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PROGRAM AND ABSTRACTS

Symposium on

Sediment-Hosted Stratiform Copper Deposits

OTTAWA
May 17 - 19 1986

Sponsored by
Mineral Deposits Division, Geological Association of Canada

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Mineralogical Association of Canada

PROGRAM

Symposium on Sediment-Hosted Stratiform Copper Deposits

Friday PM, May 16, 1986 through Monday PM, May 19, 1986
Technical Sessions: Southam Hall (Theatre A), Carleton University
Poster Sessions: Loeb Lounge, Carleton University

Friday PM

Registration (14:00-20:00) Foyer, Commons Building, Carleton University
Reception (18:00-22:00) Foyer, Tory Building, Carleton University

Saturday AM INTRODUCTION AND NORTH AMERICAN PROTEROZOIC DEPOSITS

8:30- 8:45	J.A. Coope and A.J. Naldrett	Welcome and Opening Comments
8:45- 9:05	R.V. Kirkham	Distribution of sediment-hosted stratiform copper deposits: an introduction
9:05- 9:25	D. Winston*, M. Woods, C.W. Jefferson, R.V. Kirkham, J.A. Donaldson	Middle to Late Proterozoic (1.8–0.6 Ga) sedimentation, North America
9:25- 9:35	C.W. Jefferson	Stratigraphic, tectonic and sedimentological setting of deposits in the Redstone copper belt, Mackenzie Mountains, Northwest Territories
9:35- 9:50	F.M. Chartrand*, A.C. Brown, R.V. Kirkham	Diagenesis, sulfides and metal zoning in the Redstone copper deposit, Northwest Territories
9:50- 10:05	R.L. Lustwerk*, M.D. Wasserman	Water-escape phenomena in the Coates Lake Group, Northwest Territories, and their relationship to mineralization in the Redstone stratiform copper deposit.
10:05-10:25	J.T. Nash*, G.A. Hahn	Volcanogenic character of sediment-hosted Co-Cu deposits in the Blackbird mining district, Lemhi County, Idaho
10:25-10:50		Coffee Break
10:50-11:10	T.S. Hayes*, R.O. Rye, J.F. Whelan, G.P. Landis	Temperatures of ore deposition at the Spar Lake stratabound Cu–Ag deposit in the Belt Supergroup, Montana.
11:10-11:30	T.A. Henricksen*, R.G. Smith, R.J. Franklin	Revett-type stratiform silver-copper deposits at the U.S. Borax Noxon project, northwest Montana

*Speaker

11:30-11:50	I.M. Lange*, D. Herberger, J.W. Whipple	Stratabound Cu–Ag and Pb–Zn mineralization in the Spokane and Helena Formations in the eastern part of the Belt basin, Montana: a common origin?
11:50-12:10	C.R. Stanley*, A.J. Sinclair	Stratigraphic correlation of stratabound Cu–Ag deposits of the Bonner Quartzite, Belt Supergroup, western Montana
12:10-12:30	R. Seasor, A.C. Brown*	Syngenetic and diagenetic concepts at White Pine, Michigan
12:30-14:00		Lunch

Saturday PM AFRICAN, CHINESE AND AUSTRALIAN PROTEROZOIC DEPOSITS

14:00-14:20	F. Mendelsohn	African Ore Shale copper deposits
14:20-14:40	J.-J. Lefebvre	Lithostratigraphy of copper occurrences in southern Shaba (Zaire), and correlations with the Zambian copperbelt
14:40-15:00	W.G. Garlick	Genetic interpretation from ore relations to algal reefs in Zambia and Zaire
15:00-15:20	A.E. Annels	Ore genesis in the Zambia copperbelt, with particular reference to the northern sector of the Chambishi basin
15:20-15:40		Coffee Break
15:40-16:00	K.J. Maiden, S. Master*	The Mangula copper-silver-gold deposit, Zimbabwe: a Lower Proterozoic Olympic-Dam-type deposit?
16:00-16:20	M.A. Sweeney, P.L. Binda*	The role of diagenesis in the formation of the Konkola Cu–Co orebody of the Zambian copperbelt
16:20-16:40	Ran Chongying	On a genetic model for the Dongchuan type of stratabound copper deposit
16:40-17:00	D.G. Tonkin, K.J. Maiden*	The role of permeability in localizing the stratabound copper deposits of Mount Gunson, South Australia
20:00-23:00		Poster Sessions (20:00–22:00) and Cash Bar (to 23:00)

Sunday AM KUPFERSCHIEFER DEPOSITS

8:30- 8:50	J. Kulick, D. Leifeld*, A.-K. Theuerjahr	A geochemical and petrofacies study of the Kupferschiefer in Hessia, West Germany
8:50- 9:10	W. Ryka	Rotliegendes volcanic rocks, sediment lithologies and paleoenvironments, and basin history
9:10- 9:30	T.M. Peryt	Basal Zechstein in southwestern Poland: sedimentation, diagenesis, and gas accumulations
9:30- 9:50	K.W. Glennie	Some effects of the mid-Permian Zechstein transgression in northwestern Europe
9:50-10:10	A. Rydzewski	Stratiform Zechstein copper ore-deposits in Poland: geology, metal zoning and exploration
10:10-10:30		Coffee Break

*Speaker

AMERICAN AND CHINESE PHANEROZOIC DEPOSITS

10:30-10:50	G.E. Smith	Ore-mineral zonation and paleoaquifers as clues to ore genesis in a postorogenic tectonic setting, North Texas copper district
10:50-11:00	D.J. Lapoint	Genesis of Permian and Triassic sandstone-hosted copper deposits in New Mexico
11:10-11:30	G.R. Robinson, Jr., J.P. Smoot*	Depositionally controlled stratabound Cu–Zn mineralization in Early Mesozoic continental rift-basins
11:30-11:50	Liu Baojun*, Xu Xinhuang	Sediment-hosted stratiform copper deposits in southern China
11:50-12:10	Cheng Shoude	The geology and genesis of Tertiary sandstone copper deposits on the western margin of the Tarim basin, Xinjiang
12:10-12:30	S.S. Flint	Sediment-hosted stratiform copper deposits of the central Andes: sedimentological, tectonic and geochemical aspects
12:30-14:00		Lunch
Sunday PM		SPECIAL LECTURES
14:00-14:30	K.W. Glennie	A summary of desert sedimentary environments, present and past
14:30-15:00	T.R. Walker	Diagenetic alterations in red beds and their application to the origin of copper and other heavy metals in stratiform ore-deposits
15:00-15:30	A.W. Rose	Mobility of copper and other chalcophile elements in low-temperature near-surface environments
15:30-15:50		Coffee Break
		ORE PROCESSES
15:50-16:10	H.P. Eugster	Geochemical environments of sediment-hosted ore deposits
16:10-16:30	D.A. Sverjensky	Chemical evolution of basinal brines that form sediment-hosted Cu–Pb–Zn deposits
16:30-16:50	E.C. Jowett	Late-diagenetic origin of Kupferschiefer Cu–Ag deposits in Poland by convective fluid-flow of Rotliegendes brines
16:50-17:10	W.E. Galloway	Hydrogeology and sulfidic alteration history of shallow fluvial aquifers, northwest Gulf of Mexico sedimentary basin
20:00-22:00		Posters and Cash Bar
Monday AM	EXAMPLES FROM CHINA; GEOCHEMICAL ASPECTS; CLOSING REMARKS	
8:00- 8:20	Pei Rongfu*, Wu Liangshi	Mineral exploration and assessment of sediment-hosted stratiform copper deposits of China
8:20- 8:40	Jing Qingming	Geological features of the stratabound Cu ore belt, Daban County, northern Tianshan Mountains, Xingjiang, China

*Speaker

8:40- 9:00	T. Branam*, E.M. Ripley	Chemical and isotopic studies pertaining to the genesis of sediment-hosted Cu mineralization in south-central Kansas
9:00- 9:20	L.D. Hoy*, H. Ohmoto, A.W. Rose, F. Dimanche, J. Coipel	Constraints for the genesis of red-bed-associated stratiform Cu deposits from S and C mass-balance relations
9:20- 9:40	D.W. Haynes*, M.F. Bloom	Possible controls on metal ratios in stratiform copper deposits
9:40-10:00	T.N. Walthier	The role of scientific research in mineral exploration
10:00-10:20		Coffee Break
10:20-11:20	Naldrett (Chairman), Rose, Binda, Haynes, Mendelsohn, Brown	Panel discussion and question period
Monday PM		Poster Session (14:00-16:00)

*Speaker

POSTER PRESENTATIONS

The poster presentations will be exhibited in rooms adjacent to Southam Hall. Authors of posters will be available for consultations on the evenings of Saturday and Sunday, May 17 and 18; posters will also be on exhibit during the afternoon of Monday, May 19, in the Loeb Building, Upper Level.

Pier L. Binda, Henry T. Koopman and Elizabeth R. Koopman
A stratiform copper occurrence in the Helikian Siyeh Formation of Alberta and British Columbia

Gregor Borg and Kenneth J. Maiden
Stratabound copper–silver–gold mineralization of Late Proterozoic age along the margin of the Kalahari craton in SWA/Namibia and Botswana

Alex C. Brown
A case for exhalative or pene-exhalative hydrothermal activity in the genesis of sediment-hosted, stratiform copper deposits

Alex C. Brown
Terminology for sediment-hosted stratiform copper deposits

Frederick W. Chandler
Stratabound copper mineralization in Early Proterozoic marine-transgression-related quartz arenite, Cobalt Group, Ontario

Chen Wenming
Sediment-hosted stratiform copper deposits in China

Chen Wenming
The diagenesis and minerogenesis of the sandstone- and shale-hosted stratiform copper deposits in South China

Dominique Cluzel and Louis Guilloux
Hydrothermal character of the Shaba Cu–Co–U mineralization

Peter F. Folger
The geology and geochemistry of the carbonate-hosted Omar copper deposit, Baird Mountains, Alaska

I.F. Gablina
Transformation of copper-bearing sandstones and shales in the process of metamorphism and hypergenesis

Simon J. Haynes
Kuhne-mes, southern Iran: a sabkha-related stratiform Cu–Pb deposit.

Jan Hoeve and David Quirt
A diagenetic-hydrothermal origin for unconformity-associated and stratiform copper deposits in the Central African and Michigan copper districts

E. Craig Jowett
Effects of tectonic environment on Kupferschiefer-type deposits

A.M. Lur'ye
Some aspects of evolution of copper metallogenesis in red-bed formations

Kenneth J. Maiden, Gregor Borg and Sharad Master
Structural traps for stratabound copper deposits

Sharad Master and Kenneth J. Maiden
Metamorphic features of stratabound copper–silver deposits at Mhangura, Zimbabwe

Morteza Momenzadeh
Submarine volcanism as the only source for stratiform copper: two examples from Iran

Ananda D. Mukherjee, N. Bhattacharyya and A.B. Chowdhury
Sediment-hosted stratiform copper mineralization from Early Proterozoic rocks of southern India

Slawomir Oszczepalski
Copper shale in southwestern Poland: paleoenvironments, distribution of metals, and ore controls

Ran Chongying
Environmental significance of algal stromatolites and their relation to copper ore in the Luoxue Formation of the Kunyang Group in Dongchuan, Yunnan

Jeremy P. Richards and Edward T.C. Spooner
Evidence for a magmatic fluid association in Keweenawan Cu-sulfide fissure-vein deposits at Mamainse Point, Ontario: possible relationships to stratabound basalt-hosted native copper

Robert J. Ryan, Robert C. Boehner, Ralph R. Stea and Peter J. Rogers
Geology, geochemistry and the exploration potential of sediment-hosted stratiform copper–silver occurrences in Permo-Carboniferous strata, eastern part of the Cumberland basin, Nova Scotia

Kees Schrijver, Serge R. Chevé and Normand Tassé
Mineral assemblages in fenestral structures in carbonate rocks: a possible aid in exploration for copper deposits

Amit Segev
Syngenetic copper-enriched dolostones as a source for epigenetic copper mineralization in sandstones and shales, Timna, Israel

Stanislaw Speczik, Czeslaw Skowronek, Gunther Friedrich, Ralf Diedel, Franz-Peter Schmidt and Claus Schumacher
The environment of formation and source of metals for some Kupferschiefer occurrences in central Europe

Raphael Unrug
Landsat-based structural map of Lufilian arc and the Kundelungu aulacogen, Shaba (Zaire), Zambia, and Angola, and the tectonic position of Cu, Co, U, Au, Zn, Pb, and Fe mineralization

Wang Daohua
On the origin of carbonate-hosted stratiform Cu deposits in the Lower Yangtze region, eastern China

Wang Wenbin, Ji Shaoxing, Xing Wenchen, Wu Huairen, Zhou Hanming and Xue Yuyi
Geological characteristics and genesis of stratabound deposits of Cu-bearing pyrite in the Jiujiang–Ruichang area, Jiangxi, China

Halina Wazny
Trace-element distribution in the lowermost Zechstein copper-bearing deposits of the southern part of the Fore-Sudetic area, southwestern Poland.

Donald Winston
An alluvial apron and playa-margin interpretation of Cu- and Ag-bearing sedimentary rocks, Middle Proterozoic Belt Supergroup of Montana and Idaho

ABSTRACTS

ORE GENESIS IN THE ZAMBIA COPPERBELT, WITH PARTICULAR REFERENCE TO THE NORTHERN SECTOR OF THE CHAMBISHI BASIN

ALWYN E. ANNELS

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Proposals have been made by the author (Annels 1984, Annels & Simmonds 1984) that the Ore Shale of the Zambian Copperbelt was deposited within a northwesterly oriented rift-zone and that the metallization of this horizon was due to hydrothermal leakage from the bounding fractures, either directly onto the sea floor or into relatively unconsolidated sediment. In an attempt to provide a firm basis for this hypothesis, a study of the sulfide deposits around the northern rim of the Chambishi Basin was undertaken. These deposits are, from west to east, Mwambashi B, Pitanda, Chambishi (East and West) and Chambishi South East. Within these deposits there is a range in type, from small localized deposits in footwall arenites and conglomerates deep within the FW Formation, to similar deposits in the immediate footwall of the Ore Shale, to extensive deposits in the Ore Shale itself. Some of the problems confronted include the depth and stage of emplacement of the sulfides and the source and temperature of the transporting fluids. Evidence is presented from Chambishi that structures in the basement rocks could have allowed the escape of metal-rich fluids into the overlying cover-rocks of the Lower Roan. The results of preliminary studies of fluid inclusions and stable isotopes are also reviewed, along with details of the various styles of mineralization and of the diagenetic – metamorphic fabric of the rock. An attempt is made to fit all this information into a unified theory that explains the disposition and stratigraphic location of these deposits.

REFERENCES

ANNELS, A.E. (1984): The geotectonic environment of Zambian copper-cobalt mineralization. *J. Geol. Soc.* **141**, 279-289.

______ & SIMMONDS, J.R. (1984): Cobalt in the Zambian copperbelt. *Precambrian Res.* **25**, 75-98.

A STRATIFORM COPPER OCCURRENCE IN THE HELIKIAN SIYEH FORMATION OF ALBERTA AND BRITISH COLUMBIA

PIER L. BINDA, HENRY T. KOOPMAN AND ELIZABETH R. KOOPMAN

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In the Clark Range, the boundary between the upper Grinnell and lower Siyeh Formations of the Middle Proterozoic Purcell Supergroup marks a major marine transgression. The upper Grinnell is a coarsening-upward sequence, from red argillites deposited on a cyclically desiccated and flooded marginal marine mud-flat to clean quartz-arenites formed in a beach complex. Black and green argillites and arenites of the basal Siyeh Formation were deposited in a shallow marine reducing environment, whereas the overlying carbonates were deposited on a broad shelf developed beyond the reach of clastic supply. Stromatolites developed on tempestite mounds that were deposited by storms on the carbonate shelf. Two cycles of sand deposition mark the progradation of coastal deposits toward the end of Lower Siyeh time. Facies relations and paleocurrent directions are consistent with a west-to-east transgression and longshore transport of sand from the south. Laterally impersistent ore-grade Cu occurrences have been reported from Grinnell quartz-arenites by several authors. Our examination of the argillites and arenites in the basal few metres of the Siyeh Formation at 25 localities has revealed a stratiform Cu occurrence that is continuous around the Akamina Syncline. Copper values range from a few hundred to a few thousand ppm. Stromatolitic carbonates of the lower Siyeh host a Pb occurrence that may have considerable stratigraphic continuity.

STRATABOUND COPPER–SILVER–GOLD MINERALIZATION OF LATE PROTEROZOIC AGE ALONG THE MARGIN OF THE KALAHARI CRATON IN SWA/NAMIBIA AND BOTSWANA

GREGOR BORG AND KENNETH J. MAIDEN

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A number of late Proterozoic basins form a belt 2500 km in length that stretches along the northern margin of the Kalahari Craton. The basins have formed in an extensional tectonic environment, with intensive block-faulting. A lower volcanic suite is overlain by a succession of continental red-beds. Above these beds lie grey and green, fine clastic sediments and carbonates deposited in a shallow marine environment. The whole succession is affected by metamorphism in the lower greenschist facies and is slightly deformed by tectonism of Damaran age. In the volcanic suite, copper mineralization occurs in basaltic lavas that are strongly altered locally, and gold mineralization is hosted by felsic porphyries. Stratabound copper deposits in the fine clastic sediments consist of Cu–Ag–Au–(Pb)–(Zn)–Mo–Co, with chalcocite, bornite and chalcopyrite as the principal ore-minerals. Exploration to date has shown the existence of five mineralized districts, with orebodies of between 1 and 20 million tonnes. Although the mineralization shows a stratabound character, it is not limited to a single horizon or host-rock. Copper mineralization occurs in pyritic slate, metasiltstone, pyritic sandstone, calcareous slate and detrital and algal limestone. Fluids are considered to have moved upward through the succession; they leached metals out of the volcanic rocks and precipitated them in favorable host-rocks. Basement faults, forming horst and graben structures, had a channeling effect on the moving fluids and determined the localization of the orebodies. An early- to late-diagenetic origin of the mineralization is proposed, and a comparison is drawn with the deposits of White Pine, Michigan.

