UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

WORKSHOP ON APPLICATION OF STRUCTURAL GEOLOGY TO MINERAL AND ENERGY RESOURCES OF THE CENTRAL REGION

Edited by

CHARLES H. THORMAN[1]

Open-File Report 90-0508

1990

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

[1]U.S. Geological Survey
Denver, Colorado

INTRODUCTION TO A WORKSHOP ON APPLICATION OF STRUCTURAL GEOLOGY TO MINERAL AND ENERGY RESOURCES OF THE CENTRAL REGION

CHARLES H. THORMAN, Branch of Central Mineral Resources, U.S. Geological Survey, Box 25046 MS 905, Denver, CO 80225

This workshop presents current research by U.S. Geological Survey scientists who are using structural geology in their investigations into the mineral and energy resources of the United States. Figure 1 shows the areal distribution of the 14 papers presented herein; the papers are numbered on figure 1 according to their position in the text of this report and will be referred to herein by those numbers. One of the most important aspects of this workshop is a demonstration of the integrating of many disciplines in unraveling the structural evolution of an area, regardless of scale. The application of structural geology by itself provides only a limited amount of information and leaves many aspects of the evolution of an area unresolved.

The subject matter and scale of the studies presented in the workshop are extremely broad. Four papers (4, 6, 7, 13) integrate geophysical techniques (gravity, seismic, and audio-magnetotelluric) with detailed and regional geology in sedimentary and volcanic terranes, establishing the basis for new approaches to exploration for hydrocarbons and mineral deposits in Arizona, Colorado, Utah, Wyoming, and Montana. Field studies at detailed to regional scale (2, 3, 5, 8, 9, 10, 11, 12, 14) present data that call for moderate to major revision of thinking in areas often thought to be well understood. These investigations emphasize the continuing need to remap so-called well understood areas as well as the need to map those areas having only limited data available. Detailed petrologic studies in Missouri and Arizona (2, 3), of both carbonate and volcanic rocks, have caused us to reconsider our concepts of the origin of well established rock units and thus their implications regarding the structural evolution of those areas. The application of isotopic dating in structurally complex areas has greatly increased our knowledge of the relative timing and duration of events that influenced the migration of mineralizing and hydrocarbon fluids and gases. With a better grasp of the time involved, we are doing a better job of correlating the various deformational and migrational events as presented in papers on eastern Nevada, Utah, and Idaho (9, 10, 12).

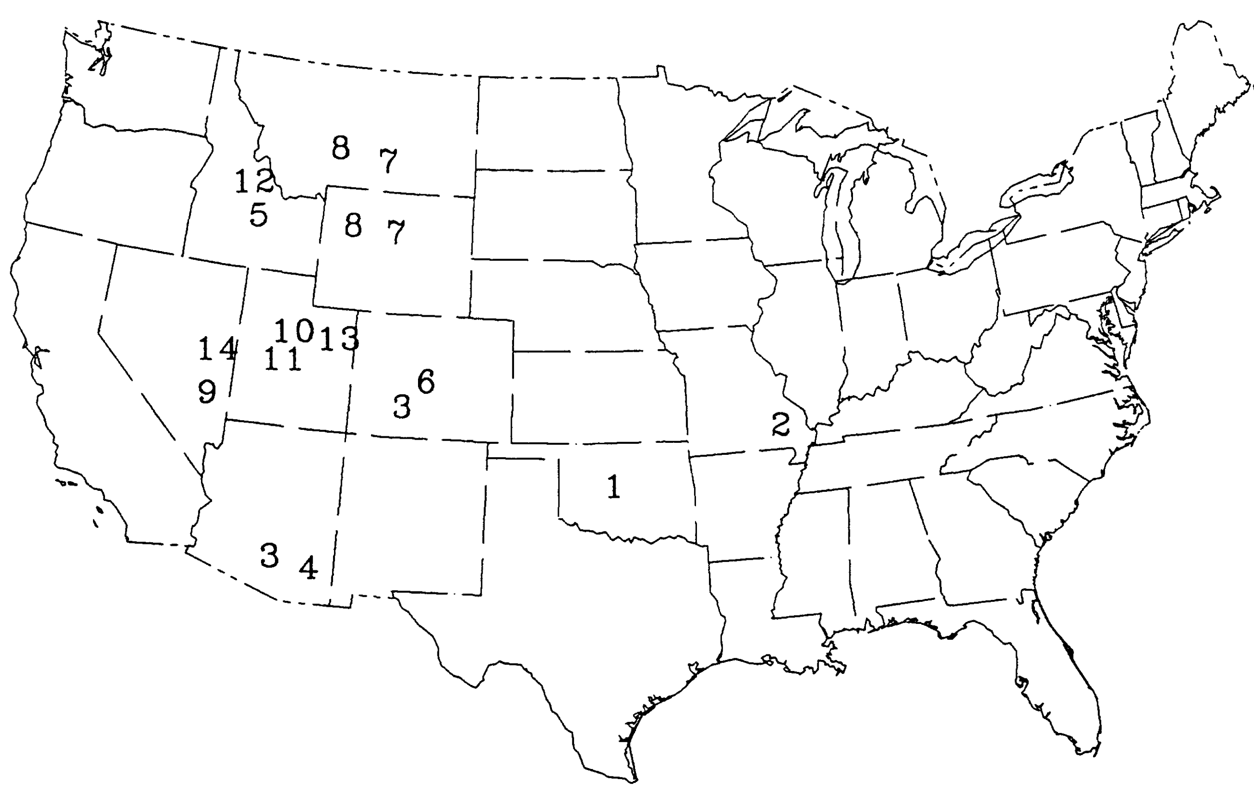


Figure 1. Map showing the location of areas discussed in the workshop. The numbers refer to the papers by the order in which they are listed.

Table 1. Selected thin-section descriptions of microfractures and stylolites in core samples from the Reelfoot rift, Mississippi Embayment, and Ozark uplift structural regimes

[na, not applicable]

Core sample and depth (ft)	Structural setting	Fracture orientation and host rock	Mineral assemblage in fracture	Number of fracture generations	Stylolite orientation	Mineral assemblage in stylolite	Remarks
Dow Wilson 12,633	Reelfoot rift; basal clastics	Normal to bedding; feldspathic arenite	Quartz, siderite, Fe-poor dolomite, Fe-rich dolomite	5	na	na	Incremental cracking and resealing of fractures
Dow Wilson 12,782D	Reelfoot rift; basal clastics	Normal to bedding; quartz arenite	Quartz, Fe-poor dolomite, chlorite, minor pyrite	3-4?	Horizontal to bedding	Minor pyrite, barite, monazite, organic matter	Tension gashes associated with stylolites
Dow Wilson 13,649	Reelfoot rift; basal clastics	Normal to bedding; feldspathic arenite	Dolomite, illitic clay, quartz, hematite	3	Horizontal to bedding	Minor pyrite, monazite, organic matter	Incremental cracking and resealing of fractures
Dow Garrigan 11,420	Reelfoot rift; Bonneterre	Normal to bedding; black shale, siltstone	Quartz, Fe-poor dolomite, Fe-rich dolomite, Fe-rich calcite	4	Horizontal to bedding	Calcium phosphate, illitic clay, minor pyrite	Incremental cracking and resealing of fractures; thrust zone
Dow Garrigan 7,999.9	Reelfoot rift; Bonneterre	Normal to bedding; black shale	Quartz, siderite, Fe-rich dolomite, Fe-rich calcite	4	Horizontal to bedding	Siderite, illitic clay, thorite, sphalerite	Stylolite is zoned, deformed
GP-10 1817.2	Mississippi Embayment; Bonneterre	Normal to bedding; silty dolostone	Marcasite, pyrite, breccia, marcasite	3-4?	Horizontal to bedding	Major marcasite, pyrite, breccia	Tension gashes associated with stylolites; brecciation between periods of sulfide deposition
GP-10 2654.4	Mississippi Embayment; Lamotte SS	Normal to bedding; litharenite	Dolomite	1	Horizontal to bedding	Illitic clay, pyrite, minor stannite	Illitic clay shows horizontal slickensides, demonstrating thrust movement
GP-IO 2671.1	Mississippi Embayment; Lamotte SS	silty limestone/ litharenite	na	na	Horizontal to bedding	Illitic clay, pyrite, minor monazite, barite, Fe-Mn oxides, calcium phosphate	

