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Article abstract

The science of mineral deposits (economic geology) has greatly evolved since its inception in the late 19th century, and has subsequently been strongly influenced by mining discoveries. It is a science that has moved from a descriptive phase to a deeper understanding of ore-body genesis. As a result, deposit types are increasing in number, classification systems are improving, and we are beginning to recognize how spatial and temporal distributions relate to plate tectonic mechanisms. Our understanding of ore-forming mechanisms has broadened, thanks, in part, to widely available isotopic dating methods and to advances in analytical techniques that determine the ore-element sources, transport conditions and depositional processes. It also appears that the climate and fundamental geodynamic processes (i.e. mantle plumes) play important roles in ore-deposit formation.

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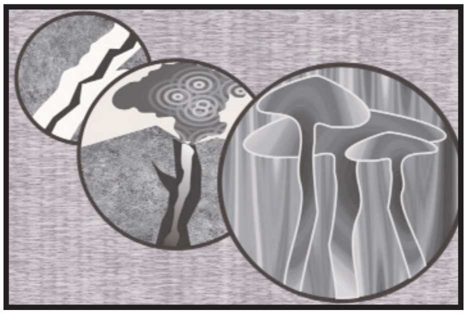

Economic Geology: Then and Now

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SUMMARY
The science of mineral deposits (economic geology) has greatly evolved since its inception in the late 19^{th} century, and has subsequently been strongly influenced by mining discoveries. It is a science that has moved from a descriptive phase to a deeper understanding of orebody genesis. As a result, deposit types are increasing in number, classification systems are improving, and we are beginning to recognize how spatial and temporal distributions relate to plate tectonic mechanisms. Our understanding of ore-forming mechanisms has broadened, thanks, in part, to widely available isotopic dating methods and to advances in analytical techniques that determine the ore-element sources, transport conditions and depositional processes. It also appears that the climate and fundamental geodynamic processes (i.e. mantle plumes) play important roles in ore-deposit formation.

SOMMAIRE
La science des gîtes minéraux (métallogénie) s'est beaucoup développée depuis sa création à la fin du XIXème siècle, et a été fortement influencée par les découvertes minières. On est passé de la description à la compréhension des gisements, avec une augmentation du nombre de type, de meilleures classifications et les débuts d'une compréhension des distributions spatiale et temporelle en liaison avec les mécanismes de la tectonique des plaques. Les mécanismes de formation ont été mieux compris, en partie grâce aux nombreuses datations isotopiques disponibles, et aux progrès dans l'analyse des processus de source, de transport, et des conditions de dépôt. Le climat et les processus de crises géodynamiques (plumes mantelliques) semblent jouer un rôle significatif dans la formation des gisements.

INTRODUCTION
Although exploration and mining can be traced back to Neolithic times, the science of ore deposits is still a relatively recent field of study. Mining was one of the first areas worthy of intellectual investigation by Renaissance scholars, yet economic geology–in the present sense of the term–did not emerge until the end of the 19^{th} century in either Europe or the United States. The origins of the science revolved around two nuclei: the North American school, from which sprang the Economic Geology Publishing Company founded in 1905 (Skinner 2005), and the European school, from which the term 'metallogeny' was coined by de Launay (1913), the same year that W. Lindgren published his landmark book entitled, *Mineral Deposits*. Within a period of 100 years, a significant body of knowledge has emerged and economic geology has become an established university discipline. Many countries, like Canada, now require a degree to become a professional geoscientist, and links between economic geology and other geoscience disciplines continue to be forged around the world.

Geoscientific progress has been most remarkable since World War II, although we still lack the hindsight needed to fully appreciate this fact. The transformation of conceptual insights into mining discoveries is a slow process, and it generally takes several decades for the real economic impact of innovations in fundamental science to materialize. Regardless, the field of economic geology has expanded from one of descriptive methodology to an explanatory and predictive science applied to mineral resource exploration and utilization.

Several publications collectively synthesize the post-1980s understanding of economic geology. Following Routhier's (1980) essay on predictive metallogeny, contributions have come from Nicolini (1990) and Pélissonnier (2001) from France; Mitchell and Garson (1981) and Edwards and Atkinson (1986) from England; Lunar and Oyarzun (1991) from Spain; Hutchinson (1982), Sawkins (1984), Eckstrand et al. (1995), Kirkham et al. (1995) and Laznicka (1985) from Canada; Guilbert and Park (1986), Kesler (1994) and Misra (2000) from the United States; Pirajno (1992, 2000) and Robb (2004) from South Africa; Solomon and Groves (1994) from Australia; and Dardenne and Schobbenhaus (2001) from Brazil.

The study of ore deposits is primarily an applied science and is thus influenced by other discoveries in theoretical science as well as changes–often rapid–in related industries. The last twenty years were marked by economic globalization accompanied by the reorganization of political structures, notably those of Russia, China and

South Africa. Such sweeping globalization caused profound changes in the basic funding structure and economic landscape of mineral exploration and development, influenced by fluctuating and unpredictable metals markets. These factors resulted in the perceived necessity for mining companies, even the largest, to regroup into increasingly larger entities. These changes in the industry were coincident with a radical reduction in the size of government geoscience programs in an attempt to reduce deficits. Combined with the gains in efficiency accorded by technological advancements, the net effect has been a worldwide drop in the number of mineral industry personnel from 18 million to 15 million in only one decade (Anonymous 2004).

The decline in the number of experienced exploration geologists in recent years has produced a precarious situation with negative repercussions for a profession that is already undervalued by the public, particularly after the Bre-X stock scandal in the late 1990s and the poor environmental reputation in most developed countries. Globalization has also led to job specialization at the international level. Also witnessed, is the demise of the traditional mining industry in parts of many industrialized countries, as much in Europe as in North America. Historical base-metal districts–once the economic backbone in frontier regions–have now closed: Noranda (Québec), Sullivan (British Columbia), Les Malines and St-Yrieix (France), Laisvall (Sweden), Leadville (Colorado), Touissit-Bediane (Morocco), and Tsumeb (Namibia). Figure 1 shows that a large number of the mines in developed countries, which were the focus of metallogenic studies in the 1970s, are now closed. Exploration in developed countries holds little promise, even if the geological potential is excellent, because there is slim prospect that a discovery can be turned into a mine despite the fact that recycling cannot meet either present or future resource needs. Instead, explorationists have concentrated their efforts in sparsely populated regions in the north (Scandinavia, Canada) and south (Spain, Mexico, Australia). These efforts have resulted in the discovery of new ore deposits, particularly in South America but also in the Pacific region and likely soon in China. Western Africa's potential is slowly emerging, whereas the former Soviet world waits in the wings.

