Is Metallogeny a Practical Exploration Tool?

by G. Rex Davis

This article, based on a keynote address to the recent MEGS V Conference in Dubrovnik, is a personal review of the application of metallogenic concepts to the exploration of minerals. The aim is to assist in making the most cost-effective use of metallogenic theory in prospecting for new mineral fields and exploring for additional resources in established mining districts. Practical and philosophical aspects of metallogenic research are also being addressed by the IUGS-Unesco Mineral Deposit Modelling Program. (Ed.)

Introduction

The genesis of mineral deposits and their relationships with the total geological environment is, by definition, the subject of metallogeny. Geological, tectonic and metallogenic maps provide a helpful scientific basis for mineral exploration, and mineral explorers may elect also to apply metallogenic theories as guides to undiscovered mineralization. There are now many such theories based upon a multitude of geophysical and geochemical data, yet the genesis of most classes of mineral deposit remains controversial. Furthermore, little credit for new mineral discoveries appears to be given to metallogenic studies, at least in comparison to that accorded to applications of geophysics and geochemistry. Is this general lack of credit for the theoretical basis of mineral exploration justified, or are geologists simply not active enough in highlighting the part played by conceptual thinking in the successes and failures of mineral exploration?

Although the exploration industry has successfully met society's increasing demands for minerals in recent times, less than 1 in 50 prospects develops into a mine, and not all producers bring economic returns on investment. In attempting to optimize the successful discovery rate per exploration dollar risked, those in charge must consider various management options. These include the effectiveness of the search techniques used in locating any mineralization that exists within the target area, and the predictive quality and precision of the conceptual model of where mineralization will be found. Both components are normally involved, but marked emphasis may be placed on one or the other.

Some enthusiastic theorists would like to see every exploration program based upon conceptual metallogenic models, whereas some sceptical managers discount contentious theories and pin their hopes for cost-effective discoveries on saturating target regions with search techniques such as geophysical surveys or drainage surveys using heavy minerals or trace element geochemistry. In any case, all mineral search is based upon favoured ideas of where mineralization may be found by following critical clues, whether these be the twist of the divining rod, grains of gold panned from streams, mappable metalotects (i.e. observed associations of mineralization) such as controlling shear zones, or metallogenic theories such as hydrothermal convection cells associated with subduction zones. Our predictive skills have certainly improved, but discoveries based primarily on metallogenic theory are not yet commonplace.

Some Guiding Rules

My own experience suggests a series of "rules" that should be followed to improve exploration performance by optimizing the application of increasing technical knowledge. These are as follows:

- Sound and unbiased field and laboratory observations and measurements are the foundation stones on which to build.
- Data should be critically appraised before accepting current interpretations and authoritarian theories.
- Data for which no coherent genetic mechanism is apparent should not be discarded, but continually reviewed.
- When exploration progress is slow, seek and test alternative genetic models for guidance.
- Persistence often brings rewards if all data continue to make good geological sense.
- Be receptive to unexpected experimental results.
- When a revised and better genetic concept emerges, apply it to extend exploration programs.

These rules are some of the basic tenets of science, but by their very simplicity they may easily be overlooked in routine day-to-day exploration, as illustrated in the following examples.

Neves Corvo

Copper production will shortly commence from the high-quality polymetallic sulphide deposit of Neves Corvo, in the Portuguese sector of the Iberian pyrite belt (Fig. 1). This concealed mineralization was discovered by drilling in 1977, following an unsuccessful drillhole of four years earlier. The part played in this important discovery by geological observation and inference, and particularly by metallogenic theory, is not as clear as it might be.

A senior geologist of Rio Tinto Zinc Corporation, one of the owners, notes that the discovery "came about because a geophysicist realized that a certain borehole had not accounted for the gravity anomaly it was supposed to test and insisted on having it deepened" (Morrissey, 1980). He goes on to regret that the discovery "has come to be regarded as a fortuitous bonanza and a triumph for geophysics, whereas it could have been hailed as a vindication of the conceptual approach to targeting a high quality copper deposit," for with hindsight it can be seen that known geological data made such a discovery predictable. On the other hand, a local geologist credits the discovery to careful core logging in the light of modern knowledge and concepts, which placed the position of a sulphide ore source deeper than the hole drilled to test the gravity anomaly.

