UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Tooele 1°x2° Quadrangle, Northwest Utah
A CUSMAP Preassessment Study

by

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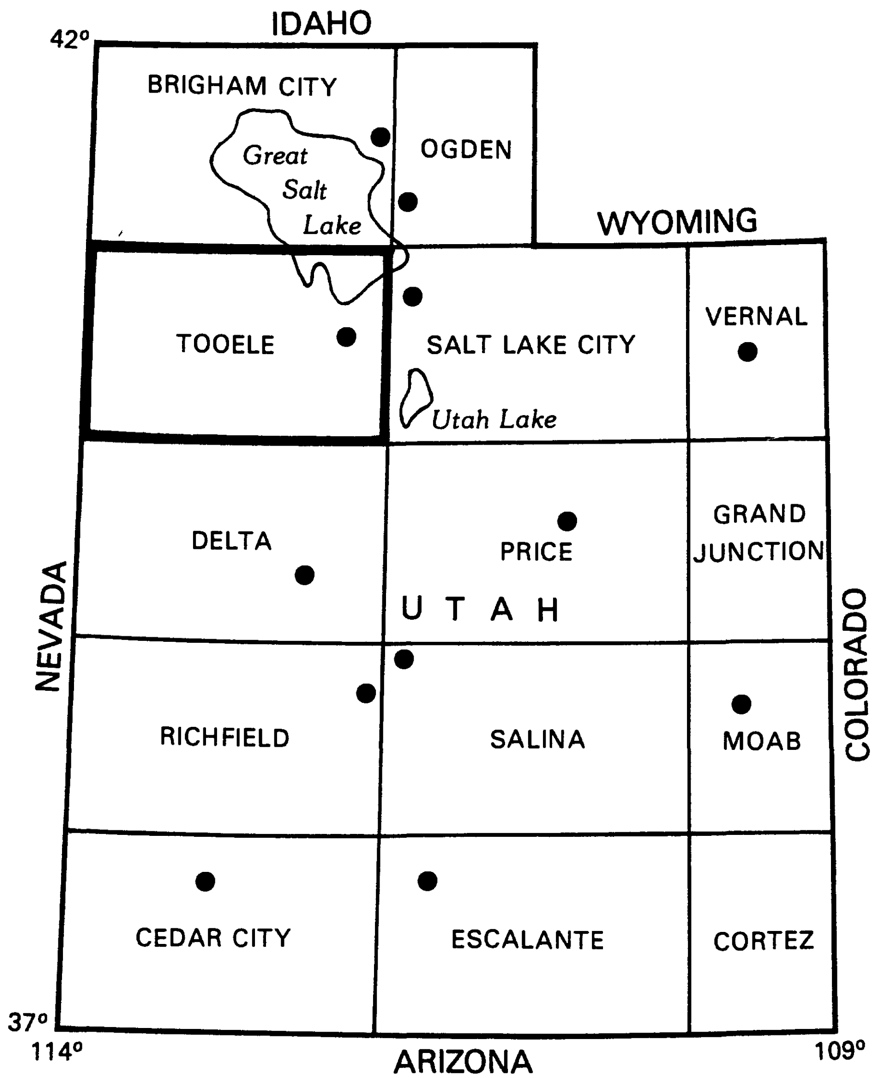


Index map showing location of the Tooele 1° x 2° quadrangle.

PREFACE

This CUSMAP (Conterminous United States Mineral Resource Assessment Program) Preassessment document is the product of an interdisciplinary team effort to gather, in a limited period of time, existing geologic, geochemical, geophysical, and mineral occurrence data for the purpose of writing a preliminary evaluation or "preassessment" of mineral resource potential for the Tooele 1^o X 2^o quadrangle in northwest Utah. The Preassessment team configuration resulted in an intense and exciting exchange of ideas and information from different disciplines of geology. A background summary of previously published works and available data, plus proposals and recommendations for future CUSMAP study of this quadrangle, constitute the chapters in this Preassessment report. As much as possible, we combined data from different disciplines to raise very specific questions concerning mineral potential and ore deposits. Early establishment of contacts between the U.S. Geological Survey and university professors, students, companies, and the Utah Geological and Mineral Survey (UGMS) fosters working relations with geologists in academia, industry, and other federal and state agencies. The Tooele Preassessment group includes a geologist from the Utah Geological and Mineral Survey (UGMS) as a full team member and author of this report. Interaction with state level geologists brings to light current information on geologic activities in the Tooele quadrangle which might otherwise be overlooked.

The Tooele 1^o X 2^o quadrangle has great potential for the discovery of additional mineral resources. This Preassessment report serves as a planning document to be used during CUSMAP quadrangle selection. The Tooele 1^o X 2^o quadrangle forms the northernmost of three quadrangles which contain Utah's major mineral belts. From south to north these are the (1) Richfield 1^o X 2^o sheet (CUSMAP completed), (2) Delta 1^o X 2^o sheet (CUSMAP in progress), and (3) Tooele 1^o X 2^o sheet (CUSMAP Preassessment). Together these three quadrangles host some of the richest, most spectacular mineral deposits in western U.S., including the famous Bingham copper deposit in the Tooele quadrangle.

Holly J. Stein
U.S. Geological Survey

September 1, 1989
Denver, Colorado

SUMMARY

by

Holly J. Stein

The Tooele 1^{o} X 2^{o} quadrangle is located in northwest Utah in the eastern Basin and Range geographic province. The quadrangle contains a wealth of base- and precious-metal mineral districts whose production history began in the mid to late 1800's and has continued intermittently throughout the 1900's (fig. 1a). Today (1989) the quadrangle is the scene of intense exploratory activity by numerous mining companies searching primarily for precious metals, particularly gold. The quadrangle contains the famous Bingham, Mercur, and Gold Hill districts in addition to numerous smaller metallic deposits. Major non-metallic deposits are associated with saline brines containing sodium, potassium, and magnesium chlorides; sand and gravel, clays, and limestone are also important. The quadrangle also contains oil, gas, oil shale, and coal resources, as well as several geothermal areas (fig. 1b).

The ore deposits in the Tooele quadrangle are intimately related to the geology and structural evolution of the Great Basin. Complex, east-directed, Sevier age (Cretaceous) compression has created folds and thrusts in Paleozoic rocks which were subsequently dissected by northwesterly and northeasterly trending normal and listric faults developed during Tertiary extension. These two periods of mechanical modification of the crust produced structures which later localized ore solutions and provided ore hosts. Bedrock exposure in the Tooele quadrangle is reduced by the large regions of unconsolidated basin fill, characteristic of Basin and Range topography. This fill includes the Great Salt Lake Desert which occupies the western half of the quadrangle. Bedrock is primarily exposed in three major ranges in the eastern half of the quadrangle. These exposures are, from east to west, the Oquirrh, Stansbury, and Cedar Mountains. All three ranges are composed almost exclusively of Paleozoic sedimentary rocks whose regional outcrop is a ribbon-like pattern of generally north-south striking units. Correlation of sedimentary rock units between ranges is difficult. Limited exposures of Precambrian igneous and metamorphic rocks occur in the Antelope Island, Stansbury Island, and Granite Peak areas. Several Jurassic plutons and numerous Tertiary intrusives, all generally of intermediate chemical composition, are present in the Tooele quadrangle. The actual outcrop area of Tertiary intrusives is small but the geology suggests that they may be connected at depth to larger intrusive systems. A modest amount of Tertiary volcanic rock including minor occurrences of topaz rhyolite is also present in the quadrangle, but major caldera or vent complexes have not been recognized.

The merging of written geologic observations with existing geophysical and geochemical data, compiled during the course of this CUSMAP Preassessment study, indicates a high potential for major undiscovered ore deposits including types which characteristically contain gold, silver, copper, molybdenum, lead, zinc, tungsten, fluorine, beryllium, and scandium. Opportunity to define and describe two new deposit types (scandium and gold skarn) exists. Geochemical and remote sensing data define broad tracts of metal anomalous and altered ground, particularly in the Oquirrh Mountains. These tracts may be related to the Oquirrh-Uinta axis or mineral belt. Aeromagnetic and gravity data indicate hidden plutons, volcanic rocks, and

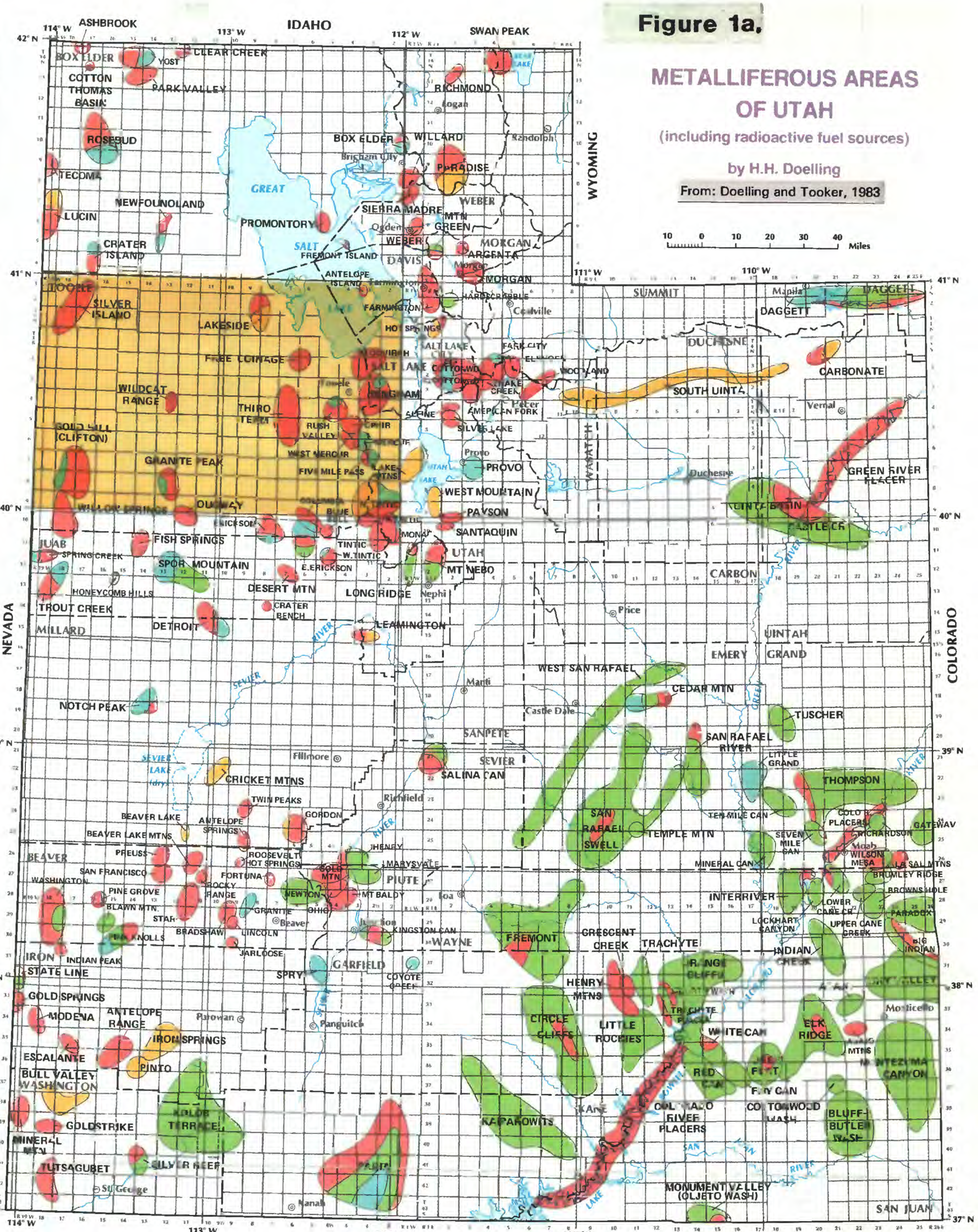


Figure 1a.

METALLIFEROUS AREAS OF UTAH

(including radioactive fuel sources)

by H.H. Doelling

From: Doelling and Tooker, 1983

PRECIOUS AND BASE METALS (Gold, Silver, Copper, Lead and Zinc)

IRON

TINTIC SILVER = METALLIFEROUS AREA NAME

RADIOACTIVE OCCURRENCES (Uranium, Thorium, including Vanadium)

MISCELLANEOUS METALS (Antimony, Beryllium, Bismuth, Manganese, Mercury, Molybdenum, Tungsten, etc.)

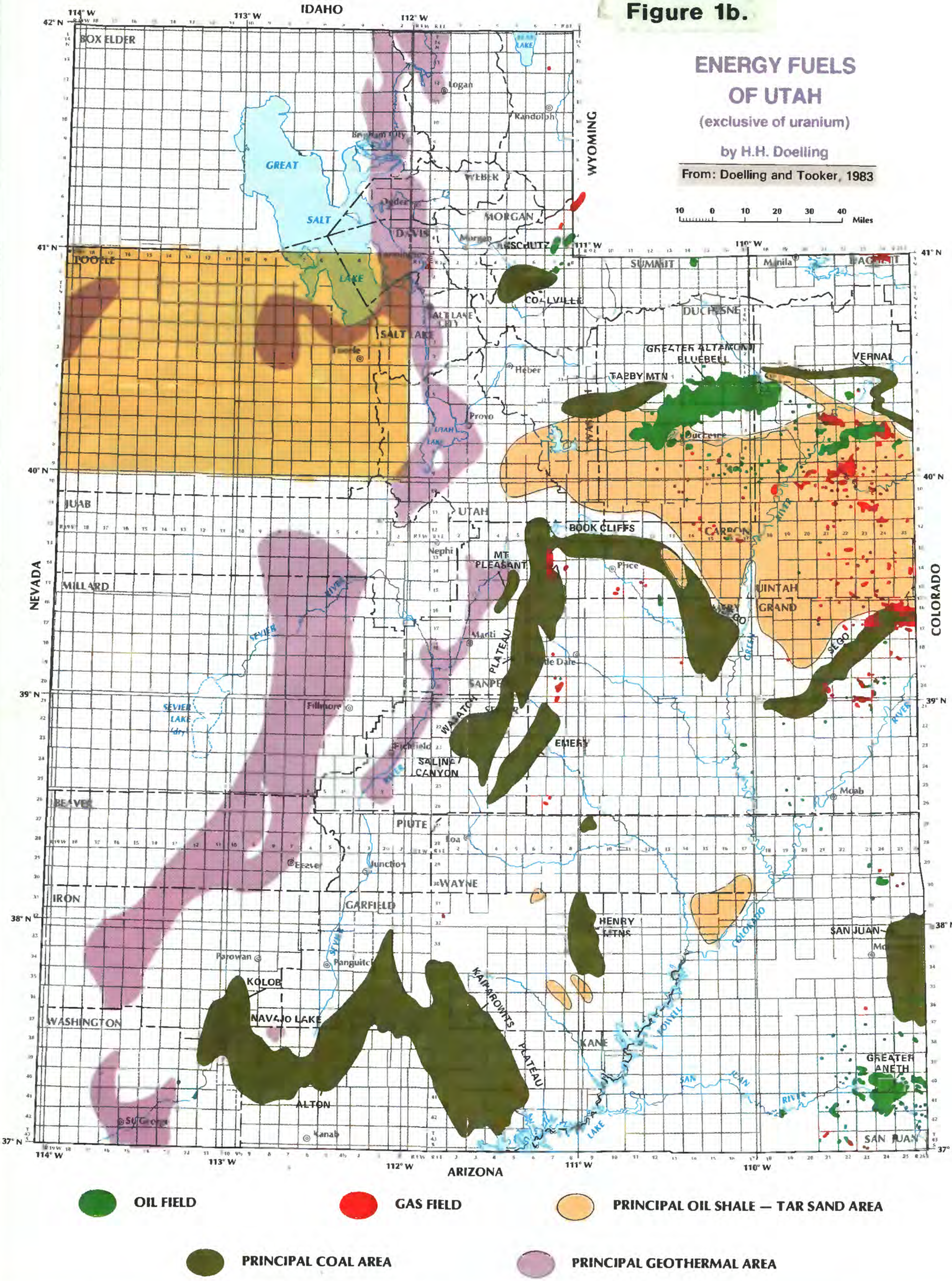
Figure 1b.

ENERGY FUELS OF UTAH

(exclusive of uranium)

by H.H. Doelling

From: Doelling and Tooker, 1983



buried structures which are known to be associated with ore deposits in other regions of western Utah. Numerous and highly varied interdisciplinary projects, all relating to mineral assessment and understanding ore deposits in the geologic framework of the Tooele quadrangle, were proposed during this Preassessment study.

This report has benefitted greatly from mutual exchange and cooperation between the U.S. Geological Survey and the Utah Geological and Mineral Survey, utilizing the expertise of both agencies.

INTRODUCTION

by

Holly J. Stein

The purpose of the CUSMAP program is to inventory identified mineral resources and assess the potential for undiscovered mineral resources in 1^{o} X 2^{o} quadrangle areas (1:250,000) using geological, geochemical, and geophysical data. Interdisciplinary study and the large 1^{o} X 2^{o} size of CUSMAP regions selected for mineral resource appraisal provide several advantages to the CUSMAP program: (1) major geologic and geographic provinces are incorporated, (2) known deposits can be inventoried and studied to predict and assess the potential for similar undiscovered deposits, (3) all land classifications are included in the study, (4) a national data base at a constant scale may be developed, (5) the approach used and the topics addressed in each CUSMAP study may be individually tailored for that quadrangle, and (6) the results and interpretations accommodate data from several disciplines within geoscience.

This report is a CUSMAP Preassessment document for the Tooele 1^{o} X 2^{o} quadrangle in northwestern Utah. A Preassessment is now a CUSMAP prerequisite and is used in the planning and budgeting stages of a quadrangle selected for CUSMAP funding. This Preassessment report was completed in about 6 months time by a team of eight geologists. Seven geologists are from the U.S. Geological Survey (USGS) in Menlo Park, CA, Reston, VA, and Denver, CO, and one geologist, Michael Shubat, is from the Utah Geological and Mineral Survey (UGMS). The team convened twice for intense, several day-long sessions of discussion and exchange in March and April of 1988. This team of geoscientists brought together persons with highly different backgrounds and areas of expertise. Each chapter targets specific areas requiring extensive work at the CUSMAP level. Topical studies concerning ore deposits and mineral resources in the Tooele quadrangle are recommended. Verbal contact with recent and present workers in the Tooele quadrangle greatly enhanced the content of this report.

Scientific Gains

The Tooele quadrangle is brimming with diverse topical studies relating to ore deposits and their geology. Based on classical porphyry-related ore deposit models, it appears that many of the metallic deposits in the Tooele quadrangle are part of the upper levels of larger, buried magmatic systems. The array of porphyry deposit types suggests that belts of shallow intrusive systems are being intersected and sampled at differing high levels. The Tooele quadrangle offers an opportunity to increase our understanding of the vertical dimension in porphyry-related ore deposits. The presence of Au-bearing skarns provides opportunity for study and documentation of an exciting new type of mineral deposit. Models for scandium ore deposits, also present in the quadrangle, are needed. The geophysical refinement of large scale, buried structures, recognized during this Preassessment study, will add to our understanding of regional mineral belts and trends in western Utah and in western U.S. More detailed geophysical studies will elucidate the geological and structural nature of buried terranes associated with ore deposits and their mineral potential in nearby areas. Geochemical studies in the Tooele quadrangle will further define mineral trends and help distinguish between major ore deposits, prospects with high mineral potential, and occurrences with little or no mineral potential. More detailed geochemical studies of Au-bearing hydrothermal systems will help define differences between Carlin-type Au deposits, common in the central Basin and Range in Nevada, and Mercur-type deposits, more characteristic in the eastern Basin and Range in western Utah. In the Oquirrh Mountains, geochemical studies can be used to establish regional scale relations between hydrothermal-meteoric systems -- beginning at Bingham (north end of the Oquirrh Mountains) and extending through Stockton and Ophir down to Mercur (south end of the Oquirrh Mountains). The North Tintic district, located at the northern end of the East Tintic Mountains in the southeast corner of the quadrangle, as well as the reknowned Tintic district (just barely off the quadrangle to the south) are probably structurally related to deposits in the Oquirrh Mountains to the north. Analysis of remotely sensed data has targeted specific areas of altered rock that might otherwise be missed in field geologic or geochemical reconnaissance work. Using the new generation of multi-spectral imaging spectrometers can provide rapid and accurate mapping of potentially mineralized areas, and improve and refine the capabilities of these spectrometers.

Industrial Profits

The Tooele quadrangle is the site of intense exploration activity by numerous mining companies and industrial firms. Although gold is the most sought after commodity, exploration for other metals including copper, lead, zinc, silver, scandium, beryllium, tungsten, molybdenum, as well as non-metals such as fluorine, brines, and gravel is also at a high level. The Tooele quadrangle offers opportunity for cooperation between USGS personnel and mining and exploration geologists in industry. A CUSMAP study of the Tooele quadrangle would encourage continued spending of industry dollars in the region. New U.S. Geological Survey reports and maps would provide information for industry geologists engaged in mineral exploration.

Benefits to Other Agencies

A number of agencies involved in making land-use decisions could contribute to and would benefit from CUSMAP work in the Tooele quadrangle. Chief among these are the Bureau of Mines (BOM), who have formally expressed an interest in CUSMAP/AMRAP programs. The BOM would bring expertise in areas such as (1) economic evaluation of identified and undiscovered resources, (2) mine development and associated problems of power supply, water, transportation networks, taxation, and regulation, and (3) marketing prospects including supply and price patterns, and predictions of demand.

Other federal agencies which would benefit from a role in CUSMAP work are the Bureau of Land Management (BLM) and the Forest Service (USFS). There are three wilderness study areas (WSA's) controlled by BLM in the Tooele quadrangle. These include the northern Stansbury Mountains (Foose and others, 1989), the northern Deep Creek Mountains which include the Gold Hill mining district (studies in progress by C.J. Nutt), and the northern two-thirds of the Cedar Mountains (U.S. Bureau of Land Management, 1986). The USFS controls two regions of Wasatch National Forest located in the northern portion of the Sheeprock Mountains and the southern three-fourths of the Stansbury Mountains. Part of the Wasatch National Forest in the Stansbury Mountains is a designated wilderness area.

The western half of the Tooele quadrangle is almost completely occupied by the Dugway Proving Ground and the Wendover Bombing and Gunnery Range (fig. 2). At the surface, this broad region consists of economically important salt flats and unconsolidated sand. However, a few isolated outcrops of Paleozoic carbonate rocks and an outcrop of Precambrian rock at Granite Mountain are economically intriguing and it is important that their mineral potential be carefully checked. These large regions of military reservation may limit ease of access, but present an opportunity to work with the Department of Defense to better understand the geology and mineral potential beneath these Army and Air Force Ranges.

Still other federal agencies as diverse as the Park Service, Fish and Wildlife Service, and Environmental Protection Agency would have an interest in and benefit from CUSMAP studies in the Tooele quadrangle. The recreational and industrial facilities associated with the southern end of the Great Salt Lake and the proximity of this region to the major metropolitan center of Salt Lake City warrant monitoring of natural changes, such as the level of the Great Salt Lake, as well as any man-produced impact on the region.

At the state level, the U.S. Geological Survey has a long established working relationship with the Utah Geological and Mineral Survey. As in past and ongoing CUSMAP studies (Richfield and Delta $1^{\circ} \times 2^{\circ}$ quadrangles, respectively) the Tooele CUSMAP Preassessment has received the full cooperation of Genevieve Atwood, Utah State Geologist. She designated one of her geologic staff (Michael Shubat) as liaison and member of the Tooele Preassessment team.

GEOLOGY AND THE FORMATION OF MINERAL DEPOSITS

by

Holly J. Stein

The geologic history of exposed bedrock in the Tooele 1^{o} X 2^{o} quadrangle has two main chapters which are separated by the Cretaceous Sevier Orogeny. Most of the rocks in the quadrangle are comprised of allochthonous thin-skinned thrust sheets of Paleozoic sedimentary rocks which were folded and faulted during Sevier compression and their eastward transport. Post-Sevier, Tertiary volcanic and intrusive rocks make up a volumetrically small part of the surface bedrock though geophysical data suggest that these igneous rocks are present in greater volume at shallow depths. Minor amounts of Precambrian basement rocks are exposed on Stansbury and Antelope Island, and Granite Mountain. Further dissection of thrust sequences occurred during Tertiary Basin and Range extension. This complex history of thrusting and extension created upper crustal structures which helped localize Tertiary intrusive rocks and associated ore deposits. Only about 20 percent of the bedrock in the Tooele quadrangle is exposed. The remaining 80 percent of the quadrangle is occupied by unconsolidated basin fill, mostly in the Great Salt Lake Desert, and a large body of water, the southern end of the Great Salt Lake (see pl. 1).

The Oquirrh-Uinta Mineral Belt

Three major mineral belts are located in the eastern Great Basin region of western Utah (fig. 2). The Oquirrh-Uinta mineral belt is roughly coincident with the western extension of the Uinta-Cortez axis, a broad Precambrian structural zone positioned against the Archean Shield which controlled Paleozoic sedimentation in northwestern Utah, northeastern Nevada, and south-central Idaho (fig. 2). Early workers observed this mineral trend and named it the Bingham-Park City Uplift (for example, Butler and others, 1920). The Oquirrh-Uinta mineral belt, as defined in figure 2, contains the Park City and Cottonwood districts at its eastern end and the Bingham and Mercur deposits at its western end. The mineral deposits at Gold Hill were initially included in the Deep Creek-Tintic mineral belt to the south (Hilpert and Roberts, 1964). More recently, however, workers have extended the Oquirrh-Uinta belt westward across the Tooele quadrangle through Gold Hill into the Kingsley Range of extreme eastern Nevada, calling the feature the "Uinta-Gold Hill mineral trend" (Erickson, 1976). In this report, we often refer to the belt as the Bingham-Gold Hill mineral trend, given the confines of the Tooele 1^{o} X 2^{o} quadrangle (fig. 1). The westward continuation of the Oquirrh-Uinta mineral belt beyond Gold Hill is a question that needs to be addressed at the CUSMAP level. Gravity and aeromagnetic data suggest a possible break in the Bingham-Gold Hill mineral trend. This geophysical break shows up as a buried, northwest-trending feature of unknown age beneath the Great Salt Lake Desert, separating Gold Hill from the southwesterly trend of ore deposits and mineral occurrences in the Oquirrh, Stansbury, and Cedar Mountains. Interestingly, this northwest-trending geophysical feature parallels the Oregon-Nevada lineament (Stewart and others, 1975), a deep-seated fracture zone believed to have had a complex history of strike-slip and tension-related movement. The Oregon-Nevada lineament is associated with voluminous late Miocene and younger felsic and mafic volcanic rocks. If the geophysical feature in the Tooele

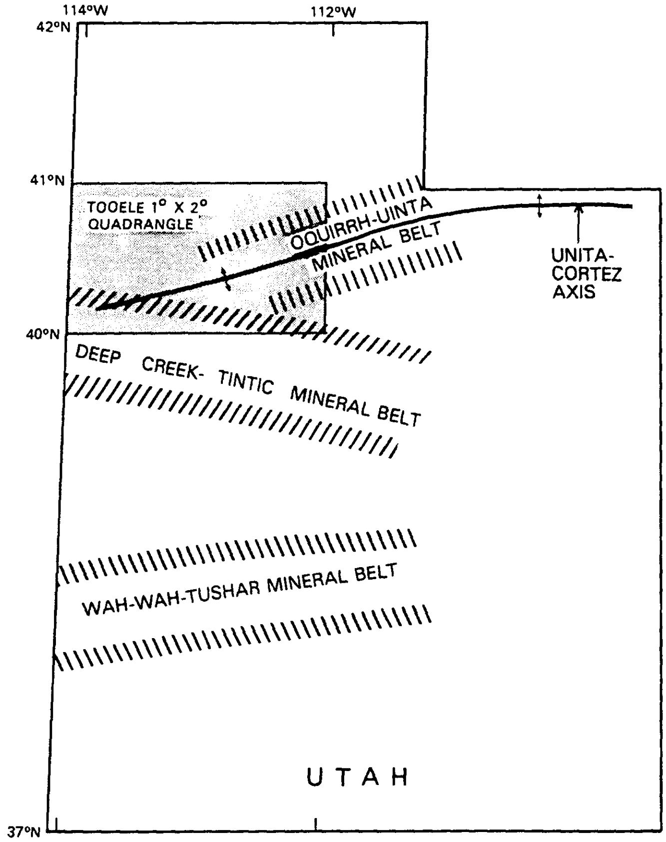
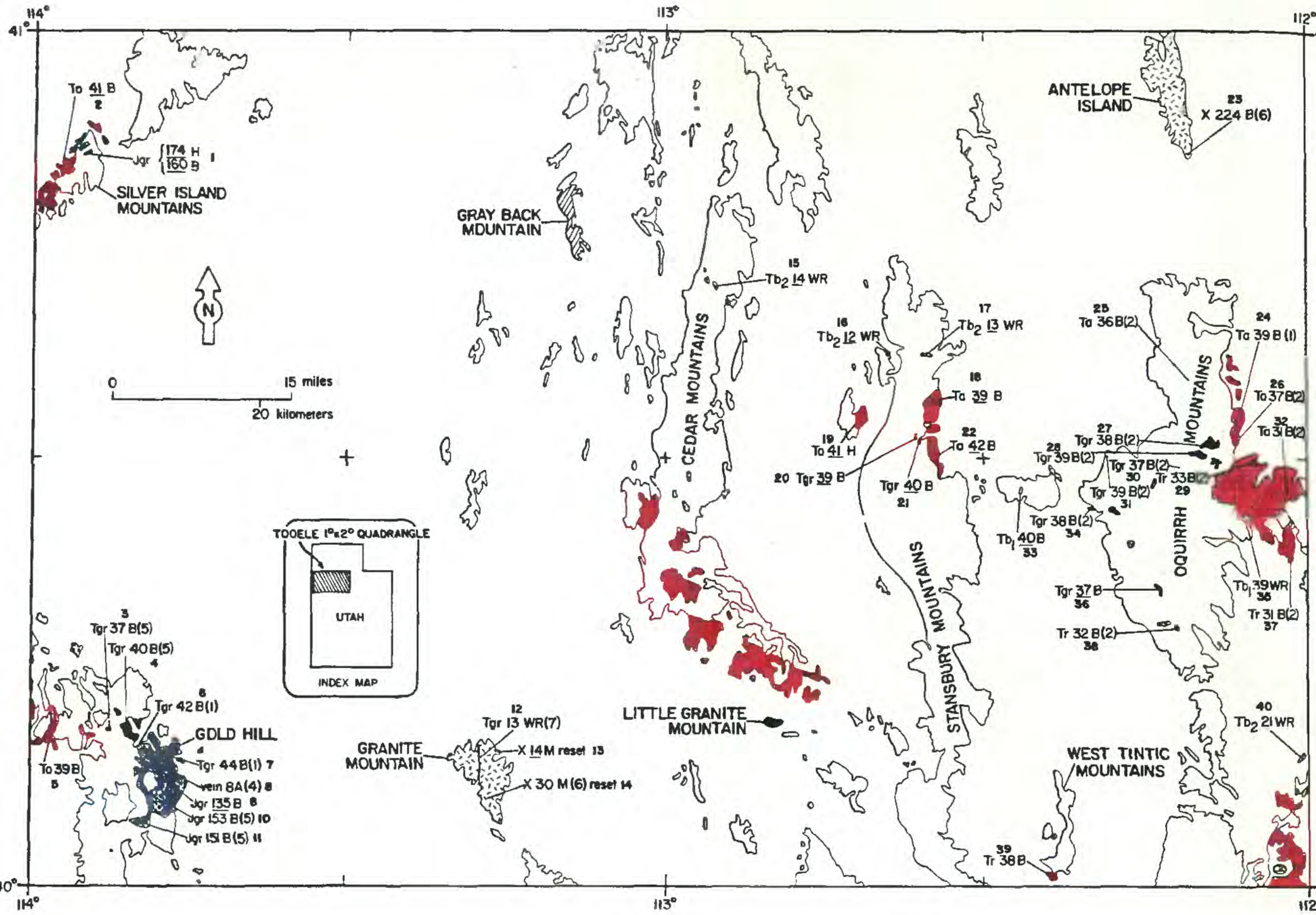
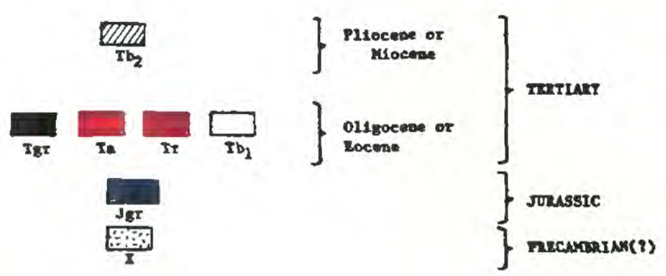