This essay summarizes the prominent shifts and new ideas in metallogeny, which have emerged during the past 20 years and have been heralded as major advances in the field. The focus is on contributions published in French

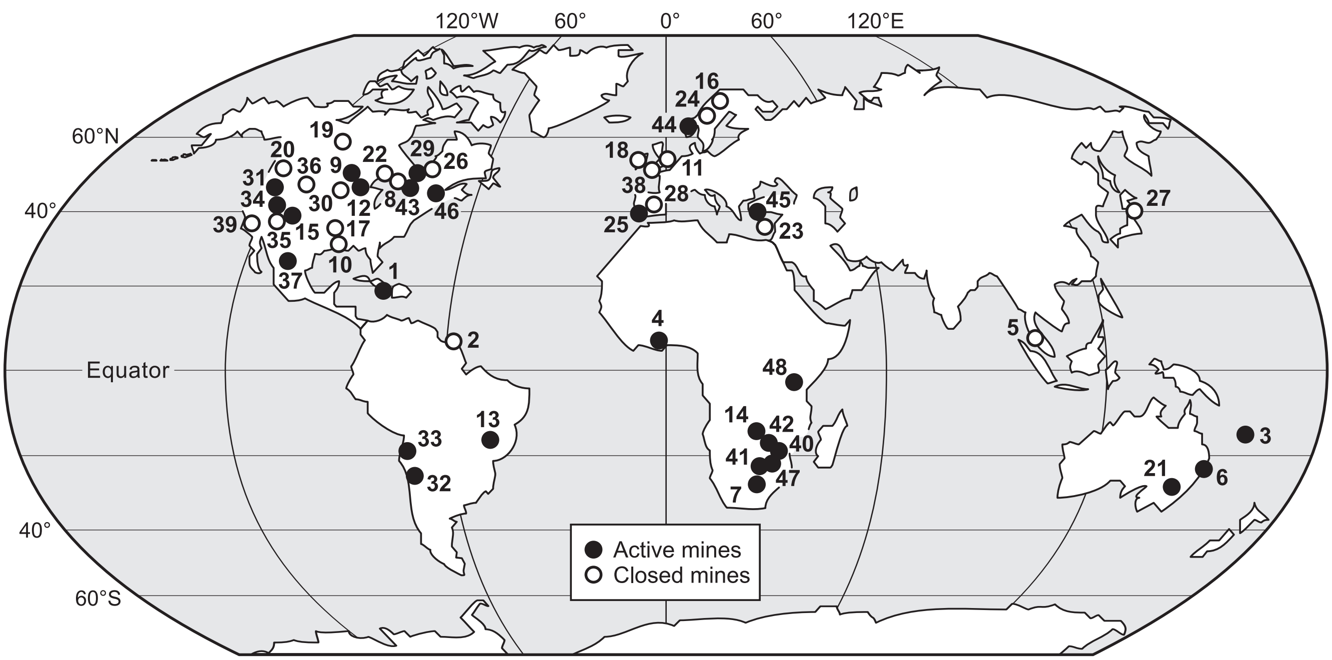

Figure 1. Distribution of open and closed mines or districts, at the beginning of the XXI° century, after the selection of Dixon (1979): 1. Jamaican bauxite deposits; 2. Onverdacht bauxite deposit, Surinam; 3. New Caledonia Ni deposits; 4. Nsuta Mn deposit, Ghana; 5. Kinta Valley tin deposits, Malaysia; 6. Beach-sand deposits of North Stradbroke Island, Australia; 7. Witwatersrand gold-uranium deposit, RSA; 8. Blind River U deposit, Canada; 9. The Esterhazy K deposit, Canada; 10. Sulphur Salt Dome, USA; 11. Fe deposit Northampton, UK; 12. The Mesabi Fe range, USA; 13. Fe deposits of the Itabira district, Brazil; 14. Luanshya Cu deposit, Zambia; 15. South Colorado Ambrosi Lake U field, USA; 16. Laisvall Pb-Zn deposit, Sweden; 17. Picher Pb-Zn field, Tri-state district, USA; 18. Silvermines district, Ireland; 19. Pine Point, Canada; 20. Sullivan deposit, Canada; 21. Broken Hill, Australia; 22. Helen iron deposit, Canada; 23. Tamasos Cu field, Cyprus; 24. Skorovas pyritic VMS-ophiolite deposit, Norway; 25. Rio Tinto deposits, Spain; 26. Noranda, Canada; 27. Kosaka, Kuroko, Japan; 28. Almaden Hg district, Spain; 29. McIntyre-Hollinger, Canada; 30. Homestake, USA; 31. Bunker Hill Ag deposit, USA; 32. El Salvador porphyry, Chile; 33. Chuquicamata Cu deposit, Chili; 34. Bingham, USA; 35. Climax Mo deposits of Colorado, USA; 36. Butte deposits, USA; 37. Santa Eulaila deposit, Mexico; 38. Southwest England district; 39. Pine Creek W deposit, USA; 40. Bikita pegmatite deposits, Zimbabwe; 41. Merensky reef Pt deposits, RSA; 42. Great Dyke chromite deposits, Rhodesia; 43. Sudbury Ni deposits, Canada; 44. Tellnes ilmenite deposit, Norway; 45. Mugla chromite district, Turkey; 46. Asbestos deposits, Canada; 47. Palabora carbonatite complex, RSA; 48. Mwadui diamond pipe, Tanzania.

and English. It is an exercise that can only be incomplete: more than 20,000 articles have been published since 1980. Only the most pronounced trends are emphasized and the reader is asked to excuse any omissions, which are inevitable in such a short text. Progress in the field of mineral deposits will be summarized first, followed by an overview of the most significant advances in the key aspects of metallogeny: depositional conditions, mode of transport, and sources of ore elements.

THE SCIENCE OF MINERAL DEPOSITS

The two terms 'metallogeny' and 'gitology' are used to describe the science of mineral deposits (Nicolini 1990). 'Metallogeny' was widely adopted by the French after being introduced by de Launay (1913); however, the word took on a genetic connotation and became fairly restricted to mineralogical and physio-chemical approaches. 'Gitology' was a term invented near the end of the 1960s by geologists from France's *Bureau de recherches géologiques et minières* to describe a more naturalistic approach based on geological context and descriptive classification (Nicolini 1970; Rabinovitch 2000).

