# 8. STRATABOUND CLASTIC-HOSTED URANIUM, LEAD, COPPER

## 8.1 Sandstone uranium

## 8.2 Sandstone lead

## 8.3 Sediment-hosted stratiform copper

### 8.3a Kupferschiefer-type
### 8.3b Redbed-type

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## INTRODUCTION

Disseminations of the ore minerals in clastic sedimentary rocks characterize this deposit type. Deposits occur in marine, paralic, lacustrine, and continental host rocks at or near a redox boundary. Three subtypes are distinguished on the basis of the major, economically-viable commodity and on the relation to the redox boundary. Sandstone uranium (8.1) and sandstone lead (8.2) deposits are associated with reductants within porous oxidizing sandstones; sediment-hosted stratiform copper (8.3) deposits occur in reduced host rocks adjacent to redbeds.

# 8.1 SANDSTONE URANIUM

R.T. Bell

## IDENTIFICATION

The deposits occur as disseminated (mainly pore fillings) uranium minerals in arenaceous rocks, predominantly of continental origin and setting, in successor or foreland basins, and are mainly of post-Silurian age. Vanadium, molybdenum, selenium, copper, phosphorus, manganese, and chromium enrichments are common but at present are of negligible economic importance. The first three elements are commonly used as pathfinder elements for uranium.

The historically most important examples are in the U.S.A. There are several subtypes: roll, peneconcordant (blanket or trend), stacked, coal or lignite, and basal channel. The economically significant examples in Canada are restricted to the basal channel subtype in the Beaverdell area in southern British Columbia and a hybrid (vein modified trend type) at Mountain Lake in the northwestern part of District of Mackenzie, Northwest Territories.

## IMPORTANCE

### Canada

In 1990, the economic deposits, all in British Columbia, accounted for less than 2% of Canada's Reasonably Assured Resources of uranium. The deposits have yet to be exploited and remain dormant.

### Foreign

In the western world prior to 1982, sandstone uranium deposits accounted for 40% of Reasonably Assured Resources and 54% of Estimated Additional Resources, but are steadily declining in importance. These deposits are mainly in the U.S.A. where they are the dominant source.

Significant deposits are (or have been) exploited in Niger, Gabon (of Precambrian age), Argentina, former Czechoslovakia, China, the former U.S.S.R. (Russia, Kazakhstan, Uzbekistan; Ruzicka, 1992), the former Yugoslavia (Slovenia), and France. Significant resources occur in Australia, Brazil, Mexico, Turkey, South Africa, and Japan.

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## SIZE AND GRADES

### Canada

The deposits contain as much as 4000 t U in ore bodies grading from 0.1 to 0.2% U. Blizzard is the largest deposit with about 4000 t U at an average grade of about 0.18% U.

### Foreign

The common range is 1000 to 10 000 t of contained U in ores grading from 0.03 to 2%. Many are smaller and a few contain as much as 30 000 t U. Clusters of small, very low grade (averaging as little as 0.04% U) deposits at shallow depths in very friable sandstones and in surficial deposits are economically recovered by relatively inexpensive in situ leaching processes (examples: Crow Butte, Nebraska and others in Texas, U.S.A.).

## GEOLOGICAL FEATURES

### Geological setting

Most uranium sandstone deposits are in continental sandstones and associated conglomerates that compositionally are immature to submature (i.e., arkosic, lithic, and/or tuffaceous), and texturally are mature (well sorted). Predominantly the sandstone sequences, as successor or foreland basins, lie on, or adjacent to, uplifted, deformed, and metamorphosed basement of felsic rocks such as the foreland basins to Nevadan-Laramide orogenies in western North America or as successor basins to the Hercynian orogeny in Europe.

### Relation of ore to host rocks

Generally, deposits are confined to porous arenaceous units commonly bound by relatively impermeable mudstones. The deposits may follow organic-rich, high porosity trends roughly concordant with the strata (peneconcordant subtypes) in the sequence; if they are equidimensional in plan, they are referred to as blanket subtype (classical area: Lisbon Valley, Utah) or, if elongate in plan, trend subtypes (classical area: Ambrosia Lake, New Mexico). Basal channel subtypes (classical area: Tono, Japan) occur near the base of fluvial sediments in paleovalleys; coal or lignite subtype (classical area: South Dakota) is found in very organic-rich layers adjacent to porous sand strata. The deposits may occur at discordant oxidation-reduction (redox) boundaries (roll subtype, commonly C-shaped in section, (classical areas: Wyoming, Texas Gulf Coast, and Uravan Belt in Colorado) within individual porous sandstone units. In these roll subtype deposits, geochemical zoning (for example, Se⇒U⇒U+Mo) across the roll front is common. In some oxidized sandstones the deposits follow vague discordant and concordant bleached zones and occur as irregular stacked peneconcordant tabular bodies at or near faults or fracture systems (stacked subtype, linear in plan and rectangular in section; classical area: Ambrosia Lake, New Mexico). Some writers include the polymetallic deposits in collapse structures in sandstones (collapse breccia pipe type; Organization for Economic Cooperation Development/International Atomic Energy Agency, 1992) as in the Grand Canyon area, Arizona (Finch, 1967) as a sandstone type deposit. Some consider coal or lignite subtypes as a separate type.

## Nature of the ore

Vertical and horizontal (facies trends) changes, resulting in porosity differences, control deposits by acting as conduits for, or as barriers to, mineralizing fluids. Faults may also serve as barriers or as conduits; fluids moving along faults are most likely to be those that act as reductants.

Dominance of uranium-bearing minerals in pore spaces and/or as partial to complete replacement of particles (clasts, matrix, cement, organic debris) in contrast to veins and gashes in arenaceous rocks is the most definitive feature of this deposit class. In the reverse situation the deposit is classified as vein type. Hybrid cases as at Mountain Lake, Northwest Territories occur (see "Mountain Lake", below).

## Mineralogy

The ore occurs dominantly as pitchblende and/or coffinite in pore spaces or strongly absorbed by organic material, or weakly absorbed by clays and zeolitic material. In strongly oxidized portions of ore bodies, uranium occurs as a large variety of secondary (U in hexavalent form) minerals, of which autunite, uranophane, carnotite, and torbernite are common in pore spaces, in clays, limonite, opaline wood, and phosphates.

## Canadian examples

*(See Fig. 8.1-1 for locations)*

### *Beaverdell area*

The Beaverdell area deposits lie in the Okanagan Highlands of south-central British Columbia (Fig. 8.1-2). The basement rocks are felsic gneisses and granites formed during Mesozoic compressive orogenies. This basement has been "loosened" by pervasive faulting during east-west extension and uplift during the Eocene, which accompanied emplacement of high level granitic and volcanic rocks. Ductile and brittle low-angle normal and listric faulting and tectonic denudation also occurred in the Okanagan metamorphic core complex. This Eocene environment has been compared with that of the later Tertiary of the Basin and Range in the southwestern U.S.A. Rate of uplift in the Okanagan region has gradually decreased since the Eocene.

The host sequences for the uranium deposits are in paleovalleys produced in these uplands during the Miocene (Fig. 8.1-2, 8.1-3, and 8.1-4). The sediments comprise a basal sequence of very coarse conglomeratic sediments of torrential and braided stream environment with a few lenses of mud-rich, debris-flow or slump deposits. These give way abruptly to an overlying fine sequence of sandstone, siltstone, and mudstone of lacustrine and meandering stream environments. The onset of the fine sequence coincided with local onset of olivine basaltic volcanism which produced flows that dammed the stream valleys and with which the finer sediments were interstratified in the lower reaches of the valleys.

In the Intermontane region to the west and to the north the main 'plateau basalts' were formed during numerous extrusive events peaking at 11 and 6 Ma. The basalts in the Okanagan Highlands are the distal aspects of these and range from earlier 'valley basalts' to a later blanket or 'plateau' phase. Locally the earlier valley basalts caused damming and diversion of the streams and resulted in widespread development of the fine facies. The later blanketing basalts are about 5 Ma in age and effectively ended the sedimentary phase, and for a time protected much of the basement terrane of this area from erosion while regional uplift proceeded.

Late Pliocene and Quaternary erosion has removed most of these basalts in the Okanagan Highlands, and particularly so in the lower reaches of the Miocene paleodrainage. The catch-up of erosion into the basement, after prolonged protection by the 'plateau' basalt cover, gives the appearance of renewed uplift. There remain only small basalt caps in tributary paleovalleys and on the flanks of the main or trunk paleovalleys.

The uranium deposits lie in both coarse and fine sedimentary facies immediately beneath and adjacent to basalt caps in the uppermost tributary paleovalleys (Fig. 8.1-3, 8.1-4). Sediment thickness rarely exceeds 45 m. The individual deposits are roughly lenticular, tabular bodies usually only a metre or two in thickness. In the coarse facies ore boundaries are fairly gradational, whereas in the fine facies boundaries are sharp. Carbonaceous material and minor pyrite or marcasite accompany most ore but with two important exceptions.

The first exception is in the Blizzard deposit where virtually all the ore at the top of the coarse facies (Fig. 8.1-3, 8.1-4: zones B and C) is in the form of saléeite, autunite, and uranophane in light brown sandstone. Here, and in all but a very few places (usually restricted to the top) in the coarse sandstones, virtually all pyrite has been oxidized to limonite and only plant imprints and a few silicified wood fragments remain. Much of the ore in the lowest part of the fine facies (Fig. 8.1-3: zone A) is likewise oxidized in the northernmost part of the deposit. In the highest levels (fine facies, zone A) uranium, in association with black organic material and minor pyrite, occurs as pitchblende and coffinite(?). Between the oxidized and reduced facies both saléeite and ningyoite occur. Boyle (1982) has documented the sequence of ningyoite replacing saléeite and suggests that saléeite and autunite are primary and ningyoite and pitchblende are secondary. The predominance of reduced facies ore elsewhere suggests the reverse and that the phenomenon at Blizzard is due to fluctuating redox boundaries in the presence of a high phosphate background.

The other exception is in the Tyee deposit (Fig. 8.1-2) in which the core of the lower part of the orebody is heavily cemented by marcasite. The uranium mineralization is associated with organic material and was identified as ningyoite.

Minor ore grade zones occur along the baked mudstone contacts of basalt flows (Fig. 8.1-3, 8.1-4: zone F) and rarely in fractures in feeder dykes. A very minor part occurs in the regolith beneath the sediments (Fig. 8.1-3, 8.1-4: zone D) where the base of zone B reaches the base of the channel of the coarse facies (elsewhere the base of zone B is several metres above the base of the coarse facies). Another interesting potential ore zone is in the fine matrix of the uppermost (100 m) oxidized (rusty) part of a breccia pipe at the northern part of the Blizzard deposit (Fig. 8.1-3, 8.1-4: zone E).

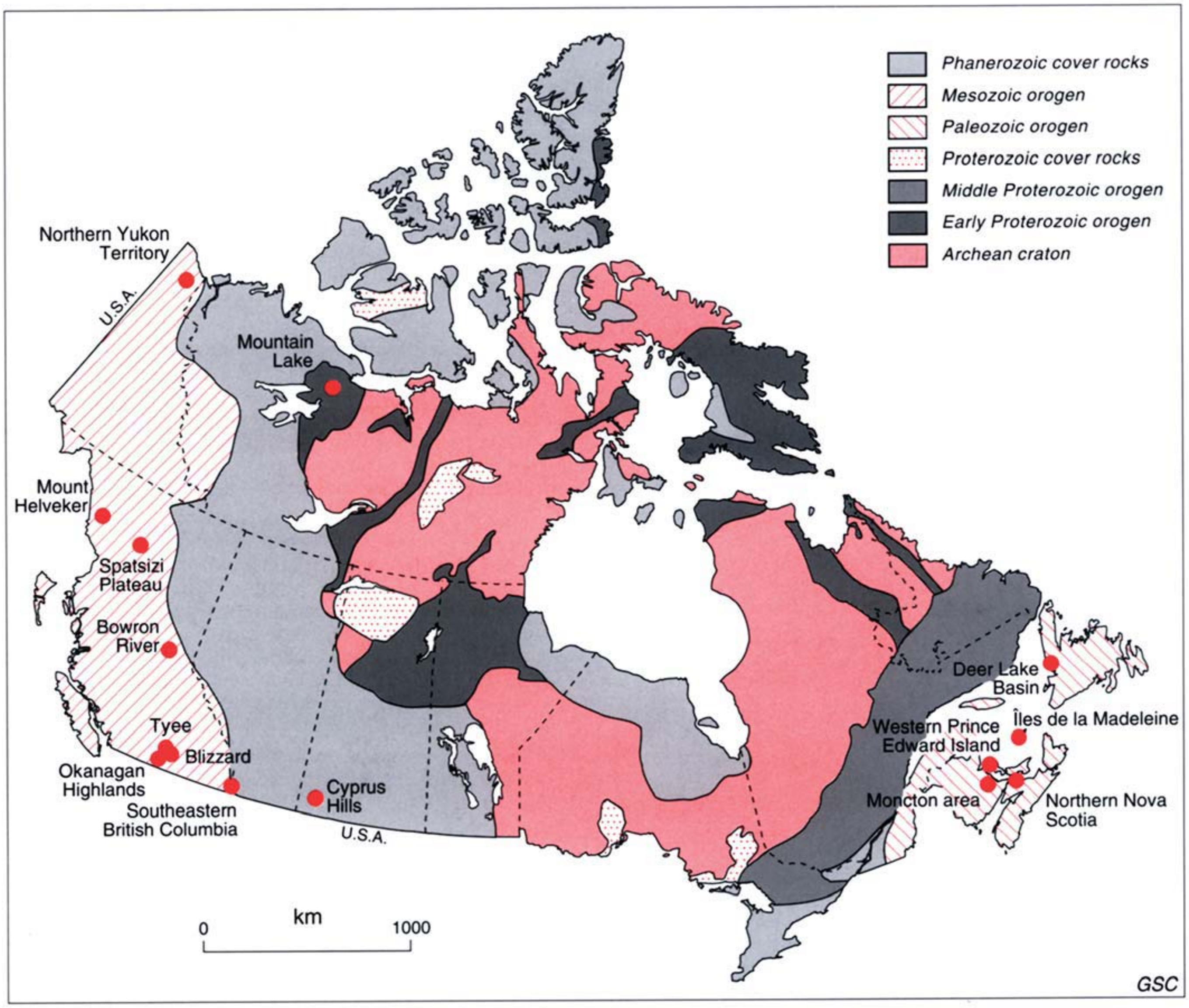


**Figure 8.1-1.** Canadian uranium deposits and significant occurrences (after Bell, 1976, 1981, 1982; Bell et al.,1976; Dunsmore, 1977a, b; Bell and Jones, 1979; Geological Survey of Canada, 1980, 1981; Boyle, 1982; and Jones, 1990). 1 – Blizzard (Cup lake, Lassie, and Fuki-Donan nearby); 2 – Tyee (a.k.a. Hydraulic Lake, with Venus and Haynes Lake nearby); 3 – Okanagan surficial (22 clusters of deposits between Oliver and Kelowna); 4 – Mountain Lake (PEC-YUK); Significant groups of occurrences: 5 – southeastern British Columbia (Lin, Commerce); 6 – Bowron River; 7 – Spatsizi Plateau (Edozadelly); 8 – Mount Helveker; 9 – northern Yukon Territory (Bou, Bon); 10 – Cypress Hills; 11 – Moncton area; 12 – western Prince Edward Island; 13 – northern Nova Scotia (Tatamagouche); 14 – Îles de la Madeleine; 15 – Deer Lake Basin.

Content of P (but not Th, Mo, V, or Se) is slightly elevated in the Beaverdell deposits, although Mo is strongly elevated in the Recent surficial occurrences west of the Okanagan valley.

