

The changing technology of search: The Perception of Problems, Knowledge, Tools and Scale in Mineral Exploration

Abstract

The technology of innovation is changing (Arora and Gambardella 1994, Nightingale 2000). Such changes may regenerate the pool of technological opportunities and offset decreasing returns to R&D. This paper analyses the technological changes of search in mineral exploration. The paper demonstrates major reorientations in the perception and theoretical understanding of the problems of mineral concentrations and a shift towards more fundamental knowledge. The paper show how these paradigmatic changes have co-evolved with major improvements in instrumentation, computation, automation and *selective* increase in scale in search of exploration. These complementary improvements have regenerated the pool of exploration opportunities.

1. Introduction

A core issue in industrial dynamics is the study of search for novelties of economic value. Much work has concentrated on how novelties, such as technological inventions or innovations, are created by firms or other types of actors and who appropriates the returns of innovations (Teece 1986, Malerba 2005). However, some novelties are the consequence of discoveries of something that already exists ‘out there,’ rather than being developed by, say, a firm. Thus, the novelty may simply consist of the perception, knowledge or documentation of some existing physical entity. Regardless of whether the novelty is created or discovered, some discoveries or innovations are ‘accidental’ in that they depend on a combination of serendipities together with the ability of somebody to identify and act upon the discovery. Nonetheless, search for novelties ‘out there’ may be just as purposeful as in-house innovative work (Blainey 1970, 1993, David and Wright 1997). Consequently, discovery and development processes entail both purposeful and ad-hoc or ‘accidental’ search and/or creation of novelties. This paper will analyse mineral exploration, where both purposeful and ‘accidental’ search prevail but where the former in recent years has become far more likely to make major discoveries than the latter.

An analysis of search or discovery processes is related to some conceptualization or assumption of the temporal dependency of discoveries or innovations. Economic models such as the search model suggest that R&D on the level of a sector is subject to diminishing returns so that each new novelty tends to be harder to find. However, changes in the technology and organization of search may alter this and lead to increasing returns of search (Dosi 1988, Klevorick et al 1995). Indeed, some scholars argue that there are changes in the technology and scale of R&D which are changing the way technologies are developed (Arora and Gambardella 1994, Nightingale 2000). The essence of this argument is that complementary advances in knowledge and instruments improve the problem-solving capability of industrial researchers to handle increasingly complex problem to a ‘reasonable’ cost (Rosenberg 1976).

The empirical support of these arguments is primarily related to innovation processes where something is created within, say, a research laboratory while less work has

analysed how 'pure' discovery processes change over time. Thus, this paper aims to analyse the changing nature of discovery processes. Specifically, the purpose of this article is to analyse the changing technology of discovery processes in mineral exploration and relate these to the regeneration of opportunities. The paper will show that there are complementary changes in knowledge and conceptualization of the exploration problem, instrumentation, computation, and scale and size and that these are changing the nature of discovery processes in line with the arguments of Arora and Gambardella (1994) and Nightingale (2000).

For the present purpose, mineral exploration is a particularly relevant area to analyse because exploration by definition consists of the search, discovery, characterisation and delineation of prospective ground (ore). That is, exploration entails the search for and the delineation of an ore body that from a geological perspective consists of a certain concentration, size and character of mineral that is deemed to be technologically feasible and economically valuable to extract. Mineral exploration does not create the mining target (the ore body) but instead the explorer tries to characterise the nature of the ore body.

Much exploration is characterised by true uncertainty and complexity. One reason is that in nature ore consists of a certain concentration, which means that the economic cutoff, the boundary for where mining is economically viable for a given technology, scale and market prices, rarely is the same as the geological cut-off. Obviously, given that exploration is a forward looking activity, exploration is based upon a range of expectations and perceptions of market prices, mining innovations etc. However, exploration is an uncertain endeavour also from a 'factual' or objective point of view because of the inherent ambiguity of much geological, geophysical and geochemical data (Trenrove 1979). That is, the creation of ore concentrations is based on complex processes that cannot be re-created in any simple models. Exploration is light on rules but heavy on data and information, which means that the probability of exploration success is impossible to assess quantitatively with any confidence (Horn 1987). Indeed, it is well-known among investors and explorers that true size of ore body is only apparent after some time.

From this perspective, it seems as if exploration can be viewed as an ideal type of discovery processes. Despite this, with the notable exception of David and Wright (1997) this 'sector' has not been given much empirical attention in the industrial dynamics literature.

The paper analyses the changes in exploration focusing on the periods between World War II to 1970 and 1970-2004 from the perspective of the leading exploration countries, especially Australia and North-America.

The paper is structured in the following way. Section 2 discusses the literature on the technology of search and outlines a data-centric model which is used to structure the empirical data. Section 3 discusses the methodology and the limitations of the study. Section 4 analyzes the case, where Section 4.1 deals with the perception of the exploration problem and knowledge, while the rest of Section 4 deals with changes across different activities/functions. Section 5 discusses the findings and draws some conclusions.

Section 2 Conceptualizing discovery processes

Economic models of R&D or search tend to assume that new discoveries and innovations are increasingly difficult to make. Specifically, this refers to the search model of R&D, which assumes that R&D on the level of the firm or industry is subject to diminishing returns (Klevorick et al 1995). This model predicts that as innovative efforts accumulate, the pool of technological opportunities can be exhausted.

However, such models are rejected by Klevorick et al (1995) who argue that technological opportunities could be more usefully viewed as a flow instead of as a stock where the pool of opportunities is regenerated through activities that may be both internal and external to the sector. Klevorick et al (1995) identify three main mechanisms through which opportunities are regenerated; advances in scientific understanding and technique, technological advances originating outside the sector and feedbacks from the sector's own technological advances. In other words, an increased understanding and reorganisation of innovation or discovery processes is needed to maintain a flow of new innovations or discoveries over time. Nelson and Winter (2002, p 39) stated that our understanding of problems, the nature and use of technological artifacts and practice co-evolve. I will discuss these aspects in turn.