Table 1 (Continued)

Core sample and depth (ft)	Structural setting	Fracture orientation and host rock	Mineral assemblage in fracture	Number of fracture generations	Stylolite orientation	Mineral assemblage in stylolite	Remarks
Sth2-1 2700	Mississippi Embayment; Lamotte SS	Normal to bedding; quartz arenite	Dolomite, pyrite	2?	na	na	
317A 2474	Mississippi Embayment; Lamotte SS	quartz arenite	na	na	Horizontal to bedding	Illitic clay, pyrite, carbonate, organic matter	Stylolites are zoned--similar to mineral succession in fractures
MT-l 2131	Ozark uplift; Bonneterre	Normal to bedding	Dolomite	1	Horizontal to bedding	Illitic and chloritic? clay, siderite, pyrite, organic matter	Stylolites are zoned; core from SE down-thrown side of fault
B-4 1349	Ozark uplift; Lamotte SS	quartz arenite	na	na	Horizontal to bedding	Major pyrite	Colloform texture of sulfides in stylolite
BCC-4 1284	Ozark uplift; Lamotte SS	quartz arenite	na	na	Horizontal to bedding	Major pyrite	Colloform texture of sulfides in stylolite
BCC-4 1482.5	Ozark uplift; Lamotte SS	quartz arenite	na	na	Horizontal to bedding	Major pyrite	Pyrite brecciated along stylolite
BCC-4 1509.5	Ozark uplift; Lamotte SS	quartz arenite	na	na	Horizontal to bedding	Pyrite	Poikiolitic carbonate enclosing detrital clay and quartz grains indicates a fluctuation in the static water level
63W72 1500	Ozark uplift; Lamotte SS	Normal to bedding; quartz arenite	Barite	1	na	na	Barite shows vertical slickensides; leisengang bands associated with fracture
16-15 917.9	Ozark uplift; Bonneterre	silty limestone	na	na	Horizontal to bedding	Galena, pyrite, chalcopyrite	Deformed galena at upper surface of stylolite

layers may be brecciated because of concurrent precipitation and shear movement along the stylolite; clay layers commonly have slickensides (table 1).

Extensional microfractures that are filled with authigenic minerals including quartz, barite, siderite, dolomite, clay, calcite, and pyrite intersect the stylolites. Structurally controlled fluid flow is indicated by repeated opening and sealing of microfractures by different generations of these minerals. The number of fracture generations is greatest in the Reelfoot rift; they decrease in frequency to the northwest at the edge of the Mississippi Embayment and on to the Ozark uplift (Table 1).

Sulfide mineral deposition in both horizontal stylolites and vertical microfractures throughout the Bonneterre and Lamotte regionally is evidence for ore fluid migration along microstructures. Deformation events are associated with the flow of mineralizing fluids because the microstructures have several generations of authigenic-cement fillings. The localization of epigenetic minerals in microstructures also attests to the fact that the Lamotte was not a homogeneous conduit as it has been envisioned in many models of metals transport.

Map number 3

ASH-FLOW CALDERAS AS STRUCTURAL CONTROLS OF ORE DEPOSITS: RECENT WORK AND FUTURE PROBLEMS

PETER W. LIPMAN, Branch of Igneous and Geothermal Processes, U.S. Geological Survey, Box 25046 MS 903, Denver, Colorado 80225

Recent USGS field, petrologic, geochronologic, and geophysical studies of Oligocene ash-flow calderas and associated igneous rocks in the southern Rocky Mountains and of Mesozoic volcanic systems in southeastern Arizona illustrate the applications of volcanic structural geology to problems of localization of ore deposits and associated hydrothermal systems. Examples include: (1) Mo deposits along the most deeply subsided and recurrently intruded southern margin of the 26-Ma Questa caldera; (2) 25-Ma mineralization along the recurrently faulted Creede graben in the central San Juan Mountains; (3) little-studied hydrothermal alteration south of Creede that defines a coherent pattern related to ring intrusions along the south margin of the newly recognized 27.1-Ma South River caldera; and (4) localization of porphyry Cu mineralization along intrusions related to several Late Cretaceous-early Tertiary calderas in southern Arizona. Caldera structures are common loci for mineralization because they are the near-surface structural expression of crustal magmatic processes involving major petrologic modification of crustal compositions. Misinterpretation of caldera features in complex mineralized terranes has commonly led to inappropriate exploration strategies.

Map number 4

AUDIO-MAGNETOTELLURIC INVESTIGATION AT TURKEY CREEK CALDERA, CHIRICAHUA MOUNTAINS, SOUTHEASTERN ARIZONA

ROBERT M. SENTERFIT and DOUGLAS P. KLEIN, Branch of Geophysics, U.S. Geological Survey, Box 25046 MS 964, Denver, CO 80225

Electromagnetic induction data using distant field sources, mostly of natural origins in the audio-magnetotelluric (AMT) frequency range of 4.5-27,000 hertz (HZ) were analyzed to depict the geoelectric structure of the Turkey Creek volcanic center, an inferred mid-Tertiary rhyolitic caldera located about ten kilometers south of the Chiricahua National Monument in the Chiricahua mountains of southeastern Arizona. The data for each station consist of scalar electromagnetic measurements at discrete frequencies for two-orthogonal magnetic and electric field pairs. Observations were made along profiles across the caldera ring structure and on either side of the structure. The Turkey Creek caldera is about twenty miles in diameter. Thirty-two AMT stations were occupied, with soundings spaced about 0.5 kilometers apart. Observations along the profiles indicate a unit of about 2,500 ohm-meters resistivity which is inferred to represent the monzonite within the mapped caldera ring structure. A unit of similar resistivity is at a depth of about 2,000 meters in the Cretaceous-Precambrian sedimentary rocks surrounding the caldera, and is overlain by a unit of lower resistivity, which probably indicates the Cretaceous sedimentary rocks and weathered near-surface material. High resistivity values were noted for the deeper core intrusion which is mapped in contrast with the lower resistivity tuffs and lavas. The data do not sense high resistivity units associated with inferred ring structures on the north or west flanks of the volcanic center.

Map number 5

MESOZOIC STRUCTURAL CONTROL OF TERTIARY MINERALIZED VEINS IN CHAMPAGNE CREEK AREA, BUTTE COUNTY, IDAHO

BETTY A. SKIPP, Branch of Central Regional Geology, U.S. Geological Survey, Box 25046 MS 913, Denver, CO 80225 and **RONALD G. WORL,** Branch of Western Mineral Resources, U.S. Geological Survey, U.S. Court House, W. 920 Riverside Ave., Spokane, WA 99201

The Champagne Creek area is a subdistrict of the Lava Creek mining district (fig. 1). Silver was produced from the subdistrict as early as 1884 when oxidized-enriched silver ores were exploited at the surface (Anderson, 1929, 1947). In the mid-1940's, lead and zinc from primary sulfide ores were mined (Anderson, 1947). In recent years, several companies have prospected and tested the Champagne Creek area. In 1988, the Bema Gold Corporation of Canada started a pilot heap leach test at the Champagne Mine location (fig. 2). Bema Gold later reported that an oxide ore body containing 2.4 million tons of mineable reserves at 0.038/short ton gold equivalent had been defined; production of gold and silver at the Champagne Mine commenced in June 1989. Further exploration for additional oxide reserves and deeper sulfide targets is taking place by Bema Gold (Engineering and Mining Journal, 1989).

