

## **GEOCHEMICAL STUDIES FOR THE PROPOSED UNDERGROUND SCIENCE LABORATORY**

The proposed Underground Science Laboratory at the Homestake Mine, Lead, South Dakota, provides an important opportunity to advance geochemical research on several important topics. The planned laboratory has two main advantages for geochemical research. First, and most importantly, it is a controlled, though still natural, environment that can be sampled at a multitude of scales in both time and space. Scales of variability and durations of processes are poorly known in geochemistry, particularly in systems involving natural waters. This limits our ability to extrapolate results from the laboratory to larger, natural scales and this, in turn, limits our ability to use laboratory results to benefit society. The second tremendously important advantage of the laboratory is the large number and wide variety of scientists that will focus on the problems. This will allow almost unparalleled cooperation among geochemists, microbiologists, hydrologists and engineers. This sort of cross-fertilization is required for us to solve problems involving movement and fate of fluid flow in the crust, which is on the most important factors governing the quality of our environment and water supplies.

The main areas in which geochemical research might be focused are environmental geochemistry and mineralogy, stable and radiogenic isotope geochemistry and regional and ore deposit geology and geochemistry. Research in environmental geochemistry and mineralogy will focus on acid mine drainage and other processes that control the chemical interaction of rocks and waters that pass through them. These processes are fundamentally important to water quality and supplies. Investigations in isotope geochemistry will focus on a range of problems important to the dissolution and transport of solutes in water and by offering a way of labeling microbial materials, it will be the main bridge between geochemistry and microbiology. Studies on the regional and ore deposit geology in the Homestake area take advantage of the large vertical extent of the underground mine and the opportunity that it offers for us to study changes at all scales in the upper crust.

The following sections contain brief descriptions of typical geochemistry research projects that might be undertaken at the laboratory.

### **ENVIRONMENTAL GEOCHEMISTRY AND MINERALOGY**

**Acid Mine Drainage** (Michael Hochella, Virginia Polytechnic Institute)

#### Overview

Ore sampled directly from the Homestake Mine, as well as ore and resulting secondary phases found in dumps, tailings piles, and stream sediments associated with mine waste from over a century of mining activity there, provide a unique opportunity to study the mineralogical and (bio)geochemical controls of heavy metal dissemination into the surrounding surface environment.

#### Background

Mineral-water interfacial interactions associated with working and abandoned sulfide-bearing mines and mining wastes are among the most complex, dynamic, and environmentally important of all near-surface rock-water systems (e.g. Jambor and Blowes, 1994; Alpers and Blowes, 1994). These mining sites, numbering approximately 200,000 in the United States alone, typically release large amounts of metals into the environment ranging up to hundreds of kilometers along hydrologic gradients in relatively short times. Contamination occurs when high solute concentrations of iron form during the weathering of pyrite and associated metal sulfides. Acidic effluent from mine entrances and waste piles mix with air and oxygenated surface water and precipitate iron oxides, oxyhydroxides, and/or hydroxysulfates. These phases form mineral/rock coatings and metal-rich sediments that may contain very high concentrations of heavy metals detrimental to the environment.

Field and laboratory studies suggest that both the growth or dissolution of discrete metal-bearing precipitates and adsorption/desorption reactions are the most important processes in the attenuation or release of toxic metals. However, many of the phases that contain Fe and toxic metals of interest have not been identified with reliable certainty (e.g. McCarty et al., 1998; Webster et al., 1998), although important progress is being made (e.g. Schwertmann et al., 1995; Webster et al., 1998). Some phases are presumed to be present, usually via thermodynamic arguments, because direct evidence is lacking. In other cases, the thermodynamic database is insufficient to reasonably presume anything. A much better understanding of the minerals and mineral coatings present, as well as their composition, degree of crystallinity, and microfabric, are critical in understanding toxic metal partitioning (including sorption/desorption reactions) under various Eh/pH environments in these complex natural systems. Further, modeling the formation of acid mine drainage (AMD) environments, and the transport of toxic metals through and away from these sites, would be greatly aided by a much more complete knowledge

of the bulk and interface phases that contain these metals sampled from “cradle to grave” in a system mined over many decades, and in an otherwise well-studied system. The Homestake Mine in South Dakota provides just such an opportunity.

