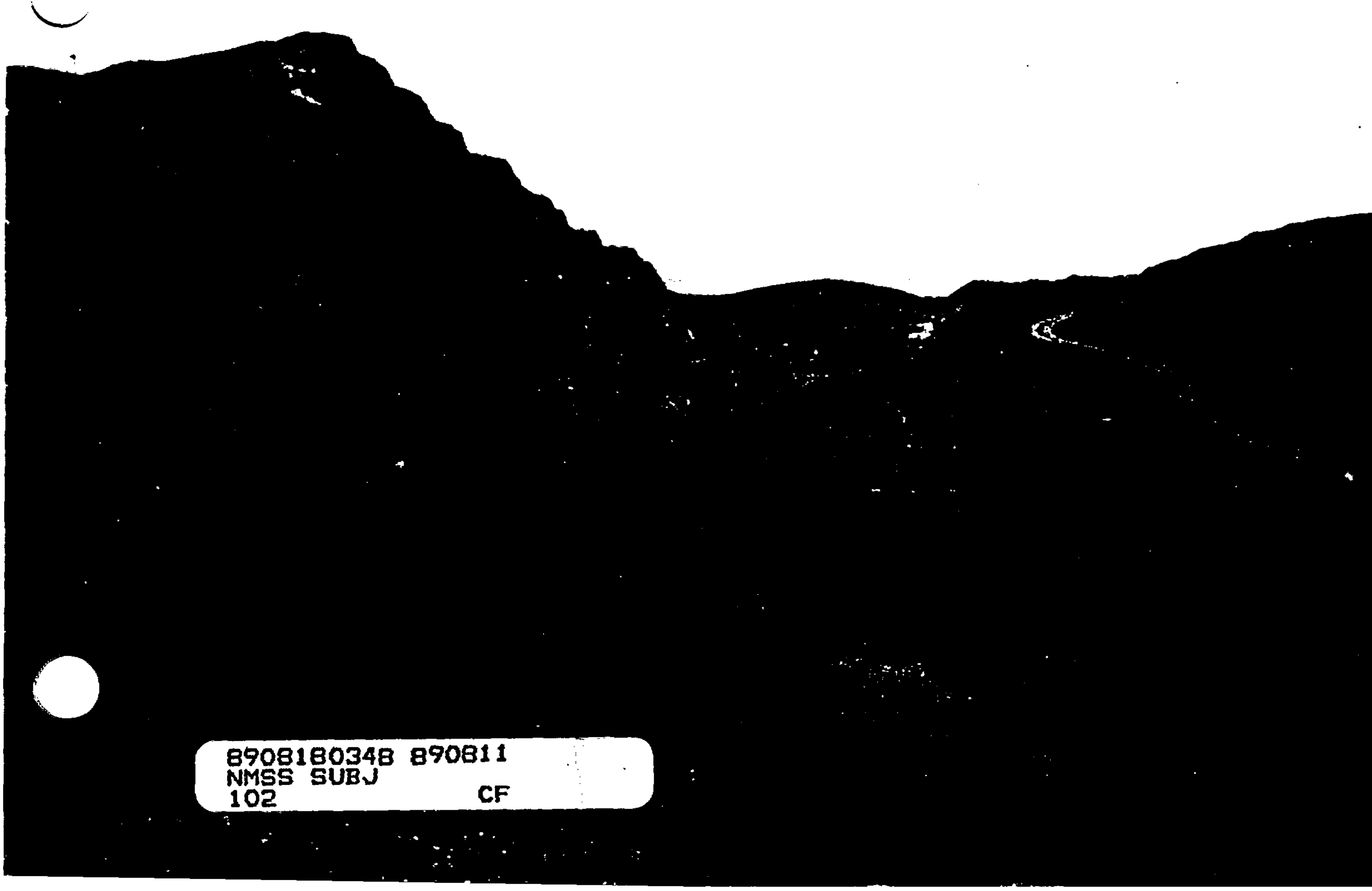
ENCLOSURE 3

USGS Research on Mineral Resources—1989 Program and Abstracts

Fifth Annual V.E. McKelvey Forum on Mineral and Energy Resources

U.S. GEOLOGICAL SURVEY CIRCULAR 1035



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ENCLOSURE 4

TECTONIC ANALYSIS GROUP, INC.

8020 Braesmain, Suite 1802 • Houston, Texas 77025

TECTONIC SYNTHESIS OF THE CENTRAL WALKER LANE

Project: The project is a synthesis of the Mesozoic and Cenozoic regional geology of the central Walker Lane (Fig. 1) and adjacent regions in Nevada and California. Tectonic analysis focuses on the Tertiary evolution of extensional and strike-slip fault systems, particularly in light of their relationship to the development of low-angle detachment faults. Geochronological data are combined with sequence-stratigraphic techniques to define regionally extensive sequences of volcanic and volcaniclastic units. The geometric and kinematic relations of these regionally extensive stratigraphic markers with various Tertiary and pre-Tertiary structures allow recognition of major structural domains. Kinematic analysis of Tertiary structures reveals regional variations in extension direction through time. The spatial and secular change in the extension direction is related to the history of Tertiary and Quaternary faulting. Mineralization is controlled, at least in part, by Tertiary structures and trends can be placed in a regional framework by recognition of the distribution of structural domains and unconformity bound stratigraphic units. Additional subsurface control for the distribution of Tertiary structural domains is constrained by application of Bouguer and Isostatic Residual gravity analysis coupled with residual aeromagnetic data for the region.

Report: The results of this study are presented in a technical report supported by:

1) about eight 30 minute quadrangle geologic maps (scale of 1:100,000) of the central Walker Lane, depicting pre-Tertiary and Cenozoic structures and the distribution of pre-Tertiary and Cenozoic lithologic units;

2) a regional tectonic map of the central Walker Lane compiled at a scale of 1:250,000;

3) terrain corrected Bouguer and Isostatic Residual gravity maps of the central Walker Lane and adjacent areas at a scale of 1:250,000, and;

4) a residual aeromagnetic map of the central Walker Lane and adjacent areas at a scale of 1:250,000.

Delivery: The report and maps will be available for delivery on May 1, 1989.

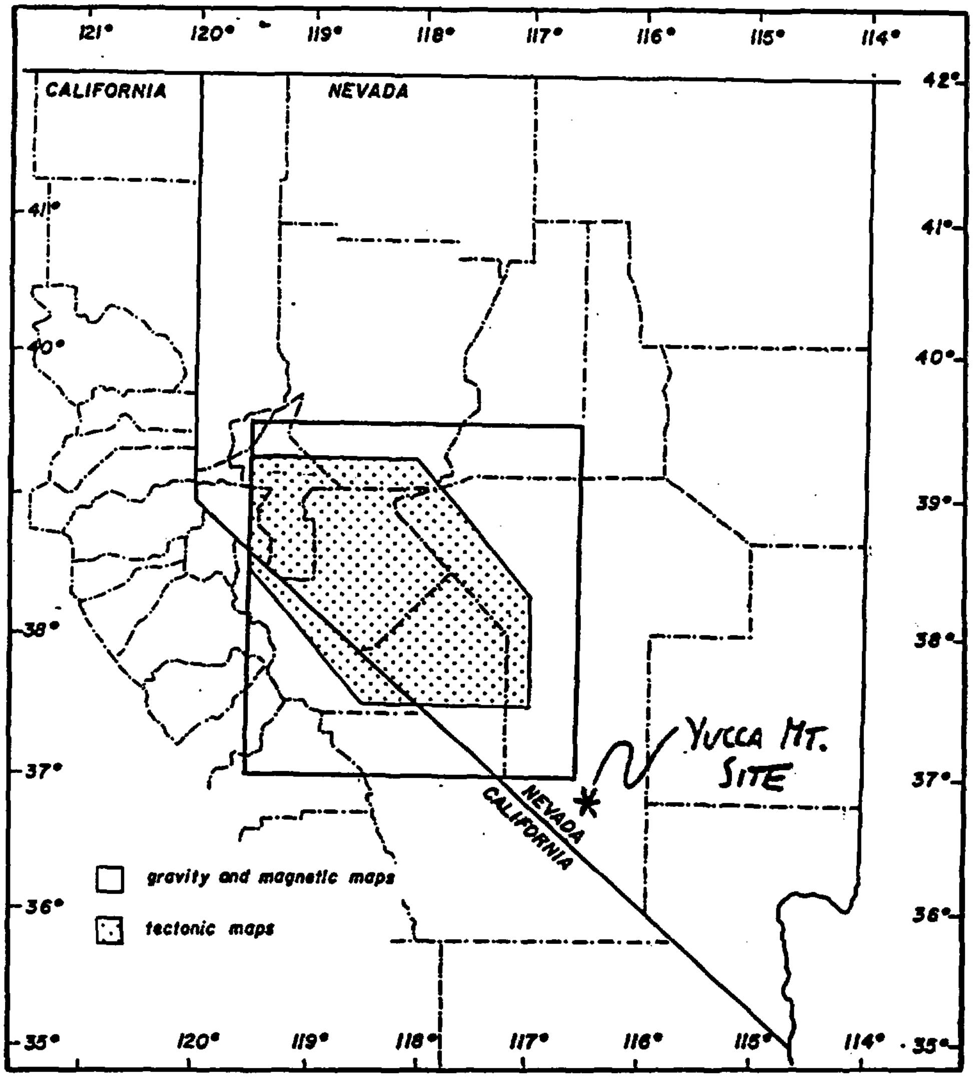

Figure 1 Index map of study area.

Date:____________________

Dr. John S. Oldow
President
Tectonic Analysis Group, Inc.
8020 Braesmain, Suite 1802
Houston, Texas 77025

PROSPECTUS

TECTONIC SYNTHESIS OF THE CENTRAL WALKER LANE

We are interested in receiving additional information concerning the above referenced regional study from Tectonic Analysis Group, Inc.

Signed on behalf of: Company:________________________________

Name:________________________________

Address:________________________________

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By: Name:________________________________

Title:________________________________

Signature:________________________________

ENCLOSURE 3

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A view of the main ore zone at the Carlin mine, Nevada. Popovich Hill is on the left and is underlain by carbonaceous rocks of the Silurian Roberts Mountains Formation. The discovery of this disseminated gold deposit in the 1960's inspired much of the subsequent gold exploration in the Western United States.

USGS Research on Mineral Resources—1989

Program and Abstracts

Edited by Katharine S. Schindler

Fifth Annual V.E. McKelvey Forum on Mineral and Energy Resources

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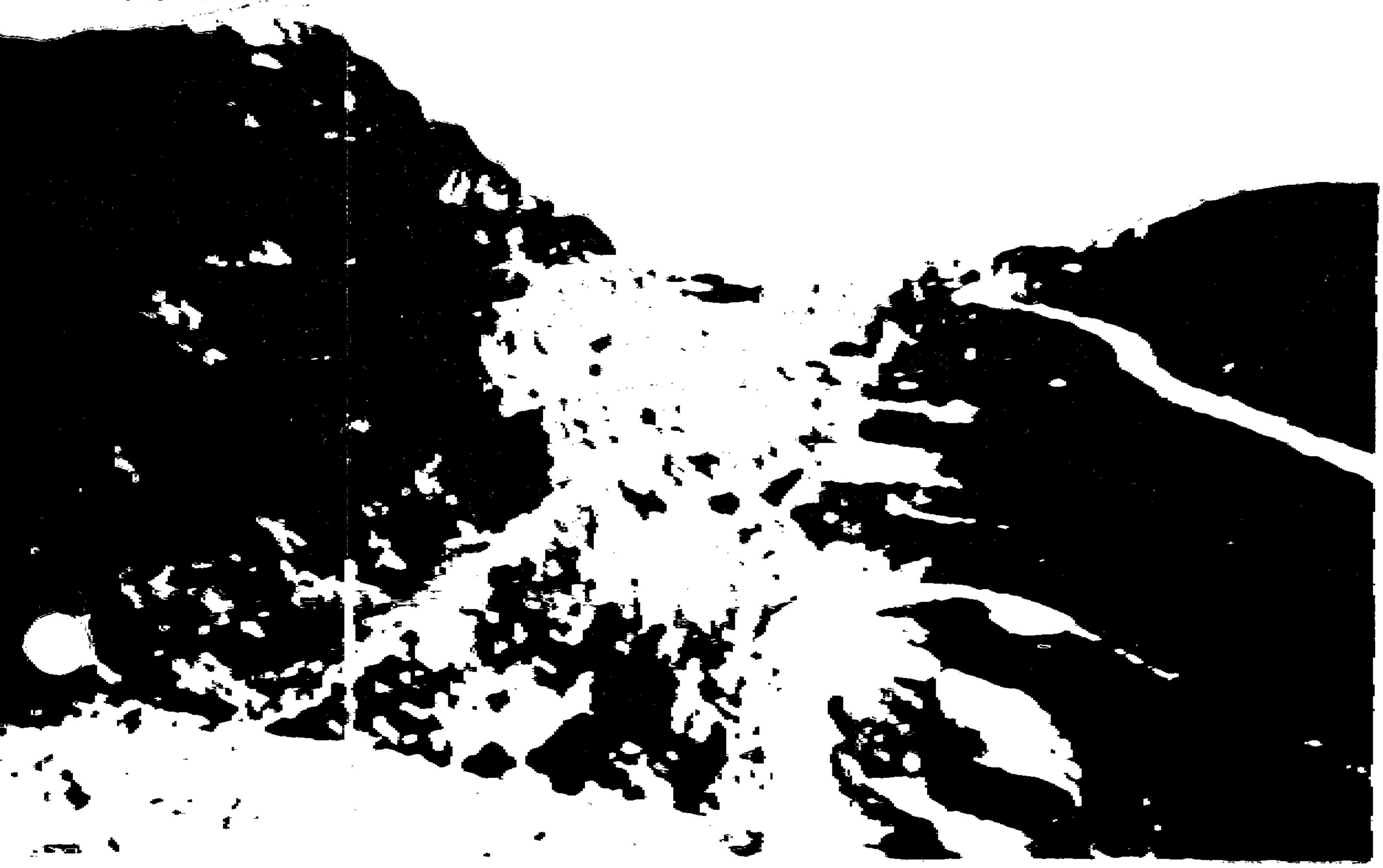

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A society's wealth depends on the use it makes of raw materials, energy, and especially ingenuity.
—V.E. McKelvey

FOREWORD

The V.E. McKelvey Forum is named for Vincent E. McKelvey in recognition of his lifelong contributions in mineral and energy resources as a research scientist, as Chief Geologist of the U.S. Geological Survey (USGS), and as Director of the USGS. The Forum is an annual event, and its purpose is to encourage direct communication between USGS scientists and earth scientists in the private sector, academia, and other government agencies. The first four V.E. McKelvey Forums have been well attended and clearly have been successful in fostering better communication.

Traditionally, the subject of the Forum has alternated between mineral and energy resources. This year the focus is again on minerals and has as its general theme collaborative research between the USGS and co-workers from industry, academia, and other State and Federal Government agencies. I am extremely pleased to report that the abstracts in this volume attest to a healthy interaction with our counterparts in the rest of the earth science community. We hope that this Forum will foster additional collaborative studies.

As a result of responses we have received during past Forums, our programs are taking some new directions. Current mineral-resource programs in the USGS include basic research on ore-deposit systems, studies of strategic and critical minerals, and the evaluation of the mineral resources of specific regions. These programs support diverse work such as the development of geochemical and geophysical exploration techniques, the detailed geologic study of specific mineral deposits, evaluation of unconventional environments for strategic commodities, and the assessment of resources of public lands.

The papers for the 1989 Forum cover these topics as well as many other areas and demonstrate the wide range of topics that characterize USGS research. However, because of the location of the Forum in Reno, Nev., there is a special emphasis on gold and other precious-metal deposits in the Western United States. The diverse topics covered in this Forum include airborne geophysical studies of concealed mineral deposits in Nevada and elsewhere, evaluation of the regional geological factors controlling the occurrence of disseminated gold deposits, mineral-resource assessments of the midcontinent area, presentations of new digital techniques for geologic mapping and the handling of mineral information, studies of offshore deposits of titanium and of ferromanganese and polymetallic sulfides, and specific deposit studies of Red Dog, Alaska; Paradise Peak, Jerritt Canyon, Battle Mountain, and the Comstock Lode, Nev.; Mesquite, Calif.; Gilman, Colo.; and Bayan Obo, China.

I am pleased with the success of previous Forums, and I look forward to a productive and enlightening meeting in 1989. We welcome the opportunity to discuss USGS research with our colleagues and to hear suggestions that will help us serve the mineral resource needs of the Nation.

Dallas L. Peck
Director

An Introduction to the Mineral Resources Programs of the U.S. Geological Survey

Over the last decade, there has been a dramatic increase in public concern over issues related to the availability of minerals, the use of public lands, and the environment. To a large extent, these concerns have directly affected the nature of mineral-related investigations. These investigations, which have been carried out by geoscientists in academia, government, and industry, are essential to making informed decisions on land use, mineral exploration, and mineral development. As in 1985 and 1987, this year's Forum will highlight the results of recent and ongoing mineral-related research within the U.S. Geological Survey (USGS). The USGS has three national programs in mineral-related studies.

The *Development of Assessment Techniques Program* (DAT) is oriented principally toward basic and applied research on the origin and the geologic, geochemical, and geophysical expression of mineral-deposit systems. The program's goal is to develop concepts and techniques to improve the capability of identifying and evaluating mineral resources. To this end, the program supports a broad spectrum of multidisciplinary field and laboratory research directed toward understanding how mineral deposits form. DAT also supports research to develop new technologies that can be used to locate mineral deposits and to develop new methods to make areal mineral-resource assessments. In addition to specifically supporting research on the geologic characteristics of ore deposits, geochemical exploration techniques, geophysical exploration techniques, deposit and district studies, and laboratory research, the program also has developed three multidisciplinary research efforts that focus on (1) disseminated gold deposits, (2) the role of organics in ore deposits, and (3) the formation of polymetallic sulfide deposits.

The *Strategic and Critical Minerals Program* (SCM) provides a continuing assessment of the Nation's strategic mineral endowment. This information is essential for formulating a national mineral policy and for identifying secure foreign sources of strategic and critical minerals. Major activities within this program include (1) studies of geologic characteristics of major mineral commodities, (2) the development and maintenance of mineral data files that are used for research on the characteristics of mineral deposits and in the development of statistical techniques for mineral resource assessments, (3) the geologic study of domestic environments that may host deposits of strategic and critical minerals, (4) basic research on mineral-deposit genesis and metallogeny and other geologic studies that pertain to resource information analysis, and (5) support for international programs of mineral deposit data exchange and cooperative resource studies. Recently, a major new initiative has been approved for this program for work directed toward evaluating the mineral resources in covered areas of Alaska.

The *National Mineral Resources Assessment Program* (NAMRAP) provides the areal mineral resource information necessary for identifying, assessing, and facilitating the long-term mineral supply of the Nation. This program is most directly responsible for assessing the mineral resources of the Nation's public and other lands. These assessments, and supporting geologic, geochemical, and geophysical studies, provide extensive mineral resource information to the public, industry, academic communities, and all those who are concerned with national mineral policy and land use decisions. These mineral-resource studies include (1) large-scale studies (greater than 1:250,000) that recently have primarily involved mineral surveys of areas managed by the Bureau of Land Management, (2) studies of $1° \times 2°$ quadrangles (1:250,000) or similar sized areas, which involve multidisciplinary studies by geologists, geochemists, geophysicists, and mineral economists, (3) studies at scales of 1:250,000 to 1:1,000,000 that use published literature but involve little fieldwork, and (4) statewide and multistate syntheses of mineral resources.

These three programs support each other. They range from work that involves basic and fundamental mineral-deposit research (DAT) to studies that are more focused on specific commodities, geologic environments, and data acquisition (SCM) to very specific work directed toward the assessment of resources of specific tracts of land. The result is an integrated approach to national mineral-resource problems.

PROGRAM

TUESDAY, 24 JANUARY

7:00 to 10:00 PM POSTER SESSION

WEDNESDAY, 25 JANUARY

8:30 AM Welcome and opening remarks

8:40 AM An introduction to the research programs of the U.S. Geological Survey—by Michael P. Foose

9:00 AM Overview and preview of U.S. Geological Survey ore deposit research: Fifth Annual V.E. McKelvey Forum—by Lorraine H. Filipek

9:30 AM Methodology for analysis of concealed mineral resources in Nevada: A progress report—by Dennis P. Cox, Steve Ludington, Maureen G. Sherlock, Donald A. Singer, Byron R. Berger, Richard J. Blakely, John C. Dohrenwend, Donald F. Huber, Robert C. Jachens, Edwin H. McKee, Christopher M. Menges, Barry C. Moring, and Joe Tingley

10:00 AM Analysis of concealed mineral resources in Nevada: Constraints from gravity and magnetic studies—by Robert C. Jachens, Richard J. Blakely, and Barry C. Moring

10:30 AM COFFEE AND POSTER BREAK

11:00 AM KEYNOTE LECTURE: Modern geoscience in the quest for gold: An Australian perspective—by Richard W. Henley

12:00 LUNCH

1:00 PM The Getchell trend airborne geophysical demonstration project, north-central Nevada—by D.B. Hoover, V.J.S. Grauch, M.D. Krohn, V.F. Labson, and J.A. Pitkin

1:30 PM Geology and origin of the Jerritt Canyon sediment-hosted disseminated gold deposits, Nevada—by A.H. Hofstra, G.P. Landis, R.O. Rye, D.J. Birak, A.R. Dahl, W.E. Daly, and M.B. Jones

2:00 PM Volcanic-tectonic setting and geology of the Paradise Peak gold-silver-mercury deposit, Nye County, Nevada—by David A. John, Robert E. Thomason, Charles W. Clark, and Edwin H. McKee

2:30 PM Structural control on epithermal gold veins and breccias in the Mesquite district, southeastern California—by G.F. Willis, R.M. Tosdal, and S.L. Manske

3:00 PM COFFEE AND POSTER BREAK

3:30 PM INTRODUCTION (5 MINUTES): Evolution of the five Midcontinent CUSMAPs and the Midcontinent SCM project—by Walden P. Pratt

3:35 PM Late Cambrian lithofacies and their control on the Mississippi Valley-type mineralizing system in the Ozark region—by James R. Palmer and Timothy S. Hayes

4:00 PM Tectonic and stratigraphic control of subsurface geochemical patterns in the Ozark region—by R.L. Erickson, Barbara Chazin, M.S. Erickson, E.L. Mosier, and Helen Whitney

4:30 PM A conodont color alteration anomaly in central Indiana—Possibility of Mississippi Valley-type hydrothermal activity—by A.G. Harris, C.B. Rexroad, R.T. Lierman, and R.A. Askin

5:00 PM Proterozoic anorogenic granite-rhyolite terranes in the midcontinental United States—Possible hosts for Cu-, Au-, Ag-, U-, and REE-bearing iron-oxide deposits similar to the Olympic Dam orebody—by P.K. Sims, K.J. Schulz, and Eva B. Kisvarsanyi

7:00 PM DIRECTOR'S LECTURE: New perspectives on the interrelationship of tectonics and ore-forming processes in the Great Basin: Implications for exploration—by Byron R. Berger

8:00 to 10:00 PM POSTER SESSION

THURSDAY, 26 JANUARY

8:30 AM Evaluation of Advanced Visible and Infrared Imaging Spectrometer and other remotely sensed data for mineral exploration in semiarid terrains—by G.B. Bailey and J.L. Dwyer

9:00 AM Interpreting concealed range-front faults in Nevada from gravity and digital fault data and the significance for gold exploration—by V.J.S. Grauch and Don L. Sawatzky

9:30 AM Mosaic faulting as a guide to mineral exploration in the Richfield 1° × 2° quadrangle, western Utah—by Thomas A. Steven

10:00 AM Volcanism, extensional tectonics, and epithermal mineralization in the northern Basin and Range province, California, Nevada, Oregon, and Idaho—by James J. Rytuba

10:30 AM COFFEE AND POSTER BREAK

11:00 AM Genetic model for the carbonate-hosted Pb-Zn-Cu-Ag-Au manto-chimney deposits of the Gilman, Colorado district, based on fluid inclusion, stable isotope, geologic, and fission-track time-temperature studies—by D.W. Beaty, C.G. Cunningham, C.W. Naeser, and G.P. Landis

11:30 AM A deposit model for gold-bearing skarns—by Jane M. Hammarstrom, Greta J. Orris, James D. Bliss, and Ted G. Theodore

12:00 McKELVEY FORUM LUNCHEON
LUNCHEON ADDRESS: Gold-rich massive sulfides on the modern sea floor and their ancient analogs—by Steven D. Scott

2:00 PM Active deposition of sediment-hosted massive sulfide in Escanaba trough, Gorda Ridge—by Robert A. Zierenberg, J.M. Edmond, J.F. Grassle, A.C. Campbell, S.L. Ross, and W.C. Shanks III

2:30 PM Potential for epigenetic gold and sedex-type Pb-Zn-Ag-Ba deposits in the Taconic Allochthons, eastern New York and western Vermont—by John F. Slack and Kenneth C. Watts, Jr.

3:00 PM COFFEE AND POSTER BREAK

3:30 PM Early-middle Proterozoic unconformities: Unconventional sources for platinum group and precious metals—by Richard I. Grauch

4:00 PM Oxygen isotope map of the fossil hydrothermal system in the Comstock Lode mining district, Nevada—by Robert E. Criss, Duane E. Champion, and Mary F. Horan

4:30 PM Multiple sources for gold in the Juneau gold belt, Alaska—by Rainer J. Newberry and David A. Brew

5:00 PM Metallogenesis of lode mineral deposits of "mainland" Alaska—by Warren J. Nokleberg, Thomas K. Bundtzen, Donald J. Grybeck, and Thomas E. Smith

LIST OF POSTERS

I. GENERAL TOPICS and GEOLOGICAL INFORMATION SYSTEMS

1. Minerals Information Office—by Susan M. Marcus, Raymond E. Arndt, Paul G. Schruben, Carl Carlson, and Jane Jenness
2. Geologic-map information and where to find it—by H. Kit Fuller
3. The Development of Assessment Techniques Program (DAT) of the U.S. Geological Survey—by Michael P. Foose
4. The Strategic and Critical Minerals Program (SCM) of the U.S. Geological Survey—by William C. Bagby
5. A review of the proposed standard for digital cartographic data—by Robin G. Fegeas, Hedy J. Rossmeissl, and Robert D. Rugg
6. Multidisciplinary considerations in a digital geologic map—Applications and afterthoughts—by S.H. Moll, J.L. Dwyer, C.A. Wallace, J.E. Elliott, C.M. Trautwein, and J.E. Harrison
7. A simplified digital geologic map of Nevada for regional gold resource assessment—by S.P. Marsh, E. Sandoval, and J.L. Plesha
8. Three-dimensional characterization of regional structures using an advanced geographic information system—by D.B. Stewart, B.E. Wright, J.D. Unger, J.D. Phillips, and L.H. Liberty
9. Mineral resource assessment of the Butte 1° × 2° quadrangle using geographic information system technology—by J.E. Elliott, C.M. Trautwein, J.L. Dwyer, and S.H. Moll

II. MINERAL RESOURCE ASSESSMENTS

10. Mineral resource assessment of the White Mountains National Recreation Area, east-central Alaska—by Florence R. Weber, Thomas D. Light, Richard B. McCammon, and C. Dean Rinehart
11. Geology and mineral resources of the Port Moller region, western Alaska Peninsula, Aleutian Arc—by Frederic H. Wilson, Willis H. White, and Robert L. Detterman
12. Mineral resource assessment, Bendeleben and Solomon quadrangles, western Alaska—by Bruce M. Gamble
13. Regional geochemical studies of the Ajo and Lukeville 1° × 2° quadrangles, Arizona—by Harlan Barton and Paul K. Theobald
14. Delta CUSMAP Project: Mineral assessment in the Tintic-Deep Creek mineral belt of the eastern Great Basin, Utah—by Douglas B. Stoeser, Carol N. Gerlitz, Constance J. Nutt, Holly J. Stein, John Hand, Michael A. Shubat, and Judith L. Hannah
15. Geoelectric studies in the Delta, Utah, quadrangle—by D.L. Campbell and V.F. Labson
16. The Tooele 1° × 2° quadrangle, western Utah: An example of a CUSMAP preassessment study—by Holly J. Stein, Viki Bankey, C.G. Cunningham, David R. Zimbelman, Michael A. Shubat, David W. Brickey, D.L. Campbell, and M.H. Podwysocki
17. Precious-metal deposits in the Hailey and western Idaho Falls 1° × 2° quadrangles, Idaho—by Ronald G. Worl, Earl H. Bennett, Falma J. Moye, and P.K. Link
18. Gravity and magnetic anomaly patterns in mineral resource exploration, Hailey CUSMAP, Idaho—by M. Dean Kleinkopf
19. Geological studies of the International Falls and Roseau 1° × 2° CUSMAP quadrangles, northern Minnesota—by W.C. Day, T.L. Klein, D.L. Southwick, and K.J. Schulz
20. Regional geophysical studies for the International Falls and Roseau CUSMAP projects—by Robert J. Horton, Val W. Chandler, Robert E. Bracken, and James E. Case

III. INVESTIGATIONS OF MINERALIZING PROCESSES AND MINERALIZING SYSTEMS

A. Western U.S.

21. Geological and geophysical analysis of the subsurface geometry of basins in the central and western Great Basin: Implications for the analysis of concealed mineral resources in Nevada—by John C. Dohrenwend, Robert C. Jachens, Richard J. Blakely, Barry C. Moring, and Christopher M. Menges
22. Tertiary tectonic evolution of the central Walker Lane, western Nevada—by Richard P. Keller, John S. Oldow, Richard F. Hardyman, and John W. Geissman
23. Study of the stratigraphy of the gold-bearing Preble Formation near the type locality, north-central Nevada—Some benefits to exploration—by Dawn J. Madden-McGuire
24. Characterization of carbon in sediment-hosted disseminated gold mineralization at Jerritt Canyon, Nevada—by Joel Leventhal and A.H. Hofstra
25. Geology and geochemistry in the vicinity of the Adelaide Crown mine, Humboldt County, Nevada—by Theresa M. Cookro and Ted G. Theodore
26. Bismuth minerals associated with placer gold, Battle Mountain mining district, Nevada—by Ted G. Theodore, Gerald K. Czamanske, Terry E.C. Keith, and Robert L. Oscarson
27. $^{40}Ar/^{39}Ar$ studies of fluid inclusions in vein quartz from Battle Mountain, Nevada—by Brent D. Turrin, Edwin H. McKee, Ted G. Theodore, and James E. Conrad
28. Multiple ages of disseminated gold mineralization associated with volcanic cycles in southwestern Utah and adjacent Nevada—by W.R. Miller and J.B. McHugh
29. Reconstruction of primary features and isotopic evidence for multiple sulfur sources at the Red Dog zinc-lead-silver deposit, Noatak district, Alaska—by Jeanine M. Schmidt and Robert A. Zierenberg
30. Sulfur isotope characteristics of bedded and vein barite deposits, north-central Nevada—by Stephen S. Howe
31. Volcanogenic massive sulfide deposits in pre-Tertiary island arc and ocean basin environments in Nevada—by Maureen G. Sherlock
32. Composition and geologic setting of stratiform manganese deposits in the southern Basin and Range province—by Randolph A. Koski, Robin M. Bouse, James R. Hein, and Marilyn L. DeRosa
33. Industrial rock and mineral resources of Arizona: A survey of resource problems and opportunities by the producers and users of resource information—by Edwin W. Tooker and Larry D. Fellows
34. Preliminary map showing the location of productive lode and placer gold deposits and significant gold prospects in Montana—by David Frishman, J.E. Elliott, E.E. Foord, R.C. Pearson, and W.H. Raymond
35. As, Bi, Hg, S, Sb, and Te geochemistry of the J-M reef: Constraints on the origin of platinum group element-enriched sulfides in layered intrusions—by M.L. Zientek, T.L. Fries, and R.W. Vian

B. Midcontinent

C. Eastern U.S.

D. Marine Studies

E. International Studies

IV. GEOCHEMICAL INVESTIGATIONS

V. GEOPHYSICAL INVESTIGATIONS

Fifth Annual V.E. McKelvey Forum on Mineral and Energy Resources

USGS Research on Mineral Resources—1989 Program and Abstracts

Edited by Katharine S. Schindler

Evaluation of Advanced Visible and Infrared Imaging Spectrometer and Other Remotely Sensed Data for Mineral Exploration in Semiarid Terrains

G.B. Bailey and J.L. Dwyer

The principal role of remotely sensed data in mineral exploration is as a source of lithologic and structural information from which geologic interpretations important to the discovery of new mineral deposits can be made. The utility of remote sensing as an exploration tool has advanced dramatically since the launch of Landsat 1 in 1972, due in large measure to improvements in sensor technology, data processing capabilities, and data analysis and interpretation methodologies. Most significant have been advancements in the capability to discriminate lithologies and to determine and map rock compositions, especially in areas of good exposure. These advancements have resulted both from improvements in spectral characteristics and in spatial resolution of recent sensor systems.

The Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) is the most spectrally advanced land remote sensing system yet developed and is the prototype for a spaceborne sensor that will be launched in the mid-1990's. AVIRIS records reflected solar radiation between 0.4 and 2.5 μm in 220 spectral bands that are approximately 9.5 nm wide. The sensor is currently flown on board an ER–2 aircraft at an altitude of 20 km and acquires data over an 11-km swath at 20-m spatial resolution. The technical characteristics of AVIRIS are particularly significant to geologists working in semiarid terrains where rocks are typically well exposed. AVIRIS data from these terrains may provide geologists with improved capabilities to discriminate between different lithologies, detect rock alteration, and identify constituent mineralogies of rocks and alteration from remotely sensed data.

AVIRIS data were acquired over a test site in the Drum Mountains in west-central Utah where good exposures of many diverse rock and alteration types provide an environment well suited for geological evaluation of AVIRIS and other remotely sensed data. Rocks exposed in the field area include a thick sequence of west-dipping Cambrian and Precambrian carbonate and clastic rocks, a variety of mafic to silicic Tertiary volcanic rocks, two distinct intrusive stocks, and associated contact metamorphic rocks. The volcanic rocks have been hydrothermally altered in places, and some carbonate rocks adjacent to the volcanics have been bleached and recrystallized. One of the stocks is mineralized and exhibits intense hydrothermal alteration.

Digital AVIRIS data were analyzed and interpreted in conjunction with field spectral data, and various data products were created that display the types and amount of compositional information present in AVIRIS data. These results were compared with results of related studies that evaluated other remotely sensed data collected over the Drum Mountains test site. These data sets included Landsat multispectral scanner (MSS) and thematic mapper (TM) data, Systeme Probatoire d'Observation de la Terre (SPOT) 10-m panchromatic stereo data, and Thermal Infrared Multispectral Scanner (TIMS) data.

This paper presents the significant results and current status of these ongoing geologic remote sensing studies by describing and illustrating both the breadth of geologic information and the unique compositional information routinely available from each sensor system tested. Incremental improvements in geologic information content correspond to advancements in sensor systems and are illustrated by using data products that include mergers of enhanced TM data and 10-m SPOT data in stereo format.

Aeromagnetic and Gravity Studies of a Buried Porphyry Copper Deposit near Casa Grande, Arizona

Viki Bankey and Douglas P. Klein

The Casa Grande deposit (also known as the Santa Cruz deposit) is a buried porphyry copper deposit 7 mi west of the city of Casa Grande, Ariz. The prospect has been drilled in detail and ore was discovered between 1,000 and 2,000 ft below the surface in host rock consisting of Laramide porphyry intruded into Precambrian Oracle Granite. Diabase and other mafic dikes intrude the host rock. The deposit is similar to the Sacaton porphyry copper deposit located 6 mi northeast; both deposits are buried beneath alluvial cover and contain a host rock that consists equally of Precambrian granite and Laramide intrusive rock, unlike most porphyry copper deposits (Cummings, 1982). Sacaton and Casa Grande may have been parts of a single hydrothermal system that was later separated by faulting. The Casa Grande deposit lies along the extension of a structural lineament called the Jemez zone that trends northeast from Sacaton to Globe, Ariz.

Companies developing the deposit have proposed leaching the buried ore in place. The U.S. Geological Survey (USGS) and the U.S. Bureau of Mines are studying the geology and hydrology of the area to evaluate the environmental impact of the leaching technique and to prepare an ore deposit model. In support of the study, the USGS has recently flown two aeromagnetic surveys over the Casa Grande deposit: one flown 600 ft above terrain at ½-mi spacing and the other flown 300 ft above terrain at ¼-mi spacing. These data were modeled to determine the configuration of the basement and overlying basin. The Bouguer gravity anomaly data of the area were used to constrain the magnetic modeling.

The aeromagnetic map flown 300 ft above terrain shows a magnetic low about 2 mi in diameter surrounding the deposit and a 20-nanoTesla (nT) high centered over the deposit. A 15-nT high, also inside the relative magnetic low, occurs 1 mi northeast of the deposit. These anomalies are partially obscured by a steep, 120-nT/mi, east-northeast-trending gradient on the flanks of a 300-nT high, 2½-mi north of the deposit. The source of this northeast-trending, high-amplitude positive anomaly is hidden below alluvium. Our first task was to adequately remove this regional magnetic gradient to enhance the local anomalies. Several methods were compared, including (1) removing a two-dimensional surface calculated from the gridded aeromagnetic data by using orthogonal polynomials (USGS program SURFIT); (2) removing higher level aeromagnetic fields (such as the 600-ft field or upward continued fields) from the 300-ft magnetic field; and (3) removing a 120-nT/mi southeast-dipping gradient. Mathematical enhancement of the residual and the total fields was performed; enhancement consisted of calculating the horizontal gradient to create a boundary map that has density contrasts outlined. These functions bring out features existing in the aeromagnetic data that are not readily apparent.

The Bouguer gravity anomaly map was similarly analyzed to remove a regional gradient. The residual gravity anomaly map shows a 2-milligal high centered over the deposit.

Interpretation of aeromagnetic data began by incorporating other information, such as geologic mapping from drill holes and gravity mapping. Magnetic profiles were selected from flight lines crossing the deposit and were modeled by using the USGS program SAKI (Webring, 1985).

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Webring, Michael, 1985, SAKI: A Fortran program for generalized linear inversion of gravity and magnetic profiles: U.S. Geological Survey Open-File Report 85–122, 108 p.

Regional Geochemical Studies of the AJO and Lukeville 1° × 2° Quadrangles, Arizona

Harlan Barton and Paul K. Theobald

Regional geochemical studies were conducted during 1979 and 1980 in mountain areas of the U.S. portions of the Ajo and Lukeville 1° × 2° quadrangles, Arizona, except in the Papago Indian Reservation. Stream sediments were sampled at 971 localities within the 6,500-mi^2 study area. Sufficient heavy-mineral-concentrate sample for analysis was obtained from 952 of these localities. Sample sites were located on first- or second-order stream channels from drainage basins of less than 0.5 mi^2; and generally these sites were located where dry stream channels emerged from the narrow linear mountain ranges. The sampling density in the mountain ranges was one sample locality per 1.2 mi^2. Stream sediments were analyzed for 31 elements by optical emission spectroscopy in field laboratories.

Maps are presented showing locations of anomalous concentrations of (1) ore and ore-related elements—Sb, Bi, Cu, Pb, Mo, Ag, W, and Zn; (2) elements common to gangue minerals—Ba, Mn, and Sr; and (3) Sr depletion associated with hydrothermal alteration. Sixteen areas having anomalous element concentrations are identified, and their geological and geochemical characteristics are described.

The Mohawk Mountains anomaly is a cluster of sample localities having anomalous concentrations of lead, molybdenum, bismuth, and tungsten in heavy-mineral concentrates. One locality has anomalous molybdenum in a stream sediment.

An elongate cluster of sample localities in the Agua Dulce Mountains has anomalous concentrations of bismuth and tungsten. Some also have low-level lead and molybdenum in heavy-mineral concentrates. The western part of the anomaly, underlain by Precambrian rocks, is bismuth rich, whereas the eastern part is molybdenum rich. In addition to these elements, the area is rich in thorium, niobium, and other rare-earth elements, all characteristic of a granitophile assemblage.

Sample localities from the low hills to the north of La Abra Plain have anomalous concentrations of molybdenum, tungsten, and, less frequently, lead. The anomaly is best reflected by molybdenum in stream sediment where extensive overlap from the Sonoyta Mountains anomaly is subdued.

The tight cluster of sample localities in the Booth Hills has anomalous concentrations of Bi, W, Pb, Mo, Th, Nb, and, in some localities, Sn. The anomaly is in an area of gneiss and granite of uncertain age and may reflect a late magmatic concentration of metals.

The copper anomaly in the vicinity of Growler Pass is reflected in normalized data for both sample media. The area also has anomalous concentrations of Pb, Mo, Bi, W, Cu, Sb, and Sn, but Sr is found in abnormally low amounts. The assemblage of elements suggests erosion into the middle or upper levels of a hydrothermal system.

Heavy-mineral concentrates throughout the Sauceda Mountains are anomalously rich in manganese. Two localities have anomalous antimony, and localities at the northwest end of the mountains are anomalous for barium and strontium. The area has the largest tin anomaly in the quadrangle.

The Sonoyta Mountains anomaly is strongly reflected in the distribution of antimony and silver, includes one of the few sites that has anomalous zinc, and has abnormally low strontium, which suggests widespread depletion during hydrothermal alteration.

The intense copper anomaly at Ajo is a direct reflection of the deposit at the New Cornelia mine. It is a zoned anomaly, and molybdenum is confined to the center of a larger lead anomaly that overlaps with copper. Anomalous concentrations of bismuth and tungsten occur locally. The anomaly is of interest primarily for comparative purposes. It provides a measure of the composition size and intensity of anomalous values in the vicinity of the known deposit at the New Cornelia mine.

A number of localities in the western part of the Maricopa Mountains have anomalous concentrations of W, Bi, Pb, Mn, and Y. The anomaly is closely associated with the outcrop area of Precambrian granite and most likely reflects a hydrothermal event superimposed upon the granite.

Sample localities anomalous for copper are in the vicinity of Mohawk Pass. Secondary copper minerals in these samples are derived from vein-type deposits in the Mohawk mining district; these deposits also contain anomalous concentrations of tungsten, molybdenum, bismuth, and lead.

The Painted Rock Mountains anomaly is a cluster of sample localities having anomalous lead and molybdenum in stream sediment and lead in heavy-mineral concentrate.

Left to right: Richard Henley (Australia), Charles Cunningham (USGS), Alan Wallace (USGS), and Andre Panteleyev (Canada) prepare to go underground to visit a newly discovered, rich vein of silver at Cerro Rico, Potosi, Bolivia.

The area is also rich in manganese, barium, and strontium, and, at one locality, copper. Veins containing barite and a variety of lead and molybdenum minerals have been mined in the Painted Rock district.

The copper anomaly in the Ajo Range is represented by normalized anomalous sites. The prominent northwest trend of this anomaly is well displayed in the distribution of anomalously high concentrations of lead, molybdenum, silver, and tin and anomalously low concentrations of strontium, a common feature of hydrothermally altered zones. The general nature of the anomaly suggests remobilization of metals from older rocks beneath exposed volcanic rocks along a major northwest-trending structural zone.

The copper anomaly in the Batamote Mountains is second only to the Ajo anomaly in intensity and has a larger areal extent. The Batamote anomaly is isolated from the Ajo anomaly by an unsampled alluvial plain. Hence, it might appear to reflect a northern extremity of the Ajo anomaly. Although isolated anomalous concentrations for volatile elements and base metals have been observed in the general area, the anomaly is best characterized by copper. The Batamote Mountains are a broad, dissected shield volcano of late Tertiary age resting on latites of similar age. Both of these lithologies are younger than the mineralization at Ajo; hence, the Batamote anomaly cannot be directly related to the deposit at Ajo.

Scattered localities in the Cabeza Prieta and adjacent Tule Mountains are rich either in zinc or silver. Several other localities are weakly anomalous for either molybdenum or the assemblage of tungsten, molybdenum, and lead. Barium and strontium enrichment are probably related to a granite intrusion rather than to the hydrothermal mineral occurrences suggested by the other elements.

A single anomalous copper value in stream sediments and several normalized anomalous copper values in both the stream sediments and heavy-mineral concentrates were found in the Copper Mountains. Two of these heavy-mineral concentrates were also weakly anomalous for lead.

In samples from the low hills along State Highway 84 in the northeast corner of the Ajo quadrangle, heavy-mineral concentrates are manganese rich, and stream sediments are strontium poor. The area is anomalous for Pb, Bi, Th, La, Y, and, locally, W. The thorium, lanthanum, and yttrium association suggests a relation to the Precambrian granites exposed in the area, whereas the other elements suggest late magmatic or hydrothermal concentration of selected elements.

Genetic Model for the Carbonate-Hosted Pb-Zn-Cu-Ag-Au Manto-Chimney Deposits of the Gilman, Colorado District, Based on Fluid Inclusion, Stable Isotope, Geologic, and Fission-Track Time-Temperature Studies

D.W. Beaty, C.G. Cunningham, C.W. Naeser, and G.P. Landis

Multidisciplinary studies have resulted in the development of a comprehensive genetic model for the carbonate-hosted Pb-Zn-Cu-Ag-Au manto-chimney deposits of the Gilman, Colo. district. These deposits, located in the Colorado mineral belt, are some of the best examples of this type of deposit in the world. The model has direct application for both resource assessment and exploration.