The issue of maintaining the flow of discoveries or innovations is related to the characterisation of changes in problem-solving or discovery processes over time from the perspective of cognitive work. Newell (1969) stated that we need to consider the nature of the problem if we are to characterise problem-solving processes that may lead to some solution(s). He argued that there is a particular class of problems that are without any known solutions (algorithms) that solve the problem within some known time and cost limit. These 'ill structured problems' are thus uncertain and any solutions to the problems may also be complex (compare Knight 1921).¹

A core feature of ill-structured problems is that we need to distinguish the generality of a method from its power (Newell 1969, p. 371). A method lays claim via its

¹ Before the advent of computers, the solving of ill-structured problems belonged solely to the domain of human problem-solvers (Newell 1969).

problem statement to being applicable to a certain set of problems, namely, to all those for which the problem statement applies. The generality of a problem-solving approach is determined by how large the set of problems is. The power is determined how accurate and ‘fast’ the approach is in finding a (the) solution.

A weak method to solve ill-structured problems is the ‘generate and test’ approach. Such approaches can be thought of as trial and error or heuristics and should be seen as the foundation of discovery processes in the R&D department (e.g. Arora and Gambardella 1994). All that is required of the ‘generate and test approach’ is a way to generate possible candidates for solution plus a way to test whether they are indeed solutions (Newell 1969, p. 377).

While problem-solving does entail objective (‘factual’) features, there is also an subjective side in that there are differences in how individual actors recognize an opportunity or a chance to innovate (McKelvey and Holmén 2006). Indeed, according to Loasby (2001) the triggering mechanism for an individual (actor) identifying an opportunity or a problem can be understood in what he refers to as Pound’s principle, which states that problems (or opportunities) are identified by the difference between some existing situation and some desired situation. These differences go back to the distinction between a perception of what something could be like or how something could be done and a perception of something factual. Hence, perception and cognition are important aspects of the ability for firms and other actors to react to changes in the environment and act in advance of expected future states. Such acts may of course alter subjective perceptions and objective realities of problems and solutions.

From a cognitive perspective, changes in discovery or R&D processes may be brought about by decomposing a problem into sub-problems (Newell and Simon 1972, Mahdi 2003). Indeed, Vincenti (1990) found that initial vague formulations or specifications over time of the problem to be solved tended to become more sharply formulated as individual actors learned and ‘systems’ of actors experimented. Experts or industrialists use tacit knowledge to ‘see’ a problem, where their perception of the solution to a new problem is similar to a solution to a problem that they have seen in the past (Nightingale 1998). These perceived solutions are technology specific and follows what Nightingale (1998) refers to as technological traditions. The problem-

solving in technological traditions follow a downward spiralling hierarchy where initial vague problems increasingly become specified and decomposed. Such events hold true for an individual actor as well as for a sector.

Arora and Gambardella (1994) argue that there is a new type of knowledge underlying technological development, where development based upon trial-and-error increasingly rely on more abstract and general knowledge (Arora & Gambardella 1994). More specifically, the very nature of R&D processes is changing by becoming more fundamental or science-based (Nightingale 2000). This is important in that trial and error yield knowledge outcome that is difficult to extend to other contexts. This local knowledge remains the main aspect of search for novelties. However, the increasing degree of 'abstract and general knowledge' that allow for more systematic search for novelties complements (augments) the earlier approaches. The tendency is to try to understand the principles governing the behaviour of objects and structures, to 'observe' phenomena and test hypotheses with sophisticated instruments, and to simulate processes on computers (Arora and Gambardella 1994, p. 523). Thus, craft-based scientific processes are complemented by automated processes.

This has been shown in terms of an ongoing merger of science and technology. The argument for improved theoretical understanding of problems is related to the claim that there is an increased scientification of technological change and thus that advances in scientific disciplines have an important influence on technological change (Meyer-Krahmer and Schmoch 1998). The emphasis here is that through the use of science there are increasing attempts to capture and understand the principles that govern physical phenomena. In particular, analysis of patent citations shows that inventors increasingly refer to scientific advances in their patent applications (Narin and Noma 1985, Narin and Olivastro 1992).

While admitting the relevance of the increased scientification of technological change other scholars stress that new technological advancements are prime engines of scientific progress (Gazis 1979, de Solla-Price 1984, Meyer 2000, Rosenberg 1992, compare Smith 1795). Importantly, de Solla Price (1984) argues that advances in instrumentation and experimental techniques have driven and stimulated theoretical

advances in fundamental science and innovations. Thus, the argument is that advances in physical artefacts or tools such as instruments may generate new opportunities for knowledge creation, whether it is ‘technological knowledge’ or ‘scientific knowledge’. Thus, instruments can be understood as the capital goods of R&D, meaning that their economic significance comes from allowing researchers or engineers to reduce the costs of solving increasingly complex technical problems (Lachmann 1956, Rosenberg 1976, Nightingale 2000). While many studies used to reside in some formulation of the ‘linear model of innovation’ where scientific advances precede technological advance leading to innovation (see Mowery and Rosenberg 1979, Kline and Rosenberg 1986, Rosenberg 1992), more recent studies broadly conclude that scientific and technological advances need to be understood as being mutually dependent (Meyer-Krahmer and Schmoch 1998, Meyer 2000).

Nightingale (2000) argues that the economics of discovery is changing in that there is a shift towards economies of scale in experimentation in pharmaceuticals R&D. The argument is that there is a change in the scale of throughput and that these changes create economies of scale of R&D. The increase in scale is correlated to a decrease in the size of the analysed unit, which is also reflected by the use of more fundamental theoretical knowledge.