Many **deposit types** have been studied in detail using significantly more quantitative methods that integrate an ever-increasing number of parameters. Some of the deposit types familiar today were, in fact, only recently recognized or re-interpreted: copper porphyries (Lowell and Guilbert 1970); Carlin-type disseminated gold (Radtke and Dickson 1976); volcanogenic massive sulfides (Parmentier and Spooner 1978); unconformity-type uranium (Hoeve and Sibbald 1978); sedimentary-exhalative deposits (Large 1980); diamondiferous kimberlites (Haggerty 1986); iron-oxide Cu-Au-U deposits (Hitzman et al. 1992); and breccia-hosted platinum-group-element deposits (Lavigne and Michaud 2001). It is for this reason that the reference volume for the 1980s–*Economic Geology's 75th Anniversary Volume* (Skinner 1981)–does not contain separate chapters for such currently important deposits as epithermal invisible gold, auriferous shear zones (orogenic gold), diamonds, hydrothermal platinum group elements, unconformity-type uranium, tantalum pegmatites, or iron oxide-copper-gold. The emergence of these deposit types was largely driven by the search for high-value commodities, like gold, platinum group elements and diamonds. The conceptualization of a new deposit type is undoubtedly one of the most important factors from an economic perspective: most mining companies will develop their exploration strategy based on a type-deposit approach and the most common geological and/or tectonic setting for an ore deposit.

The **classification of deposits** has evolved considerably during the past 20 years. There are, of course, a number of different approaches based on descriptive or genetic criteria, and whether the classification of the deposit is from an internal (mineralogical) or an external perspective (geological context). Routhier (1969) warned of the risks of using poorly controlled parameters that can lead to inconsistencies. Since that time, the classification of deposits has been progressively standardized around several main geologic and geodynamic themes. In some cases, new classifications have been elegantly reconciled with existing mineralogical and volcanological parameters (Sillitoe et al. 1996). Table 1 presents the classification system used at the Université du Québec à Montréal (UQAM) and the current level of understanding attained for each deposit type. During the past few decades, the ability to determine genetic age (i.e. the development of isotopic geochronometers) was one of the most significant factors in deducing ore genesis and has helped mediate battles between syngenetic and epigenetic proponents. The *Deposit Modeling Program* supported by IUGS and UNESCO (Cox and Singer 1986; Kirkham et al. 1995; Seal and Foley 2004) popularized the North American approach and eventually squeezed out Soviet concepts. In the future, the improved documentation of deposits that have yet to be discovered in the relatively poorly documented environments of Africa and Asia will undoubtedly lead to further revision of existing classifications.

The **distribution of ore deposits** has always occupied a prominent place in economic geology studies given the significant economic advantage for anyone who can predict the location of the next big mineable deposit. Routhier (1980) proposed a belt-style distribution for major mineral deposits; however, it was only after the development of geographic information systems in the 1990s that the analysis of ore deposit distribution became a true discipline, combining ore deposit models with empirical observations and supported by statistical analysis (Carlson 1991; Bonham-Carter 1994; Agterberg 1995). Many of the findings helped to scientifically confirm the existence of districts dominated by specific metals (districts that had been informally recognized since ancient times) and to define the exclusionary relationships between certain ore families. Nonetheless, much remains to be accomplished in this area, particularly in our understanding of the vertical distribution of deposits within continents, and their link to the orogenic cycle. It is reasonable to expect that crustal architecture (in terms of thermal structure, permeability, redox barriers, etc.) acts as an important control on the sources of ore elements and their mechanisms of transfer.

Metallogenists long ago demonstrated the existence of distinct ore forming periods, and the study of metallogenic epochs has been an area of major recent progress. Classic Soviet studies systematically linked metallogenic periods to orogenic phases (Smirnov 1988); yet, it has become apparent that there are discrepancies between the productivity of certain orogenic belts, which are difficult to explain (Goldfarb et al. 2001). New insights into mantle behaviour may hold the answer by revealing that convection periodically affects the upper mantle and, less commonly, the entire mantle; it is also evident that this process produces complex distribution patterns over time (Larson 1991; Ernst and Buchan 2001; Abbott and Isley 2002). It is now understood that the mantle can provoke sudden accelerations in plate movements and that mantle convection is not regular; it is accompanied by the abrupt arrival of hot deep material representing plumes that form hot spots and possibly cause continental rupture. Plumes were more abundant during the Archean and thus influenced the plate motions of that era (Condie 2001).

An ever-increasing number of deposit classes can be linked to these mantle processes: mantle-derived magmas that form layered intrusions (e.g. platinum, chromite, titaniferous mag-

Table 1: Main types of mineral deposits using the UQAM classification scheme.

Association	Type	Deposition/ Transportation	Source
Mafic and ultramafic plutonism	Chromium, copper-nickel layered complexes	A	K
	Nickel komatiites	A	K
	Chromium and PGE ophiolites	A	K
	Hydrothermal magmatic platinum in ultramafic intrusions	?	K
	Titanium anorthosites	A	A
Alkaline volcano-plutonism	Carbonatites	A	?
	Diamondiferous kimberlites and lamproites	K	A
	Differentiated alkaline magmatism	A	A
	Cu-U-Au-REE iron oxides (IOGC)	?	A
Felsic plutonism	Granitic pegmatites	K	K
	Tin-tungsten cupolas	K	A
	Uranium episyenites	A	A
	Copper porphyries	K	A
	Molybdenum and tin porphyries	K	A
	Metasomatic Cu-Pb-Zn-W deposits	K	A
Aerial felsic volcanism	High-sulfidation epithermal copper and gold deposits	K	?
	Low-sulfidation epithermal gold and silver deposits	K	?
	Gold-bearing alkaline maars and diatremes	K	?
	Replacement gold deposits	K	?
	Replacement base metal deposits (mantos)	K	?
Vein deposits in the mid- and lower crust	Gold shear zones	K	?
	Pb-Zn-F-Ba veins	K	?
	Co, Ag veins	K	?
	Sb veins	K	?
Submarine volcanism	Cu-Zn ophiolites	K	A
	Bimodal Pb-Zn-Cu volcanism	K	A
	Sedex deposits	A	?
Sedimentary deposits	Iron formations (BIF)	A	A
	Oolitic iron	A	A
	Sedimentary phosphates	K	K
	Manganese deposits	A	A
	Barite in black shales	K	K
Diagenetic deposits	Copper in pelites	K	A
	Uranium sandstones	K	K
	Discordant uranium	A	?
	Pb-Zn-deposits in sedimentary cover rocks	K	A
	Extensional veins	K	A
Alteration deposits	Nickel laterite deposits	K	K
	Oxidized copper	K	K
	Supergene gold	K	K
	Residual manganese deposits	K	K
	Bauxite	K	A
Placers and paleoplacers	Fluvial placers	K	K
	Gold-bearing deltaic paleoplacers	K	?
	Black sand marine placers	K	K

K = known; A = assumed/inferred; ? = unknown

netite and vanadium ores at Bushveld) and continental flood basalts (e.g. copper-nickel-PGE ores at Noril'sk). Ultramafic igneous rocks from the Labrador Trough (Québec) and the Thompson nickel belt (Manitoba) have been associated with a mantle superplume event at 1.9 Ga (Condie 2001; Hulbert et al. 2005), and high-T, Mg-rich komatiites–the typical Archean expression of extensive partial melting–are associated with Ni-Cu deposits.