The composite evidence shows that both the mantos and chimneys of the main sulfide ore deposits formed during the mid-Tertiary from a high-temperature, igneous-related, hydrothermal source. There may have been a poorly preserved silver-lead-zinc precursor event. The mineralizing event that formed the main orebodies has been dated by fission tracks at 34.5±2.6 Ma on late-stage hydrothermal apatite from the chimneys. A large, district-wide, paleothermal anomaly of the same age surrounds and is centered on the orebodies. Sulfur isotope data show a homogeneous sulfur source for the main orebodies. Bulk $\delta^{34}S=+1.6$ and indicates an igneous provenance. Lead isotopic ratios in the ore are indistinguishable from those of Tertiary igneous rocks throughout western Colorado. The components of the manto and chimney orebodies were transported by a hydrothermal fluid having $\delta^{18}O=+4$ to $+8$ and $\delta D=-55$ to -75 per mil; this hydrothermal fluid is inferred to be magmatic water. The fluid had a mean salinity of about 5 weight percent equivalent NaCl and a range of 1.5 to 9.4. Fluid inclusion and sulfur isotope fractionation data indicate that sulfide deposition in the chimney deposits took place at temperatures of about 390 to 410 °C. Lower temperatures were determined for the No. 1

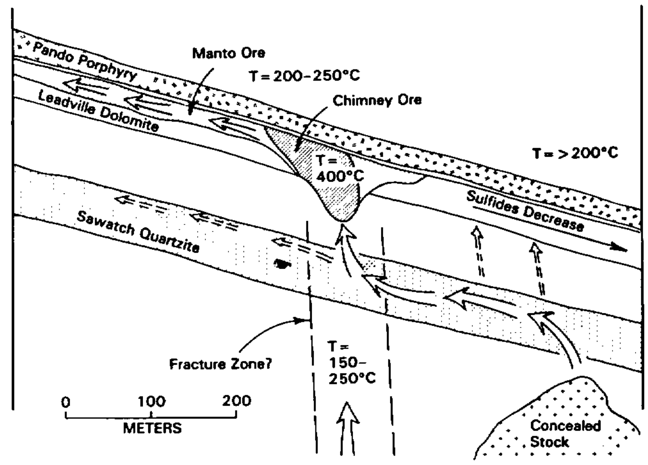


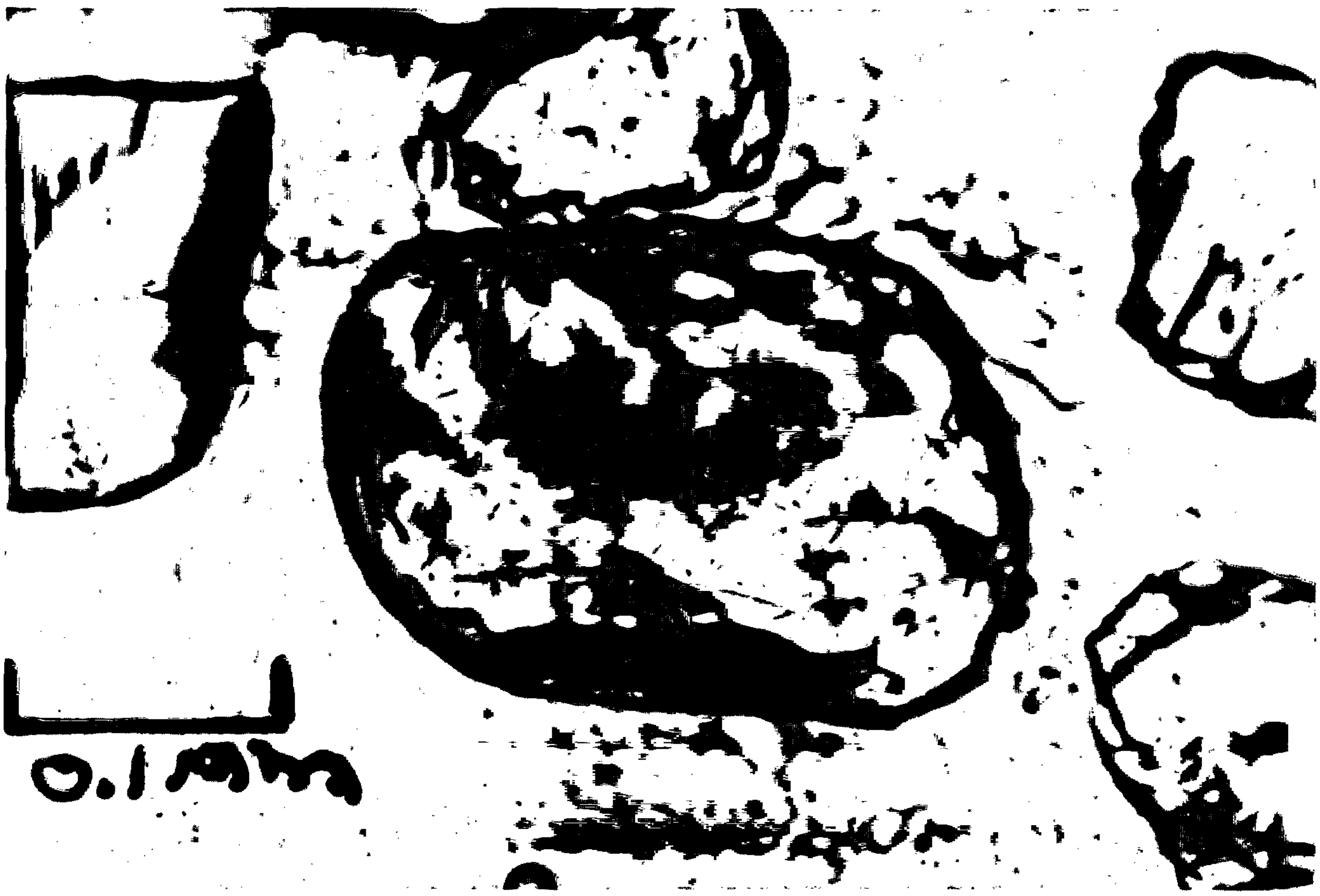
Figure 1. Paleohydrology of the carbonate-hosted Pb-Zn-Cu-Ag-Au manto-chimney deposits at Gilman, Colo. [Beaty and others abstract]

Manto (300–375 °C), for veins in the Sawatch Quartzite (230–370 °C), for late-stage apatite in vugs within the chimneys (309 °C), and for veins cutting Precambrian rock beneath the chimneys (174–306 °C, and a mean of 240 °C). Fluid movement during the ore-forming event is delimited by the distribution of fluid-inclusion temperatures, partial fission-track resetting, ore mineral assemblages, alteration mineral assemblages, and oxygen isotope exchange patterns in the orebodies and surrounding country rocks. Fluids moved updip within the Sawatch Quartzite from a source located to the northeast of the present deposits, then upsection through the chimneys to the Leadville Dolomite (an important aquifer), and then updip through the mantos where they ponded against the Pando Porphyry (fig. 1). Several small, paragenetically early, partially preserved silver-lead-zinc deposits at Gilman and Red Cliff are of uncertain origin.

Fluid Inclusion and Mineralogic Studies of a Palladium-Platinum Anomaly Zone in the Reeser's Summit Diabase, Pennsylvania: Evidence for Hydrothermal Transport

Harvey E. Belkin

The York Haven diabase sheet, of Early Jurassic age, crops out near the northern margin of the Gettysburg basin across the Susquehanna River south of Harrisburg, Pa. Gottfried and Froelich (1988), in a comprehensive study of mafic rocks in the Eastern United States Mesozoic basins, have defined a palladium and platinum anomaly associated with a ferrogabbro zone at Reeser's Summit, Pa. (Gottfried and others, this volume). The Reeser's Summit exposure consists of a 500-m section that has chilled margins characteristic of a high-titanium (1.1 weight percent) quartz-



A microscopic view of fission tracks in apatite crystals. These tracks, formed mostly by the spontaneous fission of ^{238}U, can be used to determine the age and extent of a paleothermal anomaly. [Beaty and others abstract]

normative tholeiitic magma of the York Haven type (Gottfried and Froelich, 1988). The chilled margins contain typical platinum group element (PGE) abundances (Pd=10 ppb, Pt=10 ppb), whereas the greatest anomaly in the 90-m-thick ferrogabbro zone (FeO_{total} up to 18 weight percent) contains Pd=165 ppb and Pt=21 ppb. Associated with this zone are anomalously high contents of gold (up to 54 ppb), tellurium (up to 20 ppb), and chlorine (up to 0.44 weight percent) (Gottfried and others, 1988).

A detailed petrographic, microprobe, SEM, and fluid inclusion study has been conducted to define the enrichment and transport processes that have operated in this system. A model is suggested whereby an original ferrogabbro has been hydrothermally altered by late-stage aqueous chlorine-sulfide-arsenic solutions, especially enriched in iron, that have deposited PGE elements associated with copper sulfides.

The initial diabase contained a relatively simple mineralogy of plagioclase, clinopyroxene, and opaques. The plagioclase composition (cores) ranges from An80 to An85 at the exposure margins to An55 to An60 in the ferrogabbro. The clinopyroxene composition (cores) ranges from En60Fs15Wo25 at the exposure margins to En34Fs41Wo25 in the ferrogabbro. Both plagioclase and clinopyroxene are zoned; the plagioclase rims range to An20, and the clinopyroxene rims range to En27Fs49-Wo24. The alteration is predominately characterized by destruction of the clinopyroxene with concomitant crystallization of iron-rich amphibole and chlorite. The amphiboles are halogen rich (up to 2.00 weight percent chlorine). Brown hornblende tends to occur as single crystals, whereas green ferroactinolite is usually an alteration product of clinopyroxene. The plagioclase is relatively unaltered. Myrmekitic-pegmatitic intergrowths of quartz, K-feldspar, albite, and halogen-rich apatite are common and increase in abundance to a maximum in the anomalous ferrogabbro zone.

Chalcopyrite is the most abundant sulfide and is always associated with chlorine-rich amphibole, quartz, or ilmenite. The texture suggests that chalcopyrite was a very late phase. No primary magmatic sulfides have been recognized. Bornite, galena, and sphalerite typically occur with chalcopyrite. Intimately associated with the chalcopyrite, adjacent to chlorine-rich amphibole or quartz, are very small grains of Pd+Co+Ni±Fe±S arsenides. Microprobe and energy dispersive SEM analysis suggests that the chalcopyrite contains dissolved platinum and gold.

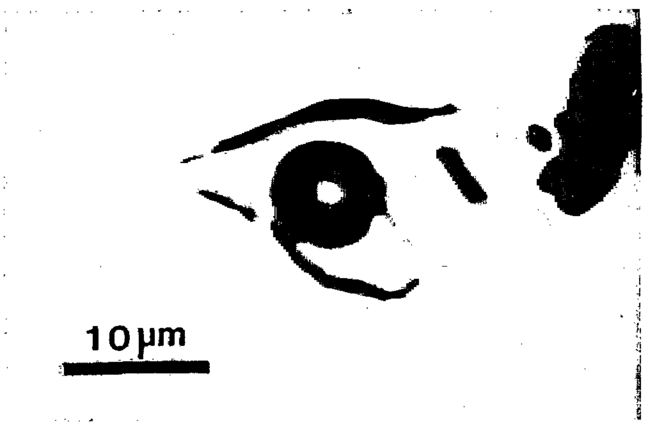


Figure 1. Primary fluid inclusion in quartz from Reeser's Summit, Pa., sample PYRS84–9, containing a bubble, a cubic daughter crystal (chloride), and concentrated brine. [Belkin abstract]

Primary fluid inclusions (fig. 1) in quartz commonly contain daughter crystals of an iron-rich chloride (SEM) and are coeval with primary gas inclusions. Secondary inclusions are abundant, especially in the quartz and plagioclase. Microthermometry yields homogenization temperatures (no P correction) for the primary inclusions that range from 500 to 600 °C and from 300 to 400 °C for the secondary inclusions. The melting and volume relations of the cubic, isotropic daughter crystals suggest a salinity of ≥40 weight percent NaCl equivalent. The quartz-sulfide texture suggests that primary fluid inclusions and sulfides formed during the same process.

The evidence suggests that a hydrothermal system developed, probably commencing during late magmatic crystallization, and that the system introduced halogen-rich, sulfide-arsenic aqueous solutions. The Reeser's Summit anomalous PGE zone is the result of deposition by these hydrothermal solutions.

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Geoelectric Studies in the Delta, Utah, Quadrangle

D.L. Campbell and V.F. Labson

Magnetotelluric (MT), audiofrequency magnetotelluric (AMT), and direct current vertical electric soundings (VES) were used during the past three field seasons of 1986 to 1988 to help with the mineral assessment of the Delta, Utah, 1° × 2° CUSMAP (Conterminous United States Mineral Assessment Program) quadrangle. MT and AMT soundings were made to study the geoelectric character of Desert Mountain, Keg Mountain, Drum Mountains, Thomas Range, Notch Peak, Fish Springs Range, and Baker Hot Springs Butte. VES were used to map the thickness of sediments in the Tule Valley and northern Fish Springs Flat.

Most Cenozoic sedimentary rocks and porous tuffs in the quadrangle have low resistivities (2–40 ohm-m), Paleozoic sedimentary rocks and most Tertiary volcanic rocks have intermediate resistivities (20–200 ohm-m), and Tertiary and Jurassic intrusive rocks have high resistivities (100–5,000 ohm-m). The geoelectric profiles show that Desert and Keg Mountains have central high resistivity plugs that extend to depths of at least 10 km. These plugs probably are composed of Oligocene intrusive rocks that crop out at the surface. Their great depth suggests that the post-Miocene extension along the 2.5-km-deep Sevier Desert detachment fault, seen in nearby seismic profiles, did not take place below those mountains; their intrusive cores may have acted as rivets to hold upper and lower plates together.

MT soundings at Notch Peak show that about 1 km of high resistivity material, probably Notch Peak granite, overlies at least 5 km of 40 ohm-m material, presumably Paleozoic country rocks. The Jurassic Notch Peak granite is either a laccolith or was truncated at depth by Cretaceous or Tertiary movement on Sevier Desert detachment fault(s). The MT results also suggest that very conductive, possibly mineralized, zones border the Notch Peak granite to the northeast and east. Magnetic data indicate another intrusive body at greater depth, offset about 2 to 5 km to the south of the outcrop area of the Notch Peak granite.

Other MT and AMT work in the quadrangle (1) has clearly characterized the boundary of the Thomas caldera along a profile crossing the western boundary, (2) is consistent with geologic evidence that another caldera may extend from the eastern edge of Desert Mountains to a point east of Cherry Creek, and (3) implies that the Baker Hot Springs basalts are not present in any substantial thickness below the adjacent surficial sediments just east of their outcrop area. The MT and AMT work also shows up to 5 km of possible Cenozoic sedimentary rocks in the pre-Bonneville basin north of the Keg-Desert Mountain axis but only about 3 km of such materials in the area just south of that axis.

Geoelectric, borehole, and seismic data were used to constrain estimates of thickness of sedimentary fill in valleys at more than 100 sites in the quadrangle. These thicknesses were then used to calibrate estimated depth to basement throughout the quadrangle by using gravity data. The results show that several valleys contain broad buried pediments that have relatively thin sedimentary veneer. The locations and extents of such pediments are significant for mineral assessment purposes because of the possibility of covered shallow mineral deposits.

Tectonic and Magmatic Development of the Midcontinent Rift: A Synthesis of New Seismic, Chemical, and Isotopic Data

W.F. Cannon, S.W. Nicholson, and Alan Green

The Midcontinent rift, the host for major resources of copper, nickel, and other metals, formed during a period of crustal extension about 1.1 Ga. The structure extends 2,000 km from Kansas, through the Lake Superior region and into southern Michigan. The rocks within the rift, the Keweenawan Supergroup, are exposed only around Lake Superior where we have concentrated our study. We present a refined model of rift evolution that can be used to place known mineral deposits into a geologic framework and establish a geologic basis for predictive metallogeny.

Development of the rift occurred in three stages:

(1) From about 1.108 to 1.094 Ga, the Archean and lower Proterozoic crust was extended and greatly attenuated to one-fourth or less of its original thickness of about 40 km. Copious volumes of flood basalt and smaller amounts of andesite and rhyolite were erupted into the developing rift depression. Earliest rift deposits accumulated in a broad (about 200 km wide) depression formed mostly by sagging during initial stages of crustal attenuation. Magmatism was widespread to form both "plateaus" of flood basalt and diabase dikes, some of which extend more than 100 km beyond the rift. Upon further extension, a central graben developed over highly attenuated crust that locally may have totally separated. Enormous volumes of basalt, up to 20 km thick, were erupted in the graben; the earlier formed flanks remained as topographic highs. Composition of basalts reflects the condition of the crust through which they were erupted and varies both with position in the rift system and with time. Basalts outside the central graben have evolved compositions and strong enrichment of incompatible trace elements. Neodymium isotope compositions reflect some crustal contamination. This magma formed from a relatively homogeneous and widespread mantle source and was erupted through a still thick crust lacking well-developed magma conduits. As the crust thinned and central magma conduits developed, basalt compositions evolved toward more primitive values, and neody-

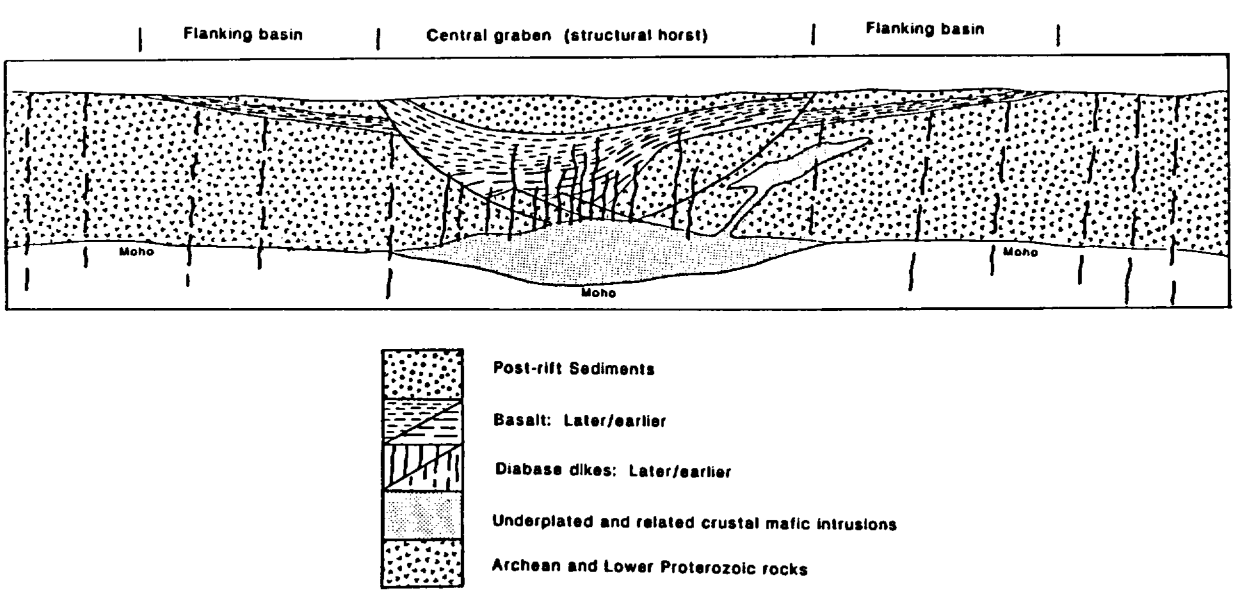

Figure 1. Schematic cross section of the Midcontinent rift in the Lake Superior region based on geologic data and seismic reflection and refraction data. Approximate width of section is 300 km. Early basalts fed by widespread dikes form a broad apron gradually thickening toward the center of the rift. Later basalts are confined mostly to a central graben and were probably fed by much more centralized dikes tapping a magma reservoir near the base of the crust. Postrift sediments are in a broad basin formed mostly by thermal collapse of the crust during cooling. The central graben was converted to a central horst by reactivation of the graben-bounding normal faults into high-angle reverse faults. [Cannon and others abstract]

Figure 1. View of a block of rare-earth-rich ore from the Bayan Obo deposit of Inner Mongolia, China. Blebs of hematite (h) are surrounded and metasomastically replaced by lamellae (m) of an assemblage of very fine-grained monazite, aegerine, and bastnaesite. The field relation shown here indicates that the episode of hematite mineralization preceded that of the rare-earth mineralization. [Chao and others abstract]

mium isotopes showed little or no crustal contamination. Major intrusive bodies, such as the Duluth Complex, were emplaced during this extensional phase.

(2) At about 1.094 Ga, extension and basaltic volcanism ended. Thermal collapse of the crust formed a broad basin in which fluvial and minor lacustrine deposits accumulated to thicknesses of about 10 km. Igneous activity was restricted to formation of a few andesitic stratovolcanoes at about 1.086 Ga.

(3) The central graben of the rift was uplifted, in places 5 km or more. Most uplift was accommodated along the original graben-bounding normal faults that were transposed into high-angle reverse faults.

The combined effect of these three phases leads to the geometry shown in figure 1, where a central horst, originally the central graben, contains huge volumes of basalt and overlying sediments. Flanking basins contain thinner basalt sequences dominated by the older part of the basalt section and a riftward thickening wedge of sediments.

The H8 Dolomite Host Rock of the Bayan Obo Iron-Niobium-Rare-Earth-Element Ore Deposit of Inner Mongolia, China—Origin, Episodic Mineralization, and Implications

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The giant Bayan Obo ore deposit of Inner Mongolia occurs geologically in the H8 dolomite of the middle Proterozoic Bayan Obo group. Recent field and laboratory investigations show that the H8 dolomite marble is not an igneous carbonatite but a metamorphic rock of sedimentary origin. Stratigraphically, the H8 dolomite is conformable with the H9 black shale-slate above and with the H7 interbedded mica schist, slate, and marble below. It exhibits sedimentary features and structures such as quartzite interbeds and crossbedding and contains detrital quartz and rare oncolite algal fossils (microstromatolites). The H8 consists

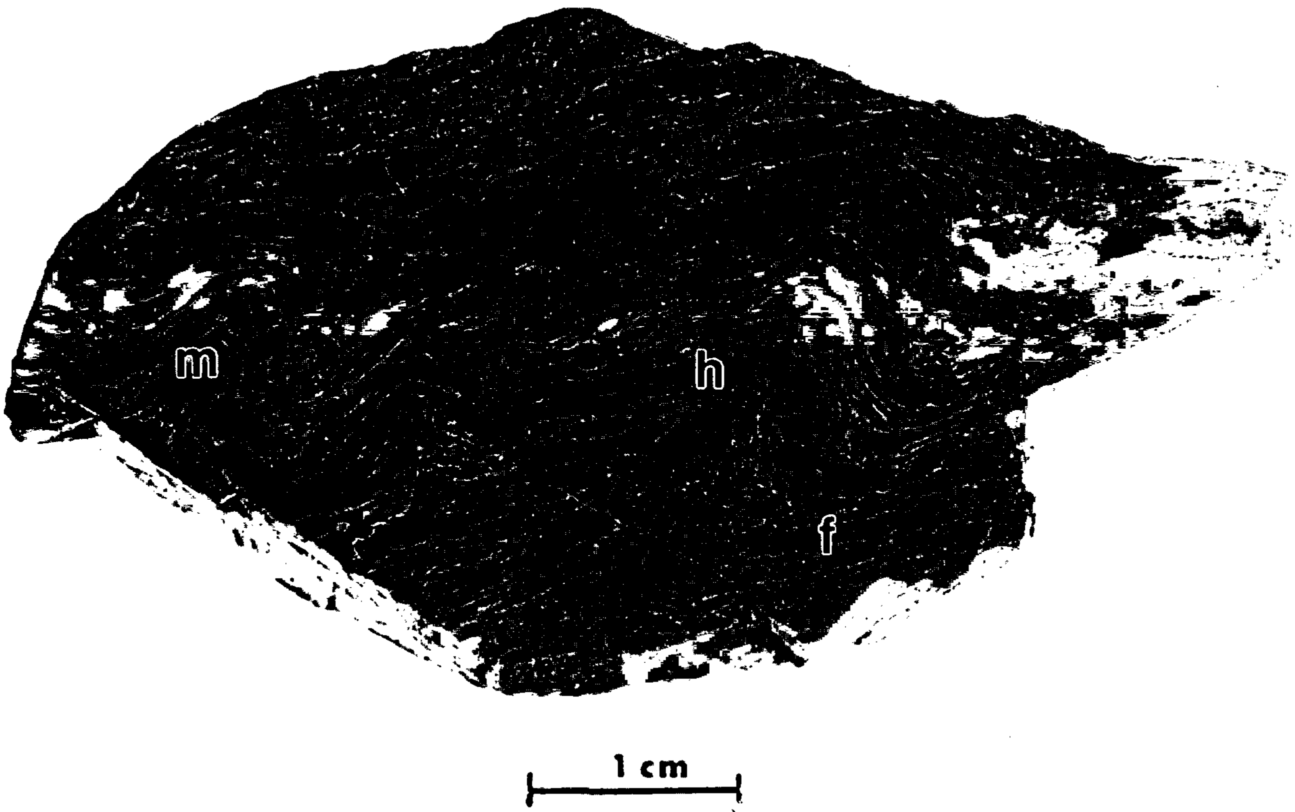

Figure 2. Hand sample of a banded iron-rare-earth ore sample from the Bayan Obo deposit of Inner Mongolia, China. Ptygmatic microfolds in banded hematite (h), fluorite (f), and monazite (m) clearly indicate that this ore was formed prior to the regional metamorphism that probably occurred in Hercynian time. [Chao and others abstract]

of a fine-grained and a coarse-grained crystalline dolomite, both of similar ferroan mineral composition. Oxygen and carbon isotope data also indicate that the H8 dolomite is of sedimentary origin, modified by regional metamorphism.

The Pb-Pb and Sm-Nd model ages for early monazites in the H8 dolomite range from 1.4 to 1.8 Ga. Textural evidence shows that such monazites within the H8 dolomite are not detrital but hydrothermal in origin. Preliminary Th:Pb ages suggest that two episodes of monazite mineralization may be represented in the disseminated monazite-bearing dolomite ores (in excess of 2 weight percent rare-earth-element (REE) oxide). The first episode may have occurred as early as 840 Ma (late Proterozoic), followed by a later episode at about 695 Ma. Thus the Bayan Obo ore deposit is not syngenetic but epigenetic in origin.

The two early episodes of monazite mineralization were followed by disseminated and banded magnetite mineralization, then hematite mineralization. The iron oxide mineralization was then followed by deposition of monazite-bastnaesite ores. These high-grade REE and iron-REE ores are extremely fine grained (mostly less than 50 μm), with the exception of magnetite (average grain size of about 100 μm). These ores are finely laminated, are discontinuously banded, and exhibit widespread metasomatic replacement textures (fig. 1). Later REE mineralization produced coarser grained monazite, bastnaesite, aeschynite (a REE niobate), huangheite (a barium-REE fluorocarbonate), and associated aegerine. This coarser grained episode of REE mineralization is dated by Th:Pb and Sm:Nd isochron methods to be about 430 Ma, or Caledonian in age; this age implies that the principal episodes of Bayan Obo mineralization are pre-Caledonian.

The principal banded iron-REE ores of Bayan Obo were then regionally metamorphosed and microfolded (fig. 2) at about 300 Ma (based on potassium-argon age of biotite in biotite schist), probably succeeded by the intrusion of Hercynian biotite granite (potassium-argon age, 265 Ma), which is widespread in the mine region. Unmetamorphosed late-stage mineralization involving iron oxides and REE's followed. This mineralization was associated with sulfides (pyrite, pyrrhotite, sphalerite, galena), K-feldspars, silica, microcline pegmatites, and numerous crosscutting calcite veins.

So far, textural and mineralogical studies indicate that episodes of REE and iron mineralization are both of hydrothermal origin but are unrelated. Based on the results to date, it appears that two types of Bayan Obo ores exist and thus further exploration in adjacent regions for the occurrence of ores containing REE's only, independent of the iron oxide, should be considered.

Geology and Geochemistry in the Vicinity of the Adelaide Crown Mine, Humboldt County, Nevada

Theresa M. Cookro and Ted G. Theodore

The Adelaide mining district, located about 16 km south of the town of Golconda, Nev., produced Au, Ag, Cu, Pb, and Zn. The sampled area is in the western part of the district where the Gold Run Creek placer mine is currently in operation, and stripping of a new gold deposit just north of the Adelaide Crown mine has just been started by Getchell Resources and Icarus Exploration Co. in a joint venture. Evidence of (sinter, tufa, and pods of black earthy oxides) ancient hot springs occurs along the mineralized north-trending fault system. Altered rock near the sinter and tufa occurrences has a porcelainlike appearance and oxide coatings of iron manganese. Cinnabar, orpiment, and realgar occur in the crusts with the oxides. The black oxides are extremely rich in manganese and carry anomalous concentrations of silver and arsenic. The tufa is also anomalous in manganese, silver, and arsenic. Silicified veins of calcite and barite also are common. Altered dikes of intermediate composition cut the host rock. Finally, a trace element assemblage of As, Sb, Hg, Tl, Au, and Ag is common in these rocks, as in many other sediment-hosted epithermal precious-metal deposits in north-central Nevada. Gold, hosted in the Cambrian Preble Formation, occurs in quartz veins, in quartz-filled vugs, associated with manganese- and iron-rich oxides, and on fracture surfaces of the rock. Gold occurs in spot anomalies, whereas silver apparently is more consistently anomalous across wide areas.

Several open cuts and clusters of underground workings, active in the late 1930's and early 1940's, along a prominent, steeply dipping, gold-silver-bearing, north-striking system of faults constitute the historic Adelaide Crown mine. Both deposits are apparently epithermal, and much of the ore is in jasperoid. To the west of this precious-metal-bearing fault system is a prominent thrust fault, speculated to correlate with the Roberts Mountains thrust. This thrust brings the allochthonous Valmy Formation, of Ordovician age, in contact with parautochthonous transitional assemblage limestone and phyllite of the Preble Formation. The thrust does not appear to be mineralized. Thus, these deposits exhibit characteristics of both sediment-hosted and hot-springs types of precious-metal deposits as currently defined.

Elsewhere in the district, the Preble Formation is strongly silicified and argillized along major strands of faults. Thin (average less than 8 cm in thickness), discontinuous stockwork quartz veins are prominent; the veins are discontinuous mainly because of several stages of postmineral movement along the faults. Some quartz coatings and veins are gray to bluish-gray in color. Red jasper and gray, red, and black jasperoid are common. Both the quartz veins and jasperoid are anomalous in silver, arsenic, and manganese.

Finally, some mafic dikes cut the epithermal gold mineralization and are associated with anomalous chromium, nickel, cadmium, and cobalt concentrations. A nearby Cu-Pd-Zn-W skarn, the Adelaide mine, contains anomalous concentrations of gold within the massive sulfide rock and in phyllite around the margins of the skarn. The deposits in the district may represent an extension of the gold-enriched Getchell trend that occurs about 40 km to the north.

Methodology for Analysis of Concealed Mineral Resources in Nevada: A Progress Report

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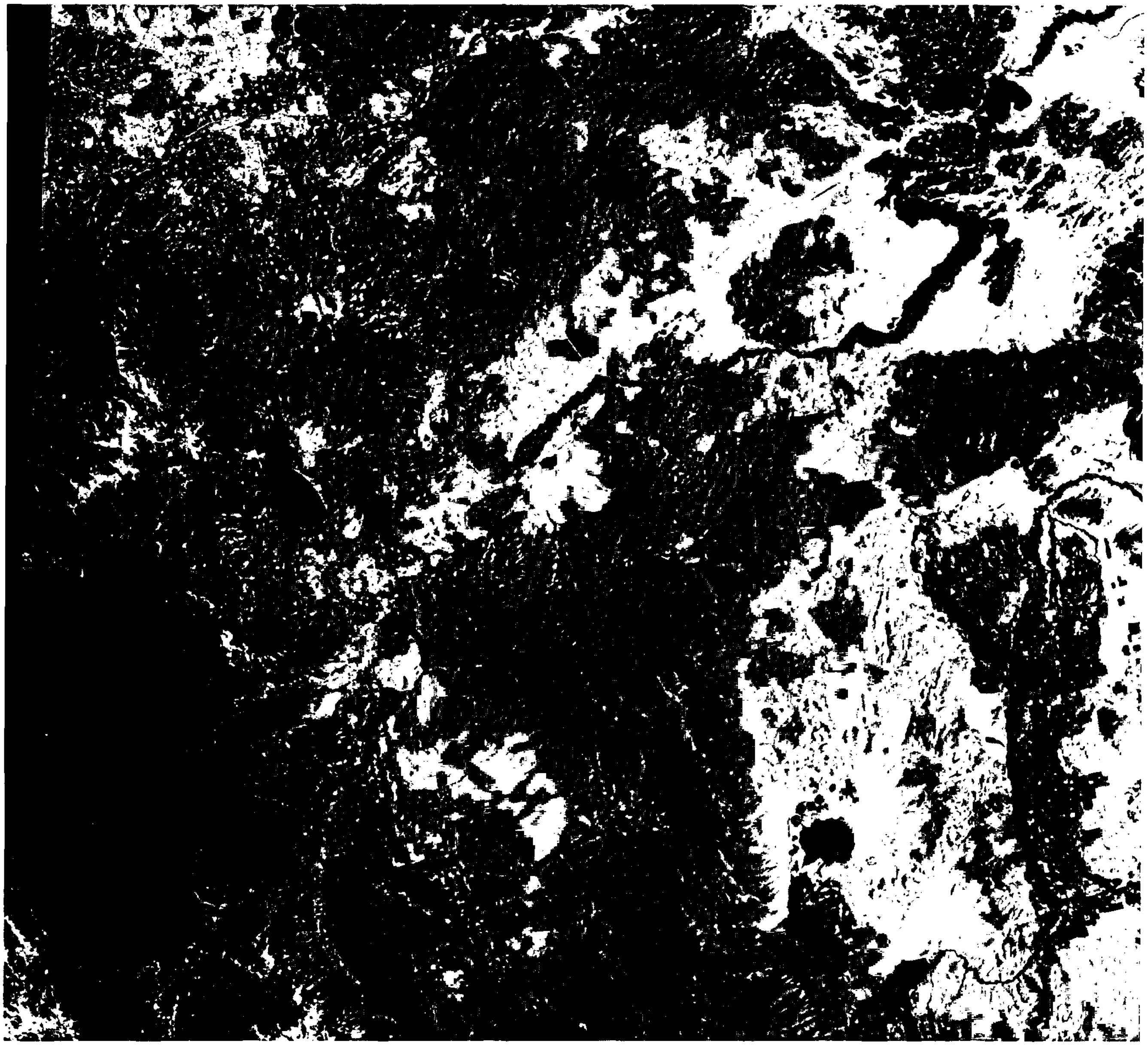
Maps (1:1,000,000 scale) showing areas in Nevada permissive for undiscovered mineral deposits by type and an estimate of the number of undiscovered deposits are being compiled by a team of U.S. Geological Survey and Nevada Bureau of Mines and Geology geologists, geophysicists, and geochemists. Results will be shared with the U.S. Bureau of Mines for an economic analysis. Permissive areas on these maps are defined as containing geologic environments in which one or more mineral deposit models may occur and include those areas in which possible host rocks are concealed but are present within 1 km of the surface. The resource delineation maps will be included in a folio showing data used in their preparation. The folio will include (1) maps and tables classifying approximately 500 deposits by deposit model, (2) grade and tonnage models appropriate to Nevada, (3) maps of regional geology and geochronology of igneous rocks, and (4) maps of gravity and magnetic data and their interpretation. These data will be used to prepare derivative maps that show (1) areas covered by up to 1 km of Cenozoic rock and sediments, (2) shallow magnetic sources, (3) neotectonic analysis, (4) subsurface basin geometry, and (5) the subsurface distribution of Mesozoic and Tertiary intrusions, Tertiary volcanic rocks, and certain pre-Tertiary sequences of sedimentary and volcanic rocks. The last-named maps show the total area of the State in which rocks permissive for certain stratabound deposit types (Cyprus, kuroko, and Besshi massive sulfide; sedimentary exhalative zinc-lead-silver; bedded barite; Appalachian zinc; and Kipushi copper-lead-zinc) are present within the upper 1 km of the crust. Considered permissive for epigenetic igneous-related



Landsat Thematic Mapper image of Lake Tahoe, Nev. Remote sensing data are being used to map hydrothermally altered rocks and to do a regional structural analysis in the Reno, Nev., 1° × 2° CUSMAP quadrangle.

deposits are volumes of rock, 1 km thick, containing permeable and (or) reactive rocks within 10 km of a plutonic body or within 5 km of a subvolcanic intrusion or caldera margin.

Oxygen Isotope Map of the Fossil Hydrothermal System in the Comstock Lode Mining District, Nevada

Robert E. Criss, Duane E. Champion, and Mary F. Horan

Oxygen isotope measurements on 200 samples of volcanic rocks from outcrops, drill cores, and mine workings in the Virginia City area, Nevada, provide unequivocal evidence that the regional propylitization and local argillization and silicification near veins were produced by interactions with low ^{18}O fluids derived from meteoric waters. A contour map (fig. 1) of $\delta^{18}O$ values from outcrops reveals that fluid-rock exchange produced an equant, 75-km^2, low ^{18}O zone centered on Mount Davidson that includes the Comstock, Silver City, and Occidental Lodes; a smaller, spatially distinct low ^{18}O zone occurs in the Flowery mining district to the east. Subsequent dip-slip movement on the Comstock fault displaced the ^{18}O anomaly and allowed preservation of a tongue of downdropped, higher ^{18}O rocks in the hanging-wall near Virginia City.

Lode mining in the Comstock mine, Virginia City, Nevada, 1868. T.H. Sullivan took this first photograph in a mine by igniting magnesium wire to obtain sufficient light.

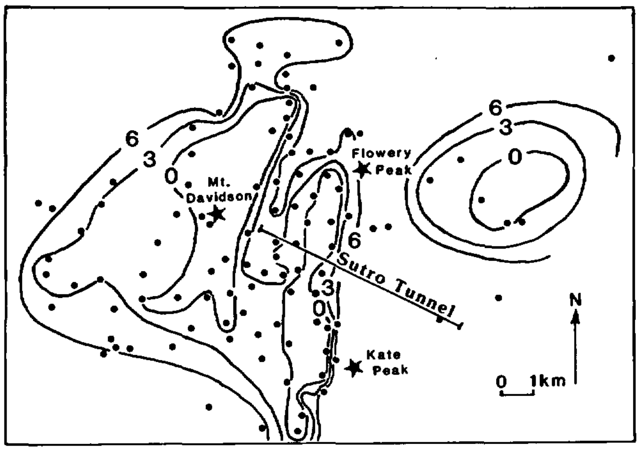


Figure 1. Contour map of $\delta^{18}O$ values (dots) from intermediate composition volcanic rocks of the Comstock Lode mining district. Contour interval is 3 per mil. [Criss and others abstract]

Analyses of subsurface samples (not shown in fig. 1) collected 100 years ago by G. Becker and others, and curated by the Smithsonian Institution and the U.S. Geological Survey, allow a 6-km long traverse into the fossil hydrothermal system along the level of the famous Sutro Tunnel, approximately 500 m below the present surface. Unaltered rocks ($\delta^{18}O$=+6 to +8) extend westward from the tunnel mouth for about 2 km. A narrow transitional zone of steep ^{18}O gradient, extending from 2 to 3 km from the tunnel mouth, marks the perimeter of the hydrothermal system and directly underlies the Flowery Range. Finally, intensely altered rocks ($\delta^{18}O$=−4 to +0) extend westward to the tunnel terminus near the Comstock fault to 6 km; this last zone includes both the Comstock and Occidental Lodes. Alteration within this part of the hydrothermal system is truly pervasive, such that the $\delta^{18}O$ values exhibit little dependence on either rock type or evident proximity to structures. In this vertical section, low ^{18}O rocks underlie higher ^{18}O outcrops of the downdropped hanging-wall. This relation demonstrates the existence of a steep vertical ^{18}O gradient, which is also indicated by analyses of rocks from the Combination Shaft.

The uniform character of the zone of intense alteration and its smooth transition to unaltered rock at distance indicates that the Comstock hydrothermal system was a coherent geographic entity. However, as in the epithermal mining districts of Bohemia, Oreg., and Yankee Fork, Idaho, no single intrusion at Comstock has sufficient mass (by a factor of 10–100X, judging from the outcrop size) to have produced the 75-km^2 low ^{18}O zone. Although much larger hypabyssal intrusions may exist in the shallow subsurface in all of these districts, it is much more likely that these low ^{18}O zones represent the roots of stratovolcanoes. Remnants of these volcanoes are present as the Kate Peak Formation, as demonstrated by similar ages of lode mineralization and time of eruption of the typically unaltered volcanics (Vikre and others, in press). Fluid convection, driven by successive pulses of magma through a locus of volcanic centers, could account for the broad and uniform field of intensely altered rocks.

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Geological Studies of the International Falls and Roseau 1° × 2° CUSMAP Quadrangles, Northern Minnesota

W.C. Day, T.L. Klein, D.L. Southwick, and K.J. Schulz

Mapping, geochemical, geophysical, and drill core studies in the International Falls and Roseau 1° × 2° quadrangles of northern Minnesota have provided new insights into the geologic evolution and the mineral resource potential of the Late Archean terrane. Basement exposure is good in the eastern part of the International Falls quadrangle. Where westward-thickening Quaternary glacial deposits obscure bedrock in the Roseau quadrangle, drill core studies and aeromagnetic and gravity data were used to establish the regional geologic framework.

The study area straddles the Minnesota-Ontario border and lies within the southern part of the Superior province of the Canadian Shield. The Superior province is composed of several northeast-trending subprovinces of alternating granite-greenstone and metasedimentary-gneiss lithotectonic terranes. The study area includes three of these major lithotectonic terranes: the Wabigoon in the north, the Quetico in the central part, and the Wawa-Shebandowan in the south.

The Wabigoon subprovince is a granite-greenstone terrane composed of low- to moderate-grade regionally metamorphosed volcanic and coeval plutonic rocks and volcaniclastic, epiclastic, and chemical sedimentary rocks. The supracrustal rocks were complexly deformed and intruded by large volumes of syn- to posttectonic granitoids. In the eastern part of the Wabigoon subprovince in the International Falls quadrangle, volcanism was bimodal. The mafic suite consists of low- and high-TiO_2 tholeiitic metabasalts, metagabbro, and minor calc-alkaline basaltic metaandesite, and the felsic suite includes both low-Al_2O_3 tholeiitic metadacite and metarhyolite, and high-Al_2O_3 calc-alkaline metarhyolite and comagmatic tonalite. To the west in the Roseau quadrangle, andesitic volcanism is more prevalent; tholeiitic metabasalt and metaandesite are commonly interlayered with calc-alkaline metaandesite, metadacite, and metarhyolite. Stratiform massive sulfide occurrences, some having enrichments up to 5 percent combined base metals (zinc>copper>lead), are spatially associated with bimodal volcanic rocks. Copper-nickel sulfide mineralization occurs in the basal parts of some synvolcanic tholeiitic metagabbro sills. In addition, epigenetic gold deposits occur mostly in dilation zones associated with major shear zones caused by regional wrench tectonics. These shear zones form, in part, subprovince boundaries.

The Quetico subprovince is a medium-grade, regionally metamorphosed metasedimentary rock and gneiss terrane. The northern part of the terrane is composed of a belt of graywacke that grades southward into rocks of the Vermilion granitic complex. The Vermilion complex is a granite-migmatite terrane consisting of supracrustal rocks that have been intruded by batholithic tonalite, monzodiorite, and granite bodies of the Lac La Croix Granite. No mineral deposits are known to occur in rocks of the Quetico subprovince in Minnesota. However, an area containing anomalous gold values in basal glacial till overlying these rocks has recently been identified by the Minnesota Department of Natural Resources; the source for this anomaly remains unknown.

Rocks of the Wawa-Shebandowan subprovince, a low-grade granite-greenstone terrane composed of mafic metavolcanic and interlayered metasedimentary rocks, are poorly exposed in the southern part of the study area. No mineral deposits or occurrences are known in these rocks within the study area, but iron deposits and minor gold and base-metal massive sulfide occurrences are found in rocks to the south and southeast.

Geological and Geophysical Analysis of the Subsurface Geometry of Basins in the Central and Western Great Basin: Implications for the Analysis of Concealed Mineral Resources in Nevada

John C. Dohrenwend, Robert C. Jachens, Richard J. Blakely, Barry C. Moring, and Christopher M. Menges

A combination of geological, geomorphic, geophysical, and well-log data has been analyzed to estimate the approximate subsurface geometry of fault-bounded basins in the western Great Basin. Compilations and analyses include (1) regional geomorphic and surficial geological analyses including photogeologic mapping of young faults, pediments, and areas of thin alluvial cover; (2) digital analysis of a statewide, gridded compilation of gravity data to estimate approximate depths to dense, generally pre-Tertiary and (or) crystalline basement within basin areas; (3) interpretive analyses of statewide compilations of both gridded and profiled aeromagnetic data to delineate bodies of shallowly buried magnetic rock; and (4) map compilation of selected oil and gas, geothermal, and water-well data. These data and derivative interpretations were combined and compiled on 1:250,000-scale maps for a 4° × 4° area of central and western Nevada. Additional work, in progress, will extend this compilation to a 6° × 7° area that includes the entire State of Nevada.

Preliminary analysis of this multidisciplinary data indicates that significant variations in basin depth, areal extent, subsurface shape, and basin fill stratigraphy are likely related to variations in the timing, intensity, and style of neotectonic activity across the region. The Great Basin is composed of an irregular mosaic of neotectonic domains; each domain is characterized by a unique history of neotectonic activity and style. The distribution and density of young faults and pediments vary significantly and often abruptly from one domain to the next, and changes in these variables can be used in combination with major neotectonic structures to define domain boundaries. Subsurface basin geometry also appears to vary significantly among these neotectonic domains. Basins within the several domains of the northern and central Walker Lane are generally small and shallow. In contrast, basins farther to the northeast within the central Great Basin are typically large, continuous, elongate, and deep. Moreover, basin geometry and stratigraphy may also change significantly within individual domains; basin size, depth, continuity, and the thickness of post-Miocene basin fill are commonly less adjacent to domain boundaries and within the transverse accommodation zones that transect the central Great Basin. These relations provide useful geometric and stratigraphic insights for mineral resource assessment of covered areas in the Basin and Range province of western North America.

Geologic Setting of Iron-Niobium-Rare-Earth Orebodies at Bayan Obo, Inner Mongolia, China, and a Proposed Regional Model

L.J. Drew, Meng Qingrun, and Sun Weijun

The Bayan Obo iron-niobium-rare-earth orebodies are situated on the northern edge of the Sino-Korean Plate. This edge is a rifted margin resulting from an intracontinental rift that took place 1.7 to 1.85 Ga. Available data suggest that this rifted margin remained passive, with the exception of the emplacement of granite plutons during the Caledonian cycle (Early Cambrian through the Silurian), until collision with the Siberian Plate during Hercynian time (296–245 Ma). During this collision, large volumes of granite were generated. The older sedimentary and magmatic rocks occur today as roof pendants or are surrounded largely by these granites. Satellite image data reveal a pattern of thrusting and folding in the Bayan Obo region that is

(SPOT DATA © CNES 1988)
Geologic map of Bayan Obo area, Inner Mongolia, China. Q, alluvium; Hg, Hercynian granites; Vc, Carboniferous subaqueous volcanics; Zs, Sinian conglomerates and carbonates; Bg, Bayan Obo group sediments; Wt, Wu Tai migmatites. [Drew and others abstract]

interpreted to be consistent with the behavior of passive margin stratigraphy during continental collision. Strong magnetic and gravity anomalies and moderate radioactive anomalies are characteristic of the deposit.

The principal orebodies are hydrothermal replacements of carbonate rocks that were deposited before the Hercynian thrusting and folding. These carbonate rocks occur in the Bayan Obo group, a package of middle Proterozoic sedimentary rocks (1.35–1.65 Ga) consisting of arkosic and quartzose clastic rocks, shale, and limestone (Jishun and others, 1987). This sedimentary section rests unconformably on the Wutai group, which is a collection of gneiss and migmatite dated at 2.2 Ga. Widespread mineralization also occurs in veins and breccia filling in the associated clastic rocks and older gneiss and migmatite. The ore minerals include iron oxides, niobates, monazite, and bastnaesite. Gangue minerals include fluorite, K- and Na-feldspar, carbonates, amphiboles, pyroxenes, biotite, apatite, and barite. The orebodies are very large and have ore reserves estimated at 1.5 billion tons of iron and 37 million tons of rare-earth oxides. This rare-earth reserve estimate probably understates the resources in the deposits by a factor of two or three. Quantitative estimates of the niobium ore reserves are not available, but these resources are considered to be very large.

Widespread sodic and potassic alteration is characteristic of the hanging-wall and footwall rocks, respectively. These altered rocks cover an area of at least 18 by 2 km in the vicinity of the orebodies. A zone of intense sodic alteration occurs in the footwall clastic rocks and in the older gneiss and migmatite directly below the main orebody. This footwall alteration is characterized by albite and sodic amphiboles. Both minor K-feldspar and sodic pyroxenes also occur. In contrast, widespread potassic alteration in the hanging-wall shale is characterized by K-feldspar and biotite.

Brecciation and veining of shales in the hanging-wall shales are also characteristic features associated with rare-earth-element mineralization. Most of the breccia fragments are altered to microcrystalline K-feldspar. The breccia matrix is composed of a variety of mineral phases: K-feldspar, biotite, fluorite, albite, iron oxides, calcite, barite, monazite, apatite, bastnaesite, niobates, pyrochlore, pyrite, and iron carbonate. A common paragenesis in the veins, from earliest to latest, is feldspar (K-feldspar and minor albite)-biotite-fluorite-iron oxides.

We interpret the Bayan Obo orebodies to be products of widespread hydrothermal alteration associated with the Proterozoic rifting event. The orebodies and associated altered rocks were subsequently metamorphosed and uplifted during the Hercynian collision. An occurrence model that can be used in other regions of the world should satisfy at least the following three genetic criteria: (1) a mechanism for tapping mantle and deep crustal magmas that provide heat for development of a hydrothermal system; (2) a stratigraphic section of sedimentary rocks that contains both host rocks (carbonate rocks) and sealing rocks (fine-grained siliciclastic rocks); and (3) a mechanism for uplifting the orebodies. At Bayan Obo, these three components were satisfied by intracontinental rifting of a carbonate-shale sequence of rocks on Precambrian basement followed by continental collision. Other geologic phenomena can satisfy these criteria, thereby forming similar orebodies.

