Success in Mineral Exploration: Confidence in Science and Ore Deposit Models

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Introduction

In a successful mineral exploration team a web of confidence, trust and respect links the investor or Company Board to the exploration manager, the exploration scientists and the field operators. There are two vital threads in this web of confidence: confidence in prosperity, i.e., believing that what we are doing is worthwhile (Woodall, 1983b) and, secondly, confidence in science and scientists.

A great ore deposit is minute in comparison with the earth, and it is easy to be very close to ore yet not see it. The search is costly in terms of human toil and resources, and is not a task for the confused, faint-hearted or the poorly trained. To marshal the resources required, especially the finance, and to have the strength to persist, requires simple, compelling logic that will win and maintain the confidence of the investor. Moreover, the challenge is not just to discover ore, it is to discover the best ore at the lowest possible cost.

The orebodies we are now seeking are largely or completely concealed beneath leached outcrops or younger soils and rocks, so what do we go out into the deserts, the forests or the mountains to see, a blade of grass or sand blowing in the wind? The outcrops, the maps, the geochemical and geophysical data, will only answer the questions we put to them. This is why we need science and scientists. This is why we need ore deposit models, i.e., concepts of what is significant in terms of ore occurrence in geological, physical and chemical data. Such concepts encourage us to look; suggest what we should look for and where; enable us to see, in patterns of geological, geophysical and geochemical data, what no one else has perhaps seen before; enable us to think what no one else has thought before; and encourage us to do what no one else has been bold enough to do before.

Science and ore deposit models have the greatest potential value during the generative stage of exploration when we are concerned with area selection. Now, you will meet people who will dispute this, but they are thinking only of exploration when *effective* reconnaissance is cheap and an early reduction of the search area is not critical. This is as it was when thousands of unpaid, hungry prospectors covered Canada, the United States and Australia in the last century and early in this one. It is the same today when looking for near-surface uranium, or for base metals beneath thin, non-conductive overburden in areas where airborne geophysical exploration is both effective and cheap. When low-cost reconnaissance is not effective, and especially when drilling is the only effective search method – as it progressively will become – the use of science and valid ore deposit models are vital to cost effective exploration.

Ore deposit models are not scientific dogma but working hypotheses, and they can be empirical, i.e., based on features observed to be associated with ore, or theoretical, i.e., based on fundamental scientific principles. However, even the development of an empirical model involves science, for it involves scientific observations and judgements of the relevance of observed associations. No ore deposit model is ever strictly empirical. Theoretical models are valuable as a check on the validity or relevance of empirical associations, and especially as a guide to new deposit types. Ore deposit models which have both empirical and theoretical support instill the greatest confidence.

The Promise of Science and Ore Deposit Models

The future is full of promise and we should be confident of the value of science in mineral exploration. There has been spectacular progress in our understanding of ore-forming processes over the last thirty years. Scientific mineral exploration is still young and is growing rapidly in wisdom and stature. It is only thirty years since Haddon King first suggested that the sediment-bound ore deposits at Broken Hill were products of a sedimentary depositional environment (King and Thomson, 1953). It is little more than thirty years since W.G. Garlick and J.J. Brummer (1951) suggested that the Copperbelt ores were sedimentary, and a little less than thirty years since Stanton (1955 a, b) first suggested that some massive sulfide deposits were formed as an integral part of eugeosynclinal environments and that their location was controlled by volcanic and sedimentary facies.

It is only in the last twenty years that we have recognized the existence of the metal-bearing brines in the Salton Sea and metal deposits forming today in the Red Sea. Only in the last five years, ore grade Zn-Cu sulfides have been discovered on the East Pacific Rise and solutions rich in sulfur and metal have been observed exhaling onto the sea floor. It is only in recent years that research by men like O'Driscoll (1980, 1981, 1982) on the coincidence of major ore deposits and zones of crustal disturbance has begun to receive serious attention.

We now take it for granted that orebodies have tops as well as bottoms, but it was not always so, and certainly not so when the famous American geologist Dr. Hugh Mckinstry came to Australia in 1933 to set up Western Mining Corporation's geological department, one of the first organizations set up anywhere to specifically use the young science of geology in ore search. And what did he and his geologists "see" at the abandoned gold mining centre at Norseman, in Western Australia? Not a mined-out quartz vein which had bottomed because of the vagaries of a mysterious hydrothermal system, but a link-structure in a major reverse fault system, and therefore the possibility of other gold-bearing reefs at depth. This simple improvement in "vision" made possible by science has already produced 3 million ounces of gold worth over $1.5 billion (Woodall, 1984a).