Leca (1980) describes the three phases of prospecting from inception in 1969 to discovery in 1977. The first phase, based on gravimetry (1969 - 1973), ended with the first

Figure 1: Location and geological setting of the Neves Corvo deposit. N2 was the discovery hole drilled in 1977 after the 1973 hole (N1) had failed. After Leca (1985).

drillhole. A second phase (1973 - 1977) involved the collection and synthesis of geochemical, geophysical and geological data including lithostratigraphic, paleogeographic and tectonic studies, and the third phase was that of successful drilling. Leca concludes that "without geophysics, Neves Corvo would not have been discovered, but neither would geophysics alone have led to its discovery." He stresses the use of a variety of prospecting methods and of the accumulated geological knowledge of the mineralized environment of the Iberian pyrite belt.

What is impressive at Neves Corvo is the persistence in the application of geological knowledge and the insistence that all data should make geological sense. Without this, the discovery might not have been made. The dramatic change in metallogenic concepts concerning the origin and controlling features of massive sulphides associated with acid volcanic rocks stemmed in part from the critical recognition by Williams (1962) that the Rio Tinto porphyry was not an intrusive but an extrusive rock. The geological thinking engendered by those new metallogenic concepts must have played an important part in the exploration success at Neves Corvo and enhanced the process of unbiased geological observation and critical appraisal of all data. This contribution seems to have been insufficiently recognized in explicit terms in the literature.

A further observation is that at Neves Corvo, as at many other discoveries, there appears to be lack of unanimity, perhaps even some degree of confusion, regarding credits for discovery, even among those closely concerned with the

ore deposit not long after the discovery date. The recorded history of discovery of many ore deposits is, unfortunately, beset with uncertainties and rival claims concerning the relative contributions of various factors to success or failure. However, in the examples that follow I can assess from my own experience the relative contribution of metallogenic theory to effective exploration.

Lessons from the Zambian Copperbelt

Most of the lessons on my list were brought home to me as a young geologist on the Zambian Copperbelt. Underground observations at the Roan Antelope mine led me to doubt (Davis, 1954) the prevailing view of ore genesis by hydrothermal activity due to nearby granite or basic intrusives. The lines of evidence and argument that support the contrary synsedimentary view need not be repeated here for they are now well known. There are, however, some relevant lessons.

The first two are that precise field observations are all-important, and that current views, however authoritarian, must be critically assessed before accepting genetic theories that influence one's approach to mineral exploration. For example, one item of evidence that was cited as favouring an epigenetic hydrothermal origin for the Roan orebody was the rare "diagrammatic crystallographic intergrowth" of chalcopyrite and bornite (Fig. 2), interpreted in the literature (Schwartz, 1942) at that time as a criterion of exsolution by rapid cooling from a temperature of 475°C. Field observation and a search of the literature, however, indicated that the microtexture at Roan Antelope could be formed also under conditions of supergene enrichment. The interpretation of laboratory data, such as stable isotope analyses, especially if backed by authoritarian academic opinion, will at times conflict with field evidence, and proper scientific scepticism must be exercised if the geologist is to be released from constraints on the conceptual thinking that guides exploration decisions.

Changes in ideas on metallogeny of the bedded Zambian sulphides, unpopular at the time, led me during the middle 1950s into regional exploration for similar mineralization in the largely unmapped reaches of southwestern Zambia. The application of known metallogenetic - notably sedimentary variations not far above a basement unconformity - together

Figure 2: A photomicrograph with the oil immersion lens showing a crystallographic intergrowth of chalcopyrite laths in bornite. This may result from exsolution at high temperatures or from low-temperature supergene processes. Field of view is 0.25 mm wide.

with applied geochemistry and reconnaissance geological mapping, resulted in the discovery, in a remote area, of weakly mineralized sediments of Copperbelt type – a technical though not a commercial success. This led in turn, on the basis of the same metallogenic philosophy, to a reconnaissance for bedded copper deposits of similar age in Namibia. During the 1950s a promising area was promptly identified (Fig. 3), and when economic conditions became favourable a decade later, the Oamites mine was opened on one of the prospects in the area.

