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Uses (and Abuses) of Ore Deposit Models in Mineral Exploration

C. J. Hogson

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Article abstract

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Uses (and Abuses) of Ore Deposit Models in Mineral Exploration

C.J. Hodgson
Department of Geological Sciences
Queen's University
Kingston, Ontario K7L 3N6

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Abstract

An ore deposit model is a conceptual and/or empirical standard, embodying both the descriptive features of the deposit type, and an explanation of these features in terms of geological processes. The descriptive features of models serve as criteria for exploration area selection ("area selection criteria"). How they are used in this function depends on the scale of their spatial association with ore, on our confidence that they are reliable indicators of ore, and on the extent to which they are preferentially associated with economically better deposits. The geological, geochemical, and geophysical techniques used in exploration, and exploration strategy depend on area selection criteria. The relative importance of area selection criteria can be determined from their relative frequency of association with ore in a representative sample of the deposit population, resulting in an empirical model. A genetic model is derived by considering the genetic relationship of area selection criteria to ore. The weak links in model building are the lack of effort which goes into systematically assembling the data on the known population of deposits, and the weak scientific underpinnings of the genetic interpretation. Both of these factors influence exploration by leading to inappropriate assessments of the relative importance of area selection criteria. In addition, there are a number of human foibles which commonly lead to shortcomings in the development and use of models. The most significant of these is our tendency to rely too much on too simple models. We do this to avoid the discomfort of uncertainty and confusion which inevitably comes when we are called on to assess exploration situations.

The history of exploration for massive base-metal sulphide deposits and gold deposits in the Canadian Shield provides a good illustration of the influence of models on area selection criteria, and thereby, on exploration strategy and techniques.

Introduction

A model in geology is a conceptual and/or empirical standard which embodies the essential features of some population of natural geological phenomena. Although a model can be strictly descriptive, most contain interpretive elements that explain the relationships among the various descriptive features in terms of geological processes. Models of ore deposits are widely used in mineral exploration as a basis for predicting the exploration potential of areas which may range in scale from large regions down to individual ore zones. Everyone uses models, but often little thought is given to how models are built, how they influence exploration programs, and how they can be improved.

The objective of this paper is to examine the structure of ore deposit models and their role in the mineral exploration process. In his famous book, *The Structure of Scientific Revolutions*, Kuhn (1962) argued that models are used, consciously or not, to predict in virtually all of our everyday interactions with our environment, including in scientific research. If this view is accepted, then models should represent as close an approximation as possible to reality, if they are to properly guide us. However, it should be emphasized that models are a two-edged sword. On the one hand, they are a powerful means of organizing data in a form that enhances understanding and prediction. But on the other hand, by operating to exclude perception of data which does not fit the model, they have a soporific effect, that may lead to unjustified confidence in the application of the model.

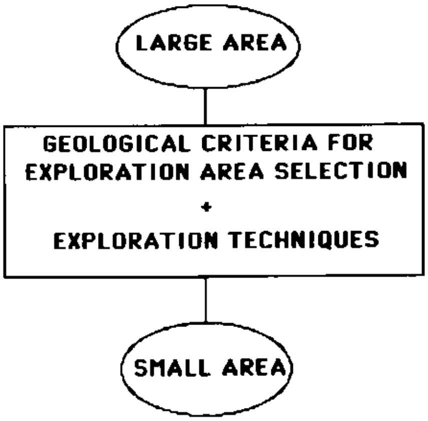


Figure 1 *The exploration process: exploration techniques (geological, geophysical, and geochemical) are used to measure the distribution of area selection criteria so that the most prospective parts of a large exploration area can be selected for further exploration.*

These concepts are illustrated by describing the influence on exploration strategy and techniques of historical changes in models for base-metal, volcanogenic massive sulphide, and for gold deposits.

Mineral Exploration

Mineral exploration involves the progressive reduction in the size of the area being explored until a mine is found (Figure 1). The starting point may be a region the size of a continent, or simply one level in a mine. Whatever its size, the objective of exploration is to focus attention progressively on the most favourable parts of the area so that as exploration proceeds, the chances of an economic mineral deposit being found continuously increase. Area reduction normally takes place in steps which are separated by area selection "decision points" (Figure 2). For example, in a regional reconnaissance program, the first decision point might follow the completion of large-scale geochemical and geophysical surveys, at which time a number of claim groups might be staked or optioned.

Area selection in mineral exploration is based on the presence or absence of specific geological features, or alternatively, geophysical and geochemical features which reflect geological features. These features can be termed "criteria for exploration area selection" or simply, "area selection criteria" (see Figure 1). Area selection criteria are concrete, measurable features, not concepts. For example, it might be considered that volcanic centres are an important regional-scale area selection criterion for volcanogenic massive sulphide deposits. However, "volcanic centre" is not a feature which shows on the legend of most geological maps. Rather, it is an interpretation based on the distribution and configuration of specific lithologies and structures in an area. The map patterns which indicate "volcanic centre" are the concrete reality, and it is these map patterns that comprise the area selection criteria.

Much of the work of exploration consists of defining the distribution of area selection criteria in the exploration area. The term "exploration strategy" can be used to refer to the sequence of activities which results in the progressive reduction in the size of the exploration area. The best exploration strategy optimizes the balance between cost and effectiveness in the area selection process (see Figure 2). Two factors are critical to good exploration strategy:

(1) optimizing on the cost, in relation to the effectiveness, of methods used to determine the presence or absence of features on which the area selection process is based, and

(2) using the appropriate criteria for exploration area selection, and correctly assessing the relative importance of these. Most of the papers given at Exploration '87 were concerned with the first factor. It is the second

aspect of exploration strategy that is the main concern of this paper.

Models as Systems Which "Rate" Area Selection Criteria

Area selection criteria must not only be features which are spatially associated with ore, but they must also be genetically related to ore in some way. Without this genetic link, the spatial association would be fortuitous or accidental, and therefore not a reliable guide to ore. In addition, area selection criteria, to be useful, must be relatively easily identified, normally by field techniques. For example, the type of gold deposit which occurs in greenstone belts is commonly associated with certain types of felsic hypabyssal intrusions, and therefore the presence of these intrusions is a useful area selection criterion, readily applied in a field situation (Hodgson *et al.*, 1982). In contrast, the observation that fluid inclusions in Archean gold deposits are CO_2-rich, while genetically significant (Wood *et al.*, 1986), is not, at our present level of geological understanding, a criterion that can be practically applied in the area selection process in most instances. In the case of epithermal-type gold deposits, on the other hand, the gas content of fluid inclusions is a criterion for area selection (Norman *et al.*, 1988).

Area selection criteria can be ordered in a three-dimensional hierarchy, according to: (1) the scale at which they are associated with mineralization, and thus the scale of area selection for which they are used, (2) the confidence one has that a feature is an essential (not fortuitous) part of the ore environment, and (3) their relation (if any) to the economic quality of a deposit.