The Kambalda nickel sulfide field in Western Australia was discovered because a geologist *saw* the significance of small ironstone outcrops at the base of ultramafics and the magmatic fingerprint of their trace element composition. Now, as a result of a major, scientific research effort at Kambalda, we can *recognize* those environments where nickel sulfides accumulated, and even the close proximity of nickel sulfide ore (Gresham and Loftus-Hills, 1981) and this is illustrated in Figure 1.

The discovery at Olympic Dam in South Australia of at least 2,000 million tonnes of 1.6% Cu, 0.6 kg U_3O_8, 0.6 g/tonne, resulted from the convergence of three separate types of "looking" with new eyes, eyes that were opened by scientific research which allowed new things to be seen and new questions to be asked. This new way of thinking was begun by D.W. Haynes, who researched the source of copper-bearing solutions (Haynes, 1979) and recommended the Stuart Shelf area of South Australia for exploration for sediment-hosted copper deposits. It was followed by "new thinking" by a geophysicist, H. Rutter, about the meaning of magnetic and gravity patterns on the Stuart Shelf, and he selected the Olympic Dam site for drilling because the coincident gravity and magnetic anomalies were similar to the geophysical patterns at the small copper deposit at Mt. Gunson (Figs. 2 and 3). At the same time, E.S.T. O'Driscoll and D. McP. Duncan applied tectonic analysis, to locate basement fracture systems, research which O'Driscoll had pioneered for thirty years, and their work independently defined the Olympic Dam location as a priority drilling target (Fig. 4).

There are hopeful signs that thermodynamics and experimental studies can now provide a screen to sift "the grains of truth" from the "chaff" of observed empirical associations. Our understanding of the chemistry of naturally occurring aqueous fluids has increased significantly, and we can now talk with modest intelligence and some confidence about solubility, mode of transport and precipitation of metals under certain conditions, and to apply the results to ore genesis and exploration strategy. On a grand scale, Meyer (1981) and Hutchinson (1981) have brought geology, chemistry and biology into a rational pattern of ore formation throughout geologic time, linking the study of ore deposits to the study of the evolution of the earth. This is an exciting concept. The fundamental controls of much of what we see in ore deposits may thus be found as we learn more about the chemical evolution of the Earth and the physics of a cooling, spinning globe, an earth which may yet be found to be expanding.

We need to expand our mental horizons so that we can *see* more clearly how things were in the past and how this is relevant to mineral exploration today. The careful, scientific documentation of ore deposits is critical in this regard, for it contributes significantly to our understanding of the physical and chemical evolution of planet Earth.

The Giants

I disagree with B.J. Skinner (1979, p. 1) when he suggests we are as much concerned with the occurrence and genesis of lean mineral deposits as with ore deposits. Although patterns of occurrence of lean deposits may be useful in signposting where to look, it is the *economic deposits* that support the mining industry and it is around *economic deposits* that additional discoveries resulting from research have the best chance of giving that research an early financial reward. Moreover, it is likely that the economic deposits, especially the giants and the bonanzas, are unique, not only in tonnage and grade, but also in their ore controls and in their associated geologic features. It is what makes the giant deposits and the bonanzas that really matters, and critical features may be absent where nature has produced only a mineral "showing".

Not only are giants and bonanzas of special interest to those who study ore deposits, they are the real prizes which encourage the investor. They are what we must search for if we aim to make the financial investment in mineral exploration an economic success, and to make discoveries which will adequately reward those who risk their savings in mineral exploration.

The giant cluster of nickel sulfide deposits at Kambalda and the giant lead-zinc-silver deposits at Broken Hill are locations where ore-forming processes were repeated many times. Giant ore deposits are centres of sustained activity, "busy" locations, locations that frequently have been tectonically active. It is thus not surprising if we find them, like Kalgoorlie, Mt. Isa, Broken Hill and Olympic Dam, on conspicuous continental lineaments (O'Driscoll, 1982).