#### Suggestions for research projects

Sulfide-bearing samples can be collected from the following: 1) the Homestake formation still exposed in the mine at depth, and 2) sulfide-bearing veins associated with the Tertiary rhyolitic dike complex, also exposed in the mine. Next, sulfide-, sulfate-, and oxyhydroxide-bearing samples can be collected from: 1) dumps and tailings piles of various ages around the mine, at various depths in the piles, and 2) sediments from the streams or washes that drain these dumps. Along with the chemistry of waters associated with all four types of samples listed above, the heavy-metal bearing phases should be characterized using TEM, SEM, and XRD as done, for example, by Hochella et al. (1999; see also attached figure). Finally, the fluid and solid-state characterization, along with thermodynamic and microbiological considerations, can be used to build perhaps the most complete story yet of heavy metal dispersion in the near-surface environment due to mining. Such a study would be a major and certainly unique contribution to the field of environmental science associated with hard-rock mining.



#### Figure caption

TEM image of ferrihydrite (the stippled portion of the image, mostly in the lower half) and hydrohetaerolite (the fibrous phase mostly in the upper half) (image collected by M. Hochella). The ferrihydrite (an iron oxyhydroxide) consists of nanometer-sized semi-crystalline particles, and the hydrohetaerolite, a Zn, Mn oxide hydrate, is a “one-dimensional” phase, with fibers as narrow as 1 nm. These phases are from an acid mine drainage site in Montana, USA, and are important in the transport of toxic metals into the environment. Scale bar = 50 nm.

#### **Background and Anthropogenic Processes** (Moira Ridley, Texas Tech University)

Two broad areas of research are presented. The first deals with background/baseline processes and the second addresses anthropogenic induced alteration (i.e. oxic environments, elevated temperatures and humidity, etc).

### Role of Colloids, Bacteria and Organic Matter

*Are submicron particles (colloids/bacteria, including organic matter and organic acids) present in subsurface interstitial waters? If present, do existing surface reactivity models and thermodynamic databases of experimental data, predict accurately the chemical reactivity, behavior and effects of particulate material and microbial activity in natural subsurface environments?*

**Background:** The chemistry at solid-solution interfaces is responsible for a variety of geochemical processes, including the transport and fate of toxic metals and anion contaminants, and mineral dissolution and precipitation reactions, etc. Furthermore, these same geochemical processes are mediated by organic acids, including the carboxylic, humic and fulvic acids. Organic acids impact the formation and preservation of secondary porosity, enhance mineral dissolution, weathering rates, and contaminant transport, etc. Consequently, numerous highly-constrained, detailed experimental (Ridley et al., 1998,1999), modeling (Machesky et al., 2001) and empirical (e.g. Shock and Koretsky, 1995) studies have been performed to improve our understanding of interface chemistry and to provided detailed thermodynamic databases. Particularly, environmentally significant phases have been studied, including crystalline metal-(hydr)oxides (Ridley et al., 1999), amorphous and crystalline colloidal material, microbial material (Fein et al., 2001), fulvic and humic acids, and recently nano-scale particles. The effect of particulates and organic acids on natural subsurface geologic systems, coupled with the extensive experimental and thermodynamic databases has not be investigated systematically.

Furthermore, there has been concern recently that colloidal transport of ions in subsurface environments may accelerate the mobility of toxic contaminants (Kersting et al., 1999). If this transport mechanism is significant, then current models may under predict contaminant movement in underground repository sites (e.g. Yucca Mountain) and contaminant migration in groundwater plumes (e.g. DOE Hanford site, Idaho National Engineering and Environmental Laboratory).