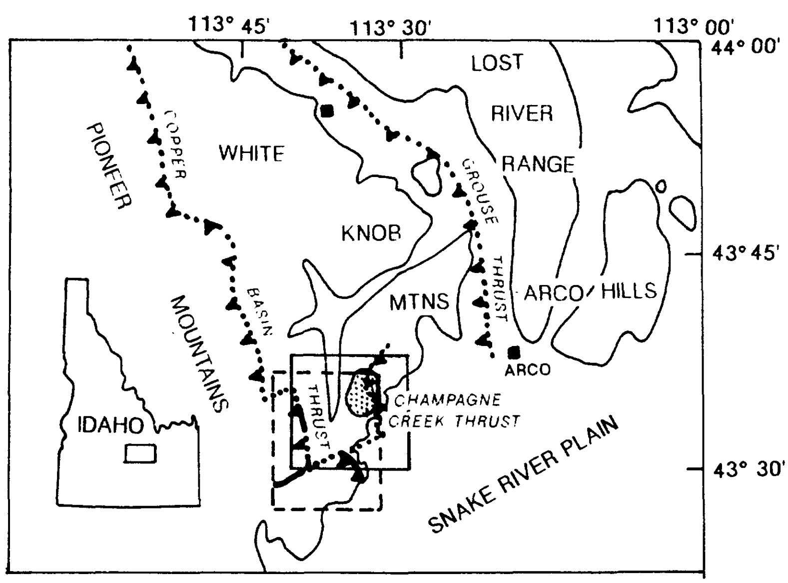


Figure 1.--Index map showing location of geologic map of figure 2 (solid line), the Lava Creek mining district (dashed line), the Champagne Creek subdistrict (stippled area).

The mineral deposits in the Champagne Creek area occur in northerly-trending veins and stockworks of veinlets in highly altered Eocene volcanic rocks of the Challis Group (Anderson, 1929, 1947). The ore deposits of the Champagne Mine are shallow epithermal or hot spring deposits localized in siliceous veins and zones contained in a larger hydrothermal breccia zone that also trends north-south (Moye and others, 1989). The dominant north-south trends of mineralized zones in the Champagne Creek subdistrict are rare in other parts of the Lava Creek mining district; west and south of the subdistrict mineralized zones trend chiefly east-west.

Subparallel to the north-trending ore zones in the Champagne Creek area is an Eocene rhyolite dike swarm that crops out west of the Champagne Mine and continues southward into an area of Paleozoic rocks exposed beneath the volcanics (fig 2.). The exhumed Paleozoic rocks southwest of the mine are folded about north-trending axes and have a subparallel axial plane cleavage. These north-trending fold axes diverge from the regional north-northwest trends of fold axes in the northeast and southwest areas of the map (fig. 2). The local cluster of north-trending axes includes all Paleozoic rocks between the trace of the Champagne Creek backthrust and the Copper Basin thrust to the west.

Anderson (1929, 1947) attributed the north-south trend of mineralized fissures in the Champagne Creek subdistrict to the presence of an underlying Tertiary stock that ruptured overlying volcanic rocks during its intrusion. Several small granitic bodies crop out east and south of the Champagne Mine (Anderson, 1947; Skipp and others, 1990), and a stock probably is present at depth as indicated by a north-northeast-trending positive aeromagnetic anomaly over the subdistrict (M. D. Kleinkopf, written commun., 1990). However, shattering above a deep intrusive body may not entirely account for the locally consistent north-south trends of the dike swarm, faults, and mineralized zones, though the stock may have provided heat and metals for the formation of the ore deposits. The north-trending Mesozoic structural fabric in the Paleozoic rocks that underlie the volcanics of the subdistrict may have determined the orientation of the Eocene dike swarm and mineralized zones of the subdistrct.

Anderson (1929, 1947) suggests that the mineral deposits of the Lava Creek District were formed by the deposition of metals from hot fluids circulating in open fractures during two periods of early Tertiary extension. During one or both of these periods, a component of local east-west extension may have pulled apart Paleozoic rocks at depth along northerly-trending cleavages and faults forming fissures in the overlying volcanic rocks and providing paths for ore-bearing solutions.

Paleozoic rocks beneath the Champagne Creek backthrust are interbedded mudstone, siltstone, sandstone, and minor granule- to pebble-conglomerate of the Lower Mississippian McGowan Creek Formation. They are part of a sequence of relatively deep-water turbidites that were derived from the west. Geochemical studies using sagebrush and heavy mineral concentrates have yielded preliminary evidence for local sediment-hosted gold in the fine-grained clastics of the formation (Erdman and others, 1988; Erdman and others, 1989). The McGowan Creek Formation also underlies the volcanic rocks at the Champagne Mine site; deep exploratory drilling could reveal north-south trending sulfide targets in the Paleozoic rocks at this site.

References Cited:

Anderson, A.L., 1929, Geology and ore deposits of the Lava Creek District: Idaho Bureau of Mines and Geology Pamphlet 32, 70 p.

______1947, Epithermal mineralization at the Last Chance and Hornsilver mines, Lava Creek District, Butte County, Idaho: Geological Society of America Bulletin, v. 56, 451-482.

Engineering and Mining Journal, 1989, A toast to the Champagne Mine: v. 190, no. 8 (August), p. 15.

Erdman J.A., Moye, Falma, and Theobald, P.K., 1989, Geochemical expression of poorly exposed metallization in the southeastern Challis volcanic field, Idaho--emphasis on biogeochemical methods, in Winkler, G.R., Soulliere, S.J., Worl, R.G., and Johnson, K.M., eds., Geology and mineral deposits of the Hailey and western Idaho Falls 1° x 2° quadrangles, Idaho: U.S. Geological Survey Open-File Report 89-639, p. 91.

Erdman, J.A., Skipp, Betty, Theobald, P.K., and Moye, Falma, 1988, Drainage-basin geochemical survey of Lava Creek district in central Idaho, using sagebrush and heavy-mineral concentrates; preliminary evidence for sediment-hosted gold in the McGowan Creek Formation [abs.]: Geological Society of America Abstracts with Programs, v. 20, no. 6, p. 414.

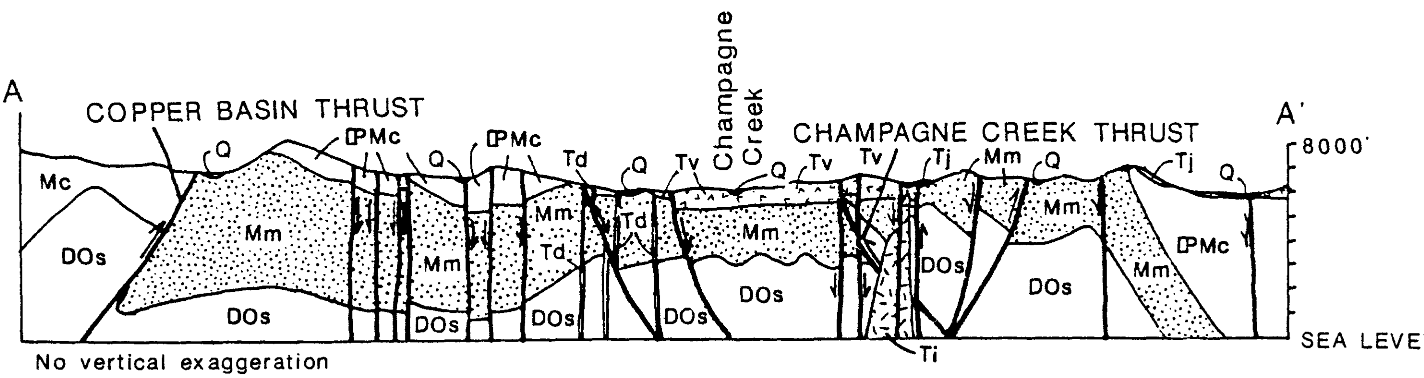
Moye, Falma, Sanford, R.F., and Erdman, J.A., and Johnson, K.M., 1989, Volcanic-hosted and intrusion-related mineral deposits in the Hailey and Idaho Falls quadrangles, Idaho, in Winkler, G.R., Soulliere, S.J., Worl, R.G., and Johnson, K.M., eds., Geology and mineral deposits of the Hailey and western Idaho Falls 1° x 2° quadrangles, Idaho: U.S. Geological Survey Open-File Report 89-639, p. 70-71.

Skipp, Betty, 1988, Geologic map of Mackay 4 (Grouse) NE quadrangle, Butte and Custer Counties, Idaho: U.S. Geological Survey Open-File Report 88-423, scale 1:24,000.

