GEOLOGICAL METHODS IN MINERAL EXPLORATION AND MINING

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PREFACE

This book is written as a practical field manual to be used by geologists engaged in mineral exploration. It is also hoped that it will serve as a text and reference for students in Applied Geology courses of universities and colleges. The book aims to outline some of the practical skills that turn the graduate geologist into an explorationist. It is intended as a practical 'how to' book, rather than as a text on geological or ore deposit theory.

An explorationist is a professional who searches for ore bodies in a scientific and structured way. Although an awkward and artificial term, this is the only available word to describe the totality of the skills which are needed to locate and define economic mineralization. Even the mine geologist, attempting to define ore blocks ahead of the mining crews, is an explorationist. The most fundamental and cost-effective skills of the explorationist relate to the acquisition, recording and presentation of geological knowledge so that it can be used to predict the presence of ore.

Practical field techniques taught at undergraduate level are often forgotten and sometimes, although taught, are not reinforced by subsequent practice; some skills may never be adequately taught in the academic environment of universities. Special techniques needed by an explorationist – for example, mapping on grids or logging drill core or cuttings – seldom figure in basic training courses. Although no book can substitute for hands-on experience and demonstration, this manual aims to address some of these deficiencies.

The book does not offer a set of standard rules to be invariably followed. It describes practical skills and techniques that, through the experience of many geologists, have been found to be effective. Each geologist has to develop his/her own techniques and will ultimately be judged on results, not the process by which these results were reached. In mineral exploration, the only 'right' way of doing anything is the way that locates ore in the quickest and most cost-effective manner. It is preferable, however, for an individual to develop his/her own method of operation after having tried, and become aware of, those procedures which experience has shown to work well and which are generally accepted in industry as good exploration practice.

The chapters of the book approximately follow the steps which a typical exploration programme would go through. In Chapter 1, the generation of new projects and prospects and the nature of the exploration process are described. In Chapters 2 and 3 are descriptions of the various techniques employed in making geological maps from surface outcrop and mine openings. Chapter 4 deals with exploration drilling and presents methods for acquiring and presenting geological information from various types of drill core and cuttings. Chapter 5 describes the procedures involved in trenching and pitting. Although this book is primarily concerned with geological methods, in Chapter 6 a brief overview is given of the more commonly used techniques of exploration geophysics and geochemistry. Finally, Chapter 7 outlines the use of geographical information systems (GIS) for the storage, manipulation and presentation of map data.

New ideas and techniques are constantly emerging and no book such as this can be regarded as being a final statement. To make this a useful document and to keep it up to date and relevant, geologists should use it critically.

The underlying philosophy behind much of this book is that, if geological data is to be of value in finding ore bodies, ideas and insights must be used in a structured way to control all stages of data handling from field collection through to final presentation. In these days of electronic storage and processing of mass data, it is worth remembering the well-known quote[1]:

Data is not information
Information is not knowledge
Knowledge is not understanding
Understanding is not wisdom

The book outlines some geological techniques for acquiring knowledge. The rest is up to the reader.

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[1] Possibly adapted from: 'Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?' (T.S. Eliot).

ACKNOWLEDGEMENTS

I am indebted to the many skilled field geologists with whom I have been privileged to work over many years, and from whom I have acquired many of the exploration and geological ideas, techniques and procedures which are described here. The book has benefited from the constructive comments and suggestions of a number of reviewers. However, all biases and errors that might be found in this text are the author's own, and he takes full responsibility for them.

PROSPECTING AND THE EXPLORATION PROCESS 1

This chapter attempts to put the detailed exploration procedures outlined in this book into the wider context of the exploration process.

1.1 DEFINITION OF TERMS

Exploration field activities take place as part of a strategy (often called a 'play') to locate and define a particular economically mineable mineral commodity (ore) in a mineral province. Large exploration plays are often broken down into individual projects (often a particular tenement[1] group) and each project may contain one or more prospects.

A prospect is a restricted volume of ground that is considered to have the possibility of directly hosting an ore body and is usually a named geographical location. The prospect could be outcropping mineralization, an old mine, an area selected on the basis of some geological idea, or perhaps some anomalous feature of the environment (usually a geophysical or geochemical measurement) that can be interpreted as having a close spatial link with ore. Prospects are the basic units with which explorationists work. The explorationist's job is to generate new prospects and then to explore them in order to locate and define any ore body which might lie within them.

1.2 GENERATING NEW PROJECTS AND PROSPECTS

Generating new prospects is the critical first stage in the exploration process and is known as prospecting. Traditionally, prospecting was the search for simple visual surface indications of mineralization. Nowadays the range of surface indications that can be recognized by the explorationist is expanded by the use of sophisticated geophysical and geochemical techniques. However, the skills and abilities involved in successful prospecting are common to all techniques. They involve activity, observation, knowledge, insight, opportunism, lateral thinking and luck. A description of traditional prospecting skills will therefore serve to illustrate these key attributes of success.

During the nineteenth century, in places like Australia or North America, it was still possible to stumble on a kilometres-long prominent ridge of secondary lead and zinc minerals, or a district where ubiquitous green secondary copper minerals indicated the huge porphyry system beneath. In this century, even as late as the 1950s and 1960s, prominent and extensive mineralized outcrop was still being identified in the more remote parts of the world. Discoveries such as Red Dog in Alaska (Koehler and Tikkanen, 1991; Young, 1989), Porgera in Papua New Guinea (Handley and Henry, 1990) and Ertsberg in West Irian (Van Leeuwen, 1994), belong to this era. Few places are left in the world today which offer such readily identified prizes. For that reason, exploration is increasingly focused on the search for ore bodies which have either subtle outcrop or no outcrop at all.

[1] The legal title to explore and mine an area goes by different names in different countries and carries a wide variety of rights and obligations. The word 'tenement' is used in this book in a non-specific way to refer to all such titles.

In spite of this, experience shows that simple prospecting methods can still find ore bodies. Good examples of this are the 1964 discovery of the West Australia nickel sulphide deposits at Kambalda (Gresham, 1991); the 1982 discovery of the massive Ladolam Gold Deposit of Lihir Island, Papua New Guinea (Moyle *et al.*, 1990), the 1993 discovery of the outcropping gossans which overlay the rich Voisey Bay Cu/Ni/Co massive sulphide ore body in Labrador, Canada, and the 1994 Busang gold discovery in Indonesia.

If recent prospecting discoveries are examined, it seems that success has come from two main factors:

- The prospector searched where no one had searched before. This may be because historical opportunity made an area accessible that previously was inaccessible. However, very often the reason for the discovery was simply that no one had previously thought to look in that particular place.
- The prospector identified and tested subtle or non-typical indications of mineralization that had previously been overlooked, either because they were very small or, more usually, because he/she recognized as significant some feature that previous observers had seen but dismissed as unimportant.

One of the most important ingredients of prospecting success has been lateral thinking. By this is meant the ability to:

- see familiar rocks in new contexts;
- question all assumptions (especially one's own) and accepted wisdom;
- be alert for small anomalies or aberrations;
- know when to follow a hunch[1] (since some of the above attributes are as much subconscious as conscious).

1.3 SOME WAYS OF GENERATING NEW EXPLORATION IDEAS

New ideas may come 'out of the blue', but more often are the result of certain well-recognized situations which the explorationist is able to combine fruitfully with knowledge which he/she already has. It pays to be alert for these situations so as to take advantage of the opportunities which they offer. Here are some of them:

Scenario 1 New knowledge of the geology or geophysics of an area becomes available from new mapping (either your own or Geological Survey maps). Combined with your own understanding of mineralization, the new mapping indicates the possibility of different styles of mineralization being present, or different places to look.

Scenario 2 Elsewhere in a district which you are exploring, a discovery is made which can be used as a new and more relevant model for mineralization than the one which you have been using.

Scenario 3 A visit to other mining camps – maybe even on the other side of the world – provides new insight into your exploration property. The formal description of an ore body in the literature is no substitute for seeing it for yourself – particularly if there is an opportunity to see the discovery outcrop.

Scenario 4 New exploration technology makes it possible to explore effectively in an area where earlier prospecting methods have been unsuccessful.

Scenario 5 Political changes make available for exploration and mining a part of the world that previously had not been subject to modern methods of exploration.

1.4 A CHECK-LIST OF NEGATIVE ASSUMPTIONS

Sooner or later, in most exploration programmes on an area, an impasse is reached in the ability to generate new exploration ideas. At this point, it is always easy to think of many good reasons why the effort should be abandoned. However, before this decision is made, it is worth while to critically check through a list of the beliefs which are held about the area. On examination, these beliefs might turn out to be mere assumptions, and the assumptions might be wrong. To assist in this process, here is a

[1] A current theory is that intuitive and often subconscious processes take place in the right side of the brain, while rational, deductive reasoning derives from the left side. Both processes play a part in successful ore finding.

check-list of five negative assumptions commonly made by explorationists about the prospectivity of an area.

- The area is not prospective because it is underlain by rock type X.
  Comment: How do you know? The geological map might be wrong or insufficiently detailed. In any case, if rock type X is not prospective for your target commodity, perhaps it is prospective for some other commodity.
- The area has already been exhaustively explored.
  Comment: An area or prospect is seldom exhaustively tested. The best any explorationist can do is to exhaustively test some idea or model that they have about mineralization, using the best tools at their disposal at that time. Generate a new model, or develop a new tool, and the area may turn out to be under-explored.
- All prospective rocks are pegged (staked) by competitors.
  Comment: When was the last check made on the existing tenements plan? Have all the opportunities for joint venture or acquisition been explored? If you have ideas about the ground which the existing tenement holder does not, then you are in a very good position to negotiate a favourable entry.[1]
- No existing ore-body model fits the area.
  Comment: Mineral deposits may belong to broad classes, but each one is unique: detailed models are usually formulated after an ore body is found. Beware of looking too closely for the last ore body, rather than the next.
- The prospective belt is excluded from exploration by reason of competing land use claims (environmental, native title, etc.).
  Comment: This one is tougher; in the regulatory climate of many countries today, the chances are high that beliefs in this area are not mere assumptions. However, with reason, common sense and preparedness to compromise, patience and negotiation can often achieve much.

[1] It is usually a legal (and also a moral) requirement that all relevant factual data be made available to all parties in any negotiation on an area. Ideas, however, are your intellectual property, and do not have to be communicated to anyone (you could after all be wrong).

1.5 STAGES IN PROSPECT EXPLORATION

Once a prospect has been identified, and the right to explore it acquired, assessing it involves advancing through a progressive series of definable exploration stages. Positive results in any stage will lead to advance to the next stage and an escalation of the exploration effort. Negative results mean that the prospect will be discarded, sold or joint ventured to another party, or simply put on hold until the acquisition of fresh information/ideas/technology leads to its being reactivated.

Although the great variety of possible prospect types mean that there will be some differences in the exploration process for individual cases, prospect exploration will generally go through the stages listed below.

1.5.1 TARGET GENERATION

This includes all exploration on the prospect undertaken prior to the drilling of holes directly targeted on potential ore. The aim of the exploration is to define such targets. The procedures carried out in this stage could include some or all of the following:

- a review of all available information on the prospect, such as government geological mapping and geophysical surveys, the results of previous exploration and the known occurrence of minerals;
- preliminary interpretations of air photographs and remote sensed imagery;
- detailed geological mapping;
- detailed rock-chip and soil sampling for geochemistry;
- detailed geophysical surveys;
- shallow pattern drilling for regolith or bedrock geochemistry;
- drilling aimed at increasing geological knowledge.

1.5.2 TARGET DRILLING

This stage is aimed at achieving an intersection of ore, or potential ore. The testing will usually be by means of carefully targeted diamond or rotary percussion drill holes, but more rarely trenching, pitting, sinking a shaft or driving an adit may be employed. This is probably the most critical stage of exploration since, depending on its results, decisions involving high costs and potential costs have to be made. If a decision is made that a potential ore body has been located, the costs of exploration will then dramatically escalate, often at the expense of other prospects. If it is decided to write a prospect off after this stage, there is always the possibility that an ore body has been missed.

1.5.3 RESOURCE EVALUATION DRILLING

This stage provides answers to economic questions relating to the grade, tonnes and mining/metallurgical characteristics of the potential ore body. A good understanding of the nature of the mineralization should already have been achieved – that understanding was probably a big factor in the confidence needed to move to this stage. Providing the data to answer the economic questions requires detailed pattern drilling and sampling. Because this can be such an expensive and time-consuming process, this drilling will often be carried out in two substages with a minor decision point in between: an initial evaluation drilling and a later definition drilling stage. Evaluation and definition drilling provide the detail and confidence levels required to proceed to the final feasibility study.

1.5.4 FEASIBILITY STUDY

This, the final stage in the process, is a desk-top study that assesses all factors – geological, mining, environmental, political, economic – relevant to the decision to mine. With very large projects, the costs involved in evaluation are such that a preliminary feasibility study is often carried out during the preceding resource evaluation stage. The preliminary feasibility study will identify whether the costs involved in exploration are appropriate to the returns that can be expected, as well as identify the nature of the data that must be acquired in order to bring the project to the final feasibility stage.

1.6 MAXIMIZING SUCCESS IN EXPLORATION PROGRAMMES

Obviously not all prospects will make it through to a mine. Most will be discarded at the target generation or target drilling stages. Of the small number that survive to evaluation drilling only a few will reach feasibility stage, and even they may fail at this last hurdle. The total number of prospects that have to be generated to provide one new mine discovery will vary according to many factors (some of these are discussed below) but will generally be a large number. Some idea of what is involved in locating an ore body can be gained by considering a prospect wastage or exploration curve (Figure 1.1). This is a graph on which the number of prospects in any given exploration play is plotted against the exploration stage reached (or against time, which is the same thing). The large number of prospects initially generated decline through the exploration stages in an exponential manner indicated by the prospect wastage curve. On Figure 1.1, the curve labelled A represents a successful exploration play resulting in an ore-body discovery. The curve labelled C represents another successful exploration play, but in this case, although fewer prospects were initially generated, the slope of the line is much less than for play A. It can be deduced that the prospects generated for play C must have been generally of higher quality than the prospects of play A because a higher percentage of them survived the initial exploration stages. The line B is a more typical prospect wastage curve: that of a failed exploration play.

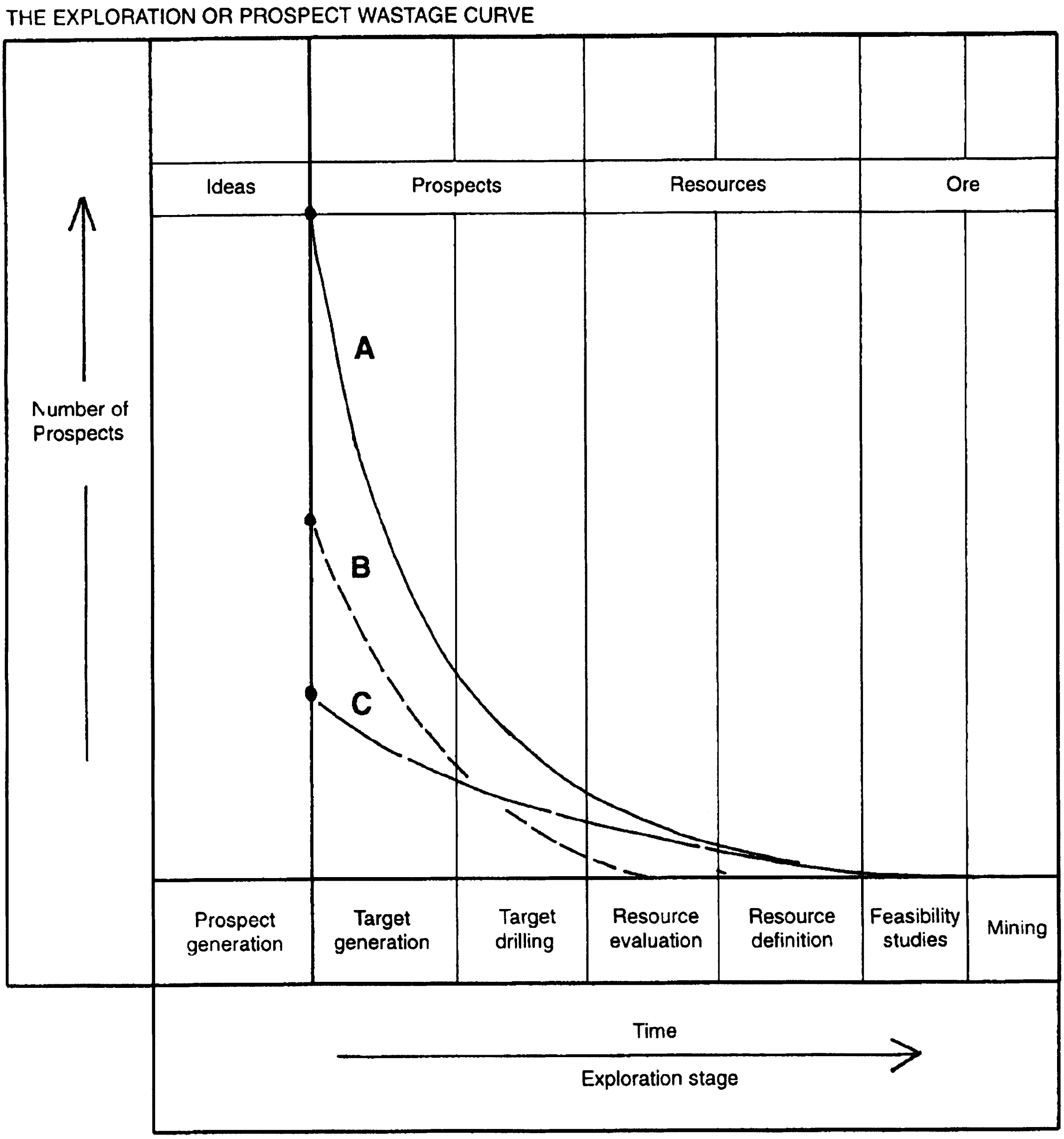

Figure 1.1 These curves show how, for any given exploration programme, the number of prospects decreases in an exponential way through the various exploration stages. In a programme based largely on empirical methods of exploration (curve A), a large number of prospects are initially generated; most of these are quickly eliminated. In a largely conceptual exploration programme (curve C), a smaller number of prospects are generated, but these will be of generally higher quality. Most programmes (B) will fall somewhere between these two curves. Most will not succeed.

It should be clear from Figure 1.1 that there are only two ways to turn an unsuccessful exploration programme into a successful one; the exploration programme either has to get bigger (i.e. increase the starting number of prospects generated) or the explorationist has to get smarter (i.e. decrease the rate of prospect wastage and hence the slope of the exploration curve). There is of course a third way: to get luckier.

Getting bigger does not necessarily mean hiring more explorationists and spending money at a faster rate. Prospects are generated over time, so the injunction to get bigger can also read as 'get bigger and/or hang in there longer'. There is, however, usually a limit to the number of worthwhile prospects which can be generated in any given exploration programme. The limits are not always (or even normally) in the ideas or anomalies which can be generated by the explorationist, but more often are to be found in the confidence of the explorationist or of those who pay the bills. This factor is often referred to as 'project fatigue'. Another common limiting factor is the availability of ground for exploration. In the industry, examples are legions of groups who explored an area and failed to find the ore body subsequently located there by someone else, because, in spite of good ideas and good exploration programmes, the earlier groups simply gave up too soon. Judging whether to persist with an unsuccessful exploration programme or to cut one's losses and try some other province can be the most difficult decision an explorationist ever has to make.

Helping the explorationist to get smarter, at least as far as the geological field aspects of exploration are concerned, is the aim of this manual. The smart explorationist will generate the best quality prospects and test them in the most efficient and cost-effective manner. At the same time, he/she will maintain a balance between generation and testing so as to maintain a continuous flow of directed activity leading to ore discovery. The achievement of a good rollover rate of prospects is a sign of a healthy exploration programme.

1.7 DIFFERENT TYPES OF EXPLORATION STRATEGY

The exploration curve provides a convenient way of illustrating another aspect of the present-day exploration process. Some regional exploration methods involve widespread systematic collection of geophysical or geochemical measurements and typically result in the production of large numbers of anomalies. This is an empirical exploration style. Generally little will be known about any of these anomalies other than the fact of their existence, but any one anomaly could reflect an ore body and must be regarded as a prospect to be followed up with a preliminary assessment, usually a field visit. Relatively few anomalies will survive the initial assessment process. The exploration curve for a programme that makes use of empirical prospect generation will therefore have a very steep slope and look something like the upper curve (A) of Figure 1.1.

The opposite type of prospect generation involves applying the theories of ore-forming processes to the known geology and mineralization of a region, so as to predict where ore might be found. This is a conceptual exploration approach. Conceptual exploration will generally lead to only a small number of prospects being defined. These are much more likely to be 'quality' prospects, in the sense that the chances are higher that any one of these prospects will contain an ore body compared to prospects generated by empirical methods. An exploration play based on conceptual target generation will have a relatively flat exploration curve and will tend to resemble the lower line (curve C) on Figure 1.1.

Empirical and conceptual generation and targeting are two end members of a spectrum of exploration techniques, and few actual exploration programmes would be characterized as purely one or the other. Conceptual generation and targeting tends to play a major role where there are high levels of geological knowledge and the style of mineralization sought is relatively well understood. Such conditions usually apply in established and well-known mining camps such as (for example) the Kambalda area in the Eastern Goldfields of Western Australia, the Noranda Camp in the Canadian Abitibi Province or the Bushveld of South Africa. Empirical techniques tend to play a greater role in greenfield exploration programmes, where the levels of regional geological knowledge are much lower and applicable mineralization models less well defined.

Most exploration programmes employ elements of both conceptual and empirical approaches and their exploration curves lie somewhere between the two end member curves shown on Figure 1.1.

GEOLOGICAL MAPPING IN EXPLORATION 2

2.1 GENERAL CONSIDERATIONS

2.1.1 WHY MAKE A MAP?

A geological map is a graphical presentation of geological observations and interpretations on a horizontal plane.[1] A geological section is identical in nature to a map except that data are recorded and interpreted on a vertical rather than a horizontal surface. Maps and sections are essential tools in visualizing spatial, three-dimensional, geological relationships. They allow theories on ore deposit controls to be applied and lead (hopefully) to predictions being made on the location, size, shape and grade of potential ore bodies.

Making, or otherwise acquiring a geological map, is invariably the first step in any mineral exploration programme, and it remains an important control document for all subsequent stages of exploration and mining, including drilling, geochemistry, geophysics, geostatistics and mine planning. In an operating mine, geological mapping records the limits to visible ore in mine openings, and provides the essential data and ideas to enable projection of assay information beyond the sample points.

Making a geological map is thus a fundamental skill for any exploration or mine geologist.

2.1.2 THE NATURE OF A GEOLOGICAL MAP

A geological map is a human artefact constructed according to the theories of geology and the intellectual abilities of its author. It presents a selection of field observations and is useful to the extent that it permits prediction of those things which cannot be observed.

There are different kinds of geological map. With large-scale[2] maps, the geologist generally aims to visit and outline every significant rock outcrop in the area of the map. For that reason these are often called 'fact' maps, although 'observational' or simply 'outcrop' maps is a better term. In a small-scale map, visiting every outcrop would be impossible; generally, only a selection of outcrops are examined in the field and interpolations have to be made between the observation points. Such interpolations may be made by simple projection of data or by making use of features seen in remote sensed images of the area, such as satellite or radar imagery, air photographs, aeromagnetic maps and so on. Small-scale maps thus generally have a much larger interpretational element than large-scale maps.

The difference between the two map types is, however, one of degree only. Every map, even at the most detailed of scales, can only present a small selection of the available geological observations and no observation is entirely free from interpretational bias. Even what is considered to represent an outcrop for mapping purposes is very much scale dependent. In practice, what the map-maker does is to make and record a

[1] The ground surface is, of course, not always horizontal and, although this can usually be ignored in small-scale maps, it can have profound effects on the outcrop patterns of large-scale maps.

[2] By convention, large-scale refers to maps with a small scale ratio – e.g. 1:1000 scale or 1:2500 scale. Small-scale refers to large scale ratios such as 1:100 000 or 1:250 000. Generally, anything over 1:5000 should be considered small-scale, but the terms are relative.

certain number of observations, selected from the almost infinite number of observations that could be made, depending on what he or she regards as important given the purpose in constructing the map. These decisions by the geologist are necessarily subjective and will never be made with an unbiased mind (although sometimes the bias is unconscious and unacknowledged).

A geological map is thus different from other types of map data that the explorationist might use. Although typical geochemical or geophysical maps can contain interpretational elements and bias, they in general aim to provide exact presentations of reproducible quantitative point data. The data on such maps can often be collected by non-professionals and the map can be compiled and plotted by computer according to pre-set formulae. A geological map, on the other hand, is not contoured point data but an analog presentation of ideas; ideas backed up by detailed, careful observation and rational theory but, nevertheless, ideas. To be a successful geological map-maker, it is necessary to keep this concept firmly in mind, and throw out any idea of the geological map-maker as an objective collector of 'ground truth' data. After all, one geologist's 'ground truth' may be another geologist's irrelevant noise!

2.1.3 SMART MAPPING

Producing a geological map is a process of problem solving. One of the best ways to approach problem solving is known as the system of multiple working hypotheses. In practice this means that the geologist does not start the field work with a completely blank mind but armed with ideas about the geology which has to be mapped. These ideas are developed from looking at published maps, from interpreting air photos or aeromagnetic data or even by following an intuitive hunch. From these ideas or hypotheses, predictions are made; areas are then selected and observations are made which will most effectively test these predictions. Sometimes this will involve walking selected traverses across strike, sometimes following a marker horizon or contact, sometimes a more irregular search pattern. The mapping sequence depends on the postulated geology: strong linear strike continuity usually indicates that across-strike traversing is the best approach; complex folding or faulting is best resolved by following marker horizons, and so on. In any case, the early working hypotheses will certainly contain several alternative scenarios and may not be precisely formulated; to check them out a very wide range of field observations will have to be made and a mix of different search patterns may need to be followed. The geologist at this stage must be open to all possible ideas, hypotheses and observations. If the observations do not fit the hypotheses, then new hypotheses must be constructed or old ones modified to accommodate the observations. These new hypotheses are then tested in their turn, and so the process is repeated.

With each step in the process the predictions become more precise and the search pattern more focused on to the key areas of interest. These are the areas where significant boundary conditions can be defined in the outcrop. Most of the time of the 'smart mapper' is thus spent in the areas of 'fertile' outcrop where there is most to be learned, and less time is spent in those areas where the rocks are uniform – in the latter areas a lower density of observation will serve (Figure 2.1).

Many structural features can be observed in individual outcrop or hand specimens which allow predictions to be made about structures occurring at the scale of a map. Most useful of such observations are the predictable geometrical relationships that occur between bedding, cleavages, lineations and folds, as well as movement indicators that can be used to deduce the sense of movement on brittle faults and ductile shear zones. Where such structures as these occur, they are a boon to the field mapper, and he or she should learn to recognize and make use of them. A detailed description of these structures is beyond the scope of this book but they are treated in many standard geology texts. Some useful references will be found in Appendix D.

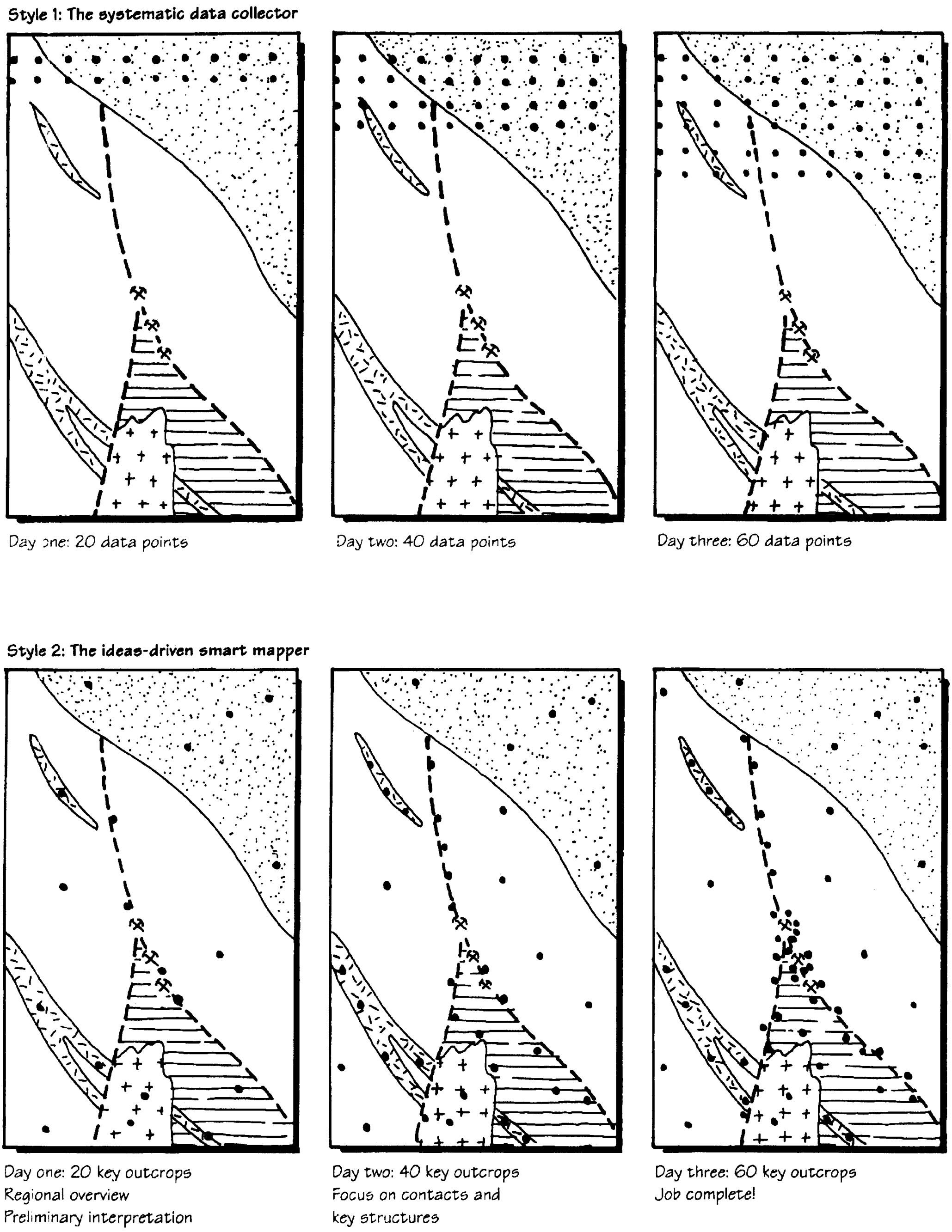

Figure 2.1 A comparison of geological mapping styles. In the first case, the 'systematic data collector', driven by technique rather than ideas, regularly traverses the ground. The task will eventually be completed, but this is not the most efficient procedure. The 'smart mapper', on the other hand, assesses the significance of each outcrop against his/her evolving ideas about geology, then determines strategy in the search for the next significant outcrop. The 'smart mapper' not only completes the job more quickly, but does it better too.

Another aspect of rocks is the way the features and relationships seen in hand specimen or outcrop often exactly mirror features occurring at map scale. This has been informally called 'Pumpelly's Rule' after Raphael Pumpelly, the nineteenth century USGS geologist who first described it.[1] Once again the Smart Mapper will be on the look out for such potential relationships in outcrop as a means of developing ideas as to the map scale patterns.

With geochemistry having a major role in most modern exploration programmes, the geological map will usually play a large part in planning and understanding the results of surface geochemical sampling programmes. In order to fulfil this role, exploration geological mapping in most cases will need to carefully show the distribution of superficial and weathered rock units (the regolith), as well as bedrock features.

Observations are thus not made randomly, nor are they collected on a regular grid or according to a fixed search pattern; rather they are selected to most effectively prove[2] or disprove the current ideas. Geological mapping is a scientific process and when carried out properly corresponds to the classic scientific method: theorizing, making predictions from the theories, and designing experiments (planning the required field observations) to test the predictions.[3]

An aspect of this technique is that thinking and theorizing are constantly being done while field work proceeds. In other words, data collection is not a separate and earlier phase from data interpretation; these two aspects are inextricably linked and must proceed together. Above all, observation and interpretation should not come to be regarded as 'field work' and 'office work'.[4]

2.1.4 CHOOSING THE BEST TECHNIQUE

The mapping technique used depends upon the availability of suitable map bases on which to record the field observations. A summary of the different techniques is given in Table 2.1.

The ideal base is an air photograph, as this offers the advantages of precise positioning on landscape/cultural/vegetation features combined with an aerial view of large-scale geological structures which might not be otherwise available. For small-scale maps (say 1:5000 to 1:100 000) air photographs are virtually the only really suitable mapping base, although if good topographic maps are available at these scales they can be used as a second-choice substitute. In Third World countries, where there is often no aerial photography available at any suitable scale, satellite imagery can provide a suitable base for regional geological mapping. Radar imagery, whether derived from satellite systems or special aircraft surveys, can also be used as a geological mapping base in much the same way as aerial photography.

In the special case of mine mapping, the mapping base is usually a survey plan of the mine opening prepared by the mine surveyor and supplemented by accurately established survey points from which distances can be taped. In open-cut mines, most available rock surfaces are vertical or near-vertical; observations are thus best recorded onto sections and afterwards transferred to the standard mine sections, level plans or a composite open-cut plan. In underground mines, observations can be made on the walls, roofs and advancing faces of openings,

[1] Today we recognize that geological processes are essentially chaotic (i.e. non-linear). Such systems typically exhibit what is called 'scale-invariance' – the example often quoted being the comparison in shape between a rock pool and a coastline. Pumpelly's Rule is an early recognition of this type of relationship.

[2] Actually, as pointed out by the philosopher Karl Popper, an experiment either falsifies a hypothesis or expands the range of conditions under which it can be said to hold good: it can never prove it.

[3] All theories in science, and that includes ideas on geology for field checking, must be formulated in such a way that they are capable of being falsified. For example, for field mapping purposes it is not very useful to postulate 'these outcrops constitute a metamorphic core complex' because there is unlikely to be a simple observation which can falsify that statement. Rather postulate 'this outcrop is felsic gneiss, that outcrop is sandstone, this contact is a mylonite' and so on.

[4] In our society from the earliest training we are conditioned to think indoors, and to enjoy less cerebral pursuits outdoors. It is a syndrome which the field geologist must learn to break.

Table 2.1 Comparison of mapping techniques

Mapping Technique	*Scales*	*Indications*	*Advantages*	*Disadvantages*
Pace and compass	1:100–1:1000	Rough prospect map. Infill between survey points.	Quick. No assistance and minimal equipment needed.	Poor survey accuracy especially on uneven ground.
Tape and compass	1:100–1:1000	Detailed prospect maps. Linear traverse maps. Mine mapping.	Quick. Good accuracy. No preparation needed.	May need assistance. Slow for large equidimensional areas.
Grid	1:500–1:2500	Detailed maps of established prospects.	Fair survey accuracy. Relatively quick. Same grid controls all exploration stages.	Expensive. Requires advance preparation. Poor survey control in dense scrub or hilly terrain.
Plane table	1:50–1:1000	Detailed prospect mapping in complex areas. Open cut mine mapping.	High survey accuracy. No ground preparation required.	Slow. Requires assistance. Geological observation and map-making are separate steps.
Topographic map sheet	1:2500–1:100 000	Regional mapping and reconnaissance where no photography available. Areas of steep topography. Mine mapping. Base for plotting GPS observations.	Accurate map base with regional coordinates. Height contours.	Difficulty in exact location. Irrelevant map detail obscures geology. Not available in large scales.
Air photographs	1:500–1:100 000	Ideal geological mapping technique at all scales. Preferred choice where available.	Geological interpretation on photo. Stereo viewing. Easy location on features. Readily enlarged for more detailed scales.	Scale distortion. Expensive survey if standard coverage not available.

and are then recorded and compiled onto a section or plan.

For surface mapping, suitable photography is often not available or is only available at too small a scale to permit photo enlargement for detailed mapping purposes. In many cases also, air photographs are difficult to use for precise field location because of vegetation cover or simply because of a lack of recognizable surface features. In areas of very high relief, photos can also be difficult to use because of extreme scale distortions. In these cases, alternative techniques are available to provide the control for detailed mapping. In order of decreasing accuracy (and increasing speed of execution) these mapping techniques are: plane table mapping, mapping on a pegged grid, tape and compass mapping, and pace and compass mapping.

Plane table mapping is seldom done nowadays because it is slow and the alternative use of pegged grid control can provide all the surveying accuracy that is normally required for a geological map. Further disadvantages of the plane table technique are the requirement for an assistant and the fact that geological observation and map-making usually have to be carried out as two separate processes. However, plane tabling provides great survey accuracy and is an invaluable technique where precision is needed in mapping small areas of complex geology. Such situations often arise in detailed prospect mapping or in open-cut mine mapping. The plane table technique is also indicated where a pegged grid cannot readily be used, for example, mapping a disused quarry or open cut. Plane table mapping is therefore a useful skill for a field geologist to acquire.

Pegged grids are used for outcrop mapping at scales of 1:500 to 1:2500 and are now one of the most commonly used controls for making detailed maps. The technique relies on placing a close network of survey pegs into the ground at regular stations on a numbered coordinate system. The coordinates are marked onto the pegs which are then used to provide the survey control for all stages of exploration over the area. The disadvantages of using a pegged grid lies in its expense, and the danger that geologists often come to regard the grid as a series of predetermined geological traverse lines, rather than a network of survey points to be used for positional control.

A measuring tape and compass or Hip-Chain®[1] and compass survey allows for quick production of detailed prospect maps, or maps to provide a base for location of sample points in areas where the geologist cannot spend long on site. With this technique it is possible to produce a high-quality, detailed geological map without needing any advance preparation (provided there is a tape or hip-chain available).

If there is no tape available then pacing distances can still allow a rough map to be constructed. Pacing is better than estimation and has the advantage of being quick. Pacing can even be reasonably accurate for short distances over open flat ground. Every field geologist should be aware of his/her normal pace length by laying out a 100 m tape along flat even ground and checking his/her pace length by walking back and forward many times (normal easy stride) and taking an average. Every time a pegged grid line is walked, the pace length over different types of terrain should be checked.

2.1.5 CHOOSING THE BEST SCALE

The scale chosen for mapping controls the type of data which can be recorded and hence the type of observations which are made in the field (see Figure 2.2). The choice of the appropriate scale depends on the purpose in making the map.

