Copper and Uranium in Pennsylvanian and Permian Sedimentary Rocks, Northern Sangre de Cristo Range, Colorado

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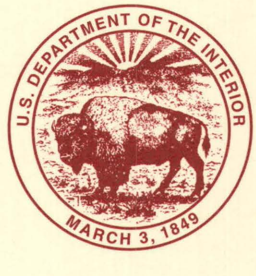

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By David A. Lindsey *and* Reino F. Clark

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U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

A description of the stratigraphy and depositional environments of host rocks and the chemical composition and possible origin of sediment-hosted copper and uranium occurrences in a redbed sequence

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COPPER AND URANIUM IN PENNSYLVANIAN AND PERMIAN SEDIMENTARY ROCKS, NORTHERN SANGRE DE CRISTO RANGE, COLORADO

By David A. Lindsey *and* Reino F. Clark[1]

ABSTRACT

Redbed copper and uranium deposits of low grade occur mainly in beds and lenses of gray siltstone beneath a major red-gray color boundary in Pennsylvanian and Permian formations of the northern Sangre de Cristo Range, south-central Colorado. The deposits also contain anomalous amounts of silver, molybdenum, lead, vanadium, and zinc. All of the deposits are uneconomic, having low tonnages (1,000–2,000 to as much as 500,000 metric tons) and grades (about 0.025–0.085 percent Cu and 0.01–0.025 percent U_3O_8). Mineralized rocks contain small amounts of organic carbon preserved as plant remains. Uranium is disseminated in plant remains, probably as a urano-organic complex. Copper occurs as sulfides and as secondary malachite and azurite.

Gray siltstone host rocks containing organic matter were deposited in both alluvial and marine environments. The lateral extent of some alluvial and nearshore-marine siltstone lenses, typically 100–300 m, was restricted by torrential deposition and erosion in alluvial-fan environments. In contrast, siltstone and shale lenses extending as much as 11 km were deposited in more stable nearshore-marine environments.

During Pennsylvanian and Permian time, extensive redbeds were formed when oxidizing ground water altered alluvial sandstone and siltstone around basin margins. Gray siltstone containing organic carbon from plant remains was preserved locally in the Minturn Formation. The present-day distribution of reduced siltstone is generally restricted to strata below the red-gray color boundary that marks the limit of redbed formation in the Sangre de Cristo and Minturn Formations.

Copper occurs separately from uranium at the scale of sampling, which consisted of 0.3- to 1-m intervals representing the thickness of mineralized beds. Uranium and vanadium are correlated, and lead and chromium are correlated with vanadium. R-mode factor analysis of data from mineralized rocks indicates (1) concentration of iron, cobalt, and nickel by sedimentation and diagenesis, (2) four separate modes of mineralization for vanadium-chromium-lead-uranium, molybdenum-uranium, zinc, and copper, and (3) concentration (or preservation) of sulphur (probably as sulfides) and organic carbon.

Copper and uranium were probably transported by dilute mineralizing chloride-sulfate brines that originated in evaporite-bearing strata of the central Colorado trough. Brines probably equilibrated with abundant hematite and carbonate as they encountered oxidized sandstone and redbeds. Upon equilibration, brines became mildly oxidizing and alkaline, allowing transport of copper as cuprous chloride and uranium as uranyl phosphate or carbonate complexes. The brines leached copper from oxidized rocks and deposited it later as sulfide minerals in chemically reducing carbonaceous siltstone. Uranium was probably fixed as a urano-organic complex on insoluble organic matter. Only small, low-grade deposits were formed because the mineralizing brines were probably too dilute and (or) too alkaline to transport sufficient copper.

INTRODUCTION

Investigations of so-called "redbed" copper-uranium occurrences in the northern Sangre de Cristo Range of south-central Colorado were begun as part of a mineral resource assessment of the proposed Sangre de Cristo Wilderness (Johnson and others, 1984). Although these redbed occurrences and others like them share some characteristics with much larger, economically important shale-hosted copper (copper-shale) deposits in other parts of the world, economically important redbed deposits are rarely found. Using samples and data collected for the mineral resource assessment of the wilderness, this investigation was pursued further to identify geologic controls that can affect the size and distribution of sediment-hosted copper deposits.

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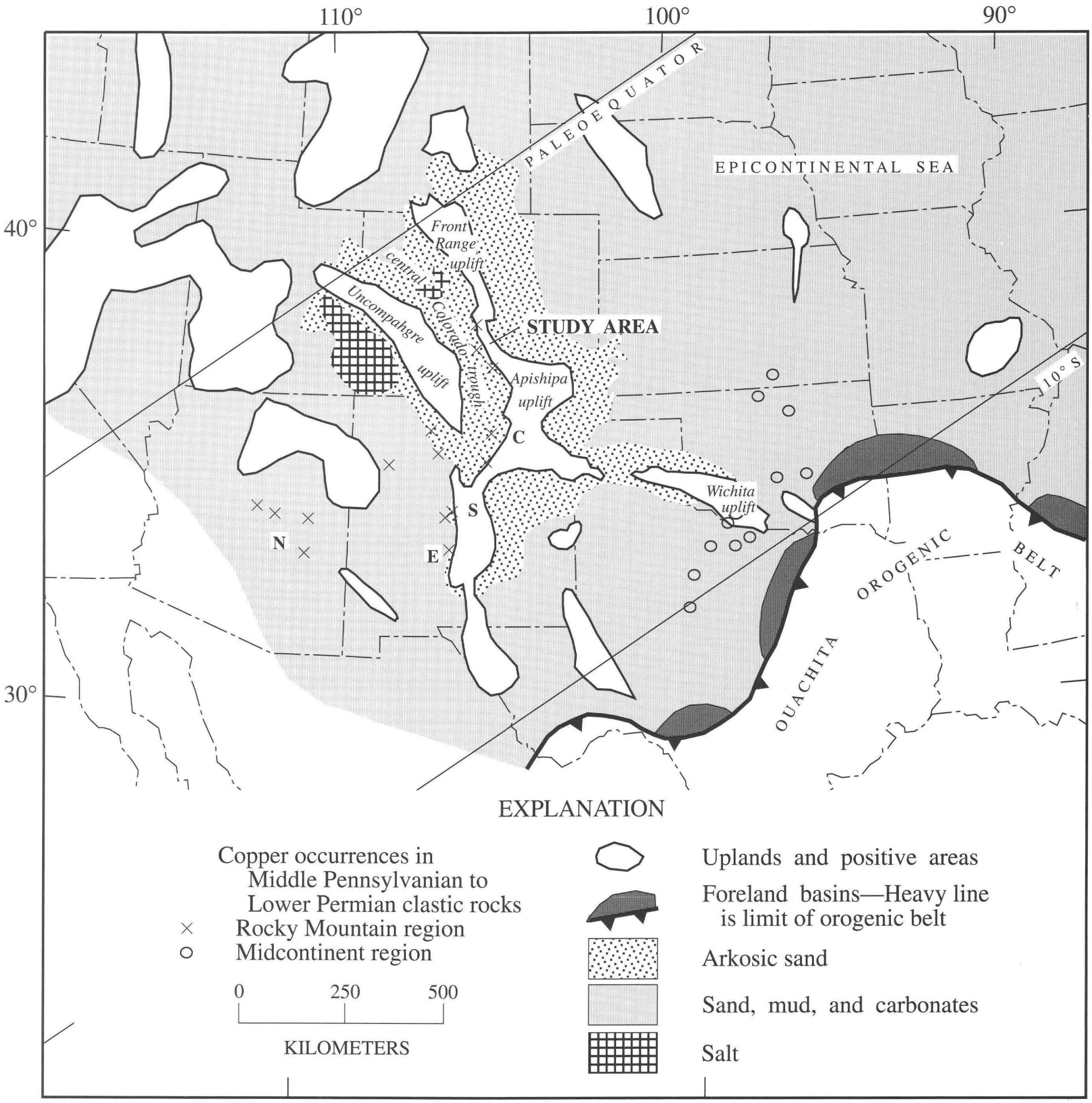

Figure 1. Paleogeographic setting of the Ancestral Rocky Mountains and Ouachita orogenic belt in Middle Pennsylvanian to Early Permian time, and distribution of copper occurrences in rocks of that age. Modified from McKee and others (1975, plates 15B and 15C); paleoequator from Smith and others (1981); distribution of arkosic sand from Mallory (1972) and Dutton (1982). Occurrences of copper in Middle Pennsylvanian to Lower Permian rocks in Arizona and New Mexico as follows: C, Coyote district; E, Estey district; N, general area of occurrences in Naco Formation; S, Scholle district.

The designation "redbed copper" (redbed-hosted copper deposits of Eugster, 1989) is somewhat misleading because, although redbed deposits occur in redbed sandstone sequences, the host beds themselves are mostly gray. Redbed copper deposits are typically found in alluvial or mixed alluvial-marine strata. Sandstone and shale are both common host rocks, and siltstone is a common host in the Sangre de Cristo Range.

Redbed copper deposits tend to be small, local deposits. In contrast, copper-shale (Kupferschiefer-type) deposits, such as those in the Permian Flowerpot Shale (Johnson, 1976) of southwestern Oklahoma and northern Texas and the

Permian Kupferschiefer of Germany and Poland (Vaughan and others, 1989), are laterally extensive and economically important despite the fact that the mineralized interval may be less than a meter thick. Copper-shale deposits tend to occur in rocks that were deposited in restricted-circulation marine settings; they directly overlie redbeds and are closely associated with evaporites (Kirkham, 1989). Both redbed and copper-shale deposits appear to have been localized by a reducing host, and both exhibit features compatible with an epigenetic (early or late diagenetic) origin (see, for example, Jowett and others, 1987, for the Kupferschiefer of Poland; and Ensign and others, 1968, for the White Pine shale-hosted deposit of northern Michigan).

Pennsylvanian and Lower Permian clastic sedimentary rocks in the southern Rocky Mountain and Midcontinent regions contain many occurrences of redbed copper (fig. 1). In the northern Sangre de Cristo Range of Colorado, copper occurs with uranium in the Middle Pennsylvanian Minturn Formation and in the lower part of the Middle Pennsylvanian to Lower Permian Sangre de Cristo Formation (Clark, 1982; Clark and Walz, 1985). In the southern Sangre de Cristo Range of New Mexico, copper occurs with uranium in the lower part of the Sangre de Cristo Formation in the Coyote district (C, fig. 1; Tschanz and others, 1958). Elsewhere in New Mexico, copper occurs at numerous localities in Pennsylvanian and Lower Permian rocks. Occurrences that appear to resemble those of the Sangre de Cristo Range are located in the Lower Permian Abo Formation in the Scholle district (S, fig. 1; LaPoint, 1976; Hatchell and others, 1982) and in the Lower Permian Bursum Formation in the Estey district (E, fig. 1; Bachman, 1968, p. J38–J41). Uranium is reported with copper at some mines and prospects in both the Scholle and Estey districts (Gibson, 1952). In Arizona, uranium and copper occur together in the uppermost part of the Middle and Upper Pennsylvanian Naco Formation (N, fig. 1) and the lower part of the Upper Pennsylvanian and Lower Permian Supai Formation (Peirce and others, 1977).

Known redbed copper deposits in clastic sedimentary rocks of Pennsylvanian and Early Permian age are not currently (1995) economic. Mining has been attempted at scattered localities, with the greatest production (12,340 metric tons of ore at 3.85 percent Cu, and 21.5 grams Ag per metric ton) from the Scholle district in New Mexico (Hatchell and others, 1982), but deposit sizes are generally too small to be economic. The occurrences in the northern Sangre de Cristo Range, described in this report, have had virtually no production (Nelson-Moore and others, 1978).

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We thank D.M. Walz for his assistance in measuring sections and collecting samples in the field and for identifying opaque minerals in polished sections. Mineralized samples were analyzed for major oxides by J.E. Taggart, J.S. Wahlberg, A. Bartel, and J. Baker; for total sulfur and organic carbon by G.T. Mason, Jr., J. Karasik, and V.E. Shaw; for Ag, Co, Cu, Mo, Ni, Pb, V, and Zn by L.A. Bradley, P. Briggs, J.G. Crock, M.J. Malcolm, V.M. Merritt, and G.D. Shipley; and for Th and U by H.T. Millard, Jr., M. Coughlin, S. Danahey, B.A. Keaton, S. Lester, F.M. Lumun, S. Storey, and B. Vaughn. Sandstone samples were analyzed for major oxides by J.S. Mee and D.F. Siems; for Cu, Mo, Pb, and Zn by J.M. Motooka; for Th and U by R.J. Knight; and for other trace elements by E.F. Cooley. R.E. Phillips determined modal mineralogy in thin sections of sandstones. R.A. Zielinski prepared fission-track maps of five thin sections and assisted in interpretation. D.P. Cox and R.A. Zielinski provided comments on drafts of the manuscript. All are, or were at the time work was performed, employees of the U.S. Geological Survey.