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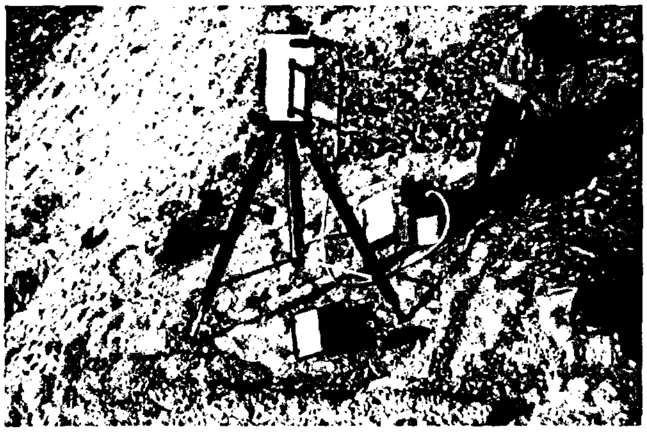
Spectral Reflectance Changes in Vegetation Associated with Anomalous Concentrations of Metallic Elements—A Potential Tool for Mineral Exploration

Barbara A. Eiswerth, Nancy M. Milton, and David A. Mouat

Certain metals, when present in anomalously high concentrations in the substrate, have been shown to cause significant and detectable changes in the spectral reflectance characteristics of plants. We are documenting these changes and developing techniques to determine the identity and concentration of elements that cause changes in spectral



U.S. Geological Survey scientist measuring spectral reflectance of a hydrothermally altered rock sample using the visible and near-infrared field spectrometer. The measurements are correlated with Landsat Thematic Mapper data to map hydrothermally altered rocks in Nevada. [Eiswerth and others abstract]

signatures of vegetation. Understanding the link between substrate mineral content and vegetation reflectance is especially important for mineral assessment studies in heavily vegetated and inaccessible areas. The use of remotely sensed data provides a regional view that is rapid and cost effective while allowing the assessment of the biogeochemical environment.

Controlled greenhouse experiments have provided quantitative data on the effect of anomalous concentrations of Ni, Cu, Zn, Co, and As in spectral reflectance of hosta and soybean plants. Spectral reflectance of leaves was measured from 0.40 μm to 0.80 μm at weekly intervals on a laboratory spectrophotometer. Spectral changes observed included (1) a shift in the long wavelength edge of the chlorophyll absorption band (known as the red edge shift) centered at 0.68 μm to shorter wavelengths and (2) higher reflectance in the 0.55- to 0.65-μm region compared with reflectance of control plants. The inflection point of the red edge, as defined by the first derivative spectrum, shifted significantly to shorter wavelengths in plants dosed with nickel, cobalt, zinc, and arsenic. Results were ambiguous for copper-dosed plants.

Spectral reflectance measurements of native vegetation collected by using field spectrometers and high-resolution airborne spectrometers corroborated the greenhouse results. Field spectral measurements of sagebrush were analyzed from Owens Valley, Calif. Spectral changes in the vegetation reflectance patterns were used to distinguish areas of hydrothermally altered limestones from unaltered limestones. In another sagebrush study, spectral measurements were made in southern and south-central Idaho where gold mineralization is associated with high arsenic levels and other metals in the substrate. In the Idaho cobalt belt, anomalous spectral reflectance was detected in conifers growing in soils having anomalous levels of cobalt and copper.

High-resolution airborne data were collected over deciduous forests in North Carolina and mixed hardwood-coniferous forests in the Vermont copper belt to delineate mineralized zones. In Randolph County, N.C., spectral anomalies in the canopy, which represent the red edge shift, correlated with soils containing anomalously high amounts of copper, molybdenum, and tin. This area of the Carolina slate belt is of interest because it has zones of intense hydrothermal alteration classified as a porphyry gold system. In Cuttingsville and Pike Hill, Vt., airborne spectroradiometer data were used to map spectral anomalies correlating with areas of hydrothermal alteration and mineralization. An airborne prototype for a spaceborne platform is being tested. By using this technology, the methods described can be applied to a variety of geographical regions and geologic problems.

Mineral Resource Assessment of the Butte 1° × 2° Quadrangle Using Geographic Information System Technology

J.E. Elliott, C.M. Trautwein, J.L. Dwyer, and S.H. Moll

The mineral resource potential of the Butte 1° × 2° quadrangle has been assessed under the auspices of the U.S. Geological Survey's CUSMAP (Conterminous United States Mineral Assessment Program) project. By using geographic information system (GIS) technology, the following deposit types were assessed: vein and replacement base- and precious-metal, porphyry-stockwork copper and molybdenum, skarn gold-silver-copper-tungsten, stockwork-disseminated gold-silver, and placer gold deposits. The steps followed in this method of assessment were (1) data acquisition, (2) data compilation and entry into the GIS, and (3) mineral resource assessment. The GIS used for the assessment consists of three main subsystems (vector, raster, and tabular) for processing diverse types of geographically referenced data. The mineral resource assessment procedure involved (1) developing descriptive mineral deposit models and recognition criteria for each of these models, (2) using GIS techniques to develop images that are based on recognition criteria for each descriptive model, and (3) using GIS technology to combine these images into a final image or map.

New data were acquired through geologic mapping, geochemical and geophysical surveys, remote sensing and geochronologic studies, and examination of mines and prospects. The acquired data were combined with previously published and unpublished data and compiled either as tables or as maps at a scale of 1:250,000. Maps, including a generalized geologic map, a map of mining district and area boundaries, an interpretive geophysical map, a map showing limonitic alteration, and a map showing domains of linear features, were digitized by using the vector subsystem. After editing, these maps were converted to a raster format for entry into the raster subsystem. Analytical data from geochemical surveys were entered into the tabular subsystem. By using a minimum-curvature surface-generation algorithm, the analytical data were combined with sample locations to produce a raster map for each required element. Other data entered and converted to raster files included the digital elevation model, as gridded data, and previously digitized linear feature data.

The final resource assessment maps show areas of low, moderate, high, and, for some deposit types, very high resource potential for each type of deposit. These maps indicate that much of the Butte quadrangle is favorable for the occurrence of one or more of the assessed deposit types. Although most of the areas of high or very high potential are within or adjacent to known mining districts, some areas of high and very high potential occur in parts of the quadrangle that have few or no known mines and prospects. These areas are geologically favorable for mineral exploration.

Tectonic and Stratigraphic Control of Subsurface Geochemical Patterns in the Ozark Region

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Subsurface geochemical studies in four contiguous 1° × 2° quadrangles in parts of Missouri, Arkansas, and Kansas and along a north-south transect of drill holes in western Illinois reveal surprisingly consistent regional patterns of distribution and abundance of metals that have important implications for the genesis of Mississippi Valley-type (MVT) deposits. Throughout this broad area, insoluble residues of "barren" carbonate rocks of Cambrian age commonly are lead rich and contain an extensive suite of other metals (Zn, Cu, Ni, Co, Mo, Ag, As). This lead-rich metal suite is characteristic of Cambrian-hosted ore deposits in the Southeast Missouri lead district. Insoluble residues of carbonate strata of Ordovician, Mississippian, and Pennsylvanian age tend to be zinc rich, and anomalous concentrations of other metals (Cu, Ni, Co, Mo, Ag, As) are rare.

The widespread occurrence of ore-related metals in insoluble residues of Paleozoic carbonate rocks attests to the passage of metal-bearing fluids through vast areas of the Ozark region. Leach and Rowan (1986) give compelling evidence that MVT deposits in the Ozark region formed from a single hydrologic system related to fluid migration northward out of the Arkoma basin in response to Ouachita tectonism. Our geochemical data generally support this model, but recently acquired data from drill holes along the western margin of the Mississippi embayment and the Illinois basin suggest that fluids migrating from the Illinois basin and (or) the New Madrid rift zone may have played a significant role in the genesis of the Southeast Missouri lead district. All of our data, however, suggest that Cambrian strata were the major regional aquifers in the Ozark region for transport of an extensive suite of metals, regardless of which sedimentary basin is favored as a metal-brine source. Further, the geochemical data suggest an explanation for the differences in ore composition (that is, lead rich versus zinc rich) between vertically stacked host rocks and between MVT mineral districts in the Ozark region. If Cambrian strata were the major regional aquifers for fluids, then mineral districts hosted by post-Cambrian rocks could have formed where geologic structures intersected and tapped the Cambrian aquifers. Fluids released up these structures would selectively deposit metal sulfides according to their relative solubility in the presence of reduced sulfur ($Ag<Cu<Pb<Co<Ni<Zn$). Zinc, the most mobile metal in the suite, should travel farther and should become enriched upward relative to the other metals as the fluid is selectively depleted in the less mobile metals. This process could result in formation of structurally controlled, zinc-rich districts in post-Cambrian carbonate strata (Mississippian-hosted Tri-State and Ordovician-hosted Northern Arkansas zinc districts). Fluids remaining in the Cambrian aquifers would maintain their characteristic lead-rich metal suite and continue to migrate through Cambrian strata in search of a depository for their metal burden. The Cambrian-hosted Southeast Missouri lead district with its extensive suite of metals may be such a depository. The implications of the subsurface geochemical patterns are that Cambrian aquifers provided the plumbing system for all Ozark MVT districts and that the Illinois basin, the New Madrid rift zone, and the Arkoma basin may have served as metal-brine sources in the Ozark region.

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A Review of the Proposed Standard for Digital Cartographic Data

Robin G. Fegeas, Hedy J. Rossmeissl, and Robert D. Rugg

The proposed Standard for Digital Cartographic Data, published in the January 1988 issue of "The American Cartographer," is the result of 6 years of effort by committees of the American Congress on Surveying and Mapping and the Federal Government. Intended to help eliminate duplication of effort and to promote cooperation in digital mapping activities, the proposed standard specifies certain elements of content and a common format for the exchange of spatial data.

Thorough testing of the proposed standard was completed first by those agencies most active in its development and then by a cross section of government, university, and private sector organizations. The testers volunteered considerable resources to perform one of four types of tests: (1) detailed conceptual mapping of the tester's data to and from the standard, (2) decoding of one or more of the sample test data sets into the tester's system, (3) encoding of the tester's data into the standard, and (4) actual transfer of data from one tester's system to another tester's system by using the standard.

As a result of the testing, modifications were made to the proposed standard to clarify and to refine its content. Software was developed to verify successful transfer of data to the common exchange format. The proposed standard was submitted to the United States National Bureau of Standards for consideration as a national Federal Information Processing Standard.

Mineral Resource and Geochemical Exploration Potential of Coal that has Anomalous Metal Concentrations

Robert B. Finkelman and Robert D. Brown, Jr.

The potential for using coal and coal wastes as mineral resources has intrigued the coal and mineral industries for many years. However, to date there has not been any significant use of these sources. Is there any justification for continued interest? We believe that the potential exists for mineral recovery from coal and coal wastes, provided that we apply our knowledge properly. We envision three aspects to this concept: (1) byproduct recovery from coal and coal wastes, (2) coal as a byproduct of a mineral extraction process, and (3) coal as a geochemical indicator of mineralization.

1. *Byproduct recovery from coal and coal wastes.*—In the United States, more than 900 million short tons of coal are produced annually and yield about 100 million short tons of waste products. Using national means for ash yield and trace element concentrations, calculations indicate that coal and coal ash could provide at least half of the U.S. annual consumption of As, Be, Bi, Co, Ga, Ge, Hf, Nb, Se, Sr, Te, Tl, Y, the rare-earth elements, and significant contributions of many other elements. Detailed studies have been conducted on the extraction of Al, Cd, Ga, Ge, Fe, Mo, Ti, U, Zn, and other elements. Extraction of these elements has not been economic except for sporadic local production of uranium.

The reasons for this bleak track record include (1) widely dispersed sources of coal and coal wastes (only one U.S. mine produced more than 13 million tons of coal in 1986, and few powerplants burn more than 5 million tons of coal annually), (2) significant production of low-ash and low-sulfur coals that have considerably lower trace element concentrations than the national average, (3) no viable extraction procedure, and (4) depressed markets. We believe recovery of selected elements of strategic importance is possible. Among the more attractive possibilities are Bi (coal mean 1.61 ppm versus 0.01 ppm in shale), Se (2.78 versus 0.6), Sb (1.17 versus 1.5), Cd (0.55 versus 0.3), Ag (0.09 versus 0.07), Tl (3.5 versus 0.4), Te (0.X versus 0.01), and In (0.X versus 0.1). These elements generally have chalcophile tendencies and therefore were concentrated in coal by the same mechanisms, are highly concentrated in coal with respect to crustal abundances, are moderately to highly volatile and therefore may be collected from flue gas, form readily soluble compounds that could be extracted by a single chemical process, and are environmentally deleterious, therefore, extraction from coal or coal wastes would reduce pollution.

2. *Coal as a byproduct of a mineral extraction process.*—Some coals are extraordinarily enriched in certain trace elements. A coal in Alabama contains almost 2,200 ppm arsenic (12,500 ppm arsenic in the ash); a coal in Texas contains 300 to 600 ppm silver in the ash; the ash of an Illinois coal contains almost 2,000 ppm cadmium; coals containing almost 8,000 ppm germanium in the ash are known from several locations; lignites in Mississippi average over 10 ppm selenium; coals that have several thousand ppm uranium have been found in several western States. These and other examples of exceptional concentrations of elements in coal are on file in the U.S. Geological Survey's National Coal Resources Data System (NCRDS).

Generally, coals containing these high element concentrations are not mined because of environmental and coal quality (high ash yield or high sulfur content) concerns. However, mining these coals for their mineral resources and using the cleaned coal as a byproduct to generate heat may make some of these deposits economically viable. An example of this symbiotic relation can be seen in the mining of clays and associated lignites in Texas and California.

3. *Coal as a geochemical indicator of mineralization.*—The concept of biogeochemical prospecting for mineral resources has been successfully applied to a number of elements, and coal can be used in the same way. Some of the high elemental concentrations noted in the previous section may not be economically recoverable, but they may be indicative of nearby mineralization. Many of the 13,000 coal analyses in the NCRDS are from sedimentary basins that have virtually no other chemical analyses. These NCRDS data offer a unique opportunity to assess the mineral resource potential of these basins. An example of how this concept can be applied is the diamonds that have

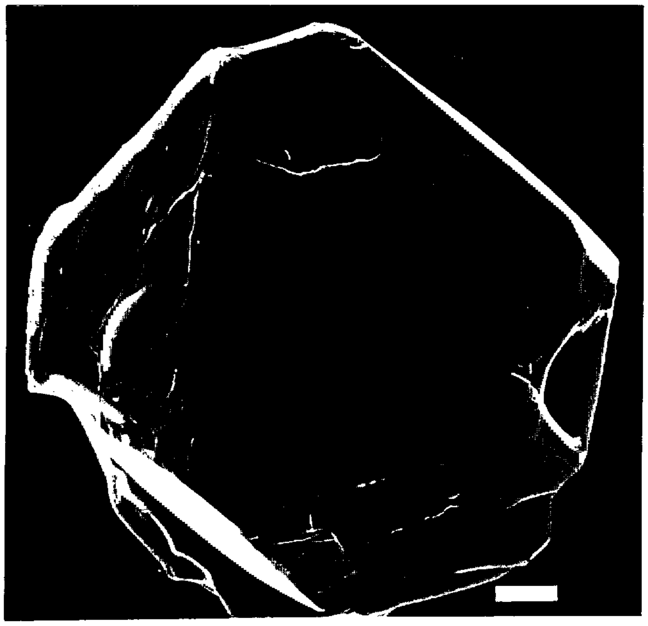


Figure 1. Scanning electron micrograph of a diamond crystal extracted from coal. Scale bar=10 micrometers. [Finkelman and Brown abstract]

been found recently in a Wyoming coal in an area that has no known diamond-bearing source rocks (fig. 1). A careful reconnaissance study in the vicinity of the coal deposit may lead to the diamond source.

In conclusion, although byproduct recovery from coal and coal ash has not been successful in the past, new analytical data justify our continued interest in this concept.

Preliminary Map Showing the Location of Productive Lode and Placer Gold Deposits and Significant Gold Prospects in Montana

David Frishman, J.E. Elliott, E.E. Foord, R.C. Pearson, and W.H. Raymond

"Gold is where you find it," and one of the best places to find it is where someone else has found it before. The Montana gold map and accompanying data base provide a comprehensive inventory of placer and lode mines in Montana that produced and (or) contain as plausible resources more than 500 troy ounces of gold. Mine and prospect locations are shown by different sized, shaped, and colored spots. Spot size denotes one of four size classes (500–5,000 oz., 5,000–50,000 oz., 50,000–500,000 oz., and >500,000 oz. production+reserves). Spot shape is coded for deposit type (placer, vein-replacement, disseminated, breccia pipe, stratabound, skarn, and other), and spot color is keyed to the age of mineralization (rarely well known). The map, at a scale of 1:500,000, shows the locations of more than 450 mines and prospects; areas having a high density of mines are shown in more detail at a larger scale. An accompanying pamphlet lists the name of each mine, synonymous names, mining district, location (latitude and longitude), commodities produced, host rock lithology and age, lithology and age of associated igneous rocks (if any), and selected references. In addition to the published map and pamphlet, the data will be made available as a U.S. Geological Survey (USGS) Open-File Report in the form of a 5¼ in DOS-formatted diskette containing the data in both ASCII and dBase III formats. Although the map will be published at 1:500,000 scale, location information for mines and prospects has been compiled from the most accurate maps available, usually USGS 1:24,000-scale topographic quadrangles. Therefore, latitude and longitude for most mines listed in the data base should be accurate when plotted at scales as large as 1:24,000.

Geologic-Map Information and Where to Find It

H. Kit Fuller

Geologic maps can be somewhat difficult to obtain. To help alleviate this problem, the U.S. Geological Survey (USGS) and many State geoscience agencies produce geologic map indexes.

USGS Geologic Map Indexes (GMI's) are published State-by-State compilations that include index maps (sorted by scale), a bibliography, and an explanation. To use a GMI, identify an area of interest on the index maps (fig. 1) and use the numbers of the geologic maps to find complete reference data in the bibliography. The geologic map indexes produced by State agencies vary in format and content, and many of them include information not found in USGS GMI's.

In addition to these information sources, a USGS data base (GEOINDEX) having the bibliographic data from the GMI's is now available. GEOINDEX and two other USGS data bases—USGS Library and the Earth Science Data Directory, were recently released on a CD–ROM disk. In this format, the data can be kept more up-to-date than GMI's.

Other sources of geologic-map information include State publication lists, USGS publication catalogs, library map catalogs, and commercially available lists of USGS maps. These sources usually include references other than geologic maps, and searching them can be more time consuming than searching only the geologic-map literature. However, well-prepared indexes or other methods of organizing the geologic-map information make some of these products excellent reference sources.

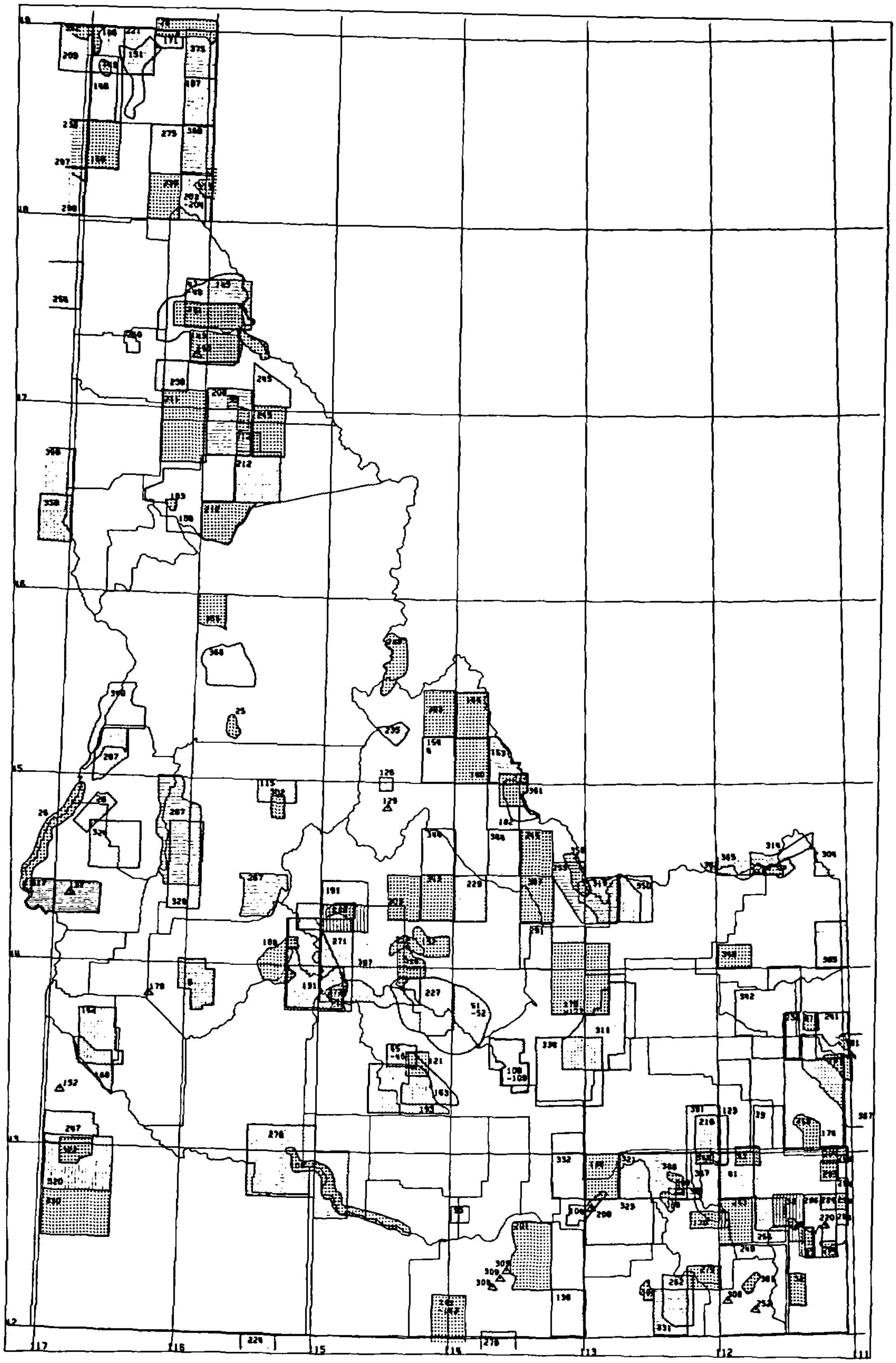
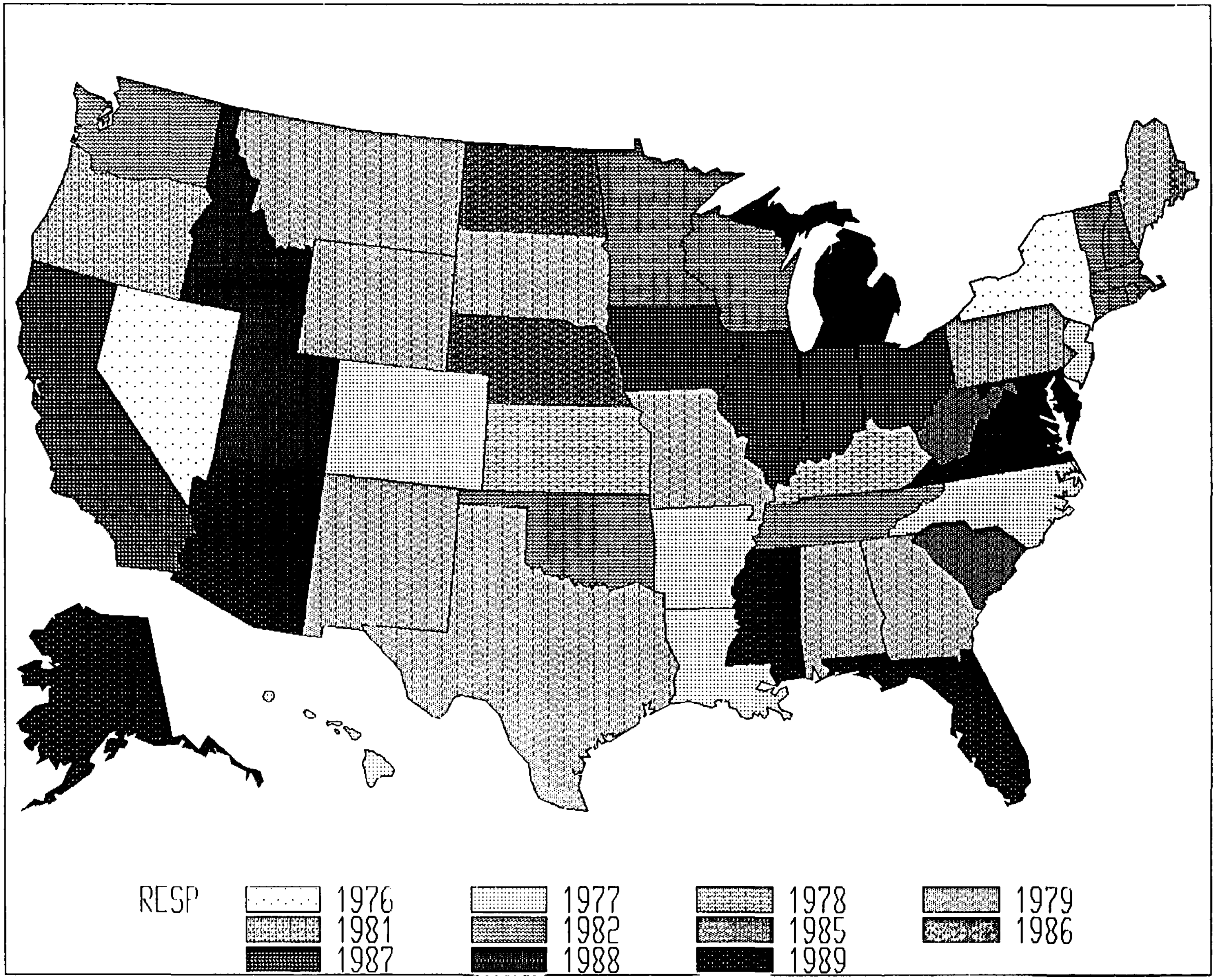


Figure 1. Index map from the 1988 Geologic Map Index (GMI) of Idaho showing general purpose and topical geologic maps at scales between 1:24,000 and 1:63,360 (inclusive). Patterns indicate map coverage, not type of map. Some references include more than one map (for example, no. 309); some boundaries represent more than one reference (for example, nos. 51–52). The GMI of Idaho includes four other index maps to show maps at other scales. Each index map shows State and County boundaries and latitude/longitude grid. [Fuller abstract]



Status map showing recent progress in updating the published USGS Geologic Map Index series. 1989 dates indicate maps being updated. GEOINDEX, the bibliographic database of geologic maps, is updated through December 1988.

Classic tundra tussocks in southwestern Alaska.

Mineral Resource Assessment, Bendeleben and Solomon Quadrangles, Western Alaska

Bruce M. Gamble

A multidisciplinary mineral resource assessment of the Bendeleben and Solomon quadrangles, western Alaska, has identified 13 permissible mineral deposit types. These include deposit types that are currently known to exist and those that are speculative based on available data. Thirty-five tracts (shown on three poster session maps) are favorable for the following mineral deposit types:

- Map 1: Tin vein, greisen, skarn, and replacement; iron-(copper), tungsten, and lead-zinc skarn; polymetallic replacement and vein; and molybdenum stockwork.
- Map 2: Volcanogenic massive sulfide and sediment-hosted exhalative zinc-lead.
- Map 3: Low-sulfide gold-quartz veins.

Gold placers account for the majority of metallic mineral production from these quadrangles; approximately 2 million ounces of gold were produced between 1898 and 1985. From 1903 to 1907, about 27,000 ounces of gold were obtained from low-sulfide gold-quartz veins at the Big Hurrah mine. Small amounts of silver-rich galena ore were mined from the Omilak mine (polymetallic replacement?) and the Independence mine (polymetallic vein).

Deposit types that occur in the quadrangles but have not produced ore are sedimentary exhalative zinc-lead, iron-(copper) skarn, molybdenum stockwork, and polymetallic tin veins.

Concealed tin deposits are possible around the Oonatut Granite Complex—the easternmost of the tin granites on the Seward Peninsula. A small, prominent aeromagnetic high above a buried portion of the granite may be related to a concealed tin skarn or a tin replacement deposit. Aeromagnetic data also indicate the potential for additional iron-(copper) skarn mineralization. Concealed polymetallic vein, replacement, and lead-zinc skarn deposits may be present near several plutons. Molybdenum stockwork mineralization associated with the Windy Creek pluton could represent the outer portions of an ore deposit.

The Hannum-Harrys Creek deposit is the only example of a sedimentary exhalative zinc-lead deposit in these two quadrangles; however, several similar occurrences are in the Nome quadrangle to the west, and there is potential for additional deposits of this type in the Bendeleben and Solomon quadrangles. Volcanogenic massive sulfide deposits have not been found in this area; however, favorable host rocks and anomalous stream sediment geochemistry indicate that there is some potential for Besshi-type deposits.

Low-sulfide gold-quartz veins may represent the best hope for future mineral production in these quadrangles. Most of the veins, with the exception of those at the Big Hurrah mine, are too narrow (mostly <10 cm) and discontinuous to have warranted much interest in the past. However, higher gold prices and other factors have contributed to increased exploration in the area. Most of the low-sulfide gold-quartz veins examined on the Seward Peninsula occur in a mixed unit of interlayered quartz-graphite schist, pure and impure marbles, and lesser pelitic and chlorite-albite schist. Some occur in a unit composed of chlorite-albite and mafic volcanic schists that overlies the mixed unit.

Contrasting Sulfur Sources for Lower Versus Upper Midcontinent Mississippi Valley-Type Ores—Implications for Ore Genesis

Martin Goldhaber

Basic genetic concepts for Mississippi Valley-type (MVT) lead-zinc deposits cannot be considered complete until the mechanism(s) and the site(s) of sulfide generation are known. To address these issues, data from regional sulfur isotope studies (more than 300 analyses) to assess sulfur sources have been combined with petrographic observations to constrain relative timing of sulfide emplacement. These data have defined "footprints" of aqueous sulfide migration in the form of trace epigenetic sulfide minerals along likely ore fluid flow paths.

Regional studies of the lower midcontinent (LMC) comprising Upper Cambrian through Mississippian carbonates in Missouri, Arkansas, and Illinois show widespread development of sulfides (dominantly FeS_2) that were precipitated epigenetically during hydrothermal fluid flow associated with the regional mineralizing event(s). There is a marked stratigraphic trend in $\delta^{34}S$ of these sulfides. The broadest range and heaviest $\delta^{34}S$ values (-10 to $+40$ per mil, mean $+8$) are found in the oldest part of the section, specifically the Upper Cambrian Bonneterre Formation. Progressively lighter epigenetic sulfides occur upsection. For example, Mississippian-hosted FeS_2 has a mean $\delta^{34}S$ of -9 per mil.

These stratigraphic trends in $\delta^{34}S$ from unmineralized rocks closely parallel isotope values from major ore districts. Published studies of LMC ores of the Southeast Missouri lead belts, hosted by the Bonneterre Formation, show a broad range of $\delta^{34}S$ values (-2 to $+30$ per mil), whereas the Mississippian-hosted Tri-State district of southwest Missouri and adjoining States has a much narrower range of isotopic compositions (from 1 to -9 per mil) centered around -5 per mil.

This parallelism is best explained by a widespread migration of H_2S-bearing hydrothermal brines that have at least two distinct sulfur sources. Isotopically heavy H_2S deeper in the section arose from thermochemical SO_4^{2-} reduction of Cambrian and Ordovician evaporates whose $\delta^{34}S$ is known to be 25 to 30 per mil. Evaporates of this age occur in association with mature petroleum source beds in the southern Illinois basin to the east of the lead belts, and fluids from this area are therefore a potential sulfur source for the ores. A separate H_2S source, having $\delta^{34}S$ of about -5 per mil, is present as organosulfur in Pennsylvanian coals and hydrocarbons and would have been released during regional thermal maturation.

Fluid mixing of two low pH, H_2S- and metal-bearing brines having distinct $\delta^{34}S$ values gave rise to the lead belt mineralization. This mechanism explains the wide range in $\delta^{34}S$ of these ores and is also consistent with constraints from lead-isotope data, ore textures, and ore mineralogy. In contrast, Tri-State ores formed from a single isotopically homogeneous sulfur source. Although fluids bearing sulfide of this isotopic composition were regionally widespread, the present data do not define whether or not precipitation was produced by fluid mixing.

Upper midcontinent mineralization in Illinois and Wisconsin is characterized by a constant $\delta^{34}S$ of 13 per mil for ore-forming H_2S. Data from several cores peripheral to orebodies demonstrate that residual organic sulfur in the Gutenberg Member of the Decorah Formation contains organic sulfur that is also near 13 per mil. This similarity suggests that sulfur was partially released during mineralization and provided a local trap for migrating metal-bearing brines.

In summary, the examination of geochemical and geologic information reveals that MVT deposits form from both local and distant sulfur sources and by more than one mechanism of precipitation.

Anomalous Palladium-Platinum Occurrences in Mesozoic Quartz-Normative Tholeiitic Suites in the Eastern United States

David Gottfried, A.J. Froelich, P.J. Aruscavage, and Norma Rait

Several Mesozoic diabase-granophyre sheets in the Eastern United States were assessed, through the analysis of 250 samples, for their potential as sources or hosts of platinum group metals. Systematic distribution, abundance patterns, and ratios of palladium and platinum through differentiated sheets between upper and lower chilled margins have greatly improved our understanding of palladium-platinum behavior during the differentiation of typical high-titanium, quartz-normative (HTQ) tholeiitic magmas (Gottfried and Froelich, 1988). Palladium and platinum

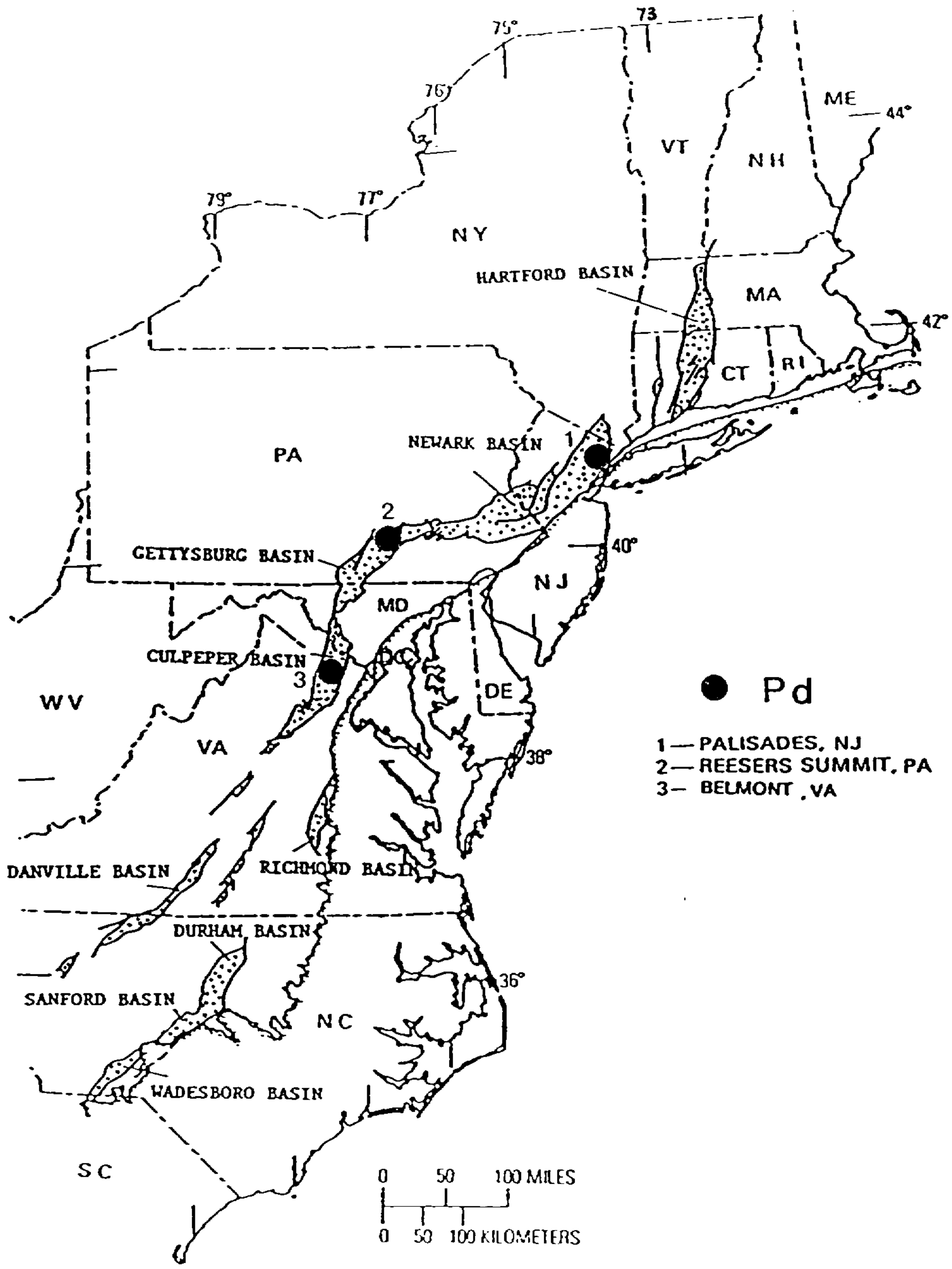


Figure 1. Index map of the Eastern United States showing the location of early Mesozoic basins (dotted areas) and anomalous palladium occurrences in late-stage ferrogabbroic differentiates of high-titanium, quartz-normative diabase sheets. [Gottfried and others abstract]

contents of chilled margins of HTQ suites average about 10 ppb each. During differentiation, platinum is enriched relative to palladium in cumulate layers, whereas in the more evolved later differentiates, palladium is enriched relative to platinum.

Anomalous abundances of palladium+platinum, more than 200 ppb, occur in ferrogabbro and ferrodiorite and represent an order of magnitude enrichment over other rocks of similar composition in the Mesozoic basins. Palladium anomalies have thus far been noted in similar rocks from three widely separated differentiated HTQ sheets: (1) Palisades sill in New Jersey, (2) Reeser's Summit in the York Haven sheet, Pennsylvania, and (3) Belmont sheet, Virginia (fig. 1). The highly evolved portion of the York Haven sheet at Reeser's Summit, typical of the other anomalous palladium occurrences, is well exposed and is being studied in considerable detail. The distribution of MgO, Pd, and Pt and Pd:Pt from the

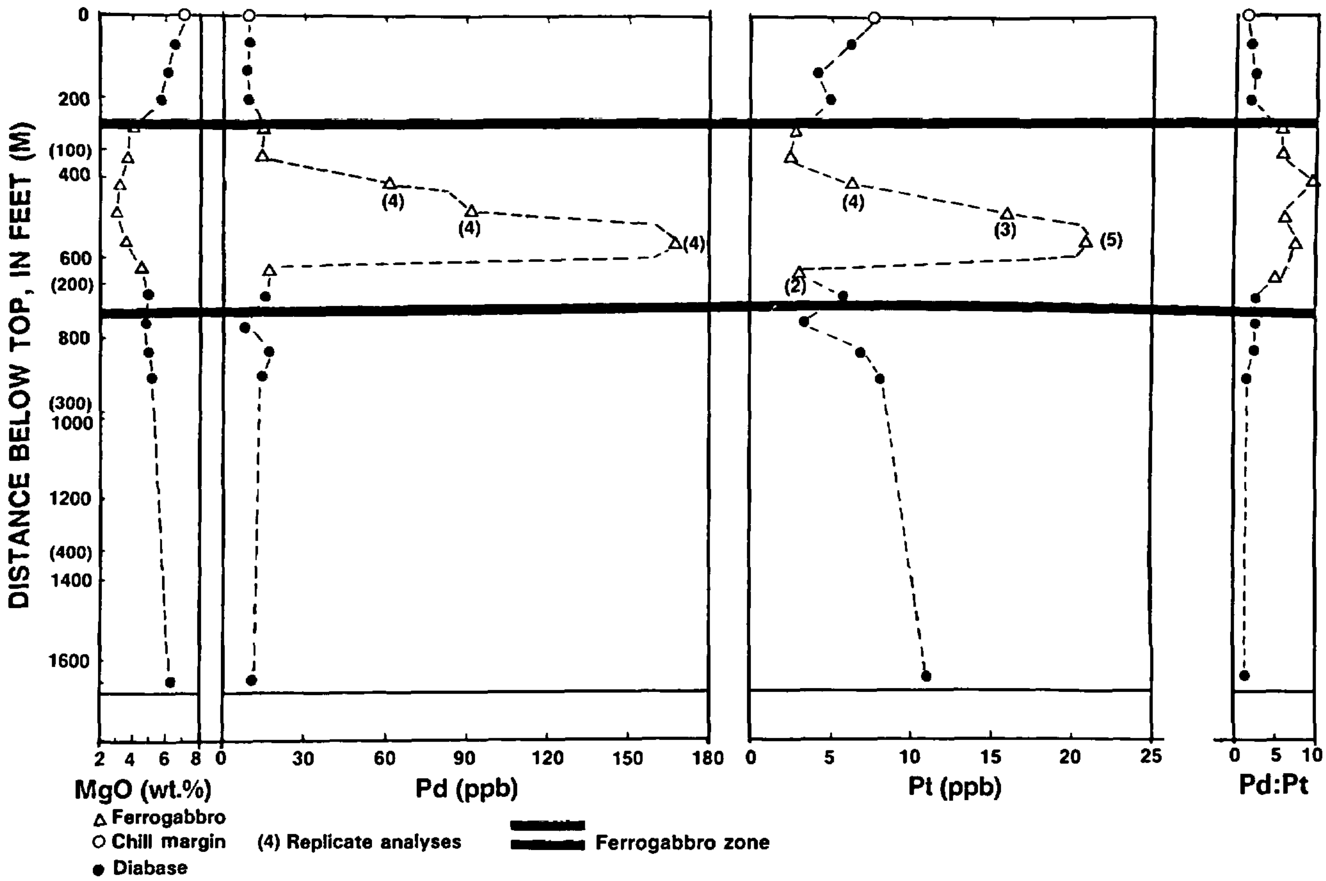


Figure 2. Distribution of MgO, Pd, and Pt and Pd:Pt in ferrogabbro differentiate of high-titanium, quartz-normative York Haven diabase sheet, Reeser's Summit, Pa. (Analysts, Norma Rait and Hezekiah Smith, U.S. Geological Survey.) [Gottfried and others abstract]

chilled margin across this section are shown in figure 2. The anomaly zone in the ferrogabbro, near the upper part of this sheet, is accompanied by relatively high contents of copper (to 360 ppm), gold (to 54 ppb), and tellurium (to 26 ppb) and has high iron (to 18 percent), titanium (to 3.5 percent), and chlorine (to 0.44 percent).

The occurrence of high contents of palladium and copper in the late stage differentiates indicates that silicate fractionation proceeded without early precipitation of an immiscible sulfide phase. This absence of early precipitation is not unexpected inasmuch as the sulfur content of HTQ margins is generally quite low, 100 to 200 ppm (Gottfried and others, in press). Petrologic and geochemical data, however, indicate that the marked enrichments of Fe, Ti, Cl, Te, Au, Pd, and, to a lesser extent, Pt in the ferrogabbro zone cannot be accounted for solely by tholeiitic differentiation. It appears more likely that late magmatic or postmagmatic fluids, predominately chlorine rich, have played an important role in their transport and enrichment (Belkin, this volume).

The comprehensive geologic, petrologic, and geochemical data obtained in our ongoing studies provide a framework within which must fit any genetic models or processes proposed to account for high concentrations of precious metals in the HTQ tholeiites. Furthermore, integration of field geologic observations and geochemical and petrographic data provides a means of delineating areas favorable for prospecting for either subtle or concealed palladium-platinum mineralization in differentiated HTQ tholeiitic diabase sheets.

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Early-Middle Proterozoic Unconformities: Unconventional Sources for Platinum Group and Precious Metals

Richard I. Grauch

Important amounts of platinum group elements (PGE), gold, and nickel are contained in some of the world's largest high-grade, unconformity-related uranium deposits. Most of these deposits are hosted by rocks on either side of the early-middle Proterozoic unconformity in the Pine Creek geosyncline (Australia) and in the Athabasca basin (Canada). The Coronation Hill deposit (South Alligator River area, Australia) contains a minimum of 8×10^5 tonnes (t) of ore, at a grade of 5 g/t gold. The average grades for platinum and palladium are 0.62 g/t and 1.33 g/t, respectively, for gold-bearing samples (>1 g/t gold) (Needham, 1987). The Kasner Group (1987), working in the vicinity of the Nicholson uranium deposit (Beaverlodge area, Canada), reported gold between 58.63 and 361.37 g/t, platinum between 6.51 and 12.0 g/t, and palladium values of 14.06 g/t for three intercepts ranging between 0.9 and 1.6 m in length. A 54.9-m-long trench averages 97.72 g/t gold. In addition, gold has been produced from the tailings at the Cluff Lake uranium deposit (Canada), and the minimum gold reserves at the Jabiluka uranium-gold deposit (Australia) are 8,100 kg (palladium is present, but reserves have not been calculated). The significant amounts of PGE and gold in these deposits, all related to early-middle Proterozoic unconformities preserved in Precambrian cratons, suggest that there is potential for unconventional resources of PGE and gold in this geologic environment.

The genesis of these unconformity-related deposits has been a topic of intense debate, and genetic hypotheses range from supergene to hypogene (magmatic-hydrothermal) to diagenetic. These varied hypotheses inadequately address the problems presented by the presence of a suite of metals not normally found in the same deposit. However, the following hypothesis addresses those problems.

Initially, a basement of metamorphosed, metal-rich sediments and volcanics is formed. Next and most important, an extensive and deeply weathered surface is developed on the basement. Ideally, the surface is developed in response to several different climatic conditions in much the same way that the present surface of the Yilgarn block of western Australia has developed. This complex process of forming a continental unconformity results in the concentration of seemingly incompatible elements in the same, in a gross sense, stratigraphic unit—the soil profile and underlying altered rocks. On the Yilgarn block, gold was concentrated in laterites (the Boddington and Mount Gibson deposits), uranium in calcretes (the Yeelirrie deposit), nickel in laterites, and platinum-palladium in laterites. Not only are some elements concentrated by this natural heap-leaching process, but many can be fractionated. Uranium can be separated from its daughter lead and from thorium, platinum can be partially separated from palladium, and gold can be separated from silver. The next and equally critical step is the preservation of most of the soil horizon at the base of a large sedimentary basin. During basin evolution, deeply circulating brines, which had ready access to a diversity of metals within the paleosol, carried some of those metals in solution and reconcentrated them in new chemicostructural traps. This, also, is a lengthy and complex process that results in the spatial, not necessarily temporal, superposition of different fluids and thus different metal concentrations.

This conceptual model helps to explain the diversity of metals found in unconformity-related deposits and supports the proposition that significant new PGE and precious-metal resources exist in the unconformity environment.

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Interpreting Concealed Range-Front Faults in Nevada from Gravity and Digital Fault Data and the Significance for Gold Exploration

V.J.S. Grauch and Don L. Sawatzky

Locating concealed exploration targets is becoming increasingly important now that exposed deposits are being exhausted. Discovery of the bonanza Sleeper deposit in north-central Nevada, which is spatially associated with a partially concealed range-front fault system, is one reason new exploration efforts have been directed toward this kind of target. Under the auspices of the Bureau of Indian Affairs, the U.S. Geological Survey is conducting a regional gold resource assessment project involving the interpretation of concealed range-front faults.

Concealed range-front faults were interpreted for this study by digitally comparing a derivative product of regional gravity anomaly data to digitized mapped faults. The derivative gravity product was created by applying a mathematical technique to regional gravity data from Nevada. The technique, based on the properties of the horizontal gravity gradient, estimates the locations of density boundaries, which are steeply dipping boundaries between rocks having contrasting densities, such as at geologic contacts or faults. In Nevada, the boundaries exhibiting the greatest density contrast correspond to extensional range-front faults, where high-density, indurated rocks in the ranges abut low-density basin fill.

Digital comparison of the calculated density boundaries to digital fault data shows that many density boundaries correspond to at least some portion of mapped range-front faults (allowing for discrepancies owing to limitations in the data sets). For example, such correspondences occur along the western side of the Egan Range next to White River Valley and along the eastern side of the Stillwater Range next to Dixie Valley. Other density boundaries confirm large portions of faults that can be inferred only geologically, such as along the east sides of the Kawich and Hot Creek Ranges next to Hot Creek Valley and along the east side of the Toiyabe Range next to Big Smoky Valley. Still other density boundaries track along a range front but then extend beyond the range into the adjoining basin, such as along the west side of the Red Hills, extending into the Kobeh Valley and along the northwest side of the East Range, extending northward into the valley west of Winnemucca. Some density boundaries parallel mapped range-front faults but are significantly offset from the faults and are covered entirely by alluvium. These boundaries probably indicate the edge of the pediment under cover, whereas the range-front fault represents only a minor step in a fault set stepping down toward the basin. Examples are density boundaries located in Huntington Valley, Diamond Valley, Railroad Valley, and White River Valley.