A small-scale map – say 1:25 000 or smaller – shows broad regional patterns of rock distribution and major structures. From an exploration point of view this is the scale at which the prospectivity of a basin, fold belt, tectonic unit or other large geological subdivision might be determined. It is a scale appropriate for developing ideas for new project generation. Explorationists do not often make maps at these small scales. There are two reasons for this: firstly, this is the type of mapping undertaken by Geological Surveys and can often be bought off the shelf; secondly, explorationists in most cases cannot obtain a sufficiently large tenement holding to make this kind of mapping worth while.

Maps with intermediate-range scales between 1:25 000 and 1:5000 could be described as detailed regional maps. These are appropriate scales for the first-pass mapping of large tenement holdings. They are also ideal scales to use when combining geological mapping with regional prospecting or regional geochemistry

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[1] Hip-Chain® is a reel of disposable, biodegradable cotton thread. As it reels from its spool, a meter records the length wound off, and hence the distance travelled. The thread is then simply broken and left on the ground. Another brand name is Fieldranger™.

(such as stream sediment sampling). At scales in this range, some of the larger features which might have had an effect on the localization of ore are capable of being shown, although the outline of an ore deposit itself could not generally be shown. The intermediate range of map scales is therefore suitable for the control and development of new prospect generation.

On maps at scales more detailed than 1:5000, individual outcrops or outcrop areas and the surface expression of significant areas of mineralization can be shown. The scale is appropriate for showing the features which directly control and localize ore. Maps at these scales are often called outcrop maps and the need to make them generally arises after a prospect has been defined. The purpose of such maps is to identify the size, shape and other characteristics of the potential ore body. The map is then used to help specify, control and evaluate all subsequent programmes of detailed prospect exploration including geophysics, geochemistry and drilling.

2.1.6 THE USE OF SATELLITE NAVIGATION (GPS)

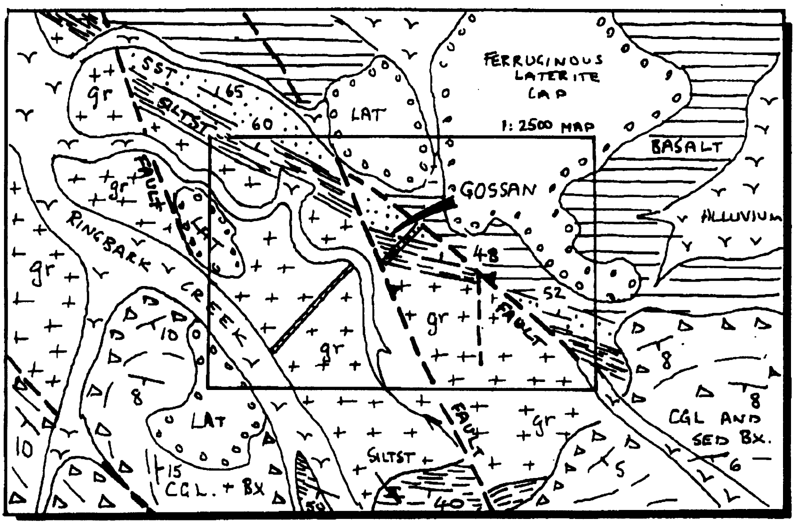
Small, battery-operated, man-portable instruments have been available since the late 1980s to make use of the satellite global positioning system (GPS). They are a boon to many aspects of field geology. Since the GPS provides location data based on latitude/longitude or regional metric grid coordinates, it is of most value for fixing position or navigating on a published map sheet on which these coordinates are marked. This makes GPS ideal for regional geological mapping onto published map bases or for regional prospecting and regional and detailed geochemical and geophysical data collection. Observations and sample locations can be quickly recorded against locational coordinates and the position of each data point readily found again should that become necessary. In addition, the explorationist can roam around the country on foot, vehicle or plane, following outcrop, evolving ideas or hunches, confident that anything interesting found can be easily located again, and at the end of the day the GPS will provide a direct route back to base camp.

Some limitations in the operation of GPS instruments should be noted however:

- GPS needs an unobstructed line of sight to the satellites which provide the location signal (at least three correctly positioned satellites must be 'seen' for an accurate triangulated fix). In particular, this means that GPS will not work in wooded or forested areas except where large clearings can be found. However, GPS is a boon for aeroplane or helicopter operations in these areas. The geologist dropped off in a clearing in the rain forest to collect a stream sediment sample need never again fear that the pilot will not be able to find that particular hole in the canopy again.
- At the time of writing (1996) GPS signals only allow for a maximum accuracy from small portable units of around 30 m. Since this is a specification rather than a limitation of the system, this might change. GPS is thus of limited use for mapping at detailed scales of 1:5000 or greater (at 1:5000 scale, 30 m on the ground is represented by 6 mm on a map; at 1:1000 scale, the equivalent map distance is 30 mm).

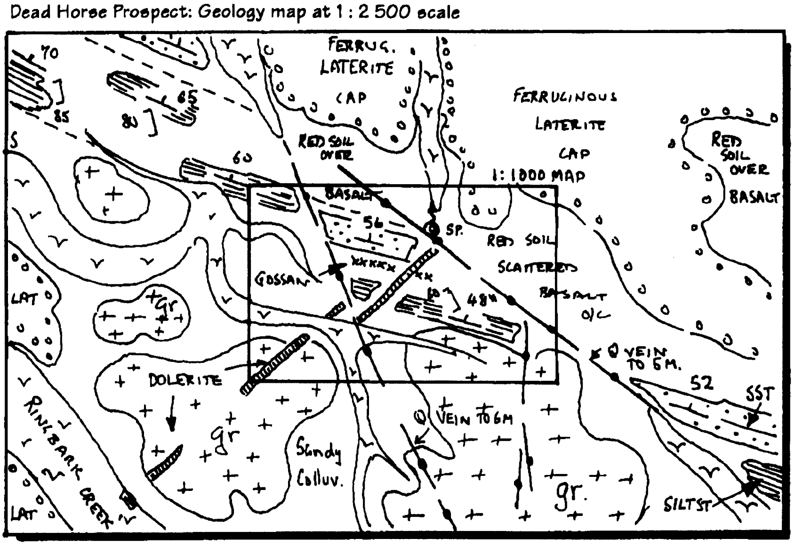
  Slightly better accuracy can be provided by averaging a number of fixes over a period (some GPS units can do this automatically) but this process takes time. Very high accuracies can be achieved by the use of two time-coordinated GPS units, the location of one of which is fixed. This process (known as differential operation) is used for accurate surveying applications (such as surveying claims or levelling gravity stations), but since the positional fixes are only available when data from the two units are subsequently downloaded to computer, the system is too cumbersome for many field applications.
- Relying exclusively on GPS for navigation can create problems (potentially serious) should the unit become inoperative. Never rely on GPS to the point where, if the instrument stops working for whatever reason, you cannot find your way safely back to base.

Dead Horse Prospect: Geology map at 1 : 5000 scale



Very detailed regional mapping. Suitable scale for prospect generation and establishing controls on mineralization. Generally provides insufficient detail for the control of prospect exploration or targeting drill holes on ore

Dead Horse Prospect: Geology map at 1 : 2 500 scale

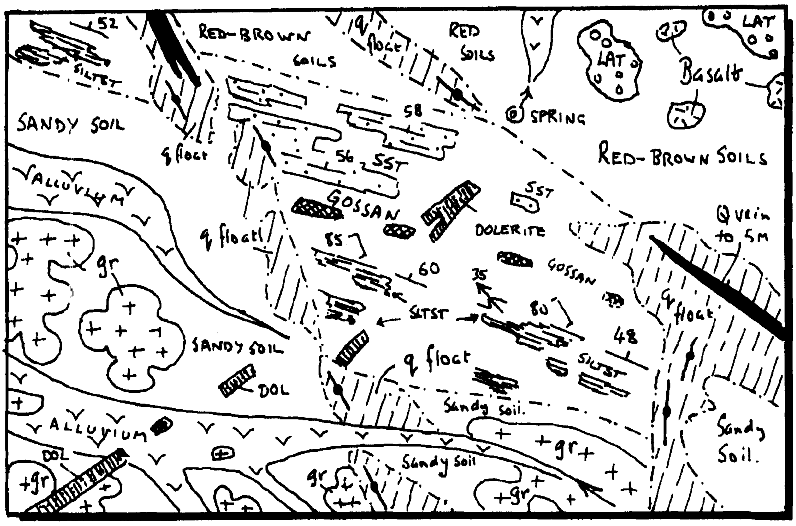


Semi-detailed outcrop mapping. Suitable scale for first-pass prospect mapping and new project generation

Figure 2.2 *continued opposite*

- GPS cannot be used to provide accurate positioning on air photographs since these lack coordinates and contain scale and angle distortions. However, it is still useful to approximately locate oneself on a photo by using the GPS to provide a distance and bearing to a known feature of the photo scene. The feature has been previously entered as a way point in the GPS instrument's memory. In most cases, knowing an approximate position on an air photo will enable an exact fix to be quickly obtained by means of feature matching. Ground-located photo features for entering as way points should ideally be located in the

Dead Horse Prospect: Geology map at 1 : 1000 scale



Detailed outcrop mapping. Suitable scale for the control of all phases of prospect exploration for targets of small to medium dimensions

Figure 2.2 An illustration of the effect of scale on the style of geological mapping of the same area. Generalization is required at all scales and there is no such thing as a 'fact map'. However, field observation content is greatest in large-scale maps and such maps should most closely correspond to 'fact' maps.

central two-thirds of the photo scene, where distortion of the image is minimal.

- Plotting latitude and longitude coordinates in the field is difficult. Metric grid coordinates are much easier to use. Make sure your GPS unit can provide a fix in both latitude/longitude and regional metric grid coordinates.
- In many parts of the Third World where explorationists operate, available published maps are often based on poor-quality photogrammetry with little or no ground checking. Such maps can be highly inaccurate. Even where photogrammetry-based maps have been made with care, in heavily forested country the map-maker has often been unable to accurately position smaller streams, roads or villages because of the obscuring tree canopy. In these areas, the GPS fix, being more accurate than the map, can be very misleading when it comes to trying to locate a particular feature.

2.2 AIR PHOTO MAPPING

2.2.1 GEOLOGICAL INTERPRETATION

Air photographs (along with other similar remote sensed products such as satellite and radar imagery) provide both a mapping base on which to record field observations and an integrated view of landscape on which large-scale patterns of lithology and structure can be directly observed or interpreted.

For any geological mapping programme making use of air photographs, photo interpretation represents the idea-generating, integrative, control and planning phases of that programme. The initial interpretation made from the photographs will provide:

- definition of areas of outcrop and areas of superficial cover;
- preliminary geological interpretation based on topographic features, drainage patterns, colours and textures of rocks, soils and vegetation, trend lines of linear features, etc.;

- geological hypotheses for field checking;
- selection of the best areas to test these hypotheses;
- familiarity with the topography and access routes to assist in logistic planning of the field programme – fording points for streams and gullies, potential helicopter landing sites, etc.

Air photo interpretation needs to be carried out before, during and after the field phases of the mapping process. Obviously, detailed interpretation making use of stereo viewing can be most conveniently done at an office desk, but, as ideas change or evolve, interpretation of photo features will usually have to be attempted in the field as well. The ability to use a pocket stereoscope on the outcrop is an essential skill to acquire.

Since making and interpreting geological observations on the photo and outcrop are two aspects of the same process, they should ideally be carried out by the same person.[1] Whenever possible, the field geologist should do his or her own interpretation.

Geological interpretation of air photos complements field mapping and should never be regarded as a substitute for it.

Skills required for the geological interpretation of air photographs are very much the same as those needed for field mapping. However, some practical techniques need to be learned in order to turn air photo observations into usable geological maps. The next section describes some of these techniques.

2.2.2 SCALES

The scale of an air photograph is determined by the height above the ground of the aeroplane taking the photograph divided by the focal length of the camera used (Figure 2.3). Thus:

$$\text{Photo scale} = 1{:}\frac{\text{Aeroplane height above ground}}{\text{Focal length of camera}}$$

A scale is generally printed onto the edge of an air photograph but this is a nominal scale only and should always be checked for a number of scenes across the area of the air photo survey.

The aeroplane altimeter height (i.e. height above sea level) and camera focal length are also normally marked on to the edges of an air photograph and provide a means of calculating the exact scale, using the above formula, provided the height of the ground above sea level is known for that scene. Even though the plane tries to maintain a constant ground height whilst flying a photographic survey, this is not always possible. The scale can thus vary from image to image. The variation in scale from this cause is usually small, but is greatest for large-scale photographs and in areas of strong relief.

Another way of checking the scale is to measure the length of a known feature in the central portion of the photo (such as a section of road or stream) and compare it with the same section identified on a detailed topographic map of the same area.

In addition to these scale variations, the stated photo scale is correct only for the centre of the photograph and is progressively distorted

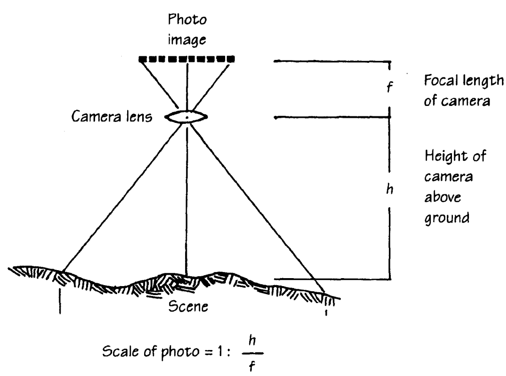


Figure 2.3 How to calculate the scale of an air photograph.

[1] Highly skilled and experienced geologists are available who specialize in the field of air photo interpretation. Their use is indicated for training purposes; where they have particular knowledge of the geology or landforms in the area to be mapped; or where there is little possibility of any substantial field access to the region.

towards its edges. This scale distortion also affects angular relationships. For this reason, if at all possible, interpretation should not be carried to the edges of a photograph. This is easy to do on the edges of photos along the flight line (the forward lap) where a 60% overlap is usually available with adjacent frames, but more difficult on the photo edges across the flight line (the side lap) where the overlap with adjacent runs is generally only 20%[1] or less (Figure 2.4).

Air photos usually have a north arrow plotted on their edge but this arrow cannot necessarily be taken as accurate – any yawing of the plane at the moment when the photo was taken can make this considerably in error. This problem will usually affect only a few photographs and can be picked up and corrected when adjacent photos are compared during the initial interpretation period. It is also a good idea to compare each photo with the base map and, where necessary, correct the north arrow marked on the photograph.

2.2.3 PHOTO HANDLING TECHNIQUES

- Surface reflectance can be a problem on highly glazed prints. Such prints also tend to curl and dog-ear more easily than matt prints. For this reason most geologists prefer to order prints with a matt surface for field work. However, high-gloss prints reflect more light and can be easier to read below a film overlay.
- It is recommended that interpretations of the photograph be marked on to a clear overlay.[2] The overlay should be attached to the top (i.e. the side lap) edge of the photograph so that it can be rolled back clear from the adjacent print and stereo viewer frame. Experience shows that drafting tape is best for attaching the overlay to the print as it will not split along the fold and can be easily removed (Figure 2.5). When working with full stereo photo coverage (60% forward lap), it is only necessary to put overlays on every second photograph.
- An alternative method used by some geologists is to mark observations directly onto the surface of the photograph using a pencil that does not damage the print and can be readily removed (e.g. a chinagraph or omnichrome pencil). However, putting interpretation lines on a photo surface obscures the original detail of the photograph on which these lines were based and makes it hard to see alternative interpretations. This can make it difficult to change early interpretations.
- The overlay should be labelled with the run number and photo sequence number (Figure 2.5).
- The centre point (sometimes called the principal point) of the photo should be located. This point lies at the intersection of lines joining special location marks which are printed in the centre of each edge of the photo (these marks are called collimation marks and are sometimes in the corner of the photo).
- Locate (by inspection) on each photo the centre points of the adjacent photos – this can be done because of the 60% forward lap between photos. There will thus be three points located on each photo. Transfer these points to the overlay.
- In order to position adjacent photographs so that they are exactly aligned for stereo viewing the following procedure can now be used. Place adjacent photos side by side below the stereo-viewer so that the three centre points marked on to each photo lie as nearly as possible along a single straight line. Looking at the photographs through the viewer, move the photos together or apart along that line to bring them into stereoscopic alignment. The two photographs are now positioned so that most[3] of their area of overlap is correctly aligned for stereo viewing and should need only minimal subsequent

[1] Photography for mountainous areas, where flying predetermined flight lines may be difficult, needs a wider side lap of 25% or more.

[2] Overlays are available in pre-cut sheets of clear to semi-opaque drafting film. Clear sheets do not obscure the photo below, but are difficult to write on. Matt surface films readily take pencil but may have to be flicked out of the way when detail of the photo has to be observed.

[3] It is generally impossible to exactly align all the overlap area of the photos due to edge distortions.

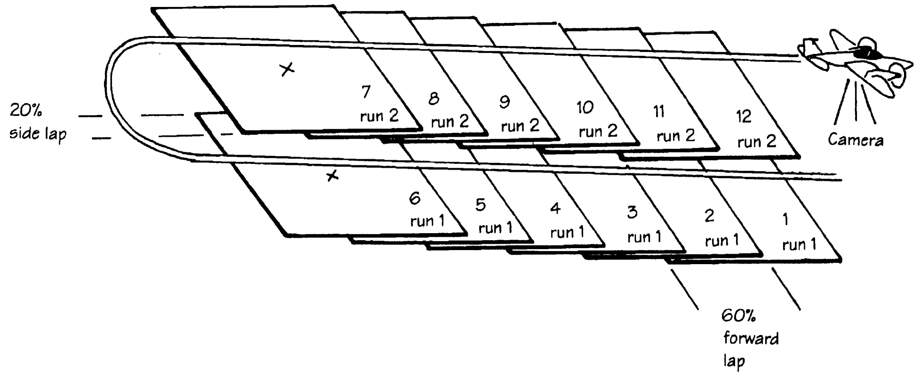


Figure 2.4 Typical specifications for an air photo survey designed to obtain full stereo coverage.

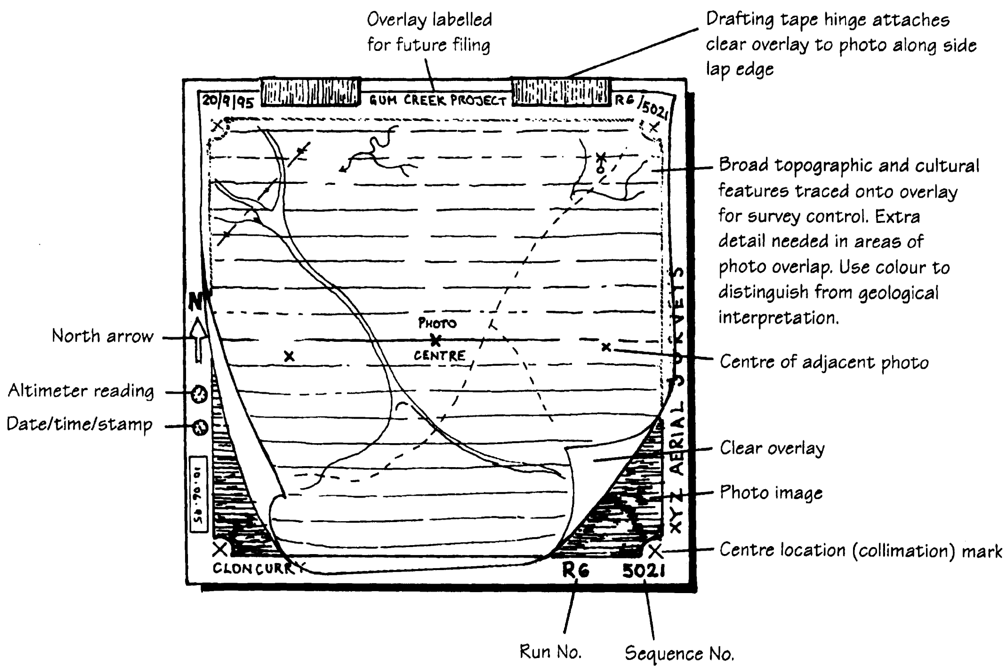


Figure 2.5 An air photograph prepared for geological mapping.

adjustment as the field of the viewer is moved across the images.

- When working in areas with complex geology and mineralization, annotations marked on to an air photo overlay can become very crowded. Many geologists overcome this by using up to three overlays, mounted separately on three sides of the photo. One overlay is then used for showing lithologies, one for structural observations and the third for mineralization and alteration.
- Another way of organizing information on the photo overlay is to mark a location by means of a small pin-hole pricked through the

print. Information about that location, such as sample number, notebook reference number, GPS way point number and so on, is then written on the back of the print.

2.2.4 WORKING WITH ENLARGED AIR PHOTOGRAPHS

Photographs can be enlarged many times[1] and still provide a workable base for field work. Only the central parts of each photo (where distortion is least) should be selected for enlargement. Enlarged photos cannot be viewed stereoscopically so a standard-scale stereo pair should be kept handy to aid in field positioning and interpretation.

The enlarged photo will usually be too big to be handled in the field and will have to be cut into smaller pieces. Such cut-down photos have to be treated with great care because mapping will have to be carried right to their edges (there is no overlap) and there is no protective border around each piece. To overcome this problem the following procedure is recommended:

- Cut the photos into as large portions as can be conveniently handled in the field. For most geologists this is probably about 60 × 40 cm.
- Glue each photo portion to a backing of thin card using a spray adhesive. The backing should be slightly larger than the photo to protect its edges from becoming dog-eared.
- Clearly label each photo portion on the back with a code so that adjacent photos can be quickly identified. A matrix system using letters for columns and numbers for rows works well. The back of each photo portion should also be marked with the scale, north arrow, original run and print number and any other relevant details about the project.
- Attach drafting film overlays to the photos in the manner described for preparing standard size prints.
- Make a field mapping clip-board out of a piece of hardboard and several spring clips. The board should be a few millimetres wider all round than the photos. When not in use, a second board of the same size can be used as a protective cover for the prints.

[1] Air photos enlarged up to 20 times have been successfully used as mapping bases.

2.2.5 DATA TRANSFER TO BASE MAP

Because of the scale distortion, geological boundaries plotted on an air photo overlay do not represent an accurate map projection. Although the errors on any one photograph may not be great, if interpretations from adjacent photos are combined to make a larger map, the resulting errors can be cumulative and eventually may cause a gross distortion of true geological relationships. Ideally, the interpretation of each photo can be transferred on to an orthophoto[2] by matching features. Orthophotos are, however, seldom available. Geological interpretation can also be plotted on to a photo-mosaic, but such mosaics also contain localized scale distortions and discontinuities. The normal solution, therefore, is to transfer the interpreted data from each photo overlay on to a scale-correct map base.

The ideal topographic base map for plotting photo geology should have the following features:

- the same scale as the photographs (a print can be photo-enlarged if necessary);
- sufficient topographic/cultural features (creeks, tracks, fence lines, buildings, etc.) to enable the photos to be exactly located;
- no unnecessary detail which would tend to obscure the geological information to be plotted on it;
- availability on transparent drafting film.

Maps with these features can often be bought directly from government mapping agencies and are known as a 'line base'. In most developed countries topographic map data are also available in digital form. It is possible to buy these

[2] An orthophoto is a distortion-free photographic image produced from standard air photos by computer scanning. An orthophoto map is an orthophoto to which metric grid coordinates and some annotated line work identifying topographic/cultural features has been added.

data on disc and to edit the base map required using a CAD (computer aided drafting software) system. A print-out of a line base can then be made at an appropriate scale on film or paper.

The procedures recommended for transferring geology from a photo overlay to the line base are as follows:

- Check with the base map to see which features on the map can also be seen on the photograph. Ideal features are points such as fence corners, bends in roads, bends in rivers or river junctions, wind-pumps, buildings, etc. Trace the more important of these features on to the photo overlay. It is particularly important to pick up features near the edges of the photo where a match will need to be made with data on the adjacent photo; this is also the area where scale distortion is greatest. Fewer control points need to be identified in the photo centre. It is a good idea to use colour to distinguish this topographic/cultural detail on the overlay from lines and symbols showing the interpreted geology (see Figure 2.5).
- Place the photo overlay below the base map and position its centre point by matching the selected features common to map and photograph. Mark the photo centre onto the base map. Maps showing plotted photo centres can often be bought but such maps are usually designed as a guide for purchasing and are not very accurate. Plot your own centres.
- Trace the geological interpretation on to the base map starting from the centre of the overlay. As the tracing moves out from the centre, move the overlay so as to maintain a match between overlay and line base, using the reference topographic features adjacent to the geology being traced.

There is an element of necessary fudging in this technique to achieve smooth geological boundaries. Special care has to be taken in the overlap areas between photographs. Limited scale and angular distortions will inevitably creep in, but if the above procedure is followed these errors will be small and localized, and will not affect essential geological relationships.

2.3 MAPPING WITH A PLANE TABLE

This section describes how to make a geological map using a simple plane table. Before the map-making process begins, the geologist must study the area and determine what features are to be recorded.

The plane table is a small board, generally about 50–60 cm square, mounted horizontally on a tripod and locked to face in any chosen direction. Plane tables (often called 'traverse boards') are made specially for this job, but one can readily be made to fit on to the tripod support of a theodolite (Figure 2.6).

The essential beginning for the survey is establishing two points in the survey area at a known distance apart and within easy sighting distance of each other (say up to 200 m). These positions will be referred to as the first and second survey points; they should be marked on the ground with a sighting peg or flagging tape or both.

The plane table is mounted in a horizontal position directly above the first survey point and oriented with a compass so that one edge faces north. It is locked in that position. A sheet of paper is fixed on to the table and a mark is made at some suitable place on the paper to indicate the position of the table. A sighting instrument called an alidade is laid on the map with one

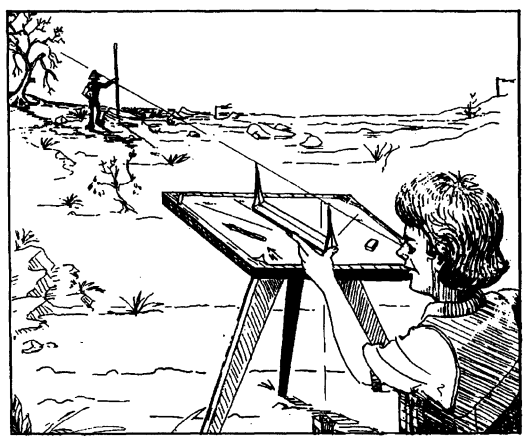


Figure 2.6 Detailed geological mapping using a plane table for survey control. In this example a simple home-made peepsight alidade is being used.

edge on the marked set-up point. In the illustration of Figure 2.6, a simple home-made alidade, called a peepsight alidade, is being used.

The sighter is rotated around the marked point so as to sight on to the second survey point (Figure 2.6). A pencil line is then drawn along the edge of the ruler, marking the bearing to the second point. Because the distance between the two points is known, the position of the second point can be plotted on the map according to a suitable scale.

Now the lines marking the bearings to any other points of interest within the view of the observer can be marked on to the map in the same way, radiating out from the first set-up point (see Figure 2.7). It is not necessary to measure any of these bearings with a compass. The features on which sightings are made can be geological, topographic or cultural features, or arbitrary survey points. The best technique is to sight on to a survey pole which is moved from point to point by an assistant on the instructions of the mapper. The assistant then identifies and labels each survey point (using a marker such as a peg or flagging tape). The identification of the bearing is also recorded on to the map.

When the bearings of as many features as required have been recorded in this way as a series of lines on the map, the plane table is then moved to a position above the second starting point. The table is then rotated about its vertical axis so that the line marking the bearing between the two starting points is back-sighted on starting point one; the table is then locked in this position. Now a second set of bearing lines, radiating out from the second start position, are taken to all the features which were identified. Where the two bearing lines on any one feature cross, that point is exactly positioned on the map – this process is known as triangulation (Figure 2.7). Any difference in relative levels between the surveyed points does not affect the accuracy of the map projection. Once a network of survey points have been established in this way, the survey can be infinitely extended in any direction by selecting any two of these points as the base line for new triangulations.

Plotting geological observations on to the survey base depends on using the exactly positioned survey points for control. In most cases these points will have been chosen on geological features and will have been put in closely where the geology is complex. With a large network of suitably positioned survey points, it is a relatively easy task to sketch in geological boundaries between the known points. In a plane table survey, it is necessary to know in advance what geological features are to be recorded and to select the survey points accordingly. Another technique is for the geologist to walk the outcrop with survey marker in hand, calling out (or using a radio transceiver) to the assistant to take the appropriate bearings and record geological data which he dictates. The technique or mix of techniques that are chosen will depend on the geologist, the assistance available, and the nature of the surveying/geological problem.

In heavily vegetated or hilly country, survey points can only be established where sighting lines are possible. Detail between the network of triangulated points will have to be subsequently mapped in by means of a tape and compass survey.

For exploration mapping, the simple set-up described above is probably all that the geologist will need, especially as more complex survey instruments may not be available. However, more sophisticated alidades can simplify the mapping process. By sighting through the ocular of a telescopic alidade, bearings over much greater distances can be made. If the assistant carries a graduated survey staff, the interval between two sighting hairs (called stadia hairs) superimposed on the telescopic image of the staff, provide a direct measure of the distance to the staff. The position of the point can then be directly plotted on the map without the need for triangulation. This surveying process is called tacheometry. The inclination of the telescope, recorded on a built-in scale, gives the vertical angle to the plotted point, and can be used to make a contour map of the area of the survey. Modern electronic distance-measuring survey instruments, employing reflected infra-red or

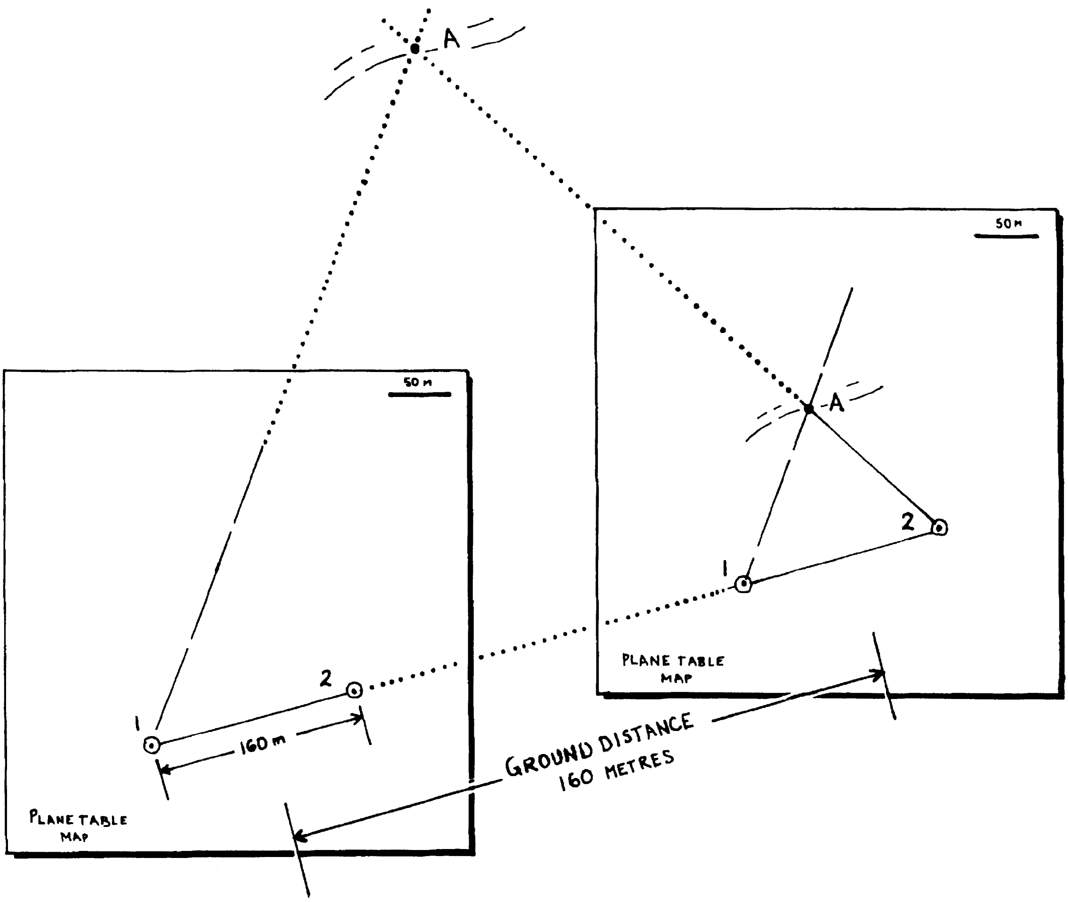


Figure 2.7 Positioning a point by triangulation during a plane table survey. Points 1 and 2 are at a known distance apart – in this case, 160 m. By positioning the plane table over each point in turn and taking bearings on the Feature A, its map position can be established.

laser beams, can also be used for plane table map-making.

2.4 MAPPING ON A PEGGED GRID

2.4.1 REQUIREMENTS OF THE GRID

A pegged grid consists of a regular array of pegs or stakes placed in the ground at accurately surveyed positions and used to provide quickly accessible survey control points to locate all subsequent exploration stages. The following points should be borne in mind:

- Ideally, for detailed geological mapping purposes, at least one grid peg should be visible from any point within the area to be mapped. Such grids may therefore need to be closer spaced than a grid designed solely for collection of geochemical or geophysical data. This aspect should be considered at the planning stage of the programme. In relatively open country, a grid spacing of 80 × 40 m is ideal.
- The orientation of grid lines should be at a high angle to the dominant strike of the rocks, to the extent that the strike is known.

- As a general rule, grids used for mineral exploration do not have to be established with extreme accuracy – placing pegs to within a metre or so of their correct position is acceptable. All types of data collected on the grid – geology, geochemistry, geophysics, drill hole data – will still correlate. If it ever becomes important, the position of any feature can be subsequently established to whatever accuracy is desired.
- To prevent small surveying errors from accumulating into very large errors, the grid should be established by first surveying a base line at right angles to the proposed grid lines. Points on the base line should be surveyed in as precisely as possible using a theodolite and chain. The theodolite is then used to accurately establish the right angle bearing of the first few pegs on each cross line of the grid.[1] From this point, the remainder of the grid pegs can be rapidly placed by using a tape for distance and simply back-sighting to maintain a straight pegged line. Where dense vegetation or rugged topography prevents back-sighting, short cross lines can be pegged using a compass and tape. For grid lines over about 1 km long, tape and compass surveying can cause unacceptable cumulative errors, and positioning with a theodolite is recommended.
- In hilly country, the establishment of an accurate grid requires the use of slope corrections. The slope angle between the two grid positions is measured with a clinometer. To obtain the slope distance which corresponds to a given horizontal grid distance, divide the required grid distance by the cosine of the slope angle. This calculation can easily be done with a pocket calculator but since the grid spacings are fixed, a sufficiently accurate slope distance for any given slope angle can quickly be read off from a table of pre-calculated values such as Table 2.2

[1] Establishing a cross line at right angles to a base line can also be done using an optical square – a sighting instrument which enables two pegs to be placed forming a right angle with the observer.

- If a detailed contour map is not otherwise available, the slope angles between pegs should be recorded and used to compile a contour map of the area. Contours are essential in hilly country to understand the outcrop patterns of rock units on the map, particularly in regions of shallow dipping beds.
- Grid peg spacing in distances which are multiples of 20 m should be considered, as this allows for more subdivision than the more traditional multiples of 50 m.
- The origin of the grid should lie well beyond the area of interest so that all grid coordinates are positive whole numbers. Conventionally, the origin is placed to the southwest of the area so that all coordinates can be expressed as distances north (northing) or east (easting) of the grid origin.
- If possible, choose the origin of the grid so that easting and northing coordinates through the prospect(s) of principal interest have dissimilar numbers. This will help to reduce potential future errors.
- Where a grid oriented N–S and E–W is required, consider using national metric grid

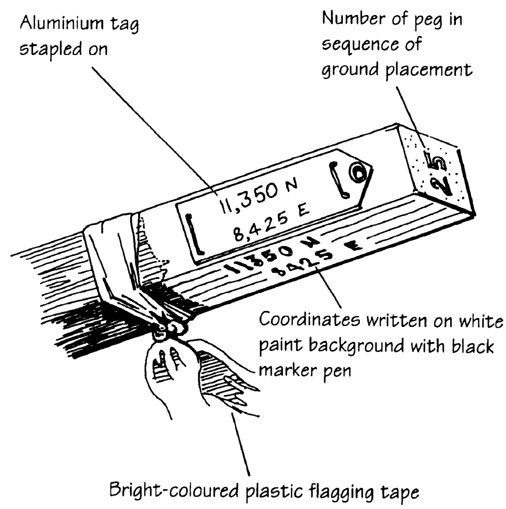


Figure 2.8 Recommended labelling for grid pegs. These are short survey stakes placed into the ground at regular station intervals for survey control of all exploration stages from geological mapping to drilling.

Table 2.2 Table for converting the standard spacings of 40 and 50 m grids into slope distances[a] given (in metres)

Slope angles (degrees)	*Horizontal distance (m)*									
	5	*10*	*20*	*25*	*40*	*50*	*60*	*75*	*80*	*100*
5	5.0	10.0	20.1	25.1	40.2	50.2	60.2	75.3	80.3	100.4
10	5.1	10.1	20.3	25.4	40.6	50.8	60.9	76.1	81.2	101.5
15	5.2	10.3	20.7	25.9	41.4	51.8	62.1	77.6	82.8	103.5
20	5.4	10.6	21.3	26.6	42.5	53.2	63.8	79.8	85.1	106.4
25	5.5	11.0	22.1	27.6	44.1	55.2	66.2	82.8	88.3	110.4
30	5.8	11.5	23.1	28.9	46.2	57.7	69.3	86.6	92.4	115.4
35	6.1	12.2	24.4	30.5	48.8	61.0	73.3	91.6	97.7	122.1
40	6.5	13.0	26.1	32.6	52.2	65.3	78.3	97.9	104.4	130.5
45	7.1	14.1	28.3	35.4	56.6	70.7	84.9	106.1	113.1	141.4
50	7.8	15.5	31.1	38.9	62.2	77.8	93.3	116.6	124.4	155.5
55	8.7	17.4	34.8	43.5	69.7	87.1	104.5	130.7	139.4	174.2
60	10.0	20.0	40.0	50.0	80.0	100.0	120.0	150.0	160.0	200.0

[a] The slope distance is found by dividing the horizontal distance by the cosine of the slope angle.

coordinates. The advantage of this is that published map-based data sets can be easily tied to the local grid observations. Using national metric coordinates requires that at least one point on the ground grid is accurately positioned by survey into the national grid. Only the last four digits of the regional grid need be shown on the grid pegs.