______1989, Geologic map of Mackay 4 (Grouse) NW quadrangle, Butte and Custer Counties, Idaho: U.S. Geological Survey Open-File Report 89-142, scale 1:24,000.

Skipp, Betty, and Bollmann, D.D., in press, Geologic map of the Mackay 4 (Grouse) SW quadrangle, Blaine and Butte Counties, Idaho: U.S. Geological Survey Open-File Report, scale 1:24,000.

Skipp, Betty, Kuntz, M.A., and Morgan, L.A., 1990, Geologic map of Mackay 4 (Grouse) SE Quadrangle, Butte County, Idaho: U.S. Geological Survey Open-File Report 89-431, scale 1:24,000.



MAP UNITS

Q	Quaternary surficial deposits
Qb	Quaternary basalts
Ti	Tertiary granitoid intrusions
Tj	Tertiary jasperoid
Td	Tertiary rhyolite dikes
Tv	Teritary volcanics
ⅣPMc	Pennsylvanian and Mississippian carbonate rocks
Mm	Mississippian McGowan Creek Formation
Mc	Mississippian Copper Basin Formation
DOs	Devonian and Ordovician rocks undivided

EXPLANATION

Contact

Thrust fault; dotted where concealed; teeth on upper plate

Normal fault; dashed where approximate; dotted wnere concealed; bar and ball on downthrown side

Concealed fault with apparent lateral displacement indicated by arrows

Photo lineament--probable fault or fracture with undetermined offset

Anticline--Dashed where approximate

Overturned anticline

Syncline--Dashed where approximate

Overturned syncline

Strike and dip of beds

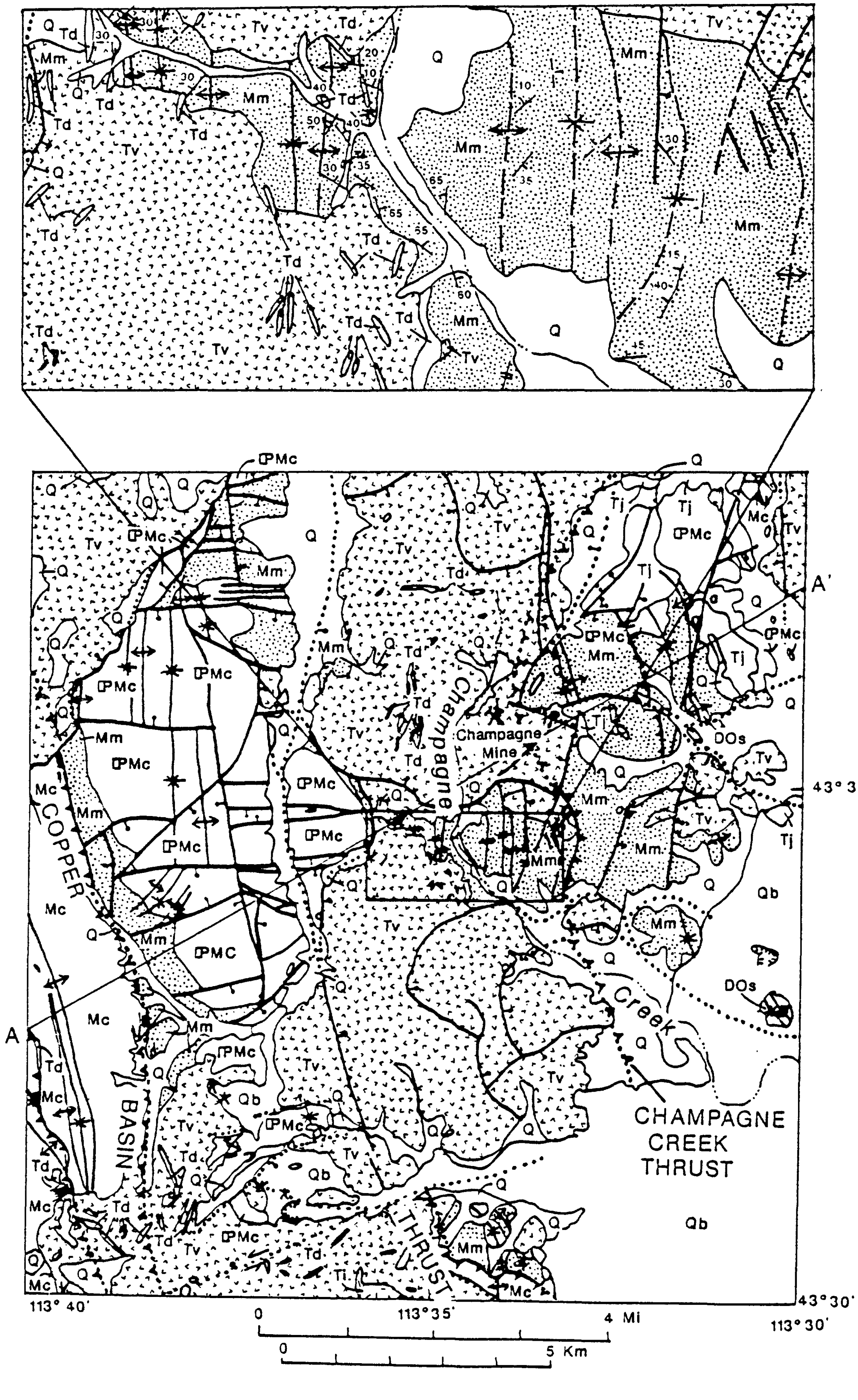
30 Inclined

Approximate (from aerial photos)

Strike and dip of cleavage

Vertical

Figure 2.--Simplified geologic map and cross section of most of the Lava Creek mining district and the Champagne Creek subdistrict showing location of the Champagne Mine, the Copper Basin thrust, the Champagne Creek backthrust, and an enlarged map of structures in Paleozoic rocks of the footwall of the Champagne Creek thrust about 1 mi (1.6 km) south of the Champagne Mine. The Grouse thrust lies below the level of the cross section. Adapted from Skipp (1988; 1989), Skipp and others (1990); and Skipp and Bollman (in press).


Q
Td
Tv
Mm
Champagne
Champagne Mine
PMc
PMC
Tj
Mc
DOs
Qb
Ti
A
A'
COPPER
BASIN
THRUST
Creek
CHAMPAGNE CREEK THRUST
43° 35'
43°30'
113° 40'
113°35'
113° 30'
0
4 Mi
5 Km

Map number 6

INFLUENCE OF CRUSTAL STRUCTURE ON THE COURSE OF ARKANSAS RIVER, SOUTH-CENTRAL COLORADO: SOME OBSERVATIONS

KENNETH WATSON, DANIEL H. KNEPPER, JR., and MICHAEL W. WEBRING, Branch of Geophysics, U.S. Geological Survey, Box 25046 MS 964, Denver, CO 80225

On small-scale aerial photos, satellite images, topographic maps, and digital terrain images, the linear northeast-trending segment of the Arkansas River between Coaldale and Parkdale, south-central Colorado, suggests to even the casual observer an element of geologic control. Although joints in Proterozoic crystalline rocks probably exert control on the path of the river on a local scale, no regional structural control (fault, shear zone, broad-scale folding) is apparent on published geologic maps. This segment of the river is generally considered to be a superposed stream established during regional uplift and incised in late Pliocene and Pleistocene time.

We have been conducting a reexamination of published geologic and geophysical maps and digital geophysical data as part of on-going studies of the USGS GEM (Geophysics Environmental and Minerals) demonstration area in the western half of the Pueblo 1° X 2° quadrangle. This study indicates that crustal structure, as interpreted from geophysical anomalies, the distribution of Proterozoic lithologies and Cambrian mafic plutons, and patterns of faults and fault blocks, may have provided the setting for establishing the northeast trend of this segment of the Arkansas River in late Pliocene time.

The pattern and nature of aeromagnetic and gravity anomalies in south-central Colorado indicate an enigmatic crustal difference between the Front Range and Wet Mountain-DeWeese Plateau blocks; the junction of these blocks, as seen in the geophysical data, occurs at approximately the Arkansas River. The geophysical anomalies can only be partially explained by the exposed rocks defined by published detailed and reconnaissance geologic mapping.

