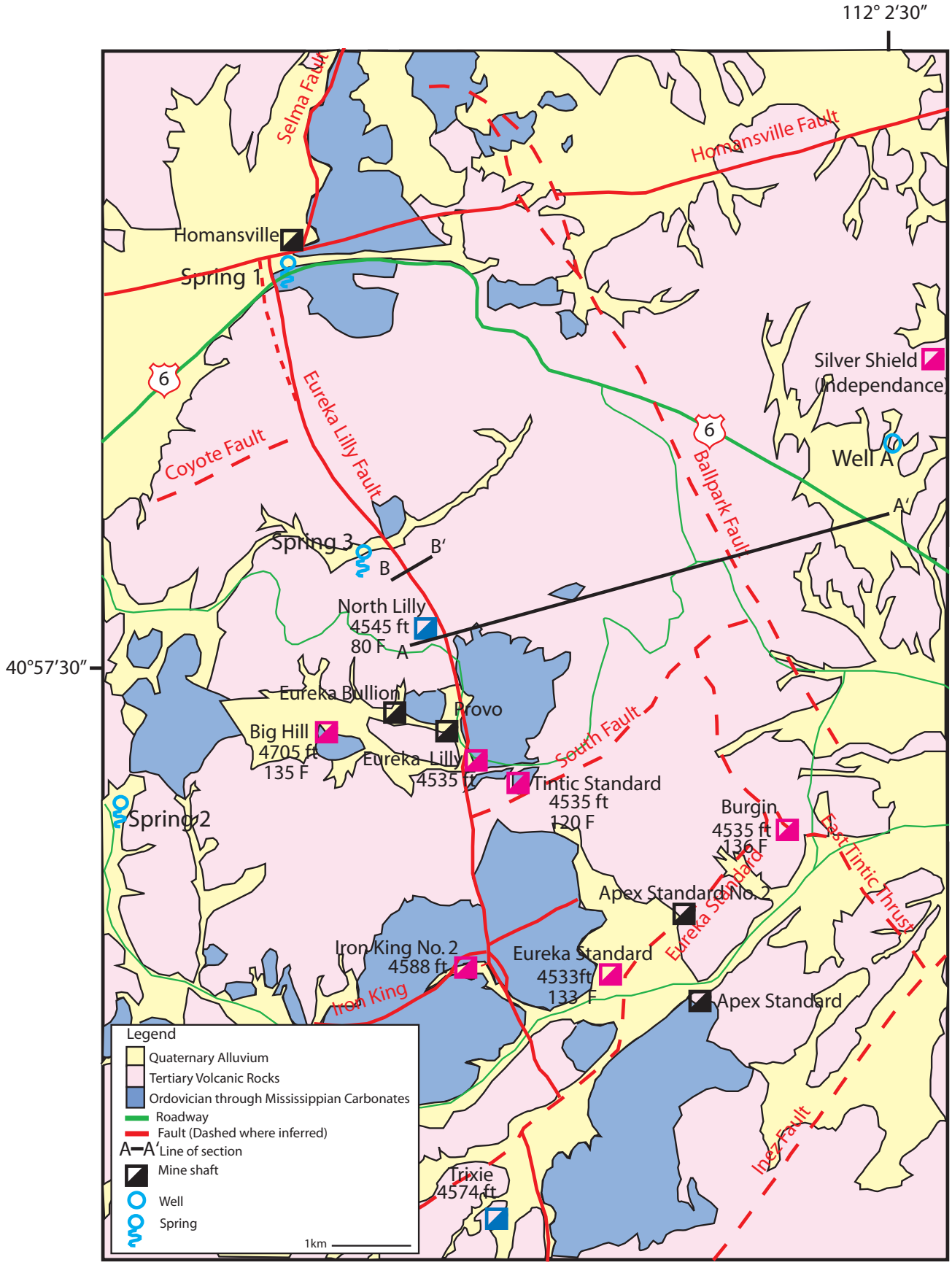

Figure 3. *Major geologic features of the East Tintic mining district. Fault zones, mine shafts, and spring locations are discussed in text. Water temperature in mine shafts: red = warm water, black = cool water, unknown for Trixie and North Lilly shafts. Cross section A-A′ is shown on figure 4, and B-B′ on figure 10. Map adapted from Lovering and Morris (1965).*

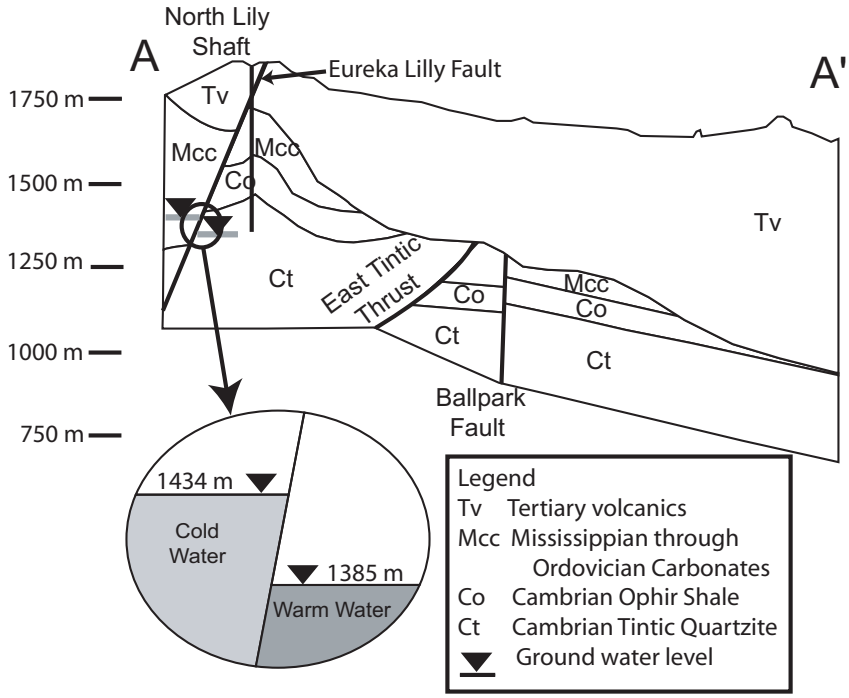

Figure 4. *West-to-east cross section through the East Tintic mining district (see figure 3 for location) showing extensional overprint of Sevier thrust sheets, and Tertiary volcanic cap. Note different water levels across the Eureka Lilly fault indicating that this is a boundary for ground-water compartmentalization.*

Table 1. *Porosity and permeability measurements (ρ = density; mD = milliDarcy). Samples A through E are from a drilling core near the Trixie mine along the Trixie fault. Samples A and B are from the hanging wall of the fault; Sample C is from the fault core zone; Sample D is from the footwall. SH is from the location shown in figure 8. These rocks are all very tight, with the only permeability shown in the fault core zone samples or in the highly brecciated zones. The rocks away from the fault damage zone have unmeasured permeability and low porosity, indicating that they would be poor ground-water hosts.*

Sample	Description	Porosity %	ρ, grain (g/cm^3)	ρ, rock (mD)	Permeability
A	Tintic Quartzite – slightly altered (iron rich veining)	6.0	2.63	2.48	0.0
B	Tintic Quartzite	0.6	2.61	2.59	0.0
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

The quartzite is characteristically brittle and develops wide zones of fracture damage near faults (Lovering and Morris, 1965). Fractures in the Tintic Quartzite are an important host for pyritic copper-filled veins and other ore bodies. The contact between the Tintic Quartzite and 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 (Morris and Lovering, 1961). The lack of fractures in these impermeable clay-rich units forms a barrier for fluid circulation from fractures in the Tintic Quartzite into other units. In the East Tintic mining district, the Ophir Formation consists of upper and lower shale members and a middle limestone member.

The Ophir Formation is overlain by a thick section of predominantly carbonate rocks that include units of Cambrian, Ordovician, and Mississippian age that form the bulk of the rock units in the East Tintic Mountains. These units are also the primary host of ore mineralization (Morris and Lovering, 1961).

A major angular unconformity separates Paleozoic units from overlying Cenozoic volcanic rocks. Volcanic units in the East Tintic Mountains are remnants of a large composite volcano of Oligocene age located slightly northeast of our study area (Morris and Lovering, 1964; Keith and others, 1991). The eruptive center is characterized by multiple intrusions of monzonitic plutons.