Figure 3: Copper-stained sediments are host to the Oamites copper-silver deposit in Namibia, south of Windhoek.

the 1950s on sedimentary and diagenetic processes, through the new appreciation of volcanic processes in the 1960s and the plate tectonics age of the 1970s into a new view of magmatism. The pendulum will no doubt continue to swing, but inconvenient facts should never be swept under the carpet. There is no better example of this than the denial by many scientists of the evidence for continental drift until the new global tectonics provided a convenient mechanism for embracing that same evidence.

Another example of the limitations imposed by favourite theories is the discovery in the early 1960s of nickel sulphide orebodies in ultramafic rocks in Australia and Zimbabwe. Geologists of at least one major company declined at first to take the new prospects seriously because of their misplaced conviction that nickel sulphide orebodies are confined to layered gabbroic bodies of Sudbury type. Others were similarly reluctant to accept the economic importance of lamproites discovered in Australia, because they believed kimberlite to be the sole host rock for diamonds. Failure to admit good field evidence simply because of a perceived lack of a coherent genetic mechanism is a dangerous philosophical trap.

Studies of metallogenic provinces and epochs, and of the distribution of mineralization in space and time, have now brought us to the realization that mineralization is seldom an isolated event, but rather one result from a dynamic system linking magmatism, orogeny and sedimentation in complex ways. To guide exploration to best advantage the entire system should be investigated and understood as far as possible.

Figure 4: The relative popularity of Pluto and Neptune in ore genesis theory continues to change over the years. From Mackay (1954).

One might argue that metallogenic theory had nothing to do with these discoveries, and that all was achieved by the application of metallotects and of search techniques to find Copperbelt look-alikes. However, metallogenic theory contributed the important factors of philosophical confidence and overall geological guidance at a time when a prominent mining geologist in the U.S.A. was advising the Society of Economic Geologists that "an exploration program based upon a magmatic theory of origin would have found most of the important known non-ferrous metal deposits of the world" (Sales, 1960).

The Pendulum of Opinion

There are always pressures of authoritarian opinion upon mining and exploration geologists to be led by prevailing and popular metallogenic theories. But the trend of opinion may swing in time like a pendulum, as older geologists will appreciate, and as shown by the sort of historical comparison made by Mackay in 1954. His curve (Fig. 4) can be extended to the present day, swinging past the emphasis in

An example of changing trends in metallogenic theory, and an appreciation of the entire ore-forming system, is provided by that greatest of mineral fields, the Witwatersrand basin. Dominant views on the origin of its uranium and gold mineralization have swung, amidst great controversy, between hydrothermalist and placerist. Current research is concerned with the possibility that the source rocks are hydrothermally altered granites from the hinterland of the basin

rather than Archaean greenstone belts farther afield (Klemm and Hallbauer, 1987; Robb and Meyer, 1987). This work highlights once again the role played by magmatism and the associated tectonic activity. The Witwatersrand mine geologist successfully applies sedimentary controls to the search for ore, but the prospector searching the globe for a similar mineralized sedimentary basin cannot afford to ignore metallogenic theories concerning the nature of the source rock.

A Lesson from Kilembe

Finding extensions to ore reserves is relatively difficult in deposits that are small, economically marginal, and altered. Application of the correct theories of ore control and metallogeny here are correspondingly more important to exploration success. The practical importance of considering and testing alternative genetic models was brought home to me by the exploration and development of the Kilembe Cu-Co sulphide prospect in the Ruwenzori Mountains of Uganda.

By the end of 1949, funds for underground exploration and drilling were drying up at the sulphide prospect, termination was in sight, and a geological breakthrough was needed to

boost the financial incentive. This came the next year when a new concept of the metallogenesis was successfully tested by a surface drillhole. By 1949 the pyritic mineralization, though metamorphosed, strongly folded, sneared and faulted, had been recognized as layered. The exploration philosophy, however, was based upon ore genesis centered on shear zones and masses of alaskite pegmatites (Fig. 5).

Figure 5: Kilembe, Uganda. A - The ore zones, were, initially considered to be genetically related to shear zones and alaskite pegmatites; B - A broader mining opportunity followed recognition of Kilembe ore as tectonized stratabound sulphide ore. From Davis (1967).

Recognition in the field of a pre-shearing age to layered mineralization, structural overturning in a critical exposure of ore, and a metamorphic origin for the alaskite pegmatites, led to a revised exploration philosophy. This resulted first in definition of ore reserves sufficient to support the development of a mine, and then in regional prospecting, which identified signs of Kilembe-style mineralization for 30 km westwards to Zaire and even farther eastwards (Davis, 1967). Kilembe provides an example of the value of testing more than one concept of ore formation in cases where extensions to known deposits are difficult to find.