Figure 2. Mineral belts of western Utah (defined by L.S. Hilpert and R.J. Roberts, 1964).

quadrangle is a similar, volcanic-filled fracture zone, this could have significant bearing on the mineral potential for beryllium deposits. Major beryllium deposits are associated with late Miocene topaz rhyolites containing carbonate clasts at Spor Mountain in the Delta 1° X 2° quadrangle to the immediate south. A northwesterly trend of evolved rhyolite outcrops can be traced from Spor Mountain in the Delta quadrangle to the Silver Island Mountains in the northwest corner of the Tooele quadrangle. Sapphire Mountain, just south of Granite Peak, and outcrops in the northern Deep Creek Mountains are occurrences of topaz and alkali rhyolite which fall along the margins of this northwest trending geophysical anomaly (pl. 2, 3, and 4). Regional geophysical trends are important in tracing extensions of known mineral belts beneath their outcrop surface as well as in suggesting potential new mineral trends. An increased understanding of the rich Bingham-Gold Hill mineral trend would have great impact on accurately accessing the potential for buried mineral deposits beneath basin pediment surfaces, especially the Great Salt Lake Desert. Precious and base metal deposits in western Utah, consisting of replacement, vein, disseminated and skarn ore bodies, are associated with Mesozoic and Tertiary intrusive and volcanic rocks (Shawe and Stewart, 1976). These intrusive and volcanic rocks closely follow the mineral belts of western Utah (figs. 2 and 3). The region between the Deep Creek-Tintic and Wah-Wah Tushar mineral belts, devoid of exposed Tertiary igneous rocks, is known as the mid-Utah magmatic gap (Jerome and Cook, 1967). The distinct east-west patterns of Tertiary igneous activity in western Utah are not readily related to generally accepted plate tectonic models for western



EXPLANATION



Tb_2	BASALT AND BASALTIC ANDESITE FLOWS
Tgr	GRANODIORITE, QUARTZ MONZONITE, AND QUARTZ LATITE
Ta	ANDESITE, DACITE, AND QUARTZ LATITE FLOWS AND BRECCIAS
Tr	RHYOLITE FLOWS AND BRECCIAS
Tb_1	BASALT AND BASALTIC ANDESITE FLOWS AND SILLS
Jgr	DIORITE, GRANODIORITE, AND QUARTZ MONZONITE
X	CRYSTALLINE METAMORPHIC ROCKS

Notation

Map unit	Age in m.y.	References	Sample material	Locality
Granodiorite, quartz, monzonite, and quartz latite	40	(1) Armstrong (1970)	B, biotite	33
		(2) Moore (1973)	H, hornblende	
		(3) Stacey and Zartman (1978)	WR, whole rock	
		(4) Whelan (1970)	M, muscovite	
		(5) C. E. Hedge (oral commun, 1982)	A, adularia	
		(6) Warnaars and others (1978)		
		(7) This report (Table 1)		

Figure 3. Outcrop of igneous rocks in the Tooele 1° X 2° quadrangle, northwestern Utah and location of dated samples. Outcrop areas of sedimentary rocks are unpatterned. Geology by Moore and Sorensen (1979). Figure from Moore and McKee (1983).

North America, as the expected pattern for volcanic and plutonic belts might more typically parallel the subduction zone or Pacific margin of the North American continent. These perpendicular-to-the-subduction-zone Tertiary igneous and mineral trends in western Utah are sometimes attributed to transverse discontinuities or fault-like breaks in the subducting plate, or east-west structural warps or weaknesses. Whatever their origin, volcanic-plutonic belts and their relation to mineral trends in western Utah are clearly critical to understanding ore deposits and assessing mineral potential in this region of the Eastern Great Basin.

Rock Types: Age, Structural History, and Relation to Ore Deposits

Though rock types may be described in a chronologic manner on a geographically small scale, bedrock in western Utah is not easily correlated and chronologically assembled on the regional scale. The non-contiguous nature of stratigraphic sections between major mountain ranges is the product of complex east-directed thrusting (fig. 4) which resulted in the imbricate stacking of sedimentary slices on the back of the Wasatch autochthon (fig. 5). Precambrian basement is rare in this region of thin-skinned thrusting. Though Paleozoic sedimentary rock sequences, particularly those containing carbonates and quartzites, are often hosts for metallic ore deposits, their description is not a part of this report, except for brief mention in a later section concerning non-metallic mineral commodities. Rather, major attention is given to the intruding igneous rocks, which are genetically associated with most ore deposit types. Ages of igneous rocks and their affiliation with ore deposits have been succinctly described in the following abstract by Moore and McKee (1983):

"A comprehensive suite of radiometric age determination clearly defines three periods of igneous activity in the Tooele 1^{o} X 2^{o} quadrangle, Utah. These periods and the associated igneous activity are (1) Jurassic calc-alkaline plutonism, (2) late Eocene to early Miocene calc-alkaline plutonism and volcanism, and (3) middle and late Miocene bimodal basaltic and rhyolitic volcanism. These periods are recognized throughout the entire Great Basin. A characteristic metal or suite of metals is associated with each period. Tungsten skarns are commonly related to Jurassic plutonism; base-metal and precious-metal deposits are characteristic of the late Eocene to early Miocene igneous activity; and beryllium, fluorine, and uranium are elements associated with silicic rocks of the middle and late Miocene period of igneous activity."

A more detailed discussion of igneous rocks and associated mineral deposits is contained in the following sections.

Precambrian Rocks

The amount of Precambrian outcrop in the Tooele 1^{o} X 2^{o} quadrangle is minimal and in all cases Precambrian rock types have little bearing on modeling sources for post-thrusting Mesozoic and Cenozoic intrusions because the Precambrian rocks reside on allochthonous thrust sheets and true basement is probably at greater that 10 km depth in this region. The two areas of Precambrian outcrop in the Tooele quadrangle are at Granite Mountain and on Stansbury and Antelope Islands. A major report on the geology of Antelope Island, based on new geologic mapping, has just been completed by the Utah Geological and Mineral Survey (Doelling and others, 1988). The Precambrian

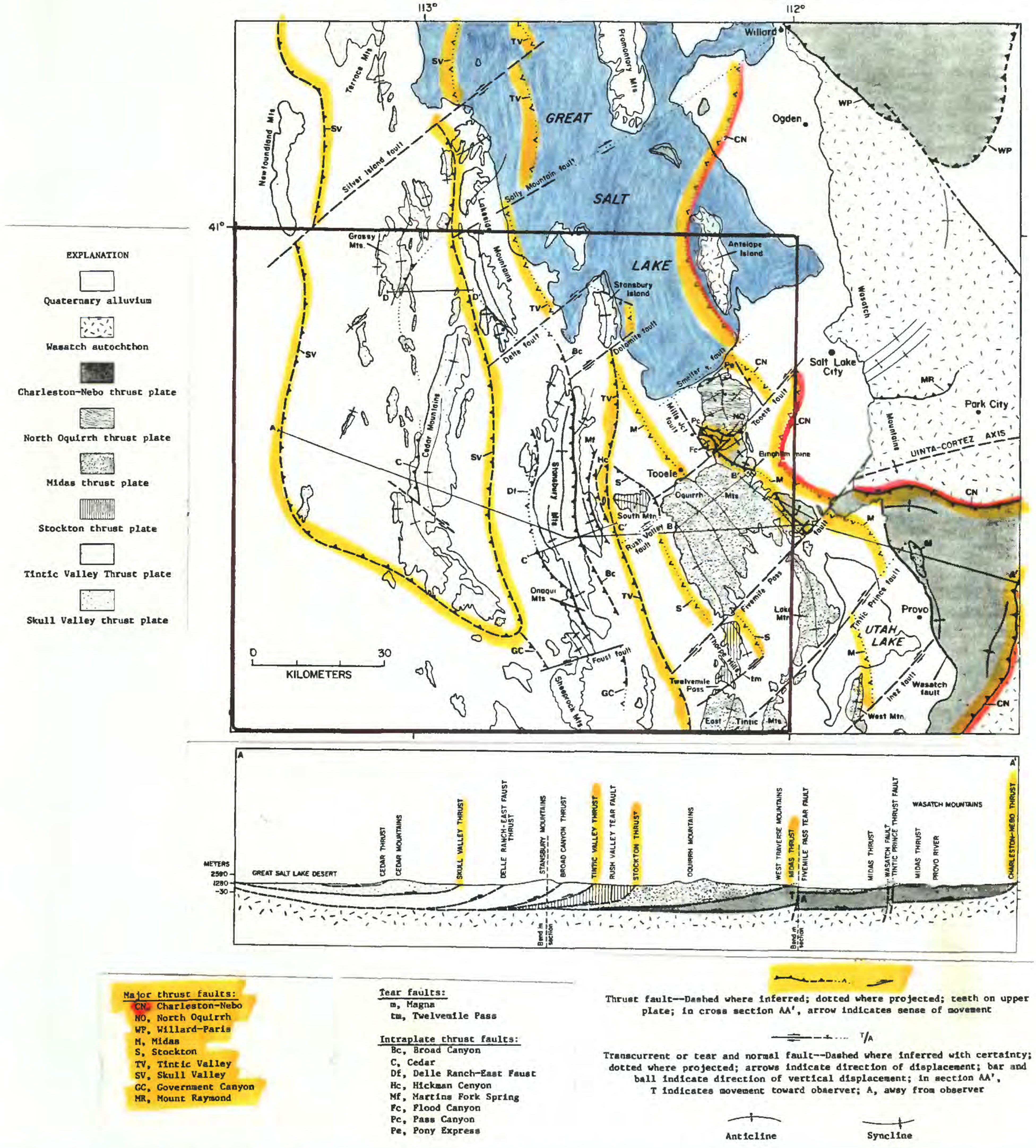
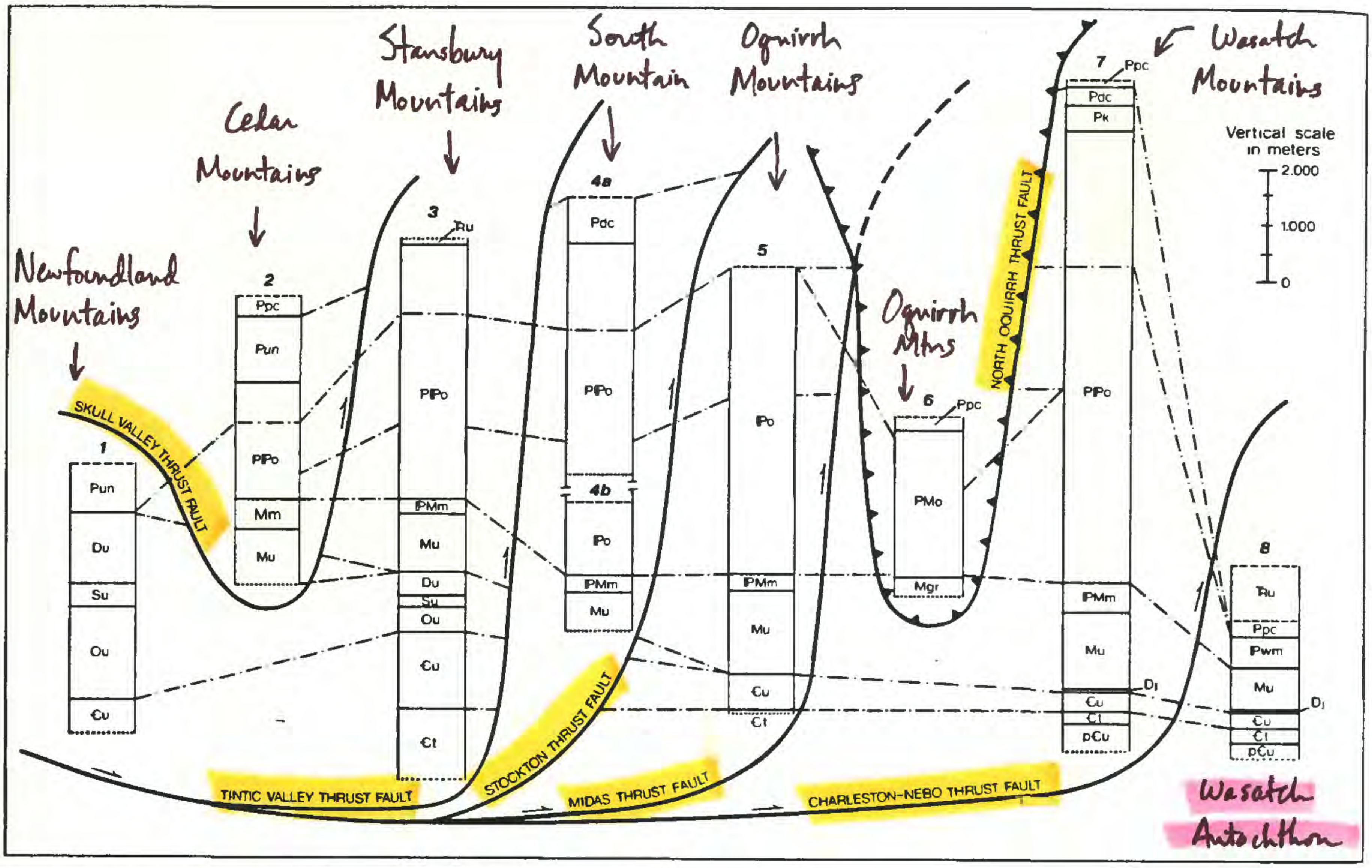


Figure 4. Location of major thrust plates and plate segments, principal fold axes, and inferred transcurrent or tear and thrust faults. Red outline marks the Charleston-Nebo thrust fault, the eastern limit of major Sevier deformation. Basin and Range faults are not shown. Eastern 75 percent of the Tooele 1° X 2° quadrangle is shown in boxed region. Proposed patterns of thrust plate imbrication are shown in cross-section along AA'. Figure from Tooker (1983).



EXPLANATION

Erosion surface at top of section

Covered base of section

Unconformity

Formation or Member correlation

Formation contact

Thrust fault--Dotted where concealed; arrows indicate sense of motion

Thrust fault--Movement normal to page

pЄu, undivided Precambrian rocks
Єt, Tintic Quartzite of Cambrian age
Єu, undivided post-Tintic Quartzite Cambrian rocks
Ou, undivided Ordovician rocks
Su, undivided Silurian rocks
Du, undivided Devonian rocks
Dj, Jefferson(?) Dolomite of Devonian age
Mgr, Green Ravine Formation of Mississippian age
Mu, undivided Mississippian rocks
Mm and IPMm, Manning Canyon Shale of Mississippian and Pennsylvanian and Mississippian ages, respectively
IPwm, Weber and Morgan Formations of Pennsylvanian age
PMo, IPo, PIPo, and Po, Oquirrh Formation or Group of Permian to Mississippian, Pennsylvanian, Permian and Pennsylvanian, and Permian ages, respectively
Pu, post-Oquirrh Permian rocks
Pun, unnamed Permian formation
Pk, Pdc, and Ppc, Kirkman Limestone, Diamond Creek Sandstone, and Park City Formation, respectively, all of Permian age
TRu, undivided Triassic rocks

Figure 5. Correlation of generalized stratigraphic section of pre-Cretaceous rocks of the Wasatch autochthon and major allochthonous thrust plates composing the foreland of the Sevier Orogenic Belt. References for thicknesses of major lithologic units are in Tooker (1983). Figure modified from Tooker (1983).

rocks on Stansbury Island are quite different from those on Antelope Island, as the two islands are separated by the East Great Salt Lake Fault Zone, defined primarily by AMOCO drilling and geophysics (Mark Jensen, personal communication, 1988). At Granite Mountain very little detailed geologic mapping has been undertaken, primarily because it lies entirely within the Dugway Proving Ground and access must be scheduled around U.S. Army activities. However, two recent geochronologic studies of nearby Precambrian complexes are useful in discussing the Precambrian rocks in the Tooele quadrangle. These are a study of the Farmington Canyon complex in the Wasatch Mountains on the eastern edge of the Sevier orogenic belt (Hedge and others, 1983) within which Antelope Island forms the western part (pl. 2), and a study of the intrusive and metamorphic rocks of the Pilot Range on the Utah-Nevada border (Miller and others, 1987) located just northwest of the Silver Island Mountains (pl. 1) on the Brigham City 1^{o} X 2^{o} quadrangle. The Tooele quadrangle lies in a geologically interesting region which appears to record a marked decrease from east to west in the influence of Archean basement associated with the Wyoming craton. This has been documented by lead isotope studies of Tertiary ore deposits (Stacey and others, 1968; Stacey and Zartman, 1978) and in the Precambrian rocks themselves (Hedge and others, 1983).

The Farmington Canyon complex consists of high grade metamorphic rocks and migmatites derived from igneous and sedimentary rocks at least as old as 3.0 b.y. (Hedge and others, 1983). Samarium-neodymium data indicate that a component of crustal material, possibly as old as 2800 to 3600 m.y., is included in the complex. Rubidium-strontium data for layered metamorphic rocks do not define an isochron age, but support the input of varying amounts of Archean material into initial Farmington Canyon sedimentary sequences. High grade metamorphic events affected Rb-Sr systems at 2600 and 1790 Ma. The 1790 Ma event includes production of quartz monzonite ($^{87}Sr/^{86}Sr = 0.769$) from melting of leucocratic parts of older layered gneisses. Granite plutons intruded Antelope Island in the Tooele quadrangle at about 2020 Ma. The observed scatter in the Nd and Sr isotopic data may not only be attributed to inheritance of variable amounts of older crustal material, but may have been amplified by partial isotopic resetting during multiple metamorphic events in the Precambrian and possibly during the Sevier Orogeny (Hedge and others, 1983).

In the Pilot Range of Utah and Nevada, some greenschist to amphibolite facies rocks of Late Proterozoic age (McCoy Creek Group) are exposed in a window underlying the Pilot Peak decollement (Miller, 1984; Miller and others, 1987). This exposure of Proterozoic rock in the lower plate consists of gneissic units with numerous small, foliated, muscovite- and biotite-bearing granite bodies and small hornblende-biotite granodiorite bodies. K-Ar and U-Pb isotopic studies indicate a widespread middle Mesozoic (165 to 150 Ma) greenschist facies metamorphism accompanied by plutonism in the lower plate. Unmetamorphosed Cambrian to Permian rocks of the upper plate were emplaced during low-angle (normal) detachment faulting and were subsequently tilted during Cenozoic upper crustal thinning. This Mesozoic metamorphic event thoroughly overprinted Proterozoic and Cambrian rocks in the lower plate (Miller and others, 1987).

Granite Mountain is dominated by biotite granite gneiss with indistinct foliation (Fowkes, 1964). A small patch of phyllite is exposed at the south end of the mountain, separated from the gneiss by scattered outcrops of biotite schist. The northern end of the mountain is underlain by a two-mica leucogranite. Both the gneiss and the granite are cut by tabular pegmatite dikes, containing microcline, quartz, plagioclase, and muscovite, and variable amounts of beryl, tourmaline, garnet, and hematite. Except for some beryllium prospects associated with beryl-bearing pegmatites on Granite Mountain (Hanley and others, 1950), Precambrian rocks in the Tooele quadrangle have held little economic interest.

Mesozoic Plutons

In the Tooele 1^{o} X 2^{o} sheet, Mesozoic plutons of Late Jurassic age are restricted to the westernmost regions of the quadrangle, along the Nevada-Utah border. The origin of this Mesozoic magmatism and its relationship to Late Cretaceous magmatism in eastern Nevada and Tertiary magmatism throughout western Utah is poorly understood. Geophysics suggests that these plutons are not "rooted", meaning that they were torn from their base and transported eastward during Sevier thrusting (D.L. Campbell, personal communication, 1988). However, some field evidence suggests that they may have formed beneath their present outcrop location, as they cross-cut presumed Sevier age structures (Robinson, 1988). Mesozoic plutons in the Tooele quadrangle occur in the northern Deep Creek Mountains (Gold Hill area) and in the Silver Island Mountains (pl. 1). Stacey and Zartman (1978) reported 151 Ma and 153 Ma ages from the southern part of the main Gold Hill stock. Previously determined Eocene ages for the Gold Hill stock (Armstrong, 1970) were apparently the result of thermal resetting by a Tertiary pluton emplaced along the northern margin of the Gold Hill stock. In the Silver Island Mountains, located in the northwest corner of the Tooele quadrangle and extending beyond the quadrangle boundary to the northeast, a 140 Ma K-Ar biotite age for the quartz monzonite of Crater Mountain, in the Brigham City 1^{o} X 2^{o} quadrangle immediately north of the Tooele quadrangle, was obtained (Moore and McKee, 1983). This Jurassic age was reaffirmed when a biotite and hornblende from other previously undated granodiorites in the Silver Island Mountains within the Tooele quadrangle yielded ages of 160 Ma and 174 Ma, respectively (Moore and McKee, 1983). The Newfoundland stock, about 40 km northeast of Crater Island in the Brigham City 1^{o} X 2^{o} quadrangle, also has a Jurassic age (Caroon, 1977) and the granite at Notch Peak in the House Range of the Delta 1^{o} X 2^{o} quadrangle has a 143 Ma K-Ar biotite age (Armstrong and Suppe, 1973). No Jurassic plutons are present in the Tooele 1^{o} X 2^{o} quadrangle east of the Great Salt Lake Desert (about 113^{o}W longitude). Jurassic magmatism, exclusive of Tertiary magmatic patterns, appears to define a north-south belt, perhaps related to a subduction-induced magmatic arc in Mesozoic time. Outcrops of Mesozoic igneous rocks, however, are very few over great north-south distances. Late Cretaceous (Laramide age) magmatism has not been recognized in the Tooele quadrangle.

Mesozoic magmatism is important in western Utah, particularly in the Tooele 1^{o} X 2^{o} quadrangle, in that it produced major skarn-related ore deposits. Of special interest are the newly recognized gold skarn deposits associated with Mesozoic, calc-alkaline quartz monzonite and granodiorite plutons (Orris and others, 1987). Mesozoic plutons in western Utah are also associated with economic tungsten, copper, and arsenic mineral formation in a contact metasomatic and replacement setting. The Gold Hill and Silver Island districts contain skarn and replacement mineral deposits associated with Late Jurassic plutons. These districts are discussed in greater detail in later sections of this report. Further CUSMAP study of gold-skarn deposits in the Tooele quadrangle is warranted, given present exploration interest for Basin and Range gold. In recent months exploration activity has intensified, moving eastward from Nevada into western Utah.

Barton (1987) has noted that Late Cretaceous two-mica granitoids in the Eastern Great Basin of Nevada are associated with a lithophile element (Be, F, W, Mo, Sn, and Zn) mineral occurrence, characterized by greisen-like zones in the intrusions, distinctive F- and Al-rich skarns in surrounding carbonate rocks, F-deficient quartz veins in surrounding clastic rocks, and distal metal-bearing, quartz-carbonate veins. Locally, these lithophile element concentrations achieve economic proportion and Barton (1987) proposes a new metallogenic province associated with Late Cretaceous granitoids in eastern Nevada extending to the Nevada-Utah state line. The Gold Hill and Silver Island districts of extreme western Utah, though associated with Late Jurassic plutons, need to be reexamined in light of Barton's newly proposed metallogenic province. The tungsten-copper-gold skarns, characterizing deposits associated with Jurassic plutons in the Tooele quadrangle, are mineralogically and chemically different than mineral occurrences associated with evolved two-mica granitoids of Late Cretaceous age in eastern Nevada. However, at least one two-mica granite body (Trout Creek alaskite intrusives, as described by Thomson, 1973) is present in the southern Deep Creek Mountains (Delta 1^{o} X 2^{o} quadrangle). The granite petrology and associated ore deposits at Trout Creek bear a striking resemblance to pluton and mineral occurrence descriptions given in Barton (1987) for eastern Nevada. The late Jurassic granites and associated ore deposits in extreme western Utah are chemically and mineralogically not part of Barton's new lithophile element province, but relationships between Late Jurassic calc-alkaline and Late Cretaceous silicic-felsic magmatism need to be explored during the Tooele CUSMAP study. Questions such as (1) have any evolved lithophile element-rich granites and related mineral occurrences been overlooked in the Tooele quadrangle, and (2) might the less evolved Jurassic granodiorites and granite monzonites in the Tooele quadrangle, interior to the highly evolved silicic-felsic Late Cretaceous bodies in eastern Nevada, be part of a zoned Mesozoic mineral belt? Resolution of structural and tectonic questions relating Mesozoic plutonism to the timing of thrusting and the number and origin of plates involved is needed.

Eocene and Oligocene Intrusions

Some of the first dates for Eocene and Oligocene igneous rocks in the eastern Great Basin (fig. 3) were obtained from the Bingham mining district in the Oquirrh Mountains (Armstrong, 1963). Later studies documented an abundance of 37-40 Ma ages for suites of epizonal calc-alkaline plutons and coeval volcanic rocks in the Oquirrh and Stansbury Mountains (Whelan, 1970; Moore, 1973a; Warnaars and others, 1978; Moore and McKee, 1983). There has been little attempt to date the small oxidized and weathered outcrops of igneous rocks in the Cedar Mountains; however, these intermediate lavas, breccias, and inferred feeders have been assigned a Middle Tertiary age on the basis of lithologic similarity to dated rocks in the Stansbury and Oquirrh Mountains. Ages for andesitic eruptive rocks in the Silver Island and northern Deep Creek Mountains affirm a widespread middle Tertiary volcanic-plutonic event. Several spurious Oligocene and Miocene ages for Precambrian pegmatites (Granite Mountain) and Jurassic plutons (Gold Hill area) are the result of resetting during this widespread, intermediate to felsic composition Tertiary magmatic activity.

Eocene and Oligocene magmatism, associated with base and precious metal deposits in the Tooele quadrangle, took place over a period of about 5 to 15 million years in latest Eocene to latest Oligocene time (40 to 25 Ma). Eocene and Oligocene calc-alkaline plutonism, coeval volcanism, and spatially associated mineralization occurs in all exposed mountain ranges in the Tooele quadrangle (figs. 1 and 3, pl. 1). Nearly all metallic mineral production is associated with this widespread Eocene and Oligocene magmatic event. Copper, argentiferous lead, and zinc sulfides are typical of most mineralized areas, though other metallic commodities, such as gold or molybdenum may be present or dominate some systems. The two most well-known deposits in the Tooele quadrangle are of Tertiary age. These are the Bingham porphyry Cu-Mo deposit and the Mercur Au deposit; both are discussed in more detail in later sections specifically concerned with ore deposits. In general, the outcrop area of Eocene and Oligocene intrusions is quite small, and in some cases only porphyritic dikes are known in mineralized areas. However, geophysical information suggests that shallow plutons immediately underlie these dikes. It appears that most Eocene-Oligocene mineral deposits can be described using variations on the porphyry model. Base and precious metal deposits in the Tooele quadrangle may simply reflect different structural levels of similar porphyry systems. The result is a belt of ore deposits representing different, generally high level, horizontal slices through vertically complex porphyry systems. In the Tooele quadrangle, the very top portions of igneous systems (dikes) and the shallow intersection of pluton cupolas, typically exposed in mineral districts, offer a chance for increased understanding of the development and evolution of Tertiary magmatic systems on a regional scale. This should be a major effort during CUSMAP study of the Tooele quadrangle.

Miocene Basalts and Rhyolites

Olivine-bearing and quartz normative basalts plus basaltic andesite flows occur throughout the Tooele 1^{o} X 2^{o} quadrangle and are part of widespread mafic magmatism that began about 17 Ma ago in the Great Basin. Four dated basalts from the Tooele quadrangle range from 12 to 21 Ma (Moore and McKee, 1983). Several bimodally associated, silicic lavas are also present in the Tooele quadrangle (pl. 1). These include undated topaz or alkali rhyolites (1) at Sapphire Mountain, south of Granite Peak, (2) in the northern Deep Creek Mountains, and (3) in the Silver Island Mountains. These topaz or alkali rhyolites are all presumed to be Miocene age, probably between 3 and 21 Ma, which is the age range for topaz rhyolites in the Delta 1^{o} X 2^{o} quadrangle to the south (Lindsey, 1977).