Structure

Paleozoic units were first deformed by extension during the opening of Mississippian intracratonic basins (Gutschick and Sandberg, 1983). During the Cretaceous–early Tertiary Sevier orogeny, these units were shortened by eastward-propagating fold-thrust deformation, which formed a series of overturned, asymmetric folds throughout the area (Morris, 1964). At ~15 Ma, normal faults formed as a result of regional basin-and-range extension (Hintze, 1988). Earlier–formed structures were later reactivated as normal faults. Active normal faults bound the East Tintic district horst block on the west and east; the district is on the footwall of the East Tintic Mountains fault to the west, and hanging wall of the Long Ridge fault to the east.

Faults in the East Tintic mining district are broadly categorized (Morris and Lovering, 1979) as follows:

(1) Extensional faults associated with Paleozoic basin development.

(2) Contractional faults formed during fold-thrust deformation associated with the Mesozoic Sevier orogeny (figure 5).

(3) Extensional faults formed after contraction, but before volcanic activity commenced.

(4) Synvolcanic mineralized normal faults and fractures of smaller magnitude (figure 6).

(5) Basin-and-range-style normal faults that initiated in early Miocene time and offset Quaternary deposits (figure 7).

The East Tintic mining district is bounded on three sides by major faults: the Homansville fault to the north, Eureka Lilly fault to the west, and Inez fault to the south (figure 3). The Eureka thrust underlies the entire district

Figure 5. *Fault intersections in footwall damage zone of the Eureka Lilly fault. The high-angle normal fault is slightly offset by reactivation of the thrust fault as a low-angle normal structure.*

Figure 6. *Mineralized normal fault zone with alteration of wall rock into clay. Notice the variation in fracture density parallel and normal to systematic fracture sets striking nearly parallel to the plane of the photo.*

Figure 7. *Localized extensional shear along conjugate fracture set in limestone footwall of Eureka Lilly fault. The blocks between fractures are brecciated in many places with some gouge-rich zones. The zone of breccia encased in gouge is about 150 cm across at the bottom and decreases to 30 cm near the top.*

and is one of the most important structures in terms of mineralization and thermal water influx (Lovering and Morris, 1965). The purpose of this study is to investigate if, and how, these brittle structures may influence ground-water movement, particularly near the Eureka Lilly fault zone.

The Eureka Lilly fault was first identified and described by Morris (1964). It strikes northward through the western part of the East Tintic district (figure 3). Although it originated as a thrust fault during the Sevier orogeny, it has been reactivated at least twice, once between the time volcanic rocks were deposited and the time of ore mineralization, and again during basin-and-range extension (figure 5). Displacement along the fault varies from 152 m near the Eureka Lilly shaft to 182 m near the Homansville fault.

The Homansville fault is a steeply dipping (80°N) normal fault that trends east to northeast, and is partially buried by volcanic rocks. The subsurface throw on the fault is 914 m (Morris and Lovering, 1979).

The Selma fault is a normal fault that extends northward from the Homansville area. It is mentioned here because of its proximity and close relationship to the northern part of the Eureka Lilly fault. The Selma fault initiated during basin-and-range extension and broke the East Tintic Mountains into two major fault blocks (Lovering and Morris, 1979).

Eureka Lilly Fault Zone Architecture

Descriptions of both surface and subsurface expressions of the architecture of a fault are rare. Data from mines bridge this gap and help evaluate the lateral continuity of fault architecture and its control on ground-water flow. Many faults in the East Tintic mining district are found only in the subsurface beneath blankets of volcanic rocks. However, surface exposures of the Eureka Lilly fault are present in erosional windows through the volcanic units.

We examined surface traces of the Eureka Lilly fault in a road cut on U.S. Highway 6 and above volcanic units near Mineral Hill (figures 3 and 8). We made additional observations of an exposure of a subsidiary structure to the Eureka Lilly fault system near the Apex mine.

The Eureka Lilly fault zone is a multiply-deformed structure with overprinted fault cores and damage zones from repeated slip events having different senses of motion. Preserved core zones are commonly impermeable areas of clay gouge and re-cemented breccia with a silica and calcite matrix (figure 9). Re-cementation effectively sealed cracks to reduce permeability (table 1). Re-cemented breccia is also very resistant to erosion, and unlike most damage zones that are preferentially eroded into valleys, breccias form ridges throughout the East Tintic mining district.

Damage zones, located adjacent to fault cores, consist of abundant open fractures that show extensive connectivity and localization of fluid flow through otherwise impermeable units (figures 5, 7, and 8). The lateral extent of core and damage zones largely depends upon rock type and amounts of displacement (Caine and others, 1996). However, although fracture density is higher adjacent to fault zones, background levels are also high in Paleozoic units throughout the mining district, with highest fracture densities found at fault intersections.

The surface expression of the Eureka Lilly fault is characterized by abrupt changes in bedding attitude and rock type on either side of a fault-parallel valley with small linear ridges of breccia. The valley eroded through broken units of the damage zone and clay-rich parts of the core zone of the fault. Cemented breccia ridges are ~30 m across and protrude above valley fill in several places. The damage zone dissipates into mostly intact outcrops about 50 to 60 m away from the brecciated core of the fault.

Most drainage in the area is highly influenced by fault architecture. Valley margins occur where the damage zone transitions into less-fractured country rock, producing damage zone-controlled stream valleys with scattered outcrops of resistant breccia from the core zone and occasional bluffs of less-fractured limestone and dolomite country rock.

The surface trace of the Eureka Lilly fault is also delineated by the many mine adits and tunnels used to extract ore concentrated along the fault. The localization of mineralization indicates that faults also controlled the flow of hot mineralizing fluids during Tertiary magmatic activity in the region (Lovering and Morris, 1979).

A cross section through the Eureka Lilly fault exposed in a road cut for Highway 6 (figure 8) yielded a strike of 342˚ and dip of ~90˚. At this location, the fault juxtaposes Cambrian limestone in the footwall with Tertiary volcanic rocks for a total displacement of about 250 m (Lovering and Morris, 1979). The fault core generally consists of a 3- to 4-m zone of breccia encased in clay gouge with a gradual shift from limestone to volcanic-rich clasts extending from the footwall into the hanging wall. 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 tuffaceous units on the hanging wall. A limestone block around 3 m in diameter that was detached from the footwall is present 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° N, indicating that the block has rotated during slip.

Most of the rocks that make up the core and damage zones manifest the effects of iron oxide bleaching (white) and precipitation (orange and brown stains) as fluids moved through the early core zone of the fault. Veining indicates that formerly open fracture zones have now been sealed by clay minerals and calcite.

The damage zone adjacent to the core zone consists of high-density, interconnected, extensional and shear fractures. The limestone footwall is more fractured (figure 8A), which creates zones of multiple reactivated slip surfaces with small interconnected fractures. Closer to the fault core, the limestone is locally shattered to the