The Pitfalls of Science and Ore Deposit Models

We all start our careers in the minerals industry with enthusiasm about the value of the science we have so diligently learned while at university, but many lose heart because they find their managers are not really interested in science. But even when we have an enlightened management, there are pitfalls which we need to be aware of if we are to avoid them, for these pitfalls can erode our confidence in science and its confident application to mineral exploration.

Lack of Belief in Ore as a Rock. Some still regard ore deposits as extraneous oddities which generate museum specimens, and whose occurrence is random and accidental. Yet it is seventy years since Thomas Crook made an eloquent plea for the incorporation of "economic geology" into petrology "in its best and widest sense", and for the study of ores as rocks in their own right (Crook, 1914).

We must avoid just producing catalogues of the characteristics of ore deposits in ever greater detail without adequate thought as to the relevance of those characteristics to the total environment, or the geologic history of that environment. A catalogue of characteristics belongs in a museum: it does not point to the next ore deposit. Ore is a rock, with an origin: it is part of a geological environment and a product of an evolving Earth. Unfortunately, many research workers lack this belief and the courage to attempt to judge the significance of what they observe.

The Sampling Problem. Sampling error can be a serious problem. The pitfall of inadequate sampling can result in an empirical model being very misleading, e.g., the Sudbury-based model for nickel sulfide deposits which led explorers in the 1950s to consider norite to be an essential requirement for nickel sulfide ore occurrence.

Similarly, in the early 1970s the potential of mid-Proterozoic unconformities for uranium orebodies was not appreciated, as at

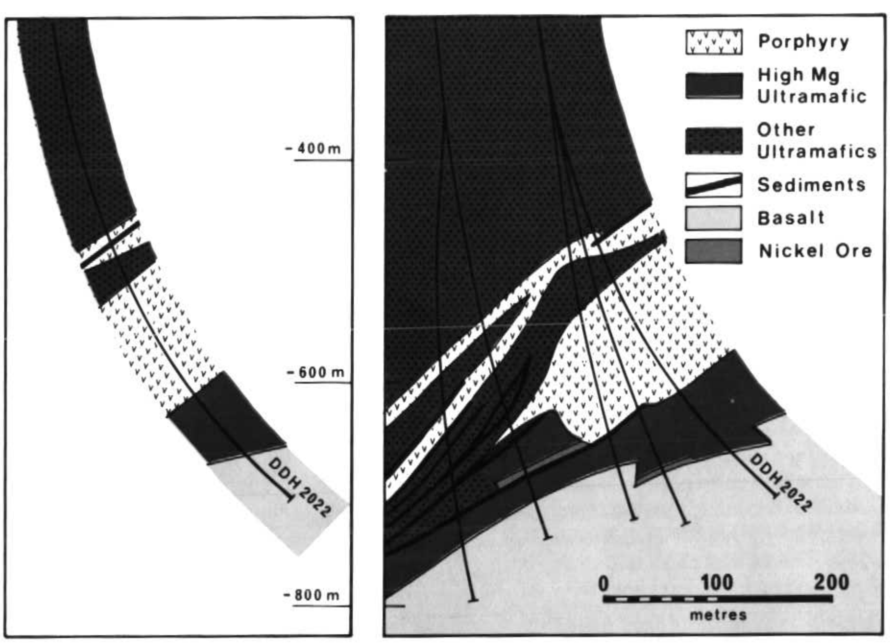

Figure 1 *Kambalda cross sections. Left: Initial drill hole discovers ore environment. Right: Subsequent drill holes discover ore*

the time there were few deposits known in this class and none had been recognized for what they really were.

Ore deposits are the result of extremely complex systems, and careful scientific documentation, preferably by mine-site geological scientists, is essential if visiting specialists are to be able to sample intelligently.

The Logic Problem: Cause, Time and Scale. It is so easy in geology to misinterpret the *cause* of what we see. We see folds and may think the cause was simple compression, when folding may result from gravity sliding, vertical or transverse tectonics. We see replacement of one mineral phase by another, and may assume changing composition of mineralizing fluid when it could be due to changing temperature or pressure or the advance of a reaction front. We may think a major basement shear must be shown by faulting parallel to that shear, when its expression in cover rocks may be either compression, tension, rotation or parallel shear. Moreover, some features found associated with ore may have no relevance to the genesis of that ore.