PALEOENVIRONMENTAL SETTING

PALEOGEOGRAPHY

The host rocks of copper and uranium in the northern Sangre de Cristo Range—the Minturn and Sangre de Cristo Formations—were deposited in coastal areas and shallow seas in the central Colorado trough (fig. 1). The central Colorado trough lay between the Ancestral Uncompahgre uplift and the Front Range and Apishipa uplifts of the Ancestral Rocky Mountains (fig. 1). The Minturn and Sangre de Cristo Formations comprise a sequence of about 4,000 meters (m) of mostly clastic sediment deposited by prograding fan deltas and alluvial fans (fig. 2) (Lindsey, Clark, and Soulliere, 1986). Subsidence of the trough was sufficient for fan deltas to prograde onto the sea floor during Middle Pennsylvanian time, depositing coarse alluvial sediments and complex intertongued marine limestones and shales in cyclic sequences. Afterward, during Late Pennsylvanian and Permian time, extensive erosion of the Ancestral Rocky Mountains produced great fans of coarse alluvial sediment that spread over the mixed marine-continental fill of the central Colorado trough.

Environmental conditions were essentially similar throughout the Ancestral Rocky Mountains, so that the stratigraphic setting of host rocks for copper and uranium is more or less the same in all basins (fig. 1). The uplift history of most ranges of the Ancestral Rocky Mountains is more or less the same (Kluth, 1986). Most of the region lay within 10° south of the equator during Pennsylvanian and Permian time (Smith and others, 1981; Ziegler, 1989). The climate was probably monsoonal, with arid conditions prevailing on the west sides of ranges (Mack and others, 1979), and it probably became increasingly arid in Permian time (Suttner, 1984). East of the Ancestral Rocky Mountains, a vast epicontinental sea extended from the Ouachita orogenic belt north onto the craton (Heckel, 1977). On the craton, the

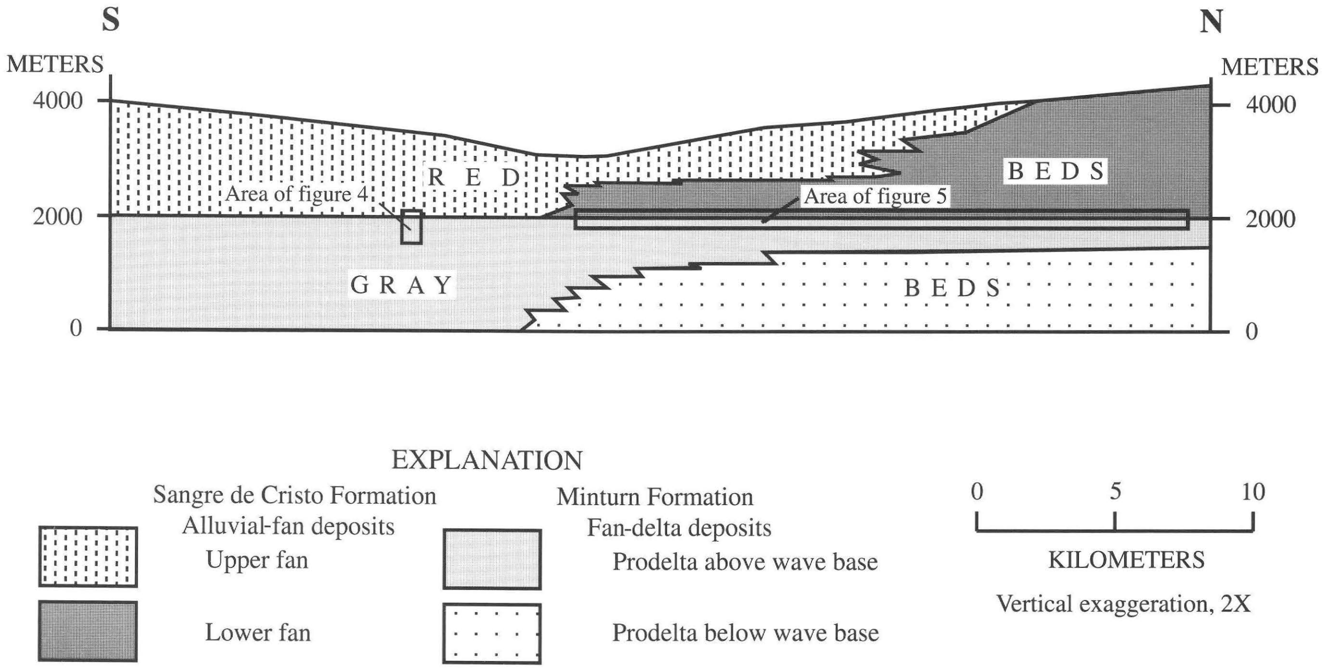


Figure 2. Restored cross section of the Minturn and Sangre de Cristo Formations in northern Sangre de Cristo Range, Colorado (from Lindsey, Clark, and Soulliere, 1986). Section, located as line S–N in figure 3, is parallel to present structural strike and approximately 30° northwest of depositional strike.

red-on-gray sequence of clastic rocks in basins of the Ancestral Rocky Mountains is replaced by cyclic sequences of limestone, shale, and evaporites.

PALEOHYDROLOGY AND REDBED FORMATION

By the end of the Pennsylvanian Period an extensive series of alluvial deposits filled the basins and mantled the eroded uplifts of the Ancestral Rocky Mountains (fig. 1) (Mallory, 1972; McKee and others, 1975, pl. 15). During and after deposition, these sediments must have served as regional aquifers. Oxygenated, relatively fresh ground water flowed through permeable fan deposits while reducing conditions prevailed in saline water derived from compaction of basin sediment. The shape and location of oxidizing-reducing interfaces in intrastratal waters would have been dynamic, depending upon the recharge rate of fresh ground water, the location of permeable zones and reduced sediment, and the thickness of basin fill, among other factors.

Water flowing through fan deposits altered arkosic detritus to a deep red color as it oxidized iron in mafic minerals (Walker, 1967, 1989). Alteration was most intense around the margins of basins, where oxidizing conditions prevailed in intrastratal water. Iron from detrital ferromagnesian minerals such as hornblende and biotite was redeposited as grain coatings and pore fillings of secondary iron oxides or hydroxides. Ultimately, these amorphous iron compounds were converted to finely crystallized hematite that colored the rock red (Walker, 1967, 1989).

The basinward flow of oxidizing water produced redbeds near the highlands of the Ancestral Rocky Mountains. As conditions became more continental during Pennsylvanian and Permian time, oxidizing water reached the centers of basins, extending the zone of reddening through much of the upper basin fill. In the central Colorado trough, the former extent of complete oxidation is marked by a laterally extensive color boundary that in many places corresponds approximately, but not in detail, to the nonmarine Sangre de Cristo Formation–marine Minturn Formation boundary (fig. 2) (Lindsey, Clark, and Soulliere, 1986). Above the red-gray boundary, the Sangre de Cristo was oxidized to redbeds; below the red-gray boundary, the Minturn was oxidized incompletely, so that gray beds predominate over redbeds. Even these gray Minturn beds contain considerable hematite, indicating partial oxidation; and near the basin margin, the Minturn was oxidized completely to redbeds. Most importantly, some carbonaceous beds in the gray Minturn survived oxidation; these beds provided reducing traps for later fixation of metals from mineralizing fluids.

The red-gray color distinction is an important control for copper-uranium deposits in the Pennsylvanian and Permian rocks of the Sangre de Cristo Range. Nearly all of the stratiform occurrences in the northern Sangre de Cristo Range lie within an interval of about 500 m below the major color boundary, and within that interval mineralized lenses are nearly all in gray, carbonaceous beds and lenses. In the southern Sangre de Cristo Range of New Mexico (Coyote district, fig. 1), copper and uranium occur mostly within a 300- to 400-m-thick interval of gray and interbedded red and gray beds (Tschanz and others, 1958). Additional examples of copper and uranium in predominantly gray intervals of Pennsylvanian and Permian rocks are described in the literature of New Mexico and Arizona. In east-central Arizona (fig. 1), copper and uranium are confined to an interval spanning the red-gray transition from the uppermost part of the Middle and Upper Pennsylvanian Naco Formation to the lower part of the Upper Pennsylvanian and Lower Permian Supai Formation (Peirce and others, 1977). In the Scholle district of New Mexico (fig. 1), copper occurs with small amounts of uranium and organic matter in gray shale, siltstone, and sandstone interbedded with redbeds of the lower part of the Lower Permian Abo Formation (LaPoint, 1976). In the Estey district (fig. 1), copper occurs mostly in gray beds within the Abo and the underlying Lower Permian Bursum Formation (Bachman, 1968).

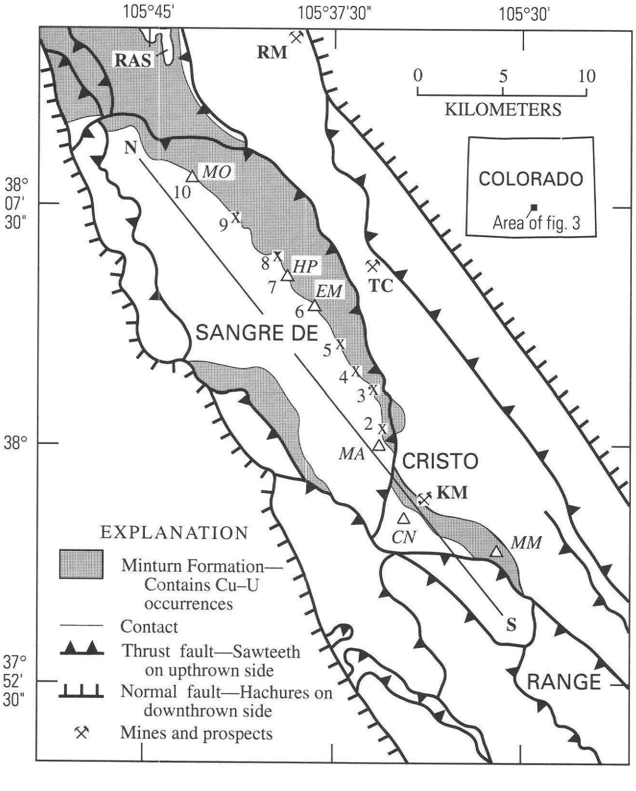


Figure 3. Generalized geologic setting and location of sediment-hosted copper-uranium occurrences in the northern Sangre de Cristo Range, Colorado. Line S–N is cross section of figure 2; numbered localities 2–10 are measured sections of figure 5. Peaks referenced in text are: CN, Crestone Needle; EM, Eureka Mountain; HP, Hermit Peak; MA, Mt. Adams; MM, Marble Mountain; MO, Mt. Owen. Mines and prospects are: KM, King Midas claims; TC, Middle Fork Taylor Creek prospects; RM, Rita Alta mine. RAS, Rito Alto stock.

SAMPLING AND ANALYTICAL METHODS

Mineralized and potentially mineralized beds in the Minturn and Sangre de Cristo Formations were sampled in measured sections (Clark and Walz, 1985). Using a hand-held gamma-ray scintillometer to guide sampling, composite chip samples weighing about 400–500 grams (g) were collected from approximately 0.3- to 1-m intervals representing individual beds or lenses. Most samples were from outcrops, but a few prospects were sampled. A total of 120 samples were collected and analyzed for major oxides, C, S, metals, Th, and U (table 1). Of these, 98 samples contained at least 50 parts per million (ppm) Cu or 30 ppm U and, based on inspection of the data, were considered mineralized; 22 samples were determined to be unmineralized. Of the 98 mineralized samples, 65 are from the King Midas claims and the area between Mt. Adams and Mt. Owen (fig. 3). Data from these samples are the basis for this report. In addition, some copper prospects in veins are described but not sampled.

Arkosic sandstones from measured sections (Lindsey and Schaefer, 1984; Lindsey and others, 1985; and D.A. Lindsey, unpub. data) across the entire thickness of the Minturn and Sangre de Cristo Formations were also sampled to determine geochemical background. All samples are single hand specimens weighing about 200–300 g and were collected from outcrops. A total of 50 samples of sandstone was collected, of which 42 were accepted for determination of background. The other eight samples were rejected because they were collected from a section within 2 kilometers (km) of the Rito Alto stock and contained anomalous concentrations of trace metals. Of the 42 samples, 18 are distinctly red and 24 are pale pink to gray in color. All samples were analyzed for major oxides, metals, Th, and U (table 1). Thin sections of all but four samples were examined. Typically, sandstones of the Minturn and Sangre de Cristo Formations contain abundant feldspar and a chloritic matrix.