**Research:** Initially the project will focus on sampling interstitial waters to determine: source of the water e.g. formation water vs. mine water, presence and composition of particulates, colloidal and organic materials (collaboration with geomicrobiologists will be necessary if microbial material is present), solution composition (temperature, pH, ionic strength, etc.). Any particles would be characterized through X-ray and electron based techniques; and interface chemical properties would be studied, (e.g. kinetic studies of adsorption/desorption reactions, application of existing experimental models and predictions, determining the extent of permanent adsorbate sequestration, links between initial adsorption and precipitation of amorphous/crystalline phases.

In collaboration with hydrogeologists, the scope and 'scalability' could be expanded greatly. In the first instance, the behavior of submicron particles would be studied further. Using tracer and reactive transport experiments various particulate materials could be injected into an isolated system, permitting examination of the sorption properties of the added particulates, determining whether dissolution and alteration of host minerals are accelerated, and whether certain contaminants/metals are selectively adsorbed and transported. Alternatively, the chemistry of the interstitial water could be varied e.g. changing pH, adding metals, and short-duration temperature variations - again the effects of host mineral and particulate transport, etc. would be investigated.

In a second task, the role of organic acids would be investigated further. The proposed research would need to be completed in collaboration with long-term heater studies. Following an initial base-level study, brines comprising organic acids would be allowed to infiltrate a heated (>60°C) rock unit. At selected intervals over a period of years, interstitial water compositions would be analyzed for changes in metal and organic acid composition, pH changes, ionic strength etc. Solution composition monitoring would be combined with solubility, porosity and permeability studies. Predictions made using the existing thermodynamic data bases would be evaluated with respect to the field measurements.

### Sulfide Weathering - Anthropogenic Alteration

*Acid mine/rock drainage (AMD) is a multi-billion dollar problem in North America; therefore, much studied, but still not fully understood. Conversely, AMD is responsible for the supergene enrichment of some ore deposits (Anderson, 1955).*

**Background:** The oxidation of metal sulfide minerals can generate solutions with pH values as low as negative 3.6. AMD can be generated in any locality where sulfide minerals are exposed to aerobic weathering processes, most frequently mine workings and waste. The reaction most commonly responsible for the formation of AMD is the oxidation of pyrite in the presence of water, this process is accelerated dramatically by microbial mediated reactions (Nordstrom and Alpers, 1999).

AMD sites are almost exclusively studied after extensive environmental degradation, including the formation of extremely acidic run-off waters and metal contamination. Exotic alteration and secondary minerals, efflorescent salts, and amorphous iron-hydroxyl phases are frequently associated with AMD systems (Plumlee, 1999). With time, the amorphous iron-hydroxyl phases alter to meta-stable and stable crystal forms, which may sequester toxic elements (e.g. As, Se, Pb); alternatively, supergene enrichment may occur.

Research: An underground laboratory located in geological units comprising sulfide minerals provides a unique opportunity to study sulfide weathering from pristine (time zero) conditions. Initially, pristine sulfide and host mineral samples would be collected, i.e. exact redox conditions would be maintained. This sampling may be coupled with geomicrobiology sampling, which will require that samples be collected without introducing contaminants. Very detailed surface studies of the samples will be performed to establish 'base-line' conditions prior to any weathering (e.g. the task discussed above), then alteration kinetics may be monitored over time scales from the initial few seconds following exposure to oxidizing conditions, to durations of several years. Small samples would be collected over the varied time frame from a focused study area. Furthermore, additional weathering information will be available from mined areas within the Homestake mine that have been exposed for several decades.

The sulfide weathering studies would focus on measuring *in situ* kinetics of AMD generation, determining the influence of microbial communities on AMD processes, monitoring surface alteration of sulfide minerals including formation of secondary phases, and monitoring changes in AMD solution composition including release and transport of toxic elements (e.g. As, Se) or precipitation of secondary minerals. The AMD solution component of this study could be combined with metal mobility and transport studies described above. Furthermore, the need for field-deployable, long-term, remote-monitoring instruments may promote the use and specific design of microelectromechanical systems (MEMS) for geochemical field applications.

#### Additional Studies

- Geochemistry of reaction barriers: coupled with hydrogeology studies
- Long-term remote geochemical monitoring of all waters: interstitial, mine, tunnel seepage, etc.
- Application of specifically designed long-term monitoring techniques e.g. MEMS.