We also tend to forget the importance of *time*. Not only must the enormous duration of geological time be considered, but also the critical importance of events occurring in the correct sequence, e.g., sourcing *must preceed* trapping and traps or trapping mechanisms *must be present* at the time of migration.

Observations also can be at the wrong scale. This is why eminent scientists initially refused to accept, in fact aggressively challenged, the work of King and others at Broken Hill. Their observations were on ore samples and were at the wrong scale, while King and his co-workers were studying the total ore environment (King, 1968).

The Problem of the Missing Events. The dynamic Earth has many opportunities to erase the effects of earlier, significant events. Look at the case of the Yeelirrie uranium deposit in Western Australia, a world class deposit in surface calcrete which contains 40,000 tonnes of U_3O_8 amenable to cheap, open pit mining. Superficially, nothing could be simpler to explain: abundant Archean granites to source uranium, Tertiary streams into which to channel and concentrate leached uranium, evaporation or reaction with reductants to cause precipitation. But why only one deposit of any size in 800,000 square kilometres of favourable environment where Archean granite, Tertiary drainage, reduced environments and aridity are everywhere superimposed? Can it be that during the enormous period of time between the Archean and the Tertiary there were other events, controlled by unrecognized features, which concentrated uranium at or near Yeelirrie, concentrations which have now been erased from the geologic record (Cameron, personal communication)?

A thick pile of sediments is not a record of continuous sinking and deposition, for "much of what we have been thinking and saying about bedding and conformable deposition is misleading. It is clear that most of the time may be taken up by non-deposition . . . " (Weeks, 1958, p. 26).

The People Problem. The history of science contains many examples of the innovative thinker being ridiculed and of the majority being wrong (Carey, 1981). Our wisest advisor may be someone disregarded by those in power and those who monopolize the literature. At times, a generation or two must die before the wisdom of some original and fundamentally important research is accepted. A generation after Wegener proposed continental drift Carey was still fighting for its acceptance against fierce opposition from many of the world's most eminent and highly regarded geologists. A further generation later it is universally accepted. The idea that lead-zinc sulfides in sedimentary and metamorphic rocks could have formed at the time of sedimentation was proposed in 1953 by King, and the idea that massive sulfides could be an integral part of a volcanic environment was first proposed by Stanton in 1954. Both concepts met strong opposition from the conservative halls of fame and power at the time, even though mention of observations consistent with ore being a sediment and related to volcanism date back over a hundred years.