Saudi Arabia

The acid test for the practical usefulness of metallogeny lies in its predictive application to the search for undiscovered mineral deposits and orefields. Many such attempts are not greeted by immediate success, but persistence in prospecting may be encouraged if sound geological sense results from early phases of work. An example of this is the reconnaissance during the late 1970s of the Phanerozoic cover rock sequences of Saudi Arabia, based on metallogenic concepts of carbonate-hosted Zn-Pb mineralization. The work was conducted under contract to the Government of Saudi Arabia by a team from Imperial College London (U.K.), based on a proposal from the writer in 1973.

A review of apparent controlling ore associations worldwide led to the conclusion that the Saudi cover rocks constituted a prospective geological environment, although no base metal mineralization was known. Information then recorded

about these cover rocks indicated a reasonable match with some regional associations of carbonate-hosted orefields (Davis and Morrissey, 1976). The latter occur typically in shallow water Paleozoic and Mesozoic marine carbonates on the flanks of large and long-lived sedimentary basins. The basins contain evaporite sequences and hydrocarbon fields with marked spatial relationships to structural and erosional highs involving the Precambrian basement, and in places, to major faults or tectonic lineaments. There are also associations with dolomite, unconformities and rapid facies changes.

The metallogenesis of carbonate-hosted Pb-Zn deposits was at that time, as it still is today, a subject of active controversy world-wide, including European examples in Ireland, Spain, Sardinia, Poland, and the belt at the borders of Austria-Italy-Yugoslavia. The preferred metallogenic model adopted by the Imperial College team involved a close association between oil and ore, including a single-fluid, basinal brine emulsion charged with hydrocarbons, sulphur and metals (Dunsmore and Shearman, 1977). This model implies derivation of metals and hydrocarbons from the same source rocks, which might be carbonate-sabkha sequences, with hydrocarbon and ore fluids driven by the same forces along similar subsurface migration paths. It also implies a corrosive fluid capable under certain conditions of dolomitization, attacking carbonate rocks by exothermic reaction between sulphates and hydrocarbons, and precipitating sulphur and metal sulphides.

Reconnaissance work (Fig. 6) between 1979 and 1981 produced several lines of evidence that enhanced the prospectivity of the geological environment (Davis and Shearman, in press.) However, the Imperial College team and others found no direct visual or geochemical indication of base metal mineralization over a strike distance of about 900 km. The sceptic might say that the lesson learned from this exercise is that effort should not be wasted on theoretical considerations. However, another common lesson in prospecting is the value of persistence - the story is seldom told in a single chapter.

In 1985, Broomhall and Allan reported, at depth in the Saudi cover rocks, large areas of transgressive dolomitization that destroyed potential petroleum reservoir caprocks, accompanied by solution collapse and mineralization of pyrite, sphalerite, fluorite and anhydrite. Fluid inclusions in sparry dolomite contain hydrocarbon, and salinity averages 233,000 ppm with filling temperatures between 102° and 155°C. This discovery conforms with the metallogenic model, and Broomhall and Allan regard it as "most likely formed by the same processes which produce carbonate-hosted lead-zinc mineralization."

Figure 6: Jurassic carbonate rocks of the Tuwaig Mountain Limestone tower 450 m above sediments of the Dhurma and Marrat Formations at Wadi Birk in central Saudi Arabia.

The Saudi Arabian exercise also illustrates one other possible benefit from the application of metallogenic studies. During the course of geological and geochemical reconnaissance by Riofinex Limited (as contractors to the Saudi Arabian Deputy Minister for Mineral Resources), it was discovered that a recorded but long-overlooked occurrence of bauxitic clay was in fact an extensive paleobauxite horizon, which exploration soon showed to be of economic interest. Such tales of the unexpected are not rare in prospecting, but to attribute them to luck would fail to give credit both to the enterprise that placed the geologist in position to make the serendipitous discovery, and to a wide-awake attitude in the field.

