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INTRODUCTION

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Cu – Au – Pb – Zn – Ag metallogeny of the Alpine – Balkan – Carpathian – Dinaride geodynamic province

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The Alpine-Balkan-Carpathian-Dinaride (ABCD) belt is one of the world's oldest mining areas and played a major role in the history of European civilizations, from well before the peak of the Greek and Roman civilizations up until the present day. Today, it is Europe's premier Cu-Au (-Pb-Zn-Ag) province, especially for gold-rich deposits associated with calc-alkaline magmatism, which have become a focus of renewed exploration interest after the political change in the eastern part of Central Europe.

The Alpine–Balkan–Carpathian–Dinaride metallogenic and geodynamic province is part of the Alpine-Himalayan orogenic system which extends from western Europe through Iran and the Himalayas to China and Malaysia. This orogenic system is the result of convergence of the African, Arabian and Indian plates and their collision with Eurasia, mainly from the Cretaceous to the present. Along the Alpine-Himalayan system, major calc-alkaline magmatism is associated with certain segments only, whereas other segments are characterised by extensive regional metamorphism. This is a reflection of the complex geometry of the collision interface, with interfering microplates giving rise to several discontinuous sutures, highly diachronous magmatism, and transient subduction of continental crust leading to variable crustal thickening followed by extension and orogenic collapse. These interfering processes led to a very complex arcuate trace of the orogen, especially in the ABCD segment (e.g. Channell and Horváth 1976; Csontos 1995; Nemcok et al. 1998; Wortel and Spakman 2000; Ciobanu et al. 2002, this volume). The segmented geodynamic character of the orogen is reflected in an equally discontinuous distribution of ore deposits (Mitchell 1996; Jankovic 1997). This character stands in marked contrast to the long-lasting subduction of oceanic plates along the margins of the Pacific basin, which resulted in relatively stable magmatic arcs with elongate belts of magmatic-hydrothermal ore deposits, notably in the Andes.

As a result of the complex geodynamic history, with several oceanic sub-basins and indenting continental microplates, the metallogeny of the ABCD region comprises several phases of major ore formation, in segments of limited lateral extent along the trace of the orogen. Major chromite deposits and copper-rich volcanic rock-hosted massive sulphides formed during pre-collisional oceanic magmatism between Early Jurassic and Middle Cretaceous, but probably in an oceanic arc rather than in a mid-ocean spreading environment.

Three spatially and temporally distinct tectonic and metallogenic belts are associated with the Late Cretaceous to Neogene tectonic evolution of the ABCD belt (Fig. 1; Table 1) and are the focus of this Issue of *Mineralium Deposita*.

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Cretaceous arc magmatism and early continental collision: porphyry-related Cu-Au

Calc-alkaline arc magmatism in the Late Cretaceous formed major porphyry Cu and associated high-sulfidation epithermal deposits, the economically most significant metallic resources in the ABCD region. The tectonic and metallogenic history of this belt may include multiple subduction zones. Intrusive and extrusive magmatism extends over at least 30 Ma from ~90 to ~60 Ma, as reviewed by Ciobanu et al. (2002, this volume). Abundant volcanic and intrusive rocks are preserved in a nearly continuous L-shaped belt extending from Romania through Yugoslavia to Bulgaria, known