Although most analytical methods used for the two sample sets are the same, some differ somewhat because the unmineralized samples were analyzed about 10 years later than the mineralized samples. Mineralized samples only were analyzed for total sulfur by the combustion method and for organic carbon. Organic carbon was determined by difference between total carbon (analyzed by combustion) and carbonate carbon (method of coulimetric cell collection and colorimetric titration) (Jackson and others, 1987). Mineralized samples were analyzed for Ag, Co, Cu, Mo, Ni, Pb, V, and Zn by inductively coupled plasma–atomic emission spectroscopy (ICP–AES) (Lichte and others, 1987). Unmineralized sandstones were analyzed for Cu, Mo, Pb, and Zn by the ICP–AES method also, but other trace metals, including Ag, Co, Ni, and V, were determined by the six-step semi-quantitative spectrographic method (Golightly and

Table 1. Chemical composition of sampled mineralized rocks (40 siltstones, 14 sandstones, 8 shales, and 3 silty limestones) compared to that of unmineralized sandstones, Minturn and Sangre de Cristo Formations

[Sample localities shown on figs. 3, 4, and 5. Fe_TO_3, total Fe as Fe_2O_3; LOI, loss on ignition; C_{CO_3}, carbonate carbon; C_{Org}, organic carbon; S_T, total sulphur; leaders (- -), not analyzed; <, less than]

Oxide or element	Mineralized rocks Median	Mineralized rocks Range[1]	Unmineralized sandstone Median	Unmineralized sandstone Range
Concentration in weight per cent				
SiO_2	58.6	51.8-68.7	66.8	59.2-80.1
Al_2O_3	16.5	13.6-19.6	13.7	9.35-16.2
Fe_TO_3	5.95	3.87-8.61	5.13	1.91-7.95
MgO	4.07	2.45-6.20	2.73	0.27-4.64
CaO	0.86	0.43-5.55	0.69	0.08-6.95
Na_2O	2.28	0.37-3.04	2.88	0.58-4.27
K_2O	3.91	2.51-5.73	3.32	2.37-4.70
TiO_2	0.84	0.46-1.14	0.57	0.18-1.06
P_2O_5	0.28	0.15-0.46	0.16	0.05-0.51
MnO	0.09	0.04-0.21	0.08	0.02-0.22
LOI	4.32	2.76-7.60	2.67	0.75-6.07
C_{CO_3}	<0.01	<0.01-0.63	- -	- -
C_{Org}	0.40	<0.02-1.77	- -	- -
S_T	0.04	<0.01-0.48	- -	- -
Concentration in parts per million				
Ag[2]	<1	<1-16	- -	- -
As	5.7	0.7-26	- -	- -
B	52	10-150	100	10-700
Ba	957	196-3,400	1,000	300-5,000
Co	16	6-34	15	3-50
Cr	61	21-679	70	7-300
Cu	161	2-8,500	6.2	0.4-34
La	- -	- -	50	30-200
Mo[3]	5	<2-43	0.13	<0.05-0.68
Ni	30	7-61	20	5-50
Pb	51	5-7,480	5	1-21
Sc	- -	- -	20	7-30
Sr	- -	- -	100	70-500
Th[4]	14.3	7.3-30.1	7.3	3.8-15.6
U	52.7	3.55-1,080	2.68	0.83-7.85
V	110	38-1,730	100	50-200
Y	- -	- -	30	10-300
Zn	100	45-520	55	13-130

[1] Three limestone samples omitted from range of major oxides.

[2] Only 26 mineralized rocks analyzed for silver.

[3] Detection limits differ for mineralized rocks (<2 ppm) and unmineralized sandstone (< 0.05 ppm).

[4] Only 17 valid measurements of thorium concentration among mineralized rocks because of high values for uranium. All other mineralized rocks determined as "less than" values.

others, 1987). Detection levels and reporting intervals are different for the two methods. Values determined by the six-step method are reported in six logarithmic classes per decimal place in the series 1, 1.5, 2, 3, 5, 7, 10, and so forth. Thorium and uranium were determined by the delayed neutron method (McKown and Millard, 1987) for both mineralized and unmineralized rocks. Finally, all samples were analyzed for major oxides by wavelength-dispersive X-ray fluorescence spectrometry (Taggart and others, 1987).

No investigation of analytical or sampling error was made. Previous investigations (for example, Lindsey, 1985, table 3) show that, for mineralized samples, analytical error (including errors due to preparing and splitting the sample for analysis) for metals accounts for only a small part of total variation. Sampling error (local variation) may account for a large proportion of the total variation in mineralized samples. Although local variation is a handicap to precise estimation of average values at individual sample sites, such variation is useful in studying covariation among elements. Lower limits of detection, where encountered during analysis, are indicated in table 1.

DESCRIPTION OF COPPER-URANIUM OCCURRENCES

All of the occurrences of copper and uranium in the northern Sangre de Cristo Range described here are stratiform deposits in the Minturn Formation and the lowermost Sangre de Cristo Formation; most are within the upper 500 m of the Minturn Formation. Many occurrences have been explored by shallow prospect pits. Two groups of occurrences are described to illustrate typical sedimentary facies of host rocks for stratiform copper and uranium (figs. 2 and 3). These groups are located in the upper part of the Minturn Formation at the King Midas claims (at the foot of Crestone Needle, east side) and in the upper part of the Minturn from Mt. Adams to Mt. Owen. Small, structurally controlled veins in the Sangre de Cristo Formation are discussed separately at the end of this section.

Most stratiform copper-uranium deposits in the northern Sangre de Cristo Range are in dark-gray siltstone, and less commonly in fine-grained gray sandstone, silty limestone, and shale. Most of the host rocks contain carbonaceous plant remains; some contain marine fossils but many do not. Mineralized rock commonly contains tiny pyrite tetrahedra, rusty spots of oxidized pyrite, and, less commonly, yellow secondary uranium minerals (radioactive, but unidentified), malachite, and azurite. The principal copper minerals, visible only under the microscope, are disseminated chalcopyrite and chalcocite; bornite and covellite were identified in a few samples. The host of uranium is organic matter, although the presence of primary uranium minerals cannot be excluded. Fission-track maps confirm the tendency for uranium to concentrate in carbonaceous matter and reveal no obvious point sources of radiation that might indicate discrete grains of uranium minerals. Radioactivity, as measured by scintillometer, is commonly 100–200 counts per second (cps) but almost never more than 2,000 cps; background is about 50 cps.

KING MIDAS CLAIMS

Lenses of mineralized siltstone in the upper part of the Minturn Formation have been explored by numerous prospects at the King Midas claims (KM, fig. 3), located on the east side of the foot of Crestone Needle. The King Midas claims produced only 0.22 short tons (0.20 metric tons) of ore at an average grade of 0.39 percent U_3O_8 (Nelson-Moore and others, 1978, p. 122); copper is present but evidently was not recovered. The main adit, located on the lower east slope of the ridge running northwest to Crestone Needle, intersects and follows gray-black radioactive siltstone and small quartz veins (Ellis and others, 1983, p. 96). At the surface, the mineralized siltstone is seen to consist of a number of individual beds separated by thin beds of sandstone (fig. 4, left section). The thickest mineralized siltstone bed is as thick as 3 m at the surface and is correlated with a thinner, similar bed 500 m northwest (fig. 4, right section). A small tear fault of probable Laramide age offsets the bed. Prospect pits have been dug in radioactive siltstone beds located along strike to the northwest.

Most mineralized beds on the claims are 1–3 m thick and extend for 100–300 m along strike; these dimensions indicate that each mineralized bed contains about 1,000–2,000 metric tons of rock or less. Metal values in siltstone exclusive of vein quartz range from 28 to 5,400 ppm Cu and 20 to 227 ppm U among 10 analyses from 8 mineralized beds; the average grade of these beds is only about 0.085 percent Cu and 0.010 percent U_3O_8.

The main mineralized bed above the King Midas adit is composed of 3 m of shaly siltstone containing plant remains and rusty spots; a middle interval, 1 m thick, contains calcareous nodules having lower metal values than the surrounding rock. No marine fossils were found. The mineralized bed overlies red conglomeratic sandstone of braided alluvial origin that, together with the siltstone, forms a fining-upward cycle of sediment deposited on an alluvial fan. The siltstone is interpreted to have been deposited in a wetland depression on the fan surface. Two overlying fining-upward cycles of conglomeratic sandstone and radioactive siltstone are also interpreted as alluvial cycles ending in wetland deposition.

Some fining-upward cycles at the King Midas claims are overlain by impure silty limestone containing marine fossils (fig. 4), indicating that these alluvial cycles ended with marine submergence. Some silty limestones are mineralized; others grade into mineralized (anomalously radioactive) siltstone above or below.

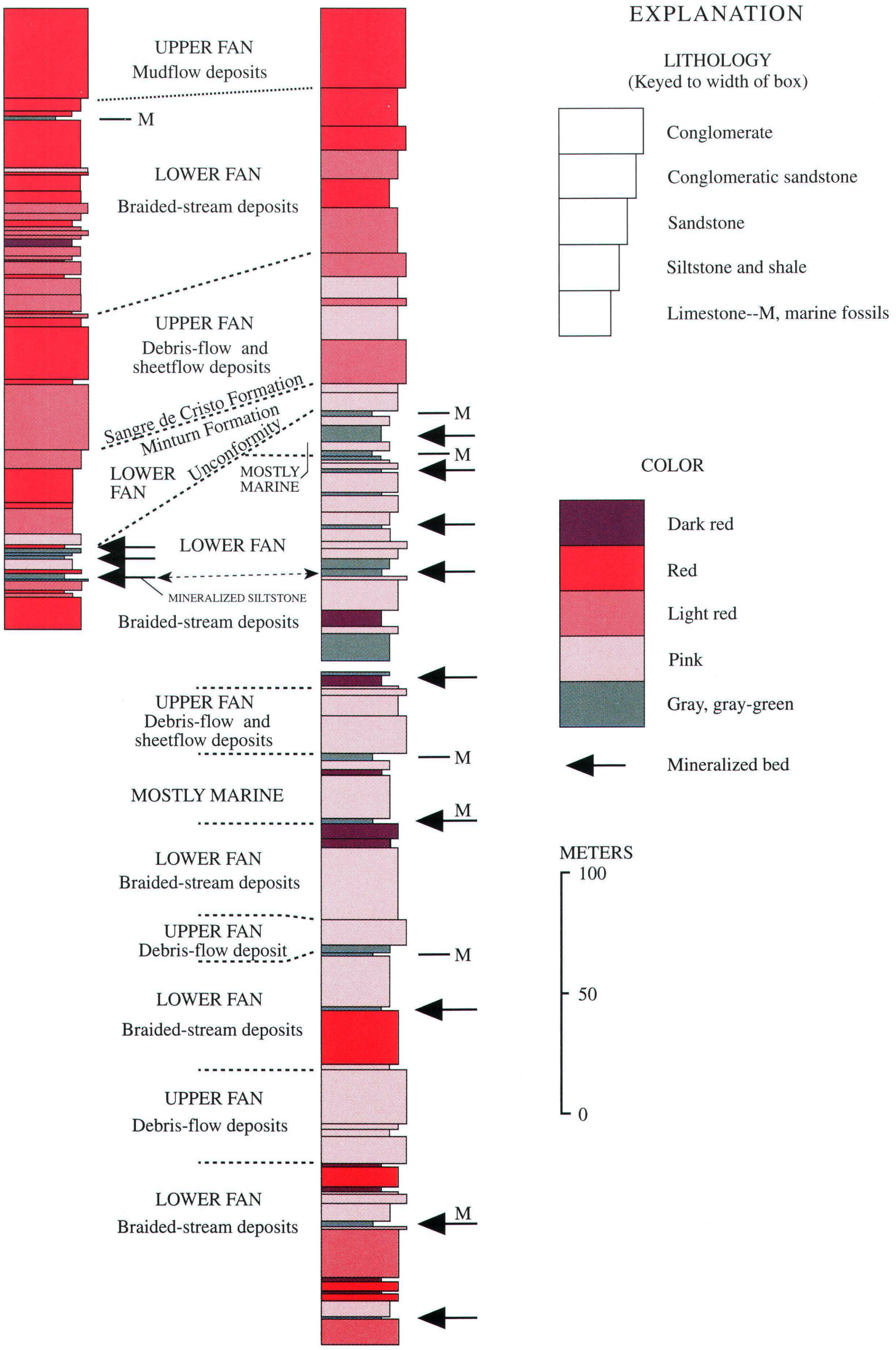
Study of the two measured sections at the King Midas claims (fig. 4) reveals that typical alluvial cycles in the upper Minturn Formation at Crestone Needle consist of (1) a coarse channel-filling conglomerate deposited by floods and debris flows, (2) cross-bedded conglomeratic sandstone deposited in braided channels and on fan surfaces, (3) lenses of shaly siltstone deposited in local wetland depressions on the fan surface, and (4) sporadic beds of impure limestone, shale, and siltstone deposited in shallow-marine environments between fan distributaries. Rocks of environments (3) and (4) are typically reduced (gray-black in color) and contain fragmentary plant remains; many are mineralized. Rocks of facies (1) and (2) are partly to completely oxidized (pink to red color) and are not mineralized. Alternating torrential alluvial and shallow-marine conditions, represented by interbedded debris-flow conglomerate and marine limestone, respectively, indicate that alluvial-fan and marine environments were telescoped together. Such telescoped depositional environments yielded lenticular siltstone bodies capable of hosting small, local copper-uranium deposits. Local unconformities contribute further to the lenticular geometry of host rocks.

MT. ADAMS TO MT. OWEN

Copper and uranium occur in anomalous amounts for more than 18 km along the top of the Minturn Formation from Mt. Adams to Mt. Owen (fig. 5) (Clark and Walz, 1985). These occurrences have been prospected locally, such as at the now-caved Mercury prospect, located 300 m north of the summit of Hermit Peak (fig. 3). Mineralized rocks occur at three stratigraphic intervals, listed in descending order: (1) numerous thin lenses of mineralized siltstone and sandstone scattered throughout a distinctive interval of gray to pink cross-bedded sandstone and siltstone, 36–81 m thick, that extends for more than 18 km along strike, (2) variably mineralized siltstone and shale, 1–2 m thick, that extends along strike for about 11 km, and (3) weakly mineralized lenses of siltstone and shale in the upper 500 m of the Minturn Formation. The cross-bedded sandstone and siltstone (interval 1) is located directly above a widespread marine marker limestone bed and directly beneath the Sangre de Cristo Formation; the mineralized siltstone and shale (interval 2) is located immediately below the marker bed of marine limestone.