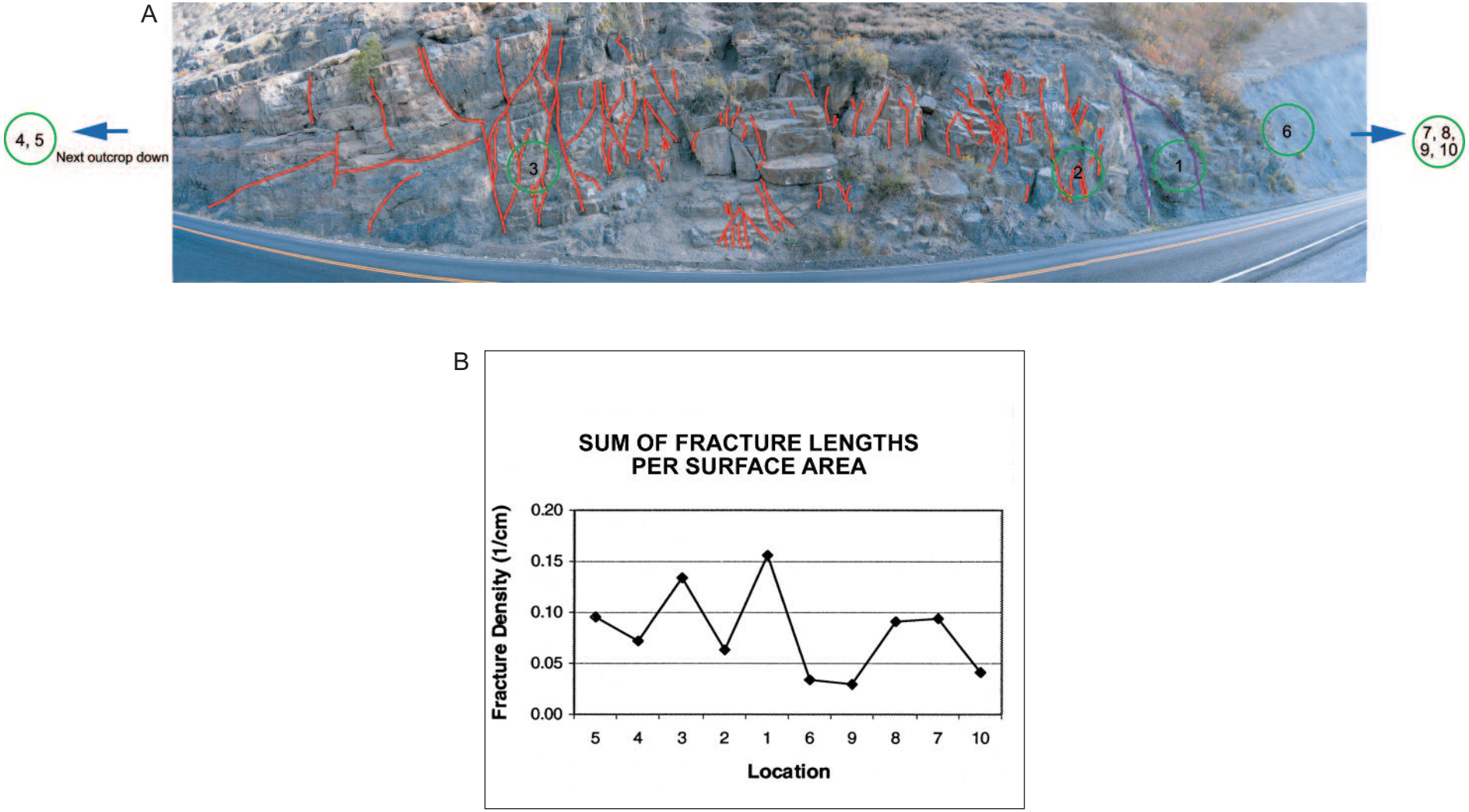

Figure 8. *(A) Major fractures in limestone and dolomite footwall. Circles are locations of fracture density measurements. The fault core zone is at location 1. (B) Fracture density measurements at various locations across fault zone. The fault core zone is between locations 1 and 9. Locations 2 and 4 are relatively unfractured blocks within the damage zone.*

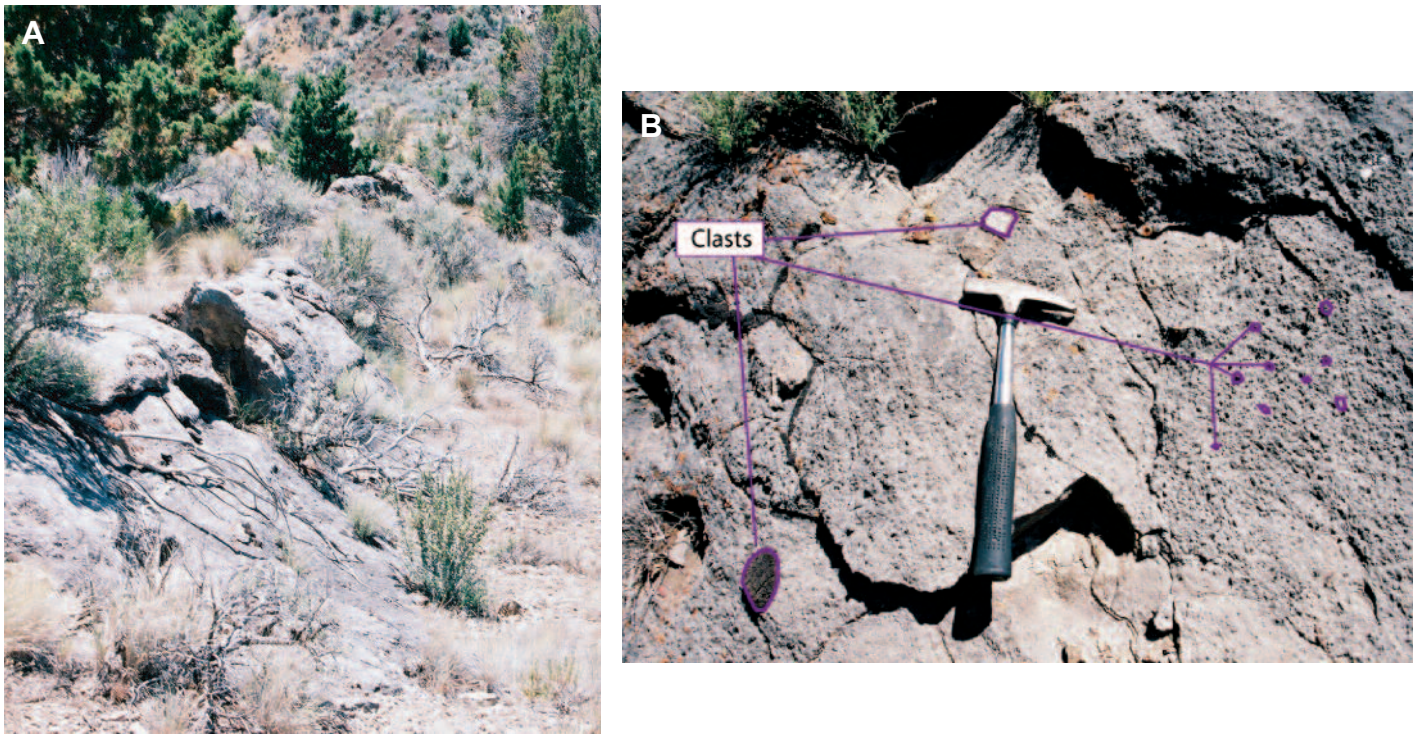

Figure 9. *Re-cemented breccia zone. (A) The line of resistant outcrops of re-cemented breccia marks the surface exposure of the Eureka Lilly fault core zone near the Apex mine. (B) Detail of breccia re-cemented by carbonate with clasts ranging in size from 0.5 to 15 cm.*

extent that no unfractured rock is found. The damage zone also consists of faults associated with the main slip surface in the core zone. Just 2.5 m from the fault core is a large fracture zone filled with thin films of gouge. Slip is mostly localized along discrete shear fractures in the damage zone within the limestone footwall.

There are also areas where damage-zone fractures have reactivated older faults (figure 5). Farther 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 that hot fluids moved along fractures in the damage zone.

The hanging wall of the Eureka Lilly fault at the road cut is composed of successions of highly fractured welded tuff and unfractured poorly welded tuff. Strain is more distributed in poorly welded tuff, which creates a thick expandable clay gouge in the fault core zone. Faults seen in the volcanic units are at least 100 m from the fault core, which may indicate that the entire zone is extremely altered and crushed from movement.

Fracture Density

We measured the total length of fractures within a fixed area to determine fracture density at various distances from the fault core (figure 8). Although fracture lengths at all of these locations range from microscopic to regional scale, measurements were made only of those fractures greater than 5 cm in length.

In limestone footwall units, there is an irregular correlation between fracture density and distance from the core zone (figure 8B). Spikes in the data occur at the intersections of shear zones. Types of shear fractures also vary with distance from the core zone where extensional faults are pervasive. Farther away from the core zone, extensional faults overprint localized pre-existing thrust faults.

Fracture density clustering in the limestone footwall (locations 1 through 5 on figure 8) demonstrates that strain was very localized, which would also channel fluid flow through the damage zone. The variation in fracture density measurements demonstrates that much of the damage zone consists of non-fractured material that is surrounded by dense fracture arrays. The damage zone develops by widening and interlinking of the fracture arrays as the non-fractured blocks become smaller with increased shear. Few, if any, non-fractured blocks are found in the core zone of the fault. The high degree of fracture clustering indicates localization of strain along pre-existing fractures in the limestone footwall.

The volcanic rocks of the hanging wall consist of layers having very different physical properties. Welded tuffs are shattered by fractures similar to the limestone footwall, whereas non-welded tuffs manifest ductile behavior like that in mudstones. Fractures cannot propagate through non-welded units, which distribute strain throughout the entire unit. Within decimeters of the fault zone nearly all of the volcanic units are pulverized into a clay-rich gouge.

The lateral extent of the damage zone in volcanic rock is difficult to precisely define, and it likely 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 with its intersecting shear fractures along the fault allow for the fault zone to potentially hold large amounts of ground water within otherwise low-porosity rocks. In an area like the East Tintic district, where faults are overprinted and reactivated several times, damage zones can coalesce and result in high rates of fluid flux parallel to the fault.

Subsurface Exposure

Examination of the Eureka Lilly fault zone 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 ground water. 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 Lilly, Eureka Lilly, Iron King No. 2, Trixie, and South Standard shafts (figure 3). For a short time, there was access to an associated fault in the Trixie mine.