Silicic Miocene rhyolites, present as evolved topaz-bearing rhyolites in the Thomas Range and in the Spor Mountain area immediately south of the Tooele 1^{o} X 2^{o} quadrangle, are associated with economic concentrations of beryllium, fluorine, and/or uranium in western Utah (Shawe, 1966; Lindsey, 1977, 1978; Lindsey and others, 1973). The Sapphire Mountain alkali rhyolite lava at the southern tip of Granite Mountain (pl. 1) may be an erosional remnant of Spor Mountain eruptives or may have originated from an unrecognized vent, perhaps beneath the silicic flow itself. An alkali rhyolite porphyry dike intruding metacrystalline rocks of Granite Mountain yielded an age of about 13 Ma (C.E.

Hedge, personal communication, 1988). The intrusion of young rhyolite dikes into Precambrian rocks explains several erroneous Oligocene-Miocene dates obtained for Precambrian units at Granite Mountain (Moore and McKee, 1983). The presence of several other alkali rhyolites in the western part of the Tooele quadrangle suggests that silicic Miocene magmatism extends northwest of regions where associated beryllium ore deposits are known. At Wildcat Mountain in the eastern part of the Great Salt Lake Desert, fluorite has been mined from veins in an isolated outlier of Pennsylvanian-Permian(?) sedimentary rock (Thurston and others, 1954). Though no silicic rhyolites have been recognized at Wildcat Mountain, a small dike of Miocene basalt has been mapped, and host carbonate rocks are locally altered. Bertrandite, the beryllium silicate mineral in economic concentration at Spor Mountain, is present in an 8 Ma (Whelan, 1970) quartz + calcite + adularia vein that cuts the main Jurassic pluton at Gold Hill (Griffitts, 1965). Beryl occurs in pegmatite dike swarms of unknown age that intrude biotite granite gneiss on Granite Peak Mountain (Hanley and others, 1950). D.L. Kelley (personal communication, 1988) has obtained anomalous beryllium values equivalent to ore grade material at Spor Mountain in the northern Dugway district. Again, no topaz rhyolite outcrop is known, but breccia vents in the Dugway district contain minor amounts of unrecognizable igneous rock, and large regions of intensely altered (silicified) carbonate host rock suggest felsic intrusive rock at shallow depths (Kelley and Yambrick, 1988). Fluorite and beryllium occurrences in the Tooele quadrangle indicate potential for undiscovered Be-F-U deposits similar to those in the Delta quadrangle. Potential is particularly high in regions where topaz rhyolite has intruded carbonate rock sequences. More detailed work on alkali and topaz rhyolites, including definition of their shallow subsurface extension and their spatial relation to carbonate rocks, is a critical task for CUSMAP.

Quaternary and Recent Evaporite Sequences and Brines

Quaternary and Recent processes operating on closed bodies of water in the arid Tooele climate have produced and continue to produce evaporites and salt deposits, which are important non-metallic and non-fuel mineral commodities in the United States. Quaternary rocks are important in a discussion of rock types in the Tooele $1^{\circ} \times 2^{\circ}$ quadrangle because they cover 80 percent of the geographic surface and are directly associated with major deposits of "industrial rocks and minerals" or "geologic commodities not exclusively processed into metals and not used as fuels"; these generally low-profile commodities comprise a very large industry in the quadrangle (Tripp, 1987). Industrial commodities include limestone, alumina, silica, and gypsum to make Portland cement, potassium and magnesium salts, halite, phosphate, construction sand and gravel, and lime. The production of Portland cement is associated with particularly pure Paleozoic and Mesozoic sedimentary formations. Recent salt flats and shallow subsurface brines underlying the vast Great Salt Lake Desert (the residue of Pleistocene Lake Bonneville) as well as surface brines ponded for solar evaporation in the Great Salt Lake provide significant amounts of other industrial commodities. Some phosphatic shales of Mississippian and Permian age have been exploited for phosphate. Just beyond the northeast corner of the Tooele quadrangle, phosphate from the Permian Phosphoria Formation has been commercially produced. Outcrops of similar, potentially phosphatic-rich shale units occur in the Oquirrh, Grassy, and Cedar Mountains in the Tooele quadrangle. Pleistocene Lake Bonneville shoreline deposits provide sand and gravel, used primarily in the construction industry. Industrial rock and mineral resources in the Tooele quadrangle will require extensive and careful examination, as they are widespread and their future potential is perhaps underestimated.

Thrust and Normal Faults: Settings for Fluid Migration and Ore Formation

Strong structural control of mineralization in western Utah has been recognized for several decades (e.g., Stokes, 1968; Shawe and Stewart, 1976). More recently, T.A. Steven (personal communication, 1988) pointed out that a pronounced orthogonal fault pattern is common to the major mineral belts in western Utah (fig. 2). E.W. Tooker (written communication, 1988) has documented orthogonal fault patterns in great detail in the Oquirrh Mountains; these faults partially served as sites for ore deposition. Many older reports emphasize the association of ore with older northeast-trending faults rather than younger, north-trending Basin and Range faults. Still other reports have demonstrated a spatial relationship between thrust faults and precious metal deposits (Stein and others, 1988), through the faults may have served only to localize younger ore. Wernicke (1981, 1982) and Wernicke and others (1982) were among the first to point out the complex connection between thrust and normal faults in the Basin and Range. Deep plumbing systems which make use of numerous fault systems on the regional scale allow potential ore solutions to migrate great distances at depth before ascending in favorable, localized terranes for ore deposition. Recent evidence for gold mineralization along Miocene and younger normal faults suggests that strong structural control of hydrothermal ore deposition may have persisted into the Neogene. Bartley and Glazner (1985) noted the common correlation between low-angle normal faults and intense potassic hydrothermal alteration. They suggested that an existing hydrothermal system may have been a requirement for development of low-angle normal faults; the fluids were not simply following existing conduits. If their suggestion is correct, Neogene low-angle normal faults may be important targets for epithermal mineral deposits.

Geotectonic Summary

The established geologic history of the Tooele 1° X 2° quadrangle region begins with deposition of miogeoclinal sedimentary sequences along the western margin of the North American craton during the Paleozoic and early Mesozoic. Several exposures of Precambrian rocks (Granite Mountain and Antelope Island) hint at an older cratonic history, but structural and genetic relationships between Precambrian outcrops are lacking. From Mississippian to Triassic time, localized deep basins formed rapidly, and accumulated enormous thicknesses of marine sediments. Paleozoic strata were strongly deformed by east-vergent thrust faulting during the late Mesozoic Sevier orogeny, forming rugged highlands of stacked thrust sheets in western Utah which shed thick clastic deposits eastward into shallow marine and lacustrine basins. The late Cretaceous to Eocene Laramide orogeny marked an eastward shift in the locus of mountain-building, and terminated marine deposition in Utah. Laramide-related rocks and structures are not, however, present in the Tooele quadrangle. Widespread magmatism occurred in western Utah during the Oligocene, including emplacement of plutonic rocks associated with the Bingham copper district and Mercur gold deposit. Extensional tectonism and Basin and Range normal faulting began in Miocene time, and was accompanied by a shift to bimodal, basalt-(topaz) rhyolite magmatism. Fault-block uplift produced the observed mountain ranges, and sediment accumulation continued in major intermountain valleys. Pleistocene and younger geomorphology has been dominated by periodic flooding of the valleys, including the Recent Lake Bonneville, and its remnant, the Great Salt Lake.

CURRENT STATUS OF GEOLOGIC MAPPING

by

Holly J. Stein and Michael Shubat

Geologic Maps

Geologic mapping provides the fundamental data base on which subsequent geochemical and geophysical studies are built. The Tooele 1^{o} X 2^{o} quadrangle already has a published 1:250,000 scale geologic map (USGS Map I-1132) by Moore and Sorensen (1979). The 1^{o} X 2^{o} map was constructed from previous geologic maps (85 percent), plus new geologic mapping (15 percent), particularly in the Simpson Mountains and along the west side of the Stansbury Mountains (Sorensen, personal communication, 1988). Because the Tooele 1^{o} X 2^{o} quadrangle has been a long-time region of active mining, a considerable number of more detailed geologic maps are available. However, large areas of seemingly high mineral potential could benefit from additional detailed geologic and alteration mapping. These areas include the southern two-thirds of the Oquirrh Mountains, a region of intense mineral exploration at present, as well as portions of the Stansbury and Cedar Mountains. No detailed geologic mapping is available for most of the Silver Island Mountains. Recently completed mapping studies in areas of high mineral potential include (1) two new geologic maps for the Ophir and Mercur 7.5 minute quadrangles, Oquirrh Mountains, by E.W. Tooker (USGS Open-File Report 87-152, 1987), (2) a new geologic map of the Gold Hill 7.5 minute quadrangle, northern Deep Creek Mountains, by J.P. Robinson (UGMS Open-File Report 118, 1988), and (3) a 1:12,000 scale map showing wallrock alteration and geology in the Dugway mining district, northern Dugway Range, by D.L. Kelley and R.A. Yambrick (USGS Map MF-2045, 1988). Another field study pertaining to mineral resource potential was just completed by M.P. Foose, K.A. Duttweiler, and C.L. Almquist (USGS Bulletin 1745) for the north Stansbury Mountains wilderness area; this study, however, does not have a new map product associated with it as Foose (personal communication, 1988) said that the geologic mapping and interpretations made by J.K. Rigby in the 1950's were generally correct and were used in their mineral resource assessment.

The Utah Geological and Mineral Survey (UGMS) maintains a data base of completed, published and unpublished geologic maps for the state of Utah. Figures 6 through 10 show, by scale, the locations of existing geologic maps (as of March, 1988) in the Tooele 1^{o} X 2^{o} quadrangle. Map index numbers shown in figures 6 through 10 are listed in table 1 with their associated reference. The geologic maps listed in table 1 are either published or represent available, but unpublished thesis or dissertation maps. A geologic map of the Tooele 1^{o} X 2^{o} quadrangle by Moore and Sorensen (1979), not listed in table 1, was available when this Preassessment began, but is now out of stock or possibly out of print. Mapping of the Antelope Island, Plug Peak NE, and Gold Hill 7.5 minute quadrangles (to be published by the Utah Geological and Mineral Survey) is currently (1988) in progress.

Table 1. Current status of geologic mapping reference list keyed to geologic map index numbers in figures 6 through 10. Complete reference list for below cited references is available from the Utah Geological and Mineral Survey. A U.S. Geological Survey map reference list is included at the end of this chapter.

Index Number	Reference
13	Gregory, H.E., Moore, R.C. (1931)
14	Gilluly, James (1932)
22	Nolan, T.B. (1935)
78	Bick, K.F. (1966)
84	Whitebread, D.H. (1969)
269	Morris, H.T. (1964)
357	Mancuso, J.D. (1954)
540	Miller, D.M., Lush, A.P. (1981)
596	Everett, K.R. (1957)
597	Lambert, H.C. (1941)
598	Teichert, J.A. (1958)
599	Harrill, J.R. (1962)
600	Cohenour, R.E. (1957)
601	Chapusa, F.W.P. (1969)
602	Young, J.C. (1953)
603	Larsen, N.W. (1960)
604	Groff, S.L. (1959)
605	Axenfeld, Sheldon (1952)
606	Renzetti, B.L. (1952)
607	Sargent, R.E. (1953)
608	Johns, K.H. (1950)
620	Doelling, H.H. (1964)
625	Anderson, W.L. (1957)
626	Larsen, W.N. (1957)
650	Sharp, B.J. (1955)
652	Neff, T.R. (1963)
657	Hoffman, F.H. (1951)
658	Ornelas, R.H. (1953)
659	Smith, G.M. (1951)
660	Calderwood, K.W. (1951)
662	Schindler, S.F. (1952)
663	Elison, J.H. (1952)
714	Muessig, S.J. (1951)
736	Gardner, W.C. (1954)
738	Slentz, L.W. (1955)
753	Okerlund, M.D. (1951)
755	Williams, F.E. (1951)
760	Lofgren, B.E. (1947)
771	Schaeffer, F.E. (1961)
777	Christiansen, W.J. (1977)
785	Maurer, R.E. (1970)
801	Pitcher, G.G. (1957)
805	Bick, K.F. (1958)
806	Thomson, K.C. (1970)

Table 1 (Continued)

Index Number	Reference
809	Croft, M.G. (1956)
811	Davies, S.E. (1980)
828	Arnold, D.E. (1956)
833	Bullock, K.C. (1949)
834	Christensen, A.L. (1928)
849	Hedden, A.H., Jr. (1948)
856	Madsen, R.A. (1952)
869	Rigby, J.K. (1949)
879	Morris, H.T. (1947)
896	Murphy, C.M. (1975)
901	Armin, R.A. (1979)
908	Bullock, R.L. (1958)
912	Davis, B.L. (1959)
914	Dearden, M.O. (1954)
919	Foster, J.M. (1959)
925	Harris, D.P. (1958)
930	Johnson, K.D. (1959)
934	Larsen, N.W. (1960)
936	Lawton, T.F. (1980)
941	Lufkin, J.L. (1965)
942	McFarland, C.R. (1955)
947	Olivera, M.E. (1975)
950	Palmer, D.E. (1969)
965	Thomas, G.H. (1958)
989	Fowkes, E.J. (1964)
1004	Harris, A.W. (1936)
1025	Pampeyan, E.H. (1984)
1056	Witkind, I.J., Lidke, D.J., McBroome, L.A. (1978)
1070	Everitt, B.L., Kaliser, B.N. (1980)
1113	Pratt, A.R., Callaghan, E. (1970)
1115	Marsel, R.E., Threet, R.L. (1964)
1124	Schaeffer, F.E. (1960)
1126	Bissell, H.J., Rigby, J.K. (1959)
1127	Bissell, H.J., Proctor, P.D. (1959)
1128	James, A.H., Smith, W.H., Welsh, J.E. (1961)
1139	Morris, H.T. (1957)
1140	Ribgy, J.K. (1958)
1168	Jensen, M.E. (1984)
1171	Kornze, L.D. (1984)
1271	Levy, E., Cook, D.R., compiled (1961)
1306	Le Vot, Michel (1984)
1337	Lufkin, J.L. (1965)
1428	Kelley, D.L., Arbogast, B.F., Adrian, B.M., Yambrick, R.A. (1987)
1451	Robinson, J.P. (1988)
1453	Tooker, E.W. (1987)

Table 1 (Continued)

Index Number	Reference
GQ-141	Disbrow, A.E. (1961)
GQ-922	Tooker, E.W., Roberts, R.J. (1971a)
GQ-923	Tooker, E.W., Roberts, R.J. (1971b)
GQ-924	Tooker, E.W., Roberts, R.J. (1981)
GQ-992	Staatz, M.H. (1972)
MF-45	Proctor, P.D. and others (1956)
MF-131	Disbrow, A.E. (1957)
MF-490	Moore, W.J. (1973b)
MF-1147	Hintze, L.F. (1980)
MF-1148	Hintze, L.F. (1980)
MF-2045	Kelley, D.L., Yambrick, R.A. (1988)
I-1132	Moore, W.J., and Sorensen, M.L. (1979)
I-1173	Van Horn, Richard (1979)
I-1330	Van Horn, Richard (1981)

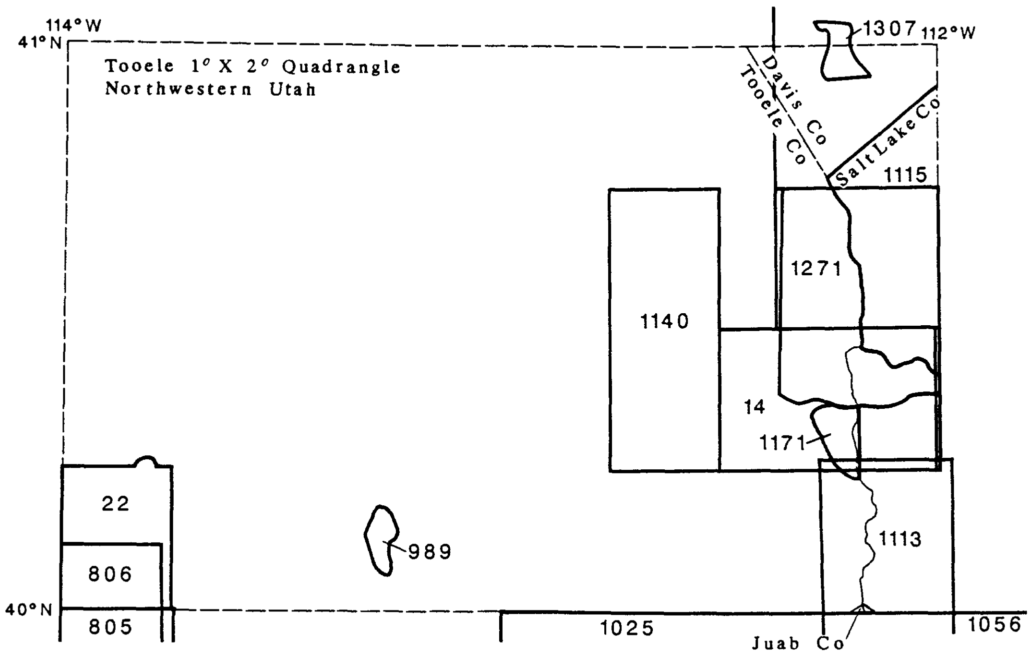


Figure 6. Geologic map index for the Tooele 1° X 2° quadrangle, scales 1:60,000 to 1:150,000. Index numbers and associated references are listed in table 1. Data from Utah Geological and Mineral Survey.

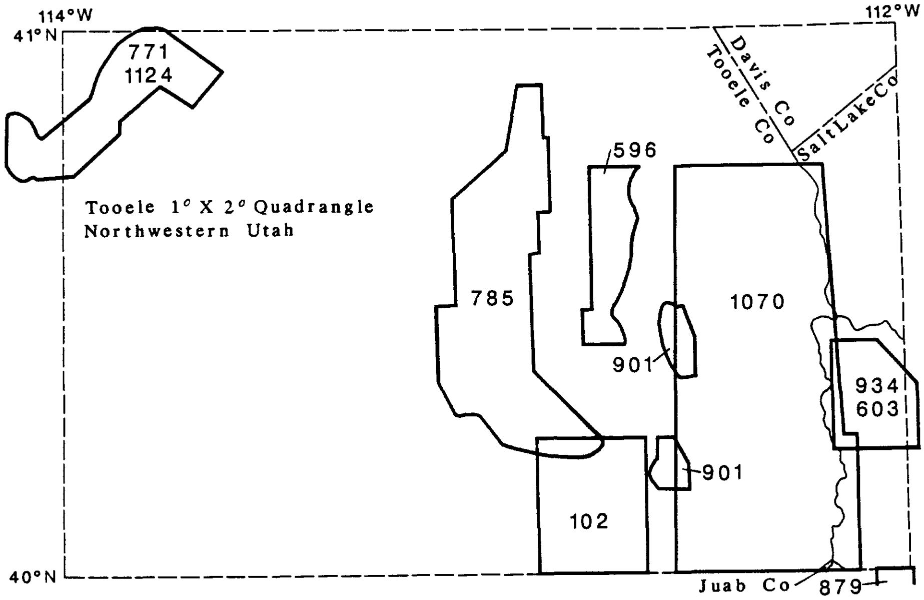


Figure 7. Geologic map index for the Tooele 1° X 2° quadrangle, scales 1:40,000 to 1:60,000. Index numbers and associated references are listed in table 1. Data from Utah Geological and Mineral Survey.

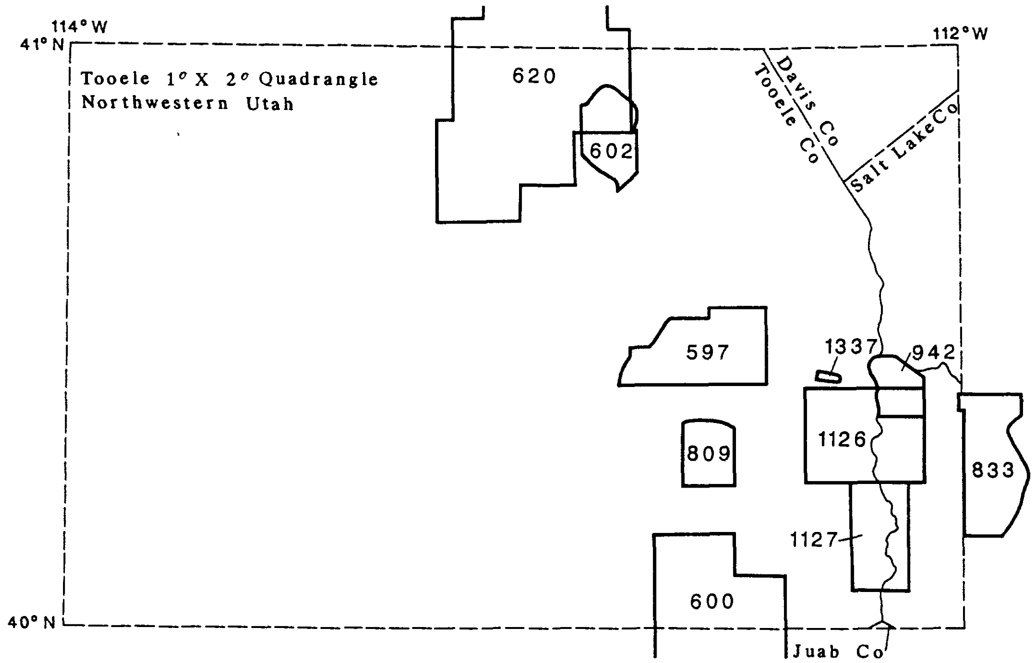


Figure 8. Geologic map index for the Tooele 1° X 2° quadrangle, scales 1:30,000 to 1:40,000. Index numbers and associated references are listed in table 1. Data from Utah Geological and Mineral Survey.

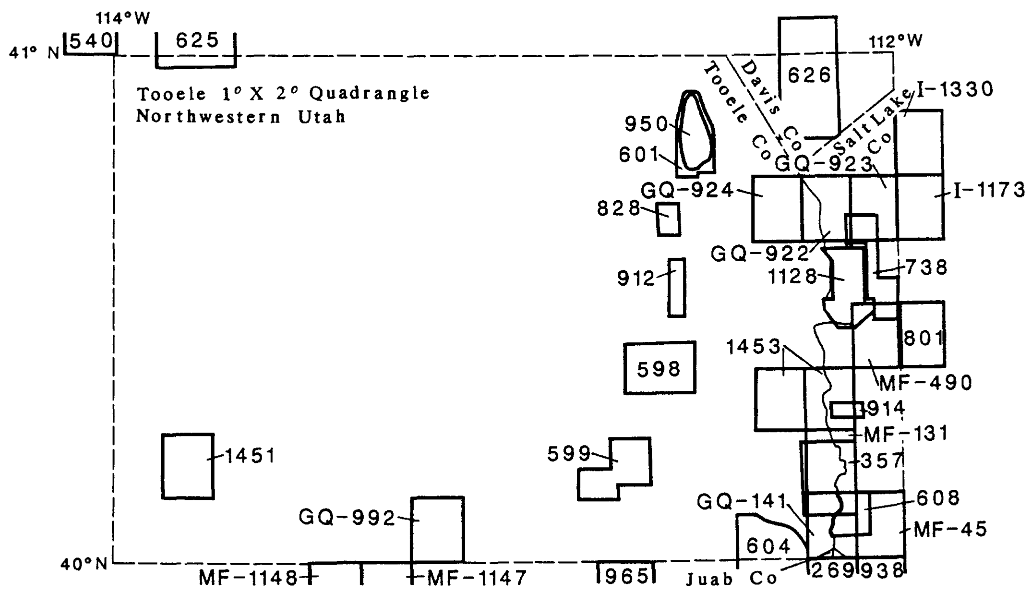


Figure 9. Geologic map index for the Tooele 1° X 2° quadrangle, scales 1:20,000 to 1:30,000. U.S. Geological Survey MF, I, and GQ series maps are identified. Index numbers and associated references are listed in table 1. Data from Utah Geological and Mineral Survey.

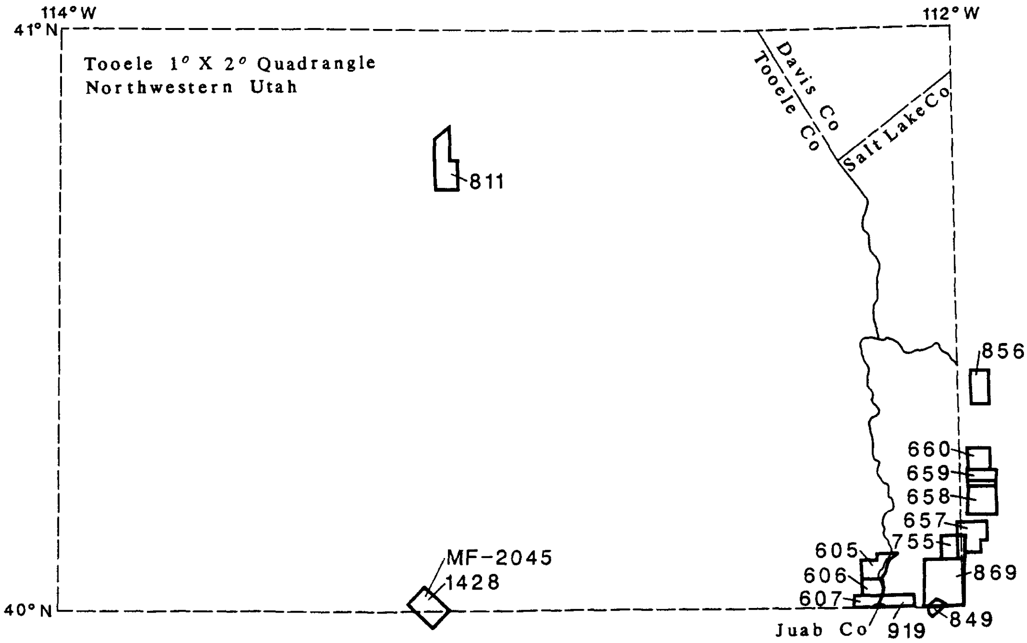


Figure 10. Geologic map index for the Tooele 1° X 2° quadrangle, scales 1:1 to 1:20,000. U.S. Geological Survey MF, I, and GQ series maps are identified. Index numbers and associated references are listed in table 1. Data from Utah Geological and Mineral Survey.

Listing of U.S. Geological Survey Map References:
Tooele 1^{o} X 2^{o} Quadrangle and Areas Immediately Adjacent

The following is a list of maps published by the U.S. Geological Survey pertaining to the Tooele 1^{o} X 2^{o} quadrangle and immediately adjacent areas. The list also contains some USGS maps not shown on figures 8 through 12; these maps are apparently missing from the UGMS geologic mapping data base. Update and revision of the UGMS geologic mapping data base is a CUSMAP level task to be undertaken jointly by the UGMS and USGS. Listings in this map reference compilation which are within the bounds of the Tooele 1^{o} X 2^{o} quadrangle are repeated in the master reference list near the end of this preassessment report.

++

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Disbrow, A.E., 1961, Geology of the Boulter Peak Quadrangle, Utah: U.S. Geological Survey Map GQ-141, 1:24,000

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Mabey, D.R., Crittenden, M.D., Jr., Morris, H.T., Roberts, R.J., and Tooker, E.W., 1964, Aeromagnetic and Generalized Geologic Map of Part of North-Central Utah: U.S. Geological Survey Map GP-422, 1:250,000.

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Moore, W.J., and Sorensen, M.L., 1979, Geologic Map of the Tooele 1^{o} by 2^{o} Quadrangle, Utah: U.S. Geological Survey Map I-1132, 1:250,000.

Moore, W.J., Sorensen, M.L., and Armin, R.A., 1978, Reconnaissance Geologic Map of Onaqui Mountains South Quadrangle, Tooele County, Utah: U.S. Geological Survey Map MF-921, 1:48,000.

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Staatz, M.H., 1972, Geologic Map of the Dugway Proving Ground SW Quadrangle, Tooele County, Utah: U.S. Geological Survey Map GQ-992, 1:24,000.

Sorensen, M.L., 1982, Geologic Map of the Stansbury Roadless Areas, Tooele County, Utah: U.S. Geological Survey Map MF-1353-A, 1:62,500.

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Tooker, E.W., and Roberts, R.J., 1971, Geologic Map of the Magna Quadrangle, Salt Lake County, Utah: U.S. Geological Survey Map GQ-923, 1:24,000.

Tooker, E.W., and Roberts, R.J., 1971, Geologic Map of the Mills Junction Quadrangle, Tooele County, Utah: U.S. Geological Survey Map GQ-924, 1:24,000.