Area selection criteria are scale-specific: what is important at one scale may be irrelevant at another. For example, there is an association of Archean gold mining camps with the contacts of mafic ± ultramafic volcanic sequences with sedimentary rock sequences, but this feature is of little or no use in selecting drill targets within mining camps (Figure 3). Large-scale area selection criteria are more important than small-scale criteria, since even the most technically strong program cannot succeed if it is carried out in the wrong general area. However, the scale at which an area selection criterion is applicable, and the confidence that one has that the feature is related to ore, tend to be inversely related — it generally is more difficult to characterize, and determine the genetic relations among large-scale phenomena than it is among small-scale phenomena. The larger scale area selection criteria are commonly considered to define the geological environment which is favourable for mineralization, whereas the smaller scale features define the deposit (Figure 4).

One of the major problems in exploration is assessing the reliability of criteria for area selection, the second dimension of the rating hierarchy above. There are basically two approaches to this problem. In the first approach, the distribution of features in the known natural population of deposits is recorded. Features are rated for their reliability according to their relative frequency of association with ore, and their absence in areas

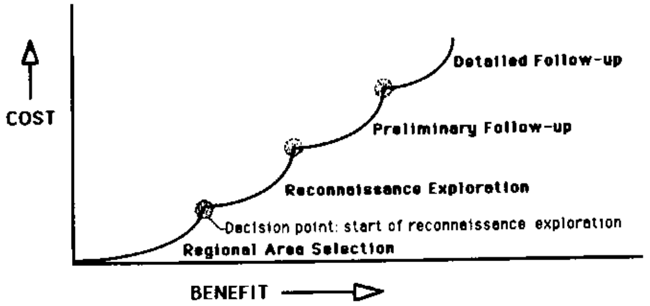


Figure 2 *Diagrammatic representation of the exploration sequence, in terms of cost/benefit ratio. The optimal exploration strategy is that succession of exploration activities which in aggregate has the lowest total cost, relative to the economic return. Each type of exploration activity gives a diminishing return on investment as it is pursued, and is replaced by the next most cost-efficient type of activity at the decision points where the size of the area being explored is reduced.*

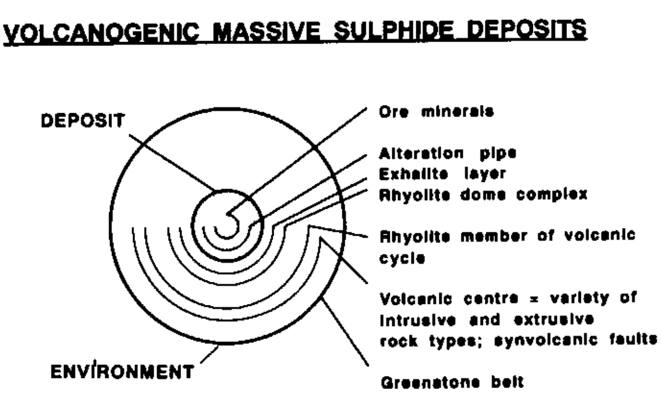


Figure 3 *Area selection criteria for gold deposits in the Superior Province of the Canadian Shield, showing how the relative importance of different criteria changes as target size decreases during the exploration process. (From Hodgson* et al.*, 1982).*

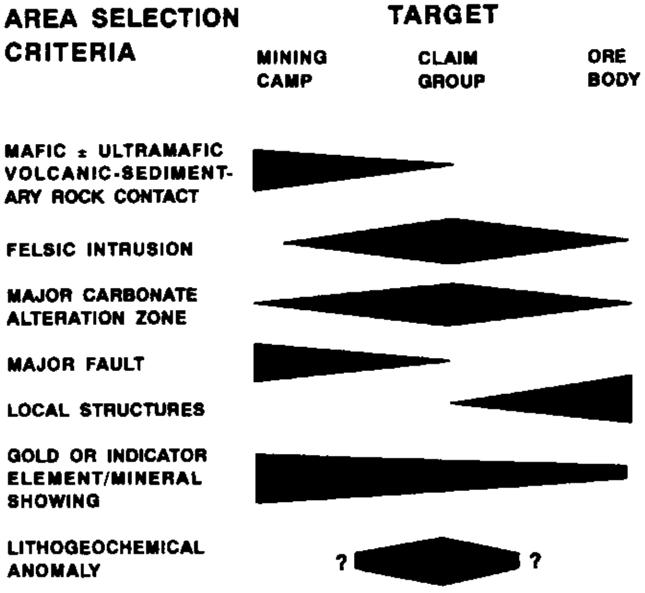


Figure 4 *Diagrammatic illustration showing how the distinction between geological characteristics of the "deposit", and the geological characteristics of the "deposit environment" depends on the scale of the geological feature associated with mineralization.*

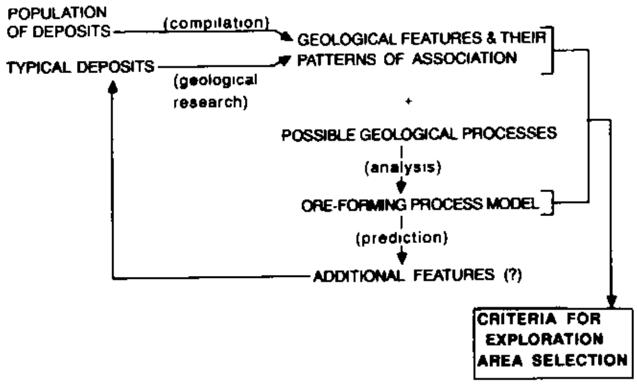


Figure 5 *Idealized method for building a genetic model for an ore deposit type, and using it to rate area selection criteria.*

without ore. Thus, a feature which occurs in nine out of ten deposits, but is otherwise rare, would be considered a much more significant area selection criterion than a feature which occurs in only half the deposits and also occurs in areas without mineralization. A model generated in this manner is termed an "empirical model". To construct an empirical model, the presence or absence of each feature must be recorded for a statistically significant and unbiased sample of the entire population. Herein lies the main weakness of the purely empirical approach: data for only a small part of the population cannot be used to formulate the model. For example, fluid inclusion or isotope data on a single deposit cannot be used as empirical area selection criteria, because without applying interpretive, genetic arguments, it is not possible to say that the data will be characteristic of other deposits of the total population. However, these data may be critical to understanding the origin of ore-forming fluids, which in turn may be critical to assessing the importance and reliability of certain lithological associations as exploration guides. Another major weakness of empirical models is they cannot predict features not in the original data base.

The second type of approach to rating area selection criteria is through the use of a genetic model. Genetic models differ from empirical models in that they explain empirical relationships in terms of the causative geological processes. The descriptive features are then rated in importance and reliability as area selection criteria, according to their relationship to the ore-forming process. For example, if it was thought that ore solutions were derived from the same magma as gave rise to felsic intrusions associated with a deposit, the petrological character of the intrusions would be worthy of detailed study in the hope that diagnostic characteristics might be identified which would serve as area selection criteria. But if the association of mineralization and felsic intrusion was considered only the result of their being in the same structural system, then the presence and type of intrusion would seem less important. Genetic models are capable of predicting relationships and data not in the original data base, but have the weakness of typically being based predominantly on a few well-studied deposits (which may not be typical). They also tend to ignore or debase features not "explained" by the geological theories in vogue at the time. Invariably it is beneficial to use the theory and data of geology to upgrade a raw empirical model to a more refined genetic model, provided that features which show a strong association with ore, but cannot be explained, are retained as area selection criteria.