From 1973 to 1974, the Anaconda Company ran an exploration program in the North Lilly area with three boreholes intended to locate mineralized limestone in the footwall of the East Tintic thrust fault. The holes did not encounter significant silver-lead-zinc ore, but did shed light on the geologic structure in the vicinity of the North Lilly mine. The first hole, TUL-1, encountered a thrust fault about 762 m below the surface that is interpreted as the East Tintic thrust (figure 10). At about 427 m, the hole intersects the North Lilly normal fault, which is likely a synthetic fault strand of the Eureka Lilly fault.

Drilling revealed that the Eureka Lilly fault clearly offsets the Cambrian Tintic Quartzite in the subsurface, and there is also evidence that it cuts the Tertiary Packard Quartz Latite in the mine area (figure 10). In spite of the projection of the Eureka Lilly fault to the north of this location, where it clearly offsets the Tertiary rocks, Anaconda concluded that the Eureka Lilly fault in the Tintic

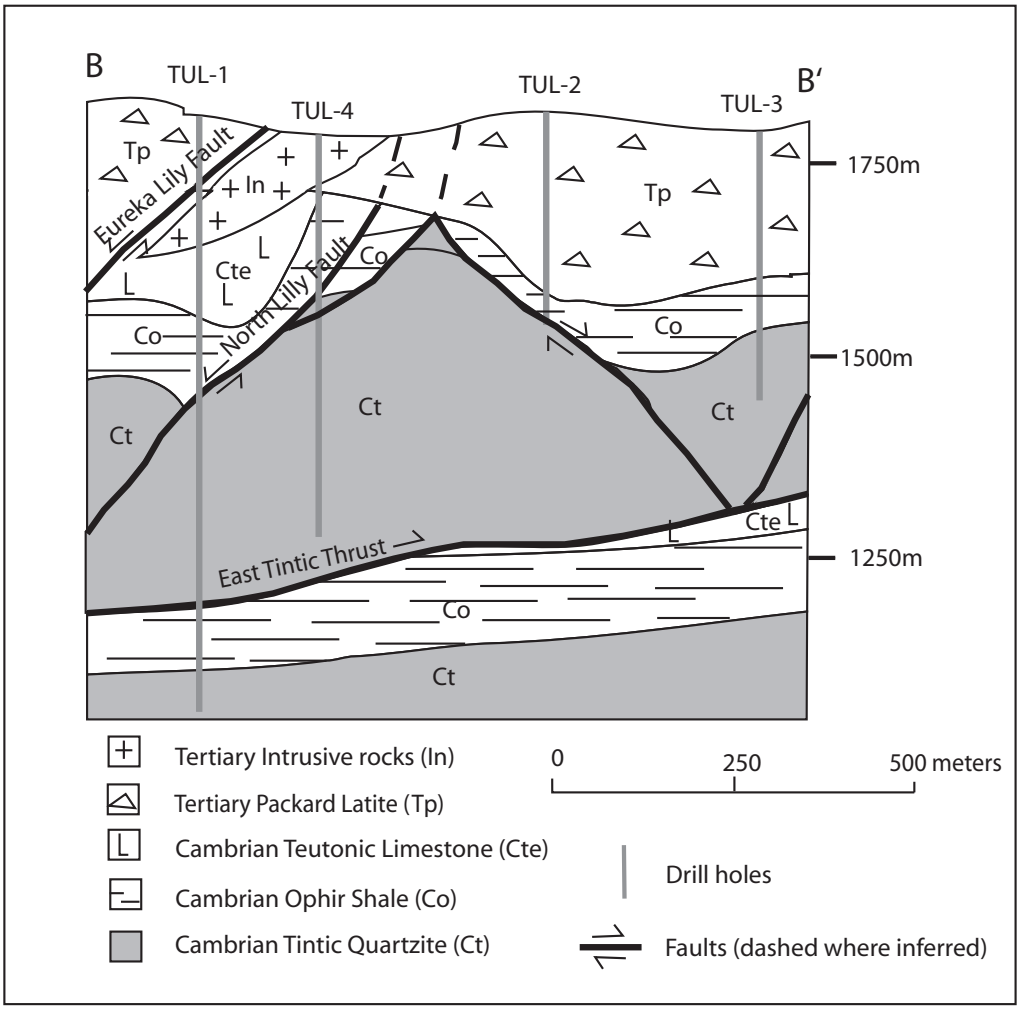

Figure 10. *Structural section connecting observations from drill holes. The clay-rich Ophir Shale forms the basal detachment of the East Tintic thrust. Normal faults in the hanging wall of the thrust terminate into this detachment and may locally reactivate thrust faults. Varying thicknesses of volcanic cover units indicates a pre-eruption topography. See figure 3 for line of section.*

Standard and North Lilly mines is pre-Packard 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, and cross-cutting relationships are commonly ambiguous. These conflicting interpretations are in part due to extensive overprinting of the hanging wall of the East Tintic thrust by subsequent normal faults.

Mine Descriptions

North Lilly: Ore mineralization is essentially in faults on the footwall of the Eureka Lilly fault that may relate not only to the Eureka Lilly fault, but also to the Tintic Standard thrust, which is intersected by the mine shaft (figure 11). This relationship shows that extension in this area is both pre- and post-Packard Latite (Lovering and Morris, 1979).

Several maps of subsurface mining operations (Chief Consolidated, 2000) provide further insight into the detailed structure of the Eureka Lilly fault zone. On one map of the Coyote area of the North Lilly mine, the Eureka Lilly fault is represented as a series of parallel structures about 90 m apart. It also indicates that the Eureka Lilly fault damage zone is about 150 m across in this section.

Eureka Lilly: In this area, the Eureka Lilly fault has placed latite against Cambrian sedimentary units. The total throw is estimated at 180 to 210 m (figure 4). 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 m below the surface near the intersection with the Iron King fault. Most of the mine workings encountered mineralization in brecciated fault core zones along several intersecting faults through impermeable Cambrian limestone and quartzite units with little to no clay gouge (Chief Consolidated, 2000).

Trixie: During excavation in the Trixie mine along an unnamed fault near the Eureka Lilly fault zone, an attempt was made to explore the fault intersection as a 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. Exploratory drilling was able to penetrate only 2 to 3 m into the breccia, preventing any further measurements of its thickness and