CHEMICAL AND ISOTOPIC STUDIES PERTAINING TO THE GENESIS OF SEDIMENT-HOSTED Cu MINERALIZATION IN SOUTH-CENTRAL KANSAS

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Subeconomic sulfide mineralization occurs in unmetamorphosed Permian sedimentary rocks of south-central Kansas, primarily in carbonates and grey-green shales that are interlayered with barren red-beds. The principal sulfide minerals are pyrite, chalcopyrite, bornite, digenite and chalcocite. Petrographic evidence, sulfur isotope values and a good positive correlation between sulfide sulfur (S) and organic carbon (C) indicate that pyrite is of early diagenetic origin. Within most mineralized rocks examined, textural evidence indicates that copper-enriched sediments are characterized by a poor S/C correlation. The amount of S is quite variable, whereas the amount of C present is consistently lower than that in pyrite-bearing sediments.

Sulfur isotope values range from –30 to –40 ‰ for pyrite-bearing sediments, –8 to –19 ‰ for Cu-rich sulfides in carbonates, and –23 to –35 ‰ for Cu-enriched sulfides in shales. We suggest that a Cu- and SO_4^{2-}-bearing fluid, with a $\delta^{34}S$ value similar to those of sulfate minerals in the sedimentary sequence (+12 to +15 ‰), was involved in the genesis of post-pyrite sulfides. Observed isotopic signatures of sulfides were produced as a result of differing reaction-mechanisms related to the amount of initial pyrite present and the amount of reduced sulfate utilized in mineral precipitation. In shales, abundant initial pyrite relative to the Cu content of the fluid caused little utilization of reduced sulfate, resulting in Cu-sulfides isotopically similar to initial pyrite. In carbonates, insufficient pyrite relative to the amount of Cu in the fluid allowed unfractionated, reduced sulfate to be utilized in Cu-sulfide formation, producing sulfides isotopically heavier than initial pyrite. In both cases, sulfate reduction was accompanied by oxidation and depletion of organic matter.

*Speaker.

A CASE FOR EXHALATIVE OR PENE-EXHALATIVE HYDROTHERMAL ACTIVITY IN THE GENESIS OF SEDIMENT-HOSTED, STRATIFORM COPPER DEPOSITS

ALEX C. BROWN
Département de Génie minéral, École Polytechnique, Case postale 6079, succursale A, Montréal, Québec H3C 3A7

Most recent studies of sediment-hosted stratiform copper deposits indicate that copper and associated metals were added to the host rocks after sedimentation and after at least very early syndiagenetic accumulations of sulfate and sulfide (*e.g.*, anhydrite, pyrite or their precursors). The amount of time between sedimentation and metal emplacement in a given bed or lamina may approach zero, but many features (such as overgrowths and replacement textures) indicate clearly that within the sequence of recognizable syndiagenetic and diagenetic events, metal deposition was postsedimentary. Consequently, the case for a direct exhalative model for metal emplacement is excluded. However, the widespread, abnormally high background content of metals of Kupferschiefer-type host rocks could be attributed to dispersed exhalations into the depositional basin. Sulfur-rich Cu–Fe–S mineral assemblages such as pyrite–chalcopyrite would result from the paucity of copper relative to syndiagenetic biogenic sulfide production, and are typical of this environment.

Pene-exhalative hydrothermal activity would be consistent with ore-grade concentrations, which commonly include copper-rich, sulfur-poor mineral assemblages such as chalcocite–digenite–bornite. In this model, exhalative-type metalliferous fluids encounter porous oxidized strata, such as red-bed clastic units, before reaching the sediment–water interface; in effect, the ascending fluids "vent" into an aquifer and establish a reservoir of ore solutions, typically confined beneath very fine-grained, highly impermeable beds rich in organic matter. These grey beds contain sulfides (or sulfates that may be reduced biogenically during very early diagenesis) and form a chemical sink for copper. The short-range introduction of copper from the adjacent red-beds is achieved by infiltration or diffusion (or both). A continued influx of copper and a fixed supply of original sulfur within given laminae would assure the typical copper-rich mineral assemblage. The pene-exhalative model merely accounts for the required adequate source of copper within the red-bed reservoir.

Suitable environments for the generation and circulation of exhalative-type ore fluids can be found in the regional tectonic settings of most sediment-hosted stratiform copper deposits; rift features contemporaneous with host sediments are readily apparent in many cases, and have been inferred in most other cases. Local features, such as effects of low-temperature hydrothermal alteration and polymetallic mineral assemblages, should be re-examined as possible support for this model.

TERMINOLOGY FOR SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS

ALEX C. BROWN
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Efforts to determine the genesis of stratiform copper deposits hosted by sediments are frustrated not only by the nature of the deposits and their settings, but also by our improper and inconsistent usage of terms. Furthermore, there are no totally satisfactory terms in some cases. Among the most prominent "problems" in the literature today, we find that 1) The term *sedimentary* is commonly used loosely and incorrectly in place of *stratiform* (or better, *sediment-hosted, stratiform*). *Post-sedimentary* clearly applies where an event follows sedimentation, but does not distinguish among all events of such nature: diagenetic, metamorphic, structural, *etc.* 2) Allusion to a type locality, such as "Kupferschiefer-type", is inadequate where a particular deposit is dominated by features not seen in that type locality. 3) The terms *syngenetic, syndiagenetic, diagenetic* and *epigenetic* are commonly used ambiguously. Are these terms applied to the metals(s) and sulfur separately (the "diplogenetic" concept), or to the metal(s) and sulfur together? How important is the "dia-" component of a syndiagenetic deposit relative to the "syn-"? Does *diagenetic* refer to a process or to a product? The term ought to be restricted to those processes involving internal ingredients of the host rock. Or does it refer to a post-sedimentary timing of deposition? Does the author erroneously restrict *epigenetic* to structurally controlled processes or products (shades of the so-called "Lindgren school")? 4) *Early diagenesis* may be used without sufficient qualification of the term *early*: such usage is excusable only where a diagenetic process or event precedes an identified "later" event, and preferably used only where a feature (*e.g.*, a mineral deposition or a textural transformation) identifies a specific early diagenetic moment or event. 5) *Remobilization* is commonly used without adquate specification of the scale of observation or distance of transport: intended dimensions may vary from the microscopic scale to the regional, and the author must specify his intent.

On the other hand, attempts to use accurate terminology can produce awkward results, the title for this symposium itself being an example. The geometry of some deposits included under this title surpasses configurations permitted by the term "stratiform"; are we committed historically to this term?

STRATABOUND COPPER MINERALIZATION IN EARLY PROTEROZOIC MARINE-TRANSGRESSION-RELATED QUARTZ ARENITE, COBALT GROUP, ONTARIO

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Within the Huronian Cobalt Group, the upper part of the Lorrain Formation consists of 1500 m of drab quartz arenite with minor red-beds at the top. It is conformably overlain by up to 60 m of red sandstone and brecciated red mudstone containing up to 36 horizons of anhydrite nodules and their silicified equivalents. The nodule-bearing zone is conformably overlain by about 800 m of drab, pyritic sandstone-to-mudstone turbidite-like cycles, generally less than 50 cm thick, which comprise the bulk of the Gordon Lake Formation. The depositional environment of these rocks has been controversial. They were believed to have been deposited under a climate changing from hot and wet to cold and dry, unusual climatic conditions for the chalcopyrite mineralization present in the upper part of the quartz arenite and the nodule-bearing zone.

New petrographic and isotopic data suggest that the quartz arenite is alluvial in origin and was feldspathic on deposition. The nodular red sandstone is of sabkha origin, and the overlying turbidite-like beds are marine-shelf storm deposits. The climate was warm and relatively dry. Therefore the revised sedimentary and paleoclimatic interpretations are better in tune with those of other examples of marine-transgression-related copper mineralization.

Diagenetic leaching of the previously feldspathic quartz arenite may have released copper, with greatest concentrations in secondarily reddened discordant tongues in the sandstone. Sulfur, present as pyrite in the lower part of the Gordon Lake Formation, is far in excess of that contained in the copper sulfide, indicating that the amount of sulfur or reductants present did not limit the copper mineralization. Sparseness of the copper is possibly due to lack of copper-rich material in the diagenetic quartz arenite.

DIAGENESIS, SULFIDES AND METAL ZONING IN THE REDSTONE COPPER DEPOSIT, NORTHWEST TERRITORIES

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RODNEY V. KIRKHAM

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The Redstone copper deposit, hosted by Upper Proterozoic sediments of Coates Lake Group, occurs in the cyclically transgressive stratigraphic interval between continental red-bed strata of the Redstone River Formation and euxinic subaqueous carbonates of the overlying Coppercap Formation. Subaqueous and subaerial mafic volcanic rocks lying stratigraphically beneath the red beds may have provided cupriferous detritus to the depositional basin. Metalliferous sulfide minerals (principally chalcocite, digenite, bornite, chalcopyrite and pyrite, as well as minor amounts of sphalerite, galena and molybdenite) are hosted by dolosiltites, dololutites and microbially laminated limestones and dolostones. These carbonates are inter-

*Speaker

calated with continental siltstones and mudstones, and form as many as seven red-bed clastic-to-marginal marine carbonate cycles within a transition from continental to subaqueous sedimentary rocks.

Geochemical profiles across the deposit show copper enrichment in the lowermost three clastic-to-carbonate cycles, and iron mineralization together with minor lead–zinc enrichment in the upper four cycles; minor molybdenum enrichment occurs in the basal cycle. The distribution of sulfide minerals reflects this geochemical zoning. Petrographic studies at the regional and local scales suggest that the host rocks were deposited in environments comparable to those of modern sabkhas. Paragenetic analyses indicate a consistent sequence of deposition of gangue and ore-forming minerals that formed through syngenetic to early diagenetic time: (1) precipitation of syndiagenetic gypsum, anhydrite, followed by dolomitization and precipitation of framboidal pyrite and calcite; (2) very early diagenetic precipitation of quartz and feldspar, and (3) subsequent early diagenetic precipitation of cupriferous sulfide minerals (also minor quantities of molybdenite, galena, sphalerite and a second generation of pyrite).

SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS IN CHINA

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A detailed description is made of the type, scale, ore grades and spatial distribution of sediment-hosted stratiform copper deposits in Archean to Tertiary rocks in China. The minerogenetic and geological character, distribution and ore guides are also documented. The reserves of stratiform copper deposits make up 25% of the total reserves of copper in China. Proterozoic carbonate-hosted stratiform copper deposits rank first among the stratiform copper deposits in China (63%). Most of the deposits in carbonate rocks are large or medium in size; the tenor of the ore in these deposits is intermediate (0.5–1%). These deposits were formed mainly in lower terrigenous carbonate strata in the early stages of geosyncline development. The second most important deposits are Mesozoic and Cenozoic sandstone- and shale-hosted stratiform copper deposits. Their reserves make up 21% of the total stratiform copper reserves in China. Most of these deposits are moderate in size, but they are richer in grade than the ores of other types. They were formed mainly in molasse-type strata during the later stages of platform development.

A change in paleoclimates (the transition between a hot-dry climate and a humid-dry climate) and the formation of copper-bearing zones of weathering were favorable for mineralization. Sediment-hosted stratiform copper deposits were formed through three progressive processes: (1) weathering and enrichment, forming surficial copper-bearing zones, (2) sedimentary enrichment, forming copper-bearing protores, and (3) diagenetic enrichment, forming orebodies.

THE DIAGENESIS AND MINEROGENESIS OF THE SANDSTONE- AND SHALE-HOSTED STRATIFORM COPPER DEPOSITS IN SOUTH CHINA

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This paper proposes that sandstone-hosted copper deposits are enriched and form mainly during diagenesis, and identifies the criteria, conditions and mechanisms of diagenetic mineralization. The following factors are responsible for the migration and concentration of copper and other metals during diagenesis: (1) changes in the T, P, Eh and pH of host rocks during diagenesis, (2) variabilities in the content of reductants (organic matter, pyrite) and in the intensity of gas escaping in the sediment, and (3) the nature of overlying sediments: variations in pressure, crystallization, cementation and gravitation give rise to variable degrees of filter dehydration and crystallization–cementation dehydration. Copper and other metals migrate from those sediments with low amounts of reductants and poor porosities to sediments with more reductants and higher porosities or better developed systems of fractures. For this reason, copper and other metals in sandstone copper deposits move from violet-colored argillaceous rocks and concentrate in the light-colored sandstone.

THE GEOLOGY AND GENESIS OF TERTIARY SANDSTONE COPPER DEPOSITS ON THE WESTERN MARGIN OF THE TARIM BASIN, XINJIANG

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The sandstone copper deposits of Xinjiang, China are located at the western margin of the Tarim Basin. One of these deposits occurs in the lower part of the Pliocene strata and in the upper part of the Miocene and is located in green sandstones. The sandstone copper deposits are generally many kilometres in extent. The enriched zone of the copper ores is located at 220 m depth. The average thickness of the orebody is about 40 cm, and the greatest thickness is more than 2 m. The host rocks consist predominantly of quartz as well as minor amounts of feldspar and lithic fragments. The principal cement is calcareous and includes an abundance of copper-bearing mineral fragments. Abundant malachite, cupriferous mica and cuprite occur within the oxidized zone of the deposits. According to the character of the deposits, the genesis of these deposits can be considered to be syngenetic. They formed initially in lake sediments of the Tertiary period and then underwent concentration in the course of diagenesis.

HYDROTHERMAL CHARACTER OF THE SHABA Cu–Co–U MINERALIZATION

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The origin of the Shaba stratiform Cu–Co–U mineralization of the Mines Series is still subject to contention. The present paper deals with the study of the host rocks and puts forward arguments for a possible hydrothermal origin. Three types of parageneses are distinguished in the host metasediments of the Luisha, Lwiswshi, Lukuni, Etoile and Kakanda deposits: 1) aluminous, with chlorite + clinochlore + phengite + kyanite + dolomite + quartz; 2) magnesian, with clinochlore + phlogopite + magnesite (+ quartz); 3) potassic, with microcline + phengite + quartz. In many cases, these potassic minerals were formed after the early albite- and paragonite-bearing associations.

In spite of the retrograde alteration, which is indicated by the presence of argillaceous minerals (*e.g.*, kaolinite after kyanite, chlorite after phlogopite), most mineralogical associations derive from regional hydrothermal alteration, with temperatures ranging from 300 to 350°C and pressures ranging between 1 and 2 kbar. These minimum conditions were estimated by the study of the extent of Na–K and Al–Si substitutions, the measurement of the crystallinity index of the aluminous potassic micas, and the study of fluid inclusions.

In the Shaba Cu–Co–U host sediments, the presence of kyanite in association with dolomite poses a problem. Kyanite usually occurs in the regional metamorphism of argillaceous sediments under higher metamorphic grades. Temperature and, in particular, pressure, reached by the Shaba sediments are clearly higher than those previously determined. The mineralogical assemblages are closely associated with sulfides and are scattered in the immediate environment of the metasediments. These assemblages are different from those that occur farther away from the deposits and suggest an aureole of Al–Mg–K hydrothermal alteration around the mineralized zone.

The occurrence of and geological relationships between the stratiform Cu–Co–U mineralization and Al–Mg–K host sediments suggest that the genesis of the sulfides is closely related to processes responsible for the formation of host-rock minerals at shallow depths in a playa environment. A hydrothermal process involving an intra- or extrasedimentary Cu–Co–Cl-enriched water is the most obvious explanation for the data. These elements may have resulted from leaching of the volcanic basement and would then have been deposited around the points of fluid emergence and would have impregnated the high-permeability formation. The authors present a model of hydrothermal circulation contemporaneous with sedimentation; circulation continued during compaction and became more intense with pre- and syntectonic diapiric rise of the Mine Series through the Kundelungu Formation. On the basis of the geothermal system, the sediment-hosted stratiform Cu–Co–U deposits of Shaba appear to correspond to incipient stratabound sulfide accumulations that were overprinted by hydrothermal and diagenetic processes. Regional metamorphism has modified the initial features of the host sediments, forming new mineralogical assemblages.

GEOCHEMICAL ENVIRONMENTS OF SEDIMENT-HOSTED ORE DEPOSITS

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Sediment-hosted Cu-Zn-Pb deposits can be classified with respect to their geochemical environment represented by pH and temperature of the ore fluids and nature of host rocks. MVT (Mississippi-Valley-type) deposits involve interaction of hot, acid brines with carbonate host-rocks, with the brines carrying metals and perhaps also sulfur for long distances. The KST (Kupferschiefer-type) deposits include the Permian Kupferschiefer of northern Europe, the Creta Lake deposit of Oklahoma, the Zambian Copperbelt, the Cretaceous of Angola and many others; they are characterized by shale host-rocks and by cool acid brines derived locally. Alkaline brines of continental basins form the GRT (Green-River-type) deposits such as McArthur River, Mt. Isa and Dugald River of northern Australia. Williams & Ross (1981) proposed a lacustrine setting for McArthur River, and Muir (1983) identified an alkaline lake for Dugald River. Outokumpu in Finland may also be a GRT deposit (Eugster 1985). Sandstone-hosted copper deposits (SHT) can be fitted into a class related to KST. Existence of acid and alkaline ore-fluids reflects the pH dependence of mineral solubilities. Temperature is largely a function of depth of circulation. Acidity is created by mineral precipitation, mineral alteration, boiling and decay of organic matter. Its presence can be recognized by wall-rock alteration. Alkaline brines are identified by the presence of Magadi-type chert and volcanic tuffs altered to zeolite - analcime - potassium feldspar zones. Much work remains to be done to refine this approach.