Exposed Cambrian mafic plutons are restricted to the Wet Mountain-DeWeese Plateau block and account for some of the observed geophysical anomalies. However, rocks characteristic of the southern Front Range block have an uncharacteristically low magnetic field immediately adjacent to the DeWeese Plateau on the north. The cause of the unexpected magnetic signature of the southern Front Range block rocks in this area and the nature of the boundary between these rocks and the DeWeese Plateau block is unknown; however, the geophysical boundary between these blocks is spatially coincident with and appears to be controlled by northeast-trending faults subparallel to the Arkansas River in this region.

Along the 35 kilometer northeast-trending segment of the Arkansas River between Coaldale and Parkdale, Colorado, granitic rocks of Boulder Creek age to the north are in contact with older Proterozoic metasedimentary and metavolcanic rocks to the south. The regional trend of this contact is essentially parallel to the Arkansas River and for 25 kilometers along this stretch of the river the contact is within 2 kilometers of the river and commonly within 1 kilometer. This spatial relationship strongly suggests that the granite-metamorphic contact has influenced the course of the river, although the nature of this influence is unknown.

The predominant faults in the Wet Mountain-DeWeese Plateau block trend northwesterly northward to the vicinity of the Arkansas River. In this area, a zone of northeast-trending faults subparallel to the Arkansas River and spatially related to the geophysical boundary between the Wet Mountain-DeWeese Plateau and southern Front Range blocks signals a rather abrupt change in structural style. The northeast-trending fault zone can be projected northeastward along trend across the Canon City embayment to a similar zone of northeast-trending faults cutting across the southern end of the Front Range south of the Pikes Peak batholith. The subparallelism of the Arkansas River between Coaldale and Parkdale, the northeast-trending faults, and the present course of the river within the zone suggests an element of structural control that remains to be defined in detail.

Examination of regional terrain, gravity, seismicity, distribution of volcanic centers and mineral deposits suggests that a more extensive zone may exist well beyond the 35 km segment of the Arkansas River, but no hard evidence has been developed to prove a direct relationship or suggest an underlying cause. The distribution of mineral deposits, including the Cripple Creek world-class gold-telluride deposit, and the potential for discovery of concealed mineral deposits are incentives for better understanding the crustal structure in this region.

Map number 7

STRUCTURAL AND BASEMENT LITHOLOGICAL IMPLICATIONS FROM GRAVITY AND SEISMIC-REFLECTION DATA IN LARAMIDE MOUNTAIN RANGES AND BASINS OF WYOMING AND MONTANA

STEPHEN L. ROBBINS, Branch of Sedimentary Processes, U.S. Geological Survey, Box 25046 MS 921, Denver, CO 80225 and **JOHN A. GROW**, Branch of Petroleum Geology, U.S. Geological Survey, Box 25046 MS 960, Denver, CO 80225

Gravity profiles and some seismic-reflection profiles, where available, indicate low-angle thrusting of several Laramide mountain ranges onto basins in Wyoming and Montana. Examples include thrusting of the Bighorn Mountains northeastward onto the western Powder River basin, the Wind River Mountains southwestward onto the Green River basin, the Owl Creek Mountains southward onto the Wind River basin, the Shirley Mountains southward onto the Hanna basin, the Granite Mountains southwestward toward the Great Divide basin, and the Beartooth Mountains northeastward onto the Crazy Mountain basin. Interpretations of the profiles contain several similarities: (1) thrust angles of 20-30° ; (2) thrust distances onto the basins of 10-20 km; and (3) thrusts that do not extend into the mantle.

Isostatic residual anomalies (IRA) in Wyoming range from -77 mGal over Hanna Basin to +75 mGal over the Laramie Mountains but average near zero. Large positive IRA values (+40 to +70 mGal) occur over all of the Laramide mountain ranges and indicate the absence of local roots beneath these mountain ranges. IRA lows of -20 to -70 mGal occur over the deeper basins and are primarily a reflection of low-density basin-fill deposits. The fact that the IRA values average near zero indicates that the longer wavelength elevation changes (greater than 100 km) must be isostatically compensated; that is, the crustal thickness compensates for regional elevation changes but not for local mountain ranges.

Positive gravity anomalies within some of the basins in areas of little structural relief (areas such as the central Powder River basin where some borehole and seismic data are available) suggest significant lateral density variation within the Precambrian basement rocks, probably caused by differences in basement lithologies. Aeromagnetic patterns within these basins also support this idea.

A better understanding of the geometry of thrust faults that have carried mountain ranges over the edges of adjacent sedimentary basins, and of the structural relief within these basins, is needed in order to effectively explore for future hydrocarbon resources.

Map number 8

SEQUENTIAL LARAMIDE DEFORMATION OF THE ROCKY MOUNTAIN FORELAND

WILLIAM J. PERRY, JR., Branch of Petroleum Geology, U.S. Geological Survey, Box 25046 MS 940, Denver, CO 80225; **THADDEUS S. DYMAN**, Branch of Petroleum Geology, U.S. Geological Survey, Box 25046 MS 934, Denver, CO 80225; and **DOUGLAS J. NICHOLS**, Branch of Paleontology and Stratigraphy, U.S. Geological Survey, Box 25046 MS 919, Denver, CO 80225

Basement-involved compressional and transpressional deformation of the Rocky Mountain foreland began more than 90 Ma ago during Late Cenomanian to Turonian time, in the Lima region of southwest Montana, when the upper part of the Frontier Formation was being deposited. Here Laramide-style foreland deformation culminated prior to mid-Campanian time (approximately 80 Ma), based on palynostratigraphic determinations from sediments shed from the early Laramide Blacktail-Snowcrest uplift. In northwestern Wyoming, the Wind River uplift also started to develop between 80 to 90 Ma ago, based on fission-track and sedimentologic studies by M.W. Shuster and J.R. Steidtmann. Subsequent to development of the Blacktail-Snowcrest uplift, the next youngest Laramide uplift of the northern Rocky Mountain foreland appears to be the Madison-Gravelly uplift, immediately northwest of Yellowstone Park. Laramide deformation in this area was virtually completed by the close of Cretaceous time, whereas deformation of the Wind River uplift culminated in early Tertiary time. Available data on timing suggest that Rocky Mountain foreland deformation proceeded eastward and southward, from a locus in southwestern Montana, reaching the Colorado Front Range by latest Maastrichtian time.

In support of this contention, no evidence of Campanian or older Cretaceous Laramide-style deformation is present in the Rocky Mountain foreland east or southeast of the Blacktail-Snowcrest and Wind River uplifts, based on available palynostratigraphic dating of preorogenic and synorogenic sediments. Such dating reveals that the Front Range uplift of Colorado began to grow in latest Cretaceous time, culminating in the early Paleocene. However, broad structural welts of relatively low relief, such as the San Rafael swell in eastern Utah, had begun to grow in the Rocky Mountain foreland by mid-Cretaceous time.

South of the major east-west crustal discontinuity along the Wyoming-Colorado border, which separates Archean basement rocks on the north from Proterozoic basement rocks to the south, Laramide deformation appears to have proceeded from east to west, culminating along the eastern boundary of the Colorado Plateau in late Eocene, chiefly post-Green River, time. This timing appears to eliminate the Colorado Plateau block from consideration as a major factor in Laramide deformation of the Rocky Mountain foreland.

Economic implications of this new model of deformation of the Rocky Mountain foreland include progressive opening and subsequent blockage of eastward migration paths for hydrocarbons generated from Paleozoic source rocks in east-central and southeastern Idaho, southwestern Montana, Wyoming, Colorado, and eastern Utah.