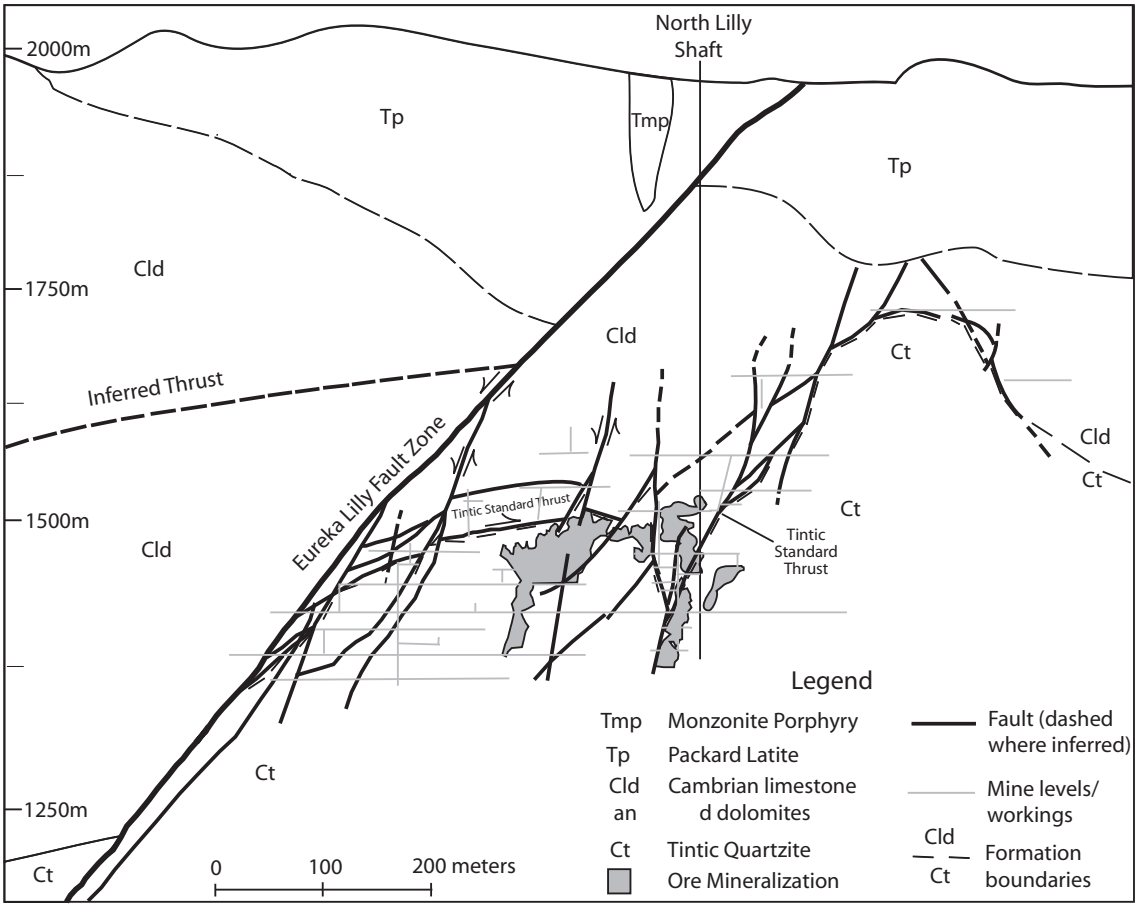

Figure 11. *Simplified cross section of North Lilly shaft showing relationship to Eureka Lilly fault and mineralization (adapted from Lovering and Morris, 1979). The water table is at the base of the mine workings.*

extent. In the tunnel approaching this intersection, several parallel smaller-scale faults were observed that all have small amounts of mineralization along slip surfaces (Chief Consolidated, 2000). 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

We collected subsurface rock samples from a drill core (ET-162) located near the Trixie mine for measurements of porosity and permeability (figure 3, table 1). Samples A through E are from the same vertical core at increments across the Trixie fault. Samples A and B were taken from the hanging wall of the fault, sample C from the core zone, sample D from Tintic Quartzite in the footwall, and sample E from an associated breccia zone in the footwall. Sample SH was taken from a surface exposure of re-cemented breccia along the trace of the Eureka Lilly fault.

Measurements of porosity (table 1) show that the Tintic Quartzite is relatively tight with very low pore volume. Fluids cannot flow through this rock unit and must use connected systems of open fractures, which are found primarily in fault damage zones. Measurements of brecciated limestone in the footwall indicate much of the damage zone has fracture porosity and permeability. However, measurements taken in the core zone (C and SH) show significant reduction in permeability of fault core breccia.

Summary of Eureka Lilly Fault Zone Architecture

Brittle deformation involves multiple modes and phases of fracturing, commonly along pre-existing weak zones, which results in the formation of thick (hundreds of meters) damage zones with well-connected fracture networks. These fractures open fault-parallel flow paths for ground water through otherwise mostly impermeable rock. This type of ground-water flow system differs significantly from those in rocks with primary porosity and permeability.

Flow of mineral-rich fluids along the most fractured and brecciated parts of the fault zone can reduce permeability by sealing fractures through mineralization and precipitation of calcite and quartz. Along the Eureka Lilly fault zone, where initial slip involved rock units having little to no clay in core zones, breccia with open fractures was abundant as demonstrated by mineralization along fault core zones. Decreased core-zone permeability followed through crack sealing and wall-rock alteration to clay. Post-mineralization slip during basin-and-range extension further pulverized the altered wall rock and also juxtaposed clay-rich units, such as the Ophir Shale and volcanic cover units, with quartzite and limestone. Expandable clays from these units contributed significantly to the impermeability of fault core zones, but not adjacent damage zones.

Discharge of water through fault damage zones is enhanced by dissolution of limestone, which may explain the sustained high discharge rates of damage-zone water in the mining district. Hurlow (1999) concluded that Cambrian units may be the best prospective aquifers in the region due to high fracture density, stratigraphic location (overlain by units of lower hydraulic conductivity), and relationship with major faults.

GROUND-WATER SYSTEMS

Previous Work

The only published study of ground-water characteristics in the East Tintic mining district was conducted by Lovering and Morris (1965). They focused on the thermal water system and found a correlation between anomalous temperatures, geologic structure, and certain rock units. High-temperature water is generally restricted to mines east of the Eureka Lilly fault (figures 3 and 4). Sources for the geothermic water were traceable to fault intersections, such as the South and Eureka Standard fault with the East Tintic thrust. Thermal-gradient measurements indicated that water generally moved upward from the East Tintic thrust and toward the east or northeast through fault damage zones. Water temperatures ranged between 40°C and 49°C, with increasing temperatures towards the Eureka Lilly fault.

Hydrologic studies of other thermal water systems and surface waters near the East Tintic mining district, such as at Goshen Valley, Lincoln Point, and Goshen Bay, provide additional information on regional ground-water characteristics and possible hydrologic connectivity (Cordova, 1970; Dustin and Merritt, 1980; Cook, 1983; Davis and Cook, 1983; Baskin and others, 1994; Brooks and Stolp, 1995). Cole (1982) 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 ground waters, characterize lower temperature springs. The deeper waters adjacent to the Eureka Lilly fault zone generally correlate with these observations.

Klauk and Davis (1984) and Cordova (1970) identified ground water of moderate salinity in Goshen Valley, only a few kilometers east of the Eureka mining district (figure 1). Ground water from many of the Goshen Valley sources is chemically similar to water encountered in the Burgin mine, as well as to thermal ground water discharging near Lincoln Point in Utah Lake (Klauk and Davis, 1984). Previous ground-water sampling in Goshen Valley indicated that this chemical and thermal similarity occurs naturally rather than being influenced by mine-water discharge (Hood, 1975; Dames and Moore, 1985).

Hot, saline ground water is found in deep areas east of the Eureka Lilly fault, and affects the North Lilly, Tintic Standard, Eureka Lilly, Eureka Standard, Apex

Standard, and Burgin mines. This water was pumped from the Burgin mine at rates of 11,000 to 34,000 L/min for 13 years without a measurable decrease in volume, water temperature, or salinity (Kennecott Minerals, 1994). This pumping rate represents a total volume of discharged water of 207 x 10^9 L. Pumped water from the Burgin mine was discharged at the surface to a natural ephemeral stream channel and allowed to flow to a series of disposal ponds constructed on an alluvial fan about 5 km downstream. Discharge from ponds was through evaporation and seepage (Earthfax Engineering, 1988).

Originally, the early mine geologists thought that the high ground-water temperatures were a result of exothermic oxidation of sulfides associated with the ore deposits (Lovering and Morris, 1965). However, subsequent exploration showed little correlation between mineralization and higher wall-rock temperatures, but showed increases in total dissolved solids (TDS) with depth, which indicated correlation with hot-spring sources (Lovering and Morris, 1979). This interpretation was supported by similarities in chemistry between 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) are characterized by high chloride, low to moderate sulfate, and low to moderate bicarbonate concentrations, which correlates well with the Burgin water (Cole, 1982).

One of the most important observations in our study is the abrupt difference in water levels, temperatures, and chemistry across the Eureka Lilly fault (figure 4). High-TDS geothermal water in the footwall of the fault (east) is consistently encountered at around 1371 m elevation and slopes upward to the southeast to the Burgin mine where it is found at 1382 m. However, moderate-TDS, cooler water is found to the west in the hanging wall of the fault at 1434 m elevation and slopes upward to the southwest. This difference is in spite of regional water levels that may be controlled by the elevation of Utah Lake (1367 m), about 16 km northeast of the East Tintic mining district.

The abundance of limestone units in the area suggests the possibility of some cavernous permeability. Caves may also explain some of the rapid discharge that was found in the Burgin mine. Some blind caves have been found in early mine workings (Walker, 1928; Hall, 1949).

Water in Specific Mines

Many of the mines (figure 3) in the East Tintic mining district encountered ground water, and provided direct measurements of water levels and temperatures that were reported by Lovering and Morris (1965) and in unpublished mining records (Chief Consolidated, 2000).

Burgin

In the Burgin mine, wall-rock temperatures varied widely from 35°C in broken carbonate rocks to 58°C in or near exposures of Tintic Quartzite in the northwest part of the mine. These temperatures were nearly 20°C higher than would be expected at this depth from the geothermal gradient calculated from mean annual air temperatures (Western Regional Climate Center, 2005). As the mine developed below the 1382 m water level, temperatures increased with depth to as much as 64°C.