Anorogenic magmatism is linked to lithospheric extension, hotspots and intraplate rifting and various types of mineralization associated with this style of magmatism, including Sn, Nb, Ta, U, Th, F and Be in anorogenic granites (Sawkins 1984), and Olympic Dam-type Cu-Au-U iron-oxide deposits. Plume-related crustal magmatism can also exert a major influence on mineralizing processes. The giant massive sulfide deposits of Kidd Creek are genetically associated with the emplacement of a high-temperature volcanic pile of komatiites and rhyolites (Barrie 1999), and several F-Ba vein systems have been linked to rifting, such as the Rio Grande rift and the Rhine Graben, although such rift systems do not necessarily require deeply rooted mantle processes (Hamilton 2003).

Deposit size is a key economic factor. Size distribution has been studied by a number of USGS researchers, beginning with the pioneering work of Cox and Singer (1986). Two distribution patterns have emerged: fractal and exceptional. A fractal distribution is observed for most hydrothermal deposits, reflecting continuity and similarity in the processes that created both small and giant deposits (Whiting et al. 1993). If mineral deposits are the result of growth and preservation (Veizer et al. 1989), then the dynamics of these fractal systems suggest that their size and distribution depend heavily on the rate of accumulation of ore, which is an almost unknown parameter for ore deposits at the present time. Exceptional distribution is observed in deposit systems that appear to be truly exceptional in size and scale, and must reflect extreme events in the Earth, like meteoritic impacts (Ni-Cu in Sudbury: Naldrett 2004; possible U in Athabaska: Duhamel et al. 2004), superplume events (Larson 1991), or major climatic events (e.g.

bauxite, manganese, iron). These deposits represent scalar breaks in both spatial (referring to size) and temporal distribution patterns.

MECHANISMS OF FORMATION

Three factors must be considered in the formation of mineral deposits: the source(s) of the ore elements, the transport mechanism of those elements (silicate melt or hydrothermal fluid), and the mode of deposition. These components constitute a system for which an external source of energy acts as the engine that drives the processes. Although the formation of a deposit begins at the source, our understanding of the processes involved usually operates in reverse by first deciphering the depositional conditions and then working backward to the source(s) of the ore elements.

Knowing the age of a deposit relative to its surroundings is typically the key factor in determining the mechanism of formation. The careful use of radiogenic isotope geochronometers represented a significant advancement in this area and resolved the considerable speculation surrounding the petrogenesis of various deposits, including Carlin-type deposits in Nevada (Tretbar et al. 2000); gold in Witwatersrand, South Africa (Kirk et al. 2002); laterites in New Caledonia (Samama 1986); vein-type fluorite deposits in France (Jébrak 1984; Marignac and Cuney 1999); and the multiple events that led to iron-rich formations (Powell et al. 1999).

Deposition

Our knowledge of ore deposition processes decreases with depth, which is why we have witnessed significant improvements in our understanding of two families of near-surface deposits: epithermal and submarine volcanogenic (exhalative) deposits. Both these deposit types have present-day analogues.

Epithermal mineralization includes gold and silver deposits associated with felsic volcanism in island and continental arcs. Mineral exploration has thus focused on Pacific regions during the past 20 years because they have hosted favourable geological environments since, at least, the early Mesozoic. Richard H. Sillitoe played a pivotal role by demonstrating how volcanic domains could be used in the exploration for epithermal gold and silver deposits (Sillitoe and Bonham 1986; Sillitoe 1994). The scales of the studies have also changed, moving from detailed mineralogical work (Barton et al. 1977) to the study of plutonic and volcanic complexes, and finally to a dynamically based understanding of systems through comparisons with active geothermal fields (Hedenquist and Lowenstern 1994; Sasaki et al. 2003).

The existence of black smokers was predicted by numerous observations in the Canadian Shield, Norway and Japan, but their discovery on the sea floor in 1978 represented the first direct observation of hydrothermal metal precipitation in a submarine setting (Francheteau et al. 1979; Rona 2003). It was one of the most important and exciting discoveries in metallogeny and it completely changed the direction of massive sulfide research (Fig. 2). Early studies in the 1970s helped decipher the stratigraphy of Archean VMS systems in the Rouyn-Noranda camp of Québec (de Rosen-Spence 1976). This set the groundwork for the years following the black smoker discovery when an understanding of the link between physical volcanology and ore deposition rapidly became an indispensable guide for finding volcanic centres and distinguishing different families of deposits (Dimroth et al. 1982; Morton and Franklin 1987). In France, the BRGM developed an exploration specialty for massive sulfide deposits by linking stratigraphy and alteration (Pouit 1989; Milési and Lescuyer 1993). This approach led them, along with the Mining and Metallurgical Company of Peñarroya and the Portuguese State Mining Company, to discover Neves Corvo, the biggest European copper deposit. Other work focused on processes that occurred beneath volcanic vents, and the study of alteration rapidly became an essential tool for delineating upwelling and downwelling convective cells related to ore formation (Franklin 1993; Barrie and Hannington 2000; Piché and Jébrak 2004). Understanding the mineralogical evolution of massive sulfides during the final stages of deposition ('zone refining' of Ohmoto 1996; Gibson et al. 2000) explained the distribution of economically viable zones within a deposit and helped predict where to look for them elsewhere. However, the role of biological processes–critical to petroleum geology and commonly leaving odorous traces in metallic deposits–remains poorly understood. We suffer from a segmentation of the disciplines that separates life sciences from the material sciences.

Of course, it is not always possible to use our present world to reconstruct the depositional conditions of ancient mineral deposits. We are aware that great variations have occurred in the history of our planet's climate, from very hot phases with a pronounced greenhouse effect (like that at the end of Cretaceous time), to possible "Snowball Earth" scenarios (like the one proposed for the Neoproterozoic; Hoffman et al. 1998). Each of these time intervals appears to have produced exceptional deposits, like the diamond-petroleum-gold association of the Cretaceous (Larson 1991).