Age of mineralization is still poorly defined. A single U-Pb date of 2.8 Ma in the transition from oxidized to reduced facies in the Blizzard deposit suggests that the original accumulation was at least of the same age and it is likely that remobilization is still going on in that deposit. Elsewhere uranium concentrations in the basal baked zones of the earliest basalt flows suggest a (re)mobilization at the time of the earliest basalt in this area, likely at least before 5 Ma.

## *Others*

### Mountain Lake

A Precambrian deposit occurs near Mountain Lake, Northwest Territories in the middle part of the lower white and light brown sandstone unit of the Neohelikian Dismal Lakes

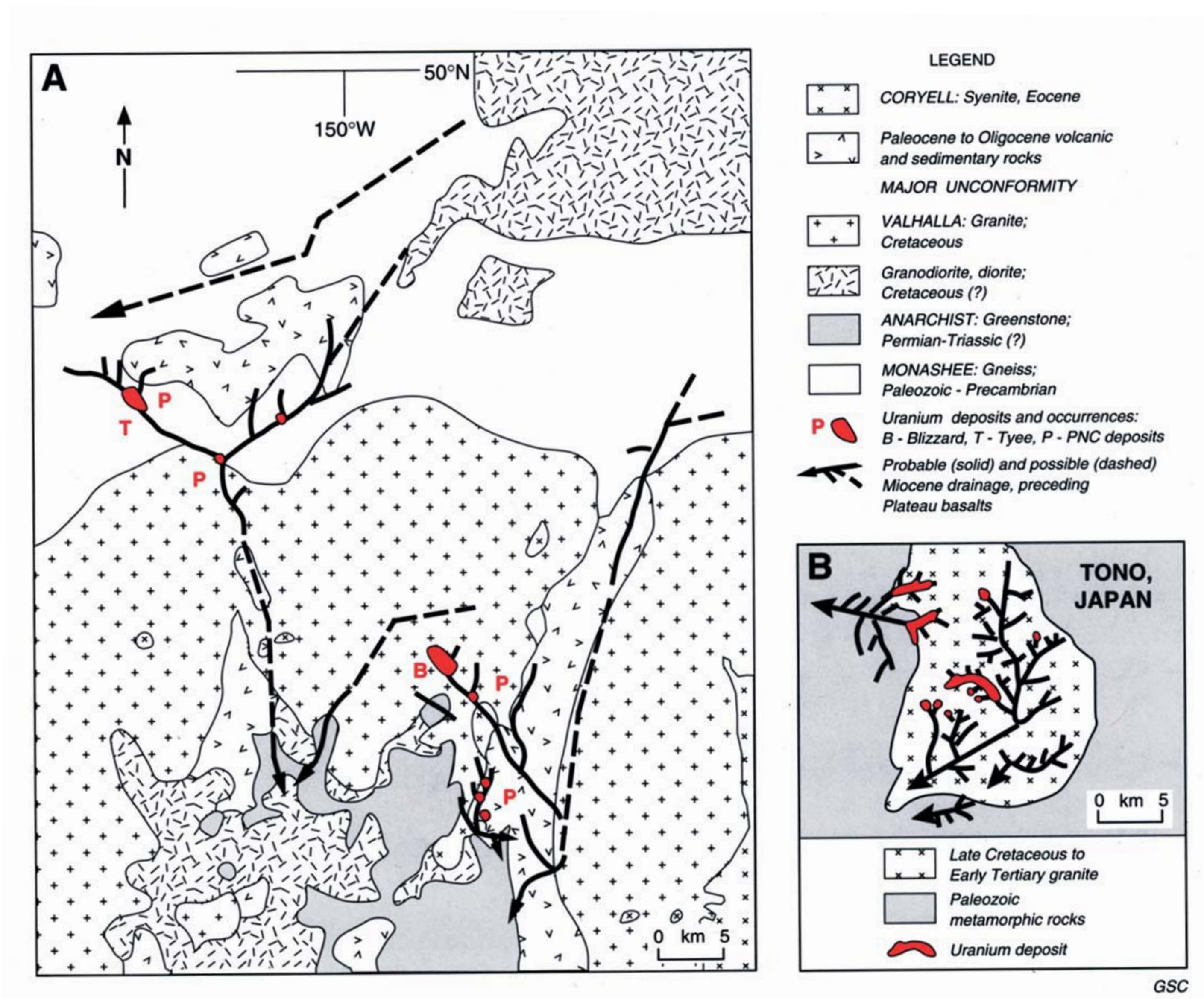


**Figure 8.1-2. A)** Simplified geology of Beaverdell area (after Boyle, 1982; Tempelman-Kluit, 1989 and references therein) showing uranium deposits and late Miocene paleodrainage. Plateau basalts (late Miocene-Pliocene) not shown. **B)** Paleodrainage and deposits in Tono area, Japan (after Katayama et al., 1974).

Group. The unit unconformably overlies the Paleohelikian Hornby Bay Group and, locally, Aphebian basement gneisses and felsic volcanic rocks. The unit is conformably overlain by grey siltstone and shale.

The uranium occurs as disseminated sooty pitchblende and coffinite(?) in irregular stratiform lenses, 2 m thick, as much as 400 m long, and 200 m wide. Grades are of the order of 0.1 to 0.3% U but actual size and overall grade have not been reported. Yellow and green secondary minerals occur in fractures and in weathered zones. Some chalcopyrite and pyrite are present, as well as traces of cobalt-nickel arsenides. Trigg (1986) reported up to 0.5% Cu, and associated high Co, Ni, and Ag values. Red hematite staining is common along the margins.

Trigg (1986) also reported grades up to about 5% U (as both pitchblende and secondaries) that occur in a zone characterized by veins occupying steeply dipping fractures at the north end of the deposit in association with a major fault. This part of the deposit may be regarded as vein-modified sandstone uranium.

The host sequence is between 1500 and 1275 Ma old and a single U-Pb isotope analysis suggests an age of 794 Ma (Gandhi, 1986) for latest (re)mobilization of uranium.

## Surficial deposits of the Okanagan valley

West of the Okanagan valley a large number of small, 'surficial' or 'young' low grade deposits of uranium occur to depths of 10 m in Recent sediments (Culbert et al., 1984) in mainly fine grained fluvial, lacustrine, and bog deposits. They are accompanied by high Mo content and have grades the order of 0.01% U and are young in that there are negligible daughter elements present (hence normal gamma-ray geophysical methods are useless for exploration and delineation). At present these 'young' deposits are uneconomic. Despite being small and of low grade these occurrences could eventually prove economic, as indicated by the attempt at development of a similar deposit just south of there at Flodelle Creek in the state of Washington.

## Miscellaneous occurrences

Occurrences of uranium with vanadium (Prince Edward Island), with copper (northern Nova Scotia), and with silver (Newfoundland) are found in Carboniferous redbed successions, commonly associated with carbonaceous debris (Dunsmore, 1977a, b). Dunsmore (1977a) pointed to an association with evaporites for some of these occurrences.

In northern Yukon Territory, latest Devonian or Early Carboniferous continental, basal sandstones and conglomerates south and east of the Barn Mountains contain phosphatic uraniferous occurrences. These are deeply weathered and the uranium occurs in part as uranophane.

Uranium in lignites and in organic-rich siltstones occurs in Upper Cretaceous sequences in Cypress Hills, Saskatchewan, and Bowren River Basin, British Columbia. Large mammal bones in the gravels of the Cypress Hills Formation (Oligocene) of southwestern Saskatchewan and in the Echo Lake aquifer (Pleistocene) near Fort Qu'Appelle, Saskatchewan, are uraniferous. Ash-tuffs containing organic fragments and

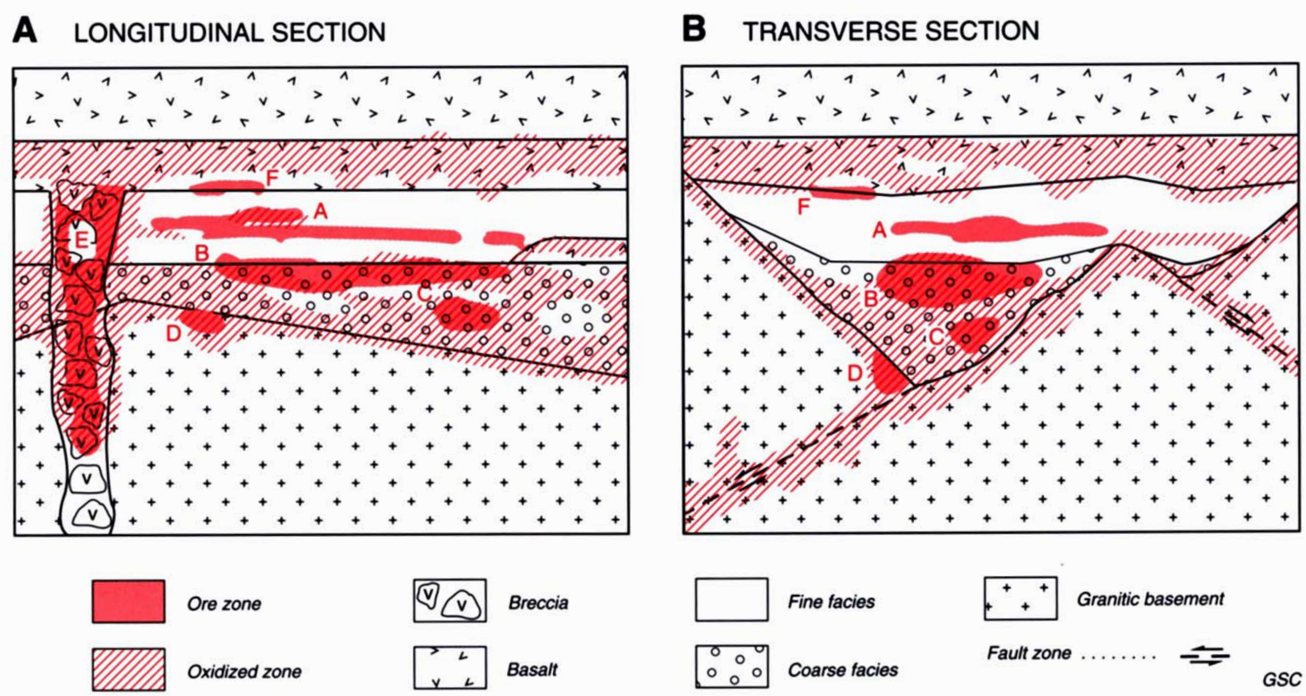


**Figure 8.1-3.** Schematic diagram of host sequence of the Blizzard deposit with sections **A)** longitudinal and **B)** transverse to the paleovalleys illustrating location of ore zones (in red): A – fine facies; B – transecting upper border of coarse facies; C – entirely in coarse facies; D – in regolith; E – in upper most part of breccia pipe; and F – at basal margins of flows and in dykes.

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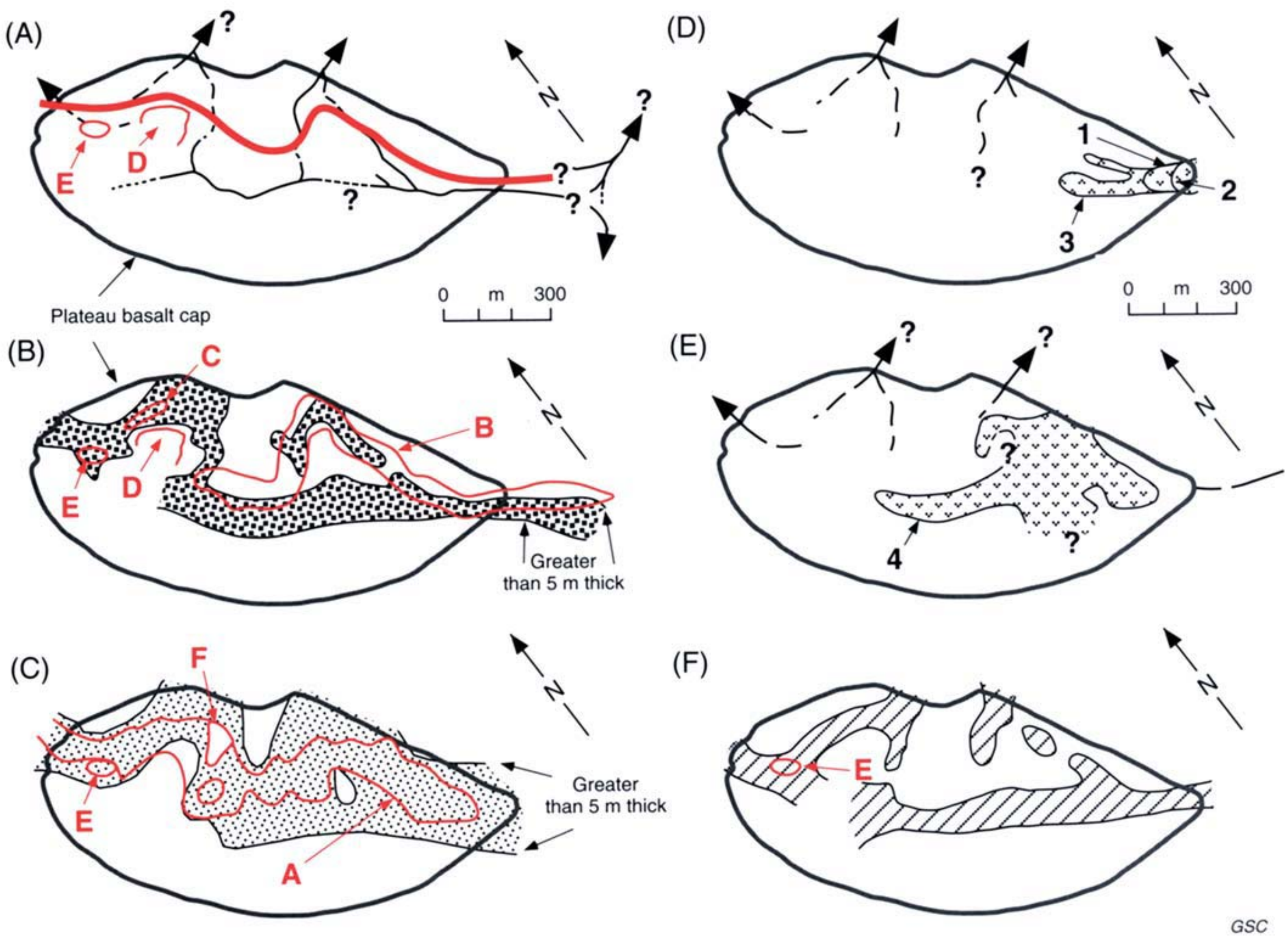


**Figure 8.1-4.** Plan views of Blizzard deposit showing ore zones (A to E) listed in Figure 8.1-3 and described in text. Plateau basalt cap shown as heavy outline. Based in part from Norcen (1979) and their submissions to the Bates Commission (Bates et al., 1980).

**A)** Initial paleodrainage at the base of the sedimentary sequence. Note the offset from the initial paleodrainage, of the trend of the axis of maximum ore grade-thickness (heavy red line) which coincides roughly with the initial drainage divide.

**B)** Distribution of coarse facies thicker than 5 m.

**C)** Distribution of fine facies thicker than 5 m.

**D)** Distribution of first (1), second (2), and third (3) basaltic flow units (valley basalts) and suggested stream diversion (dashed lines).

**E)** Distribution of fourth (4) flow. Succeeding flows (true 'Plateau' basalts) cover the area. A sixth flow (not shown) is very heavily oxidized (weathered) and in turn covered by two very thick and massive flows which constitute the main Plateau flows in the area.

**F)** Distribution of continuous and thick oxidized facies in sediments below basalt cap. Almost entirely in the coarse facies (see Fig. 8.1-4B).

some sandstones are uraniferous in the Upper Cretaceous of the Spatsizi Plateau and Mount Helveker areas in British Columbia. Radioactive anomalies occur in association with small copper showings in Grinnell Formation Purcell (Precambrian) rocks in the Sage Creek area in southeastern British Columbia.