Mine water was high in dissolved materials, chiefly NaCl, but also K^+ and Ca^{2+}, SO_4^{2-}, and HCO_3^- and other constituents (table 2). Continued monitoring of the mine discharge water indicated an average content of 3500 ppm chloride. Samples collected at the deepest levels of the west part of the mine contained about 4500 ppm chloride with a temperature of 69°C. These values are consistent with Cole's (1982) survey of the hydrochemistry of warm springs associated with normal faults in Utah. In contrast, in the east part of the mine, water had only 2200 ppm chloride and a temperature of 35°C. This indicated a local deep source of thermal brine inflow in an undetermined area to the west of the Burgin mine was being diluted with water that was both cooler and had a lower TDS content.

Eureka Standard

Burgin-like water was encountered in the Eureka Standard mine at an elevation of 1381 m. It contained more than 5500 ppm dissolved solids and reached temperatures of at least 56°C. Precipitated salts from the ground water were more than 50% NaCl, and included $CaSO_4$, $CaCO_3$, MgCl, and KCl. The large volume of ground water, along with its high temperature and corrosive nature, prevented any deeper development of the mine.

Eureka Lilly

The Eureka Lilly mine extensively mined the Eureka Lilly fault zone, but never reached the water level at 1382 m. Determined from exploration drill core logs, this water was described as hot, saline, and Burgin-like.

Tintic Standard No. 1 and 2

Water in this mine was encountered at an elevation of 1382 m with an average wall-rock temperature of 48.8°C. During the 1940s, the No. 2 shaft was deepened to the 1570 m level and ore was mined below the water table, resulting in pumping of considerable volumes of water to the surface. Although we did not find records of chemical analysis for the water, it was described as slightly to moderately saline (Morris and Lovering, 1979).

Independence or Silver Shield Shaft

Temperature data indicated that this 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.

Table 2. *Burgin mine water characteristics from 1962 to 1981. Concentrations are given in parts per million (ppm). This water is characterized by extremely high sodium, chloride, bicarbonate, TDS, and temperature (Chief Consolidated, 2000).*

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 $CaCO_3$)	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 $CaCO_3$)	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

Trixie

The water level in the Trixie mine stood at an elevation of 1394 m. There was also a small, perched water table in the volcanic rocks in the upper part of the shaft. The water in this mine was fresh and maintained a constant temperature of about 24°C at 750 m below the surface.

Big Hill

Strong inflows of water first appeared at 1434 m elevation in this mine, and halted any subsequent development. The water was cool, but we found no records of water chemistry.

Apex

Wall-rock temperatures in this mine exceeded 57°C at 1558 m elevation and were 51°C at 1493 m. Ground water was never encountered, which corroborated the localized nature of ground-water reservoirs and flow channels.

North Standard

Although water was not encountered, reports indicated the mine was exceptionally hot and gassy, especially in the deeper levels.

North Lilly

Ground water was at an elevation of 1385 m, which was close to water levels throughout the footwall block of the Eureka Lilly fault. In the hanging-wall block, the water level rose sharply to an elevation of 1434 m in the nearby Big Hill shaft. This water was relatively cool (27°C) in contrast to that of the Burgin mine (about 49°C), but was still higher than predicted from the geo-

thermal gradient for this depth (assuming 2.5°C per 100 m depth, normal geothermal gradient should yield a temperature of 21.5°C at a depth of 535 m). It is likely that the water encountered in this mine was farther from the thermal spring source and that a temperature gradient existed between this well and those to the south and east, which are closer to the source.

Water Analysis

Methods

We collected samples of the available ground-water systems to test for evidence of isolation or mixing, and possible origins. Splits of water for cation and anion analysis were filtered in the field with a 0.45 μm filter. Cation splits were acidified with five to six drops of 7N (normal) 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. Amber vials (50 mL) with polyseal caps were collected for isotopic analysis.

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 using methods similar to Epstein and Mayeda (1953).

Water was sampled from five locations in the study area (figure 3 and table 3) and at Goshen Warm Springs southeast of the town of Goshen (figure 1). These were the only sites that had any water flowing during the summer of 2002.

Stable Isotopes

Our study samples show δD (deuterium) values that vary from -112‰ to -121‰, whereas $\delta^{18}O$ values range from -13.5‰ to -14.9‰ (table 4, figure 12). Water from Well A is most enriched in ^{18}O compared to the other samples, which may be caused by some evaporation. The Goshen Warm Spring samples are comparatively depleted in ^{18}O and ^{2}H, which indicates a significantly different source consistent with its proximity to Utah Lake and the Wasatch fault zone.

When compared to the meteoric water line, both the $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios indicate the water for the three springs may have undergone slight evaporation, although this may also just be the effect of precipitation in this region (figure 12).

Water Chemistry

Geochemical analyses of water samples from the East Tintic mining district indicate high abundances of

Table 3. *Field measurements for sampled waters. Springs 1 and 2 have similar chemistries, as do Well A and Spring 3. Goshen Warm Springs have a significantly higher conductivity and lower temperature, indicating that they are likely from a different source.*

Sample Location	Latitude	Longitude	pH (μS)	Conductivity (˚C)	Temperature
Well A	39°58'4.43"N	112° 2'59.54"W	7.21	845	17.5
Spring 1	39°57'52.88"N	112° 5'45.72"W	8.28	351.3	20.3
Spring 2	39°56'28.80"N	112° 5'6.99"W	6.87	278	10.4
Spring 3	39°57'34.67"N	112° 4'36.43"W	7.78	714	11.8
Goshen Warm Springs	39°57'33.37"N	111°51'18.51"W	7.75	1907	7.75

Table 4. *Oxygen and hydrogen isotope ratios (‰) determined for sampled waters.*

	$^{18/16}O$	$^{2/1}H$
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

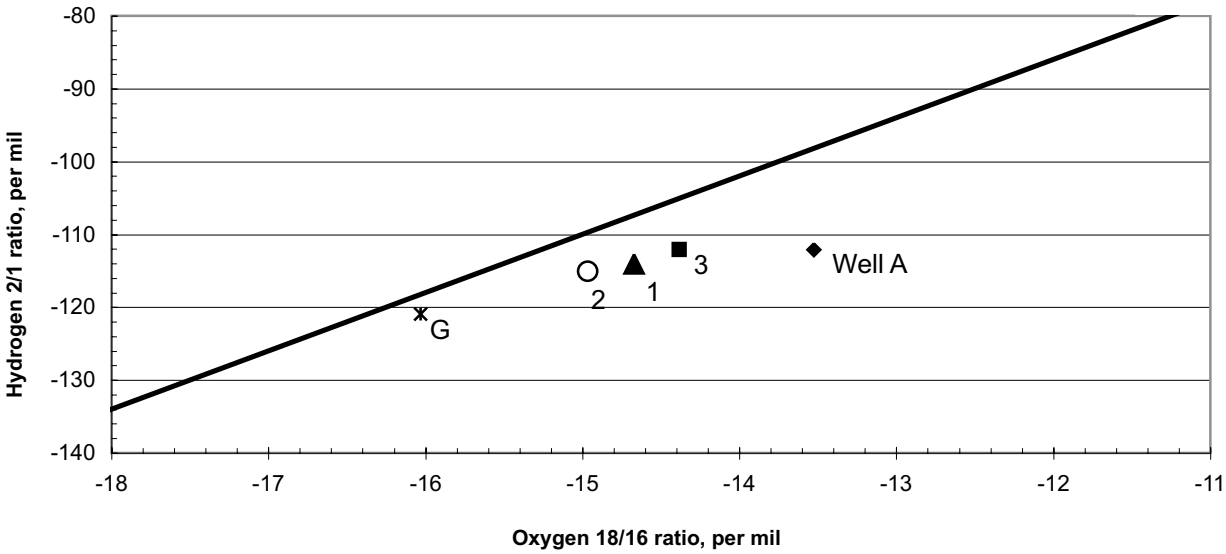

Figure 12. *Graph showing stable isotopes of Eureka mining district water in comparison to the meteoric water line (heavy line). All waters fall slightly below the meteoric water line. The three springs (1,2,3) may have undergone slight evaporation, although this could be the effect of precipitation in this region. Goshen Warm Springs (G) is more depleted and appears to be from a different source. Data from table 4.*

Ca-Na and HCO_3-SO_4 (table 5, figure 13). Goshen Warm Springs is the most saline of the samples and is likely the result of water moving up the Long Ridge fault mapped adjacent to the spring. The Goshen Springs sample also is most similar to the trend of the reported Burgin area water—perhaps it represents a dilution of a similar or common source. Concentrations of Ca^{2+} and Mg^{2+} correlate with the HCO_{3-} except at Spring 3, where SO_4^{2-} is much higher in concentration. This could mean that Spring 3 is flowing through less-carbonate-rich rocks than the other sampled waters, 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.