Van Horn, Richard, 1979, Surficial geologic map of the Salt Lake City South quadrangle, Salt Lake City, Utah: U.S. Geological Survey Map I-1173, 1:24,000

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CURRENT STATUS OF MAJOR MINING DISTRICTS

by

Holly J. Stein

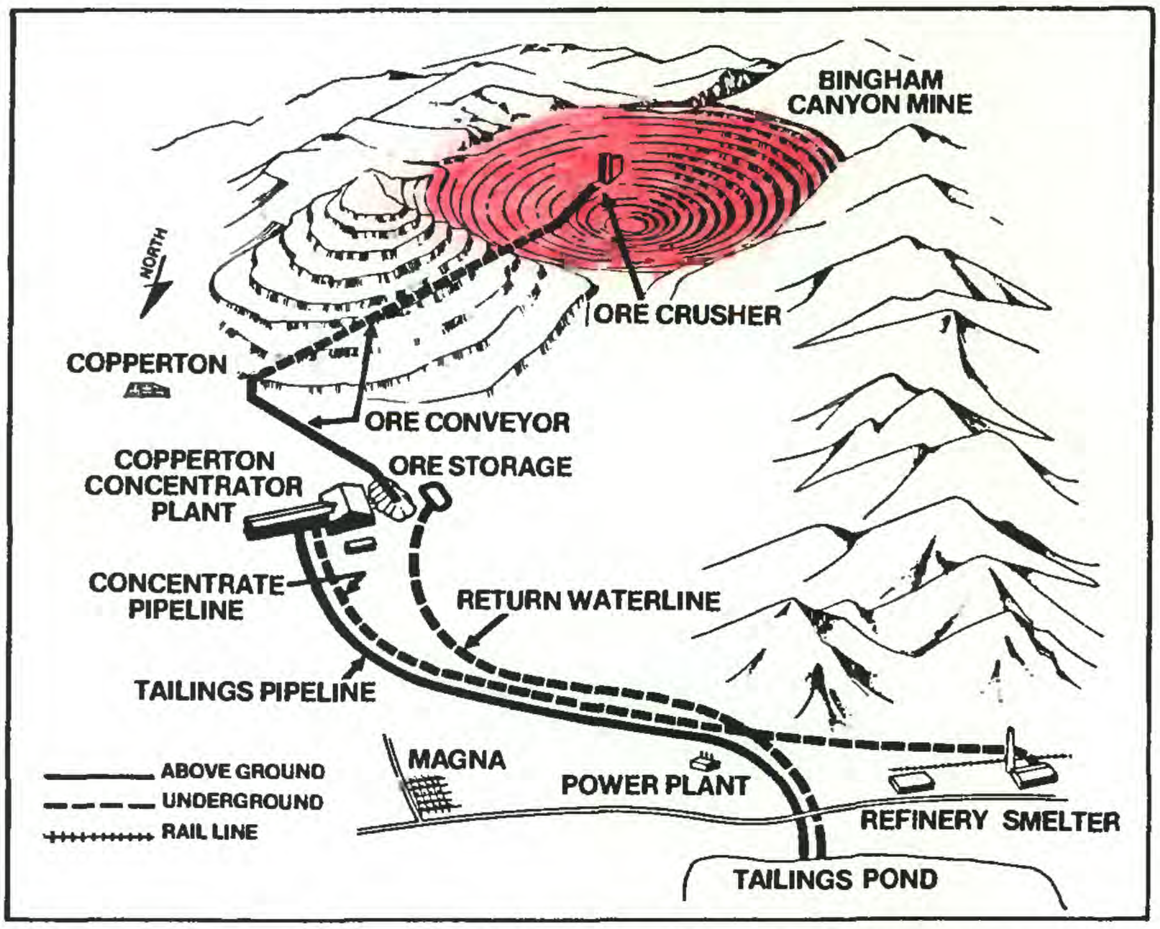
A discussion of major mining districts, their production history, reserves, and present state-of-affairs is an important part of a mineral preassessment document. Although the Tooele 1^{o} X 2^{o} quadrangle contains numerous small mining camps which sporadically produced ore in the last century, we note two major mining districts, Bingham and Mercur, which have been major ore producers. The surface geology at these two districts is distinct. However, these and other smaller districts may represent different structural levels of similar, porphyry-related hydrothermal systems. In fact, most ore deposits in the Tooele quadrangle could be described using variations on a "porphyry model". Refinement of the more general "porphyry model" using the ore deposits in the Tooele quadrangle is a topic worthy of study at the CUSMAP level. Associated, major subdistricts include Carr Fork and Barney's Canyon at Bingham, and Ophir and Stockton (Rush Valley) in the vicinity of Mercur. Spatial and geologic similarities between districts, subdistricts, and smaller mining camps may be ascertained by comparing figure 1, which shows major mineral districts, with plate 1, which shows mine locations and geology.

Though total ore production does not justify classification as a major district, the Gold Hill area (Clifton District) is geologically important. Recently, the Gold Hill area has been the site of exploration for a new type of mineral deposit, gold skarns. The ore and gangue mineralogy and the age of plutonism are distinctly different from the major deposits in the Oquirrh Mountains. Though some Tertiary intrusions are present at Gold Hill, much of the mineralization is peripheral to larger Jurassic plutons which produced extensive skarn assemblages and copper tactite in host carbonate rocks. Replacement and vein-type ore bodies in this contact metamorphic zone host the Gold Hill area ores. The region has received very little attention since about 1925, although some tungsten mining continued until about 1945. Because the Gold Hill area constitutes a geologically and geographically distinct district of intriguing mineral potential, it has been emphasized somewhat more than other similar size districts in this report. We recommend that this area be given much attention in a CUSMAP study.

The following three sections briefly summarize the history and present day mining activity at Bingham, Mercur, and Gold Hill in the Tooele quadrangle.

Bingham

The famous Bingham mining district is located at the southern end of the Oquirrh Mountains (pl. 1), forming a prominent open pit which can be readily observed from Salt Lake City located 40 km to the east. The Bingham pit is the largest mining excavation made by man and measures 0.5 miles deep and 2.5 miles in diameter. The Bingham mine is owned by BP Minerals America (a subsidiary of BP America, Inc., formerly Standard Oil Company of Ohio), which was formed in September 1987 by combining the assets of Kennecott Corporation headquartered in Salt Lake City with Amselco Minerals, Incorporated in Denver. BP Minerals America is completing a $400 million modernization program (fig. 11), begun by Kennecott's Utah Copper Division (UCD) in 1985, to



Schematic diagram showing the main features of the modernization project.

Figure 11. The $400 million modernization at the Bingham copper deposit. Major changes include an in-pit crusher, a new conveyer system, new grinding and concentrating facilities, and new pipelines for transporting concentrates, tailings, and return water (diagram from Mining Magazine, November 1987, p. 408, article by A. Kennedy).

replace old equipment with state-of-the-art facilities and to streamline production processes. The program was scheduled for completion in late 1988.

The Bingham district was discovered in 1863 by a party of picnickers who picked up pieces of oxidized lead-silver ore. Shortly afterwards, mining activity commenced with the processing of lead, silver, and gold ores in limestone beds surrounding the altered Bingham stock. Early miners did not know the importance of the yellow and red stained Bingham porphyry stock and it was not until the turn of the century that the value of the low-grade copper sulfide ore in the Bingham stock was realized. Daniel C. Jackling, an American mining engineer, fought criticism and laughter when he first suggested that one could mine low-grade ore at a profit if large quantities of rock were processed. Jackling formed the Utah Copper Company in 1903 and began work on a large mill which would process 5,000 tons of rock per day. In 1907, Jackling's company bought out Boston Consolidated Mining Company, which owned adjoining properties, and the Utah Copper Company began production, reaping large profits. In the first 25 years, Jackling's company produced 4 billion pounds of copper and paid more than $200 million in dividends from what became known as the lowest-cost copper mine in America. In 1936, the Bingham property was acquired by Kennecott and became the backbone of its Utah Copper Division (UCD). Twelve million tons of copper has been produced from Bingham Canyon, more than any other mine in history. Substantial gold, silver, and molybdenum has also been mined. In 1984, Bingham ranked second nationally in copper production, fourth in gold, ninth in silver, and fifth in molybdenum. Kennecott, the long-time leader in copper production, fell behind Phelps Dodge in 1984, ranking the company second. This was largely the result of copper production cut-backs by UCD, preceding its closure in March 1985. In Spring 1985, a world-wide depressed copper market and rising costs associated with out-dated mining techniques, haulage systems, and milling and concentrating facilities at Bingham forced the closure of the mine. A few months later, a $400 million modernization project was announced by the then owner, SOHIO. Mining operations resumed in July 1987, after a 2-year shut-down while modernization was underway.

The UCD modernization project, nearing completion, consists of four major changes at the Bingham mine (fig. 11):

(1) Crushing facilities <u>in</u> the Bingham pit
(2) A five-mile belt conveyer system to transport ore from the mine to the grinding plant (replacing the old railroad network)
(3) New grinding and flotation facilities closer to the mine (at Copperton)
(4) Three new pipelines for transporting concentrates, tailings, and return water

These new facilities replace obsolete equipment and will eliminate double handling of ore, giving greater efficiency and lower production costs. After completion of the $400 million modernization project, the UCD staff will slim to about 1800 employees (compared to 6,700 workers in 1981 when refined copper production totaled 200,000 tons). The Bingham mine has a 30-year life expectancy and the modernization is expected to save $85 million per year in overall operating costs.

The Bingham district also includes the Carr Fork mine, purchased by Kennecott from Atlantic Richfield's Anaconda Minerals Company in 1984, and the newly discovered North Ore Shoot and Barney's Canyon deposit, located beneath the open pit and extending 6 km northwestward beyond the pit ore body. The Carr Fork property contains significant ore reserves in a copper skarn setting at 2000 to 6000' depth. Anaconda's $230 million development of the Carr Fork Mine, acquired in 1948 and brought into production in 1979, was plagued by mishap and disaster, earning it the nickname of "Hard-Luck Carr Fork". In May 1980 a hoisting accident sent a loaded skip crashing to the bottom of the main production shaft, sling-shotting an empty counterweight skip through the headframe. In 1984 the mine, which had been closed for "technical problems" in November 1981 and was functioning only in a maintenance and pumping mode, was buried in a million ton mudslide which claimed the life of one man. The transfer of the Carr Fork property to Kennecott for a bargain price ended Anaconda's bad luck at Carr Fork and eliminated boundary problems associated with the deep skarn ore body. The Barney's Canyon deposit or North Ore Shoot is presumably an extension of the Carr Fork ore body. Exploratory drilling at the Barney's Canyon deposit is nearing completion and production is scheduled to commence in 1989. Barney's Canyon is predominantly a gold discovery.

Mercur

The Mercur district is located at the southern end of the Oquirrh Mountains (pl. 1). The district was organized in 1870 when silver was discovered as prospectors moved south from the nearby Ophir district. Initially, gold was not realized because all the gold at Mercur is micron size. In 1879 a Bavarian immigrant found gold in assays of mercury ore (cinnabar) and the district and mining town received the name of Mercur -- the German word for cinnabar. However, the micron size of the gold made it very difficult to extract using conventional mining methods at that time. By 1892 the McArthur-Forrest cyanide leaching technique had been refined, and Mercur became was the first mine in the United States to employ the new cyanide leaching method. Although in 1913 grade became poorer, forcing the closure of the Mercur mine, the district had already produced 1.2 million troy ounces of gold. Operations were resumed by Snyder Mining Company for a short time in 1932 with an increase from about $20.60/oz to $35.00/oz in the price of gold. However, this revival was short-lived and in 1942 Mercur again became a ghost town, the result of World War II and the Federal Gold Mine Closure Act. In 1973, nearly four decades later, Getty Oil Company optioned the Mercur property from its owner, Gold Standard Company, and in March 1982, Getty began work on a $90 million open pit mine and mill operation. By 1983 Getty had drilled over 1200 holes in Mercur and the first gold bar was produced. Production continued at an annual rate of 80,000 ounces of gold per year. In 1984 Texaco purchased Getty Oil Company. With the Kennecott Utah Copper Division shut-down in 1985 (Bingham and Tintic districts), Mercur became the largest producer of gold in Utah and one of the largest producers in western United States. Texaco was interested in selling the Mercur mine because the mine did not fit into its long term business strategy and in 1985 the Mercur property was purchased by its current operator, American Barrick Resources Corporation based in Toronto, Ontario, Canada. Barrick is a major and very successful producer of gold in North America. American Barrick Resources has transformed the Mercur mine into an ultra-modern operation whose mill and stockpiles consume 46,000 tons of rock per day at a waste to ore ratio of 3.5. The Mercur district produces 109,000 ounces of gold annually using both a cyanide leaching and pressure oxidation (autoclaving) technique for gold extraction. Assuming continuation of present mining techniques and preservation of today's economic conditions, the Mercur mine has an expected lifetime of about 14 years.

Gold Hill (Clifton)

The Gold Hill area, or Clifton district as it is less frequently called, is located at the northern end of the Deep Creek Mountains in the southwest corner of the Tooele 1° X 2° quadrangle (pl. 1). The district was discovered in 1858. The total value of mineral production from gold, silver, copper, lead, zinc, tungsten, arsenic, and bismuth ores is estimated at $6,800,000. Minor amounts of antimony, vanadium, tin, molybdenum, and mercury occur in some of the ores. During the period 1871 to 1906, a small amount of production is recorded from two small smelters, one at Gold Hill, and one at Clifton, 6 miles to the south. In 1906 the Western Utah Copper Company was formed and from 1906 to 1925 the company developed the Gold Hill properties, producing relatively large tonnages of ore. In 1923 and 1924 arsenopyrite was discovered in several ore bodies, and large tonnages of arsenic ore were shipped until the collapse of the arsenic market in 1925. During World War II arsenic ore, averaging 15.2 percent As, was again mined prior to abandonment of the district. The district is also known for its tungsten production from high-grade scheelite ore discovered on several properties in 1914. However, the collapse of the tungsten market at the end of 1918 forced cessation of underground mining operations. Only a small amount of tungsten mining continued during the period 1918 to 1937 with most of the production coming from properties owned by Star Dust Mines, Incorporated. About 9000 units of WO_3 from high-grade tungsten ore (some with an average assay value greater than 2 percent WO_3) was produced in the Gold Hill district from about 1937 to 1945. During World War II, dumps from some of the earlier mined tungsten deposits were reworked.

In addition to arsenic and tungsten, the district is known for its high-grade, spectacular, coarse-grained native gold. Some of the gold ore had assay values from 2 to 24 ounces per ton. These high-grade gold assays and the recent realization of skarn-related gold deposits have created renewed interest in the Gold Hill district. At present, numerous mining companies are actively exploring in the Gold Hill area.

Recent Mining Activity References

The following list, chronologically compiled, gives a quick history of recent happenings in two long established, major mining districts (Bingham and Mercur) in the Tooele 1° X 2° quadrangle, northwestern Utah. Many of the listed articles are from <u>Pay Dirt</u>, a monthly publication bearing news of mining activities and developments in western United States. Other more internationally oriented mining journals occasionally feature articles on western Utah mines. The historical information on Gold Hill was taken largely from the single article by Wilson (1959), as the district has been inactive in recent years.

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STATUS OF GEOPHYSICAL DATA BASE

by

Viki Bankey and David L. Campbell

Using Geophysics to Detect Mineral Occurrences

Gravity Anomalies

Gravity stations often are too sparsely scattered to define or locate small mineral deposits. Furthermore, density variations in a hydrothermal system are not large and the geologic setting is often complex. A detailed gravity survey can fail to detect dense mineralized rock that may be surrounded by leached, oxidized, or fractured rock of abnormally low density, a combination resulting in little net gravity expression. On a regional scale, however, gravity can be a useful mapping tool for pinpointing structural breaks and folds and for delineating shallow buried pediments. The gravity map of the Tooele quadrangle (pl. 2) shows typical Basin and Range structure of the eastern Great Basin as well as several interesting new features in desert areas that have no outcrops.

Magnetic Anomalies

Aeromagnetic data can be used to locate and estimate depths to igneous intrusions that may be related to possible mineral deposits. Magnetic highs are associated with almost all known intrusions in west-central Utah (the magnetic anomaly at Bingham Canyon is an example). Especially intense magnetic lows may indicate intrusions emplaced and solidified during a period of magnetic field reversal, but these lows are rare because the direction of magnetization of most intrusive rocks in Utah has "decayed" over time to approach and align with the present day Earth's magnetic field. Rings of magnetic highs with central or reentrant lows may indicate porphyry systems in which hydrothermal alteration has destroyed preexisting magnetic minerals. Local magnetic highs may exist where hydrothermal alteration has created secondary magnetic minerals, for example, in a magnetite-bearing skarn.

In general, magnetic anomaly shape and intensity can be used to estimate the shape and depth to the magnetic source. Magnetic anomalies can also suggest possible lithologies of the source and sometimes its general geologic age. Grauch and others (1988a, 1988b) relate magnetization strength of granitic plutons in Nevada to geologic age as follows:

- Precambrian plutons are magnetic.
- Triassic and Jurassic plutons are weakly magnetic.
- Cretaceous plutons are generally magnetic.
- Undifferentiated Mesozoic and Tertiary plutons are variable; neither magnetic nor weakly magnetic rocks predominate.
- Undifferentiated Tertiary to Mesozoic plutons are generally weakly magnetic.

The results and methods used in this Nevada study may also be applied to the Tooele quadrangle in Utah.

Many known mineral deposits have no aeromagnetic expression--Mercur is one example--suggesting that a lack of magnetic expression does not necessarily downgrade a terrane otherwise deemed favorable for the formation of mineral deposits. Deposit types with no associated magnetite or pyrrhotite are not expected to be magnetic. Deposits may be severed from their more magnetic roots by subsequent thrust faults (Calvin Moss, USGS, written communication). Still other deposits may have lost their early-stage magnetite during subsequent hydrothermal alteration.

All magnetic bodies become secondary magnets in the Earth's magnetic field and may produce polarity effects; in Utah these typically show up as local lows along the northern edge of a magnetic high. Sometimes the polarity lows are too diffuse to be seen or are obscured by the fields of other nearby magnetic bodies. Their presence generally complicates the interpretation of primary magnetic anomalies. Using the Fourier transform method and a computer program by Hildenbrand (1983), the magnetic anomaly data were mathematically reduced to the pole in order to eliminate polarity lows and center all anomalies over their magnetic sources. In this reduction process, we have assumed that remanent magnetization direction in the source rocks is the same as the present day magnetic field direction, a condition that is often, but by no means always, true. The magnetic data, reduced to the pole, are shown in plate 3.

Electrical Anomalies

Several different kinds of geoelectric studies are available depending on whether the object is to characterize regional geologic setting or define local targets like mineral deposits. Magnetotelluric (MT) soundings detect electrically anomalous structures to tens of kilometers depth and are used to define or refine the geologic characteristics of terranes on a regional scale. Audiomagnetotelluric (AMT) soundings can resolve features to a depth of several kilometers and are used both for regional characterizations and for resolving more local features. Vertical electrical soundings (VES), also called d.c. soundings, give results similar to AMT. VES are especially good at delineating layers of high electrical resistivity, and AMT at delineating low resistivity layers. MT, AMT, and VES yield information on the electrical conductivity or resistivity of units at depth and suggest the presence or absence of conductive materials (such as saturated sedimentary rocks, altered zones, black shales, or magmas) or resistant materials (such as intrusive bodies, compacted sedimentary rocks, or metamorphic complexes). Ongoing work in the Delta quadrangle to the south, however, demonstrates that many pediment rocks initially expected to be relatively resistant are conductive, presumably the result of chloritization produced by the changing ground water levels of Lake Bonneville. In the Delta quadrangle, Tertiary plutonic rocks are resistant. Pediment surfaces and Tertiary plutonic rocks may have a similar electrical signature in the adjacent Tooele quadrangle.

Many specific electrical methods have been developed to map probable extents of local mineralized areas by targeting conductive and polarizable minerals of interest such as metallic sulfides. The induced polarization (IP) method can detect a pyrite halo (phyllic alteration zone) associated with a large porphyry copper system to depths of 2,000 ft (Calvin Moss, USGS, written communication). A decrease in resistivity is common across the inner zones of porphyry-related alteration. If sulfides are present within a few hundred feet of the surface, an electromagnetic (EM) anomaly may be detected using special airborne or ground-based equipment.

Radiometric anomalies

Near-surface measurements and ratios of the radioactive elements uranium, thorium, and potassium can be used to help locate felsic igneous rocks, such as granites and rhyolites, and certain sedimentary rocks, such as uraniferous black shales or immature sandstones and arkosic rocks (pl. 4,5,6,7, and 8). In addition, changes in the ratio of thorium to uranium, occurring naturally at 4:1, can be used to locate areas of groundwater leaching, high-grade metamorphism, or hydrothermal alteration. This ratio is important because uranium may be mobilized under conditions of high water/rock ratios, whereas thorium does not migrate easily. Therefore, a Th/U ratio greater than 4:1 most likely implies uranium depletion, and a Th/U ratio less than 4:1 implies uranium enrichment (pl. 8).

Gravity Anomaly Map and Interpretation

A review of previous gravity surveys in the Tooele 1^{o} X 2^{o} quadrangle was conducted to help assess the mineral resource potential, to correlate known geology and structure with gravity anomalies, and to target areas needing further study. The complete-Bouguer gravity anomaly map (pl. 2) contains edited data from 2,996 stations selected from available gravity stations used to make the Utah State Bouguer gravity anomaly map (Cook and others, in press). Figure 12 shows areas for which reports that include both maps and interpretations of gravity anomalies are published. Plate 2 includes an overlay which shows major structures discussed in these reports and additional structures noted during the course of this study.

Plate 2 is a color contour map of gravity anomalies. Warm colors correspond to positive gravity anomalies (highs), and cool colors correspond to negative gravity anomalies (lows). Gravity station locations are shown by the symbol "x". The horizontal gradient of the gravity field was calculated using the method of Cordell and Grauch (1985), and maximum gradient trends are plotted with long dashed lines. These linear or sinuous patterns of maximum gradients often follow geologic boundaries resulting from a measurable density contrast such as a lithologic contact, facies change, or juxaposition of two contrasting units by a fault. The method best reflects the surface projection of vertical boundaries between shallow units; dipping boundaries will be offset from the maximum gradient (Blakely and Simpson, 1986). These inaccuracies are minimized at regional scales (Grauch and Cordell, 1987; Grauch and others, 1988a, 1988b).

Gravity Anomalies and Interpretation

Basin and Range structures are the dominant feature on plate 2, and the gravity data for the Tooele quadrangle clearly delineate many horsts and grabens. Gravity data have been previously used to map these structures (Johnson and Cook, 1957; Cook and Berg, 1961; Cook and others, 1964; Cook and others, 1980; Budding and others, 1984; and Baer and Benson, 1987) as shown in figure 12. These gravity data show buried fault traces, basin centers, and shallow pediment blocks. The relatively large density contrast between Quaternary basin or valley sediments and older rocks makes gravity data particularly useful for regional structural mapping in the Tooele quadrangle.

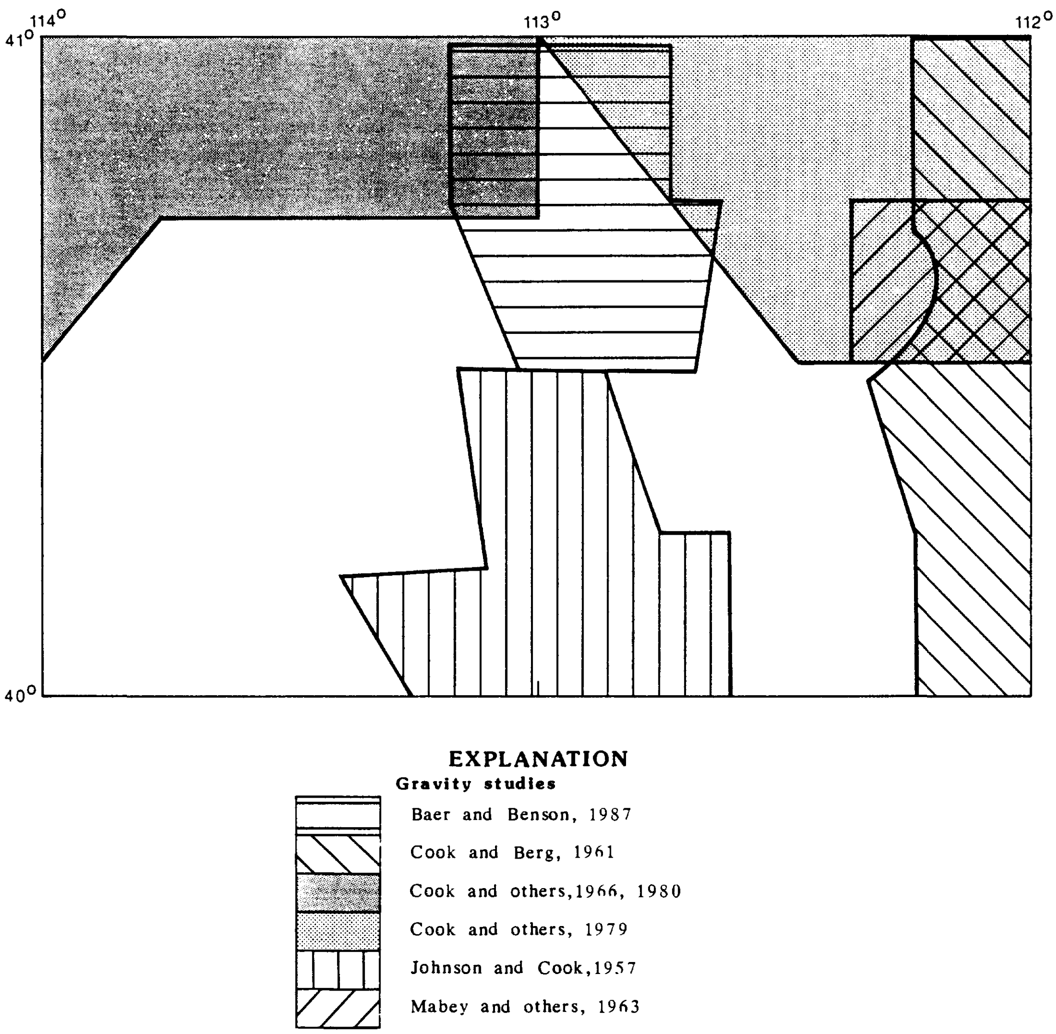


Figure 12. Gravity surveys covering the Tooele 1° X 2° quadrangle.

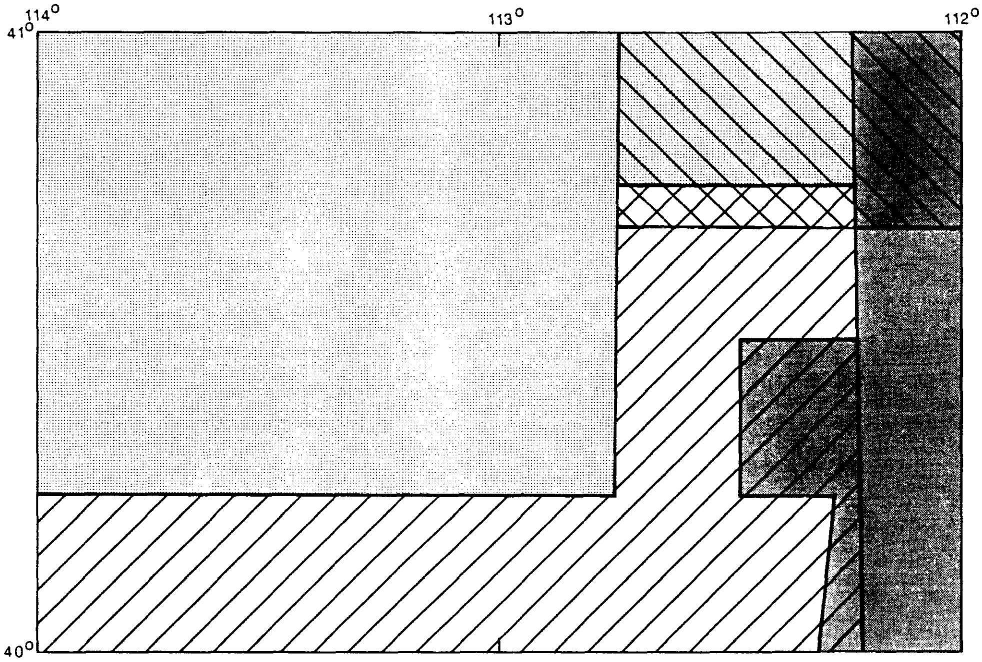
Gravity anomalies also can indicate shallow buried extentions of outcrops, such as the gravity highs associated with Floating Island, and areas southeast of Granite Peak, east of Antelope Island, east of Gold Hill, east of Lookout Pass, west of Tooele, and north of the Skull Valley Indian Reservation (pl. 2).

A striking feature on the Tooele quadrangle is the broad gravity high in the Great Salt Lake Desert south of I-80 (U.S. 40 and U.S. 50 alt.). This feature contradicts the typical gravity low generally associated with basin fill. Although gravity stations in the Great Salt Lake Desert are sparse, enough control exists to suggest that this gravity high reflects a real geologic feature. The report of Whelan and Petersen (1974) contains a drill hole log for Shell Salduro #1 well which describes basic igneous rocks at a depth of 2,830 ft. This well lies on the northwest flank of the large gravity high (pl. 2). We have postulated that this gravity high reflects a subsurface Precambrian highland that includes Stansbury Island, the Lakeside Mountains, Silver Island Mountains, and Granite Peak, as labeled on the overlay of plate 2. Alternatively, this gravity high could reflect a tipped block with two different components: Precambrian rocks may underlie the area of the Great Salt Lake Desert magnetic terrane (described later in the section on aeromagnetic anomalies) and Paleozoic rocks may underlie the non-magnetic area to the northeast. The relationship between the highland and the basic igneous intrusion should be explored with more gravity and aeromagnetic data. Preliminary gravity profiles from the southwestern part of the Desert (Budding and others, 1984) show buried leucocratic granite extending away from Granite Mountain, but they do not model the gravity high to the northwest.

Baer and Benson (1987) conducted a gravity survey in Skull and Ripple Valleys and vicinity in conjunction with geological studies made to select a Utah site for the superconducting super collider. Approximately half of the gravity data from their survey is included in plate 2. Baer and Benson found significant differences between Skull Valley and Ripple Valley. Skull Valley is asymmetric and filled with 6,000 to 8,000 ft of Tertiary and younger sediments. Ripple Valley contains less sediment fill, on the order of 2,000 to 3,000 ft with some local, shallower areas. Ripple Valley is more complexly faulted than Skull Valley and is characterized by blocks of Oquirrh Formation that are not rooted but are floating on lower-density material.

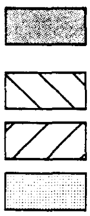
Aeromagnetic Anomaly Map and Interpretation

Figure 13 is a reference map for aeromagnetic surveys in the Tooele quadrangle showing the locations of surveys, flight line spacing and direction, and original flight elevation. Plate 3 is a color-contour map merged using three of these surveys (Mabey and others, 1964; USGS, 1971; and Zietz and others, 1976). These three maps were digitized, gridded, analytically continued to an elevation of 11,000 ft, and adjusted across survey boundaries (by adding or subtracting a constant) prior to final merging. This merged data set was reduced to the pole using Fourier transform (Hildenbrand, 1983).
An airborne survey can detect point sources in a swath on the ground vertically below the aircraft and up to 45 degrees out to each side. Table 2 shows estimates of ground coverage for mountainous terrain, low-lying terrain, and a depth at which 100 percent coverage is expected for each survey. Such coverage is theoretical because anomaly strength diminishes with distance so that deeply buried sources may easily be undetected by the magnetometer.