- Clearly and permanently label grid pegs as shown in Figure 2.8. Wooden pegs are usually cheapest and are ultimately biodegradable. For a more permanent survey consider using galvanized steel markers (fence droppers make good survey pegs). Steel pegs are essential in areas where bush fires and/or termite activity is common and the grid is required to last for more than one season.

2.4.2 MAKING THE MAP

Mapping is carried out on to field sheets which are generally graph paper of A3 or A4 size. The thin, shiny-surface papers of most commercially available pads of graph paper make poor field mapping sheets. If possible, use a heavyweight, matt-surface paper with a 1 cm ruled grid (you may have to get these specially printed). Waterproof sheets of A4 graph paper are available if mapping has to be carried out in wet conditions.

The positions of the grid pegs are marked on to the map sheets according to the scale chosen before field work commences. Field map sheets are valuable documents and, along with any field notebooks, should be carefully labelled and filed at the end of the work.

Usually the area to be mapped is larger than can be covered by one field sheet. In setting up the field sheets, allow for an overlap between adjacent sheets and clearly label each sheet so that adjacent sheets can be quickly located.

As a surveying aid, at an early stage in the mapping process, it is of great value to create an extra network of location lines on the map sheet by surveying on to the map any topographic or cultural features of the area such as ridge lines, streams, tracks, fence lines, etc. that may be present. In the example shown (Figure 2.9), the survey control provided by a 100 × 50 m pegged grid was supplemented by first surveying the stream, track, fence line, costeans and drill holes

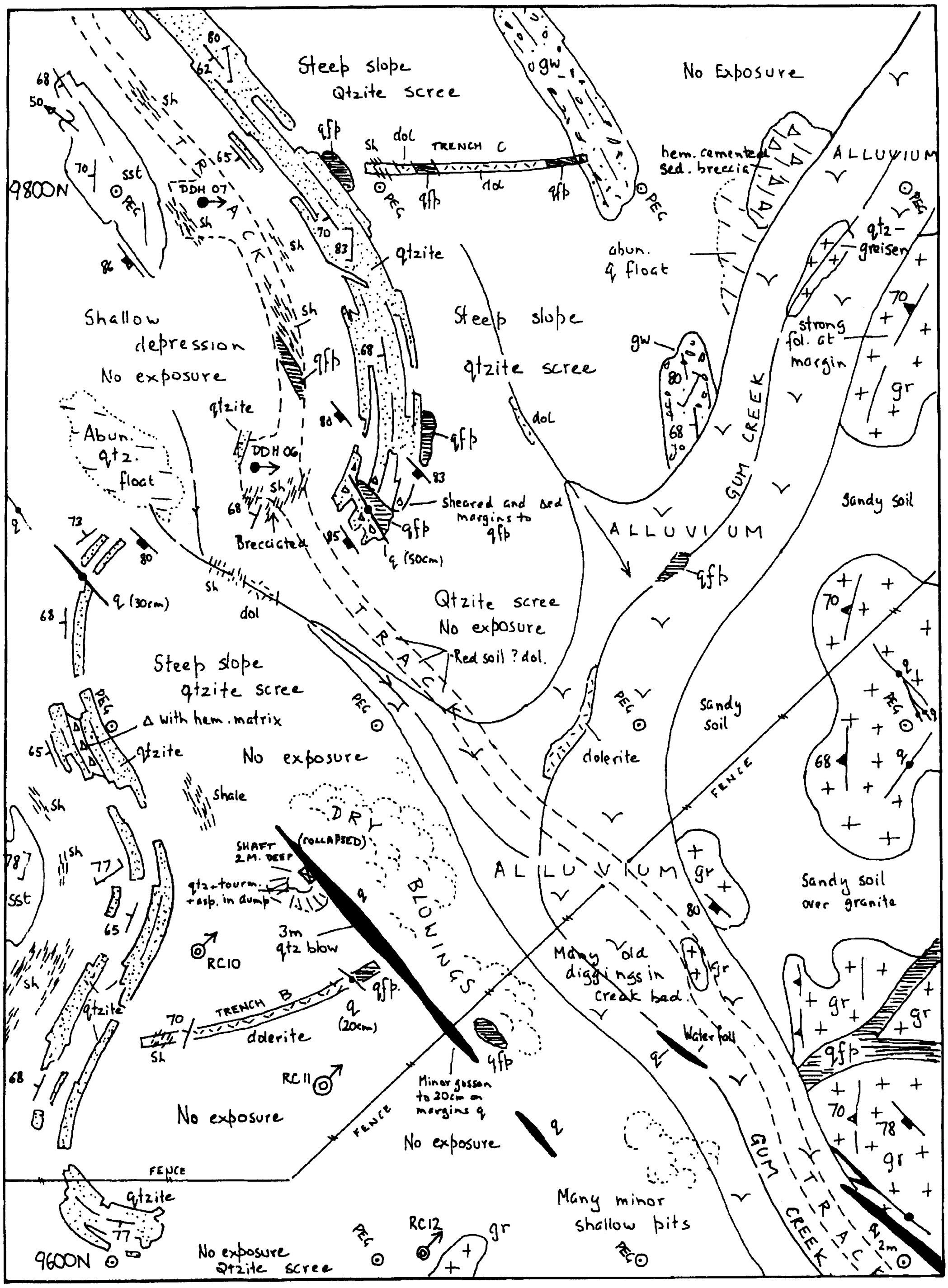


Figure 2.9 An example of outcrop geological mapping of a mineral prospect. Mapping at 1:1000 scale was controlled by a pegged grid established on a 100 × 50 m spacing.

on to the map before the detail of the geology was recorded. As well as a survey control, in hilly country the position of ridge lines and drainages are necessary to complement the topographic contour information in order to understand the outcrop patterns of shallow-dipping beds.

As a general rule, the pegged grid should be regarded as a survey aid with no geological significance. Above all, the grid is not necessarily to be regarded as a predetermined set of traverse lines. In the field the geologist should follow his or her own ideas on the geology, and not the grid line.[1] If the chosen mapping strategy is to walk a traverse across strike then a traverse should be planned according to where the most productive outcrop is to be found, always bearing in mind that traverses do not have to be ruler-straight lines. For example, in many areas, often the only outcrop is in the stream beds, and these will feature prominently in the mapping route chosen. The important thing to try to achieve is that the amount of attention which any outcrop receives is in proportion to its geological importance, not its closeness to a grid peg.

When it comes to positioning a feature on the map, a compass bearing can be taken from the feature to the nearest grid peg. Usually, the peg will be sufficiently close so that distance from peg to feature can be measured by pacing or even by estimate, although more accurate location of the feature can be achieved by triangulation between two or more grid pegs. To plot these measurements, a protractor and scale ruler are necessary and important field mapping tools. Every point or line placed on the map does not need to be accurately surveyed in. Once a network of key points or lines has been exactly positioned, the remainder of the geological boundaries are simply sketched in, so as to preserve the correct style and relationships seen in the outcrop. This is illustrated in Figure 2.9. On this map, the outcrop boundaries are drawn so as to reflect the characteristic shapes of outcrop observed for the different rock types: the quartzite outcrop is well-defined and rectilinear; the sandstone outcrop massive and blocky; the shale has insignificant low outcrop in narrow strike runs whilst the granite presents ovoid and somewhat amoeboid outcrop shapes.[2]

Observations are plotted as they are made, in pencil, on to the field map sheets with the aim of creating a complete map in the field. Structural measurements are plotted with the appropriate map symbol (using a square protractor), thus continually building up the geological picture as work progresses. There is no need to record the measurements separately in a notebook, unless they are required for subsequent structural analysis. Since the principal function of geological maps is, by definition,[3] to show the distribution of strike, it is generally more useful to plot the strike and dip of measured planes on to the map, rather than dip and dip direction.

As far as map-scale pattern and outcrop distribution is concerned, the strike is the most important measurement to make in terrain characterized by steep-dipping structures. The opposite is true where shallow-dipping beds predominate: in such terrains, the strike can be quite variable and may have little significance, but dips tend to be more constant and have much greater control on outcrop patterns of rock units.

As the elements of the map are slowly assembled in this way, the map can be used to make predictions about the areas not yet mapped and so guide the next set of field observations, as described in Section 2.1.3.

2.5 MAPPING WITH TAPE AND COMPASS

This technique is ideal for making quick detailed geological maps of small areas of high interest.

[1] In very dense scrub or forest, the cleared grid line often provides the only practicable traverse route. Even here, however, every effort should be made to pick up significant outcrops between the lines and to map cross-cutting access lines such as any tracks or creek sections.

[2] This sort of thing used to be called map-makers' (or geologists') wobble – chaos theory provides a better description of the process. For each lithology, the outline of the outcrops has a characteristic fractal dimension – a fraction somewhere between 1 and 2. The fractal number is lowest for a 'smooth' outline such as the granite, and highest for a 'rough' outline such as the quartzite.

[3] Strikes are the trace of planes on maps just as dips are their trace on sections.

The logistics of the technique mean that it is particularly suited to making linear 'strip' maps, such as maps of a stream section, ridge line, trench, road cutting or a line of old pits and diggings. It is also a useful technique for surveying in geological, topographic or cultural detail between the pegs of a widely spaced grid or the established traverse points of a triangulation survey. A surveyor's steel chain or tape measure are the most accurate distance measuring devices but they can only be easily used if an assistant is available. A Hip-Chain® (see footnote on page 14) is less accurate but is an acceptable alternative when time is short or there is no assistance available.

In the example shown (Figure 2.10) a tape and compass survey has been used to map a short drainage which was identified as anomalous during a regional stream sediment survey. The map provides an accurate base for plotting geological observations and recording the location of the sample points of detailed follow-up geochemical sampling.

The recommended procedure to make such maps is as follows:

- Start at one end of the area to be mapped. Knowing the approximate size and orientation of the area to be covered, select a suitable scale and label the field map sheet accordingly. Position the starting point of the traverse on the map.
- The assistant walks with one end of the tape to the first chosen survey point. The geologist takes a bearing on the assistant and, knowing the distance, plots the position of that point on to his or her field map sheet, using a protractor and scale ruler. Alternatively, the geologist takes a bearing on the first point and then walks to it, measuring the distance with the hip-chain. If possible, a good bearing compass should be used (e.g. a Suunto® or prismatic).
- If the ground is very steep, a correction for the vertical distance traversed will have to be made to the tape interval. Measure the slope angle with a clinometer and, knowing the ground distance between the points, correct the position of the survey point as marked on to the map. To do this, use a pocket calculator to multiply the slope distance traversed by the cosine of the slope angle between these points. (Alternatively, if a specific horizontal distance is required on the ground, divide that distance by the cosine of the slope angle.)
- Leaving the tape stretched along the ground, walk to the first survey point, plotting geological observations along the traverse. Topographic details (such as bends in a river bed) can be sketched in between the known points.

  Observations of geology away from the survey line can be plotted by pacing or estimating distances to them combined with a compass bearing. Exact positioning can be obtained by taking bearings from the known points (i.e. the starting and finishing points) and triangulating, or by taking one bearing from the known point and taping the distance to the feature. It is not necessary to exactly survey in every feature that is to be recorded: once a few points are established, all other observations can usually be positioned by eye in relation to them with sufficient accuracy.
- Repeat the process to the next survey point and so on, to complete the traverse.
- It is a good idea to flag and number each survey point. These represent exact positions on the map and can subsequently be used as a base for starting new survey/mapping traverses away from the original line of observations.
- Make geological or geophysical observations or collect geochemical samples as mapping proceeds, locating sample points directly on the map.

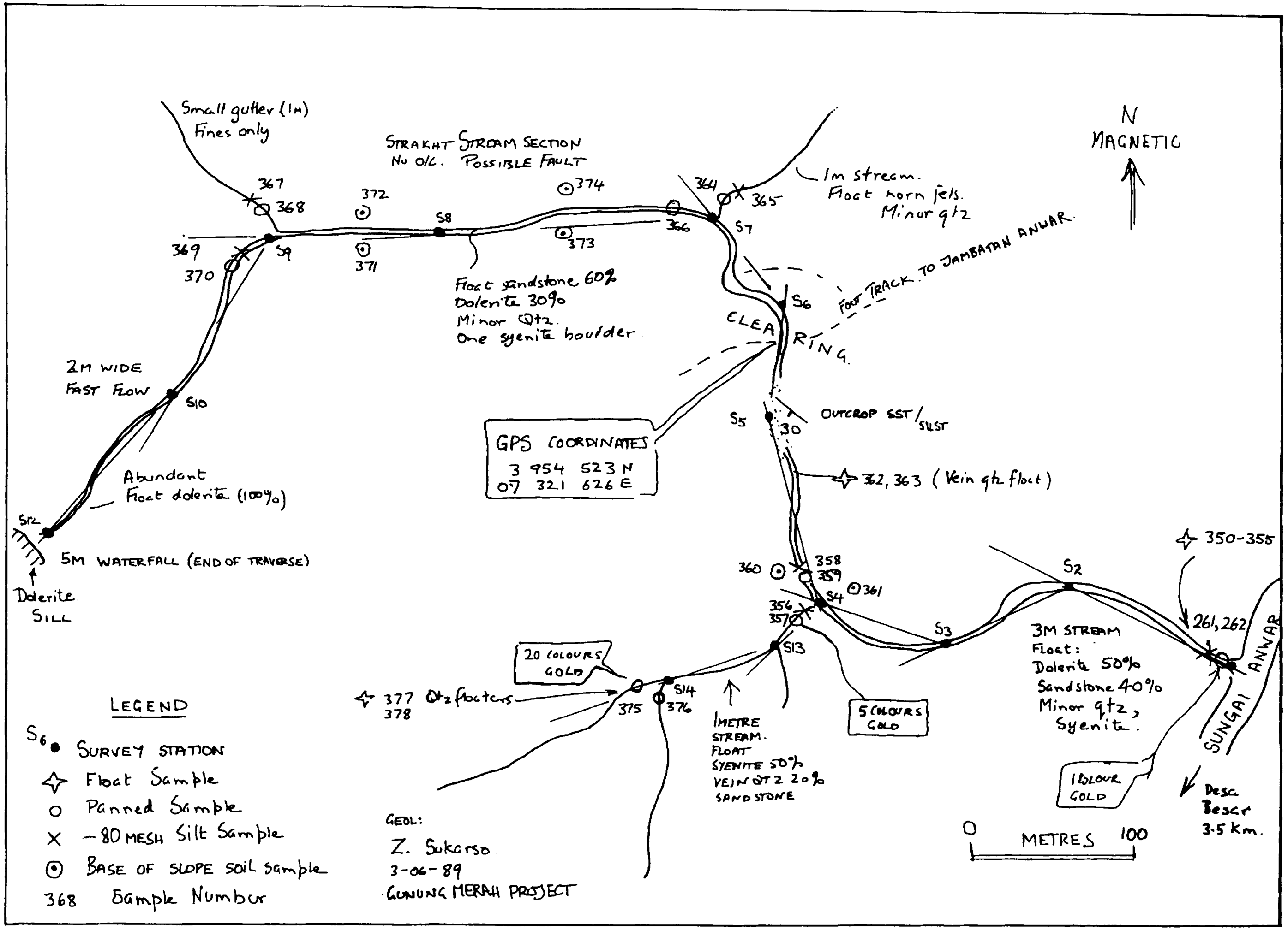


Figure 2.10 An example of a tape and compass map prepared during first-pass exploration of a tropical rain-forest covered area. The map was used as a base to record sample positions and geological observations along a small stream during the follow-up of an initial stream sediment gold anomaly.

MINE MAPPING 3

3.1 GENERAL

Detailed, scientific geological mine mapping began in the early years of the twentieth century with the work of Reno Sales at Butte, Montana. The mapping was done in-house for the Anaconda Company, but the results were subsequently published in a monumental work (Sales, 1913). The instigation for this work was partly to solve legal disputes consequent upon the North American Apex Law of mineral ownership, but the value of quality geological mapping in the search for extensions to ore and in the development of theories on ore genesis was recognized early on.

The distribution of economic minerals within an ore deposit is a result of geological controls. If the mineral distribution cannot be directly observed, other geological effects related to that distribution often can be. Even with the most detailed assaying based on grade-control drilling and sampling, the boundaries of ore can only be adequately defined with the assistance of a geological map which shows the spatial distribution of these geological features. Only by preparing accurate, detailed and up-to-date geological plans and sections of the mine can a drilling programme be effectively planned to locate extensions to ore beyond the confines of the mine openings.

Routine geological mapping of exposed rock faces within open-cut and underground mines is thus an essential part of the mine geologist's job.

3.2 MAPPING IN OPEN CUTS

Most basic geological data in open cuts are collected on vertical or near-vertical exposed surfaces. Even before mining, although a surface geological plan is often the starting point, the bulk of the information comes from holes drilled on vertical sections. The interpretations of mine geology and ore-body shapes made prior to mining are of necessity largely based on analysis of standard sections.[1]

Open-cut strip mining requires removing a series of horizontal slices (called flitches) through an ore body. The high-density, vertically distributed geological and assay data therefore have to be 'flipped over' and otherwise suitably extended in order to predict and control the grade distribution of the flitches.

Mapping the exposed faces in the pit should be done on to field sheets (such as graph paper). It is recommended that a detailed map be made of the vertical face, as this is the surface which can be directly observed and so will contain the highest density of information (Figure 3.1). A scale of 1:250 is generally adequate for pit mapping but, in areas of complexity, mapping at more detailed scales may be necessary. The actual mapping procedure is in most cases a specialized application of the tape and compass 'strip mapping' procedures described in the previous chapter. In some cases, particularly where extreme complexity is encountered (and the miners allow the geologist sufficient time!), plane tabling is an effective mapping technique. The position of the mapped face relative to the mine coordinates is established by measuring a distance and bearing to some known surveyed point in the mine.

At the same time as making the face map, the geologist should construct a plan of the bottom (or 'toe') of the face, putting on to the plan

[1] The observational data contained on standard level plans at this stage are usually an order of magnitude less dense than those of the standard mine sections.

structural measurements and the position and strike of all significant contacts or structures seen (Figure 3.1). This plan provides a line of geological observation across the top of the level below that being currently mined. As the base of the face is usually covered in rubble, structures are plotted at the point where their down-dip projection intersects the plan.

The plan view of the toe of the face is now used with plan views from previous face positions to construct a geological map of the floor of the pit (Figure 3.2). In constructing the level plan, the face mapping can be complemented by pit-floor lithological mapping using a variety of techniques. These include:

- Mapping any outcrop, *in situ* rock fragments or colour changes on the pit floor.
- Using cuttings from grade-control or blast-hole drilling to map lithologies.
- Digging a shallow scrape or trench across the pit floor using a bulldozer, grader or trenching machine in order to expose identifiable rock.

Although level plans are necessary to help determine grade boundaries along the mining benches, complex geological relationships are best displayed, and are most readily interpreted, on section. The full value of face mapping will not be realized unless faces mapped on different levels can be combined to give a complete section through the ore body, as shown in Figure 3.3. A section such as this is based on near-continuous observation, and since it can readily be combined with drill hole data, is an accurate and powerful tool for resolving details of geology and mineralization. Such composite face maps are best compiled on standard mine sections. These are the close-spaced drill sections, arranged at regular intervals along the strike of the ore body, which were used to define the ore body prior to mining. Obviously, most faces exposed in a pit will not exactly correspond to a mine section. However, with the progressive advance of mining, some faces will be developed which lie on such a section, or close enough to it to allow projection of data on to the section. It is worth making considerable effort to ensure that these particular faces are not missed in the mapping programme.

Pits being developed in oxidized material (in some deep weathering regimes this can include the major part of the pit) can present special mapping problems. In such deposits, mining usually proceeds at a fast pace, making it difficult to gain sufficient access to a representative number of faces. In addition, weathered rocks are

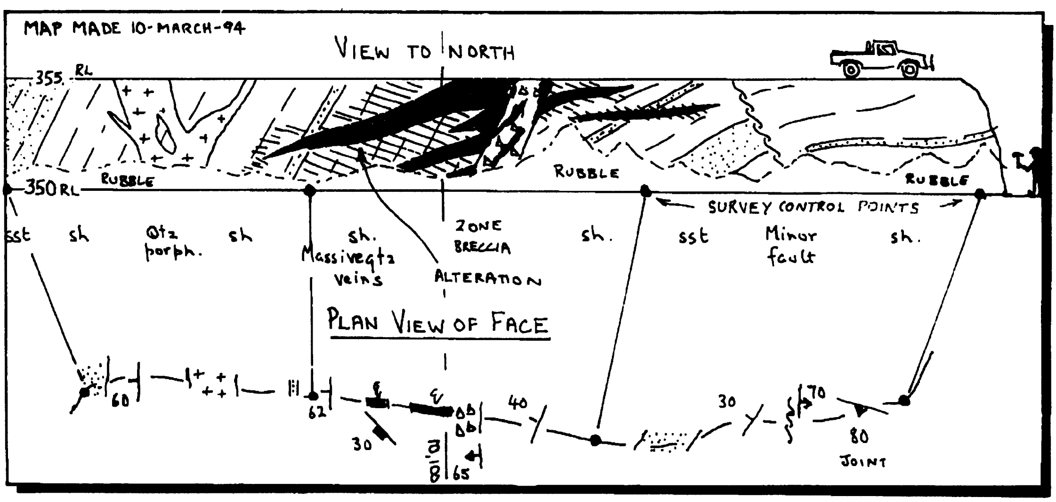


Figure 3.1 Geological mapping in open-cut mines – 1. Field sheet showing map of a 5 m high vertical face and a plan view of the base, or toe, of the same face.

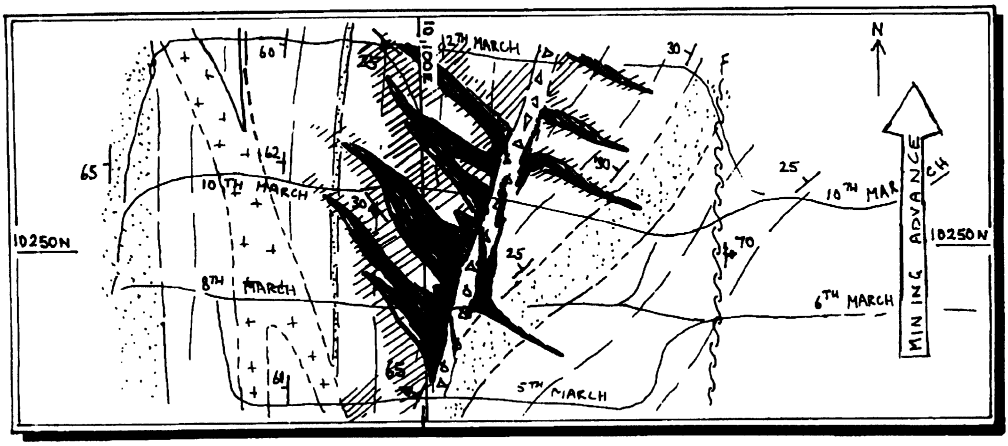


Figure 3.2 Geological mapping in open-cut mines – 2. Interpreted level plan prepared from the face 'toe' plan of Figure 3.1, along with adjacent toe plans from successive advances of the working face.

inherently difficult to extract meaningful geological information from, particularly when, as often happens, earth-moving equipment smears the high clay content across the face. Obviously in such circumstances, observing and recording fine detail, particularly structural detail, is often not possible. However, face mapping should still be attempted as even a limited amount of mapping is better than none at all.

Field mapping sheets do not need to be drafted but they should be carefully filed for future reference. As soon as possible the field section and map should be directly transferred (photoreduce if necessary) to a set of standard scale geological level plans and sections which are maintained for the ore body. Such plans and sections are usually at 1:250 or 1:500 scale. Geological information that is collected, but not compiled in this way to build up a continuous three-dimensional picture of the ore body and its host environment, is ultimately of little value.

Mapping the open cut should not just be confined to those faces developed in ore. All exposures within and adjacent to the ore body are relevant to understanding the deposit and should be routinely mapped.

Knowing what is mappable in an open cut can only come from experience. Initially, mapping may be slow and tedious until it is determined what geological features can be consistently identified and correlated from face to face and level to level. It is recommended that a reference set of rock-type specimens be collected to ensure consistency in description. Similarly, photographs can be taken to help build up an atlas of structural and textural features.

The sorts of geological features which might normally be mapped in an open cut (and this is not an exclusive list) are:

- visible boundaries of ore and any other significant mineralization;
- boundaries of major lithological units;
- position and orientation of major structures such as folds, faults, prominent joint sets, etc.;
- alteration patterns;
- major veins or vein sets;
- geotechnical data such as degree of fracturing, rock hardness, etc., as required by the engineers.

In the absence of mappable and well-defined lithological boundaries, use trend lines to show the trace of continuous features which can be

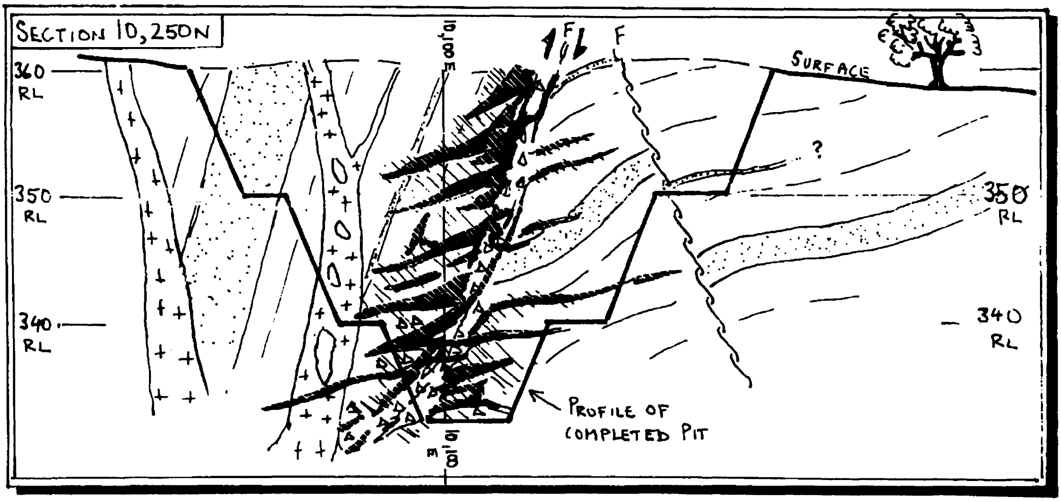


Figure 3.3 Geological mapping in open-cut mines – 3. An interpreted standard mine section compiled from adjacent face maps and from drill hole information.

observed in the rock, such as bedding planes, cleavage, joints or vein sets. Even where there are no discontinuities to place on the map as a line, continuously variable parameters such as degree of alteration, or number of veins (joints/fractures/shears) per metre, etc., can be recorded as a map annotation. Such annotations can be in words (i.e. 'highly altered'), but it is usually better, if at all possible, to express the observation in a semi-quantitative way (i.e. as a number between 1 and 5; as a percentage; as a number of units per metre, and so on).

3.3 MAPPING UNDERGROUND OPENINGS

Geological mapping in underground mines is normally done on to a plan or section of the opening provided by the mine surveyor. The great detail that can be observed requires mapping at very large scales, generally 1:100 to 1:10.

Rock exposure is effectively 100%, but it is usually necessary to arrange to wash down walls and backs (the roof) before detailed features can be seen.

Rock can generally be observed on the backs and walls of the opening, and also on advancing faces. A fully detailed mapping job would therefore require that three or four maps be produced, one for each surface. Such detailed mapping is often necessary where particular complexity needs to be resolved in a critical part of an ore body. In the example illustrated (Figure 3.4), narrow, gold-bearing quartz reefs are offset by a series of faults resulting in a complex geometry which only detailed mapping can resolve. However, this sort of detail is often unnecessary and the mine geologist will choose to map either the roof, wall section or face. There is no hard rule – the choice of the reference frame on which to record observations depends on the nature of the available surfaces, the attitude of rock structures, the time available and how the map is to be used.

Flat-lying units such as bedding, veins, etc., are best shown on vertical section. If such features are present and are considered important, then mapping of the walls or face of the opening would be appropriate (Figure 3.5). Conversely, steep-dipping structures are best recorded on a plan view (Figure 3.6). In underground open stopes, virtually the only exposure available may be the roof of the opening. In this case, a map of the backs would be the obvious and indeed the only available choice. In cross-cuts, which are at

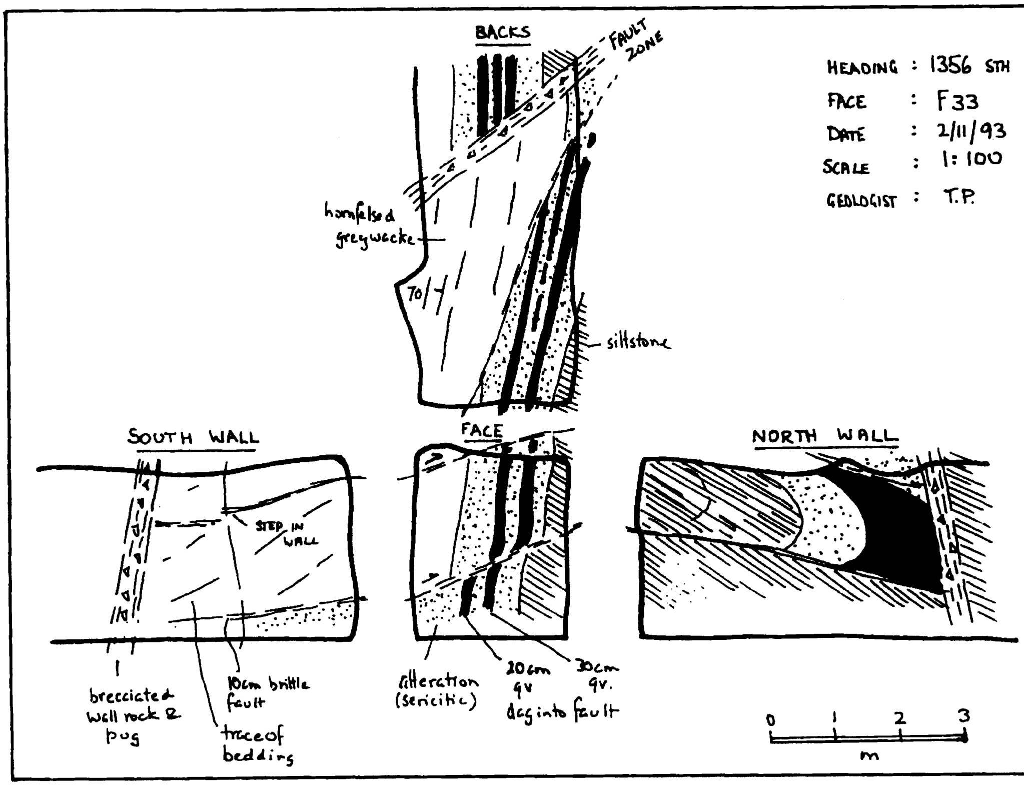


Figure 3.4 Geological mapping in underground mines – 1. Complex geology may require mapping of all available surfaces. In this example, both walls, the roof (backs) and advancing face of a drive in ore have been mapped at 1:100 scale. The mapping can be compiled onto cross-section, long-section or level plan.

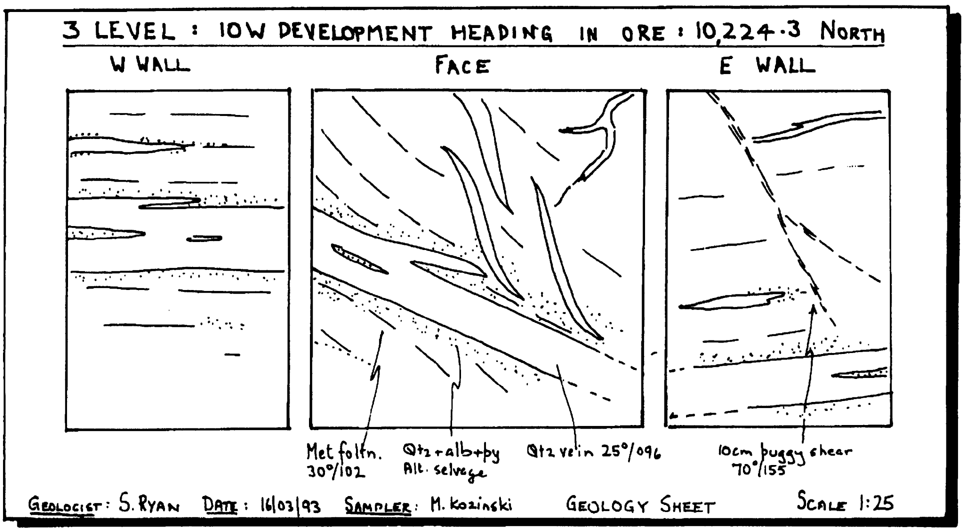
high angle to the dominant rock structure, there would be little point in mapping the advancing face of an opening as this would lie parallel to the structure. A map of the wall and backs is indicated (Figure 3.6). However, in drives running along the dominant strike, the advancing face will usually give the most effective view of the structures (Figures 3.4 and 3.5).

Another consideration in the choice of a mapping frame is the type of plans that are required for mine planning purposes. For example, geological interpretation in a mine is often based on underground or surface drilling, and it is necessary to map geological data in such a fashion that they can be readily compiled, with a minimum of projection or manipulation, on to the drill sections. An example of mapping which is compiled on to a drill section in this way is shown in Figure 3.5.

Clearly, mapping of shafts or other essentially vertical openings will have to be done on to a section.

A good compromise, often adopted for mine mapping where steep-dipping structures predominate, is to project rock structures seen on walls and backs on to a single level plan located at about waist height above the floor (Figure 3.6). This is typically the height of the level plan produced by the mine surveyor and also the height of any channel samples collected for assay along the walls of a cross-cut. The geological map compiled in this way is thus a composite of observations

Geologists mapping and sampling a development heading in ore. After each blast, the miners remove the ore then bar down the roof and walls to make safe. The geologist hoses down the rock, measures the face advance with a tape, then maps face and walls at 1 : 25 scale. An assistant, meanwhile, collects a chip-channel sample. A portable, re-chargable flood-light illuminates the scene



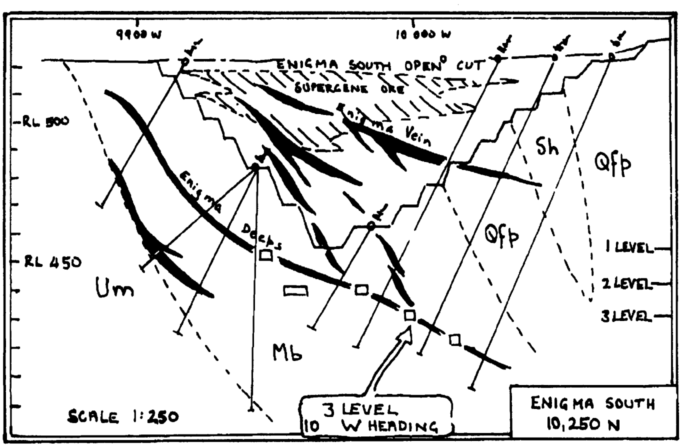


Figure 3.5 Geological mapping in underground mines – 2. Shallow-dipping structures are best mapped where they intersect the walls or advancing face of the opening. In the example shown, the mapping has been compiled along with drill hole data on to a standard mine cross-section.

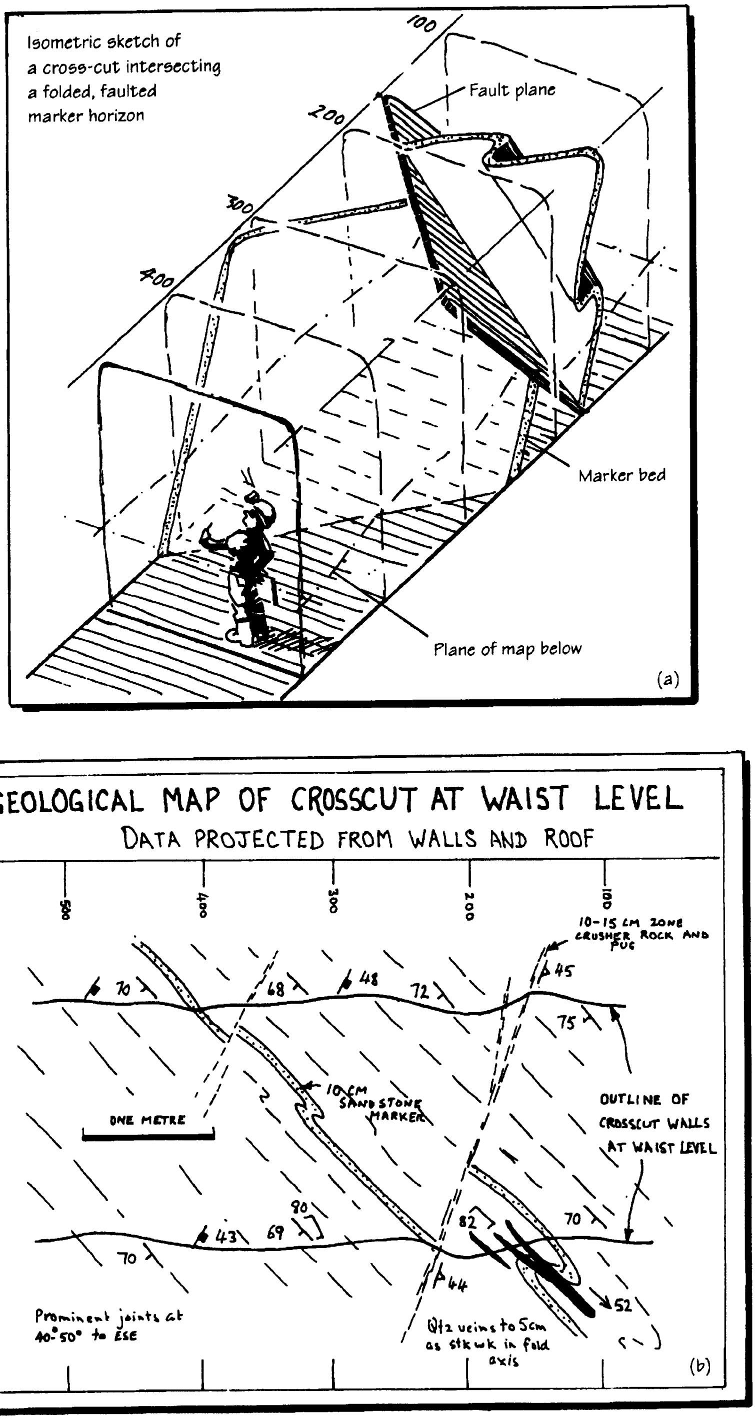


Figure 3.6 Geological mapping in underground mines – 3. Steep-dipping structure is best mapped in plan view. In this example, structures seen on the walls and roof of the opening (3.6a) are projected down-dip and down-plunge on to a single plan view at waist level (3.6b). The resulting map will usually cover an area that is wider than the opening. This type of mapping would not be appropriate for complex structures such as the example of Figure 3.4.

made from all available surfaces; the data is nowhere projected more than a few metres on to the map plane, and is exactly located along both walls. For most geological mapping purposes, but particularly for cross-cuts, such a map is sufficiently accurate.