At the present time, the observations of

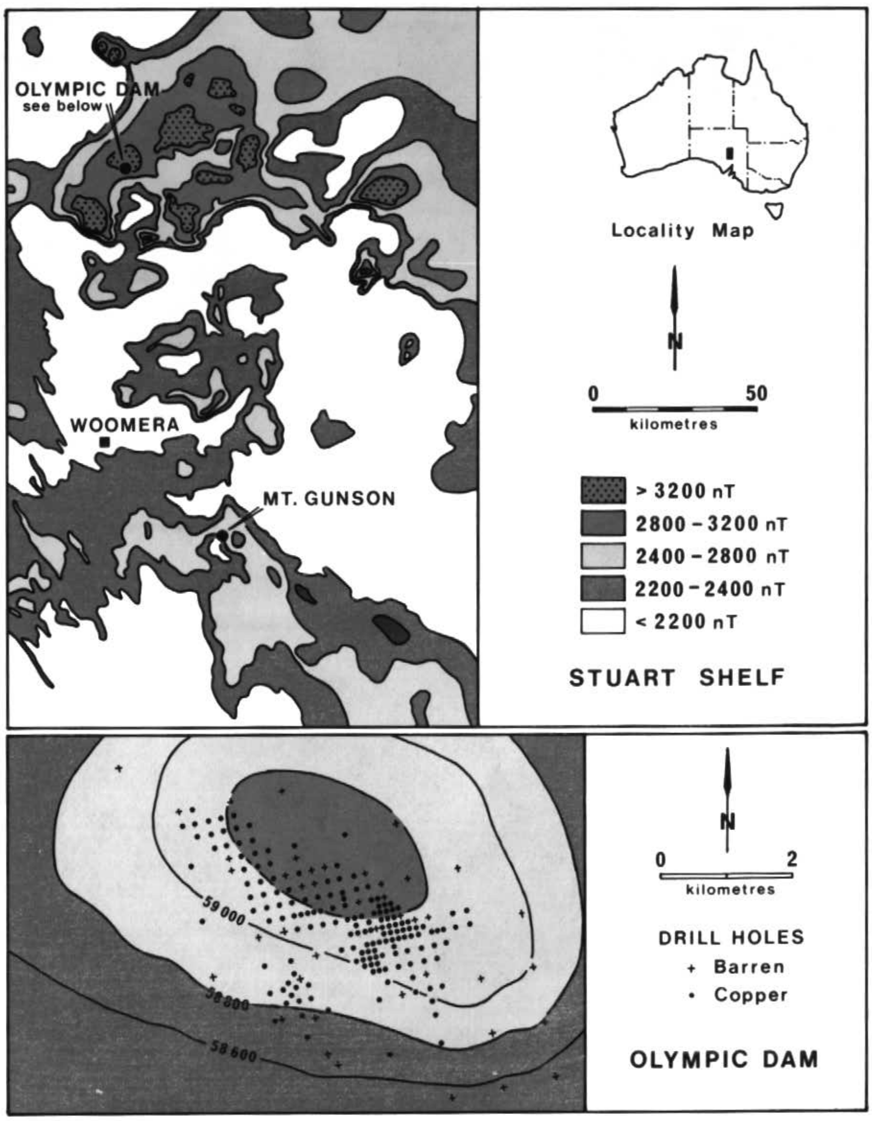

Figure 2 *Top: 1974 aeromagnetic contour map of the Stuart Shelf. Bottom: Detailed magnetic contours and drilling results of Olympic Dam*

O'Driscoll (1980, 1981, 1982) on global tectonics meet strong opposition because they challenge the work and writings of many, and question the blind acceptance of some aspects of such fashionable beliefs as plate tectonics. Similarly, earth expansion is dismissed as a heresy by most geologists today, but even its acceptance may be close at hand (Carey, 1981).

The Problem of the Literature. We all rely on the literature to build up our understanding of ore environments and geologic processes, but there are pitfalls. Much geologic mapping is poor, and hence the interpretations we see in literature may be wrong. Much sampling is poorly directed, and therefore measurements are unreliable. Weeks (1978, p. 71) has pointed out when commenting on the literature that "inaccuracies creep in and are picked up and repeated in the literature until they are solidified into the truth. So first-hand knowledge is generally best". The interpretation of observations and measurements on fluid inclusions is an example of this. An observer reports a certain fluid being present in an inclusion and concludes that the mineral grew in the presence of that fluid. This observation may then be quoted by another author *as evidence* that this fluid was *the mineralizing fluid.* Similarly, plate tectonics is frequently referred to as if it is an ultimate truth when it is not an adequate explanation of all that we see at continental margins and on the sea floor.