EXPLANATION

Aeromagnetic surveys



Mabey and others, 1964, 12,000 ft. barometric, 2 mile flight-line spacing, east-west flight-line direction (flown in 1955)

Mikulich and Smith, 1974, 500 ft. above terrain, 5-10 mile flight-line spacing, east-west flight-line direction

USGS, 1971, 9,000 ft. barometric, 1 mile flight-line spacing, north-south flight-line direction

Zietz and others, 1976, 12,000 ft. barometric, 5 mile flight-line spacing, north-south flight-line direction

Figure 13. Aeromagnetic surveys covering the Tooele 1° X 2° quadrangle.

Table 2. Aeromagnetic survey ground coverage.

Survey and date	Elevation	Percent Coverage
Zietz and others (1976)	4,200 ft	59
	7,000 ft	38
	-1,200 ft	100
USGS (1971)	4,200 ft	180
	8,000 ft	38
	6,360 ft	100
Mabey and others (1964)	4,200 ft	147
	9,000 ft	75
	5,280 ft	100
NURE, eastern half (U.S. Department of Energy, 1979)	surface	6
	-7,500 ft below terrain	100
NURE, western half (U.S. Department of Energy, 1979)	surface	3
	-15,000 ft below terrain	100

Note: Minimum elevations are estimates of topographic lows and maximum elevations are estimates of topographic highs from terrain covered by each survey. They are used as surface elevations. Elevations corresponding to 100 percent coverage may be at, above, or below the surface.

Poisson's relation allows a magnetic anomaly to be transformed into the equivalent gravity anomaly ("pseudogravity") that would result if magnetization distribution equals density distribution. The gridded aeromagnetic data were transformed to pseudogravity data, and the horizontal gradient was calculated using the method of Cordell and Grauch (1985). The maximum gradient values (plotted on plate 3 with dashed lines) often follow geologic boundaries associated with magnetic contrasts in the same way that the gravity gradient values follow geologic boundaries associated with density contrasts.

Other aeromagnetic surveys not included in the merged data set but used to augment interpretation include a survey by Mikulich and Smith (1974) and a NURE (National Uranium Resource Evaluation) survey that covers the entire quadrangle (U.S. Department of Energy, 1979). The NURE survey was flown 400 ft above terrain and at 3-mile spacing east of 113° W and 6-mile spacing west of 113° W. The digital data set that is normally available was not released from storage during the period of this preassessment, but a paper copy was available.

An interpretive overlay was made for plate 3 using all available aeromagnetic data and interpretations made by Mabey and others (1964) and Mikulich and

Smith (1974). Anomalies that do not appear on plate 3 but are found on the NURE map are so indicated. Flight line locations from the original maps constrain the interpretive overlay. Anomalies that lie on one flight line but do not extend to adjacent ones are centered on that one flight line.

Silver Island Mountains and Great Salt Lake Desert Magnetic Anomalies

The northwestern survey (Zietz and others, 1976) has the poorest coverage of the three merged surveys comprising the aeromagnetic map with flight line spacing of 5 miles (NURE, U.S. Department of Energy, 1979, has 6-mile spacing in this area). The highs associated with the Silver Island Mountains are too poorly defined to allow correlation with individual rock units. A broad, northwest-trending, magnetically high terrane in this area is outlined on plate 3, and small, low-intensity highs are scattered within this broad terrane. The southwestern margin of the magnetically high terrane correlates with the southwestern margin of the broad gravity high on plate 2, suggesting the presence of a large, deep or broad structural feature. The magnetic terrane does not correlate with the gravity high in the northern part of the quadrangle. High-frequency anomalies that might distinguish Tertiary volcanic rocks from Precambrian basement are not apparent on this map due to poor resolution of the data. Possible sources of magnetic anomalies in this terrane are:

1. **Jurassic or Mesozoic plutons.** Local magnetic highs may reflect cupolas atop a deeper batholith. Development of economically interesting skarn is a possibility.
2. **A local horst of Precambrian(?) basement rock associated with Basin and Range faulting.** Local magnetic highs may reflect heterogeneous basement composition rather than areas of ore formation.
3. **A Precambrian metamorphic core complex, with possible Paleocene or Miocene intrusions.** Precambrian core complexes form in the ductily deformed lower plate that is overlain by a brittly deformed upper plate. The brittle-ductile transition zone presumably associated with a strong thermal gradient could have been the site for a variety of mineralizing solutions.
4. **A graben filled with intermediate to mafic, Oligocene or younger volcanic rocks, either injected as sills at depth or extruded as basalt flows on a pre-graben surface.** Mafic igneous rocks are present at a depth of 2,830 ft in the Shell Salduro Well #1 (pl. 3). Injected volcanic rocks could have provided heat for the formation of 12-14 Ma beryllium deposits at Granite Mountain (Tooele quadrangle) and Spor Mountain (Delta quadrangle to the south.)
5. **Rifting and subsequent injection of basalt dike swarms potentially coalescing as rift fill.** A similar northwest-trending, basalt-filled rift is known to occur in the southern part of the Oregon-Nevada lineament (McKee and Noble, 1986). This explanation, however, offers little potential for ore formation.

Other magnetic highs in the Great Salt Lake Desert occur northeast of the magnetically high terrain. They may reflect shallowly buried, slightly magnetic sources beneath Quaternary alluvium, but poor resolution precludes accurate depth estimates. Because the flight line direction is north-south and widely spaced, the north and south edges of anomalies are better defined than the east and west edges.

Deep Creek Mountains Magnetic Anomalies

The southern survey (USGS, 1971), has 1 mile spacing and shows good magnetic detail, especially in the Gold Hill area of the northern Deep Creek Mountains (pl. 3). A magnetic high is associated with outcropping Jurassic granite. A local high superimposed on this larger anomaly (found on the original 9,000 ft elevation survey) is located east of the Deep Creek Mountains within valley fill and correlates with a gravity anomaly, delineating an eastward extension of the Jurassic granite. Smaller-amplitude magnetic anomalies extend farther east and also to the west into Deep Creek Valley.

Tintic Valley and Skull Valley Magnetic Anomalies

Magnetic highs are coupled with gravity lows at the north end of Tintic Valley (Tooele and Delta quadrangles) and at Skull Valley (Tooele quadrangle). This high magnetic-low gravity signature is relatively unusual. Mabey and Morris (1967) attribute magnetic anomalies in Tintic Valley to thin, deeply buried (3,000-6,000 feet), Tertiary welded tuffs, pyroclastic rocks, and flows beneath non-magnetic, valley-fill sediments. In Skull Valley, a similar broad magnetic high, with a locally shallower anomaly within it, could represent a situation similar to that at Tintic Valley. The Skull Valley magnetic high is not associated with any outcropping rock, but it lies within the proposed Uinta-Gold Hill trend, which is characterized by volcanic rocks and small igneous plugs (Erickson, 1976). A smaller magnetic high just east of Salt Mountain may be caused by Tertiary andesites, dacites, or quartz latite flows cropping out nearby. Another magnetic high in the southern Cedar Mountains is situated over similar Tertiary outcrops; however, only a small proportion of these igneous outcrops have associated magnetic anomalies.

Oquirrh Mountains Magnetic Anomalies

A deep magnetic low at the northern end of the Oquirrh Mountains is not clearly related to a particular rock unit. This low may be caused by a thick carbonate sequence and may also be augmented by an unreduced polarity low from the large magnetic highs associated with Bingham Canyon to the immediate south. Paleomagnetic study of the Bingham stock may be needed to correctly remove the suspected polarity low.

A zone of magnetic highs coincides with a belt of Tertiary intrusive and extrusive rocks from Park City to Stockton. One such anomaly lies over the Last Chance stock which adjoins the Bingham stock. A second, probably deeper, extension of this magnetic high appears to be related to Tertiary intrusions near Stockton. It has been suggested that the Oquirrhs are underlain by a greater volume of intrusive rock than is exposed (Mabey and others, 1964). The Bingham and Stockton highs are aligned along the proposed Park City-Bingham-Gold Hill mineralized belt, which has a similar magnetic signature to the Tintic-Deep Creek mineralized belt in the Delta quadrangle to the south. However, it could be argued that the Park City-Bingham-Gold Hill trend is not as magnetically smooth and continuous as is the Tintic-Deep Creek trend and it may actually be truncated west of the Oquirrhs or west of Skull Valley, and in either case may not extend as far as Gold Hill (pl. 3).

Antelope and Stansbury Island Magnetic Anomalies

Two high-amplitude anomalies at and just east of Antelope Island are caused by magnetic Precambrian Farmington Canyon complex rocks that crop out (Mabey and others, 1964, Hedge and others, 1983). A new aeromagnetic study, flown in 1987 by the USGS for the UGMS, examined these anomalies in greater detail. This aeromagnetic study was undertaken to assist in geologic mapping and assess earthquake hazards for Antelope Island, which has recently become a new Utah State Park.

A large, broad magnetic anomaly occurs over Stansbury Island and suggests a deep intrusive. Preliminary studies by Mikulich and Smith (1974) suggest a magnetic source approximately 12 miles long and 8 miles wide, buried at a depth of 10,500 ft. The southern extension of the anomaly into Tooele Valley may reflect a spur on this large intrusion or a different, shallower source whose magnetic expression is superimposed on the larger anomaly to the north.

Aeroradiometric Anomaly Maps and Interpretation

A gamma-ray radiometric survey of the Tooele quadrangle was flown simultaneously with the aeromagnetic survey as part of the NURE program (U.S. Department of Energy, 1979). These data were collected from an aircraft flying 400 ft above terrain ("draped"), with a flight line-spacing of 3 miles in the eastern half of the quadrangle and 6 miles in the western half. Because an aerial gamma-ray system at 400-ft elevation can detect radiation along a swath 800 ft wide along the flight line, the eastern survey should detect 5 percent of the gamma-ray point sources exposed at the surface, but miss the remaining 95 percent of ground between adjacent lines.

Plates 4, 5, and 6 are respectively the uranium (U), thorium (Th), and potassium (K) black-and-white contour maps of the Tooele quadrangle. These data represent the near surface (less than 50 vertical cm) distribution of the natural radioelements U, Th, and K. The U and Th values are "equivalent" values because of possible disequilibrium in the decay series for those elements.

Plate 7 is a color-composite radioelements map of these three elements, which uses the technique of Duval (1983) to simultaneously depict three parameters using the primary colors red (for U), green (for K), and blue (for Th). This qualitative product shows nuances in radioelement distribution. Combined highs for all three elements are white and combined lows are dark brown. Areas where non-primary colors are dominant indicate mixing of radioelements. Figure 14 is a schematic color additive chart for the U, Th, and K color composite map (pl. 7).

Aeroradiometric Anomalies and Interpretation

Most exposed granites and rhyolites that were overflown showed anomalous values of the three radioelements. Rocks that have high anomalies in all three elements include the Precambrian granite at Antelope Island, Precambrian Granite Peak, the Jurassic granite at Gold Hill, the Triassic rhyolite at the northern tip of the Deep Creek Mountains, the granites at Bingham Canyon and areas west of the canyon, and the tailings ponds near Magna. The Tertiary igneous rocks identified on the geologic map (pl. 1) as T_a were not anomalous

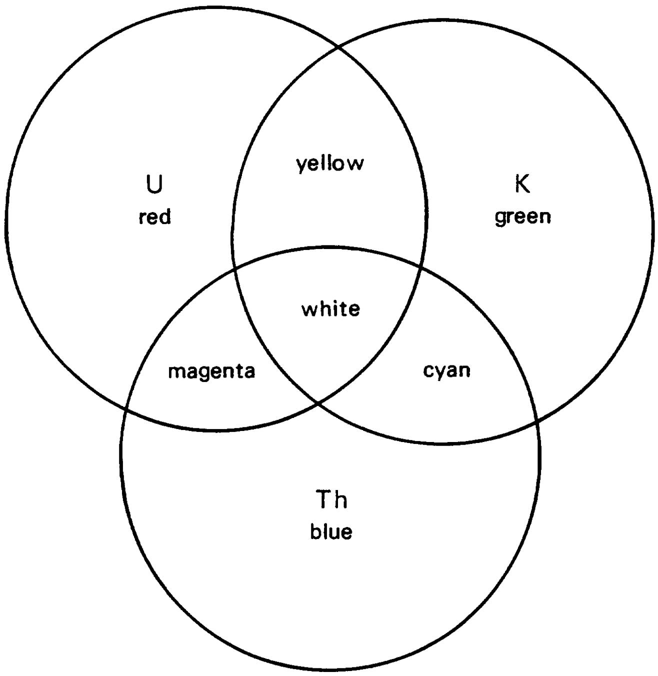


Figure 14. Color composite map color wheel

Other colors on the composite map are generally interpreted as follows:

Thorium (blue):	low values are muddy greens and orange-browns; high values are cyan (bright blue), pinkish, purplish, and white.
Potassium (green):	low values are muddy blues, browns, and orange-browns; high values are blue-green, cyan, yellow, beige or slightly pink, or white.
Uranium (red):	low values are blue, cyan, or blue-green; high values are orange, pink, yellow, or white.

in any of the three elements, except for an outcrop at South Mountain west of the Oquirrh Mountains, which yields high values in all three elements. Many other local anomalies in one, two, or all three elements are also present. Chainman shale, for example, contains anomalous uranium concentrations and appears red on plate 7.

Plate 8 is a generalized Th/U map designed to emphasize regions where the Th/U ratio deviates from 4. Areas shown in red signify that uranium may be locally depleted; areas in blue signify possible uranium enrichment. Either blue or red may indicate areas that have experienced hydrothermal activity. Because ground coverage is so sparse in this survey, this map should be used only to supplement other information.

Other Geophysical Studies

Other published geophysical studies in the Tooele quadrangle include a seismic reflection survey covering the Great Salt Lake (Mikulich and Smith, 1974) and several M.S. theses by students at the University of Oklahoma detailing seismic reflection studies in the area of the Silver Island Mountains and the Great Salt Lake Desert (Murray, 1984; Walters, 1984; Fitter, 1985; Forsyth, 1985; Kim, 1985; Shrestha, 1986; Westerman, 1986; and Banta, 1987). Additional ongoing geophysical studies in Skull Valley by Baer (Professor, Brigham Young University) and students include surface magnetometer measurements, close-order gravity surveys, and resistivity surveys. A telluric current survey was conducted by Anderson (1966) in Skull and Cedar Valleys. Geothermal mapping was carried out southeast of Wendover by the Potash Company and high thermal gradients were discovered showing temperatures that increase towards the Wendover Bombing Range (D.R. Mabey, oral communication). The USGS is conducting ground water studies and test drilling in Tooele Valley, and has made preliminary ground water studies in Rush Valley, Skull Valley, Dugway Valley, Deep Creek Valley, Puddle Valley, the Great Salt Lake Desert, and the Bonneville Salt Flats (Joseph Gates, USGS Salt Lake City, oral communication).

Topical Studies

Geophysics is vital to map the large area with no outcrops and to better understand the Tooele quadrangle and its history of compression and extension. Some important questions that should be considered in the CUSMAP stage of study for the Tooele quadrangle are:
(1) What type of terrane produces the magnetic and gravity highs in the Great Salt Lake Desert? How deeply buried is this terrane? What is the geologic and economic potential for mineral deposits in this terrane?
(2) Is the Park City-Bingham-Gold Hill trend continuous or is Gold Hill a separate feature?
(3) Are the magnetic lows across the southeastern part of the quadrangle and north of Bingham Canyon polarity lows?
(4) What is the magnetic feature beneath the southern end of Skull Valley?
(5) How are the magnetic sources of Antelope and Stansbury Islands connected or related?

Geophysical Survey Recommendations

Gravity Studies

Additional gravity mapping should concentrate on improving the station density in order to more accurately map Basin and Range structure and outline suspected extensions of felsic plutons. Some of the gravity studies might be accomplished jointly with faculty and students from Brigham Young University or the University of Utah. The Utah Geological and Mineral Survey (UGMS) is another possibility for cooperative gravity studies. About 1,500 - 2,000 additional gravity stations are needed, which would require access using truck and helicopter. Special surveying techniques are probably needed in the Great Salt Lake Desert and one option would be to use the Global Positioning System (GPS) to determine location. GPS uses portable equipment to receive satellite signals, and this system is accurate to about 25 meters on the ground with less accuracy in elevation (R.E. Bracken, USGS, oral communication). Although signals are only useable for about 4 hours out of 24, more satellites are being added yearly and this will eventually increase signal reception time. The Office of Mineral Resources does not own a ground receiver; the crew would have to borrow one. Much of the gravity work in the Great Salt Lake Desert and elsewhere in the Tooele quadrangle would have to be coordinated with the military activities at Dugway Proving Ground. The Great Salt Lake Desert might also be considered for an airborne gravity survey, thus eliminating ground navigation difficulties in this extensively flat, featureless terrain.

Major mountain ranges also have few gravity stations at present, making detailed structure impossible to map using gravity data. Helicopter support is a requirement for access in mountainous regions. In particular, the northern Deep Creek Mountains and the Gold Hill area contain a gravity gradient that does not match horst and graben patterns found elsewhere on the Tooele quadrangle. Additional gravity studies are needed in this area.

Aeromagnetic and Radiometric Surveys

Because of poor coverage of the northwestern aeromagnetic survey and the interesting features detected but not yet understood in the Great Salt Lake Desert, this 3,700 sq mi area should be reflown at a spacing of 1 mile. A second, more detailed aeromagnetic survey at 1/4 mi spacing should be flown over the Oquirrh Mountains to search for small, shallow intrusions that could be associated with additional ore deposits in this region. The USGS Branch of Geophysics has the capability to fly this kind of closely-spaced aeromagnetic survey.

Geoelectric Studies

Recent experience in the adjacent Delta quadrangle to the south has shown the great value of magnetotelluric (MT) and audiomagnetotelluric (AMT) soundings in regionally characterizing and determining depth to and extent of plutons, thickness of valley fill, and gross locations of large conducting (altered) zones. Geoelectric studies are valuable to constrain gravity and magnetic interpretations and suggest possible lithologies of buried rocks, local structural setting, and particular areas in need of more detailed studies. In the Delta quadrangle, MT and AMT work have made an impact and contribution to the mineral appraisal of this CUSMAP sheet.

We recommend that MT work be done together with AMT (or Vertical Electrical Soundings (VES) depending on logistic and scheduling considerations) at scattered sites throughout the Tooele quadrangle. Operationally, VES require that several miles of wire be laid on the ground while the measurements are made, whereas AMT equipment can be set up in an area the size of a football field. At least 100 MT and 300 AMT/VES soundings should be made. Subsequently, other Electromagnetic (EM) techniques (such as IP, airborne or ground Slingram, time domain EM, or large-loop EM) may be warranted to follow up on specific targets.

Seismic Studies

Seismic studies are most useful in addressing stratigraphic and structural problems. With the current geophysical data, such questions are unformulated or only dimly perceived. As they come into focus, particularly as gravity and aeromagnetic studies target specific areas, seismic studies may be called for. Some speculation surveys may already be available for purchase, if agreement can be reached with the owners to release the data to the public (often not possible). Reflection seismic surveying must be contracted, but refraction seismic surveys are done in the USGS by the Branch of Seismology, Office of Earthquakes, Volcanoes, and Engineering.

ANALYSIS OF LANDSAT THEMATIC MAPPER DATA

by

David W. Brickey, Melvin H. Podwysocki and Daniel H. Knepper, Jr.

Introduction

Each and every mineral has a characteristic reflectance spectrum that is produced by alteration of incident light as it interacts with a mineral and is subsequently reflected. Specific parts of the reflected electromagnetic (EM) spectrum are recorded by the seven detectors of the Landsat Thematic Mapper (TM), permitting the discrimination of minerals often associated with hydrothermally altered, potentially mineralized rocks (tables 3 and 4). TM data also senses the earth with a relatively fine spatial resolution, represented by a 30 meter square on the ground. The Landsat Multispectral Scanner (MSS) has a more limited usefulness in detecting hydrothermally altered rocks because of its fewer detectors (four) and coarser ground resolution (79 meters). The advantages of TM's greater number of detectors (i.e., spectral channels) and greater spatial resolution is partially offset by the greater volume of data. It requires more computer analysis as well as added digital processing in order to eliminate several ambiguities arising from seasonal vegetation variations.

The quadrangle is covered by two TM data sets taken approximately 13 months apart; the western half of the quadrangle is covered by scene ID 50123-17425 (July 2, 1984), and the eastern part of the quadrangle is covered by scene ID 50532-17375 (August 15, 1985). Several products were created from these digital data sets. A false-color infrared (CIR) composite was created from each of the two scenes for location purposes. These two TM data sets were digitally mosaicked using a set of control points located on the two CIR images to produce one data set geographically co-registered to the standard 1:250,000 map of the Tooele quadrangle. By this means, all subsequent data products generated from the TM data were co-registered to the map.

A color-ratio-composite (CRC) image composed of the band ratios TM3/TM1, TM5/TM4, and TM5/TM7 projected respectively as blue, green, and red, was used to detect areas that might contain hydrothermally altered rocks, potential indicators of mineralization (pl. 9) (Podwysocki and others, 1985). Hydrothermally altered rocks commonly contain an abundance of sheet silicate minerals and/or ferric iron-bearing minerals (Hunt and Ashley, 1979; Hunt, 1981). Band ratio images were used in this study because they tend to subdue differences in slope orientation and aspect, and enhance spectral contrasts that are generally not obvious in standard color composites of the original bands (Rowan and others, 1974).

The TM3/TM1 ratio emphasizes the strong falloff in reflectance that occurs from TM3 to TM1 due to a strong Fe^{+3} electronic absorption band located in the ultraviolet part of the spectrum (spectrum B, fig. 15).

Table 3. Landsat Multispectral Scanner channels, their wavelengths, and spectral features of common natural materials located within the channels

Channel Number	Wavelength in Micrometers	Spectral Features
1	0.50 - 0.60	Chlorophyll reflectance peak; Fe^{+3} absorption band; Fe^{+2} reflectance peak.
2	0.60 - 0.70	Chlorophyll absorption band; Short-wavelength shoulder of Fe^{+3} reflectance peak; Fe^{+2} absorption band.
3	0.70 - 0.80	Long-wavelength shoulder of chlorophyll absorption band; Fe^{+3} reflectance peak.
4	0.80 - 1.10	Vegetation reflectance peak; Fe^{+2} and Fe^{+3} absorption bands.

Table 4. Landsat Thematic Mapper Scanner channels, their wavelengths, and spectral features of common natural materials located within the channels

Channel Number	Wavelength in Micrometers	Spectral Features
1	0.45 - 0.52	Chlorophyll absorption band; Fe^{+2} and Fe^{+3} absorption bands.
2	0.52 - 0.60	Chlorophyll reflectance peak; Fe^{+3} absorption band; Fe^{+2} reflectance peak.
3	0.63 - 0.69	Chlorophyll absorption band; Short-wavelength shoulder of Fe^{+2} reflectance peak; Fe^{+3} absorption band.
4	0.76 - 0.90	Vegetation reflectance peak; Long-wavelength shoulder of Fe^{+3} absorption band; Short-wavelength shoulder of Fe^{+2} absorption band.
5	1.55 - 1.75	Vegetation "water absorption"; Geologic materials commonly at maximum reflectance.
7	2.08 - 2.35	Vegetation "water absorption"; Al-O-H, H-O-H, Mg-O-H, and CO_3^{-2} absorption bands.

Rocks with minerals containing ferric iron oxides, oxyhydrides, and sulfates (these minerals are referred to here collectively as limonite) exhibit this characteristic. The TM3/TM1 ratio will be high for most rocks containing small to moderate amounts of limonite, whereas those rocks lacking limonite will have a lower TM3/TM1 ratio value. Thus, areas on the CRC image with high ratio values will have a blue component, whereas low ratio values will lack blue.

The TM5/TM4 ratio emphasizes the relatively strong falloff in reflectance that occurs from TM5 to TM4 due to a strong Fe^{+3} electronic absorption band in the 0.8 - 0.9 m region (spectrum B, fig. 15). Rocks containing relatively large amounts of ferric iron oxides will have high TM5/TM4 ratios, whereas rocks lacking ferric iron oxides will have low ratios (compare spectra B and A, fig. 15). Because the Fe^{+2} electronic absorption band situated in the 1.0 m region also causes a falloff in reflectance from TM5 to TM4, rocks containing minerals such as chlorites also can be detected with this ratio. Therefore, areas on the CRC image with high ratio values will have a green component, whereas areas with low ratio values will lack green.

The TM5/TM7 ratio emphasizes the falloff in reflectance from TM5 to TM7 due to the presence of the OH^{-1} and CO_3^{-2} radicals. These absorption features are actually overtones and combinations of vibrational absorption bands located at wavelengths greater than 2.5 m. Minerals containing H-O-H, Al-O-H, and Si-O-H will have relatively high TM5/TM7 ratios because their absorption features are centrally located within the bandpass of TM7 (spectra A and B, fig. 15). Given the same relative brightness of rocks, those rocks containing Mg-O-H, and Fe-O-H, and the carbonate minerals, typically will have lower TM5/TM7 ratios because their absorption features lie at the extreme long wavelength edge of the TM7 bandpass. Those rocks lacking these mineral constituents will have lower TM5/TM7 ratios. Thus, areas with rocks containing significant quantities of hydroxyl-bearing minerals (i.e., sheet silicates such as clays and micas, and hydrated sulfates such as gypsum and alunite) will have high ratio values and a red component on the CRC image, whereas areas lacking these minerals will have low ratio values and will lack a red component on the CRC image.

The CRC image is created by projecting each of the three band ratio images through the appropriate filter, creating an additive color image. In this manner, white is formed by the presence of all three primary colors, red, green, and blue, at or near their maximum intensities (fig. 16). Shades of gray are the result of equal amounts of intermediate to low values for all three primary colors. The lack of all three colors produces black. Yellow is produced by equally high intensities of red and green. Table 5 relates the intensities of the three band ratio images to the resultant color and its interpretation in terms of the materials detected in the CRC image.

Unfortunately, other rocks also may display signatures in the TM data similar to hydrothermally altered rocks. Such false anomalies may be caused by supergene weathering of the ferromagnesian minerals, producing both hematite and goethite, and by the presence of large quantities of micas and clays as original mineral constituents in shales, phyllites, schists, and mica-rich igneous rocks. Bright unaltered carbonates also are detected as false anomalies in the TM data. Therefore, field checking MUST be an important component of the work.

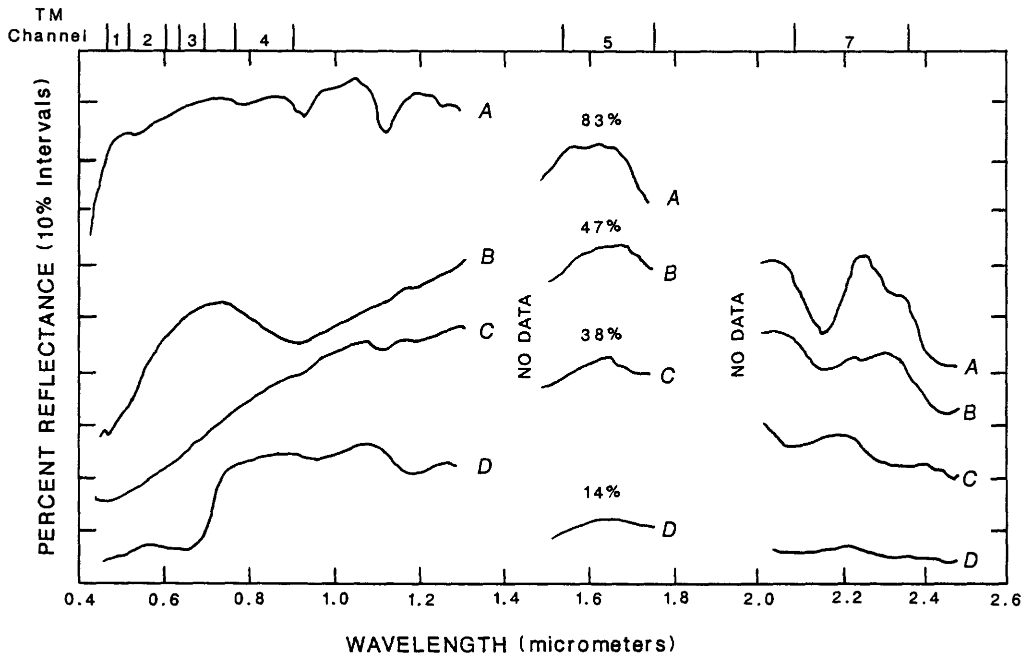


Figure 15. Field spectra of selected natural materials in the visible and near infrared parts of the spectrum. The spectra are vertically stacked with tic-marks along the ordinate representing 10 percent increments of reflectance. Percent values are shown for each material at 1.6 μm for reference purposes. Areas of no data are the result of atmospheric absorption. Explanation: A = nearly pure white alunite; B = volcanic rock altered to jarosite and kaolinite; C = Spectrum of senescent cheat grass (*Bromus tectorum*); D = Spectrum of big sagebrush (*Artemesia tridentata*). Note the relatively sharp absorption features in the 2.1-2.2 μm region due to Al-O-H absorption features in spectra A and B and the lack of sharp features in the same region for spectra C and D. Spectrum D taken from Milton (1978).

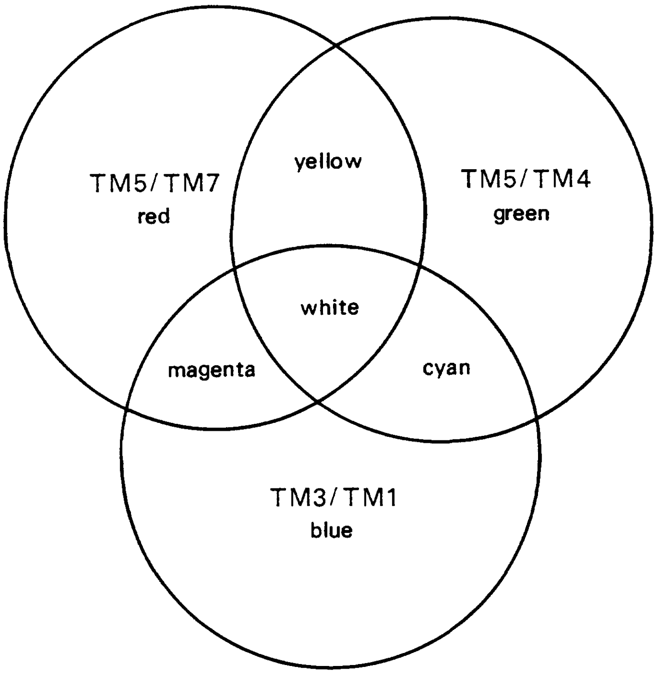


Figure 16. Color additive scheme with TM5/TM7 as red, TM5/TM4 as green, and TM3/TM1 as blue.