A point to bear in mind is that a geological map is normally compiled to show geology as if viewed from above. Care must be taken when projecting geology seen on the backs (which are naturally viewed from below) on to such a plan, as the different viewpoint causes a mirror image change in angular relationships. Folds with an 'S' profile (for example) when viewed from below become 'Z' profile folds when viewed from above (see Figure 3.6). The mine geologist must learn to mentally 'flip over' the geology before plotting it on to his or her map.

Whatever mapping choice is adopted, it is inevitable that many observed relationships will be seen which cannot be shown on the map. These can be recorded using detailed sketches or separate maps and sections drawn to the side of the main map and keyed to it with a line or arrow.

MINERAL EXPLORATION DRILLING 4

4.1 GENERAL

4.1.1 THE IMPORTANCE OF DRILLING

Drilling is one of the most important, and can be the most expensive, of all mineral exploration procedures. In almost all cases, it is drilling that locates and defines economic mineralization, and drilling provides the ultimate test for all the ideas, theories and predictions that are generated in the preceding prospect generation and target generation phases of the exploration process.

In any exploration group, the percentage of the budget that is put into drilling worthwhile targeted[1] holes provides a measure of the efficiency of that group. To use management school jargon, it is the key performance indicator (KPI) of an exploration group. Many well-managed and successful exploration companies believe that, averaged over a period of time, at least 40% of their exploration dollars should be spent on drilling targeted holes.

4.1.2 TYPES OF DRILLING

There are a large number of different drilling techniques. This chapter does not attempt to describe them all, but focuses instead on the three basic types which are most commonly used in mineral exploration. In order of increasing cost, these are auger drilling, rotary percussion drilling and diamond drilling (see Figure 4.1 and Table 4.1).

[1] The term 'targeted hole' is used here to refer to holes drilled on defined prospects where there is expectation of intersecting economic mineralization, as distinct from holes which are drilled primarily to increase geological or geochemical background knowledge.

Auger drilling

In this drilling system, rock is cut and broken with a simple blade bit mounted on the end of a rotating string of rods. As the drill advances, extra rod sections are added to the top of the drill string. The broken rock can be collected in two ways. In the bucket auger, the rock is collected in a small barrel behind the bit which, when full, is simply pulled from the ground to be emptied. The hand auger is an example of a small bucket auger. In the other system, called a screw auger, the broken rock is passed to the surface by a spiral screw thread along the rod string. Screw augers are lightweight, power-driven machines which are generally mounted on the back of a small truck or trailer.

Rotary percussion drilling

In rotary percussion drilling, a variety of blade or roller bits (Figure 4.1) mounted on the end of a rotating string of rods cut and break the rock. A percussion or hammer action in conjunction with a chisel bit can be used to penetrate hard material. High-pressure air pumped to the face of the bit down the centre of the rods serves to lubricate the cutting surfaces and to remove the broken rock. The cutting action produces a sample consisting of broken, disoriented rock fragments ranging in size from rock flour to chips up to 2–3 cm diameter. In standard rotary percussion drilling, the broken rock is blown to the surface along the narrow space between the drill rods and the side of the hole. In a mineral exploration programme all the cuttings emerging from the hole at surface are generally collected in a container called a cyclone which is designed to

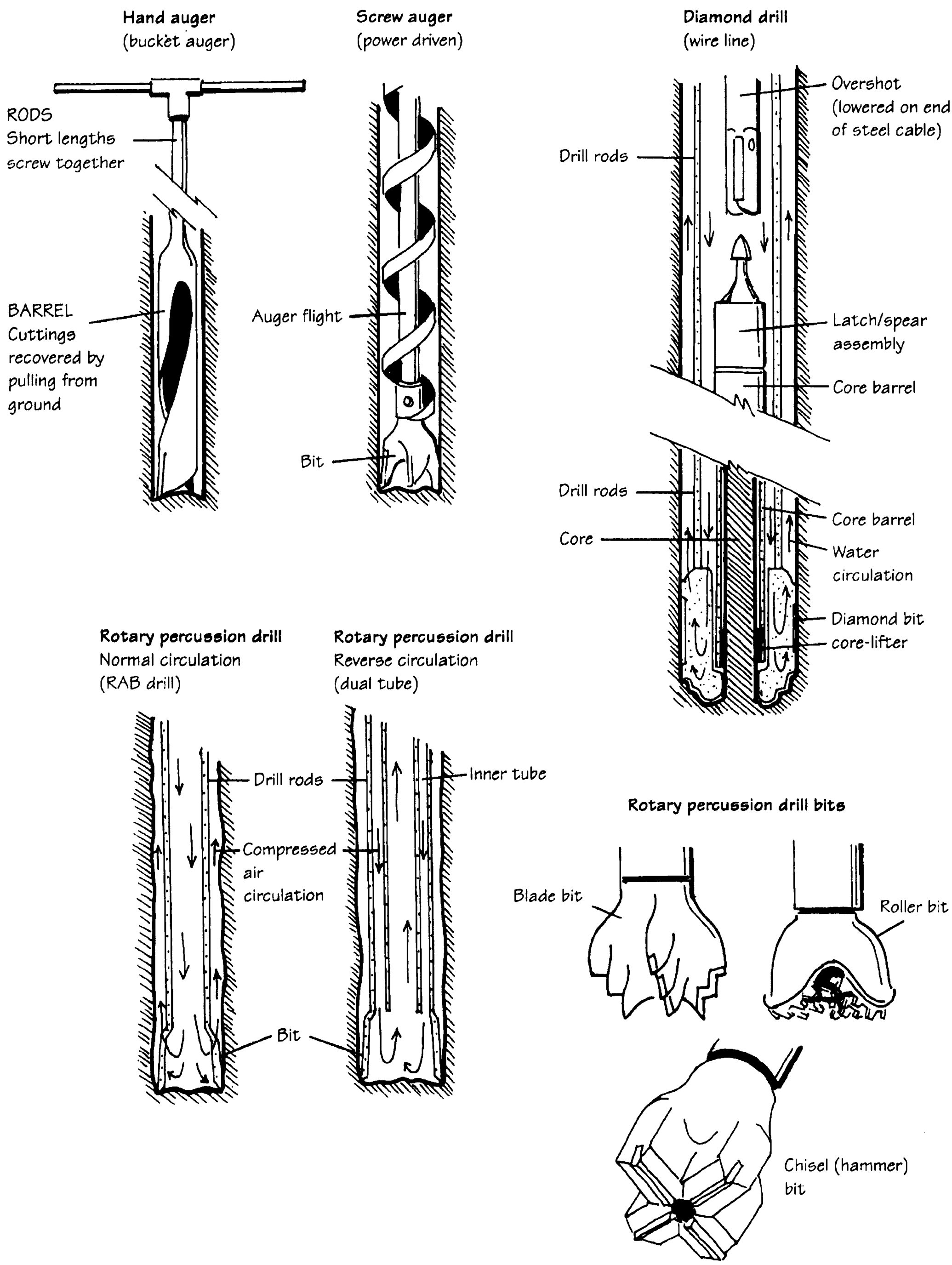


Figure 4.1 Types of drill and drilling equipment commonly used in mineral exploration.

prevent the fine material from being blown into the atmosphere by the escaping air.

Small rotary percussion drills using standard recovery of broken rock to the surface are usually known as rotary air blast or RAB drills. Some models of very lightweight, power-driven percussion drills are available, which are capable of being hand held and can be ideal for operation in very remote or hard to access sites.

Reverse circulation (RC) drilling is a type of rotary percussion drilling in which broken rock from the cutting face passes to the surface inside a separate tube within the drill stem (the system is properly called dual-tube reverse circulation). The compressed air delivery to the bit is pumped down the space between these two tubes (Figure 4.1).

Air core is another type of specialized RC drilling where a small annular bit is used to cut a solid core of rock from relatively soft or easily broken material. The bit produces short sections of core which are recovered, along with broken rock chips, up the centre of the drill stem in the manner of a standard RC rig. The system is often capable of penetrating and coring soft sticky clays which might bind a normal blade bit.

In diamond drilling, an annular, diamond-impregnated bit mounted on the end of a rotating string of rods cuts a solid cylinder of rock (the core) which passes up inside the drill rods as the bit advances (Figure 4.1). The bit is lubricated with water (or sometimes a special water/mud mixture) which is pumped to the cutting face down the inside of the rods, before returning to the surface between the rods and the sides of the hole. At surface, the return water is usually collected in a sump where fine suspended ground rock material can settle. The water can then be recirculated to the drill bit.

Standard core sizes range from 27 to 85 mm diameter.[1] The core enters an inner tube (called the core barrel) located inside the main drill rod, immediately behind the bit. The cut rock is prevented from falling back into the hole by a wedge-shaped sleeve (called a core-lifter) mounted at the base of the barrel. Core barrels normally hold 3 m of core. When the barrel is full, the drilling is halted and a special device called an overshot is lowered down the inside of the rods on the end of a wire cable. The overshot locks on to the top of the core barrel. A pull on the cable then causes the core-lifter to grip the base of the drilled core in the barrel, thus breaking it free. The barrel containing the core can then be drawn to surface up the inside of the rod string.[2] Once on the surface, the core is removed from the barrel and laid out in core trays. A split-tube barrel is available which splits into two pieces lengthways, so facilitating core removal. Once emptied, the barrel is dropped down the hole to automatically lock into its position just behind the bit, and the drill advance is resumed.

4.1.3 CHOOSING THE RIGHT TECHNIQUE

Selecting the right technique or combination of techniques is always a trade-off between speed, cost, required sample quality, sample volume, logistics and environmental considerations (see Table 4.1). Augering and RAB drilling provide relatively low levels of geological knowledge but are quick and cheap and so are useful principally as geochemical reconnaissance tools for collecting samples below areas of shallow overburden. A well-designed and run RAB programme can also provide large-volume samples with good recovery and minimal contamination. It can therefore be useful for drilling out mineralization in weathered rocks above the water table.

Large rotary percussion rigs can quickly drill a large-diameter hole (100–150 mm) with good sample volume and at reasonable cost. They are powerful machines capable of penetrating much deeper and through harder rock than the RAB rig. However, in normal rotary percussion drilling, the long sample return from drill bit to the surface along the outside of the rods may

[1] The commonly used standard core diameters for wireline drilling are: AQ, 27 mm; BQ, 36.5 mm; NQ, 47.6 mm; HQ, 63.5 mm and PQ, 85 mm.

[2] The system described here, called wire-line drilling, is now almost universally used. Before its introduction in the early 1960s, the whole string of rods had to be pulled from the ground in order to recover core from each advance of the drill.

Table 4.1 Exploration drilling

Drill type	*Indications*	*Advantages*	*Disadvantages*
Hand Auger	Geochemical sampling in upper few metres of unconsolidated material.	Human portable. Uncontaminated sample. Quick. Cheap.	Poor penetration.
Rotary Air Blast (RAB)	Geochemical sampling to base of regolith.	Large sample volume. No site preparation needed. Quick and cheap. Some rock-chip geological return.	Poor hard rock penetration. Sample contamination. Limited depth. No structural data.
Air Core	Geochemical sampling where good bedrock description required.	Small rock-core return. Minimal contamination. Relatively quick and cheap.	Small sample size.
Reverse Circulation (RC)	Geochemical sampling in hard and soft rock to 200 m plus. Ore body proving above water table.	Uncontaminated large volume sample. Rock-chip geological returns. Relatively quick and cheap.	Large heavy rig. No structural data. Poor hole orientation control. Some sample contamination/loss below water table.
Diamond	Ore targeting and proving to 1000 m plus depth. High-quality sample. Geological understanding.	Maximizes geological information. Uncontaminated high recovery sample. Accurate hole positioning.	Some site preparation required. Water supply required. Relatively small sample size. Slow. Expensive.

produce contamination from the walls of the hole. This problem can be especially acute when dealing with the low and often erratic concentrations typical of gold mineralization. The sample recovery system used in the RC rig is designed to overcome the contamination problem and for this reason RC rigs are nowadays specified in most rotary percussion drilling programmes.

Diamond drilling provides the *premier* sample for both geology and geochemistry. The rock sample can be obtained from any depth which is capable of being mined. Diamond drill core permits sophisticated geological and structural observations to be made, and can also yield a large-volume, uncontaminated sample with high recovery suitable for geochemical assay. Diamond drilling is also the most expensive technique. As a general rule, for the cost of 1 m of diamond drilling, up to 4 m of RC or 20 m of RAB can be drilled. From almost all points of view, the larger the core diameter the better. Large-diameter holes provide better core recovery and deviate less. Lithology and structure are much easier to recognize in the larger core sizes and a larger volume sample is better for geochemical assay. However, as the cost of diamond drilling is roughly in proportion to the core size, a compromise on hole size is usually necessary.

The specific requirements of an exploration programme play a large part in the choice of drilling technique. For example, if the area is geologically complex, or the exposure is poor, and there are no clearly defined targets (or perhaps too many targets), it may be imperative to increase the level of geological knowledge by diamond drilling. In this case, the geological knowledge gained from the diamond drill core can be used to help prioritize surface geochemical anomalies or develop conceptual targets. On the other hand, if discrete and clearly defined surface geochemical anomalies are to be tested to see if they are the expression of blind but shallow ore bodies, it may be sufficient to simply test them with a large number of RC or even RAB drill holes.

In arid terrains, such as the Yilgarn Province of Western Australia, the RC drill has been used in the discovery and development of a large number of gold ore bodies within the weathered rocks of the upper 80 m or so of the surface. It has proved to be an excellent compromise between cost, good sample quality for geochemistry, and some geological return in the form of small rock chips. In spite of this success, the RC rig is principally a geochemical sampling tool and it is dangerous to attempt to define an ore body on assay numbers alone. RC drilling data can seldom give an adequate geological understanding of mineralizing processes and in most cases will need to be supplemented with detailed mapping (where outcrop is available), by trenching and/or a selected smaller number of diamond drill holes.

The logistical requirements of the different drilling types also play a large part in selection of the best technique. RC rigs (and the larger RAB rigs) are generally very large, truck-mounted machines which have difficulty getting into some rugged areas without track preparation, and cannot operate on very steep slopes.[1] Diamond rigs are much more mobile; they are truck- or skid-mounted, have modest power requirements compared to an RC rig, and can be disassembled if necessary and flown to site by helicopter. Diamond rigs, however, require a large, nearby water source. The ability to be flown into a site also makes the diamond rig suitable for operation in environmentally sensitive areas.

The air core machine is a compromise which has some of the features of RC, diamond and RAB drills. In ideal conditions the drill can produce small pieces of core and so provide better material on which to determine lithology and structure than normal RC cuttings. It is often capable of penetrating and producing a sample from sticky clays which might stop a conventional drill rig. As with all RC cuttings, recovery is usually good with minimal sample contamination. However, the sample volume is small compared to that from a large RC rig, and hence less suitable for gold geochemistry. Air core is usually intermediate in cost between normal RC and RAB drilling. Some available rigs are track mounted and are capable of getting into difficult-to-access sites.

[1] Although track-mounted RC rigs are available.

4.1.4 TARGETING DRILL HOLES

In order to obtain the most accurate sampling for determining grade, drill holes will normally be aimed at intersecting a potential ore body at a high angle. The hole will also be targeted to intersect mineralization at a depth where good core or cuttings return can be expected. If the target is primary mineralization, the hole will be aimed to intersect below the anticipated level of the oxidized zone. If the mineralization has a tabular, steep-dipping shape, the ideal drill holes to test it will be angle holes with an inclination opposed to the direction of dip of the body. If the direction of dip is not known (as is often the case when drilling a geophysical or geochemical anomaly), then at least two holes with opposed dips, intersecting below the anomalous body, will need to be planned in order to be sure of an intersection of the target. Flat-lying mineralization (such as a recent placer deposit, a supergene-enriched zone above primary mineralization, or perhaps a manto deposit) is tested by vertical holes.

Ore bodies such as stockwork or disseminated deposits, which are normally mined in bulk, can present special problems for drill targeting. The boundaries of the mineralized zone determine its size and hence the tonnage of ore present; mineralized structures within the body, however, control the distribution of grade, and these structures may not be parallel to the overall boundaries of the zone. In the case of such deposits, the drilling direction which is ideal to assess grade may be very inefficient at defining tonnage. However, for initial exploration drilling, it is normally better for the first holes to be aimed at proving grade, rather than tonnage.

Once an intersection in a potential ore body has been achieved, step-out holes from the first intersection are drilled to determine the extent of the mineralization. The most efficient drill sampling of a tabular, steep-dipping ore body is to position deep holes and shallow holes in a staggered pattern on alternate drill sections. However, the positions selected for the first few post-discovery holes depend on confidence levels about the expected size and shape of the deposit and, of course, on the minimum target size sought. Since the potential horizontal extent of mineralization is usually better known than its potential depth extent, the first step-out hole will in most cases be positioned along strike (at a regular grid spacing in multiples of 40 or 50 m) from the discovery hole and aimed to intersect the mineralization at a similar depth. Once a significant strike extent to the mineralization has been proven, deeper holes on the drill sections can be planned.

4.2 DIAMOND DRILLING

4.2.1 PREAMBLE

As described in Chapter 1, diamond drilling of a prospect typically goes through two phases. The required geological inputs for the two phases are different.

The first phase comprises initial exploration drilling – the target generation and target drilling exploration stages (sections 1.5.1 and 1.5.2). Drilling is aimed at a geological understanding of the prospect and a qualitative assessment of the potential for ore. This is the most critical stage of prospect drilling. The geological logging process is often difficult – unfamiliar rocks are being encountered and it is difficult to know which of the many features of the core can be correlated between holes and are critical to understanding the mineralization. Yet if the mineralization is not understood an ore body might be missed. The geological returns gained from the first few drill holes into any prospect therefore need to be maximized, and observation and recording should be as detailed as can be achieved. As a general guide, a geologist should not expect to average more than 5 m of core logging per hour when logging mineralized rock, and he or she should be prepared to pick up and examine every surface of every piece of core.

The second phase of drilling is undertaken after it is determined that there is a good probability that an ore body is present. This is resource evaluation and definition drilling and is largely aimed at establishing economic parameters (such as grade and tonnes) and engineering parameters. If a project gets as far as this stage (and the majority will not), the main geological questions should have been answered and the geologist should have passed the steep part of his or her learning curve. With resource evaluation drilling, there is normally an increase in the metreage of core being produced and the logging requirement is for speedy and accurate collection and recording of large volumes of standardized data.

4.2.2 BEFORE YOU BEGIN

A number of steps should be carried out before commencing any first-phase drill hole into a prospect. These are:

- Map the surface outcrop around the drill hole in as detailed a scale as possible (preferably 1:1000 or better) before drilling commences. Ideally, the scale of core logging and surface mapping should be comparable, but the lower density of geological information available on surface means that the surface map is usually compiled at a smaller scale.
- Draw a geological section along the line of the proposed hole. If there is any surface relief then the section should show this with a vertical accuracy of at least a metre.[1] If existing topographic data are not sufficiently accurate to draw the profile, then a special topographic

[1] The position in three dimensions of surface features should be determined to a comparable accuracy to the location of features in the drill core. Even where there is no surface outcrop, the surface profile of the section may still reflect the underlying geology and should be shown on the section.

survey of the section line should be undertaken.

- Plot on to the section the trace of the proposed hole (and any other existing holes) and all known surface geology, geochemistry and geophysics data. If necessary, project the data on to the section.
- From the section, make predictions on the expected down-hole intersections of important geological elements.
- These predictions should be written down, along with a brief drill hole justification statement. Figure A.1 (Appendix A) provides an example of such a justification statement. This practice forces the project geologist to think about the important questions: 'Why am I drilling this hole?' and 'What do I expect to find?'. Apart from this, a hole justification statement such as this keeps the geologist honest when the actual hole results become known.

4.2.3 SETTING UP A DIAMOND HOLE

It is usually essential that a drill rig be set up with precise azimuth and inclination.[1] The following procedure is recommended to ensure that this is done correctly:

- Mark the approximate position of the drill site with a peg or some flagging.
- Clear the site by bulldozer (if necessary) and dig the water-return sump. A square area measuring 15–20 m of side will need to be cleared.
- The original peg has by now generally been destroyed. Reposition and mark the hole collar with a new peg. The exact collar positioning to within a metre or so is seldom vital. The important thing is that the actual coordinates of the collar can be exactly determined by survey after the hole has been drilled.
- Mark the peg with hole number, bearing and inclination.
- Establish the azimuth of the proposed hole by placing fore-sight and back-sight pegs 20–50 m on either side of the collar. The drillers will use these sighters to position their rig. Make sure they know which is the fore-sight and which the back-sight!
- After the rig is set up, but before any drilling takes place, check both azimuth and inclination with clinometer and compass.

4.2.4 GEOLOGICAL OBSERVATION

Core should ideally be observed in direct, bright natural light. If full sunlight is too hot, logging under a light shadecloth screen can be acceptable. If weather is too cold or wet to log the core outdoors, a space indoors before large windows should, if at all possible, be made available. Core trays to be logged should be arranged at a comfortable height on racks. The core should be cleaned down of any grease or mud left from the drilling process and should be observed wet.

Having arranged a comfortable physical environment in which to examine diamond drill core, one of the first problems often found is that the detail of observation possible is so great that major features and contacts of the rock are difficult to spot. In other words, it can be hard to see the wood for the trees. To overcome this, it is a good idea to initially make a complete summary log of the entire hole as the core is being drilled. This first-pass scan of the core will establish the immediate and paramount question of whether there is any mineralization present, and if there is, provide the control for an immediate start on the process of sampling for assay.[2] At the same time, the summary log should define the major boundaries and structures present, and give the context within which the more detailed log can subsequently be prepared.

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[1] Azimuth is the bearing of the hole. Inclination is the dip of the hole, expressed as a negative angle if below the horizontal, and a positive angle if above. Since holes collared at surface will almost always be below the horizontal, the negative sign is usually omitted.

[2] As W.C. Peters says in his book *Exploration and Mining Geology* (see Appendix D) 'Logging is ... most quickly done for the main objective of the moment. The main objective of the moment is to find or to outline an orebody, not to log core.'

Many geologists find it easier to log the detail of lithology, structure, mineralization, alteration and so on in separate passes over the core rather than trying to observe and record these different features simultaneously. The job of the geologist can be made very much easier if routine procedures, such as measuring core recovery, or transferring orientation marks, is carried out by an experienced field technician.

Important decisions such as deepening or terminating a hole, or siting the next hole, may have to be made whilst drilling is progressing. Core should therefore be logged in as much detail as possible, hand-plotted on to section, and its significance assessed on a daily basis as drilling progresses. More detailed logging can subsequently be made when more time is available. Indeed, in many if not most cases, as new ideas evolve, or between-hole correlations are sought, the core will have to be logged and re-logged many times. There are undoubtedly many ore bodies stacked away in core farms still waiting to be discovered.[1]

4.2.5 RECOGNIZING AND INTERPRETING STRUCTURES IN CORE

A problem often encountered is the recognition of the patterns which different structures make when intersected by the cylindrical surface of a core of rock. Structures have characteristic intersection patterns on core but these are different from the patterns which the same structure would make on the more familiar flat surfaces of an outcrop, map or section. The characteristic appearances of common structures are illustrated in Figures 4.2 to 4.7.

The trace on core of a planar surface (bedding, fault, vein, etc.), is usually that of an ellipse, but where the surface is normal to the core axis, the trace is circular, and where the intersection is parallel to the core axis, the trace on the core surface is a straight line (Figure 4.2). In the general case of an elliptical core trace, the positions of the two ends of the long axis of the ellipse are marked by inflection points on the trace. The lower inflection point is labelled E, and that pointing up-hole is labelled E′.

Penetrative linear features of a rock also vary in appearance depending upon the angle at which they intersect the core, as shown in Figure 4.3. For lineations with a rod-like shape, those that pass through the core axis have the smallest cross-section on the core surface: those that are furthest from the core axis have the largest cross-section.

Small fold structures intersected in a drill core are relatively simple to interpret where the fold axis is normal to the core axis (Figure 4.4). In this case, the core surface displays the true fold profile and the inflection points for the two fold limbs and the axial plane cleavage (if present) all coincide. However, in the more general case, where the fold axis and core axis are not normal to each other, the effect is to give the fold an apparently asymmetric shape. The inflection points for the various surfaces which define the fold geometry do not coincide (Figure 4.5). Where the wavelength of a fold is much greater than the diameter of the core, the hinge area of the fold can often be hard to recognize. Careful observation, however, will often spot the high strain effects associated with the hinge region (Figure 4.5).

Minor faults can be easy to spot where they displace marker beds in the core (Figure 4.6). Although the observed displacement may be minor, such minor faults could indicate the sense of displacement on an adjacent major structure. They are well worth recording. Larger brittle faults are often recovered as zones of broken disoriented rock fragments and clay. It can be difficult to obtain any orientation data or sense of displacement from such fractured core. Ductile faults appear as zones of high strain and intense foliation. Once recognized, their orientation is readily measured.

Finally, it is possible to use the relationship between bedding and cleavage in drill core to determine a vector towards the adjacent

[1] Roy Woodall, Exploration Director for Western Mining Corporation, was recently (1995) quoted as saying 'We've relogged the drill core from the Kambalda area (West Australian Ni/Au Camp) three times and each time we do it, we find a new orebody'.

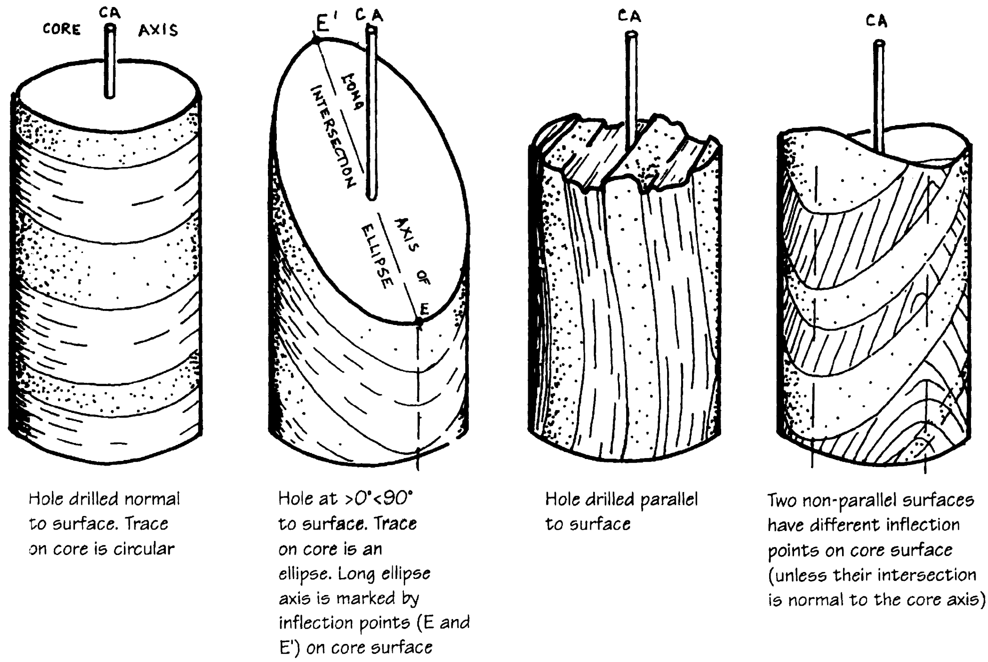


Figure 4.2 How planar structures appear in drill core.

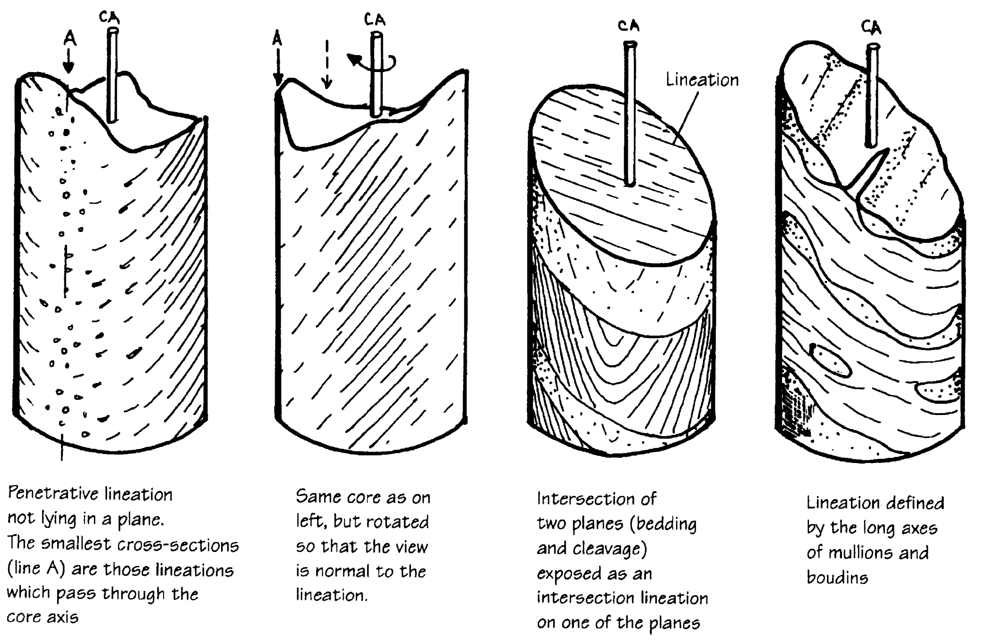


Figure 4.3 How linear structures appear in drill core.

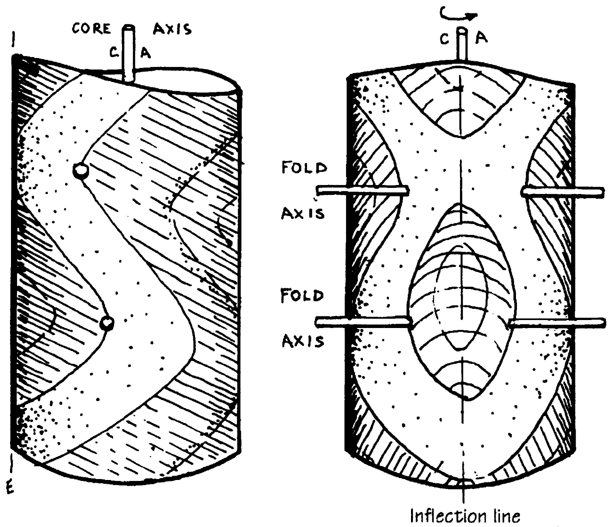


Figure 4.4 How small folds with axes normal to the core axis appear in drill core.

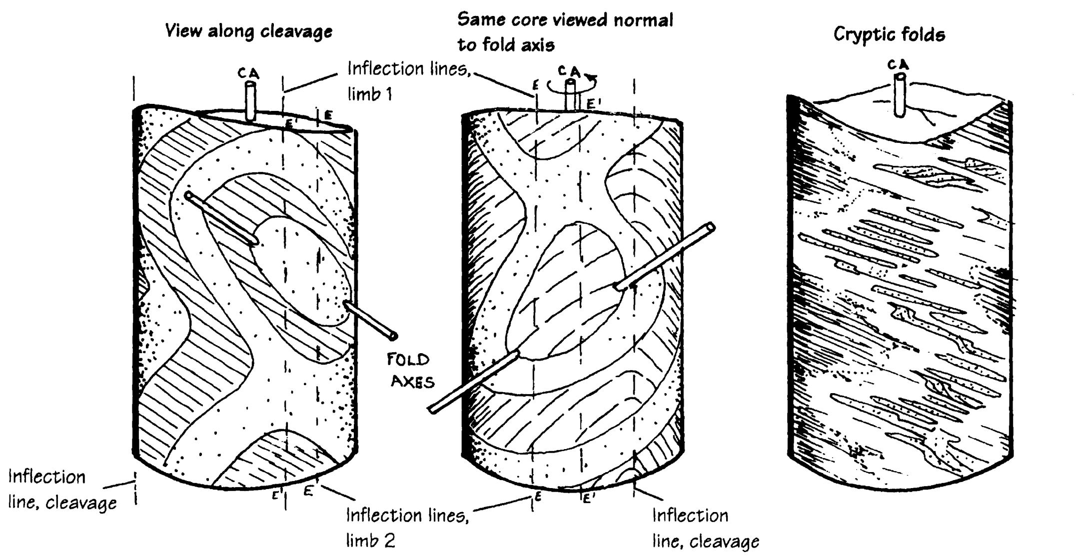


Figure 4.5 How small folds with axes not normal to the core axis appear in drill core.

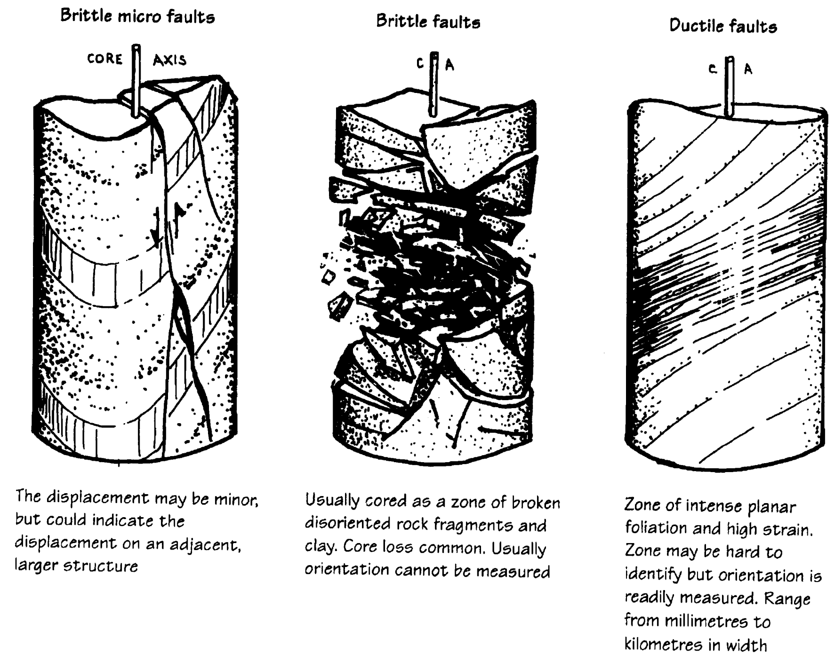


Figure 4.6 How faults appear in drill core.

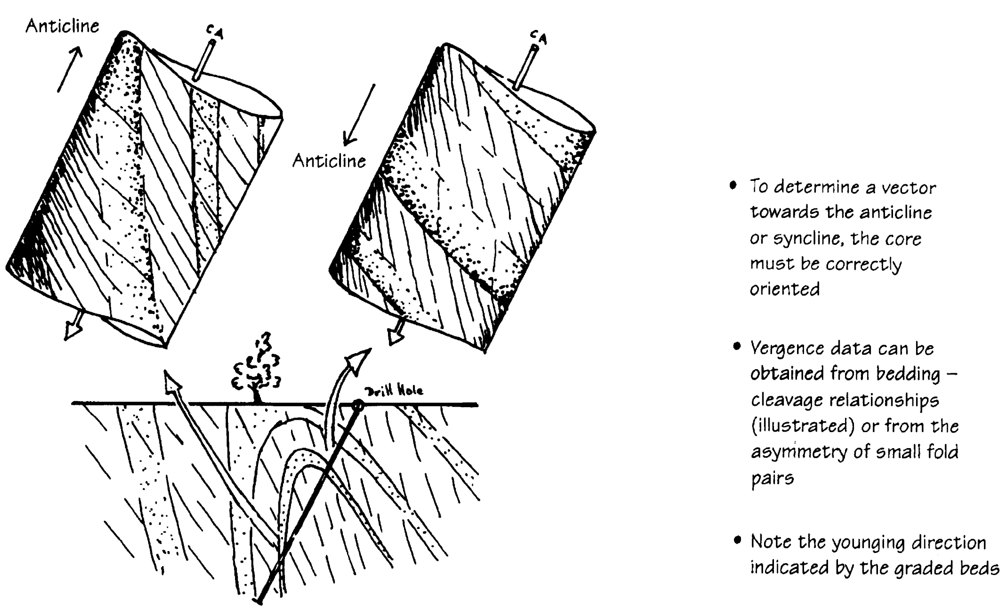


Figure 4.7 How bedding/cleavage relationships (vergences) appear in drill core, and how they can be used to resolve large-scale structure.

anticline or syncline (Figure 4.7). However, this can only be done if the core is oriented (see Appendix B).

4.2.6 MEASURING AND RECORDING STRUCTURES IN CORE

Down-hole orientation surveys (see section 4.2.8) record the deviation of the hole from its initial azimuth and inclination. However, the solid stick of drill core (sometimes, not so solid) recovered from the hole is not fully oriented by a down-hole survey. Although the azimuth and inclination of the core are known, it has another degree of freedom in that it can rotate about its long axis. This does not affect a lithological log made of the core (the down-hole depth to any given point on the core can still be measured) but the original attitude of structures cannot be directly determined. However, techniques are available to orient the drill core.

In many cases rocks contain a penetrative planar fabric such as bedding or cleavage whose orientation is known from surface mapping. In these cases, if this surface can be identified in the core, and the assumption can be made that its attitude is constant, the surface can be used to orient the core. A cleavage is a better surface to use for this than bedding because the attitude of a cleavage is generally more constant than that of bedding (Annels and Hellewell, 1988). Once the core is oriented by this means, other structures present can be directly measured.

A common situation occurs when a hole is drilled at right angles to the strike of a planar fabric whose dip is either not known or else changes through the length of the hole, perhaps as the result of folding. In this case all that can be measured is the angle which the surface makes with the long axis of the core (the long core axis or LCA). Measurement is done by means of a transparent protractor held against the core. A simple home-made device to facilitate this measurement is shown in Figure 4.8. The measurement is quoted as the acute angle and by convention is called angle alpha (α). Since the strike is known, the surface can be plotted on the drill section in only two possible attitudes, that is, symmetrically disposed about the hole trace (Figure 4.9). In many cases, simple inspection of the two geometric possibilities for the attitude of the measured surface will lead to one of them being discarded as unlikely.