## **ISOTOPE GEOCHEMISTRY**

### **Stable Isotope Labeling of Microbial Material – John Valley (University of Wisconsin)**

NESS offers unique opportunities for investigating the geochemical interactions of non-photosynthetic biota with minerals, liquids and gas in their environment. One of the challenges in such studies will be the identification and isolation of experimental organisms while maintaining a natural setting. These are low productivity systems and the act of observing them increases the potential for surface- or human-derived contamination. Stable isotope labels offer a non-poisonous solution, but they must be applied at a scale appropriate to the investigation. For complex microbial communities, this requires resolution of single organisms at the  $\mu\text{m}$ -scale.

New technology employing an ion microprobe/secondary ion mass-spectrometer (SIMS) allows measurement of stable isotope ratios *in situ* from small spots on a microscope slide. There is a trade-off of sample size to accuracy:  $\pm 1\%$  at  $20\mu\text{m}$  (Valley et al. 1998),  $\pm 10\%$  at  $2\mu\text{m}$  (Orphan et al. 2001), and  $\pm 100\%$  at  $<1\mu\text{m}$  (Lechene and Ito 2001). A wide range of experiments is possible and the use of compounds enriched in a rare stable isotope (i.e.,  $^{13}\text{C}$ ,  $^{15}\text{N}$ ,  $^{18}\text{O}$ ,  $^{36}\text{S}$ ,  $^{81}\text{Br}$ , etc.) will provide isotope contrast much greater than 1000 and at sub- $\mu\text{m}$  spatial resolution. In an extreme example, it was possible to independently label DNA and RNA and to determine areas of co-localization at the sub-cellular scale in single rat embryo fibroblasts (Lechene and Ito 2001). At a slightly larger scale, it is possible to stain and image microbes with DNA or RNA-specific Fluorescent In Situ Hybridization (FISH) and then to analyze the isotope ratio of single identified cells by ion microprobe (FISH-SIMS, Orphan et al. 2001).

Many areas have been identified for subsurface study of geomicrobiology at NESS, which will particularly benefit from the FISH-SIMS approach, including study of microbes concentrated at the gas/liquid interface (T Onstott), insertion of colonizable/ retrievable substrates (F Colwell), and injection of surface organisms into instrumented fractures at depth (T Kieft). Stable isotope labels will enable researchers to identify new organisms grown as part of each experiment, providing a census at time-0 for each experiment and eliminating contaminants. In addition, isotopically labeled mineral and fluid nutrients can be injected to assess various metabolic pathways. The site of growth can be identified for specific organisms and mineral interfaces evaluated as inert substrate vs. nutrient.

Experiments of the type proposed here are practical today, but will require close collaboration in experimental design, sample preparation and analysis between researchers at NESS and scientists at a multi-collector ion microprobe laboratory that is dedicated to analysis of stable isotope ratios.

### **Sulfur Isotopic Studies** (E.M. Ripley, Indiana University)

The recent discovery by Farquhar *et al.* (2000) of mass-independent fractionation of S isotopes ( $\delta^{33}\text{S}$ ,  $\delta^{34}\text{S}$ ,  $\delta^{36}\text{S}$  of both sulfide and sulfate) in rocks older than ~2090 Ma has led to the postulation that atmospheric conditions changed from anoxic to oxic at approximately this time. Farquhar *et al.* (2000) suggest that gas-phase atmospheric reactions control the isotopic systematics, and that atmospheric photolysis via ultraviolet light in the absence of an ozone shield is responsible for the mass-independent fractionation observed in the old rocks.