Most of these occurrences are unimportant, but the sequences bearing them are all favourable targets for further uranium exploration and, in the case of the eastern Canadian Carboniferous basins, the environments are favourable for copper, silver, and lead deposits as well.

## DEFINITIVE CHARACTERISTICS

### General

1. Continental sandstones adjacent/superjacent to felsic basement rocks;
2. Sandstones with permeability contrasts (shale/mudstone beds);
3. Submature sandstone, especially with felsic clasts;
4. Poorly cemented (at least during mineralization);
5. Presence of reductants (coaly material, sulphides);
6. Presence of secondary oxidation/reduction features;
7. Sequence generally younger than Silurian.

### Specific (Beaverdell area)

8. Upper reaches of paleodrainage;
9. Protective cap of volcanics and mudstone;
10. Structurally "loosened" basement (extensional tectonics).

Most of these features (1 to 7) are brought together in continental successor and foreland basins adjacent to, or in terrains dominated by, felsic rocks. Younger deposits are favoured by the present preservation potential (poor in the long term) and by the presence of abundant reductants (advent of land plants in the Silurian). Most importantly, continental conditions favour input of oxidized and oxidizing surface and groundwaters.

## GENETIC MODEL

The general genetic model hinges on the divalent nature of uranium – being strongly soluble in oxidizing conditions (uranic: $U^{+6}$) and relatively insoluble in reducing conditions (uranous: $U^{+4}$). The paleohydrology of meteoric groundwaters comprise the most important aspect for the primary mineralizing solutions. The model involves three stages: i) oxidative leaching of uranium from slightly enriched felsic rocks (in basement, clasts within host sequence); ii) transportation by oxidizing surface waters and groundwaters into and through porous rocks; and iii) precipitation on entering reducing environments. Active bacterial biochemical effects in organic and sulphide-rich sediments enhance this trap. However reductant fluids may be introduced through fault zones or other aquifers or from brines from rising salt domes to mix and react with the uranium-bearing meteoric waters. Phosphates and vanadates also effect precipitation.

Semiarid (wet-dry climatic) conditions during sedimentation and especially during diagenesis and mineralization, afford favourable conditions. If the climate is too wet, heavy and rapid flow of oxidizing groundwaters will eventually flush out the deposits. If too dry, sufficient indigenous organic material and sulphides may not accumulate in the sediments. Semiarid conditions favour the development of more mature groundwaters (bicarbonate-rich) at shallow depths, which in turn favour complexing with uranyl ions in the upstream end of the aquifer.

Shale (mudstone) layers and lateral facies changes help constrain the plumbing system for groundwater flow and may, along with local closed basins, produce stagnation zones. Lower rates and volume of groundwater flow in first- and second-order (paleo)stream channels are likely critical to affording the proper conditions for deposition as significant deposits of the basal channel subtype are restricted to the first- and second-order paleochannels in both Japan and the Beaverdell area (Fig. 8.1-2). Organic-rich fine facies, as well as providing physical restraints to the plumbing system, may also provide reductant buffers. Impermeable mudstones or volcanic rocks provide the deposits a degree of protection from severe destruction.

The mineralization occurs during (and is a part of) the process of diagenesis of the sandstones. Commonly this process starts shortly after deposition of the sands, but may become dormant and then restart several times and much later, and continues until porosity and permeability is greatly restricted by more or less complete lithification of the sandstone.

## RELATED DEPOSIT TYPES

In general sandstone-hosted uranium deposits share definitive characteristics with other sandstone-hosted Cu, V, and Pb(-Zn±Ag) deposits and commonly occur in the same district (for example, Uravan district in Utah, U.S.A.).

Some sandstone-hosted uranium deposits contain juvenile and eroded felsic volcanic material. The host sequence may grade laterally and/or vertically to fully volcanic rocks, and all gradations may be present from volcanic- to sandstone-hosted deposits (for example, those in northern Italy).

In some unconformity-type uranium deposits, part or most of the deposit may be in overlying continental sandstones, such as in the Athabasca Basin in Saskatchewan. In such cases the reductants appear to have originated in the basement and the uranium appears to have been entrapped as a stationary plume in the overlying sandstones and regoliths. Conversely, in basal channel subtype deposits there are some minor zones of mineralization within the regolith, as in deposits in the Beaverdell area (Fig. 8.1-3 and 8.1-4, zone D).

Some, if not all, paleoplacer-uranium deposits show minor remobilization (modified placer model).

## EXPLORATION GUIDES

1. Attention should be paid to the geological characteristics as described previously, in particular, elevated amounts of uranium in basement rocks and abundance of uranium occurrences (even if small) in associated felsic

volcanics, in late stage and post-tectonic granites and pegmatites. Basement metamorphic complexes should also be regarded as favourable geological environments.

2. Some caution must be exercised with geochemical methods. For example, in south-central British Columbia the most arid areas give high responses for uranium in surface (stream) waters and low responses in stream sediments, whereas in the damper areas, as in the nearby Okanagan Highlands, the reverse is true.
3. Similarly, caution must be used with radiometric methods. Younger (some Tertiary and most Quaternary) deposits are commonly out of equilibrium or have not yet reached equilibrium with daughter elements. This is especially true for surficial deposits (see Culbert et al., 1984).

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1981: Sandstone stratigraphy and uranium potential of the eastern Hornby Bay Basin, in Mineral Industry Report 1977, Northwest Territories, (ed.) C. Lord, P.J. Laporte, W.A. Gibbins, J.B. Seaton, J.A. Goodwin, and W.A. Padgham; Indian and Northern Affairs, Canada, Exploration and Geological Services Unit, EGS 1981-11, p. 132-147.

# 8.2 SANDSTONE LEAD

D.F. Sangster

## INTRODUCTION

Disseminated galena and minor sphalerite, in transgressive basal quartzite or quartzofeldspathic sandstones resting on sialic basement are the definitive geological features of sandstone-lead deposits. The commodities produced from this type of deposit are mainly lead with lesser zinc; silver is rarely recovered. Important examples include: Yava, Nova Scotia; George Lake, Saskatchewan; Laisvall, Sweden; Maubach and Mechernich, Germany; Largentière, France; and Zeida, Morocco.

## IMPORTANCE

Only two examples of this deposit type are known in Canada (Fig. 8.2-1); neither is in production at the present time. Compared with other deposit types, sandstone-lead deposits are a relatively minor type, although in some countries they constitute a major source of metal (e.g. Sweden).

## SIZE OF DEPOSIT

Deposits range in grade from 2 to 5% Pb, 0.2 to 0.8% Zn, and 1 to 20 g/t Ag; most are less than 10 million tonnes in size. Because of the disseminated nature of the ore, tonnages and grades can be markedly affected by changes in cut-off grades. At Yava, for example, at cut-off grades of 1, 2, and 3%, tonnages and grades are as follows: 71.2 million at 2.09% Pb, 30.3 million at 3.01%, and 12.6 million at 3.95%, respectively.

## GEOLOGICAL FEATURES

### Geological setting

Host rock sandstones, quartzitic or quartzofeldspathic in composition, were deposited in environments ranging from continental fluvial (Yava) to shallow marine or tidal beach (Laisvall). The most common environment is one of mixed continental and marine character (i.e. paralic). Host rocks in most districts are succeeded by marine sediments, suggestive of marine transgression onto the craton.

Without exception, basement rocks underlying sandstone-lead deposits are of sialic composition and most are granites or granitic gneisses (Bjørlykke and Sangster, 1981). In several instances, basement rocks are demonstrably anomalous in lead content compared to the world average for granitic rocks (~22 ppm).

**Sangster, D.F.**
1996: Sandstone lead; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 220-223 (also Geological Society of America, The Geology of North America, v. P-1).

Sandstone-lead deposits occur in marine sandstone or in fluvial sandstone with terrestrial organic material. Host rock sandstones are grey or white but never red.

Paleomagnetic data available in several districts indicate a low paleolatitude position (0-30°). The presence of evaporites in some deposits indicates that paleoclimatic conditions during deposition of host rocks ranged from warm arid to semiarid. Alternatively, abundant organic debris in other districts may suggest a somewhat more humid climate prevailed in those areas. Taken together, paleoclimatic conditions for sandstone-lead deposits indicates host rock depositional conditions varied from area to area but with a majority of them being semiarid and warm (Bjørlykke and Sangster, 1981).

### Age of host rocks

Deposits are found in rocks ranging from Middle Proterozoic to Cretaceous; those in Canada are Middle Proterozoic (George Lake) and Pennsylvanian (Yava). Rocks of Late Proterozoic-Early Cambrian (Norway, Sweden) and Triassic (France, Germany, Morocco) ages contain a majority of deposits of this type.

### Relations of ore to host rocks

The orebodies are commonly conformable to bedding in the sandstone, especially on a mine scale. In detail, however, the ore zones may actually transgress bedding at a low angle. Sedimentary channels in the sandstone are preferentially mineralized.

### Form of deposits

Because sedimentary channels are the preferred sites for sandstone-lead deposits (Bjørlykke and Sangster, 1981; Sangster and Vaillancourt, 1990a), most of them have a generally lensoid, broadly conformable form. In plan, ore zones tend to be sinuous, again illustrating the sedimentary control, and laterally discontinuous. At Largentière (France), higher grade zones occur in, and adjacent to, steep faults; consequently, in this deposit, many ore zones are narrow, lenticular bodies oriented at high angles to bedding.

### Distribution of ore minerals

The preferred site of ore minerals is as cement between sand grains resulting in disseminated sulphide blebs or spots in massive sandstones or concentrations of sulphides along the lower, more porous, portions of graded beds. Where carbonaceous material is present, sulphides fill wood cells or replace cell walls. Concretionary-like sulphide concentrations are abundant in most deposits.

Ore zones tend to be delimited by assay, rather than by geological boundaries. Characteristically, a higher grade core is surrounded by material that progressively decreases in grade outward.

## Ore compositions; zoning of ore

Deposits are normally lead dominant; Pb/(Pb+Zn) values are all greater than 0.85 and most are greater than 0.95. George Lake (Canada), in contrast, is zinc-dominant but all other geological features are typical of this deposit type. Few data are available on metal zoning but there is evidence of an upward, and basinward, increase in zinc relative to lead in some deposits (e.g. Yava, Laisvall).

## Alteration

Hosted as they are in siliciclastic rocks, it is not surprising, perhaps, that evidence of strong wall rock alteration is characteristically lacking in sandstone-lead deposits. In fact, alteration is generally restricted to weathering of basement rocks underlying the ore-bearing sandstones.

## Mineralogy

The most common sulphide minerals are galena, sphalerite, pyrite, and chalcopyrite although they differ markedly in abundance both within, and between, deposits. Replacement of these minerals by secondary analogues have been reported in several deposits (e.g. Zeida, Maubach, Mechernich).

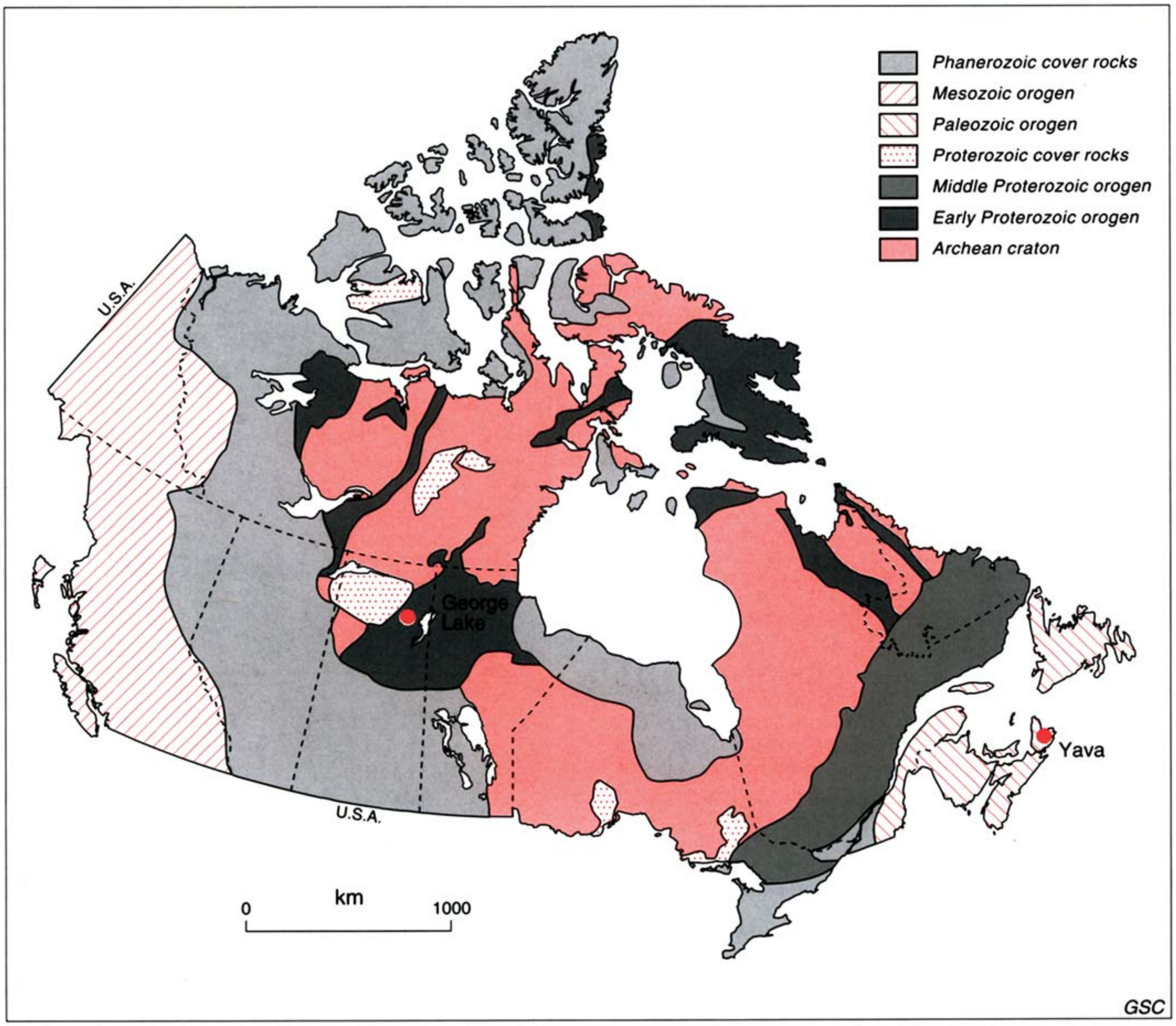


**Figure 8.2-1.** Location of sandstone-lead deposits in Canada.

Quartz and various carbonate minerals constitute the most abundant nonsulphide cement; barite and fluorite are minor cements in some deposits. Silica, usually chalcedonic, is characteristically more abundant than carbonate.

### Ore textures

Sulphide minerals in sandstone-lead deposits, as a result of their typical occurrence as cement between detrital sand grains, characteristically display a disseminated texture. However, the disseminated sulphides are not normally homogeneously dispersed throughout the sandstone. Two very common textures are: i) poikiloblastic "spots" as much as 2 cm in diameter, representing local accumulations of galena; spots may be randomly distributed in the sandstone or may show a slight preferential alignment parallel to bedding; ii) discontinuous galena-rich streaks distributed parallel to bedding, including crossbedding.

Another characteristic texture is the abundant epitaxial quartz overgrowths on detrital quartz grains (Fig. 8.2-2). This texture, in some deposits at least, is more abundant within or near ore zones than regionally. Paragenetic studies indicate the epitaxial quartz predates galena.