A little-considered aspect of mineral deposits geology is the relation between geological features and economic quality of deposits. Many explorationists believe that the economically better deposits of any one type are more mineralogically, structurally, and petrologically complex than the economically poorer deposits of the same type. Hodgson and Troop (1988) noted an empirical relationship between the presence of the certain minerals, including scheelite, tourmaline, molybdenite, sphalerite, and galena, and the economic quality of gold deposits in the Abitibi Belt in Ontario. However, there are few quantitative studies of such phenomena, and few geological studies of any kind of economically poor deposits.

The Ideal Method of Model Building

The ideal method of model building, and the generation of a set of area selection criteria are outlined in Figure 5. Compilation of data on the known population of deposits is an essential first stage in model building. This process can be expected to result in many surprises, since the tendency is to generalize to the world-scale the essence of parochial individual experience. Using models with an incomplete descriptive base is a common cause of poor exploration decisions. For example, failure to recognize that not all large porphyry copper deposits of the world have well-developed quartz-sericite-pyrite alteration envelopes led a generation of geologists from large, southwest USA-based copper mining companies to write off the low-pyrite deposits of the Highland Valley, BC, as economically unimportant (Mustard, 1976). Lack of awareness of the common association of molybdenite with gold, well documented in the descriptive literature on Ontario gold deposits, and the idea that large gold deposits do not occur in high metamorphic grade rocks (contradicted by many examples, including the super-giant Kolar deposit of India) were among the factors which led numerous geologists to underestimate the potential of the Hemlo deposit.

Detailed studies of typical deposits, especially if these are representative of the range of characteristics found in the population as a whole, are invaluable in defining in detail the spatial, temporal, and genetic relationships among deposit characteristics. For example, although the compilation of Lowell and Guilbert (1970) was invaluable in defining the general descriptive characteristics of porphyry copper deposits (albeit biased toward southwest USA deposits), it was not until the detailed study of Gustafson and Hunt (1976) of El Salvador that the relationships among many of these features were determined, and their genetic meaning correctly interpreted.

Following compilation and during the progress of detailed studies of typical deposits, the significance of features is analyzed in terms of known geological processes and physical-chemical theory. This leads to the formulation of an ore-forming process model, in the light of which the genetic significance of the features is assessed and their reliability as area selection criteria is rated. This assessment must be done on a continuing basis, since the theory and data base of geology are evolving rapidly. Correctly interpreting descriptive data presents a special problem for industry geologists, who have little time to keep current with the flood of new geological literature, and even less time to upgrade educational skills so they are able to assess the value of this material.

Rationalizing the descriptive features of a population of deposits in terms of the ore-forming process commonly results in questions being raised about the validity of the original data base. The appropriate action at this point is to check out the facts by re-examining the field relations. However, in many cases this is not done, but instead the offending facts are rejected as "unreasonable" (*i.e.*, errors in measurement), or "unimportant anomalies". The formulator of the model is normally uncomfortable with this and other expediencies involved in the model-building process, and will apply the model cautiously, in full awareness of its imperfections. Typically not so cautious are the second generation of users, who see the model as reality, not an imperfect abstraction of reality, and who may actively avoid or reject any fact which does not fit this reality. Personal contact between the formulators of models (mostly academic and government geologists) and explorationists can be very useful in increasing awareness of the limitations of models.

Pitfalls in the Making and Using of Models

A number of human foibles interfere with the ideal process of model building, and the proper use of models in exploration. These attitudes commonly take the form of "corporate or institutional cults", and pervade industry, and academic and government institutions to an equal extent. Human foibles are most insidious and deceptive when people are organized in groups, since individuals tend to lose the restraining effects of their conscience when they are in groups. Furthermore, self-interest dictates that an individual intent on promotion or recognition within a group will not jeopardize his aspirations by contradicting what he perceives to be the accepted dogma of the group. Each of these "cults" incorporates attitudes that are valid: the error comes in the narrowness of the vision, and in the quasi-religious zeal with which one path is followed, to the exclusion of all others.

One of the most common of these cults is the "fads and fashions" school (Figure 6). The defining characteristic here is an obsession with being up-to-date and in possession of the latest, most modern model. An infatuation with the new, the improved, is a characteristic of our whole society, and is exploited by all who are in the business of selling,

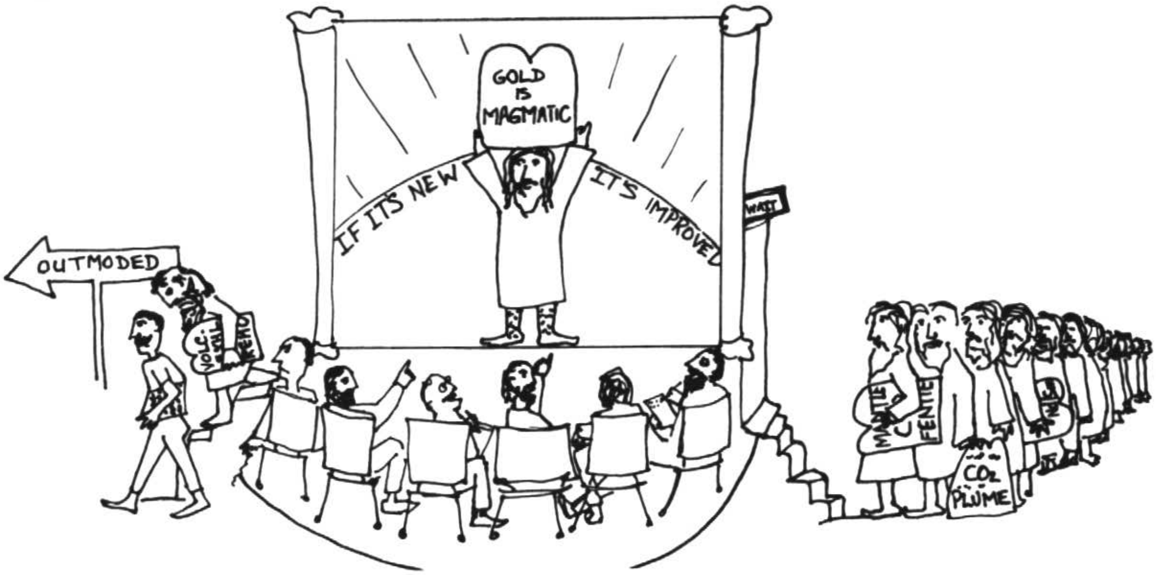


Figure 6 *Pitfalls in the making and using of models: the school of fads and fashions.*