This method of interpreting faults from calculated density boundaries could be an important exploration tool at both regional and local scales. At regional scales, the interpreted range-front faults represent major faults having large density contrasts and considerable depth extent. These faults may have been part of a deep plumbing system genetically related to mineralization. Minor faults at local scales, important in locally controlling ore deposition, could be interpreted in the same fashion if gravity data were collected in more detail.

A Deposit Model for Gold-Bearing Skarns

Jane M. Hammarstrom, Greta J. Orris, James D. Bliss, and Ted G. Theodore

Data for more than 300 skarn deposits (of which 65 percent report gold in trace amounts to 25 g/t) suggest that gold-bearing skarns can be separated into two subtypes that do not differ geologically, but do differ statistically, in gold, silver, and base-metal grade distributions. Deposits that have an average gold grade of 1 g/t or more and that exhibit distinctive skarn mineralogy can be subdivided into (1) skarns in which gold is the primary commodity (median grade 7.7 g/t gold, 1.3 g/t silver) and (2) skarns in which gold has been recovered as a byproduct but assumes the role of primary commodity given sufficient grade due to current metal prices (median grade 3.0 g/t gold, 18 g/t silver). By using these criteria, many byproduct gold skarn deposits may be included in existing deposit models for copper, iron, and lead-zinc skarns.

Gold-bearing skarns typically form in Mesozoic and Cenozoic orogenic belts and island-arc settings; the skarns are spatially and genetically related to I-type felsic to intermediate intrusive rocks. Common features of these deposits include (1) gradational changes to other deposit types within very large mineralized systems and (2) localized gold enrichment within or peripheral to iron or base-metal skarn. Host rocks usually include a premetamorphic calcareous component, but gold-bearing skarns also are known in conglomerate, shale, and tuff; granitoid endoskarn is economically significant in some deposits. Meinert (1987) cites a clastic or volcaniclastic component in the host rock as characteristic of gold skarns. Gold-bearing skarns generally occur in calcic exoskarn associated with intense retrograde alteration. In north-central Nevada, the Fortitude and McCoy deposits formed near granodiorite stocks, whereas gold-bearing skarns in British Columbia, such as those at Hedley and Tillicum Mountains, are associated with diorites and gabbros.

A generalized paragenetic sequence for gold-bearing skarns involves early formation of hornfels, K-feldspar and quartz veining, prograde skarn crystallization of diopside-hedenbergite that is subsequently replaced by grossular-

Euhedral gold crystals from the Roraima placer, Brazil. Recent evidence suggests that crystals such as these may actually grow in place, aided by organic transport of gold and deposition nucleated by bacteria.

andradite garnet in some deposits, and retrograde alteration of the anhydrous minerals to form a hydrous mineral suite characterized by chlorite, epidote, amphibole, quartz, calcite, and (or) nontronite commonly accompanied by sulfides and iron-oxide minerals. Gold is generally deposited during retrograde stages with, or subsequent to, sulfide deposition from relatively low temperature (<300 °C) saline fluids; some deposits include significant concentrations of gold in late quartz. Retrograde assemblages and high-grade ores are particularly concentrated along structures favorable for fluid migration, such as faults and contacts between contrasting lithologies. Opaque minerals reported for gold-bearing skarns include native gold, electrum, pyrite, chalcopyrite, pyrrhotite, arsenopyrite, sphalerite, galena, bismuth minerals, magnetite or hematite, and tellurides. Garnet and pyroxene compositions, retrograde and ore assemblage mineralogy, and igneous rock types associated with gold-bearing skarns apparently cannot always be distinguished from those associated with copper or iron skarns. Myers and Meinert (1988) note that the mineralogy and high grade of the Fortitude deposit are atypical of other base-metal skarns. Gold occurs in relatively oxidized skarns characterized by andradite-diopside-chalcopyrite assemblages and in relatively reduced skarns characterized by hedenbergite-pyrrhotite. Ore guides include (1) all rocks favorable for development of skarn in districts known for other types of precious-metal deposits, (2) reported gold in base-metal and iron skarn, and (3) gold placers in regions of well-developed skarn. Anomalous bismuth, tellurium, arsenic, and selenium values are useful geochemical signatures for some gold-bearing skarns.

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A Conodont Color Alteration Anomaly in Central Indiana—Possibility of Mississippi Valley-Type Hydrothermal Activity

A.G. Harris, C.B. Rexroad, R.T. Lierman, and R.A. Askin

Anomalously high conodont color alteration indices (CAI) of 2 through 4 and 6 and 7 occur sporadically in lower Carboniferous rocks in part of Putnam County, Ind. A range of CAI values has been found within a sample, a stratigraphic section, and the area. These rocks have regional CAI values of 1 to 1.5. Based on 62 localities in a 700-km^2 area, the CAI anomaly forms a north-trending, elongate area about 28 km long and 9 km wide. Precise limits of the anomaly could not be determined because these rocks are concealed beneath thick glacial deposits to the north and northeast and younger, nonmarine Paleozoic rocks to the west. Rocks exposed in the anomalous area range from the Borden Group to the Ste. Genevieve Limestone (Mississippian) and the Mansfield Formation (Lower and Middle Pennsylvanian), which unconformably overlies the Mississippian rocks.

Palynomorphs were concentrated from some of the samples that produced conodonts having anomalously high CAI values or samples that were stratigraphically close to them. Individual samples contain palynomorphs having a relatively broad range of thermal alteration indices (TAI); most specimens have low TAI values (2.5–2.7; =CAI of 1–1.5); less common specimens have even lower values; and rare specimens have higher to considerably higher values. These variations may be caused by differential carbonization and (or) oxidation. In this geologic setting, the darkest palynomorphs are probably not recycled. Some of the lighter spores show evidence of corrosion. The event(s) that produced conodonts having anomalously high CAI values and oxidized conodonts (CAI 6 and 7) also may have oxidized some of the palynomorphs and caused bleaching and abnormally low TAI values. Relative proximity of hydrothermal fluids causing competing carbonization and oxidation processes, as well as physical and chemical differences between palynomorphs and conodonts, probably affected rates of alteration and may help to explain inconsistencies between CAI and TAI values in these samples.

The CAI values and their irregular distribution areally, locally, and even within a sample, together with the textural alteration of some of the conodonts, suggest a hydrothermal event involving fluids having some temperatures of at least 200 °C. There appears to be no correlation between petrographic and conodont data; the lack of correlation indicates that hydrothermal flow patterns were not related to petrographic factors but, more likely, were related to fluid channelways or some local chemical environments. A few exposures of marine Pennsylvanian shales of the Mansfield Formation occur within the area of the anomaly. Conodonts from these rocks have a CAI of 1; this value could indicate either that the thermal event preceded deposition of the Mansfield or that the alteration was hydrothermal and did not affect the impermeable shale. We prefer the latter hypothesis because most hydrothermal events in the eastern midcontinent region are of Late Pennsylvanian or younger age. There are no magnetic anomalies corresponding to the CAI anomaly, but the CAI anomaly overlaps an area of above-average geothermal gradient and overlies a prominent subsidiary topographic basement high offset from the main gradient that trends from the Illinois basin to a culmination at the Cincinnati arch. No local source for heated fluids has been identified, but this is characteristic of

Mississippi Valley-type (MVT) hydrothermal systems where fluids are presumed to be far traveled and to have moved updip during basin evolution. Consequently, this area and its downdip equivalent are possible sites for the localization of MVT ores.

Hydrothermal and Hydrogenetic Ferromanganese Oxide Mineralization of Active Volcanic Arcs

James R. Hein, Marjorie S. Schulz, and Jung-Keuk Kang

Ferromanganese oxide deposits form in four tectonic environments in the Pacific: island arcs, spreading axes, midplate volcanic edifices, and abyssal plains. Three types of iron-manganese deposits occur in island arcs: (1) crusts, (2) manganiferous sandstone, and (3) stratabound and, in places, stratiform manganese. (1) Iron-manganese crusts that precipitate from seawater on rock substrates in island arcs are partly hydrogenetic and partly low-temperature hydrothermal in origin. Compositionally these crusts are intermediate between crusts formed at midplate edifices and those of spreading axes. Based on rare-earth-element (REE) and minor element compositions, the hydrothermal contribution to these crusts ranges from 60 to 90 percent. (2) Low-temperature hydrothermal iron-manganese oxide cements volcaniclastic sandstone. In the Northern Mariana Islands arc, these deposits are low grade (average 17 percent manganese) but large tonnage. Iron averages 6.8 percent and copper averages 0.04 percent. These deposits form by impregnation of porous volcaniclastic deposits by low-temperature hydrothermal fluids. (3) Hydrothermal manganese oxides form stratabound layers and lenses that average 40 percent manganese for the Northern Mariana ridge deposits and 43 percent manganese in the Tonga Ridge-Lau Basin area. These are high-grade, low- to medium-tonnage manganese deposits. In addition to manganese, molybdenum, barium, and zinc are strongly enriched in these deposits; molybdenum averages 0.1 percent. Stratabound manganese deposits formed at higher temperatures than the manganiferous-sandstone deposits and resulted, in part, from leaching of the volcanic arc rocks. These various types of iron-manganese deposits can be distinguished by their mineralogy, iron-manganese ratios, trace metals, and REE patterns (table 1). For example, Fe:Mn is invariably greater than 1.0 for crusts, 0.1 to 1.0 for manganiferous sandstone, and less than 0.1 for stratabound deposits.

Hydrothermal mineralization of the deposits sampled on the Northern Mariana volcanic arc occurred during the past 700,000 years, based on incorporated microfossils. The deposits formed during late-stage volcanic processes on the active arc, probably during submarine flank fissure eruptions. On the Tonga Ridge, most of the manganese mineralization is Quaternary in age.

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Table 1. Average chemical composition for selected elements of iron-manganese deposits of active volcanic arcs, midplate volcanic edifices, and manganese nodules. All data are in weight percent, except Pt, which is in ppm. *n* is number of analyses for various elements. All samples are from water depths less than 2,500 m except for the abyssal nodules. —, no data. [Hein and others abstract]

Area	*n*	Mn	Fe	Co	Ni	Cu	Pb	Ti	Mo	Si	P	Pt	Fe/Mn
N. Mariana arc crusts [1]	12–23	12	16	0.14	0.13	0.04	0.09	0.65	0.02	9.6	0.38	0.08	1.53
N. Mariana Mn-sandstone[1]	9–18	17	6.8	.02	.03	.04	.01	.32	.02	13.8	.09	.02	.51
N. Mariana stratiform Mn[1]	8–11	40	1.5	.01	.02	.01	.003	.07	.06	3.1	.04	.01	.05
Tonga Ridge-Lau Basin crusts[2,3]	2–13	15	20	.28	.21	.06	.13	.87	.03	4.2	.44	.12	1.34
Tonga Ridge-Lau Basin stratiform Mn[2]	2–12	43	1.5	<.01	.005	.01	.005	.06	.11	2.1	.03	.005	.04
Tonumea Island Tonga[2]	1–4	71	5.6	.03	.002	.02	—	.01	.02	—	.02	—	.08
Pacific hydrogenetic crusts[4]	36–319	22	15	.63	.44	.08	.16	.98	.04	5.1	.48	.26[2]	.81
Clarion-Clipperton ferromanganese nodules[5]	43–409	29	6.6	.23	1.22	.99	.048	.61	.05	7.8	.23	—	.2

[1]Hein, Fleishman, and others, 1987.
[2]Hein and others, 1988.
[3]Koski and others, 1985.
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Seasonal Variations in Concentrations of Helium and Carbon Dioxide in Soil Gases at the Roosevelt Hot Springs Known Geothermal Resource Area, Utah

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Although soil gases are frequently collected for geochemical exploration, variations in concentrations of the gases measured and the causes of the variations are not thoroughly understood. To increase understanding of these variations and their causes, concentrations of He, CO_2, O_2, and N_2 were measured in soil gases collected regularly for several months from sites at the Roosevelt Hot Springs Known Geothermal Resource Area (KGRA), Utah. Soil temperature, air temperature, percent relative humidity, barometric pressure, and amounts of rain and snowfall also were measured to determine the effect of meteorological parameters on concentrations of the measured gases. Sample collection and meteorological measurements were made by employees of the Chevron Resources Company Geothermal Division, which operates the powerplant at the KGRA.

The Roosevelt Hot Springs KGRA is located about 20 km northeast of the town of Milford, in Beaver County, southwestern Utah. The producing part of the geothermal field is bounded on the west by a wide north-south-trending fault zone called the Opal Mound fault and on the east by the foothills of the Mineral Mountains. Previous studies showed anomalous concentrations of He and CO_2 over the producing field.

Four sites were selected for soil gas collection. Site A was located directly over the producing geothermal field, and sites B, C, and D were located peripheral to the field. Soil gases were collected from hollow probes at 0.75-m depth in the ground; the probes were left in place throughout the study.

Data from the study indicate that considerable seasonal variation exists in concentrations of CO_2 and He in soil gases. Concentrations of CO_2 and He varied throughout the year at all the sites. The meteorological parameters that most affected the soil gas concentrations were soil and air temperatures. Moisture from rain and snow probably affected soil gas concentrations in an erratic manner. However, small variations in meteorological parameters did not appear to affect measurements of anomalous concentrations in samples collected within a time period of a few days.

At sites B, C, and D, soil and air temperatures correlated positively with concentrations of CO_2 and inversely with concentrations of He. Concentrations of CO_2 at these sites averaged about 10 times the concentration of CO_2 in the air during the winter but about 25 times this concentration in the air during the summer. Concentrations of He at these sites were slightly above the concentration of He in the air during the winter and slightly below this concentration in the air during the summer. There was no correlation between concentrations of He and CO_2; this lack of correlation suggests that most of the He and CO_2 came from atmospheric air. Concentrations of O_2 and N_2 in the soil gases were about the same as O_2 and N_2 concentrations in the air. This similarity suggests that the soil gas samples at these sites were composed mostly of atmospheric air.

However, concentrations of CO_2 at site A over the geothermal field were 50 to 100 times greater throughout the year than at the peripheral sites. Concentrations of He at this site were 2 to 4 times greater throughout the year than at the other sites. In contrast to sites B, C, and D, concentrations of CO_2 and He at site A were higher during the winter and lower during the summer. In addition, concentrations of CO_2 and He were closely correlated, and this correlation suggests that CO_2 and He were related to the geothermal activity. Concentrations of O_2 and N_2 at this site were about 60 to 70 percent of these concentrations at the other sites and indicate that samples from site A had a much lower component of atmospheric air than the other samples.

Geology and Origin of the Jerritt Canyon Sediment-Hosted Disseminated Gold Deposits, Nevada

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The Jerritt Canyon district is located in the Independence Mountains, 80 km northwest of Elko, Nev. The district contains eight ore deposits distributed across a 16-

by 16-km area. The Enfield Bell mine has produced about 1.5 million ounces of gold from 3 of these deposits and has additional proven reserves of 2.8 million ounces. Ore grade averages 0.142 oz/ton. The deposits are disseminated, epigenetic, stratabound bodies that are hosted in miogeoclinal carbonaceous limestones, carbonaceous calcareous siltstones, and cherts of the Upper Ordovician to Lower Silurian Hanson Creek and Lower Silurian to Lower Devonian Roberts Mountains Formations. These rocks are exposed locally in windows through overlying eugeoclinal, siliceous sedimentary and volcanic rocks of the Ordovician Snow Canyon Formation.

The district has a long and complex structural history consisting of at least six episodes of deformation. (1) Early Paleozoic tectonism produced local disconformities between the Roberts Mountains and Hanson Creek Formations. (2) Early Mississippian east-west compression (Antler orogeny) thrust the older Snow Canyon Formation over the younger Roberts Mountains and Hanson Creek Formations along the Roberts Mountains thrust. Exposures of the thrust in the mine show a wide zone of anastomosing fault strands, tectonic foliation, and rotated blocks. These features are typical of large regional thrusts. (3) North-south compression (Sonoran orogeny?) produced east-west-trending,south-verging folds, south-directed thrusting, and related northeast- and northwest-trending fractures. (4) East-west compression (Laramide? Sevier? orogeny) produced north-south- to northwest-trending, large-wavelength, open folds and east-west- and northeast-trending faults and fractures. (5) West-southwest-east-northeast extensional tectonism (~35–10 my) produced northwest-trending high-angle faults. (6) West-northwest-east-southeast- to east-west-directed extension produced basin-and-range-style block faulting (~10 my–Present) and north-northeast-trending, high-angle, normal faults that further dissect the range. The orebodies are most often localized along east-west- and northeast-trending high-angle fault and along low-angle faults but also occur in the limbs of east-west-trending folds, along northwest-trending high-angle faults, and at intersections of these features.

Although intrusive rocks are uncommon in the district, three types have been recognized. (1) A small diorite stock (30 by 150 m) that was dry and unreactive with the surrounding carbonate host rocks occurs in the southern part of the district. It is within 150 m of gold mineralization, and yet it is unaltered. (2) Several small (<6 m wide) porphyritic andesite dikes that commonly have northwest orientations are sparsely distributed across most of the district and may be contemporaneous with the 17 to 14 my old northwest-trending Northern Nevada rift. These dikes are propylitically altered to chlorite, smectite, calcite, and pyrite, and some of these dikes are mineralized. (3) Porphyritic mafic dikes that were probably emplaced during basin-and-range magmatism (<10 my?) occupy north-northeast-trending fractures, are unmineralized, propylitically altered, and crosscut mineralization. The absolute ages of these rocks are currently under investigation.

The white mineral is stibiconite $Sb^{+3}Sb_2^{+5}O_6(OH)$ a common alteration product of stibnite. The sample is from the Enfield Bell mine in the Jerritt Canyon district in northern Nevada. [Hofstra and others abstract]

Detailed mineralogic, petrographic, geochemical, fluid inclusion, and stable isotope studies of jasperoid show that gold deposition was a result of the mixing of two meteoric fluids having contrasting water-rock exchange histories. The ore fluid underwent extensive exchange with wallrocks at low water-rock ratios and elevated temperatures to produce an ^{18}O-enriched, moderately acid, Cl-CO_2-H_2S-rich brine. This fluid scavenged gold from rocks along fluid flowpaths and transported it as a bisulfide complex. The other fluid was an oxidizing, very low salinity, near-neutral pH fluid that exchanged very little with wallrocks. Jasperoid produced during the mixing of these two fluids shows a direct correlation between ^{18}O and log gold concentration. Most of the gold precipitated at the onset of mixing when small increases in fO_2 destroyed the bisulfide ligand. Fluid inclusion data indicate that gold deposition took place at depths greater than 1 km, and possibly as deep as 5 km, at temperatures of 200 to 250 °C.

The geologic relations suggest that mineralization took place after deformation that produced east-west-, northeast-, and northwest-trending high-angle faults and before or during basin-and-range magmatism and block faulting. At present there is no evidence to indicate that mineralization is related to a localized intrusive heat source. Our current hypothesis is that mineralization is related to extension that allowed meteoric water to circulate along open faults to great depths where it was heated, due to high regional heat flow, underwent extensive exchange with wallrocks, and scavenged gold. In the upwelling part of the system, the ore fluid was focused along open fracture systems, especially east-west- and northeast-trending faults. Gold deposition occurred at sites where the ore fluid encountered oxidizing unexchanged meteoric waters descending along permeable pathways below the Roberts Mountains thrust. The Snow Canyon Formation is rarely mineralized, except within a few feet of mineralizing structures, and apparently acted as a hydrologic barrier to upwelling ore-forming fluids. The deposits in the Jerritt Canyon district share many features with other sediment-hosted disseminated gold deposits in Nevada, and the results of this work may have important implications for the origin and age of many of these deposits.

The Getchell Trend Airborne Geophysical Demonstration Project, North-Central Nevada

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Today, the search for minerals is increasingly focused on methods for exploration in covered areas. Airborne geophysical methods look below the cover or identify subtle features within the cover and provide important data early in an exploration or assessment program. The U.S. Geological Survey (USGS), as part of its Development of Assessment Techniques program, is conducting an airborne geophysical demonstration along the Getchell trend in Humboldt County, Nev., to illustrate the advantages of a multidisciplinary approach to exploration and assessment. The primary objective of the program is to evaluate the use of multiple airborne methods for exploration through cover. A secondary objective is to determine the geophysical signatures of ore deposits in the study area.

The Getchell trend was chosen for study because of the presence of five known Carlin-type gold deposits (Preble, Pinson, Getchell, Chimney Creek, and Rabbit Creek), inactive barite and tungsten deposits, and potential for molybdenum and additional gold mineralization. A unique opportunity is provided by the Rabbit Creek deposit, which is covered and over which the airborne and some ground studies will be completed prior to the start of mining. This airborne demonstration program is being conducted with close cooperation between industry and government in both the planning and execution of the study.

The principal area to be flown is a 450-km^2 strip on the eastern flank of the Osgood Mountains and adjacent pediment that includes all the known gold deposits. In this strip, thermal infrared and near-infrared to visible multispectral scanner remote sensing data will be acquired under contract. Low-level helicopter surveys will provide gamma-ray spectrometry, and combined very low frequency electromagnetic (EM), magnetic, and deep-looking multifrequency EM data, also under contract. The USGS will conduct tests of two experimental low-frequency EM techniques by using its own airborne systems. These experimental EM techniques are expected to increase exploration depths in comparison with commercially available systems. Nominal flight line spacing for the low-level surveys is 0.4 km (1/4 mi).

Airborne data will be acquired during September and October 1988, and the preliminary results will be presented at the McKelvey Forum. By using these integrated geophysical surveys, we expect to be able to map some lithologies and structures important for control of ore deposition from outcrop into covered areas. An additional important aspect of this research is acquiring better understanding of the formation of geochemical haloes within cover rocks and the detection of these haloes by shallow penetrating airborne methods. Research on the haloes is being closely coordinated with ground geologic, geochemical, and geophysical studies in the area.

Flow Injection Analysis Applications in Mineral Resource Exploration and Environmental Chemistry

Delmont M. Hopkins

Flow injection analysis (FIA) can be extremely useful for geochemical and environmental analyses. FIA, coupled with a wide assortment of atomic spectroscopic, potentiometric, amperometric, and spectrophotometric detectors, is useful for trace-metal analyses. Other favorable qualities of FIA include minimal reagent consumption, minimum sample handling, excellent reproducibility (percent relative standard deviation (RSD) ≤ 1.0–≤ 4.0), online pretreatments such as dilutions, standard additions, chemical reactions, preconcentration-separation, and a high sample throughput. Sample volumes typically range from 10 to 500 μL, and, because samples, once injected, are completely contained in the system manifold, contamination is avoided. The sample zone disperses in an unsegmented carrier stream, and, because the dispersion response curve reflects a continuum of concentrations, any point (a transient signal) on the peak is valid to construct the calibration curve, provided that readout is taken from the corresponding section. FIA gradient techniques can also be exploited in reaction rate determinations, the study of chemical reactions, and other timely applications to environmental and mineral resource studies (Růžička, 1983).

In our research, a method using FIA and flame atomic absorption spectroscopy (FAAS) was developed for the determination of gold in geologic materials. An organic solvent, methyl isobutyl ketone (MIBK), was the carrier stream and also the analyte extractant. A single rotary injection valve was placed between the carrier reservoir and spectrometer, which provided the carrier flow by aspiration. Samples and reference standards weighing 10 gm each were digested by using hydrobromic acid and bromine and then extracted with 2 mL MIBK. Approximately 1 mL of analyte extractant was typically recovered from each 2-mL treatment; however, the gold was equivalently dissolved in the separated phase and that dispersed in the aqueous layer. Three 250-μL injections were permitted—a distinct advantage compared with the usual continuous introduction of 2 to 3 mL per sample. A detection limit of 5 ppb and an injection rate of 60 to 100 samples per hour were obtained. The precision determined at 50 ppb was 2 percent RSD, and the mean values (N=6) determined for six geochemical exploration reference standards compared well with reported values.

We plan to develop a rapid method for iron (II) and iron (III) speciation in rocks using FIA techniques and FAAS detection. The nature of the depositional environment (oxidizing or reducing) and possible routes of subsequent geochemical processes can be inferred from iron species in rocks.

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Regional Geophysical Studies for the International Falls and Roseau CUSMAP Projects

Robert J. Horton, Val W. Chandler, Robert E. Bracken, and James E. Case

Regional aeromagnetic and gravity data have been compiled for the International Falls and Roseau 1° × 2° quadrangles by the U.S. Geological Survey (USGS) in cooperation with the Minnesota Geological Survey (MGS) and the Geological Survey of Canada (GSC). This compilation was done as part of the Conterminous United States Mineral Assessment Program (CUSMAP) for these two quadrangles located along the United States-Canadian border. Bedrock in the area is largely buried by Quaternary glacial deposits. Therefore, maps of the bedrock geology are based primarily on interpretation of regional aeromagnetic and gravity data supplemented by mapping of sparse outcrops and lithologic logging of a limited number of drill holes. Maps of gravity and magnetic anomalies are presented here along with various maps illustrating computer-process-enhanced maps produced to aid geologic interpretation of the study area.

Preparation of aeromagnetic maps includes compiling existing data from MGS and GSC that supplements new data collected by the USGS. The new airborne survey was flown with a line spacing of 1/4 mi at an elevation of 200 ft and using a high-precision proton sensor. A variety of navigation systems, including radar transponder, LORAN, and photo recovery, was used in the USGS project to overcome problems in flight line location over largely featureless terrain. The new USGS data were incorporated with the other aeromagnetic data to produce an IGRF-corrected total magnetic field map of quadrangles.

Complete Bouguer anomaly gravity maps also were prepared as part of the CUSMAP study by using new data collected for the project, combined with a U.S. Department of Defense gravity data base. The new data were collected in cooperation with the Minnesota Department of Natural Resources—Division of Minerals and in cooperation with ongoing gravity surveys being done by the MGS. Detailed profiles were made by the USGS to better define important geologic features interpreted from preliminary gravity anomaly maps. The total data set was then processed to produce terrain-corrected Bouguer anomaly maps of the two quadrangles.

The compiled aeromagnetic data were processed to compensate for inclination and declination of induced magnetic fields that offset boundaries of causative sources from magnetic highs. The reduction-to-the-pole program shifts the magnetic highs associated with dipolar magnetic lows to be more coincident with the source. Judicial use of this enhanced map with the original magnetic map facilitates geological interpretation of the geophysical data.

Gravity and magnetic data were further processed to produce color-shaded relief (CSR), horizontal-derivative, and edge-enhanced maps. The CSR and horizontal-derivative maps emphasize subtle linear features and level changes in anomaly intensity. For example, the CSR map of the reduced aeromagnetic data dramatically emphasizes linear anomalies due to northwest-striking diabase dikes. Edge-enhanced magnetic and gravity maps emphasize possible boundaries between geologic units that have contrasting densities and (or) susceptibilities.

Interpretation of detailed profiles of ground gravity and magnetic surveys through computer modeling of possible bedrock contacts suggests size, shape, attitude, and physical properties of causative bodies. Geophysical interpretation of these maps can be integrated with interpretation of geologic data to yield an effective mineral resource assessment of the study area.

Sulfur Isotope Characteristics of Bedded and Vein Barite Deposits, North-Central Nevada

Stephen S. Howe

Nearly all of the bedded barite deposits in north-central Nevada are contained within lower Paleozoic eugeosynclinal rocks of the siliceous (western) assemblage that constitutes the upper plate of the Roberts Mountains thrust (the Roberts Mountains allochthon), emplaced during the Late Devonian-Early Mississippian Antler orogeny. In con-

Shaded relief aeromagnetic map of the International Falls 1° by 2° sheet. This map is a compilation of U.S. Geological Survey, Minnesota Geological Survey, and Geological Survey of Canada aeromagnetic data. Lighter areas indicate magnetic field highs, and darker areas indicate magnetic lows. The apparent relief is produced by computer-generated northeast illumination. The irregular white line through the center of the image is the International boundary between Minnesota and Ontario. Prominent structural features within the map include the Quetico and Rainy Lake-Seine River faults, which strike east and east-northeast across the northern third of the map. In the southern portion of the image, a northwest-trending dike swarm cuts a folded migmatite terrain. Map is approximately 100 by 150 km. [Horton and others abstract] trast, vein barite deposits in north-central Nevada occur (1) in pre-Antler rocks of the transitional and miogeosynclinal carbonate (eastern) assemblages that constitute the lower plate of the Roberts Mountains thrust, (2) in pre-Antler rocks of the siliceous assemblage, and (3) in post-Antler rocks deposited west of, within, and east of the Antler orogenic belt.

Of the eight bedded barite samples analyzed to date, one is from a middle to late Ashgillian horizon in the Ordovician Valmy Formation, and seven are from early Famennian horizons in the Devonian Slaven Chert. The Ordovician deposit has a $\delta^{34}S$ value of +29.6 per mil, which, considering the fractionation between sulfate minerals and seawater sulfate of +1.6 per mil, matches exactly the $\delta^{34}S$ value of +28±2 per mil for Late Ordovician seawater sulfate (Claypool and others, 1980). The $\delta^{34}S$ values of the Devonian deposits are tightly clustered in two groups averaging +22.4 and +27.4 per mil, which, again considering the fractionation between sulfate minerals and seawater sulfate, are both nearly identical to the $\delta^{34}S$ value of +23±3 per mil for Late Devonian seawater sulfate. Although the isotopically lighter deposits are only 4 km northwest of the heavier deposits, the barite horizon is stratigraphically higher. This slight depletion in ^{34}S with stratigraphic height was also observed in bedded barite from the Slaven Chert in south-central Nevada by Rye and others (1978) and may be a result of the marine environment becoming increasingly oxic and open to seawater sulfate with the onset of the Antler orogeny, as Goodfellow and Jonasson (1984) have shown for the Famennian in the Selwyn basin of western Canada.

The $\delta^{34}S$ values of 45 samples of vein barite range from +9.0 to +45.5 per mil; 85 percent of the values are between +20 and +35 per mil. Although the barite in most of the veins is slightly heavier isotopically than the barite in the bedded deposits, the sulfur in the veins could have been, with a few notable exceptions, derived from locally associated bedded barite or other crustal sources, and ultimately, therefore, from seawater sulfate. The exceptions are barite samples from three veins in the Valmy Formation from the Battle Mountain-Eureka trend and from two veins in the Dry Hills south of Beowawe. The three veins in the Valmy Formation are located near the Marigold gold mine, the Betty O'Neal silver-lead-gold-copper mine, and the Kattenhorn gold-antimony mine and contain barite that has $\delta^{34}S$ values of +9.0, +12.6, and +10.8 per mil, respectively. The barite from the Marigold mine area is in jasperoid localized in a north-trending fault zone thought to be the feeder of the Marigold hydrothermal system; the sample has anomalously high gold, arsenic, and antimony and a gold-silver ratio greater than 11. In the Dry Hills, one vein at the northeast end near Scotts Gulch cuts Jurassic volcanic rocks and contains barite having a $\delta^{34}S$ value of +17.3 per mil. The vein at the southwest end is in the Pennsylvanian-Permian Brock Canyon Formation 5 km from the sulfur(±mercury±antimony) deposits at Hot Springs Point and contains barite having a $\delta^{34}S$ value of +10.5 per mil. These five barite samples depleted in ^{34}S may contain sulfur derived, in part, from magmatic sources. Excluding these isotopically light samples, the $\delta^{34}S$ values of the vein barite samples appear to be independent of host rock age and lithology and of the types of other mineral deposits spatially and (or) temporally associated with the barite veins. In contrast, however, vein barite samples from the Battle Mountain-Eureka trend average more than 5 per mil lower than those from the Carlin trend, consistent not only with the more frequent occurrence of felsic intrusive rocks near the Battle Mountain-Eureka trend veins but also with the larger size of the intrusions.

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Analysis of Concealed Mineral Resources in Nevada: Constraints from Gravity and Magnetic Studies

Robert C. Jachens, Richard J. Blakely, and Barry C. Moring

Regional gravity and magnetic studies of Nevada are being used to infer subsurface structure and lithology, primarily in areas beneath Cenozoic cover, as part of an analysis of concealed mineral resources of the entire State. Major goals of the geophysical studies are (1) to define the thickness of Cenozoic cover, (2) to constrain permissible lithologic identity of buried pre-Cenozoic basement, (3) to map the location and extent of concealed plutons, (4) to delineate known and identify unknown calderas, (5) to define areas of shallowly buried Tertiary volcanic rocks, and (6) to delineate areas (both exposed and concealed) of possible hydrothermal alteration. Primary statewide data sources for these studies are a digital isostatic residual gravity map based on approximately 71,000 point observations, a digital map of the magnetic field compiled from 38 separate surveys and analytically continued to 300 m above terrain, detailed but widely spaced aeromagnetic profiles

Photo mosaic of the State of Nevada compiled from Landsat Multispectral scanner imagery by aerial photographers of Nevada. Scale 1:3,576,774 from original scale 1:1,000,000.

collected at 120 m above the ground surface, a compilation of drill-hole data, a simplified digital geologic map, and digital topography.

Combined analysis of these data sets will result in statewide maps showing approximate depth to dense (generally pre-Cenozoic) basement and the distribution of concealed but near-surface magnetic sources (generally Tertiary and Quaternary volcanic rocks). Other derivative products will include a "basement" gravity map from which the effects of Cenozoic rock and unconsolidated sediments have been removed, maps showing subsurface density and magnetization boundaries, and a map showing the distribution of nonmagnetic Cenozoic volcanic rocks.

These continuing investigations have yielded results important to the analysis of concealed mineral resources. Depth-to-dense-basement calculations indicate that, although more than 75 percent of northern Nevada is covered by young deposits, the deposits are thicker than 1 km in only about 20 percent of the area. Likewise, magnetic data indicate that most basins in northern Nevada have volcanic and (or) granitic sources at shallow depth (<1 km), especially along basin perimeters. The "basement" gravity map reveals extensive areas of low gravity that probably reflect concealed felsic plutonic rocks and also shows evidence of major pre-Cenozoic crustal boundaries, one of which is spatially correlated with the Battle Mountain-Eureka trend of mineral deposits. Preliminary results also indicate a region in northern Nevada where many exposed volcanic and granitic rocks are relatively nonmagnetic. This region, coincident with the Battle Mountain heat-flow anomaly, may, in part, represent an area of subtle hydrothermal alteration.

Volcanic-Tectonic Setting and Geology of the Paradise Peak Gold-Silver-Mercury Deposit, Nye County, Nevada

David A. John, Robert E. Thomason, Charles W. Clark, and Edwin H. McKee

The Paradise Peak deposit is a large hot-spring type gold-silver-mercury deposit discovered in 1983 in the low hills of the southwestern Paradise Range near Gabbs, Nev. It contained preproduction reserves estimated at 12 million tons averaging 0.097 oz gold and 3.53 oz silver per ton and greater than 50 ppm mercury. The deposit occurs in Oligocene and early Miocene volcanic rocks that have been divided into three sequences: an older sequence of 26 to 24 Ma intermediate lavas, a middle sequence of 24 to 22 Ma silicic ash-flow tuffs, and a younger sequence of 20 to 15 Ma intermediate lavas. Most of the orebody occurs in rhyolite tuffs in the lower part of the middle tuff sequence. Potassium-argon ages of hypogene alunite suggest that the orebody formed about 19 to 18 Ma, several million years after formation of the host rocks.

The deposit is temporally and spatially associated with the younger intermediate lavas and occurs near the eastern edge of an early Miocene lava field that covers approximately 1,000 km^2. In the Paradise Range, these younger lavas are calc-alkaline or calcic (Peacock index approximately 61). They range in composition from 55 to 70 percent SiO_2, although most are andesites and dacites that have 60 to 65 percent SiO_2. Compared to the older intermediate lavas, these younger lavas are higher in Ca and Sr and lower in Mg, K, P, and Rb. They generally have higher Sr:Rb (11–39) and K:Rb (328–581) and lower initial $^{87}Sr/^{86}Sr$ (0.7046–0.7051) than the older lavas (Sr:Rb=5–18, K:Rb=248–355, initial $^{87}Sr/^{86}Sr$=0.7050–0.7055). The genetic relation of the deposit to these younger lavas is unclear, because intrusive bodies are not present near the mine and have not been encountered in drill holes.

The Paradise Peak deposit formed during a period of early Miocene (approximately 22 to 18 Ma) crustal extension. This early, pre-basin-and-range extension was widespread in west-central Nevada, extending from the Yerington district on the west to the San Antonio Mountains on the east and from the southern Stillwater Range on the north to the Goldfield district on the south. Early extension is indicated by major angular unconformities in early Miocene rocks (commonly >50°), rotated high-angle normal faults, and changes in the orientations and abundance of high-angle faults. Initiation of early extension broadly coincided with a regional change in the style of volcanism from dominantly silicic ash-flow tuffs, erupted between approximately 30 to 22 Ma, to eruption of intermediate lavas. Voluminous early Miocene (20–15 Ma) intermediate lavas are restricted to areas that underwent early extension. Other major precious-metal deposits that formed during or shortly following this extensional event include the Tonopah, Goldfield, Santa Fe, and, perhaps, Rawhide deposits. Early Miocene age precious-metal mineralization appears limited to areas of throughgoing high-angle faulting and is generally absent in areas of low-angle faulting and areas of steep stratal tilts.

The age of early extension in the southwestern part of the Paradise Range is bracketed between 20 and 16 Ma. Although low-angle normal faults and steeply dipping early Miocene rocks are present less than 5 km northeast of the Paradise Peak mine, only high-angle faults and gently dipping rocks are present near the mine. High-angle faults that cut early quartz-pyrite alteration, control mercury mineralization, and are cut by mineralized hydrothermal breccias indicate that high-angle faulting occurred synchronous with ore formation.

Preliminary studies of the deposit suggest that gold-silver mineralization occurred in at least three stages. Low-grade gold values (≤0.06 oz gold per ton) are associated with early silicification. This alteration consists of pervasive quartz+pyrite±opal and is mostly stratiform within gently dipping tuffs. Early silicification is overlain and partially replaced by alunitic alteration (alunite+quartz ±opal ±kaolinite±jarosite) that occurs in a 20- to 40-m-thick blanketlike acid-leach zone developed primarily in intermediate lavas. Most high-grade ore (0.4–1.0 oz gold per ton) occurs in hydrothermal breccias that crosscut early quartz-pyrite and alunitic alteration. These breccias contain subrounded to angular clasts of silicified, locally leached tuff and alunitized intermediate lava in a matrix of dark-gray to black quartz, barite, and local sulfide minerals. Breccias vary from matrix to clast supported and commonly show evidence of multiple stages of brecciation. A third stage of gold mineralization consists of coarser grained gold-filling vugs and coating fractures. Most mercury mineralization postdates gold mineralization and occurs as cinnabar coating fractures and filling vugs in breccias and silicified tuffs.

The Applications of Airborne Radar for Mineral and Energy Resources Exploration

John E. Jones, Allan N. Kover, and Bruce F. Molnia

Since 1980, the U.S. Geological Survey (USGS) has been collecting side-looking airborne radar (SLAR) data in support of research for mineral and energy resources exploration and other earth-science applications. Radar systems provide an unsurpassed source of terrain information because of their ability to produce images without regard to cloud cover or light conditions. Radars provide their own source of illumination; as a consequence, the radar beam can be directed to provide optimum look direction and range of depression angles to enhance structural features for particular applications. Because SLAR's transmit directed illumination at an oblique angle, usually between 10° and 30°, subtle features such as faults, fracture zones, and salt domes often can be identified more easily on radar images than on conventional aerial or space photographs. The return signal from the radar beam is affected by variations in surface roughness, slope, topographic expression, moisture, and the dielectric effects of the materials irradiated. These characteristics have enabled interpreters to differentiate lithology, vegetation, soil, and rock types in some localities. Tonal anomalies on the radar images have been useful in identifying peat deposits in Maine and locating uraniferous breccia pipes in Arizona.

The USGS has compiled 195 radar mosaics of 1° × 2° quadrangles at 1:250,000 scale. These mosaics have been used, in conjunction with geologic mapping, for structural studies in areas of mineral or energy resource potential from the Appalachians to the Western Overthrust Belt. Many quadrangles in the area have been studied under the USGS CUSMAP (Conterminous United States Mineral Assessment Program), AMRAP (Alaska Mineral Resource Assessment Program), and State cooperative programs.

The USGS has acquired radar image data of more than 30 percent of the conterminous United States and Alaska, and all of Puerto Rico and the American Virgin Islands. Mosaics, image strips, and indexes can be ordered from the USGS EROS Data Center, Sioux Falls, SD 57198. Computer compatible tapes are available for data collected since 1985.

Tertiary Tectonic Evolution of the Central Walker Lane, Western Nevada

Richard P. Keller, John S. Oldow, Richard F. Hardyman, and John W. Geissman

The Walker Lane of western Nevada is an important northwest-trending boundary region that stretches from Las Vegas, Nev., to Honey Lake, Calif. Within this region, the structural grain has a north-northwest orientation in contrast to the typical north-northeast-trending basin-and-range structural grain of elongate fault-bounded mountains to the east.

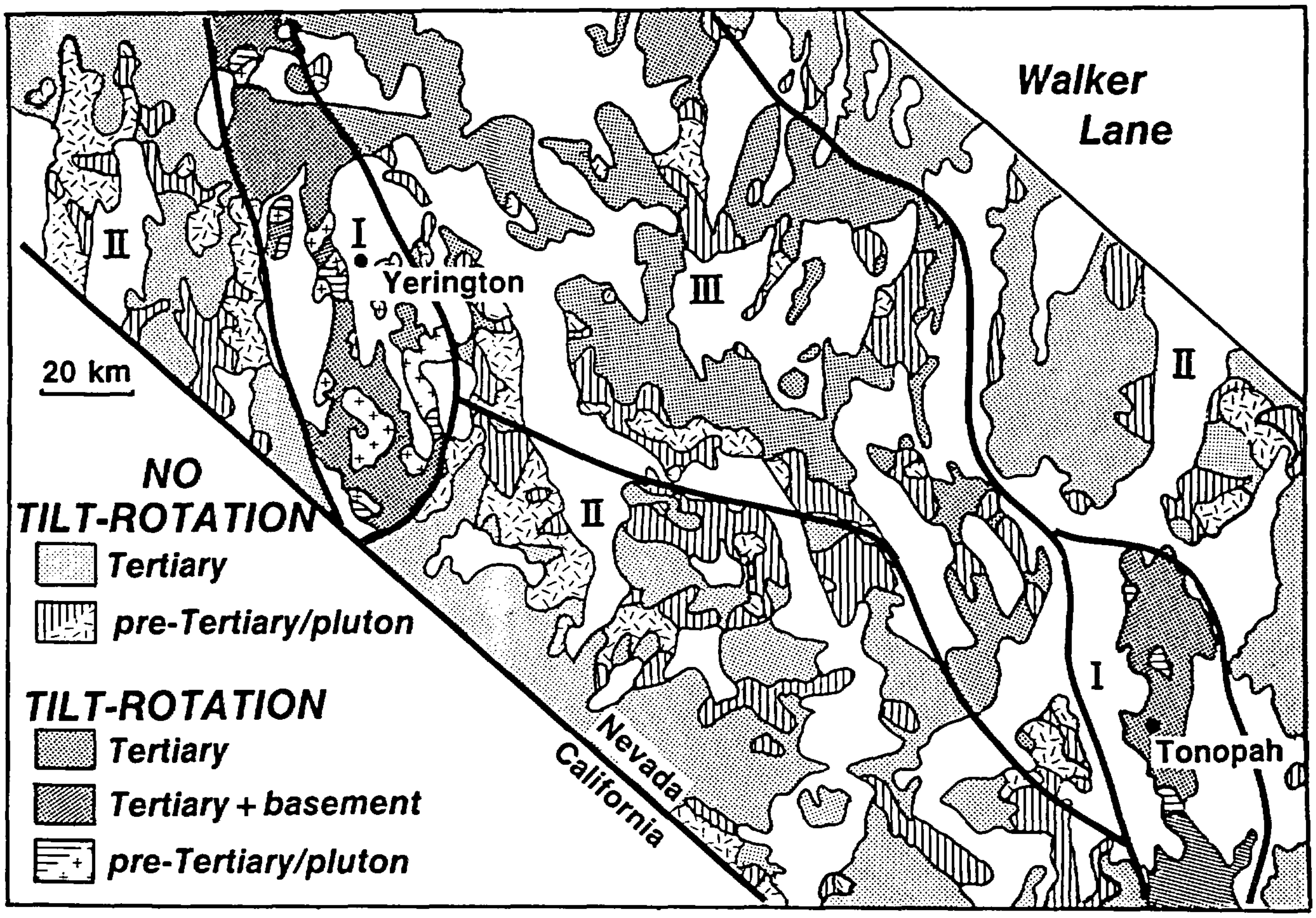
The central part of the Walker Lane is characterized by an en echelon series of linear, throughgoing and range-bounding, northwest-trending faults. Within this region, 30- to 3.5-Ma Tertiary volcanic and interlayered sedimentary rocks unconformably overlie a basement composed of Mesozoic plutons and deformed pre-Tertiary rocks. Tertiary rock attitudes vary from flat lying to nearly vertical; dips are especially steep in rocks adjacent to large-scale fault zones.

A model for the tectonic evolution of the central Walker Lane is based on (1) a compilation of detailed geologic maps, keyed to a framework that incorporates radiometric age data, tilt domains, and sequence stratigraphy within the 30- to 3.5-Ma Tertiary section; (2) structural fabric data from the pre-Tertiary basement; and (3) paleomagnetic data from pre-Tertiary plutonic bodies within the region. On the basis of these data sets, three structural domains are recognized.

Domain I.—Areally restricted regions in which both the pre-Tertiary basement and the unconformably overlying Tertiary section are strongly tilted. This domain includes the Yerington and Hall districts.

Domain II.—A broad region bordering the central Walker Lane on both the east and west, in which the pre-Tertiary and Tertiary sections are essentially untilted by Tertiary-age deformation and where dips of the Tertiary section generally do not exceed 25°.

Domain III.—A 70-km-wide, northwest-southeast-trending zone of linear, subparallel, strike-slip faults. The zone covers more than 6,000 km^2 between Yerington and Tonopah, Nev. This part of the Walker Lane is characterized by a strongly tilted Tertiary section (attitudes ranging from 25° to nearly vertical) that is structurally detached from an untilted pre-Tertiary basement.



Regional domains (I, II, III) of tilt of Tertiary and pre-Tertiary rocks in the central Walker Lane, west-central Nevada. [Keller and others abstract]

The stratigraphic-structural relations in the Tertiary section and the structural fabric data in the pre-Tertiary basement, combined with age, paleomagnetic, crosscutting fault, and fault-controlled dike orientation data, provide constraints for an interpretation of the tectonic evolution of the central Walker Lane. The model requires a clockwise rotation of the least principle stress direction from north-northeast to south-southwest to northwest-southeast from approximately 30 Ma to the present. Between 30 and 19 Ma, the central Walker Lane experienced north-northeast to south-southwest extension that resulted in east-west-trending half-grabens (well preserved in structural domain II) and left-lateral strike-slip on northwest-trending high-angle faults and kinematically related detachment faulting in domain III. Between 19 and 10 Ma, extension was oriented east-west and dominant normal faulting and rotation occurred about north-south-trending faults in domain I; strike-slip occurred on preexisting east-west faults (evidence preserved in domain II); and dikes were emplaced along northwest-southeast-trending high-angle faults in domain III, with some rotation of earlier low-angle detachment faults. From about 10 Ma to present, the central Walker Lane has experienced northwest-southeast-oriented extension resulting in predominant right-lateral slip on northwest-southeast-trending high-angle faults.