## DEFINITIVE CHARACTERISTICS

Sandstone-lead deposits can be recognized by the following characteristic features:

1. Host rock is a relatively clean, reasonably mature, quartz sandstone which is transgressive onto a sialic platform.
2. Galena is the dominant sulphide; pyrite and sphalerite are present in decidedly subordinate amounts. Copper minerals occur in trace quantities only.
3. Sulphide minerals are mainly disseminated, either as random aggregates or distributed along bedding planes in the host sandstone.
4. Epitaxial quartz overgrowths are abundant, especially in the ore zones.
5. Ore zones tend to follow sedimentary channels in the sandstone; higher grade zones are surrounded by lower grade material.

## GENETIC MODEL

As discussed by Bjørlykke and Sangster (1981), two main genetic models have been proposed: 1) the hydrothermal or basin brine model, and 2) the groundwater or meteoric model. Inasmuch as deposits are found in both marine and continental depositional environments, it is unlikely that either of these models applies to all sandstone-lead deposits.

Based on research in the marine sandstone-hosted Laisvall deposit (Sweden), Rickard et al. (1979) proposed a basin brine model, relating migration of the ore fluid with nappe movement in the Caledonides. They suggested that compression by the overriding nappes was the main force driving ore fluids eastward. Marine shales, lying westward (i.e. basinward) of the Laisvall area were suggested as the source of metals; seawater sulphate was identified as the source of sulphur. This model has many points in common with that of the "squeegee" model for Mississippi Valley-type (MVT) deposits (Oliver, 1986), also hosted in marine sedimentary rocks. A variation on the basin brine model was proposed by Bjørlykke et al. (1991) who drew attention to the presence of high heat-producing (HHP) granites beneath certain MVT and sandstone-lead deposits and suggested that basinal brines might have participated in vertically-directed convection cells generated by high heat-producing basement granites.

For sandstone-lead deposits in a continental environment, the author prefers a meteoric groundwater model involving the following: i) in situ breakdown, by passage of groundwaters, of potassium feldspar in arkosic sandstone; ii) transport of the lead released in this way, through porous channels in the sandstone, to an environment having a sufficiently high reduced sulphur content to precipitate sulphides. Detailed lead isotopic studies at Yava (Sangster and Vaillancourt, 1990b) have shown lead in the deposit was derived from underlying basement. During weathering, lead, released from the basement-derived feldspar in the sandstone, was carried in groundwater to the site of ore formation. Within the oxidizing environment of meteoric and shallow groundwater, lead will remain in solution provided the dissolved carbonate and sulphate content of


**Figure 8.2-2.** Photomicrograph illustrating detrital quartz grains (light grey) partially surrounded by silica overgrowths (dark grey) in characteristic straight-edge contact with galena cement (white), Yava (from Sangster and Vaillancourt, 1990b). GSC 204077-F

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the groundwater is low. Upon reaching a reducing environment provided by the accumulation of organic material in the sediments, lead combined with biogenically reduced sulphur and precipitated as galena. Source of sulphur in the continental sandstone deposits is conjectural although, at Yava, gypsum nodules in underlying marine shale was suggested as a sulphur source (Sangster and Vaillancourt, 1990b).

## RELATED DEPOSIT TYPES

Sandstone-uranium and sedimentary copper deposit types share the following genetic features with sandstone-lead deposits, particularly those hosted in continental sandstones: i) metals were derived from basement rocks (felsic in the case of Pb and U; mafic in the case of Cu); ii) transport was effected by oxidized subsurface waters through permeable clastic rocks; iii) precipitation occurred upon reaching a reducing environment. Sandstone-lead deposits in marine or paralic sandstones may share a basin brine-related genetic model with Mississippi Valley-type lead-zinc deposits, especially those situated immediately above basement containing high heat-producing granites.

## EXPLORATION GUIDES

The following parameters may be useful in the search for sandstone-lead deposits:

1. Sialic basement; those with average lead content greater than ~30 ppm are particularly significant.
2. Basal portion of grey or white (not red) quartzitic sandstone of a transgressive sequence on sialic basement.
3. Channels in sandstone, especially on the periphery of the sedimentary basin.
4. Permeable zones in sandstone, i.e. the "cleaner" portions with minimum intergranular material.
5. Epitaxial quartz overgrowths on detrital quartz grains.

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# 8.3 SEDIMENT-HOSTED STRATIFORM COPPER

**R.V. Kirkham**

Sediment-hosted stratiform copper (SSC) or 'diagenetic sedimentary' copper deposits belong to a large family of diverse, more or less concordant and discordant copper deposits and occurrences that show a close relationship to their sedimentary host rocks. In this sense they are 'sedimentary', even though available evidence supports diagenetic precipitation of metals at redox boundaries rather than syngenetic metal deposition. Nomenclature for deposits of this type is problematic and no general term referring to them is entirely satisfactory. Individual deposits have been variously referred to as syngenetic, sedimentary, syndiagenetic, diagenetic, stratiform, concordant, peneconcordant, stratabound, sediment-hosted, shale-hosted, sandstone-hosted, and carbonate-hosted. Because of the diverse lithologies of host rocks and different morphologies, close relationship of these deposits to the environment of formation of their host rocks and inferred diagenetic origin, the term 'diagenetic sedimentary' copper deposits is a reasonable designation for these deposits, but as the term 'sediment-hosted stratiform' copper deposits is

**Kirkham, R.V.**
1996: Sediment-hosted stratiform copper; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 223-240 (also Geological Society of America, The Geology of North America, v. P-1).

widely accepted for such deposits (e.g., Boyle et al., 1989) it will be used in this paper. Nevertheless, the deposits under consideration are not truly 'stratiform' and this nongenetic term also permits inclusion of deposits of entirely unrelated genesis, such as syngenetic exhalative (Sedex) and high-temperature replacement deposits. However, in this paper only 'diagenetic sedimentary sediment-hosted stratiform' copper deposits will be considered. 'Diagenetic sedimentary' copper deposits can be divided into two subtypes: 'Kupferschiefer-type' which occur in rocks deposited in paralic marine (or large-scale saline lacustrine) environments, and 'redbed-type' which occur in rocks deposited in continental environments. Much of the data presented here is from recent compilations by Kirkham (1989) and Kirkham et al. (1994). Kirkham (1989) and sources in Boyle et al. (1989) should be consulted for further information and discussion.

# 8.3a Kupferschiefer-type

## IDENTIFICATION

Kupferschiefer-type deposits occur typically as zonally distributed, disseminated sulphides at oxidation-reduction boundaries in anoxic rocks at the base of a marine or large-scale saline lacustrine transgressive cycle overlying or interbedded with continental redbeds. Redbeds and evaporites are characteristic associated rock types.

Copper is the most important metal found in these deposits and silver and cobalt are the most important byproduct or, in a few localities, coproduct metals. Other characteristic associated base metals, such as lead and zinc, are either of little or no economic importance. Platinum group elements have been reported to occur in some deposits in Zaire and the Lubin deposit in Poland.

The Redstone (Coates Lake) deposit in the Northwest Territories (Fig. 8.3-1) (Kirkham, 1974; Ruelle, 1982; Chartrand and Brown, 1985; Jefferson and Ruelle, 1986; Chartrand et al., 1989; Lustwerk and Wasserman, 1989) is the most completely documented deposit of this type in Canada. Most Kupferschiefer-type occurrences shown in Figure 8.3-1, apart from the Redstone area, are thin, low grade, and of minor importance. Nevertheless, their distribution indicates areas that might be prospective for this deposit type. Kupferschiefer deposits in Germany and Poland (Rentzsch, 1974; Jung and Knitzschke, 1976; Oszczepalski and Rydzewski, 1983; Jowett et al., 1987; Oszczepalski, 1989; Peryt, 1989), most of the main deposits in the central African Copperbelt of Zambia and Zaire (Darnley, 1960; Garlick, 1961, 1969; Mendelsohn, 1961; Lombard and Nicolini, 1962, 1963; Bartholomé et al., 1972; Bartholomé, 1974; Fleischer et al., 1976; Annels, 1979a, b, 1989; Lefebvre, 1989a, b) and the White Pine deposit in Michigan (White and Wright, 1966; Ensign et al., 1968; Brown, 1971; White, 1971) are typical examples of this type in other parts of the world.

## IMPORTANCE

In Canada, no significant production has come from Kupferschiefer-type deposits and none is anticipated in the near future. Nevertheless, they are the world's second most important source of copper (after porphyry deposits) and areas favourable for their occurrence, such as the Redstone copperbelt in the Northwest Territories, have been identified in Canada.

Most world production from deposits of this type comes from a few very large deposits and districts, such as the Lubin deposit in Poland and the central African Copperbelt of Zambia and Zaire. The White Pine deposit in Michigan is the only current producer of this type in North America. The Dongchuan district in southern China and deposits in the Aynak area near Kabul, Afghanistan could be of Kupferchiefer-type.

Kupferschiefer-type deposits in the central African Copperbelt are also the world's most important source of cobalt, and some Kupferschiefer-type deposits, such as Lubin in Poland, produce significant amounts of silver. Small amounts of platinum group elements, gold, lead, uranium, and rhenium(?) have also been recovered from deposits of this type.

## SIZE AND GRADE OF DEPOSITS

Figure 8.3-2 shows the grade and tonnage distribution for 74 sediment-hosted stratiform copper deposits. Kupferschiefer- and redbed-type deposits are indicated by separate symbols. This plot shows that Kupferschiefer-type deposits tend to be larger and richer than most redbed-type deposits and that some of them contain as much copper as some of the world's largest porphyry copper deposits. An average grade and tonnage for Kupferschiefer-type deposits is 44 million tonnes at 1.8% Cu, amounting to about 0.8 million

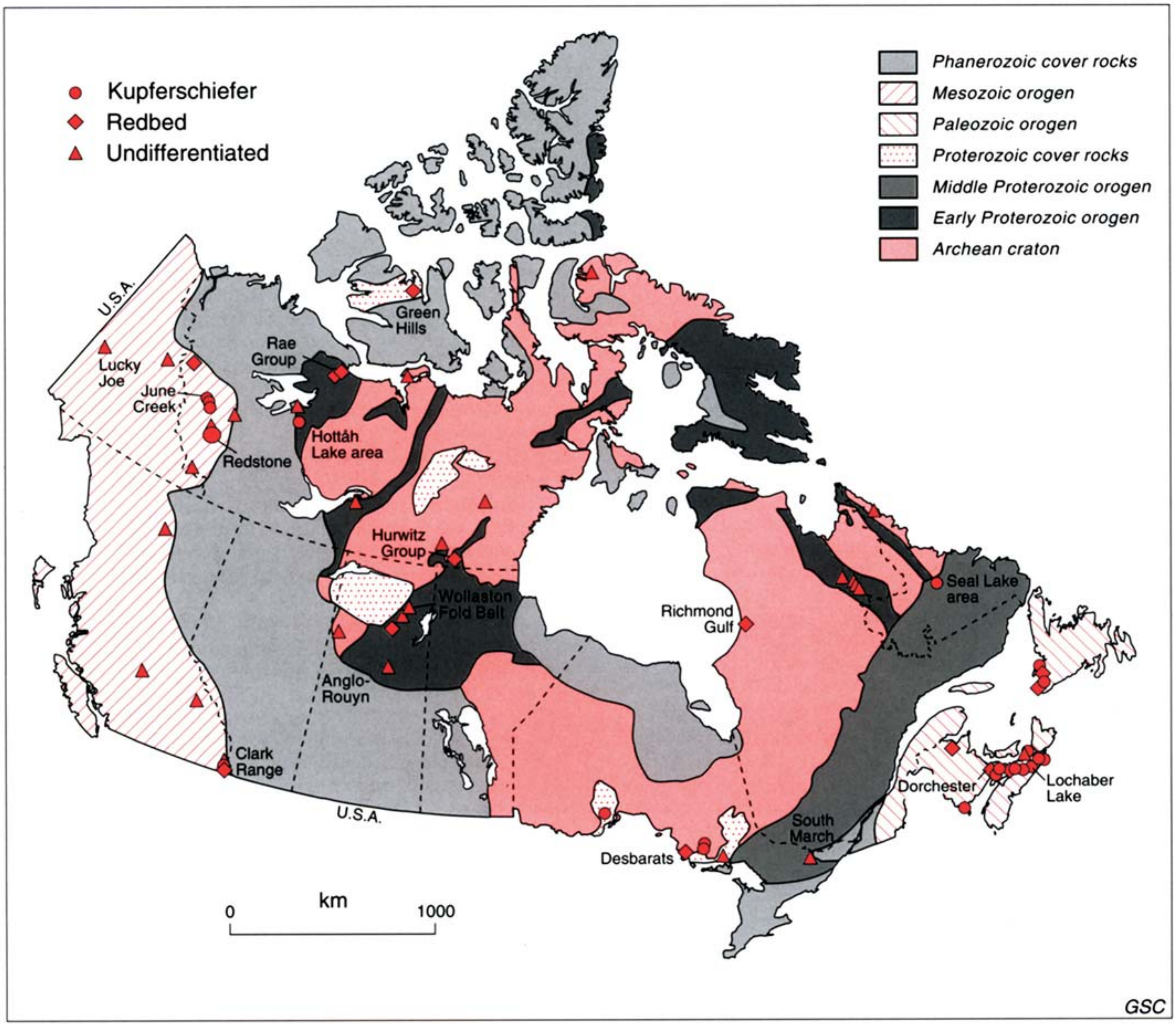


**Figure 8.3-1.** Distribution of selected sediment-hosted stratiform copper (SSC) deposits and occurrences in Canada. Beside the Redstone deposit in the Northwest Territories, most of the localities shown are of minor importance. Nevertheless, they outline areas and rock sequences favourable for the occurrence of such deposits. See Kirkham et al. (1994) for deposit listings.

tonnes of copper metal. The Redstone deposit, even though it is of significant size and grade (drill-indicated 37 million tonnes averaging 3.9% Cu and 11.3 g/t Ag), is not attractive for mining because it occurs in a remote, undeveloped region with a severe climate, dips about 35° to 45°, and only averages about 1 m thick (Ruelle, 1982).

The tabular nature of most Kupferschiefer-type deposits is not conducive to open-pit or block-caving, low-cost mining methods, and therefore higher grades are necessary in these deposits to support relatively selective underground mining methods. Cut-off grades generally define sharp ore limits and mining of barren adjacent rocks can lead to significant dilution.

## GEOLOGICAL FEATURES

The classic setting of the very bituminous, anoxic Permian Kupferschiefer (copper shale) of Europe at the base of a marine transgressive sequence overlying continental redbeds is illustrated in Figure 8.3-3. However, in some areas, such as the central African Copperbelt of Zambia (Clemmey, 1978); White Pine, Michigan (Daniels, 1982); and Redstone, Northwest Territories (Jefferson and Ruelle, 1986), it has been suggested that ore host rocks were deposited in large-scale saline lacustrine, rather than marine, environments. Some lacustrine evaporite environments are similar in many respects to marine evaporite environments (e.g., Dead Sea). Both Kupferschiefer- and redbed-type sedimentary copper deposits typically occur in rocks that were deposited in arid and semiarid areas within 20 to 30 degrees of the paleoequator (e.g., Fig. 8.3-4). This consistent feature of deposits of these types is an important factor bearing on their genesis. For further discussion of this subject and for plots for other geological periods see Kirkham (1989). They also only occur in rocks that postdate oxygenation of the Earth's atmosphere or "oxyatmoversion" at about 2.4 Ga (Roscoe, 1973; Kirkham and Roscoe, 1993).

Many Kupferschiefer-type deposits occur in rifts, in areas where basalts, redbeds, and evaporites form part of the stratigraphic succession. Typical features of a Kupferschiefer-type deposit occurring in a rift are shown in Figure 8.3-5, modelled after the Redstone deposit. In some areas, such as Creta in Oklahoma (Johnson and Croy, 1976; Dingess, 1976; Smith, 1976) and in upper Windsor Group rocks in Nova Scotia and New Brunswick (Kirkham, 1985), Kupferschiefer-type deposits are interbedded with, rather than overlying, redbeds.