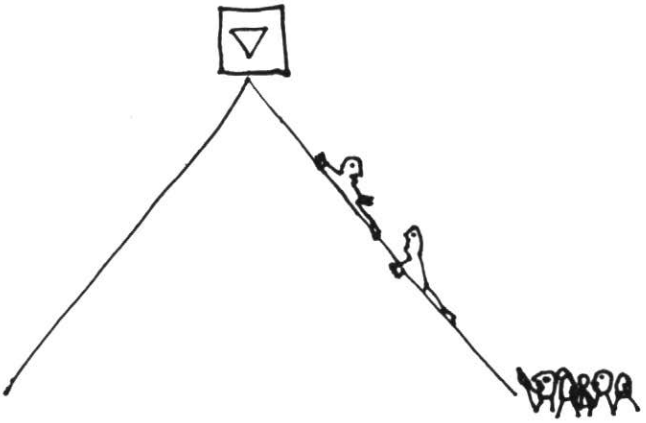


Figure 7 *Pitfalls in the making and using of models: the cult of the panacea.*

Figure 8 *Pitfalls in the making and using of models: the cult of the romantics.*

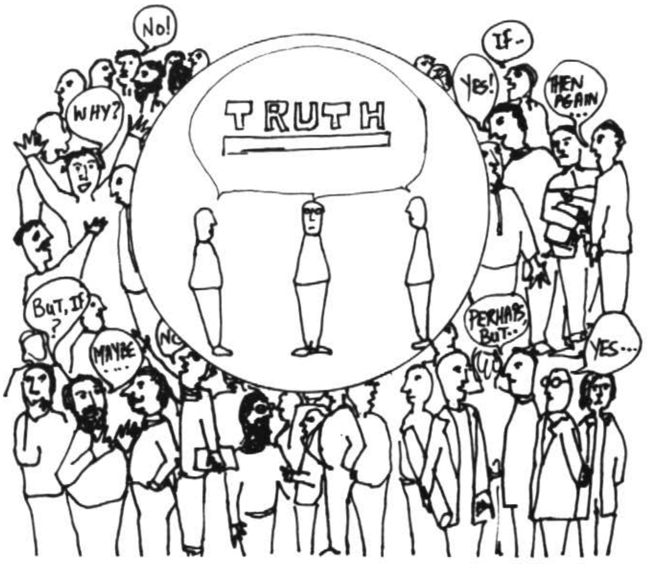


Figure 9 *Pitfalls in the making and using of models: the corporate iconoclasts.*

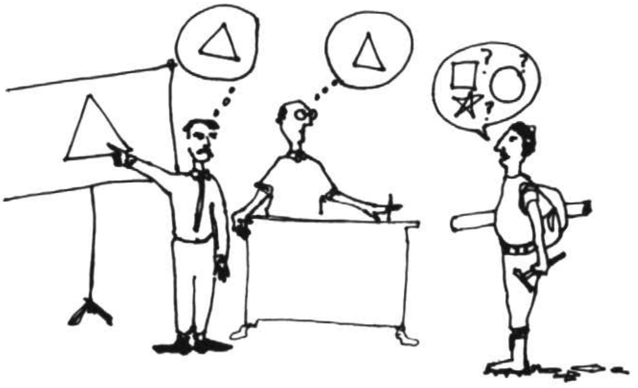


Figure 10 *Pitfalls in the making and using of models: the school of role specialization.*

whether it be soap, geophysical instruments, scientific concepts, or mineral deposit models. Implicit in this cult is a sort of blind faith in the inevitability of progress, the idea that if it is new, then it must be improved. True believers in progress on the consumer end of geology, the explorationists, are symbiotically linked to like-minded academics and other researchers who feel that unless their work results in new models (and the newer, the better), they are not successful. The policies of scientific funding agencies reflect and, at the same time, promote this attitude, exerting a constant pressure on researchers to come up with extravagant and radical models which differ as much as possible from those previously proposed to explain the same phenomena, in order to justify increasing expenditures on complex modern equipment. An allied phenomenon, almost as religious in character, is the attitude that if the data and arguments upon which the model is based are not obscure and incomprehensible, then the model cannot really be new and, therefore, cannot really be valid.

The proliferation of "trendy" models is also a consequence of the increasing specialization in science, combined with the emphasis on "productivity" of researchers, *i.e.*, the number of publications generated per research dollar spent. This has resulted in fragmentation of the literature into numerous small contributions, commonly reporting data collected without consideration of phenomena outside of the area of specialization. Models based on this data may quite adequately explain it, but may be strongly at odds with other data on the deposit.

Related to the fads and fashions school is the "cult of the panacea" (Figure 7). This is the attitude (perhaps better termed a faith) that out there, somewhere, is the ultimate area selection criterion that will banish forever all the hard work of mineral exploration. After its discovery, all other data will be irrelevant, all arguments and controversy silenced, forever. This ultimate criterion will only be detectable with the newest and most expensive equipment, and why or how it works will be totally incomprehensible to all but a few high priests of science. The search for a panacea to the problems of area selection in exploration is laudable, and has resulted in many significant advances; the problem comes with really believing that there is such a thing, and with the readiness of some exploration geologists to throw all traditional evidence (and plain common sense) to the wind when they are presented with yet one more data type purported to provide the final answer.

In complete contrast to the fads and fashions cult is the "cult of romantics" who reject out-of-hand all that is new because it has been generated in the decadent hothouses of modern universities or government (Figure 8). Cult members commonly have an antipathy for models of any type, because the recognition that models play a role in exploration is, in itself, viewed as "bookish" and therefore, suspect. Most romantics believe that the practice of science and exploration is a completely objective process, which is unnecessarily biased by subjective constructs like models. They are constantly reaffirmed in their faith by the actions of those who fail through the use of inadequate models, or the misuse of good models, and by the inevitable occasional failures of modern technology. Every discovery by someone who has consciously swum against the current of popular models, every failure by a modern, technology-oriented multinational corporation is heralded as a justification of their point of view.

Another common cult is that of the "corporate iconoclasts", who have their own models, carefully nurtured and protected from outside influences (Figure 9). Corporate iconoclasm seems to be a form of nationalism, arising, like nationalism, from our need to feel that we are an integral and important part of a group, not an isolated and alienated cog in some vast and incomprehensible machine. The models developed and used in such groups may in fact be superior, but the chances of them remaining so, in such a protected and often secretive environment, are poor. In this environment, for any changes to be acceptable, they must be invented within the group, since by definition the group is superior to the outside world. This type of arrogance, while perhaps conducive to the development of group solidarity, tends to generate a need to prove that the corporate or institutional model is superior and valid, which can lead to selective perception, *i.e.*, only that data which supports the model is seen, and the rest is ignored.

In many organizations there is a policy of promoting specialization, in the interest of efficiency. The idea is that each does his special job, which he then gets extremely good at doing. This is the cult of "role specialization" (Figure 10). A problem arises here because the roles of data gathering (field work), and data interpretation (office work) become uncoupled, with the inevitable outcome that nothing that is not specifically asked for by the data interpreters ever finds its way into the data base. Models in this environment have a very constraining influence, and are never subjected to the type of continuous field testing needed to ensure that they are of optimal quality.

In summary, models are blamed for many mistakes, as well as being credited for many successes, in mineral exploration. But it is not the use of models which is the problem, since models are always used, whether this is admitted or not. Rather, the problem is which models are used (which involves how the models were constructed, and how they are kept up to date), and how they are used, (which involves the function of models in exploration).