Still other deposits form at great depth, which makes it impossible to use an actualistic approach. Advances in petrology will be crucial for understanding the formation of mantle-derived nickel, copper, chromium and PGE deposits (Naldrett 2004). The mechanisms of ore genesis for such deposits in layered complexes (Sudbury) and sills (Noril'sk) have now been modelled thanks to a number of experimental studies on magmas. A number of key factors played a role, including a better understanding of ore-element behaviour, an exponential increase in computing power, and the creation of specialized laboratories. How ore elements are concentrated, the duration of ore systems, and the reaction processes all remain subjects of debate. Fluid-reaction-path, geochemical modelling combined with hydrodynamic modelling may soon provide some of the answers.

Transport

One of the means of ore element transport is by **silicate magma**. The metals in nickel-copper, chromium and PGE deposits were transported by magmas, and the formation of magmatic deposits thus depends largely on magma history. It appears that the mechanisms are much more complex than originally imagined just 20 years ago. The sulfur in sulfide deposits, for example, is commonly of crustal origin (Arndt et al. 2003), and sulfur saturation is not related to the cooling of an enriched magma,

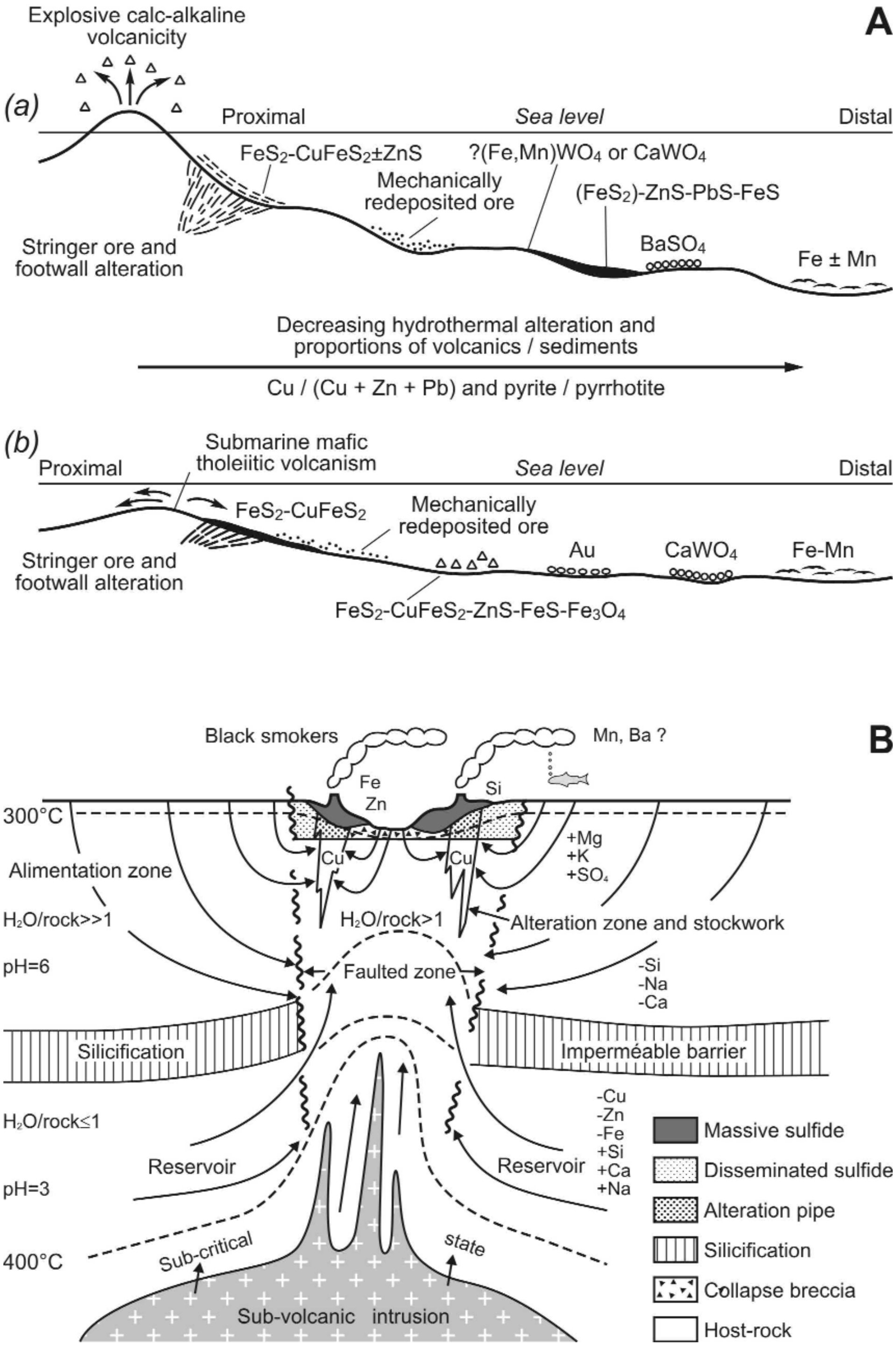

Figure 2. Representation of the evolution from (A) a rudimentary understanding of massive volcanogenic sulfide deposition (Guilbert and Park 1986), to (B) a predictive model of an exhalative system that integrates source, transportation and deposition (Eckstrand et al. 1995).

but to the interaction between magma and crustal rocks to produce sulfide immiscibility. It has also become apparent that crustal rocks must react with enough magma to scavenge sufficient quantities of metals (Naldrett 2004).

Hydrodynamic processes, such as differential settling of immiscible liquids or crystals due to density contrast, also favour metal concentration during silicate magma transport. It is a concept that applies equally well to massive sulfides (e.g. Voisey's Bay) as it does to chromite pockets in magma conduits (Leblanc and Nicolas 1992; Naldrett 2004).

The mechanisms that operate at the transition between magmatic and hydrothermal processes are also better understood (Hedenquist and Lowenstern 1994; Heinrich 2005). For example, two possible stages are now recognized in the boiling of magmatically derived fluids. First, H_2O saturation occurs by exsolution of an aqueous fluid to form a distinct phase in the silicate melt, at which point the fluid boils and gas bubbles form. In high-level systems at shallow depths, the necessary H_2O saturation can only be achieved after 10% crystallization (Candela 1997). A second boiling event may occur because of progressive crystallization of dominantly anhydrous minerals in more deep-seated magmatic systems at a relatively advanced stage.