Chemical Analysis of Ocean Floor Manganese Crusts

Herbert Kirschenbaum, F.T. Manheim, P.J. Aruscavage, and C.M. Lane-Bostwick

In recent years, interest in the chemical composition of ferromanganese crusts from the ocean floor has increased, in part, because these crusts are potential sources of metals such as cobalt, manganese, and nickel. We are conducting a worldwide survey of the occurrence and composition of these crusts. The crusts show geographic variations in composition. The concentration of the elements in the ferromanganese-oxide phase, especially Co, Ni, Cu, Zn, Ce, Pb, As, Pt, and Cd, reflects the time-integrated chemical concentrations in ocean bottom waters and therefore is of considerable geochemical interest. In support of the survey of manganese crusts, we are analyzing large numbers of such crusts and have attempted to optimize analytical techniques. Various procedures for decomposing these crusts were tested, but the best results were obtained by using three separate methods for different groups of elements. (1) Because of the volatility of silicon tetrafluoride, open-system hydrofluoric acid dissolution results in loss of silicon. Therefore, a fusion of the sample with lithium metaborate-tetraborate mixture, similar to that used for the routine determination of rock-forming major elements in silicates, is used for silicon and sodium decomposition. However, because of the large blanks and high dilutions required to lower the salt content from the fusion, an acid decomposition was most useful for analyzing the trace and minor elements. (2) The decomposition for arsenic presented a special problem in that its fluoride is also volatile, and special precautions must be taken to avoid loss when using a hydrofluoric digestion. However, we found that greater than 95 percent of total arsenic was leached by using hydrochloric acid from a test set of nodules when compared with a total decomposition of the sample by using hydrofluoric acid in a teflon-lined bomb, thus making for simpler sample processing. (3) High contents of manganese and iron in the crusts cause severe spectral interference in fixed-slit inductively coupled plasma-atomic emission spectrometric analysis for arsenic, cadmium, and chromium. However, these elements are adequately determined by graphite furnace atomic absorption.

Gravity and Magnetic Anomaly Patterns in Mineral Resource Exploration, Hailey CUSMAP, Idaho

M. Dean Kleinkopf

Mines and prospects of precious metals are widely scattered in the area of the Hailey CUSMAP (Conterminous United States Mineral Assessment Program) project. Many of the deposits are associated with granitic intrusions and fault zones of the trans-Challis fault system. The Hailey gold belt is of particular interest. The study area also covers the western part of the Idaho Falls 1° × 2° sheet.

Interpretation of aeromagnetic and gravity anomaly data is an integral part of the study. The anomaly data are applied in conjunction with geologic investigations to map buried intrusive complexes, delineate major fault and shear zones, and identify localities that might be hydrothermally altered or mineralized. The aeromagnetic anomaly data are applicable for direct detection of mineralized features, and the gravity anomaly data define structural settings and distinguish low density Tertiary granitic intrusions from Cretaceous granitic intrusions of the Idaho batholith.

Three crustal provinces can be distinguished by their contrasting aeromagnetic and gravity signatures and provide a framework for the mineral resource evaluation. (1) In the northwest, Cretaceous granitic terranes of the Idaho batholith are weakly magnetic and have slowly varying, highly negative Bouguer anomaly values. (2) In the northeast, heterogeneous terranes of thrust- and block-faulted Paleozoic sedimentary rocks, Precambrian metamorphic rocks of the Pioneer Mountains core complex, Tertiary granitic rocks, and deposits of Eocene Challis and Miocene volcanic rocks produce a variety of weak to strong magnetic anomalies. This assemblage gives an overall negative mass effect on the gravity field similar to that of the Idaho batholith. (3) In the south, the Snake River Plain province, composed predominantly of Cenozoic basalt, is much more magnetic and is denser than the terranes to the north. Boundaries between the three provinces are irregular. Granitic blocks probably locally underlie basalt near the northern margin of the Snake River Plain.

The highest magnetic values correlate spatially with high elevation Tertiary epizonal granitic intrusions. Examples include the Sawtooth batholith, north of Atlanta; the stock at Steel Mountain, just north of Rocky Bar; and the major intrusion, just east of Twin Springs. These plutons lie along the northwest side of a prominent northeast-trending steep magnetic gradient zone that suggests a buried shear zone perhaps related to northeast structures of the trans-Challis fault system. Regional faults, such as the Deer Park, Montezuma, and Sawtooth faults and correlative magnetic trends, systematically change strike from south to southeast, north of the postulated shear zone to southeast on the south side of this steep gradient zone. Along the magnetic gradient zone, the gravity map exhibits low amplitude anomalies and subtle changes of gradient.

The Hailey gold belt is a zone of variably mineralized ground and precious-metal localities that extends from the White Knob and Pioneer Mountains for some 150 km southwest across the southeastern part of the Idaho batholith. The magnetic and gravity anomaly data superimposed on the generalized geology illustrate the geophysical signatures of the various structural and lithologic units within the batholith and suggest projections of these features in the subsurface. Magnetic and gravity derivative maps enhance definition and interpretation of the anomalies.

Caraway-Back Creek Volcanic Center, Central Slate Belt, North Carolina: Newly Recognized Thermal Source for Precious- and Base-Metal Mineralization

Robert P. Koeppen and Terry L. Klein

The Carolina slate belt (CSB), a probable volcanic arc remnant of late Precambrian to Cambrian age that extends 600 km from Virginia to Georgia, consists of weakly metamorphosed volcanic, sedimentary, and intrusive rocks. A variety of mineral deposits occur in the slate belt, including those that contain precious and (or) base metals. Models for these deposits have generally favored a volcanogenic origin; however, because either constraining geologic details or adequate model analogs were not available, such models typically have been speculative about the mechanism of formation. Our studies suggest a connection between a rhyolitic volcanic-intrusive complex and associated epithermal gold deposits that occur along the boundary between the Eocambrian-Cambrian Uwharrie and Tillery Formations near Asheboro, N.C. Although our studies are not completed, the available field, geochemical, and petrological data warrant a preliminary summary of the relationship between the volcanic and intrusive rocks at Back Creek and Caraway Mountains (CBCV) and spatially associated gold deposits.

The CBCV eruptives occur in the lowest part of the Tillery Formation, where they were deposited on and crosscut the dominantly rhyolitic Uwharrie Formation. They form domes, pyroclastics, and derivative epiclastics, consisting dominantly of quartz-plagioclase phyric- and plagioclase phyric- (quartz-free) rhyolite; these are interbedded with regionally extensive argillites and are cut by gabbroic intrusives. The eastern half of the volcanic complex is inscribed by a microgranophyre ring dike; near the western end of this dike, the volcanic rocks are cut by a granophyric subvolcanic stock that is several kilometers in diameter. The stock and dike appear to be contemporaneous.

Four gold deposits (Hoover Hill, Scarlett, Sawyer, and New Sawyer) and several alteration zones, each characterized by quartz or zoned quartz-K-feldspar veins and (or) sulfide disseminations in strongly silicified or chlorite-sericite-altered host rocks, surround the ring dike structure at a distance of 1 to 5 km. These polymetallic (Zn, Cu, Pb, Ag, Mo) gold deposits are relatively base metal rich (0.5–>2 percent base metals), have silver-gold ratios of 0.5 to 200, and probably formed at relatively deep levels (>0.5 km?) within fossil hot springs systems related to the CBCV. The solutions responsible for the deposits, based on alteration assemblages and stable isotope data (oxygen, sulfur), and by analogy with other deep-level polymetallic vein systems, were probably near-neutral pH, chlorine-bearing fluids that have a large component of meteoric water and an igneous sulfur source. These characteristics are shared with many precious-metal deposits in the Western United States, such as those at Creede, Silverton, Comstock Lode, Tonopah, and Bodie.

Anomalous Cu, Zn, Ag, and Au occur at locations adjacent to and within the CBCV and reflect both known deposits and areas having no previous production. An area of relatively high total-count airborne radiometric values also effectively outlines the felsic volcanic center.

Identification of the CBCV and its possible role in the formation of epithermal gold mineralization bears significantly upon future exploration strategies in the CSB. In the past, exploration in the slate belt has commonly used an exhalative model in which the gold was believed to be roughly stratabound. Recognition of probable epigenetic synvolcanic mineralization surrounding a mappable volcanic center requires development of an alternative exploration strategy, in which the integration of geologic, geochemical, isotopic, and geophysical studies may prove successful.

Composition and Geologic Setting of Stratiform Manganese Deposits in the Southern Basin and Range Province, Arizona and Nevada

Randolph A. Koski, Robin M. Bouse, James R. Hein, and Marilyn L. DeRosa

The largest accumulations of manganese in the western Cordillera of the United States are stratiform manganese-oxide deposits in Miocene sedimentary and volcanic rocks of the southern Basin and Range province, Nevada and Arizona. The host rocks are lacustrine-alluvial sequences that were deposited in structural basins during Neogene crustal extension.

Gently dipping manganese-bearing strata on the west flank of the Artillery Mountains in west-central Arizona include fanglomerate, sandstone, siltstone, felsic tuff, and limestone. The manganese mineralization is distributed within sedimentary facies that range from alluvial fan deposits near the basin margin to thinly laminated fine-grained clastic deposits and limestone in the basin interior. The manganese oxides hollandite, coronadite, and cryptomelane constitute deposits gradational from massive beds to thin interstitial films around sediment grains. Samples of stratiform manganese oxide contain high amounts of lead (to 14 weight percent), barium (5.0 weight percent), arsenic (0.5 weight percent), and uranium (40 ppm).

At the Three Kids mine west of Lake Mead in southern Nevada, the stratiform manganese horizon occurs in a section of tuffaceous siltstone, sandstone, conglomerate, and tuff that is capped by gypsum. Potassium-argon ages of biotites from interbedded tuff units indicate that the manganese-bearing beds were deposited at approximately 13.8 Ma. In the same district, the Virgin River manganese deposit on the north shore of Lake Mead consists of alternating manganiferous and ferruginous sandstone beds in a sequence of gypsum, gypsum-bearing sandstone and siltstone, green tuff, and lava flows of andesite and basalt compositions. The manganese mineralization in the Three Kids and Virgin River deposits consists of transported clasts of colloform manganese oxide (todorokite and coronadite), manganese-oxide cement (pyrolusite), and manganese-oxide cavity infillings (cryptomelane and coronadite). Bulk chemical analyses of manganese-rich samples show that the Three Kids deposit contains greater amounts of barium, strontium, and lead relative to the Virgin River deposit that contains more iron, copper, and arsenic.

The occurrence, composition, and textural characteristics of the stratiform manganese deposits suggest that manganese was deposited from oxidized, low-temperature fluids in contact with unconsolidated clastic sediment on and below the floor of stratified saline lakes. The initial $^{87}Sr/^{86}Sr$ (0.71005–0.71666) of evaporite and limestone interbedded with the manganese deposits are consistent with a lacustrine depositional environment. Lead isotope ratios for manganese samples from the Artillery Mountains and the Three Kids deposits are more radiogenic than their enclosing sedimentary and volcanic rocks and indicate that a source for manganese and other metals from Proterozoic and Mesozoic rocks is deeper in the crust. In contrast, the similarity of lead isotope ratios of the Virgin River deposits and their Tertiary host rocks implies a source of metals within upper levels of the crust.

Study of the manganese deposits combined with ongoing regional framework investigations suggests that extensional tectonics, detachment faulting, volcanism, and manganese mineralization were synchronous during the Miocene in the southern Basin and Range province. We propose that the proximity of detachment surfaces to heat sources, such as the magma chambers of active volcanoes, resulted in thermal regimes suitable for the development of large hydrothermal convection cells. Normal faults bounding extensional basins in the upper plate above detachment faults may have been pathways for recharge of saline basin waters and discharge of metal-enriched hydrothermal fluids.

Characterization of Carbon in Sediment-Hosted Disseminated Gold Mineralization at Jerritt Canyon, Nevada

Joel Leventhal and A.H. Hofstra

An integrated multidisciplinary study of gold mineralization at Jerritt Canyon, Nev., is in progress. Gray, dark-gray, and black sediments in the Marlboro Canyon and North Generator orebodies indicate that these rocks are not oxidized with respect to carbon. Both ore and non-ore host rocks can be dark colored, and noncarbonate carbon content is not related to gold content. These rocks contain a few tenths to a few percent noncarbonate carbon. The term noncarbonate is used to distinguish carbon not bound to hydrogen from organic carbon in which carbon is bound to hydrogen. Normally rocks that have these levels of carbon are gray, but at Jerritt Canyon the rocks are darker because they have experienced higher temperatures at which organic matter catagenesis occurs. Contrary to published reports, the rocks do not contain significant amounts of humic acids, extractable hydrocarbons (bitumen), or carbonaceous material.

Cryptocrystalline graphite, which occurs as angular fragments, vein fillings, and spherical blebs of carbon, can be recognized by reflected and transmitted light microscopy. Jasperoid paragenesis indicates that these mineralogies are all premineralization.

In addition to elemental analysis (carbon, hydrogen, and nitrogen content; Rock-eval) and X-ray diffraction, laser Raman spectroscopy has been used to study the carbon. Laser Raman spectra can distinguish between highly developed graphite crystals (>1 micron in diameter) that exhibit a sharp peak near 1600 cm^{-1} and less well-developed crystals (<1 micron in diameter) that exhibit a broadened peak near 1600 cm^{-1} and another broad peak near 1350 cm^{-1}. The broadness, shape, and relative heights of these peaks are related to the size of the graphite crystal domain. The spectra from Jerritt Canyon samples in jasperoid, carbonate, and shale are distinctively similar; they all indicate poorly ordered graphite crystals less than 0.03 microns (cryptocrystalline).

These measurements (1) confirm the maturity of the carbon as initially indicated by elemental analysis, Rock-eval, and X-ray diffraction, (2) further elucidate the nature of the carbon, and (3) based on paragenesis indicate that the carbon was matured early in the geologic history of these rocks prior to gold mineralization.

Study of the Stratigraphy of the Gold-Bearing Preble Formation Near the Type Locality, North-Central Nevada—Some Benefits to Exploration

Dawn J. Madden-McGuire

Outcrops of the Lower Cambrian to Lower Ordovician Preble Formation of north-central Nevada extend from the northwestern flank of the Osgood Mountains southward into the Sonoma Range. The formation is the host rock for gold deposits in the Preble and Getchell mines in the Osgood Mountains, Humboldt County, Nev. The type locality of the Preble Formation is in the southern Osgood Mountains in Emigrant Canyon, at the site of the old Preble railroad station. Near the type locality, the age of the Preble Formation ranges from late Early Cambrian to Early Ordovician. The latter age is based on the identification of a recent collection of Early Ordovician graptolites from a Preble locality. In the type area, the Preble Formation is weakly metamorphosed, and the strata are tightly folded, plunge southward, and are structurally overturned to the west; strata dip eastward 40° to 75°.

Some basic questions have remained unanswered during previous regional mapping in the Preble Formation.

To answer some of these questions, mapping and sampling were done near the type locality at more detailed scales. The present study indicates that the stratigraphic succession consists of sedimentary quartzite, bedded barite, interbedded phyllite, and at least five subunits of limestone rather than only one limestone subunit repeated many times by folding. The thickness of the mapped strata is estimated crudely at 650 m, on the basis of the dip of strata and the distribution of outcrops of mapped units. The total thickness of the Preble Formation, variously estimated at 3,660 m and 1,000 m in previous regional studies, is still unknown. Omission and offset of known subunits indicate the location of mappable faults. North-south-trending basin-and-range-parallel faults and northeast-trending Humboldt structural zone-parallel faults occur in the mapped area. The Emigrant Canyon trend, which is parallel to faults and lineaments of the regional Humboldt structural zone, may be controlled by a fracture rather than by a fault because individual marker beds are not appreciably offset across Emigrant Canyon.

Locally exposed subunits in the type area of the Preble Formation, from oldest to youngest, are (1) clastic fossiliferous limestone consisting of lenses of gray to brown bioclastic packstone and grainstone, (2) siliciclastic channel deposits consisting of fine-grained, micaceous, sedimentary quartzite, (3) bedded barite, (4) clastic limestone and local(?) conglomerate, (5) oolitic limestone (a marker bed), and (6) clastic, pale-orange, fossiliferous limestone (a marker bed). Subunits 1 and 4 have yielded fossils identified in a previous study as Early and Middle Cambrian, respectively (Rees and Rowell, 1980). The oolith locally is an ooid packstone consisting of silt-size ooids and interstitial micrite, an association suggesting deposition as a turbidite.

The study of the stratigraphy and sedimentology of the Preble Formation should help identify favorable host rocks, lithologic subunits within the formation, structures, and patterns of alteration that may be associated with gold mineralization. The recognition of marker beds should help delineate faults and shear zones that are important to recognize in gold exploration in the Preble Formation; zones of broken and sheared rocks are thought to have formed the fluid pathways that focused and directed the silicifying and mineralizing fluids (Bagby and Berger, 1985).

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Minerals Information Office

Susan M. Marcus, Raymond E. Arndt, Paul G. Schruben, Carl Carlson, and Jane Jenness

The Minerals Information Office is a new, cooperative endeavor of the U.S. Geological Survey (USGS) and the U.S. Bureau of Mines (USBM) that is designed as a "one-stop shopping place" for mineral resource inquiries. The office is located in Room 2647 of the Department of the Interior Building, 18th and C Streets N.W., Washington, D.C. The office provides information and access to USGS and USBM data bases, commodity specialists, and publications for the benefit of the public, industry, and Federal and State officials. The office also seeks to improve the exchange of information among the Federal agencies and other minerals-information generators and users. Under Secretary of the Department of the Interior, Earl Gjelde, and Assistant Secretary for Water and Science, James Ziglar, joined USGS Director Dallas L. Peck and USBM Director T S Ary in cutting a platinum ribbon at the opening ceremony on June 21, 1988. The event also inaugurated the new USGS Earth Science Information Center (formerly the Public Information Office). The Earth Science Information Center, adjacent to the Minerals Information Office, provides public distribution of USGS publications and maps.

A dedicated computer system in the office can provide clients and users with responses to their questions while they wait. The USGS Resource-Oriented Computer System permits retrieval of graphic and tabular data on mineral deposits and occurrences throughout the world by using the Mineral Resource Data System (MRDS). The data base, which currently includes 70,000 MRDS records, also includes political and administrative boundaries, geology for selected areas, and a guide to selected USGS minerals research. These data may be searched in ways designed to meet each user's specific needs. Paper copies of graphic displays and tabular and textual information are prepared and distributed.

The Minerals Information Office also serves as a collector of data useful to USGS scientists. Data are compiled, and digital files are acquired to enhance the breadth and depth of information available to the government researchers. Sources of data include Federal and State Government agencies and private industry.

Mineral commodities are featured in a series of activities sponsored by the Minerals Information Office. Platinum and gold were the featured commodities during fiscal year 1988. Exhibits showed regions of the United

States thought to have potential for undiscovered traditional and nontraditional platinum resources. Gold-related activities included a series of well-received public lectures in the Interior Museum and distribution of fact sheets and brochures about gold. Samples of platinum ore from the Stillwater mine in Montana and gold ore from the Homestake mine in South Dakota were given away.

The office has replied to both general and technical inquiries and is a favorite stop of visitors to the Interior Building. Additional Minerals Information Offices are being established in conjunction with USGS field centers in Tucson, Ariz., Reno, Nev., and Spokane, Wash., to serve the needs of information users and USGS researchers in those regions. The western Minerals Information Offices will become operational during 1989.

A Simplified Digital Geologic Map of Nevada for Regional Gold Resource Assessment

S.P. Marsh, E. Sandoval, and J.L. Plesha

A 1:500,000-scale geologic map of Nevada has been digitized by the U.S. Geological Survey (USGS) as part of a regional gold resource assessment program funded by the Bureau of Indian Affairs. The resource assessment involves interpretation and comparison of many different digital data sets. The digital geologic data base has been prepared for input into a computer geographic information system (GIS), used to facilitate interpretation. The objective of this presentation is to discuss construction of a simplified digital geologic map for use in GIS analysis of potential gold resources of Nevada.

The original geologic map consists of more than 104 distinct geologic units. These units have been simplified into 15 lithologic units on the basis of several different geologic models of basin-and-range gold-bearing systems. Additional guidance in combining geologic units was taken from preliminary interpretations of airborne magnetic, radiometric, and satellite data. For example, all Paleozoic carbonate rocks deposited in foreland basins (seven geologic units) have been grouped together. The simplified geologic units were digitized by using a USGS Open-File computer program, GSMAP (versions 4.0 and 5.0). This program and file format are compatible with IBM desk top or equivalent computers that use the MS-DOS operating system.

The digital geologic map was prepared in several steps. The 1:500,000-scale geologic map in stable-base form was divided into 18 sections. Hand-colored coding of the 15 simplified units facilitated digitization using GSMAP. The complete digital data set, transferred to a VAX 11/750, was edited and assembled into 1° × 2° quadrangles by using a commercial GIS computer program

A panoramic view of the Gold Quarry open pit, Carlin trend, Nevada.

(ARC/INFO). Each file was then converted back into GSMAP format and returned to the IBM PC to format files for public distribution. The completed data set requires just over eight megabytes of uncompressed storage.

GIS programs can be used for analysis of these and other digital data, including gravity, compiled airborne magnetic, and topography, available for the State of Nevada. Data interpretation has begun by using the GRASS program developed for GIS applications by the Army Corps of Engineers. This public domain program offers analytical methods particularly suited to analysis of these data.

Grauch and Sawatzky (this volume) have used the correlations between digital structural features and digitally enhanced aeromagnetics to interpret tectonic features associated with gold mineralization. Correlation of carbonate units from the simplified digital geologic map with potassium lows interpreted from the airborne radiometric data indicates areas of favorable host rocks for certain types of gold-bearing systems. Generally, digital geologic data used with other digital data will provide further insight into the significance of correlated features associated with known gold deposits for inference of undiscovered resources.

Evaluation of Multiple Geochemical Sample Media at the Betze Gold Deposit, Eureka County, Nevada

J.H. McCarthy, Jr., J.A. Erdman, T.G. Lovering, and K.H. Bettles

The Betze gold deposit, discovered by the Barrick Goldstrike Mines, Inc., in 1986, is located along the Carlin trend in Eureka County, Nev. The northwest-trending orebody is up to 1,000 ft wide (northeast-southwest) and 4,000 ft long (northwest-southeast). The mineralization is hosted in carbonate rocks of the Devonian Popovich Formation and is overlain by 800 to 1,100 ft of mostly unmineralized siltstone and argillite.

Five sample media were collected along one or more of three traverses that crossed over the deposit. The sample media were (1) rock outcrop, (2) soil, (3) vegetation (sagebrush), (4) pebbles (for coating analysis), and (5) soil gases. The east-west traverses were separated by about 500 ft; sample intervals were 200 ft.

Altered and mineralized bedrock samples were collected from five localities over the deposit, five localities

Barrick Goldstrike Mines, Inc.'s Post open pit. Oxidized ore is above a major zone of sulfide ore, Carlin trend, Nevada.

west of the deposit, and seven localities east of the deposit. All were analyzed quantitatively for Au, Ag, As, Cd, Hg, Sb, and Zn by using atomic absorption methods; also semiquantitatively for 25 other elements by using emission spectroscopy. The highest values for gold (3.0 ppm), arsenic (5,000 ppm), and cadmium (7.9 ppm) were found in samples from an outcrop over the eastern part of the deposit. Cadmium is the only element that correlates significantly with gold (correlation coefficient=0.76). High values for mercury (1.2 ppm), antimony (32 ppm), and copper (500 ppm) were also found in rocks over the deposit, but the highest values for mercury (1.8 ppm) and antimony (450 ppm) were 800 ft east of the deposit, and the highest values for zinc (3,000 ppm) were found 1,500 ft west of it. The rock samples that were highest in many trace elements, including gold, were silicified, brecciated, and contained fine-grained pyrite.

On one traverse, the gold in soil was highest (0.012 ppm) over the deposit, and on another traverse, it was highest (0.018 ppm), 1,500 ft east of the deposit.

In sagebrush, the highest gold values were found east and west of the deposit. However, the highest values for arsenic (2,973 ppm), antimony (146 ppm), and gallium (156 ppm) were found in sagebrush samples over the deposit.

Limonitic coatings from pebbles collected on the surface over and near the Betze deposit were analyzed by the oxalic acid leach method and were found to contain up to 42 ppb gold. Less gold was found in corresponding soil samples. Wherever bedrock samples contain measurable gold, adjacent pebble coatings contain several times background concentrations (2 ppb) of gold. Pebble coatings over and near the deposit consistently contain more Fe, Mn, Be, Co, Ni, Pb, V, and Ga and show a greater range in Ag, Ba, Cr, Cu, La, Mo, Sb, Sn, W, Y, Zn, and P than do either bedrock or soil samples. These coatings also show systematic variations in many elements; Mn, Co, Ni, and Zn are highest over the ore zone; Cr, La, Mo, Sb, and Y are highest 500 to 1,000 ft east of the ore zone; and W, Sn, and V are highest at the easternmost locality, 1,200 ft from the ore zone.

Soil air was sampled at a depth of 2 ft, and the gases were analyzed at the site by using a truck-mounted mass spectrometer. Positive gas anomalies were found over the deposit on two of the traverses for ions having mass/charge

12 (C+), 15 (CH_3+), 26 (C_2H_2+), and 29 (C_2H_5+), and 17 (NH_3) and these anomalies may be related to organic matter associated with gold. Carbon dioxide, which is commonly enriched over sulfide deposits, was low and did not correlate with the deposit. Organic gas species show some promise as geochemical guides to concealed, sediment-hosted gold deposits.

Geochemical anomalies in rocks and pebble coatings occur directly above the deposit. Anomalies in the other media (gas, soil, sagebrush) showed a halo or offset relation to the deposit.

Multiple Ages of Disseminated Gold Mineralization Associated with Volcanic Cycles in Southwestern Utah and Adjacent Nevada

W.R. Miller and J.B. McHugh

Recent studies in the Richfield 1° × 2° quadrangle, Utah, and adjacent areas in Utah and Nevada indicate five possible episodes and three types of disseminated gold mineralization. These episodes range in age from at least 27 Ma, and possibly 39 Ma, to probably less than 5 Ma, and each is associated with a local volcanic cycle. The volcanic terrains of southwestern Utah and adjacent Nevada have been studied by Best and associates at Brigham Young University and by Steven and associates at the U.S. Geological Survey in connection with a Conterminous United States Mineral Assessment Program (CUSMAP) study of the Richfield quadrangle. Recent reexamination of geochemical data from the Richfield CUSMAP study and collection of additional samples from geochemically anomalous areas, altered areas, and mines have resulted in the recognition of multiple episodes of disseminated gold mineralization that took place in this part of the Basin and Range and High Plateaus physiographic provinces.

The oldest deposits appear to have formed 39 to 35 Ma. The age of mineralization is speculative and is based on proximity to dated volcanic rocks and gold deposits to the north and to nearby volcanic rocks of about 35 Ma. Further work to date this occurrence is in progress. These deposits are characterized by disseminated gold, hosted within carbonate rocks. High-angle normal faults acted as conduits for the hydrothermal fluids, and mineralization took place within favorable beds adjacent to the faults. The carbonate rocks are commonly silicified to jasperoid, which locally forms bodies that can be traced for several hundred meters along strike. Gold values up to 0.1 oz/ton are present at the surface.

A somewhat younger period of gold mineralization took place at the Atlanta mine, Nevada, in association with the collapse of the Indian Peak caldera. Mineralization deposited gold in the topographic wall of the caldera and adjacent limestone beds. The age of mineralization can be bracketed by altered and unaltered tuff units at 28 to 27 Ma that occurred at the end of the caldera cycle. Other deposits of this age may occur along the margins of the Indian Peak and White Rock calderas, especially where carbonate rocks are present.

The third period of mineralization deposited gold adjacent to and within fissures hosted by rhyolite lava flows of the 23 to 18 Ma Blawn Formation. Stateline mining district is an example of this age of mineralization, and other potential areas occur throughout the western part of the Richfield quadrangle from the Shauntie Hills to the Nevada border.

Another episode of gold mineralization is represented by iron-oxide veins cutting the 13 to 12 Ma Steamboat Mountain Formation; these veins contain gold values up to 400 ppb. These late Miocene rocks are considered to have potential for disseminated gold deposits similar to those hosted by Blawn Formation rhyolites.

The youngest known gold mineralization took place in the southeastern part of the Richfield quadrangle where a zone several hundred meters wide and several kilometers long contains local quartz stockwork and a series of parallel quartz veins up to a meter wide. Open-space cavities lined by coxcomb quartz and sulfide minerals are present. Limited sampling has disclosed gold values up to 1 ppm at the surface. These veins and associated altered rocks appear to be associated with the 5 Ma Phonolite Hill rhyolite.

Multidisciplinary Considerations in a Digital Geologic Map—Applications and Afterthoughts

S.H. Moll, J.L. Dwyer, C.A. Wallace, J.E. Elliott, C.M. Trautwein, and J.E. Harrison

The U.S. Geological Survey (USGS) has been digitizing geologic maps for use in a variety of geologic, hydrologic, and related resource investigations for more than 20 years. In the 1970's, capabilities to digitally capture information presented on a geologic map were limited both functionally and logistically. Consequently, early applications were directed at discipline-specific research and technique development activities. In the 1980's, computer-based geographic information system (GIS) technology has evolved to meet many of the USGS's increasing spatial data processing requirements. Capabilities to efficiently capture, edit, analyze, manipulate, and display various elements of a geologic map offer new opportunities for application to the USGS's multidisciplinary investigations. To fully realize the data processing efficiencies offered by a modern GIS environment, immediate and foreseeable multidisciplinary requirements of the digital geologic map must be taken into account during its preparation. Experiences in the preparation and application of digital geologic maps during recent multidisciplinary GIS-based CUSMAP (Conterminous United States Mineral Assessment Program) and related investigations have resulted in the recognition of two fundamental rules for digitizing a geologic map: (1) never generalize explicit detail and (2) always include implicit detail.

Features on a geologic map should be encoded for explicit retrieval. Although generalization of geologic units simplifies immediate digitizing tasks, this practice precludes utilization of any information removed from the detailed map. For example, aggregating Paleozoic sediments negates efforts to correlate lithofacies with geochemistry. Subdivision of features prior to digitizing also may be necessary; Quaternary and Tertiary units may be coded secondarily with the identity of underlying units to facilitate removal of the younger units within the GIS. In either case, detail may be added later, but retrofitting is far more costly, inaccurate, and complicated.

Coding practices that account for implied attributes improve data management and, hence, analytical tasks. Implicit detail is usually contained in ordinal attributes such as the stratigraphic order of geologic units. For example, for the assessment of vein-type mineral deposits, the relative ages of plutonic bodies are important in establishing the temporal and spatial relations of potential mineralization events. Nominal attributes such as rock type can also imply order, such as degree of geochemical reactivity.

Criteria for coding must be developed prior to digitizing to facilitate the logical extraction of pertinent data. Guidelines for scale, accuracy, and spatial resolution also must be established at the onset of a project. Informal standards have evolved that permit consistency of attribute handling and continuity between projects. However, more widely accepted and rigorous standards need to be established to permit the exchange of digital geologic map data among different users.

The reality of the rain forest in southeastern Alaska. (Note the notorious Devil's Club plant at left center.)

Multiple Sources for Gold in the Juneau Gold Belt, Alaska

Rainer J. Newberry and David A. Brew

Vein gold deposits of the Juneau gold belt vary in host rock, mineralogy, metamorphic setting, metal ratios, and source of the gold. Geological, geochemical, and isotopic studies indicate there are at least two major sources of the gold: remobilized from preexisting low-grade gold deposits and exotic, or introduced. In remobilized deposits there are two subsources: remobilized plutonic-hosted deposits and remobilized volcanogenic deposits.

Remobilized plutonic-hosted gold deposits are north of Berners Bay (for example, Kensington, Jualin) and on eastern Douglas Island (Treadwell group). Major-element analyses of the least-altered rocks and trace-element analyses of altered rocks indicate that the host plutonic rocks have distinctive alkalic chemistry and range from monzodiorite to monzonite and quartz monzonite. The altered and least-altered host rocks and the deposits are probably of Late Cretaceous age, and all have experienced Late Cretaceous, lowest grade greenschist facies metamorphism. Orebodies are massive quartz-ferroan dolomite-pyrite "main-stage" veins and breccias that have moderately wide (<100 m) carbonate alteration envelopes; gold-bearing "pre-main-stage" quartz-K-feldspar-pyrite-magnetite±biotite-chlorite-chalcopyrite-molybdenite veinlets and veins occur in deeper exposures of both systems. The main-stage gold-quartz-carbonate veins are characterized mineralogically by: (1) relatively high oxidation and sulfidization state assemblages, such as hematite-rutile-bornite-pyrite; (2) the presence of telluride minerals; (3) high Au:Ag (2:1–20:1); (4) high Cu and Mo content; and (5) low As, Sb, Pb, and Zn abundances. Sulfur isotope ratios vary from +1.2 to −3.8 per mil, compatible with a plutonic-hydrothermal sulfur source. Lead isotope ratios are compatible with a Mesozoic, subduction-derived lead source.

Remobilized volcanogenic deposits are represented by the Alaska Treasure mine on southeastern Douglas Island and the Fremming-Valentine deposits north of Bern-

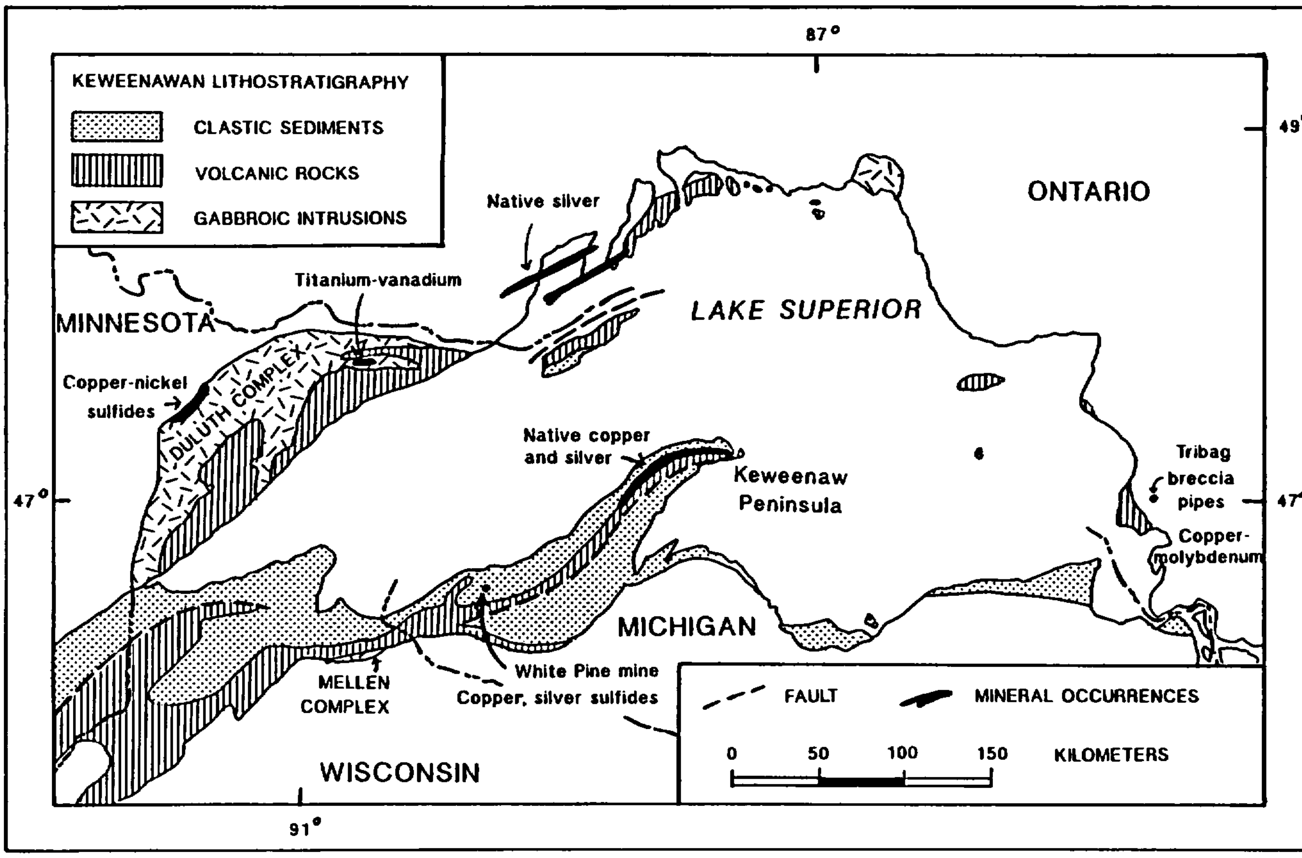

Figure 1. Locations of the major known mineral occurrences associated with the Midcontinent rift in the Lake Superior region. [Nicholson and others abstract]

ers Bay. Host rocks are Lower Cretaceous bimodal(?) volcanics of the Gravina overlap assemblage that have been overprinted by Late Cretaceous lower greenschist facies metamorphism. The gold veins are postmetamorphic quartz-ferroan dolomite-albite-pyrite-galena veins that have very narrow (<1 m) alteration envelopes. They occur near massive and semi-massive volcanogenic pyrite-sphalerite-chalcopyrite-galena deposits in quartz-dolomite gangue. The veins have gold abundances about three times higher than the nearby deposits and are characterized by: (1) low Au:Ag (1:2–1:20); (2) low Te, Mo, As, and Sb content; and (3) high Pb, Zn, and Cu abundances. Vein sulfur isotope ratios are similar to massive sulfide ratios: both vary from +2 to +4.3 per mil and are similar to ratios for Mesozoic volcanogenic massive sulfide deposits. Lead isotopic ratios are compatible with a Mesozoic, subduction-derived lead source.

"Exotic" gold deposits are veins and vein swarms for which there is no evidence of a preexisting gold concentration in the country rocks. The Alaska-Juneau (A–J) group, east of Juneau, is the largest deposit of this type, and the Eagle River and Sumdum deposits are smaller. All are hosted by metamorphic rocks of late Paleozoic to early Mesozoic age and postdate Late Cretaceous-earliest Tertiary metamorphism. The A–J vein swarm is enclosed in a ≥0.5-km-wide biotite-chlorite-ankerite alteration envelope. All of these deposits have (1) variably high As, Sb, Bi, W, Pb, and Zn; (2) low Mo, Cu, and Te; (3) highly variable Au:Ag (10:1–1:100); and (4) low oxidation and low sulfidization state mineral assemblages, such as pyrrhotite-arsenopyrite. Sulfur isotope ratios for these deposits are very light, −12 to −18 per mil, suggesting a sedimentary sulfur source. Lead isotope ratios are very radiogenic, indicating lead derivation from a sedimentary source and an appreciable residence time.

Metallogeny of the Midcontinent Rift in the Lake Superior Region

S.W. Nicholson, K.J. Schulz, and W.F. Cannon

The tectonic model presented by Cannon and others (this volume) for the evolution of the Midcontinent rift provides a new geologic framework within which to constrain the settings of known rift-related mineral deposits. This study reports the initial results of a long-term program to evaluate the mineral resource potential of the Midcontinent rift system and to establish a basis for predictive metallogeny.

The Midcontinent rift in the Lake Superior region comprises several segments separated by accommodation zones or transform faults. The segments consist of asymmetric central grabens that contain up to 20 km of basalt overlain by up to 10 km of sediments. The central grabens are flanked by shallow basins that contain exposures of up to 5 km of the oldest volcanic units of the system and minor sediments. The original structural relations within the rift segments have been somewhat modified by postrift compression.

Rift-related rocks are exposed only in the Lake Superior region, and, in this area, the rift contains several large mineral deposits. Perhaps the best known are the world-class native copper (and silver) deposits of the Keweenaw Peninsula, Mich., which are restricted to the central graben (fig. 1). These deposits occur as stratabound deposits within amygdaloidal basalt flow tops and interflow conglomerates and within fissures. Although inactive today, these deposits yielded nearly 5½ million short tons of native copper from about 1845 to 1968.

Other rift-related deposits appear to be localized within the original flanking basins of the rift. Native silver deposits and associated base-metal sulfides occur in fissures cutting Early Proterozoic black slates in a shallow flanking basin in the Thunder Bay area, Ontario (fig. 1), where mining from 1869 to 1922 produced more than 2½ million troy ounces of silver. Also, stratiform copper sulfides (mostly chalcocite) and lesser native copper and silver are still actively mined at the White Pine mine, Michigan (fig. 1), where ore production has yielded nearly 1 million short tons of copper. This deposit resides in a lacustrine black shale deposited in a restricted basin on the south side of the rift.

Several large mafic intrusions are exposed along the margins of some flanking basins; the Duluth complex, Minnesota, and the Mellen complex, Wisconsin, are two examples. Large subeconomic deposits of copper-nickel sulfides are located near the base of the Duluth complex (fig. 1); estimates indicate resources of about 4.4 billion tons of 0.66-percent copper and 0.17-percent nickel. These intrusions are also known to contain titanium and vanadium deposits and are being investigated for platinum-group minerals.

In addition, the Tribag breccia pipes of the Batchawana area, Ontario, are located just outside the present extent of the rift (fig. 1). These pipes, containing copper-molybdenum mineralization, produced 32.2 million pounds of copper from 1967 to 1974 and appear to be related to nearby rift-related felsic intrusions.

Metallogenesis of Lode Mineral Deposits of "Mainland" Alaska

Warren J. Nokleberg, Thomas K. Bundtzen, Donald J. Grybeck, and Thomas E. Smith

For "mainland" Alaska, west of 141° W. longitude, regional metallogenetic patterns are delineated by classification of metalliferous lode mineral deposits, according to recently developed mineral deposit models and bedrock geologic and tectonic setting. In each region, the origin and modification of many of these lode mineral deposits can be related to specific sedimentary, magmatic, metamorphic, and (or) deformational events.

Major belts of middle Paleozoic sedimentary exhalative zinc-lead-silver, bedded barite, and kuroko volcanogenic massive sulfide deposits occur in the Brooks Range and in the Alaska Range. In the northwestern Brooks Range is a belt of Mississippian and Pennsylvanian sedimentary exhalative zinc-lead-silver and bedded barite deposits that probably formed during late Paleozoic rifting. Belts of Devonian and Mississippian kuroko volcanogenic massive sulfide and associated Kipushi copper-lead-zinc (carbonate-hosted copper) deposits occur in the southern Brooks Range and in the eastern Alaska Range and probably formed during middle Paleozoic continental margin volcanism. A major belt of Devonian and Mississippian granitic-magmatism-related deposits occurs in the southern and eastern Brooks Range. These deposits consist of suites of polymetallic vein, Sb-Au vein, porphyry Cu and Mo, and Cu-Pb-Zn and Sn skarn deposits.

Major belts of Jurassic, Cretaceous, and early Tertiary granitic-magmatism-related deposits occur throughout the State. On the Seward Peninsula is an extensive suite of tin vein, skarn, and greisen; polymetallic vein; porphyry molybdenum; and felsic plutonic uranium deposits. In southwestern and west-central Alaska are suites of Sb-Au vein, polymetallic and epithermal vein, porphyry Mo and Cu, Cu and Fe skarn, and felsic plutonic U deposits. In east-central Alaska are suites of polymetallic vein, Sb-Au vein, porphyry Cu-Mo, felsic plutonic U, and Sn greisen and vein deposits. On the Aleutian Islands and the southwestern Alaska Peninsula are extensive suites of early Tertiary epithermal, polymetallic vein, and porphyry copper-molybdenum deposits. Farther northeast in the Aleutian-Alaskan Range batholith, the Alaska Range, and the Wrangell Mountains are belts of Jurassic, Cretaceous, and (or) early Tertiary Cu-Zn-Au-Ag and Fe skarn, polymetallic and Sb-Au vein, Sn greisen and vein, and porphyry Cu-Au and Cu-Mo deposits. These granitic-magmatism-related deposits are related mainly to a succession of Jurassic through early Tertiary subductions.

A suite of moderate-size podiform chromite deposits that has local platinum group element occurrences and serpentinite-hosted asbestos deposits occurs around the margins of the Yukon-Koyukuk basin in west- and east-central Alaska. These deposits are hosted in thin discontinuous thrust sheets of late Paleozoic and early Mesozoic ophiolites that were probably thrust onto continental margin rocks in the Jurassic and (or) Cretaceous. A lesser suite of podiform chromite and related platinum group element occurrences in ultramafic rocks is exposed along the Border

Ranges fault system in southern Alaska. These deposits probably formed at the base of an island arc.

Major belts of gold and copper-silver quartz vein deposits occur in low-grade, regionally metamorphosed sedimentary and volcanic rocks in several regions and are related to metamorphism that accompanied accretion or subduction. These metamorphic deposits occur on the Seward Peninsula and in the southern Brooks Range in Jurassic and (or) Cretaceous rocks; in east-central Alaska, the Alaska Range, and the Wrangell Mountains in mid-Cretaceous rocks; and in southern Alaska in early Tertiary rocks. Extensive basaltic copper deposits, which, in part, may be related to mid-Cretaceous regional metamorphism, occur in the Kennecott district in eastern southern Alaska.

An extensive suite of Besshi and Cyprus massive sulfide deposits occurs in the Prince William Sound region in coastal southern Alaska. These deposits are related mostly to mafic rocks interbedded with Upper Cretaceous and lower Tertiary flysch and probably formed during late Mesozoic and early Cenozoic sea-floor spreading.

Rare-Earth Resource Potential: Monazite Distribution in the Fall Zone Coastal Plain Sediments of Western South Carolina

James P. Owens and Andrew E. Grosz

Aeroradiometric (RAD) maps were made for most of the Atlantic Coastal Plain through a cooperative between the Regional Coastal Plain Commission and the U.S. Geological Survey. One of the RAD map areas in western South Carolina was geologically mapped (Owens, 1988). The geologic map was then overlain on the RAD map to look for relations between the anomalies and the mapped formations (Owens and others, in press). In general, the most intense RAD anomalies were clustered in the Fall Zone. The number and intensity of anomalies decreased rapidly east of the Fall Zone and were uniformly very low near the coast.

The most intense anomalies in the Fall Zone occurred in all the formations ranging in age from Cretaceous to Pleistocene. It appears that minerals causing the RAD anomalies were deposited in a zone where the higher(?) stream gradient of the Piedmont streams changed to the lower(?) stream gradient of the Coastal Plain streams.

The most intense and least intense RAD anomalies were checked by using a ground-based gamma-ray spectrometer to precisely define the radioelements (uranium, thorium, potassium) responsible for the anomaly. The anomalous sediments were then sampled, some to several feet below the surface. The samples were analyzed mineralogically to determine the abundance of radioactive mineral species (monazite, zircon) for each anomaly. In all, the most intense RAD anomalies were associated with sediments that had significant concentrations of monazite. Conversely, the lowest anomalies have little or no monazite.

In general, in spite of the high intensity of some of the anomalies, the concentrations of heavy minerals are typically low (less than 1 percent by weight of the samples taken). Within these heavy-mineral assemblages, however, monazite percentages were as much as 16 percent. Studies of the vertical distribution of the heavy minerals within thick (>100 ft) Cretaceous (and younger) sections in the vicinity of the Fall Zone may, therefore, lead to the definition of potential rare-earth resources such as those formerly mined at the Horse Creek deposit near the South Carolina-Georgia border.