Sulphides in Kupferschiefer-type deposits are characteristically disseminated and occur in a series of overlapping mineral zones (hematite, native copper, chalcocite, bornite, chalcopyrite, galena, to sphalerite and/or pyrite), outward and upward, from the oxidized to the reduced side (Fig. 8.3-3, 8.3-5). Not all of these minerals are present in every deposit. In a given deposit not all beds are equally mineralized. Very bituminous, reduced beds (such as the Kupferschiefer ore unit) are high grade, whereas less reduced or oxidized beds are typically lower grade. In a sequence containing many reduced beds, the lowest one typically has the highest grade and reduced beds above the deposit can be entirely barren. In some deposits carbonaceous shale and microbial carbonates (e.g., Redstone) contain higher metal concentrations than adjacent arenaceous and evaporitic units. Other deposits, such as that in the Kona Dolomite (Taylor, 1972); Mufulira (Annels, 1979a, b); and White Pine (Hamilton, 1967; Kelly and Niskioka, 1985) show that arenaceous aquifers have been important in controlling fluid flow, mineral zoning, and possibly, also in containing fluid hydrocarbons that controlled metal deposition.

Veins, ranging from small discontinuous gash structures 1 to 2 cm long to more through-going structures, are common, but in most deposits have complex histories and have not been studied in detail. Some veins, such as ones at White Pine, Michigan (Carpenter, 1963) and at Spar Lake, Montana (Hayes and Balla, 1986) have copper depletion halos around them and clearly postdate the main disseminated stratiform sulphides. In some deposits, such as those in the Kupferschiefer and White Pine, veins with addition halos are also common (Gregory, 1930; Jowett, 1987; Mauk et al., 1992), indicating at least local addition of metals from the fractures. Nevertheless, in all Kupferschiefer-type deposits stratigraphic controls are more important than structural controls and the deposits show no relationship to igneous rocks. In many deposits, the disseminated sulphides fill original porosity and, in the case of microbial carbonate host rocks in Zaire and at Redstone, which should lose their permeability readily, support an early diagenetic age for mineralization (Bartholomé et al., 1972; Chartrand and Brown, 1985; Chartrand et al., 1989). Jowett (1987) and Jowett et al. (1987), however, have argued for a late diagenetic origin for deposits in the Kupferschiefer.

Kupferschiefer-type deposits are characterized by a red, hematitic, oxidative alteration (Rote Fäule) beneath and adjacent to the copper deposit, indicative of infiltration of metalliferous, oxic fluids into the anoxic host rocks (Rentzsch, 1974; Jung and Knitzschke, 1976; Oszczepalski and Rydzewski, 1983; Jowett et al., 1987).

In some Kupferschiefer-type deposits, particularly favourable host rocks are uniformly mineralized over large areas and only at the outer limits of the deposit do the sulphide zones cut the stratigraphy (e.g., White Pine). In some deposits they cut 10 m to as much as 100 m of section. In deposits containing other base metals, copper sulphide zones are flanked and/or overlain by lead and zinc zones. In the central African Copperbelt cobalt is generally concentrated in pyritic rocks near the outer edge of copper zones.

## DEFINITIVE CHARACTERISTICS

1. The deposits are peneconcordant concentrations of copper at oxidation-reduction boundaries in anoxic marine (or lacustrine) rocks in contact with continental redbeds.
2. Deposits in many cases occur in association with redbeds and evaporites.
3. Sulphides are generally disseminated and occur in overlapping mineral zones upward and outward from the base of the deposit.
4. The economic deposits are dominated by copper, with variable amounts of silver as the most diagnostic associated ore element. In the central African Copperbelt and a few other areas, cobalt is also an important associated element. In many deposits lead and zinc are present in upper and outer mineral zones in subeconomic concentrations.

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## GENETIC MODEL

Genesis of Kupferschiefer-type deposits has been debated widely since their recognition. For perhaps 70 years or more views have tended to be polarized, supporting either a syngenetic or late hydrothermal epigenetic origin. As can be seen in a number of papers in Boyle et al. (1989), several different views of genesis are currently held. If any consensus exists, an intermediate diagenetic origin has the greatest support (e.g., White and Wright, 1966; Ensign et al., 1968; Brown, 1971, 1992; Bartholomé et al., 1972; Rentzsch, 1974; Gustafson and Williams, 1981; Chartrand and Brown, 1985; Haynes, 1986; Jowett et al., 1987; and many papers cited in Boyle et al., 1989). This writer favours a diagenetic origin(s) and recognizes no convincing evidence supporting syngenesis or late hydrothermal epigenetic origins. On the other hand, the consistent relationship of these deposits with redbeds and evaporites and low-latitude arid and semiarid areas of deposition, despite diagenetic origins, indicates an essential control by the environment of sedimentation. This important relationship between redbeds, evaporites, and the environment of sedimentation has been known for some time and was emphasized by Strakhov (1962) and other workers.

Kirkham (1989) has considered briefly some of the main factors in the genesis of sediment-hosted stratiform copper deposits and has discussed some of their variability. Some of these factors are timing of ore emplacement, nature and source of ore fluids, sources of metals, sources of sulphur and reductants, and controls on fluid migration. For elaboration on these and other aspects of genesis the reader should consult Kirkham (1989) and other papers in Boyle et al. (1989).

As mentioned previously, evidence from little deformed and well studied deposits can be interpreted to support a diagenetic origin, but the precise timing and duration of ore formation, even for well-documented deposits, is difficult to determine. Probably a spectrum of time of formation ranging from early to late diagenesis, but definitely predating folding and metamorphism of the rocks (e.g., Garlick, 1965; Hayes and Einaudi, 1986), is most reasonable. The most likely ore fluids are brines derived from evaporites. Experimental work (Rose, 1976, 1989) indicated that the solubilities of Cu and Ag at low temperatures are dependent on chloride ion concentration, which supports the concept of evaporitic brines as the ore fluids and is consistent with the observed spatial association with evaporites. Labile constituents, such as mafic rock fragments and minerals (e.g., hornblende, pyroxene, biotite, oxides, and sulphides) in first-cycle redbeds, are viewed as the most likely source of the copper. The presence of lead in the deposits probably indicates a mixed provenance of the redbeds and that they contained silicate components such as potassium feldspar. The copper might be released directly into the pore fluid or converted to a form that could be stripped easily by the later passage of brines during the oxidative diagenetic formation of redbeds (Walker, 1967, 1989; Zielinski et al., 1983). Experimental studies by Rose and Bianchi-Mosquera (1993) indicate that metal associations (e.g., Cu-Ag, Cu-Co, Cu-Pb-Zn-Ag) can be explained by differences in pH, Eh, temperature, chemical composition of ore fluids, and Fe-oxide character of the diagenetic environment, but that in some circumstances copper and other metals are strongly absorbed on goethite and hematite and would be relatively immobile in diagenetic redbed environments. Older ore deposits in basement rocks are not viewed as likely sources of metals, as cupriferous formations hosting some Kupferschiefer-type deposits contain an enormous amount of copper, far exceeding that found in most economic deposits.

The sources of sulphur and reductants are important aspects of the oxidation-reduction processes controlling ore deposition. Reductants could be such materials as pyrite, solid carbonaceous matter, $H_2S$, $CH_4$, or liquid hydrocarbons indigenous to, or added to, the host rocks. Work by Hoy et al. (1986) and Hoy and Ohmoto (1989) indicated that significant sulphur, as sulphate in the ore fluid, might have been added to deposits during ore deposition. The nature and distribution of sulphur and reductants probably differed considerably from deposit to deposit and had profound effects on metal grades and distribution.

The paleohydrology of the ore systems is not well understood and is only now receiving considerable attention. The lack of definitive data on the timing and on constraints on the nature of the ore-forming systems has precluded rigorous analysis of the paleohydrology. Many possibilities exist (see Kirkham, 1989), but a body of evidence is appearing for many deposits supporting relatively early diagenetic formation dewatering, while coarse grained sediments were still permeable and fine grained sediments were compacting (White, 1971; Ruelle, 1982; Kirkham, 1989; Lustwerk and Wasserman, 1989). Magara (1976) and Bredehoeft et al. (1988) indicated that in an active, compacting sedimentary basin with mixed sand and shale, the sand will act as drains for compactional fluids and most of the fluids will migrate laterally within the sandstone aquifers towards the edge of the basin. In thick shale sequences without sand, fluid flow will be primarily vertically upward. Galloway (1982) summarized basic fluid genesis and migration in dynamic compacting sedimentary basins. Jowett (1986) and Jowett et al. (1987), however, have proposed a late diagenetic, thermally driven fluid flow model for the Kupferschiefer deposit in Germany and Poland.

The general aspects of evaporite-derived ore fluid, redbed metal source rocks and aquifers, and an overlying anoxic transgressive marine (or lacustrine) succession of ore host rocks in a rift environment are illustrated schematically in Figure 8.3-5. The processes that controlled ore formation probably differed considerably from one area to another, but, whatever the details of processes were, available information indicates that large amounts of metals (Cu, Ag, Co) were moved and concentrated into economic deposits in such sedimentary sequences of many different ages in several parts of the world. So much copper (and cobalt) has been concentrated into so many large, rich deposits in the central African Copperbelt that no copper source or concentrating process seem adequate. Possibly in this exceptional area, compressional forces related to collision events to the south and west in the Zambesi and/or Damaran belts at a critical stage during diagenesis formed large gravity-driven fluid-flow systems that moved vast quantities of cupriferous fluids that were responsible for the formation of these extraordinary deposits (Fig. 8.3-6). Higher temperatures of ore deposition could be expected of deep basinal brines and could account for the high cobalt contents of these ores (Annels, 1989; Rose and Bianchi-Mosquera, 1993).

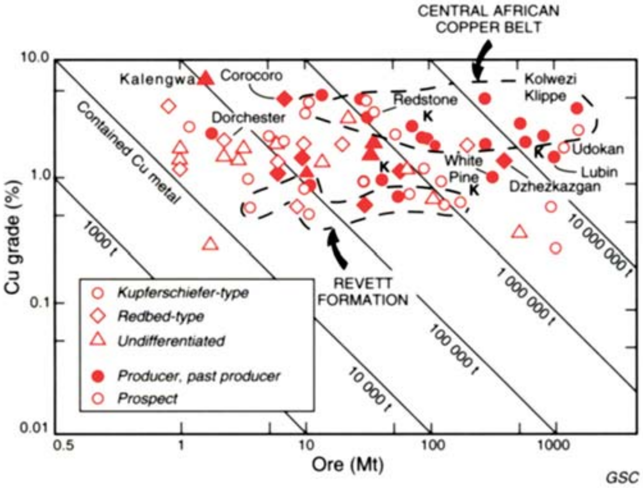



**Figure 8.3-2.** Size and grade of 74 sedimentary copper deposits. Producers and past producers are shown in solid and undeveloped deposits are shown as open symbols. "K" denotes deposits in the Kupferschiefer in Europe.

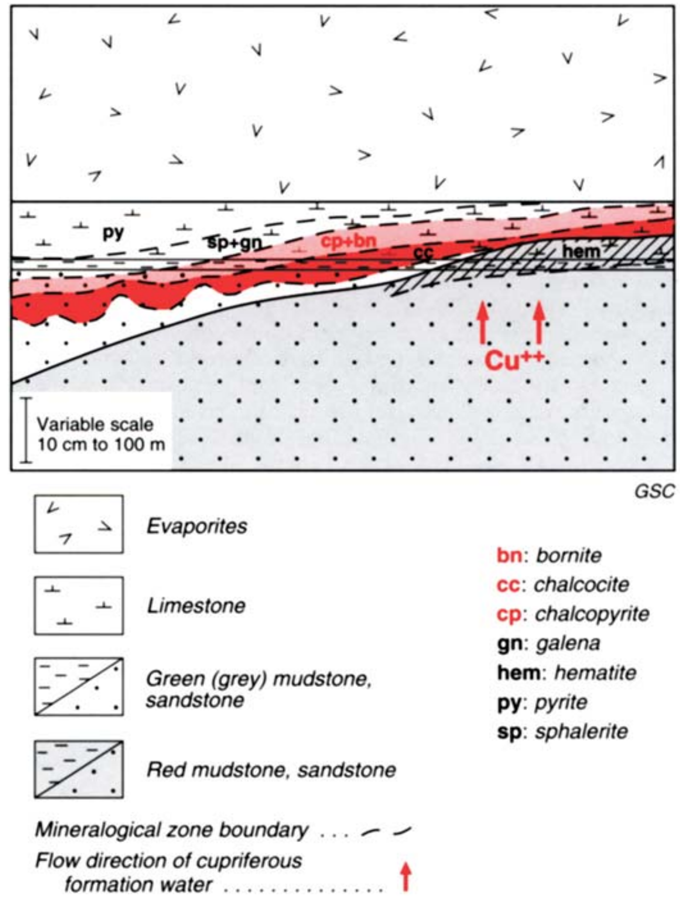
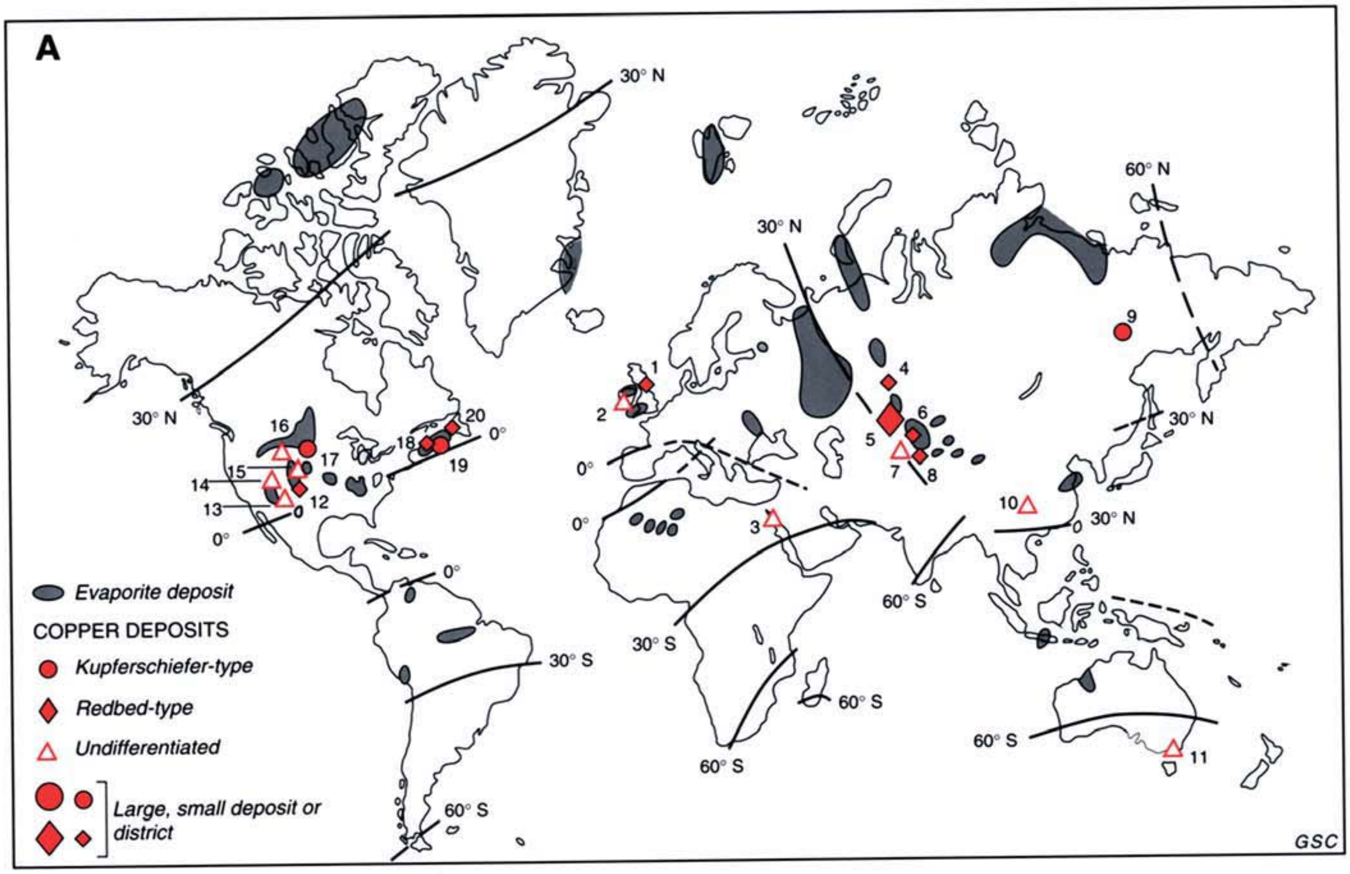



**Figure 8.3-3.** Typical setting, rock units, and metal zonation for the Kupferschiefer-type deposits. The zonal pattern of sulphides (Cu sulphide zones in red) is from White and Wright, 1966; Jung, 1968; Brown, 1971; Rentzsch, 1974; Jung and Knitzschke, 1976; Oszczepalski and Rydzewski, 1983; and several other studies (after Kirkham, 1989).