The ultimate, ideal model incorporates all of the data on a known population of deposits, and explains these features in terms of an ore-forming process which is consistent with the rest of the data and theory of geology. Many ore deposit models fall short of this ideal by being based on too small a sample of the population, *i.e.*, they have too parochial a bias. In addition, the scientific underpinnings of many models are weak, because the full range of modern geological theory has not been considered in explaining the features of deposits in terms of the ore-forming process. Or the theory behind the model may have been adequate when the model was formulated, but advances in geology have since rendered it obsolete. A poor theoretical basis leads to incorrect assessments of the significance of the descriptive features of the model, and thus their relative importance as criteria for exploration area selection.

In application, most problems arise because of unwarranted veneration of specific models. This leads to models, with their necessarily condensed and idealized version of reality, becoming a comfortable substitute for reality, a crutch which allows the true believer to avoid the confusion and ambiguity of reality. A model, like any other concept in geology or science, is a tentative and necessarily imperfect creation which should be constantly tested as new field data and theoretical concepts become available. Models are guides to help sort the more important from the less important, and throw into bold light the anomalies which do not fit. A model is developed and improved by being modified and elaborated to incorportate increasingly more of the unexplained data. It should never become a filter which allows only certain data to be seen.

It is unlikely that there will be an abrupt improvement in the published data base of mineral deposits geology, or in the proliferation of narrowly based and ill-considered models in the geological literature. Therefore, the onus is on the mineral explorationist to develop the attitudes and educational skills needed to assess the practical implications of new data and ideas. Education and experience provide the only real protection against scientific salesmanship.

Models in Canadian Mineral Exploration

The history of mineral exploration in Canada has been dominated by the search for gold deposits, volcanogenic massive sulphide deposits, and porphyry copper deposits. Models for the first two types of deposits have changed radically in the years since modern geophysical and geochemical prospecting techniques have come into widespread use, and so they provide an excellent opportunity to examine the effect of models on exploration.

Models for volcanogenic massive sulphide deposits.

The first major volcanogenic massive sulphide (VMS) deposits discovered in eastern Canada, apart from those in Newfoundland (not part of Canada at the time) were the Horne, Waite, and Amulet deposits of the Noranda area, and the Normetal deposit located to the north of Noranda, discovered by prospectors in the early- to mid-1920s. Up until the early-1950s, these were interpreted as belonging to the general class of structurally controlled, epigenetic base-metal replacement deposits. In the mid- to late-1950s, there was a gradual evolution in thinking which finally cumulated in the presently accepted, exhalative-sedimentary model gaining ascendancy by the mid-1960s (see review by Lydon (p. 569-573) *in* Franklin *et al.*, 1981). By the late-1960s, this new model dominated the thinking of explorationists in eastern Canada.

The change in ideas about the origin of VMS deposits did not result in major changes in deposit-scale area selection criteria, since most of the important descriptive features of the deposits had been clearly recognized by earlier workers. However, the new ideas had a profound effect on the relative emphasis placed on these criteria. They also led to an entirely new definition of what constituted a favourable, larger-scale environment for ore occurrence, *i.e.*, on the regional-scale criteria for exploration area selection. These relationships are outlined in Table 1 and Figure 11, and described below. The generalizations

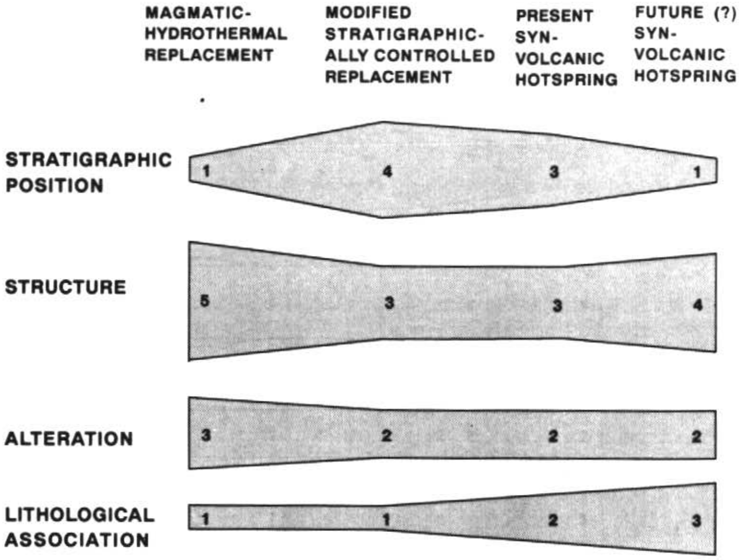


Figure 11 *Diagrammatic representation of the change in relative emphasis on different area selection criteria with historical changes in the genetic model for volcanogenic massive sulphide deposits.*

Table 1 Area selection criteria for volcanogenic massive sulphide deposits and their genetic significance according to the late epigenetic replacement model and the synvolcanic exhalative model for ore formation.

Feature	**Genetic Significance of Feature**	
	Late epigenetic replacement model	***Synvolcanic exhalative model***
Rocks		
Felsic intrusive complex	Source of ore-forming fluids	Source of heat and possibly magmatic fluid components
Felsic volcanic, especially high-silica rhyolite domes, tuff-breccia complexes (near contact with)	Fluids trapped in permeable and reactive rhyolite below impermeable, unreactive basalt; competency contrast during deformation	Vent-proximal extrusions, hydrothermal products formed during ore-favourable stage in evolution of volcanic complex
Mafic volcanic		
Lithic volcaniclastic layer, especially with sulphidic and/or altered clasts	Permeable and chemically reactive zones favourable for replacement	Hydrothermal explosion products, indicating submarine hot spring vent nearby
Sulphidic sediment layer	Zone of selective replacement; indicator of favourable horizon for ore occurrence	Distal exhalite; indicator of favourable horizon for ore occurrence
Abundant dykes	Fluid barriers confining ore solutions to rhyolite	Structure permeable to magma and ore fluids
Structures		
Faults, fractures	Magma and fluid conduits	Magma and fluid conduits
Mineralization and alteration		
Chloritic pipe	Ore-related hydrothermal activity	Sub-sea floor, ore-related hydrothermal activity
Zn, Fe addition; Na-depletion anomalies in footwall sequence	Ore-related hydrothermal activity	Widespread self-sealing of cap rock
Disseminated to massive sulphide	Partial to complete replacement of rhyolite	Sub-sea floor replacement grading to sea floor exhalite

which follow are based on the description of the epigenetic model, as it was applied to the Noranda area, by Wilson (1941) and articles by Brown, Hawley, Price, Price and Bancroft, Suffel, and Scott in the first volume of *Structural Geology of Canadian Ore Deposits* (Canadian Institute of Mining and Metallurgy, 1948). There are many reviews of the synvolcanic model, but that of Franklin *et al.* (1981) is as complete as any. Hodgson and Lydon (1977) described the implications of the synvolcanic model for exploration.

Epigenetic Replacement Model. According to the epigenetic replacement hypothesis, the major characteristics of VMS deposits, and the control of the localization of mineralization, could be explained in terms of four basic principles: (1) permeability variations in the host rocks, a function of both the original volcanic structures, and of later deformation; (2) variations in the susceptibility of different rock types to alteration and replacement by reaction with hydrothermal solutions; (3) the damming or constraining of fluid flow by impermeable and unreactive rock units, suitably positioned in relation to the favourable ore host rocks; and (4) the major, structurally controlled, fluid conduit or "plumbing" system.