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SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS OF THE CENTRAL ANDES: SEDIMENTOLOGICAL, TECTONIC AND GEOCHEMICAL ASPECTS

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Although famous for porphyry-style copper mineralization, the Central Andes contains several economic to subeconomic sediment-hosted, stratiform copper (+ silver) deposits of small size but relatively high grade. They range in age from possibly Permian to Pleistocene and are hosted exclusively by red beds. Host rocks vary in grain size from conglomerates to siltstones, representing a series of alluvial fan and playa subenvironments within arid, intermontane basins. These fault-controlled molasse basins evolved during extensional periods within the generally compressive Andean orogen. The location of orebodies is controlled by sedimentary facies and host-rock diagenesis. In all cases the ore minerals occur dominantly as an intergranular matrix that postdates early diagenetic modifications to the assemblage of detrital minerals. Local remobilization related to deformation has produced later systems of discordant veins in some examples. Ore minerals are dominated by binary copper sulfides and native copper with later oxides. These assemblages were precipitated in secondary pore-spaces following dissolution of early cements: reduced copper species were fixed during temporary reducing conditions within the generally oxidizing intrastratal system. Such local conditions were produced in some cases by detrital organic material, which is commonly replaced by ore minerals; however, in many examples, organic matter is either absent or represented by epigenetic matrix-residues. In the latter, there is a spatial relationship between generation of secondary porosity, organic residues and mineralization. It is postulated that humate-rich groundwater was a prerequisite for mineralization. A possible source for such dissolved organic acids could be *via* diagenesis of preserved organic-matter-rich sediments, as found in recent arid playas in the Andes.

THE GEOLOGY AND GEOCHEMISTRY OF THE CARBONATE-HOSTED OMAR COPPER DEPOSIT, BAIRD MOUNTAINS, ALASKA

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The study area, located in the western Brooks Range, contains Paleozoic shallow-water platformal carbonate rocks that comprise part of the Brooks Range fold-and-thrust belt. Mineralized zones exposed on the surface range from a few metres to 20 metres square, and are stratabound in a dark grey, fine-grained Devonian dolostone. Sulfide mineralization was most extensive where patches of locally abundant megafossils, including rugose corals and stromatoporoids, occur within the Devonian dolostone. The most common sulfides in outcrop are bornite and chalcopyrite, with lesser chalcocite, tennantite–tetrahedrite and pyrite. Galena and sphalerite are found in minor amounts at depth. Most sulfides occur as veinlets, irregular stringers, and blebs within the commonly brecciated host dolostone. Dolomite, calcite, and quartz gangue accompany the sulfide minerals. The cross-cutting texture of the veinlets and the angular fragments of breccia suggest that brecciation and mineralization occurred after lithification of the original carbonate. Chalcopyrite is found in minor amounts within 3- to 6-cm-thick calcite–quartz veins that cut a platy limestone unit adjacent to the Devonian dolostone. The calcite–quartz–chalcopyrite veins may represent a remobilization of copper from the dolostone-hosted zones during or after the mid-Jurassic through Cretaceous Brooks Range orogeny. Analyses of rocks, soils and stream sediments from the mineralized zones reveal that Co, Ag and As concentrations are anomalously high and, together with Cu and Zn, provide the most useful pathfinders to mineralization. Lack of evidence for solution-collapse features within the host dolostone and the predominance of Cu over Pb and Zn sulfides suggest that this deposit is not a Mississippi-Valley-type occurrence.

HYDROGEOLOGY AND SULFIDIC ALTERATION HISTORY OF SHALLOW FLUVIAL AQUIFERS, NORTHWEST GULF OF MEXICO SEDIMENTARY BASIN

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Emplacement of stratabound metal sulfide deposits requires a large-scale flux of metal or sulfide, or both, into the host rock. Although such fluxes may be syndepositional, evidence in many deposits suggests postdepositional ore-genesis that must be related to the evolving systems of groundwater flow in the sedimentary basin. Uraniferous Neogene aquifer systems of the northwest Gulf of Mexico sedimentary basin were deposited on an arid to subarid coastal plain as oxidized sands and muds. Structurally localized, early and continuing influx of reactive, sulfide-enriched waters has produced large intrastratal "islands" of epigenetic sulfidic alteration within the regionally oxidized aquifers. The epigenetic pyrite displays discrete replacement textures and is characterized by isotopically heavy sulfur. The only known reservoir for such heavy sulfur is the deeply buried Mesozoic basinal carbonate sequence that underlies the thick, abnormally pressured Cenozoic fill. Repeated flushing of shallow aquifers by oxidizing meteoric waters containing anomalous amounts of U, Se and Mo alternated with invasions by sulfidic thermobaric waters to create repeated cycles of iron disulfide precipitation and oxidation. A record of multiple epigenetic events is preserved locally by imperfectly superimposed, multiple fronts of epigenetic oxidation. The required model of extremely dynamic mineralization may be representative of processes active in many large, compacting sedimentary basins.

GENETIC INTERPRETATION FROM ORE RELATIONS TO ALGAL REEFS IN ZAMBIA AND ZAIRE

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Barren algal reefs sandwiched between stratiform Cu–Co orebodies of Zaire are related to bioherms adjacent to both mineralized arenites and shales of the Zambian Copperbelt and require similar transgressions of marine waters over red beds and sabkhas. Elimination of the "younger" granite as a mineral source and proof of a pre-folding age for mineralization are of historic interest. Sulfide zoning in relation to transgressive beach conglomerates and then to prograding terrestrial deposits is described for the Nkana and Roan Antelope deposits, with emphasis on effects of algal bioherms. Channelling by groundwaters to allow ingress and diagenetic replacement in the sediments is lacking. Channelling and erosion of mineralized sediments by surface waters, with reworking of sulfides, are emphatic evidence for syngenesis. Mufulira B has ore on subtidal slopes and on the bottom of lagoonal basins adjacent to both barren shore red-beds and off-shore algal reefs; anhydrite is antipathetic to ore. The first stratiform mineralization in the Zambian Upper Roan was found at Mufulira. Cu–Co sulfides in 22.2 metres of dolomite and siltstone overlie anhydrite-bearing sabkha beds and are overlain by a reef comparable to the reefs of the Shaban orebodies of Zaire, where a 270-km arcuate belt of stratiform Cu–Co orebodies are exposed in anticlines, diapiric and nappe structures in the Upper Roan. Barren algal reefs separate upper and lower orebodies. A basal pebble layer lying unconformably on red beds compares with the Footwall Conglomerate of the Zambian ore shale, representing a marine transgression. A similar model for the Shaban deposits requires deposition of the lower orebody in a transgressive marine lagoon, followed by a transgressive off-shore barren reef, and then by the upper orebody in a fore-reef shale grading in deeper water to a carbonaceous pyritic shale. High-magnesium brines containing enhanced Cu and Co concentrations resulting from sabkha evaporation would be transported by normal tidal channels between the sabkhas, with dumping of detritus and chemical precipitation into the lagoon, where normal diagenetic transformations take place in subtidal sediments. Gaps in the algal reef allowed brines into the fore reef.

SOME EFFECTS OF THE MID-PERMIAN ZECHSTEIN TRANSGRESSION IN NORTHWESTERN EUROPE

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The Zechstein Sea transgressed a Rotliegend desert surface that possibly reached 300 m below global sea-level. Surface and subsurface data indicate that a large Rotliegend desert-lake "buffer" prevented the flooding from being destructive except locally. There was little reworking of the surfaces of unconsolidated sand dunes, which maintained most of their relief. Thus flooding must also have been very rapid. Large volumes of air trapped beneath the wetted surfaces of the dunes caused strong local deformation as the air escaped. Marine flooding was too rapid to permit reddening of the "Weissliegend" dunes, which earlier had been above the water table. The enclosed tropical Zechstein Sea was "instantly" deep, and its clear surface-waters were initially ideal for fauna, but the floor of this basin rapidly became anoxic with deposition of the bituminous Kupferschiefer. As shallow-marine carbonates prograded basinward, the sea became increasingly saline and, eventually, evaporites were precipitated.

The interface between formation waters of terrestrial and marine origin resulted in precipitation of sulfide minerals within, above and below the Kupferschiefer, and of calcite within the upper Rotliegend–Weissliegend sandstones.

A SUMMARY OF DESERT SEDIMENTARY ENVIRONMENTS, PRESENT AND PAST

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Tropical deserts develop where the potential rate of evaporation exceeds that of precipitation, where rainfall is too low or spasmodic to support vegetation. These regions usually occur in the trade-wind belts north and south of the equator and in the rain shadow of mountain ranges. About half the area of deserts comprise outcrop subject to erosion and deflation. The rest consists of sediments of fluvial (wadi), lacustrine (salina), paralic (coastal sabkha) and eolian origin, and of evaporites.

Ephemeral streams deposit sands and gravels over basin-margin alluvial fans, and over desert plains where subsurface cementation commonly takes place. Evaporation of temporary basin-centre lakes results in a crust of halite (inland sabkha). Fluvial sands are an important source of dune sand; the finer fractions are removed from the desert in suspension to become loess, and the coarser grains remain as a deflation lag. The axes of sand dunes are transverse to moderate winds and parallel to strong winds. Giant forms of the latter type of dune were prevalent during the last ice age, and in coastal areas, carbonate-cemented dune sands extend below present sea-level; this observation suggests a causal relationship between polar glaciations and strong desert winds. Desert fluvial sediments rarely reach the sea, so that the warm and clear coastal waters are ideal for the manufacture of organic carbonates. Longshore currents sweep them into offshore bars, behind which evaporitic lagoonal conditions develop. The lagoons become sabkhas as they are filled with algae-bound marine and wind-blown sediment.

Although there are desert sequences as old as about 2000 Ma, they seem to have occurred only sporadically during the earth's history. It seems likely that their occurrence was controlled by the past size of continents, by their location relative to the equator, by the freedom of circulation of global oceanic water and by the presence of ice caps. The Permo-Triassic was a time of extensive deposition of evaporite and dune activity. By implication, other known occurrences of evaporites may be marginal to wadi and dune sequences that have yet to be identified.

TEMPERATURES OF ORE DEPOSITION AT THE SPAR LAKE STRATABOUND Cu–Ag DEPOSIT IN THE BELT SUPERGROUP, MONTANA

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At Spar Lake, sandstone-cementing ore and gangue minerals form the following bed-transgressive mineral zones, grading from the southeasterly root to the northwesterly tip of the tongue-shaped deposit: (1) chalcopyrite - leucoxene - chlorite - ankerite - albite (CP–ANK zone), (2) chalcocite - hematite - chlorite - ankerite - barite - albite (CC–CHL zone), (3) bornite - hematite - calcite - barite - K-feldspar (BN–CAL zone), (4) galena - chalcopyrite - leucoxene - calcite - K-feldspar (GN–CAL zone), and (5) pyrite - leucoxene - calcite (PY–CAL zone). Minerals of the CP–ANK zone overprinted red beds that lay southeast of the deposit. The CP–ANK zone extends from within a graben along the deposit's east side to tongue into the southeast end of the CC–CHL (ore) zone, the site where either barite or hydrocarbons were concentrated prior to mineralization. Minerals from the CC–CHL and BN–CAL zones replaced the GN–CAL assemblage, which had earlier replaced the assemblage of the PY–CAL zone. Ore solutions followed sandstone permeability from the southeast (proximal side) toward the northwest (distal side). Themodynamic modeling and a modern analogue of the gangue mineralogy of the CP–ANK zone indicate temperatures as high as 150°C on the proximal side. Galena - chalcopyrite pairs from the distal side show that isotopic equilibrium of sulfur was attained at 50–90°C. Provided that the CP–ANK zone formed synchronously with the other zones as part of an advancing system of mineralogical fronts, this temperature gradient suggests that a warm ore-solution invaded the deposit from the southeast side and below, implicating the graben as a conduit for the ore solution.

*Speaker

POSSIBLE CONTROLS ON METAL RATIOS IN STRATIFORM COPPER DEPOSITS

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Stratiform copper deposits in low-energy clastic sediments have Cu/Pb weight ratios >2.5, Cu/Zn weight ratios > 1.5, Cu/Co weight ratios > 15 and Cu/Ag weight ratios > 200. Modeling of Cu, Pb, Zn, Co and Ag solubilities in water likely to have transported metals into stratiform copper deposits, together with considerations of constraints imposed on metal availability to the metal-transporting water, suggests that metal concentrations in the water are controlled by water composition, by abundance of metals in source rocks and by water–rock ratios in the source rocks. Water composition determines maximum concentrations of Pb and Zn; source-rock composition and water–rock ratio usually determine maximum concentrations of Ag, Co and Cu. Modeling of sulfide precipitation from the metal-transporting water suggests that the concentration of reduced sulfur in the host rocks determines relative amounts of metals precipitated from the through-flowing water. Low concentrations of reduced sulfur result in precipitation of Ag and Cu alone, and high concentrations can result in the simultaneous precipitation of Ag, Cu, Co, Pb and Zn. The modeling suggests that weight ratios of metals in stratiform copper deposits will be determined by source-rock composition, that of the metal-transporting water, and the concentration of reduced sulfur in the host rocks. Modeling, using basalt- and granite-derived source rocks with a water/rock ratio of 30%, predicts a Cu/Pb weight ratio greater than 3, a Cu/Zn weight ratio greater than 0.6, a Cu/Co weight ratio greater than 5 and a Cu/Ag weight ratio greater than 200.

KUHNE-MES, SOUTHERN IRAN: A SABKHA-RELATED STRATIFORM Cu–Pb DEPOSIT

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The Kuhne-mes stratiform Cu–Pb deposit, a site of ancient mining and smelting, is located in conglomeratic clastic rocks and dolomite at the junction of siliciclastic sediments of the Eocene Sachun Formation and intratidal dolomite and gypsum of the overlying Eocene Jahrum Formation. The ore comprises a complex mixture of supergene "oxides" of copper, lead and iron and minor barite. The Sachun Formation, which is of limited extent, represents the final phase of arid continental erosion of the Zagros Suture Zone during the Paleocene lacuna that followed ophiolite obduction after plate collision of Africa and Asia in the late Cretaceous. Later marine transgression of the Jahrum Formation, from the south, resulted in formation of massive carbonate reefs over much of southern Iran and intratidal sedimentation over the Suture Zone in the north. As subsidence continued, the Jahrum reefs grew northward, transgressing the intratidal sediments. The position of stratiform ore at the interface of arid continental sediments and intratidal chemical sediments and the polarity of facies changes in the Jahrum Formation are consistent with a sabkha model of origin.

REVETT-TYPE STRATIFORM SILVER–COPPER DEPOSITS AT THE U.S. BORAX NOXON PROJECT, NORTHWEST MONTANA

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The Revett Formation of the Proterozoic Belt Supergroup in northwestern Montana and northern

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Idaho is the host for more than 30 prospects and deposits of stratiform Ag–Cu in an area about 80 km long by 50 km wide. The Revett Formation, averaging approximately 600 metres in thickness in the area of interest, is a transgressive sequence consisting principally of clean quartzites, silty quartzites and siltites metamorphosed to the lower greenschist facies. Regionally, economic concentrations of metal are present in all three members of the Revett Formation, the upper quartzite member (Troy deposit), the middle siltite member (Rock Peak deposit), and the lower quartzite member (Rock Lake deposit).

The principal ore sulfides are chalcocite, bornite and chalcopyrite that are commonly zoned outward and upward, with native Ag locally visible in drill core within the bornite–chalcopyrite transition. Sulfide minerals occur principally as fine disseminations on bedding and shear planes, as fracture coatings, sulfide balls and rods, and as partial fillings of quartz veinlets. A distinctive zone of galena, commonly exhibiting 0.5% Pb or more, is present ten to fifty metres stratigraphically above the Ag–Cu zones.

At the Noxon Project, approximately 70 million tonnes of drill-indicated and probable ore grading 54 grams of Ag per tonne and 0.77% Cu have been developed in four tabular zones. The largest zone, the B zone of the Rock Lake deposit, averages 14.3 metres in thickness, and 350–425 metres in width, and has a drill-indicated length of 1200 metres with a probable length of 2400 metres or more.

The zoning of copper–iron sulfides, the slight discordance relative to bedding of the Ag–Cu mineralization, replacement features suggesting copper sulfides after pyrite, and the close relationship of faults with ore zones collectively suggest a post-sedimentation, probably diagenetic, origin for the Ag–Cu mineralization.