The economic importance of increasing throughput in R&D is that the increase in scale of operation per unit of time lies in the ability to avoid failures or dead ends (Nightingale 2000). Thus, there is a focus on the ability of actors to for new discoveries. This means that changes in the throughput, such as the increase in speed per unit of time, should be related to the speed of interpretation or analysis per unit of time, not the speed of data per se.² Automation is of major importance in this respect in that it may allow for data analysis which otherwise would be prohibitively costly or simply impossible to perform.

Search includes both knowledge and data or information, where knowledge is the framework within which data or information is interpreted. From a throughput perspective, discovery processes consists of flows of data and data that is interpreted

² The interpretation may be done by either machines humans humans.

data through the application of knowledge. Thus, the scale of the throughput of search depends on how much data can be collected and analysed per unit of time, see Figure 2.1.³

Figure 2.1 Throughput in discovery

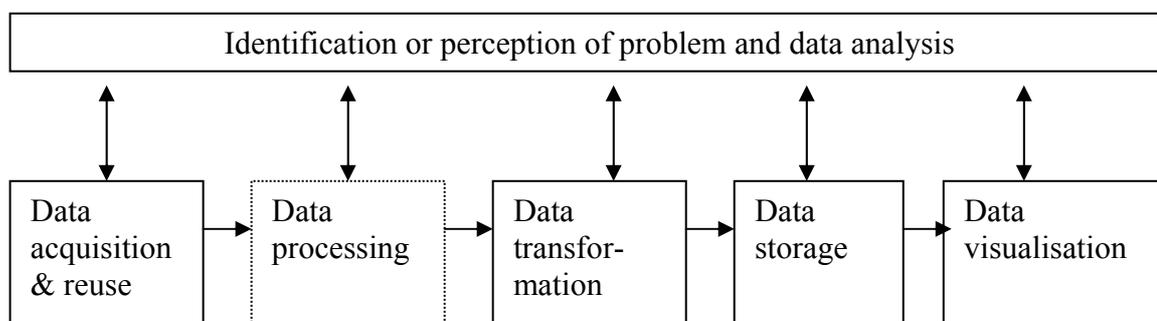


Figure 2.1 characterises the throughput of data in discovery processes in terms of abstract time invariant functions.⁴ The upper level of Figure 1 emphasises that discovery processes can be understood as the identification, conceptualization of a particular task or problem at hand, and the analysis of a proposed solution.⁵

The lower level of the model is an overtly simplified sequential construction of the data flow in discovery processes.⁶ The basic idea is that data initially, e.g. at the beginning of a project, is acquired and or reused from an earlier project. The data may be ‘dirty,’ including spurious features which mean that an analysis of the collected data could be meaningless or flawed unless the data is processed (‘cleaned’) in some manner. After the data has been cleaned, it may need to be stored on paper or in a

³ This throughput is dependent on the ontology of actors, that is what they perceive to be ‘there’ and what know, and the available capital structure of R&D.

⁴ This model is used to structure the empirical analysis in Section 4. That is, the paper structures exploration-related activities in terms of how data is collected and analysed from a functional view, where the functions are related to data flows. These functions are abstract representations that encompass the multitude of different activities that are part of any discovery process. The model makes no distinction from whether a person, organisation or set of actors are involved in the activities of collecting and analysing the data.

⁵ This solution may be related to the discovery processes or an intermediate problem, which is to contribute to the solving of the overarching problem. For example, problem-solving may be used in any of the different functions portrayed in the lower level. The importance of having both the data flow perspective together with a cognitive or knowledge level is both are necessary elements in discovery processes (e.g. Nightingale 1998).

⁶ While the lower level portrays the data flow as sequential, in reality some of there may be many feedback loops, some functions may be ignored (such as data processing) and the sequences may change.

database. However, the data in this form may not be useful in this form because they are on the on wrong form, thus the data may need to be transformed into another format, standard or domain. The stored or transformed data may need to be visualised in some manner so that an observer can view the data.

While the literature review has focus on changes in cognition and instrumentation and argued that these may regenerate the pool of (technological) opportunities, it is clear that these changes may be driven by a range of actors, such as a sector (Klevorick et al 1995, Malerba 2005). Thus, there is a connection between the cognitive approaches and the issue of specialization and division of labour. Knight (1921) claimed that core issues in reducing uncertainty to risk is for actors to accumulate experiences (learn) and to increase the scale of operations, and thus increase the division of labour. Young (1928) stated that the progressive division of labour among firms is organized around the reduction of complexity to simplicity via sequencing of tasks. Such arguments are in line with the view of problems as being better specified and decomposed over time.⁷

In summary, the literature review has highlighted the importance of analysing changes and complementarities in both the perception and the understanding of problems. At the same time, the analysis pointed out the importance of characterising the changes in tools or instruments, automation and scale of operation in order to capture changes in the technology of search. Given the need to view data throughput in terms of the use of the data, the literature review stressed the importance of analysing complementary advancements in the throughput, i.e. as in the ability to interpret the data. Section 4 will analyse these two aspects in mineral exploration.

⁷ Figure 2.1 structures the throughput of data and does reflect the division of labour and the division of innovative labour in mineral exploration.

Section 3 Research design

This paper uses a case study to illustrate changes in search. There are limits to the generalizability of a case study methodology and thus caution must be taken in terms of its implications. Specifically, while this case study could be expected (but yet to be shown) to be relevant for search for things ‘out there’, the usefulness of this approach may be limited in other more creative areas.

The definition of mineral exploration delineates the case study. Modern mineral exploration comprises the (systematic) acquisition, processing and analysis of geologically interpretable data to assess the economic value of ore. Ore is a metal-bearing mineral valuable enough to be mined (Postle et al 2000) whereas a mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes (Nickel 1995). Exploration determines whether a mine should be created or if the outlay of a mine should be extended, mining activities continued or terminated.