Some estimates of tonnage and grade, based on reconnaissance sections and limited analytical data, are given to provide a general sense of the amount of mineralized rock. Average grades were estimated by calculating weighted means, dependent upon the tonnage of rock represented by adjacent analyses. Despite high local variation and the very limited number of analyses, estimates of the average grade of mineralized rock above and below the marker limestone are remarkably consistent. Both mineralized intervals have very low grades and low tonnages compared to economic deposits. No estimates of grades and tonnages were made for scattered mineralized lenses of interval 3, below the marker limestone. The range of values for copper and uranium in interval 3 is about the same as for intervals 1 and 2.

Scattered lenses of mineralized siltstone and sandstone in interval 1 (fig. 5) are about 1–4 m thick and less than 100 m in strike length. They make up as much as 8 percent of nine measured sections along a strike length of 18 km;


UPPER FAN
Mudflow deposits
M
LOWER FAN
Braided-stream deposits
UPPER FAN
Debris-flow and sheetflow deposits
Sangre de Cristo Formation
Minturn Formation
Unconformity
LOWER FAN
MOSTLY MARINE
LOWER FAN
MINERALIZED SILTSTONE
Braided-stream deposits
UPPER FAN
Debris-flow and sheetflow deposits
MOSTLY MARINE
LOWER FAN
Braided-stream deposits
UPPER FAN
Debris-flow deposit
LOWER FAN
Braided-stream deposits
UPPER FAN
Debris-flow deposits
LOWER FAN
Braided-stream deposits
M
M
M
M
M
M
EXPLANATION
LITHOLOGY
(Keyed to width of box)
Conglomerate
Conglomeratic sandstone
Sandstone
Siltstone and shale
Limestone--M, marine fossils
COLOR
Dark red
Red
Light red
Pink
Gray, gray-green
Mineralized bed
METERS
100
50
0

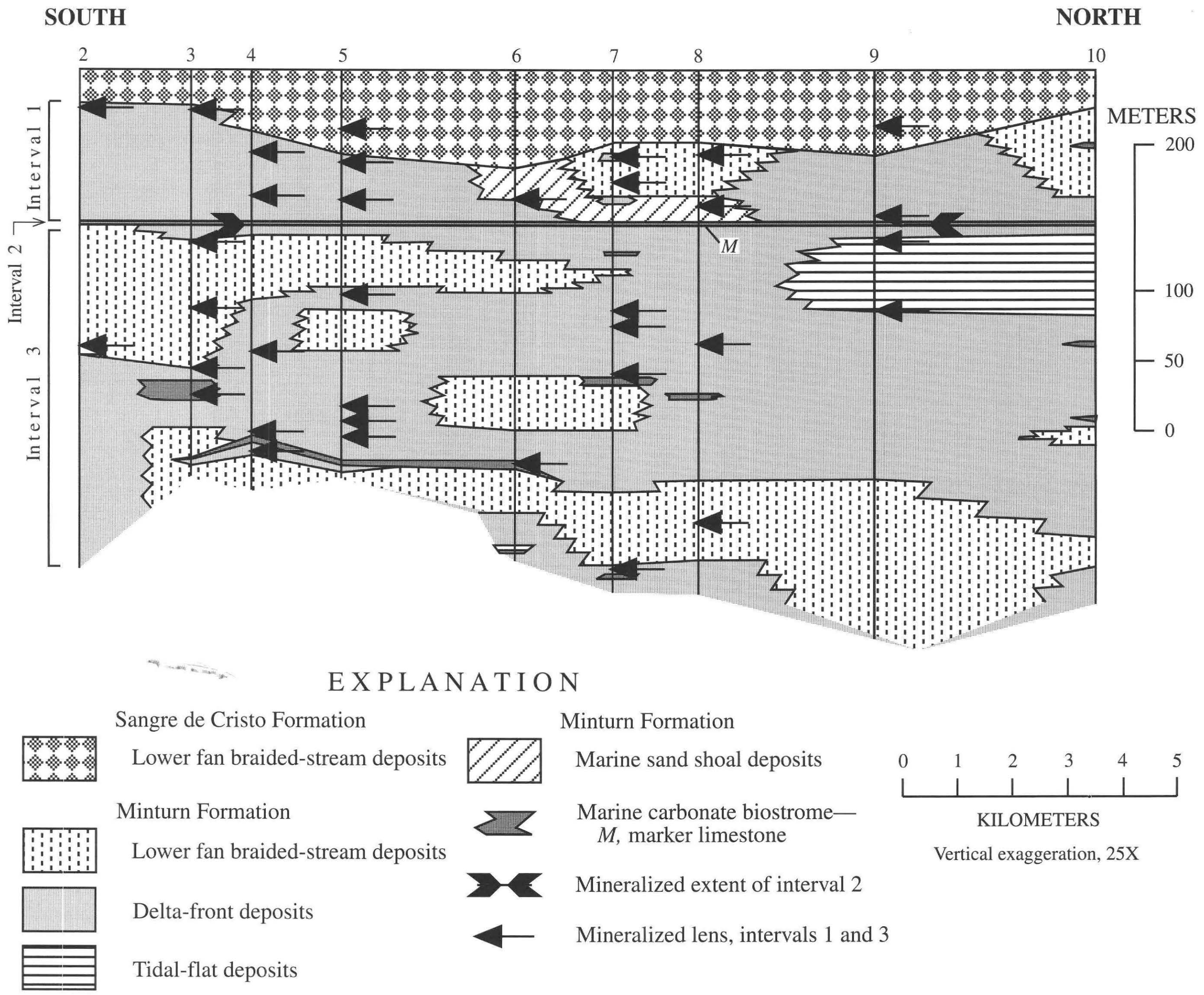


Figure 5. Distribution of mineralized rock and general depositional environments in the upper part of the Minturn Formation and lowermost Sangre de Cristo Formation, Mt. Adams to Mt. Owen, Colorado. Mineralized lenses (arrows) shown only on lines of measured sections. Sections based on Clark and Walz (1985); numbers correspond to their sections, located on figure 3.

however, no mineralized lenses were found in two sections. Analysis of 10 composite samples, each from a different mineralized lens, yielded a range of 30–8,500 ppm Cu and 4–951 ppm U; median values were about 100 ppm Cu and 135 ppm U. Assuming a downdip extension of 1 km, the aggregate amount of rock in mineralized lenses is estimated at about 1 million metric tons and the estimated average grade (arithmetic mean value) is 0.026 percent Cu and 0.025 percent U_3O_8.

Figure 4 (facing page). Distribution of mineralized rock, general depositional environments, and rock color in measured sections at the King Midas claims, Crestone Needle, Colorado. Left section begins at main adit, end of jeep trail; right section located on ridge approximately 500 m north of adit.

The distinctive gray to pink cross-bedded sandstone and siltstone of interval 1 was divided into three facies: marine sandstone (interpreted as sand-shoal deposits by Clark and Walz, 1985), delta-front and prodelta marine sandstones, and braided alluvial sandstones (fig. 5). Mineralized lenses of gray silty, limey, shaly, and, less commonly, sandy rock are found in each facies. The lenses are typified by two that occur about 5 and 30 m below the top of the Minturn Formation on Hermit Peak. The upper lens is composed of calcareous siltstone in delta-front deposits; it contains abundant plant remains and molds of brachiopods and crinoid columnals. The lower lens is composed of sandstone within otherwise unmineralized pink arkosic sandstone beds interpreted as braided-stream deposits. A composite sample of the upper siltstone lens yielded 2,500 ppm Cu but only 14 ppm U, even though the lens is anomalously radioactive (300 cps). A composite sample of the mineralized sandstone lens contained 426 ppm Cu and 209 ppm U.

Mineralized siltstone and shale of interval 2 (fig. 5) may contain about 500,000 metric tons at a possible average grade of 0.025 percent Cu and 0.025 percent U_3O_8. Analyses of seven composite samples from six localities along the 11-km strike length of the bed (sections 4–9, fig. 5) gave wide ranges of 86–537 ppm Cu and 6–728 ppm U, making estimates of grade error-prone. Although the mineralized interval is anomalously radioactive at many places and can be traced with a scintillometer, it may not be completely continuous. Median values are about 190 ppm Cu and 105 ppm U, well above those for some samples analyzed, and average values representing grade are even higher owing to the presence of individual high values. Tonnage was calculated assuming a conservative downdip extension of 1 km. Actual downdip extension might be 3–4 km, which would yield a tonnage three to four times that given.

Dark-gray siltstone and shale of interval 2 contains carbonaceous plant remains and was probably deposited in a delta-front environment (Clark and Walz, 1985). It is overlain by a continuous marker limestone that contains shallow-marine fossils, including crinoid columnals, brachiopods, and stromatolites. Commonly, the mineralized interval extends into the lower, silty part of the marker limestone, but at some localities the mineralized interval is separated from the marker limestone by as much as 1 m of unmineralized gray-pink arkosic sandstone. At sections 4 and 9 (fig. 5), the mineralized interval extends into sandstone below. At section 6, only the lower, silty part of the marker limestone is mineralized; the beds immediately below have been oxidized red and are unmineralized. Evidently, mineralized interval 2 transects bedding slightly. The overall continuity of the mineralized interval is due to deposition of laterally extensive carbonaceous siltstone and shale in a marine environment and preservation from later erosion. Subsequent deposition by aggrading fan deltas and streams assured preservation.

Below the marker limestone, braided alluvial sandstones and conglomerates of interval 3 are intertongued with delta-front, prodelta, and tidal-flat sandstones, siltstones, and shales and thin marine carbonate biostromes (fig. 5). These rocks were deposited in fining-upward cycles by prograding fan deltas in the Minturn Formation (Lindsey and others, 1985). Thin (1–2 m) mineralized lenses of siltstone and some shale are scattered throughout the upper Minturn; 21 such lenses were mapped below the marker limestone (fig. 5) and many others doubtless occur between sections. Within this interval, mineralized lenses occur in every depositional environment from braided alluvial to marine biostrome. The lenses themselves commonly extend only a few hundred meters, but they appear to be almost as numerous as those above the marker limestone, and in nearly the same variety of depositional environments.

A mineralized lens in the upper part of the Minturn Formation at an elevation of 12,300 feet on the east spur of peak 13,325, located about 1 km northeast of Mt. Adams, is noteworthy for a clearly interpretable sequence of depositional environments and for localization in carbonaceous host rock (fig. 6). The depositional sequence consists of delta-front sandstones containing marine invertebrate fossils and rare shark's teeth, gray stromatolitic calcareous shale deposited in the intertidal zone, the mineralized lens of dark-gray to black carbonaceous shale deposited in nearshore wetlands, and red braided alluvial sandstones arranged in fining-upward cycles. Trunks of *Calamites* occur in place, still rooted in the wetland shale and enveloped by overlying alluvial sand that inundated them. The mineralized shale contains about 1 percent organic carbon and as much as 1,470 ppm Cu. Malachite stains are visible on the outcrop. Lead (324 ppm) is also anomalous.

Nearly all of the mineralized localities (in all three intervals) between Mt. Adams and Mt. Owen are located in gray (or a color variant of gray) beds in the upper part of the Minturn Formation. A few occurrences were found in thin gray siltstone and shale interbedded with redbeds of the lower Sangre de Cristo Formation. Only near Mt. Owen are the principal mineralized beds located in the lowermost part of the Sangre de Cristo Formation (above the level of section in fig. 5); there, gray marine strata interfinger with red fluvial strata of the Sangre de Cristo Formation. Where redbeds are locally abundant in the upper Minturn, as for example within a 50-m interval located immediately below the marker limestone at section 6, no mineralized beds were found.

COPPER IN VEINS

Quartz and metal sulfide veins containing copper minerals cut redbeds of the Sangre de Cristo Formation at a variety of locations in the northern Sangre de Cristo Range. Principal localities (fig. 3) are (1) quartz veins at the King Midas claims (KM), (2) quartz veins with malachite and azurite in the Middle Fork of Taylor Creek (TC), and (3) copper-iron sulfides in quartz-barite veins at the Rita Alta Mine (RM). All of these veins fill fractures; veins at the Rita Alta Mine occur in fractures located at the crests of folded beds. Many of the veins do not contain detectable uranium.

The fracture-filling relation of copper-bearing veins indicates that their formation postdates Laramide deformation, and may even be contemporary with late Oligocene to recent Rio Grande rifting. Thus, their origin has little bearing on that of the redbed copper-uranium deposits described above. Although these vein deposits offer the possibility for collection of fluid-inclusion data on temperatures and salinities, such data would be irrelevant to the origin of the redbed deposits. The veins are described briefly here to substantiate their post-redbed-copper interpretation.