Vegetation impedes the identification of hydrothermally altered rocks in several ways. Because the water content of healthy vegetation also causes a falloff in reflectance from TM4 to TM5 to TM7, a cover of approximately 25 percent or more vegetation can mask the spectral signature of an underlying rock (spectra C and D, fig. 15). Although the general shape of the spectral curve of vegetation in the TM7 bandpass does not show the sharp absorption features commonly associated with OH-bearing minerals, the overall lowering of the reflectance in TM7 relative to TM5 due to water content does give a TM5/TM7 ratio similar to that caused by the OH-bearing minerals. High spectral resolution data such as that of an Airborne Imaging Spectrometer would allow the detection of the sharp hydroxyl absorption features of minerals in vegetation cover of up to approximately 50 percent (Brickey and others, 1987).

Healthy vegetation can be distinguished by its very low TM5/TM4 and TM3/TM4 ratios, however, the spectral discrimination of senescent grasses from hydrothermally altered rocks causes additional detection problems. Commonly, the range grasses of this region, such as cheat grass (Bromus tectorum), tend to bloom in the months of April and May. At this time, the grasses display a healthy green color due to chloryphyll absorption, and have a typical spectral response of healthy vegetation. Although spectrum D is that of big sagebrush (Artemesia tridentata), a common basin and range shrub, the falloff in reflectance from 0.8 m to 0.65m also is typical of that shown by range grasses

Table 5. Colors depicted on Landsat Thematic Mapper Color-Ratio-Composite (CRC) and Thematic Classification images (pl. 9 and 10, respectively) and their interpretation.

Thematic Classification Color*	TM5/TM7 Red**	TM5/TM4 Green**	TM3/TM1 Blue**	Resultant Color**	Interpretation
Green	H	H	H	White	Relatively bright rocks with high OH^{-1} or CO_3^{-2} and high Fe^{+3}
Yellow	H	H	L	Yellow	1) Relatively dark rocks containing high OH^{-1} or CO_3^{-2} and high Fe^{+3}; 2) yellow grasses
Magenta	H	L	H	Magenta	Relatively bright rocks containing high OH^{-1} or CO_3^{-2} and weak to moderate Fe^{+3}
Red	H	M	M	Pale Orange to Pale Magenta	Relatively bright rocks containing high OH^{-1} or CO_3^{-2} and moderate Fe^{+3}
Cyan	M	H	H	Pale Cyan	Relatively bright rocks containing weak to moderate OH^{-1} or CO_3^{-2} and moderate to strong Fe^{+3}
	H	L	L	Red	1) Healthy vegetation; 2) water bodies; or 3) strong shadows
	L	L	H	Blue	Bright rocks containing no OH^{-1} or CO_3^{-2} and weak to moderate Fe^{+3}
	L	H	L	Green	1) Rocks covered by desert varnish; 2) dead grasses

H = high; M = medium; and L = low intensity

* Refers to color on Thematic Classification (pl. 10)
** Refers to color on Color-Ratio-Composite (CRC) image (pl. 9)

in their green state. By late June and into July, depending upon the abundance of water in the region, the grasses begin to senesce; they first lose their chloryphyll absorption, which is responsible for the reflectance minima at 0.45m (blue) and 0.65 m (red) and the reflectance peak at 0.55 m (green) (spectrum D, fig. 15); hence they begin to turn yellow (spectrum C, fig. 15). At this time the grasses still have strong water absorption in TM7, and thus have a high TM5/TM7 band ratio. Areas containing these grasses at this stage of senescence appear the same as some of the hydrothermally altered rocks. Only with careful multivariate digital masking can these areas of conflicting signatures be eliminated, a time-intensive task which could not be done for this report. By August, however, in areas with a severe moisture deficit, these grasses tend to lose their moisture, so that the reflectances in TM5 and TM7 rise and are approximately equal; at the same time the grasses become spectrally featureless in the visible part of the spectrum (gray). At this time, they are easily distinguished from hydrothermally altered rocks without the need for extraordinary processing techniques. However, grasses in areas lacking a severe moisture deficit, can still be confused with altered rocks.

As discussed in an earlier section, different types of altered rocks display specific colors on the CRC image (table 5). Because the visual perception of color is often difficult to quantify on an image, the colors of interest were digitally characterized from the CRC image. This was achieved by converting the CRC image from its red, green, and blue color space into a Munsell coordinate system that quantifies colors based on their hue (H - the actual color), saturation (S - the richness of the color) and intensity (I - the brightness of the color), known as an HSI image (Raines, 1977; Gillespie and others, 1987). Areas of known altered rocks within the Tooele quadrangle and the Delta quadrangle to the south, which displayed the characteristic colors of altered rocks listed in table 5, were used to determine the statistics from the HSI image. Because two temporally different TM data sets (July, 1984, and August, 1985) were required to cover the whole Tooele quadrangle, separate statistics were gathered for altered areas from each. To cover the possible range of alteration types, targets were selected from both the Tooele and Delta quadrangles, because both quadrangles are covered by the same TM imagery. The training targets include Bingham Canyon, Mercur, and East Tintic for the eastern data set (August, 1985 image) and Gold Hill, The Dell in the Thomas Range, North Fish Springs, and the Drum Mountains for the western data set (July, 1984 image). The training statistics of HSI values for each half of the Tooele quadrangle were applied only to their respective HSI image data set in a digital classification scheme using a parallelepiped classifier, an unsophisticated but efficient method to extract areas of like colors on a consistent basis. The resultant two thematic classification maps were then merged and co-registered into a single map using the mosaicking procedure developed for the CIR image. The single thematic classification map is shown in plate 10.

Plate 10 shows the results of this first attempt at digital thematic classification. A TM4 black-and-white background image underlies the classification for location purposes. The colored pixels on the thematic classification map indicate areas of interest for different types of potentially hydrothermally altered rocks. The legend for the colors is found in table 5.

Discussion

About 7 to 8 percent of the total area of the Tooele quadrangle was classified. Much of this represents true targets that require field investigation, however, at least half probably are false targets that can be eliminated from further investigation. The areas of prime interest are those colored pixels in bedrock areas located mostly in the mountain ranges. Those pixels located in the surrounding Quaternary alluvium of the valley bottoms, primarily the magenta thematic color class (pl. 10) (magenta on the CRC image, pl. 9) as well as some in the red (pale orange to pale magenta colors on the CRC image, pl. 9) and cyan (cyan on the CRC image, pl. 9) thematic color classes (pl. 10), can be eliminated. The magenta thematic color class (pl. 10) makes up the largest class and contains the most false anomalies. In the valley bottoms the sufficiently abundant ferric iron-bearing minerals as well as the clays that in part make up the soils along with a small but significant shrub cover produce the magenta false anomalies. The red thematic color class (pl. 10) has a similar explanation.

As discussed earlier, cheat grass can produce a yellow signature on the CRC image (pl. 9) akin to that of hydrothermally altered rocks. Typically, it is found on the lower mountain slopes and in the bottoms of canyons. Yellow targets in these areas may be considered suspicious. Only a rigorous digital filtering, which has been tested on imagery for the Delta CUSMAP, can eliminate most of these with any confidence. It should be noted that only those yellow classified pixels for the western (July, 1984) CRC image may show this type of false anomaly.

The magenta and red thematic classes of pixels also indicate map areas that are intimate mixtures of bare unaltered rock and soil as well as vegetation within a single given pixel. An examination of the CRC image (pl. 9) for magenta to orange pixels adjacent to red areas in the middle of mountain ranges suggests this type of false anomaly.

In plate 9, the remaining magenta, orange/magenta (red thematic class, pl. 10), yellow, and cyan pixels as well as the white pixels (green thematic color class, pl. 10) may have a real potential for being indicators of hydrothermally altered rocks. The overlay for plate 10 is an interpretation depicting the important anomalies as determined from the thematic classification map. The same overlay is also located on plate 9. This interpretation discounts many of the false anomalies discussed earlier and considers only those anomalies that cannot easily be regarded as false. Thus, those color themes on the thematic classification map (pl. 10) that are not outlined on the overlay are considered false anomalies and therefore are unimportant. Note, however, that the Great Salt Lake Desert is outlined (a lighter line weight), as is the pan at the north end of Skull Valley. All the magenta anomalies within these bounds are considered false anomalies.

Along the southern margin of the map, Cambrian quartzites (Prospect Mountain Quartzite in the west and Tintic Quartzite in the east) crop out and produce magenta signatures. These are considered false anomalies; evidence from the Delta quadrangle to the south indicates that similar anomalies are related to tan to buff to pinkish quartzites. The quartzites contain some ferric iron-bearing minerals, as well as sericite, which is most likely related to regional metamorphism of illitic clays present in the original quartzites. The sericite often occurs along fracture surfaces.

Most of the cyan anomalies are underlain by Paleozoic carbonates. Many of these are most likely carbonates that produce a moderate TM5/TM7 ratio and have a weathering surface containing ferric iron-bearing minerals, thus producing a strong TM3/TM1 and TM5/TM4 ratio. However, it should be noted that in the Oquirrh Mountains, for example, most of the cyan anomalies overlay carbonates, but do not overlay all their exposures, suggesting some unexplained intraformational differences, or perhaps the juxtaposition of different nappe plates. This requires further investigation. Another interesting cyan anomaly is located at the southern end of the Cedar Mountains. The northwest-southeast elongate part of this large anomaly is underlain by carbonates, but the western appendage of this anomaly is underlain by Tertiary andesites. Of the several exposures of Tertiary andesites in the southern Cedar Mountains, only this particular one has a cyan signature, which suggests a weak alteration pattern in volcanic rocks that might be related to an increased clay mineral concentration. Just to the north, a red color theme anomaly (pl. 10) should be noted. This area is underlain by carbonates and Tertiary andesites and other flows, and suggests a pattern of altered rocks similar to the Fish Springs mining district in the Delta 1^{o} X 2^{o} quadrangle to the south, where this pale orange to magenta thematic signature was first developed.

On the west side of the quadrangle, known areas of altered rocks have been mapped in the Gold Hill District and in the Silver Island Mountains, and other areas have been targeted as possibly containing hydrothermally altered rocks (red and magenta color themes on plate 10). Precambrian granites and gneisses in the south part of Granite Mountain show a magenta anomaly, indicating potentially hydrothermally altered rocks. However, the presence of granite with a high primary mica content also can produce such an anomaly. Antelope Island in the northeast corner of the quadrangle also shows similar magenta anomalies as well as cyan anomalies in its Precambrian rocks. The several small yellow and white anomalies (yellow and green color themes on plate 10) adjacent to the western flank of the Cedar Mountains are in Quaternary alluvium and are probably related to cheat grass. These small anomalies are mentioned because cheat grass normally does not have a white signature; however, it is possible that the "white" anomalies are actually very low saturation and high intensity yellow anomalies.

Additional laboratory refinements of the digital classification, along with field data needed to spectrally characterize the various types of altered rocks as well as the common false anomalies, ought to produce a better classification map free of most false anomalies.

Recommendations

The following paragraphs discuss additional work that would benefit the mineral assessment of the Tooele quadrangle.

In order to get the processed data in the hands of the remainder of the CUSMAP working team for the quadrangle, the remote sensing analysis part of the program should start one year before geologic mapping, detailed potential field and electrical sounding geophysical surveys, geochemical sampling, etc., is started. This adjustment in the usual schedule would allow a large part of the remote sensing that is at a reconnaissance level to be investigated in added detail by the field mappers.

Because of the thematic classification problems related to seasonal differences in vegetation, temporally closely related TM scenes should be examined. Acquisition of an August, 1985 TM scene for the west half of the quadrangle or a July, 1984 scene for the east half of the quadrangle would permit the use of a single consistent classification across the entire quadrangle.

With the advent of airborne imaging spectrometers, such as the Geophysical Environmental Research, Inc. 64 channel scanner, district level studies could be performed that would allow identification of many individual minerals or at least families of minerals.

Airborne Thermal Infrared Multispectral Scanner (TIMS) data is useful for discriminating rocks based on their varying silicate contents and therefore is particularly useful for studying hydrothermal systems and igneous rocks at the district level. It is especially useful for identifying hydrothermal jasperoids and other quartz-rich rocks. Typically, NASA has "piggybacked" user requests so that the high cost of mobilizing the aircraft is not a burden for an individual user.

A structural analysis using TM or other data could be used to study the relationships between various structures, structural styles, and mineralized rocks in the quadrangle. CIR images from TM with their 30 m spatial resolution would be adequate for such a study, however, stereoscopic viewing would most likely yield additional information. The French SPOT satellite has such a capability, and can produce either 20 m CIR or 10 m panchromatic stereo pair images.

In order to achieve a better classification of the TM images, additional computer time would be required. This would require further research for image enhancements, extraction of suitable areas for classification, and added time for the use of more sophisticated classification techniques. Also, spectral analysis of field samples from selected areas are needed to refine the classification. Field work of approximately three person-months for the first three years of the project is required.

STATUS OF GEOCHEMICAL STUDIES

by

David R. Zimbelman

Trace-element data that may be useful for aiding in the evaluation of mineral resource potential in the Tooele two-degree quadrangle, Utah include soil, stream sediment, talus, well water, and stream water samples collected during the NURE Program (National Uranium Resource Evaluation Program) and stream sediment, heavy-mineral concentrate derived from stream sediment, and rock samples collected from the North Stansbury Wilderness Study Area (Foose and others, 1989) and the Stansbury Roadless Area (Sorensen, 1982b; Sorensen and Kness, 1983) by the USGS. The types and numbers of geochemical samples are summarized in table 6.

Much information on the NURE geochemical data is lacking, making it difficult to evaluate in a mineral assessment framework. Sample collection was apparently supervised by persons at the Savannah River Laboratories but chemical analyses were performed at the Oak Ridge Gaseous Diffusion Plant. Documentation of analytical methods apparently does not exist. Because of uncertainties regarding the methods used during the collection and analysis of the water samples, and given the small number of samples collected, these data were not evaluated during this project.

Geochemical samples were collected and analyzed by the USGS from two wilderness study areas. Both of these areas are in the Stansbury Mountains and results from the geochemical portions of these studies are summarized below.

Brief discussions of geochemical data from water, stream sediment, talus, and soil samples collected during the NURE program are presented in the following pages.

Trace Element Geochemistry

NURE Water Samples

Water samples from 35 wells and 38 streams in the Tooele quadrangle were collected during the NURE program. Basic statistics (including: minimum, maximum, mean, and standard deviation of samples within the upper and lower detection limits) for the water samples are presented in tables 7 and 8. Because of the small number of samples collected, the lack of any geochemically important variance in the data sets, and numerous problems concerning sample collection and analysis the water geochemical data from the NURE program have not been evaluated.

NURE Stream Sediment Samples

Twenty-eight stream sediment samples were collected in the Tooele quadrangle during the NURE program. These samples were sieved to less than 149 microns, dried at less than or equal to 110 C, and analyzed by plasma source emission spectrometry. Basic statistics for the NURE stream sediment samples are listed in table 9. The samples have very little geochemical variation, generally the variation for any given element is less than a factor of three and almost always less than one order of magnitude. Only three samples were considered anomalous. These include sample AF003 from the west side of Stansbury Island which contained 2 ppm (parts-per-million) silver, sample DA040 from Deep Creek (Deep Creek Range) which contained 6 ppm molybdenum, and sample CG006 from a short distance east of Stockton which contained 6 ppm silver, 1646 ppm lead, and 777 ppm zinc. The latter two samples are from known mineralized areas and reflect mineralization near the Stockton and Gold Hill areas. However, the sample from the west side of Stansbury Island (AF003) is from an area which is not known to contain any metallic mineral deposits and indicates that further geologic study is this area is warranted.

Table 6. Existing geochemical studies, Tooele 1^{o} X 2^{o} quadrangle, northwestern Utah.

Study	Sample Type	Number of Samples	Analytical Method
Sorensen, 1982	Heavy-mineral Concentrate	29	SQES
Sorensen and Kness, 1983	Rock	125	FA and SPEC
Foose and others, in press	Minus-30 mesh Stream Sediment	21	SQES
	Heavy-mineral Concentrate	21	SQES
	Rock	69	SQES
NURE Samples, data on magnetic tape, USGS, Branch of Geochemistry	Soil	692	PSES
	Stream sediment	28	PSES
	Talus	80	PSES
	Well water	35	*
	Stream water	38	*

NOTE: SQES=Semiquantitative Emission Spectrography
FA=Fire assay
SPEC=Spectrographic (details unknown)
PSES=Plasma Source Emission Spectrometry
*=Analytical method unknown

Univariate Statistics:

Element	Minimum	Maximum	Mean	Deviation	Valid	L
Ag	2.0	4.0	2.8	.9	9	26
Al	29.0	811.0	194.0	195.8	35	0
As	1.0	194.0	14.3	37.2	31	4
B	31	700	203	187	35	0
Ba	27.0	344.0	113.9	69.7	35	0
Be	1.0	1.0	1.0	NA	1	34
Ca	11000	264000	72057	48516	35	0
Co	3.0	6.0	4.2	1.1	8	27
Cr	4.0	8.0	5.6	1.6	6	29
Cu	2.0	42.0	11.1	10.3	34	1
Fe	14	1220	195	267	35	0
K	1000	59000	8857	11847	35	0
Li	10	794	102	145	35	0
Mg	7000	112000	31371	23634	35	0
Mn	2.0	255.0	30.4	47.5	35	0
Mo	4.0	26.0	8.6	5.7	12	23
Na	21000	1476000	300028	377278	35	0
Nb	4.0	23.0	11.8	6.4	12	23
Ni	4.0	25.0	10.5	5.7	20	15
P	41	367	111	103	9	26
Sc	1.0	3.0	1.3	.6	11	24
Sr	250	6277	988	1136	35	0
Th	6.0	6.0	6.0	NA	3	32
Ti	2.0	12.0	4.8	3.1	29	6
V	4.0	11.0	6.1	2.0	15	20
Y	1.0	1.0	1.0	NA	8	27
Zn	8	616	100	130	32	3
Zr	2.0	5.0	3.0	1.1	10	25

Table 7. Basic statistics for well water samples collected during the NURE program, Tooele 1^{o} X 2^{o} quadrangle, northwestern Utah.

L = Less than detection limit
NA = Not applicable
minimum and maximum values in ppm

Univariate Statistics:

Element	Minimum	Maximum	Mean	Deviation	Valid	L
Ag	2.0	3.0	2.3	.4	10	28
Al	12	1829	165	300	38	0
As	1.0	14.0	4.5	3.1	23	15
B	19	1243	159	225	38	0
Ba	21	584	99	92	38	0
Be	1.0	2.0	1.6	.5	3	35
Ca	37000	312000	88342	46906	38	0
Co	2.0	7.0	3.0	1.6	13	25
Cr	4.0	4.0	4.0	NA	2	36
Cu	2.0	29.0	8.8	6.9	33	5
Fe	11	1235	157	272	35	3
K	1000	38000	7162	8744	37	0
Li	4.0	714	75	132	38	0
Mg	10000	204000	37526	39002	38	0
Mn	2	427	39	78	37	1
Mo	12.0	42.0	20.7	14.2	4	34
Na	6000	1965000	224157	405104	38	0
Nb	4.0	19.0	10.0	5.3	13	25
Ni	4.0	125.0	16.9	24.7	23	15
P	40	219	86	51	11	27
Sc	1.0	5.0	1.8	1.4	11	27
Sr	156	4350	848	961	38	0
Th	5.0	5.0	5.0	NA	1	37
Ti	2.0	27.0	5.7	5.4	29	9
V	4.0	9.0	6.1	1.8	11	27
Y	1.0	2.0	1.1	.3	15	23
Zn	4	732	84	153	38	0
Zr	2.0	6.0	3.0	1.1	12	26

Table 8. Basic statistics for <u>stream water</u> samples collected during the NURE program, Tooele 1^o X 2^o quadrangle, northwestern Utah.

L = Less than detection limit
NA = Not applicable
minimum and maximum values in ppm

Univariate Statistics:

Element	Minimum	Maximum	Mean	Deviation	Valid	L
Ag	2.0	6.0	4.0	2.8	2	26
Al	26100	54900	39917	7288	28	0
B	10.0	39.0	23.0	6.3	27	1
Ba	273	1610	508	251	28	0
Be	1.0	2.0	1.2	.4	28	0
Ca	7900	136500	62542	34258	28	0
Co	4.0	7.0	5.2	1.0	23	5
Cr	24.0	54.0	33.6	8.7	28	0
Cu	6.0	43.0	15.0	7.0	28	0
Fe	10400	22800	17450	3260	28	0
Hf	15.0	20.0	17.5	3.5	2	26
K	6500	16700	11550	2419	28	0
La	9.0	36.0	21.5	5.7	28	0
Li	20.0	47.0	30.0	7.4	28	0
Mg	4300	33900	13535	7152	28	0
Mn	196	1235	418	190	28	0
Mo	6.0	6.0	6.0	NA	1	27
Na	2400	10800	5717	1768	28	0
Nb	5.0	16.0	9.5	2.5	27	1
Ni	10.0	29.0	14.7	4.4	28	0
P	359	3209	757	571	28	0
Pb	12	1646	109	372	19	9
Sc	3.0	6.0	4.6	.7	28	0
Sr	147	445	265	76	28	0
Th	4.0	23.0	10.3	5.0	25	3
Ti	1233	2431	1777	323	28	0
V	30.0	65.0	47.4	9.8	28	0
Y	10.0	23.0	12.0	2.5	28	0
Zn	27.0	777.0	82.3	137.0	28	0
Zr	30.0	76.0	49.6	11.7	28	0

Table 9. Basic statistics for stream-sediment samples collected during the NURE program, Tooele 1^{o} X 2^{o} quadrangle, northwestern Utah.

L = Less than detection limit
NA = Not applicable
minimum and maximum values in ppm

Because of the small number of stream sediment samples and the small geochemical variation present in the data from these samples, no further statistical analysis was done on these data.

NURE Talus Samples

Eighty talus samples were collected from the Tooele quadrangle during the NURE program. The samples were probably analyzed by plasma source emission spectrometry. Talus samples were collected from only a few of the mountain ranges in the quadrangle (table 10). The talus samples are the closest thing to a rock sample collected from this quadrangle during the NURE program. Basic statistics for geochemical data generated from talus samples are presented in table 11. Single element distribution maps were made for silver, barium, copper, molybdenum, lead, and zinc. A summary of anomalous occurrences of these six metals in talus samples is presented on plate 11.

Single Element Distributions

Bearing in mind the limitations inherent in the talus data set, plate 11 suggests the following: The highest concentration of samples with elevated barium values is in the Silver Island Mountains whereas moderately and highly elevated barium values also occur in the Deep Creek Range and in the southern part of the Oquirrh Mountains. Elevated molybdenum values generally occur in the northern part of the Oquirrh Mountains, elevated zinc values are generally confined to the Oquirrh and East Tintic Mountains, and elevated lead and copper values generally occur in the Oquirrh and East Tintic Mountains and in the Deep Creek Range.

This limited number of talus samples confirms the presence of known hydrothermally mineralized rock in the East Tintic and Oquirrh Mountains and in the Deep Creek Range, but adds very little knowledge to the mineral resource potential portion of this study.

Discussion

Several factors limit the usefulness of the NURE talus samples in a mineral resource assessment project of the Tooele quadrangle. These factors include the small number of samples that were collected (80) and the limited number of chemical elements analyzed for in each sample. Elements which were not analyzed and which are necessary to fully evaluate mineral resource potential in this quadrangle include the platinum group elements, gold, arsenic, antimony, mercury, tin, and thallium.

NURE Soil Samples

Samples of soil (unconsolidated materials sieved to less than 149 microns) were collected at 692 sites in the Tooele quadrangle. The samples were probably analyzed by plasma source emission spectrometry. These samples were mostly collected from the eastern five-eighths of the quadrangle and the northern part of the Deep Creek Range, and were not collected from the Great Salt Lake Desert or the Silver Island Mountains (table 10). Soil samples collected from basins are assumed to be highly diluted, with respect to material derived from the mountain ranges, by eolian and lacustrine material and are not representative of discrete stream basins.

Table 10. Mountain ranges and approximate number of talus and soil samples collected during the NURE program in each range

Range Talus Samples	Number of Soil Samples	Number of
Antelope Island	0	0
Camels Back Ridge	0	1
Cedar Mountains	10	64
Davis Mountain	0	2
Deep Creek Range	2	50
Dugway Range	0	1
East Tintic Mountains	16	12
Granite Peak	0	10
Grassy Mountains	0	15
Lakeside Mountains	4	12
Oquirrh Mountains	22	51
Onaqui Mountains	0	19
Sheeprock Mountains	0	11
Silver Island Mountains	21	0
Simpson Mountains	0	6
South Mountain	2	4
Stansbury Island	0	1
Stansbury Mountains	3	48
Miscellaneous Valleys	0	385

Single element distribution maps were made for silver, beryllium, copper, lead, molybdenum, and zinc (pl. 12) and R-mode factor analysis was performed on the data set.

Single Element Distributions

Basic statistics for the soil samples are presented in table 12. Single element distribution maps of selected elements are shown on plate 12. A brief summary of the distributions of these elements follows.

Elevated silver values occur in the Deep Creek Range and along the western part of the Oquirrh Mountains. Elevated lead, zinc, and copper values occur in the Deep Creek Range and throughout most of the eastern one-quarter of the quadrangle, especially in and surrounding the Oquirrh Mountains. Elevated molybdenum values are generally confined to the northeastern part of the Oquirrh Mountains and elevated beryllium values generally occur in the eastern part of the Deep Creek Range and in the Granite Peak Mountain area.

Univariate Statistics:

Element	Minimum	Maximum	Mean	Deviation	Valid	L
Ag	2.0	11.0	6.2	4.9	4	76
Al	15400	58200	37742	8142	80	0
B	10.0	243.0	27.2	26.6	74	6
Ba	120	2582	566	331	80	0
Be	1.0	3.0	1.1	.3	80	0
Ca	4700	177000	66736	45052	80	0
Co	4.0	16.0	5.6	2.5	60	20
Cr	12.0	81.0	29.9	10.1	80	0
Cu	8.0	10496.0	195.2	1188.2	79	1
Fe	8600	35100	17402	5552	80	0
Hf	15.0	25.0	20.3	3.4	6	74
K	2400	16300	10728	2731	80	0
La	6.0	59.0	19.6	7.0	79	1
Li	11.0	65.0	31.8	8.7	80	0
Mg	1500	49300	15321	8906	80	0
Mn	33.0	2541.0	403.4	269.2	80	0
Mo	4.0	258.0	35.1	83.6	9	71
Na	1000	10000	5690	1435	80	0
Nb	4.0	23.0	9.0	2.8	77	3
Ni	4.0	37.0	12.9	5.2	80	0
P	128	1743	700	281	80	0
Pb	10	3444	145	494	67	13
Sc	2.0	9.0	4.4	1.2	79	1
Sr	118	2019	354	250	80	0
Th	2.0	22.0	8.9	4.4	69	11
Ti	465	2770	1763	461	80	0
V	26.0	105.0	46.0	13.3	80	0
Y	6.0	50.0	11.6	4.8	80	0
Zn	18.0	808.0	99.5	138.5	80	0
Zr	2.0	90.0	49.3	13.0	80	0

Table 11. Basic statistics for talus samples collected during the NURE program, Tooele 1° X 2° quadrangle, northwestern Utah.

L = Less than detection limit
NA = Not applicable
minimum and maximum values in ppm

Univariate Statistics:

Element	Minimum	Maximum	Mean	Deviation	Valid	L
Ag	2.0	6.0	2.4	1.2	21	671
Al	9600	67200	40399	8007	692	0
B	10.0	209.0	31.9	21.0	654	38
Ba	201	1640	507	118	692	0
Be	1.0	8.0	1.2	.5	685	7
Ca	4100	227599	63556	33156	692	0
Co	4.0	15.0	5.3	1.3	577	115
Cr	9.0	125.0	28.9	11.0	692	0
Cu	4.0	1773.0	29.4	96.5	692	0
Fe	4500	42800	17042	5032	692	0
Hf	15.0	76.0	21.8	10.7	48	644
K	2500	21000	11945	2606	692	0
La	3.0	127.0	20.9	9.0	691	1
Li	12.0	116.0	36.7	12.7	692	0
Mg	2800	49500	14537	5521	692	0
Mn	134	1004	404	107	692	0
Mo	4.0	84.0	12.5	18.8	33	659
Na	2000	97300	7956	5044	692	0
Nb	4.0	59.0	9.9	4.1	690	2
Ni	2.0	176.0	12.1	7.9	692	0
P	239	4401	727	347	692	0
Pb	10.0	2248.0	49.3	170.9	558	134
Sc	1.0	9.0	4.6	1.1	692	0
Sr	85	2490	417	251	692	0
Th	2.0	48.0	9.0	5.1	633	59
Ti	402	5308	1879	483	692	0
V	13.0	292.0	46.4	16.7	692	0
Y	4.0	29.0	11.5	2.4	692	0
Zn	17.0	2576.0	70.0	116.9	692	0
Zr	16.0	102.0	51.9	10.9	692	0

Table 12. Basic statistics for <u>soil</u> samples collected during the NURE program, Tooele 1^{o} X 2^{o} quadrangle, northwestern Utah.

L = Less than detection limit
NA = Not applicable
minimum and maximum values in ppm

In summary, elevated values for most of the likely ore or ore-related elements for which analyses were made are confined to broad areas that contain proven mineralized or altered rock. These areas include much of the Oquirrh Mountains, the northern part of the Deep Creek Range, and Granite Peak Mountain. The single element maps are of limited usefulness in a mineral resource assessment study because of the limited number of elements that were analyzed, because the samples do not represent discrete stream drainage basins, and because the samples are highly diluted by eolian and lacustrine materials. Thus, we can make generalizations such as "the Deep Creek Range and Oquirrh Mountains contain geochemically anomalous amounts of several elements which suggest the presence of hydrothermally altered rock", but we can not make any sound conclusions about the potential for concealed or hidden mineral deposits.