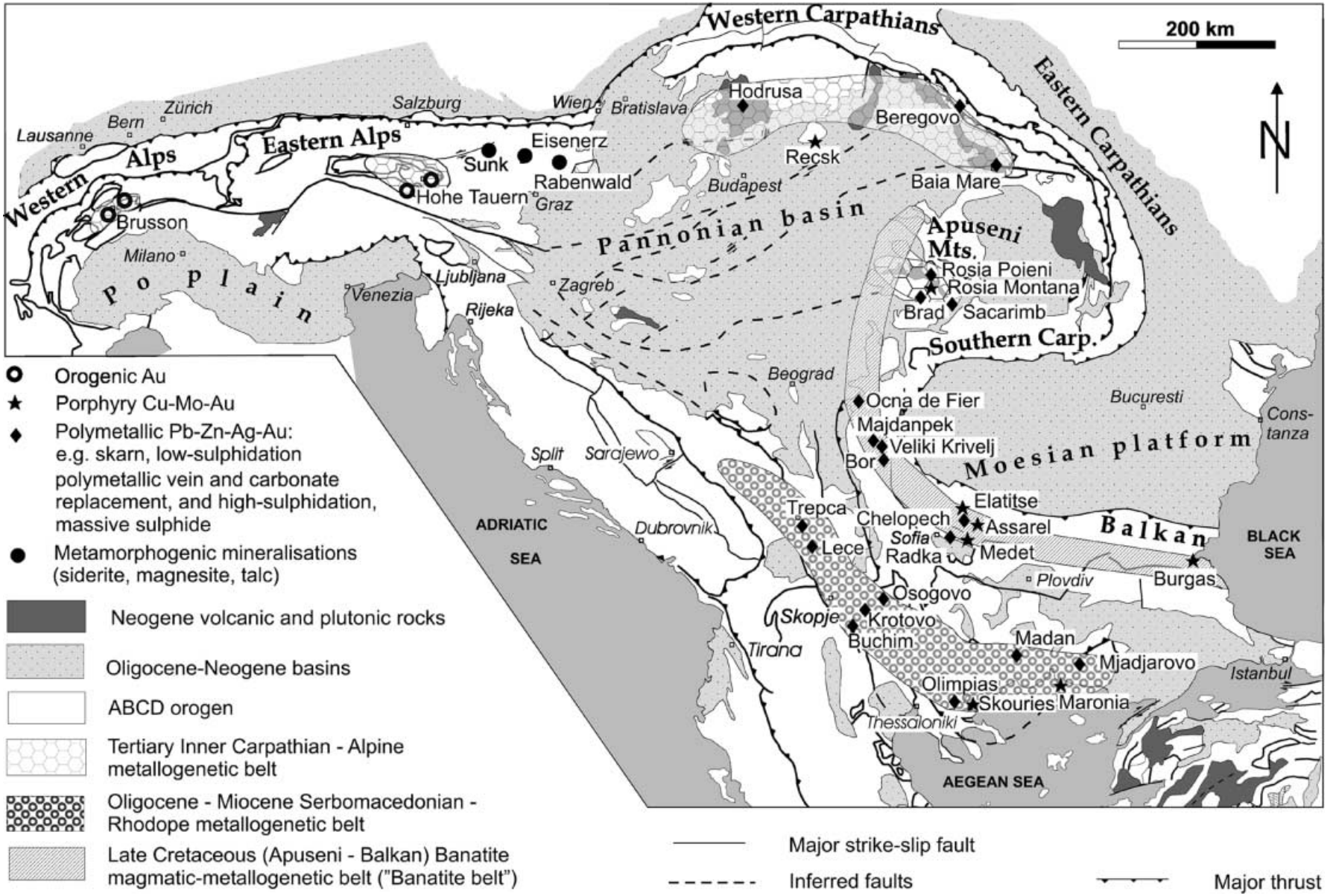

Fig. 1 Simplified tectonic map displaying the distribution of major tectonic units and ore deposits in the Alpine–Balkan–Carpathian–Dinaride (ABCD) region. Three belts of mineralisation, associated with regional metamorphism and calc-alkaline magmatism of Late Cretaceous to Miocene age, are the focus of this Thematic Issue

Table 1 Selected ore deposits of magmatic or metamorphic affiliation in the Alpine-Balkan-Carpathian-Dinaride province. Economic data are indicative only and do not agree among all accessible references (especially for Au). The *LODE* data base of Large Ore Deposits of Europe (http://www.gl.rhul.ac.uk/geode/) is in continued development as part of the European Science Foundation Programme 'Geodynamics and Ore Deposit Evolution', GEODE