Small quartz veins occupy fractures in the upper part of the Minturn Formation at the King Midas claims. A small

Figure 6. Sequence of depositional environments for mineralized shale of the upper part of the Minturn Formation. From bottom to top of picture, marine sandstone (m), stromatolitic limestone (ls) and shale of tidal-flat environment, mineralized shale (sh) of nearshore wetland environment, and braided alluvial sandstone (ss). Man is pointing to *Calamites* trunk, rooted in coastal swamp shale. Note stromatolite (s) structure in sample, left foreground. Located at lowermost mineralized lens shown on section 2, figure 5.

tear fault of probable Laramide age passes within a few meters of the main adit. Quartz veins collected underground contained small amounts of copper (as malachite) and uranium (Ellis and others, 1983, p. 96).

Fractures filled with quartz, calcite, and malachite (as observed in adits and samples on prospect dumps) in the Sangre de Cristo Formation in the Middle Fork of Taylor Creek are typical of fracture-controlled copper mineralization observed at scattered localities in the northern Sangre de Cristo Range. No primary (sulfide) minerals and no anomalous radioactivity have been observed there. At the Taylor Creek prospects, sandstone beds of the Sangre de Cristo Formation have been rotated to near-vertical position and extensively fractured and sheared during emplacement of the superjacent Laramide Spread Eagle Peak thrust plate. The Taylor Creek veins are located only 3–4 km south of the Verde Creek area, which contains many quartz-chalcopyrite-galena-barite veins of probable hydrothermal origin in fractured and faulted Precambrian rocks (Ellis and others, 1983, p. 18, 80–84).

Veins at the Rita Alta Mine (Bagg, 1908) occur in both steeply dipping and flat fractures in the hinge of a small anticline between two larger folds; clearly, the Rita Alta deposit postdates Laramide folding. The steep fractures in the anticlinal hinge may represent local extension in the crest of the anticline during folding; the flat fractures developed perpendicular to the minimum direction of stress during folding. Fractures of both orientations are filled with barite, quartz, chalcopyrite, pyrite, bornite, and sparse azurite (Ellis and others, 1983, p. 57).

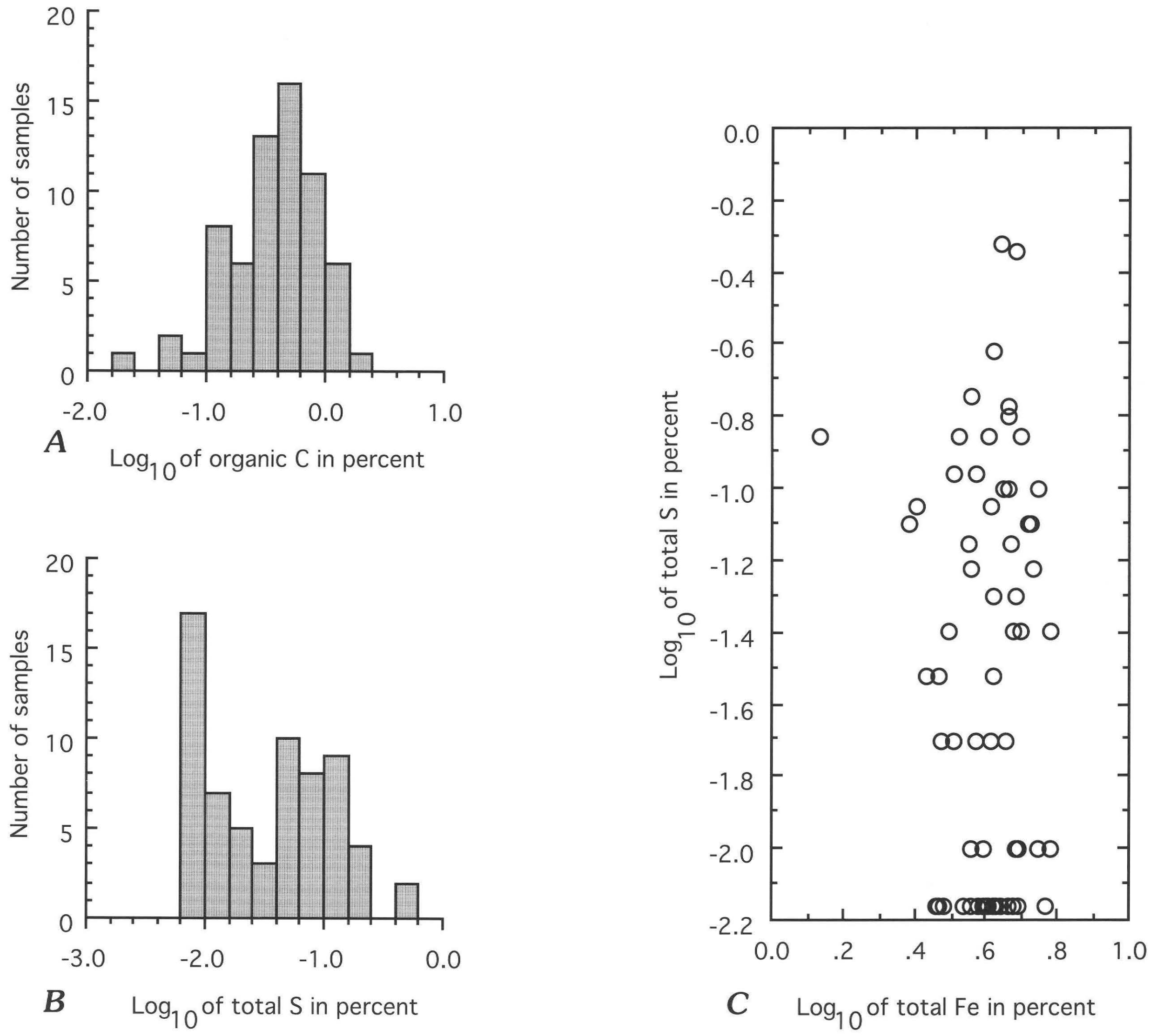


Figure 7. Frequency distributions for *A*, organic carbon and *B*, total sulphur, and *C*, scattergram showing total sulphur versus total iron in mineralized rocks of the Minturn and Sangre de Cristo Formations. Total iron calculated from total Fe as Fe_2O_3.

CHEMICAL COMPOSITION

COMPOSITION AND CLASSIFICATION OF MINERALIZED ROCKS

The major-element composition of mineralized rocks sampled from the Minturn and Sangre de Cristo Formations is mostly comparable to that of unmineralized sandstones (table 1) even though the mineralized rocks (40 siltstones, 14 sandstones, 8 shales, and 3 silty limestones) are finer grained. Both groups are chemically and texturally immature, contain abundant feldspar and chlorite, and contain comparable amounts of Al_2O_3, CaO, total Fe as Fe_2O_3, Na_2O, K_2O, and MnO. Although the median value of SiO_2 is lower for mineralized rocks and medians for MgO, TiO_2, and P_2O_5 are higher by roughly one and one-half to two times, the ranges of these oxides overlap. Large differences in pre-mineralization metal content between the two groups would not be expected.

Mineralized rocks are not particularly rich in organic carbon (median value of 0.40 percent, range of <0.02–1.77 percent) or total sulphur (median value of 0.04 percent, range of <0.01–0.48 percent) (table 1). Most organic carbon values are below 1 percent ($\log_{10}$ value of 0, fig. 7*A*). The frequency distribution of total sulphur is bimodal (fig. 7*B*), with the lower mode below the limit of detection at <0.01 percent ($\log_{10}$ value of –2) and the higher mode at 0.1 percent ($\log_{10}$ value of –1). Low values for sulphur and lack of correlation between sulphur and iron indicate that only a small part of total iron is present as pyrite (fig. 7*C*). Also, sulphur probably occurs as sulfate in some mineralized rocks and thus is not in pyrite. Preservation of both organic carbon and pyrite in some mineralized rocks, however, indicates local isolation from oxidizing fluids.

Comparison of the metals content of mineralized rocks with that of unmineralized sandstone in the Minturn and Sangre de Cristo Formations (table 1) reveals anomalous values for Cu, Mo, Pb, Zn, V, and U. Silver values above 1 ppm in mineralized rocks are probably also anomalous because silver is seldom detected at that level in unmineralized rocks; however, no data for comparison with unmineralized sandstone are available. Median values (and ranges) for mineralized rocks are 161 (2–8,500) ppm Cu, 5 (<2–43) ppm Mo, 51 (5–7,480) ppm Pb, 52.7 (3.55–1,080) ppm U, 110 (38–1,730) ppm V, and 100 (45–520) ppm Zn (table 1). Although the median value for vanadium is near the background level of unmineralized sandstone (100 ppm), maximum metal values are clearly anomalous. Anomalous values for cobalt, which occurs in some sediment-hosted copper deposits (Kirkham, 1989), were not found in the Sangre de Cristo occurrences.

The values for copper and uranium in mineralized rocks (2–8,500 ppm Cu, 3.55–1,080 ppm U) are nearly all above those for unmineralized sandstone (0.4–34 ppm Cu, 0.83–7.85 ppm U) (figs. 8*A–D*). The frequency distribution of copper in mineralized rocks is skewed toward high values approaching 10,000 ppm ($\log_{10}$ value of 4) Cu (fig. 8*A*). The frequency distribution of uranium in mineralized rocks has modes at about 10, 100, and perhaps 1,000 ppm ($\log_{10}$ values of 1, 2, and 3, respectively, fig. 8*C*); all are above background. In contrast to mineralized rocks, frequency distributions for copper and uranium in unmineralized sandstone are leptokurtic and nearly symmetrical, with no anomalously high values (figs. 8*B*, *D*). As noted in the "Sampling and analytical methods" section, rocks were considered mineralized if they contained at least 50 ppm Cu or 30 ppm U, but not necessarily both. These threshold values are above the range of background values for unmineralized sandstone (figs. 8*B*, *D*) and roughly 10 times median background values, thus making inclusion of unmineralized rocks unlikely.

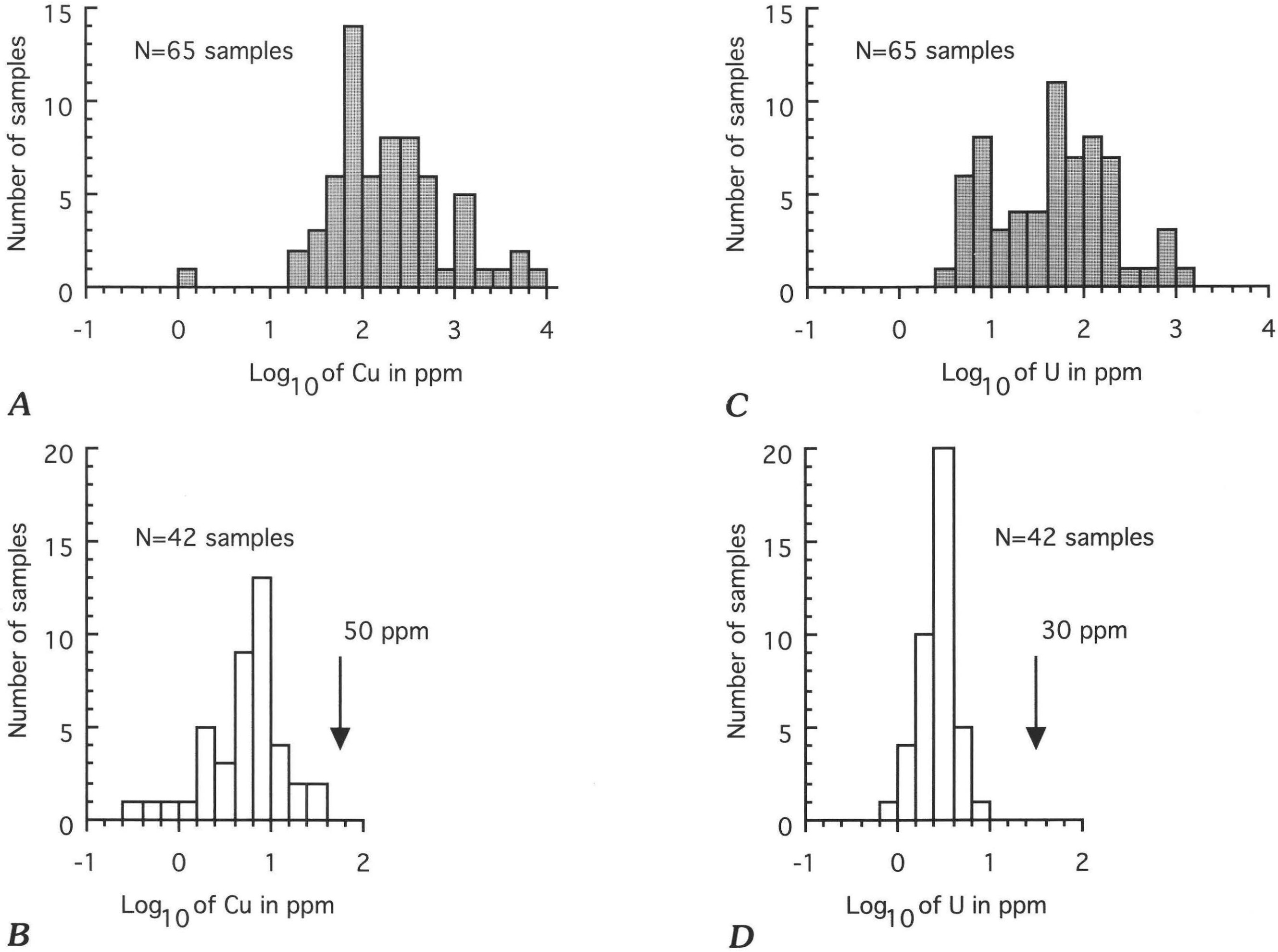


Figure 8. Frequency distributions for *A*, copper in mineralized rocks, *B*, copper in unmineralized sandstones, *C*, uranium in mineralized rocks, and *D*, uranium in unmineralized sandstones of the Minturn and Sangre de Cristo Formations.