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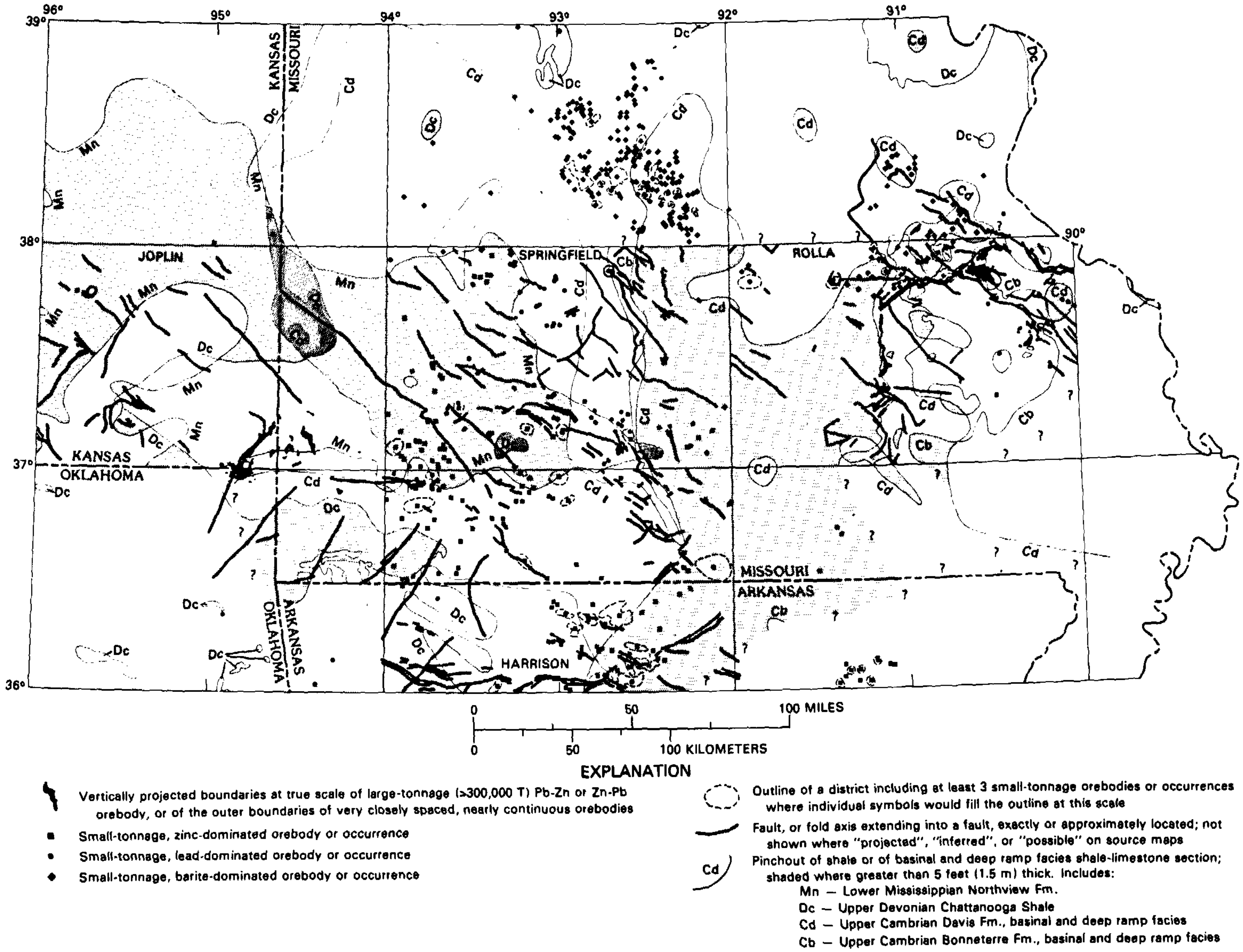
Late Cambrian Lithofacies and Their Control on the Mississippi Valley-Type Mineralizing System in the Ozark Region

James R. Palmer and Timothy S. Hayes

Upper Cambrian sedimentary rocks of the Ozark region were deposited by seas that onlapped the southeast-sloping Precambrian craton in at least three major transgressive-regressive stages. During deposition of the Cambrian sediments, local lithofacies varied dramatically, controlled, in part, by topography. Geometrically variable carbonate platforms first formed around several highland areas on the Precambrian erosional surface. The platforms then prograded across shallow intrashelf basins where interbedded carbonates and shales had been deposited earlier. Transgressions superposed shaley basinal facies rocks over the ramp and platform facies. Lithofacies variation in the Cambrian rocks determined where subsurface solutions would later permeate.

Basinal and deep ramp shaley carbonate lithofacies acted as aquitards to subsurface movement of solutions, including dolomitizing and later mineralizing solutions. The basinal and deep ramp lithofacies were the only facies that remained undolomitized over most of the region. Some



Map of the Ozark region showing locations of Mississippi Valley-type lead, zinc, and barite deposits relative to pinchouts of shale or shaley carbonate lithofacies and faults. Note the occurrence of important ores and well-mineralized districts adjacent to and upsection from shale pinchouts. Geologic features ending or changing at political boundaries are probably ending against quadrangles not yet studied. Information for this map was compiled from 24 separate source maps including 13 different CUSMAP or Midcontinent Strategic and Critical Minerals Program sources, 8 of which are still in preparation. A list of source maps is available on request from the authors. [Palmer and Hayes abstract] dolomitization of the Cambrian rocks took place during deep burial as indicated by dolostone distribution and by formerly hematitic limestones that were bleached and pyritized to form "whiterock" dolostones (Howe, 1968). Pre-ore sulfidization and dolomitization probably precluded the presence of host rock sulfates during later Mississippi Valley-type (MVT) mineralization in the Southeast Missouri lead district. The distribution of ore deposits relative to windows through shales, including facies windows through the Cambrian basinal and deep ramp shaley rocks, suggests that MVT ore precipitated where brines driven by artesian pressure escaped confinement and migrated upsection. All major districts of the Ozark region occur at the margins of and upsection from windows through one or more of the shales. Other Ozark region MVT ores are found where the aquitards were structurally breached and the brines were allowed to climb section.

MVT sulfide mineralization in the Ozark region is associated with a series of fracture- and vug-crusting or limestone-replacing, coarse, saddle dolomites having the color sequence: (1) tan, (2) white, and (3) pink (fig. 1). These paragenetically late dolomite crusts are interlayered with ore sulfides at orebodies. The dolomite crusts also occur at numerous places across the region (fig. 2), interlayered with the trace-metals-anomalous pyrite, marcasite, pyrobitumen blebs, and other organic matter reported by Erickson and others (this volume). At many additional places regionally, the hydrothermal dolomite crusts occur without any accompanying sulfides or organics. Abundance of the hydrothermal dolomite crusts is directly proportional to the insoluble-residue-metals results of Erickson and others (this volume). Very low hydrothermal dolomite abundance within and above the shaley aquitards grades to anomalous abundance across paleohighs and especially in halos around ores. The hydrothermal dolomite crusts allow distinction of the regional mineralization stages from all other stages of the rock history, before or after.

Most hydrothermal-stage minerals regionwide are within secondary or secondarily enhanced porosity or are replacement bodies in nonshaley limestones. Thus, there were not just one or two favorable carbonate lithofacies. Rather, only the shaley aquitards were unfavorable—all other lithofacies were favorable, particularly where they were marginal to and upsection from a shale pinchout.

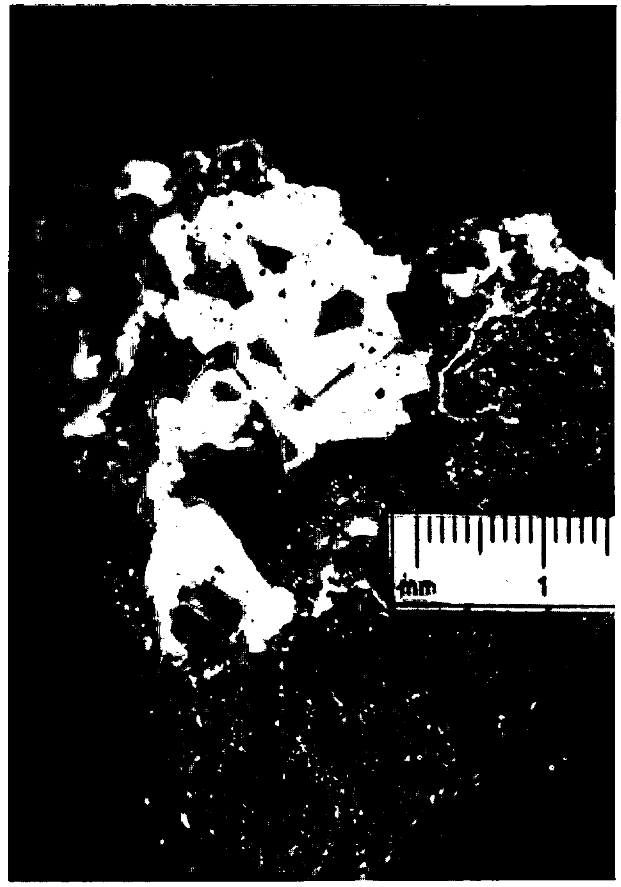


Figure 1. Pink-stage saddle dolomites (note curved crystal faces) sitting in a vug in jasperoidal sphalerite ore, atop drusy quartz, and beneath 1/4-mm chalcopyrite crystals, in a sample from Philadelphia mine, Middle Ordovician Everton Formation host rocks, Northern Arkansas district. All these minerals in the same sequence are more familiar in mineralogy collections from samples from the Tri-State district, 140 miles to the northwest. In fact, though, all these mineral paragenetic relations, two other hydrothermal dolomite stages, and numerous other hydrothermal sulfide stages are correlatible throughout the Ozark region, from basal Cambrian to Early Pennsylvanian host rocks, from the Southeast Missouri district to west of the Tri-State district, and from the northern edge of the Arkoma Basin to central Missouri: more than 25,000 cubic miles of rock affected by a single hydrothermal system. Small-scale divisions are 1 mm. [Palmer and Hayes abstract]

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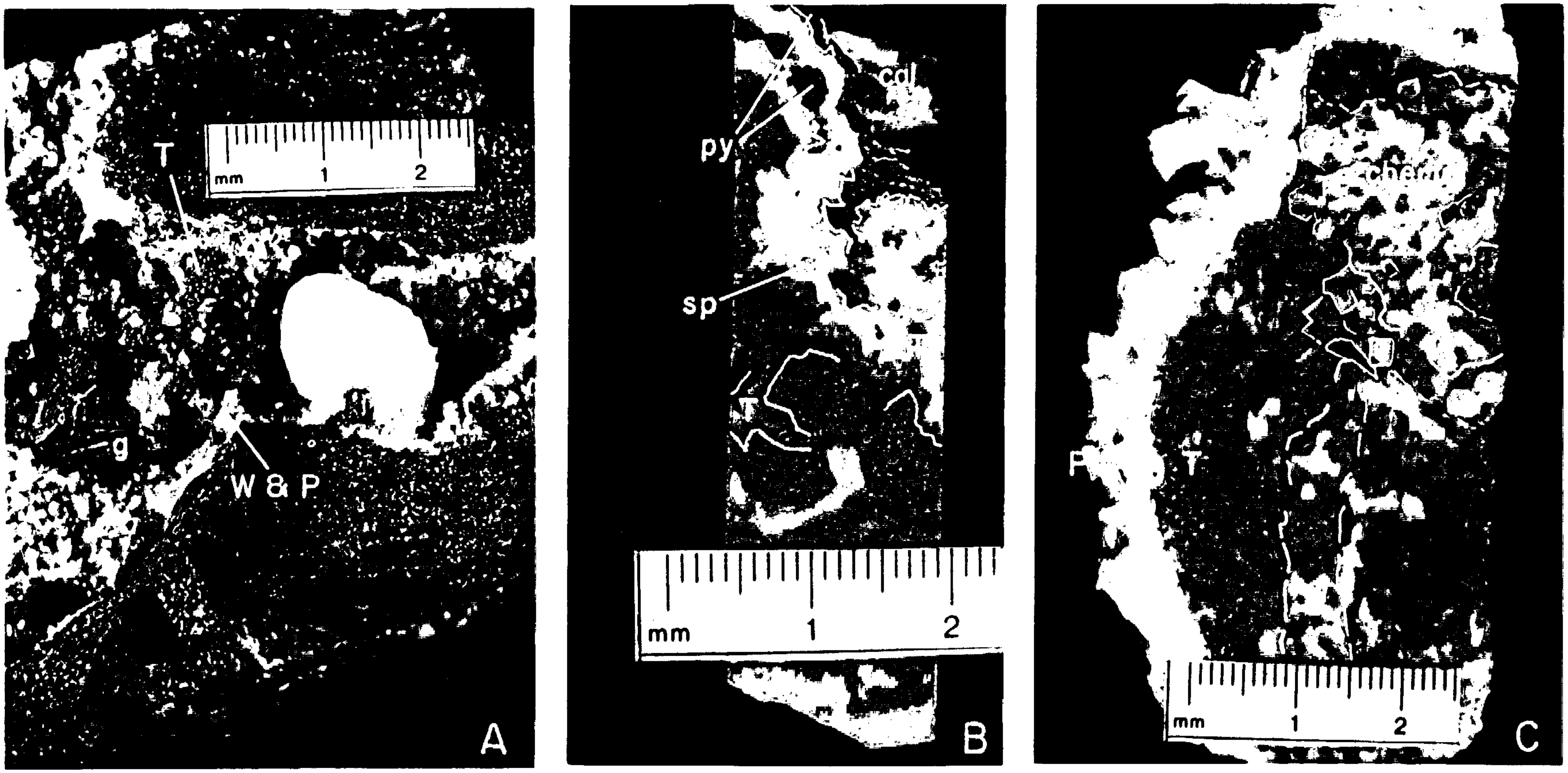
Petrography, Chemistry, Age, and Origin of the Rare-Earth Iron Deposit at Bayan Obo, China, and Implications of Proterozoic Iron Ores in Earth Evolution

J.A. Philpotts, M. Tatsumoto, K. Wang, and P-F. Fan

The world's largest known rare-earth deposit occurs at Bayan Obo (lat 42° N., long 110° E.), Inner Mongolia,



A is from the West Fork mine, Viburnum trend, Southeast Missouri district, from the Cambrian Bonneterre Formation, lowest carbonate unit in the Paleozoic section. A vug in dolostone wallrock was crustified in the sequence: (1) tan-stage hydrothermal dolomite (T) coarser than wallrock but finer and darker than white-stage dolomite, (2) octahedral galena (g), (3) 1-mm rhombs of white-stage hydrothermal dolomite with (4) limpid, pink-stage hydrothermal dolomite overgrowths (W&P), and (5) scalenohedral calcite (cal).

B is from the Cambrian Potosi Formation in north-central Arkansas, 300 m upsection and 135 miles southwest of the West Fork sample, from an exploration core. It shows a dolostone breccia cementation and crustification sequence of (1) recrystallized wallrock selvage with intercrystalline pyrite (dark rims on breccia clasts; early tan-stage), (2) tan-stage hydrothermal dolomite (T), (3) botryoidal sphalerite (sp) and pyrite (py), (4) white-stage hydrothermal dolomite (W), (5) botryoidal pyrite, and (6) scalenohedral calcite (cal).

C is from the Semple mine in Tri-State district's Picher Field, from Middle Mississippian Warsaw Formation host rocks, another 200 m upsection, and now 220 miles west-southwest from the first sample. It shows a sequence of chert breccia cementation and crustification of (1) tan-stage hydrothermal dolomite (T) with intercrystalline dark brown clay and sphalerite (the "gray dolomite" of the Tri-State literature), (2) white-stage hydrothermal dolomite, and (3) pink-stage hydrothermal dolomite (P).

Figure 2. Examples showing correlation of hydrothermal dolomite crustification sequences across the Ozark region (Small-scale divisions in each photograph are 1 mm. Paragenetic boundaries have been partly highlighted and partly left in natural shades on photographs B and C). [Palmer and Hayes abstract]

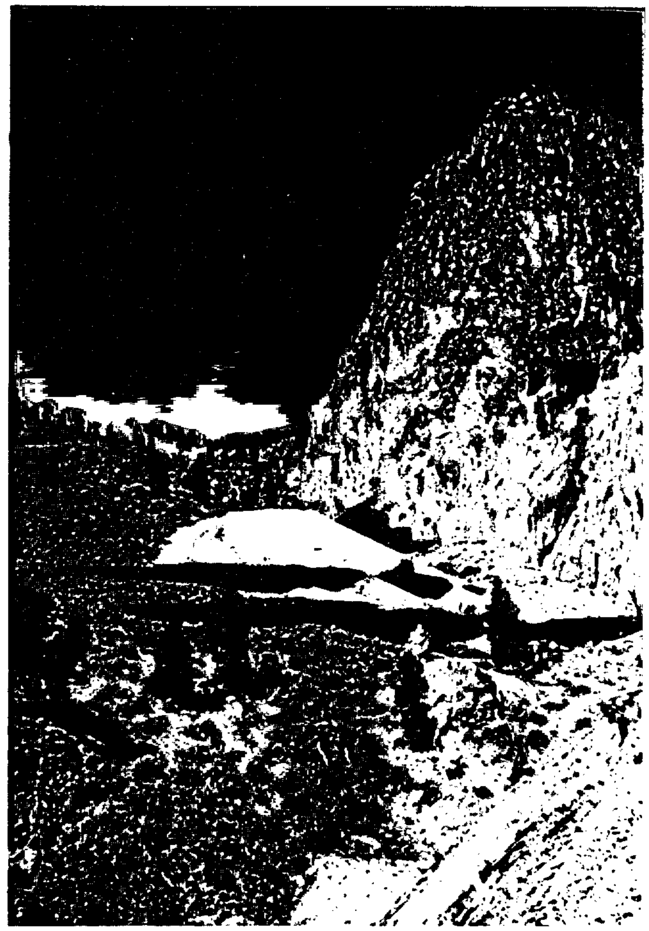
China, in hematite-magnetite iron ore, carbonate, and aegirinite, toward the top of a thick Proterozoic clastic sequence that has been folded, faulted, and regionally metamorphosed. Monazite and bastnaesite are the major rare-earth ore minerals; rare-earth mineralization is commonly disseminated widely within samples. Fluorite and niobium minerals are locally abundant. Many textures are metamorphic-metasomatic; some textures may be sedimentary. At least some of the rare-earth and iron deposition is contemporaneous. Rare-earth abundances are at percent levels in the ore samples and show extreme light-rare-earth enrichment and, typically, neither cerium nor europium anomalies. These rare-earth patterns do not resemble those of clastic or chemical sediments and, indeed, are not typically crustal but resemble the rare-earth patterns of limited partial melts derived from the mantle. Low $^{87}Sr/^{86}Sr$ measured for Bayan Obo carbonates also support mantle derivation. Sm-Nd isotopic systematics of the Bayan Obo ore samples do not yield a whole-rock isochron; internal two-point Nd "isochrons" reveal complexity in rare-earth mineralization and suggest both Proterozoic and Paleozoic crystallization. The grouping of Nd model ages suggests that the rare-earths may have separated from a near-chondritic mantle reservoir at about 1.4 Ga.

Large iron-oxide deposits (other than the banded iron formations) considered to be of mid- to late-Proterozoic age include (1) the internally derived billion-ton deposits at Olympic Dam, Australia; Kiruna, Sweden; and the Missouri ferroan felsics; and (2) iron- and titanium-rich deposits associated with anorthosite-suite rocks. The largest rare-earth deposit in the United States, the carbonatite at Mountain Pass, Calif., is of mid-Proterozoic age. Bayan Obo and these other deposits may share common genetic features. At the very least, the deposits appear to reflect unusual conditions in the crust and (or) involvement of mantle convection or major plume activity during this period. The lack of proportionately extensive orogenesis or basaltic volcanism may favor plumes. Origin of the internally derived iron ores by hydrothermal processes or by igneous processes involving contamination or extreme fractionation, perhaps including liquid immiscibility, appears feasible; each process, however, presents difficulties in interpretation. Volatiles other than water may have played a role in some cases of iron enrichment.

Chemical Modeling of Ore and Gangue Deposition in the Creede, Colorado, Epithermal System

Geoffrey S. Plumlee

Strongly zoned, mineralogically complex epithermal deposits at Creede, Colo. (fig. 1), resulted from the interactions of diverse chemical processes in the hydrothermal system. By using data from previous geological and geochemical studies (such as, Bethke, 1988), chemical modeling calculations help elucidate many of these processes.



The Commodore mine, Creede, Colo., was one of the major mines in a district that has produced over $100 million worth of silver and base metals since its discovery in the San Juan volcanic field in 1889.

It is inferred (Bethke, 1988) that the Creede hydrothermal system was recharged by two meteoric fluids of strongly contrasting chemistries. Chemically and isotopically evolved meteoric waters rich in chlorine, sodium, carbonate, sulfate, and soluble organics entered the system from Creede caldera moat sediments at the south end of the district, and dilute meteoric waters entered the system from highlands in the northern district. At depth, fluid chemistries were modified through internal chemical reactions, reactions with wallrocks, and possible interactions with magmatic fluids. During high-temperature (T) stages (T>200 °C), most constituents of the fluids approached equilibrium K-feldspar-mica pH values and redox-sulfidation conditions near those defined by the assemblage pyrite-chlorite-hematite (PCH). Aqueous sulfate-sulfide

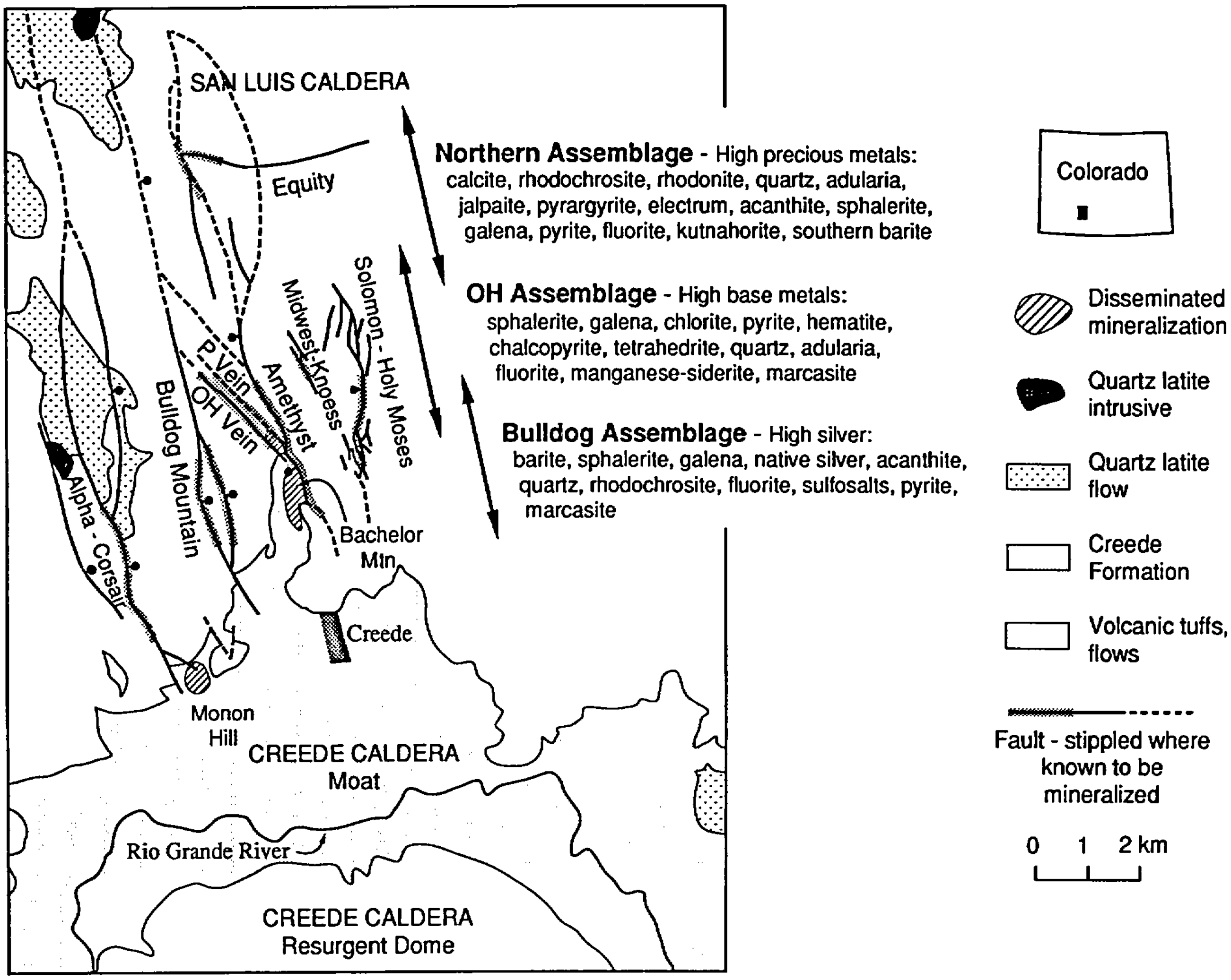


Figure 1. Creede, Colo., district geology and mineral zoning. Northern assemblage unpublished data from N. Foley and S. Caddey. Southern and Bulldog assemblages from references in Bethke (1988). [Plumlee abstract]

◄ A banded sphalerite that has a quartz-adularia core, OH vein, Creede, Colo. The variations in color are due mainly to differences in the amount of iron.

and hydrocarbon-fluid reactions did not equilibrate, even at temperatures up to 300 °C. The southern-recharge brines (salinities up to 13 weight percent NaCl equivalent) picked up and transported from depth large quantities of chloride-complexed metals (zinc, lead, copper, silver); the dilute northern-recharge fluids carried much smaller quantities of chloride-complexed metals but greater quantities of bisulfide-complexed metals (gold, arsenic, antimony). The southern-recharge fluids produced base-metal- and silver-rich mineralization during most stages along the central and southern vein systems and during at least one stage in the northern vein systems. The dilute northern-recharge fluids produced precious-metal-rich stages along the northern vein systems. Mixing of the two fluids across the system's upwelling plume promoted metal deposition due to changes in salinity, pH, and temperature.

Shallow boiling and mixing in the system's ore zones further modified fluid chemistries. Due to a north-to-south topographic gradient across the district, the hydrothermal fluids flowed predominantly from north to south through the central and southern district ore zones. Chemical reaction path modeling suggests that, in the hotter, deeper portions of ore zones in the central vein systems (OH vein, P vein, central Amethyst, and Bulldog Mountain; fig. 1), hydrothermal brines boiled over a restricted-temperature interval (ΔT 5–10 °C) to deposit chlorite-hematite-quartz-base-metal sulfide ores. Due to the high salinities and initially high oxidation conditions of the hydrothermal brines (near the PCH buffer), more extensive boiling over a greater temperature drop (ΔT 10–40 °C) would cause the brines to become undersaturated with sulfides and would produce a simple quartz-adularia-hematite-fluorite assemblage; a middle gangue stage along the central and southern vein systems that has this mineralogy probably formed in this manner. Lateral mixing to the south with cooler, dilute, oxidizing ground waters caused boiling to cease in the hydrothermal fluids. Calculations show that initial mixing could have produced base-metal sulfide-rich ores observed along the central district vein systems. With increased mixing, the base-metal ores would become more silver rich and have increasing proportions of barite, acanthite, native silver, and various copper sulfides; such mineralogies are observed along the district's southern vein systems (southern Amethyst and Bulldog Mountains). Extreme barite-rich mineralization in the district's southernmost vein systems may have formed through mixing of the brines with sulfate-rich pore fluids from Creede caldera moat sediments. In the district's northern vein systems, calculations indicate that boiling of the dilute northern-recharge fluids likely triggered deposition of carbonate-adularia-quartz-precious-metal assemblages that have high gold to base-metal ratios.

REFERENCE

Bethke, P.M., 1988, The Creede, Colorado, ore-forming system: A summary model: U.S. Geological Survey Open-File Report 88–403, 29 p.

Airborne Imaging Spectrometer Data as an Aid to Mineral Mapping, Cuprite, Nevada

M.H. Podwysocki and O.D. Jones

Within the last several years, new airborne multispectral scanners that measure spectral radiance in numerous (as many as 224) discrete wavelength channels have become available. Because their spectral sampling intervals approach those of laboratory spectrometers, the new instruments are called airborne imaging spectrometers (AIS). AIS data can be used to identify diagnostic absorption bands associated with hydroxyl-, carbonate-, and ammonium-bearing minerals, some of which may be indicators of potential economic mineral deposits. In the present study, AIS data for the Cuprite mining district in western Nevada are examined to analyze data calibration procedures and to determine the utility of these data for distinguishing several types of hydrothermally altered rocks.

Figure 1 shows 3 of the 32 channels of data from the GER, Inc., AIS (GERAIS), which cover a range of approximately 2.0 to 2.5 μm. For comparison, the Landsat Thematic Mapper digital scanner has only one channel in this important spectral region. Spectral response curves, which can be related to mineral composition, can be determined by choosing selected ground sites within a GERAIS image and extracting digital number values for each of the 32 channels.

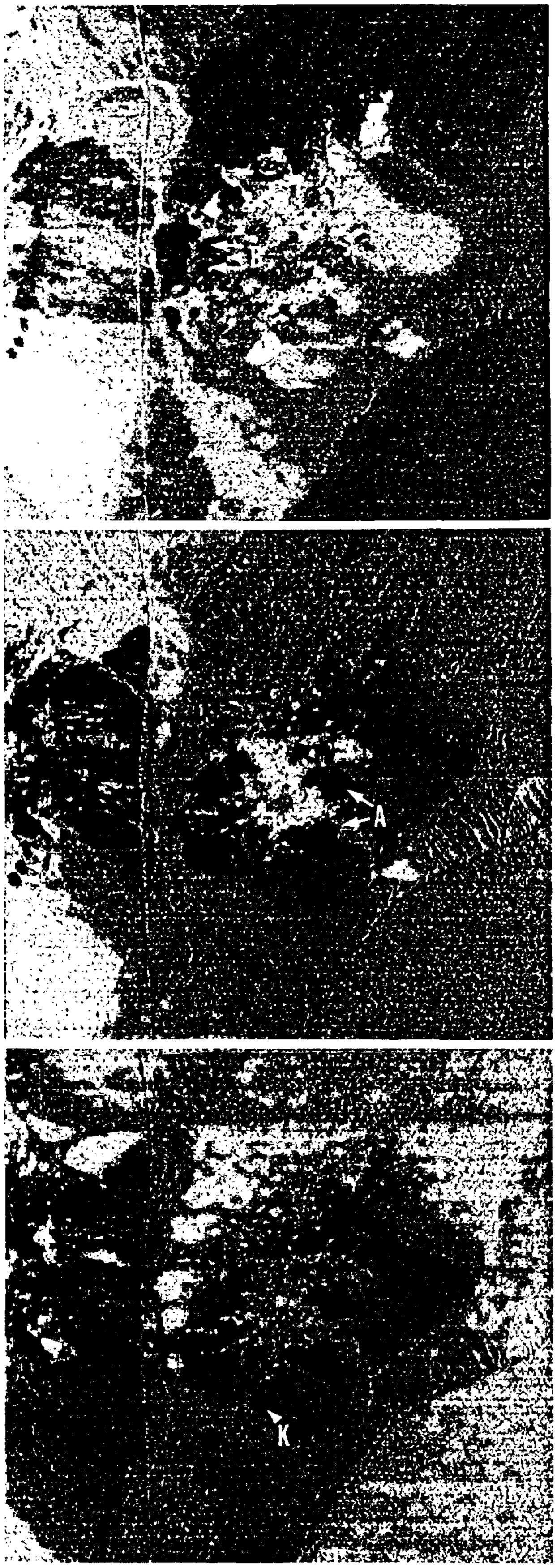
Figure 2 shows spectral response curves extracted from the Cuprite, Nev., study area for three different materials. These curves closely match laboratory spectra for alunite, kaolinite, and buddingtonite.

Stratabound Copper and Zinc Mineralization in Triassic Lacustrine Beds of the Culpeper Basin, Virginia

Gilpin R. Robinson, Jr., and Joseph P. Smoot

Anomalous concentrations of stratabound zinc, copper, and other metal sulfides occur in dark-gray to black lacustrine mudstones of the early Mesozoic Newark Supergroup in the Culpeper, Gettysburg, and Newark rift-basins of the Eastern United States. In the Culpeper Stone Company Quarry, Stevensburg, Va., a cyclic sequence of lacustrine beds contains four black, calcareous, silty mudstone layers enriched in base and precious metals. In fresh samples, mineralized mudstones have 1,000 to 7,000 ppm Zn, 200 to 28,000 ppm Cu, 5 to 40 ppm Ag, and as much as 200 ppm Mo, 1,000 ppm Pb, 17,000 ppm Mn, and 0.5 ppm Au. Two black mudstone intervals, each containing two metal-rich zones ranging from 10 cm to nearly 2 m thick, are traceable along strike 3.5 km north of the quarry and 3 km to the south. The cyclic lacustrine sequence appears to represent the repeated transgressions and regressions of a sediment-starved, closed-basin lake during prolonged periods of dessication.

The mineralized beds consist of gray to black sandy mudstone or muddy siltstone that have abundant carbonate- and sediment-filled tubes (root structures), some deep, narrow, sinuous silt-filled mudcracks, and local carbonate nodules. This lithology is interpreted as a vegetated, shallow-water shoreline to mudflat that was subaerially exposed at intermittent intervals. Within cement-filled root



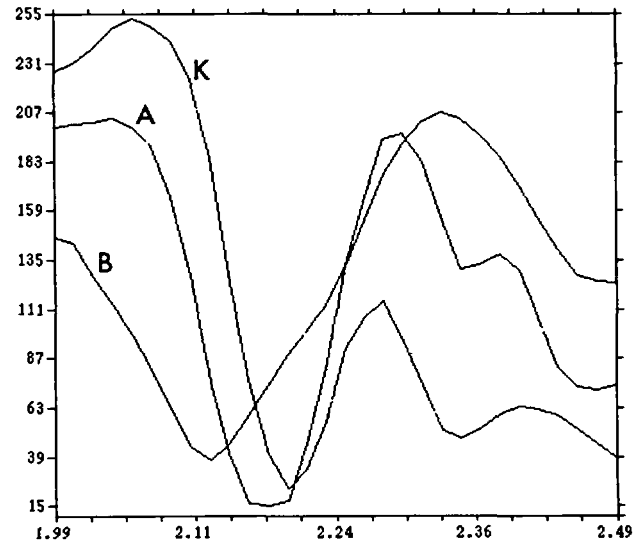


Figure 2. Relative spectral response curves derived from the GERAIS data for Cuprite, Nev. Spectral response in digital numbers is plotted along the ordinate, and spectral wavelength is plotted along the abscissa. Note that the minimum reflectance of alunite (A) occurs at approximately 2.16 μm, which corresponds to channel 43 of the spectrometer, whereas the minimum reflectance of kaolinite (K) occurs at approximately 2.20 μm, which corresponds to channel 45. The minimum for buddingtonite (B) occurs at 2.12 μm in channel 40. [Podwysocki and Jones abstract]

tubes and silt-filled mudcracks are small disseminated aggregates of intergrown sphalerite, chalcopyrite, and bornite that have minor galena and pyrite and isolated patches of arsenopyrite, pyrite, and pyrrhotite. The sulfides partially replace diagenetic pyrite and carbonate cements that apparently grew around the roots during their decay. Chalcopyrite, pyrite, and minor sphalerite replace wallrock adjacent to thin, near-vertical, calcite-filled fractures and veins. These sulfides are preferentially developed where the veins and fractures cut the mineralized sandy mudstone beds. Chalcopyrite replaced coarse carbonate cements in silt-filled mudcrack and root tubes, apparently by reactions with vein fluids, within a few inches of sulfide-bearing veins.

The stratabound mineralization appears to be controlled by the immediate superposition of organic-matter-

◀ **Figure 1.** A set of images depicting 3 of the 32 GERAIS channels that cover the 2.0- to 2.5-μm spectral range for the Cuprite, Nev., study area. The images are approximately 9.8 km wide by 11.0 km long. Spatial resolution is approximately 20 m. North is at the top of the images. Note the three small, dark areas (B) in channel 40 at 2.12 μm (fig. 1A), which is the spectral response minimum for buddingtonite. Alunitic areas (A) appear darkest in channel 43 (2.16 μm) (fig. 1B), whereas a kaolinitic area (K) appears darkest in channel 45 (2.20 μm) (fig. 1C). [Podwysocki and Jones abstract] rich laminated lacustrine shales of deep-water origin over sandy, root-disrupted, and mudcracked siltstone. This suggests that depositional porosity and preservation of reactive organic material were important controls on base-metal mineralization. Reducing conditions cannot be the only control on the localization of sulfide mineralization, however, because associated organic-matter-rich, deep-water shales are unmineralized. The metal-bearing fluids may have been introduced along fractures long after lithification, with sulfide precipitation occurring by reaction with and dissolution of carbonate cements. Faults may have acted as fluid conduits to the more permeable and reactive layers.

The metal-rich samples in the early Mesozoic basins resemble unmineralized black mudstones in outcrop, and weathering tends to greatly reduce copper and contents, so that extensive deposits containing this type of mineralization may go unrecognized if not carefully sampled. Although the known stratabound base-metal occurrences in the Newark Supergroup are currently subeconomic, their tectonic and depositional sedimentary environment is similar to important copper, lead, and zinc deposits such as those at Mount Isa and McArthur River, Australia. By analogy, the black lacustrine mudstones of the Newark Supergroup may be potential hosts for extensive and economically significant base-metal sulfide deposits, particularly in areas where bulk mining techniques are feasible and waste rock can be marketed as construction aggregate.

Volcanism, Extensional Tectonics, and Epithermal Mineralization in the Northern Basin and Range Province, California, Nevada, Oregon, and Idaho

James J. Rytuba

The northern part of the Basin and Range province, extending from northwestern Nevada and northeastern California into eastern Oregon and western Idaho, is composed primarily of regionally extensive volcanic fields related to extensional tectonism of middle Miocene age. An important feature of this part of the province is the absence of Precambrian continental crust, as defined by the Sr^{87}/Sr^{86} of 0.706 (fig. 1), and the lack of exposed Paleozoic and Mesozoic rocks. In northwestern Nevada, the boundary of

Siliceous sinter from the Gold Hill mine, located 4.6 mi north of Round Mountain, Nev., on the western slope of the central Toquima Range.

the province is marked by two large fault zones, the northeast-trending Black Rock Structural Boundary (BRSB) and the northwest-trending Orevada rift (OR) (fig. 1). Paleozoic and Mesozoic rocks are displaced downward more than 1 km along these fault zones, and fundamental changes in regional gravity and magnetics occur across these structures.

The most voluminous and widespread volcanic event in the province was the eruption of Steens-type tholeiitic basalt at about 16 Ma. The basalts form a large shield volcano whose central vent, defined by a circular magnetic anomaly, is located near the crest of Steens Mountain, Oreg. Following the Steens event, widespread and voluminous eruption of peralkaline ash-flow tuffs occurred from 16 to 15 Ma. The peralkaline volcanic centers were emplaced along the BRSB and the OR and extend from northwestern Nevada into eastern Oregon. Fifteen calderas related to this event have been identified (fig. 1). The peralkaline ash-flow tuffs are often chemically zoned and become metaluminous in their upper parts. Postcollapse domes and intrusions range from peralkaline to metaluminous.

Ore metals concentrated in the peralkaline rhyolites include (maximum value in ppm) Ag (0.4), As (6.4), Cs (112), Hg (0.96), Li (213), Sb (2.2), Tl (2.5), Th (23), U (12), and Zn (600). The rhyolites are depleted in Au, Co, Cu, Cr, Pb, Ba, and Sr. Widespread epithermal uranium, mercury, and precious-metal-bearing systems developed during the waning stage of the peralkaline volcanic event and were localized along caldera ring faults and northwest-trending zones of extensional faulting along which rhyolite domes and plugs were emplaced. The DeLamar and Milestone gold-silver deposits are localized along the DeLamar-Duck Valley extensional fault zone. This narrow zone of faulting extends 180 km from the southwestern Idaho-Nevada border to eastern Oregon. The deposits are closely related to rhyolite vent and dome complexes localized along this zone of extensional faulting. At the same time in Nevada, a similarly narrow zone of extensional faulting and associated rhyolite vent complexes developed and localized the Buckskin mercury-gold-silver deposits and the National gold-silver veins. These zones of extensional faulting and hydrothermal activity were less than 1 million years in duration and developed above near-surface rhyolite magma

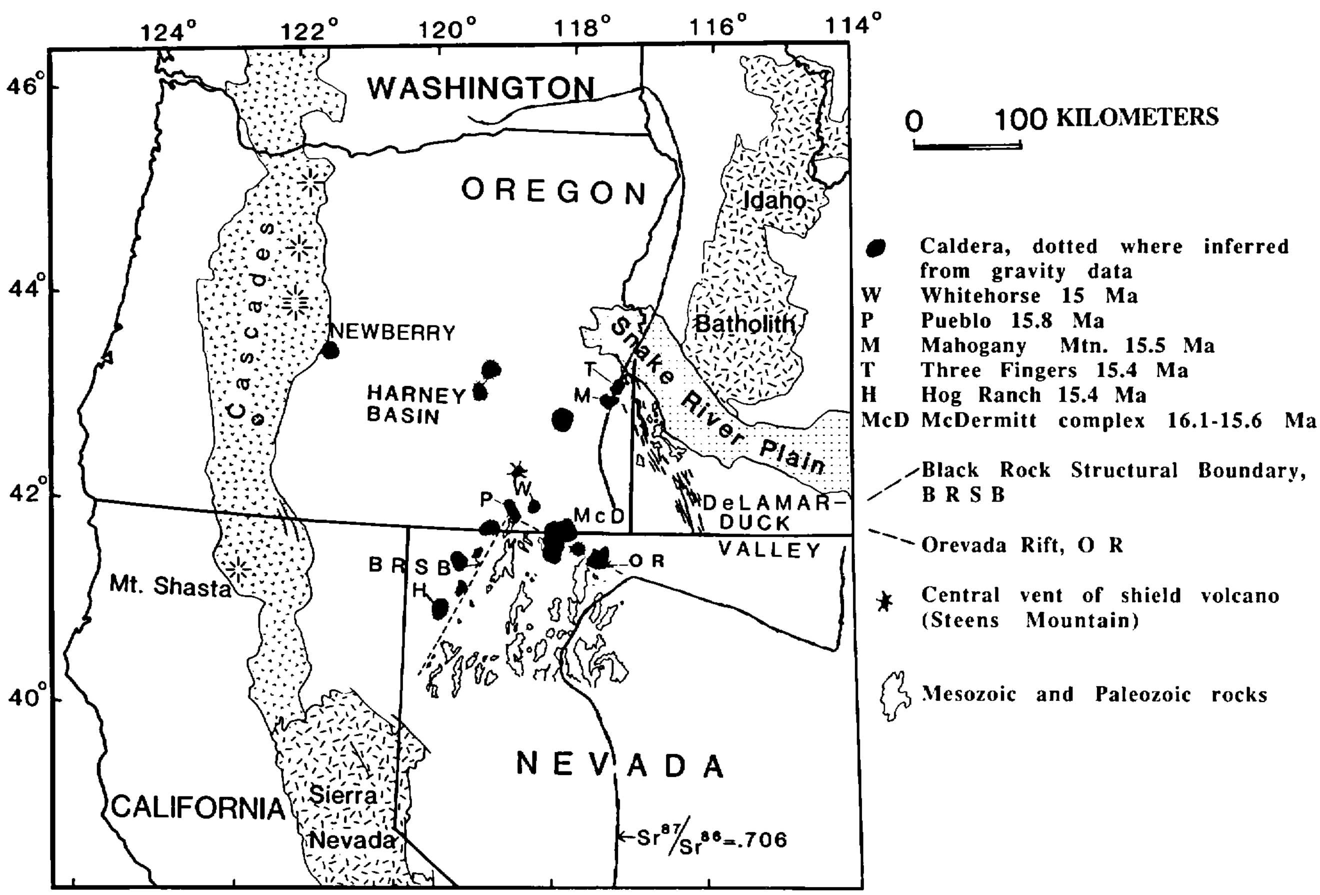


Figure 1. Volcanic and tectonic features in the northern Basin and Range province. [Rytuba abstract]

Copperstone gold mine, La Paz County, Ariz. The photograph faces south toward the main ranges of the Dome Rock Mountains, which are on the skyline. The low foothills in the upper right-hand part of the photograph are called the Moon Mountains by some but referred to as the Dome Rock Mountains at the mine. A large detachment fault that strikes northwest-southeast daylights in these foothills and dips to the northeast (for example, toward the lower left corner of the photograph) under the orebody. The ore at the mine is in the Copperstone fault that dips to the northeast at about 30° and is exposed in the pit. The pit parallels the strike of this fault. The dark dump between the pit and the office-plant complex is ore. The access road to the property can be seen at the upper left edge of the photograph. (Caption courtesy of Hugo Dummett, Arizona Geological Society. Photograph courtesy of Cyprus Minerals Company, Denver, Colo. Photographer is Mickey Prim, Manley-Prim Photography, Inc.)

bodies. Hydrothermal systems commonly developed where these magmas vented as domes or tuff cones. Other epithermal deposits, formed at this time and localized along or adjacent to caldera structures, include the McDermitt and Cordero mercury deposits, Hog Ranch gold deposit, and numerous undeveloped prospects such as at Red Butte and Grassy Mountain, Oreg. The level of erosion in these volcanic and epithermal systems is slight, and so only the uppermost parts of the hydrothermal systems are exposed. Hot-spring sinter and hydrothermal explosion craters, such as at Red Butte, are well preserved.

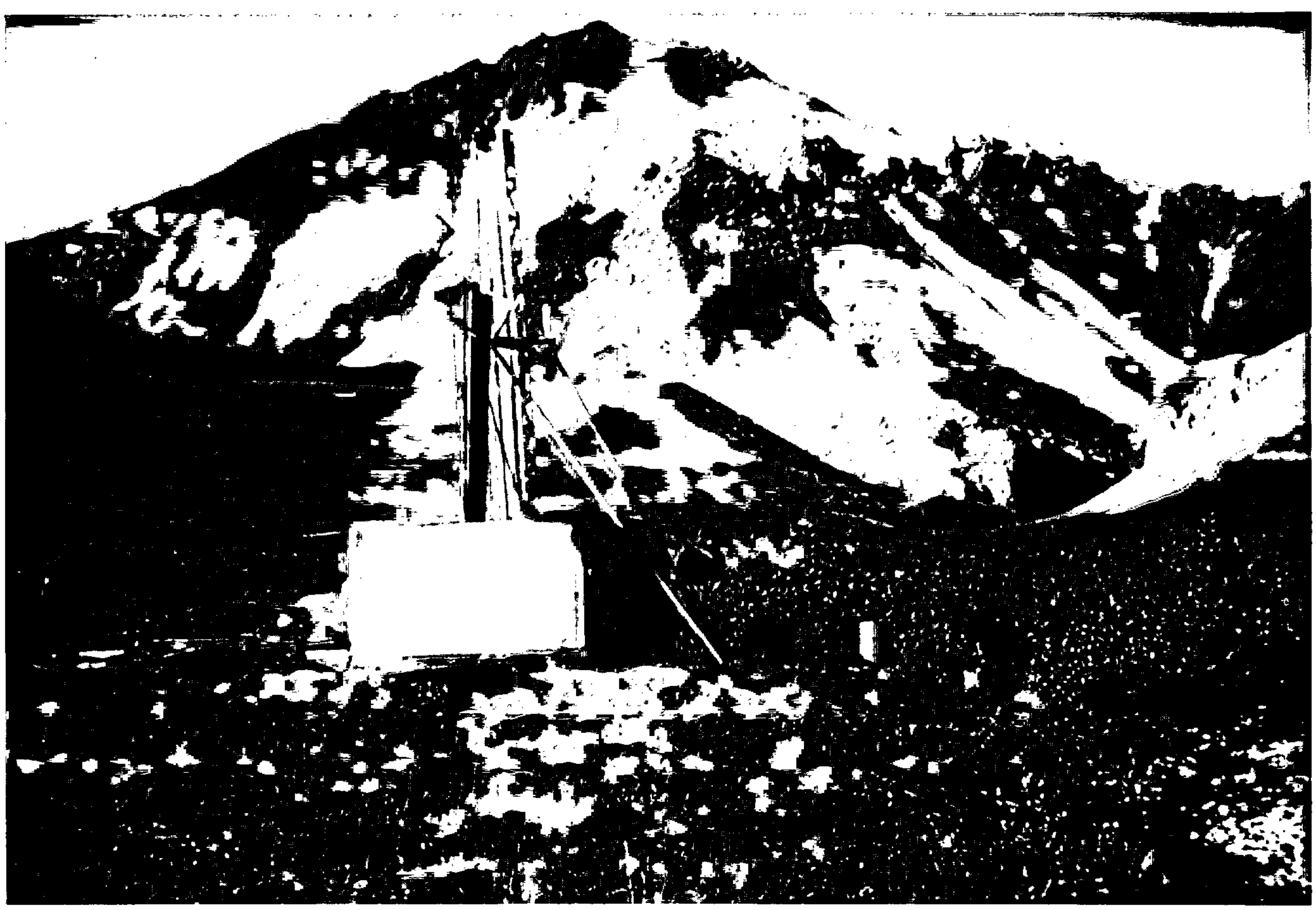
After the peralkaline volcanic event, the locus of volcanism moved northwest through the province with the emplacement of small volume domes and lavas until 10 Ma when major peralkaline ash-flow tuffs were erupted from the Harney basin caldera complex. The locus of dome emplacement continued to move to the northwest; most recent activity was near Newberry caldera. Epithermal systems, such as the Quartz Mountain gold and mercury deposits, are closely associated with rhyolite domes emplaced along northwest-trending zones of extensional faulting. Basin-and-range-type extension responsible for much of the present topography began at about 8 Ma, just after the last voluminous ash-flow eruptions from Harney basin. The basins are relatively shallow and consist of numerous horst and graben structures. Active geothermal systems are localized along basin margins and horsts within the basins. Northwest-trending zones of extension, such as the Brothers fault zone and the Honey Lakes zone, cut across the northeast basin-and-range trend and developed concurrently with extension. The youngest tectonic feature in the province is a large east-west-trending graben (150 km strike length) associated with Holocene basaltic volcanism.