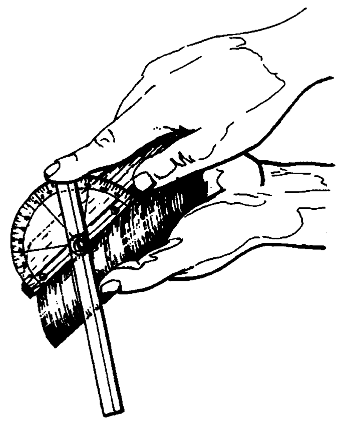


Figure 4.8 Measuring the angle between the down-hole core axis and a surface in the core (the α angle) using a simple home-made core goniometer (see also Figure B.9).

If the strike of a surface seen within the drill core cannot be assumed, then the angle between that surface and the core axis (alpha, α) defines half of the apical angle of the cone that is produced as the surface is rotated around the core axis. This is illustrated in Figure 4.9. The best way to appreciate this effect is to rotate about the core axis a piece of drill core containing a planar surface. In this case, no absolute measurement of the surface is possible, but it is still worth while to plot the boundaries of the cone of lines on to the drill section to represent the limits to the range of possible solutions to the true orientation of the surface.

A special case exists where the hole is drilled exactly normal to a surface. In this case, rotation of the surface around the core axis will provide no apparent change of attitude. The surface can therefore be plotted directly on to the drill section (Figure 4.9). However, note that the core is still not oriented, and other planar or linear

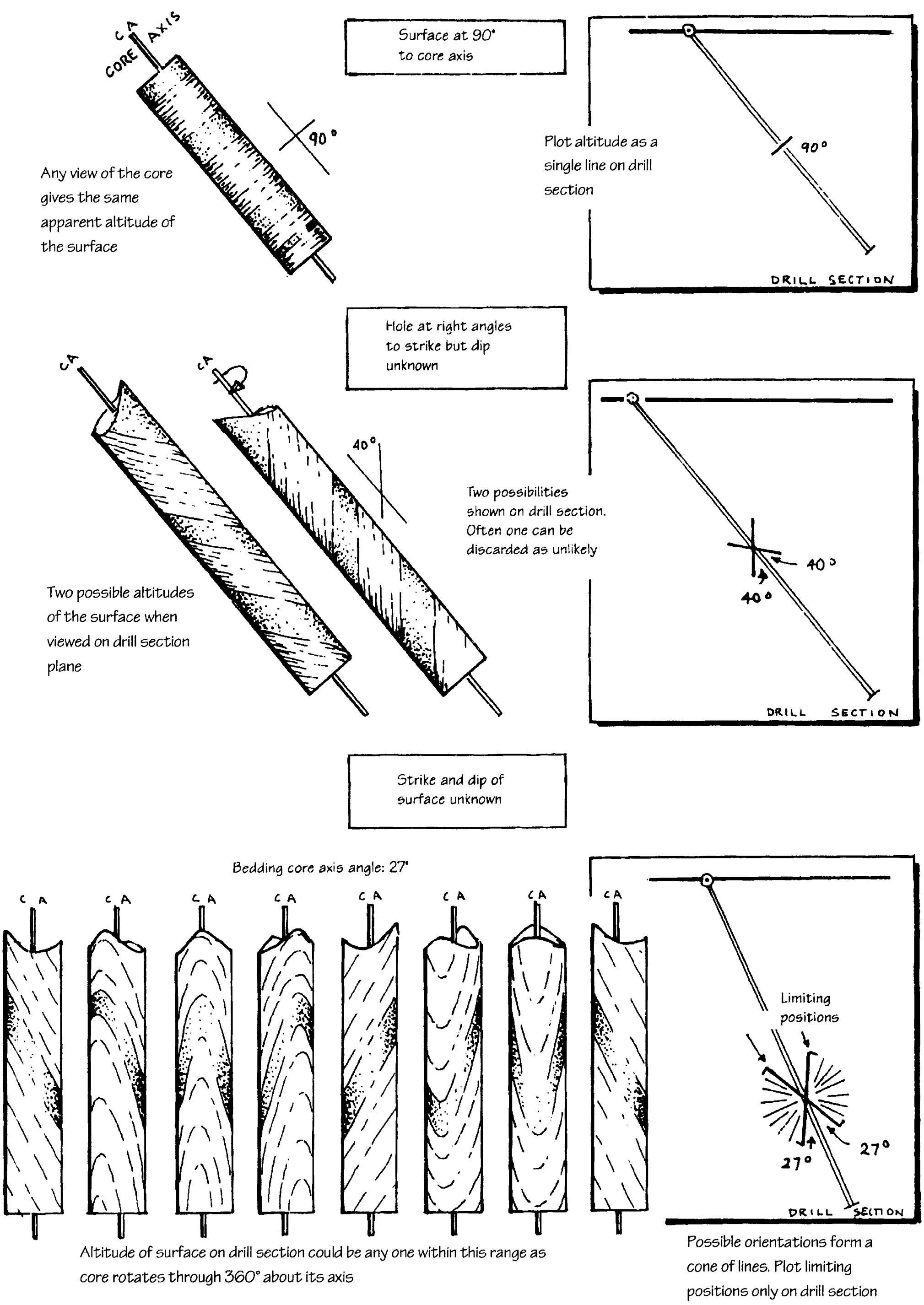


Figure 4.9 How to plot on to a drill section the measured core to surface angle (the α angle) in non-oriented drill core.

structures that might occur within it (i.e. not normal to the LCA) cannot be absolutely measured.

For the general case where no assumptions can be made about the attitude of structures in the core, absolute measurement can only be made if the core is mechanically oriented by means of a core-orienting device. The specialized procedures involved in handling and measuring oriented core are fully described in Appendix B.

4.2.7 CORE LOGGING SYSTEMS

The way data are to be recorded influences in a significant way the amount and type of data that are observed.[1] Using the most appropriate system for recording geological observations of drill core is therefore very important. Although a huge number of different logging forms are used in industry (almost every exploration group has its own design), there are only three basic types of method for recording observations on drill core and cuttings. All individual logging systems correspond to one or other, or a combination, of these basic methodologies. The three logging styles are characterized here as prose logging, analytical spread-sheet logging and graphical scale logging.

In prose logging, an interval is selected, identified by its down-hole depth limits, and then described in words. Such a log will look like the example of Figure 4.10.

Words are a powerful means of summarizing information and prose is an invaluable way of presenting argument, explanation or discussion. However, long passages of prose are a laborious and ineffective way of recording the complex relationships which can exist between the observable features of a rock. It is also unlikely that any two geologists would ever describe a rock using quite the same words. This means that extracting precise objective information from a prose log, so as to construct a drill section or to understand the relationships seen in the core, is difficult and time consuming. As a general rule, literary efforts should be reserved for report writing and not be used as a means of routine drill core description. It is therefore recommended that this style of logging be used only to provide brief verbal commentaries to complement one of the other two logging styles.

In analytical spread-sheet logging,[2] the characteristics of the rock are described under a number of precise, prior-defined categories such as colour, grain size, mineral content, number and type of veins, etc. For descriptive purposes the rock is thus reduced (analysed) to its individual components. These separate descriptive parameters then form the headings for the columns of a spread-sheet. The rock is then described under selected depth intervals which form the rows of the sheet. To keep the log compact and precise, symbols, standard abbreviations and numbers can be used whenever possible to record this information. Such a log looks something like the example of Figure 4.11. This is a simplified example; an actual log would provide many more columns allowing greater detail of description and probably also include a small 'remarks' column allowing some prose or graphical description to be made.

The great strength of this style of logging is that it precisely defines the type of data to be recorded and presents them in a standardized and easily accessible format. All geologists logging the same section of core should produce much the same log. In addition, the spread-sheet log is ideal for direct computer entry of data as observations are made, and it is compatible with electronic data storage and geological presentation software. All the possible observations which can be made in each column of the log can be printed out in advance, along with a bar code. If these pages (usually laminated) are kept to hand during logging, a simple swipe of a barcode reader can then instantly enter data into a portable notebook or palm-top computer.

In spite of these advantages, the problems associated with spread-sheet logs can be

[1] This is a good illustration of the aphorism, coined by Marshall McCluhan (*Understanding Media*, 1964), 'The Medium is the Message.'

[2] This type of logging is often referred to as fixed-format logging using alpha-numeric codes. The term used here is considered to better reflect the methodology behind this system.

DEPTH DESCRIPTION

DEPTH	DESCRIPTION
123.45-136.90	Sandstone with calcareous cement. Pale khaki colour. Medium, somewhat-gritty grain size. Bedding defined by thin shale partings at 124.34m, 126.59m and 132.35m. Bedding at 40° to LCA but becoming flatter to end of section. Numerous thin, wispy quartz veins associated with pyrite speckling along their margins occur throughout.....

Figure 4.10 An example of the prose style of recording geological observations of drill core or cuttings. An interval is selected, defined by precise down-hole depth intervals, and then described in words. It can be difficult to extract precise, objective information from such logs and they are generally tedious to read. The style is not recommended.

DEPTH		UNIT	ROCK	TEXT	VEIN	ALT	
From	To		TYPE			Type	Intst
123.62	129.40	UG	Sst	cg	Q	Ab, Py	1
129.40	134.32	UG	Sh	fg	Q, Calc	CO3	3
134.32	136.59	UG	QFP	mg	Q, Calc	Py, Tm	2

Figure 4.11 A simple example of the analytical spread-sheet style of geological logging. Observations on the rock are broken down (analysed) into a number of objective, prior-defined categories (the columns). Nominated down-hole depth intervals (the rows) are then described under these categories. Numbers, abbreviations and symbols are used wherever possible. The log provides for reproducible, easy-to-access information and is suitable for direct entry into a computer spread-sheet as logging takes place. The system is ideal for logging rotary percussion drill holes, for mine drilling and for the advanced definition drilling stages of an exploration programme.

extreme. They set limits to the range of possible observations which can be made. There is an obvious danger inherent in defining the categories of observation, and the ranges within each category, before logging takes place. Even more importantly, such a format provides no really adequate way to record the relationships between the different categories of observation. The horizontal rows on the log sheet only allow for definition of observed characteristics between precise depth limits, whereas, in reality, many features in a rock vary in a smooth way, and different features may vary at different rates, or have different down-hole depth ranges.

Use of spread-sheet logging is indicated in second-phase drilling programmes (resource evaluation and definition) where the main geological problems associated with the ore body have been solved, and the aim of the logging is the routine recording of masses of reproducible data. It is also an ideal technique for recording geological data obtained from rotary percussion (RAB and RC) drill cuttings. Analytical spread-sheet logging, should not be used for first-phase exploration diamond drilling.

For the early stages of exploration diamond drilling, it is recommended that graphical scale logging be used. Examples of this style of logging

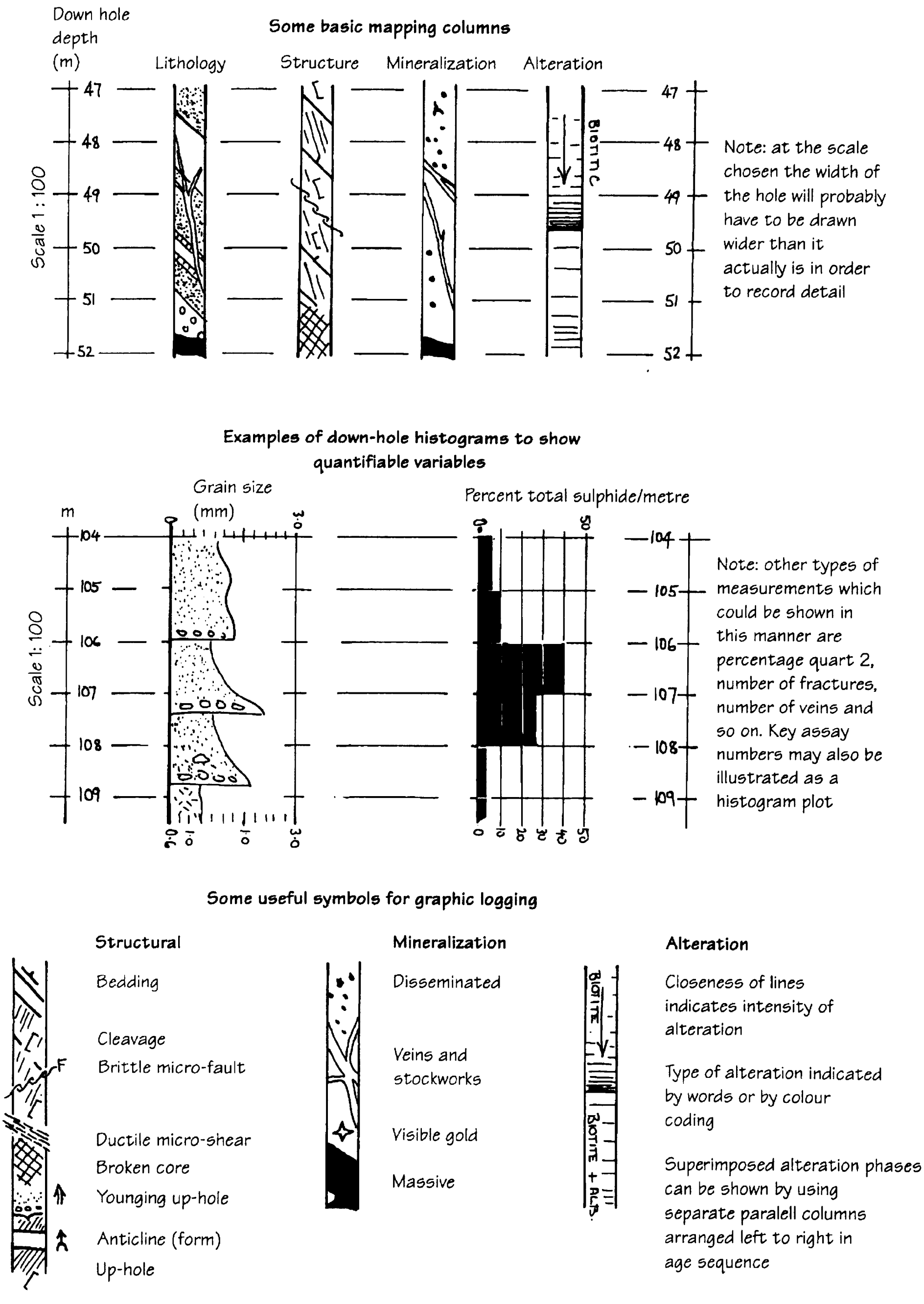


Figure 4.12 Examples of graphical scale logging. This is an analog recording method: down-hole position is according to a chosen scale. Structures are drawn as they appear in correct attitude relative to the core axis. Measurable core parameters appear as down-hole histograms. Graphical logging is a powerful and flexible technique which supports detailed observation. It is recommended for the early stages of exploration diamond drilling (see the example of an actual log in Plate 1).

are shown in Figure 4.12 and detailed instructions for its use, along with a completed example of an actual form (Plate 1) in which graphical scale logging is a major component, are given in Appendix A. Recording observations in this format encourages and facilitates detailed quality geological observation of core.

The key feature of this type of logging is that observations are positioned on the log sheet according to a down-hole metre scale which is chosen for the hole and marked down the length of the log sheet. This contrasts with other types of logging, where the down-hole range of a particular observation is defined by numbers (i.e. depths down hole) which are written on to the log. In graphical scale logging the observer makes a 'map' of the core which can then be annotated as appropriate with graphical, numerical, textual or symbolic methods of showing observations. The scale, and hence the detail, of the logging, as well as the features to be observed and the mix of recording methods, are selected by the geologist to suit the prospect. The logging style is thus very flexible and can be used for almost any type of mineralization.

Graphical scale logging is an analog recording method and thus reflects the way most geologists actually see and think about rocks. It emphasizes the relationships between features of the core. The graphical format provides an easy and quick way to record visual detail. The particular log form described and illustrated in this book (see Appendix A) combines the best features of analytical and even prose types of logging into the analog format.

Such logs are not just a means of recording observations. By offering a detailed visualization of the core, the log can be used for correlating features both within and between holes, and is thus in itself a powerful way of integrating data and thus determining geological relationships.

4.2.8 DOWN-HOLE SURVEYING

The orientation of a drill hole is defined by its azimuth and inclination (for definitions see footnote on page 45). Azimuth and inclination, along with collar coordinates and collar relative level (RL), are part of the commencing specifications for a drill hole. However, because a string of drill rods is not rigid, the attitude of the hole can progressively change with depth – this is called deviation. In the majority of cases holes flatten (because of downwards drilling pressure) and swing to the right (with the turning of the rods), but this is not always the case. Holes will tend to deflect so as to make a greater angle with the dominant foliation (usually bedding or cleavage) of the rock, unless the hole is already at a very low angle to that foliation, in which case the hole will tend to deflect along the foliation. Only experience of drilling in a particular area can allow exact prediction.

Although deviation is at most only of the order of a few degrees per hundred metres, this is usually cumulative and, if not allowed for, the bottom of a deep hole can be many tens of metres away from its straight-line course. The expected deviation of the hole needs to be allowed for when designing a drill hole to intersect a particular target at depth.

Holes over 50 m deep generally will need to be surveyed to determine their deviation. The instrument normally employed for this is a specially designed down-hole survey camera. The camera is lowered down the hole to the required depth on the end of the wire-line overshot. After a predetermined time, a clockwork mechanism activates the camera to take a photograph of a small built-in compass card and clinometer. On processing, a photographic record is obtained of the orientation of the hole at that depth. With a multi-shot bore-hole camera, the mechanism can be set to take a number of readings at predetermined times, thus allowing orientation measurements at different depths to be obtained as the instrument is withdrawn from the hole. Results from the down-hole camera are generally very accurate, but care has to be taken with the following points:

- The survey instrument should be isolated from the steel drill stem which can affect the compass needle. The drilling rods and bits have to be pulled back from the bottom of the hole, to allow the brass or aluminium casing of the down-hole camera to project at least 3 m beyond them at the time of the survey.

- Magnetic rock units may affect the compass. Such effects can usually be spotted if one azimuth reading is out of phase with measurements on either side. This reading should be discarded.
- If long sections of the hole are magnetic then the magnetic-based down-hole survey camera cannot be used for azimuth determinations. In this case it may be possible to measure the attitude of the hole from the angle which the core makes with known planar features of the rocks, such as bedding or cleavage. Failing that, it is possible to orient holes using gyroscope-based instruments, but these are not always readily available and are generally expensive.
- Do not use metal-jacketed batteries to power the survey instrument as these are magnetic and can affect the compass.

When drilling in a new area, surveys should initially be carried out every 30–50 m down hole, but if experience indicates that there is no strong deviation, this interval may be subsequently increased. Experienced drillers will normally carry out the down-hole survey on the instruction of the geologist.

As soon as they are obtained, the down-hole survey data should be used to construct a section and plan view of the hole (section 4.2.9). By doing this, the progress and effectiveness of the hole in reaching the planned target can be monitored. If strong deviations are encountered, the driller can be alerted to the problem, and it may be possible to take corrective action.

4.2.9 USING DOWN-HOLE SURVEY DATA TO PLOT SECTIONS AND PLANS

Nowadays, once down-hole survey data have been entered into a computer, the task of plotting the trace of the hole on to a section or plan is usually taken care of by one of the many mining/exploration software programs. However, in exploration drilling, plotting observations on a daily basis usually means that a drill section will have to be plotted by hand. It is not hard to do this.

Changes in inclination and azimuth record a downwards spiralling of the hole. This appears as a curved trace on both plan and section views of the hole (Figure 4.13). The curved trace on plan view means that data have to be projected horizontally to create the drill section. However, in the early stages of exploration drilling, where the exact position (i.e. to the nearest few metres) of the hole in space is not especially relevant, changes in azimuth can usually be ignored and it is only necessary to plot a section of the hole showing changes in inclination. A section like this is quick and easy to draw and, provided changes in azimuth are not too extreme, is adequate for most initial plotting and interpretation of geology.

The effects of deviation are progressive, so with deep holes (say, over 300 m depth), particularly where large azimuth deviations are encountered (more than 5° per 100 m), the simple drill section plot described below will tend to be increasingly inaccurate. A plotting procedure that allows for the simultaneous changes in inclination and azimuth is necessary. This more complicated procedure is also necessary if the trace of a hole has to be projected on to a section which is at an angle to the standard drill section. Both the simple (but approximate), and the more complex (but exact), procedures for plotting drill sections and plans are described below, using the set of hole survey data in Table 4.2.

Table 4.2 Hole survey data

Survey Point	*Depth (m)*	*Inclination (°)*	*Azimuth (°)*
1	0	70	270
2	52	66	280
3	106	64	288
4	160	62	290
5	205	58	296

Plotting an approximate section

1. From the surface (Survey Point 1) to Survey Point 2 at 52 m, the hole flattened from 70° to 66°. The average inclination for this sector of the hole is therefore 68°.
2. Using an appropriate scale, a point is plotted on the section representing 52 m from the starting point (hole collar) at an angle from the horizontal of 68°.
3. In a similar manner, Survey Point 3, at 106 m down hole, is 54 m (106 – 52 m) from Point 2 at an inclination of 65° (the mean of 66° and 64°); Point 4 is 54 m from Point 3 at an inclination of 63°, and so on to the end of the hole. A smooth curve joining the plotted points will be a close approximation to the actual trace of the hole.
4. In this example, ignoring the azimuth variation means that there is a progressive error in the position of the hole on the drawn section which amounts to around 5 m by the bottom of the hole.

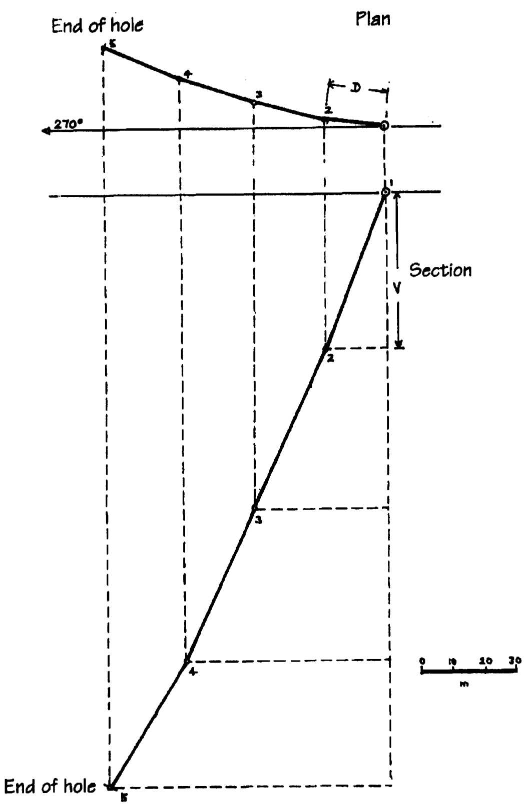


Figure 4.13 How to prepare an exact drill section and plan from the results of down-hole orientation surveys. The plot illustrated is based on the survey data of Table 4.2.

Plotting an exact plan and section

1. On the same sheet, draw both the plan and section views of the hole, with the collar position on plan and section vertically aligned on the page (see Figure 4.13). Sections can now be drawn at any angle required to the trace of the hole; the one illustrated is at 270°, the starting azimuth of the hole.
2. From Survey Point 1 (collar) to Survey Point 2, the down-hole distance is 52 m, the mean azimuth is 275° (the average of the starting azimuth and final azimuth), and the mean inclination is 68°.
3. Using trigonometry, the horizontal (*D*) and vertical (*V*) distances between Points 1 and 2 are calculated: $D = 52 \times \cos 68° = 19.48$ m; and $V = 52 \times \sin 68° = 48.2$ m.
4. Using a suitable scale, on plan view, plot Point 2 at 19.48 m from Point 1 at a bearing of 275°.
5. On the plan, draw a line from Point 2 to intersect the trace of the proposed section at right angles. From this intersection point, draw a vertical line down the sheet and across the section below.
6. Survey Point 2 is now plotted on the section where the line marking 48.2 m vertically below surface intersects the vertical line projected from the plan view above. The same scale is used for plan and section.
7. The same procedure is used for plotting each successive down-hole survey point. A smooth curve through the points will give an accurate trace of the drill hole on plan and section.

4.2.10 SAMPLING AND ASSAYING

Assaying diamond drill core during early phases of exploration has two purposes. The first is to provide an indication of whether potentially mineable grade is present. The second is to give an understanding of where economically significant elements are reporting in the system, so that controls on ore distribution can be defined and understood. This understanding is necessary in order to target new holes.

In first-phase exploration drilling, intervals for sampling should be determined by geology. The intervals are selected by the geologist and marked on to the core at the time of logging. The boundaries of the intervals should correspond as far as possible to mineralization boundaries that the geologist either observes or postulates. Each sample for assay should be selected to answer a question which the geologist has about the core. Only where core to be sampled is relatively uniform should regular samples of predetermined length be taken.

Where core has been lost, sample intervals should not span the zones where the loss has taken place. To mix a sample of, say, 70% recovery with a sample of 100% recovery is to contaminate good sample data with bad. There is potential information of value to be had by comparing the assays for a sample with good core recovery with that for a similar sample for which the recovery is poor. This can only be done if the samples are kept separate.

The decision to use half, quarter or whole core as a sample for assay depends upon the need for a sample size adequate to overcome any nugget effects. When sampling gold prospects, the larger the sample size the better. However, sampling whole core should only be undertaken as a last resort, as this destroys the core and prevents any possibility of re-logging. In general half the core, split lengthwise, is taken for assay.

Methods of sampling core depend upon its condition. They are:

1. *'Knife and fork sampling'* This is employed when damp clays are encountered. The material is often so soft that it can only be sampled by cutting it lengthways with a knife.
2. *'Spoon sampling'* If the material is badly broken, the only realistic method is to use a spoon or trowel to collect a representative section through each chosen interval. Split the broken core into halves lengthways with a broad-bladed spatula and, whilst retaining one half with the spatula, spoon the other half into the sample bag.
3. *Core grinding* If the core is not considered sufficiently interesting to be sawn in half, but an assay is still wanted as a check, or for a geochemical scan, then the core grinder is a very useful tool (see Figure 4.14). The grinder takes a shallow shave of rock along the length of the core. This sample is much quicker and cheaper to collect than sawing the core in half with a diamond saw.
4. *Chisel splitting* Relatively homogeneous crystalline rocks such as igneous rocks or some metasediments can often be split lengthways with a chisel. Special core splitters can be bought for this purpose. The method is quick and can be employed on remote sites where no power is available for a core saw. However, any strong pre-existing rock fabric generally ensures that the core will not split as required.
5. *Diamond sawing* This is the standard and preferred way to sample solid core. The core is

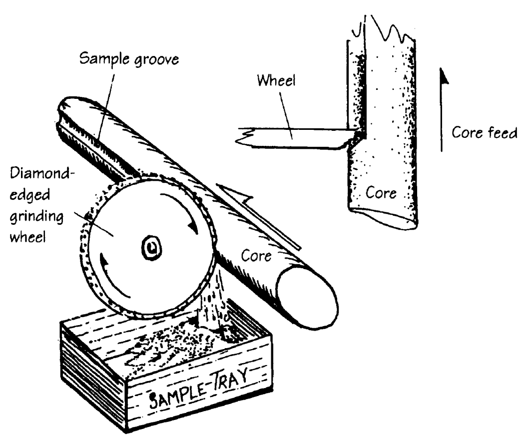


Figure 4.14 Sampling diamond drill core with a core grinder. The tool is useful for collecting a quick, cheap sample of the core as a geochemical scan.

sawn lengthways into two halves using a diamond-impregnated saw (Figure 4.15). The method is slow and relatively expensive but, except where a splitter can be used, is the only way of providing an accurate split of solid core pieces.

6. *Sludge sampling* The fine rock flour created by the drilling action, which spills onto the surface at the collar with the return wash water, is known as sludge. Where drilling recoveries are poor, either because small broken pieces cannot be gripped by the core-lifter, or because the pressured drilling water is removing a clay or silt fraction from permeable rock, the sludge represents some of that lost material. Since poor recoveries are often a feature of zones of mineralization and alteration, it is a good idea in these circumstances to gain some idea of what is being lost by sampling the sludge for assay.

   The return water is guided by a channel from the collar to the water-return sump. To take a sample of the sludge, dig a small pit on this channel deep enough to hold a 10 litre plastic bucket. The silt that collects in the bucket provides the sample for the given drilled interval. The sludge sample can then be stored in an open polyweave bag until dry before being despatched to the laboratory for assay. Note that such an assay provides an indication of grade only. The exact down-hole position of the sludge can never be known. The water action may well have caused a bias in the sample through a sorting by weight of different components of the sludge.

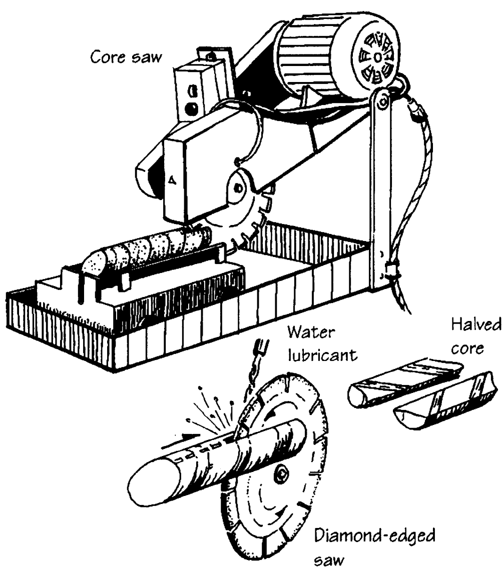


Figure 4.15 Sampling core with a diamond core saw. The core is cut in half lengthways and one half taken for assay. This provides the ideal sample but the process is slow and expensive. The saw used is generally a brick saw modified with a special channel to hold the core piece on the feed tray.

4.2.11 CORE HANDLING

Routine core handling is a role for a suitably trained and experienced field technician, working under the supervision and direction of a geologist. If the technician's job is done properly, the geologist is free to concentrate on observation and recording of the core. The duties of the field technician are set out below.

- Carrying out down-hole orientation surveys.
- Measuring core recovery.
- Measuring RQD[1] (if required).
- Supervising the drillers' core-handling procedure by ensuring core is correctly placed in trays (e.g. not jammed too tightly or too loosely in the tray; ensuring that pieces of core are not rotated in the tray with respect to each other, etc.).
- Ensuring that the drillers' core blocks, which mark the down-hole depths at the end of each drilled interval, are correctly placed and permanently legible (Figure 4.16). When the blocks become misplaced (which readily happens when core is transported), the correct position for the block can usually be spotted by the parallel grooves which the core-lifter leaves on the base of each barrel of core.
- Measuring hole depth at the beginning and end of each tray.

[1] RQD or rock quality designation is defined as percentage core recovered during drilling, counting only those pieces of intact rock over 100 mm long.

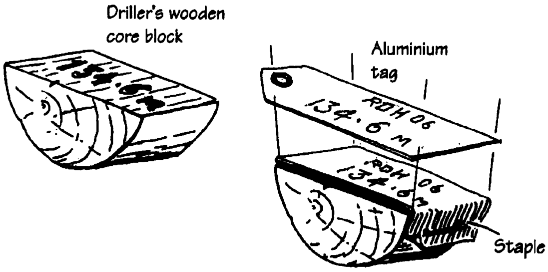


Figure 4.16 Permanent marking of drill core – 1. Drill core is expensive and worth preserving, but its usefulness is only as good as the markers which identify its position and depth. The core blocks (often of wood) which the driller uses to mark the down-hole depths of each run should be permanently labelled using a system such as that illustrated.

- Marking hole depth, hole number and tray number on to each tray (Figure 4.17).
- Marking the core in 1 m intervals as an aid to subsequent logging and sampling. The measurements are taken with a flexible steel tape from the nearest core block. The most accurate way to do this is to remove the core from each drilled interval and then to reassemble it, piece by piece, in a separate V-section channel, by carefully fitting the broken ends together. When laid out in this way, measuring depth intervals, or marking a line along the core to indicate the proposed cutting line for sampling (see bulleted item below), is both easy and accurate. A set-up for doing this is illustrated in Figure B.3 (Appendix B). Reassembly of the core in this manner is essential when dealing with oriented core, or where complex structural relationships need to be resolved. However, the technique is time consuming. For most purposes, non-oriented core can be measured with sufficient accuracy without removing it from the core tray.

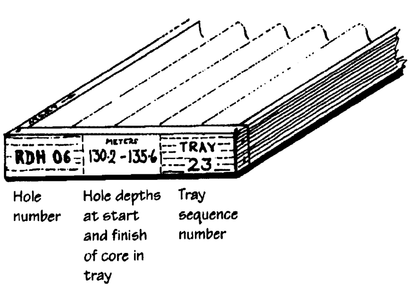
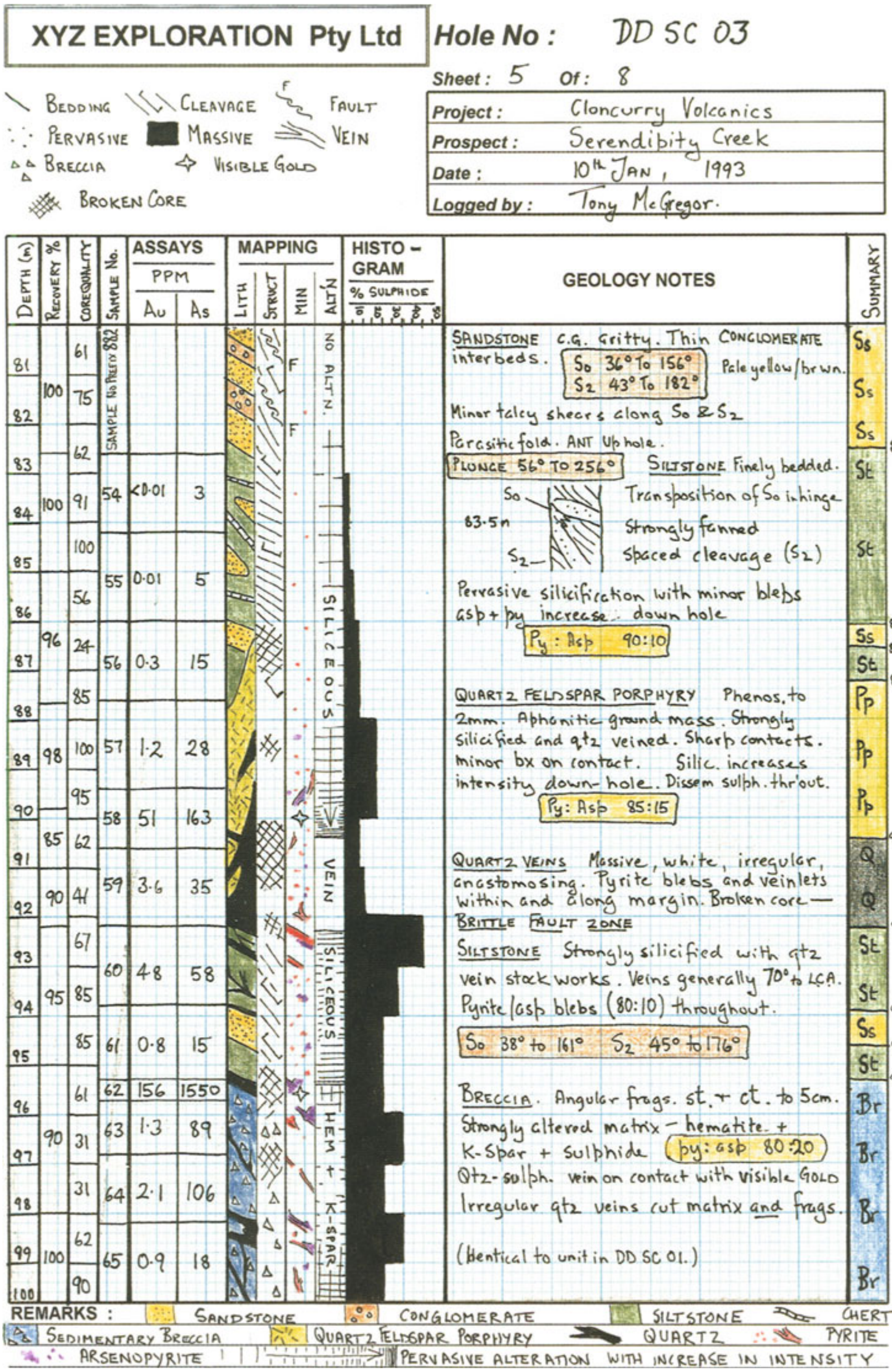


Figure 4.17 Permanent marking of drill core – 2. The ends of core trays should be labelled as shown. Use a permanent labelling method – most felt-tipped pen markers fade rapidly.

- Marking the core for sampling. Core is normally cut or split lengthways at right angles to the dominant planar structures within it. The geologist will indicate this position and also which half of the core is to be taken for the sample. The proposed saw cut is then marked by drawing a line along the length of the core. The half-core to be retained after sampling is marked by placing a small arrow on each piece of core to be retained. The arrow points down-hole and serves to orient each piece of core. The half-core to be retained is selected so that its cut surface will correspond (as far as core orientation can be determined) to the view of the drill section. Conventionally, this usually means that in E–W oriented holes, the northern half of the core will be retained; on N–S oriented holes, the western half is retained (Figure 4.18). Section B.2 presents more detail on marking out drill core.
- Cutting or splitting the core and collecting the sample. The sample is collected between the intervals nominated by the geologist. Where half-core is taken as a sample, the technician should ensure that the same half of the core is always taken; the retained half-core should be a continuous section of rock with the separate pieces correctly oriented with respect to each other (Figure 4.18).
- Marking the sample number on to the tray where an interval has been split for assay. Adhesive sample number tags carrying the same sample numbers as those in the sample books are available and can be used for this purpose.
- Permanently marking and sealing the drill hole collar (Figure 4.19). This is necessary, not only because open holes can be dangerous, but because hole collars often need to be



Colour plate. An example of graphical scale logging of diamond drill core. The original of this plate was an A4-size form with a chosen scale of 1:100. Using colour to record data on logs of this type greatly increases the amount and clarity of the detail that can be shown.