Deposit	Country	Geology, type	Metals	Economics, status	Age	References
Late Cretaceous belt: magmatic-hydrothermal (porphyry-style and epithermal) Cu-Au deposits and metamorphogenic talc and magnesite deposits						
Bor	Yugoslavia	'Massive sulphide' high-sulphidation epithermal Cu-Au with subjacent porphyry-style stockwork	Cu, Au (Pb, Zn)	Underground below old open cut; 540 Mt @ 0.67% Cu, 0.2 g/t Au	L. Cretaceous	Ciobanu et al. (2002, this volume)
Majdanpek	Yugoslavia	Porphyry-style epithermal, mostly along fault cutting basement rocks	Cu (Au)	Mine on standby; >850 Mt @ 0.4% Cu, 0.25 g/t Au	L. Cretaceous	Ciobanu et al. (2002, this volume)
Veliki Krivelj	Yugoslavia	Porphyry-style with skarns	Cu	Active; 750 Mt @ 0.44% Cu	L. Cretaceous	Ciobanu et al. (2002, this volume)
Medet	Bulgaria	Porphyry copper deposit	Cu (Au, Ag, Bi, Te)	Mined out 1994; 163 Mt @ 0.32% Cu, 0.1 g/t Au	L. Cretaceous	Strashimirov et al. (2002, this volume)
Elatsite	Bulgaria	Porphyry copper deposit in dykes and basement rocks	Cu, Au (Ag, Bi, Te, Pt, Pd)	Active open pit; total ~320 Mt @ 0.35% Cu, 0.2 g/t Au	L. Cretaceous	Strashimirov et al. (2002, this volume)
Assarel	Bulgaria	Porphyry copper deposit with supergene enrichment	Cu (Ag, Bi, Te)	Active open pit; total ~350 Mt @ 0.41–0.53% Cu	L. Cretaceous	Strashimirov et al. (2002, this volume)
Chelopech	Bulgaria	'Massive sulphide' high-sulphidation epithermal Cu-Au	Au, Cu	Active underground mine; total ~42 Mt @ >3 g/t Au, >1% Cu	L. Cretaceous	Strashimirov et al. (2002, this volume), Bonev et al. (2002, this volume)
Radka	Bulgaria	'Massive sulphide' high-sulphidation epithermal Cu-Au	Cu, S, Au	Closed 1997; >6 Mt @ 1% Cu	L. Cretaceous	Kouzmanov et al. (2002, this volume)
Ocna de Fier .... Dognecea	Romania	Skarn system, zoned at district scale Fe(Cu)–Pb, Zn	Fe (Cu) ... and Pb, Zn	Closed 1993; 13 Mt @30% Fe, 0.5% Cu; 2 Mt 3.7% Zn, 2% Pb	L. Cret.	Ciobanu et al. (2002, this volume)
Oligocene to Miocene Serbomacedonian-Rhodope belt: magmatic-related polymetallic vein and replacement deposits						
Trepça	Kosovo	Breccia pipe with skarns and stratiform mantos	Pb, Zn, Ag (Au)	>150Mt @ 6% Pb, 4% Zn	Miocene	LODE (no recent data)
Buchim	Macedonia	Porphyry copper deposit, Cu-Au mineralization around andesitic stock in basement gneiss	Cu, Au (Ag, Mo, Pd, Pt, Bi, Se)	Active open pit; total ~100 Mt @ 0.30% Cu, 0.33 g/t Au, 1.1 g/t Ag	Oligocene–Miocene	Serafimovski et al. (1996)

Table 1 (Contd.)

Deposit	Country	Geology, type	Metals	Economics, status	Age	References
Madan (– Termes)	Bulgaria (– Greece)	Epi- to mesothermal Pb-Zn veins in gneiss, and mantos replacing marbles	Pb, Zn	Several mining centres: Madan, Luki, Eniovche together >17 Mt @ 2.5% Pb, 2.1% Zn	Oligocene	Milev et al. (1996), Naftali (2002, this volume)
Madjarovo	Bulgaria	Polymetallic low-sulfidation epithermal veins	Pb, Zn, Au	Closed; >10 Mt Pb, Zn ore mined; ex. resource 2 Mt @ 3.9 g/t Au	Oligocene	Marchev et al. (2002, this volume)
Olympias	Greece	Replacement deposits (skarns, mantos)	Au, Ag, Pb, Zn	Proven/probable reserve 140 t Au, 2,000 t Ag, 0.53 Mt Pb, 0.7 t Zn	Oligocene	LODE; Kilias et al. (1996)
Maronia	Greece	Porphyry-style, disseminated silicified	Cu, Mo (Au, Re)	Subeconomic prospect	Oligocene	Melfos et al. (2002, this volume)
Tertiary Alpine-Carpathian belt: mesothermal Au and polymetallic magmatic-hydrothermal deposits						
Recsk-Lahóca	Hungary	Porphyry, skarn and high-sulphidation epithermal deposits	Cu, Mo, Pb, Zn	Deep dormant Cu resource with >130 Mt @ >1% Cu plus Pb, Zn	Eocene	LODE; Gatter et al. (1999)
Lahóca	Hungary	High-sulphidation epithermal deposit next to Recsk	Au (Ag, Pb, Zn)	Resource 37 Mt @ 1.4 g/t Au	Eocene	Földessy (1997)
Hodrusa district	Slovakia	Low sulphidation epithermal veins (numerous, mostly exhausted deposits)	Au, Ag, Zn, Pb	Past metal production entire district 129 t Au; 4,980 t Ag; Pb, Zn	Miocene	LODE
Brad in 'gold quadrilateral'	Romania	Low-sulfidation epithermal veins ± breccias in sedimentary and volcanic rocks and subvolcanic stocks	Au (Ag, Te) and Cu	Historic mining centre + active exploration; total 1,000 t Au ?	Miocene	Alderton et al. (2000)
Sacarimb	Romania	Low-sulphidation epithermal vein swarm centred on subvolcanic stock; abundant tellurides	Au (Ag, Te)	Biggest mine in historic centre; past production ~84 t Au	Miocene	LODE; 2000
Rosia Montana	Romania	Breccia pipe and veins in dacite porphyry near northern end of 'gold 7quadrilateral'	Au (Ag)	Feasibility study: total resource 296 Mt @ 1.4 g/t Au, 6 g/t Ag	Miocene	LODE; www.gabrielre-sources.com
Rosia Poieni	Romania	Porphyry-copper near Rosia Montana	Cu (Au)	Closed 1999; reserves 350 Mt @ 0.36% Cu, heap-leach feasibility	Miocene	LODE