Map number 9

STRUCTURAL SETTING OF THE CHIEF MINING DISTRICT, EASTERN CHIEF RANGE, LINCOLN COUNTY, NEVADA

PETER D. ROWLEY, Branch of Central Regional Geology, U.S. Geological Survey, Box 25046 MS 913, Denver, CO 80225; **LAWRENCE W. SNEE**, Branch of Central Mineral Resources, U.S. Geological Survey, Box 25046 MS 905, Denver, CO 80225; **HARALD H. MEHNERT**, Branch of Isotope Geology, U.S. Geological Survey, Box 25046 MS 963, Denver, CO 80225; **R. ERNEST ANDERSON**, Branch of Geological Risk Assessment, U.S. Geological Survey, Box 25046 MS 966, Denver, CO 80225; **GARY J. AXEN**, Harvard University, Department of Earth and Planetary Sciences, 20 Oxford Street, Hoffman Laboratory, Cambridge, MA 02138; **KELLY J. BURKE**, Northern Arizona University, Department of Geology, Box 6030, Flagstaff, AZ 86011; and **F. WILLIAM SIMONDS, and RALPH R. SHROBA**, Branch of Central Regional Geology, U.S. Geological Survey, Box 25046 MS 913, Denver, CO 80225

The Chief mining district produced at least 2,000 ounces of gold, 11,000 ounces of silver, and minor lead and copper from 1870 until the 1960's. The production was from fissure-vein precious-metal deposits containing highly oxidized mineral aggregates within breccia zones of mostly low-angle faults. The main veins consisted of scorodite and related minerals that replaced arsenopyrite and of barite, galena, quartz, and iron and manganese oxides (Callaghan, 1936). The deposits probably represent the lower part of an epithermal gold-silver system that was deeply eroded to the present level. Prospects for finding additional economic ore bodies do not appear to be good.

Most veins occur in Proterozoic and Cambrian quartzite (Stirling Quartzite, Wood Canyon Formation, Zabriskie Quartzite) and Cambrian limestone (Highland Peak Formation). A large shallow intrusive body of quartz monzonite porphyry, the Cobalt Canyon stock, underlies the district and was the source of the mineralization, perhaps from convection cells of heated meteoric water. The stock is Oligocene, with two preliminary concordant $^{40}Ar/^{39}Ar$ ages on sanidine and biotite of 24.9 ± 0.1 Ma and 24.7 ± 0.1 Ma, respectively. Known igneous activity in the Caliente caldera complex, which is about 1 km south of the stock, ranges from 23 to 14 Ma, but isopach data (Williams, 1967) suggest that the northern part of the complex is the source of the 25-Ma ash-flow tuffs of the Leach Canyon Formation. Thus the stock may be an early phase of igneous activity at the caldera complex. Other epithermal gold districts occur in and near the caldera complex, including the large, deeply eroded Delamar district outside the southeastern margin, the small, high-level Taylor (Easter) mine in the western part of the complex, and the small Pennsylvania district in the southern part.

The Chief mining district is near the western end of the east-trending Delamar-Iron Springs mineral belt. This belt may have resulted from igneous activity along early Tertiary east-striking faults, which seem to have controlled other east-striking structural features in the area, including the Timpahute lineament (Ekren and others, 1977) that cuts through the mining district. The gold districts in and near the Caliente caldera complex also contain east-trending igneous bodies and structural features that suggest control of igneous activity and mineralization by the same faults.

Recent detailed geologic mapping demonstrates at least three major episodes of Tertiary extensional faulting in and near the Chief district. The oldest episode was along the low-angle Stampede detachment fault zone, a major east-dipping structure, with upper plate movement to the east, that separates Zabriskie Quartzite from Highland Peak Formation (Axen and others, 1988). The timing of detachment is not well constrained; it predates Tertiary volcanism, which in this area started in the late Oligocene (about 31 Ma). Faults of the oldest episode provided sites for fissure-vein ore bodies.

The second episode of extensional faulting, which may be the main episode, took place in the middle Miocene and was characterized in the district by high-angle strike-, oblique-, and normal-slip faults; outside the district, the episode included detachment faults. Most of the high-angle faults strike north-northeast or north-northwest; the main detachment fault, the Highland detachment (Axen and others, 1988) north of the district, dips west, and its upper plate has moved to the west. Hypabyssal dikes and plugs of a distinctive porphyry, mapped as the intrusive dacite of Meadow Valley Wash, were emplaced along some of the larger strike-slip and oblique-slip faults near the district. Two preliminary concordant $^{40}Ar/^{39}Ar$ ages on sanidine and hornblende from the porphyry of 19.3 ± 0.1 Ma and 19.5 ± 0.1 Ma, respectively, demonstrate that significant extension had taken place by this time. Faulting of this episode continued to at least 12 Ma following caldera volcanism in the western Caliente caldera complex. Some of these faults cut clastic sedimentary rocks that contain basalt lava flows dated by K-Ar techniques at 12 Ma (Mehnert and others, 1989). However, in other places, the post-caldera sedimentary rocks cap many large and small faults related to the same episode.

The youngest episode of extensional faulting, basin-range faulting (Zoback and others, 1981), formed the major elements of the present topography, including the north-trending Chief Range and, to the east, the Panaca basin. Some of the youngest faults also strike north and cut basin-fill sedimentary rocks of the Panaca Formation, which is as young as 3 Ma. Other north-striking faults with well-defined scarps displace Quaternary sediments west of the Chief Range (Ekren and others, 1977). Neither the second nor the youngest episode of faulting seems to have had any direct influence on the emplacement of ore deposits in the Chief district.

References Cited:

Axen, G.J., Lewis, P.R., Burke, K.J., Sleeper, K.G., and Fletcher, J.M., 1988, Tertiary extension in the Pioche area, Lincoln County, Nevada, in Bartley, J.M., Axen, G.J., Taylor, W.J., and Fryxell, J.E., Cenozoic tectonics of a transect through eastern Nevada near 38° N latitude, in Weide, D.L., and Faber, M.L., eds., This extended land--Geological journeys in the southern Basin and Range: Geological Society of America, Cordilleran Section, Field Trip Guidebook, p. 3-5.

Callahgan, Eugene, 1936, Geology of the Chief district, Lincoln County, Nevada: University of Nevada Bulletin, v. 30, no. 2 (Nevada Bureau of Mines Bulletin, no. 26), 29 p.

Ekren, E.B., Orkild, P.P., Sargent, K.A., and Dixon, G.L., 1977, Geologic map of Tertiary rocks, Lincoln County, Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1041, scale 1:250,000.

Mehnert, H.H., Anderson, R.E., and Rowley, P.D., 1989, Constraints on age of faulting and youngest volcanism, western Caliente caldera complex and vicinity, Lincoln County, Nevada (abs.): EOS, Transactions, American Geophysical Union, v. 70, no. 43, p. 1414.

Williams, P.L., 1967, Stratigraphy and petrography of the Quichapa Group, southwestern Utah and southeastern Nevada: Unpublished Ph.D. dissertation, Seattle, University of Washington, 182 p.

Zoback, M.L., Anderson, R.E., and Thompson, G.A., 1981, Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States: Philosophical Transactions of Royal Society of London, v. A300, p. 407-434.

Map number 10

GEOLOGY AND HIGH-PRECISION $^{40}AR/^{39}AR$ GEOCHRONOLOGY OF KEG MOUNTAIN, WEST-CENTRAL UTAH: IMPLICATION FOR VOLCANIC HISTORY AND MINERAL DEPOSITS

MICHAEL A. SHUBAT, Utah Geological and Mineral Survey, 606 Black Hawk Way, Salt Lake City, Utah 84108-1280 and **LAWRENCE W. SNEE,** Branch of Central Mineral Resources, U.S. Geological Survey, Box 25046 MS 905, Denver, CO 80225

High-precision $^{40}Ar/^{39}Ar$ age spectrum dates combined with geologic control significantly revise the Eocene-Oligocene history of Keg Mountain, which straddles the center of the Deep Creek-Tintic mineral belt in west-central Utah. We propose the following chronology of volcanic events: (1) eruption of the Dead Ox Tuff and subsidence of the associated Flint Spring cauldron (late Eocene); (2) eruption of the Keg Tuff (36.77 ± 0.12 Ma) and subsidence of the Keg cauldron, followed by resurgent doming; (3) eruption of the Mt. Laird Tuff (36.54 ± 0.06 Ma), collapse of the Thomas caldera, and intrusion of hypabyssal dacite (36.49 ± 0.15 Ma); and (4) eruption of the Joy Tuff (34.88 ± 0.06 Ma), collapse of the Dugway Valley cauldron and possibly connected Picture Rock caldera, and intrusion of rhyolite porphyry (35.14 ± 0.15 Ma).