Our understanding of **hydrothermal fluids** as transport agents for ore elements has benefited greatly from recent geochemical developments (Barnes 1997). Technological progress has been enormous in this field, spurred on by the computerization of all stages of the analytical process. Conditions of transport and deposition have also been quantified thanks to studies on fluid inclusions and mineral assemblage stabilities.

An excellent example of the progress in hydrothermal geochemistry is that of lead-zinc deposits in carbonate environments (Mississippi Valley-type deposits). In the 1960s, the prominent French team of P. Routhier, J. Bernard and J.C. Samama studied local deposits and suggested that emplacement was synchronous with sedimentation. The idea was shared by a number of stratiform base metal specialists around the world (Renfro 1974). After numerous debates, fluid inclusion work combined with isotopic dating and paleomagnetic studies eventually demonstrated that the deposits were clearly post-sedimentation and a product of fluid circulation in basins. The expertise of petroleum geologists proved to be an essential component in resolving the controversy given their sophisticated knowledge of how basin systems work. Garven (1985: Pine Point, Canada) and Bethke and Marshak (1990) proposed that Mississippi Valley-type deposits represent large-scale fluid migration in basins driven by orogenic processes. This model eventually became established and was applied to other ore-forming systems: uranium in Proterozoic basins (Hiatt et al. 2003); copper-cobalt in the red sandstones and shales of Michigan (Brown 1992) and the Zambian Copperbelt (McGowan et al. 2003); and even emeralds in Andean basins (Branquet et al. 1999). On the other hand, the debate is hardly over for unconformity uranium deposits (Dahlkamp 1993). Several uranium deposits grading more than 15% U_3O_8 were discovered in the Athabaska basin (e.g. Cigar Lake, McArthur; Fouques et al. 1986). Either of the two end-member metallogenic models may apply: oxidizing U-transporting basin fluids reacted with basement graphite to create methane, thus prompting U precipitation during peak diagenesis (Fayek and Kyser 1997); or U-transporting brines percolated deeply in the basement and became part of a protracted series of hydrothermal events (Cuney et al. 2003).

There is still much to be done to improve our understanding of ore element transport mechanisms. Today's distinct advantage is that existing technologies have become increasingly efficient. Cryometric and thermometric techniques for fluid inclusions –still standard after almost 50 years (Roedder 1984)– have improved through the application of multi-method analytical techniques to determine the contents of a group of fluid inclusions or even single inclusions. We will soon know the metal contents of most hydrothermal fluids, thanks to new analytical methods (Rowins et al. 2002), and this will provide remarkably better constraints on the conditions of metal transport.

In other respects, our understanding of fluid movement has greatly improved thanks to advances in the field of crustal permeability. It was just 20 years ago that we were beginning to imagine the depths at which fluids could be found in the crust, and today's advanced understanding of the hydrogeology of mid-crustal rocks is the result of considerable work by structural geologists and geophysicists. In orogenic systems, detailed field observations of gold deposits (Robert and Brown 1986) produced a model of seismic pumping (Sibson et al. 1988; Jébrak 1997; Cox et al. 2000) that links seismic activity and regional metamorphism to the episodic circulation of deep fluids in fractured basement rocks (Kerrich and Ludden 2000; Groves et al. 2003). In basins, metallogenists follow in the footsteps of petroleum geologists, albeit several years behind, by modelling the migration of ancient and modern fluid systems with ever greater precision (Kyser 2000).

It was long believed that only liquids could transport metals (e.g. Candela 1997), yet recent discoveries have thrown this axiom into question. It is now known that ore elements can also be transported in **gas phases**, and it is becoming increasingly evident that gases play a significant–perhaps essential–role in the formation of some base and precious metal deposits. The following examples illustrate the emergence of this new paradigm.

- ***Platinum:*** The formation of platinum deposits was traditionally attributed to the arrival of upper mantle magma in the upper crust. Several deposits cannot, however, be explained by direct crystallization from magma. The Lac des Isles deposit in Ontario, for example, has demonstrated the importance of hydrothermal processes during late magmatic mobilization of platinum group elements (Lavigne and Michaud 2001), an idea that was already well documented by Soviet metallogenists. However, the recent experimental work of Peregoedova et al. (2004) demonstrates that even PGEs can be mobilized as gas phases at high temperatures.
- ***Gold, silver and copper:*** Volcanic systems give rise to major deposits of gold and copper in volcanic arcs, including copper and molybdenum porphyries, and gold and silver epithermal deposits. The origin of these deposits has traditionally been attributed to the circulation of hypersaline fluids, enriched by successive boiling phases that concentrate the metals in the residual phase. Carbon dioxide is recognized as being important in deep systems (Baker 2002), and the amount of sulfur emitted by volcanoes can be so great that it affects the climate. Fluid inclusion studies and geochemical studies have established the possibility of gaseous transport for these metals (Heinrich et al. 1993; Rowins et al. 2002; Williams-Jones et al. 2002), and Yudosvskaya et al. (2006) have identified a modern example (the Kudryavi volcano, Kurile Archipelago, Russia) that is characterized by surface fumaroles depositing gold, silver and copper. Finally, it has been confirmed that a number of breccia bodies may have formed by fluidizing processes, thus implying that fluids transported the metals, possibly as high-speed gases.
- ***Zinc and lead:*** The most important base-metal deposits in sedimentary environments are associated with exhalative phenomena related to submarine thermal sources. It appears that the origin of these deposits may be linked to mud volcanoes that are produced by degassing of organically generated CO_2 and CH_4 (Slack et al. 1998). Mud volcanoes are abundant around the Caspian Sea and recent studies reveal that their importance has been largely underestimated in terms of their metal transport capacities and their ability to affect the atmosphere (Etiope et al. 2004).

The role of gases in the formation of ore deposits is thus a developing field of study that could significantly boost our current understanding of ore deposits. In some ways, the current models resurrect the pneumatolytic hypotheses developed by metallogenists in the 1960s (e.g. Raguin 1961), who did not have the necessary tools to advance their ideas at the time.

Sources

The source of ore elements has been debated since the first confrontations between Plutonists and Neptunists about 220 years ago, and the debate continues to this day. A unique source certainly does not exist; instead, multiple sources are proposed, in some cases even for a single deposit. It is also thought that the transport medium can be independent of the ore-element source. For example, meteoric waters can transport magmatic copper, and diamonds can be collected by passing kimberlite magma that originated at much greater depth (Haggerty 1986).