Rye and Rye (1974) demonstrated that the  $\delta^{34}\text{S}$  values of S in the Ellison, Homestake, and Pooman formations varied between ~1 and 30‰. The  $\delta^{34}\text{S}$  values of each formation are different, suggesting that the S in the ore minerals was derived from local sedimentary sources. Elevated  $\delta^{34}\text{S}$  values suggest that bacterial sulfate reduction may have been an important process during formation of the Precambrian sedimentary units. Rye and Rye (1974) and Rye and Shelton (1983) suggested that S and metals accumulated in the rocks as part of a seafloor hydrothermal vent system. Later metamorphism caused the movement of the sulfur and metals into dilatant zones consisting primarily of veins in fold hinges or cross folds. More recent studies by Caddey *et al.* (1990) and Bachman *et al.* (1990) have suggested an epigenetic, shear-controlled, origin for the ores and a Precambrian, rather than Tertiary, age.

The age of the metasedimentary rocks is bracketed by those of the ~2.5 Ga Little Bear and Elk Creek granite gneisses, and the 1.7 Ga Harney Peak Granite (Krogstad *et al.*, 1993). Most researchers assign an Early Proterozoic age to the metasedimentary units. It would be of interest to investigate the S-bearing units to determine if mass-independent isotopic fractionation is detectable. If the S is of syngenetic origin, it is older than ~2.0 Ga and mass-independent fractionation should be present. If the mineralization was epigenetic and derived from igneous sources, mass-independent fractionation should be absent. In any case we should learn more not only about the origin of the sulfide and gold mineralization, but also about the nature and preservation of mass-independent S isotopic fractionation, and how bacterial sulfate reduction may retard or enhance the isotopic effects.

### **Radiogenic Isotope Geochemistry** (Joaquin Ruiz, University of Arizona)

The primary source of production to depths of about 3 meters in the lithosphere of low-level radionuclides (such as  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$ ) and trace stable nuclides such as Ne and Ar is spallation from secondary cosmic radiation (mostly neutrons). From 3 to about 50 meter depths, the primary source of production are interactions with muons (Heisinger *et al.*, 2002a, 2002b). Below 50 meter depths, the primary source of production (and at a low level) of such nuclides are reactions with neutrons originating from the spontaneous fission of  $^{238}\text{U}$  and from decays of  $^{235}\text{U}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$ . This radiogenic production of nuclides has been of interest for many years and was first discussed by Wetherill (1953). Fission products such as  $^{85}\text{Kr}$  and  $^{129}\text{I}$  are also of interest, as are the cosmogenic radionuclides  $^{39}\text{Ar}$ ,  $^{81}\text{Kr}$ .

Andrews *et al.* (1989) discussed the subsurface production of radionuclides in great detail with reference to the Stripa mine project in Sweden. These authors studied the subsurface neutron flux and limits on production of *in-situ*-produced radionuclides. Heisinger & Nolte (2000) discuss generally the production rates from muons and compare them to spallation from cosmic rays. The production rate at the surface is ~0.01 to 0.001 of the production rate from spallation by nucleons in cosmic rays. At depth, muons become increasingly important. These authors calculated the production rates for several radionuclides down to ~1000 meter depth of water equivalent. The levels at 1-2 kilometer depths would be extremely small and production from radiogenic sources would be a serious problem.

Further tests of these phenomena are needed and could be carried out by way of an experiment that monitored the flux of various secondary cosmic-ray particles from the surface to depths of about ~100 meters. A very deep mine environment would also be useful to establish the blank levels that can be achieved in extractions of noble gases and radionuclides from rocks used in cosmogenic surface-exposure dating, and the production of various nuclides caused by radiogenic processes could be studied.

## **REGIONAL AND ORE DEPOSIT GEOLOGY**

**Igneous and Magmatic-Hydrothermal Research** (Philip A. Candela Department of Geology, University of Maryland, College Park, Maryland, 20742-4211)

Gold has been produced from the world class Homestake Mine, a Precambrian iron formation-hosted deposit in Lead, South Dakota since 1876. Whereas the main deposit is clearly non-magmatic, the Precambrian phyllites hosting the Homestake ore are cut by mineralized Tertiary rhyolite and related dikes that are spatially associated with hydrothermal Ag-Au-Pb-Zn-Mo-Cu mineralization (Unzunlar et al., 1990, Hariri et al, 1995). Both dikes and mineralization are well exposed in the mine.