Current minerals exploration at Keg Mountain focuses on recently discovered volcanic-hosted gold prospects associated with intensely argillized rock. Other mineral occurrences include sediment-hosted, Tintic-like polymetallic veins and jasperoid bodies. Mineralized rocks occur along high-angle normal faults and some gold occurrences lie near pebble dikes cutting Mt. Laird Tuff-related intrusions. The northern margin of the older Keg cauldron may have controlled the emplacement of some of the hypabyssal intrusions. This study shows that the magmatic systems related to both the Mt. Laird and Joy Tuff eruptive events, expressed as hypabyssal intrusions and related mineral deposits, extended many kilometers (> 10) out from known or inferred source caldera margins.

Map number 11

SEVIER-AGE STRUCTURES AND THEIR CONTROL OF TERTIARY MINERALIZATION AT THE DRUM MINE, WEST-CENTRAL UTAH

CONSTANCE J. NUTT and CHARLES H. THORMAN, Branch of Central Mineral Resources, U.S. Geological Survey, Box 25046 MS 905, Denver, CO 80225 and **ROBERT W. GLOYN**, Utah Geological and Mineral Survey, 606 Black Hawk Way, Salt Lake City, Utah 84108-1280

The Drum mine, in the eastern Great Basin of Utah, produced gold from a sedimentary- and igneous-hosted deposit largely controlled by bedding-parallel faults and cross-cutting high-angle faults and fractures. About 120,000 oz of gold were recovered from 3 million tons of ore with an average grade of 0.04 oz/ton. The mine is at the southern margin of the Tintic-Deep Creek mineral belt, which is coincident with a belt of Eocene-Oligocene calderas, calc-alkaline volcanic rocks and porphyry intrusions, and Miocene basalt and alkali rhyolite.

The mine is in the central part of the Drum Mountains, in an area underlain by Late Proterozoic to Lower Cambrian quartzite and subordinate shale, carbonate rocks and subordinate shale of Middle to Late Cambrian age, and subvolcanic to volcanic rocks and porphyry-related pebble dikes and breccias of Eocene to Oligocene age. The following units are exposed in the mine: the upper part of the quartzite sequence (lower member of the Pioche Formation); the lower part of the carbonate sequence (Tatow Member of the Pioche Formation, Howell Limestone, Chisholm Formation, and Dome Limestone); and numerous Tertiary igneous and pebble dikes and sills. At least five types of igneous rocks crop out in or near the mine, which is at the southern margin of a 3-mile-long zone of igneous-related explosion breccia. Most gold was recovered from silicified and(or) clay-altered limestone and shale in the Howell Limestone and Chisholm Formation and from pebble dike and igneous rock.

Bedding-parallel faults that primarily thin units are major controls of ore at the Drum mine. In the Drum Mountains, these faults are concentrated in and near shale units in the Cambrian sequence. Because the shale units outcrop poorly and because stratigraphic thinning is the only expression of the bedding-parallel faults, the faults are difficult to detect by surface mapping. Similar faults have been recognized to the west, and may be present throughout west-central Utah, in the hinterland of the Sevier orogeny.

At the Drum mine, ore is localized along bedding-parallel faults and associated ramp structures, and is particularly high-grade where the ramps are cut by high-angle fractures and faults with little offset. The bedding-parallel faults, with offset ranging from inches to at least hundreds of feet, are concentrated in and near shale units near the contact separating the quartzite and carbonate sequences, in the Howell Limestone, and in the Chisholm Formation. Bedding-parallel faults caused some small-scale repetition of beds that bound the shale units, but the most obvious effect is thinning of shale units. Most movement on the bedding-parallel faults was Eocene or older because igneous and pebble sills follow the faults, but are not noticeably deformed by them.

The mine area is bounded by two large faults that strike east-west. The southern fault, the Drum Peak fault, is well exposed. The northern fault is not exposed, but is postulated to control an east-west paleovalley that is filled with ±42 Ma rhyodacite flows. We propose that these structures are tear faults associated with Sevier deformation and that bedding-parallel faults and associated attenuation of beds are particularly concentrated between such faults.

Gold mineralization at the Drum mine and throughout the Drum Mountains was probably related to Eocene-Oligocene porphyry hydrothermal systems, but a Miocene mineralization overprinting has not been disproved. Regardless of the age of mineralization, bedding-parallel faults and associated ramps were primary controls for gold mineralization as well as for Eocene-Oligocene igneous and pebble sills and dikes.

Map number 12

GEOLOGY, AGE, AND ORIGIN OF FRACTURE-CONTROLLED MINERAL DEPOSITS OF THE IDAHO BATHOLITH: IMPORTANCE OF CRETACEOUS MINERALIZATION

LAWRENCE W. SNEE and KAREN LUND, Branch of Central Mineral Resources, U.S. Geological Survey, Box 25046 MS 905, Federal Center, Denver, CO 80225 and **CHRISTOPHER H. GAMMONS**, Department of Earth Sciences, Monash University, Clayton, Victoria 3168, Australia

The age and origin of gold-bearing quartz-vein deposits in central Idaho was the subject of debate prior to detailed isotopic dating. The quartz veins are hosted in Cretaceous Idaho batholith or older rocks. Eocene plutonic and dike rocks crop out in many of the mining districts and, locally, disseminated gold deposits occur in Eocene volcanic rocks such as at the Thunder Mountain mining district. Thus, it has been long argued that the numerous gold-bearing quartz veins throughout the Idaho batholith were genetically related to the Eocene plutonic/volcanic event. The argument concerning age of mineralization is not simply academic because an understanding of the age, as well as origin, of these deposits is important for mineral exploration programs.

Many quartz-vein deposits in the Salmon River and Clearwater River Mountains of central Idaho occur near the roof zones of Late Cretaceous (78-70 Ma) marginally peraluminous granite-granodiorite (primarily biotite granodiorite and muscovite-biotite granite) plutonic rocks or in the older metaluminous granodiorite-tonalite (93-87 Ma) and metamorphic rocks that were intruded by the younger plutons. The deposits occur both in discrete quartz-filled fissure veins and in more disseminated deposits along silicified shear zones. Some districts (e.g., Florence, Warren, Dixie, and Elk City) are better known as placer districts than as lode districts because the best gold production was from saprolite, grus, and minimally transported sediment derived from deeply weathered plutonic and metamorphic host rocks that contained gold-bearing quartz veins. The regional orientation of the quartz-vein deposits is dominantly north-northeast although local (district-wide) structures influenced the orientation in individual districts. All deposits are characterized by quartz flooding, episodic brecciation, and open-space filling. Only minor wall-rock alteration is associated with these deposits. The fissure-vein and shear-zone hosted deposits are sulfide-bearing and have produced gold, silver, copper, lead, zinc, molybdenum, tungsten, antimony, and mercury. The sulfide mineralogy of the veins varies from district to district; this is probably related to depth of exposure of the vein system and possibly to the source of the metals. Although parallel Eocene dike swarms are common in several districts, they cut mineralized rock and are neither silicified nor mineralized; thus, where present, the Eocene dikes are younger than the quartz-vein deposits.