Reconstruction of Primary Features and Isotopic Evidence for Multiple Sulfur Sources at the Red Dog Zinc-Lead-Silver Deposit, Noatak District, Alaska

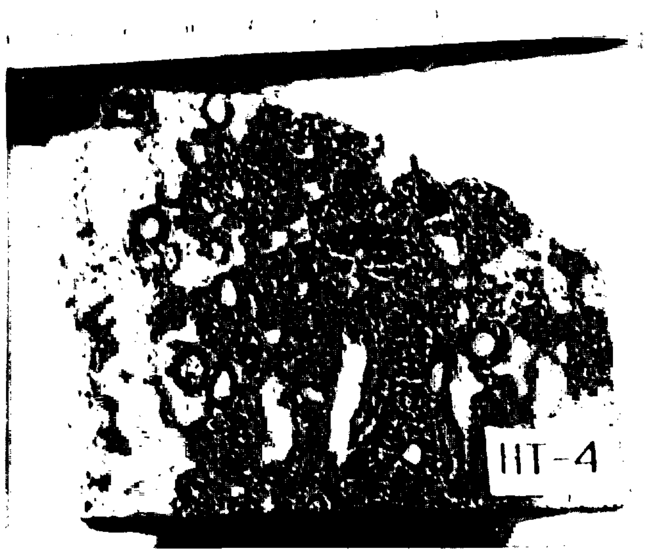
Jeanine M. Schmidt and Robert A. Zierenberg

The giant Red Dog sediment-hosted sulfide deposit (77 million metric tonne, 17.1 percent zinc, 5.0 percent lead, 82.0 g/metric tonne silver) consists of at least three, and probably five thrust panels of ore, each folded during and after thrusting. The three most important panels are the Hilltop deposit and the upper and lower ore plates of the Main deposit. Core logging (at 1:120, on 60-m spacings) in the Main deposit has enabled a partial reconstruction of the orebody prior to its deformation in the Cretaceous Brooks Range fold- and thrust-belt orogeny. The first thrust emplaced the entire deposit, Mississippian footwall, and Permian to Cretaceous hanging-wall rocks over Cretaceous sedimentary rocks. There was a minimum of 2 km displacement, but more likely tens of kilometers displacement. A second thrust, having <500 m northeasterly displacement, stacked the upper ore plate over the lower. A 200 by <300 m area in the upper plate having apparently upside-down zonation (silicified barite to mineralized barite to barren barite to baritic shale downward) may be the overturned limb of a drag fold associated with this second thrust. The two ore plates of the Main deposit and their bounding thrusts were then broadly folded beneath the third thrust, which emplaced footwall rocks and the Hilltop part of the deposit above the upper ore plate.

Massive (70–100 percent) and semi-massive (30–70 percent) sulfides and lower grade (0–30 percent) siliceous ores are texturally heterogenous and interfinger on scales of <40 m vertically and <300 m laterally. Unlike most shale-hosted deposits, pyritic massive sulfide ores are uncommon and small (<10×<100 m). Vein and disseminated sulfides occur in footwall rocks wherever they are preserved below the Main deposit. Silicification of both shale and massive barite is common, and silicification fronts between ore and host shales are locally steep. Burrows of vent-specific infauna, probably worms, increase in frequency upward in the upper ore plate and to the northwest in the deposit, but discrete vent sites have not yet been identified. Clastic ores of fine sand to conglomerate are rare, spatially restricted, but locally thick (40 m); their



Diamond drill in the Noatak camp near the Red Dog deposit, Alaska Brooks Range.[Schmidt and Zierenberg abstract]



Worm tubes and pellitoids in massive barite from the Red Dog zinc-lead-silver shale-hosted massive sulfide deposit. These Mississippian-age trace fossils are evidence for some of the oldest known hydrothermal vent specific fauna. [Schmidt and Zierenberg abstract]

distribution indicates local sea floor relief during ore deposition. Mineralization at Red Dog occurred prior to lithification of Carboniferous siliceous black shale host rocks, but Red Dog differs from standard models of sedimentary exhalative deposits in that much of the mineralization occurred below the seawater-sediment interface. Diagenetic growth of minerals in unlithified sediment and progressive replacement of sediment and previously deposited ore minerals are well documented in the Main deposit.

Massive barite locally formed an upper cap to the deposit and was partially replaced from below by hydrothermal sphalerite, galena, and silica. Although Red Dog is hosted by black, organic carbon-rich rocks indicative of anoxic conditions of deposition, the sulfur source for the massive barite has $\delta^{34}S$ values of 16 to 19 per mil, near those of normal mid-Carboniferous seawater sulfate. Disseminated, diagenetic barite precipitated in unlithified shale at the margins of the Red Dog deposit has $\delta^{34}S$ values up to 50 per mil; these values suggest formation from residual pore water sulfate modified by open-system sulfate reduction. In contrast, other zinc-lead massive sulfide deposits of similar age in the district lack barite and have $\delta^{34}S$ values indicative of total reduction of seawater sulfate to sulfide.

Sphalerite and galena in the Red Dog Main deposit generally have $\delta^{34}S$ values of -5 to 5 per mil. Sphalerite that replaces massive barite is isotopically similar to both massive sulfide and sphalerite in footwall veins and reflects a uniform $\delta^{34}S$ value of the hydrothermal fluid. Therefore, replacement of barite proceeded by dissolution and reprecipitation and did not involve direct reduction of barite sulfate to sulfide. The reduced (hydrothermal) sulfur probably formed by water-rock interaction in clastic rocks below the mineralized horizon and was transported to the site of sulfide deposition by the metal-bearing ore fluid. Pyrite is a minor component of the massive ore and formed from isotopically distinct fluids before the majority of zinc-lead mineralization. Paragenetically early disseminated and nodular diagenetic pyrite in the distal portions of the deposit formed by biogenic reduction of pore-water sulfate having $\delta^{34}S$ values as low as -40 per mil, but this source of reduced sulfur was not quantitatively important in the formation of the ore deposit. Pyrite enriched in $\delta^{34}S$ (8–18 per mil) occurs in massive ore, in pyritic silicified shale, and in paragenetically late pyrite veins and probably formed by partial reduction of seawater sulfate.

Geochemistry of Igneous Rocks of the Penokean Orogen: Implications for Metallogeny and Tectonic Setting

K.J. Schulz and P.K. Sims

The Penokean orogen, a major Early Proterozoic tectonic belt along the southern margin of the Archean Superior craton, consists of a northern epicratonic sedimentary and lesser volcanic assemblage overlying an Archean basement and a southern volcanic-plutonic assemblage, termed the Wisconsin magmatic terrane. These two portions of the Penokean orogen are separated by the east-west-trending Niagara fault zone. Recent geochemical studies of igneous rocks in the Penokean orogen provide important new constraints on the geologic and tectonic evolution of the orogen and help establish a basis for predictive metallogeny.

The volcanic rocks of the northern epicratonic assemblage consist of a bimodal tholeiitic basalt and lesser rhyolite suite having chemical characteristics (major and trace elements including rare-earth elements) typical of within-plate, rift-related magma types. The compositional characteristics of the volcanic rocks, coupled with results from recent studies of the sedimentary rocks, support a rifted continental margin history for the northern portion of the Penokean orogen. This interpretation of the tectonic setting provides a new framework for modeling the depositional environment of the region's Superior-type iron formations and the occurrence of local carbonate-hosted copper deposits.

The Wisconsin magmatic terrane consists of widespread island-arc tholeiitic and calc-alkaline sequences ranging in age from 1860 to 1880 Ma and an aerially more restricted calc-alkaline suite that formed between about 1835 and 1845 Ma. Ophiolitic ultramafic and basaltic rocks are found along the Niagara fault zone that forms the boundary (suture zone) between the northern and southern portions of the Penokean orogen. Synvolcanic intrusions within the terrane are dominantly calcic to calc-alkaline. Present data indicate that the Wisconsin magmatic terrane is a composite island-arc system that collided with the continental margin of the Superior province circa 1860 Ma. Base-metal sulfide deposits appear to be restricted to bimodal, calc-alkaline volcanic units that are compositionally distinct from other volcanic units within the terrane. These compositionally distinctive, massive sulfide-hosting volcanic rocks may have formed in a within-arc rift. Their distinctive composition enhances the use of lithogeochemistry in massive sulfide exploration within the Wisconsin magmatic terrane.

Late-orogenic, postorogenic, and younger anorogenic (1760 Ma and 1470–1500 Ma) intrusions and lesser volcanic rocks are locally abundant within the orogen, particularly in the southern portion of the Wisconsin magmatic terrane, and range from alkali-calcic to alkalic in character. Minor molybdenum mineralization is associated with some intrusions while other intrusions have anomalous Sn, Ta, Nb, U, and Th. In particular, a recently discovered 1733-Ma alkali-feldspar granite in the northern portion of the Southern Complex south of Humboldt, Mich., is compositionally similar to rare-metal-rich granites of Nigeria and the Arabian Shield and suggests a possible potential for tin-tungsten (tantalum-niobium) mineralization in upper Michigan.

Manganese Potential of the Cretaceous Rocks Flanking the Sioux Ridge, Minnesota and South Dakota

Dale R. Setterholm and Richard H. Hammond

Cretaceous strata in southwestern Minnesota and eastern South Dakota have lithologic, geochemical, and depositional attributes similar to attributes of strata that host economic deposits of manganese at several localities around the world. Investigations are underway to determine if the conditions described in several depositional models (Cannon and Force, 1983; Frakes and Bolton, 1984; Force and Cannon, 1988), which have been proposed to explain these ores, existed in Minnesota and South Dakota, and if so, whether any anomalous manganese concentrations are present.

The models propose that a dilute ore-forming solution can develop in anoxic portions of stratified seas where iron is removed as pyrite and where manganese concentrates to values up to 500 times those common in normal seawater. If this manganese-rich solution is transported to an oxygenated environment, such as along the margins of a depositional basin, the dissolved manganese precipitates as either an oxide or a carbonate mineral species. Physical processes nearshore may concentrate the manganese-rich material to yet higher grades.

In southwestern Minnesota and in adjoining parts of South Dakota, Upper Cretaceous strata were deposited along the eastern edge of the Western Interior Seaway on a gently sloping surface flanked by the Sioux Ridge. The Sioux Ridge is a quartzite highland that, at times, formed either a peninsula or a group of islands. Rocks of the Dakota Formation, Graneros Shale, Greenhorn Limestone, Carlile Shale, Niobrara Formation, and Pierre Shale define a shelf facies that passes into nearshore facies, such as the Split Rock Creek Formation along the Sioux Ridge paleocoast, and a regionally consistent lithostratigraphic succession of shallow marine and coastal sediments in Minnesota. Although decidedly more clastic, the Minnesota rocks correlate well with parts of the established Upper Cretaceous shelf sequence in South Dakota.

Two key components of the manganese depositional models have been observed in the study area. First, high manganese-low iron anomalies, although subeconomic, have been observed at several places in rocks deposited on an open shelf environment. These anomalies demonstrate that ore-producing solutions may have been present periodically in the seaway and that at times, the solutions flowed onto the eastern shelf. Second, strata reflecting cyclic oxic-anoxic conditions have been observed in both the nearshore facies and the shelf facies. The presence of these strata implies that anoxic flowpaths existed between anoxic parts of the basin, where manganese-rich solutions may have formed, and nearshore sites where oxic conditions favorable for ore formation existed.

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Volcanogenic Massive Sulfide Deposits in Pre-Tertiary Island Arc and Ocean Basin Environments in Nevada

Maureen G. Sherlock

Volcanogenic massive sulfides are mineral deposit types that are inferred to be associated with the development of ancient volcanic arcs or with rift systems in a mostly submarine environment and that formed at or near the site of active volcanic and hydrothermal activity. The general type of massive sulfide deposit is described as a stratabound (stratiform), lenticular accumulation of massive pyrite that has copper-, zinc-, and lead-bearing sulfide ore minerals; sulfide content characteristically amounts to greater than 60 percent, and chalcopyrite, sphalerite, and galena are the primary ore minerals.

Nevada contains many rock types that host volcanogenic massive sulfide deposits, and a map and correlation chart have been constructed to delineate lithologies permissive for the occurrence of these deposits. Descriptions of mineral-deposit occurrences in Nevada have been examined, and those meeting the definitions of massive sulfide deposits are shown on the map. The permissive massive sulfide-bearing units are grouped into the lithotectonic terranes as defined by Silberling and others (1987). Rock types that have an inferred depositional environment known to host the three main types of massive sulfide deposits are common throughout most of northern and western Nevada, relatively well exposed, and locally well studied in Nevada. Several prospects and a few scattered occurrences of mineralization suggestive of stringer mineralization commonly underlying massive sulfide deposits occur. Only two volcanogenic massive sulfide type deposits have been mined in Nevada.

The Rio Tinto and the Big Mike massive sulfide deposits occur in Paleozoic terranes, characterized by lithologies that are thought to originate as back-arc-basin or oceanic-basin accumulations. Small prospects in western Nevada interpreted to be volcanogenic massive sulfide deposits are in terranes that contain pre-Tertiary, predominantly Mesozoic, volcanic island-arc rocks. The Rio Tinto deposit (9.7 percent copper, 0.0057 oz/t gold) is classified as a Besshi-type massive sulfide deposit. The Big Mike deposit (10.5 percent copper) is classified as a Cyprus-type massive sulfide deposit. Small prospects (generally a few percent copper and ranging widely in gold grade) in the western terranes are classified as kuroko-type massive sulfide deposits. Other massive sulfide deposits may not be recognized as such because of the overprint of intense hydrothermal mineralization of Tertiary age.

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Characteristics and Geochemistry of Gold Deposits in Northern Sonora, Mexico

Miles L. Silberman and David A. Giles

Northern Sonora, Mexico, typical of the southern Basin and Range physiographic province, is characterized by elongate, northwest-trending ranges separated by wide alluviated valleys. Basement rocks, consisting of Precambrian gneisses, metamorphosed andesites, and granites, are overlain by younger Proterozoic quartzites and limestones, Paleozoic carbonate rocks, and Mesozoic volcanic, clastic, and carbonate sedimentary rocks. Pre-Laramide Mesozoic plutonic and volcanic rocks and post-Laramide Tertiary extrusive and intrusive rocks, related to volcanic activity of the Sierra Madre Occidental, are widely distributed. Broad areas are underlain by plutonic and associated volcanic rocks of the Sonora-Sinaloa batholith of Cretaceous to early Tertiary (Laramide) age.

Four main types of lode-gold deposits have been recognized in northern Sonora during reconnaissance field investigations (Silberman and others, 1987). Additional detailed field investigations will most likely refine this classification.

(1) *Epithermal quartz veins and hydrothermal breccias.*—Hosted in volcanic rocks, the veins can have strike lengths of several hundred meters. The breccias are related to volcanic domes, some of which are alkalic in composition. The deposits are characterized by elevated contents of Ag and As, moderate Sb, and Cu, Pb, Zn, and Mo. Examples are Tajitos (veins) and Cerro Colorado and Magallanes (breccias related to domes).

(2) *Discontinuous bull quartz veins.*—Thin (centimeter to m wide), discontinuous veins of strike length generally less than several tens of meters occur in volcanic, carbonate, and clastic sedimentary and metamorphic host rocks. They have, in addition to gold, low to moderate silver contents (silver-gold ratio=1–70), variable but generally low arsenic (<30 ppm), and variable but generally low to moderate base metals (copper, lead, and zinc <300 ppm). Examples are the area east of Altar, north of Highway 2, and parts of Banco de Oro.

(3) *Low-angle structurally controlled gold.*—Gold mineralization occurs along or is spatially associated with low-angle shears and faults related to thrusting or detachment faulting. Gold occurs in breccias, in quartz veins, and in quartz vein stockworks along low-angle structures and high-angle splays, or in the hanging-wall or footwall of the structures. Host rocks include Precambrian gneisses and granites, Paleozoic and Mesozoic clastic sedimentary and volcanic rocks, Mesozoic granitic rocks, and Tertiary volcanic rocks.

The structurally controlled category includes several deposit varieties. Distinctions can be made on the basis of the types of host lithologies involved, the physical nature of the low-angle structures, and the spatial relations of gold mineralization and its characteristics to the low-angle structures.

The geochemistry of these prospects is quite variable. Gold is usually associated with elevated contents of Ag, Pb, Zn, Cu, and, frequently, Ba and Mn. In general, lead content is greater than zinc or copper, but copper-dominated examples occur. Many of the prospects have elevated arsenic (>100 ppm). Antimony is more variable but still can be elevated (>20 ppm). Boron is strongly anomalous in a few prospects. Gold is most frequently associated with high lead and arsenic. Examples are Quitovac, La Cienega, Lluvia de Oro, San Francisco mine at Llano, La Choya, part of Banco de Oro, Las Laminas, and La Herradura.

(4) *Carbonate sedimentary-hosted disseminated gold.*— This "Carlin-type" gold mineralization is in carbonaceous, silty, carbonate rocks and associated jasperoids and breccias. Significant gold mineralization at the Amelia prospect east of Magdalena de Kino is in a Cretaceous(?) carbonate sequence. The trace element suite Au, Ag, As, Sb, and Ba is similar to that found in similar deposits in the Western United States and reflects the geologic similarity of the Basin and Range province in Sonora with that in Nevada.

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Proterozoic Anorogenic Granite-Rhyolite Terranes in the Midcontinental United States—Possible Hosts for Cu-, Au-, Ag-, U-, and REE-Bearing Iron-Oxide Deposits Similar to the Olympic Dam Orebody

P.K. Sims, K.J. Schulz, and Eva B. Kisvarsanyi

The Olympic Dam orebody is the largest and most valuable of several iron-oxide-rich deposits on the Stuart shelf in South Australia. Its copper content ranks with that of Chuquicamata, and its uranium content constitutes about 10 percent of the world's estimated uranium resources. It contains about 1.2×10^6 kg of gold, 7×10^6 kg of silver, and about 0.15 percent rare-earth elements (REE's). By any standard, it is one of the world's largest orebodies.

It has been suggested that the Olympic Dam orebody is a variant of a class of iron-oxide-rich deposits that includes the deposits of Kirunavaara, Sweden, and southeastern Missouri. These deposits are characterized by large tonnages of iron ore (magnetite and (or) hematite), ubiquitous apatite, local carbonate, and anomalous abundances of barium, fluorine, uranium, thorium, and REE. Contents of metals other than iron are extremely variable. The deposits occur in a continental setting, have a close spatial and temporal association with anorogenic (A-type) granite and rhyolite, and at the orebody scale are enclosed in brecciated wall rock. Their ages cluster at about 1.4 to 1.7 Ga.

Because of the extensive Proterozoic anorogenic terranes in the midcontinental United States and the several known iron-oxide orebodies in southeastern Missouri, the 1.48-Ga St. Francois terrane, in particular, and other terranes of both older and younger ages merit consideration as possible exploration targets for mineral deposits similar to the Olympic Dam deposit. The anorogenic terranes are the (1) 1.83-Ga granite-rhyolite suite in central Wisconsin, (2) 1.76-Ga granite-rhyolite terrane in southern Wisconsin, (3) 1.48-Ga St. Francois terrane in southeastern Missouri, and (4) 1.35- to 1.40-Ga Spavinaw terrane in southern Missouri, southern Kansas, and northern Oklahoma. Mesozonal anorogenic granite bodies (1.35–1.50 Ga), which are possible deeper seated intrusions related to the high-level granite and rhyolite, are widely scattered within a northeast-trending belt that traverses the midcontinent region. The dominant rock types in all the bodies are potassium-rich, alkali feldspar granite and associated ash-flow tuffs. These rocks contain anomalous amounts of the same lithophyllic minor elements present in the iron orebodies. The anorogenic rocks have been interpreted as partial melts of older (1.7–1.9 Ga) calc-alkaline crustal rocks that experienced one or more episodes of partial melting during earlier orogenic activity. The anorogenic rocks are believed to have formed in an extensional environment and could have had associated evolved, oxidized iron-rich hydrothermal systems capable of generating metal deposits similar to that at Olympic Dam.

Alteration patterns can be a guide to mineral deposits. In the St. Francois Mountains, propylitic alteration of the country rocks is apparently spatially associated with iron orebodies. The alteration of primary biotite and hornblende to hematite and magnetite could be related to hydrothermal activity associated with the ore-forming process.

Potential for Epigenetic Gold and Sedex-type Pb-Zn-Ag-Ba Deposits in the Taconic Allochthons, Eastern New York and Western Vermont

John F. Slack and Kenneth C. Watts, Jr.

Geologically based ore deposit models, supported by mineral occurrences and geochemical data, suggest a potential for epigenetic gold and sedimentary exhalative (sedex) type Pb-Zn-Ag-Ba deposits in the Taconic Allochthons of eastern New York and western Vermont. The Taconic Allochthons consist of a largely metasedimentary slope-rise sequence of late Proterozoic through Middle Ordovician age. Principal lithologies are slate and graywacke; some sequences contain minor intercalated carbonate, quartzite, and (or) chert. The slates include red, green, purple, and black varieties; the black slates are carbonaceous and commonly sulfidic. These rocks are deformed by complex folds and many thrust faults and are metamorphosed to the lower greenschist facies. Posttectonic, high-angle extensional faults of Mesozoic age occur locally, some of which are filled by mafic dikes.

The best potential for stratabound Pb-Zn-Ag-Ba deposits exists at two stratigraphic levels in rocks of the Giddings Brook tectonic slice within the structurally (and topographically) low Taconics. Several lines of evidence indicate a sedex potential within the Early Cambrian Browns Pond Formation (=Nassau Formation). This evidence includes (1) a small stratabound lead-zinc deposit within the Mudd Pond Quartzite Member near White Creek, N.Y.; (2) widespread products of syndepositional faulting, including intraformational conglomerates that locally contain clasts of massive pyritic sulfide; and (3) significant geochemical anomalies in panned heavy-mineral concentrates of stream sediments from outcrop areas of the Browns Pond Formation. The second potential is assigned to the cherts and black slates that constitute the Middle Ordovician Mt. Merino Formation (also within the Giddings Brook slice). The Mt. Merino is a time-stratigraphic equivalent of the Beauceville Formation in southeastern Quebec. The Beauceville hosts the stratiform Champagne deposit, a pyrite- and pyrrhotite-rich massive sulfide body that contains significant Au, Ag, Zn, Pb, and minor Cu. The overall sedex potential of the Taconic Allochthons is further supported by comparison with the geology and ore deposits of the Selwyn basin in the Yukon-Northwest Territories, the Meggen-Rammelsberg region of West Germany, and the black shale mineral belt in central Idaho.

Geochemical data obtained from panned concentrates include elevated values for Pb (to 10,000 ppm), Cu (to 7,000 ppm), Ba (to >10,000 ppm), Zn (to 1,000 ppm), Sn (to >2,000 ppm), and Mn (to 7,000 ppm) in many samples, and concentrations of Ag, Au, As, Be, Bi, Sb, Co, and Mo in some samples. Map plots of these element distributions show that drainages containing anomalous Ba, Zn, Sn, Ag, Au, As, Bi, and Sb are largely restricted to the Giddings Brook slice in the low Taconics, whereas elevated values for cobalt and arsenic are more widespread in the high Taconics (Dorset Mountain slice); anomalous lead and copper occur in both the low and high Taconics. Barite, celestite, and fluorapatite have been identified in the concentrates, but the mineralogic host of the tin, which is currently being investigated, is still uncertain. In preliminary microscope scans, cassiterite appears to be absent, and tin could be present in stannite or other sulfosalt minerals.

The gold anomalies may have sources in disseminated and (or) epigenetic vein mineralization. The anomaly pattern for gold is scattered and erratic, which is partly a function of limited sampling and poor analytical precision and partly a reflection of the discrete distribution of bedrock source(s). Significantly, rocks in part coeval with those of the low Taconics in southeastern Quebec (Ordovician Magog Group) contain local concentrations of gold in black slates (such as at Ruisseau Castle and Rapides du Diable). Comparable geologic settings are found in the Jeseniky Mountains of the Bohemian Massif in Czechoslovakia and in the black shale belt of central Idaho. In the Bohemian Massif, significant gold is known in veinlet and stockwork deposits within complexly deformed black slates; these deposits also contain anomalous tin. In central Idaho, gold occurs locally in high-grade lead-silver vein deposits that have concentrations of Cu, Sb, As, and Sn. Favorable areas for the occurrence of these types of epigenetic gold deposits in the Taconic Allochthons are along and near Ordovician thrust faults and at the intersection of these thrust faults and high-angle Mesozoic faults.

Application of Developing Technology in Airborne Geophysics, Effie-Coon Lake Complex, Minnesota

Bruce D. Smith, V.F. Labson, Robert E. Bracken, Robert J. Bisdorf, Viki Bankey, Robert P. Kucks, Robert J. Horton, Michael G. Medberry, Jay A. Sampson, and J.L. Plesha

A program to improve airborne geophysical data acquisition and interpretation has been implemented by the U.S. Geological Survey (USGS). The Effie-Coon Lake area is one of four areas chosen to test new geophysical methods to map geologic features favorable for buried mineral deposits. Airborne geophysical applications are particularly important because glacial and Quaternary sediments cover 95 percent of the bedrock in the area. This presentation describes preliminary results from a new magnetic data acquisition system and from two new airborne electromagnetic (EM) systems.

The Effie-Coon Lake study area, located in north-central Minnesota, is a 2.7-Ga Precambrian terrain and consists of the Effie granitic intrusive complex and the Zeisser's Island zoned intrusive body surrounded by metasediments and metavolcanics. The zoned intrusive body thought, from limited outcrops and shallow drilling, to be mainly quartz monzonite is defined mostly from aeromagnetic data. A northwest-southeast-trending 2.1-Ga mafic dike system, interpreted from aeromagnetic maps, intrudes the metamorphic sequences and intrusive complexes. Several types of mineral deposits could be present in the area including base-metal, gold, and platinum group element deposits. Advanced airborne geophysical methods are needed to identify subtle geologic features favorable for buried mineral deposits.

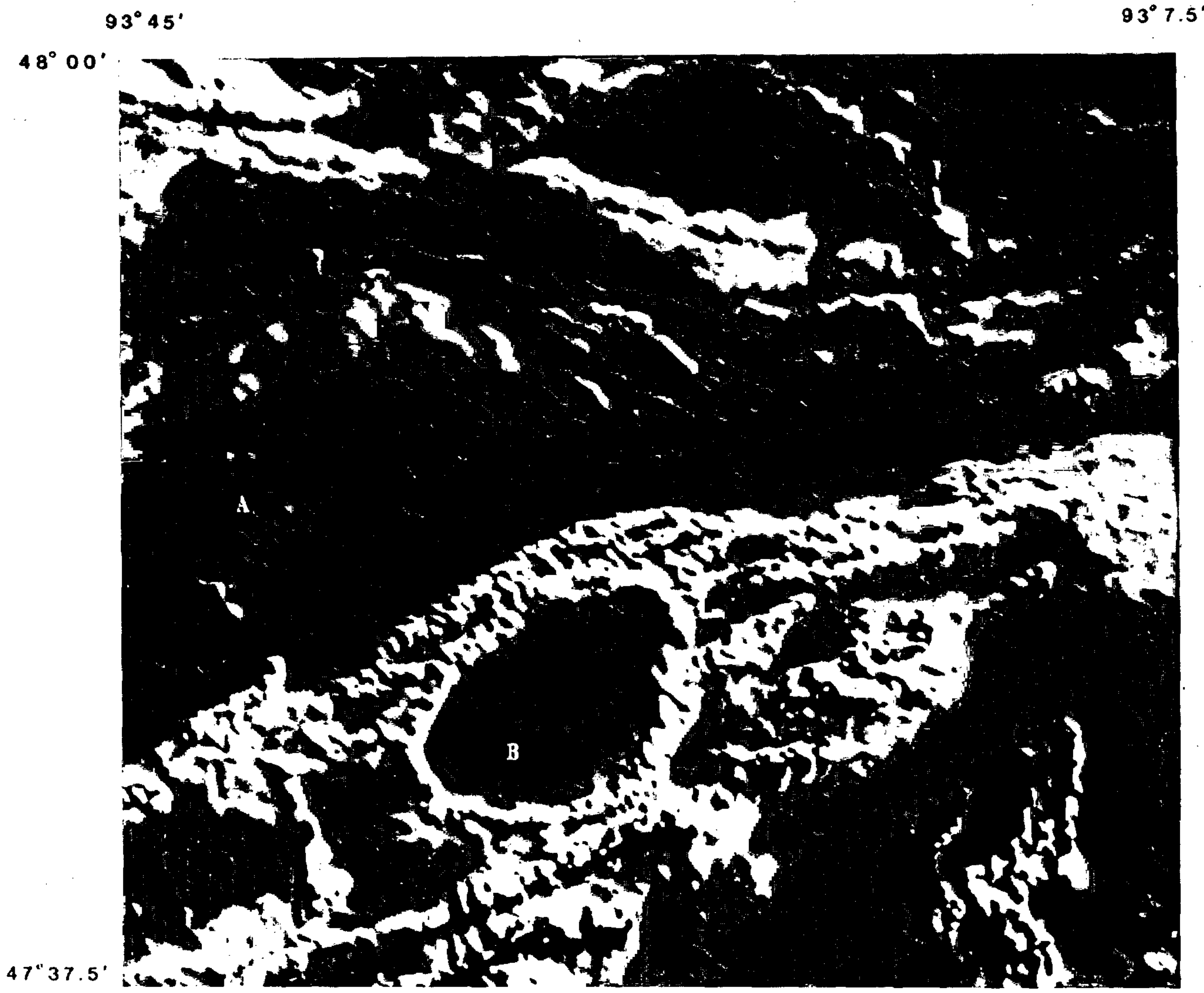

Figure 1. Aeromagnetic signatures of two intrusive complexes, north-central Minnesota. The gray-scale-shaded relief map shows magnetic field highs as light areas and lows as dark areas. Shading has been produced mathematically by simulated illumination from the northeast that produces shadows on the southwest side of magnetic highs. The epipluton (A) is a granitic complex having subtle magnetic expression. The Zeisser's Island zoned intrusive body (B) is thought to be a quartz monzanite. Map is approximately 40 by 40 km. [Smith and others abstract]

New airborne magnetic field surveying instrumentation with improved resolution has been tested for geologic mapping applications. The instrument, a ring core flux-gate magnetometer, measures vertical and horizontal components of the Earth's magnetic field. Systems commonly used in airborne surveys measure only the total magnetic field. Additional high precision data from component measurements can be used to improve interpretation of the location and magnetization of bedrock features (fig. 1). For example, more detailed interpretation of highly magnetic iron formations and mafic bodies is important in identifying geologic features (host rock, alteration, and structures) that could be associated with gold deposits in the Effie-Coon Lake area.

The two new EM systems may be effective tools for regional and detailed three-dimensional mapping of electrical resistivity. In general, mapping of electrical properties provides complementary information to aeromagnetic and radiometric surveys. The two EM systems map shallow and deep resistivity variations. The shallow penetrating system, termed VLF for Very Low Frequency, measures EM fields generated by distant Naval communication stations at about 25,000 Hz. Unlike commercial VLF instrumentation, the components measured by the USGS system are used to compute apparent resistivity maps. The deeper penetrating system developed by the USGS measures the effect of magnetic fields generated by power lines at 60, 180, and 300 Hz.

Apparent resistivities computed from the VLF data average 300 to 400 ohm-m; some areas have resistivities as high as 1,000 to 2,000 ohm-m and as low as tens of ohm-m. High resistivities are a guide to locating shallow or exposed resistive bedrock that is helpful in geologic mapping. The Effie complex is characterized by high apparent resistivities (>400 ohm-m) that may help to define the boundaries of the intrusive complex not clearly defined by the gravity or magnetic data. Areas of low resistivities can be attributed to either thick glacial till or conductive shallow bedrock (for example, graphite in metasediments).

The airborne EM instrument that measures magnetic fields generated by power lines has a depth of penetration approximately ten times that of the VLF system. This depth of penetration is deeper than many commercial active source systems. Thus, the system is much more sensitive to variations in bedrock resistivity than the VLF system. The measurements are processed to enhance mapping of conductive bedrock features that may be buried at depths of hundreds of meters. Important conductive bedrock features in the study area are mainly graphitic units in the metasediments. The distribution of these units is useful in understanding bedrock stratigraphy and structure. In addition, some conductive anomalies may indicate massive metallic mineralization.

The VLF and power line EM methods are passive because the instrumentation does not include a transmitter; absence of a transmitter greatly reduces the complexity, weight, and cost of the systems. Successful development and application of methods described in this study are critical steps in the development of electrical methods that can be routinely used to complement other airborne geophysical data such as magnetic and radiometric measurements.

Geology, Geochemistry, and Age of the Gejiu Batholith and Associated Polymetallic Deposits, Southern China

Lawrence W. Snee and Wang Zhifen

The 320-km^2 Gejiu batholith, composed of more than 10 mafic and felsic intrusions, is well known for its large granite-hosted tin deposits but also is mined for Cu, Pb, Zn, W, Bi, Be, F, and S. The batholith is divided into eastern and western parts by the postmineralization, north-trending Gejiu normal fault. Intrusion compositions and mineral deposit types are distinctly different on opposite sides of the fault. Plutons in the west, grouped by age from oldest to youngest, include (1) gabbro, diorite, and monzonite; (2) granodiorite, granite porphyry, and granite; and (3) syenite and nepheline syenite. Lead and zinc are disseminated as galena and sphalerite in many western plutons; tin occurs as disseminated cassiterite in granite porphyry. East of the Gejiu fault, minor exposures of a large, subsurface granite body crop out within Triassic sedimentary rocks. Core drilling indicates that these outcrops represent parts of a continuous, 20-km-long granite pluton of relatively uniform composition but variable texture. Major tin deposits are associated with the numerous cupolas of this pluton and occur in skarn, greisen, and open-space veins.

Preliminary $^{40}Ar/^{39}Ar$ age spectra constrain the age and the duration of tin mineralization and intrusive activity. Diorite in the west is 84.1 ± 0.2 Ma. Granite emplacement and tin mineralization in the east took place between 82.6 ± 0.2 and 80.6 ± 0.1 Ma. Nepheline syenite was intruded in the west at 79.9 ± 0.5 Ma. The age spectra show that tin mineralization and emplacement of associated granites occurred over at least 2 million years and that temporal-spatial relations among the tin-mineralized granites are resolvable. Relative age relations and isotopic data indicate that emplacement of nepheline syenite and formation of associated disseminated galena and sphalerite took place near the end of, or subsequent to, tin mineralization. Thus, because lead-bearing mineral deposits, associated with plutons that are older than the tin-mineralized granites, are also found west of the Gejiu fault, formation of lead deposits was either a multicycle phenomenon or occurred over a longer time period than formation of tin deposits.

Compositional and isotopic data are available for approximately 200 samples of plutonic rocks, altered and unaltered country rocks, and minerals from the Gejiu area. The majority of the granitic rocks are weakly to moderately peraluminous; gabbro, diorite, and syenite are metaluminous. Mafic, intermediate, and syenitic plutons east of the Gejiu fault are not related by simple magmatic processes to granites east and west of the fault. Relative to other Gejiu plutons, granites are variably enriched in rubidium, cesium, tantalum, and uranium and depleted in barium, strontium, and hafnium. Concentrations of Rb, Cs, Ta, U, Hf, and Th are uniform in nongranitic plutons, but strontium and barium decrease with increasing SiO_2. Granites are depleted in light rare-earth elements (LREE) (<200 times chondrite abundance) and enriched in heavy rare-earth elements (HREE) (>20 times chondrite abundance) relative to nongranitic rocks (LREE=200–800 and HREE=5–20 times chondrite abundance). Large europium anomalies are characteristic of granites. Strontium initial ratios for all Gejiu plutons are elevated, but the ratios for western plutons are less than 0.712, whereas the ratios of eastern plutons are greater than 0.716. The strontium isotopic signature and the major and trace element compositions of all plutons were probably derived from a heterogeneous, chemically evolved, continental source.

Granitic plutons associated with Gejiu tin deposits are compositionally distinct from nonproductive granites. Productive granites are characterized by 69 to 75 weight percent SiO_2; Na_2O/K_2O of 0.59 to 0.74; enrichment in Rb (300–1,000 ppm), Cs (10–70 ppm), Ta (3–17 ppm), U (10–60 ppm), F (1,000–4,000 ppm), and Sn (10–30 ppm); and depletion in Ba (<300 ppm), Sr (<300 ppm), and Hf (<7 ppm). Rare-earth-element (REE) patterns of productive granites show relative depletion in LREE (35–110 times chondrite abundance), large europium anomalies, and enrichment in HREE (20–40 times chondrite abundance). REE patterns for biotite from these granites are similar to the REE patterns of the whole rock except that biotite, which forms about 10 modal percent of the rock, is enriched 10 times in total REE; thus, biotite is the principal REE carrier. In contrast, biotite from nonproductive plutons is not the primary REE carrier. The tin content of biotite from plutons that have less than 69 weight percent SiO_2 is less than 32 ppm. In contrast, the tin content of biotite from granites that have more than 69 weight percent SiO_2 is greater than 100 ppm to nearly 700 ppm. However, plutons that have significant tin deposits contain biotite having lower tin contents (that is, nearer 100 ppm).

A possible mechanism for tin mineralization that would account for these chemical characteristics might include (1) a plutonic source region relatively enriched in tin, (2) an evolved granitic magma that concentrated tin, (3) episodic thermal activity that occurred over at least 2 million years, and (4) either a late-stage fluid phase into which tin from the granitic magma was partitioned or a late-stage fluid phase that leached tin from biotite and deposited tin in the altered host rock.

The Tooele 1° × 2° Quadrangle, Western Utah: An Example of a CUSMAP Preassessment Study

Holly J. Stein, Viki Bankey, C.G. Cunningham, David R. Zimbelman, Michael A. Shubat, David W. Brickey, D.L. Campbell, and M.H. Podwysocki

The Tooele 1° × 2° quadrangle in western Utah lies along the eastern margin of the Basin and Range province and contains a wealth of mineral deposits, including the Bingham copper and Mercur gold deposits. It is located north of the Richfield and Delta 1° × 2° quadrangles, which represent completed and in progress CUSMAP (Conterminous United States Mineral Assessment Program) quadrangles, respectively. The eastern half of the Tooele quadrangle has been the site of continuous, intensive mineral exploration for over a century. The western half of the quadrangle is covered largely by the Great Salt Lake Desert, and this area offers an excellent opportunity to test new methods for evaluating mineral potential in concealed geologic terranes. A preassessment of the status of geologic, geochemical, geophysical, remote sensing, and mineral resource information for the Tooele quadrangle was conducted by a team of U.S. Geological Survey and Utah Geological and Mineral Survey geologists. As part of our preassessment, more than 40 persons from academia, industry, and Federal and State surveys, who are working in or have geologic knowledge of the Tooele quadrangle, were contacted.

Results of the Tooele CUSMAP preassessment study include

(1) Geologically favorable indicators for gold-bearing skarns resembling those at Carr Fork were recognized throughout much of the quadrangle.

(2) A preliminary model was developed for the occurrence of deposits of scandium, a strategic and critical commodity. Ore deposit models for scandium need further development.

(3) Variations in previously established mineral trends were recognized. For example, the Oquirrh-Uinta mineral belt may end at Bingham or, alternatively, may extend through the Dugway district to Gold Hill at the southwest corner of the Tooele quadrangle. The Oquirrh Mountains may represent a mineral belt that extends south from the North Oquirrh mineral occurrences through the Barney's Canyon, Bingham, Stockton, Ophir, and Mercur deposits to the rich base- and precious-metal deposits of the North, Main, and East Tintic districts in the East Tintic Mountains.

(4) Porphyry-related ore systems are exposed at generally high levels. Surface exposures that intersect high levels of economically productive porphyry systems are generally characterized by a lack of significant igneous rock outcrop and an enrichment in elements that concentrate at the margins and tops of large, ore-bearing systems. This observation suggests that additional porphyry-related deposit types may be present at shallow depths.

(5) A structurally complex, concealed terrane beneath the Great Salt Lake Desert that has potential for Spor Mountain-type beryllium-fluorine-uranium deposits was recognized. Geophysical gravity and aeromagnetic data have targeted a buried, northwest-trending, grabenlike structure beneath the Great Salt Lake Desert that intersects Spor Mountain-type deposits in the Delta 1° × 2° quadrangle to the south. Topaz rhyolites, which are associated with Spor Mountain-type mineral deposits in the Delta quadrangle, are present in small quantities along the margins of this proposed graben in the Tooele quadrangle.

(6) The quadrangle has high potential for nonmetallic mineral deposits, especially salt, brine, sand and gravel, and geothermal resources.

A new CUSMAP study of the Tooele quadrangle would offer benefits to Federal, State, and local agencies, industry, and academia. Information from a new study would assist mineral exploration and define the mineral resource potential of the region.

Mosaic Faulting as a Guide to Mineral Exploration in the Richfield 1° × 2° Quadrangle, Western Utah

Thomas A. Steven

A complex network of faults in the Richfield 1° × 2° quadrangle of western Utah not only divides the area into fault-block mountains and basins typical of the Basin and Range and High Plateaus provinces, but also breaks the larger blocks into numerous smaller structural units. Over most of the area, a network of north-northwest- and north-northeast-trending faults of late Cenozoic age and basin-and-range orogenic affinity creates a rhombic to linear fracture pattern reflected in the modern topography. Local areas showing distinctly different fracture patterns occur within the more closely restricted east-northeast-trending Pioche-Marysvale mineral belt that includes most of the igneous intrusions and virtually all of the known igneous-related ore deposits in the quadrangle. In general, these fracture patterns are mosaic but exhibit numerous local variations. In many places these mosaic patterns can be dated as having formed in Miocene time; locally they are closely associated with mineralized or altered rocks.

The areas of mosaic faulting correspond spatially to areas interpreted as being underlain by early Miocene igneous centers, and the mosaic faulting is interpreted to have formed above rising bodies of coeval magma. Small cylindrical intrusive bodies are believed to underlie areas that show crudely radial and concentric fracture patterns. Moderately sized, elongate intrusive bodies are reflected by box or ladder mosaic patterns that consist of rectilinear groups of longitudinal and transverse fractures. Equally important, no fractures exist in areas where intrusions are widely exposed. Some mosaic fault patterns closely reflect known mineralized areas, and others include areas believed to have good exploration potential.

Separating mosaic fault patterns from coexisting fault patterns of different origins can be likened to producing many kinds of residual maps. Reasonably detailed geologic maps are essential, and a detailed knowledge of local geology is extremely important. Experimentation using both logical analysis and subjective imagination is required. Visual representations seem more valuable than statistical summaries in recognizing many fault patterns.

Three-Dimensional Characterization of Regional Structures Using an Advanced Geographic Information System

D.B. Stewart, B.E. Wright, J.D. Unger, J.D. Phillips, and L.H. Liberty

Exceptionally detailed images of geologic structures in the upper 10 km of the Earth's crust can be obtained by using three-dimensional geographic information systems (GIS) at the U.S. Geological Survey's GIS laboratory in Reston, Va. The GIS is accessed through a network of computers to produce images that are composed of geographic, geologic, and geophysical data. These data sets are mostly independent, and models, such as those developed by using geologic and gravity data, can be tested by comparison with seismic reflection or refraction results. Models that can satisfy all the data sets are quite detailed and have a strong probability of being correct.

Structures readily imaged in the upper 10 km of the crust include large dikes, stocks, and batholiths (with indications of their overall composition); folds to depths of 4 km in pyrrhotite-bearing carbonaceous metapelite; cover-basement relations in the Connecticut Valley-Gaspé synclinorium in Quebec; the Merrimack synclinorium in central Maine; and major thrust and strike-slip faults in the region.

Details of midcrustal features, such as major Taconic thrusts along which the former Iapetus ocean was closed and the Chain Lakes Massif and its cover sequence were emplaced upon North American crust of Grenville age, can be resolved to depths approaching 24 km. The boundaries between other tectonostratigraphic terranes in the northern Appalachians seem to penetrate the entire crust. The Moho at the base of the crust can be readily contoured on the basis of coincident results from seismic reflection and refraction. Taken together, these data sets greatly facilitate description and modeling of the processes that created the Appalachian orogen.

Development of the models has required the assembly of each data set based upon consistent geographic projections and compatible formats. A digital line graph (DLG) attribute code was created to identify the lines and areas of all stratified and plutonic rocks shown on the digitized geologic maps of southeastern Quebec, Maine, and the Gulf of Maine. Each mapped sedimentary or volcanic rock type contains an attribute code for age, lithology, inferred tectonic setting, and formation (member, lentil) name. Each intrusive rock contains an attribute code describing the age, name, composition, and distinctive minerals or textures. Linear geologic features on the map are also assigned DLG codes. The digital data sets are being assembled on CD-ROM disks. Appropriate software also is being included to display selected images. Thus, users will be able to evaluate the basic data used for the models and can view certain selected models by using micro- or minicomputers that support CD–ROM disk drives. Users also will be able to change scales, edit or add new data, and create new models for their specific purposes.

Delta CUSMAP Project: Mineral Assessment in the Tintic-Deep Creek Mineral Belt of the Eastern Great Basin, Utah

Douglas B. Stoeser, Carol N. Gerlitz, Constance J. Nutt, Holly J. Stein, John Hand, Michael A. Shubat, and Judith L. Hannah

The Delta CUSMAP (Conterminous United States Mineral Assessment Program) project is an appraisal of the mineral resource potential of the Delta 1° × 2° quadrangle (lat 39–40° N. and long 112–114° W.) of western Utah. The project began in November 1985 and is scheduled for completion in November 1990.

Most major mineral occurrences and deposits in the quadrangle are associated with Cenozoic magmatism concentrated in the Tintic-Deep Creek mineral belt in the northern part of the quadrangle. The mineral belt, explored for high-grade base- and precious-metal deposits since the late 1800's and for porphyry copper, molybdenum, and gold since the 1950's, contains vein and replacement deposits, jasperoids, and skarns that are being explored and developed for gold. New mining operations are underway in the Tintic and West Tintic districts, and one carbonate-hosted disseminated gold deposit in the Drum Mountains was recently mined out.

Cenozoic igneous rocks in the Delta quadrangle are divided into two groups: precrustal extension (41–31 Ma) and syncrustal extension (21 Ma–present). The older group consists of shoshenitic, andesitic, latitic, dacitic, and rhyolitic volcanic and related intrusive rocks. These rocks are related to poorly understood multiple caldera-forming events within the mineral belt. The younger group is bimodal and consists of rhyolite and basalt to basaltic andesite in the north-central and southeastern part of the quadrangle. Many of the rhyolites are peraluminous and contain topaz.

Preextensional hydrothermal metallic mineral deposits are present in most mountain ranges within the mineral belt, including the important Main Tintic, East and West Tintic, and Detroit (Drum Mountains) mining districts. These deposits include vein and replacement base- and precious-metal deposits, low-grade porphyry copper-molybdenum deposits, and contact metasomatic tungsten-copper-gold deposits. These deposits formed from zoned hydrothermal systems related to granitoid intrusions. Subeconomic copper-molybdenum porphyry deposits may be present in the intrusive core, and zonation outward from the core includes (1) Cu±Au veins, (2) Pb±Ag replacement deposits, and (3) zinc and (or) manganese replacement deposits. Jasperoids (±Au) occur in the two outer zones.

Synextensional mineral deposits include the beryllium-fluorine-uranium deposits at Spor Mountain and other similar but minor occurrences elsewhere in the quadrangle. The Spor Mountain deposits may be related to a larger hydrothermal system associated with evolved granitic intrusions from which other deposit types may have formed.

Bismuth Minerals Associated with Placer Gold, Battle Mountain Mining District, Nevada

Ted G. Theodore, Gerald K. Czamanske, Terry E.C. Keith, and Robert L. Oscarson

Placer gold nuggets collected at Paiute Gulch, in the northern part of the Battle Mountain mining district, Nevada, include several that show gold intergrown with bismuth-bearing phases, including bismutite ($Bi_2(CO_3)O_2$), tellurobismuthite (Bi_2Te_3), and sillenite (γ-Bi_2O_3). Sillenite, an unusual polymorph, which is body-centered cubic and has been reported elsewhere to possibly contain minor silicon, occurs in a wormy myrmekitic or eutectoid-type intergrowth with gold. Electron microprobe analyses show the Battle Mountain sillenite to be relatively homogeneous, to be free of silicon, calcium, and iron, and to contain less than 0.04 weight percent sulfur. The bismutite seems to paragenetically postdate the sillenite.