Industrialists characterise exploration consisting of firms mainly engaged in exploring for minerals (except for crude petroleum or natural gas) on their own account, or contract exploration services. However, to cover the changes in exploration, a broader view is warranted. Thus, the data is based on 31 interviews during 2004 with experienced geologists, geophysicists and geochemists in exploration firms, mining companies, Geological Surveys, industry associations and universities. These types of actors covers the major types of actors in exploration.

There are several potential weaknesses in the data. *First*, while interviewees were all active in Australia. However, the focus on Australian actors should not limit the value of the research in that Australia is one of the world’s leading countries in exploration. Exploration is also a distinctly global service sector and many of the interviewees had extensive international experience. In average the interviews lasted for 2-2.5 hours.

Second, the paper analyses the transformation of minerals exploration in leading countries from around 1970 until 2005. It should be noted that this date is simply a proxy of ongoing changes there are many deviations across nations and across types

of ore.⁸ However, while the precision is therefore of limited value, the general changes should not be flawed.

Third, given the purpose of the paper, there is an overemphasis on ‘fundamental’ changes in exploration compared to daily routines of explorers. The changes that are shown should be viewed as extension of earlier activities rather than as substitutes.

⁸ Some issues that are portrayed as belonging to recent history have a long history in some countries. For example, airborne electromagnetics was used in Canada and in Scandinavia during the 1950s even if a more systematic and widespread usage did not become common until the 1990s. Reasons for this include the type of ore deposits, the type of ground and relative maturity of the exploration sector in a country.

4. Knowledge and tools of mineral exploration

This section characterises the transformation of search in minerals exploration. *First*, Section 4.1 analyses changes in how explorers perceive and conceptualize the exploration problem from the perspective of the exploration ‘sector’ (Malerba 2005). This means that the focus is on changes in the technological trajectories (paradigms) of mineral exploration. *Second*, Section 4.2 and 4.3 analyses changes in exploration from the perspective of throughput of data across a set of ‘connected functions’. These functions are data acquisition and processing; and data transformation, storage and visualization respectively. This analysis follows the structure of Figure 2.1 and changes will be analysed in terms of perception of problems, knowledge, tools and scale for each of the functions.

4.1. Problems and understanding in exploration

Over the last fifty years, mineral exploration has been fundamentally transformed in that systematic exploration activities have taken over the activities performed by individuals or small groups of prospector that were looking for ore on the ground (Trenrove 1979). From an economic perspective, this can be understood as ongoing work to shift exploration from an empiricist ad hoc approach to search to a more systematic search. This shift has removed people, especially geologists, from the ground and has greatly increased the capital/labour ratio of exploration.⁹

Exploration is the first step in the business of increasing the concentrations of minerals. In later phases, concentrations are extracted (mined) and further concentrated through smelting etc. Thus, the main economic value of exploration comes from finding existing high concentrations of mineral in the ground and thus exploration focuses on the search for natural occurrences of high concentrations of minerals. The economic value of ore is determined by the combination of geological,

⁹ Exploration often refers solely to the search for commercially viable concentrations of mineral. For the sake of convenience, this paper makes no distinction between these and non-commercial activities such as scientific mapping. One rationale for this is that both activities relate to the throughput, and there are many instances where non-commercial activities move over to commercial domains and vice versa.

technological, economic (e.g. transportation, capital investments, market prices), and institutional factors.

A core feature of exploration is that it entails the search for *concentrations*. Thus, changes in extraction technologies or market prices of minerals may regenerate or terminate business opportunities of exploration. However, such exogenous features are far from the only means by which exploration opportunities are regenerated. Empirically, this is well understood by actors in that old, tested ground may be searched anew and major discoveries are made very close to the activities of antecedent exploration activities.

Such findings are often the results of improved exploration tools but they are also the results of new models of the ground. One reason for this is the empirical fact that minerals are concentrated within geologically defined regions. These regions are empirically known to be rare. Furthermore, concentrations within geological regions that are of economic value are small, and consequently easily overlooked, and rare. The reason for the rarity of ore bodies of economic value is that mineral concentrations have been created by particular sequences of geological, physical, chemical or biological events over long periods of time. These - denoted geological controls - can from an exploration perspective be understood and used as guidelines for search.

Indeed, the first major shift in terms of perception of the problem in exploration is related to the identification and analysis of the geological controls. One important change was work to *empirically* characterise the controls to understand the processes that led to creation of mines. Many models of ore formation were created from a theoretical perspective and these tended to be far too simple and were also contrary to all empirical evidence (King 1989). This shift towards an empirical foundation of exploration took place during the entire 1900s but did not gain much strength until after World War 2. Case studies of ore formation processes on the mine scale became very common.

However, a consequence of the focus on geological controls is that it may be worthwhile to increase the scale of search. Today, it is known that ore exist in some

geologically defined regions; these are of a much larger size than an individual mine. Thus, to understand the geological controls exploration should characterise the processes of the region. To do this, systematic and standardized mapping of ground is essential. As an example, since 1979, 80% of all ore discoveries in China is based on large scale geochemical mapping (Xuejing et al 2004).

Indeed, there is an increasing emphasis among exploration companies and Geological surveys to address the issue of why a certain concentration of ore exist in particular location and why it does not exist elsewhere. If such questions are understood, this can allow for a greatly improved prediction of findings. This is a more fundamental question than the empirically based case studies of ore formation where search for novel finds rather than understanding old discoveries change from analogous reasoning to prediction. Some of this work takes place on a larger scale. (However, exploration is done in connected sequences of projects ranging from the large to small scale).

The second major shift is related to where explorers search. Over time, much land has been surveyed several times by explorers. Statistically, the largest finds in a geological region are found early. Over time, the discoveries tend to be of smaller and smaller size. This is not surprising given that the larger an ore body is, the more likely it is to have outcrops, that is where a mineral is visible to the naked eye. The existence of outcrops and the larger they be, the more likely the ore is to be discovered. Thus, the easy finds are made first.