Clearly, the Burgin-area water has more Cl^-, HCO_3^-, Na^+, and SO_4^{2-} than the sampled waters (figure 13). 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 sampled water is from the same source as the Burgin mine water.

In the conceptual model proposed here, hot, saline ground water 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 differs in temperature, elevation, and chemical characteristics, it is most likely from a different source. The Eureka Lilly fault is the only major structure in the area and thus forms a barrier between these two waters. There is no evidence of mixing between these two waters.

Summary

Three separate ground waters are present in the area:

1. Strongly thermal, high-TDS, Na^+- and Cl^--rich ground water characterized by temperatures of at least 54°C and an elevation of 1385 m. The water 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+}-and SO_4^{2-}-rich ground water with a temperature of 27°C and an elevation of 1434 m, found in the hanging wall of the Eureka Lilly fault.

3. Cold, low-TDS, shallow ground water with shallow circulation through volcanic rocks and limestone. A >500-m-thick dry region separates this water from ground waters 1 and 2.

DISCUSSION

Lateral Variation Along Eureka Lilly Fault

The expression of the Eureka Lilly fault varies laterally across the East Tintic mining district. In the north, at the road cut site on Highway 6, it is a narrow, brecciated fault core with a wide, extensive damage zone. The damage-zone limestone unit extends laterally, over-

Table 5. *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
Spring 3	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	HCO_3	F	Cl	NO_3	Br	HPO_4	SO_4	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
Spring 3	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

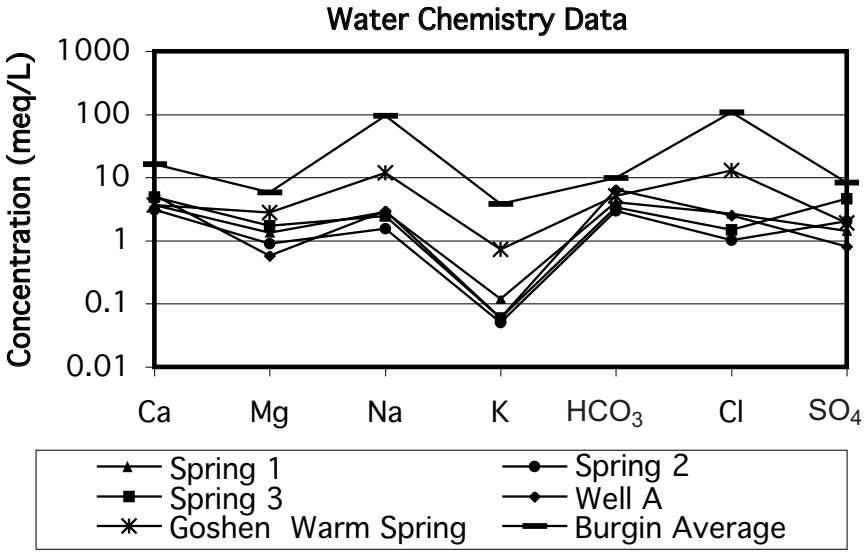

Figure 13. *Water chemistry by location shows that the Burgin water is much higher in Na, HCO_3, Cl, and SO_4 ions than collected surface samples.*

lapping small-scale thrust and normal faults, with discreet zones where the rock has been shattered by slip events and altered by fluid flow. In the hanging wall, tuff is pulverized in the unwelded units, whereas in welded units, we see the same normal faults that show overprinting of multiple events. In contrast, near Mineral Hill, the Eureka Lilly fault briefly surfaces in a canyon where it shows very little brecciation and no evidence of a thick core zone. Instead, we found a narrow damage zone that is extremely fractured and has been largely eroded, with damage-zone fractures apparent in the valley walls. Subsurface descriptions indicate much more extensive zones of brecciation and altered rock in zones as much as 50 m wide. Mine shafts also intersect several strands of overlapping and curvilinear faults.

Structural discontinuities may act to further compartmentalize water, as these differentiate how fault architecture limits or enhances ground-water flow. As demonstrated by Gudmundsson and others (2001), the breccia zone associated with the fault core is normally the greatest barrier to ground-water flow. This is supported by compartmentalization evident along the Eureka Lilly fault in this area.

Aquifer Definition

In rocks with low porosity and permeability, ground water can be held only in the secondary porosity provided by fracture networks and dissolution associated with fault zones. In this way, ground water cannot be described in terms of a regional water table or by stratigraphic units, as traditional aquifers are, but instead by the relationship with and architecture of faults. Ground water held only in damage zones will be compartmentalized by the lateral extent of the fault zone.

Fault Intersections

Intersections of fault zones significantly increase the width of fracture permeability, enabling more ground-water flow. It can also increase ground-water compartmentalization. The multiple phases of faulting in the East Tintic district results in overprinted fracture networks that extend laterally from major faults. In this area, fault intersections are so extensive that massive blocks of unfractured country rock are rare. Instead, overlapping damage zones extend fracture networks outward in several places where they coalesce, and thus greatly increase the capacity to hold and transmit ground water. If some of these conduits later become cemented, then compartmentalization of ground water increases.

Ground-Water Flow Regime

Ground-water flow through fracture networks is fundamentally different than flow in shallow, unconsolidated sediments. In shallow, unconsolidated units, ground water 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 such as shale, only fractures provide enough permeability to allow ground-water flow. Fracture networks associated with faults are not laterally continuous, uniform, or dependent on stratigraphy and may both enhance and retard ground-water flow, depending on the geologic history of the region. Where the rock matrix is impermeable, flow through the fractured rock is mostly controlled by a combination of conductivity of individual fractures and fracture zones (Evans and others, 1997; Odling, 1997).

In the East Tintic 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 ground-water transmission.

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

Pumping of Burgin Mine

When the Burgin mine was pumped for several years, there was no change in temperature, chemical composition, or discharge rate (Hall, 1949). This indicates that the fracture network that held this ground water was very effective at transmitting fluids, but was not in communication with the cooler, lower Na-Cl ground water in the hanging wall of the Eureka Lilly fault. Even within the same fault zone, fracture networks can compartmentalize ground waters.

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 Lilly fault zone has characteristics of a distributed deformation zone in which 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 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. These complicated barriers add to ground-water compartmentalization and argue against models for interbasin flow through bedrock horst blocks (Nelson and others, 2004).

Related Studies

Lachmar and others (2002) studied the effect of fractures, faults, and other structures 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 against utilizing it exclusively due to its limited size (and thus water potential).

The East Tintic mining district also demonstrates the transient nature of ground-water systems in multiply-deformed regions, such as the Basin and Range Province. Although there is evidence for large reservoirs of ground water stored in damage zones, these reservoirs are isolated and compartmentalized across fault core zones.

CONCLUSIONS

1. Faults of the East Tintic mining district have controlled water circulation patterns throughout the Tertiary Period. Fault cores were initially zones of high-permeability breccia that provided conduits for mineral-rich fluids. Alteration and precipitation in

fault core zones during mineralization, and continued deformation from basin-and-range extension, transformed the Eureka Lilly fault core zone and others faults into impermeable barriers due to breccia re-cementation and clay gouge development. The adjacent damage zone of these faults holds huge but hydrodynamically isolated reserves of ground water in open fractures.

2. Ground water in the hanging wall and footwall of the Eureka Lilly fault, and surface water, are not in communication, but are compartmentalized. This is evident by abrupt differences in water on either side of the fault zone, such as elevation of water levels, temperature, composition, and isotopic geochemistry.

3. Significant lateral variations in fault geometry, slip, architecture, and fluid transmissivity are observed along even single strands of the Eureka Lilly fault zone.

These observations indicate that water in the East Tintic mining district is highly compartmentalized. It is free to flow at high discharge rates parallel to fault damage zones, but not across faults like the Eureka Lilly fault. It also indicates that fault architecture has a profound influence on the amount of water stored in impermeable rocks and along the flow path. These results bring into question simple interbasin flow models in multiply-deformed and mineralized geologic settings such as the Basin and Range Province.

ACKNOWLEDGMENTS

We thank Ray Irwin, Paul Spor, and the staff of Chief Consolidated Mines for providing access to mining lands and operations, and for opening their offices and providing unlimited access to mining records and data. Stephen Nelson assisted with isotope geochemistry and provided helpful feedback. Tom Morris assisted with permeability and porosity measurements, and provided an excellent review. Alan Mayo also provided assistance with hydrologic measurements, laboratory use, and manuscript revision.

REFERENCES

Anaconda Copper Company, 1975, Reinterpretation of geology and ore potential in North Lilly area, Tintic unit lease project, Utah County, Utah: Internal document and logs prepared by R. Sekleman.