Baia Mare district	Romania	Low sulphidation epithermal, ~15 vein deposits, largest vein (Baia Sprie) 5 km×1 km×1–25 m width	Pb, Zn (Au)	Active underground mines; total metal ~6 Mt Pb+Zn, 37 t Au	Miocene	LODE, Grancea et al. (2002, this volume)
Brusson	Italy	Regional metamorphic mesothermal quartz-gold lodes	Au	~3 t Au estimated past production	Oligocene	Pettke et al. (2000)
Hohe Tauern	Austria	Regional metamorphic mesothermal quartz-gold lodes	Au (Ag, As, Sb)	No economic data	Oligocene	Horner et al. (1997)

as the Banatitic magmatic and metallogenetic belt (Berza et al. 1998) or the Apuseni–Banat–Timok–Srednogorie belt (Strashimirov and Popov 2000). The magmas show typical subduction-related geochemical signatures and include normal calc-alkaline to high-K calc-alkaline compositions, even within restricted parts of the belt (Dupont et al. 2002, this volume, Von Quadt et al. 2002). However, only two segments along the continuous magmatic belt are richly mineralised, probably controlled by deep-seated transverse structures. Porphyry copper (-gold ± platinum-group elements) and intimately associated high-sulphidation epithermal Au-Cu deposits occur in the Timok area of Serbia (Majdanpek, Bor; Robertson and Karamata 1994; Berza et al. 1998), and in the Panagyurishte district of Bulgaria (Elatsite, Chelopech, Assarel), as described in the papers by Strashimirov et al. (2002), Bonev et al. (2002) and Kouzmanov (2002) in this volume. Of particular economic and scientific interest are gold- and copper-rich 'massive sulphide' deposits including Chelopech and Bor, which have a close spatial association with porphyry copper deposits and share certain characteristics of high-sulphidation epithermal as well as seafloor massive sulphide deposits (Karamata et al. 1997; Bonev et al. 2002, this volume). While subduction-related arc magmatism prevailed in the Southern Carpathian and Balkan domain, beginning continental collision in the Eastern Alps generated approximately coeval siderite, magnesite, and talc deposits and some hydrothermal Cu veins, as a result of regional metamorphic fluid processes (Weber et al. 1997; Pohl and Belocky 1998).

The Oligocene–Miocene Serbomacedonian–Rhodope Pb-Zn and Cu-Au belt

The Serbomacedonian–Rhodope metallogenetic belt is also related to calc-alkaline magmatism. However, it shows little evidence for a direct relation to subduction, but rather to continent-continent collision (e.g. Harkovska et al. 1998). It includes two types of deposits: (1) porphyry Cu-Mo-Au and subordinate epithermal Au deposits which are more common in the south-eastern sector; (2) several significant epi- to mesothermal Pb-Zn (-Ag-Au) vein and carbonate replacement deposits of Late Eocene to Oligocene age, extending from Bosnia (e.g. Trepca) through Serbia and Macedonia to Greece and southern Bulgaria, including Madan–Termes (Fig. 1) and the caldera-related vein system of Madjarovo described by Marchev et al. (2002, this volume). The Serbomacedonian–Rhodope metallogenetic belt also hosts some porphyry Cu deposits in Macedonia (Buchim; Serafimofski 2000) and in northern Greece (Kroll et al. 2002), including the Maronia prospect described by Melfos et al. (2002, this volume). The belt comprises various isolated magmatic-hydrothermal centres of similar but not precisely known age, which are broadly aligned along a strip which seems to cut across several tectonic belts (Mitchell 1996). This observation,

and mantle tomography evidence for an underlying zone of reduced shear-wave velocities have led De Boorder et al. (1998) to propose post-collisional slab break-off and incursion of asthenosphere to shallow depths as a trigger for metallogeny in this belt.