Geochemical methods, particularly isotopic methods, have played an essential role in the debate about where ore elements originate. The proliferation of lithogeochemical analyses has created enormous volumes of data–hundreds of thousands of assays for each of the large geological provinces–and Stanton (1994) used such data to demonstrate that a genetic relationship exists between lava composition and the nature of related ores. Some felsic magmas appear particularly fertile (Carlile and Mitchell 1994; Thiéblemont et al. 1997; Mungall 2002), but their fertility may also be explained by crystallization processes or mixing.

The widespread use of oxygen, hydrogen, sulfur and carbon isotopes allows today's geologists to distinguish among surficial, oceanic, magmatic, and mantle sources of fluids that transport ore elements. As a result, we now know that the sulfur in nickel-copper deposits is of crustal origin, whereas the sulfur in zinciferous shale deposits is oceanic (Sangster 1990). But, the same certainty cannot be applied to mantle sources: we still wonder if it is necessary to have a concentrated source in the mantle to produce an ore deposit, or if a combination of geochemical and hydrological processes will lead to an economic accumulation. In all likelihood, there is no universal answer. Isotopic research has provided surprises too, one of the most recent being that the largest barite deposits in the world are most likely of biogenic origin (Torres et al. 2003). Other mysteries regarding ore element sources will undoubtedly be solved soon when iron, copper and molybdenum isotopic methods, currently under development (Rouxel et al. 2004), begin to provide insights about ore element reservoirs, something that traditional oxygen and hydrogen isotopic work cannot do.

To better understand how ore deposits form, it is also necessary to study the sources of the ore elements. Some are inaccessible, which explains why the genesis of carrier magmas is so poorly understood, especially in subduction settings. Basic questions still need to be answered:

- What is the composition of the lithospheric root?
- Is it necessary to pre-concentrate metals to form an ore deposit, and do such pre-concentrations even exist in some reservoirs?
- How does mineral partitioning occur, especially at the nanometre scale?

Detailed geophysical surveys and the geochemical analyses of inclusions, brought to the surface via mantle magmatism, have the potential to considerably enlighten us on the subject of source environments. As much as our understanding of the mantle has greatly improved during the past twenty years, plenty of work remains for geochemists and geophysicists.

METALLOGENY AND GEODYNAMICS

During the last two decades, the scale of metallogenic studies has continued to grow, covering increasingly vast regions of the Earth. Fortunately, the development of geodynamics as a discipline has led to an improved understanding of a number of deposit types. For example, it was determined early on that exhalative deposits follow a geodynamic pattern, where copper deposits are oceanic and lead-zinc deposits are more continental (Hutchinson 1982; Large 1992). Vein-type gold deposits were also integrated into their seismological and orogenic contexts (Cox et al. 2000; Goldfarb et al. 2001). Yet this approach could not explain the temporal distribution of deposits, i.e. why particular epochs, like the late Archean or Cretaceous, show a distinct tendency to have more deposits than others.

Two important fields of study, climate-related ore formation and ore deposit research in the context of mantle dynamics, have emerged in the last ten years, which will provide the keys to answering some of the remaining dilemmas. The past decade saw a strong reversal of actualism in favour of a more complex vision of the climatic system. It began more than 20 years ago when the classifications of Gross (1980) and James and Trendall (1982) helped us understand that Lake Superior-type iron formations are evidence of an atmosphere that became increasingly oxidizing during Proterozoic time–the great rust age that remains to this day the best example of atmospheric pollution by living organisms–and from this realization was born the field of atmospheric and oceanic geology (Berner 2001; Holland 2002). Periods of cooling have also been recently linked to oceanic geochemistry and the formation of deposits (e.g. manganese). We can now tackle the issue of continental climates and contemplate the consequences of a 70°C average atmospheric temperature in Archean time.

Since the beginning of plate tectonic theory, it has been accepted that plate movement was surficial and that stationary hot spots existed, most likely rooted at great depth. The last few years have witnessed some important advances in this field (Courtillot et al. 2003; Anderson 2006), and it now appears that it may be necessary to invoke two styles of convection to account for deep plutonism: fairly surficial convection that represents the causal mechanism for plate tectonics, and deeper convection marked by sub-stationary hot spots capable of transferring material from the core-mantle boundary.

The early work on hot spots concentrated on long intra-oceanic chains, like the Hawaiian-Emperor seamount chain, which proved to be fairly barren in terms of economic mineralization. The ban on mineral exploration in Yellowstone National Park in the United States also hindered the recognition of a link between epithermal mineralization, geothermal gradient and hot spots. Nevertheless, the relationship between hot spots and mineralization was eventually established and documentation is continually improving (Pirajno 2000, 2004; Fig. 3). Hot spot basaltic magmatism is now seen as the most likely cause of giant komatiitic Ni-Cu deposits in the Archean, and Norilsk-type deposits in the Paleozoic (Yakubchuk and Nikishin 2004). Concentrations of platinum group elements and chromite accumulate in the plutonic chambers underlying these immense mafic complexes. If the hot spot causes melting of continental crust, a volcano-plutonic system will develop (like that of Yellowstone) generating both high and low-sulfidation epithermal mineralization with the probability of additional porphyry systems at depth. It was even proposed at one point that the Yellowstone hot spot caused regional hydrothermal fluid flow that produced the deposits of the Carlin district (Glen and Ponce 2002), but isotopic ages subsequently refuted this hypothesis. If the region is submerged during hot spot activity, then volcano-sedimentary deposits (the submarine equivalent of epithermal deposits) may develop in association with high-temperature rhyolites erupting over the hot spot (Barrie and Hannington 2000).

With this in mind, it seems that giant mineral deposits could be indicators of extraordinary terrestrial condi-

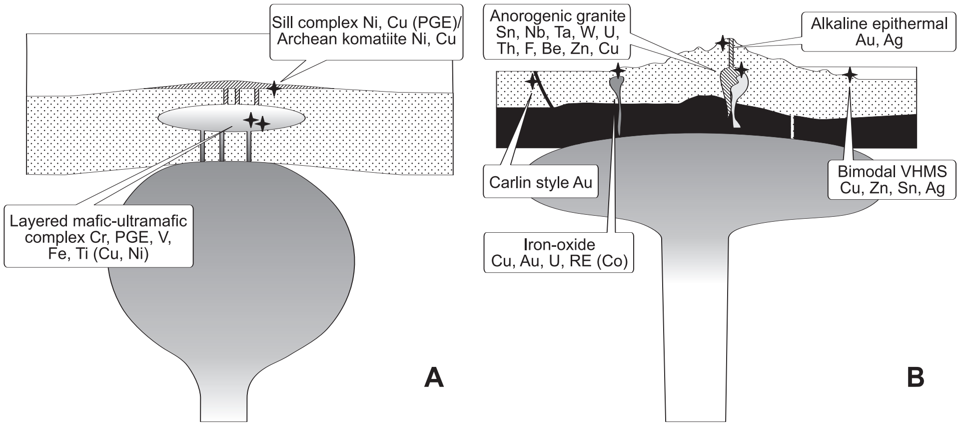

Figure 3. Examples of mineralization associated with an emerging hot spot. (A) oceanic environment; (B) continental environment.

tions – the result of global-scale events. Moments in Earth's history marked by superplume episodes completely disrupted the planetary landscape-from the bottoms of the ocean right to the atmosphere-leading to the formation of a variety of deposits. It is a fact that invalidates any purely actualistic notions (Condie 2001).