The Olympic Dam Deposit

Perhaps the most spectacular tale of an unexpected result from scientific prospecting based on application of predictive theoretical modelling was the discovery by Western Mining Limited of the great Olympic Dam deposit under 350 m of barren cover sediments of the Stuart Shelf in South Australia. To test a carefully researched metallogenic concept of sediment-hosted copper associated with source rocks of basaltic lavas, stratigraphic drilling was targeted on a suitable area of coincident magnetic and gravity geophysical anomalies, and intersected ferruginous breccias with associated mineralization of copper, gold, uranium and rare earths. The discovery has now been shown to be one of the world's greatest orebodies in extent and thickness, and one of the most intriguing since it represents a type of ore new to science (Roberts, 1986).

Metallogenic explanation and speculation, as in the case of other discoveries of new ore types, can necessarily follow only after field and laboratory observations of the host and

enclosing rocks and structures provide a sufficient clue to the geological environment of ore formation. This topic has doubtless already exercised the minds of prospecting companies who hope to find a Roxby Downs look-alike deposit on the basis of rock recognition, geophysical anomalies, and a preferred genetic model.

Figure 8: Mining of stratabound gold at Telfer, Western Australia, has revealed the domed structure of the host sediments.

New Challenges in Metallogeny

Olympic Dam is by no means the only surprising challenge that has been brought to metallogeny by prospecting and exploration discoveries in recent times. Several examples may be quoted of relatively recent discoveries of new ore types of gold alone, a metal now being actively sought everywhere because of the higher market price and improved mining costs and technology. The first is the occurrence of gold at currently economic levels in laterite at Boddington, Western Australia, where the discovery was associated with mining of bauxite (Fig. 7). What are the factors controlling the concentration of gold in near surface geological environments, and the conditions under which it may be remobilized and re-precipitated, so that we can

Figure 7: Multi-layered concentrations of gold in clay-laterite horizons developed on an Archaean greenstone belt, Boddington, Western Australia. After BHP (1987) and Davy and El-Ansary (1986).

Figure 9: The geological setting at Telfer poses a typical metallogenic problem that bears on exploration strategy. After BHP (1987).

predict further sites for mineralization of Boddington and related types?

Another example is Telfer in Western Australia. The main gold mineralization, first staked in 1972 (Tyrwhitt, 1985), occupies a structural dome in stratabound style (Fig. 8, 9) in Proterozoic sediments intruded by granite. Metallogenic study has yet to resolve the controversy, evident to some extent even from the geological outline map, as to whether further orebodies should be sought in the region on the prime basis of stratigraphic control, or of intrusive granites, or perhaps of subsurface structure and hydro-fracture related to the fluid dynamics of rising basinal fluids.

A further example is the Loulo deposit in Mali, where gold occurs in a quartz-carbonate-pyrite stockwork confined to a tourmalinized Birrimian sandstone (Dommanget et al., 1985). This is interpreted by the authors as an exhalation type stratiform stockwork. Will this new occurrence lead to discovery of gold deposits elsewhere?

There are also the discoveries of epithermal gold deposits now making headlines from the western Pacific island arcs. Our knowledge of tectonics, magmatism and volcanism associated with the active plate margins of that region has grown apace, as have metallogenic theories concerning the physics and chemistry of hydrothermal systems, where the old antagonists Pluto and Neptune are now seen to have been working together. It is to be hoped that at least some of the sites of future discoveries will have been specifically targeted by application of metallogenic theory as well as by exploration technologies.

Conclusions

I believe that geologists should be devoting more attention to the critical application of their metallogenic concepts in exploration, and giving more publicity to the contribution made by conceptual thinking. In doing so, the approach should not be oversold by over enthusiastic claims for

genetic models, but confidence should be maintained and enhanced through a sound and critical scientific approach, neither arrogant nor complacent.

Science generally progresses from concept to experiment, the results of which can lead to revision of the concept. In the case of Neves Corvo, the concept of massive sulphide ore as the cause of a gravity anomaly was followed by an experimental borehole, the failed results of which produced a revised concept tested successfully in the next experiment. This spiral of progress is a dynamic pathway, complex and strewn with pitfalls, and easily broken at any point. For metallogeny it has come through many cycles and, no doubt, still has many exciting turns to go.

Though very few publications claim the successful predictive use in exploration of metallogenic theories, the examples reviewed here suggest a significant potential contribution from metallogenic research. Publication of case histories should emphasize to the entire exploration industry the likely practical benefits of metallogenic research, and the need to provide facilities to stimulate that research.

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