The emplacement of the tertiary intrusions, which are exposed over a 9000 foot (~3 kilometer) interval in the mine, resulted in the uplift of the Lead-Deadwood dome, the dominant geomorphic feature of the Homestake region. The dikes are variably altered, porphyritic, and variably textured. The mineralization comprises auriferous pyrite with quartz, anhydrite and molybdenite as well as argentiferous galena with chalcopyrite, sphalerite, and fluorite. The veins show lateral as well as vertical zoning (Unzunlar et al, 1990), with Au-Mo-Bi-Cu increasing with depth, suggesting that the magmatic-hydrothermal system of the Homestake mine represents the top-most portion of a buried porphyry-type ore system. Mine workings extend to a depth of 8000 feet and core is available from depths extending to 13,000 feet, allowing the three dimensional structure of the upper levels of this fossil magmatic-hydrothermal system to be studied in great detail. This unique environment suggests a number of possible directions for research on magmatic and hydrothermal systems, all of which should be priorities for the future.

1) The excellent vertical and lateral exposure will allow researchers to fully explore the uppermost reaches of a buried porphyry-type system, and will allow an integrated structural, geochemical and mineralogical study of a system that contains precious (Ag, Au), base (Cu, Zn, Pb) and ferrous alloy (Mo) metals, complete with observed lateral and vertical zoning.

2) The structural interplay between diking and veining should become a fertile area of research that bridges the fields of igneous geology, hydrology, structural geology and economic geology. Why are some fractures filled with magma, whereas others are conduits for hydrothermal fluids? How do near-field and far-field stresses combine and change with time and space, and how do they influence the magmatic and hydrothermal products?

3) When the time scale of igneous crystallization (i.e., the time scales of nucleation and growth) is greater or equal to the time scale of igneous cooling, textural variability results (cf. Hort and Spohn, 1991). These conditions are satisfied by many shallow dike systems, and the 3-D exposure at Homestake will allow for extensive study of igneous textures in the dike complex, and their relation to undercooling, magma transport, etc.

4) The detailed study of zoning of ore mineralogy, as well as ore, gangue, and alteration mineral compositions for major, minor and trace elements and isotopes by LAICPMS and other state of the art methods can be performed, allowing a detailed understanding of the 3-D chemical structure of a magmatic-hydrothermal system.

### **Ore Geology Research** (Ed Duke, SD School of Mines and Technology)

*Giant metamorphic-hydrothermal system.* The network of mineralized quartz veins in Homestake mine is an enormous mid-crustal fluid flow system. Simple calculations based on the amount of gold or the amount of quartz in the veins require that an immense volume of hydrothermal solution passed through the crust in this area. The exact nature of this fluid-flow system, the reasons that it localized at the Homestake mine, and longevity of the system are fundamentally important geochemical questions for our understanding of the evolution of Earth's crust.

The Homestake mine provides an unprecedented three-dimensional environment to study this giant hydrothermal system. The quartz veins are exposed almost continuously over approximately 11,000 feet of length as they plunge to the southeast in the mine. Physical and chemical changes in the fluid/wallrock system can be evaluated over this interval using chemical, isotopic, and fluid inclusion techniques.

Virtually all gold mineralization at the Homestake mine occurs in the Homestake formation, a relatively thin sedimentary rock unit that has been metamorphosed and tightly folded during Lower Proterozoic orogenic events (approx. 1.7-1.8 Ga) (Caddey et al., 1990; Redden et al., 1990). The Homestake formation is generally considered an iron-formation, an unusual type of chemical sedimentary rock that apparently formed in greater abundance during the Lower Proterozoic when the earth's

atmosphere and oceans were first developing free oxygen. The chemistry of the Homestake formation, however, is unlike typical iron formations; it has more Al, K, and REE and appears to represent a mixture of chemical sedimentation, perhaps from seafloor hydrothermal vents, and normal fine clastic input similar to marine shales or volcanic tuffs (DeWitt, 1996). Geologists have long debated about the possible concentration of gold and other metals in the original chemical sediment and whether most of the gold at Homestake was syngenetic and only redistributed into quartz veins during subsequent deformation and metamorphic events. Modern geochemical and isotopic methods may help pinpoint the nature of the Homestake formation, produce a better understanding of the unique sedimentary and tectonic environment in which it formed, and determine the relative importance of syngenetic mineralization. The Homestake mine offers a unique opportunity to sample and study this rock over a great vertical and lateral extent, at different metamorphic grades, and in mineralized and unmineralized occurrences.