Oligocene-Neogene deposits of the Inner Carpathian-Alpine orogen

The closure of oceanic sub-basins, the indentation of continental microplates into the evolving orogen along transfer structures, and probably slab break-off and asthenosphere incursion have variably contributed to localised centres and short belts of Oligocene to Recent calc-alkaline to alkaline magmatism in the Inner Carpathians and the Apuseni Mountains. Oligocene magmatism generated the Recs-Lahóca porphyry-copper and epithermal gold centre in Hungary (Lexa 1999), and Miocene calc-alkaline volcanism and intrusive activity in the Inner Carpathians of Romania and Slovakia formed numerous Pb-Zn (-Ag-Au) vein deposits. The largest of these are the Baia Sprie and Cavnic vein systems near Baia Mare in northern Romania, studied by Grancea et al. (2002, this volume).

The 'gold quadrilateral' of the Apuseni Mountains (also known as the Transsylvanian gold province; e.g. Lexa 1999; Alderton et al. 2000) includes a cluster of large, low-sulfidation epithermal Au-Te vein deposits including Sacarimb and Rosia Montana, which is probably Europe's largest gold resource. The epithermal veins are spatially and temporally associated with small to medium-sized porphyry-style Cu (-Au) deposits in calc-alkaline intrusive centres of Miocene age. Magma generation and the emplacement of numerous intrusive stocks are probably related to extensional accommodation of major strike-slip motions, associated with the north-eastward incursion of the Adriatic-Pannonian microcontinent which generated the prominent S-shaped arc of the present Carpathian chain (Fig. 1; Linzer 1996; Nemcok et al. 1998).

In the Western and Eastern Alps, collision of major continental blocks during the Oligocene led to extensive Barrovian-type regional metamorphism, commonly preceded by an eclogite facies stage. Associated with the subsequent orogenic collapse and exhumation of high-grade metamorphic domes, orogenic (mesothermal) gold deposits were formed (Brusson, Hohe Tauern). These deposits are small but in every respect similar to the larger ancient deposits of this type, and high-precision geochronology has provided some of the most clear-cut evidence for a metamorphogenic origin of mesothermal lode gold deposits (Pettke et al. 2000).

Contents and background of this Thematic Issue

This issue of *Mineralium Deposita* is the first product of a major research initiative on Geodynamics and Ore Deposit Evolution (GEODE), funded by the European Science Foundation through support to scientists in a number of European countries. One of the projects of this programme, the ABCD–GEODE Project, is focussed on the Alpine–Balkan–Carpathian–Dinaride geodynamic and metallogenic province. This geologically youthful province was the subject of major, recent geodynamic studies (e.g. Csontos 1995; Dallmeyer et al. 1996; PANCARDI 1998) which were motivated, in part, by seismic risk assessment (Wenzel et al. 2000). High-resolution geophysical data (Flower et al. 1998), including lithosphere-scale seismic tomography (De Boorder et al. 1998) and detailed tectonic reconstructions (e.g. Csontos 1995; Channell and Kozur 1997; Nemcok et al. 1998), provide an ideal framework for investigating the critical geodynamic factors required for the formation of ore deposits in convergent plate settings.

A major limitation to the interpretation of the bigger metallogenic picture has been the restricted access to geological information about the ore deposits in the countries under former Soviet influence, even though excellent data have been generated especially by Bulgarian, Romanian and Yugoslav colleagues. The ambitious aim for this Thematic Issue was to collect and publish some of the existing data obtained by geologists who were working in the ABCD region for many years, but who never had the opportunity or encouragement to publish in refereed international journals.

This Thematic Issue was planned at an international ABCD–GEODE Workshop held at Borovets near Sofia in May 2000. Not all invited authors responded in time, so it is unavoidable that the resulting issue is incomplete. For example, it lacks descriptions of some of the most important deposits and districts such as Yugoslavia's porphyry copper deposits. We cannot claim that this issue is a balanced account of the state of knowledge about the metallogeny of the ABCD region, but it presents a selection of original papers by local specialists with access to the primary literature, and it documents specific observations which were not previously available to the international academic and exploration community. Although incomplete and not always consistent, the collection of papers presents some of the best information presently available about parts of the ABCD metallogenic province. It is a basis for ongoing work within the ABCD–GEODE Project, which aims at integrating existing and new data and expertise in a team of international collaborators who previously were largely isolated from each other.

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