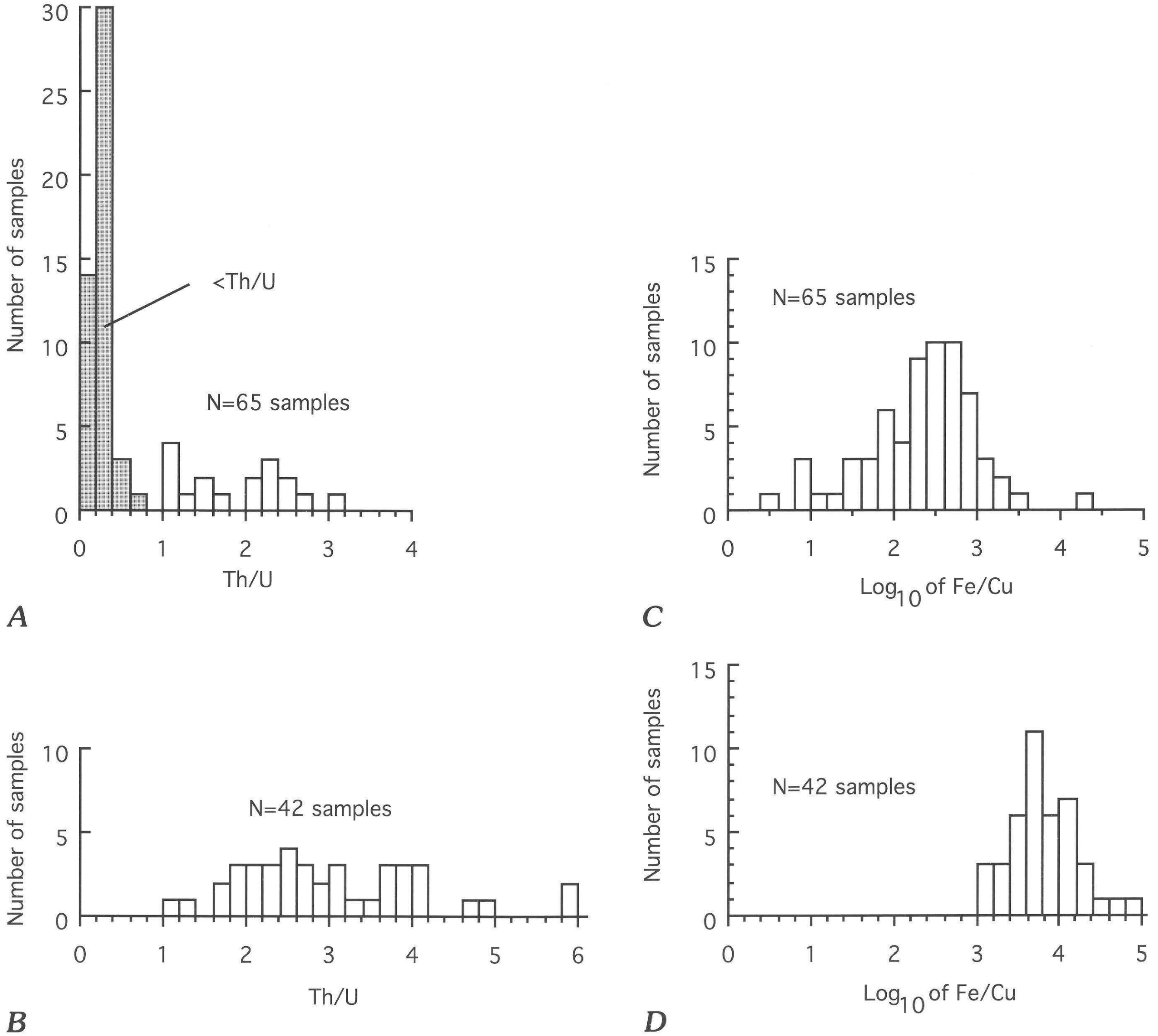


Figure 9. Frequency distributions for *A*, Th/U in mineralized rocks, *B*, Th/U in unmineralized sandstones, *C*, Fe/Cu in mineralized rocks, and *D*, Fe/Cu in unmineralized sandstones of the Minturn and Sangre de Cristo Formations.

Evidence for enrichment (or depletion) of copper and uranium in mineralized rocks and unmineralized sandstones was examined by means of ratios. Ratios have advantages over values for individual elements in that they are less sensitive to variations in the abundance of individual minerals, such as might occur if rocks contain varying amounts of detrital iron minerals, carbonate, chlorite matrix, or alteration products. Ratios are also less affected by the tendency toward negative correlation of major constituents (closure effect of Chayes, 1960). Typically, continental crustal rocks have Th/U values of two to seven (Rogers and Adams, 1972), whereas uranium-mineralized rocks have much lower Th/U. Values of Th/U above seven might suggest depletion. Although we lacked guidelines for metal ratios involving copper, we experimented with Fe/Cu and Ni/Cu. Judging from comparable values in mineralized and unmineralized rock, values for iron and nickel are not believed to have been affected by mineralization. Values of Th/U, Fe/Cu, and Ni/Cu are fairly uniform in unmineralized sandstones of the Minturn and Sangre de Cristo Formations, as would be expected if neither appreciable enrichment nor depletion had taken place. These metal ratios for unmineralized sandstones were used as a basis for comparison with those for mineralized rocks.

The frequency distribution of Th/U in mineralized rocks is strongly skewed and appears to be bimodal or polymodal (fig. 9*A*). A major mode below 1 is strongly indicative of uranium enrichment. Values of Th/U above unity in mineralized rocks overlap the range of unmineralized sandstones, which have normal crustal values of Th/U=1–6 (fig. 9*B*). No uranium depletion was identified. The precise values of Th/U below unity could not be determined because delayed-neutron radiation counting of thorium is masked by high uranium. Only less-than (<) values, higher than the probable actual values, were reported. These "<Th" values represent maximum values, and resulting <Th/U values are also maximum values. Thus, the Th/U mode below unity may be even lower than shown.

In contrast to metals that appear to have been concentrated by mineralization, iron (total Fe as Fe_2O_3) and nickel are present at levels comparable to those found in unmineralized sandstones of the Minturn and Sangre de Cristo Formations (table 1). Thus Fe/Cu and Ni/Cu should reflect enrichment (or depletion) of copper. The frequency distributions of $\log_{10}$ of Fe/Cu in mineralized rocks (fig. 9*C*) and unmineralized sandstones (fig. 9*D*) illustrate enrichment in copper in mineralized rocks. In contrast to Th/U, the frequency distribution for $\log_{10}$ of Fe/Cu in mineralized rocks appears to be unimodal and somewhat overlaps that of unmineralized sandstones, indicating a continuous range

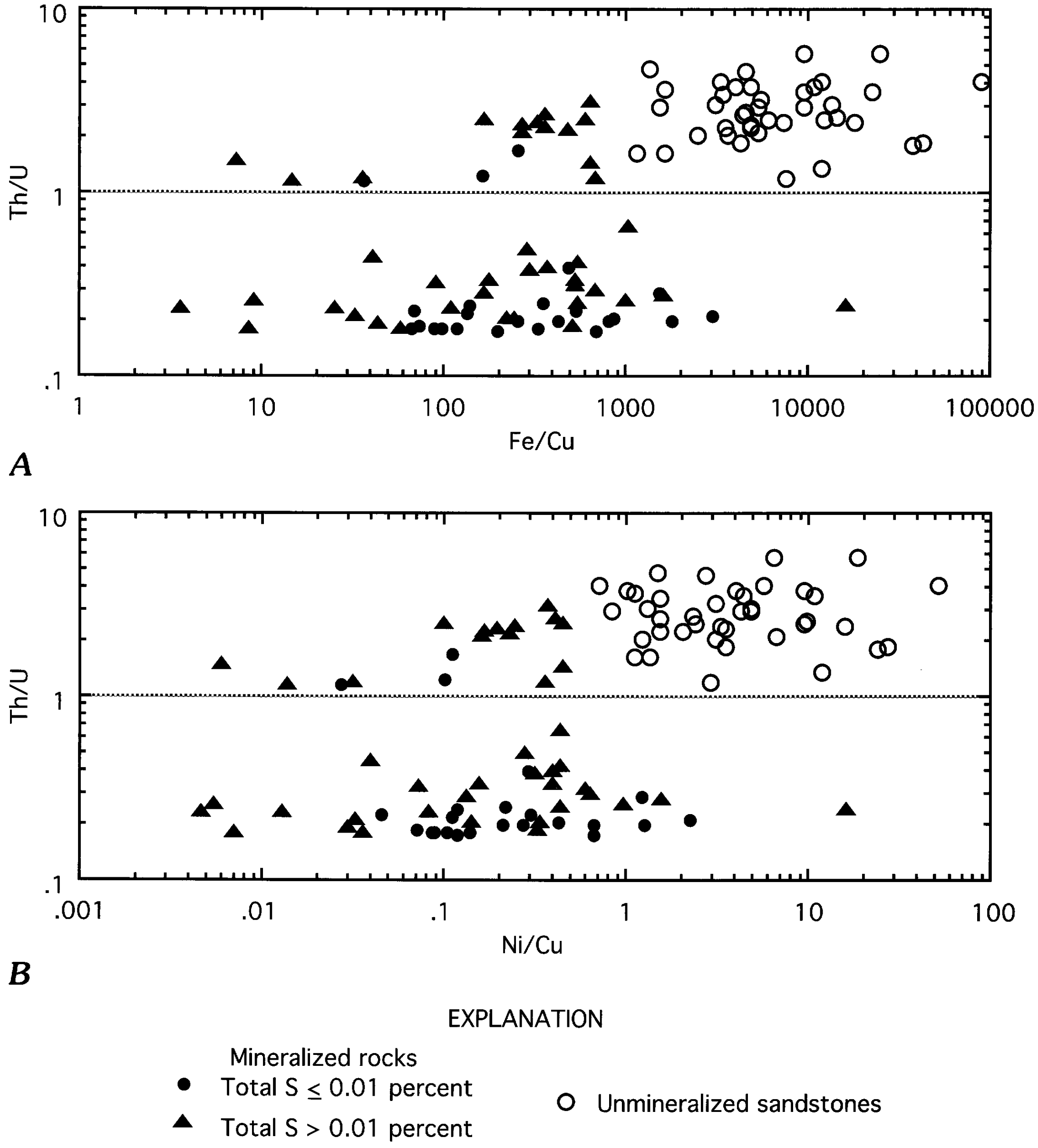


Figure 10. Scattergrams showing *A*, Th/U versus Fe/Cu and *B*, Th/U versus Ni/Cu for mineralized rocks and unmineralized sandstones of the Minturn and Sangre de Cristo Formations.

from unmineralized to copper-mineralized rock. No obvious copper depletion was identified from frequency distributions, but the possibility of small depletion of copper in individual samples cannot be excluded. The ratios of Fe/Cu were transformed to logarithms because untransformed ratios have a wide range. Skewness of Th/U, Fe/Cu, and Ni/Cu indicates that all should be transformed to logarithms, or plotted on logarithmic scales, for further analysis. Logarithmic scales were used to summarize ratio data (fig. 10).

Relationships among mineralized and unmineralized rocks are well defined by plots of Th/U versus Fe/Cu (fig. 10*A*). Mineralized rocks are divisible into two groups: (1) highly uranium mineralized (distinguished by Th/U<1) and (2) not appreciably uranium mineralized (Th/U=1–3). Both groups were subjected to varying degrees of copper mineralization. Neither copper nor uranium shows a preference for groups classified by sulphur content (>0.01 percent and ≤0.01 percent). Thus, copper, uranium, and total sulphur values are independent of one another. Unmineralized sandstones plot outside both groups; Fe/Cu values form a continuum with values for mineralized rocks (fig. 10*A*). A plot of Th/U versus Ni/Cu gave nearly identical results (fig. 10*B*).

RELATIONSHIPS AMONG ELEMENTS

Relationships among organic carbon, total sulphur, and metals in mineralized rocks were investigated by means of correlation coefficients (table 2) and R-mode factor analysis (Cooley and Lohnes, 1962, p. 151–172). The methodological approach has been described more completely elsewhere (Lindsey, 1985). After some experimentation, only 12 elements of interest in this investigation were included in the data matrix to simplify statistical analysis and interpretation. Values for all elements except cobalt and nickel were transformed to logarithms to reduce skewness of frequency distributions. The 12 by 12 matrix of correlation coefficients was solved for twelve roots (eigenvalues). Six eigenvalues are near unity or greater (fig. 11*A*) and account for 80 percent of the total variance (fig. 11*B*). Six uncorrelated principal components were defined by an initial matrix of factor loadings. A final matrix of loadings (table 3) was derived by the Varimax criterion (Harman, 1960) and used as a basis for factor interpretation (table 3). The six-factor model accounts for 70 percent or more of the variance of each element, as shown by the communalities (table 3).