R-Mode Factor Analysis

R-mode factor analysis was run on the soil sample data set of 29 elements (Ag, Al, B, Ba, Be, Ca, Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Sc, Sr, Th, Ti, V, Y, Zn, and Zr).

The factor analysis grouped the data into six factors as summarized in table 13. These factors represent several of the more chemically dominant geologic units in the quadrangle. Factor 1 (Al-K-Zr-Ti-Sc-Y-Mn-Fe-Co) reflects common stratigraphic rock formations found in the mountain ranges and factor 2 (B-Ca-Li-Mg-Na-Sr) reflects material deposited in the basins, including lacustrine deposits. Factor 3 (Ag-Pb-Zn) reflects "moderate temperature" (relative to factor 5) hydrothermally altered or mineralized rock, factor 4 (Be-La-Nb-P-Th-Y) reflects accessory minerals commonly found in igneous and metamorphic rocks, and factor 5 (Cu-Mo) reflects "high temperature" (relative to factor 3) hydrothermally altered and mineralized rock. Factor 6 (Cr-Ni-V) reflects elements derived from (black?) shales and/or mafic igneous rocks.

Table 13. Element associations, R-mode factor analysis model of soil samples.

FACTOR	**ELEMENTS**
Factor 1	Al, K, Zr, Ti, Sc, Y, Mn, Fe, Co
Factor 2	B, Ca, Li, Mg, Na, Sr
Factor 3	Ag, Pb, Zn
Factor 4	Be, La, Nb, P, Th, Y
Factor 5	Cu, Mo
Factor 6	Cr, Ni, V

For the purposes of this report, factors 3 and 5 are considered to be most useful. Areas where these two factors load highly correlate with anomalous areas of silver, copper, lead, or zinc as shown on plate 14.

Discussion

Although the quantity of samples (692) is impressive, several factors limit the usefulness of soil samples in assessing mineral resource potential for the Tooele quadrangle. These factors include the limited number of chemical elements analyzed and the uncertainty associated with the precise origin of the material collected. Elements that were not analyzed and which are necessary to fully evaluate mineral resource potential in this quadrangle include gold, the platinum group elements, arsenic, antimony, mercury, tin, and thallium. Although the soil sample data set may be perceived as a regional-scale data set, the inability to link a discrete drainage basin with a particular soil sample severely limits the usefulness of these data. In fact, the vast majority of mountainous terrain in this quadrangle is essentially not represented in this survey.

Summary of NURE Geochemistry

Because of several problems with the NURE geochemical data set the data were not massaged or analyzed as much as they might have been if these problems did not exist. These problems include:

(a) The lack of data specifically directed at the mineral deposits types known to occur in the Tooele quadrangle; this would require a geochemical pilot study of known major mineral deposits to correctly and completely define anomalous element suites and to determine the sample media which best displays the suites. In the Tooele quadrangle this sample medium is probably <u>not</u> the minus-100 mesh medium used in the NURE study.

(b) The lack of adequate sample distribution on the regional scale; geochemical coverage for many areas with a high potential for the metallic mineral deposits, such as stream drainage samples in mountainous areas or areas with relatively thin basin deposits is poor.

(c) The general disregard for known geologic and mineralogical characteristics in the quadrangle during the NURE study, including known mineral deposit types (other than uranium), favorable structures, and source and host rocks; in short, the emphasis on uranium in the 1970's has severely limited the usefulness of data generated by this program for mineral potential type studies in the Tooele quadrangle.

A highly schematic anomaly map based on NURE soil and talus samples is presented on plate 13. This figure outlines tracts of land using the following categories: (a) geochemical data are lacking, (b) geochemical data exist, but do not include anomalous values, (c) geochemical anomalies of lead, zinc, copper, beryllium, barium, and/or molybdenum or high factor loadings for soil sample factor analysis factors 3 or 5 occur in the area, and (d) geochemical anomalies of silver are present. Plate 13 is of little use at the CUSMAP level; however, it reflects the present state of geochemical studies and serves well in outlining areas of mineral potential at a CUSMAP preassessment level.

Wilderness Study Areas

Geochemical studies were conducted as part of a mineral resource investigations in the Stansbury Roadless Area (Sorensen, 1982b; Sorensen and Kness, 1983) and the North Stansbury Wilderness Study Area (Foose and others, 1989).

Sorensen (1982b) presents trace-element geochemical data for 29 heavy-mineral concentrate samples from the Stansbury Roadless Area. These samples were collected from only a small part of the area and the analyses did not suggest the existence of undiscovered mineral deposits (Sorensen and Kness, 1983). Sorensen and Kness (1983) report results of analyses for gold, silver, copper, lead, and zinc from 125 rock samples collected along the north, east, and south margins of the Roadless Area. None of their samples from within the study area appear to be of economic interest (Sorensen and Kness, 1983).

In 1985 the U.S. Geological Survey and the U.S. Bureau of Mines conducted a mineral resource assessment of the North Stansbury Wilderness Study Area (Foose and others, 1989). This area covers approximately 16 square miles near the northern end of the Stansbury Mountains, located approximately 20 miles west of the Oquirrh Mountains which are noted for several large base and precious metal deposits. The geochemical portion of this study included the analysis of 21 minus-30 mesh stream sediment samples, 21 heavy-mineral concentrate of stream sediment samples, and 69 rock samples. Analytical data and a description of sampling and analytical techniques are given in Adrian and others (1988).

Geochemical anomalies associated with mineral occurrences in and near the eastern and southwestern parts of the study area are similar to those associated with deposits in the Oquirrh Mountains (Foose and others, 1989). These anomalies suggest that the eastern and southwestern parts of the North Stansbury Wilderness Area have moderate resource potential for lead, zinc, silver, mercury, and gold in vein and replacement deposits (Foose and others, 1989).

Geochemistry of Major Mineral Deposits

Table 14 is a list of major metallic mineral deposit types known to occur in the Tooele quadrangle and, thus, it is likely that additional deposits of these types exist and will be found. Also listed are ore and anomalous elements, as reported in the literature, associated with the types of deposits. This combination of ore and anomalous elements is a good indication of the element suites we can expect to find associated with additional occurrences for each of these deposit types. The element suites of mineral deposit types known to occur in the Tooele quadrangle suggest that any trace element study should include analyses for at least the following elements:

> Au, Ag, As, Sb, Bi, Cu, Mo, Sn, W, Pb, Zn, Cd, Hg, Tl, Te, Ba, B, Mn, F, Co, Ni, Cr, and Be.

Locally, the platinum group elements, rare-earth elements, and miscellaneous other elements (such as scandium and lithium) should also be analyzed.

Strategic and Critical Minerals Program and Development of Assessment Techniques Program Applications

Several CUSMAP studies would interact well with the Strategic and Critical Minerals (SCM) and/or Development of Assessment Techniques (DAT) Programs in the Tooele quadrangle within the Branch of Geochemistry. Multi-program benefits might include:

(1) a better understanding of nonconventional beryllium deposits and resources,
(2) knowledge of platinum group mineralization related to the Bingham and other porphyry systems,
(3) the possible delineation of rare-earth element and scandium mineral deposits peripheral to the Mercur gold mine and other areas,
(4) the determination of relationships between organic maturity, gold transport, and the formation of disseminated gold deposits in the eastern Great Basin, and
(5) the application of biogeochemical prospecting, especially near range fronts, for gold and other metal deposits in the Tooele quadrangle and throughout the Great Basin.

Recommendations for Geochemical Sampling

Because of numerous problems with the existing regional-scale geochemical data set, as outlined above, the entire Tooele quadrangle would have to be sampled in order to provide a data set that is useful in a mineral resource assessment project. This sampling program should include stream drainage samples (using a sample medium determined by a pilot study of the known mineral deposit types) from first- and second-order drainages in all areas of exposed bedrock throughout the quadrangle and rock samples from proven, suggestive, and permissive areas of mineral occurrences. The proposed number of stream drainage and rock samples, referenced by mountain range, are summarized in table 15.

Goals and Expected Benefits

New geochemical studies in the Tooele quadrangle could be tailored to address questions at two levels: Level I would address basic mineral assessment questions and Level II would address questions which might be solved using a more research-oriented approach. All questions and studies would lead to a better understanding of ore deposits, their location and formation, and the general metallogenic history of the eastern Great Basin.

Table 14. Major mineral deposit types and associated ore and anomalous element suites for areas within and near the Tooele $1^{\circ} \times 2^{\circ}$ quadrangle, northwestern Utah.

DEPOSIT TYPE (EXAMPLES) {ASSOCIATED DEPOSIT TYPES}	ASSOCIATED ELEMENT SUITE
Porphyry Copper (Bingham) {Skarns, Replacements, Veins}	Cu-Au-Ag-Mo-Bi-Pt-Pd-Se-Re-Pb-Zn-As-Hg-Tl-Ba-Mn-F
Carbonate-hosted replacements (Ophir, Bingham, Gold Hill, Tintic) {Porphyries, veins, skarns}	Pb-Zn-Ag-Au-Cu-Bi-Mn-As-Sb-Te-Cd-Mo-Sn-Ba-W-B
Disseminated gold (Mercur)	Au-As-Sb-Hg-Tl-Ba-Ag
Beryllium (Spor Mountain, Granite Peak, Dugway Range)	Be-U-F-Li-Sn-B
Tungsten skarn (Newfoundland Range, Gold Hill, Silver Island Mountains, House Range) {Placer gold-House Range}	W-Mo-Bi-Cu-Sn-Au
Saline Brines (Great Salt Lake, Bonneville Salt Flats, and other closed basins)	Na-K-Mg-Ba-Ra-Cu-Zn-Cd-Hg-Pb-As-Mn-Mo-Se

Table 15. Proposed number of stream drainage and rock samples needed to complete a regional-scale geochemical survey of the Tooele 1° X 2° quadrangle, northwestern Utah.

Range	Area (square miles)	Number of stream drainage samples	Number of rock samples
Antelope Island	35	70	35
Camels Back Ridge	3	10	10
Cedar Mountains	290	580	300
Davis Mountain	16	30	35
Deep Creek Mountains	230	300	500
Dugway Range	7	20	40
East Tintic Mountains	150	200	300
Granite Peak	20	40	50
Grassy Mountains	25	50	50
Lakeside Mountains	50	100	100
Oquirrh Mountains	400	500	1000
Onaqui Mountains	90	180	300
Sheeprock Mountains	30	60	100
Silver Island Mountains	100	200	300
Simpson Mountains	25	50	100
South Mountain	8	20	30
Stansbury Island	20	40	50
Stansbury Mountains	200	400	500
Miscellaneous valleys	5570	0	0
TOTALS	7270	2850	3800

Level I. Basic mineral assessment questions

(a) How can we refine the geochemical signature of the major metallic mineral deposits?
(b) How do geochemical signatures of deposits compare with the signatures of prospects?
(c) Can we define regional-scale geochemical patterns that outline geologic trends that might be useful for evaluating mineral resources?
(d) Where are likely places to explore for concealed or undiscovered mineral deposits?

Level II. Research-oriented questions

(a) Are the circulation paths for hydrothermal and/or meteoric fluids at Bingham, Stockton, Ophir, and Mercur related: That is, are they all part of a very large hydrologic system or does each district have its own distinct hydrothermal and/or meteoric circulation cell?
(b) How can the geochemical signature of major mineral deposits be used to further understand ore genesis?
(c) Is there a genetic relationship between the major mineral deposit types in the eastern Great Basin, including Tintic, Mercur, and Bingham?

STATUS OF MINERAL OCCURRENCE DATABASE

by

Michael Shubat

Mineral occurrence data for the Tooele 1° X 2° quadrangle in the MRDS system (Mineral Resource Data System) consists of over 1140 records that describe mines, prospects, and potential resources. Each record contains information (of varying degrees of completeness) on the geologic setting, mineralogy, exploration and mining history, production and reserves, and location of the mine or prospect. Editing of these data by the Utah Geological and Mineral Survey reduced the number of records to 755 by eliminating duplicate entries and excluding sand and gravel deposits. Of these records, 407 refer to metallic deposits, 232 refer to non-metallics, and 116 refer to unclassified deposits (no defined commodity). Of the metallic and non-metallic records, 24 percent contain information on production or reserves, and 48 percent contain some quantitative information on commodities present. An index map and listing of the mineral occurrences in the Tooele 1° X 2° quadrangle is available from the Utah Geological and Mineral Survey (Tripp and others, 1989).

D.F. Huber (USGS, Menlo Park) made five plots, at a 1:250,000 scale, using the edited data file (pl. 14 through 20). Plate 14 shows the locations of all deposits or prospects that lack the quantitative data necessary to unambiguously determine what commodities are present, thus representing targets for future geochemical sampling. Plate 15 shows the location of deposits that contain (or produced) dominantly copper, lead, or zinc. Plate 16 shows the location of metallic deposits that contain (or produced) either gold or silver as the dominant commodity. Also shown on plate 16 are the locations of deposits containing significant amounts of arsenic, antimony, mercury, or thallium (indicators of the epithermal environment). Plate 17 shows the locations of deposits containing the lithophile elements beryllium, fluorine, and tungsten. Plate 18 shows the locations of non-metallic deposits, including saline minerals, carbonates, silica, crushed stone, and clay. The Great Salt Lake constitutes a vast reserve of halite, magnesium, and chlorine. Subsurface brines under the Great Salt Lake Desert produce potassium chloride and halite. Also not shown on the map are voluminous sand and gravel deposits that blanket much of the Tooele quadrangle. Sand and gravel deposits reflect the many depositional environments of Pleistocene Lake Bonneville, including spits, bars, deltas, channels, and beaches.

Three mining districts, Mercur, Gold Hill, and Bingham, dominate the precious metals distribution in the quadrangle (pl. 16); however, several other areas have significant precious metals potential. Prospects located at the north end of the Oquirrh Range contain arsenic associated with copper, lead, and minor silver. These prospects lie in an area of possible hydrothermal alteration detected by TM data and descriptions of the prospects indicate dolomitization and silicification of host carbonate rocks. Given the recent discovery of the nearby Barney's Canyon gold deposit, this area may be of interest to gold explorationists. A cluster of gold prospects located in the southern Onaqui and Cedar Mountains coincide with much recent exploration for sedimentary rock-hosted disseminated gold deposits. This area may constitute a westward extension of the Bingham-Park City mineral belt. Distributions of base metals prospects and mines (pl. 15) and lithophile elements deposits (pl. 17) outline known mining districts. Metals zonation at the Bingham district is expressed on the base metals map as a copper-rich core fringed by lead-dominated deposits. Beryllium and fluorspar prospects are confined to Granite Mountain and a lone occurrence at Wildcat Mountain in the Great Salt Lake Desert.

In its present state, the MRDS data for the Tooele quadrangle provides qualitative input to mineral resource evaluation. Nearly all mines and prospects within the quadrangle are represented by records, but the information contained in each record may or may not be complete or entirely accurate. Deficiencies are particularly apparent in the reporting of production figures and the determination of deposit types.

PRELIMINARY MINERAL RESOURCE ASSESSMENT

by

Charles G. Cunningham and Holly J. Stein

The Tooele quadrangle contains abundant mineral resources, including some of the largest and most important mineral deposits in Utah and the Nation. The kind, magnitude, and location of these resources of metals, nonmetals, brines, industrial minerals, and petroleum products are highly varied because of the complex geologic history of the area. The Tooele quadrangle contains several major ore deposits and districts (Bingham, Mercur and Gold Hill), as well as many smaller ones such as Stockton and Ophir. It also contains major saline, or evaporite, deposits in the Great Salt Lake and Great Salt Lake Desert, and abundant industrial materials. Geologic, geochemical, and geophysical data on these known deposits and districts provides a foundation for mineral resource assessment.

Mineral Deposits

Bingham

The Bingham mine is located 32 km southwest of Salt Lake City, Utah in the central Oquirrh Mountains (fig. 17). Early studies of the deposit and its geologic setting included those by Boutwell (1905), Butler and others (1920), Stringham (1953), Roberts and Tooker (1961), and James and others (1969). Other studies include those in the collections of papers in a Society of Economic Geologists guidebook (Bray and Wilson, 1975), and a special issue of Economic Geology devoted to the Bingham Mining District (Einaudi and other workers, 1978), structural studies of Tooker (1983, 1986b), geochronology of Moore and McKee (1983), the high-grade gold skarn at the Carr Fork mine (Cameron and Garmoe, 1987), gold in the Bingham district (Tooker, 1989), a suite of new 7.5′ maps (Tooker, 1987; Tooker and Roberts, 1988a,b; and E.W. Tooker, written communication, 1988). The discussion of the district in this report draws heavily on these and other reports.

The Bingham deposit, discovered in 1863, produced argentiferous galena-sphalerite ore and gold from peripheral placer deposits for many decades. The porphyry copper deposit at the center of the district was recognized by the late 1800s and became the center of the largest mining operation in the northern hemisphere. The Bingham mine and adjacent Carr Fork mine are now operated by Kennecott's Utah Copper Division, which is a subsidiary of British Petroleum, and are nearing completion of a $400 million modernization project. A third mine, Barney's Canyon, immediately north of Bingham, is scheduled to began production in 1989. The Bingham district (fig. 18) includes not only the largest known porphyry copper deposit in North America, but also the world's largest known skarn copper deposit (Carr Fork), replacement base-metal deposits, and peripheral disseminated, carbonate-hosted precious metal deposits (Barney's Canyon). Production of gold, silver, copper, lead, zinc and molybdenum from the main Oquirrh Mountains mining districts is shown in table 16. Proven and probable reserves, and grades, are shown in table 17. For comparison, production data from other districts in the Tooele quadrangle is shown in table 18. Total gold production in the Bingham deposit is estimated to have been about 590,628 kg (18.99 million troy

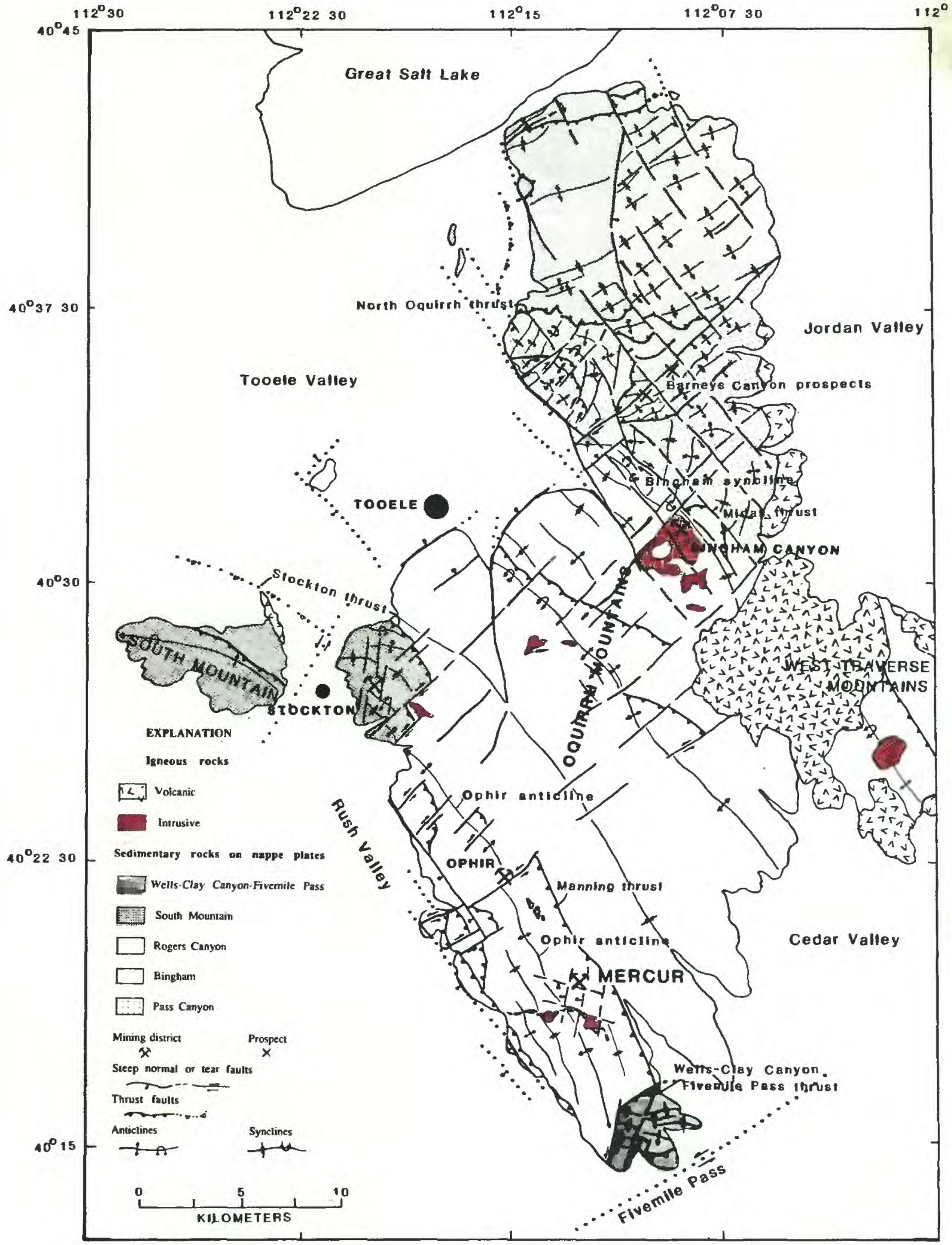


Figure 17. Generalized geologic map of the Oquirrh Mountains showing the distribution of major rock types, structural features, and mining districts (E.W. Tooker, written communication, 1988).

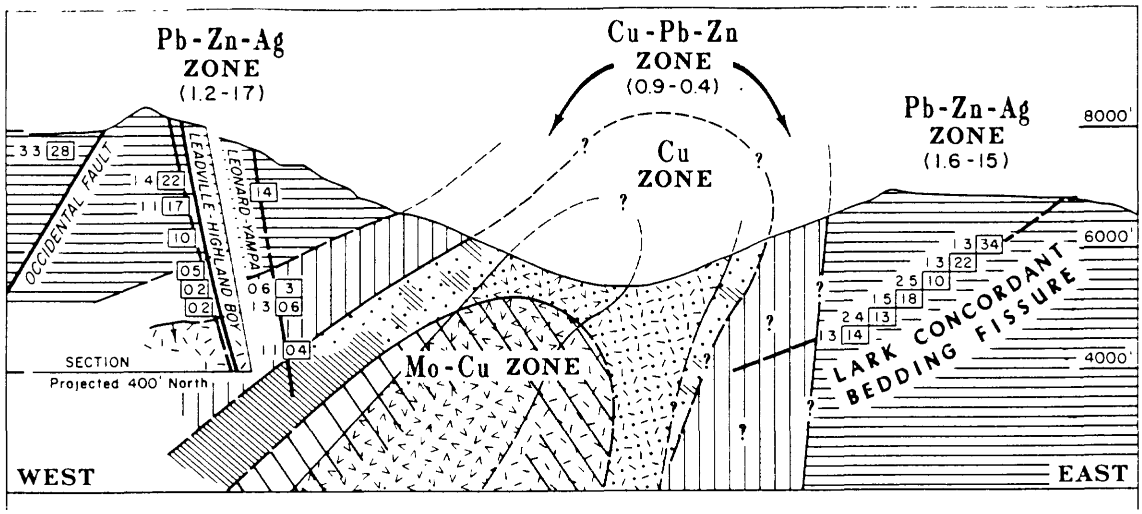


Figure 18. East-west cross section illustrating metal zonation in the Bingham district (modified slightly from Atkinson and Einaudi, 1978).

ounces, table 16) and total gold reserves are are 462,211 kg (14.86 million troy ounces); total silver production has been at least 8,000,000 kg (257 million troy ounces) and total silver reserves are 4,011,070 kg (128.96 million troy ounces, table 17). The total gold content of the deposit (production plus reserves) equals 1,052,839 kg (33.85 million troy ounces), and there is still about as much known gold in the ground as Bingham as has been mined there in the many years that the mine has been in operation! In addition, byproduct platinum, palladium, selenium, rhenium, and bismuth are recovered from the ore (John, 1978).

Paleozoic sedimentary rocks in the Oquirrh Mountains range from the Cambrian to Permian, and those in the Bingham district are from Middle Pennsylvanian Lower Permian. The Middle Pennsylvanian Butterfield Peaks Formation (Tooker and Roberts, 1970), part of the Oquirrh Group, is the oldest geologic unit in the mine area. It consists predominantly of feldspathic orthoquartzite and calcareous quartzite with interbedded limestone and calcareous sandstone beds (Lanier and others, 1978). The overlying Upper Pennsylvanian Bingham Mine

Table 16. Production from the major Oquirrh Mountains mining districts.

	Gold (kg)	Silver (kg)	Copper (t)	Lead (t)	Zinc (t)	Molybdenum (t)	Mercury (flasks)
Bingham							
1865-1972[1]	457,765	7,637,919	9,764,101	2,036,303	855,241	360,000[2]	
1973-1981[3]	113,704	--	1,669,661	--	--	--	
1982-1986[4]	19,159	253,552	551,000			6,200	
	590,628		11,984,762			366,200	
Mercur							
1871-1950[5]	34,704	6,980	0.2	1.8	0.7	--	3,338
1983-1987[6]	13,244						
	47,948						
Ophir & Stockton[5]							
1870-1961	3,171	1,558,919	21,168	328,598	16,591	--	--
Ophir[5]							
1962-1972	39	62,926	1,744	21,762	14,662	--	--
Stockton[5]							
1962-1970	5	826	9	260	214	--	--

[1] Stowe (1975; p. 44-45; 50-56) includes production from the porphyry and contiguous polymetallic vein and replacement deposits
[2] Production 1938-1955 of 181,363 t (James, 1978); 1956-1972, estimated at about double assuming comparable production
[3] Projected, based on company annual reports, previous and later production, and published grade/tonnage data
[4] Data from British Petroleum (1986)
[5] Stowe (1975)
[6] Wicks (1987); production of gold from January 1983-February 1987 was at a grade of 3.01 g/t

kg = kilograms; t = metric tonnes; -- = no data

Table 17. Proven and probable reserves and grades from the major Oquirrh Mountains mining district.

Bingham Canyon[1]	Copper t	Copper %	Molybdenum t	Molybdenum %	Gold kg	Gold g/t	Silver kg	Silver g/t
Contained metal/grade[2]	4,920,000	.705	350,000	.05	335,040	.48	2,317,360	3.32
Contained metal/grade[3]	2,280,000	2.81	20,000	.03	127,171	1.57	1,693,710	20.91
	7,200,000		370,000		462,211		4,011,070	
Barneys Canyon[1]								
Contained metal/grade[4]					13,623	2.39		
Mercur[5]								
Oxide mill ore					29,560	2.47		
Oxide heap leach ore					8,930	1.13		
Refractory mill ore					10,327	2.16		
					48,817			

[1] Data from British Petroleum (1986)
[2] 698 million t of ore mineable by opencast methods
[3] 81 million t of ore mineable by underground methods
[4] 5.7 million t of ore
[5] Wicks (1987)

kg = kilograms; g = grams; t = metric tonnes

Table 18. Production from districts in the Tooele 1° X 2° quadrangle outside of the Oquirrh Mountains mining districts.

	Gold (kg)	Silver (kg)	Copper (t)	Lead (t)	Zn (t)	As (t)
Gold Hill (Clifton)						
1892-1961[1]	804	25,888	1,574	4,967	14	
Dugway						
1916-1961[1]	5	897	34	1,318	1,321	98,000[2]
1969[1]	tr	15	tr	2	2	
Silver Island						
1965[1]	--	tr	--	tr	tr	
Free Coinage						
1917-1948[3]	tr	192	1	204	3	
North Tintic						
1902-1917[4]	tr	1,136	tr	5,177	8,530	

[1] Stowe (1975)
[2] Nolan (1935)
[3] Foose et al. (1988)
[4] Butler et al. (1920)

kg = kilograms; t = metric tonnes; tr = trace; -- = no data

Formation, also part of the Oquirrh Group, includes the Jordan and Commercial limestones that are important marker beds and the most important ore hosts (Swensen, 1975).

The Bingham district is located along the Uinta-Cortez axis, a major east-west trending structural feature that can be traced from Colorado to Nevada (Roberts and others, 1965). Sevier Thrust Belt folds are generally characterized by large, asymmetrical, northwest trending folds (fig. 17), but, in the vicinity of the mine, northeast anticlinal limbs steepen, locally overturn, and fold axes strike more westerly (Lanier and others, 1978). The results of two directions of compression are evident on figure 17. One from the southwest resulted in the northwest-trending folds of the southern Oquirrh Mountains associated with the regional Midas thrust system, and the other from the north resulting in the northeast-trending folds of the northern Oquirrh Mountains and the north Oquirrh thrust system (Roberts and Tooker, 1961; Lanier, and others, 1978). In the vicinity of the mine, two systems of faults intersecting at approximately right angles have created much of the deformation and fracturing that localized magmatic and hydrothermal systems (Smith, 1975).

The Bingham mine is centered on a composite monzonite to quartz monzonite pluton that is mineralized and hydrothermally altered. The Bingham stock and apparently the Bingham system vented, based on the similar ages and composition of breccia pipes (Rubright and Hart, 1968) and volcanic rocks to the east (Moore, 1973). The nearby unaltered Last Chance stock and dikes and sills of similar composition may be connected at depth to the Bingham system. All altered and unaltered igneous rocks in and around the Bingham mine give K-Ar ages between 39.8 ± 0.4 Ma and 36.6 ± 0.3 Ma, suggesting a close genetic relationship between igneous and hydrothermal activity (Warnaars and others, 1978).

Several types of ore deposits are present in the Bingham district: 1) low grade copper ore dispersed in and around the Bingham stock; 2) copper, lead, and zinc fissure fillings; and 3) copper in skarn and related lead-zinc replacements; 4) high-grade gold skarn ore overprinting the copper-gold skarns at the Carr Fork mine; 5) disseminated gold at the Barney's Canyon deposit, and 6) alluvial gold deposits. Sulfide minerals are zoned in inverted shells in and around the Bingham stock in typical porphyry fashion (Lowell and Guilbert, 1970; Guilbert and Lowell, 1974; Chaffee, 1982; Einaudi, 1983) (fig. 18). The dominant sulfide zones from the interior outward are deep, low grade core (containing less than 0.5 percent sulfides), molybdenite, bornite-chalcopyrite, chalcopyrite-pyrite, pyrite, and galena-sphalerite (John, 1978). Isolated barite, fluorite, and manganese occur near the outer limits of the lead-zinc zone (Rubright and Hart, 1968). High-grade gold deposits associated with copper-gold skarns have recently been described at the Carr Fork mine (Cameron and Garmoe, 1987; Tooker, 1989). The gold occurs both with copper in skarn ores and as high-grade deposits that overprint the skarn. Somewhat similiar, gold-bearing carbonate-hosted replacement deposits related to porphyritic igneous rocks have also been recently recognized in the Tintic-Deep Creek mineral belt (Zimbelman and others, 1988). Alluvial gold was produced from the Bingham district beginning in 1864. These were the most important placer deposits in Utah and produced more than 2,333 kg of gold (Johnson, 1973).