High-precision $^{40}Ar/^{39}Ar$ age-spectrum dates of muscovites and potassium feldspar from mineralized quartz veins and altered host rock from 9 districts range from 78 to 68 Ma. Ages of the deposits within any district tend to form clusters and multiple mineralization events occurred in some districts (e.g., Edwardsburg, Profile Gap, Yellow Pine). Ages of the deposits are slightly younger than cooling ages of marginally peraluminous granites in each district. Therefore the vein deposits are Cretaceous and were not formed by hydrothermal activity associated with Eocene plutons. Furthermore, based on the character of the $^{40}Ar/^{39}Ar$ age spectra for minerals from the deposits and the cooling history of the Cretaceous granites, constraints are derived for the thermal and spatial effects of younger events. Age spectra of quartz-vein muscovites commonly show ^{40}Ar-loss that occurred during younger Cretaceous mineralization activity but only those collected within a few meters of Eocene dikes, plutons, and volcanic centers display partial ^{40}Ar-loss incurred during Eocene events. In addition, microcline from nearby Cretaceous plutons yields $^{40}Ar/^{39}Ar$ dates of Late Cretaceous to Paleocene indicating that the ambient temperature of host rocks and mineral deposits was already below about 150° C (the argon closure temperature of microcline) before Eocene magmatic events. Thus, after Cretaceous formation, only those deposits that were cut by Eocene plutons or dike swarms show the effects of temperatures exceeding 150° C. However, one mixed layer illite/muscovite sample with an estimated argon closure temperature less than 150° C is 52 Ma. There is, therefore, a possibility that local remobilization of metals occurred during Eocene magmatic activity but the importance has not been evaluated.

These data end the debate about the age of many quartz-vein and shear-zone hosted mineral deposits in the Idaho batholith. The deposits are genetically related to Cretaceous marginally peraluminous granite plutons. The quartz veins were episodically emplaced into fractures at or near the roof of the granite, either in extensional fissures that formed during post-emplacement cooling and uplift of the granite plutons or in pre-existing shear zones near the roof of the plutons. Subsequently, most of these same fracture systems were also avenues for emplacement of Eocene dikes.

Map number 13

SEISMIC REFLECTION DATA REVEAL BURIED LATE PALEOZOIC STRUCTURES BENEATH THE SOUTHERN UINTA BASIN

CHRISTOPHER J. POTTER, Branch of Sedimentary Processes, U.S. Geological Survey, Box 25046 MS 939, Denver, CO 80225 and **REX TANG and TIMOTHY J. HAINSWORTH,** Louisiana Land and Exploration Co., 1 Civic Center Plaza, Denver, CO 80202

Seismic reflection data from the southern part of the Uinta Basin near Price, Utah, reveal a network of late Paleozoic faults that produced a 50-km-wide east-west trending trough in which Pennsylvanian-Permian clastic rocks are several thousand feet thicker than in directly adjacent areas to the north and south. This trough lies between the ancestral Uncompahgre uplift (to the east) and the Oquirrh basin (to the west). Pennsylvanian rocks are locally absent along the southern margin, adjacent to the Emery uplift.

Although many of the Paleozoic faults were clearly reactivated during Mesozoic and/or Cenozoic time, this study addresses only those faults that displaced strata below the Kaibab Limestone, but did not displace the Kaibab. These faults were active between Morrowan (Manning Canyon Shale) and Guadalupian (Kaibab Limestone) time. Fault styles include: (1) high-angle reverse and normal faults in a "block faulting" pattern similar to that observed in upper Paleozoic rocks in the Piceance Basin in northwestern Colorado (Waechter and Johnson, 1986); and (2) thrust faults having obvious hanging-wall and footwall cutoffs and hanging-wall anticlines, features commonly seen in fold-thrust belts.

West of Price, along the northern edge of the Emery uplift, the principal Paleozoic faults are northwest-striking, northeast-directed reverse faults that have as much as 5000 feet of throw. This fault set is nearly colinear with the Uncompahgre fault, (which also underwent late Paleozoic reverse movement; Frahme and Vaughan, 1983), but dips in the opposite direction. Steep northwest-striking normal faults are also present.

East and northeast of Price, west-directed thrust faults controlled late Paleozoic deformation, although high-angle reverse and normal faults are also present. A few backthrusts were also identified.

The major northwest-striking reverse faults and the west-directed thrusts accommodated displacements that are compatible with late Paleozoic oblique sinistral/reverse slip on the Uncompahgre fault, proposed by Stone (1977). The major reverse faults record shortening parallel to that accomplished by the Uncompahgre fault. The west-directed thrust faults probably formed in response to the strike-slip component of movement of the Uncompahgre block as it moved west against the late Paleozoic basin. This interpretation suggests that these buried faults were produced during Ancestral Rockies orogenesis and have been little modified since then. Alternatively, the overall pattern may be that of an east-trending late Paleozoic rift system that cut from the hingeline into the craton and was modified during Sevier and Laramide shortening.

References cited:

Frahme, C. W., and Vaughn, E. B., 1983, Paleozoic geology and seismic stratigraphy of the northern Uncompagre front, Grand County, Utah, in Lowell, J. D., ed., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists Guidebook, p. 201-211.

Stone, D. S., 1977, Tectonic history of the Uncompahgre uplift, in H. K. Veal, ed., Exploration frontiers of the central and southern Rockies: Rocky Mountain Association of Geologists 1977 Symposium, p. 23-30.

Waechter, N. B., and Johnson, W. B., 1986, Seismic interpretation in the Piceance Basin, northwest Colorado, in R. R. Gries and R. C. Dyer, ed., Seismic exploration of the Rocky Mountain region: Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 247-258.

Map number 14

EXTENSIONAL GEOMETRIES IN THE NORTHERN GRANT RANGE, EAST-CENTRAL NEVADA: IMPLICATIONS FOR OIL OCCURRENCES IN RAILROAD VALLEY

KAREN LUND, Branch of Central Mineral Resources, U.S. Geological Survey, Box 25046 MS 905, Denver, CO 80225 and **L. SUE BEARD**, Branch of Western Regional Geology, U.S. Geological Survey, Flagstaff, AZ 86001

Heterogeneous extension in the northern Grant Range is manifested by a stacked set of curviplanar low-angle normal faults that formed concurrent with arching of the range. Both the rock units and low-angle normal faults that cut them are arched about a north-northwest trending axis such that strata and structures on the east side are east-dipping, in the center are nearly horizontal, and on the west side are west-dipping.

The style and amount of attenuation was controlled by the lithology and structural depth of the units, and locally by the geometry of the arch. 1) At high structural levels large blocks of Pennsylvanian and Tertiary rocks rotated above a low-angle fault system mostly localized in Mississippian shale units. This decoupled Pennsylvanian and younger rocks from older rocks below. 2) At middle structural levels, massive dolostones of Ordovician to Devonian age are in normal stratigraphic succession, but units are brittlely attenuated and separated by subparallel-to-bedding low-angle normal faults. Thus, the lithologic packages are bounded by low-angle faults that are in part a product of many high- to moderate-angle, small- to medium-scale rotational faults which coalesce into specific stratigraphic horizons. 3) At deepest structural levels, metamorphosed and ductilely deformed Ordovician to Cambrian carbonate rocks are attenuated but less brittlely disrupted and Mesozoic compressional structures are exposed as isolated remnants. 4) On the west side of the range (steeper side of the arch), the curviplanar, subparallel-to-bedding, low-angle faults coalesce into a single fault zone along which the amount of extension appears to be greatest; the greatest stratigraphic separation or juxtapositioning of units occurs where metamorphosed Middle Cambrian units are structurally overlain by unmetamorphosed Mississippian units. The juxtapositioning results in a lower plate structural culmination.

Windows into the lower plate culmination occur in several valleys on the west side of the range, exposing curviplanar low-angle faults with a distinct geometry: higher-level faults cut lower-level faults and lower (generally older) faults are more tightly folded than higher (younger) faults. These geometries indicate that low-angle attenuation faulting was synchronous with arching of the range. Cross-sections incorporating seismic and drill hole data suggest that the low-angle attenuation faults seen in the range extend into Railroad Valley to the west of the Grant Range with no significant offset by high-angle normal faults. Therefore, the topographic expression of the Grant Range and Railroad Valley may be, in large part, due to synchronous arching and low-angle faulting.

Our interpretation that the major low-angle attenuation fault system observed in the range extends into the valley suggests a new model for petroleum exploration in Railroad Valley and the region. Petroleum source and reservoir rocks in Railroad Valley oil fields are both located in relatively immature but extensively fractured rocks of the upper plate to the structural culmination. This structural geometry and the associated intense fracturing of upper plate rocks and juxtapositioning of immature source rocks over less fractured,