A DIAGENETIC–HYDROTHERMAL ORIGIN FOR UNCONFORMITY-RELATED AND STRATIFORM COPPER DEPOSITS IN THE CENTRAL AFRICAN AND MICHIGAN COPPER DISTRICTS

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Copper deposits of Central Africa and Michigan and unconformity-type uranium deposits of the Athabasca basin, Saskatchewan, share a common geological setting, characterized by the presence of a thick section of fluviatile red-beds sandwiched between a metamorphic basement and a shale-rich marine unit. Based on clay-mineral studies, a diagenetic–hydrothermal metallogenetic model has been developed for the uranium deposits of the Athabasca basin; it relates ore formation to diagenesis and fluid interaction between the oxidized red-bed aquifer and the reduced basement, under conditions of deep burial during an advanced stage of basin evolution. Diagenesis and hydrothermal mineralization are aspects of one process of convection-mediated mass transfer that was regulated by temporal variations in heat flow associated with episodic tectonic reactivation and deepening of the basin accompanied by diabase magmatic activity. In such a geological setting, a potential for mineralization also exists at the top of the aquifer, if the overlying shale is rich in organic matter and chemically reduced. We will argue that the stratiform copper deposits of Central Africa may represent diagenetic–hydrothermal mineralization at the top of the aquifer and that the mineralized pipes of Tsumeb and Kipushi may be their unconformity-type equivalents. For the Michigan district, stratiform ore in the Nonesuch Shale and vein ore in the Portage Lake lavas may be interpreted as diagenetic–hydrothermal mineralization, at the top and the base, respectively, of the Copper Harbor red-bed aquifer. In a broader perspective, we consider ore formation as an inherent aspect of diagenesis and basin evolution. This opens the prospect of developing a unified metallogenic model for a spectrum of sediment-hosted and unconformity-associated metal deposits, whose unifying feature is an origin that is intimately tied to red-bed diagenesis. Giant Proterozoic stratiform copper deposits may relate to red-bed copper deposits as unconformity-type uranium deposits are related to sandstone-type uranium deposits; these represent, respectively, end products and transient, intermediate products of a process of basin evolution and red-bed diagenesis that has gone to completion in the Athabasca basin.

CONSTRAINTS FOR THE GENESIS OF RED-BED-ASSOCIATED STRATIFORM Cu DEPOSITS FROM S AND C MASS-BALANCE RELATIONS

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Most genetic models for red-bed-associated Cu deposits postulate, mainly on the basis of the wide variation observed in the sulfur isotope values, that sulfide was produced at low T by bacterial reduction of sulfate. However, the observed relationships among the total sulfide and residual organic carbon content of the host sediments, $\delta^{34}S$ of sulfides, and $\delta^{13}C$ of carbonates (where present) from some deposits are difficult to explain by this process only. Secondary additions of reduced sulfur at deposits such as Kamoto (Zaire), Musoshi (Zambia) and White Pine (Michigan) are suggested by the data, this additional sulfide most likely being generated at the site of deposition by abiogenic reduction of sulfate during introduction of the Cu-bearing fluid. Application of such a model has enabled the calculation of a number of relevant parameters during each stage for the deposit at Kamoto. During the process of bacterial reduction, an average of 0.6 wt.% sulfide was added to the rock, requiring oxidation of 0.45 wt.% organic carbon. Less than 10 g of water per g of rock is required for this process. These quantities are not unusual for diagenetic processes. During the ore-deposition stage, an average of 1.6 wt.% sulfide was added, more than ⅔ of the total sulfide, necessitating a minimum of 1.25 wt.% oxidized organic carbon and more than 260 g of water per g of rock. Results using this approach for other deposits will be reported.

STRATIGRAPHIC, TECTONIC AND SEDIMENTOLOGICAL SETTING OF DEPOSITS IN THE REDSTONE COPPER BELT, MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES

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Several stratabound copper deposits are localized at the top of thick sequences of red mudstones and interbedded evaporites (Redstone River Formation) overlain by grey turbiditic limestones (Coppercap Formation). These sequences are part of the Late Proterozoic Coates Lake Group (CLG), which forms a lenticular arcuate belt about 300 km long in the Mackenzie Mountains fold-and-thrust belt, northwestern Canada. The CLG forms a transitional sequence between platformal carbonate and siliciclastic strata of the Mackenzie Mountains Supergroup, and glaciomarine deposits and iron formation of the Rapitan Group.

Tectonically, the CLG is preserved mainly in six fault-controlled basins that were initiated during a plateau-basalt eruption at the top of the Mackenzie Mountains Supergroup. These basins underwent intermittent tectonism during and after deposition of the CLG. The basins controlled internal sedimentation by drainage systems that had local provenance. The basin shapes restricted or prevented access by marine waters. The largest copper deposits are spatially associated with those basins containing the thickest stratigraphic sequences.

Sedimentologically, the base of CLG records weathering and alluvial deposition of conglomerates to mudstones eroded from the plateau lavas. Rhythmic sabkha dolostones and distal sheet-flood deposits of red mudstones covered the basal conglomerates. The sabkhas in turn were inundated by hypersaline waters that deposited thick-bedded Na–Ca–Mg sulfates. These evaporites were covered by up to 1000 m of distal sheet-flood deposits: red, fine-grained, carbonate-dominated clastic rhythmites (Redstone River Formation) that underwent early mechanical dewatering. Cyclic, incipient saline lacustrine transgressions then deposited evaporitic algal carbonate sheets, intercalated with red mudstones (Transition Zone). The algal carbonates host the copper deposits. Subsequent abrupt subsidence resulted in continued deposition of fine to coarse carbonate detritus as turbidites in two shoaling- and coarsening-upward cycles, each culminating in stromatolite units (Coppercap Formation). An episode of regional uplift, renewed tectonism and climatic change preceded deposition of the glacigene Rapitan Group.

*Speaker

GEOLOGICAL FEATURES OF THE STRATABOUND Cu ORE BELT, DABAN COUNTY, NORTHERN TIANSHAN MOUNTAINS, XINGJIANG, CHINA

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Located at the south limb of Bodeda anticlinorium of the North Tianshan geosynclinical fold region, the Daban County Cu ore belt follows in an E–W direction for 20 km and consists of 9 medium-to-small ore deposits and several mineralized occurrences. The ore-bearing strata are Permian in age and hosted by siltstones intercalated with volcaniclastic rocks within a flysch formation. The orebody is distributed along the two limbs of an anticlinal–synclinal fold, and were controlled by stratigraphy and lithology. The stratabound orebody occurs in black and grey-black siltstones, gravel-bearing sandstones, sandy conglomerate rocks, and medium- to coarse-grained debris sandstones. There are two or three mineralized beds. The orebody is conformable with the host-rock formation, which is hundreds of metres long; blind ore existed in its deep part. Those metallic minerals in ores with brecciated, massive, banded, disseminated and porphyritic structures are chalcopyrite, chalcomiclite, chalcocite, pyrrhotite, galena and sphalerite. The ores generally contain 1–3% Cu; some contain as high as 22.5% Cu. The associated elements are Pb, Zn, Co, Ni, V, Sn, B and Mn. Pb and Zn are so abundant that they may form individual Pb and Zn orebodies or cupriferous-polymetallic orebodies. The paragenetic order among metallic minerals is magnetite – pyrite – chalcopyrite – chalcomiclite – sphalerite – galena – polybasite.

The Cu ore belt is laterally zoned according to variations in minerogenetic temperatures, with medium-temperature Cu ores to the north, and medium- to lower-temperature Cu–Pb–Zn ores to the south. The enrichment in mineralization was closely related to fault activity. Mylonitized zones and tension and shear fractures were paths for the movement of ore-bearing fluids and were sites for mineralization.

EFFECTS OF TECTONIC ENVIRONMENT ON KUPFERSCHIEFER-TYPE DEPOSITS

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Stratiform Cu–Ag deposits of the Kupferschiefer (Ks) type typically occur at the upper contact of continental volcanic and red-bed sequences which contain features characteristic of continental rift-basins. These include: basaltic or bimodal igneous suites; normal to listric block-faulting causing basin-and-range topography; isolated, narrow, closed basins containing immature clastic and evaporite sediments; and, in cases, abnormally thin upper lithosphere. This tectonic environment appears to have influenced deposit genesis in several ways. Alkaline basaltic igneous suites in continental rifts are derived from uncontaminated mantle and, thus, contain more Cu, Pt and Pd than igneous suites near subduction zones. Rapid, fault-controlled sedimentation and local derivation allow volcanic detritus to be incorporated in the basin fill, thus providing an easily accessible source of base, precious, and possibly PG metals. Internal, closed drainage allows saline brines to form concomitantly with early diagenetic red-bed formation. Basin-and-range topography, with basement highs flanked by coarse clastic rocks, provides the geometry that allows channelling of oxidized metalliferous brines to the reduced beds above during early or late diagenesis. Commonly, the ore deposits are directly above one particular rift-sequence [*e.g.*, White Pine, Redstone, Kupferschiefer, Dzhezkazgan (?)]. Otherwise, the deposits are situated within thick supergroups with a long history of fault-controlled sedimentation, and no particular source-rock is obvious (*e.g.*, Creta, Spar Lake). Syngenetic, stratiform Pb–Zn–(Cu) deposits (*e.g.*, Sullivan or Rammelsberg) are also contained in rift environments, although the sedimentary environment above and below the ore is typically all deep marine with no red-beds. In these cases, major tectonism (locally with volcanic activity) contemporaneous with sedimentation and mineralization provides evidence for a syngenetic hydrothermal process, whereas in Ks-type deposits, the reduced strata that act as chemical traps (*e.g.*, Kupferschiefer, Nonesuch shales) are deposited in a tectonically quiescent period compared to the underlying volcanic rocks and red beds. It is proposed that the continental rift environment is the primary control in the location of these deposits, and this setting produces the necessary ingredients (metal source, brines, channelways, topography) before the basin is filled and covered by the reduced strata. Ore formation can occur when some later thermal or tectonic event (possibly another rifting event) induces migration of diagenetic fluids and causes the 'potential orebody' to be channelled up to overlying reduced strata.

LATE-DIAGENETIC ORIGIN OF KUPFERSCHIEFER Cu-Ag DEPOSITS IN POLAND BY CONVECTIVE FLUID-FLOW OF ROTLIEGENDES BRINES

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Kupferschiefer (Ks) mineralization in the Lubin and Konrad districts of southwest Poland occurs as thin irregular blankets of zoned sulfides directly underlain and controlled by the Rote Fäule (RF), a barren oxidized and reddened portion of the normally pyritic, basal Zechstein rocks of Upper Permian age. In plan view, successive belts enriched in copper (silver), lead and zinc encircle the irregular oval RF zones and sharply transgress the depositional strike and lithologic bedding of the basal Zechstein. The RF-copper zones, the presumed site of upwelling of mineralizing fluids, are coincident with underlying buried basement-highs and occur above Lower Permian Rotliegendes rift basins of continental red-beds and alkaline bimodal volcanic rocks. The metal zoning generally dips away from the highs toward the basin centres. Sulfides, as disseminations and streaks, commonly replace earlier calcite cement, lithic fragments, quartz grains, as well as other sulfides. Subhorizontal and vertical dilatant sulfide veinlets were formed after lithification, before Cretaceous Alpine tectonism, and contemporaneous with the disseminations and streaks. The stable paleomagnetic direction of the chemical remanence of the RF hematite (49.0°N, 157.2°E; $A_{63} = 2.2°$) is Middle Triassic in age, and the Kimmerian age (mid-Triassic to late Jurassic) of the veinlet orientations supports this late diagenetic timing, which coincides with a second continental rifting associated with the opening of the Tethys ocean. These associations and controls suggest that the ore was formed during late diagenesis, when formational brines leached metals from the Rotliegendes volcanic detritus and migrated up the flanks of basement highs to the Kupferschiefer above. Lower Zechstein evaporites preclude a vertical flow-through model, but attitudes of metal zoning instead suggest a convective flow of fluid within the Rotliegendes. The Rotliegendes basins are typically isolated and closed, and the coarse alluvial fan and braided-river clastic material are flanked by basement highs on one side, and by shale beds in the basin centres. Modeling of conductive heat-flow under simulated conditions of the Triassic rift suggests that a vertical ΔT of 25°C will result from thermal blanketing effects, and that warm basement-highs and cold shale-basin centres will result simply from differences in the thermal conductivities of basement (4.2 W/m°C), sandstone (2.5 W/m°C), and shale rocks (1.25 W/m°C). These lateral boundary-conditions imposed by the basin-and-range geometry would induce convective flow of fluid in a unicellular manner. With a slope angle of 2° and a permeability of 1 darcy, a fluid velocity of 13 cm/year can result, which, with a copper solubility of 1000 mg/kg in 20% to 30% Ca–Na–Cl brines in equilibrium with hematite, can form the Lubin deposit in less than 6 Ma. Using fracture permeability of 2 darcy and a solubility of 300 mg/kg, the time needed is less than 10 Ma. Natural gases generated from Carboniferous coals likely migrated along with the metalliferous brines and helped convection by creating secondary porosity and increasing the buoyancy of the fluids.

DISTRIBUTION OF SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS: AN INTRODUCTION

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Sediment-hosted stratiform copper deposits are a major source of industrial copper, second in importance only to porphyry copper deposits. Production from the sediment-hosted type is dominated by a few very large deposits and districts such as the Zambian and Zairian copperbelts, Dzhezkazgan in the Soviet Union, and Lubin in Poland. White Pine (Michigan) and Spar Lake (Montana) have been the only significant producers of this type in North America. Most major sediment-hosted stratiform copper deposits comprise disseminated sulfides in anoxic, paralic marine sedimentary rocks immediately overlying typically red, continental clastic sedimentary rocks ("Kupferschiefer-type"). With the exception of Dzhezkazgan, those deposits contained entirely within continental red-bed sequences ("Red-bed copper deposits") are of lesser importance. Deposits of this type are found in rock sequences that postdate the first occurrence of undisputed red-beds and cyanophytes (*ca.*2.25 Ga ago); thus they range in age from Precambrian

to Recent. The most important and abundant deposits occur in Late Proterozoic and Late Paleozoic rocks and correlate closely with widespread desert environments of sedimentation. Host rocks characteristically were deposited in arid and semiarid areas, within 20° to 30° of the paleoequator; in many areas, they are interbedded with evaporites. Many sediment-hosted stratiform copper deposits, even though probably products of diagenetic oxidation-reduction processes, show a close relationship to the environment of sedimentation.

A GEOCHEMICAL AND PETROFACIES STUDY OF THE KUPFERSCHIEFER IN HESSIA, WEST GERMANY

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A large part of the most important copper deposits of central Europe is linked to sub-basins on the southern margin of the Zechstein Sea. In our research program, the Rote Fäule (hematitic facies) was examined for the possibility that it could be an indicator of an ore-forming environment. Much knowledge was gained about paleogeography, and a geochemical inventory was made of the Kupferschiefer and the overlying and underlying beds. With respect to paleogeography, the discovery of further Hercynian-trending structures permits a transverse subdivision to be made of the Hessia sector of the Rotliegend trough, which has a predominantly Erzgebirge trend. Copper concentrations are predominantly bound to Hercynian-trending structures. The presence of the Rote Fäule, as the oxidized side of a redox front, proved to be a useful criterion for the prospecting of copper-rich parageneses. The hematitic facies is bound to Hercynian-trending structures in the Werra basin, clearly connected with paleogeography and paleostructures. An inverse zonation of metals, with a Cu maximum above the highest Pb and Zn concentrations, originated by the overlying diagenetic hematite facies in the Zechstein limestone. The present ore-bearing minerals and their distributions are attributed to epigenetic processes. The Hercynian tectonic structures in the marginal areas between the Rotliegend troughs and the rising basement possibly played an important role in the ascent of solutions.

STRATABOUND Cu–Ag AND Pb–Zn MINERALIZATION IN THE SPOKANE AND HELENA FORMATIONS IN THE EASTERN PART OF THE BELT BASIN, MONTANA: A COMMON ORIGIN?

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The structurally complex eastern margin of the Middle Proterozoic Belt basin contains stratabound Cu–Ag and Laisvall-type Pb–Zn occurrences. Cu–Ag mineralization occurs in beds of light-colored arenite

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within a thick sequence of red clastic strata of the Spokane Formation. The tabular occurrences reach 30 m in thickness. Copper sulfides occur as disseminations that in part replace pyrite and silicates. Sulfides at one locality (Canyon Creek) are intimately associated with organic material. Occurrences of Ag-poor galena and Fe-poor sphalerite (± chalcopyrite) are found in basal arenite beds of the Helena Formation dolomite along strike for 60 km. Mineralized beds range from a few cm to more than 2 m thick. Galena generally óccurs stratigraphically lower than sphalerite. Sulfides occur as disseminations and clots replacing authigenic pyrite and carbonate and quartz cement. Values of $\delta^{34}S$ are similar (range = -2.5 to $+15.5‰$) and compatible with derivation from seawater sulfate for both Pb–Zn and Cu–Ag occurrences.