Criteria for selection of the factor model included: (1) eigenvalues must be near one or greater, (2) the total of all eigenvalues must account for more than one-half the total variance, (3) the model must account for more than one-half the variance of each element (communalities >0.5), and (4) the model must be amenable to interpretation. The six-factor model meets or exceeds these requirements.

Inspection of the correlation coefficients (table 2) reveals that, in general, correlations are weak (r<0.58, commonly r=0.2–0.4), although even a coefficient of r=0.1 is significant at the 0.05 level for N=65 (that is, the probability of noncorrelation is 1 in 20). Such low correlations may arise from (1) independent occurrence of elements at the scale of sampling and (2) a high proportion of analytical

Table 2. Correlation coefficients for selected elements in mineralized rocks of Minturn and Sangre de Cristo Formations

[Coefficients based on 65 values for each element; all values except Co and Ni transformed to logarithms prior to calculation. pct, percent; ppm, parts per million]

	log C_{Org} pct	log S_T pct	Co ppm	log Cr ppm	log Cu ppm	log Mo ppm	Ni ppm	log Pb ppm	log U ppm	log V ppm	log Zn ppm
log Fe_TO_3 pct	0.29	-0.05	0.39	0.21	0.01	-0.03	0.54	-0.18	-0.31	0.07	-0.04
log C_{Org} pct		0.31	0.23	0.07	-0.07	-0.04	0.39	-0.02	-0.18	-0.10	0.20
log S_T pct			-0.07	0.08	0.04	0.08	0.11	0.07	-0.16	-0.11	-0.07
Co ppm				0.28	0.29	0.26	0.66	0.10	0.21	0.25	0.11
log Cr ppm					0.22	-0.01	0.28	0.24	0.02	0.58	-0.09
log Cu ppm						0.26	0.15	-0.16	0.02	0.17	0.18
log Mo ppm							-0.04	0.27	0.27	0.09	0.05
Ni ppm								-0.04	-0.02	0.14	0.19
log Pb ppm									0.35	0.48	0.18
log U ppm										0.57	-0.02
log V ppm											-0.04

Table 3. A six-factor geochemical model for mineralized rocks of Minturn and Sangre de Cristo Formations

	Varimax factor loadings on orthogonal axes						
Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Communality
log Fe_TO_3 pct	0.80	-0.11	-0.18	-0.01	-0.18	-0.01	0.72
log C_{Org} pct	0.49	-0.08	-0.06	0.55	0.31	-0.23	0.70
log S_T pct	-0.06	-0.01	0.08	0.91	0.09	0.06	0.85
Co ppm	0.77	0.19	0.36	-0.10	0.08	0.18	0.80
log Cr ppm	0.28	0.69	-0.31	0.18	-0.18	0.37	0.84
log Cu ppm	0.08	0.02	0.17	0	0.13	0.93	0.91
log Mo ppm	0.02	0.05	0.86	0.12	-0.02	0.20	0.80
Ni ppm	0.86	0.10	-0.03	0.10	0.16	0.07	0.79
log Pb ppm	-0.14	0.71	0.26	0.16	0.26	-0.29	0.77
log U ppm	-0.09	0.56	0.53	-0.33	0.01	-0.14	0.73
log V ppm	0.12	0.90	0.04	-0.16	-0.08	0.12	0.87
log Zn ppm	0.06	0	-0.01	-0.03	0.96	0.12	0.93

Interpretation of model

Factor I (Fe_TO_3, Co, and Ni)—Concentration of iron oxides by sedimentation and diagenesis.

Factor II (V, Pb, Cr, and U)—Mineralization by vanadium, lead, chromium, and uranium.

Factor III (Mo and U)—Mineralization by molybdenum and uranium.

Factor IV (S_T and C_{Org})—Concentration (or preservation from oxidation) of sulfides and organic matter.

Factor V (Zn)—Unique factor for zinc mineralization.

Factor VI (Cu)—Unique factor for copper mineralization.

variance (error) relative to total variance. Because the mineralized rocks contain highly anomalous amounts of Cu, Pb, U, V, and Zn, and therefore have high natural variance for these elements, analytical error should not contribute greatly to their low correlation. Thus, for example, the low correlation of copper and zinc with other elements probably reflects their independent occurrence at the scale of sampling, which consisted of composite chips from mineralized intervals about 0.3–1 m thick.

Six independent factors are defined in the model selected for interpretation (table 3). The six factors are interpreted as effects of sedimentation and diagenesis (factor I), mineralization (factors II, III, V, and VI), and concentration (or preservation) of sulfides and organic matter (factor IV).

Factor I has high loadings for total iron, cobalt, and nickel and evidently reflects concentration of these metals, probably in iron oxide minerals and in chlorite matrix, by sedimentation and diagenesis. Iron, cobalt, and nickel were not affected by copper or uranium mineralization, and thus their use in metal ratios (Fe/Cu, Ni/Cu) to detect enrichment or depletion appears to be appropriate.

Factors II, III, V, and VI represent effects of mineralization. Vanadium, lead, chromium, and uranium have high loadings on factor II, reflecting relatively high correlations for V-Cr, V-Pb, and V-U; chromium, lead, and uranium are common in various vanadium minerals, and their correlation with vanadium, but only weakly or not at all with each other, suggests that several vanadium minerals may be present in small amounts. Molybdenum and uranium have high loadings on factor III; however, molybdenum is only weakly correlated ($r=<0.27$) with uranium (and with cobalt, copper, and lead) (table 2). Factor III may reflect minor enrichment in molybdenum during mineralization. Factors V and VI, termed "unique factors" because they have high loadings for only one element, represent zinc and copper mineralization, respectively. According to the model, mineralization by zinc and copper was spatially separate (at the scale of sampling) and separate also from vanadium-chromium-lead-uranium mineralization. This conclusion is in accord with evidence presented previously that copper and uranium have different patterns of enrichment (fig. 10).

Factor IV represents concentration or preservation of sulfides and organic matter. Total sulphur and, to a lesser extent, organic carbon have high loadings on factor IV. Association with metals is nil as indicated by low factor loadings and by vanishingly small correlation coefficients with total sulphur. Noncorrelation of total sulphur and organic carbon with metals may be explained if metals have been redistributed from their original site of precipitation, even if redistribution was only local. Values from samples spanning the thickness of an entire mineralized bed (commonly, ≤1 m) would mask metal redistribution by averaging values across the bed, and thus might yield low correlations between metal values and metal-fixing elements such as sulphur and organic carbon. Because most of the enclosing strata, including gray beds in the Minturn Formation, contain

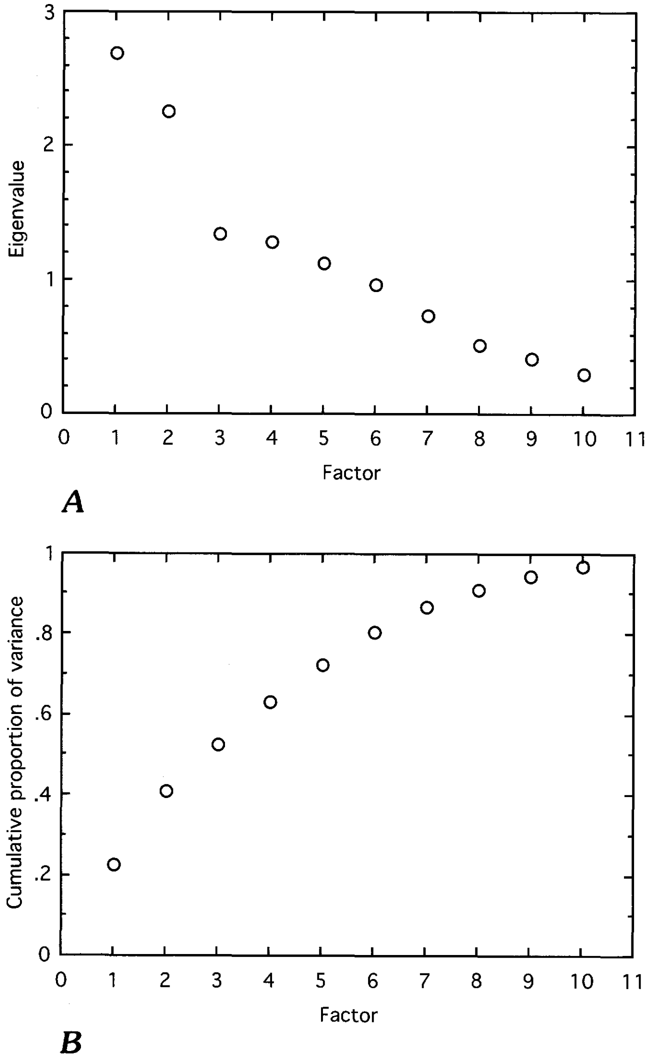


Figure 11. Plots showing *A*, eigenvalues and *B*, cumulative proportion of total variance explained by first ten principal factors.

hematite and thus represent an overall oxidizing environment, factor IV is interpreted tentatively as an expression of preservation of sulfides (probably, as minor amounts of pyrite and copper sulfides) and organic matter from oxidation.

PROPOSED MODEL FOR MINERALIZATION

A model for copper and uranium mineralization (fig. 12) is proposed that requires (1) deposition of sediment containing organic carbon and pyrite in reducing environments, (2) local preservation of some reducing environments during redbed formation, and (3) introduction of copper and uranium in the surviving reducing environments.

Depositional environments played a broad role in determining the distribution of mineralized host rock (fig. 12*A*). Marine depositional environments, where plant debris accumulated in silt or mud, were relatively stable and extensive compared to nearby alluvial environments. Mineralized rocks of interval 2 (approximately 11 km long) were deposited in nearshore-marine environments and preserved by continued sedimentation. Euxinic lagoonal or marine environments did not develop, however, and these would be required for deposition of a host bed like the Kupferschiefer. In contrast, the small (approximately 100–300 m wide) lenses of mineralized rocks at the King Midas claims were deposited near a shoreline that was dominated by alluvial sedimentation near rugged uplands. Local marine and wetland environments, where organic-rich host sediments were deposited, were subject to erosion and inundation by alluvial fans.

As deposition in the central Colorado trough proceeded, mildly alkaline, oxidizing ground water altered arkosic sediment to redbeds in alluvial fans along the margin of the central Colorado trough (fig. 12*B*). In later Pennsylvanian and Permian time, redbed alteration spread throughout most of the basin. Redbed alteration left remnants of unoxidized sediment buried in the lower and central parts of the basin fill, however. Organic matter and minor pyrite preserved in these sediments provided a reducing and adsorptive trap for metals that were introduced later by brines (fig. 12*C*).

COPPER

Brines rich in chloride are the most likely agent of copper transport in redbed sequences (Rose, 1989). Initial basin fluids may have evolved into oxidizing brines during passage through evaporites and redbeds (Eugster, 1989; Sverjensky, 1989) in basin fill of the Ancestral Rocky Mountains (fig. 1). If chloride ion is present, such brines are capable of transporting copper even if pH is neutral or weakly alkaline. Although no salt deposits are known near the Sangre de Cristo Range, the central Colorado trough does contain gypsum, anyhdrite, and halite. Chloride-sulfate brines might well have originated from contact with the Swissvale Gypsum Member of Brill (1952), located about 600 m below the top of the Minturn Formation and about 50 km north of the mineral occurrences described here, and from the Middle Pennsylvanian Eagle Valley Evaporite, located farther north (inset map, fig. 12). Other gypsum- and salt-bearing formations of Jurassic, Triassic, and Permian age were not deposited over Pennsylvanian-Permian rocks in much of south-central Colorado (MacLachlan, 1972; Peterson, 1972; Rascoe and Baars, 1972).

Brines driven updip by burial compaction and lateral expulsion or by thermal convection (for example, Jowett, 1986) from the central Colorado trough (fig. 12*C*) or its buried basin fill after Permian time, would necessarily have equilibrated with hematite, carbonate, and silicate minerals in oxidized rocks as described by Rose (1989). After equilibration, the Eh and pH of brines would be within the hematite stability field, with pH additionally buffered by reaction with silicate and carbonate minerals. Equilibration would have occurred not only in redbeds but also in gray, hematite-bearing beds of the Minturn Formation. Reducing environments were confined to local beds and lenses containing organic matter and minor pyrite, mostly in the Minturn Formation. Carbonate was present initially as lime mud in marine strata of the Minturn Formation and in paleocaliche deposits in the Sangre de Cristo Formation; eventually, it was redistributed widely as calcite cement in both the Minturn and Sangre de Cristo Formations.

Hypothetically, chloride-sulfate brines from the central Colorado trough migrated into basin-margin fill, where they could have leached copper and zinc from sandstone. Copper is soluble as a cuprous chloride complex over a wide range of pH; zinc is soluble as a sulfate complex to a pH of 8.6 (Rose, 1989). Where mineralizing brines encountered reducing conditions in beds containing organic matter and pyrite, copper and zinc were precipitated (probably as sulfides). After mineralization, sufficient pyrite and organic matter remained to maintain a reducing environment in which sulfide minerals were preserved. Considering the apparent continued availability of reductants, the low level of mineralization suggests low metal concentrations in mineralizing brines. Perhaps the brines were too dilute or too alkaline to leach and transport large quantities of copper and other metals.