*Metamorphic processes and gold mineralization.* In addition to the vertical sampling opportunities, there are also critical changes laterally (roughly east-west) in the mine that may have been important to the development of this unique system. (Some levels in the mine extend as much as 3 km in the east-west direction.) A steep metamorphic gradient exists in the mine; metamorphic temperature estimates for the western ledges (or ore zones) are ~360°C, whereas those in the eastern ledges are roughly 580°C (Kath and Redden, 1990). The garnet isograd is well exposed in the mine and appears to have a near vertical orientation. The reasons for this metamorphic setting are poorly known but it appears likely that it had a profound influence on the development of the hydrothermal system and subsequent gold mineralization.

A key question centers on metamorphic devolatilization reactions in the Homestake formation; at low metamorphic grade in the eastern part of the mine it is composed primarily of iron-bearing carbonates (siderite and ankerite). In the western part of the mine where it is more metamorphosed, the carbonates have reacted to form iron silicates including grunerite, almandine, and iron-rich biotite. Devolatilization would have produced vast amounts of metamorphic fluids rich in H<sub>2</sub>O and CO<sub>2</sub>; these could serve to mobilize gold and other metals. Equally important, the production of these fluids could fracture the rocks, providing pathways for fluid flow, and the loss of volatile components would result in significant decrease in volume of the solid rock (approx. 30% volume decrease), which would further promote fluid flow and plastic deformation. Indeed, the Homestake formation appears to be thinner and more highly deformed west of the garnet isograd, possibly reflecting the devolatilization process. (See Powerpoint slides.)

Combined petrologic and geochemical studies including geothermobarometry, stable isotope research, fluid inclusion analysis, and thermochronometry are required to evaluate the role of metamorphic processes in the development of the Homestake gold deposit. It is important to compare not only mineralogy but also trace element geochemistry of west/shallow with east/deep parts of the mine to see if devolatilization reactions have occurred and to determine whether these reactions could be the source of gold or other metals.

Another question that should be addressed is the potential role of granitic plutons in the structural, metamorphic, and hydrothermal development in the Homestake mine area. A buried leucogranite-pegmatite body similar in character to the Harney Peak granite in the southern Black Hills lies within 10 km of the mine to the northwest. It appears to have affected the metamorphic gradient in the mine area, and it is not known whether any of the ore bearing fluids were actually derived from the granite.

*Local and regional tectonic setting.* Many gold provinces, such as those in eastern Canada, are located on major structural features or shear zones that penetrate deep into or through the continental crust. Petrologic and geochemical studies in and around the Homestake mine may clarify the role of deep crustal structures in localizing fluid flow and gold mineralization. Coupled with deep seismic and other geophysical measurements proposed for the mine, these studies may lead to a better understanding of regional crustal structure beneath the northern Great Plains and details of continental growth during the Lower Proterozoic.

Precambrian rocks exposed in the Black Hills are largely Lower Proterozoic in age, but include minor Archean rocks similar to the Wyoming Archean Province to the west. Most workers believe that the boundary between the Wyoming Archean Province on the west and the southern extension of the ~1.8 Ga Trans-Hudson Orogenic belt lies just east of the Black Hills beneath the prairie. North-northwest-trending shear zones in the mine appear to be part of a more extensive structural trend that strikes southward through the Proterozoic rocks of the Black Hills. It is possible that this structural trend

parallels, and is controlled by, the deep crustal margin of the Wyoming Province. (See Powerpoint slides.)