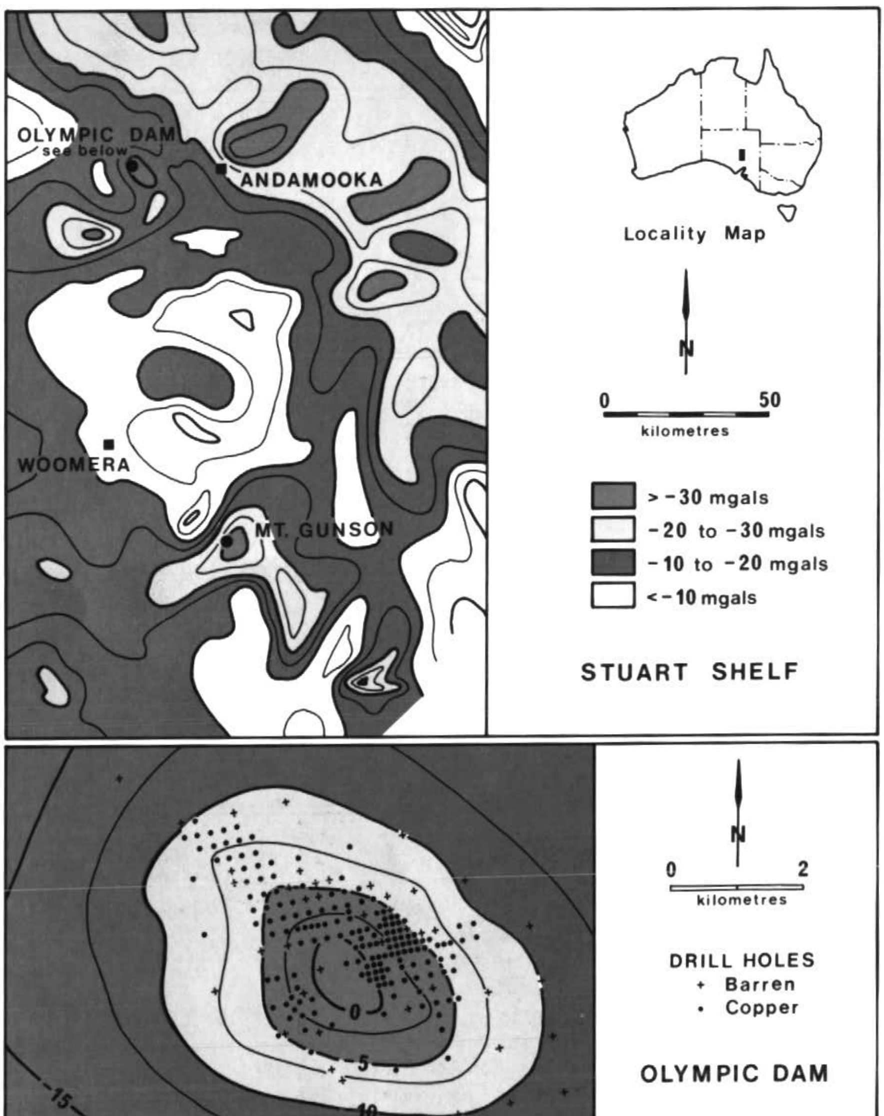

Figure 3 *Top: 1974 Bouguer gravity contours of the Stuart Shelf. Bottom: Gravity contours and drilling results of Olympic Dam*

The problem of the literature is exacerbated by reviewers and editors who often screen out the controversial or unpopular instead of the unsound and erroneous.

Bureaucracies. Bureaucracies do not normally have a management structure which encourages delegation of responsibility, and therefore they discourage scientific exploration. When responsibility is not delegated down to the most informed scientists, exploration decisions are not made by the best informed and tend to be made on the basis of "experience" or on numerical data such as financial estimates and probabilities, rather than on the basis of scientific judgement. Bureaucractic sickness is unfortunately being spread in the mining industry by merger and takeover.

The Complexity of the Problem. We are dealing with very complex systems and problems when we set out to describe or explain an ore deposit. There is still considerable debate about the origin and migration and entrapment of petroleum and they are simpler problems than the origin, migration and entrapment of metals.

It is also chastening to remember that there is still no agreement as to the origin of many important classes of igneous rocks which are associated with ore deposits. Andesite is associated with volcanogenic massive sulfides, but are such rocks the result of partial melting of the mantle (Green, 1979), contamination of magma, the fractionation and loss of an iron-rich fluid phase (Stanton and Ramsay, 1980) or the leaching of tholeiitic basalt (MacGeehan, 1978)?

A Philosophy of Ore Search

The use of science in mineral exploration is encouraged by the following:

1. Initially, the ore deposit geologist studied only the ore, then the ore deposit, but now, with the help of the geochemist and geophysicist, we must study the total ore environment. This is what we must seek to model, and it is in the total ore environment that we must seek to recognize critical patterns. Patterns give us features which can be extrapolated and which, therefore, help answer that most vital question, "where to look".

We are not really concerned with how unless it can tell us why, and we are not really concerned with why unless it can also tell us where: where shall we explore!

2. Many of the major advances that have been made in the search for wisdom and understanding in these matters have been made by geoscientists working in the mining industry. The geologist on the mine is not the poor relation. It is foolish to attempt to unravel the genesis of ore envi-

ronments if mines are staffed by technicians and the "study" of ore deposits is in the hands of a few visiting "experts".

Not only is the company that mines a deposit best equipped to study that deposit, but it is also their responsibility to science and the nation to do so. The incentive of new ore discoveries should encourage management to do this work early and well.

3. The documentation of the Kambalda nickel sulfide deposits in Western Australia (Gresham and Loftus-Hills, 1981) is the result of fifteen years' work by ten to twenty mine geologists, supported by seventy man-years of special studies by full time company research geologists and the part time work of visiting research scientists from universities and government research organizations. This is the order-of-magnitude of the scientific effort required to come to grips with a giant ore occurrence.