By using an image-processing system, we determined the areal percentages of the component minerals in the eutectoid-type intergrowth. The overall range for eight areas examined is 34.5 to 46.3 areal percent gold. However, seven of the eight determinations fall in the narrow range of 42.0 to 46.3 areal percent gold; this content corresponds well with the gold content of maldonite (Au_2Bi). The system gold-bismuth shows a peritectic at 373 °C, the upper stability limit for Au_2Bi (Hansen, 1958). Thus, the nugget texture is unlikely to have developed from deposition above 373 °C. This gold-sillenite intergrowth, of maldonite bulk composition, is considered to have resulted from initial crystallization of maldonite at or below 373 °C and perhaps even from a melt (temperatures between 373 and 241 °C). Subsequently, the maldonite is presumed to have broken down to yield the eutectoid-type texture. Barton and Skinner (1979) noted that maldonite becomes unstable with respect to gold and bismuth at approximately 113 °C. Ramdohr (1969) noted that he had never seen maldonite and suspected that myrmekitically intergrown gold and bismuth in an approximate 1 to 1 ratio represents decomposed maldonite. At Paiute Gulch, the bismuth fraction of the intergrowth has been oxidized to sillenite at a temperature less than 113 °C.

Other placer gold nuggets contain abundant, euhedrally terminated quartz crystals draped with gold. At room temperature, fluid inclusions in the quartz are liquid rich and vapor rich, suggesting boiling. Homogenization temperatures of liquid-rich fluid inclusions range from 150 to 355 °C (mean, 265 °C). The lack of fluid inclusions containing daughter minerals suggests that the bulk of the placer gold was not genetically associated with high-temperature saline stages of nearby vein, breccia pipe, and skarn formation. Rather, the nuggets containing bismuth minerals are thought to have been derived from lower temperature stages in gold-bearing skarn that are known to contain significant late-stage bismuth minerals.

Although a gold-bismuth association has been reported previously in the district at the Fortitude gold skarn deposit, this study further confirms a strong association between gold and bismuth. Antweiler and Campbell (1982), Orris and others (1987), and Meinert (1988) have shown that bismuth is a characteristic trace element in many gold-bearing contact metasomatic systems. There are skarns southeast of Paiute Gulch, proximal to the southeastern lobe of a 38-Ma composite tonalite. However, these skarns apparently are high-temperature deposits and show abundant liquid-vapor homogenization of highly saline (30 to 60 weight percent NaCl equivalent) fluid inclusions in the range from 500 to 600 °C. Moreover, these skarns are essentially free of retrograde, hydrosilicate alteration stages and are unmineralized. Some of the more distal skarns, as at the Overlook group of claims, may be likely candidates for lode sources that contributed to the placers at Paiute Gulch. Indeed, some wire gold has been panned from gossans at this locality. Other possible sources for the placer gold may be the quartz stockworks that surround a breccia pipe and the monzogranite at a nearby promontory named Bluff.

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New Tin Deposits in the Amazon Basin, Brazil

C.H. Thorman, L.J. Drew, and M. Drucker

Two new tin deposits, Pitinga and Serrinha, are having a major positive impact on Brazil's tin production. Pitinga, the world's largest tin mine, in the Mapuera district, began production in 1982 and is still in an early stage of development (presently only placer operations). Serrinha, in the well-known Rondônia district, was discovered in 1987 and is a high-grade placer mine.

The Mapuera mineral district, north of Manaus, was established in 1982. A suite of Early to Middle Proterozoic volcanic, intrusive, and sedimentary rocks underlies the district. The intrusive rocks include an older biotite granite suite (about 1800 Ma) and a younger biotite-rapakivi granite suite, including the rocks that host the Pitinga deposit. The Madeira granite (about 1685 Ma) is an alkali feldspar granite and includes a rapakivi granite, an extremely homogeneous biotite granite, and a metasomatic granite. This latter granite forms a narrow band that encompasses the albitized younger tin-bearing apogranite, which hosts the primary Pitinga deposit and is the source of rich alluvial deposits. Ore minerals in the apogranite include cassiterite, zircon, pyrochlore, columbite, tantalite, and xenotime. Pitinga has large reserves of tin (>500,000 metric tons), zirconium, niobium, tantalum, and some rare-earth elements.

The Rondônia tin district, in the western part of the Brazilian Amazon basin, includes many producing and abandoned tin mines. The Rondônia suite of anorogenic plutons, ranging in age from about 1150 to 925 Ma, includes rapakivi to biotite granites (most are chemically evolved) that were emplaced in shallow to subvolcanic settings as circular bodies up to 20 km across. Many of these granites have associated ring fracture systems. The granites intruded a gneissic basement (Xingu complex, >1500 Ma) and formed primary deposits in greisen caps (Santa Barbara), veins adjacent to the plutons (Serra da Onca), veins in the ring fracture systems (Massangana), and explosively brecciated greisenized gneiss (Potosi). The present land surface is probably not much below the Precambrian land surface when the primary deposits were formed, because explosion breccias, ring fractures, and associated volcanic rocks in and near the deposits indicate shallow emplacement (perhaps 2–3 km deep). Rondônian placer deposits are high grade; they include deeply weathered primary deposits as eluvial material and grade outward into colluvial and alluvial material 3 to 4 km downstream.

At Serrinha, an area of about 20 km^2 is being mined by more than 12,000 laborers and about 8,000 to 10,000 metric tons of tin will be produced in 1988. The setting is reminiscent of the 1849 California gold rush placer operations. Quartz-cassiterite veins (3 m wide) and cassiterite boulders weighing up to 20 kg crop out on the discovery hill. A breccia containing cassiterite greisen with topaz matrix underlies a smaller hill. The country rock appears to be entirely basement gneiss and schist (Xingu complex). The deposit at Serrinha occurs on the northern edge of a circular feature 18 to 20 km across and may be part of a large near-surface explosive vein-greisen system like that at Potosi.

The potential for discovery of new tin deposits in the well-known Rondônia district is very high, as indicated by the recent discovery of Serrinha. This is extremely important because production, which began in 1965 in Rondônia, is rapidly declining and because most of the mines in the district are expected to close in 3 to 5 years. The potential for discovery of new deposits in the Mapuera district is less clear because only one deposit has been found. Several factors will slow tin exploration in the near future in the Amazon: the static demand for tin and its probable continued low price; the enormity of the Pitinga deposit, making competition by other companies difficult; and the difficult and expensive exploration logistics in the Amazon.

Geochemistry of Soils in the Carson River Valley, Nevada

Ronald R. Tidball

The Carson River, a major drainage system originating on the eastern flank of the Sierra Nevada near the California-Nevada border, flows east to the Carson sink, a closed basin. The upper half of the drainage system has a sufficient gradient such that coarse-grained alluvial fans are common, and, in part, the river is entrenched through intervening hilly terrain. In the lower half of the valley, the river emerges onto the former shores of Lake Lahontan of Pleistocene age and finally terminates in the lowest depression of the Lahontan lake bed, the Carson sink, where the water either accumulates or evaporates depending on the climatic cycle. Fine-grained lacustrine sediments and sand dunes are common on the higher slopes of the lake bed, and clayey alkali flats are extensive on the lower parts of the sink.

The Carson River valley is the site of a National Water Quality Assessment (NAWQA) study where the relation between the quality of ground water and the solid materials in contact with the water is under investigation by the U.S. Geological Survey in cooperation with the U.S. Fish and Wildlife Service. One phase of the study is the geochemical characterization of the surficial materials (soils) throughout the river valley to show the surface expression of the elements that might impact the ground-water system.

Soil samples collected from 397 sites were analyzed for total amounts of about 40 elements. Because there appear to be two distinct sedimentation provinces, the data were divided into two parts: (1) the upper valley, characterized by bedload type deposits and (2) the lake bed, characterized by fine-grained water-suspended sediments. Element associations were estimated for each area by R-mode factor analysis.

A five-factor model describes the upper valley. The factors include (1) a common association of ferride elements—Ti, Fe, Co, V, Sc, Cr, Y, and others, (2) Pb and Hg, (3) Th and La, (4) Mo, Li, and Se, and (5) Ca, Mg, P, and Sr.

The lake bed area is described by a six-factor model that has similar element associations but differs in detail. The factors include (1) an association of ferride elements, (2) Th, Ce, La, and Nd, (3) Ca, Sr, and Mg, (4) Hg and Pb, (5) Mo, Se, and As, and (6) Na, Li, and Mo.

The results do not identify a mineralization factor in either area. A notable difference between the two areas is the presence of the Na-Li-Mo association in the lake bed that characterizes the widespread alkali flats, which are absent in the upper part of the valley. The Pb-Hg and Hg-Pb factors indicate the same association. Mercury is a well-known environmental contaminant that originated from the gold processing mills, located near Carson City, and lead is an unexpected companion. Samples that have large factor scores in both the upper and lower valleys follow the Carson River drainage, indicating that these elements have been dispersed by the river system.

The lower parts of the Carson sink area are characterized by the Na-Li-Mo and the Ca-Sr-Mg factors, indicating evaporites. The Th-La factor of the upper valley area probably represents a granitic source rock. The similar Th-Ce-La-Nd factor of the lower valley area occurs near a source of young basalt and andesite of Tertiary age. These rocks tend to have a granitic-type composition rather than the ferride that might be expected from such source rocks. The Mo-Se-As factor appears to occur in an evaporite setting but may also reflect sedimentary rocks in some places.

The results indicate that the geochemistry of soils can be related to the source rocks, the depositional environment, and past mining history. The data also serve to guide the initiation of future process-related studies.

Industrial Rock and Mineral Resources of Arizona: A Survey of Resource Problems and Opportunities by the Producers and Users of Resource Information

Edwin W. Tooker and Larry D. Fellows

The Arizona Geological Survey (AZGS) and the U.S. Geological Survey (USGS) cosponsored a workshop, "Industrial rock and mineral resources of Arizona: Problems, opportunities, and recommendations," in Tempe, Ariz., May 17–18, 1988. The objectives of the workshop were to assess the current status of exploration and development of these resources and to look ahead to the potential for expanding this resource base in the State. A group of participants from diverse backgrounds in Federal, State, and Local government, industry, Indian Nations, and academia convened for the following informal discussion sessions: (1) current and emerging problem areas for search and evaluation of Arizona's industrial rock and mineral resources, including expanding sources for data acquisition, effective data management, sources of analytical laboratory and industrial testing facilities, and land access; (2) status of new geotechnical research capabilities to stimulate understanding of environments of deposition and to facilitate exploration and discovery; and (3) specialized user resource data needs from the State legislature, Federal and State land management agencies, the Indian Nations, the mining industry, and municipal government agencies. A final session was devoted to summarizing the main conclusions and presenting program recommendations to the AZGS and USGS. In particular, recommendations were made for better ways to meet specific present and continuing user needs while maintaining an applied and basic research competence within increasing budget constraints.

The workshop proceedings are being prepared for publication and public comment. This poster describes the agenda and presents some of the results of the workshop prior to the publication of the proceeding volume.

$^{40}Ar/^{39}Ar$ Studies of Fluid Inclusions in Vein Quartz from Battle Mountain, Nevada

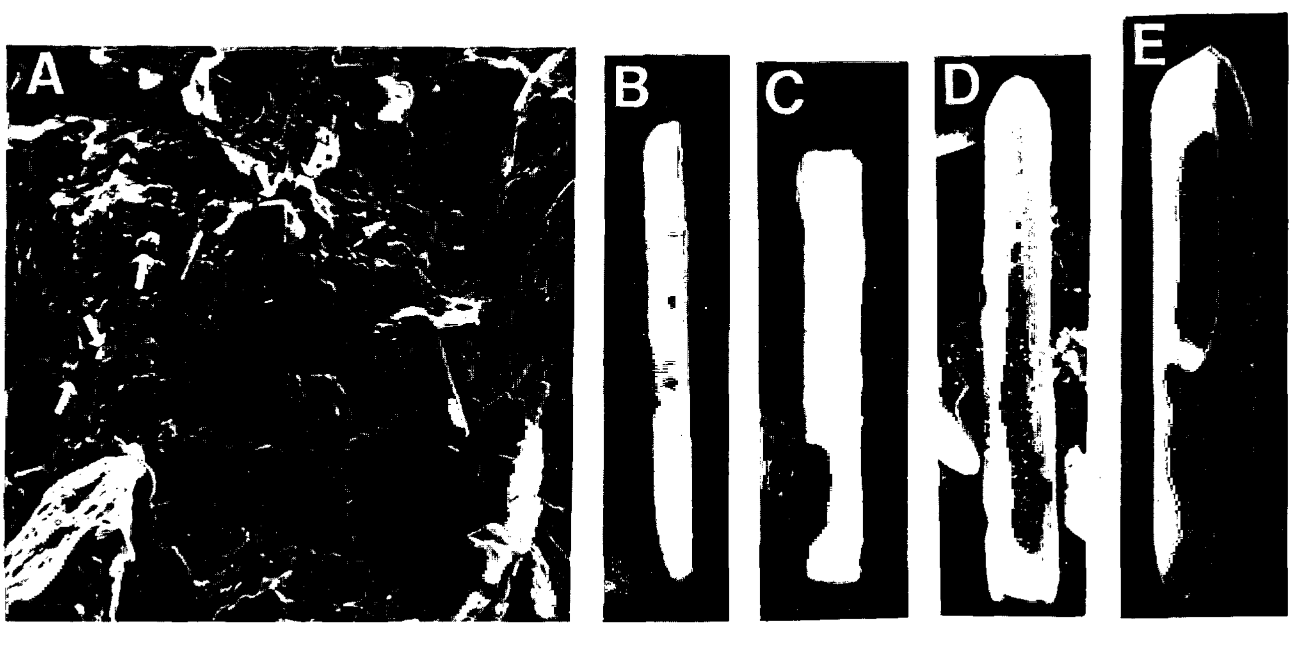
Brent D. Turrin, Edwin H. McKee, Ted G. Theodore, and James E. Conrad

K–Ar and $^{40}Ar/^{39}Ar$ age determinations indicate that igneous activity and associated hydrothermal mineralization at Battle Mountain, Nev., occurred during the Late Cretaceous and in late Eocene to early Oligocene time. Studies were undertaken to evaluate the use of fluid inclusions for determining the age of hydrothermal events. $^{40}Ar/^{39}Ar$ total fusion age determinations were done on fluid inclusion-bearing quartz veins associated with molybdenum mineralization. Ages obtained from these experiments are highly variable and unreproducible and range from about 300 to about 60 Ma. These results led to the initial conclusions that the fluid inclusions contained excess ^{40}Ar and that argon might migrate from fluid inclusions along microfractures. A series of $^{40}Ar/^{39}Ar$ incremental heating experiments were performed on a second split of the quartz samples. The results from these experiments yield argon temperature-release age patterns that suggest the presence of excess ^{40}Ar. Calculated ages are inversely proportional to potassium content, suggesting a constant amount of excess ^{40}Ar within a relatively large population of grains. The ages generally do not correspond to any known igneous or hydrothermal event in the area (Late Cretaceous or late Eocene-early Oligocene). A third split of the quartz samples was analyzed by using a single-crystal laser fusion $^{40}Ar/^{39}Ar$ system. Analyzing single grains (approximately 1 mm^3 or less) approaches analysis of the domain size of paragenetically homogeneous fluid inclusions. These analyses were used to evaluate the homogeneity of the fluid inclusion population. Results are widely variable. There is some clustering of the ages but they do not coincide with any known igneous or mineralizing event. Additional experiments to analyze the argon from fluid inclusions that have a simple, single-stage history are underway. For this purpose, late Eocene fluid inclusion-bearing vein quartz from the northern part of Battle Mountain is used. Variation in argon content in these samples that cannot be accounted for by radioactive decay of potassium since the late Eocene can only be attributed to argon loss (younger ages) or excess argon (older ages).

Silt-size Rutile in Quaternary Sediment of the Gulf of Maine—A Large, Unconventional TiO_2 Resource

Page C. Valentine and Judith A. Commeau

The Gulf of Maine, an embayment of the New England margin, is floored by shallow, glacially scoured basins that are partly filled with Pleistocene and Holocene silt and clay containing 0.7 to 0.8 weight percent TiO_2, chiefly in the form of rutile (and anatase). Eleven basins together are estimated to contain 563×10^6 metric tons (t) TiO_2 (to a depth of 10 m) in the U.S. Exclusive Economic Zone and 169×10^6 t in Canada, on the basis of analyses of surface sediment and of a 22-m core (table 1). The United States annually consumes approximately 1×10^6 mt of TiO_2 (as rutile, leucoxene, ilmenite) of which 75 percent is



Scanning electron photomicrographs of authigenic rutile and anatase crystals. A: Anatase (arrows) and rutile; coarse red sandstone (NS 3–3), Wolfville Formation, Triassic, Minas Basin, near Medford, N. S. B:Rutile; red intertidal mud (NS 1–7) near Blomidon Formation red beds, Triassic, head of St. Mary's Bay, N. S. C: Rutile; dark red intertidal mud (NS 13–3) near Cumberland Group red beds, Carboniferous, Chignecto Bay, near Joggins, N.S. D: Rutile; clayey silt from sea floor at 270 m in central Jordan basin, Gulf of Maine. E: Rutile; Cody Shale (USGS rock standard SCo–1), Upper Cretaceous, Natrona Co., Wyoming. Scale bar = 1 micron. [Valentine and Commeau abstract]

Table 1. Total titanium content of Gulf of Maine basins [Valentine and Commeau abstract]

Basin	Silt and clay weight percent[1]	TiO_2 weight percent[1]	TiO_2 avg; n[2]	Area[3] U.S. (Canada) km^2		Contained TiO_2, ($\times 10^6$ metric tons)[4] U.S. (Canada) 1 m[5]		5 m		10 m	
Jordan	95	0.70	0.74; 32	3,412	(1,750)	10.4	(5.4)	75.4	(38.7)	179.5	(92.1)
Wilkinson-Murray	95	.65	.70; 17	5,103	-	14.5	-	104.6	-	249.2	-
Crowell	60	.70	.83; 5	-	(1,503)	-	(2.9)	-	(20.9)	-	(49.9)
Sharrer-Howell	95	.65	-	834	-	2.4	-	17.1	-	40.7	-
Rodgers	95	.70	-	612	-	1.9	-	13.5	-	32.2	-
Georges	30	.80	.88; 9	103	(1,447)	.1	(1.6)	.8	(11.5)	2.0	(26.9)
Lindenkohl	95	.70	-	444	-	1.4	-	9.8	-	23.4	-
Stellwagen	96–98[6]	0.74–0.83[6]	-	218	-	.7	-	5.2	-	13.0	-
Truxton	95	.70	.78; 3	238	-	.7	-	5.2	-	12.5	-
Ammen	95	.70	.76; 3	119	-	.4	-	2.6	-	6.3	-
Davis	95	.70	-	88	-	.3	-	1.9	-	4.6	-
					Total	32.8	(9.9)	236.1	(71.1)	563.4	(168.9)

[1] Silt+clay and TiO_2 weight percent values used in calculations. TiO_2 values for unsampled basins are based on data from adjacent basins.
[2] Average weight percent TiO_2 in n surface samples from basin; n, number of samples.
[3] Basin area boundary is 200-m isobath except for Stellwagen basin (80-m isobath) and for Georges basin (300-m isobath).
[4] Based on weight percent silt+clay (and its contained TiO_2) values in surface sediment that are assumed to be constant with depth (except for Stellwagen basin) and on bulk density values of Wilkinson basin cores and of core KN 10–1 (Stellwagen basin) that vary with depth.
[5] Deposit thickness.
[6] Values vary with depth.

imported. The inferred amount of TiO_2 in the basins is large, and the unconsolidated deposits lie in shallow water (<300 m) and are relatively near the coast. No attempt has been made to beneficiate the fine-grained ore.

The Bay of Fundy and surrounding region of New Brunswick and Nova Scotia are underlain by Carboniferous and Triassic basins that contain extensive exposures of red and gray clastic sedimentary rocks. These relatively soft rocks are a major present and Wisconsinan source of the fine-grained sediment in the Gulf of Maine basins. Silt- and clay-size rutile crystals are present in the Carboniferous and Triassic rocks, in the intertidal mud of the Bay of Fundy, and in the Gulf of Maine water column and bottom sediment. We suggest that the rutile formed authigenically in Bay of Fundy clastic sedimentary rocks after the dissolution of titanium-rich detrital minerals (ilmenite, ilmenomagnetite). Following glacial and postglacial erosion and transport, the rutile was deposited in the gulf basins. Additional sources of fine-grained, authigenic TiO_2 during the Quaternary probably include sedimentary rocks of inferred Triassic age that underlie the Gulf of Maine; Ordovician, Silurian, and Devonian sandstones and shales in northern Maine and northwestern New Brunswick that also may be the source of rutile found in the fine-grained Presumpscot Formation of southern Maine; and reworked, coarse glacial debris (from all the foregoing sources) that is present in the Gulf of Maine, in New England, and in the Bay of Fundy region.

Gulf of Maine mud is comparable in TiO_2 content to typical shale. The Cody Shale (Upper Cretaceous) of Wyoming contains 0.60 weight percent TiO_2, as well as small rutile crystals that resemble those found in Gulf of Maine sediment, in the Presumpscot Formation, and in the Bay of Fundy Carboniferous and Triassic clastics. The sequence of processes that includes authigenesis of TiO_2 in coarse sedimentary rocks (especially arkose and graywacke), followed by erosion, segregation, and deposition (and recycling from shales) provides a model for interpreting the provenance of shales and for predicting and prospecting for unconsolidated deposits of fine-grained rutile.

Plans for Integrated Airborne Geophysical Study of the Geophysics Environmental and Minerals Demonstration Area, South-Central Colorado

Kenneth Watson, D.H. Knepper, R.N. Clark, J.A. Pitkin, V.F. Labson, D.L. Campbell, L.C. Rowan, F.A. Kruse, K. Lee, and E. Livo

The Cripple Creek-Cannon City region of south-central Colorado presents a wide range of geological and environmental problems that can be addressed by using airborne geophysics. The U.S. Geological Survey has recently established the Geophysics Environmental and Minerals (GEM) demonstration test area in Colorado for developing and testing geophysical techniques and data synthesis. The area contains the historic Cripple Creek gold district. The Cripple Creek gold deposits occur in hydrothermally altered Tertiary rocks, a well-exposed section of

Paleozoic sedimentary strata, a variety of Precambrian igneous and metamorphic rocks, gypsum deposits, a producing oil field, major geologic structures of Precambrian to Neogene age, and alkalic and carbonatite rocks. Because of normal faulting during the evolution of the Rio Grande rift zone, the area may have undiscovered mineral deposits on downdropped blocks that are now concealed by Tertiary sedimentary rocks and Quaternary alluvial materials.

Available regional digital data sets covering the western half of the Pueblo 1° × 2° quadrangle will be assembled. These data sets include aeromagnetics, gravity, terrain, NURE (National Uranium Resource Evaluation) 1-mi-spaced gamma-ray spectrometry and a variety of satellite data, including 80-m-resolution Landsat (Multispectral Scanner), 30-m-resolution TM (Thematic Mapper), 1-km-resolution NOAA-AVHRR (Advanced Very High Resolution Radiometer), and 500-m-resolution HCMM (Heat Capacity Mapping Mission). In addition, detailed geologic maps available for the area will be prepared in digital form and integrated into the data base, together with the geochemical data proposed for environmental studies of the historically most active mine areas. Experimental airborne imaging spectrometer (AVIRIS, GERIS) and spectral thermal emission (TIMS) data have also been recently acquired of subareas within the GEM area as part of a cooperative study with NASA and the Center For Study of Earth From Space.

Near-term data acquisition objectives include airborne VLF (Very Low Frequency) and experimental airborne EM using powerline fields, 1/4-mi airborne gamma-ray spectrometry, multispectral-multipolarization synthetic aperture radar, and airborne imaging spectrometry of selected targets within the GEM area. We also have made plans to accelerate acquisition of Digital Elevation Model (DEM) data for several 7 1/2-minute quadrangles to provide complete coverage of the area for data integration and synthesis.

Mineral Resource Assessment of the White Mountains National Recreation Area, East-Central Alaska

Florence R. Weber, Thomas D. Light, Richard B. McCammon, and C. Dean Rinehart

The U.S. Geological Survey, the Alaska Division of Geological and Geophysical Surveys, and the U.S. Bureau of Mines conducted multidisciplinary interagency investigations to evaluate the potential for undiscovered mineral resources in the White Mountains National Recreation Area (WMNRA), east-central Alaska. Research by the U.S. Geological Survey focused on geologic mapping, reconnaissance geochemical and geophysical surveys, and the synthesis of all published information on mineral deposits in the western three-fourths of the WMNRA. The results of these studies are critical to land-use planning decisions by the U.S. Bureau of Land Management.

Table 1. Estimated number of undiscovered mineral resource deposits in the western three-fourths of the WMNRA [Weber and others abstract]

Deposit type	Number of undiscovered deposits	Probability in percent
Placer gold	1 or more	50
	2 or more	25
	3 or more	5
Polymetallic veins	1 or more	50
Tin greisen	1 or more	10
U/Th/REE	1 or more	10
Lode gold	1 or more	10
Sedimentary exhalative lead-zinc	1 or more	10
Tungsten skarn	1 or more	5

The White Mountains National Recreation Area is a part of the Yukon-Tanana Upland. This terrane consists primarily of quartzitic, pelitic, and calcic metasedimentary rocks and lesser metamorphosed mafic and felsic igneous rocks that have been intruded by Mesozoic and Cenozoic granitic rocks and minor amounts of intermediate and mafic rocks. The disruptive structures in the area are major thrust faults and strike-slip faults that are splays of the Tintina fault zone.

We have made probabilistic estimates for the number of undiscovered deposits that occur within the western three-fourths of the WMNRA (table 1). Placer gold, the only commodity in the area that has been produced in significant amounts, ranks highest in probability. It has been recovered from Nome Creek and its tributaries since the turn of the century. The cumulative production to date is estimated to be 29,000 oz.

By using the estimates, we have also estimated the mean undiscovered mineral resource endowment in the area studied for Au, Ag, Pb, Sn, Th, W, Zn, rare-earth oxides, and high-calcium limestone. We do not expect significant undiscovered resources of chromium, asbestos, nickel, or diamonds even though occurrences of these commodities have been reported in or near the study area. The recent report on the occurrence of platinum in gold samples in the nearby Tolovana mining district suggests platinum may be a potential metallic resource.

Structural Control on Epithermal Gold Veins and Breccias in the Mesquite District, Southeastern California

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Gold in the Mesquite district, southeastern California, occurs in fault-related epithermal breccias, veins, and

Open pit at the Mesquite mine, Ariz., goldfields.

fractures that cut Jurassic amphibolite facies orthogneiss and Cretaceous pegmatite. The host gneiss and orebodies are restricted to a block that is bounded on the north and south by westerly striking faults. The northern fault has dextral strike-slip offset of unknown magnitude; the southern fault does not crop out, and its presence is inferred from gravity data. Gold mineralization in this block occurs along three sets of anastomosing high-angle faults and related fractures. Northwesterly striking faults are the dominant set. Westerly striking and northerly striking faults are subordinate; the relative importance of the subordinate fault sets varies among the pits. Movement on the fault sets is broadly coeval because the fault sets are mutually crosscutting. Where preserved, slickensides on the mineralized faults are subhorizontal (0°–15° plunge), and kinematic indicators suggest that at least the northwesterly and westerly striking faults are dextral strike-slip faults. No kinematic information is available on the northerly striking faults.

Gold mineralization along the faults and fractures accompanied the deposition of quartz and carbonate minerals from boiling, dilute fluids at relatively low temperatures (about 225 °C). Multiple episodes of brecciation and fine-scale chalcedonic banding in veins requires that mineralization accompanied repetitive faulting and fracturing. K-Ar dates on sericite suggest a mid-Tertiary age for the deposits. Mid- to late Tertiary clastic rocks containing rare mineralized clasts unconformably overlie the orebodies. Younger, unmineralized, strike- and normal-slip faults, marked by cohesive gouge, breccia, and clay, cut the gneiss and overlying clastic rocks, reactivated some of the mineralized structures, and partially dismembered the orebodies.

The geometrical relations between mineralized faults on all scales and the kinematics of some of the faults indicate that dextral simple shear controlled districtwide vein emplacement. The northwesterly striking mineralized faults are analogous to the Riedel (synthetic) shears, and the northerly striking faults are analogous to the conjugate Riedel (antithetic) shears. The mineralization process was cyclical and was probably linked to episodic slip on the major strike-slip faults. The genesis of epithermal gold veins at Mesquite district is thus apparently related to the mid-Tertiary evolution of Cenozoic strike-slip fault systems in the region.

Geology and Mineral Resources of the Port Moller Region, Western Alaska Peninsula, Aleutian Arc

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Geologic mapping of the Port Moller, Stepovak Bay, and Simeonof Island quadrangles was begun under the auspices of the Alaska Mineral Resource Assessment Program (AMRAP) in 1983. Two important mineral deposits are located in the Port Moller quadrangle; the Pyramid prospect is the largest copper porphyry system in the Aleutian Arc, and the Apollo Mine is the only gold mine to reach production status in the Aleutian Arc.

Geologic studies have shown a number of differences between the Port Moller region and other portions of the Alaska Peninsula. (1) In the Port Moller region, faulting is more prevalent than folding in contrast to elsewhere on the Alaska Peninsula. (2) Mesozoic rocks typical of the Alaska Peninsula are allochthonous and have been thrust from the southeast; rocks of the Port Moller region are autochthonous and have minor thrusting from the northwest. (3) Products of late Tertiary and Quaternary volcanism are more widespread. (4) A terrane boundary juxtaposes the Alaska Peninsula and Chugach tectonostratigraphic terranes. Throughout the south-central portion of the Port Moller quadrangle, late Miocene volcanic rocks are widespread; these rocks are uncommon elsewhere on the Peninsula, presumably due to erosion. South of these rocks on Popof, Unga, and Korovin Islands are extensive exposures of Oligocene volcanic rocks of the Meshik magmatic arc.

We found that the Pyramid prospect is part of a northeast-trending belt of three shallow plutons and has associated hydrothermal alteration typical of porphyry copper systems on the mainland north of Unga Island. We also found a number of other shallow plutons that have similar alteration zones in the Port Moller region; the Kawisgag (Ivanof) prospect is the best known. The Apollo mine, on southeast Unga Island, produced from an epithermal gold vein system localized along a northeast-trending fracture system. Production was 3.3 million grams of gold; the bulk was produced between 1894 and 1906.

Both Popof and southeastern Unga Islands are composed dominantly of volcanic rocks of the Popof volcanic

View looking east of the Stillwater mining companies' platinum operation, Stillwater River Valley, Mont. This is the Nation's only operating platinum deposit.

rocks, a local name informally used for rocks correlated with the Meshik Formation, and sedimentary rocks of the Stepovak Formation. Radiometric dating of the volcanic rocks yields ages of approximately 35 to 30 Ma. On the basis of fossil determinations, the sedimentary rocks are of Oligocene age. Hydrothermal alteration and mineralization is more common in the Popof volcanic rocks of Unga and Popof Islands than in the otherwise similar Meshik volcanic rocks on the mainland. The major difference between the areas may be the presence of Alaska Peninsula terrane rocks beneath the volcanic rocks on the mainland and possible Chugach terrane rocks beneath the volcanic rocks on Unga and Popof Islands. Magma passing through the compositionally and structurally different basement rocks in the two areas should yield hydrothermal fluids of different compositions, which may explain the more abundant mineralization on Unga and Popof Islands.

On the basis of historical records, industry reports to the Aleut Corporation, geologic mapping, and geochemical sampling, 117 mines, prospects, and occurrences have been catalogued in the Port Moller region. Epithermal gold vein systems and porphyry copper-type systems dominate; however, polymetallic vein and disseminated gold occurrences have also been found. In addition to U.S. Geological Survey geologic mapping and geochemical studies, large-scale industry exploration sampling and drilling programs and detailed USGS studies of hydrothermal systems in the area are helping to characterize and model mineralized areas in the region.

Precious-Metal Deposits in the Hailey and Western Idaho Falls 1° × 2° Quadrangles, Idaho

Ronald G. Worl, Earl H. Bennett, Falma J. Moye, and P.K. Link

Field studies in support of the multidisciplinary Hailey Conterminous United States Mineral Assessment Program project show that precious-metal deposits occur in a variety of geologic terranes but that most are spatially related to northeast-trending faults that have probable Eocene displacement.

The western part of the Hailey quadrangle is underlain by the Atlanta lobe of the Cretaceous Idaho batholith. Mineral deposits in this terrane are mainly veins and replacements that are found in faults and shear zones; these deposits contain precious metals and associated base metals. In the northwestern part of the Hailey quadrangle, epithermal precious-metal deposits of the Boise basin district are aligned along the northeast-trending trans-Challis fault system (TCFS).

Within the Idaho batholith southeast of the TCFS, the most important epithermal precious- and base-metal deposits are located along northeast-trending structures parallel to the TCFS. Lesser deposits are located along northwest-trending basin-and-range structures. The association of Eocene rhyolite intrusions with the deposits appears to be important in some mining districts (Boise basin, Dixie, Neal) but not in others (Atlanta, Rocky Bar, Vienna). Numerous previously unmapped Tertiary dike swarms and plutons intrude the Cretaceous batholith in this area. Some of the mineralized shear zones have potential for low-grade disseminated deposits that might be amenable to heap-leaching.

In the eastern part of the Hailey quadrangle and the western part of the Idaho Falls quadrangle, allochthonous Paleozoic metasedimentary rocks are overlain by Eocene volcanic rocks and intruded by cogenetic Eocene plutons and dike swarms. Location of volcanic centers and emplacement of intrusive bodies were controlled by northeast-trending extensional structures. Both volcanic-hosted and sediment-hosted epithermal precious-metal deposits occur in this area. Volcanic-hosted deposits in the Lava Creek, Alder Creek, and Muldoon districts are in Challis Volcanics associated with late-stage rhyolite activity. These deposits are related to hot spring activity at the intersections of northeast- and northwest-trending structures. Potential for sediment-hosted deposits is indicated by anomalous Au, Ag, Sb, As, and Hg in rock, sage, and sediment samples spatially associated with jasperoid bodies located at or near the intersection of these northwest- and northeast-trending structures. Jasperoid bodies in the Timbered Dome, Grouse, Lehman Butte, and Barlett Point areas are replacements of Paleozoic calcareous and carbonaceous sedimentary rocks.

In conclusion, areas having the best potential for undiscovered deposits are along highly sheared zones in Cretaceous and Tertiary intrusive rocks, at intersections of northeast- and northwest-trending systems in Challis volcanic rocks, and where northeast- or northwest-trending faults cut Paleozoic calcareous and carbonaceous sedimentary rocks. The potential is highest in the vicinity of intrusive rhyolites.

As, Bi, Hg, S, Sb, and Te Geochemistry of the J-M Reef: Constraints on the Origin of Platinum Group Element-Enriched Sulfides in Layered Intrusions

M.L. Zientek, T.L. Fries, and R.M. Vian

The J-M Reef is an interval of disseminated sulfides in the Lower Banded series of the Stillwater Complex that is enriched in the platinum group elements (PGE). Palladium and platinum occur in solid solution in base-metal sulfides and as discrete PGE minerals. These PGE minerals include sulfides, tellurides, arsenides, antimonides, bismuthinides, and PGE alloys with Fe, Sn, Hg, and Au.

Disturbed cumulate layering below J-M Reef, Stillwater Complex, Mont. Disturbance possibly is related to the influx of new liquid and subsequent magma mixing that may have triggered the formation of the platinum-bearing zone.

Several subpopulations that have distinctly different compositions based on whole rock compositional data (As, Bi, Cu, Hg, Pd, Pt, S, Sb, Te) can be delineated for samples collected from and adjacent to the J-M Reef. In general, samples from the reef have higher Pt:Cu, Pd:Cu, Pd:Pt, Te:Bi, and S:(Te + Bi) than those samples collected adjacent to the reef. Vertical profiles passing upsection from mineralized to barren rock through the reef suggest that Pd:Cu and Pt:Cu may decrease systematically. Most of the samples that have elevated arsenic, antimony, and tin abundances occur in samples collected adjacent to the reef, not within it, or in sulfide-poor rocks collected on the projection of the strike of higher grade areas of the reef. Te:Bi and As:Sb are controlled by mineralogy of the ores; variations in these ratios indicate that the relative proportions of the PGE minerals also change.

Neither magma-mixing nor fluid-migration models readily explain why the minor quantities of sulfide minerals immediately adjacent to the sulfide-enriched layers that form the J-M Reef have different element ratios than the sulfide minerals that form the reef. If all sulfides formed by exsolution during a magma-mixing event and the modal proportion of sulfide now in the rocks are simply the result of mechanical processes that concentrated the sulfides into some layers and not others, then the composition of the sulfide would not be different. Models that rely upon ascending liquids or fluids are incompatible with the presence of sulfides that are not enriched in PGE immediately below or interlayered with the PGE-enriched sulfide layers. PGE-enriched postcumulus fluids should have reacted to the same extent with sulfides immediately outside the reef as within the reef.

One explanation is that some of the sulfide minerals in the rocks outside the reef have a different origin than those that make up the reef. The sulfides that form the reef may represent "cumulus sulfides" that formed as the result of a magma-mixing event, achieved their high PGE contents at that time, and accumulated to form a layer. The rocks outside the reef may contain a large proportion of "postcumulus sulfides" that formed as the last dregs of intercumulus liquids trapped in the interstitial spaces between the cumulus grains reached sulfur saturation and exsolved a sulfide liquid or precipitated a sulfide mineral. The PGE contents of these sulfides would be expected to be less than the "cumulus sulfides" that form the reef because the "postcumulus sulfides" would have equilibrated with a much smaller volume of silicate liquid. An alternative explanation is that some of the sulfide droplets that formed as a result of the mixing event were trapped as inclusions in silicate minerals soon after formation. Entrapment in silicate minerals would reduce the amount of magma with which these sulfide droplets could equilibrate and effectively reduce their PGE tenor.

Active Deposition of Sediment-Hosted Massive Sulfide in the Escanaba Trough, Gorda Ridge

Robert A. Zierenberg, J.M. Edmond, J.F. Grassle, A.C. Campbell, S.L. Ross, and W.C. Shanks III

By using the submersible ALVIN (fig. 1), active hydrothermal vents have been located and sampled in the sediment-covered Escanaba trough along the spreading axis of the Gorda Ridge, offshore of northern California. The spreading center in the Escanaba trough is covered by up to 500 m of hemipelagic and turbiditic sediment derived from the Columbia River drainage. Volcanic edifices, 1 to 3 km across, rise through and locally breach the sedimentary cover. Two volcanoes at the northern Escanaba (NESCA) and southern Escanaba (SESCA) sites (fig. 2) have been investigated by camera tows and submersible dives, and both have associated large areas of sediment-hosted sulfide mineralization. Several deposits have outcropping sulfide, from 3 to 15 m thick, exposed over traverses exceeding 100 m, although none of the deposits has been fully mapped. The largest observed semicontinuous outcrop of massive sulfide is at least 500 m long and is within hundreds of meters of two other large, but incompletely explored, areas of outcropping massive sulfide. The occurrence of many large deposits in a limited area invites comparison to onland ore deposit districts. Samples recovered in sediment cores and exposures of massive sulfide on scarps indicate that some sulfide is deposited below the sediment-water interface, but the extent of subsurface sulfide is not known.

Redistribution of sediment is common in the area and occurs by mass wasting from sediment scarps formed by tectonic and (or) volcanic uplift of sediment (fig. 3) and by active erosion of sediment on steep to gentle slopes. Erosional channels from 1 to more than 20 m deep, and up

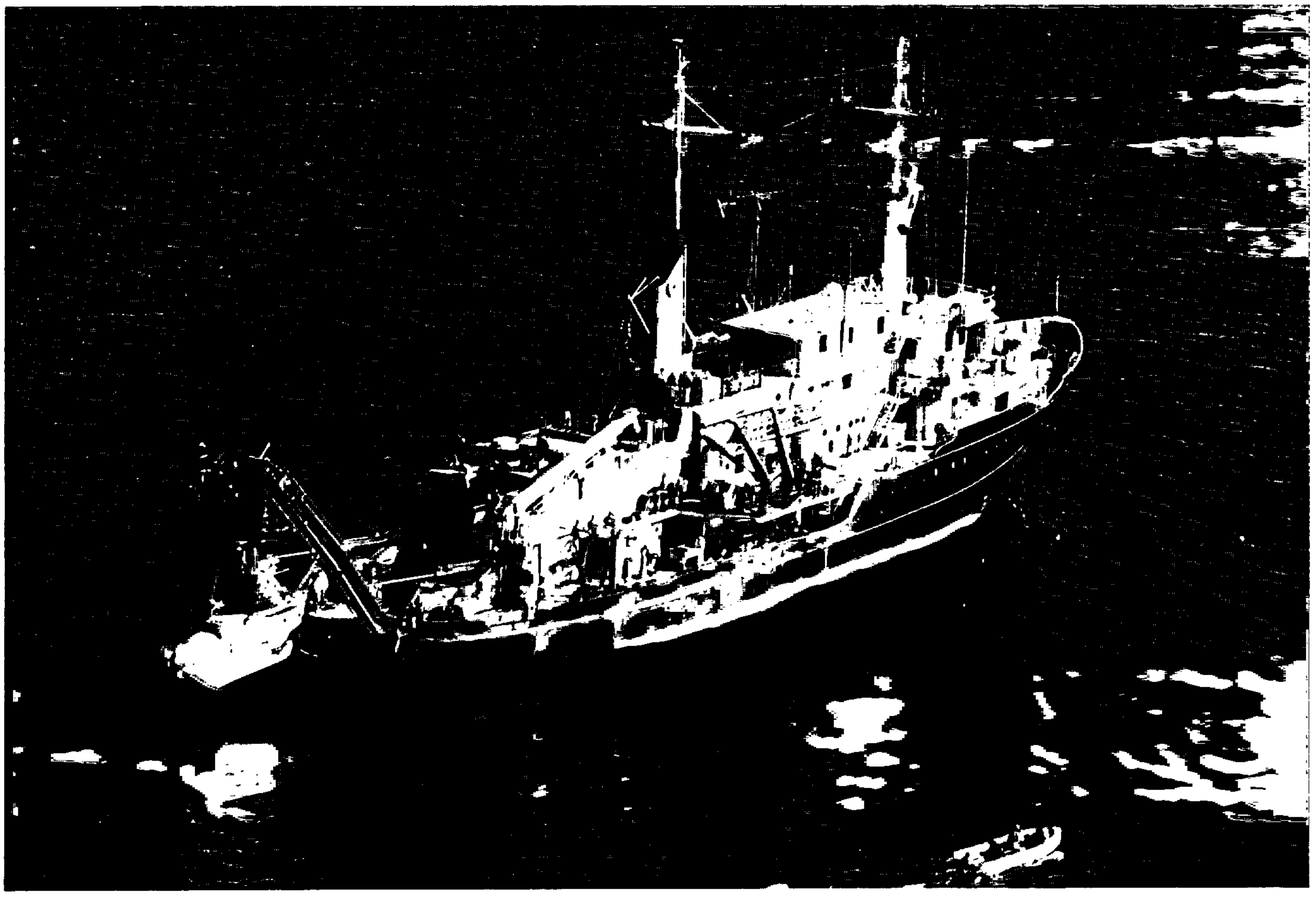

Figure 1. Research vessel ATLANTIS II and the deep submergence vehicle ALVIN, operated by the Woods Hole Oceanographic Institution, Woods Hole, Mass. [Zierenberg and others abstract]

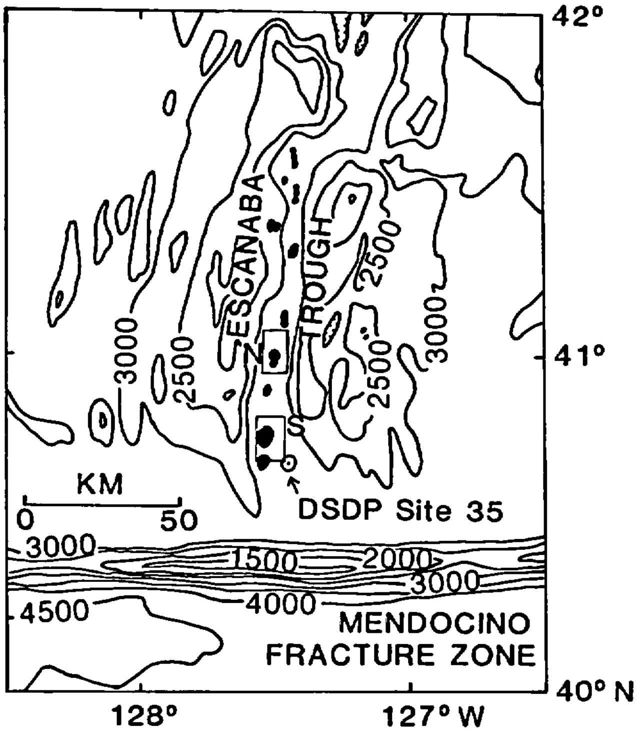

Figure 2. Map of Escanaba trough showing location of the volcanic done complexes. The location of the SESCA (S) and NESCA (N) areas and DSDP site 35 are shown. [Zierenberg and others abstract]

to tens of meters wide, generally expose unlithified sediment, and occasionally massive sulfide, along the steepest walls.

The known sulfide deposits are entirely hosted by sediment. Deposits span the evolutionary range from old oxidizing and eroding deposits to those still actively forming. Pyrrhotite forms the bulk of the deposits and is associated with minor amounts of sphalerite, barite, marcasite, isocubanite, and galena and trace amounts of chalcopyrite, arsenopyrite, loellingite ($FeAs_2$), tennantite-tetrahedrite, and alabandite (MnS). Interaction of the hydrothermal fluid and sediment enriches the deposits in Ag, As, Bi, Pb, Sb, and Sn relative to sulfides formed directly on oceanic basalt. Some samples contain hydrocarbon formed by hydrothermal alteration of organic matter in the sediment.

The ALVIN dives concentrated on the area of the NESCA site (fig. 2) around a volcanic edifice near latitude

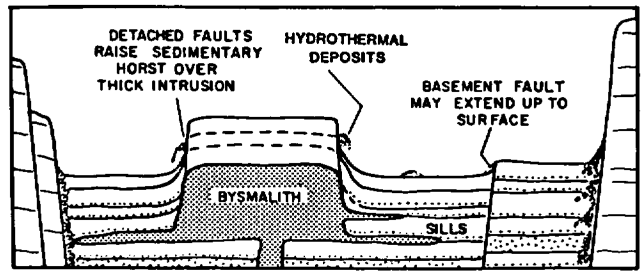

Figure 3. Schematic diagram (adapted from Lonsdale and Lawver, 1980) showing the relation of hydrothermal deposits to the sediment-capped hills and a possible mechanism for uplift of the sediment by intrusion. [Zierenberg and others abstract]

41° N., longitude 127° 29′ W. and provided the first direct observations of active hydrothermal discharge in the Escanaba trough. The active deposits observed are mounds of brecciated and massive pyrrhotite-rich sulfide a few meters to more than 20 m high and tens of meters across, topped by porous chimneys leaking clear hydrothermal fluid. The active chimneys are predominantly anhydrite and barite. The maximum stable temperature measured by using the ALVIN temperature probe was 219 °C. The fluid pH is slightly lower, and the alkalinity is higher than those of seawater; these differences suggest that the clear fluids are evolved hydrothermal fluids that have deposited their dissolved metal load in the subsurface.

Vent specific fauna were observed on several hydrothermal mounds. Thin tube worms that appear similar to those recovered from the Juan de Fuca Ridge are common and are associated with white anemones that have blood-red tentacles. Palm worms found near higher temperature vents are morphologically similar to Juan de Fuca varieties but are green orange rather than purple in color. Small limpets and snails are abundant. Weakly active hydrothermal mounds are covered by bacterial mats. Elongate bivalves up to 20 cm long are locally abundant in sediment-covered areas near hydrothermal deposits.

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Exploratory drilling in the upper part of the Stillwater Complex, Mont.

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View of Mt. Tweto in Colorado, recently named after Ogden Tweto, a U.S. Geological Survey geologist.

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U.S. DEPARTMENT OF THE INTERIOR

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