Also, a west-northwest-trending belt of Tertiary igneous bodies strikes through mine, and it has been proposed that this too is an expression of a deep crustal discontinuity active from the Lower Proterozoic through the Tertiary. Within this Tertiary trend, the Homestake mine lies close to the transition from alkalic (west) to subalkalic (east) igneous rocks. This petrogenetic relationship further points to deep-seated differences in the crust or upper mantle beneath the Homestake mine area. If research shows that the Homestake deposit is indeed localized on such deep structures, that may indicate that some of the mineralizing fluids are actually of very deep crustal (or even upper mantle) origin, a possibility that would be of great importance to our understanding of the movement of fluids in Earth's crust.

*Thermal and uplift history.* For several reasons, a better knowledge of the thermal history of the mine (Proterozoic to present) would be valuable. The P-T-t path in the Proterozoic is sketchy, and the microbiologists want to know how old their ecosystem might be. They consider apatite fission track ages (cooling through ~120°C) to be a good indicator. For parts of the Homestake mine affected by Tertiary intrusive and hydrothermal activity this age could be <40 Ma, for other parts of mine the age could be >1.5 Ga). In addition, the Laramide thermal and uplift history is important in developing models for the modern groundwater flow system, which will be valuable information for geohydrologic researchers.

**Underground Mine Mapping** (George Brimhall, University of California, Berkeley; William A. Wright, Barrick Gold Corporation, Reno, NV)

We propose establishment of a technical center in the Homestake mine to serve as a centralized national facility for advancing underground mine mapping technology and for workforce training in digital methods and information technology. Several circumstances motivate this initiative. First, we have already developed effective digital mapping and core logging methods (Brimhall and Vanegas, 2001ab; Montero and Brimhall, 2002ab) using state-of-the-art data capture software and laser hardware. Our system will function under extreme physical conditions for a broad spectrum of geological environments, including above ground, underground, and from airborne platforms. Second, while the U.S. is one of the major gold producers globally, open pit mining eventually reaches an economic limit of stripping ratio and is superseded by underground methods, requiring a workforce of geologists equipped and trained to work safely and productively under extreme physical conditions. Finally, relatively few universities currently provide training in mining geology and the on-site training once routinely provided by corporations for their technical staff is becoming a rarity. Hence, justification of the new center lies in improving and expanding the technical workforce productivity through advancing the quality, efficiency, and uniformity in scientific and technical standards of mine mapping and related activities. The full array of data acquisition activities will be enhanced, including core logging, database management, and three dimensional modeling of ore deposit structure, wall rock alteration, geo-technical properties, feasibility, development, and production. We will help insure the relevance of the work undertaken to professional industrial geology. Critical factors considered include assurance that technology used really does contribute importantly to the productivity of mappers, the quality of the data generated and the enhancement of the scientific uses of the information in the mine development and mining process, and environmental management. Geological and mineral controls on ore will be the focus of the center. Application of new digital mapping and core logging methods will make the geological records created more quantitative and will afford enhanced opportunities for data acquisition through new hyperspectral infrared methods. The laser/spectrometer combinations we have employed not only provide quantitative mineralogical data but will also function remotely, if necessary, so that a mapper can determine dominant minerals at distances up to 100 meters in, for example, large stopes where direct access is impossible or safety conditions are challenging. Research and training will include digital mine mapping, core logging, ore grade control, geo-technical rock mass characterization, as well as centralized database management and interpretation in 3-D GIS systems doing geospatial modeling, ore reserve estimation, analysis of 3-D structural data, ore grade, and recovery optimization. As an example, by combining assays for metals and sulfur, modal sulfide abundances will be calculated much more accurately than by current visual estimation procedures. Hence, useful indicator minerals for precious metals will be quantitatively correlated with precious metal assays, yielding new quantitative information about the distribution of gold occluded in indicator minerals. Variability in occluded gold associations will then be determined so that metallurgical differentiation of barren and gold-bearing phases becomes economically feasible. Research scientists and staff geologists

from mines throughout the world will be able to not only learn the new digital mapping methodologies, but will be encouraged to bring data sets for collaborative application of the new technologies.

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