The huge Olympic Dam deposit was discovered in 1975, and its first description (Roberts and Hudson, 1983) is the result of seven years' work by five geologists, and this substantial effort is just the beginning.

4. Even the substantial research effort on the Kambalda nickel field has not told us where to look for another giant cluster of ore deposits of this type. The studies in which we quite correctly become involved when documenting the environment of a major ore occurrence, such as at Kambalda, may still be at the wrong scale. Tectonic studies like those by O'Driscoll (1981) have potential in this regard. Major, continental lineaments which represent deep crustal or mantle fractures can localize centres of deep structural plumbing, can tap heat as well as metal and can be expected to be "activity centres" over long periods of time. They thus have the potential to localize the giant deposits through preparing environments for those ore formations and localizing repetitive episodes of sourcing, migration and concentration (trapping).

5. Our ability to perceive what is most relevant is improved by co-operation and sharing of data between specialists in the various spheres of geoscience: sedimentologists, volcanologists, geochemists, hydrologists, geophysicists, experts in hydrothermal deposits and experts in petroleum geology. The ideal is a successful marriage between theory and observation; the *eyes of the skilled observer and the analytical "seeing" mind* of the gifted thinker, with all aspects of science being used to resolve problems.

So important is this matter of improved vision and team co-operation, so often are we blind to significant features, so often in our blindness are we ignorant yet unaware of our ignorance. We should always keep in mind the Hindu fable of the six blind men and the elephant, by J.G. Saxe (King, 1968), which is reproduced here in the Appendix. Any specialist scientist working alone is in danger of being no more effective than any one of these blind men observing an elephant.

What do we go out into the deserts, the forests or the mountains to see? If we take the giant Olympic Dam deposit as an example, which of all the things we "see" there are the most relevant to the problem of finding a similar deposit (Fig. 5)? Is it the granite with its distinctive red, potash felspars, or the variety of breccias – low-matrix granite breccia and high-matrix, polymict breccias which host the ore? Or is it the felsic volcanics, or the hematite breccia, or the rift, or the unconformity? Some may feel it is the unusually high rare earth content, or the age of about 1,500 million years, or the mysterious lineaments and ring-structure which some can see in data (Fig. 4). Our choice will depend on our understanding of patterns of ore occurrence and ore genesis, i.e., our understanding of ore deposit models and our communications with other scientists. What we do will depend on our confidence in those models and the science on which they are based.

Mystery surrounds the origin of ore de-

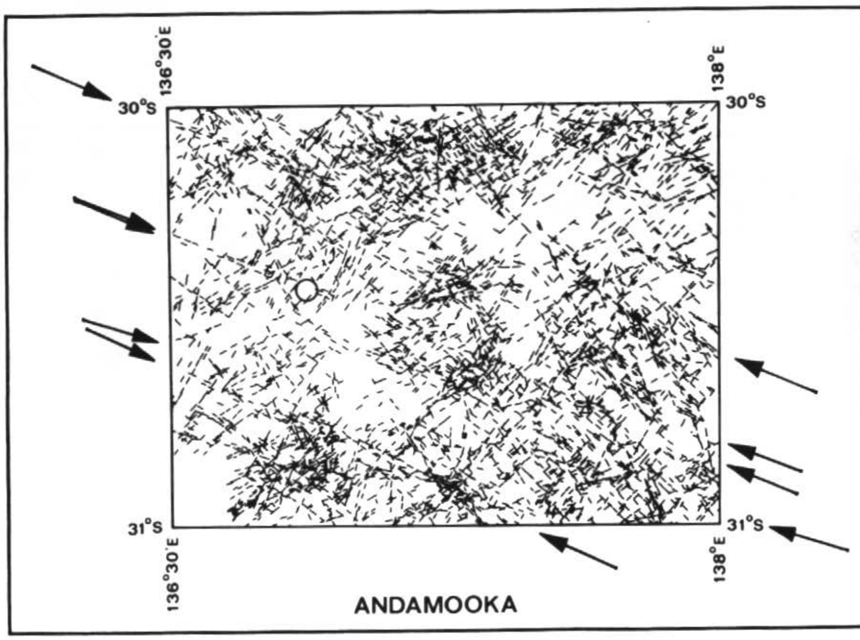

Figure 4 *Photo-lineaments of the Andamooka area showing WNW trends including that through Olympic Dam*