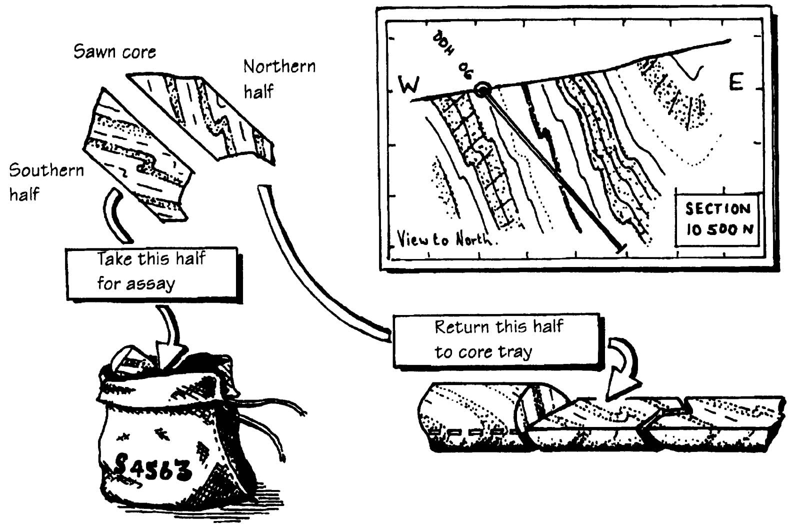


Figure 4.18 When sampling cut diamond core, always take the same half for assay. The saw cut will normally correspond to the vertical plane (the drill section). When this is done, the sawn surface of the half-core retained in the tray should present the same view as the standard drill section.

re-located, sometimes many years after they were drilled. It may also be necessary to subsequently re-enter an old hole in order to deepen it or to carry out a down-hole geophysical survey. For these reasons dirt must be kept from entering the hole.

- Measuring the specific gravity (SG) of the core, where required. SG measurements are necessary in order to calculate tonnages of rocks and for helping to interpret gravity surveys. The measurement is easily done by making use of the formula:

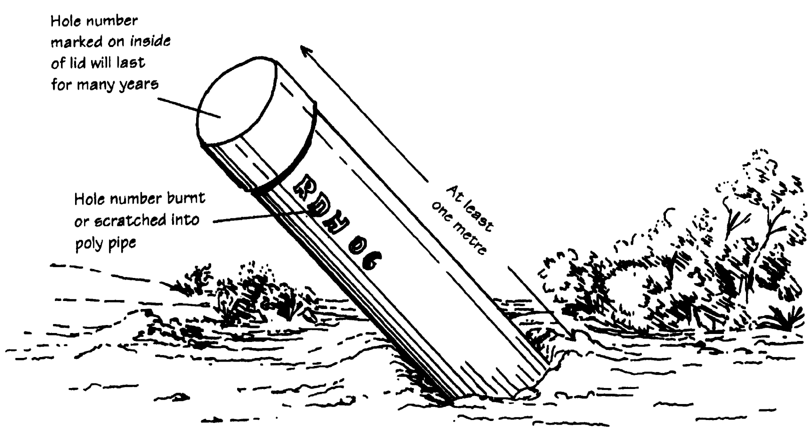


Figure 4.19 A permanently marked and labelled drill hole collar. When finished in this way, the collar can be easily re-located and identified, even after many years; stones and dirt are kept out permitting hole re-entry; and animals cannot injure themselves by stepping into open holes.

$$SG = \frac{\textit{Weight in air}}{\textit{Weight in air} - \textit{Weight in water}}$$

A simple apparatus for carrying out the weighing procedure for SG measurements is shown in Figure 4.20. It can be used for drill-core or any other small rock specimens.

- Photographing the core. Many companies like to make a permanent record of the appearance of their drill core by photographing the trays of core. Photographs of core in trays generally show little of the detail of the core, but they can record the broad appearance of the rock, including features such as colour, prominent structures or degree of fracturing. If disaster strikes and core goes missing or is destroyed for any reason, colour photographs of the core will complement the geological logs and ensure that not all is lost.

  Photographs of core in trays are easy to make, and an acceptable product can be made with a hand-held camera. However, the best quality images are produced by a camera mounted vertically above the core on a special frame. Photography should be carried out in a place where there is good natural lighting, or if this is not possible, artificial lighting will need to be installed around the photographic set-up. In most cases, two trays side by side plus a small chalk board or white board on which the prospect name, hole number and hole depths are marked, will fill the frame of a camera.

  The flat surfaces of cut core provide much better images than curved surfaces. If the core is to be cut, photography should be carried out after cutting. In some cases, wetting the core before photography will bring out its features better, but this is not always the case and each particular core type should be checked to see how it is best prepared.

  In addition to making a photographic record of the complete hole as described above, close-up photographs of significant portions of individual core pieces are an excellent way of illustrating detailed features. Such photographs can be keyed in to graphic logs, and are invaluable for making quick comparisons between different holes. A hand-held camera with a close-up lens will usually produce an acceptable image for this purpose, particularly where flat cut surfaces are available for photography.

  In many cases, an excellent monochrome image of the surface of a piece of cut core can be produced on an ordinary photocopying machine. The technique works well where there are good tonal contrasts within the core, and, provided there is a photocopier convenient to the logging area (admittedly, not always the case), this can be an excellent way

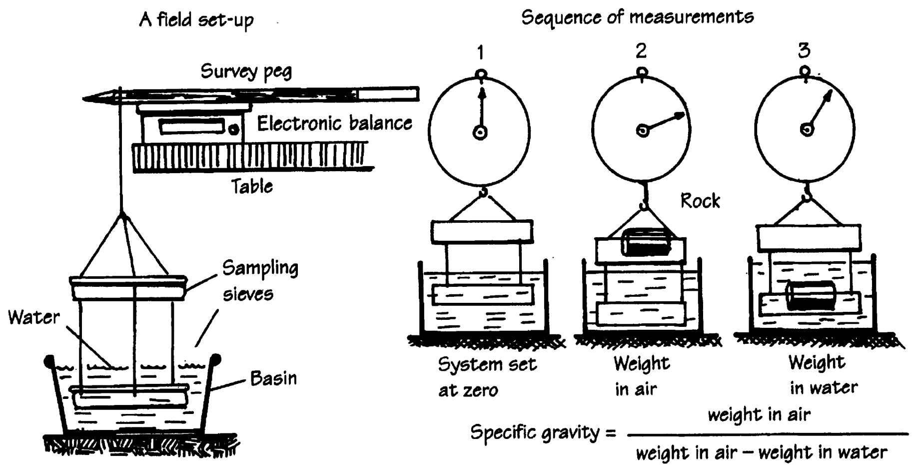


Figure 4.20 How to measure the specific gravity of rock specimens.

of quickly recording textural and structural features of a rock.

4.3 REVERSE CIRCULATION (RC) DRILLING

4.3.1 DRILLING TECHNIQUE

With dual-tube RC drilling, compressed air passes down to the drill bit along the annular space between an outer and inner drill rod to return to surface carrying the broken rock cuttings up the centre of the inside rod. This is the reverse of the air path employed in normal 'open hole' rotary percussion drilling (including RAB drilling) – hence the name of the technique (Figure 4.1). The RC drilling procedure prevents the upcoming sample from being contaminated with material broken off from the sides of the hole and so can potentially provide a sample whose downhole position is exactly known. This is obviously of great value, especially in drilling gold prospects where even low levels of contamination can produce highly misleading results.

It is important that as much of the rock as possible for a given drilled interval is collected. The driller ensures this in three ways. Firstly, the hole is sealed at its collar so that the sample is forced to travel through the drill stem and into the collector at the top of the rods. Secondly, the driller continues to apply high air pressure for a period after each advance (usually 1 m) in order to clear all cuttings from the drill stem, before continuing the advance. The technique is known as 'blowback'. Thirdly, at the drill head, all cuttings are blown into a large-volume container called a cyclone, which is designed to settle most of the fine particles which would otherwise blow away (Figure 4.21).

4.3.2 GEOLOGICAL LOGGING

Even though a drill programme is planned in advance, each hole adds to geological understanding and this can lead to changes in the programme. To most effectively use the RC rig, the geologist must be in a position to make on-site decisions on hole depth and hole position. This is only possible if geological logging and interpretation is undertaken as the hole is being drilled. Simply logging the hole is not generally enough; to fully understand the geological results, they should be hand-plotted on to a section and interpreted in a preliminary way in the field. RC

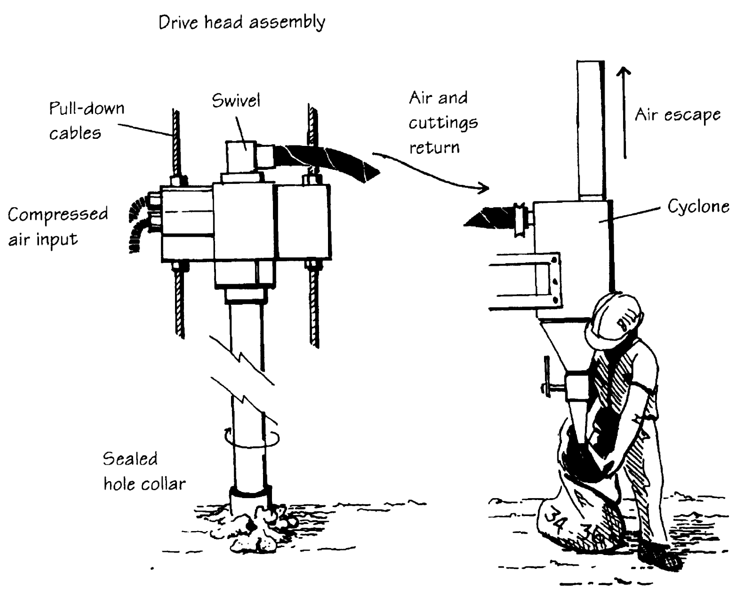


Figure 4.21 Collecting the rock cuttings from a reverse circulation drill.

drilling (unlike most RAB programmes) is relatively slow and usually gives the geologist plenty of time to log the hole and plot and interpret his or her results as drilling proceeds. To facilitate this process, a drill section should be drawn up in advance of drilling. The section will show the proposed hole as well as all other relevant geological, geochemical or geophysical information for that section, including the results of any preexisting holes. The procedure is very much the same as that described for diamond drill logging. Although, compared to diamond drilling, there is less time available for logging an RC hole, the detail of possible geological observations is also that much less.

Observation and interpretation are interactive processes – the one depends to some extent on the other. The features that are identified in logging drill chips are dependent upon the evolving geological model. Those geological features which prove able to be correlated between adjacent holes or between hole and surface will be preferentially sought for in the rock chips and recorded. It is only by specifically looking for particular features that are judged to be important, that the more subtle attributes and changes in the drill chips can be picked up.

The RC drill recovers broken rock ranging from silt size up to angular chips a few centimetres across. These allow a simple down-hole lithological profile to be determined. The normal procedure is for the geologist to wash a handful of cuttings taken from each metre of drill advance, using a bucket of water and a sieve with a coarse mesh (around 2 mm) to separate the larger pieces.[1] The clean cuttings are then identified and the rock description for that interval entered on to a logging sheet. This sounds simple, but in practice, small rock chips can be very difficult to identify. In addition, the larger rock chips recovered in the sieve may be representative of only a portion of the interval drilled – usually the harder lithologies encountered in that interval.

[1] This should be done by the geologist, not by the field technician, since washing the sample is the best way to assess the percentage of fines in the drill cuttings.

Skill in rock identification with a hand lens is necessary. However, for adequate identification, small specimens of fine-grained rock require examination with a reflecting binocular microscope with a range of magnification up to at least 50×. A simple binocular microscope set up on the back tray of the field vehicle is an invaluable logging aid and its use is strongly recommended.

As logging consists of metre by metre description of the cuttings, any log form drawn up into a series of rows and columns is adequate to record data. This is the analytical spread-sheet style of logging described in detail in section 4.2.7. The rows represent the metre intervals; the columns are labelled for particular attributes which are considered important for that project. It is better to describe the observed features of the cuttings (mineralogy, grain size, colour, texture, etc.) than to simply record a one-word rock name. Such summary descriptors (i.e. metabasalt, porphyry, greywacke, etc.) can be recorded in a separate column. Other attributes commonly recorded are percentage quartz or sulphide, degree and type of alteration, structures seen within the chips such as foliation, degree of oxidation, depth to water table and so on. A separate column should be provided on the log sheet form for verbal comment.

The detailed rock description refers only to the larger fragments recovered from the hole. Since these represent only the harder and more competent parts of the section drilled, it is important that a separate column record the estimated percentage of washed cuttings to fines. Thus 50% quartz vein fragments observed in the coarse washed portion of an interval where 50% of the total recovered cuttings consisted of fines, probably equates to only 25% quartz vein material intersected in that interval.

The spread-sheet logging form can be created in a standard software program. The observations can then be entered directly, as they are made, into a battery-operated notebook or palm-top computer at the drill site.[2] As described in

[2] Waterproof and dustproof protective covers are available for palm-top computers and make this system very practical.

Section 4.2.7, the full range of possible observations in each descriptive category can be preprinted along with a bar code on to standard laminated sheets. Data entry with a bar-code reader is then quick and simple. At the end of the day, or the end of the programme, the completed logs can then be downloaded from the field computer on to a desk-top PC for storage, handling and plotting by one of the many exploration data software programs that are commercially available. It should be emphasized, however, that even where data are recorded electronically in this way, the geologist still needs to hand-plot the geology of the hole on to a section as drilling proceeds.

RC holes can deviate substantially from their starting azimuth and inclination. Holes which are targeted on ore, and are much more than 50 m deep, need to be surveyed as described in Section 4.2.8.

4.3.3 DISPLAY AND STORAGE OF CUTTINGS

The washed and sieved drill cuttings should be permanently stored in segmented, plastic cuttings boxes for later, more leisurely examination, should that prove necessary (Figure 4.22).

In addition to this permanent storage, it is often a good idea to lay out samples of the washed cuttings from the entire hole on to a plastic sheet (sample bag) spread on the ground beside the hole collar (Figure 4.23). The sequence of rocks through the entire hole can then be seen at a glance, and it is easy to spot progressive down-hole changes. If the samples are left on display like this for the duration of the drilling programme, comparing intersections and establishing correlations between adjacent holes is made very much easier.

With particular holes which are considered to be representative of a geological environment, the washed cuttings can be glued on to a suitably labelled cuttings board (Figure 4.24). When displayed in this manner, it is easy to carry the board to site to act as a reference for future logging. A cuttings board is also invaluable for communicating the results of a drilling programme, and for helping to train geologists coming into an established project to ensure consistency of geological description.

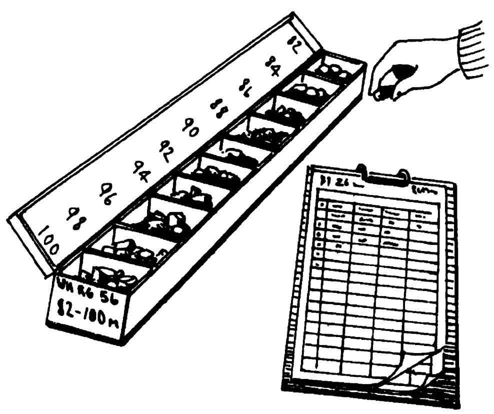


Figure 4.22 Permanent storage of washed drill cuttings in a plastic cuttings box.

4.3.4 SAMPLING

The total amount of cuttings from each drilled interval are collected from the cyclone in a large polythene or polyweave bag (Figure 4.21). Despite all precautions, it is usually impossible to avoid some sample loss – often fine dust or mud.

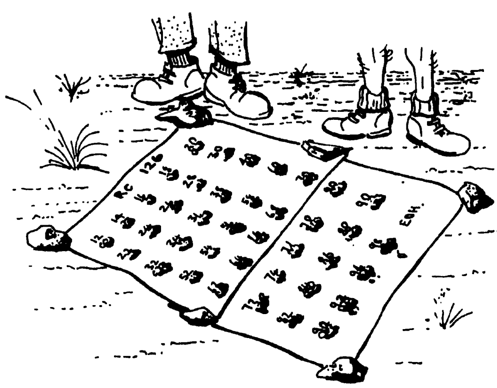


Figure 4.23 Temporary field display of washed cuttings. Samples from each interval are laid out on a plastic sheet (sample bags) beside the collar. This aids in identifying down-hole changes and permits quick and easy comparisons between adjacent holes in the course of a drilling programme.

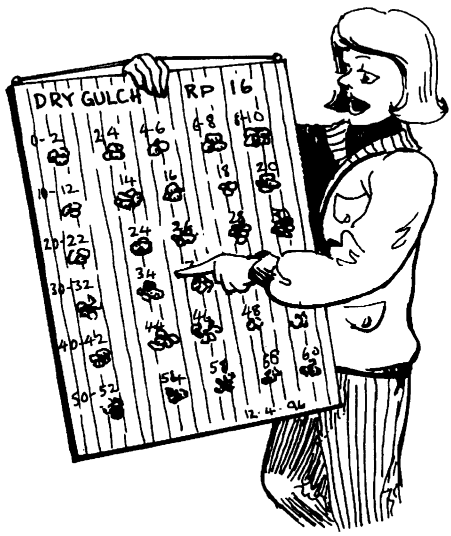


Figure 4.24 Permanent display of washed cuttings. Cuttings from a typical hole or section are glued to a suitably labelled board. The board can then be used as a reference for future logging, to maintain consistency of description between geologists, or for presentations.

Conversely, in some cases, because the hole can locally 'chamber out' below the ground, some intervals drilled will yield more sample volume than would otherwise be expected. Such variations affect the usefulness of the assay for that interval, and while this may not matter too much in reconnaissance drilling, it is obviously a serious problem in drilling out any mineralization. In detailed drilling, where sample loss (or gain) is suspected, the total material from each metre of advance should be routinely weighed and the weight recorded on the log form. Assays from intervals with significant sample loss or gain from the standard will obviously need to be treated with caution.

Cuttings from a metre interval will weigh 25–50 kg. A representative split of the cuttings will therefore have to be made to provide a sample for assay. Two methods of collecting this sample are commonly used:

1. *Pipe sampling* The bag of cuttings is thoroughly mixed by rolling and agitating the bag. Sampling from the bag is done with a plastic pipe approximately 80 cm long, an internal diameter of around 6 cm and cut at an angle at one end. With the bag on its side, the pipe is inserted lengthways and rotated as it is pushed in (take care not to punch a hole in the bag!). Three pipe samples are collected parallel to the long axis of the bag, and two pipe samples diagonally across the bag. The five pipe samples are then combined to form the combined sample to be sent for assay. After collecting the combined sample, the pipe is thoroughly cleaned, both inside and outside, with a rag.
2. *Splitting* Riffle splitters, such as that illustrated in Figure 4.25, provide probably the most effective split of a sample but the procedure is more laborious and time consuming than the pipe sampling described above. Effectively cleaning a multi-stage riffle splitter between each sample can also be a tedious process, especially if the sample is damp. However, for accurate sampling within a mineralized zone, especially in gold prospects where nugget problems are suspected, using a riffle splitter should be considered.[1]

For effective quantification of error both in sampling and laboratory, the routine use of duplicate and standard samples is recommended. It is good practice to include at least one duplicate and one standard sample (i.e. one whose metal content is known within a certain specified range – such samples with various assay ranges for different elements can be purchased commercially) in every batch of 20 samples sent to the laboratory.

4.3.5 SAMPLING BELOW THE WATER TABLE

An RC rig can provide a useful sample from below the water table, provided the water flow is not too high. However, some contamination of

[1] Some drilling companies now provide a multi-stage splitter attached directly to the cyclone which produces a 1/8–7/8 split for assay sample and retained cuttings. These splitters are designed to be quickly and simply cleaned by a built-in vibrator and compressed air hose. They offer quick convenient sampling, but need to be checked constantly for the effectiveness of the cleaning process.

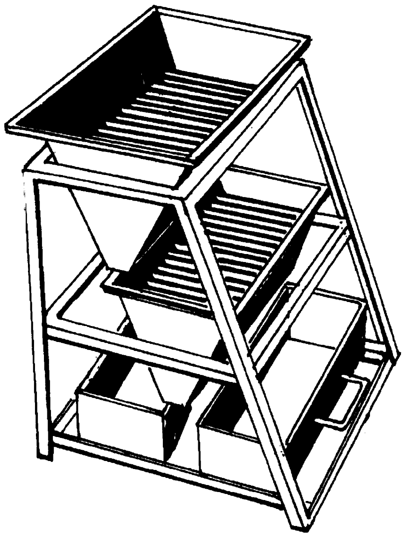


Figure 4.25 A two-stage riffle splitter of the type commonly used to split a sample for assay from rotary percussion drill cuttings. This model produces a 3:1 split.

the sample is inevitable, and for this reason RC drilling should not be considered in these conditions when detailed drilling is being undertaken to establish ore reserves.

For drilling below the water table, it is necessary to use a large rig with high air pressure, a sealed hole and a face-sampling bit. The recovered sample will be wet and so generally cannot immediately be split for assay. It is recommended that the sample be collected in a large calico or polyweave bag (say 80 × 50 cm) which is left open. In three or four days of dry weather, most of the water will have evaporated through the weave and pipe sampling can then be carried out as described above. If large amounts of water are present, it may be necessary to collect the wet slurry sample into large plastic buckets (garbage bins have been used) and allow it to settle. The settling of fine material can be speeded up by the use of a flocculant. This procedure is undoubtedly tedious but, as the only other alternative is diamond drilling, it may be worth considering in some cases.

For assessment of mineralization below the water table, the appropriate technique is to use diamond drilling, particularly diamond tails on the end of the RC holes.

4.4 ROTARY AIR BLAST (RAB) DRILLING

4.4.1 DRILLING TECHNIQUE

To obtain high-quality geochemical samples with as little environmental disturbance as possible, it is recommended that the following basic procedures be followed:

- Holes should be drilled using a cyclone for collection of the samples, as described for RC drilling.
- The driller should ensure that the air pressure used is just sufficient to lift the cuttings from the hole and not blow them into the air.
- The air used can be moistened to reduce the dust levels.
- The driller should clear the cuttings from the drill stem between samples and on each rod change by means of a blow-back.
- All holes should be capped on completion. Plastic seals, which can be inserted into the hole to retain a plug of earth which is tamped down on top of them, are available commercially.

4.4.2 GEOLOGICAL LOGGING

A limited amount of geological information can be obtained from RAB cuttings and they should be routinely logged. Because of the speed with which drilling can sometimes take place (over 1000 m a day is not uncommon when drilling shallow, close-spaced holes), detailed logging is often not possible. However, it is important to record the weathering profile down each hole so as to understand the significance of the geochemical results, and a bedrock lithology identification helps build up a subsurface geological map. A description of the vertical profile through the regolith section and a bottom-of-hole bedrock lithology descriptor should therefore, as a minimum, be made routinely for each hole.

As with other types of drilling, the geologist should attempt to keep up with the drill rig in his or her logging, and although there may not always be enough time to plot results on to a map or section as drilling proceeds, it is still important to be aware of the geology being defined by the drilling as it proceeds. In some cases this may lead to a decision to modify the planned programme or to ideas being generated which will lead to particular features being sought in the cuttings.

Recording the observations is similar to RC drill logging. The log sheet is drawn up in to rows representing the metre advances, and columns for each attribute which it is desired to record. When describing vertical profiles through the regolith, the colour, grain size and texture of the cuttings are important descriptors. Make use of Munsell soil colour charts[1] for scientifically defined colour words, and avoid such subjective terms as 'chocolate brown', 'brick red', etc.

Many of the attributes of the cuttings can be recorded by a system of abbreviations, or by code numbers and letters. The identification of the rock chip – if one can be made – should be kept for a separate entry on the log.

The rows and columns of the log sheet represent a spread-sheet and can be created on standard spread-sheet software. The logging can then be done directly into a suitably protected notebook or palm-top computer at the drill site. Data can be entered by key-stroke or by using a bar-code reader (section 4.3.2). When convenient, the data can then be downloaded to a larger PC for storage, processing or plotting with one of the many exploration data software packages that are available.

The bottom-of-hole washed sample should be stored in plastic cuttings boxes (Figure 4.22). As described in the section on RC drilling, display of representative cuttings from a hole either on plastic sheets laid on the ground beside the hole (Figure 4.23), or by gluing to a cuttings board (Figure 4.24), can greatly facilitate establishing correlations between holes. More detailed logging of the cuttings can subsequently be made from the stored sample if necessary.

[1] Munsell soil and rock charts are a commercial system for objective, repeatable scientific colour description in terms of three attributes – value (lightness), hue (colour) and chroma (strength). The charts allow matching the sample to a series of colours covering the range of normal soils and rocks.

4.4.3 SAMPLING

In the past, a common method of sampling was to grab sample the cuttings from the hole where it intersected bedrock. The danger of this procedure was that the bottom-of-hole sample could have come from a zone of metal depletion. However, sampling every drilled interval can often be prohibitively expensive. For reconnaissance drilling of gold prospects in weathered terrain, it is therefore recommended that the entire drill hole be sampled by means of composite sampling. Composite sampling takes advantage of the ability of modern assay methods to detect very low levels of gold, and the enhanced concentrations of gold and related indicator elements which can occur in different parts of the weathering profile.

Composite sampling can be accomplished by means of either grab sampling or pipe sampling.

With grab sampling, cuttings for each advance of the drill (usually 2 m) are placed on the ground and a sample is taken by running a trowel lengthways through the spoil heap. Samples from several spoil heaps constitute the composite sample. The main advantages of this method are that it is quick and relatively cheap and the cuttings can be laid directly on to the ground without bagging. The main disadvantage is that the heaps rapidly coalesce and disperse, especially if subjected to rain, and it can sometimes be difficult or impossible to subsequently carry out a more detailed sampling of the hole. It is also easy when sampling in this manner to contaminate the sample with surface material, and, of course, the reverse can also be true. For environmental reasons it is usually important to ensure that the surface material is not contaminated by the sample.

An alternative method is to bag all the cuttings for an advance of the drill, and to sample the bag using pipe sampling in the manner more fully described under RC drilling (section 4.3.4). In composite sampling of RAB cuttings, one pipe sample is taken diagonally through each bag of spoil. This determines the largest practical size of composite sample – a composited sample from five spoil bags (each representing a 2 m advance) will weigh around 4–5 kg. For this type of composite sampling, it is only necessary to clean the pipe between each composite interval. Pipe sampling is extremely rapid and one experienced field technician can easily keep up with the RAB drill.

Since composite sampling is aimed at detecting low element concentrations in weathered rocks, low detection levels must be specified for assaying the composite sample (in the case of gold at parts per billion level). Any anomalies detected by composite sampling, no matter how low, should be immediately checked by separately resampling each 2 m interval from the plastic bags of stored cuttings or the spoil heaps on the ground.

When using a RAB drill to test known mineralization or a well-defined anomaly, each 2 m advance of the drill through the mineralized zone would normally be bagged and separately sampled and assayed.

For effective quantification of error both in sampling and laboratory, the use of duplicates and standards should be routinely used. It is good practice to include at least one duplicate and one standard sample in every batch of 20 samples sent to the laboratory.

4.5 AUGER DRILLING

Power augers are usually a simple petrol-engine-driven screw auger, with a blade bit at the end, mounted on the back of a small trailer or truck (Figure 4.1). Some small power augers can also be hand held. Machines used in exploration range from simple post-hole diggers to drills designed specifically for mineral exploration. They are capable of drilling a few metres to a few tens of metres into weathered or poorly consolidated material.

Rock and soil cuttings obtained from the screw auger as drilling proceeds spill on to the surface, or into a circular sample collection box placed around the drill collar. The cuttings may be contaminated with material from the hole walls, and it is difficult to know from what exact depth any particular observed geological feature or geochemical sample is derived. The rods can be cleared of cuttings to some extent between each interval by allowing the machine to run for a few minutes before resuming the advance. When the rods are pulled, a bottom sample from around the bit and lowermost auger flight can be collected. These base-of-hole cuttings are usually reasonably uncontaminated and can provide an adequate geochemical sample.

Augers are a useful tool for quickly and cheaply collecting geochemical samples from below shallow overburden, or where some surface contamination is suspected (e.g down-wind from old mine tailings).

Hand augers offer the ultimate in portability and permit taking a sample from the top few metres of unconsolidated surface material. The sample in hand augers is usually collected from a small barrel on the lower flight which is pulled directly out of the ground (Figure 4.1); it is therefore uncontaminated and is a potentially effective geochemical sample. Hand augers work only in soft, poorly consolidated materials and will be stopped immediately by any hard rock or heavy clay.

Hand augers are extensively used as a geochemical tool for collecting C-horizon soil samples from below shallow overburden, particularly in rugged, inaccessible or rain-forest terrain. Even if the C-horizon is too deep to be accessed by hand auger, the tool permits, at the very least, taking a sample of weathered bedrock from below the surface layer of humus and leaf-litter. Hand augers are also extensively used as a reconnaissance tool in heavy-mineral sand exploration.

PITTING, TRENCHING AND STRIPPING 5

5.1 PREAMBLE

Pits and trenches, or to use the old Cornish mining term, costeans, can be a quick, cheap way of obtaining lithological and structural information in areas of shallow cover.

Pitting is usually employed to test shallow, extensive, flat-lying bodies of mineralization. An ideal example of this would be a buried heavy-mineral placer. The main advantage of pitting over a pattern-drill programme on the same deposit is that pits are capable of providing a very large volume sample. Large sample sizes are necessary to overcome problems of variable grade distribution, which are a characteristic feature of such deposits.

Trenches are usually employed to expose steep-dipping bedrock buried below shallow overburden, and are normally dug across the strike of the rocks or mineral zone being tested. Trenches are an excellent adjunct to RAB or RC drilling programmes, where the structural data from trench mapping are needed to complement the lithological information obtained from the drill cuttings.

In some cases, it may be possible to completely strip shallow unconsolidated overburden to expose large areas of bedrock. This is done by bulldozing and/or by sluicing with high-pressure water hoses. The bedrock can then be mapped and sampled in great detail. Since the process is environmentally destructive, and rehabilitation would be expensive, extensive stripping would normally only be attempted when a prospective mineralized zone had been defined, and special sampling/geological problems were present that needed this kind of 100% exposure for their resolution.

Pits and trenches can be dug by bulldozer, by excavator, by back-hoe or even by hand. Excavators and back-hoes are generally much quicker, cheaper and environmentally less damaging than bulldozers, and because of this are nowadays usually the preferred option for costeaning. A large excavator can match a bulldozer in its power to dig rock. Back-hoes are relatively light machines suitable for digging small pits or narrow trenches. Back-hoe trenches are difficult or impossible to enter and back-hoes are really more of a geochemical sampling tool than a geological tool. Continuous trenching machines, which can rapidly cut a narrow (around 20 cm) trench to 1–2 m depth in soft material, have also been used in exploration (and grade-control sampling in soft weathered material of some open cuts) for providing a continuous geochemical sample. These trenches are also generally of little use for anything other than basic lithological mapping. Hand-dug pits and trenches are a valid option in places where power excavation equipment cannot be brought to a remote site, and abundant cheap labour is available.

When digging a trench, an excavator that can dig a trench of at least 1 m width and that is capable of penetrating a minimum of 1 m into recognizable bedrock should be used. It is very hard to observe details of geology on the walls of trenches that are smaller than this.

5.2 SAFETY AND LOGISTICS

When digging a trench, attention to the following points will make subsequent mapping and sampling much safer and more convenient.

- Step back both sides of the top of the trench for one bucket width and to a depth of 50–100 cm as shown in Figure 5.1. This prevents loose unconsolidated surface material from falling into the trench (and on to the head of any geologist below!).

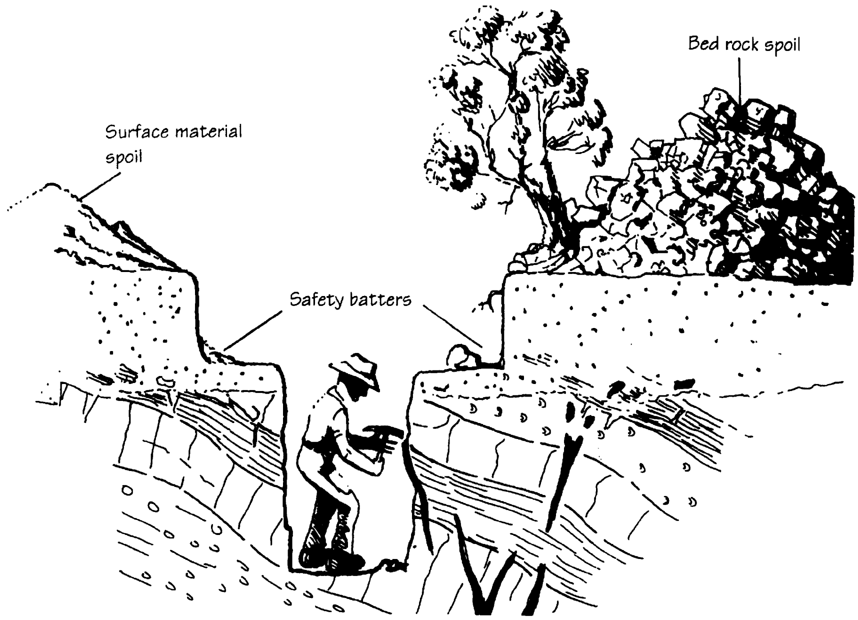


Figure 5.1 The ideal profile of an excavator trench.

- Stack all topsoil and surface superficial material from the trench on one side of the opening; stack all bedrock material to the other side. This facilitates making a quick assessment of the trench material from the spoil heaps and will permit a bulk sample to be taken if required. When re-filling the trench (a normal environmental requirement) the spoil should be replaced in reverse order so that the topsoil is preserved on top.
- If the trench is deep (i.e. cannot be easily climbed into or out of) and more than 50 m long, provide an access ramp at its midpoint.
- Most trench wall collapses take place in the first few hours after digging or else after heavy rain. With deep trenches, it is therefore advisable to leave them for at least 24 hours before entering and not to enter them immediately after rain.
- Never enter a deep trench unless accompanied by another person who should remain outside the trench and be ready to provide assistance if necessary.
- Before entering any trench, but particularly an old one, walk it out along the surface to check for incipient wall cave-ins. If in any doubt, do not enter! There is generally plenty of information to be obtained from the spoil heaps along the trench edge; the walls of old trenches are often covered in grunge anyway and certainly not worth risking one's life for.

5.3 GEOLOGICAL MAPPING

Trenches should be geologically mapped. To make the map, the following procedure has been found useful:

- Drive a peg into the ground at one end of the trench and run a tape measure from there along the trench floor.
- Using the tape, mark and number the wall of the trench with spray paint every 2 m. If the floor of the trench is sloping, a clinometer will have to be used to calculate slope corrections before marking the walls.

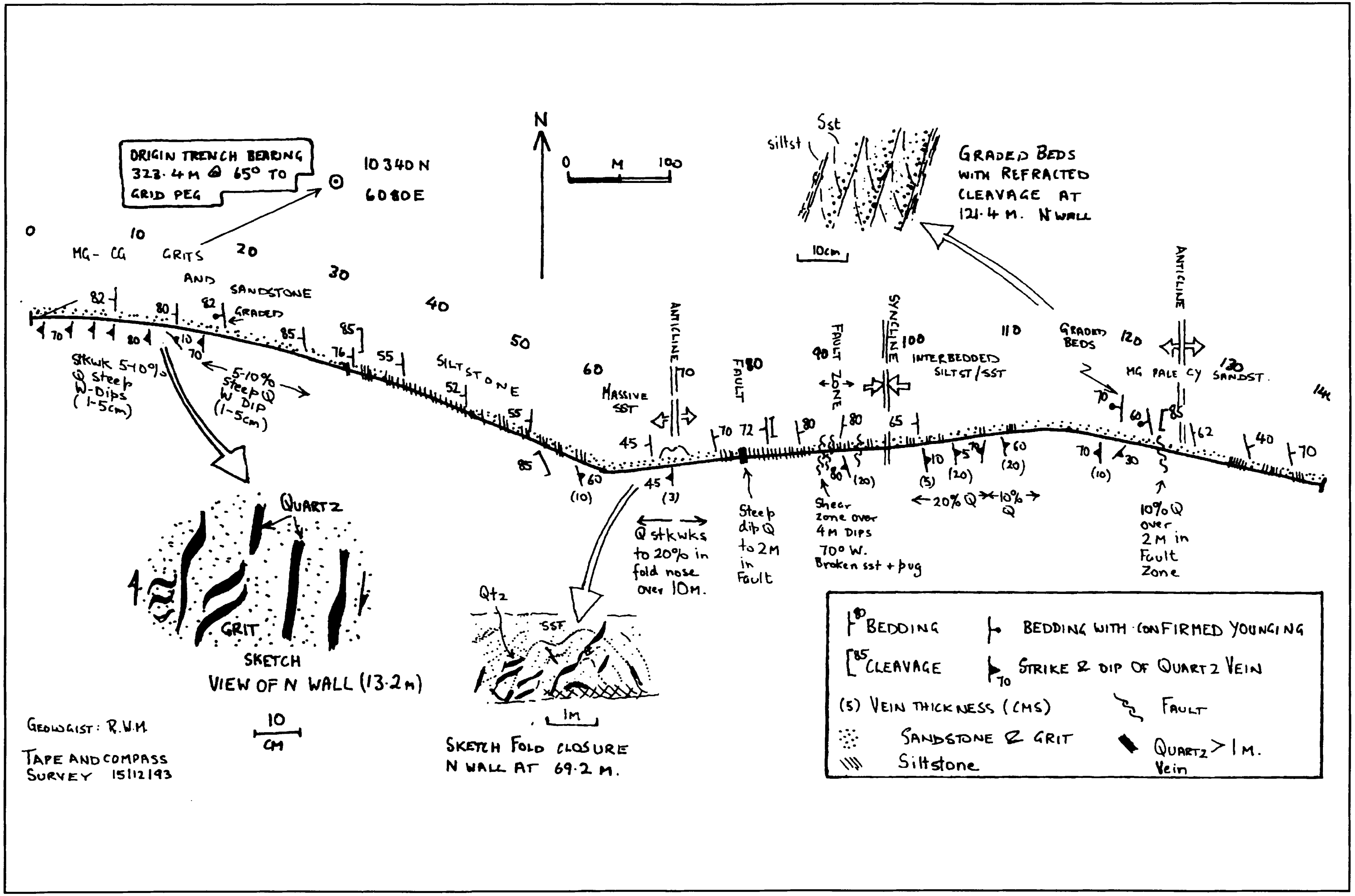


Figure 5.2 An example of 1:500 scale geological mapping of a shallow excavator trench. The trench tests a quartz-hosted gold prospect within steep-dipping and deformed Proterozoic metasediments.

- Scales from 1:50 to 1:500 are appropriate for trench mapping.
- Shallow trenches are best mapped in plan view, with information seen on the walls of the trench projected on to plan (see Figure 5.2). The strike of individual features which traverse the trench can be determined by their position on the two walls.
- Where a good vertical profile can be seen in the trench wall, make a vertical plan of the wall, as well as a horizontal plan (see Figure 5.3).

5.4 GEOCHEMICAL SAMPLING

Sampling a trench for geochemistry involves taking a number of chip channels along it. The procedure for collecting the sample will be described in some detail as it is the same as for sampling any continuous rock exposure such as an outcrop, or the walls of an open-cut or underground mine.

Intervals for sampling should be marked out by the geologist on the exposed rock and can be subsequently collected by a field technician. Sample intervals should be chosen to reflect natural geological boundaries that are considered to be mineralization controls.