However, the pool of exploration opportunities is being regenerated by a change in search. Over the last twenty years, it has become increasingly common to capture ore bodies that lie under cover, i.e. covered by dirt (Liu and Peng 2003). This shift too is based on the focus to understand the geological controls but now the search is for blind ore formations. This shift towards increasingly difficult domains is reflected in a shift in exploration activities from prospectors, via governmental actors, especially Geological Surveys, and mining companies, to specialized small exploration companies.

More precisely, the major change is the increased focus on the regolith. The regolith can be defined as the area between “fresh air and fresh rock” that consists of deeply weathered material. The regolith used to be viewed as dirt that hid mineral concentrations further down in the ground. More recently however, the regolith is viewed as a phenomenon that may provide explorers with important information, which cannot be captured in any other way. Thus, there has been an ongoing shift towards understanding the subtle signals in the regolith with is an increasing appreciation that the regolith conveys subtle signals that are far more widespread than the actual ore body. Thus, understanding and mapping these signals are very useful for explorers. The shift towards attempts to understand processes in the regolith commenced in the 1970s in but did not affect exploration in leading exploration countries with extensive overburden (regolith) such as Australia until around 1990.

A third major shift has been to complement direct search for ore to an indirect search. Direct search implies that explorers are looking for concentrations of the mineral that is of economic interest while indirect search is the use of indicator minerals. This is again a more complex undertaking, where the explorer relies on models of ore formation to be able to analyse a range of different mineral concentrations. Oversimplifying the issue a bit, indirect search is more oriented towards understanding and mapping, while direct search is more towards the delineate of a discovered ore body. In practice, sometimes these may be empirically indiscernible even if the activities are analytically distinct.

4.2 Changes in data acquisition and data processing

Data acquisition and processing have been fundamentally transformed during the last decades. First, the rise of the application of geophysical and geochemical technologies means that the cost of exploration per analysed unit per hour has decreased dramatically. This is most readily apparent in terms of airborne geophysics where aeroplanes or helicopters collect geophysical data over large areas and in three dimensions. For a comparison of the older means of exploration compared to modern exploration, see Figure 4.1 and 4.2.

** FIGURE 4.1 ABOUT HERE. **

**** FIGURE 4.2 ABOUT HERE ****

Geophysical and geochemical data acquisition is of particular significance in areas where outcrop is poor or in mature areas. Geophysical and geochemical types of data acquisition include surface reflectance of EM radiation, magnetic susceptibility, rock conductivity, copper concentrations in drainage sediments, or Ti/Zr ratios in soil. These are all used by explorers to infer and create two, three or four dimensional models of the ground. Thus, the improvements of these technologies are instrumental for renewing opportunities. Furthermore, major reason for the decreasing unit costs the greatly increased scale and scope of activities per unit of time and the systematic reuse of previously collected data.

Such data collection has two roles (Fountain 1998). One is the so called ‘bump hunting’ where geophysical instruments ‘beep’ when they find an anomaly compared to its surroundings. These anomalies are targets that explorers are looking for. This approach is based on the assumption that “what you see is what you get” and is thus aims to directly locate ore. However, ore bodies are relatively small and their delineation requires detailed, close spaced measurements and therefore very expensive. One reason that in ‘bump hunting’ has met with limited success in many nations and for many different types of minerals, is that for an anomaly to be found, there must be a difference between a particular area and its surroundings. In countries with large overburdens (regolith), this is rarely the case.¹⁰

Another role, one of increasing importance, is to map large areas to create models of the ground. These define regional geology by mapping areal distribution of a particular rock or soil characteristics. These models are then the foundation of exploration in the small where more precise information is needed.

¹⁰ The reason is that regolith, just like mineral deposits tend to be conductive while fresh rock tends to be resistive. In countries that recently were covered with ice during the last Ice Age, such as Scandinavia, Canada and Russia, this is different in that these countries were scraped clean from the regolith when the ice melted. Thus, the anomalies in these countries for iron ore tends to be very distinct.

Second, from a technological point of view, the increased scale and scope of activities are enabled from ongoing application diversification of geophysical and geochemical exploration technologies. Core to these advances is the improvements in data processing that make sure that the acquired data is sufficiently ‘clean’ to be analytically useful. One example is the launch of a commercial airborne gravity gradiometry around 2000. This technology is impossible to get to work without the use of modern technologies such as GPS and digital instruments. More generally, areas of particular importance include the digitalisation of instruments during the 1980s and the greatly improved signal to noise ratios (S/N) and the use of lower frequencies in geophysics allow for discovery under cover has allowed for much greater depth of penetration of geophysical instruments. Furthermore, the use of multicomponent measurements have become routine (Smith and Annan 1997)

Examples relates to the discovery of the Bougainville mine in Papua New Guinea during the 1960s and the recent success in Western Australia, Australia and Nevada, USA in finding gold from selective geochemical sampling during the 1990s (Phillips and Yearncombe 2003).

Third, there is a shift towards a more *selective design of data acquisition*. Until quite recently, data acquisition has been deliberately suppressed because too much noise was collected rather than useful information. The most important change here was digitalization which has allowed for a much higher control of data collection.

One example of this is geochemical soil sampling to look for ‘subtle dispersion halos’ of gold concentrations. Depending on the depth of the regolith, data is either analytically useful or analytically useless. This fundamental characteristics of regolith processes was not understood until the 1990s (Annan and NN 1997). Thus, the explorer must know the depth of the regolith to know whether sampling could be made or not.

Fourth, there have been major improvements in drilling. Drill holes are the primary tool that delineates the extension of an ore body but it is also used to ground truth geophysical data, see Section 4.3. The cost of drill holes have decreased. Routinely, reverse circulation or rotary airblast drilling is used to get a quick and dirty overview

of the ground. For a much better control and verifiability of data acquisition, diamond drills are used.