The large areal extent of the diagenetic Cu–Ag and Pb–Zn occurrences, their spatial proximity, the stratigraphic position of the Pb–Zn mineralization above the Cu–Ag occurrences and textural and isotopic similarities are suggestive of formation by upward and lateral movement of metal-bearing basin-derived solutions. Accordingly, lack of sufficient amounts of S in the Spokane Formation may have precluded the precipitation of most of the Pb and Zn there, allowing these elements to migrate. Faults would have been crucial for fluid flow through the intervening reduced, pyrite-bearing fine-grained Empire Formation to the basal Helena Formation arenite. Alternatively, one or both types of mineralization may have resulted from flow of meteoric water from the east into the basin. Finally, Pb–Zn deposits are guides to Cu–Ag deposits and *vice versa.*

GENESIS OF PERMIAN AND TRIASSIC SANDSTONE-HOSTED COPPER DEPOSITS IN NEW MEXICO

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Numerous small, uneconomic deposits of copper are associated with fluvial and transitional marine environments of Permian and Triassic age in New Mexico. Copper-bearing minerals, primarily chalcocite, replace woody organic debris in fluvial sandstones, noncompressed wood in organic-matter-rich shales that represent small swampy environments, and fine-grained micritic calcite in lacustrine sediments. In transitional marine environments, chalcocite occurs as a replacement of algal mats and as wispy disseminations in fine-grained sandstones and siltstones. In the transitional environments, mineralization occurs near oxidation fronts, passing from red to grey sediments. Except for one deposit, chalcocite is primary and does not replace an earlier generation of pyrite. Red beds, of early diagenetic origin, are always associated with these copper deposits. However, the reduced copper-rich sediments themselves show no petrographic evidence of ever having been red. For instance, mafic minerals remain fresh and unaltered.

It is proposed that these copper deposits form during early diagenesis as the surrounding oxidized sediments begin to redden. During uplift of Precambrian highlands with copper-rich rocks, clay minerals as well as detrital silicates enriched in copper are transported into adjacent basins. The clay minerals, in particular, are the first to redden. Water in contact with these minerals is nearly neutral in pH, bicarbonate-rich, and low in salinity. In this geochemical environment, iron is very immobile and precipitates as amorphous iron hydroxides, which form the red coloration. Copper would be relatively mobile as a soluble copper–carbonate species ($CuCO_3°$). Copper would migrate to nearby reducing, organic-matter-rich environments, where it would precipitate as chalcocite. The relationship between the deposits in New Mexico and those such as the Kupferschiefer is not known. However, it is suggested that as these copper-rich groundwaters continued to migrate into the basin, the waters would evolve into a more saline basinal water in which copper could continue to be transported as copper chloride complexes.

LITHOSTRATIGRAPHY OF COPPER OCCURRENCES IN SOUTHERN SHABA (ZAIRE), AND CORRELATIONS WITH THE ZAMBIAN COPPERBELT

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Deposition of the lower strata of the Lower Roan in Shaba seems to have been restricted initially to a fault-controlled basin oriented NW–SE. The overlying strata, containing the principal Lower Roan deposits, were deposited during major faulting in large arkosic delta-fan complexes that grade vertically and laterally eastward into lacustrine siltites and dolomites. Mineralization is known to occur mainly in two environments: high-energy conglomeratic arkoses of the Mutonda Formation, and low-energy feldspathic siltites at the bottom of the overlying Musoshi Formation (equivalent of the Zambian Ore Shale). The Lower Roan outcrops only in the southernmost part of Shaba.

The Upper Roan of Shaba is separated from the Lower Roan by tectonic breccias. It consists of cyclic successions of continental red-beds and lagoonal dolomites in a broad, open embayment trending approximately N–S. Copper–cobalt mineralization is restricted to the lagoonal facies directly overlying the red beds and occurs principally in the Mines Group (about 60 deposits occur in the lower part of the Upper Roan). Only a limited number of deposits are known in the Mofya and Dipeta Groups (middle portion of the Upper Roan), as well as in the volcanic-rock-bearing Mwashya Group (uppermost section of the Upper Roan). In this tectonism-related depositional model for the Roan of the Shaban Copperbelt, copper emplacement frequently occurred immediately after vertical movements of the basin, resulting in transgressive records in the stratigraphy.

SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS IN SOUTHERN CHINA

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The copper deposits of China include two major types: stratiform, and sandstone-hosted deposits. Stratiform deposits in Precambrian strata of the Kunyang Group in Yunnan Province are one of the principal sources of copper in China. The orebodies are situated in the transitional zone between purple clastic rocks and dark grey carbonate rocks. The host rocks are dolomites formed in tidal flat and sabkha environments. Among the configurations of orebodies, stratiform bodies are most important, and lenticular bodies are secondary in importance. The principal ore-minerals are copper-bearing sulfides associated with concentrations of Ag, Ge and Mo. Zoning of metals is clearly evident. The ores show replacement and horsetail-like structures. Values of $\delta^{34}S$ vary from -3.7 to $+21.3$‰. These copper deposits have been interpreted as sedimentary and metamorphic in origin, with initial emplacement of ore related to abundant algal activity in the host rocks, and subsequent enrichment related to deuterogenic alteration.

The sandstone-hosted copper deposits occur mainly in Yunnan, Sichuan and Hunan Provinces, in rift basins ranging from Sinian (Late Proterozoic) to Cretaceous in age; the majority are found in Cretaceous basins. The orebodies are situated in transitional zones between light-colored and purple beds. Most orebodies are lenticular in shape. The principal cupriferous ore-minerals are copper-bearing sulfides and native copper, associated with concentrations of Ag, Mo, Zn, Se and U. Zoning among copper-bearing sulfides is common, and replacement textures are evident. Values of $\delta^{34}S$ vary from $+2.4$ to -28.7‰. These deposits are controlled by stratigraphy, lithofacies and tectonics, and belong to a catagenetic type related closely to ground-water activity.

WATER-ESCAPE PHENOMENA IN THE COATES LAKE GROUP, NORTHWEST TERRITORIES, AND THEIR RELATIONSHIP TO MINERALIZATION IN THE REDSTONE STRATIFORM COPPER DEPOSIT

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Water-escape phenomena are a common feature of the Coates Lake Group (Thundercloud Forma-

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tion, Redstone River Formation, ore-hosting Transition Zone, Coppercap Formation) in the vicinity of the Redstone stratiform copper deposit. Fluidization features in the Redstone River Formation and the Transition Zone appear to have formed relatively late in the history of the sedimentary package, as attested to by sharp contacts between fluidization channels and hosting sediments, lack of deformation of those channels by subsequent compaction, and entrainment of both oxidized and diagenetically reduced sedimentary clasts. Water-escape structures host and, in some cases, are defined by copper and iron sulfides in the reduced beds of the Transition Zone. If the metals in the Redstone deposit were scavenged from the red beds, as suggested by selective depletion of copper in the underlying Redstone River Formation, the solutions that carried those metals had to come into contact with the algal layers of the Transition Zone, now hosting the ore. It is likely that the fluidization channels observed in the Redstone River Formation and the Transition Zone record the pathways these waters followed. Similar features are observed at the Spar Lake stratiform copper deposit in Montana and at Mount Gunson, Australia. If focusing of fluids into favorable horizons during basin dewatering is responsible for the localization of stratiform copper deposits, the occurrence and intensity of dewatering phenomena may prove to be a useful tool for exploration in depositional basins already determined to have potential.

STRUCTURAL TRAPS FOR STRATABOUND COPPER DEPOSITS

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The Upper Proterozoic Stuart Shelf sequence of South Australia contains stratabound copper deposits in a variety of host rocks and stratigraphic units. The rock sequence is unmetamorphosed and undeformed; hence orebody – host rock relationships are not obscured by postore movements, and synsedimentary structures can be determined. A consideration of the location of deposits within the framework of their regional geological setting shows that they are clustered around a basement high that was an actively rising horst-block during deposition of the metal-bearing sediments. Individual deposits are located in paleotopographic depressions which, in many cases, are graben or half-graben structures active during sedimentation. In addition, an association with a major crustal lineament is evident. For stratabound copper provinces in which the host rocks have been deformed, the determination of synsedimentary structures is more difficult. This study involved the Upper Proterozoic Klein Aub – Lake Ngami province of Namibia and Botswana and the Lower Proterozoic Lomagundi Basin of Zimbabwe. By "unfolding" the sequences, it is apparent that individual copper deposits are located in paleotopographic depressions on the flanks of fault-bounded basement highs, and may be related to major lineaments. A similar structural setting may be deduced for deposits in other major copper provinces, such as the Zechstein Basin and the Zambia Copperbelt. For stratabound copper deposits in general, there is no consistency in host-rock lithology or in timing of metal emplacement. There is not, therefore, a single ore-genesis model that is applicable to all deposits. There is, however, a consistency in the structural control on localization of deposits, and structures can be used to identify potentially ore-bearing areas.

THE MANGULA COPPER–SILVER–GOLD DEPOSIT, ZIMBABWE: A LOWER PROTEROZOIC OLYMPIC-DAM-TYPE DEPOSIT?

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The Mangula deposit, in the Lower Proterozoic Deweras Group of Zimbabwe, is hosted by alluvial fan – braided stream – playa lake sediments derived from a block-faulted granitic basement-high. Copper – silver – gold – uranium – platinum mineralization is intermittently distributed over 200 m of stratigraphy; for mining purposes, mineralization is divided into several subparallel tabular orebodies. The deposits have been subjected to four phases of deformation and two phases of metamorphism, during which partial remobilization and recrystallization have obscured initial textural relationships, although relict tex-

*Speaker

tures indicate that sulfide minerals were originally disseminated throughout the clastic sediments. Pervasive hematite alteration and local zones of magnetite, silica, K-feldspar, carbonate and tourmaline alteration are related to secondary (metamorphically remobilized) mineralization in vein structures. It is not clear from available data how much (if any) alteration predates the first event of deformation. In its Cu–Ag–Au–U–Pt metal assemblage, its association with a block-faulted basement high, its occurrence in alluvial-fan sediments related to active faulting, the distribution of mineralization over a considerable stratigraphic interval, and its association with zones of hydrothermal alteration, the Mangula deposit is more closely allied to the Olympic Dam deposit of South Australia than to Zambia-type stratabound copper deposits.

METAMORPHIC FEATURES OF STRATABOUND COPPER–SILVER DEPOSITS AT MHANGURA, ZIMBABWE

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Stratabound copper–silver deposits at Mhangura are hosted by rocks of the early Proterozoic (*ca.* 2160 Ma) Deweras Group. The host rocks were deposited in alluvial fan, braided stream and playa lake environments adjacent to a block-faulted basement high. Disseminated copper–silver mineralization was emplaced prior to multiple deformation and metamorphic events. The first deformation was the strongest cleavage-producing event and was accompanied by peak metamorphism in the upper greenschist facies. Fluids generated during this deformation produced mineralized veins parallel to cleavage in meta-argillite and along faults, joints and in hydraulically produced brittle fractures in competent lithologies (meta-arkose, dykes and granite). In all cases the syntectonic veins have a mineralogy of quartz, K-feldspar, hematite, carbonate and sulfides. At the Mangula mine, much of the syntectonically remobilized mineralization is confined to the lithologies carrying disseminated ore, whereas at the Norah mine, a considerable amount of vein mineralization was emplaced within a mafic sill that was folded with the sediments. Subsequent deformations folded the earlier mineralized veins. New mineralized veins occupied joints and brittle fractures caused by these later deformations. Shearing, folding, boudinage and fracturing of earlier vein-material was accompanied by redistribution of sulfides into low-pressure areas by pressure solution and shear flowage. The mobility of copper–iron sulfides under conditions of greenschist-facies metamorphism and high fluid-pressure may account for small structurally controlled orebodies that are common in the Deweras Group.

AFRICAN ORE-SHALE COPPER DEPOSITS

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Classification of stratiform mineral deposits primarily on the basis of the valuable metals or minerals and the age of the host rock shows that the distribution of stratiform deposits of iron, manganese, gold, uranium, copper, lead, zinc, and others is strongly time-dependent. Stratiform copper deposits tend to be concentrated in formations laid down at specific intervals during the Lower Proterozoic, Middle Proterozoic, Upper Proterozoic, Upper Paleozoic, and Cretaceous–Tertiary periods. These deposits are closely related to the overall development of the host sedimentary basins.

The Central African Copperbelt deposits lie in the Upper Proterozoic Katangan in a largely intracratonic basin that is closely related to and lies within a framework of the Middle Proterozoic Kibaran. The Ore Shale deposits of the Zambian type lie along the shoreline of what seem to be interdeltaic lagoonal areas. These deposits are restricted to this narrow elongate zone, to specific rock-types (particularly argillite and siliceous dolomite), to a particular stratigraphic level closely related to the configuration of the basement, to the first oceanic deposits above a terrestrial sequence, and to the first beds accompanied by extensive biological activity, and have a zoning pattern of sulfide minerals related to the shoreline. These and many minor characteristics place certain limits on the formation and space–time distribution of these and similar deposits.

SUBMARINE VOLCANISM AS THE ONLY SOURCE FOR STRATIFORM COPPER: TWO EXAMPLES FROM IRAN

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In the last four decades, many studies have been conducted on the genesis of stratiform copper ores. Today, it is well accepted that stratiform copper deposits and their host strata are syngenetic. The role of submarine volcanism and related exhalations in introducing copper ions into the marine environment has been the subject of a large number of studies. An alternative source of syngenetic copper would be the adjacent continents. Which source is indeed dominant? This paper propounds some questions, and at the same time some criteria, on the principle of mass balance in marine water, and discusses tentative sources of copper in marine environments. Submarine volcanism, especially its exhalative episodes, is the most probable source of metals for the principal stratiform copper resources of the world. Among examples, two are from Iran: 1) stratiform Cu–Zn–Pb–(Ag) ores in shales and carbonates of Jurassic and Lower Cretaceous age in west-central Iran; and 2) stratiform Cu–Co ores in carbonates and tuffs of Lower Cambrian age in Zagros.

SEDIMENT-HOSTED STRATIFORM COPPER MINERALIZATION FROM EARLY PROTEROZOIC ROCKS OF SOUTHERN INDIA

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Nonvolcanogenic sediment-hosted copper deposits are rare in India, but one occurrence of this type is found in association with Proterozoic sediments at Nallakonda, within the Agnigundala sulfide belt in the northeastern part of the Cuddapah basin of southern India. Shale (in part carbonaceous), quartz arenite and dolomitic limestone are the chief lithologies associated with the mineralization. These sediments overlie gneissic basement-rocks (Archean) and have undergone at least two phases of deformation; this is evident from coaxial superposition of two generations of folds. The sediments and the related primary structures, such as large-scale cross-stratification in quartz arenites and stromatolites in dolomitic limestones, suggest a near-shore platformal environment.

Copper mineralization is essentially associated with quartz arenite. Chalcopyrite and bornite are the predominant ore-minerals. A crude vertical zonation showing an increase in the bornite to chalcopyrite ratio with depth is a characteristic feature in the deposit. Regionally, sulfide mineralization displays a lateral zoning of metals, with copper mineralization at Nallakonda in the east, and lead mineralization at Bandalamottu in the west. The association of sediment-hosted stratiform copper mineralization at Nallakonda with a near-shore platformal environment and a lack of direct association with magmatic activity suggest that the mineralization formed from basinal brines. These brines originated in the near-shore sedimentary environment in the form of brine sulfate; the sulfate was subsequently reduced by bacterial activity to precipitate copper-bearing sulfides.

VOLCANOGENIC CHARACTER OF SEDIMENT-HOSTED Co–Cu DEPOSITS IN THE BLACKBIRD MINING DISTRICT, LEMHI COUNTY, IDAHO

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Cobalt–copper deposits of the Blackbird district are stratabound in quartzites and siltstones of the Proterozoic Yellowjacket Formation, but display volcanogenic associations not expected from the regional geology. Recent exploration in the district documents the existence of at least 12 Co–Cu deposits within seven sequences rich in mafic tuff in a 1,000-m-thick middle part of the Yellowjacket. Beds containing 50–100% biotite are abundant only in a 10-km^2 area where important Co–Cu deposits occur; they are judged to be metatuffs of alkaline basaltic composition based on their fabric, mineralogy, and chemical similarity to less altered coeval dykes. Penetrative deformation is minor in the newly drilled Sunshine and Merle prospects, where delicate layering of <50-μm crystals of cobaltite, mica, tourmaline, and non-clastic quartz is preserved. Chemically the mineralized zones are rich in Fe, Mg, K, B, As, Co, Cu, Bi and Au, relatively low in Ni and S, and very low in Na, Ca, Ag, Pb and Zn. Megascopic and microscopic details indicate that the Sunshine deposit is a conformable 1- to 3-m-thick layer rich in silica that probably formed as a siliceous exhalite between tuff eruptions. The Merle deposit contains eight vertically stacked layers rich in cobaltite and chalcopyrite that are coextensive with tuffaceous units 5 to 30 m thick. Most of the Co–Cu minerals at Merle are in cm- to m-scale disrupted zones that cut beds but do not extend into enclosing sand and silt beds except for minor chalcopyrite stringers. Sediment and ore in the disruption zones show soft-sediment deformation and slump folds. Throughout the district copper and cobalt occur together, but in detail chalcopyrite is spatially distinct from and crosscuts cobaltite, reflecting differences in deposition and redeposition. Some tuff beds were the locus of intense shear during polymetamorphism; Co and Cu in these beds were redistributed. However, in the Sunshine and Merle prospects, which were only slightly deformed, primary textures are preserved; these support a sea-floor or near-sea-floor origin in close association with ponded tuffs.