**Figure 8.3-4 A)** Distribution of copper deposits and occurrences and evaporite deposits (modified from Kozary et al., 1968 and Zharkov, 1984) in Carboniferous rocks and paleolatitudes at about 280 Ma ago (latest Carboniferous-earliest Permian) (after Irving, 1983). 1) Firth of Forth, Drumshantie, and Larkfield; 2) Mallow and Ballyvergin; 3) W Araba and Sarabit Al Khadmin; 4) southern end of Teniz Basin (many deposits and occurrences); 5) Dzhezkazgan district (many deposits and occurrences); 6) Chu River; 7) Mirgalim-Sai and Zhanatas; 8) northern Kirgizia and Przheval; 9) Kurpandzha (Devono-Carboniferous); 10) Tung-Chuan; 11) Kengir (Devono-Carboniferous); 12) Pajarito Azule and Coyote Creek; 13) Mogollon Rim; 14) Bronze Lake and Ridenour; 15) Western Star and Cotopaxi Cordova; 16) Watercress Canyon; 17) Hot Brook Canyon; 18) numerous occurrences (e.g., Dorchester, Midway, and Goshen); 19) numerous occurrences in Windsor, Pictou, and other groups (e.g., Canfield, Oliver, Limerock, McLellan Brook, Rights River, Yankee Line Road, and Frenchvale); 20) Searston, Bald Mountain, Boswarlos, etc. (after Kirkham, 1989). **B)** Reconstructed Earth diagram for Late Carboniferous (circa 280 Ma) (after Irving, 1983) showing the distribution of copper deposits and occurrences and evaporite deposits in Carboniferous rocks. See Irving (1983) for explanation of patterns and abbreviations on base map (after Kirkham, 1989).


A
Evaporite deposit
COPPER DEPOSITS
Kupferschiefer-type
Redbed-type
Undifferentiated
Large, small deposit or district
GSC

B


PANTHALASSA
INDO-CHINA & MALAYA
ANGARA
KAZAK
LAURENTIA
BALTICA
SIKHOTE-ALIN
WEST GONDWANA

## RELATED DEPOSIT TYPES

In some interlayered marine-continental sequences Kupferschiefer- and redbed-type copper deposits occur together, supporting a close genetic relationship for these deposit subtypes. Volcanic redbed copper (VRC) deposits, to a large degree, are probably the analogues in volcanic sequences of diagenetic sedimentary copper deposits in sedimentary sequences. In many areas, such as the Keweenaw Peninsula in Michigan, the Coppermine River area in the Northwest Territories, the Seal Lake area in Labrador, and in the Andes of Chile, both of these types of deposits occur together. Sediment-hosted stratiform copper deposits have some features in common with sandstone-lead and uranium, Mississippi Valley-type (carbonate-hosted) lead-zinc, and unconformity-type uranium deposits but, as concluded by Bjørlykke and Sangster (1981), these various types of deposits were probably formed by somewhat different processes, by different fluids, at different times, and in different places. Metalliferous brines trapped in deeply buried, pressurized redbed reservoirs, an important component in the genesis of diagenetic sedimentary copper deposits, may have been responsible for the formation of other sediment-hosted copper deposits, such as Mount Isa and Gunpowder in Queensland; Kapunda and Kanmantoo in South Australia; Nifty in Western Australia; Kipushi, Zaire; Tsumeb and Kombat in Namibia; Apex, Utah; Sheep Creek, Montana; and Ruby Creek and Kennecott, Alaska, and even for some exhalative lead-zinc deposits in sedimentary sequences. However, little evidence is available to support such connections. More work, especially isotopic tracer studies, is required to evaluate such possibilities.

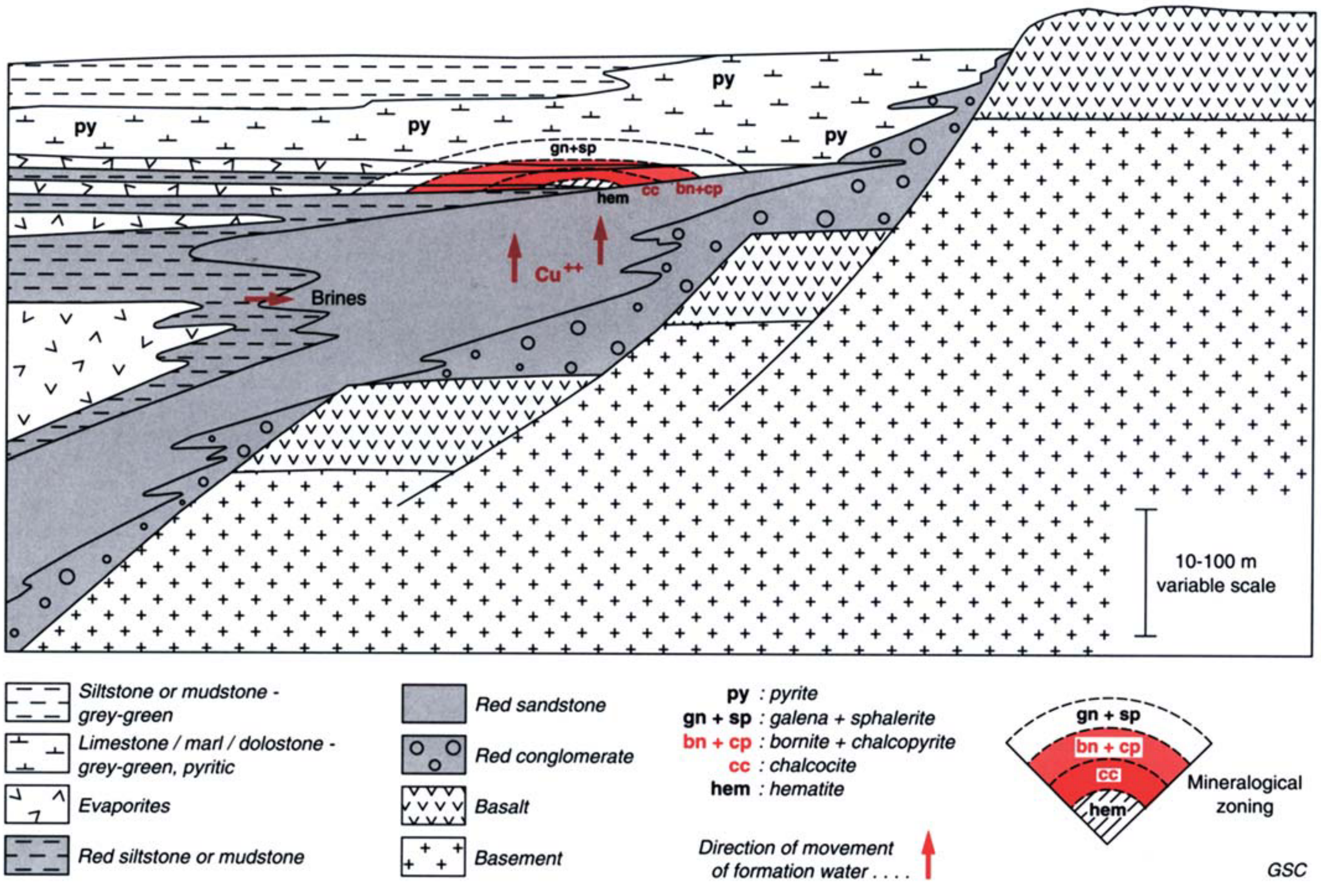



**Figure 8.3-5.** Diagrammatic section through a rift-controlled sedimentary basin showing many of the essential features in the formation of Kupferschiefer-type copper deposits. The Cu sulphide zones are shown in red. Modelled after Redstone, Northwest Territories. 'Basement' means any pre-existing rock type, at Redstone referring to platformal sedimentary rocks and tholeiitic continental basalts (after Kirkham, 1989).

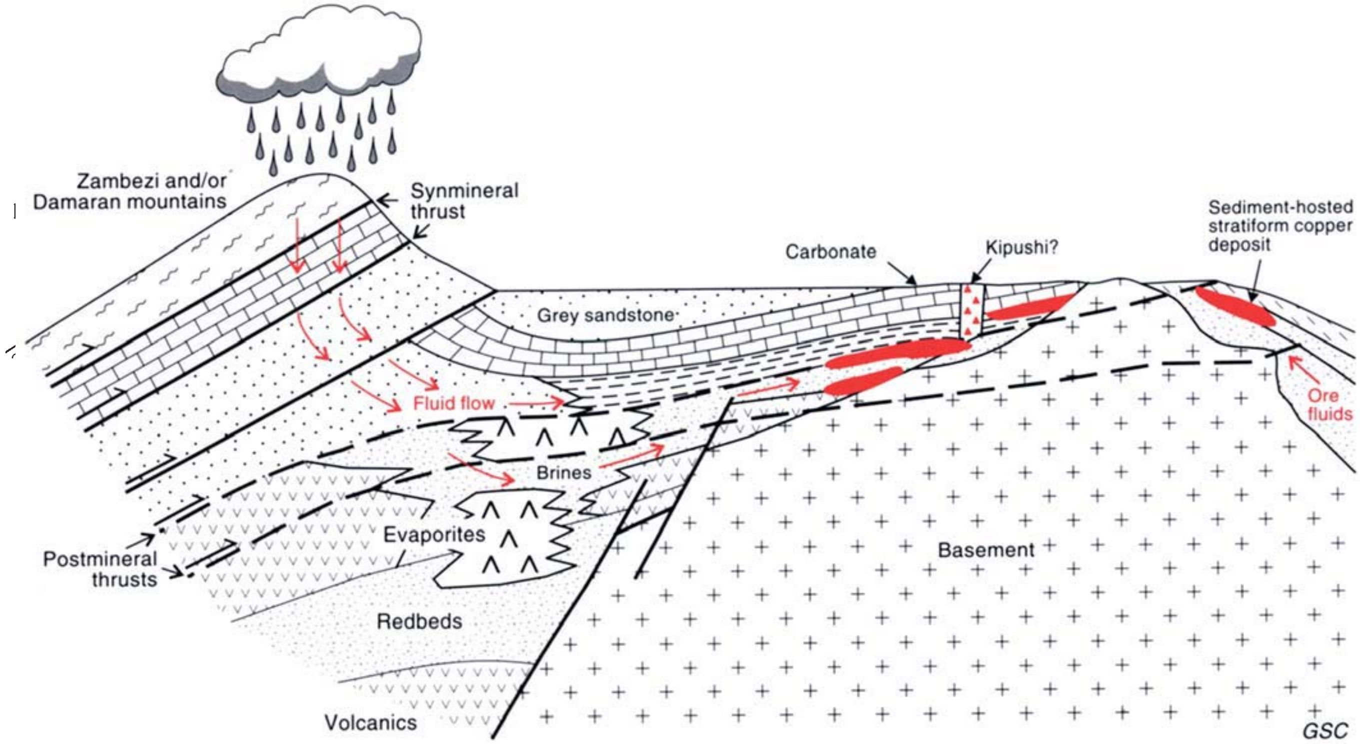



**Figure 8.3-6.** Schematic model for a gravity-driven fluid flow for genesis of sediment-hosted stratiform copper deposits in the central African Copperbelt. Diagram is not to scale but distance from source mountains to sites of copper deposition could have been several hundred kilometres (Daly, 1986).

## EXPLORATION GUIDES

Markedly reduced marine or extensive, saline lacustrine units in contact with redbeds and associated with evaporites constitute the prime settings in which to search for Kupferschiefer-type deposits. Most major Kupferschiefer-type deposits occur where the anoxic rocks overlie thick redbed sequences. A good geochemical source of copper is required, such as immature redbeds with labile detritus derived from rift-related basalts or other copper-bearing rocks or minerals, but in some districts, such as the central African Copperbelt, potential source rocks might be far removed from the deposits. Fetid microbial carbonate rocks and bituminous shales and/or sandstones in many deposits contain higher copper contents than mildly reduced units. The presence of broad-scale, well defined mineral zones covering several kilometres or tens of kilometres is a positive feature indicating large mineralized systems as opposed to small, erratically mineralized deposits. In some deposits, such as that in the Kona Dolomite and possibly Mufulira, prominent aquifers within the deposit could have controlled metal distribution, zoning, and concentration. No deposits have been found in rocks older than 2.4 Ga that predated oxygenation of the Earth's atmosphere. Significant differences between areas indicate that each deposit and area should be evaluated carefully on its own merits.

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# 8.3b Redbed-type

## IDENTIFICATION

Redbed-type copper deposits typically comprise disseminated sulphides at oxidation-reduction boundaries in anoxic rocks within or at the top of continental redbed sequences.

Copper is the most important metal found in these deposits and silver is the most important byproduct or, in some localities, coproduct metal. Lead and zinc are typical associated metals, but they have been of little or no economic value.

Reasonably typical redbed-type copper deposits are Dorchester, New Brunswick; several minor occurrences in the Carboniferous Pictou Group of Nova Scotia (Fig. 8.3-1); the Nacimiento deposit, New Mexico (Woodward et al., 1974); and other deposits in New Mexico (LaPoint, 1976). The Dzhezkazgan district in Kazakhstan, and possibly deposits in the Revett Formation in Montana and in the Lisbon Valley area, Utah are economically more important, but less typical, deposits formed in sediments deposited in continental redbed environments.

## IMPORTANCE

Redbed-type copper deposits are unimportant in Canada and, with the exception of the Dzhezkazgan and Revett Formation deposits, have been unimportant in other parts of the world. These deposits are relatively poorly understood and the economic incentives have been insufficient to justify extensive documentation and exploration. Nevertheless, deposits at Dzhezkazgan have been a major source of copper in the former Soviet Union and the Revett Formation contains some significant copper deposits with important coproduct levels of silver. The Paoli deposit in the Permian Wellington Formation in Oklahoma with 158 g/t Ag (Thomas et al., 1991) and the Silver Reef deposit in Jurassic rocks of the Moenave Formation in southwestern Utah, which contains approximately 155 g/t Ag (Proctor and Brimhall, 1986; James and Newman, 1986; L.P. James, pers. comm., 1987), are silver-rich redbed-type copper deposits.

## SIZE AND GRADE OF DEPOSITS

The size and grade of some redbed-type copper deposits are shown in Figure 8.3-2, however, data are limited. Corocoro and Charcarilla in Bolivia are the only deposits, in addition to Dzhezkazgan and the Revett deposits, that have sufficient grade and tonnage to be attractive exploration targets in Canada. Deposits with relatively low copper grades in the Revett Formation can be mined underground only because of the coproduct levels of silver (50-90 g/t Ag) and efficient trackless mining methods. A total of forty-six, 30 cm long channel samples in a roll-front type concentration in the Paoli deposit, Oklahoma averaged 158 g/t Ag and 0.68% Cu, indicating that some redbed-type copper deposits may contain substantial amounts of silver (Shockey et al., 1974; Thomas et al., 1991).