4.3. Changes in data transformation, storage and visualization

The unit costs exploration of ground has decreased dramatically during the last decades. This decrease is not visible in actual exploration budgets because the scope and the complexity of the exploration problem have increased greatly, especially in ‘mature’ areas which have been subject to exploration many times before.

A basic shift in exploration is that the scale and scope exploration has shifted from local and 2-dimensional (2D) search to a regional four-dimensional (4D) search. Section 4.1 discussed this change from a paradigmatic point of view, while Section 4.2. analysed it in terms of acquisition and data. However, the collection of data is meaningless unless some information can be inferred from the data which is of use for explorers. The most useful form of data presentation for explorers is a map of the ground. In particular, a common earth model is very valuable, depicting the ground in a ‘language’ that all types of exploration professions can understand.

The means of transforming data from the geophysical domain to the geological domain is called inversion. Inversion is a mathematically ill-posed problem and does not have a unique solution. Thus, creating a ‘useful’ map is a non-trivial issue in that there is an inherent and unavoidable problem for large scale exploration in that the data collected by geophysical instruments may come from an infinite number of grounds. Fortunately, there have been major advances in techniques to work around this problem. One is that prior data of the ground is used to constrain the solution space. Another is forward modelling, which is the opposite procedure to inversion. Forward modelling mathematically transforms geological models into geophysical signals. This process does have a unique solution and thus it is used to try out whether certain types of ground models could create the type of signal that the geophysical survey captured.

It should be noted that the issue of data transformation in terms of inversion or forward modelling hints at the classic chicken or egg problem. If the ground is

mapped, why map it by geophysical tools? If the ground is now known, why would a geophysical survey be meaningful? This hints at the fundamental problem of exploration in the large scale. These are rarely meaningful – and thus they do not substitute – for exploration activities in the large scale. The most important exploration tool is the drill, and drillhole data is used to ‘ground truth’ the survey in the large scale. Thus there is a distinct complementarity between large scale surveys and smaller scale exploration activities. The former is used to select potential ground and the latter is used to verify and delineate the findings, see Figure 4.2. Ground truthing is viewed as a demonstration, albeit in a small scale, of the existence or lack of economic value of an ore body.

The answer is that explorers have begun to use computers and a range of other tools to interactively move from one domain to the other. Thus, advances in transformation, storage and visualization depended on the advances in computers from the 1970s onwards. Data storage has changed from maps filed in cabinets during the 1970s to databases containing Gigabytes or Terabytes of data. This expansion in the size of data and the advances in computation means that explorers has gone from extremely simplified, geologically flawed models to more realistic models.

Of dramatic importance is the separation of data storage from visualization. This abstraction has allowed for a much more flexible experimentation of alternative models of geological controls that may help explain the particular shape of ground. The shift has been from two-dimensional maps, to three or four-dimensional maps. Increasingly simulation and virtual reality is used on the mine scale level so as to help explorers design the shape of a mine. The separation of storage from visualisation is thus a core feature which has allowed for an increase in data reuse.

5. Conclusion and discussion

The purpose of this article is to analyse the changes in the technology of discovery processes in mineral exploration and to analyse how these regenerates opportunities. The rationale for this purpose is that changes in the technology and scale of R&D which are changing the way technologies are developed (Arora and Gambardella 1994, Nightingale 2000) where complementary advances in knowledge and instruments improve the problem-solving capability of industrial researchers to handle increasingly complex problem to a ‘reasonable’ cost (Rosenberg 1974, 1976). Mineral exploration is an interesting case study because it consists of search for things ‘out there’ rather than being something that is created by humans and firms.

Four findings will be discussed.

First, the paper shows that there are major changes in the technology of search in mineral exploration; see Table 5.1 for a synthesis.

Table 5.1 Major changes in exploration*

Changes	Expansion of search space and proposing models	Testing	Modify understanding
From craft to systematic search (exploration)	From prospecting (individual local search) on the ground to systematic interdependent firm-firm/government exploration	From shovels and panning to ‘matrices’ of reverse circulation/rotary airblast or diamond drilling	From no consideration of why ore concentration was formed, via case studies of ore bodies formation to “why this concentration here and not elsewhere?”
Changes in scale and size	From adhoc or mine/local scale to surveys of geological region(s), may decrease to molecular size (e.g. geochronology)	Expansion of types and size of data collected (including multiple forms of geological, geophysical and geochemical data)	To systematic geochemical selective testing; formulation of regional controls and sequences of events; indirect search
Tools and automation	From vehicle based data collection in two dimensions to airborne based geophysics or remote sensing in three or four.	From wet chemistry to automated multi-element assays and data integration	From isolation geological and geophysical approaches integration geophysical and geological data

* Table based on Nightingale (2000, Table 8, p. 348) and Figure 4.1 and 4.2.

Perhaps most importantly, this paper found that there are major improvements in the perception of the problem and the understanding of the exploration problem. These can be characterised as changing search into more fundamental aspects to characterise the mechanisms underlying the formation of ore (geological controls) and increase in the scale of analysis from local to regional scale.

Furthermore, as outlined in Table 5.1, mineral exploration has shifted from being a craft to a modern industry, that there have been shifts in the scale and size of exploration, and that there have been major improvements in the tools and an increasing extent of automation.

The table also shows that there are major improvements in instrumentation, computation, automation and that there is a *selective* increase in scale in search in mineral exploration, which is in line with the arguments of Arora and Gambardella (1994) and Nightingale (2000).

The table is based on the on the ‘generate and test’ approach that is suitable and used for a broad range of ill-structured problems (Newell 1969, Nightingale 2000). At the same time, it also relates changes in understanding of the paradigmatic issues and the perception of problems. This means that it can be viewed as an alternative formulation of the ‘connected function’, see Figure 2.1. This model assumes that ‘pure’ search can be usefully characterised in terms of its data throughput, where the throughput consists of data acquisition, processing, transformation, storage and visualization.