COPPER SHALE IN SOUTHWESTERN POLAND: PALEOENVIRONMENTS, DISTRIBUTION OF METALS, AND ORE CONTROLS

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The discovery in 1957 of the Lubin–Sieroszowice copper deposit has added much new information to the long-discussed subject of the origin of the Zechstein sediment-hosted Cu–Pb–Zn mineralization in central Europe. This paper presents a model of the Kupferschiefer (Ks) sedimentation in southwestern Poland and suggests a model of origin for the Zechstein sulfide mineralization. Microlithofacies analysis and environmental interpretation of the Ks were carried out to distinguish the depositional systems of reduced sulfide facies and oxidized hematitic Rote Fäule (RF) facies. Resulting paleorelief reconstructions helped in defining regions favorable to accumulation of organic reductants. These regions are the best geochemical traps for metals without regard for the origin and timing of ore formation. Comparisons between the paleogeographical image and the distribution of metals should show whether the extent of the RF is primary (synsedimentary) or secondary (diagenetic). The timing of the RF is particularly important because the contact between the reduced and oxidized contacts is the main guide in exploration for the Zechstein ores, and should help in understanding the factors influencing the distribution of economic concentrations. Cluster analysis of microlithofacies, transformed into coefficients, permits quantitative lithofacies and paleogeographical maps to be drawn. As well, individual maps of Cu, Pb, and Zn contents, and of the Cu/(Pb + Zn) ratio were made. Descriptions were made of Ks profiles with (1) high-energy facies (cross-laminated siltstones, massive sandstones, packstones), (2) moderate-energy facies (carbonate-organic

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laminites, locally bioturbated), and (3) low-energy facies (organic-matter-rich clay laminites). Profiles mineralized with (1) Fe oxides, (2) Fe oxides and sulfides, and (3) sulfides were analyzed. These analyses distinguished three main geochemical and energetic microlithofacies groups: (1) relatively high-energy and aerobic, (2) moderate-energy and dysaerobic, and (3) low-energy and anaerobic paleoenvironments. Paleogeographic zones distinguished were: (1) an inner shelf divided into shallow (environment 1) and deeper (environment 2) parts, and (2) an outer shelf (environment 3). The Ks was deposited in a shallow, stratified sea where deposition from suspension dominated, locally influenced by storm-generated waves and currents. The development of the Ks microsequence was controlled by fluctuations in sea level and of the redoxcline. Six metal (mineral) zones are distinguished; these correspond to various sedimentary facies: (1) hematite zone in the shallow inner shelf; (2) hematite-rich with oxide pseudomorphs after sulfides, (3) zinc, and (4) pyrite zones in the deeper inner shelf; (5) copper zone (*e.g.*, Lubin - Sieroszowice orebody) at the contact of the inner and outer shelves; and (6) the lead zone in the central part of the outer shelf. In regions where the Ks was poor in organic matter (metal zone 1), the Ks could not act as a trap for metals present in the porewater or seawater, nor for metals in solutions migrating during diagenesis from underlying rocks. Sediment initially deposited under reducing conditions was partly affected by diagenetic hematitization (metal zone 2), as suggested by the transgressive contact of red-stained sediments over sulfide-bearing deposits. Considering the evidence above, as well as the tectonic setting, synsedimentary tectonic activity, the lithologic pile (with the close association of the Rotliegend red beds and volcanic rocks below), it is suggested that the influx of metals into the Ks came from regions being uplifted during the Permian. The lateral and vertical zonation of metals supports this assumption, and the Cu/(Pb + Zn) maps appear to indicate the source direction. The enlargement of the hematite zone and the crosscutting nature of the RF–sulfide contact likely result from the ascending character of the oxidized metalliferous fluids. A genetic model of ore formation was developed from the results of these studies; it considers the source of metals, flow direction, mode of transport and precipitation of metals, and timing with respect to sedimentation.

MINERAL EXPLORATION AND ASSESSMENT OF SEDIMENT-HOSTED STRATIFORM COPPER DEPOSITS OF CHINA

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In the classification of sediment-hosted stratiform copper deposits of China, this paper considers not only the tectonic settings and ore-forming processes, but also emphasizes the applications in mineral exploration. Through this approach, the author suggests a classification as follows: (1) Considering the tectonic settings as a significant geological factor in ore formation, we can, for example, divide the settings into a eugeosyncline type, a miogeosyncline type, a platform type, and a mobile platform type. (2) Considering the characteristics of the host rocks as a significant feature in the classification of ore occurrences, we observe associations of volcano-sedimentary strata with the eugeosynclinal type, clastic carbonate strata with the miogeosynclinal type, black shale and red clastic sediments with the platform type, and a complex assemblage of strata modified by magmatism associated with the mobile platform type. (3) Considering the ore-forming assemblage as an important criterion for the classification of metals in mineral deposits, we find Cu–Co and Cu–Zn–S associations in volcano-sedimentary strata, a Cu–(Co)–Pb–Zn association in clastic carbonate strata, a Cu-(U)–Pb–Zn association in red clastic rocks, a Cu-(Mo,Ni)–polymetal association in black-shale beds, and Cu–Fe–S and Cu–Pb–Zn associations in complex stratigraphic assemblages modified by magmatism.

The tectonic settings, ore-bearing formations and association of ore-forming components are important geological criteria in conducting mineral exploration and in the assessment of sediment-hosted stratiform deposits. Moreover, given the tectonic structural unit and the nature of the sedimentary strata, we can make predictions in exploring for mineral deposits containing certain associated metals. On the basis of these geological criteria, we have accumulated a wealth of practical experience in mineral exploration and evaluation in China.

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BASAL ZECHSTEIN IN SOUTHWESTERN POLAND: SEDIMENTATION, DIAGENESIS, AND GAS ACCUMULATIONS

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The transgression of the Zechstein sea, likely related to sea-level rise, resulted in the partial deformation of eolian dune sands of the underlying Rotliegendes. The oldest sediments related to the transgression are sandstones derived from reworking of the dune flanks; stabilization of marine conditions occurred during Basal Limestone deposition, indicating subtidal, low-energy conditions during the transgression. The Kupferschiefer deposits (usually a few tens of cm thick) accumulated below storm base; bioturbated shales were deposited in dysaerobic conditions, and regularly laminated shales in anaerobic conditions. In the shoal areas, the Kupferschiefer was replaced by carbonate-bank deposits, and the benthic fauna from these was transported down into the basin during storms. The Kupferschiefer gradually passes up into the marine Zechstein Limestone, which varies in thickness from a few tens of centimetres to 120 metres. Within this unit, three shallowing-upward cycles can be distinguished. The cycles are always asymmetrical, with little sedimentation during the transgression, indicating a rapid return to open-sea conditions. The regressive members are well developed, with sabkha or vadose deposits occurring in the upper part of the cycles. The cyclicity resulted from glacio-eustatic changes in sea level, probably connected to the vanishing Gondwana glaciers, and the changes in sea level were related to climatic changes. After the first two drops in sea level (estimated at about 40 m each), the sea level rose generally to the previous level; after the third cycle, the basin was almost completely dried up. The deposition of the transgressive Lower Werra Anhydrite initiated a new, evaporitic stage of development of the Zechstein basin. Evolution of pore space in the Zechstein Limestone deposits during early diagenesis was closely related to the repeated fluctuations of diagenetic environments registering sea-level changes, and during late diagenesis to the increase in temperature and pressure due to continual subsidence. The best gas-reservoirs are those facies of the Zechstein Limestone that occur at the border between the central and peripheral parts of the basin, the lower and upper slope, and the slope-adjacent part of the carbonate platform. In southwestern Poland, most accumulations of natural gas in the Zechstein Limestone and joint Zechstein Limestone – Rotliegendes reservoirs have been recorded in these paleogeographical positions, and some gas accumulations are recorded near the Lubin mine area. The increased copper mineralization is also confined to the same paleogeographical zones, suggesting a common control of sulfide and natural-gas accumulations.

ON A GENETIC MODEL FOR THE DONGCHUAN TYPE OF STRATABOUND COPPER DEPOSIT

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The Dongchuan type of stratabound copper deposit includes the stratiform copper deposits and the veined copper deposits in the Kungyang Group. Stratiform copper deposits occur in different cycles and definite facies of the cupriferous algal-reef carbonate beds precipitated in the middle stages of development of the Precambrian Kangdian geosyncline. The ore-forming conditions were determined essentially by the source bed, algal reefs and the ore-trapping bed. The mineralization proceeded throughout sedimentation, during which reef building and diagenesis played an important part. The formation of the stratiform copper deposits is tentatively referred to as "a red-bed-derived and algal-bound diagenetic–metallogenic model." In the final stages of the development of the geosyncline, copper would have been removed from the pre-existing stratiform copper deposits to be precipitated in some favorable beds to form a vein-type ore shoot or copper deposit during tectonic movement and accompanying volcanism and metamorphism.

ENVIRONMENTAL SIGNIFICANCE OF ALGAL STROMATOLITES AND THEIR RELATION TO COPPER ORE IN THE LUOXUE FORMATION OF THE KUNYANG GROUP IN DONGCHUAN, YUNNAN

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Algal stromatolites have been divided into three classes according to their shapes: lamellae, cylinders and spheres. Each class has been subdivided into forms according to detailed variations in the stromatolitic shapes (Table 1). The lamellar stromatolites usually occur in the low-energy environments of tidal flats, the cylindrical stromatolites in the more turbulent environments of the intertidal to subtidal zone, and the spherical stromatolites in the highly turbulent zone extending from the lower part of the intertidal zone into the subtidal zone. The distribution and development of algal stromatolites in the Luoxue Formation are lamellar in lower part of the formation, cylindrical in the middle part, spherical and small, cylindrical in the upper part, and mainly lamellar at the top of the formation. These observations show that the sedimentary environment was a tidal flat of a transgression series extending from the upper intertidal to subtidal facies. Copper mineralization is related to the algal dolomite at the base, and especially, the wavy algal dolomite. Copper sulfide minerals along stromatolitic laminae form a discontinuous horsetail-structure; these minerals occur as a cement in the interstitial pores of the dolomite crystals. It has been proven that the stratiform copper deposits formed essentially during diagenesis. Recently, through the study of fluid inclusions in minerals from the Luoxue stratiform copper deposits, we have discovered that there was a hot brine with temperatures of 170–220°C and a salinity of 16.5% in this region. This brine permeated the host rock during diagenesis and played an important part in the lixiviation, re-solution and removal of copper, *i.e.*, in the genesis of cupriferous beds formed by sedimentary–diagenetic processes.

TABLE 1. CLASSIFICATION OF ALGAL STROMATOLITES

				noninheritable
			symmetrical	inheritable
lamellar class	laminated form	regular	asymmetrical	
	rippled form	irregular		
	arcuate form			
	box form			
cylindrical class	amalgamative form			
	forked form			
	amalgamative–forked form			
	columnar form	irregular		
		regular	flat	
			cylindrical	
spherical class	thrombolitic form			
	knotty form			
	spherical form	round: orthocentric; eccentric		
		ellipsoidal: orthocentric; eccentric		

EVIDENCE FOR A MAGMATIC FLUID ASSOCIATION IN KEWEENAWAN Cu-SULFIDE FISSURE-VEIN DEPOSITS AT MAMAINSE POINT, ONTARIO: POSSIBLE RELATIONSHIPS TO STRATABOUND BASALT-HOSTED NATIVE COPPER

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The Keweenawan rifting and magmatic event of the Lake Superior region is famous for its deposits of stratabound basalt-hosted native copper (Keweenaw peninsula) and shale-hosted Cu-sulfides (White Pine, Michigan). Fissure veins containing native copper (Cu°), Cu-sulfides and Cu-arsenides also occur in the Michigan copper-belt, and in Keweenawan basalts at Mamainse Point, Ontario. Fluid-inclusion studies of quartz gangue in chalcocite-rich fissure-veins containing the paragenetic sequence Py–Cp–Bn–Cc–Cu°–Cu_2O at the Coppercorp mine, Ontario, give clear evidence for mixing between high-temperature (350-450°C), high-salinity (15 to 20 eq.wt.% $CaCl_2$) boiling fluid and a cooler (50-350°C), more dilute hybrid liquid (zero to 15 eq.wt.% $CaCl_2$). Values of $\delta^{13}C$ (PDB) of ten calcite samples from the fissure veins average −4.0 ‰ (σ 0.7). Comparison with data from a small coeval Qtz–Fsp, Cu–Mo mineralized porphyry stock (Jogran) 10.5 km east of Coppercorp strongly suggests a genetic link since four calcite samples give $\delta^{13}C = -4.0$ ‰ (σ 0.8). This correlation, coupled with similarities in fluid composition and temperature, suggests that the high-temperature fluids in the Coppercorp fissure veins are of magmatic origin, and were derived from felsic intrusive activity deep within the lava pile. Fluid inclusions from Cu°-bearing veinlets and amygdales in the hydrothermally altered basalts away from the main orebodies similarly contain evidence for the intermittent invasion of high-temperature saline fluids. The $\delta^{13}C$ ratio of five calcite samples from these veins ranges between the Coppercorp and atmospheric (−2.7 to +0.7 ‰) values. Hence it is suggested that the brine influxes represent residual, oxidized cupriferous fluids from the major systems of fissures, which have been discharged into the stratiform and fracture-controlled aquifers of the lava pile. A logical extension of this hypothesis would be to suggest that greater concentrations of native copper would be expected where the influx of such cupriferous brine was greater, as, possibly, in the deposits of the Keweenaw peninsula.

DEPOSITIONALLY CONTROLLED STRATABOUND Cu–Zn MINERALIZATION IN EARLY MESOZOIC CONTINENTAL RIFT-BASINS

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Primary sedimentary features control the pattern of minor Cu and Zn mineralization in the early Mesozoic basins of the eastern United States and of Morocco through their influence on porosity, permeability, redox potential, and abundance of woody material. Copper mineralization is commonly associated with moderately well-sorted, fluvial, channel-fill sandstones in the Hartford, Newark, and Culpeper basins in the U.S. and in the Argana basin in Morocco. Chalcopyrite, bornite and chalcocite typically replace plant debris, roots, and associated diagenetic pyrite, and also may be disseminated in the surrounding sediment. The plant debris is concentrated in the troughs of fluvial dune-scale bedforms, where it probably was deposited by slack water following floods. The roots penetrate channel sands; they most likely grew following channel migration or abandonment. Similar plant-replacement mineralization occurs in lacustrine shales in the Argana basin, where the organic material is concentrated in the troughs of small oscillatory ripples, probably formed during storms. These mineralized zones are traceable laterally for tens of kilometres. Zn–Cu mineralization occurs within cyclic mudstones of the Culpeper basin in Virginia. It is associated with sandy mudstone that forms the top of 2- to 4-m-thick cycles that are overlain by black laminites. The sandy mudstone is interpreted as a shallow-water shoreline deposit of a transgressing lake. Sphalerite, wurtzite and chalcopyrite replace pyrite near molds of small roots. Root molds in other mudstones representing different depositional environments in these cycles are not mineralized. The association of preserved woody organic material with beds of greater permeability than surrounding strata appear to form an important constraint on the development of copper mineralization. The spatial and temporal distribution of depositional environments producing these conditions may be predicted from depositional models for early Mesozoic basins.

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MOBILITY OF Cu AND OTHER CHALCOPHILE ELEMENTS IN LOW-TEMPERATURE NEAR-SURFACE ENVIRONMENTS

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The copper in sediment-hosted stratiform copper deposits is generally regarded as having been emplaced from solution under surface or near-surface (diagenetic) conditions. At surface temperatures in aerated fresh water, copper is soluble in significant amounts (1 ppm) only at pH values less than about 6.0. Complexing with carbonate, sulfate and other common ligands in fresh water does not change the solubility appreciably. However, complexing with chloride under conditions reducing enough to stabilize Cu^{+} rather than Cu^{2+} can lead to solubilities of hundreds of ppm at pH 7 for 1 molar Cl^{-} and significant solubilities to pH 11 for 3 M Cl. Contact of these solutions with pyrite or H_2S will precipitate various Cu and Cu–Fe sulfides, though these are probably not equilibrium processes in detail. The possible importance of organic complexing (fulvate) and of slightly acid solutions caused by oxidation of ferrous silicates and oxides will be evaluated, as will the significance of adsorption of Cu and other heavy-metal ions on hematite and colloidal Fe oxides.

GEOLOGY, GEOCHEMISTRY AND THE EXPLORATION POTENTIAL OF SEDIMENT-HOSTED STRATIFORM COPPER–SILVER OCCURRENCES IN PERMO-CARBONIFEROUS STRATA, EASTERN PART OF THE CUMBERLAND BASIN, NOVA SCOTIA

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A complex succession of predominantly continental alluvial–fluvial strata with minor evaporitic-marine rocks of Visean to Early Permian age is the host for numerous occurrences and prospects of Cu – Ag – U mineralization in the Cumberland Basin of Nova Scotia. Historically, exploitation has been confined to small-scale shallow mining and processing in the early 1900s. Recent exploration activity, however, has established a potential for deposits of larger and deeper extent. A display will illustrate the geological setting and origin of copper–silver mineral occurrences in the area, summarize the various geochemical expressions of the mineral occurrences and show their significance to exploration; a tentative model for exploration will be proposed from geological and geochemical compilations. The illustrations will include (1) bedrock geology, (2) sediment-dispersal trends, (3) the distribution of mineral occurrences, (4) till geochemistry and glacial geology, (5) soil and stream geochemistry, (6) multi-element plots, (7) exploration models, and (8) the nature and origin of the mineralization.