DISCUSSION

Until the middle of the 20th century, economic geology was basically empirical, as evidenced by haphazard mining discoveries and perplexed musings on the oddity of sufide minerals in silicate gangue. Deposits were seen as localized events, a view that prevented any real understanding of their underlying patterns.

It is evident that ore deposit formation can be linked to the six stages (magmatism, erosion, transport, deposition, lithification and metamorphism) of the rock cycle (Fig. 4). The link between ore deposits and orogeny was popular in the 1930s, whereas the link with sedimentology was the main focus of the 1960s. The role of plate tectonics in ore-forming processes was a hot topic beginning in the 1970s (Sillitoe 1972; Mitchell and Garson 1981; Sawkins 1984) and not only established a new concept of mountain building, but also a real understanding of oceanic processes and hydrothermal systems. It was only at the end of the 1980s that the role of the climate began to be truly recognized and taken into account (Samama 1986), and finally, the new millennium signals a new era that will focus on the role of the mantle (Pirajno 2000, 2004; Ernst and Buchan 2001).

Empirical observations of ore deposits began in the 16th century (Rabinovitch 2000), but it was only in the 19th century that a genetic classification stage finally superseded purely descriptive work. During the second half of the 20th century, we embarked on a new phase of ore deposit science when theoretical studies were reconciled with the pragmatic needs of the mineral exploration industry. Simulations of ore-forming processes were developed, including geochemical simulations that predict the composition of fluids and rocks in equilibrium (Barnes 1997), thermal simulations that estimate the duration of the convective phase (Barrie 1999), and geometric simulations that will ultimately allow us to predict the size of a deposit (Oliver et al. 1999).

One day it will be possible to simulate the complete formation of an orebody, and in so doing, predict its

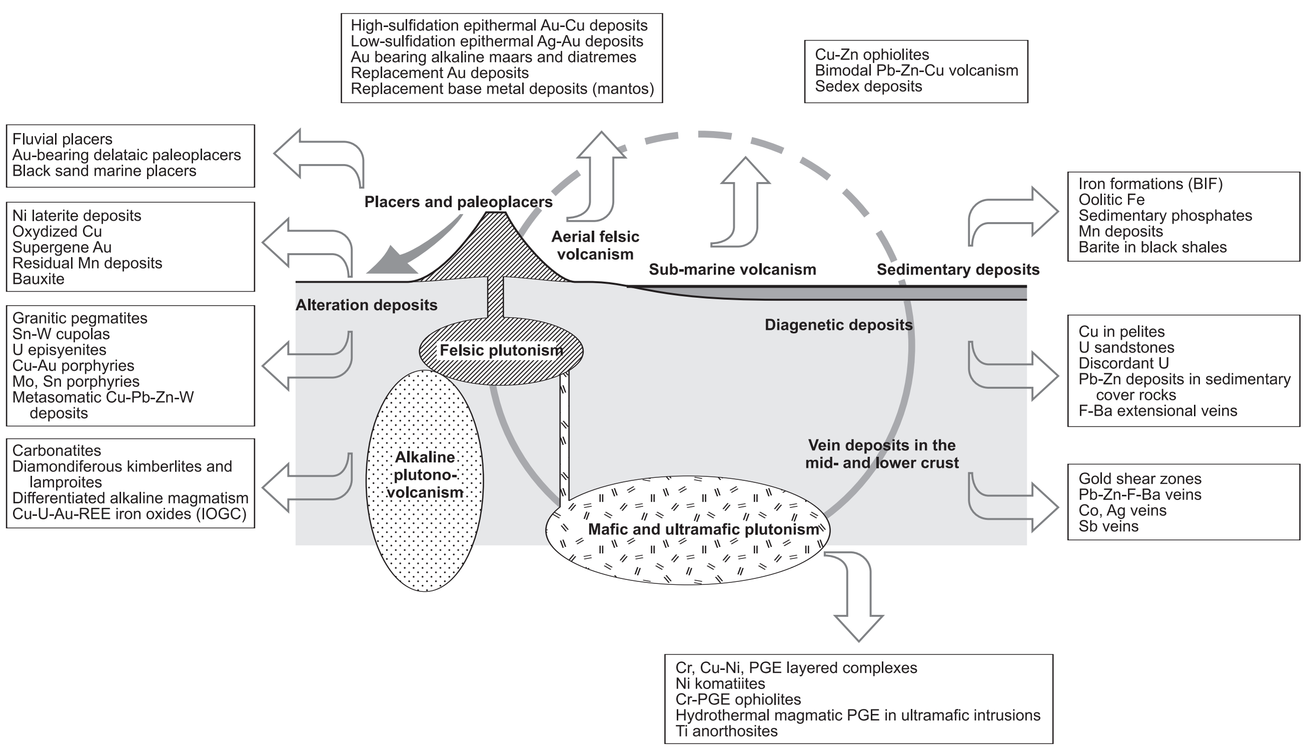

Figure 4. Positions of the main deposit types according to the rock cycle. Not to scale.

location in real space. The evolution of economic geology from description to simulation (Fig. 2) represents a fairly classic epistemological history. The history of climatology is similar in many ways, moving from the description of clouds to forecasting weather systems. However, the uncertainties that are the hallmark of field-based sciences still remain (Stengers 1994).

Economic geology in the 21st century will continue to show progress in our understanding of increasingly large systems, in our analysis of central issues in ore deposit genesis, and in the development of analytical tools that outperform their predecessors. In response to the challenges faced by the industry, it will be necessary to tie mineral systems to exploration methods (McCuaig and Hronsky 2000); analyzing the geometry of fluid transport systems in greater detail is one such example. Simulations will lead to predictions, undoubtedly still modest in scope yet continually evolving thanks to increasing computing power. And today's unconventional deposits, discovered through serendipity, will become the classic deposit of the future. The dialogue between explorationists and metallogenists is certainly here to stay!

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