Where mineralized features are steep-dipping, the appropriate sample is a horizontal channel along the trench wall (or floor, if that is where the best outcrop is). Where mineralized features are flat-lying, channel samples should be vertical. Where there is no certainty as to the attitude of mineralized zones, a sample consisting of both horizontal and vertical channels, composited over selected horizontal intervals, should be used.

Soft materials can be sampled with a geology hammer or chisel, but there is a danger that the harder bands (such as silicification) might be undersampled, and soft, easily collected material oversampled. In general, a good rock-chip channel sample can only be collected with the help of a jack hammer or rock saw.

Hand-held, electric-powered, diamond saws allow a continuous channel to be cut in the rock. The best technique is to cut out the sample using two angled cuts in the form of a V. Alternatively, two parallel cuts can be made and the rock subsequently broken free with a chisel. Diamond saws produce an excellent sample of even size, but the procedure is slow and expensive, and would only normally be used for sampling mineralized intervals.

Small, electric jack-hammers are available which work off portable petrol generator sets; these are a relatively cheap and quick way of sampling most rocks and are an ideal tool for trench sampling.

A recommended procedure which has been found useful for sampling a trench is as follows:

- Cut a continuous chip channel sample along the trench. The maximum size of the fragments should be around 50 mm. Any overlarge pieces will have to be broken with a hand-held hammer and the over-break discarded.
- Lay a canvas sheet along the bottom of the trench to collect the sample (Figure 5.4).
- The sample volume is hard to control and will usually be too great for easy bagging. It must therefore be split to a smaller representative portion (say 5–10 kg) before it can be sent for assay. If the rock fragments are sufficiently small, this can be done using a riffle splitter. However, operating a splitter in the restricted area of a trench floor can be difficult, and cleaning the splitter between each sample is tedious and time consuming.
- An effective and less labour-intensive way of collecting a split for assay is to homogenize the sample by rolling it once or twice in the canvas tarpaulin on which it was collected, so as to form a long even pile of broken rock. The action is somewhat similar to rolling a cigarette and requires at least two people. A section of lengthways-cut 100–150 mm poly-pipe is then laid alongside the rock pile and by rolling rock and pipe together in the tarpaulin once more the split pipe is filled with a portion of the broken rock pile. The contents of the half poly-pipe section can then be easily slid into a sample bag (Figure 5.5).

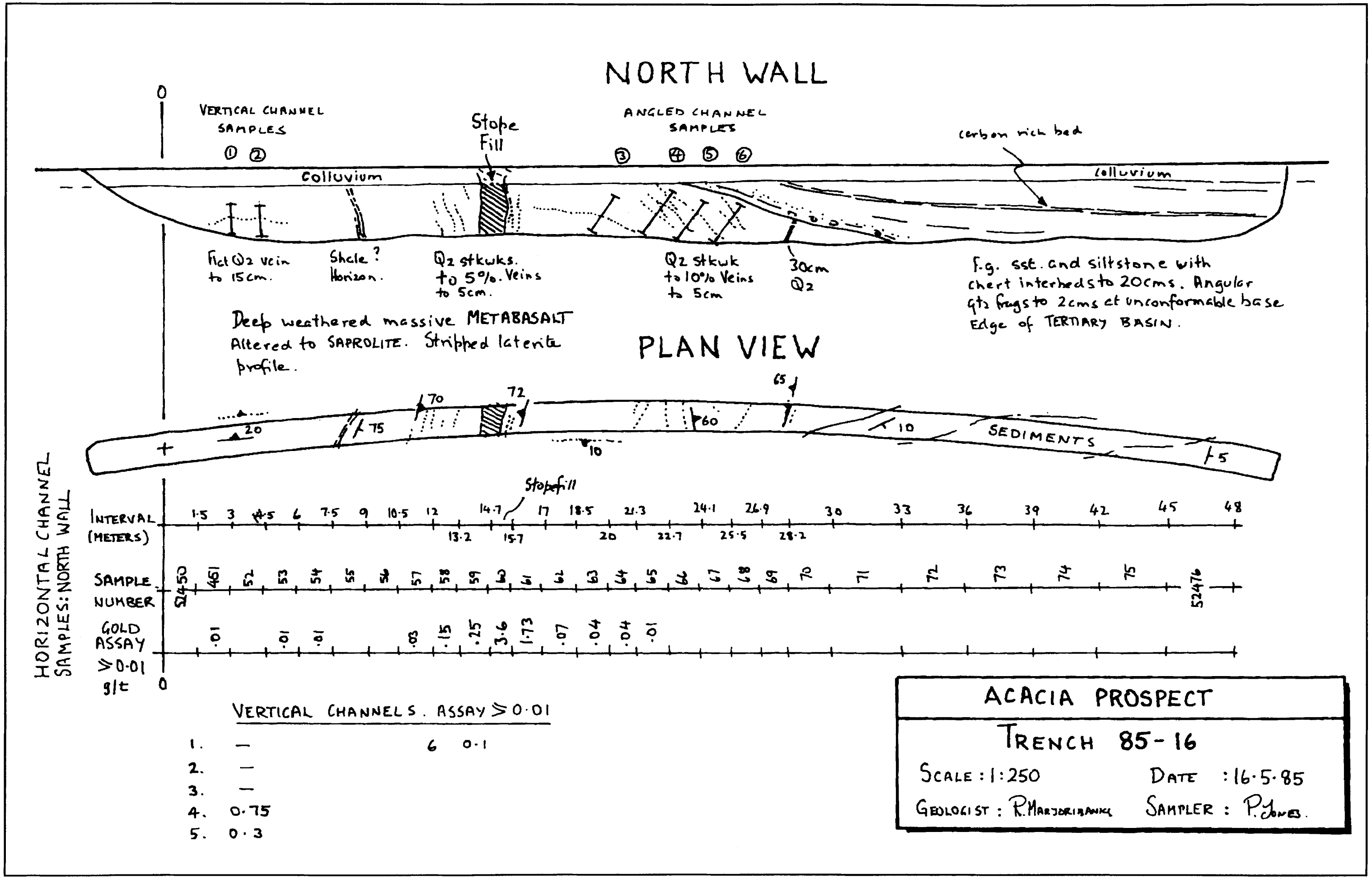


Figure 5.3 An example of 1:250 scale mapping of a relatively deep excavator trench. The trench, dug into deeply weathered Archaean metabasalt overlain by Tertiary lacustrine sediments, tests a surface gold soil anomaly. It unexpectedly encountered some old mine workings.

Figure 5.4 Collecting a continuous rock-chip sample from a trench wall. The sampler is using a small electric jack-hammer powered by a portable generator. The broken rock falls on to a tarpaulin laid along the floor of the trench. The same technique could be used for sampling any hard-rock exposure in the field or in a mine.

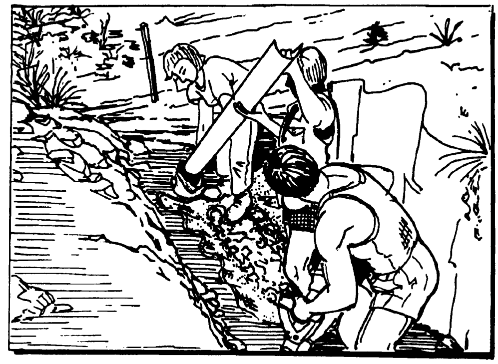


Figure 5.5 Splitting a sample for assay from an even row of small rock fragments on the ground. The rock fragments lie on a tarpaulin; a halved length of 100 mm poly-pipe is laid along the row and rocks and pipe are rolled together in the tarpaulin. Rock in the pipe is then slid into a sample bag.

GEOPHYSICAL AND GEOCHEMICAL METHODS 6

6.1 GENERAL

In prospective areas where outcrop is poor, or that have been subject to intense mineral search over a long period of time ('mature' exploration areas), the explorationist increasingly has to make use of geophysical and geochemical methods in order to extend the search into areas of shallow cover inaccessible to more traditional prospecting methods. Some of these geophysical and geochemical methods also allow for rapid regional appraisal of areas where ground access may be difficult – for example rain-forest terrain or Third World countries with poor infrastructure.

Geophysical and geochemical techniques typically measure objective characteristics that are possessed by all rocks to some degree and result in the collection of large amounts of geographically referenced digital data. Two different kinds of surveys are undertaken: those that are aimed at defining regional geology and those that aim to directly locate ore. In some cases there is an overlap between these two different types.

The first type of survey is a mapping of the areal distribution of a particular rock or soil characteristic – it could be, for example, surface reflectance of electromagnetic radiation, magnetic susceptibility, rock conductivity, copper concentrations in drainage sediments or Ti/Zr ratios in soils. These measurements need not have any immediate or direct relevance to the ore body sought. The data is used in conjunction with bedrock or regolith maps produced by the geologist from direct surface observations in order to produce an interpretation of three-dimensional geology. Geological models are then used to predict where ore might be found and so guide subsequent search. This qualitative process of geological interpretation is best carried out as a joint effort between the specialist geophysicist or geochemist who understands the nature and limitations of the data set and its presentation, and a geologist who would normally possess the best knowledge of the geology of the area and the potential styles and scales of geological and mineralization processes that might have operated within it.

The most important step in the geological interpretation of such surveys (after the technical jobs of ensuring quality of data or purely numerical analyses have been undertaken) is presentation of the data in a form which facilitates their qualitative interpretation. This step normally turns the digital data into a geologist-friendly analog form. Techniques for producing hard-copy analog maps from dense arrays of digital data are described in the next chapter.

The second type of geophysical/geochemical survey is aimed at measuring unusual or atypical features of rocks which directly reflect, and have close spatial relationships to, economic mineralization. Since ore bodies are relatively small features of the earth's crust, such surveys have to be based on detailed, close-spaced measurements and are generally expensive. Ore-targeting surveys are generally undertaken after a prospect, or at least a prospective belt, has been defined. The critical step in analysing the results of such surveys is to select those measurements which can be considered as 'anomalous'. The selected anomalies are then analysed to determine the probable nature, size, position and shape of the causative body as a prelude to a follow-up detailed exploration programme, usually drilling.

Defining 'anomalous' is never easy.[1] If, for example, a level of 20 ppb (parts per billion) gold in a geochemical soil survey is selected as a cut-off number to define anomalism, it would be hard to argue that there is some significant difference between that assay and one of 19 ppb which falls outside the cut-off line. The same problem applies in the analysis of all numerical data sets of this type. Nor can one simply rank numbers according to size – bigger in this case is not necessarily better. A moment's reflection should convince that a small number may reflect a very large source remote from the sample/measuring point, whereas a large number may have come from a relatively small source close to the sample point. Nearness to sampling point is only one of many factors which might enhance or detract from the value of a particular measurement.

This problem can often be partly overcome by looking for natural groupings and patterns within the data set and making the reasonable assumption that such groupings reflect the operation of fundamental geological factors, including mineralization processes. Sometimes the natural breaks like this are apparent by simply eyeballing a print-out of the raw data. More subtle cut-offs in the data or breaks in their trends are often definable by graphical means or by statistical analysis. Many commercially available software programs are available which can highlight these features. These programs are powerful and useful tools which nowadays form an essential part of most analyses of geophysical and geochemical surveys.

In spite of such naturally occurring patterns, if a data set represents an adequate sample of an area, then any realistic first-stage analysis will almost always divide it into at least three groups. In the first group – probably the largest one – are those measurements which are definitely not anomalous. These are the background values and they can be safely ignored, at least as far as the results of that survey are concerned. In the second group – probably a rather small one – are those measurements which are so different from the background that they cannot be ignored and must be explained in some way. Such numbers will generally be confidently labelled as anomalous. The third group is a widely defined category with the distinctly 'fuzzy' label of 'possibles'. It comprises all the remaining measurements which do not fit into the first two categories. They are numbers which are slightly above, or at the upper limit of, background values but could be readily explained by non-mineralizing processes. They could, however, equally well be subtle expressions of ore. Since there will probably be insufficient time and money to exhaustively test all of the measurements of this third 'possibles' group, a decision on which ones to follow up must be made based on other data. These may be the results of other geophysical or geochemical surveys or knowledge of the geology and mineralization of the area.

This is the main reason why no exploration technique should be conducted in isolation. The most powerful exploration programme is normally the one which combines data gathered from several different appropriate geological, geophysical and geochemical surveys. Combining different types of map data can be accomplished by overlaying same-scale maps on a light table but is greatly facilitated by modern geographical information system software (Chapter 7). Ultimately, once all processing and presentation steps have been performed, the key to interpreting the results of geophysical and geochemical surveys is an understanding of the geology and local ore-forming processes of the area.

6.2 A BRIEF OVERVIEW OF TECHNIQUES

This chapter presents a brief description of the role which the most commonly used geophysical and geochemical surveys play in mineral explo-

[1] Real data sets which provide an adequate sampling of the environment, seldom possess sharp natural cut-offs. They typically have a continuous 'fuzzy' distribution. The science of fuzzy logic describes such systems – everything is true to a degree and black and white are merely special cases in a scale of grey. Fuzzy logic is the way brains work, but is incompatible with the either/or bivalent logic of the computer. For this reason, present-day computers cannot be programmed to select all significant anomalous numbers from a data set – only a human expert can attempt to do that.

ration. A detailed description of all the geochemical and geophysical techniques available to the explorationist lies outside the scope of this book. Moreover, since these techniques tend to be technology-driven, operational details can change rapidly, and any such description would become out of date. For more detail on the implementation of these techniques the reader is referred to the references given in Appendix D. However, a more general overview of the nature of geophysical and geochemical exploration serves to illustrate how a balanced, integrated, multi-disciplinary approach to mineral exploration can produce successful results.

6.2.1 SATELLITE IMAGERY

The Landsat satellites of the United States Government and the French SPOT[1] satellite measure and record natural electromagnetic radiation being reflected off the earth's surface. Each measurement averages the reflectance from a ground area of between 100 and 1000 square metres (depending on the satellite). Arrays of receiver elements, and successive passes of the satellite over the surface of the globe, allow a complete world coverage over a period of days. Systems of this type can also be operated from an aircraft and are usually referred to as remote sensing.

The reflected radiation is sampled in a number of selected narrow wavelength 'windows', some of which correspond to wavelengths in the visible light spectrum and some, particularly in the case of the Thematic Mapper instrument on the United States Landsat IV and V satellites, to wavelengths selected to best characterize the reflectance from surface rocks and clays. Similar multi-spectral scanners have also been developed for use from aircraft.

The data are available in digital form on magnetic tape, but are usually purchased from the government agencies as pixel maps or images, at various scales, and with various standard enhancements. If colours corresponding to the visible light spectrum are allocated to appropriate reflectance bands the images look somewhat like colour air photos, and can be used in the same way as photos to interpret large-scale regional geological structure. Such images are called false colour composites. Even where good quality photography is available, satellite imagery can be invaluable to permit a regional overview of a large area.

However, the unique value of satellite or aircraft reflectance data to mineral exploration lies in the fact that many surface materials, including bedrock and regolith units, have characteristic reflectance signatures. Computer analysis of multi-spectral data can thus often define surface geology in a way that no broad-band photography can do. The system works best in arid areas where there is no vegetation cover to obscure the surface rocks and soils. Although this is a promising geophysical technique, both as an aid to regional geology mapping and in direct ore targeting, a limitation on its widespread use is that poorly vegetated arid areas also respond well to other types of exploration techniques, most notably prospecting and regional geochemistry.

6.2.2 MAGNETIC SURVEYS

The instrument used, called a magnetometer, records disturbances in the earth's magnetic field caused by magnetically susceptible rocks. Since all rocks are magnetically susceptible to some degree, a map of magnetic variation can provide an excellent image of lithology distribution – an image which to some extent reflects the three-dimensional distribution of rocks and is not affected by thin superficial cover. Magnetic maps are so generally useful to the explorationist that they are easily the most widely used geophysical technique, both as an invaluable aid in regional mapping and for the direct location of those ore bodies which have a distinct magnetic signature. As an example, airborne magnetic maps played a major role in the discovery of the massive Olympic Dam copper/gold/uranium breccia pipe of South Australia (Reeve *et al.*, 1990).

[1] Satellite Probatoire pour l'Observation de la Terre.

Regional magnetic maps are usually produced by flying the magnetometer at a low level in regular parallel passes over the ground. Aircraft positioning is nowadays controlled by a GPS system. Data are usually recorded digitally and presented as a contour or pixel map (Chapter 7). Flying at lower levels and decreasing the flight-line spacing increases the sensitivity of the survey. Very detailed surveys, comparable in their resolution to ground magnetic surveys, can be carried out by helicopter using a GPS system for positional control.

In ground-magnetic surveying, the sensor head of the magnetometer can be mounted on top of a pole to keep it clear of any near-surface magnetic 'noise'. The operator usually takes readings at stations established on a pegged grid. The station coordinates are either recorded in a notebook or entered into an electronic memory built into the instrument. Modern instruments can be linked to a GPS so that map coordinates are automatically recorded against the magnetic reading. Regular repeat readings at a fixed base station provide data to correct for diurnal drift (with modern systems this step is done automatically when time-coordinated data from a fixed base station magnetometer and a mobile magnetometer are downloaded into a field computer at the end of each day).

Computer processing of the data is normally undertaken to remove diurnal drift or to remove the components of any regional magnetic gradient (the latter is an important correction for regional surveys but can be ignored in detailed local surveys). Various enhancements can be made to magnetic pixel maps as described in Chapter 7.

If the earth's magnetic field was everywhere normal to the surface, the symmetry of magnetic anomalies would reflect only the symmetry of the causative body. A symmetrical body would produce a symmetrical anomaly located directly over it. However, the magnetic field is only normal to the earth's surface at the magnetic poles, and lies at increasingly lower angles to the surface with distance from the poles. This means that magnetic anomalies are all to some degree asymmetric. This asymmetry tends to produce anomalies consisting of a N–S oriented paired magnetic low and high. In the northern hemisphere, the low lies to the north of the high, in the southern hemisphere the opposite holds true. The asymmetry becomes more pronounced the nearer to the equator the survey is conducted. As a result of this, magnetic surveys conducted in low-latitude areas can be almost meaningless unless an appropriate mathematical correction is applied to the data. The correction process converts anomalies to the appearance which they would have if located at the magnetic pole – the process is hence known as 'correction to the pole'.

In developed countries, regional, relatively small-scale magnetic maps are usually flown by the government and are available in digital form or standard map-sheet format (usually as contours) from government survey agencies. Such maps may not be very detailed but generally do provide a comprehensive regional overview. Large exploration groups will often contract to fly their own aeromagnetic surveys over their tenements at increasingly detailed scales. In some established mining camps, geophysical survey companies have flown large areas of detailed magnetic imagery on a speculative basis, and they offer these data (or sub-sets of them) for purchase by explorers.

6.2.3 GRAVITY SURVEYS

Gravity surveys measure lateral changes in the density of subsurface rocks. The instrument used, called a gravimeter, is in effect an extremely sensitive weighing machine. By weighing a standard mass at a series of surface stations, the gravimeter detects minute changes in gravity caused by crustal density differences. Maps of gravity variation can hence be used to map subsurface distribution of rocks and structures, including the anomalous density distributions that might be associated with concealed ore.

To provide usable data, raw gravity measurements need to be corrected. The first correction (for short-term drift in the instrument) is provided by regular reading of a base station in much the same manner as in a magnetic survey. The second correction compensates for the very broad-scale variations in the earth's gravitational field – this correction is only significant in regional surveys. The third correction, much the most important one, corrects for differences in gravity caused by variations in the elevation of the survey station above a datum, usually sea level. To make this correction, stations need to be levelled with great precision – in the case of a very broad regional survey to at least 1 m; in the case of a detailed survey aimed at direct ore location, to correspondingly greater accuracies, down to centimetre scale.

The costs involved in the very accurate surveying necessary for altitude correction has, until recently, generally restricted the use of gravity surveys in mineral exploration to low-density, broad-scale, regional coverage. However, satellite navigation now allows rapid and relatively cheap levelling of stations and has made detailed gravity surveys comparable in cost to that of ground-magnetic surveys.

A good example of the successful use of a gravity survey as an aid in ore discovery is the location of the high-grade Hishikari epithermal gold deposit of Japan (Izawa *et al.*, 1990). Here, a detailed gravity survey was used to define a buried mineralized structure in an area of known mineralization. The key to the successful use of the technique in this case was the high degree of understanding of the local geology and mineralization, which was used in the design and interpretation of the survey.

6.2.4 RADIOMETRIC SURVEYS

These surveys measure the natural radiation of rocks. The data are collected and presented in a similar way to magnetic data. Radiometric measurements are often carried out from a low-flying aircraft at the same time as air-magnetic surveys. Radiometric measurements can also be taken with land-based instruments which can be used at ground stations or lowered down drill holes.

The most abundant naturally occurring radioactive element in the crust is the potassium isotope ^{40}K, largely incorporated into the mineral orthoclase. Of lesser importance as a source of radiation is thorium (found in monazite, an accessory mineral of some granites and pegmatites). The radioactive mineral normally sought by explorers – uranium – is seldom abundant, but at low concentrations can characterize particular rocks such as highly fractionated granites or some black shale sequences. Spectrometers provide selectable channels so that radiation derived from these different sources can be distinguished. Since most natural radiation comes from potassium, maps of total radiation count provide a very effective way of mapping the distribution of alkalic igneous rock and sediment (such as arkoses) derived from these rocks. Monazite weathers from bedrock to form a resistant heavy detrital mineral which often accumulates in watercourses or strand lines. For this reason, these features often stand out on radiometric maps. Maps presenting ratios of radiometric measurements made in different channels, such as U/Th and K/U, can be very useful for discriminating different rock types.

6.2.5 ELECTROMAGNETIC (EM) SURVEYS

Electromagnetic surveys aim to measure the conductivity of rocks, either by making use of naturally occurring electromagnetic fields in the crust, or by applying an external electromagnetic field (the primary field) and inducing a current to flow in conductive rocks below. The primary field is provided by passing an alternating current through a wire or coil, which is either laid out along the ground or mounted in an aircraft flying overhead. The current induced in conductive rocks produces a secondary field. Interference effects between the primary and secondary fields provide a means of locating the conductive rock body.

Since many massive metal sulphide ore bodies are significantly conductive, EM techniques are mostly used as direct ore-targeting tools in the search for this type of deposit.

EM systems work best for ore bodies within 0–200 m of the surface. Although, theoretically, larger primary fields and more widely spaced electrodes can give much deeper penetration, the problems of interpreting the results of EM surveys go up exponentially with increasing depth of penetration.

Ground-based EM techniques are relatively expensive procedures which are applicable to defining drill targets for specific mineralization styles within established prospects or highly prospective belts. EM systems are available which can be used down drill holes to measure the effects of currents flowing between the hole and the ground surface or between adjacent holes. Airborne systems have been used both for direct ore location and for regional geological mapping purposes.

Problems in interpreting EM surveys arise because many host rocks to mineralization can give a similar geophysical response to the mineralization itself. Water-filled fault lines, graphitic shales and magnetite-rich zones all can give spurious conductivity anomalies. Deep weathering or salty groundwater can make EM surveys either unworkable or at least very difficult to interpret. For this reason, EM surveys have had most success in locating ore in those parts of the world where fresh, unoxidized rocks occur close to the surface. These conditions occur, for example, in the recently glaciated areas of North America, northern Europe and Russia. Notable successes where airborne EM techniques have played a major role in discovery include the massive sulphide deposits of Kidd Creek in Canada, Crandon in the United States and Cue River in Australia.

6.2.6 ELECTRICAL SURVEYS

Electrical surveys are all ground based. In their simplest form, they put an electric current directly into the ground and measure, by means of arrays of receivers, the resistance of the rocks through which the current passes. Such surveys are therefore often called resistivity surveys. Current is normally conducted through the ground by the movement of charged ions in pore fluids. Metallic sulphides, which can conduct electric current electronically, can often be detected as zones of anomalously low resistance.

The induced polarization (IP) survey is a special type of electrical survey which utilizes electrochemical effects caused by a current passing through disseminated metal sulphides. The current creates an electro-chemical charge on the boundaries of the sulphide grains where the flow of current changes from ionic to electronic (and vice versa). Such rocks are said to be chargeable. When the primary current is switched off, the decay of this secondary voltage can be detected, and so provides a measurement of the size and position of the chargeable body. Induced polarization is virtually the only geophysical method which is capable of directly detecting concealed, disseminated sulphides in the ground. An example of the successful use of an IP survey is in the discovery of the blind, sediment-hosted, lead/zinc sulphide Gortdrum deposit of Ireland.

Electrical surveys require a generator capable of delivering a high voltage and electrodes placed directly into the ground to transmit the input current. Arrays of receivers laid along the ground measure resistivity or chargeability. The surveys are relatively expensive and labour-intensive techniques. They are therefore used as direct ore-targeting tools in established prospects where the presence of metallic sulphide ore is suspected.

Problems in using electrical surveys can be caused by the short-circuiting effects on the input current which can be caused by salty near-surface groundwater in deeply weathered terrain. Problems in interpretation result from the fact that many zones within rocks, other than bodies of massive or disseminated sulphides, have low electrical resistance or are chargeable.

Electrical methods, as with electromagnetic methods, work best in the upper few hundred metres of the surface in areas where recent uplift and erosion, or glaciation, has produced fresh unweathered rocks relatively close to the surface.

6.2.7 STREAM SEDIMENT SAMPLING

Active sediments in the channels of streams and rivers can contain low levels of metals derived from weathering of mineralized rocks within the upstream catchment. This simple fact is the basis for stream sediment sampling – one of the most widely used methods in regional geochemical prospecting. The technique has played a major part in the discovery of many ore bodies, a good example being the discovery of the Panguna porphyry copper/gold deposit on Bougainville Island, Papua New Guinea (Baumer and Fraser, 1975).

For the technique to work with maximum effectiveness, ideally the following conditions should be met:

- The area should be one of active erosion with an incised drainage pattern.
- The ideal sample point is on a primary drainage with a relatively small upstream catchment. Even very large anomalies are rapidly diluted in secondary or tertiary streams.
- Only the active sediment on the stream bed should be sampled. Bank material may be locally derived and not representative of the whole catchment.
- In the absence of an orientation survey to define the ideal sample size fraction, the silt fraction of the stream sediment (usually specified as minus 80 mesh size) should be collected. In fast-flowing streams a large volume of sediment may have to be sieved in order to collect a sample of suitable weight for assay (at least 50 g but preferably 100 g is needed). Sieving therefore has to be done at site.
- As much detail as possible about the sample site should be recorded. As a minimum this will include the following information: stream width and flow, nature of the coarse float and nature of any outcrop present. This information will be invaluable when the assay results are later analysed and potential anomalous values selected for follow-up.
- Follow-up of anomalies will usually take the form of stream sediment sampling upstream, along the anomalous drainage, to define the point of entry of the anomalous metal to the stream sediment. Further definition of the source can then be carried out by means of soil sampling.

6.2.8 SOIL SAMPLING

This technique relies on the fact that metals derived from the weathering of sub-cropping ore often form a wide, near-surface dispersion halo around, or adjacent to, the deposit. With the ability of chemical analysis to detect very low element abundance, a regularly spaced sampling grid can thus locate the surface 'footprint' of the ore body.

As a relatively expensive technique, soil sampling is typically employed in the detailed exploration of prospective mineral belts or established prospects, where it is used to define specific targets for follow-up drill testing. A good recent example of the successful use of the method is the discovery of the Century sediment-hosted zinc deposit in the Mount Isa District of Queensland, Australia.

The sample collected for assay is usually the fine silty or clayey surface material which results from weathering of the underlying bedrock. The sample is normally taken from just below the organic surface grass-roots layer. A small pick or mattock is used for this job, but in some areas (such as rain forest) a hand auger may be needed to obtain the sample. Significant anomalies may be of the target metal or of elements which are known to be associated with the style of mineralization sought.

Not all soils are simple *in situ* residual accumulations of weathered bedrock. They may, for example, have been transported for some distance laterally from their source by the action of gravity, wind or rain. The soils may be part of a landscape with a long history of evolution. That history might have involved variable water tables and cycles of chemical enrichment and depletion. To adequately interpret the results of a soil survey it is therefore essential to have an understanding of the regolith of which they are a part. Complex regoliths need to be geologically mapped and interpreted prior to planning a soil geochemistry survey, in order to define those areas suitable for this type of sampling.

6.2.9 HEAVY MINERAL CONCENTRATE SAMPLING

Panning stream sediments to extract any heavy mineral component is an ancient, but still very relevant and effective, geochemical prospecting technique. The heavy mineral concentrate (HMC) can be examined at the collection site to identify and quantify its mineral content (e.g. number of grains of gold). If required, the concentrate can then be bagged for subsequent assay. Positive results from on-site examination can be immediately followed up with upstream sampling until the source of the anomaly is located.

Heavy mineral sampling is widely employed to locate native elements such as gold, platinum, diamonds and heavy resistant mineral grains such as magnetite, zirconium, ilmenite, rutile, monazite and cassiterite. Heavy mineral identification is also a widely used technique in the search for the indicator minerals of kimberlite pipes. Skill in producing a panned concentrate sample is a very useful one for an explorationist to acquire.

6.2.10 LATERITE SAMPLING

In complex weathering profiles which have developed over a long period of time, metals derived from underlying primary mineralization can concentrate in some horizons and be depleted in others. In the weathering process which produces laterite terrains, a layer characterized by iron accumulation forms at or near the surface: this zone is often one of enrichment in metal. Sampling programmes will seek to focus on this layer.

Where a subsequent cycle of erosion has affected old regolith profiles (a situation that often occurs, for example, in the Archaean Yilgarn Province of Western Australia), the layer of iron enrichment can be stripped away, exposing the underlying leached and metal-depleted zone at surface. Surface sampling of this zone would give no indication of underlying mineralization. The stripped ferruginous gravels (called lag gravels) are resistant rocks and might accumulate down-slope. If they can be recognized and mapped, and their provenance established, ferruginous lag can provide a very useful sampling medium.

The key to devising an effective geochemical sampling programme in laterite terrain is good quality regolith mapping.

GEOGRAPHICAL INFORMATION SYSTEMS 7

7.1 DEFINITION

Geographically referenced data consist of any type of measurement or observation, whether analog or digital, which have a known distribution across the surface of the ground, and hence can be presented as a map. Data of this sort are fundamental to all phases of mineral exploration and involve geological, geophysical and geochemical data along with topographic maps, aerial photographs, remote sensed imagery, mineral occurrence information, land use maps, drill hole location maps and so on. Computer software programs designed to store, manipulate and present geographical data are known as geographical information systems (GIS).

7.2 THE NEED FOR GIS

Understanding the meaning or usefulness of a particular data set often requires that different types of map data need to be compared. This process of integration is one of the fundamental ways in which data can be converted into knowledge. For example, a map of geological observations may need to be combined with geophysical or geochemical maps for the same area in order to produce a geological interpretation. The interpretation may then need to be overlaid on a land use map to check on access details, or on an existing drill holes map to see what previous exploration has been attempted. Integration of different data sets can be done by overlaying different categories of map on a light table, but this technique is obviously limited to maps which are on the same scale and map projection.

The limitation can be overcome by preparing photo-enlargements or reductions of existing maps, or even by re-plotting the data at the required scale. However, as the amount of geographical data gets greater, the sheer mechanical process involved in handling large numbers of hard-copy maps, becomes all but impossible. In most of the major mineral exploration provinces of the world, the problem of efficiently utilizing the huge amount of available exploration data is now acute. GIS can offer a solution to this problem. Much of what a GIS does is simply an automation of what was previously done by hand – the power and value of these systems lies in their ability to handle very large data sets.

Different types of data for the same area are stored by GIS on separate 'layers' with geographical reference coordinates providing the link between information on the different layers. Once in electronic format, the data sets can be enhanced, searched, compared, combined, presented at any scale and printed, as required, to hard copy.

7.3 GIS STORAGE OF MAP DATA

Geographically referenced data are traditionally stored as paper or film maps, or on printed paper files (hard copy). However, many government geological and geodetic mapping agencies now sell their map products directly in digital format on compact disc. Digital map data, such as remote sensing imagery, most geophysical and geochemical measurements, or isolated point data such as hole collar locations, are already in a natural form for electronic storage in computer.

All these data types, whether they represent an original line, area, number, rock type, symbol or whatever, are recorded in the electronic data base against geographical reference coordinates.

Analog data, such as aerial photographs or geological maps, can be converted into digital format for electronic storage and processing in three ways (Figure 7.1). The processes all involve a sampling of the original analog data and their accuracy depends upon the closeness of the sampling points or sampling areas.

7.3.1 DIGITIZED FORMAT

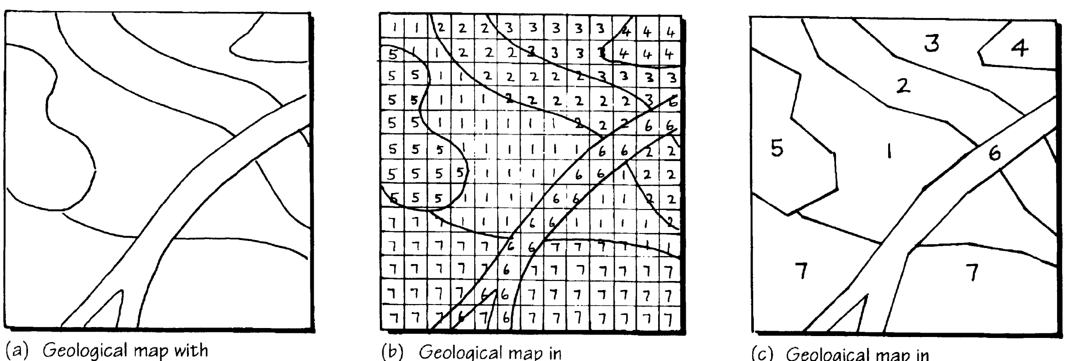
The lines which define the boundaries of the different sub-areas of the map (or photograph) can be defined by the coordinates of a series of closely spaced points along them. This is normally done manually by running an electronic cursor (called a digitizer) along the lines of a hard-copy map, and using a software program to convert the position of the cursor into a sequence of coordinates. The digitized points along a curved line are normally sufficiently close to enable a line, undistinguishable from the original curved line, to be drawn through the points. Automatic scanners are also available which can identify and digitize lines on a map.

7.3.2 POLYGON OR VECTOR FORMAT

A series of points can be manually defined, using a cursor, around the boundary of each area of the map. The software then calculates the position and direction of the straight lines between these points, thus defining a polygon. The information is recorded as vectors lying in the map plane. A vector in the third dimension can then be used to represent the attribute (e.g. sandstone, or colour red, or number 346) which is represented by that polygon. The polygon system characterizes and defines areas, rather than lines.

7.3.3 RASTER FORMAT

A fine grid (usually, but not always rectangular) is laid over the map, and those squares of the grid which have the same attribute are identified. The process can be done manually, but usually a scanning device is used. Where a grid square covers areas with more than one attribute, the largest area is recorded as the



(a) Geological map with digitized linework

(b) Geological map in raster or pixel format

(c) Geological map in polygon or vector format

Figure 7.1 Map (a) shows the lines marking the boundaries between the sub-areas of an original geological map. The lines can be digitized and electronically stored, then reproduced without losing definition. Digitizing lines provides no information about the nature (attributes) of the areas between the lines. In (b), the same geological map has been converted to raster format by overlaying a regular grid. Each cell or pixel of the grid is then characterized by its dominant attribute. In (c), the sub-areas of the map are outlined by a series of polygons. The polygons are defined by a series of vectors between points established along the boundaries of the sub-areas. The vector coordinates lie on the map plane; the third dimension is used to record the attribute of the area. Raster maps, and polygon (or vector) maps, convey information about areas.

attribute for that square. Scanned maps and photographs that are stored and presented on the grid format are known as raster maps. Like the polygon system, raster map information records the attributes of areas of the map.

7.3.4 VALIDATION OF ELECTRONICALLY STORED DATA

Data which have been collected digitally and entered directly into the computer, or read into the computer by some sort of scanning process, are likely to be relatively error free. However, where manual entry of numbers has been involved in producing computerized data bases, errors can be expected. This problem applies particularly to data bases which contain a large amount of historical information which has been typed in from old hard-copy files. Errors such as these in large data bases can be a major problem and are very hard to spot, particularly where the data have been computer-processed in some way before use. Validation of digital data bases is therefore a vital part of any data entry process. There is really no easy way of doing this (at least the author does not know of any). It is best done by comparing a hard-copy print-out of the data, visually scanning for inconsistencies, and carefully, point by point, line by line and area by area, comparing the print-out with the original sources. It can take almost as long as the original data entry, but it is essential that it be done.

7.4 MANIPULATION OF GIS DATA

Once in digital format, GIS software allows the data to be manipulated in a number of ways. Searches can be done for different attributes. Selected ranges of numbers can be highlighted. The position, size and attitude of different map areas can be compared, both within the same layer or between different layers. By selecting the appropriate presentation format, different layers of data can be combined into the one image. The types of data which are often combined in this way are regional geophysical or geochemical surveys with geology; geology or geophysics data with satellite or radar imagery; geology mapping with surface spot heights (the latter in the form of a digital terrain model or DTM). The purpose of such composite images is to facilitate visual recognition of key correlations between the data sets. Finally, the GIS program will be used to select an appropriate image for printing a hard-copy map at an appropriate scale and within selected boundaries.

7.5 PRESENTATION OF GIS DATA

The computer can do a lot of essential processing of digital data but, once this is done, qualitative interpretation requires conversion of the data to map format. Map presentation makes use of the power of the linked eye and brain system to distinguish patterns and spatial relationships in complex data sets.

Geographically referenced data can be thought of as three-dimensional data. The two horizontal dimensions are, of course, the spatial coordinates of the measurement (or attribute), the third dimension is the value of the measurement itself. Map presentation therefore involves putting three-dimensional information on to a two-dimensional plane. GIS can offer various ways of doing this.

Geochemical and geophysical data collected on closely spaced grids or scan lines are traditionally shown as contour maps (Figure 7.2a). Contouring is still a widely used and valuable technique but it can only present a relatively small sample of the data (the numbers selected for the contour intervals). Much of the information contained in a data set is not used by a contouring program and, as a result, subtle features can be smoothed over and lost.

Where the data are collected along regular scan lines (e.g. magnetometer readings, or soil sampling lines), measurements along these lines can be presented as a two-dimensional graph or section. By correctly positioning (stacking) such sections in parallel rows across a map base, all of the measured survey data can be shown and some impression gained of the spatial relationships between successive scan lines (Figure 7.2b).