One of the key descriptive features of the deposits emphasized in early exploration was the association of mineralization with rhyolite, especially rhyolite breccias. The breccias were recognized as being mainly of volcanic origin, but some were considered to be of tectonic origin. Their favourability as host rocks derived from their permeability, and the susceptibility of rhyolite to replacement. The sharp contact between breccia-hosted ores and unmineralized "andesitic" (basaltic) flows, or dykes and irregular bodies of virtually unmineralized "diorite" (gabbro), was considered the result of the impermeability and unreactivity of mafic rocks. The mafic rocks were thought to have behaved as aquacludes, constraining fluid flow to the mineralized rhyolites. A domical shape was noted in the unmineralized basalt-mineralized rhyolite contact in several deposits: this was interpreted as due to cross folding. The occurrence of ore concentrations in such "fold hinges" was considered due to damming and ponding of ore-forming fluids.

It was also recognized that mineralization occurs within zones of Mg-Fe enriched and Na-Ca depleted altered rock, being most closely associated with chloritic alteration. Vertical, pipe-like alteration zones in the Waite-Amulet area were interpreted as hydrothermal fluid conduits tapping a magmatic fluid source at depth. The mineralized zones were thought to have formed where fluids were able to penetrate laterally from these conduits along permeable and chemically favourable rhyolite horizons. The importance of the Amulet Rhyolite-Amulet Andesite contact in the central Noranda area as a major site for mineralization was recognized, but was not emphasized in exploration as much as it would be after the synvolcanic model became accepted. Any similar contact intersected by the subvertical conduit system was thought to be equally prospective for ore.

Major emphasis was placed on fault and fracture systems as fluid conduits. In the Horne Mine, in particular, faulting and shearing were considered the main reason why the deposit is localized in the wedge-shaped structural block of rhyolite breccias and andesite flows lying between the Horne Creek and Andesite faults. The location of many of the individual orebodies in the Horne Mine was thought to be controlled by splays off the Andesite fault. A complicating factor in the Horne Mine could be that the gold ore zones and the VMS ore zones have different controls, and formed at different times. It certainly appears, from the description of Price (1949), that some of the gold ore zones were controlled by structures which cut across the base-metal massive sulphide ore zones.

A great deal of attention was paid to the relation of ore to diabase dykes. This was because major diabase dykes occur in three of the four large deposits which were known at the time (Horne, Amulet and Normetal), and two major dykes intersected in the largest of the deposits, the Horne Mine. From this empirical association, it was concluded that the mineralization and diabases were related. It was then reasoned that if the ore pre-dated the diabase, it was probably related to the latest Algoman granites in the area, which meant that these might constitute important regional scale, area selection criteria. Alternatively, if the ore post-dated the diabases, then it was probably related to the magma source of these dykes, which meant that deposits might be as widespread as the diabases.

In summary, according to the epigenetic replacement model for VMS deposits, the important area selection criteria were major fault systems, and permeable rhyolite breccia bodies in contact with impermeable basalts and gabbros. Very little emphasis was given to stratigraphic location, or to the details of the volcanic rocks in the mineralized areas, and their interpretation in terms of volcanic processes. Alteration was recognized as being closely associated with ore, particularly chloritic alteration. Diabase dykes were also thought to be important.

Syngenetic Volcanic-Exhalative Model. In the mid- to late-1950s, the deposits of the Noranda area came to be recognized as part of a distinctive class of deposits found throughout the world which shared the common characteristics of being always associated with submarine volcanic rock sequences, and showing a strong element of stratigraphic control. The first serious consideration of stratigraphic position as an area selection criterion was probably by geologists working for Consolidated Zinc Corporation in the Noranda area in the mid- to late-1950s, under the influence of Haddon King, then chief geologist of Consolidated Zinc. King had become convinced of the importance of stratigraphic control from work on the Zn-Pb-Ag deposits at Broken Hill (King and Thompson, 1953). This new stratigraphic emphasis led to the discovery by Consolidated Zinc of the Vauze deposit in 1957.

It was a short step from the realization that VMS deposits were dominantly controlled by stratigraphy, to realizing that they were the product of the volcanism that produced the stratigraphic succession. Consolidated Zinc geologists had come to this conclusion by 1960, and by 1965 it was accepted by most of the explorationists working in eastern Canada (Hutchinson, 1965; Suffel, 1965; Roscoe, 1965; Gilmour, 1965). Interestingly, the acceptance of the importance of stratigraphic position as an ore guide was initially accompanied by a de-emphasis of the role of structure and the importance of alteration, perhaps in reaction to the previous domination of these features as area selection criteria (Figure 11).

It was not until the 1970s that the synvolcanic model entered the mainstream of academic thought, although similar ideas were developed and widely accepted in the mid-1960s by Japanese geologists working on the VMS deposits of Japan (Horikoshi, 1969). Especially following the discovery of sulphide-depositing black smokers on the ocean floor, there has been much "re-inventing of the wheel" as features and concepts familiar to the geological community concerned with the deposits of eastern Canada and Japan were recognized by the largely non-exploration oriented geological community that now scrambled to restudy other ancient VMS deposits.

The presently accepted model for VMS deposits in Archean greenstone belts is that they are formed around the discharge vents of submarine hot springs in the tectonically active, high heat flow environment of felsic volcanic centers (Franklin *et al.*, 1981). The environment is analogous to that of the majority of the high energy, high temperature subaerial geothermal fields associated with felsic volcanism (Hodgson and Lydon, 1977). According to this hypothesis, two major principles underlie the interpretation of the descriptive features of the deposits:

(1) Sea-floor hydrothermal activity develops at certain stages in the volcano-tectonic evolution of a volcanic complex, and is associated with a number of characteristic volcanic and tectonic effects which are reflected in the lithological and structural characteristics of the favourable stratigraphic zones.

(2) Mineralization formed in and around sea floor hot spring discharge vents. These were structurally controlled loci of a variety of volcanic and hydrothermal effects ranging in

age from pre- to post-mineralization.

The association of ore with rhyolitic breccias, recognized by early workers, is now attributed to one of at least three possible processes: (1) the formation of breccias close to structurally controlled magmatic vents, which also were hot spring vents, (2) the origin of many of the breccias by hydrothermal explosive activity associated with the ore-forming event, and (3) the formation of breccias in association with a major volcanotectonic event, such as caldera formation followed by resurgent doming, with which the ore-forming hydrothermal activity was associated.

The abundance of dykes in mineralized locales is considered to reflect the long-lived permeability of these structural sites to both magmas and ore solutions. Since the synvolcanic model allows for the possibility of post-ore but still basically synvolcanic dykes, it is now realized that orebodies may be segmented by dykes, and occur as xenoliths in larger gabbroic masses. This has important implications for exploration, since orebodies may be concealed or offset by post-ore intrusions.