STRATIFORM ZECHSTEIN COPPER ORE-DEPOSITS IN POLAND: GEOLOGY, METAL ZONING AND EXPLORATION

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In the Lower Silesia district of southwestern Poland, two anomalous concentrations of Cu, Pb and Zn of economic value are known: the 'Konrad' orebody in the North Sudetic Syncline, marginal to the Sudeten Mountains, and the 'Lubin-Polkowice' orebody in the Fore-Sudetic Monocline, the largest and richest deposit in the whole Zechstein Basin of central Europe. The host-rock sequence, the Zechstein Copper Series, consists of white sandstone (Weissliegendes), Copper Shale (Kupferschiefer), and the Werra limestone and dolomite. Metal concentrations occur in the reduced facies of the host rocks adjacent to the oxidized facies of the basal Zechstein, or 'Rote Fäule' (RF), in which the Copper Shale is colored red with

hydrated iron oxides. The distribution of the RF was studied in detail because of the evident regularity of distribution between large concentrations of metals and the RF. It was found that with increasing distance from the RF facies, the mineralization occurs in increasingly lower lithologic horizons, and the mineral assemblage changes from Cu–S type (chalcocite, digenite) to Cu–Fe–S type (bornite, chalcopyrite). In the vertical profile, zones with larger concentrations of lead and zinc appear above the copper zones, and also migrate downward with increasing distance from the red-stained RF facies. During exploration, maps of the RF facies in each stratigraphic zone of the lowermost Zechstein were made to eliminate those oxidized regions from further study. Maps of metal content were drawn, and copper-dominant [Cu > (Pb + Zn)], lead-dominant [Pb > (Cu + Zn)], and zinc-dominant [Zn > (Cu + Pb)] regions were defined. Then, in the copper zones nearest the RF, detailed exploration was carried out. This was found to be the most efficient and most economical method of prospecting. The RF zones vary in size and shape, but they are distributed with the mineralized zones in a northwest-trending belt within areas affected by the Variscan orogeny. In other regions of Poland, considerable amounts of sulfides were found in the lowermost Zechstein, but these consist mainly of pyrite and marcasite with only traces of chalcopyrite, galena and sphalerite. The dependence of mineralization on the distribution of the RF facies is clear. The presence of hematite pseudomorphs after sulfides is essential to the problem of genesis. These pseudomorphs indicate that ascending, oxidized solutions caused an epigenetic extension of the RF facies, suggesting a polygenetic origin of the RF and ore.

ROTLIEGENDES VOLCANIC ROCKS, SEDIMENT LITHOLOGIES AND PALEOENVIRONMENTS, AND BASIN HISTORY

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Toward the end of the Carboniferous, Poland was characterized by a continental environment, and the young Variscan mountain chain dominated the southwestern part of Poland. The remaining area was morphologically diverse, with Precambrian to Carboniferous rocks cropping out. At this time, a new structural plan came into existence. At the turn of the Carboniferous, sedimentation was restricted to local intermontane depressions in the Variscan chain, as well as to small basins in its foreland, where fluvial gravels and sands accumulated. The development of sedimentation was preceded by volcanic activity, which was a continuation of processes that had begun in the Carboniferous. The volcanism appeared in the Variscan mountain area, in northern Poland (an area of weakly developed Variscan trends) and in the Precambrian platform. It developed as a maximum of three (in Sudeten) or two (in Pomerania) cycles, with N–S migrating volcanic centres, with a weak explosivity, and as huge plateaus of bimodal lavas (upper-mantle basalts and crustal rhyolites). It is also characterized by intensive, regional autometasomatism, with centres located along a N–S line some 60 km east of the Nysa Luzycka and Odra Rivers. The autometasomatism usually led to a complete change of the mineral composition of the rocks. Several original techniques of studying the 'mechanical memory' were employed to reconstruct the original composition, *e.g.*, traces of pericline twinning in albite, birefringence dispersion of the main section, ultramicroscopy in the dark field of the fine dispersional phases, which includes organic matter. In the Upper Rotliegendes, two diastrophic–sedimentary megacycles related to the Saalian movements are distinguished. In the older megacycle, small isolated inland basins accumulated red-bed sands (rarely muds) surrounded by a zone of piedmont conglomerates at the foot of the highlands. The most important was the Wolsztyn Highland, which constituted the northern border of basins in the Variscan area. During this first megacycle, subsidence was small, and areas of denudation dominated. In the younger megacycle, the basin expanded, and the central Polish basin became connected to the German basin. The Wolsztyn Highland was partitioned into a series of highs and basins, and a number of small basins developed in the Precambrian platform as well. The megacycle started with coarse siliciclastic rocks, locally breccias and colluvial fans, and commonly channel deposits of braided rivers. Toward the centre of basins, sandy deposits of wide alluvial plains developed, and in the central part of the greatest basins (Central Polish and Zielona Gora basins), muds and clays accumulated. In a playa lake environment, nodules of anhydrite were formed; mudcracks and layers of clay and mud intraclasts indicate periodic emergence. At the end of the megacycle, the basins were filled up in places, and fields of eolian dunes were formed.

MINERAL ASSEMBLAGES IN FENESTRAL STRUCTURES IN CARBONATE ROCKS: A POSSIBLE AID IN EXPLORATION FOR COPPER DEPOSITS

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Cupriferous carbonate rocks occur on most continents and may form portions of world-class sediment-hosted copper deposits. In some, a close association has been noted between fenestral textures and sulfides. Detailed work on one of such deposits, presently subeconomic, has led to the conclusion that the fenestral fabric formed the major channels of transport and sites of precipitation of several generations of dolospar cement, followed by copper sulfide cement in remaining open pore-spaces. Reconcentration of sulfides occurred in dolospar–quartz veins during low-grade regional metamorphism. Subsequently, during a late, postmetamorphic event, sulfides were locally leached from fenestrae and veins, replaced by iron oxides and hydroxides, while dolospar cement recrystallized. Such oxidized domains are fracture-bound and pink, whereas contiguous sulfide-bearing rocks are white. They resemble recently weathered domains, but no zone of supergene enrichment is present, and primary or pseudosecondary aqueous fluid-inclusions of moderate salinity ($T_m = -3.5°C$) in goethite-bearing dolospar have a T_h around 160°C. Most likely, a system of circulation of aqueous oxidizing fluids of surficial or shallow subsurficial origin effected these late changes at a depth of several kilometres below the paleosurface and flushed copper-bearing solutions upward. Reprecipitation of copper could occur if zones traversed by these solutions would contain a suitable reducing environment, *e.g.*, a permeable body of sediment containing organic matter, sulfate-reducing bacteria or early-diagenetic pyrite. The potential existence of such "late" copper deposits could thus be revealed by the presence of an underlying, thoroughly oxidized carbonate rock containing iron oxides and hydroxides in its fenestrae.

SYNGENETIC AND DIAGENETIC CONCEPTS AT WHITE PINE, MICHIGAN

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The White Pine stratiform copper deposit is an excellent laboratory for studies on the genesis of this type of mineralization because of the good exposures both in underground workings and in a large number of continuous drill-core sections through the host-rock units. Both syngenetic and diagenetic concepts have been proposed.

According to syngenetic interpretations, copper was provided as complexes on clay minerals, as solid detritus and as soluble species in the basin waters (Vogel & Ehrlich 1971). The ultimate source of copper could have been mafic flows of the Portage Lake Volcanics. Weathering of this underlying basaltic unit could produce iron oxides, cupriferous montmorillonitic clay as well as soluble species, and early diagenesis in the basal Nonesuch Shale would initially produce an illite–chlorite intergrowth and, subsequently, the current muscovite-chlorite assemblage. Copper released during diagenesis would combine with biogenic sulfide. Copper-bearing detritus has also been described, suggesting a polygenetic origin for copper within the syngenetic concepts. Variations in the distribution of copper zones in the mine section are attributed to abrupt and gradual lateral changes in facies.

Diagenetic concepts derive largely from features supporting an overprint of copper on basal beds of an initially iron-sulfide-rich Nonesuch Shale: *e.g.*, pyrite replacement by cupriferous sulfides along the upper limit (fringe) of the copper zone, and chalcocitic nodules with hematitic halos suggesting replacement of pyritic nodules within the Cu-zone; Cd, Pb and Zn sulfide concentrations immediately above the

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fringe surface, as if swept ahead of an upward influx of cupriferous solution; and a screening out of influxed copper in large proportions in the most basal Nonesuch beds where the fringe surface is found at correspondingly low stratigraphic levels in the overlying sediments (Brown 1971). The source of copper is proposed to have been a reservoir of oxidized, Cl-rich solutions in the underlying hematitic Copper Harbor Conglomerate; this immature red-bed unit could have been the ultimate source of copper.

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SYNGENETIC COPPER-ENRICHED DOLOSTONES AS A SOURCE FOR EPIGENETIC COPPER MINERALIZATION IN SANDSTONES AND SHALES, TIMNA, ISRAEL

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The Cambrian Timna Formation was deposited during a short marine episode within a thick clastic sequence. Its lower part (15 m) is composed of alternating siltstones, shales and sandy dolomites, and the upper part (0–30 m) consists of bedded sandy dolomites (dolomitic lithofacies), which change laterally into manganese-rich sandstones (sandy lithofacies). Both lithofacies are overlain by a thin bed of shale. The contact between the two lithofacies is highly irregular and complicated. The dolomitic lithofacies is characterized by a high metal content (Mn 1.8%, Cu 0.06%, Zn 143 ppm) and, in places, by anomalies of Ag and U. The Mn occurs in the dolomite structure (up to 6%), and the other metals occur as principal components of their own minerals, or with clay minerals. Part of the copper occurs in thin layers and consists of the primary sulfide djurleite $Cu_{1.85}Ag_{0.05}S$, which usually forms small spheroidal nodules (1–5 mm in diameter), but most of the copper occurs in thin laminae (< 1 mm) of paratacamite $Cu_2(OH)_3Cl$, which is generally concentrated in one bed 0.2–1 m thick and yielding 0.6–1.4% Cu. The data suggest syngenetic to early diagenetic formation of the djurleite, followed by its late-diagenetic oxidation to paratacamite and malachite. The main copper mineralization is, however, hosted by the sandy lithofacies and the overlying shales, where copper silicates, carbonates, phosphates, chlorides and sulfates (in decreasing amounts) occur as irregular veins, nodules and impregnations. New evidence indicates that host rocks of the sandy lithofacies are residual following the dissolution of the sandy dolomites of the dolomitic lithofacies by subsurface processes of epigenetic "karstification". Data on the copper mineralization in the sandy lithofacies fit well with an epigenetic model in which the source rocks for the copper were the sandy dolomites that contained the paratacamite–djurleite mineralization and that generally had high concentrations of copper.

ORE-MINERAL ZONATION AND PALEOAQUIFERS AS CLUES TO ORE GENESIS IN A POSTOROGENIC TECTONIC SETTING, NORTH TEXAS COPPER DISTRICT

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Stratiform copper is hosted by several statigraphic intervals in the southwestern midcontinent. East

of the Midland basin and west of the Ouachita orogenic belt, in a sequence of Lower Permian strata, is the North Texas copper district. Tectonism in the southern midcontinent began in response to Mississippian compression in the Ouachita basin. A foreland trough shed sediment westward in Early to Middle Pennsylvanian, and the Midland basin and associated shelves and uplifts formed. Pennsylvanian fluvial-deltaic sediments on the Eastern shelf were coupled with starved sedimentation in the adjacent Midland basin. Lower Permian limestone deposited in the basin and shelf clastic rocks comprise Wolfcamp-age facies. The upper Lower Permian saw a change to tidal flats on the shelf, punctuated by fluvial-deltaic sands at the Lower to Upper Permian transition. Evaporites and shale in the northern Midland basin complemented shelf limestone and basin clastic rocks in the southern basin. Tectonic activity ceased by upper Middle Pennsylvanian, and later changes were a result of intrabasinal controls. Copper (east to west, upsection traverse) occurs in lower beds of the Wolfcamp (fluvial), Leonard (fluvial-deltaic), and transitional Guadalupe–Leonard age rocks (deltaic and tidal flat), and near the top of the Blaine Formation (lower Guadalupe, lagoonal facies). Cuttings from oil wells were used to trace surface outcrops of chalcocite downdip 40 km to a depth of 330 m. Chalcocite passes down the plane of the host horizon into a narrow covellite zone followed further downdip by chalcopyrite. Pyrite downdip from chalcopyrite is considered to reflect a distal noncupriferous edge to Cu-bearing units. Pb and Zn form a base-metal horizon above Cu. Changes in mineral composition and Cu depletion coincide with the pinching out of porous facies and a gradual change from terrestrial to subtidal facies. Compressional tectonics, which drove Cu-bearing fluids out of a relatively thin pile of sediments (average 1,600 m) in the basin and onto the shelf, had ceased by the end of Middle Pennsylvanian time. Copper deposits on a shelf, progressive change from fluvial to lagoonal hosts, copper in or above porous facies that pinch out basinward, and downdip loss in copper support deposition of copper from downdip-circulating groundwater.

THE ENVIRONMENT OF FORMATION AND SOURCE OF METALS FOR SOME KUPFERSCHIEFER OCCURRENCES IN CENTRAL EUROPE

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A comparison is made of Polish (Lena, Konrad, Lubin, Polkowice) and German (Spessart, Rhoen, Richelsdorf) base-metal Zechstein occurrences. It is shown that the main processes leading to their formation (including preconcentration of base metals during the Late Variscan, transport in oxidized solutions, and precipitation at the interface with euxinic environments) were generally similar. The regional position of individual Zechstein sub-basins is shown. The development of host rocks (*e.g.*, the shaly, marly and sandy facies of the Kupferschiefer) is controlled by distance to shore lines, sandbars, lagoonal barriers and basement paleohighs. The distribution of copper, lead, zinc and silver, and the mineralogical composition of individual occurrences correspond to the geochemical character of the associated basement. At least two sources of metals, with different geochemical compositions, are responsible for the Kupferschiefer mineralization. The first source is due to the metallogenic evolution of Caledono–Variscan basement; the second is related to oxidation and leaching of base metals from the red Rotliegendes molasse. Mobilization of elements was caused by anomalous heat-flow.

STRATIGRAPHIC CORRELATION OF STRATABOUND Cu–Ag DEPOSITS OF THE BONNER QUARTZITE, BELT SUPERGROUP, WESTERN MONTANA

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Four stratabound Cu–Ag deposits (Pacman, Bluebird – Mona Lisa, Royal Basin and Daisy Creek) have recently been discovered within the Belt Basin. These deposits are hosted by the Bonner Quartzite, a coarse- to fine-grained, well-sorted and mature, metamorphosed quartz arenite.

Depositional facies within the quartzite consist of conglomeratic distal alluvial aprons, braided channels with abundant phosphatic and cherty mud-chips as lag lamellae, and mud-cracked braidplains. Alluvial aprons and braidplain deposits are dominantly red (fine hematite) or purple (specularite), perhaps due to extensive subareal exposure during sedimentation. Channel facies are white or grey, and generally devoid of Fe-oxide pigmentation. Green beds (chloritic) are commonly interbedded with red siltite couplets.

Two periods of progradation are recognized in the Bonner Quartzite. The first, and most extensive, is represented by a conglomerate wedge grading north into cross-bedded channel quartzites. The second, smaller event is marked by a gradation into flat laminated braidplain quartzites. Three of the stratabound Cu–Ag deposits occur adjacent to the upper contact of this second progradational wedge, a probable time-stratigraphic marker.

The deposits occur within both white-to-grey channel facies and interbedded red-and-green couplet siltite–braidplain facies. All deposits contain significant concentrations of Cu and Ag, present as chalcopyrite, argentiferous bornite and argentiferous chalcocite, but are generally small, as is typical of most fluvial-channel-hosted stratabound Cu deposits.

CHEMICAL EVOLUTION OF BASINAL BRINES THAT FORM SEDIMENT-HOSTED Cu–Pb–Zn DEPOSITS

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Oil-field brines undersaturated with respect to sphalerite, but saturated with respect to galena, chalcopyrite, pyrite, pyrrhotite, kaolinite, muscovite and quartz are highly reducing in character, contain ppm quantities of Zn, Pb and S, and negligible quantities of Cu. Water–rock interactions involving these reducing brines in carbonate and in sandstone aquifers during migration to sites of ore formation produce stratabound Zn-rich and Pb-rich deposits, respectively (Sverjensky 1984). In contrast, oxidizing brines have been proposed to transport Cu, Pb and Zn to form sediment-hosted Cu-rich deposits (Brown 1971, Rose 1976, Gustafson & Williams 1981). Theoretical modeling summarized below suggests that the reducing brines can be transformed into highly oxidizing brines *via* water–rock interactions during migration through evaporitic and red-bed sequences, and that the resultant potential ore-forming fluids can form sediment-hosted Cu-rich deposits.

Calculations of the chemical mass-transfer accompanying reaction of reducing brines with anhydrite, followed by the red-bed assemblage quartz, K-feldspar, muscovite, hematite and tenorite, reveal that the aqueous phase becomes greatly undersaturated with respect to sphalerite, galena, chalcopyrite, bornite, pyrite and pyrrhotite as it achieves $\log f(O_2)$ values well above the magnetite–hematite buffer and approaches saturation with respect to anhydrite, hematite and chalcocite. Reaction with red beds alone limits the $\log f(O_2)$ to the magnetite–hematite buffer, and consequently the amount of Cu acquired by the brine. Evaporites are not only sources of salinity and (oxidized) sulfur for evolving basinal brines, but are crucial to the development of the high $f(O_2)$ brines required to transport Cu as chloride complexes. Reaction of the oxidizing brine with organic matter and diagenetic pyrite results in precipitation of native Cu followed by the classic sequence chalcocite, bornite, chalcopyrite, pyrite, sphalerite, galena.