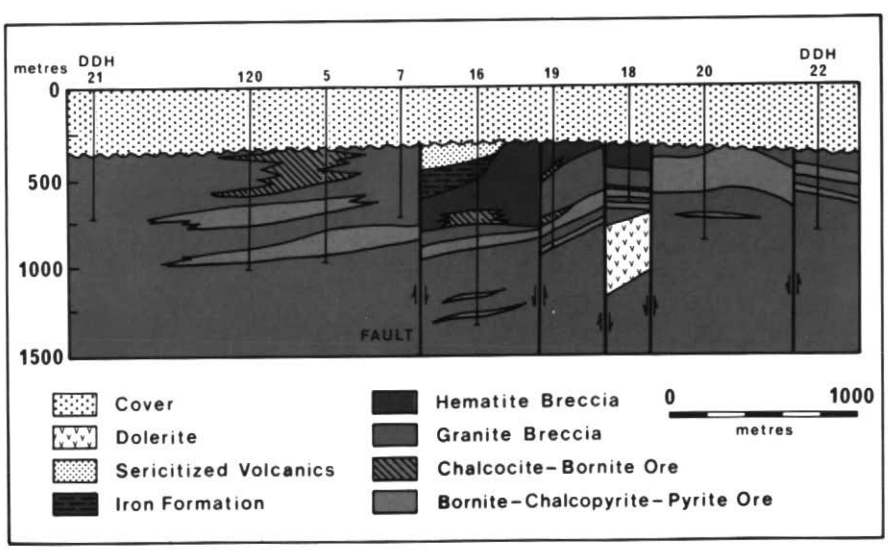

Figure 5 *Olympic Dam – cross section at 200,000 N.*

posits and may always do so, but scientific ideas and ore deposit models keep us looking, with confidence, asking questions and seeing things we either have not seen before or have not appreciated before. But the "course of history is in the hands of a few bold men", said J.H. Van Den Berg, and success in mineral exploration is above all else a matter of confidence. Earth science research and ore deposit models are only relevant if they give us a sounder basis for that confidence, make us bolder and more perceptive explorers, and help us to be more confident in the recognition of either the close proximity of ore or a new ore environment. But we can follow knowledge and reason just so far, then comes the act of faith, the leap beyond the sure path. Whether we are ultimately able to take that step is a test of our ultimate confidence in science and ore deposit models.

Acknowledgements

Such wisdom as this article, and the preceeding articles in this series on success in exploration contain (Woodall, 1983 a, b) is rarely of my own making. The ideas expressed have been formed during discussions with a great number of people over many years, and it will serve no purpose for me to name just a few. It will suffice for me to say that I was blessed with dedicated, stimulating and inspiring teachers in both my undergraduate and graduate studies and have worked for thirty years alongside those generous and exciting people who seem so abundant on the staff of Western Mining Corporation.

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Appendix

The Blind Man and the Elephant

It was six men from Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.

The *First* approached the Elephant,
And happening to fall
Against his broad and sturdy side,
At once began to bawl:
"God bless me! – but the Elephant
Is very like a wall!"

The *Second*, feeling of the tusk,
Cried, "Ho, what have we here
So very round and smooth and sharp!
To me 'tis might clear
this wonder of an Elephant
Is very like a spear!"

The *Third* approached the animal,
And happening to take
The squirming trunk within his hands,
Thus boldly up and spake:
"I see," quoth he, "the Elephant
Is very like a snake!"

The *Fourth* reached out an eager hand,
And felt about the knee.
"What most this wondrous beast is like
Is mighty plain," quoth he;
"Tis clear enough the Elephant
Is very like a tree!"

The *Fifth* who chanced to touch an ear,
Said: "E'en the blinded man
Can tell what this resembles most;
Deny the fact who can,
This marvel of an Elephant
Is very like a fan!"

The *Sixth* no sooner had begun
About the beast to grope,
Than, seizing on the swinging tail
That fell within his scope,
"I see", quoth he, "The Elephant
Is very like a rope!"
And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right
and all were in the wrong!

With apologies, I have modified the final verse of the poem as follows:

So oft in scientific wars
We argue much it seems,
And fail to take the time to see
What the other person means,
About a mineral elephant
Not one of us has really seen.