The subeconomic Dorchester deposit in New Brunswick evidently has a higher grade linear or curvilinear zone in contact with barren pyrite near an oxidation-reduction 'front' and a lower grade zone away from the 'front'. Although incompletely documented, this morphology is similar to that of uranium roll-front deposits.

## GEOLOGICAL FEATURES

In some areas, such as in rocks of the Pictou Group in Nova Scotia and Mesozoic formations in the Colorado Plateau region of the western United States, redbed-type copper occurrences are abundant. In many areas examined by the writer and based on published descriptions, mixed red and grey, fining-upward meandering stream deposits are the dominant host rocks for this deposit type (Fig. 8.3-7). As illustrated in Figure 8.3-7, in many such sequences caliche (calcite) nodules are found within the upper overbank parts of the fining-upward cycles and the cycles are reddened diagenetically from their tops toward their bases. The lowermost channel lag and point bar deposits, because of a concentration of reductants, typically are the last parts of the cycles to be oxidized and also generally contain the highest concentrations of copper. Entirely grey, reduced, in places coal-bearing, fining-upward meandering stream sequences are typically barren. Furthermore, entirely oxidized, red sequences contain only trace amounts of copper, even in copper-bearing sequences (e.g., Pictou Group, Nova Scotia). An anoxic grey unit, either overlying or within a thick sequence of redbeds, is a particularly favourable site for this type of deposit.

The consistent stratigraphic setting for many redbed-type copper occurrences indicates a relatively specialized environment of sedimentation consisting of a well developed, mature system of relatively low-gradient meandering streams that periodically became desiccated, especially in the upper overbank parts of the cycles (Fig. 8.3-7). This probably occurred in arid or semiarid areas with limited vegetation. The caliche zones (calcrete in some localities) signify soil formation. The lower channel lag and point bar deposits remained in reduced states provided that they stayed below the water table. Figure 8.3-8 is a schematic illustration of the environment of sedimentation. Occurrences in lacustrine rocks are less abundant than those in fluviatile rocks.

The Nacimiento and Eureka deposits in the Triassic Chinle Formation in New Mexico also occur in crudely fining-upward fluvial units (Woodward et al., 1974; LaPoint, 1976, 1989). However, the streams that deposited these sediments probably had steeper gradients and were more braided in nature than the more typical sinuous meandering streams that deposited host rocks of many redbed copper deposits. These large-volume stream deposits overlie lower energy redbed deposits of the saline Permian Abo Formation.

Prior to Siluro-Devonian time, fining-upward fluvial sequences were considerably different, without the stabilizing influence of vascular land plants. In the Grinnell Formation of the Middle Proterozoic Purcell Supergroup in southwestern Alberta and southeastern British Columbia, several copper occurrences are known in relatively clean, white quartzite units within a redbed sequence (Fig. 8.3-9). Collins and Smith (1977) suggested that these might be fluvial floodplain deposits. These might be Precambrian analogues of the very abundant redbed-type copper occurrences in Phanerozoic fluvial sequences.

Copper sulphides, dominantly chalcocite, are typically disseminated and replace early diagenetic pyrite and wood debris. As the early diagenetic pyrite and wood debris are commonly concentrated in the lower parts of the fluvial cycles, this is also where copper is concentrated.

Most deposits have not been studied sufficiently to document mineral and metal zoning. Nevertheless, preliminary work at Dorchester suggests that, in the lower fining-upward fluvial cycle, copper sulphides may occur in contact with barren pyrite and that in the overlying cycle, anomalous lead and zinc occur above the copper zone (Fig. 8.3-10).

In many deposits the cell structure of wood has been well preserved by sulphides. However, in most areas, insufficient information is available to indicate if copper sulphides fill-in or replace the plant structure directly or if the carbonaceous material was first filled in or replaced by pyrite. In any event, the excellent preservation of cell structures indicates preservation of plant debris by some sulphide before compaction and coalification. Isolated disseminated sulphide grains and small gash veins are also common.

At Dzhezkazgan and in the case of deposits in the Revett Formation, the redbeds might have been reduced on a regional scale by hydrocarbon-bearing formation waters emanating from underlying marine beds (Lur'ye and Gablina, 1978; Gablina, 1981; Kirkham, 1989) (Fig. 8.3-11, 8.3-12). The reduction of redbeds by mobile reductants, if such a mechanism can be substantiated, is an important variation in the genetic model for redbed-type copper deposits and may account for the deposition of much larger concentrations of metals than those in typical redbed-type deposits in which copper minerals were precipitated by immobile reductants. Ryan (1993) suggested that the location of deposits in the Revett Formation might be controlled by syndepositional faults. Recently discovered copper occurrences in the Rae Group on Victoria Island in northern Canada have some characteristics of Dzhezkazgan-type deposits (Rainbird et al., 1992, 1994).

## DEFINITIVE CHARACTERISTICS

1. Redbed-type copper deposits characteristically are disseminated deposits in reduced rocks in continental redbed sequences.
2. Evaporites, caliche, calcrete, mudcracks, and other features record arid and semiarid continental environments of sedimentation.
3. Copper is generally the dominant metal, although some deposits contain byproduct or coproduct silver.

## GENETIC MODEL

Most redbed-type copper deposits are accepted as being diagenetic replacements of early diagenetic pyrite and wood debris. They were probably formed from the infiltration of cupriferous fluids into permeable continental sediments. As illustrated in Figure 8.3-10, deposits show evidence of infiltration of oxic cupriferous fluids into reduced sandstone aquifers in otherwise less permeable redbeds. The sands probably acted as drains for the less permeable, compacting red shale and siltstone. As discussed for Kupferschiefer-type deposits, the most probable ore fluids were oxic brines derived from evaporites that extracted metals from the redbeds and deposited them by reaction with any anoxic rocks and/or fluids that they encountered. For many occurrences fluid flow was mainly in sandstone aquifers and, in deposits such as Dorchester, deposition occurred at redox boundaries or 'fronts' where the fluids came in contact with early diagenetic pyrite and wood debris.

Important variations of this diagenetic model are illustrated in Figures 8.3-11 and 8.3-12, whereby more concentrated metal precipitation occurred in a series of stacked aquifers at regional redox boundaries between redbeds and diagenetically reduced redbeds. Such environments have, with both mobile oxic ore fluids and reductants, evidently resulted in much greater concentrations of metals than in more typical redbed environments with more localized, immobile reductants.

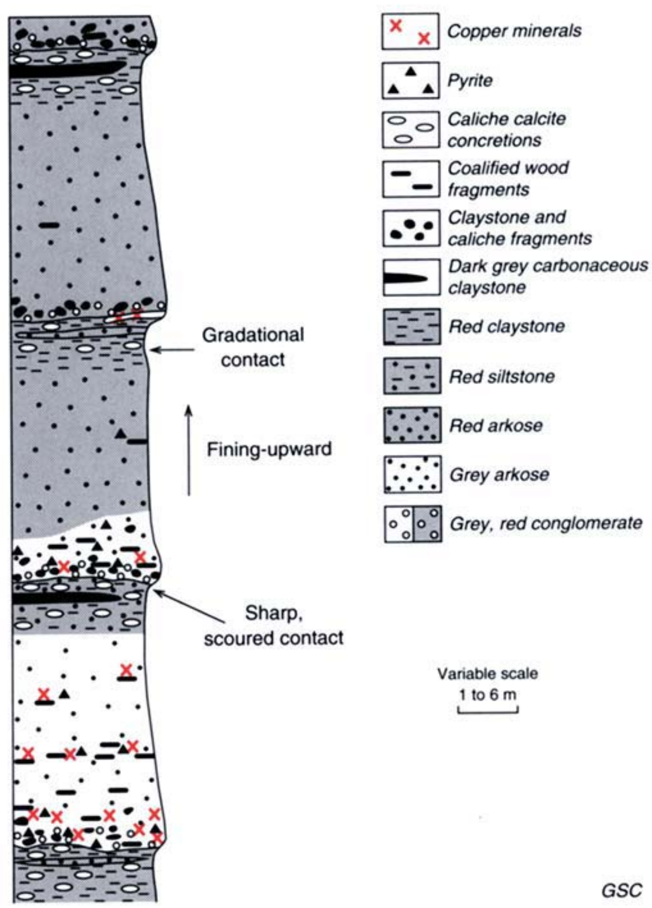


**Figure 8.3-7.** Typical sequence of fining-upward fluvial cycles. Increased oxidization (reddening) and caliche nodules are in the upper parts of the cycles. Wood debris and early diagenetic pyrite reductants and copper sulphides are in the grey, reduced lower parts of the units.

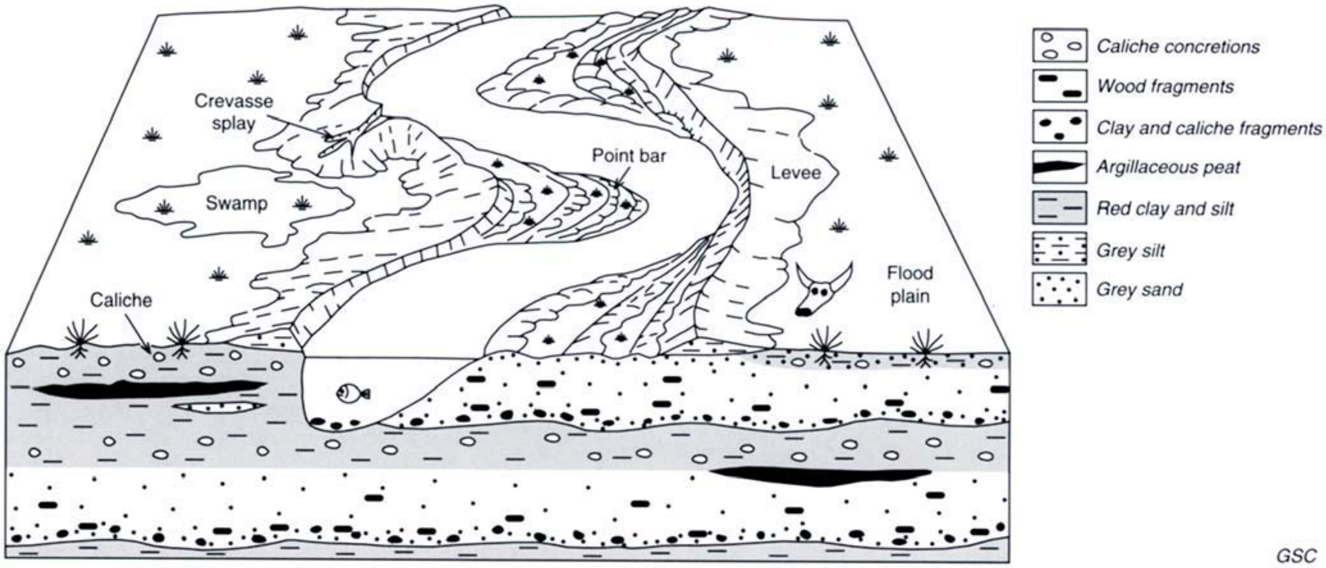


**Figure 8.3-8.** Schematic block diagram illustrating a meandering stream in a semiarid environment with near-surface oxidation and caliche formation in soils. The fining-upward fluvial cycles, typical host rocks of many redbed copper occurrences, probably formed in such an environment.

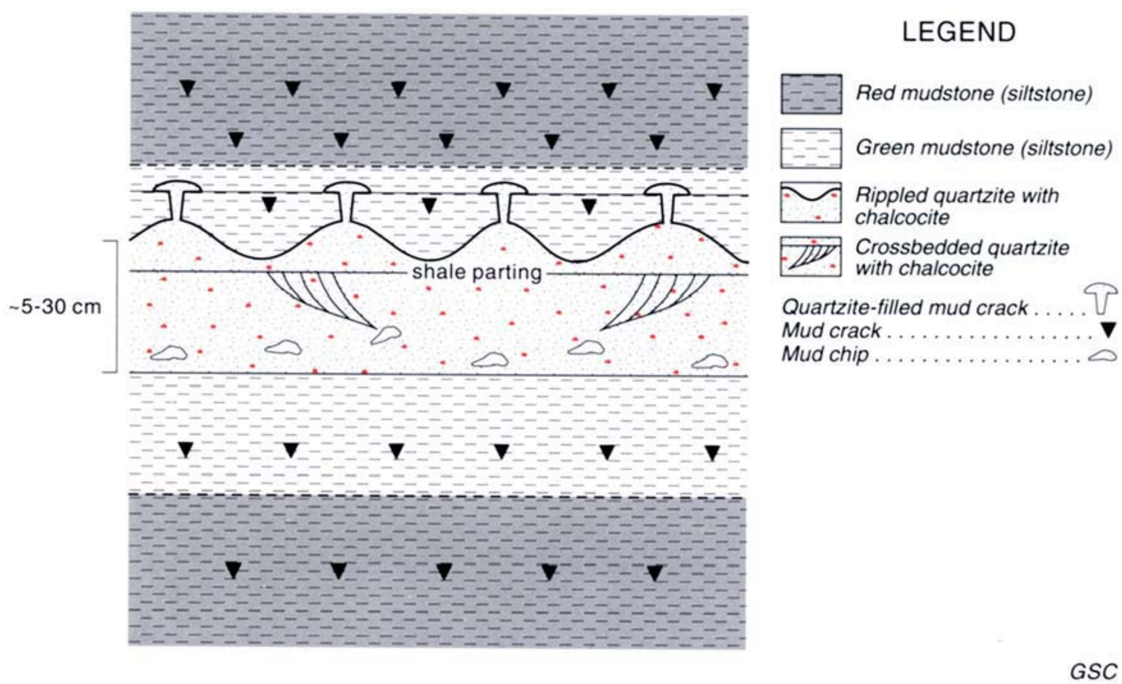


**Figure 8.3-9.** Typical copper-bearing cyclic unit in the Middle Proterozoic Grinnell Formation in Alberta and British Columbia (adapted from Collins and Smith, 1977). These cyclic quartzite-siltstone units could be Proterozoic analogues of younger fluvial host rocks of redbed copper deposits postdating vascular land plants in the Siluro-Devonian.

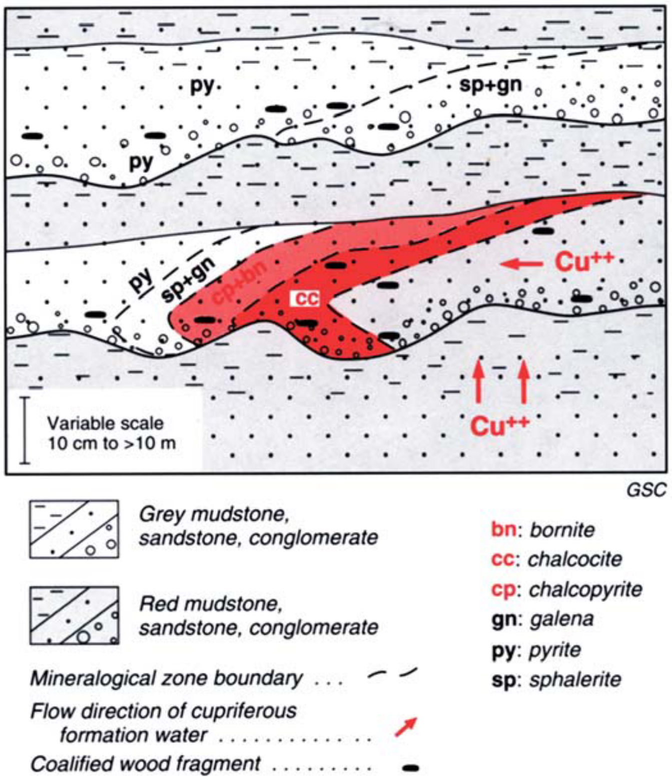


**Figure 8.3-10.** Interlayered grey, reduced and red, oxidized fining-upward fluvial host rocks typical of many redbed copper deposits. The Cu sulphide zones are shown in red. Metalliferous brines migrating in sandstone aquifers precipitated base-metal sulphides upon reaction with carbonaceous wood debris and early diagenetic pyrite reductants (after Kirkham, 1989).