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THE ROLE OF DIAGENESIS IN THE FORMATION OF THE KONKOLA Cu–Co OREBODY OF THE ZAMBIAN COPPERBELT

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A facies analysis of the Konkola Basin shows that the sediments of the Ore Shale formed in a subtidal to intertidal environment, affected by marine transgressions and regressions. Both the Ore Shale and the underlying red-beds, which may also be economically mineralized, have been investigated, and a paragenetic sequence of diagenetic events for both these units is outlined. Euhedral overgrowths of feldspar contain Cu (up to 0.25%), indicating the presence of a copper-rich pore fluid during early diagenesis. Textural data indicate that the formation of the bulk of the sulfides was associated with the replacement of sulfate and the concomitant formation of carbonate and silicate phases, and that it took place during early diagenesis. Values of $\delta^{34}S$ of sulfides in the Ore Shale are stratigraphically controlled and confirm that the source of the sulfur incorporated in the sulfides was seawater sulfate. Values of $\delta^{13}C$ of Ore Shale carbonates indicate the organic matter was oxidized during formation of the carbonates. Values of $\delta^{18}O$ and, to a lesser extent, $\delta^{13}C$ for the carbonate of the Ore Shale and the footwall rocks reflect the influence of both fresh and marine waters. This suggestion is also implied from the Na and Sr content of carbonates, and by the sympathetic variation in concentration of these elements and $\delta^{18}O$ with transgressive–regressive events deduced from sedimentary structures. Carbonates of inferred marine origin contain significant amounts of Co (up to 1.6%) which, together with the apparent lithological control of Co mineralization, suggests a basinward origin for that element. The Cu and Co sulfides are considered to have formed as an integral part of the diagenetic process; the copper and cobalt may have had different sources.

THE ROLE OF PERMEABILITY IN LOCALIZING THE STRATABOUND COPPER DEPOSITS OF MOUNT GUNSON, SOUTH AUSTRALIA

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In the Mount Gunson district of South Australia, stratabound copper deposits are hosted by Upper

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Proterozoic sediments of the Stuart Shelf. The deposits are clustered around a fault-bounded basement-high against which the Upper Proterozoic units onlap. Copper mineralization is found in several different stratigraphic situations and in a range of rock types. (i) Minor mineralization is hosted by coarse sandstone below a capping of shale and dolomite. (ii) A number of deposits are hosted by a dark-colored finely-bedded dolomitic unit; within this unit, mineralization is preferentially concentrated in coarse beds of sandstone and breccia, and the deposits overlie coarse red clastic sediments. (iii) Several deposits straddle the disconformity between Middle Proterozoic quartzite basement and Upper Proterozoic sandstone; copper mineralization is found in fractured quartzite below the disconformity, within quartzite breccia along the disconformity and in basal coarse sandstone. (iv) Minor mineralization is hosted by a unit of coarse clastic sediments overlying basalt, and partly extends down into fractured and brecciated basalt. (v) Minor mineralization is hosted by strongly fractured dolomite. From a consideration of the detailed stratigraphy of the deposits, it is clear that mineralization is concentrated either in permeable rock-types or in reduced beds above permeable rocks. On a broader scale, there is an apparent association of metal deposits with fault zones bounding the basement high. These, together with sandstone units and disconformity surfaces, may have provided, on a regional scale, the permeability required for the movement of metal-bearing water.

LANDSAT-BASED STRUCTURAL MAP OF THE LUFILIAN ARC AND THE KUNDELUNGU AULACOGEN, SHABA (ZAIRE), ZAMBIA, AND ANGOLA, AND THE TECTONIC POSITION OF Cu, Co, U, Au, Zn, Pb AND Fe MINERALIZATION

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A Landsat-based structural map (scale 1:1,000,000) of the Lufilian Arc and the Kundelungu Plateau is presented. Katangan sediments of the Kundelungu Plateau fill a graben that abuts the Lufilian Arc at an angle and is classified as an aulacogen. The fold belt – aulacogen junction is possibly related to a Late Proterozoic triple junction developed over a hot spot. Important mineralization in the fold belt is present over a wide stratigraphic range and extends geographically well beyond the established mining districts. These relationships suggest a relation of mineralization to a regional-metamorphism-driven expulsion of basinal brines.

DIAGENETIC ALTERATIONS IN RED BEDS AND THEIR APPLICATION TO THE ORIGIN OF COPPER AND OTHER HEAVY METALS IN STRATIFORM ORE-DEPOSITS

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Red beds characteristically are composed of first-cycle sediments which, when deposited, contain abundant labile detrital minerals such as plagioclase, hornblende, biotite and magnetite, all of which are known to carry trace amounts of copper and other nonferrous metals. Owing to their susceptibility to diagenetic alteration, these minerals are likely to be major sources of metals in red-bed-associated stratiform ore-deposits. Alterations that likely result in the release of the contained metals begin soon after deposition, and they may continue sporadically for many tens of millions of years. Examples of early alterations that begin at shallow depths and within a few million years after deposition include: 1) dissolution of silicates, 2) replacement of silicates by smectite, 3) leaching of biotite, and 4) conversion of magnetite to hematite. Iron also is released by these alterations; owing to the interstitial oxidizing conditions that characterize red beds, the iron is quickly reprecipitated as amorphous or poorly crystallized ferric oxide. One can infer that during these early postdepositional alterations, the nonferrous metals originally contained in the labile grains are either released to migrating groundwaters or adsorbed by the simultaneously

formed smectite and amorphous and poorly crystallized ferric oxides. If adsorbed, one can speculate that the metals may be liberated by later diagenetic alterations that are known to accompany aging and deeper burial of red beds. Examples include: 1) conversion of amorphous and poorly crystallized ferric oxides to well-crystallized hematite, 2) conversion of smectite to illite, 3) replacement of feldspar and other silicates by carbonates, 4) albitization of clays and feldspars, and 5) dissolution of earlier-formed ferric oxides (bleaching). In the case of copper, assuming that it migrates mainly as cuprous chloride complexes, as has been convincingly proposed by Rose (1976), its migration should be favored when any of the above alterations coincides with the expulsion of chloride-rich formation waters from associated marine sediments or evaporites.

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ON THE ORIGIN OF CARBONATE-HOSTED STRATIFORM Cu DEPOSITS IN THE LOWER YANGTZE REGION, EASTERN CHINA

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The Lower–Middle Yangtze region is one of many important metallogenic belts in China. In the past few years, the author has studied tens of Cu ore deposits showing sedimentary and volcanic–sedimentary origins in this area. They are hosted in carbonate sequences of Carboniferous age. The occurrences of these stratiform Cu deposits exhibit the following features: 1) they are controlled by E–W-striking fault basins; 2) the orebodies are usually bedded and conformable with the hosted rocks, and were folded at the same time as the host rocks; 3) sedimentary textures and structures are common; 4) the geochemistry of trace elements indicates that the metallic minerals are intimately related to their hosts; 5) the $\delta^{18}O$ values for quartz and siderite from the ore beds range from $+12$ to $+16‰$, and the range of $\delta^{18}O_{H2O}$ and δD_{H2O} values for different minerals reveal a mixture of seawater, meteoric water and metamorphic water (heated seawater); 6) filling temperatures from fluid inclusions do not show igneous temperature-gradients, and 7) a single-stage model for the lead isotope data is concordant with the geological age of the host strata.

GEOLOGICAL CHARACTERISTICS AND GENESIS OF STRATABOUND DEPOSITS OF Cu-BEARING PYRITE IN THE JIUJIANG–RUICHANG AREA, JIANGXI, CHINA

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The Jiujiang–Ruichang area is an important part of an iron–copper ore zone in the Lower Yangtze area, and is known to be one of principal copper districts in China. The known stratabound Cu-bearing pyrite deposits, such as Chengmanshan Wushan, are considered to have had a sedimentary submarine-exhalative origin. They occur in the transition between clastic- and carbonate-facies rocks of Carboniferous age. The orebodies are stratified or lenticular in shape. The dimensions of the orebodies range up to one thousand metres in length and several tens of metres in thickness; they occur at a depth of several hundreds metres. The occurrence of these ore deposits is related to paleostructures controlled by growth faults; they commonly formed in shallow marine basins beyond the shoreline facies and are distributed

along major northwest-trending faults. The mineral compositions are rather simple and consist mostly of pyrite, chalcopyrite, melnikovite-pyrite, marcasite, quartz, calcite and dolomite. Structures and textures in the ores can be divided into three types: sedimentary–diagenetic, metamorphic, and hydrothermal replacements. They show laminated, colloform, massive and brecciated structures with spherulitic, accordion, equilibrium and replacement textures, respectively. Isotopic data indicate that ore-forming material was derived from the upper mantle and was contaminated by crustal material. Investigations of trace elements and the compositions of fluid inclusions show that the genesis of the ore deposits is related to submarine volcanic–exhalative sedimentation.

TRACE-ELEMENT DISTRIBUTION IN THE LOWERMOST ZECHSTEIN COPPER-BEARING DEPOSITS OF THE SOUTHERN PART OF THE FORE-SUDETIC AREA, SOUTHWESTERN POLAND

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The pattern of distribution of Cu, Pb, Zn, Co, Ni, Mo, V and Ag in the basal Zechstein in the Fore–Sudetic Monocline, southwestern Poland, is nonuniform and varies with the lithology of the top of the Weissliegendes sandstone, the copper-bearing shale horizon (Kupferschiefer), and the basal parts of the Werra limestone and dolomite horizon (Zechstein Limestone). The changes seem related to the mineral composition of the host lithology and to the physicochemical characteristics of each sedimentary environment. In the Weissliegendes sandstones, the elements studied occur in trace amounts, and their distribution is irregular. In the Kupferschiefer, a marked trend to spatial ordering of the majority of these elements is found, depending on sedimentary facies. The Kupferschiefer is characterized by increased concentrations of Cu, Zn, Pb, Ni, Co, Mo, V and Ag in the whole studied zone, and a trend toward increasing concentrations to the north with increasing depth of the sedimentary basin. Accumulation of these elements in the copper-bearing shale horizon took place with active and passive contribution of the biophase and processes of sorption on particles of clay minerals. The Werra carbonate horizon is characterized by an increase in metal content in the marly dolomite facies directly overlying the Kupferschiefer. The carbonates display high concentrations of Pb and Zn, with a clearly marked vertical and horizontal zonation. Factor analysis applied to the geochemical data shows that the differences in chemical composition of the rock types can be explained by a few factors. The associations of elements investigated here are controlled by influences of mineral origin, by physical and chemical processes, and by the geochemical relationships between particular elements. The author finds that changes taking place within the lithologic horizons are influenced more by the terrigenous factor than by those factors resulting from chemical and biogenic processes.

AN ALLUVIAL APRON AND PLAYA-MARGIN INTERPRETATION OF Cu- AND Ag-BEARING SEDIMENTARY ROCKS, MIDDLE PROTEROZOIC BELT SUPERGROUP OF MONTANA AND IDAHO

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Copper and silver deposits of the Ravalli Group and middle Belt carbonate (Belt Supergroup) occur in sediments interpreted to be alluvial apron and playa-flat sequences. Critical to this interpretation is the recognition of fining-upward sand-to-mud sequences, metres to centimetres thick, that were deposited by episodic floods and that thin basinward. Cross-bedded medium- to fine-grained sand beds of the Revett Formation record braided streams that drained a continental terrane that lay west (present direction) of the Belt basin. Braided streams flowed across alluvial aprons that sloped northward and eastward toward the centre of the intracratonic basin. Channelized floodwaters approaching the toe of the apron spread

into sheet floods, depositing flat-laminated sand beds from the upper flow-regime, capped by mud drape deposited during waning flow. Floods crossing the distal sandflat deposited either fining-upward sand-to-mud sequences decimetres thick or poorly sorted muddy layers with discontinuous clay and silt laminae. Continued flow across the playa mudflat deposited silt-to-clay couplets centimetres thick that were subsequently mud-cracked. Coarse sand, derived from the stable North America craton, was deposited along the eastern margin of the basin in fluvial channels, sheet-flood layers and ephemeral, locally oolitic beaches. Barrier island and tidal channel deposits, characteristic of marine coastlines, are absent; instead, the sequence closely resembles recent and ancient alluvial fan and playa deposits. The vertical sequence from alluvial aprons and sandflats of the Ravalli Group upward into playa mudflats of the lower middle Belt carbonate records progressive expansion of the playa sea. Sediment-hosted copper and silver deposits in the Ravalli occur in braided stream and sheet-flood deposits of the alluvial apron in the western part of the basin (Revett Formation). Mineral deposits in the uppermost Ravalli and lowermost middle Belt carbonate occur in quartz sand and oolite of channels, sheet-flood deposits and ephemeral beaches.

MIDDLE TO LATE PROTEROZOIC (1.8–0.6 Ga) SEDIMENTATION, NORTH AMERICA

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The Middle to Late Proterozoic records 1.2 Ga of sedimentation similar in complexity to that in the Phanerozoic. Post-Hudsonian (< 1.8 Ga) basins from the lower Coppermine homocline to northern Greenland and in the Athabaska, Thelon, Great Lakes (including the Keweenaw district) and New Mexico regions contain one or more rift-related, unconformity-bound sequences of coarse-to-fine quartzose alluvial deposits overlain by marine sandstones, stromatolitic carbonates and local bimodal volcanic rocks (1.66 Ga in age in the Coppermine homocline). Thick Middle Proterozoic sequences of uncertain maximum age accumulated in 5 or 6 trough-like basins of the western U.S.A. (including the Belt–Purcell Supergroup), in the Tuchodi Lakes and Ogilvie-Wernecke Mountains of northwestern Canada, and in eastern Greenland. Strata are composed of shallow-water to subaerial, medium to fine siliciclastic rocks, stromatolitic and silty carbonates, local dark turbidite arenites, and thinly laminated dark mudstones.

In eastern North America, post-Hudsonian granites were intruded at 1.65–1.60 Ga. In Labrador, two-rift-related unconformity-bounded sequences of terrestrial arkoses and mafic to felsic volcanic rocks were punctuated by 1.5–1.4-Ga anorogenic granites and anorthosites. Rift-related basalt and clastic sequences dated at 1.3–1.1 Ga occur in most of the above areas (*e.g.*, Coppermine and Keweenaw). Younger strata (1.2–0.7 Ga) in northwestern Canada bridged Middle and Late Proterozoic time with platform siliciclastic rocks, carbonates and evaporites. To the southeast, the Grenville Central Metasedimentary Belt records an orogeny at 1.3 Ga, siliciclastic to carbonate and evaporite sedimentation punctuated by mafic-to-felsic volcanism at 1.29 Ga, orogenies at *ca.* 1.2 and 1.1 Ga, a second clastic to carbonate sequence, and folding with metamorphism at *ca.* 1.08 Ga.

In the Mackenzie Mountains, rift-related basalts, conglomerates, red beds, carbonates and evaporites younger than 0.8 Ga record a warm climate, as do underlying strata. Immediately following, more extensive rifting was accompanied by local volcanism, deposition of glaciomarine and other immature detritus in basins extending the length of the Cordillera and into eastern Greenland. Overlying carbonates and siliciclastic rocks are, in turn, separated by local unconformities and conglomerates from Phanerozoic marine strata of similar style and longitudinal extent. Significant stratabound, sediment-hosted copper deposits are localized in reduced parts of thick red-bed sequences that record restricted marine or lacustrine sedimentation, extensional tectonism in continental settings, and arid climates.

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TRANSFORMATION OF COPPER-BEARING SANDSTONES AND SHALES IN THE PROCESS OF METAMORPHISM AND HYPERGENESIS

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The study of copper deposits in sediments of different ages (Middle to Late Carboniferous deposits of Kazakhstan, the Vendian layered sequence of the Igarka region, the Early Proterozoic sequence of the Udokan Series) shows that after their formation, the ores underwent transformations throughout the history of the host rocks. These transformations can be classified as prograde or retrograde. Prograde transformations are related to burial of the deposits and the influence of increasing temperature and pressure. During this process, the normal paragenetic assemblage chalcocite - djurleite - digenite - bornite - tetragonal bornite - chalcopyrite - pyrite gradually loses minerals that become unstable at higher temperatures. This simplifies the ore composition in the metamorphosed deposits (pyrite - pyrrhotite - chalcopyrite) and probably leads to a decrease in the copper content. The degree of transformation of the ores and host rocks is consistent. Retrograde transformations occur when deposits of different metamorphic facies rise to the surface. Owing to oxidation and secondary enrichment of sulfides, a low-temperature paragenetic assemblage of sulfides (djurleite - digenite - covellite - bornite - chalcopyrite) forms, and a secondary zonation of minerals appears. Parameters controlling the stability of the newly formed parageneses of sulfides do not necessarily correspond to the degree of alteration of the host rocks.

SOME ASPECTS OF EVOLUTION OF COPPER METALLOGENESIS IN RED-BED FORMATIONS

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The behavior of copper in arid-climate red-bed sequences suggests the existence of two stages in the process of their formation: (1) the transfer of reactive copper from a stable (nonsoluble) form into a mobile one, and (2) a change in the stable form of copper. Existence of the first stage is proved by particularities of copper-rich sandstones and shales, which indicate that the red-bed formations served as the source of copper while ore was forming. Transfer of copper from one stable form to another is proved by the low copper values of some red-bed formations and the presence in these of microquantities of native copper and copper sulfides. Among continental arid deposits, red-bed formations appeared since the Devonian, coinciding with the development of continental vegetation, which served as a reductant. The result was a greater number of ore-bearing facies. Apart from the marine sediments in contact with red-bed formations since the Devonian, ore-bearing facies began forming widely in the river floodplains, river channels and continental sabkha sediments. The other factor defining the resources of mobile copper in the red-bed formations is the source of the initial material (area of provenance). Its role is confirmed by a variety of accompanying metals in deposits of sandstone- and shale-hosted copper deposits.