The dilute nature of mineralizing brines is predicted from the sequence and geometry of strata deposited in southern Colorado prior to Late Cretaceous time. No shale or evaporite that would provide an impermeable barrier or source of soluble salts overlay the site of the mineralization (MacLachlan, 1972; Peterson, 1972; Rascoe and Baars, 1972). Rising basinal brines could thus continue to the surface from Pennsylvanian to Early Cretaceous time, and convecting brine cells as proposed by Jowett (1986) for the central European Zechstein basin could not form. Temperature contrasts, required to drive brine convection, were probably smaller in the central Colorado trough than in the Zechstein basin because the pre-Laramide geothermal gradient was probably much lower (<13 °C/km; Lindsey, Andriessen, and Wardlaw, 1986) than during Triassic rifting of the Zechstein.

URANIUM

Uranium occurs in residual organic matter in mineralized rocks but is only broadly associated with copper. At the scale of sampling, uranium is not correlated with copper, but with vanadium. The separate distribution of uranium and copper is probably related to different mechanisms of transport or precipitation. Whereas copper is most readily mobilized as complexes of cuprous (Cu^{+1}) chloride in brines (Rose, 1989), uranium is more generally mobile as uranyl (U^{+6}) phosphate and carbonate complexes (Langmuir, 1978). Copper is usually precipitated as sulfide minerals, whereas uranium may be adsorbed by organic matter (Nakashima and others, 1984).

Uranium (as uranyl carbonate complexes) is soluble in alkaline, oxidizing waters such as those responsible for redbed formation. Redbed-forming waters would have transported uranium downdip into local reducing environments where remnants of organic matter were preserved in the Minturn Formation (fig. 12*B*). There, uranium would have been fixed by reaction with organic matter. Experimental evidence suggests that under the alkaline, oxidizing conditions of redbed formation, uranium is adsorbed by hematitic pigment; metals including uranium are held even more tightly in recrystallized hematite in older redbeds (Zielinski and others, 1983). Leaching and removal of uranium from redbeds might occur in fluids with low pH or high concentrations of metal-complexing anions (such as chloride or carbonate). If uranium was leached extensively by acid fluids, zones of bleaching in redbeds should be evident. Bleached redbeds in the study area are not abundant, however.

A second possibility is that uranium and copper may have been precipitated from the same fluid. Uranium would have been mobile as soluble uranyl phosphate or carbonate species (Langmuir, 1978) in the weakly alkaline, oxidizing chloride-sulfate brine postulated for copper transport. Soluble uranyl species can be fixed as urano-organic compounds without reduction at temperatures consistent with moderate burial, as demonstrated by experiment with lignite at 45–120 °C (Nakashima and others, 1984). In the uranium deposits studied here, uranium in mineralizing brines could have been fixed by organic (plant) matter that survived oxidation in the Minturn Formation.

Vanadium, which is correlated with uranium in mineralized rocks, may have coprecipitated with uranium. Uranium, vanadium, and possibly molybdenum and chromium may have been remobilized from their original residences by mildly alkaline, oxidizing fluids. Remobilization may have led to local dispersion and reprecipitation as secondary minerals such as carnotite. Vanadate (V^{+5}) and uranyl carbonate species are stable over much of the same range of Eh and pH and can coprecipitate as carnotite at intermediate pH values in oxidizing environments (Langmuir, 1978). If lead was also remobilized, the fluid could not have contained sulfate because $PbSO_4$ is insoluble. If more than one secondary mineral precipitated under slightly different conditions, various minerals containing uranium, vanadium, molybdenum, chromium, and perhaps lead might be dispersed locally throughout mineralized beds. Such dispersion might explain the correlations U-V, V-Cr, and V-Pb and the weak correlation U-Mo.

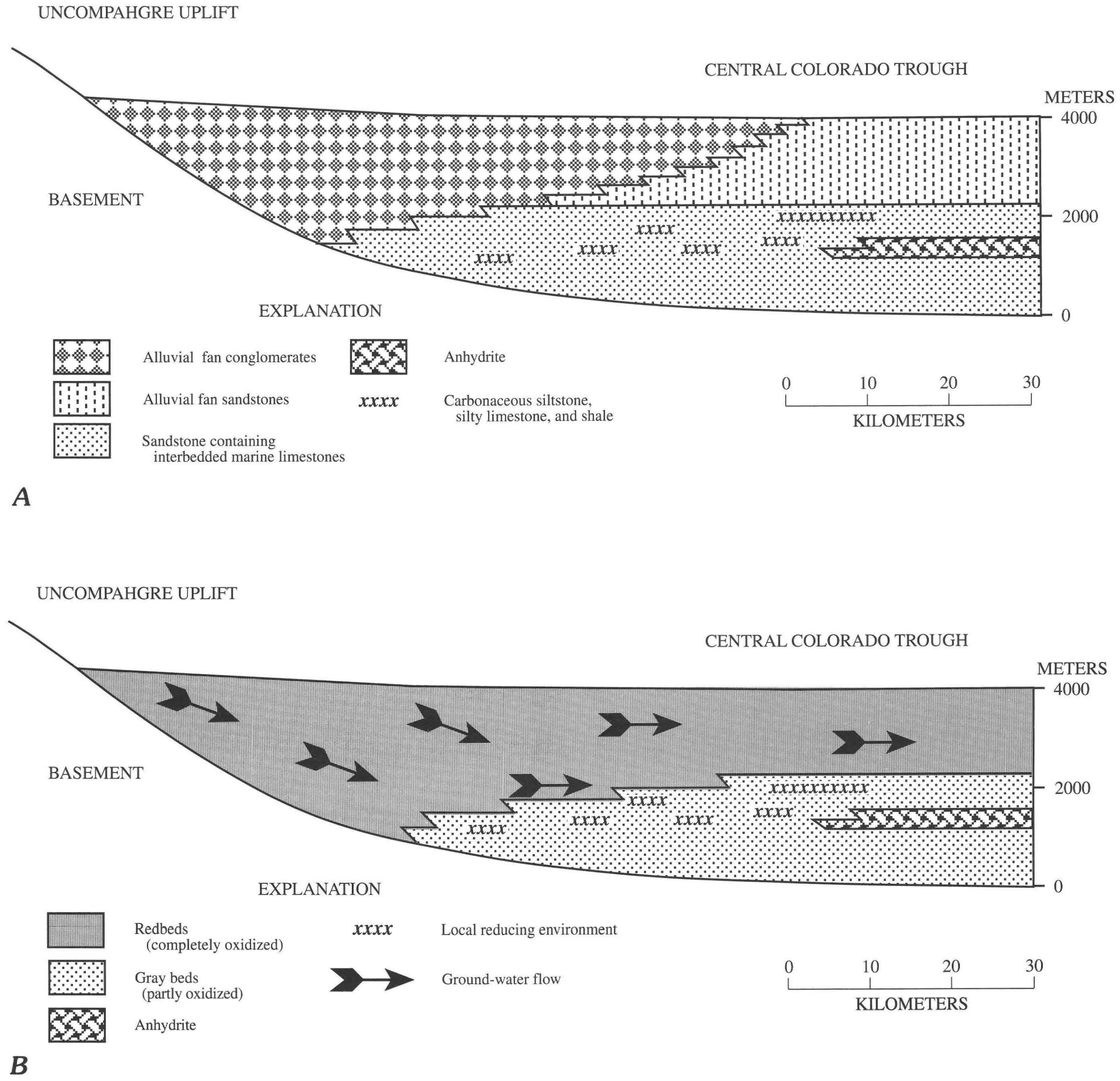


Figure 12 (above and facing page). Proposed model for formation of redbed copper-uranium deposits in basin fill of the central Colorado trough: *A*, principal lithofacies shortly after deposition, *B*, formation of redbeds by ground water flowing through fan deposits during and shortly after deposition, *C*, mineralization by through-flowing dilute brines after redbed formation.

CONCLUSIONS

Reasons for small tonnages and grades of redbed copper deposits, as represented by those studied, may include the following:

1) The thickness and lateral extent of reducing host rocks were restricted by alluvial and nearshore-marine environments that received an abundant supply of detritus.

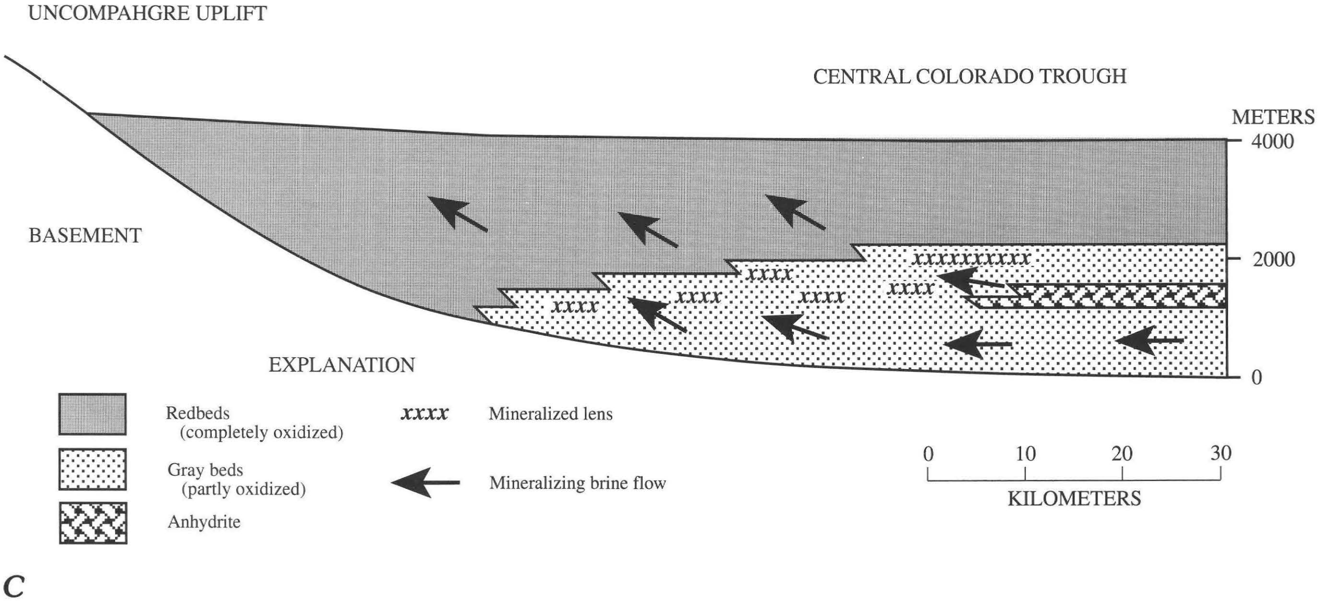
2) The size of reducing environments was limited further by oxidation during redbed formation.

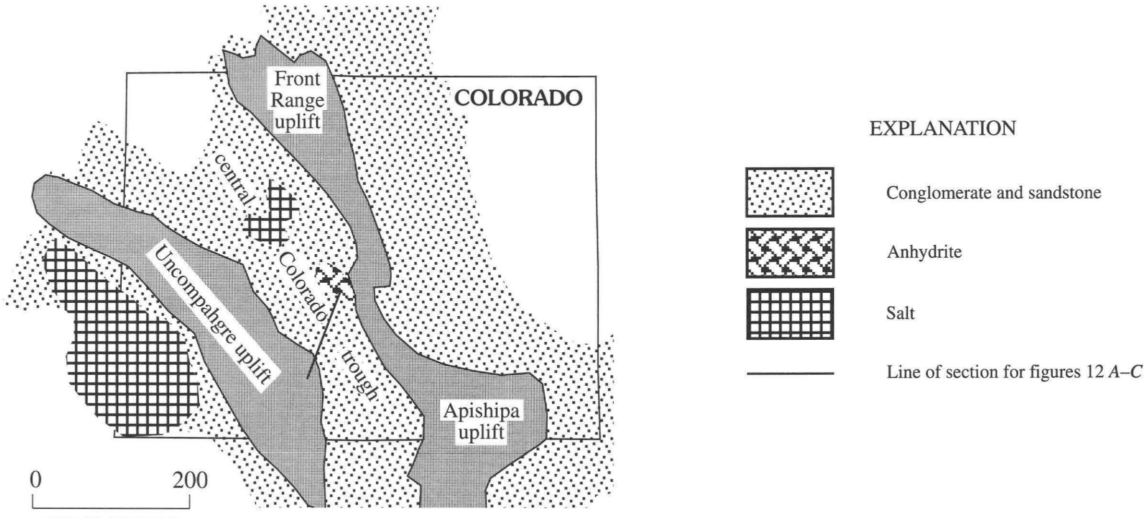
3) Adsorption in abundant hematite pigment probably limited mobility of metals in redbeds.

4) Mineralizing brines were too dilute and alkaline to leach and transport large quantities of copper.

5) The basin fill and cover rocks did not contain an impermeable cap of shale or evaporite to force brine to convect in cells and leach source rocks repeatedly.

6) The geothermal gradient was probably insufficient to produce the necessary thermal contrasts between basin fill and adjacent uplands to promote strong fluid flow.





Early Permian–Pennsylvanian paleogeographic setting

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