Figure 8.3-13, for the Lisbon Valley area in Utah and Colorado, shows another variation on the general oxidation-reduction processes responsible for the formation of Kupferschiefer- and redbed-type copper deposits. In this area, metalliferous brines trapped in redbed aquifers were evidently released upward along faults during later tectonism or a reversal of the topographic gravity gradient (Schmitt, 1968; Morrison and Parry, 1986; Breit et al., 1987; G.N. Breit, pers. comm., 1987). In the Lisbon Valley area these heated and pressurized fluids evidently rose as much as a kilometre or more along the faults until they encountered reduced aquifers, such as the Triassic Wingate Sandstone and Cretaceous Morrison Formation. Copper sulphides were precipitated as veins and disseminations near the faults and their abundance decreases rapidly away from the faults. Price et al. (1985, 1988) proposed an analogous thermally-driven model for some vein and fault-controlled Cu-Ag deposits in Precambrian, Permian, and Cretaceous redbeds in the Trans-Pecos region of Texas. Evidence supports diagenetic fluid flow of oxic metalliferous brines in aquifers and along permeable structures, such as faults, and metal precipitation where the brines encountered anoxic conditions. The basic oxidation-reduction processes of ore formation are similar for Kupferschiefer-, redbed-, and volcanic redbed-type copper deposits, but they evidently varied considerably from one area to another.

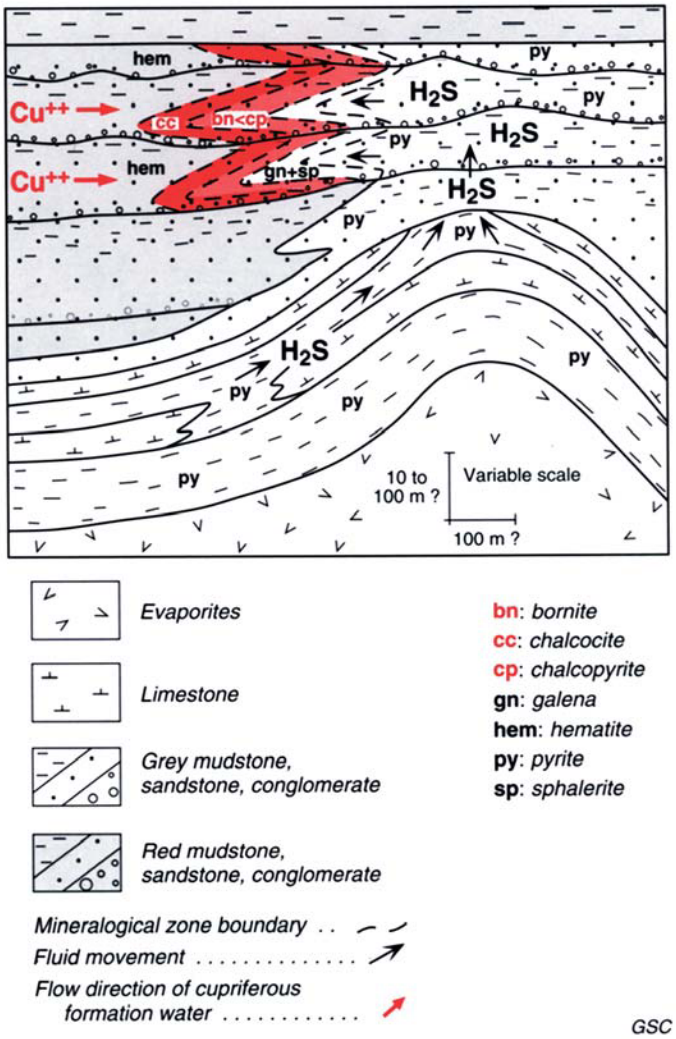


**Figure 8.3-11.** Model for the Dzhezkazgan region, Kazakhstan, involving both mobile reductants and oxic metalliferous brines (after Lur'ye and Gablina, 1978; Gablina, 1981; Kirkham, 1989). The Cu sulphide zones are shown in red.

## RELATED DEPOSIT TYPES

Kupferschiefer-, redbed-, and volcanic redbed-type copper deposits, as mentioned above for Kupferschiefer-type deposits, are all related to some degree and in many areas they occur together. Other deposit types, such as sandstone lead and uranium deposits, Mississippi Valley-type lead-zinc, and unconformity uranium deposits, have some features in common with redbed-type copper deposits, but they were probably formed at different times, in different areas, and from different ore fluids. The association of lead with copper in some redbed-type copper deposits probably indicates that the redbeds had mixed felsic and mafic provenance.

Contents



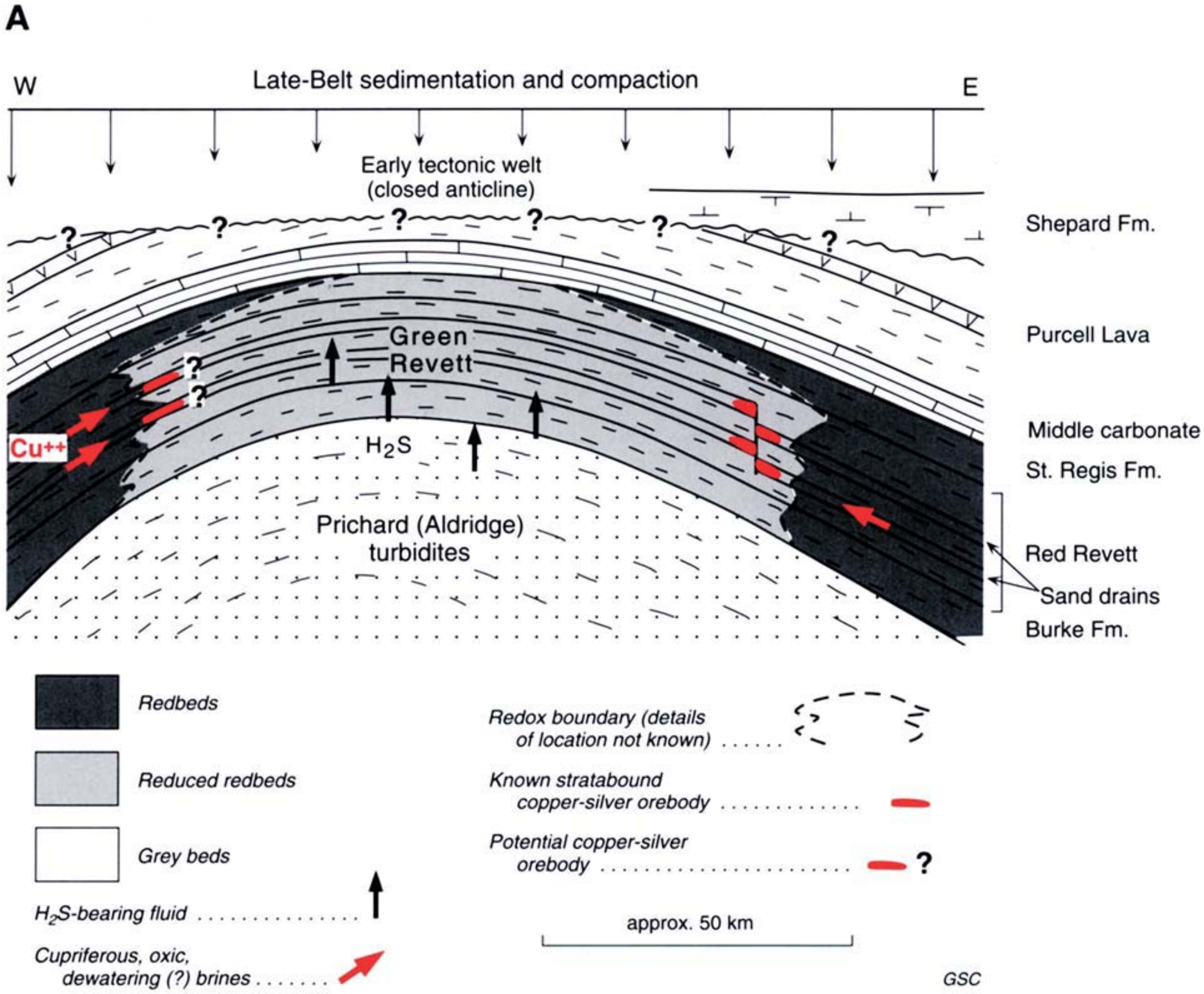


**Figure 8.3-12.** Conceptual models for zoned copper-silver deposits (shown in red) in the Revett Formation in Montana. Mobile reductants (e.g., $H_2S$, $CH_4$, hydrocarbons) are modelled as derived from the underlying Prichard Formation. Oxic metalliferous brines migrated in permeable sandstone units (mineral zoning after Hayes and Einaudi, 1986). **A)** Model for reductants trapped in early anticlinal structure. **B)** Model for reductants entering Revett aquifers along faults (after comment by Wodzicki, 1990, quoted in Adkins, 1993).

## EXPLORATION GUIDES

Reduced units within continental redbed requences deposited in low-latitude arid and semiarid areas, are suitable sites for the occurrence of redbed-type copper deposits. Fluvial rocks, especially in more permeable lower parts of fining-upward cycles, are the most typical host rocks. Higher copper grades can occur at reaction fronts between base-metal zones and barren pyritic host rocks.

Although more work is required to confirm relationships, sulphide deposition at the redox boundaries between redbeds and diagnetically reduced redbeds has resulted in larger concentrations of metals than in areas with immobile reductants. Areas that contain such diagenetically reduced redbeds might occur where redbeds overlie anoxic marine rocks and also possibly around salt domes and anticlines. Deposits might also occur in anoxic units along fault zones above redbeds and evaporites (e.g., Fig. 8.3-13) or in reduced redbed units where reductants migrating up fault zones encountered metalliferous brines in aquifers (e.g., Fig. 8.3-12).

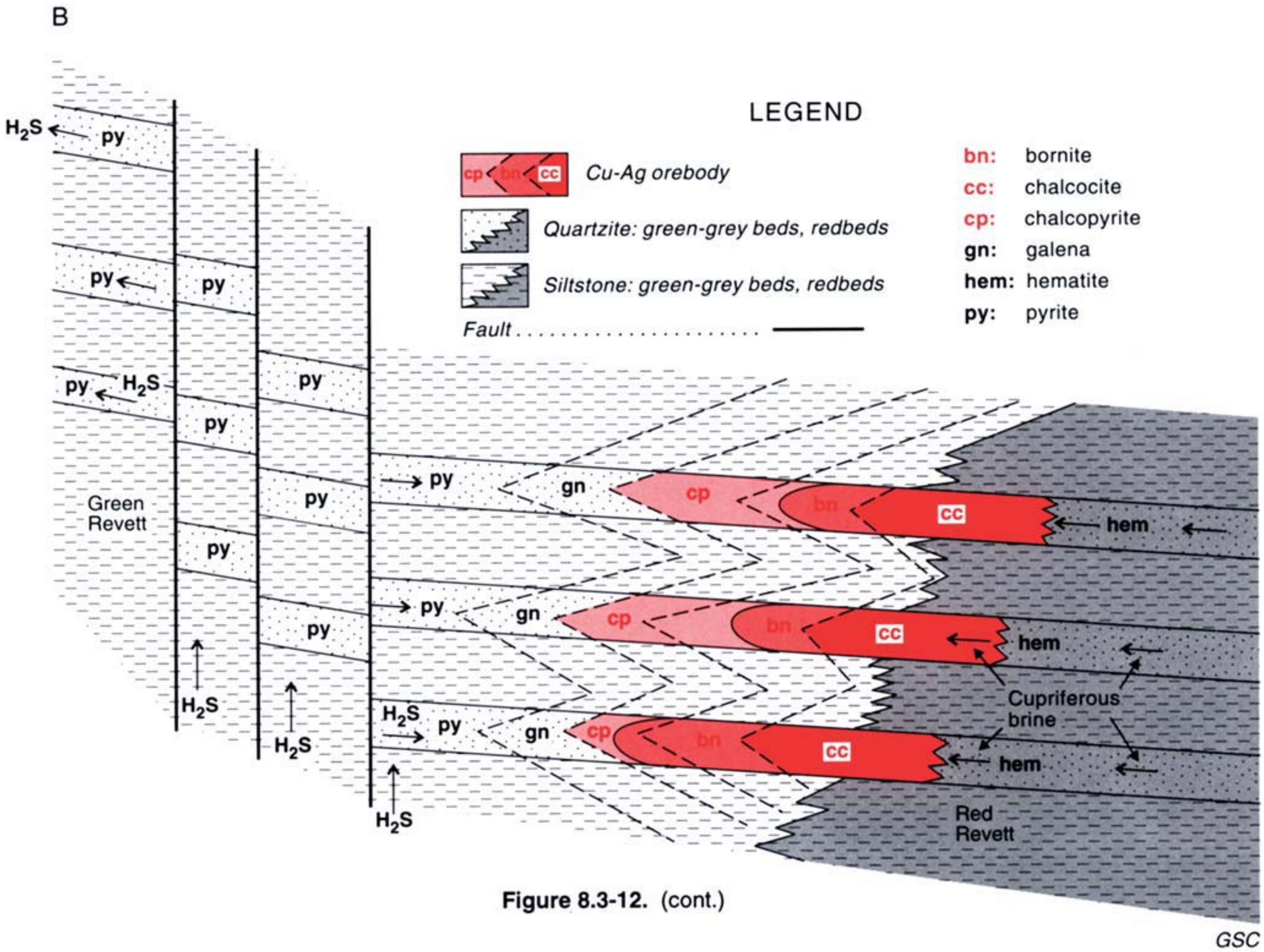


**Figure 8.3-12.** (cont.)

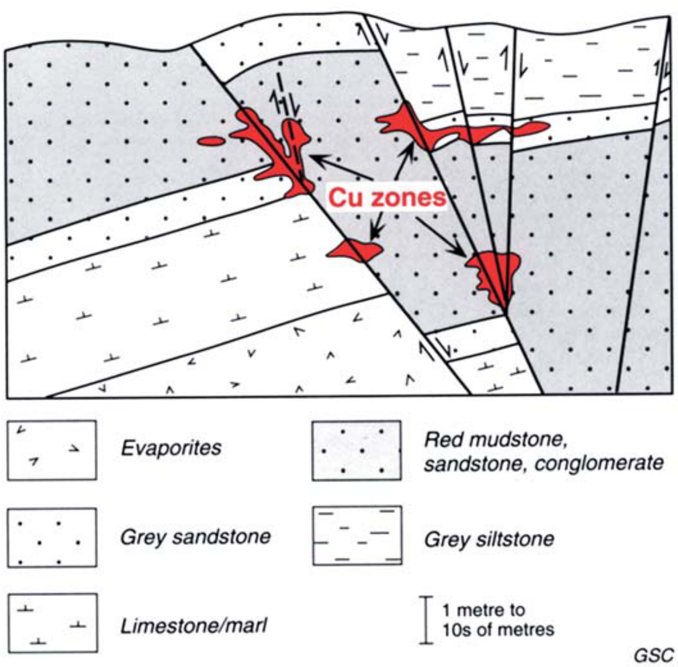


**Figure 8.3-13.** A relatively late diagenetic model for the Lisbon Valley area of Utah and Colorado, where heated oxic metalliferous brines migrated up fault-zone aquifers (after Schmitt, 1968; D.R. Shawe, pers. comm., 1980; Morrison and Parry, 1986; Breit et al., 1987; G.N. Breit, pers. comm., 1987; Kirkham, 1989).

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