Both the epigenetic and synvolcanic models emphasize the importance of structurally controlled fluid conduits. However, while any structure with late movement on it is favourable by the epigenetic model, only structures present at the time of volcanism are favourable by the synvolcanic model. Thus, the synvolcanic model dictates that considerable effort is directed toward relating structures to the type and distribution of volcanic rocks, both as a means of tracing these structures by lithological mapping, and as a means of establishing their synvolcanic origin.

It is notable that the synvolcanic model led to the end of emphasis on diabase dykes in exploration. Yet it remains a fact that major diabase dykes are spatially associated with many, although certainly not all, of the important VMS deposits in the Canadian Shield. Two questions need to be answered to determine the extent to which it is appropriate to consider diabase dykes in VMS exploration: (1) Are diabase dykes more common in VMS deposits than in similar-sized areas without mineralization, *i.e.*, is the association empirically significant? and (2) Is there any plausible genetic reason for the association?

If the answer to question (1) is "yes", as it certainly was in the early stages of exploration of the Abitibi Belt, then it is appropriate to place at least some emphasis on diabase dykes, even if the answer to question (2) is "no". However, there is a plausible explanation for the association: the dykes may have been emplaced into long-lived, fundamental structures that controlled, at a much earlier time, the distribution of volcanic rocks and synvolcanic mineralization. Therefore, diabase dykes probably should be given some emphasis in exploration.

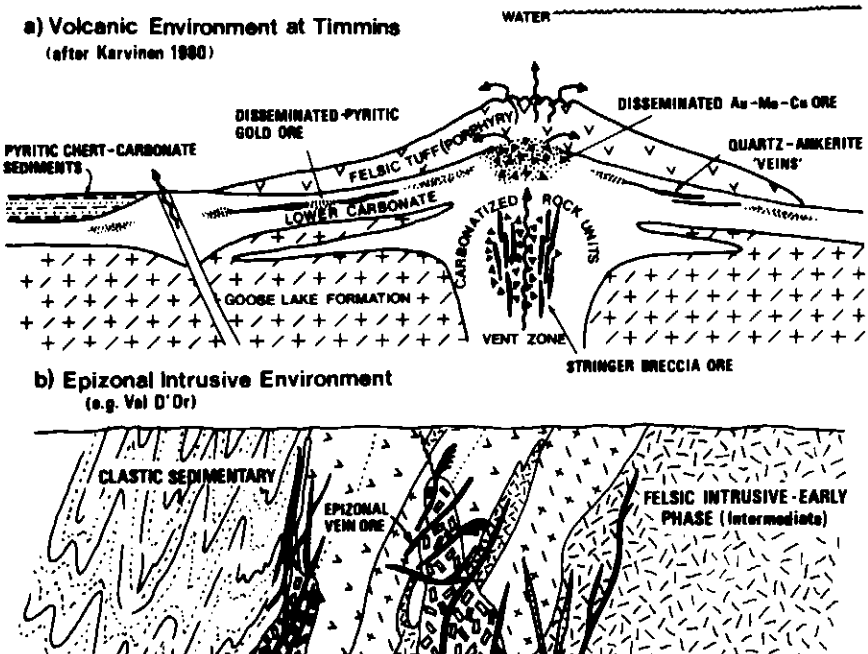
Through comparisons with active hydrothermal systems, different genetic types of hydrothermal alteration have been identified in VMS environments. It is now recognized that stratigraphically controlled alteration, probably analogous to that produced by self-sealing in active hydrothermal systems, may be characteristic of the strata immediately below ore-bearing horizons (Hodgson and Lydon, 1977; Sopuck *et al.*, 1980; Gibson *et al.*, 1983). Regional-scale zones of metal leaching and associated alteration may also be present in areas with VMS deposits (MacGeehan, 1978). The recognition that alteration, mineralization, and volcanism can overlap in time and space has led to the possibility of identifying hydrothermal centres by tracing the distribution of transported clasts of altered or mineralized rock in volcanic breccias. The Fukazawa deposit in Japan was discovered in this way (Tanimura *et al.*, 1974). Thus patterns of alteration and mineralization have become much more refined tools for orefinding than they were when the epigenetic model was dominant.

In summary, the synvolcanic model has led to an emphasis on the total volcanic environment of mineralization, as this can be interpreted from the types and distribution of volcanic extrusive and synvolcanic intrusive rocks and structures. In the future, it seems likely that there will be further refinements of the model which will enhance our ability to choose favourable sites for exploration on the basis of geology (see Figure 11). Stratigraphic position as a simple area selection criterion will be replaced by a more sophisticated set of criteria based on the details of the lithological association. These criteria will define what constitutes a favourable stage in the volcanic development of an area for the formation of an ore-forming hot spring system. Significant advances will also be made in our ability to identify the structures which are obviously so important in controlling volcanic phenomena on all scales, from the regional to the local. These advances will come as a result of improvements in our understanding of the structural framework of greenstone belts, and the relationship of geologically late to geologically early structures.

Exploration Methods in Relation to VMS Models.

The use of available exploration tools must evolve in tandem with the changing character and emphasis on specific area selection criteria. Initially, all that could be done on an outcrop was to establish the presence or absence of mineralization. Now we search for a wide variety of features which are meaningful to the interpretation of the

a) Volcanic Environment at Timmins
(after Karvinen 1980)



b) Epizonal Intrusive Environment
(e.g. Val D'Or)

Figure 12 *Models for primary gold deposition in the Superior Province. (From Hodgson and MacGeehan, 1982).*

volcanic history of an area. This interpretation, in turn, influences our assessment of the area's potential for VMS deposits. Similarly, whereas once the goal of geophysical surveys was just to locate conductors, now there is an increasing use of EM, IP, and especially magnetic data to extend and enhance geological data as a basis for interpreting the total geological environment. The application of lithogeochemical techniques has advanced with increases in our understanding of the types and significance of alteration associated with ore-forming submarine hydrothermal systems.

Models for Archean Gold Deposits

The situation with gold deposits is quite different from that of VMS deposits. Whereas the model for VMS deposits is well developed, and relatively few components which are important to exploration remain controversial, there is little agreement on the genetic significance of many of the features of gold deposits.

Magmatic-Hydrothermal Model: pre-1970.

Gold was the main target of the Canadian exploration community during the first half of the century, especially during the period preceding the First World War when the great deposits of Timmins and Kirkland Lake were discovered, and the Depression years of the 1930s. At this time, the magmatic hydrothermal theory of ore formation was in ascendency in North America and it was generally accepted for gold deposits, without much controversy. According to the model (see numerous articles in the Canadian Institute of Mining and Metallurgy, 1948), hydrothermal fluids derived from "Algoman" granitoids moved up along major structures, like the major "breaks" of the Abitibi Belt, and deposited gold and associated minerals in structurally generated dilatant zones (Figure 12b). The porphyries so commonly associated with gold were viewed as manifestations of gold-related Algoman igneous activity, and also were thought to be structurally important in many deposits, providing a competency contrast with enveloping mafic schists which was favourable to the development of dilatancy during deformation. The concept of chemically favourable units was widely accepted, although the mechanical properties of rocks generally were considered more important than their chemical properties. For example, gold was thought to have been localized in the iron formations at Geraldton mainly because they behaved as brittle units, relative to the enclosing sediments (for review of ideas, see Macdonald, 1984a).