Hydrothermally altered rocks are generally related to and in part zoned around the Bingham stock (Atkinson and Einaudi, 1978; Bowman and others, 1987). The host rocks were extensively fractured permitting easy passage for the hydrothermal fluids. Altered rocks are zoned outward, from a potassic zone characterized by hydrothermal biotite and orthoclase associated with high salinity fluid inclusions that corresponds to the approximate distribution of the disseminated copper ore zone, through zones of sericitic alteration to propylitic alteration (Moore and Nash, 1974). Alteration in quartz-rich sedimentary rocks is expressed by the development of diopside, actinolite, chlorite, sericite and clay minerals (Atkinson and Einaudi, 1978). Alteration in limestones, including the Commercial and Jordan limestones at Carr Fork, is expressed by the formation of two main zones, an inner garnet zone containing garnet, diopside, and magnetite near the quartz monzonite porphyry and an outer wollastonite/diopside zone (Atkinson and Einaudi, 1978).

The Bingham deposit is a complex deposit that is one of the type examples used in the descriptive model for porphyry copper deposits (Cox, 1986a). Bingham exhibits many of the same features found in other porphyry copper deposits around the world, such as San Manuel, Arizona (Lowell and Guilbert, 1970) and El Salvador, Chile (Gustafson and Hunt, 1975) and many others. The median size porphyry copper deposit is 140 million tonnes copper at a grade of 0.54 percent copper (Singer and others, 1986), which equals 0.76 million tonnes of contained copper, showing that Bingham is a giant among the deposits. The Carr Fork deposit, genetically part of the same ore-forming system (Bowman et al., 1987), appears to be best characterized by the model of porphyry Cu, skarn-related deposits (Cox, 1986b).

Mercur

The Mercur gold mine is located approximately 60 km southwest of Salt Lake City in the southwestern part of the Oquirrh Mountains, 25 km south of the Bingham copper mine (fig. 17). Early descriptions of the geologic setting and deposits are in Spurr (1895), Butler and others (1920), and Gilluly (1932). Recent studies include reports and maps by Faddies and Kornez (1985), Tooker (1987), Kornze (1987), Jewell and Parry (1987), Tafuri (1987), Jewell and Parry (1988), and E.W. Tooker (written communication, 1988). This report draws heavily on these studies. The Mercur deposit was mined for silver beginning in 1870, with most of the production coming from a massive jasperoid known as the "Silver Chert", or "Silver Ledge" on Marion Hill (Spurr, 1895). Gold production began in 1891 with 37,320 kg of gold produced by 1917 using cyanide leaching (Butler and others, 1920). During the interval 1895-1907, 3,338 flasks of mercury were produced from cinnabar. Getty Minerals reopened the mine in 1983 and in 1985 it was sold to the current operators, American Barrick Resources Corporation of Toronto, Canada who operate it under the name Barrick Mercur Gold Mines, Inc. Gold production and reserves are in tables 16 and 17. A total of 47,948 kg (1.54 million troy ounces) of gold have been produced from Mercur. When added to the 48,817 kg (1.57 million troy ounces) (Wicks, 1987) of proven and probable reserves, it indicates the total gold content of the deposit to be about 96,765 kg (3.1 million troy ounces); for scale, this is about one-tenth the amount of gold in the Bingham deposit.

The Oquirrh Mountains are a block-faulted range near the eastern margin of the Basin and Range physiographic province. The Mercur mine is on the east flank of the northwest-trending, south-plunging Ophir anticline (fig. 17) that is a part of the Sevier Orogeny thrust nappes (E.W. Tooker, written communication, 1988). Kornze (1987) describes three periods of faulting at Mercur. The first is associated with Sevier thrusting, the second is basin and range style faulting, and the third is a series of small-displacement, normal faults that may overlap the second in age. Rocks in the vicinity of the mine dip about 25 east.

Gold at Mercur is micron-sized and is disseminated in stratiform and stratabound ore bodies. The host rocks are altered, carbonaceous, silty limestones of the lower member of the Mississippian Great Blue Limestone. The Great Blue Limestone has three members, the lowest of which is the Paymaster Member equivalent or Gilluly (150-200 m thick) which contains most of the gold in the 8 m thick "Mercur" beds near the top. The underlying Silver Chert is a stratabound jasperoid that extends laterally for several km beyond the Mercur area (Kornze, 1987). The ore-bearing Mercur beds are a sequence of porous, bedded, packstones, wackestones, and siltstones that originally contained abundant bryozoa and diagenetic pyrite. They appear to have a higher porosity and a greater amount of siltstone and shale than the rest of the upper Topliff carbonate. Gold appears to have been localized by faulting and fracturing of the favorable lithologies in the Mercur beds (Tafuri, 1987).

The alteration and mineralization at Mercur are described by Jewell and Parry (1987, 1988), Kornze (1987), and Tafuri (1987). Silicification was the earliest and most widespread result of alteration. The Silver Chert is believed to have been silicified early because the silica associated with this event does not contain gold (Klatt and Tafuri, 1976). Silicification was followed by decarbonation of silty limestones contemporaneously with the deposition of quartz, kaolinite, and sericite to form an argillic alteration facies. Gold was deposited together with arsenan pyrite, orpiment, marcasite, realgar, barite, organic carbon and minor thallium minerals dispersed in the host rock and as sulphide-carbonate veinlets. Gold occurs in unoxidized rocks as (1) 1-2 micron inclusions in marcasite, (2) bonded to complex organic compounds, and (3) as occasional grains of native gold of up to 5 microns in size; in oxidized rocks, gold is in its native state. Hydrocarbons were mobilized during the hydrothermal event and gold is present in the asphaltene phase of extractable hydrocarbons and in activated carbon (Tafuri, 1987).

Igneous rocks are present north and south of the Mercur deposit. The Eagle Hill Rhyolite (Gilluly, 1932) is a fine-grained, porphyritic rock that occurs as a sill in the Sacramento Pit at the deposit; Moore (1973) obtained a K/Ar age of 31.6 $\pm$ 0.9 Ma on biotite from this rock. Coarsely porphyritic quartz latite stocks about 1.5 km north of Mercur give 36.7 $\pm$ 0.5 Ma ages on biotite (Moore and McKee, 1983). The igneous rocks are variably altered and are not known to be mineralized (Kornze, 1987). The precious metal mineralization at Mercur has not been dated because no suitable material for dating is known.

Mercur is classified as a sedimentary-rock hosted disseminated gold deposit and has been used as an example for carbonate-hosted Au-Ag deposit (Berger, 1986). The median size of these deposits is 5.1 million tonnes of ore grading 2.5 grams of gold per ton, (12,750 kg total contained gold) with some deposits containing significant silver (Bagby and others, 1986). Mercur has many fundamental geological features that are similiar to other sedimentary-rock hosted disseminated gold deposits whose characteristics have been described by Bagby and Berger (1985). They share common features of host lithology, structural control, gold size and distribution, and geochemical/mineralogical associations. Mercur is located much farther east than most of them (with the exception of the newly-discovered Barney's Canyon deposit), is notably larger that the median-sized deposit (96,765 kg vs 12,750 kg contained gold), and has more silver associated with it than most "Carlin-type" deposits. Also at Mercur, alteration may be more controlled by distinct lithologies within a restricted stratigraphic sequence, and jasperoids may occupy a different time/stratigraphic position (Jewell and Parry, 1987).

Gold Hill

The Gold Hill (Clifton) district is located at the northern end of the Deep Creek Mountains, in the southwest corner of the Tooele 1^{o} X 2^{o} quadrangle. The Gold Hill district is one of the oldest in Utah having produced ore intermittently since about 1869. An early comprehensive report is by Nolan (1935); more recent reports are by El-Shatoury and Whelan (1970) and Robinson, 1988. This report draws heavily on these previous reports. The district produced small quantities of tungsten ore during World War I, and small quantities of copper, gold, and lead-silver ore, as well as about 100,000 tons of arsenic (table 18). A substantial amount of the gold production may have come from the recently recognized gold skarn environment (Orris and others, 1987).

The Gold Hill district contains both folded and faulted Paleozoic sedimentary rocks and younger igneous rocks. Mississippian and older sedimentary rocks are mostly limestones and dolomites, whereas Pennsylvanian and younger rocks, are a mixture of sandstones, shales, carbonates, and quartzites. The Oquirrh Formation and the Ochre Mountain limestone are the thickest sedimentary units present, totalling over 3 km (El-Shatoury and Whelan, 1970), although parts of this stratigraphic section may have been repeated by Sevier thrust faults. Sedimentary rocks have been subjected to four and possibly five cycles of folding and faulting. Paleozoic stratigraphy and structural relations in the vicinity of Gold Hill need refining and definition at the CUSMAP level of study.

Igneous rocks in the Gold Hill district are of several different ages (Robinson, 1988). The eastern part of the district is dominated by a large quartz monzonite stock (Nolan, 1935) that has been dated at about 152 Ma (Stacey and Zartman, 1978). The only other igneous rocks of this age recognized in the quadrangle are in the Silver Island Mountains, where Moore and McKee (1983) reaffirmed a Mesozoic age for several smaller stocks (160-174 Ma). Intermediate-composition intrusive and extrusive rocks in the northern end of the Deep Creek mountains were dated at 37-44 Ma (Moore and McKee, 1983). Younger andesite, diabase, basalt, and rhyolite dikes are also present in the Gold Hill district (Robinson, 1988).

Three types of deposits have been described by Nolan (1935). These are (1) pipelike deposits containing tungsten and molybdenum, (2) vein deposits containing sulfides with silicate or carbonate gangue, and (3) replacement deposits containing either arsenic minerals or copper-lead-silver minerals. The pipelike deposits are pegmatitic masses scheelite, molybdenite, and lesser chalcopyrite, pyrite, magnetite, and specularite hosted by quartz monzonite. Three types of veins have been distinguished. They are (a) veins associated with the tungsten-bearing pipes, (b) veins characterized by fine-grained silicate minerals including widespread tourmaline and a dominance of copper over tungsten, and (c) veins containing gold in limestone hosts near the quartz monzonite contact. Replacement deposits of arsenic minerals have been found in limestone roof pendants within the quartz monzonite with arsenopyrite the dominant ore. Copper, lead, and silver limestone replacement bodies are present, and in many cases they occur peripheral to the arsenic deposits. Scheelite has been found irregularly distributed in narrow tactite zones in limestones at or near contacts of igneous rocks and in association with pegmatite dikes. The Gold Hill area has yielded the largest production of scheelite ores in the state, with much of the ores grading over 0.5 percent WO_3 (Everett, 1961). Most, if not all of the ore deposits are spatially and genetically related to the Jurassic quartz monzonite pluton. The economic contribution of the smaller Eocene granitic stocks and other dikes at the north end of the Jurassic quartz monzonite is uncertain. Robinson (1988) suggests that base and precious metal deposits are related to middle Tertiary igneous activity.

Beryllium has also been found in the Gold Hill district. Bertrandite has been discovered in quartz-calcite-adularia veins that cut the Jurassic pluton (Griffitts, 1965), but feldspar is believed to be the host mineral containing much of the beryllium (El-Shatoury and Whelan, 1970). Adularia in these veins has been dated at 8 ± 0.8 Ma (Whelan, 1970) indicating that at least some Tertiary mineralization occurred. The beryllium-bearing veins are located about 65 km northwest of the famous beryllium deposits at Spor Mountain and 55 km west-northwest of anomalous beryllium occurrences in the Dugway mining district (Kelley and others, 1987).

Ophir and Stockton (Rush Valley)

The Ophir and Stockton (Rush Valley) districts are located along the west side of the Oquirrh Mountains; Ophir is about 13 km south of Stockton. Early reports on the districts are in Butler and others (1920) and Gilluly (1932) and recent maps and reports include Tooker and Roberts (1988a) and Tooker (written communication, 1988). The districts produced mainly base metals and silver, and historical production is listed in table 16. Three small shipments of scheelite ore were made from Ophir in the 1950s (Everett, 1961). The deposits are mainly veins, pipes, and replacements in folded lower Paleozoic limestone and much of the ore has been oxidized. High grade ore shoots tended to occur at the intersection of veins with replacement deposits such as at the Treasure Hill mine in the Ophir district (Butler and others, 1920; Dunham and Gunnell, 1948) and in the vicinity of breccia pipes, faults, and intrusive rocks, such as at the Eagle Silver mine in the Stockton District (Young, 1950). Intermediate composition stocks, sills, and dikes are present in the Ophir and Stockton districts and extend as a belt from Bingham west to Stockton, and south along the crest of the Ophir anticline through Stockton, to Mercur (plate 12 in Gilluly, 1932). A quartz monzonite stock near Stockton is spatially associated with some of the mineralization (Lufkin, 1965); biotite from this stock has been dated at 38.0 ± 1.1 Ma (Moore, 1973a).

Dugway

The Dugway Mining District is located in the northern Dugway Range, near the southern border of the Tooele quadrangle. The district produced about 11,000 tonnes of lead, zinc, copper, gold, and silver ore from 1869-1956 (Kelley and

Yambrick, 1988); available data on production is in table 18. Published information includes the mining history (Butler and others, 1920), regional geology, ore mineralogy, and mine site geology (Staatz and Carr, 1964) and geochemistry and alteration (Taylor, 1977; Kelley and others, 1987, and Kelley and Yambrick (1988).

The Dugway mining district contains Cambrian to Mississippian miogeosynclinal sedimentary rocks and minor quantities of Tertiary volcanic rocks. The northwest-trending Buckhorn fault is a prominent geologic feature that influenced the location of rhyodacitic vent complexes, and altered and mineralized rocks (Kelley and others, 1988). Sulfide minerals are present in (1) fissure veins in quartzite, (2) fissure veins and replacements in carbonate rocks, and (3) quartz veins in volcanic rocks; associated altered rocks are silicified, bleached, or recrystallized. Recent geochemical studies have identified anomalous concentrations of beryllium in silicified dolomite, and gold with arsenic and antimony, that are believed to be related to volcanic vents (Kelley and others, 1987; D.L. Kelley, written communication, 1988).

Free Coinage

The Free Coinage district is located at the northern end of the Stansbury Mountains. Reports on the deposits and related geology in the vicinity of the district include Rigby (1958), Davis (1959), Sorensen (1982a) and Foose and others (1988). The district has produced mainly base metals and silver, and production is in table 18. Of particular note is that a small quantity of mercury has been produced (Rigby, 1958). Most of the production has been from replacement and vein deposits in Mississippian carbonate rocks along the east side of the Stansbury Mountains, the Monte Carlo mine and Utah Bunker Hill mine having been the largest producers. A few km to the west, in a Wilderness Study Area, hydrothermal mineralization appears to be related in part to the contact between lower and upper Devonian rocks (Foose and others, 1989). Geochemical studies in the district disclose the presence of anomalous concentrations of mercury, and gold has been collected in a panned concentrate (Almquist, 1987; Foose and others, 1989).

Granite Peak

The Granite Peak district is located at Granite Peak, just north of the Dugway Range. Most of the range is composed of leucogranite and granite gneiss that are believed to be related to the Precambrian Farmington Canyon Complex (Moore and Sorensen, 1978) and may represent the eroded central part of a metamorphic core complex (Moore and McKee, 1983). There has been very little metal production, but minor lead, copper, gold, and silver have been reported, and banded veins containing quartz, fluorite, and hematite are abundant near the southern end of the range (Butler and others, 1920). K/Ar ages of 14-30 Ma on muscovite from Granite Peak (Moore and McKee, 1983) may be related to uplift and unroofing of a core complex or igneous activity such as related to a stock of altered topaz rhyolite at Sapphire Mountain, a couple of km south of Granite Peak.

Silver Island

The Silver Island district is located in the Silver Island Mountains in the northwestern corner of the Tooele quadrangle. Small quantities of copper, lead, and silver were produced 1908-1913 (table 18) from veins and replacement deposits in limestones associated with dikes (Butler and others, 1920). Igneous rocks of at least two ages are present in the district. Moore and McKee (1983) obtained Jurassic ages of 159.6 ± 5 Ma on biotite and 173.8 ± 3 Ma on hornblende from a granodiorite stock, and a date of 40.9 ± 0.6 Ma on an hornblende-biotite andesites a few km southwest. Younger(?) rhyolites are also mapped in the vicinity (Moore and Sorensen, 1979).

North Tintic

The North Tintic district is located in the East Tintic Mountains near the southeastern corner of the Tooele quadrangle. The district contains folded and faulted Paleozoic quartzite, shales, and limestones, together with Tertiary andesite flows and breccias, and monzonite to rhyolite dikes. Base metal-silver ores have been produced from oxidized veins and replacement deposits in limestone; the production is listed in table 18 (Butler and others, 1920; Disbrow and Morris, 1957).

Lakeside

The Lakeside district, in the Lakeside Mountains along the western side of the Great Salt Lake reportedly produced a large quantity of lead-silver ore in the early days (Butler and others, 1920).

Columbia

The Columbia district is in the Simpson Range along the southern border of the Tooele quadrangle, about 35 km east of the Dugway Range. Quartz-feldspar veins with hematite and galena, quartz-fluorite veins with pyrite and chaleopyrite, and quartz veins containing pyrite, sphalerite, and galena (Butler and others, 1920) cut Cambrian quartzites and shales, and a granitic stock (Moore and Sorensen, 1979a).

Other Districts

Other mining districts within the Tooele quadrangle, such as the Third Term district and Wildcat Range have had minor production in the past, but information has not been included in this report.

Mineral Resource Preassessment

The mineral resource preassessment for the Tooele quadrangle is a synergistic product resulting from the integration of geologic, geochronologic, geochemical, and various kinds of geophysical data. It is based on our understanding of the geologic history, available geochemistry, and geophysical information, and existing mineral deposit models. A mineral deposit model is defined as the "systematic arrangement of the essential characteristics of a group of mineral deposits". The U.S. Geological Survey has recently published a compendium of mineral deposit models as USGS Bulletin 1693 (Cox and Singer, 1986). It groups deposits systematically by common characteristics, indexes them using key mineralogical and chemical signatures, interrelates them by geologic environment, and relates them to the grade and tonnage characteristics of other similiar deposits.

A new mineral deposit type, gold skarns, has been described by Orris and others (1987). Examples in the Tooele 1^{o} X 2^{o} quadrangle include the Gold Hill and Carr Fork deposits. Gold skarns have not been dealt with separately in this report, but they appear to be present, potentially in significant abundance, in the Tooele 1^{o} X 2^{o} quadrangle. This newly recognized gold skarn deposit type merits intensive investigation during CUSMAP study.

The amount, distribution, and quality of geological, geochemical, and geophysical information in the quadrangle is variable and is reflected in the confidence level of our assessment. Sufficient information was not available to justify grade and tonnage estimates of undiscovered deposits. This task is reserved for CUSMAP, following the collection and interpretation of pertinent and necessary data. Instead, tracts of favorability for various models were delineated and the geological, geochemical, and geophysical criteria in creating these tracts are explained. Tracts for some resources, such as widespread brine deposits or abundant industrial materials such as limestone, sand, and gravel were not delineated.

The Tooele quadrangle contains several major geologic tectonic features that appear to have influenced the location of ore deposits. One of these is the westward extension of the ENE-trending "Bingham-Park City" or "Oquirrh-Uinta" (Butler and others, 1920) mineral belt. This belt contains a well-defined alignment of igneous rocks, mineral deposits, and aeromagnetic anomalies; the latter, linear magnetic low, can be easily seen on the Aeromagnetic Map of Utah (Zeitz and others, 1976). This tectonic trend, referred to as the Cortez-Uinta axis, is a major E-W zone that has influenced geologic processes throughout the Phanerozoic (Roberts and others, 1965). Another major feature is the NE-trending Sevier orogenic belt that marks the eastern limit of thrusting associated with the Sevier Orogeny. The Tooele quadrangle is also very close to the eastern edge of the Basin and Range Province, marked by the Wasatch Front immediately east of the quadrangle.

The mineral resource assessment is shown on a series of 1:250,000 maps (pl. 19 through 22) that outline tracts of varying resource potential for specific types of mineral deposit models. The mineral resource potential has been divided into three levels, A, B, and C which correspond to high, moderate, and low mineral potential. An area designated A contains known deposits or obvious extensions of terrains with similar geological/geochemical/geophysical characteristics. An area designated B does not contain known deposits but has many favorable characteristics of the deposit model being considered. An area designated C contains at least one such as geologic environment, geochemical indication, or geophysical expression.

Deposit Model Types

Porphyry Copper Deposits (Cox and Singer Model 17)

An example of a porphyry copper deposit model in the Tooele quadrangle is the Bingham deposit. Favorable factors include: (1) location within the Bingham-Park City mineral belt, (2) presence of intrusive rocks, are of Eocene-Oligocene age and monzonite to quartz monzonite compositions, (3) presence of a strong, multi-element geochemical anomaly zoned outward from Cu-Mo, to Pb-Zn-Ag, to As-Au, (4) presence of a strong, positive magnetic anomaly without a corresponding positive gravity anomaly in the Last Chance stock, which contains a "magnetite core." The Stockton-Ophir districts, southwest of Bingham in the Oquirrh Mountains, have many of these favorable factors. Refer to pl. 19.

Porphyry Copper, Skarn-Related Deposits (Cox and Singer, Model 18a)

An example of a porphyry Cu, skarn-related deposit in the quadrangle is Carr Fork, located immediately west of the Bingham porphyry copper deposit. Favorable factors are the same as those listed for porphyry Cu deposits because they are genetically related. The Paleozoic sedimentary sequences which form the mountain ranges in the Tooele quadrangle include the same limestones that are hosts for porphyry Cu and skarn related deposits in the Oquirrh Mountains. The characteristic magnetic signature attributed to Bingham is actually largely from metasomatic magnetite developed in the skarn. Refer to pl. 19.

Gold skarns may represent a distinct type of deposit (Orris and others, 1987). They appear to be genetically related to diorite-granodiorite intrusions, often postdate the skarn silicates, and have been recently described at Bingham (Cameron and Garmoe, 1987). Tracts containing favorable indications for both porphyry Cu, skarn-related deposits and W-skarn deposits are viewed favorably for their gold skarn potential.

Polymetallic Replacement Deposits (Cox and Singer, Model 19a)

Polymetallic replacement deposits are widespread in the quadrangle. Favorable factors include: (1) location in or near igneous centers within the Bingham-Park City mineral belt, (2) presence of a geochemical anomaly zoned outward from Cu to Pb-Ag to Zn-Mn, (3) presence of calc-alkaline dikes, (4) presence of faulted carbonate rocks, and (5) evidence of recrystallization or bleaching of carbonate rocks. Refer to pl. 20.

Polymetallic Vein Deposits (Cox and Singer, Model 22c)

Polymetallic veins are widespread in the Tooele quadrangle. Favorable factors include: (1) location in or near the Bingham-Park City mineral belt, (2) presence of zoned base-metal geochemical anomalies along faults and unconformities, (3) presence of calc-alkaline dikes, (4) evidence of recrystallization or bleaching of carbonate rocks. Refer to pl. 20.

Carbonate-Hosted Gold-Silver Deposits (Cox and Singer, Model 26a)

An example of a carbonate-hosted Au-Ag deposit in the quadrangle is Mercur. Favorable factors include: (1) location within the Bingham-Park City mineral belt, (2) presence of mid-Tertiary igneous rocks, (3) presence of geochemically anomalous Au, As, Sb, Hg, and/or Tl, (4) presence of carbonate rocks cut by high angle faults, and (5) presence of jasperoids. The newly-discovered Barney's Canyon gold deposit north of the Bingham deposit is an indication that still more of these deposits may be present in the Tooele quadrangle. Refer to pl. 21.

Tungsten-Skarn Deposits (Cox and Singer, Model 14a)

Examples of W-skarn deposits in the quadrangle are found in the Gold Hill district. Favorable factors include: (1) presence of Jurassic intrusive rocks, (2) abundance of carbonate host rocks, and (3) presence of geochemically anomalous tungsten. Known Jurassic intrusive rocks in the Tooele quadrangle appear to be confined to the western most part of the quadrangle and include stocks in the northern Deep Creek Mountains and in the Silver Island Mountains. Refer to pl. 22.

Beryllium Vein Deposits

Beryllium is known to occur in the Gold Hill, Granite Peak, and Dugway districts within the Tooele quadrangle. The world's largest known beryllium deposits are within 100 km of these districts. Favorable factors include: (1) presence of topaz-rhyolites, (2) presence of geochemically anomalous lithophile elements, and (3) spatial proximity to the northwest-trending, magnetic-high anomaly in the western part of the quadrangle that may indicate the presence of a basalt-filled rift with genetically related rhyolites and beryllium deposits. Refer to pl. 22.

Limestone and Dolomite Deposits

Limestone and dolomite are among the most abundant and widely used mineral resources in Utah. Their low cost, chemical and physical characteristics, and relative accessibility make them a basic resource for a wide variety of industries. The Paleozoic, particularly Mississippian, sequence in the Tooele quadrangle contains abundant, relatively pure carbonate rocks. Favorable tracts include areas where Mississippian limestones crop out and can be easily mined at low cost for the Salt Lake City market, such as at the northern end of the Stansbury Mountains. Oolite deposits, used for flux material, occur along the shores of the Great Salt Lake.

Petroleum Deposits

Utah is a major oil and natural gas producer with most production coming from the Uinta and Paradox basins in the eastern and southeastern parts of the state (Gere and others, 1964). Kerns (1987) notes many oil shows in the Great Basin of western Utah, but no commercial development has occurred in this region yet. Small asphalt seeps are known around the Great Salt Lake (Heylmun, 1965), and small quantities of oil have been located in alluvial-filled Tertiary basins (Bortz, 1983, 1987), but none has proved economical to date. Favorable tracts would be where organic rich, Lower-Tertiary lake beds have been buried deeply enough to be thermally matured to the "oil window". Wilderness tracts in the Deep Creek and Stansbury Mountains have a low petroleum potential because of the thermally mature state of hydrocarbons, whereas in the Cedar Mountains, the potential is rated medium (Molenaar and Sandberg, 1983). Other favorable tracts would include areas containing known petroleum source rocks (Maughan, 1979) and/or structural traps (Moulton, 1976, 1987).

Phosphate Deposits

Northern Utah is within the Western Phosphate Field (Gere, 1964) and has been a significant producer of phosphate. Most of the phosphate comes from the Permian Phosphoria Formation; favorable tracts are where the formation crops out or is in close proximity to the surface.

Sand and Gravel Deposits

Utah contains abundant quantities of sand and gravel, especially in the basins of the Basin and Range Province. The best quality sand and gravel is where natural processes have acted to remove material that is finer than sand and coarser than gravel. Favorable tracts for high-quality material in the Tooele quadrangle are along the paleo-shorelines of Pleistocene Lake Bonneville (Kopp, 1987) and in sand dunes (Van Horn, 1964).

Saline Deposits

Saline deposits, or evaporite deposits, are mineral salts that have been derived from evaporation of concentrated brine solutions. Brines are an important source of chemicals including common salt, potash, bromine, boron, lithium, iodine, magnesium, and sodium carbonate, in fact, brines and evaporate deposits are the chief sources of potassium in forms which are usable by the fertilizer industry (Behrens, 1980). The Great Salt Lake presently supplies 10 percent of the world production of magnesium (Toomey, 1980), and a large area of the lake is underlain by a shallowly buried bed of mirabilite or Glaubers salt, a hydrated sodium sulfate (Tripp, 1987; Gwynn, 1987). Because restricted and closed basins are abundant in the Tooele quadrangle, favorable tracts for economic deposits are widespread, especially in the northeastern part in the vicinity of the Great Salt Lake, and in the western half of the quadrangle, in the Great Salt Lake Desert.

Alluvial Gold Deposits

Alluvial gold deposits were mined during the late 1800s from bench and creek gravels in the vicinity of the Bingham deposit (Johnson, 1973). A small amount of gold has been panned in the northern end of the Stansbury Mountains (Almquist, 1987). Favorable factors include the presence of porphyry-Cu or porphyry Cu-related deposits.

Zeolite Deposits

Zeolites are found in saline, alkaline lakes of Cenozoic age; they are generally associated with playa-lake complexes which can develop in volcanic-filled rift grabens such as are present in the Basin and Range Province

(Surdam, 1979). The Tooele quadrangle could contain substantial zeolite reserves.

Geothermal Resources

Geothermal resources are present in western Utah, with their heat being derived from buried igneous bodies or deep circulation. The area of the Bonneville Salt Flats has been identified as a possible geothermal resource, where deep drilling has reached hot water (35^{o}-$88^{o}C$) (Goode, 1979). Warm springs exist in Skull Valley, Tooele Valley, and along the north end of the Oquirrh Mountains, and warm water (less than $100^{o}C$) is present in the mines of the East Tintic District (Heylmun, 1966).

Other Resources

The Tooele quadrangle contains a wide variety of other geologic resources. The area is noted for its mineral and fossil specimens, and many collecting localities are listed in Bullock (1981); it is noteworthy that gem variscite has been found at the southern end of the Oquirrh Mountains (Hamilton, 1959).

GENERAL REFERENCE LIST AND BIBLIOGRAPHY FOR THE TOOELE QUADRANGLE, UTAH

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A few words about the reference compilation are in order. It is impossible, given the time frame for CUSMAP Preassessment studies, to retrieve every existing reference for the Tooele quadrangle. We know that some references have been overlooked. However, the lengthy list that follows contains the bulk of the references we have found for the Tooele sheet plus some additional, more general references that are important contributions in understanding the tectonic and geologic history of western U.S. Within the Tooele quadrangle, we have tried to be especially thorough on the subject of mineral occurrences and ore deposits. Rather than repeating references at the end of each chapter in this document, we have conserved space and trimmed volume by simply including all the references in the following massive list.

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