However, the notion fundamental or scientific should not be overemphasised. This is not how exploration works. Explorers, regardless of whether they are independent exploration companies, mining or Geological Surveys tend to shift from a scientific, probing mode to a mode based on, identify and delineate. Thus, explorers generally move between two worlds, an economic and one more scientific and fundamental. However, for exploration at large, the activities have become more fundamental even if individual projects vary greatly.

Second, the paper found that the advancements of data throughput in one function may be useless from an exploration perspective unless there are complementary

advancements. The paper suggests that analysing exploration, and more broadly search, as ‘connected functions’ may contribute to better capture and analyse bottlenecks of search in line with Rosenberg’s argument (1976). A case in point was that improvements in data acquisition for a long time were suppressed because the capture of more data would lead to new problems that could not be dealt with. Improved performance led to the capture of spurious data with a deterioration of the signal quality. These could not be handled unless there was a way to ‘clean’ the data.

In other words, advances in perception of problem, understanding and knowledge, and tools need to co-evolve. This seems to confirm the arguments of Nelson and Winter (1982).

Third, the complementary improvements have transformed exploration and regenerated the pool of exploration opportunities and have been a foundation for a new division of labour. The shift towards search under cover and the shift of exploration to be more fundamental by focusing on the geological controls of mineral concentration are some of the core phenomena.

A case in point is the increased usage of geophysical technologies. When used in the large, such as airborne geophysics, they are applied to characterise larger areas and to select ground for more detailed studies (drilling). Thus, exploration in the large scale bring about economies of scale of experimentation to avoid dead ends and lock as Nightingale (2000) argued.

Fourth, it may be pointed out that the paper has indicated a clear relation between the scale of search and the nature of knowledge creation and use of knowledge in that a larger scale of search implies entirely new technological traditions.

References

- Arora, A. and Gambardella, A. (1994). The Changing Technology of Technological Change: General and Abstract knowledge and the division of innovative labour, *Research Policy* 23, pp. 523-532.
- Blainey, G. (1970) A theory of mineral discovery: Australia in the nineteenth century, *The Economic History Review*, Vol. 23, Issue 2, pp. 298-313
- Blainey G. (1993) *The rush that never ended*, Carlton, Melbourne University Press.
- Chandra, R. and Sandilands, R. J. (2005) Does Modern Endogenous Growth Theory Adequately Represent Allyn Young? *Cambridge Journal of Economics*, Vol. 29, pp. 463-473
- de Solla Price, D. (1984). The Science-Technology Relationship, the Craft of Experimental Science, and Policy for the Improvement of High Technology Innovation, *Research Policy*, 13, pp. 3-20.
- David, P.A. and Wright, G. (1997) *Increasing returns and the genesis of American resource abundance*, *Industrial and Corporate Change*, Vol. 6, No. 2, pp. 203-245
- Fountain, D. (1998) Airborne electromagnetic systems - Fifty years of development, *Exploration Geophysics*, The Bulletin of the Australian Society of Exploration, Geophysicists, Vol. 29, No. 1 and 2, pp. 1-11.
- Holmén, M. and Sæmundsson, R. (2005) The Changing Technology of Software Creation. Submitted.
- King, H. (1989) *The rocks speak. Essays in geology – some personal responses of a willing listener*, The Australasian Institute of Mining and Metallurgy, ISBN 0 949106 39 9.
- Lachmann, L. M. (1978). *Capital and its Structure*. Sheed Andrews and McMeel, Kansas City.
- Land, R. and Pracilio, G. (2000) Visualisation of sub-surface conductivity derived from airborne EM, EEGS SAGEEP Proceedings, Washington, February, pp. 101-110.
- Langlois, R. N. (2001) Knowledge, Consumption, and Endogenous Growth, *Journal of Evolutionary Economics*, Vol. 11, pp. 77-93.
- Liu, L-M. and Peng, S-L (2003) Prediction of Hidden Ore Bodies by Synthesis of Geological, Geophysical, and Geochemical Information Based on Dynamic Model in Fenghuangshan Ore Field, Tongling District, China, *Journal of Geochemical Exploration*, Vol 81, pp. 81-98.
- McKelvey and Holmén (2006), Introduction, in McKelvey, M. and Holmén, M. (eds.), *Flexibility and Stability in the Innovating Economy*, Oxford University Press, Oxford, pp. 1-23.

Malerba, F. (ed.) (2004) Sectoral Systems of Innovation. Concepts, Issues and Analyses of Six Major Sectors in Europe. Cambridge, Cambridge University Press

Malerba, F. (2005). "Sectoral Systems of Innovation: A Framework for Linking Innovation to the Knowledge Base, Structure and Dynamics of

Marjoribanks, R.W. (1997) *Geological methods in mineral exploration and mining*, Chapman & Hall

Meyer, M. (2000) Does science push technology? Patents citing scientific literature, *Research Policy*, Vol. 29, pp. 409-434.

Nelson, R. R. and Winter, S.G. (2002) Evolutionary theorizing in economics, *Journal of Economic Perspectives*, Vol. 16, No. 2, pp. 23-46

Newell, A. (1969) Heuristic programming: Ill-structured problems, *Progress in Operations Research*, Vol. III, pp. 360-414

Nickel, E. H. (1995) Definition of a mineral, *The Canadian Minerologist*, Vol. 33, pp. 689-690.

Nightingale, P. (2000) Economies of scale in experimentation: knowledge and technology in pharmaceutical R&D, *Industrial and Corporate Change*, Vol. 9, pp. 315 - 359.

Phillips, G. N. and Vearncombe, J. R. (2003) Exploration of the Yandal gold province, Yilgarn Craton, Western Australia, in Ely, K. S. and Phillips (eds.) *Yandal Gold Province: geoscience and exploration success*, CSIRO Exploration & Mining, Melbourne

Postle, J., Haystead, B., Clow, G., Hora, D., Vallée, M. and Jensen, M. (2000) *CIM standards on mineral resources and reserves: Definitions and guidelines*, Canadian Institute of Mining, Metallurgy and Petroleum, CIM.