Synvolcanic Models: 1970-82.

There was a long period after the Second World War when little thought was given to gold, with the exception of the pioneering studies of Boyle (1961) in Yellowknife. The sudden renewal of exploration interest in gold, following the lifting of the price control by the US government in 1968, caught the geological and exploration community unprepared: very few government, company, or academic geologists knew anything about the geology of gold, in fact many had never seen a gold mine. Nevertheless, we were all quick to reject, out-of-hand, the prevailing classical magmatic hydrothermal model, with the disdain we typically reserve for all that is not new (and therefore, improved). It was perhaps predictable that the model which had worked so well in massive sulphide exploration should be transferred to gold: the ideas were new, but were also familiar to most explorationists; they provided a number of clear exploration guides; they defined a clear role for geophysics, the major exploration tool in use at the time; and they made use of the stratigraphic data which had been the almost exclusive concern of geologists working in the greenstone belts in the previous decade. There was also a prevailing opinion that the magmatic hydrothermal model for gold did not provide an adequate explanation for some of the larger-scale features of the deposits, like their common association with ultramafic rocks, while it focussed on explaining geological details. Similar "details", such as small veinlets of sulphide in dykes which blatantly cut across entire ore zones, had been major underpinnings of the epigenetic replacement model for VMS deposits, and were highly suspect as significant evidence in geological environments which had been subjected to metamorphism and deformation dating back to the Archean. Furthermore, the times were not propitious for those concerned with details; geology was undergoing a major revolution in basic concepts brought on by the new plate tectonic theory, and geological arm-waving was the style of the day.

The new model for gold deposits (Ridler, 1970, 1976; Hutchinson, 1975; Karvinen, 1978; Kerrich and Fryer, 1979; Roberts, 1981) explained the concentration of gold on the scale of individual deposits as primarily the result of sea floor and sub-sea floor hot spring activity (Figure 12a). Structurally controlled, epigenetic mineralization was interpreted as the result of remobilization, on the scale of individual deposits, during later deformation and metamorphism. As in the case with VMS deposits, many geologically complicated patterns of rocks and mineralization, previously interpreted as the result of complex structure, were re-interpreted as the result of synvolcanic processes: what had been structural truncations became stratigraphic pinch-outs; unconformities became facies changes; porphyry intrusions became intrusive-extrusive complexes; shear zones became tuff beds; banded veins and sulphide replacement zones in stratiform shear zones became auriferous exhalites; gold localized in competent conglomerate beds became metamorphically re-worked placer gold; and iron formations, previously seen as structurally and chemically favourable hosts for late gold were widely re-interpreted as primary auriferous exhalites. Even the regionally extensive "breaks" of the Abitibi Belt were re-interpreted by some (Ridler, 1970) as carbonate iron formations. A wide array of suitably modern (and generally little understood, by the average explorationist) chemical, isotopic, REE, structural, and volcanological arguments were found to support these new interpretations.

The influence on exploration of these changes in the gold model was profound. The effort which had previously gone into tracing favourable structures now was re-directed into tracing what were deemed favourable stratigraphic sequences and horizons. Stratiform conductors in favourable parts of the volcanic stratigraphy were considered priority targets, irrespective of their structural environment, as were banded oxide iron formations. Carbonate alteration zones, now seen as favourable stratigraphic zones, were carefully re-examined for facies variations related to mineralization. In the Abitibi Belt, many obvious and long-recognized patterns in the distribution of gold, such as the restriction of all the large deposits to a zone within a few kilometres of the main breaks, were de-emphasized: if the gold was due to volcanism, why should not the area distant from the breaks be as prospective as those close to them, if the volcanic sequence was the same?

At about the same time as the exhalative model for gold deposits was being developed, there was a shift away from the magmatic hydrothermal to the metamorphic hydrothermal theory for the origin of the gold-bearing fluids (Fyfe and Henley, 1973; Norris and Henley, 1976; Kerrich and Hodder, 1982). According to this latter theory, gold-bearing fluids are derived by prograde metamorphic dehydration reactions related to the initial stages of emplacement, during the waning stages of volcanism, of the granitoids which surround greenstone belts. Now that the epigenetic model has come back into fashion, metamorphogenic fluids are attributed to metamorphism caused by the emplacement of felsic magmas in the final stages of deformation and metamorphism of greenstone belts.

The metamorphic hydrothermal model reinforced the widely held idea that gold deposits do not occur in rocks of high metamorphic grade or in deep-level granitoids, by "explaining" their supposed absence in terms of gold mobilization during prograde metamorphism. Yet many large deposits occur in the granitoids bordering greenstone belts in Zimbabwe, and the super-giant Kolar deposit of India is hosted by rocks of the amphibolite facies (Hamilton and Hodgson, 1986). This model unquestionably had a significant influence on geologists examining the Hemlo deposit in the days before the main ore zone was discovered. Indirectly, it provided support for the idea that Hemlo is a totally different type of gold deposit, implying that different area selection criteria have to be used in the search for new Hemlos. This, in turn, has produced a tremendous amount of unproductive exploration in areas not previously considered prospective for gold.

The metamorphic hydrothermal hypothesis has resulted in a de-emphasis of the importance of porphyries, which can only be explained, in terms of this model, as accidental or secondary features of the gold-bearing environment, perhaps indicative of a structural environment of enhanced permeability to fluids and magmas. Whereas the magmatic hydrothermal hypothesis leads to an emphasis on the importance of spatial relationships between gold and magmatical hydrothermal deposits such as Mo deposits (Macdonald, 1984b; Burrows *et al.*, 1986), these patterns tend to be explained as fortuitous or of secondary importance in the metamorphic water hypothesis.

Recent Epigenetic Models.

In the past five years, there has been a major swing back to traditional views of gold deposits being epigenetic, structurally controlled, and late in the geological development of greenstone belts. However, many of the genetic problems are unresolved, for example, the source of the gold, and the fluid from which it is deposited. At present, the main battle is between those who profess a magmatic origin for the ore solution, and those who profess a metamorphic origin. As a consequence, there is a wide diversity of opinion on which are the important criteria for exploration area selection for gold, and where the best ground to explore is located.

Conclusions

It is concluded that models are always with us, even if their existence is denied. Therefore the issue is not "model *versus* no model" but "good *versus* poor model". Models for ore deposits embody the descriptive characteristics of the deposits, and the larger ore-bearing geological environment. As such, models contain the descriptive data used to select areas for exploration during the exploration process, which involves progressively homing in on the most prospective parts of a region in a series of discrete steps. Good models are based on a full knowledge of the deposit population characteristics, interpreted in the light of the best geological theory. This interpretation is essential to rating, in terms of their probable importance and reliability, the descriptive features of the model which are used as criteria for exploration area selection. The function of geological research applied to exploration is to develop an understanding of how mineral deposits form, so that the genetic significance of the characteristics of ore deposits is understood. An important, and very much under-studied, aspect of mineral deposits is the relation of economic quality to geological features of deposits. Although much of exploration involves gathering geophysical and geochemical data, it should be emphasized that these data are useful only in that they reflect geological features which are area selection criteria for the deposit type being sought.

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