Armstrong, R., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

Baskin, R.L., Spangler, L.E., and Holmes, W.F., 1994, Physical characteristics and quality of water from selected springs and wells in the Lincoln Point—Bird Island area, Utah Lake, Utah: U.S. Geological Survey Water Resources Investigations Report 93-4219, 54 p.

Bense, V. and Van Balen, R., 2003, Hydrogeological aspects of fault zones on various scales in the Roer Valley rift system: Journal of Geochemical Exploration, v. 78, p. 317–320.

Brooks, L.E., and Stolp, B.J., 1995, Hydrology and simulation of ground water flow in southern Utah and Goshen Valleys: Utah Department of Natural Resources Technical Publication No. 111, 96 p.

Bush, J.B., Cook, D.R., Lovering, T.S., and Morris, H.T., 1960, The Chief Oxide–Burgin area discoveries, East Tintic district, Utah—a case history: Economic Geology, v. 35, p. 1507–1540.

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025–1028.

Caine, J.S., and Forster, C.B., 1999, Fault zone architecture and fluid flow—insights from field data and numerical modeling, *in* Haneburg, W.C., Mozley, P.S., Moore, J.C., and Goodwin, L.B., editors, Faults and subsurface fluid flow in the shallow crust: Americal Geophysical Union Geophysical Monograph 113, p. 101–127.

Chief Consolidated Mines, 2000, Unpublished mine maps and diagrams.

Clark, I.D., and Fritz, P., 1997, Environmental isotopes in hydrogeology: Boca Raton, Florida, CRC Press, 352 p.

Cole, D.R., 1982, Chemical and isotopic investigation of warm springs associated with normal faults in Utah: Journal of Volcanology and Geothermal Research, v. 16, p. 65–98.

Cordova, R.M., 1970, Ground-water conditions in southern Utah Valley and Goshen Valley, Utah: Utah Department of Natural Resources Technical Publication 28, 70 p.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702–1703.

Dames and Moore, 1985, Ground water quality and hydrogeologic study—mine water dispersion pond seepage, Goshen Valley, Utah: Internal report prepared for Sunshine Mining Company.

Davis, D.A. and Cook, K.L., 1983, Evaluation of low-temperature geothermal potential in Utah and Goshen Valleys and adjacent areas, Utah: Utah Geological and Mineral Survey Report of Investigation 179, 138 p.

Davis, S.N., 1969, Porosity and permeability in natural materials—flow through porous media: New York, Academic Press, p. 53–89.

Dustin, J.D., and Merritt, L.B., 1980, Hydrogeology of Utah Lake with emphasis on Goshen Bay: Utah Geological and Mineral Survey Water Resources Bulletin 23, 50 p.

Eakin, T.I., 1966, A regional inter-basin ground water system in the White River area, southeastern Nevada: Water Resources Research, v. 2, p. 251–271.

Earthfax Engineering, 1988, Review of ground water quality in southern Goshen Valley, Utah: Unpublished consultant's

report prepared for Sunshine Mining Company, Eureka, Utah.

Epstein, S. and Mayeda, T., 1953, Variation of ^{18}O content of waters from natural sources: Geochimica et Cosmochimica Acta, v. 4, no. 5, p. 213–224.

Evans, J.P., Forster, C.B., and Goddard, J., 1997, Permeability of fault-related rocks, and implications for hydraulic structure of fault zones: Journal of Structural Geology, v. 19, p. 1393–1404.

Gudmundsson, A., Berg, S., Lyslo, K., and Skurtveit, E., 2001, Fracture networks and fluid transport in active fault zones: Journal of Structural Geology, v. 23, p. 343–353.

Gutschick, R.G., and Sandberg, C.A., 1983, Mississippian continental margins of the conterminous U.S.: Society of Economic Paleontologists and Mineralogists Special Publication 3, p. 79–96.

Hall, J.G., 1949, History of pumping at the Chief Consolidated mine, Eureka, Juab County, Utah: Mining Transactions, v. 184, p. 229–234.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Geology Studies, Special Publication 7, 202 p. (Reprinted 1993.)

Hood, W.C., 1975, A study of Burgin mine thermal water: Unpublished internal report prepared for Kennecott Copper Corporation.

Hurlow, H., 1999, Preliminary hydrogeologic framework characterization—ground-water resources along the western side of the northern Wasatch Range, eastern Box Elder County, Utah: Utah Geological Survey Circular 101, 50 p.

Keith, J.D., Dallmeyer, R.D., Kim, D.S., and Kowallis, B.J., 1991, The volcanic history and magmatic sulfide mineralogy of latites of the central East Tintic Mountains, Utah, *in* Raines, G.L., Lisle, R.E., Schafer, R.W. and Wilkinson, W.H., editors, Geology and ore deposits of the Great Basin: Reno, Geological Society of Nevada, p. 461–483.

Kennecott Annual Reports 1967–1975, Tintic Division, Eureka, Utah: Unpublished annual reports for years 1966 through 1974.

Kennecott Minerals, 1994, Ground water aspects of Burgin Mine Project—East Tintic mining district, Utah County, Utah: unpublished mine report.

Klauk, R.H., and Davis, D.A., 1984, Evaluation of low-temperature geothermal potential in Utah and Goshen Valleys and adjacent areas, Utah (Utah Co.): Unpublished data prepared for Chief Consolidated Mines.

Lachmar, T.E., Bradbury, K., and Evans, J.P., 2002, Structure and hydrogeology of deformed sedimentary bedrock aquifers, western Summit County, Utah: Environmental and Engineering Geoscience, v. 8, p. 219–236.

Lindgren, W. and Loughlin, G.F., 1919, Geology and ore deposits of the Tintic mining district: U.S. Geological Survey Professional Paper 107, 282 p.

Lovering, T.S., and Morris, H.T., 1965, Underground temperatures and heat flow in the East Tintic district, Utah: U.S. Geological Survey Professional Paper 504-F, 28 p.

Lovering, T.S., and Morris, H.T., 1979, General geology and mines of the East Tintic mining district, Utah and Juab Counties, Utah: U.S. Geological Survey Professional Paper 1024, 203 p.

Maxey, B.B., 1968, Hydrology of desert basins: Ground Water, v. 6, no. 5, p. 10–22.

Mifflin, M.D., 1968, Delineation of ground-water flow systems in Nevada: Reno, University of Nevada, Desert Research Institute, Technical Report Series H-W, publication no. 4, 24 p.

Moore, D.K., Keith, J.D., Christiansen, E.H., Kim, C.S., Tingey, D.G., Nelson, S.T., and Flamm, D.S., 2007, Petrogenesis of the Oligocene East Tintic volcanic field, Utah, *in* Willis, G.C., Hylland, M.D., Clark, D.L., and Chidsey, T.C., Jr., editors, Central Utah—diverse geology of a dynamic landscape: Utah Geological Association Publication 36, p. 163–180.

Morris, H.T., 1964, Geology of the Eureka quadrangle, Utah and Juab Counties, Utah: U.S. Geological Survey Bulletin 1142-K, 29 p.

Morris, H.T., and Lovering, T.S., 1961, The stratigraphy of the East Tintic Mountains, Utah: U.S. Geological Survey Professional Paper 361, 145 p.

Morris, H.T., Lovering, T.S., Mogensen, A.P., Shepard, W.M., Perry, L.I., and Smith, S.M., 1979, General geology and mines of the East Tintic mining district, Utah and Juab counties, Utah, with sections on the geology of the Burgin mine and the geology of the Trixie mine: U.S. Geological Survey Professional Paper 1024, 203 p.

Morris, H.T., and Mogensen, P., 1978, Tintic mining district, Utah: Brigham Young University Geology Studies, v. 25, part 1, p. 33–45.

Nelson, S.T., Anderson, K., and Mayo, A.L., 2004, Testing the inter-basin flow hypothesis at Death Valley, California: Eos, Transactions, American Geophysical Union, v. 85, no. 37, p. 355–356.

Odling, N., 1997, Scaling and connectivity of joint systems in sandstones from western Norway: Journal of Structural Geology, v. 19, no. 10, p. 1257–1271.

Wallace, R. and Morris, H., 1986, Characteristics of faults and shear zones in deep mines: Pure and Applied Geophysics, v. 124, no. 1, p. 107–125.

Walker, R.T., 1928, Deposition of ore in pre-existing limestone caves: American Institute of Mining Engineers, Technical Publication 154, p. 1–43.

Western Regional Climate Center, 2005, http://www.wrcc.dri.edu/CLIMATEDATA.html, data for Eureka townsite (site 422625).