Pounds, W. F. (1969). 'The Process of Problem Finding', *Industrial Management Review*, Vol. 11, pp. 1-19.

Rosenberg, N. (1963) Technological Change in the Machine Tool Industry 1840-1910. *Journal of Economic History*, 23 (4), pp. 414-443.

Rosenberg, N. (1992) Scientific Instrumentation and University Research. *Research Policy* 21, pp. 381-390.

Smith, R. S. and Annan, A. P. (1997) Advances in airborne Time-Domain EM technology, Proceedings of Exploration 97, Fourth Decennial International Conference on Mineral Exploration, pp. 497-504.

Teece, (1986)

Thomke, S., von Hippel, E., and Franke, R. (1998) Modes of Experimentation: An Innovation Process – and Competitive – Variable, *Research Policy*, Vol. 27, pp. 315-332

Trengove, A. (1979) *Discovery: Stories of modern mineral exploration*, Stockwell Press, Mont Albert Victoria, ISBN 0 909 316 04.

Vincenti, W. G. (1990). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: The Johns Hopkins University Press.

Walker, R. (2001) California's golden road to riches: Natural resources and regional capitalism, 1840-1940, *Annals of the Association of American Geographers*, Vol. 91, pp. 167-199.

Xuejing, X., Dawen, L., Yunchuan, X., Guangsheng, Y. and Changyun, L. (2004) Geochemical Blocks for Predicting Large Ore Deposits – Concepts and Methodology, *Journal of Geochemical Exploration*, Vol 84, pp. 77-91

Figure 4.1. 'Old' mode of exploration: technologies, instrumentation, knowledge and scale

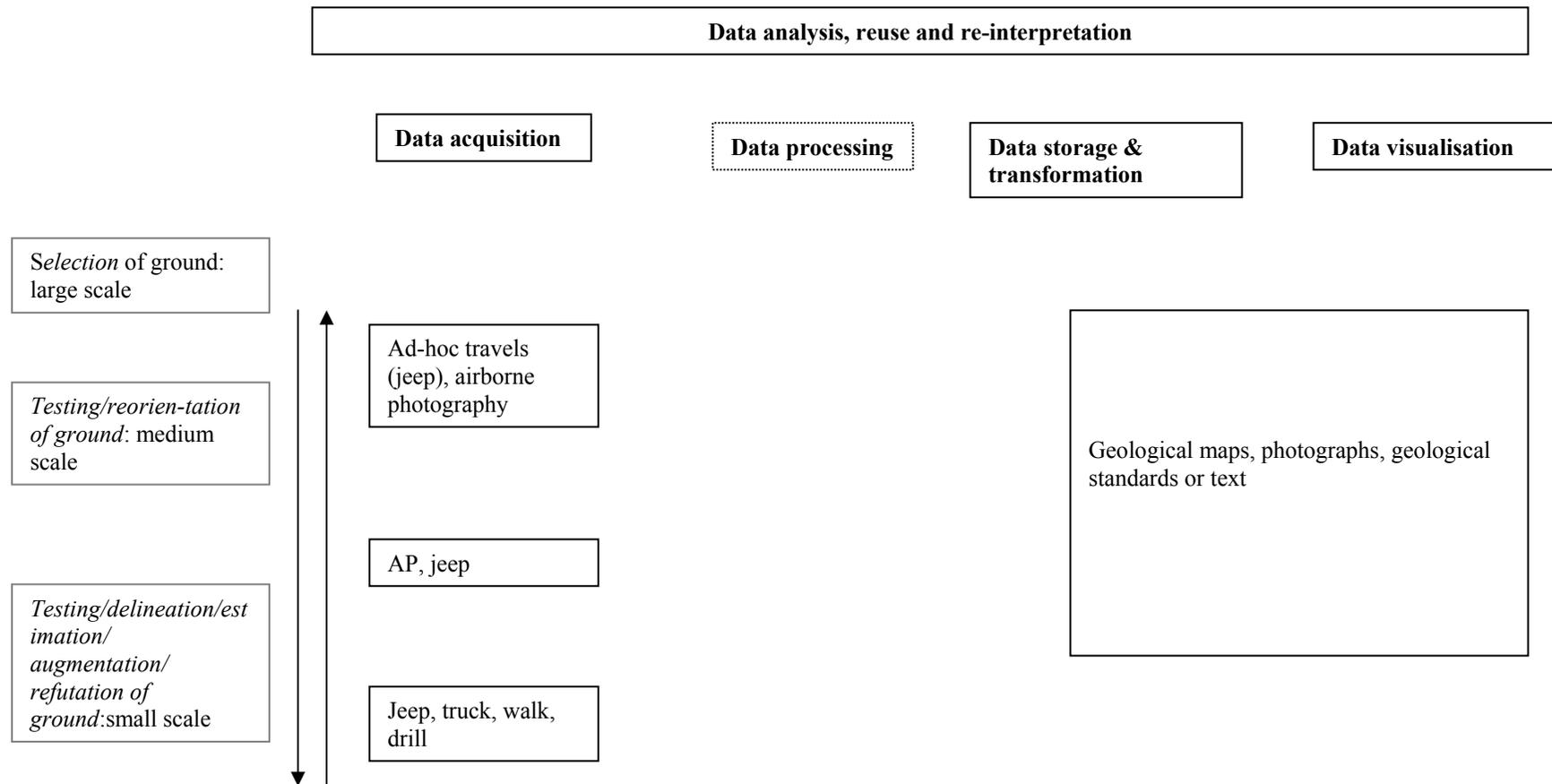


Figure 4.2. 'Modern' mode of exploration: technologies, instrumentation, knowledge and scale