(a) (b) (c)

Figure 7.2 Representation of three-dimensional data on a two-dimensional plane. These examples are from a low-level aeromagnetic survey. In map (a), the data are shown in contour form. Qualitative interpretation is facilitated but much detailed information has been lost through this form of presentation. In map (b), the magnetic data for the area are shown as a series of stacked sections. All the original magnetic measurements are now preserved, but it is harder for the eye to make spatial correlations. In (c), the magnetic measurements are indicated by a range of tones and map presentation is by pixel format. This system provides an excellent compromise between preserving the original range of magnetic measurements and presentation in a form that facilitates geological interpretation.

Because of their ability to present the full range of the measured attribute, stacked sections are widely used by geophysicists for quantitative interpretation of regularly scanned data. However, the product is still only a set of two-dimensional slices and stacking such sections in parallel rows offers only minimal help to the eye in discerning spatial relationships.

A powerful technique, now being increasingly used, overcomes the problem of three-dimensional map presentation by visually representing each attribute as a point on an infinitely variable[1] colour range or grey tone. The tone or colour is then printed on the map to characterize the area considered to have influenced that measurement (Figure 7.2c). Each area of a single tone is known as a pixel (from picture element). Provided the pixels are sufficiently small (this depends on the scale at which the map is presented and the closeness of the original measurements), such computer-generated images have the appearance of a photographic print and are relatively easy for a geologist to interpret. Original digital data such as satellite and radar imagery, or aeromagnetic surveys, can be presented in analog map format by conversion to a pixel map. Pixel maps are similar to raster maps – the only difference is in the way they are prepared.

Since pixel maps are based on a net of geographically referenced numbers, these numbers can be manipulated mathematically to enhance features of the map in a variety of ways. For example, boundaries between domains can be emphasized (a process known as edge enhancement); a visual impression of the data set as an irregular surface illuminated from any specified direction can be created, greater emphasis on particular ranges of numbers can be produced, and so on. This process is known as image enhancement.

[1] In fact, there is a limit to the range of tonal and colour variation that the human eye can distinguish, but this is still great enough to represent very fine detail.

APPENDIX A
NOTES ON THE USE OF THE GRAPHICAL SCALE DIAMOND CORE LOGGING FORM

Because some explorationists are unfamiliar with graphical logging, this appendix goes into some detail on how to use this style of core logging. The description refers to the particular logging form illustrated in Plate 1. The comments, however, apply to most graphical scale log forms and serve to illustrate the concepts behind this logging.

The amount of detail which can be shown is a function of the scale chosen, not the size of the logging sheet. The form illustrated was designed at A4 size for convenience of use in the field (it has had to be photo-reduced to fit the page size of this book). Some geologists might prefer to work with an original A3 size form. The original of the form is printed on heavy-duty drawing paper to withstand outdoor use and frequent erasing. The labelling of the various columns on the form reflects the type of information which experience suggests should be acquired when drilling many mineralized areas. However, particular projects may require particular types of information to be recorded, and the columns can be re-labelled or re-allocated as found necessary.

If the forms are completed in colour (and this is strongly recommended), some information will be lost unless photocopies are also made in colour.

The form is designed to be used in conjunction with a diamond drill hole summary form (see the example of Figure A.1). This is a single sheet that accompanies the geological log and records summary assay data, summary geological data and survey information.

A very important part of such a summary form is the provision for a statement setting out the purpose and justification of the hole and what it is expected to encounter. To be of any value, this statement should be written down in advance of drilling (see section 4.2.2).

The graphical scale logging form of Plate 1 is divided into columns. In order to describe how to record drill core observations on to the form, the columns will be referred to in numbered order from left to right

COLUMN 1 (Hole depth)
The hole depth in metres is marked off along this column according to the scale chosen. A scale of 1:100 will allow 20 m to be logged per page, a scale of 1:50 will allow 10 m to be logged per page, and so on. It is recommended that the entire hole be logged initially at a semi-detailed scale (1:100 has been found by practice to be a good general scale). If necessary, areas of interest can be separately re-logged at a more detailed scale such as 1:50 or 1:10.

COLUMN 2 (Core recovery)
This column is used to mark the advance of each barrel of core. The percentage recovery from each advance is then recorded in this interval.

COLUMN 3 (Core quality)
This column is provided for recording measurements of core quality such as RQD (see footnote on p. 59 for a definition of RQD). If

XYZ EXPLORATION Pty Ltd

DIAMOND DRILL SUMMARY LOG

Project: Cloncurry Volcanics	**Designed by:** A.C. McGREGOR	**Commenced:** 01/01/93	**Hole No :** DDSC 03
Prospect: SERENDIPITY CREEK	**Logged by:** A.C. McGREGOR	**Finished:** 15/01/93	

PURPOSE

Test continuity of gold mineralistn. 100M North along strike from discovery
hole DD SC 01. TARGET siliceous zone expected at ≈ 80M.
Porphyry @ 40M ; Dolomite 50m ; Sedimentary Bx unit from ≈ 100M.

Planned HOLE depth 150M.
21/12/92 A.C. McGregor.

GEOLOGY

From	To	
0	5 M	Alluvium of Serendipity Creek.
5	40·6	Interbedded siltstone & sandstone
40·6	48·2	Quartz-feldspar-porphyry. BASE OXIDATION @ 46·0 M. (QFP)
48·2	65·1	DOLOMITE. Massive stromatolitic. Cavities to 50cm.
65·1	67·3	BRITTLE FAULT ZONE. Fragments siltst., Qtz., with puggy clay
67·3	87·3	SANDSTONE with siltst interbeds and (minor) Cgl.
87·3	90·4	Silicified QFP. Pyrite blebs to 15%
90·4	95·4	Siltstone, silicified. Qtz stkwks to 40% Asp+py as dissem to 40%
95·4	136·0	Sedimentary Bx. Strong hem + K-spar alt. thro'out.
136·0	151·3	Interbedded siltst. & sandst.

ASSAY

From	To	Au p.p.m.	Au Rpt.	As p.p.m.		Comments
	ALL GOLD	ASSAYS	ABOVE	0·1	LISTED	
86·0	89·4	0·75		5		Visible Au @ 89.86 & 95·38 m
89·4	93·8	24·5	15·8	72		
93·8	95·24	0·85		15		85% Recovery 89·8 - 91·0
95·24	95·65	156·0	123·0	1550		
95·65	100·50	1·02	1·1	73		
	ANSERV	ICE CLON	CURRY LAB	– ASSAY	SHEET	Q 1853
	SAWN	½ CORE	GOLD	FIRE 50g chg.		Detect 0·1
			ARSENIC	AAS		Detect 1 ppm

SURVEY

Collar	Depth	Inclination	Azimuth	Depth	Inclination	Azimuth
Northing: 9500 N	49·3m	63°	078°			
Easting: 8750 E						
R.L.: 575·37m	100·5m	62·5°	080°			
Inclination: 65°						
Azimuth: 075°T (GRD E)	149·6m	61·0°	082°			
End of Hole: 151·3m						

DRILLING

Hole Size	Depth	General Comments : DINKY DI BROS. DRILLERS.
PQ	0-60	LONGYEAR 45 RIG. Core Orient. with Spear every 6m from 50m
HQ	60-150	(80% Success) Water loss in Fault zone at 66m.
		CORE Stored CLONCURRY W/HOUSE 02/93 A.C. McG.

R W Marjoribanks *Geological Methods in Mineral Exploration*

Figure A.1 An example of a diamond drill hole, one-page, summary log form. Besides essential geology, assay and survey information, the form provides a means for the geologist to record in advance the purpose and expected results of the hole.

no RQD is required, the column can be relabelled for some other parameter.

COLUMN 4 (Sample no.)
This column is used to record the identification number of the sample taken for assay. It also enables the geologist to record the intervals chosen for assay as he/she logs the core, and facilitates subsequent transferral of assay information to the form.

COLUMN 5 (Assay results)
These columns are designed so that important assay data relevant to the mineralization can be shown in juxtaposition with other related geological elements. The purpose in putting key assays on to the log sheet is to assist in drawing geological conclusions about the meaning of the data. There is room only to write a few significant assays on to the form: the full assay data for the hole would normally be stored elsewhere in a retrieval system.

COLUMN 6 (Mapping logs)
This is the pictorial log and it provides a map of the core. By dividing the columns as shown, it is possible to provide up to four parallel maps. In this example, these maps are chosen to show lithology, structure, mineralization and alteration (the analogy is with several mapping overlays used on an air photograph). As with any map, the use of colour maximizes the information content. The lithological data on the core map are recorded according to a legend which is drawn up for each drilling project. A copy of this legend should accompany each drill hole log. A number of standard symbols which can be used are shown at the head of the form. Where the geology is not complex, some of these columns (e.g. lithology and structure) can be combined.

The pictorial log does not aim to be a photographic representation of the core. As with any geological map, important contacts should be accurately plotted, but the detail shown is to some extent symbolic. The aim is to preserve in a visual way the characteristic style and relationships seen in the core. Where complex or important relationships need to be shown in a more precise and accurate way, they should be sketched separately in the Geology notes (Column 8) of the log.

At a scale of 1:100 (or less detailed scales) the width of a drill core would be less than 1 mm. In order to provide space to show observations it is therefore necessary to project the structures/lithologies seen in the core for several core widths on either side of the drill line, thus enabling a core map several millimetres wide to be made. By doing this, the horizontal and vertical scales of the core map remain the same and there is no distortion.

Planar structural elements (bedding, lithology contacts, faults, veins, etc.) will usually be shown on the pictorial log in the view that gives the maximum core axis to surface angle. However, a special case exists where the hole is not drilled at right angles to the strike of the major planar structural element (usually the lithological contacts or bedding surfaces) within it. In this case, if the orientation of the core itself is known, it is a good idea to represent the attitude of this dominant structure on the pictorial log as the apparent dip that it would make on the drill section. The apparent dip will always be less than the true dip and can be quickly calculated as logging proceeds either by looking up a table of correction factors or by the use of a stereo-net. Plotting surfaces in this way on the pictorial log and drill section will facilitate correlation of major lithological units and structures between holes on the same section. The true orientation of the surface can then be recorded as a measurement in the Geology notes column.[1]

The centre line of each of the mapping columns is the point at which the down-hole depth of a particular feature is recorded on the form, just as its intersection with the long core axis is the point at which the feature is measured in the core.

[1] For a detailed treatment of how to handle oriented core, see Appendix B.

COLUMN 7 (Histogram logs)
The histogram enables the distribution of quantitative data to be shown as a function of hole depth. The type of measurements shown, and the appropriate horizontal scale are chosen for each project. Percentage sulphide or percentage quartz are common variables which could be recorded. The use of colour will allow more than one variable to be shown. Note that the mapping of the mineralization or alteration will often show considerable detail, and it may not be necessary to try to repeat this in a quantitative way as a very detailed histogram. In most cases, bulking percentage values over intervals of a metre should be sufficient.

Remember, the various columns of the form are meant to complement each other. It is not always necessary to repeat the same data in the different recording formats offered by the log form.

COLUMN 8 (Geology notes)
The geology notes column allows recording of verbal or numerical qualifiers of information shown in the other columns. Information which cannot be otherwise shown is recorded here: for example, rock name, stratigraphic name, rock colour, texture and grain size; structural measurements; percentages of mineral components; precisely measured down-hole depths (note: most depths can be simply read off the vertical scale on the log with sufficient accuracy and do not need to be separately recorded); sketches illustrating complex relationships; and non-observational annotations such as comments, conclusions or predictions.

However, note that it is not necessary to fill in this column (or indeed any column) just because it is there – long runs of unchanging uninformative core should be expected to result in long runs of rather blank-looking log sheets.

What the column is not provided for are extended passages of descriptive prose.

COLUMN 9 (Summary log)
The use of this final column is self-explanatory. It is essentially a simplified summary of the various pictorial log columns. The summary log is for the geologist to use as a quick reference, the draftsperson as a source for plotting the standard section, or the computer operator for his or her data entry.

REMARKS AREA
These lines can be used for any type of information. They have been found useful to record drilling data such as rod sizes, water loss, etc. They can also be used to show the legend for the pictorial log, as in the example of Plate 1.

APPENDIX B
MEASUREMENT OF STRUCTURES IN ORIENTED DRILL CORE

B.1 MECHANICAL ORIENTATION OF DRILL CORE

Where no assumptions can be made about the attitude of structures in core, absolute measurement of these structures can be made only if the core is mechanically oriented by means of a core-orienting device. These tools establish the position of the vertical plane on the rock at the bottom of the hole, before each run is drilled and pulled from the ground. How often this procedure needs to be done depends on the degree of fracturing of the core. If the core is extracted in coherent sticks whose broken ends can be readily fitted together, then a single core orientation mark may serve to orient several runs of core. However, if the core is very broken with fracture zones and core loss, only a small section of the core may be oriented by a single mark. This may not matter much if the structures are simple and fairly constant throughout the hole but, where structure is complex, a large percentage of the core will need to be oriented. The best procedure when drilling blind into a new prospect is to initially attempt orientation of every barrel of core. With experience it may be found possible on subsequent holes to undertake orientation surveys less frequently. Whatever spacing between orientation surveys is finally chosen, any unsuccessful attempt to orient a run of core should be followed up with another attempt on the succeeding run.

Core-orienting tools are based on gravity and only work consistently and effectively for holes with inclinations less than about 75°. The simplest device is illustrated (Figure B.1) and consists of a heavy steel spear that is lowered down the hole on the end of the wire line after the core barrel has been pulled. The spear makes a percussion mark on the lowest point of the top surface of the core stub which is left behind when the drilled core is broken away and pulled from the hole. This surface becomes the top of the next core run: the driller will usually identify this point with a marker pen. Always check the driller's identification. The point of first impact of the spear on the core is the true bottom of the hole. This impact point is often located at the crest of a small wedge-shaped or lunate chip broken from the edge of the core. The position of this fracture on the outer core surface is often identified as the down-hole mark, but this is not always the case since the spear point can slide sideways down the core after impact.

If the core is too hard to take a percussion mark (or too soft), a piece of wax pencil inserted into the end of the spear will usually make a mark. The process is carried out by the driller and takes a few minutes depending on the hole depth. Drillers usually charge for this at their stand-by rate. Consistently achieving an orientation mark takes skill on the part of the driller. The spear should be lowered gently over the last metre or else it can 'chatter' across the surface of the core without producing any clear mark.

Another system depends on making a mould or template of the irregular surface of the core stub. The impression is taken with a device consisting of a number of spring-loaded steel pins

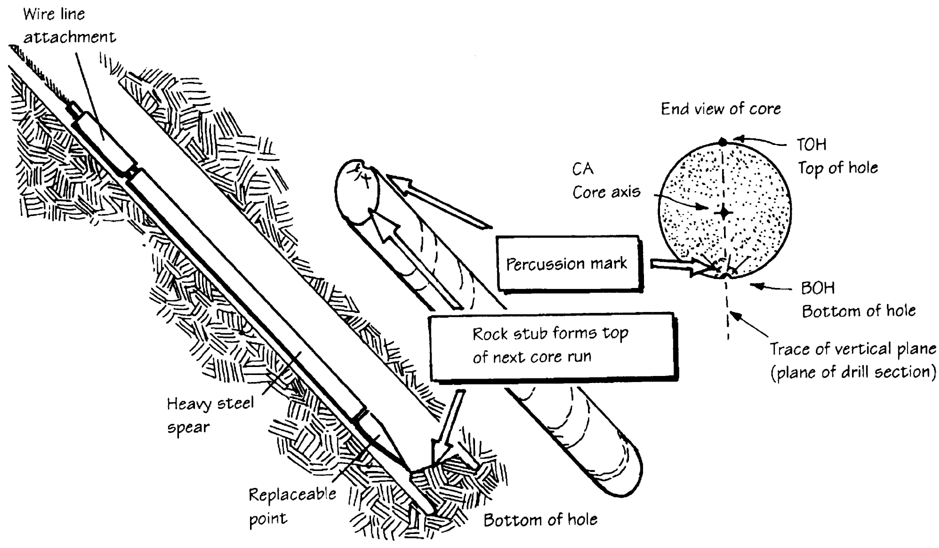


Figure B.1 Mechanical orientation of drill core by means of a spear. The spear descends inside the core barrel, which for simplicity has not been shown in this diagram.

(Figure B.2) that is oriented in the hole by means of a weight. The instrument is lowered on to the top of the core stub and the pins press against the end of the core to record an impression of its shape. Pulling the instrument from the hole locks the pins and weight in place and thus preserves the shape and orientation of the core end. The impression of the steel pins is then subsequently matched with the core end after it has been drilled and pulled from the ground. The system will not work where the end of the core is smooth and normal or close to normal to the core axis.

The bottom-of-hole (BOH) orientation mark established on the end of a core run is used to draw a reference line along the entire length of the run, and along adjacent runs that can be matched to it (see section B.2 for a description of how to do this). The orientation mark represents the bottom of the hole: this point should be transferred to the top surface of the core (TOH). A TOH line is much more useful than a BOH line when viewing structures in the core in the normal way – from above. Transferring the orientation mark to the top surface of the core can be done using a circumferential protractor (see Figure B.10), but transferring the point can generally be done by eye with sufficient accuracy.

The line drawn along the core marks the intersection on the surface of the core of the original

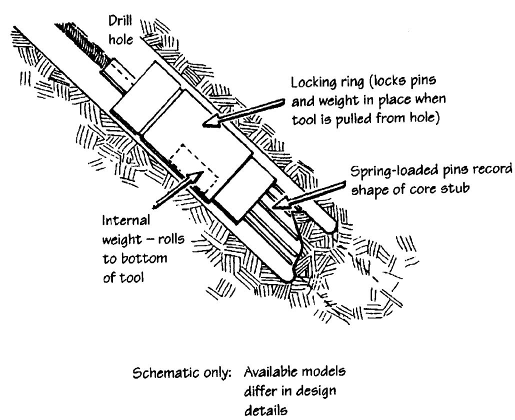


Figure B.2 Mechanical orientation of drill core using a core-end template device. The template tool descends inside the core barrel (for simplicity rods and barrel have been omitted from the diagram).

vertical plane passing through the long core axis: in other words, the plane of the drill section. Since the orientation of this plane at any given depth is known (from down-hole surveys), the marked line can now be used as a reference plane to measure all the structures in the core. How to do this is described below.

B.2 HOW TO HANDLE ORIENTED CORE

Extra handling procedures are necessary for oriented drill core. These are usually the responsibility of an experienced exploration technician. The procedures are:

- Re-assembly of the broken pieces of core going both up and down the hole from the driller's orientation mark. This is a desirable procedure with all core, whether oriented or not, but it is essential for oriented core. The pieces of core are removed from the tray and fitted together on a length of 'V'-section channel. The channel should be at least 3 m long (the length of a standard drill run) and is often made out of metal angle or wood. Two lengths of 50 mm poly-pipe bolted together edge to edge, as shown in Figure B.3, have been found to be excellent for this job. In re-assembling the core, the broken ends are carefully matched to ensure that all pieces are in their original orientation with respect to each other. If the pieces of core cannot be fitted together then material has been lost at that point and no orientation is possible for that run below the core loss point.
- Locating the orientation point on the top surface (TOH) of the core run. This point is diametrically opposite the driller's mark on the lower surface (BOH) of the core. Using a long straight edge and a felt-tipped pen, the trace of the vertical plane on the upper surface of the core is drawn.
  Tip: if the core is assembled in the channel with the TOH orientation mark touching one of its edges, this edge can then be used to guide the line drawn along the length of the re-assembled core (Figure B.3).

Because of minor errors in orienting, re-assembly and marking the core, it is seldom possible to exactly match the orientation lines from two adjacent oriented core runs. However, a large mismatch (greater than 10°) indicates that the processes described above should be carefully repeated. If no faults in the procedure are found, the TOH line should be ignored and that section of core considered unoriented.

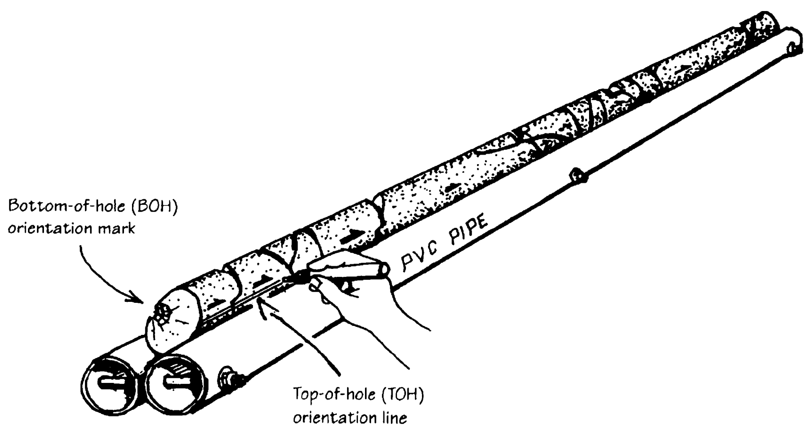


Figure B.3 Marking out oriented core. Broken pieces are removed from core tray and re-assembled, run by run, in a 'V'-section channel. The top-of-hole (TOH) point is located on the end of the core and a TOH line marked along the length of the core, using the channel as a straight edge. Each core piece is marked with a down-hole orientation arrow. The arrows are placed on the half to be retained after sampling.

- Using an ink marker, an arrow pointing down-hole is marked on the core about every 25 cm, but with at least one arrow for each separate piece of core. These arrows serve two purposes. Firstly, they provide a down-hole orientation vector for each piece of core (necessary when the core segment is removed from the tray in order to examine or measure structures). Secondly, during subsequent cutting of the core for assay (see section 4.2.10), they indicate to the sampler which half of the core is to be retained.

B.3 HOW TO MEASURE STRUCTURES IN ORIENTED CORE

B.3.1 GENERAL

Structural observations and measurements should ideally be made on whole core before it is sawn in half.

The trace of a plane such as a bedding plane, shear plane, vein, joint, etc., when intersected by the surface of cylindrical drill core, will appear as an ellipse[1] (Figures 4.2 and B.4). The lower end (when in the ground) of the ellipse axis is labelled E and the upper end labelled E′. If the line E–E′ lies within the vertical reference plane (i.e. E or E′ lies on the reference line drawn along the core), then the hole has been drilled at 90° to the strike of the surface. In this case, the acute angle between the long core axis and the long axis of the intersection ellipse, after a simple correction for the inclination of the hole, is the true dip of the plane. It is only necessary to measure this angle (by using a semi-circular transparent plastic protractor or goniometer held against the core as shown in Figure 4.8), together with the direction of dip, to exactly define the plane. The direction of dip is either the same as the hole azimuth or the reciprocal (180°+) of the azimuth. Which of these two possibilities is most likely is usually easy to determine by inspection.

A penetrative lineation in a rock has a distinctive appearance on the surface of a drill core. The shape of its intersection varies progressively around the cylindrical core surface, depending on whether the surface is parallel or at a high angle to the lineation. This appearance is illustrated in Figure 4.3. Another way in which lineations are commonly seen in core is on a planar surface (such as a cleavage) exposed where the core has broken along that surface (Figures 4.3 and B.7). The lower end of such a lineation is labelled T; the upper end is labelled T′.

In the same manner as described for planes, if a lineation passing through the core axis[2] lies within the vertical reference plane, then its trend is either the same as the hole azimuth or is the reciprocal of the azimuth; its plunge is a simple function of the core to lineation angle and the inclination of the hole. A definition of the terms 'trend' and 'plunge' will be found on Figure C.4.

Apart from these special cases, if drill core is oriented, the attitude of structures seen within it can be determined in one of three ways:

1. By measuring the angles which the structure makes with the reference planes of the core, and obtaining its attitude (relative to horizontal and vertical coordinates) graphically by means of a stereo-net.
2. By measuring the angles which the structure makes with the reference planes of the core, and determining its attitude mathematically by means of manual calculation or computer software.
3. By orienting the core in a core frame and measuring the structure with a geological compass.

At different times, and for different purposes, the explorationist may need to use all of these methods. The procedures, and the indications for their use, will be described in turn.

B.3.2 USING A STEREO-NET

The stereo-net can be used to quickly and simply calculate orientations as the core is being logged. The attitude of the structure can then be recorded directly on to the drill log form. The stereo-net

[1] Except in the special case where the hole is drilled exactly normal to a surface, in which case its trace on the core surface will be circular.

[2] Penetrative lineations which pass through the core axis are the ones with the smallest cross-sectional area on the core surface.

can also be used to calculate apparent dips for direct plotting on to a graphical log form or a drill section.

For the orientation of planes, two angles need to be measured in the core (Figures B.4 and B.5). Some simple instruments that can be used to make these measurements are shown in Figures 4.8, B.9 and B.10. The angles are:

- α (alpha) the acute angle between the core axis and the long axis of the intersection ellipse.
- β (beta) the angle between the bottom-of-hole (BOH) orientation line[1] and the lower end[2] (E) of the long axis of the intersection ellipse. The measurement is made in a clockwise direction (looking down the core axis) around the circumference of the core (called the propeller plane).

For determining the orientation of penetrative lineations, the following angles need to be measured in the core (Figure B.7).

- γ (gamma) the acute angle between the lineation and the long core axis.
- δ (delta) the angle between the BOH line on the core and the lower end (T) of a lineation passing through the core axis measured in a clockwise direction around the core circumference.

An alternative method, useful when the lineation is exposed on a cleavage or bedding surface, is to measure angle δ, plus the orientation of the surface containing the lineation. Since in most cases this surface will be measured anyway, this will often prove to be the quickest and simplest procedure.

If the linear feature is not penetrative (e.g. an elongate boudin or fold axis) then the only simple way to measure its attitude is by means of a core frame as described in Section B.3.4.

[1] To make the measurement, place the 180° mark of your propeller plane protractor on the TOH line marked along the top of the core (Figure B.10).

[2] The lower end of the long axis of the intersection ellipse is the end that was lowest when the core was in the ground. This is labelled E and the upper end labelled E′ (see Figure B.4). Distinguishing E from E′ is easy for original steep-dipping planes (small values of α); planes that were originally near-horizontal may require the core to be physically oriented (by hefting in the hand or using a core frame) to distinguish E from E′.

How to use these angles to calculate the strike and dip of a surface, or the trend and plunge of a lineation, using a stereo-net, is shown on Figures B.6, B.7 and B.8.[3] Since these figures aim to explain the full rationale behind the stereo-net solution, and include all the construction lines, they may at first glance appear quite complicated, especially if the reader is not very familiar with stereo-net constructions. However, in practice, the stereo-net solution is simple and takes less than a minute for each determination. The five-step stereo-net procedure is described below, first for planes and then for lineations.

For Planes

Step 1 Mark a point on to the net overlay to represent the azimuth and inclination of the drill hole at the depth at which the measurements were taken. Label this point CA (for core axis). This point will only have to be plotted once for all the structures measured within that particular surveyed section of the hole.

Time to complete.... 5 seconds

Step 2 Identify the two principal reference planes of the core on the stereo-net. These are:

- The plane of the drill section – i.e. the vertical plane passing through the long core axis. On the net this plane is represented by the straight line which passes through the point CA and the centre of the net.
- The propeller plane (i.e. the plane normal to the core axis) – on the stereo-net this is the great circle girdle at 90° to the point CA.

Locate the point where these two reference planes intersect. This is the point on the line BOH (bottom of hole) from which the angle β was measured on the core.

If necessary, these planes and the point BOH can be marked on to your net overlay. However, with practice this step can be omitted.

Time to complete.... 5 seconds

[3] In this discussion it is assumed that the reader has a basic knowledge of how lines and planes are plotted on a stereo-net. This information can be obtained from any structural geology textbook (see Appendix D).

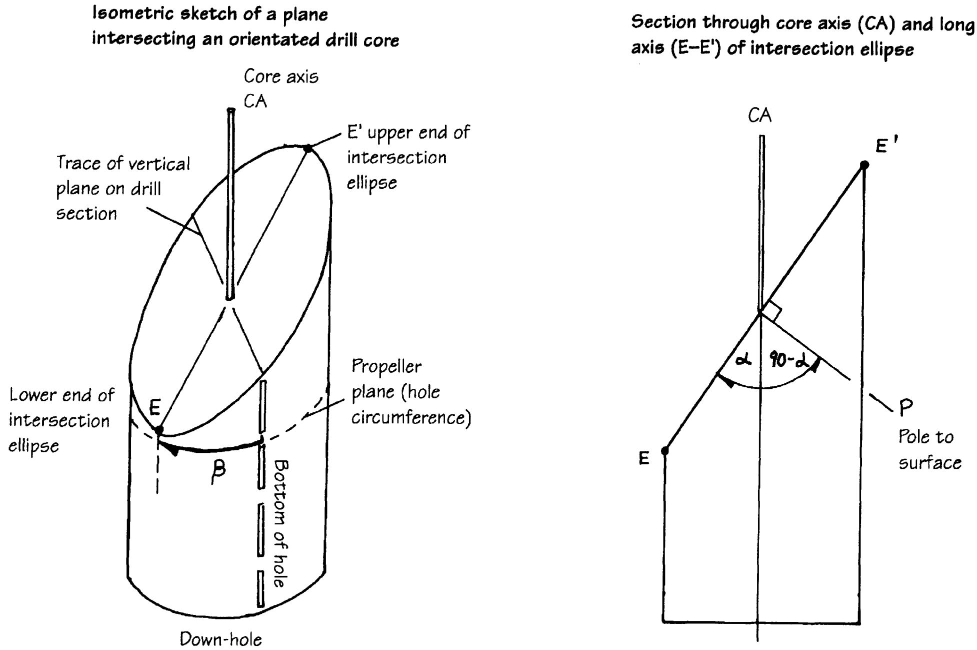


Figure B.4 Measuring the orientation of a planar structure intersected in orientated drill core. Two angles need to be measured: 1. Angle alpha (α), the angle between the long axis of the intersection ellipse (E–E′) and the long core axis (CA). 2. Angle beta (β), the angle between the bottom-of-hole position (BOH) and the lower end of the intersection ellipse (E). Beta is measured in a clockwise direction (looking down-hole) around the circumference or propeller plane of the core. The normal, or pole (P), to the structure lies in the plane containing CA and E–E′, at an angle of 90 – α from CA towards E′.

Step 3 Measure the angle β around the propeller plane in a clockwise direction from the point BOH. If you reach the circumference of the net (β = 90°), continue to count off the degrees from the diametrically opposite point of the great circle. This measurement will locate the point representing the long axis of the intersection ellipse. Mark and label this point (E or E′, see below) on the net overlay.

If the β angle is between 0° and 90° or between 270° and 360°, the point E will appear on the stereo-net. Where the β angle is between 90° and 270°, the point E′ will appear on the stereo-net. If β is exactly 90° or 270°, the points E and E′ will both appear, at opposite sides of the net.

Time to complete.... 10 seconds

Step 4 By rotating the overlay over the stereo-net, locate the great circle girdle which contains the labelled points CA and E (or E′) on your overlay. Only one great circle will be found to pass through the two points – this represents the plane containing the core axis and the long axis of the intersection ellipse.

Measure the angle 90° – α by counting off the degrees along this girdle. Begin the measurement from the marked point CA away from point E. If E′ rather than E appears on the overlay, measure the angle 90° – α in the direction from CA towards the point E′. Once the new point is located, mark and label it P. P is the pole (i.e. the line normal) to the plane that was measured in the drill core.

Time to complete.... 10 seconds

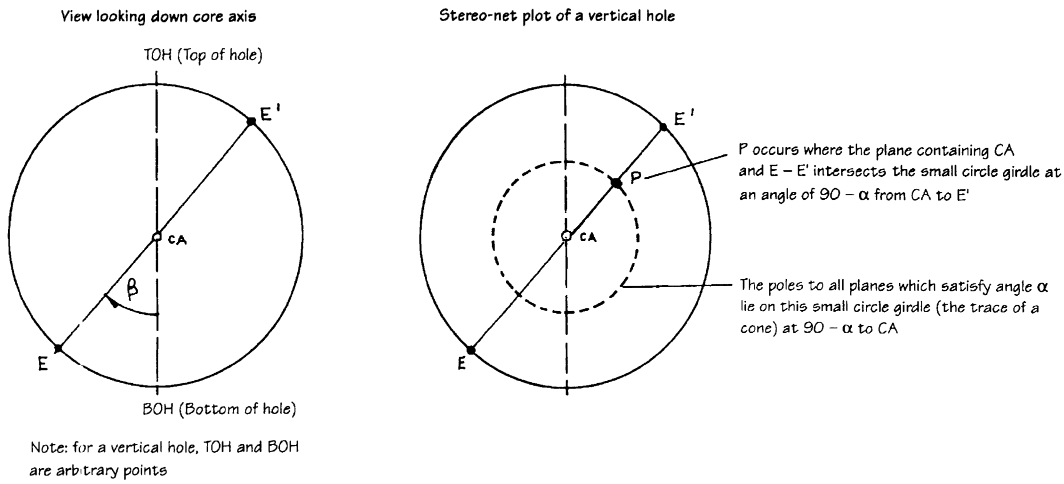


Figure B.5 Using a stereo-net to calculate the orientation of a plane – 1. This figure illustrates the easy-to-visualize case of a vertical hole: the stereo-net plot corresponds to a view down the core axis. Given the measured angles α and β, the construction determines the position of point P, the pole to the plane.

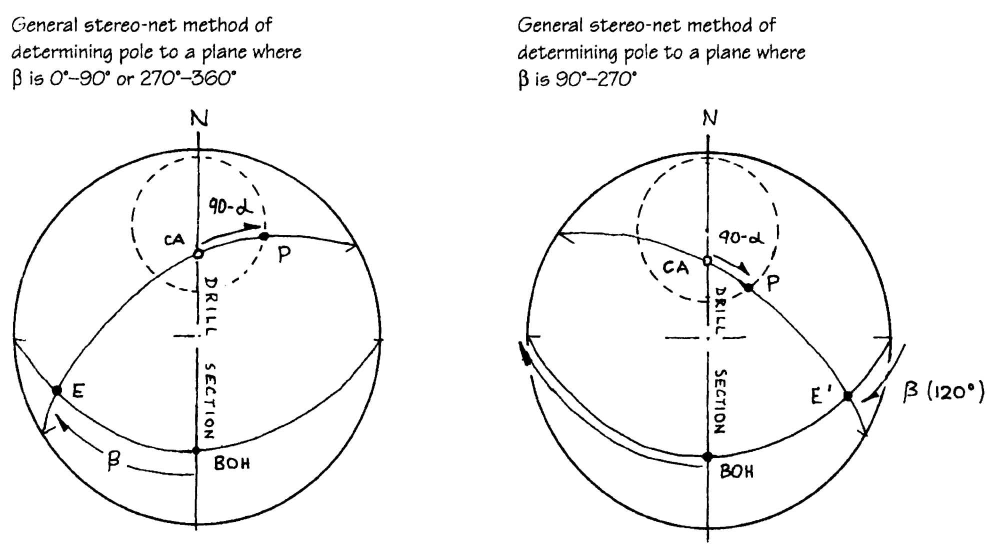


Figure B.6 Using a stereo-net to calculate the orientation of a plane – 2. The figure represents the general case of an inclined drill hole (in this example at 40° to the north). The procedures for determining the position of the pole to the measured plane are the same as in Figure B.5. Note that when angle β lies between 90° and 270°, E' rather than E plots on the stereo-net.

Step 5 From point P, read off the orientation of the measured plane in whatever format is desired. For example as:

strike and dip
dip and dip direction
apparent dip on drill section

Time to complete.... 5–10 seconds

For Lineations

The step by step procedure for determining the trend and plunge of a penetrative lineation is the same as that for a plane as far as Step 3. In Step 3 the measured angle δ is used to plot the point T or T′ in the same way as E or E′ was plotted for a plane. From this point proceed as follows:

Step 4 By rotating the overlay over the stereonet, locate the great circle girdle which contains the labelled points CA and T (or T′) on your overlay. Only one great circle will be found to pass through the two points – this represents the plane containing the core axis and a lineation passing through the core axis. Measure the angle γ by counting off the degrees along this girdle. Begin the measurement from the marked point CA towards point T. If T′ rather than T appears on the overlay, measure the angle γ in the direction from CA away from point T′. Once the new point is located, mark and label it L. L is the plot of the lineation which was measured in the drill core.

Step 5 From L read off as required the trend and plunge of the lineation, or its apparent plunge (known as pitch; see Figure C.4 for a definition of these terms) on the plane of the drill section.

B.3.3 USING MATHEMATICS

Another technique is to calculate mathematically the true orientation of the plane or lineation from the measured drill core angles. If done

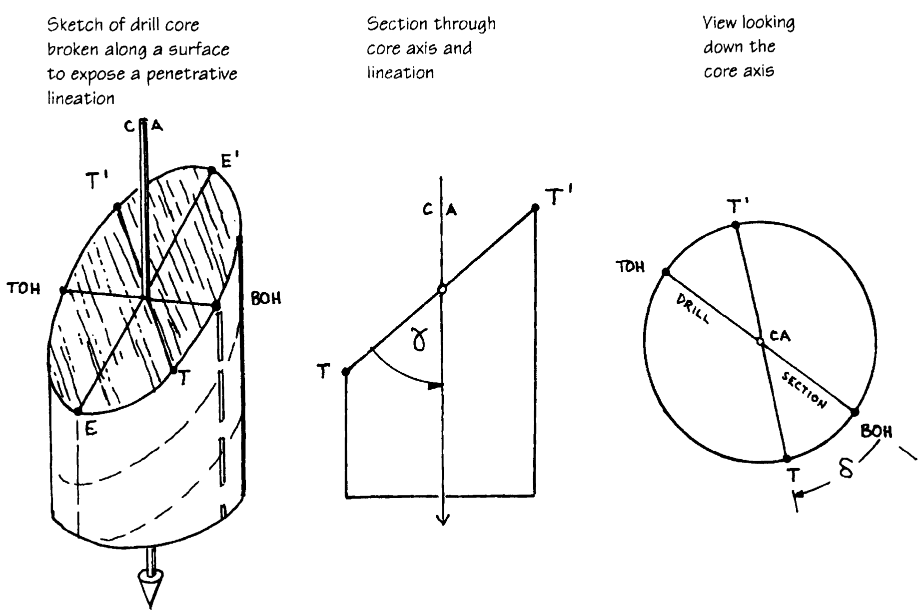


Figure B.7 A penetrative lineation passing through the core axis (CA) intersects the core surface at T–T′, where T is the lower intersection point. The lineation lies on a planar surface that is defined by the long axis of the intersection ellipse, E–E′. To determine the orientation of the lineation, two angles need to be measured: 1. Gamma (γ), the angle between the core axis (CA) and the lineation. 2. Delta (δ), the angle between the bottom-of-hole position (BOH) and T. Delta is measured around the circumference of the core (the propeller plane) in a clockwise direction (as viewed looking down the core axis).

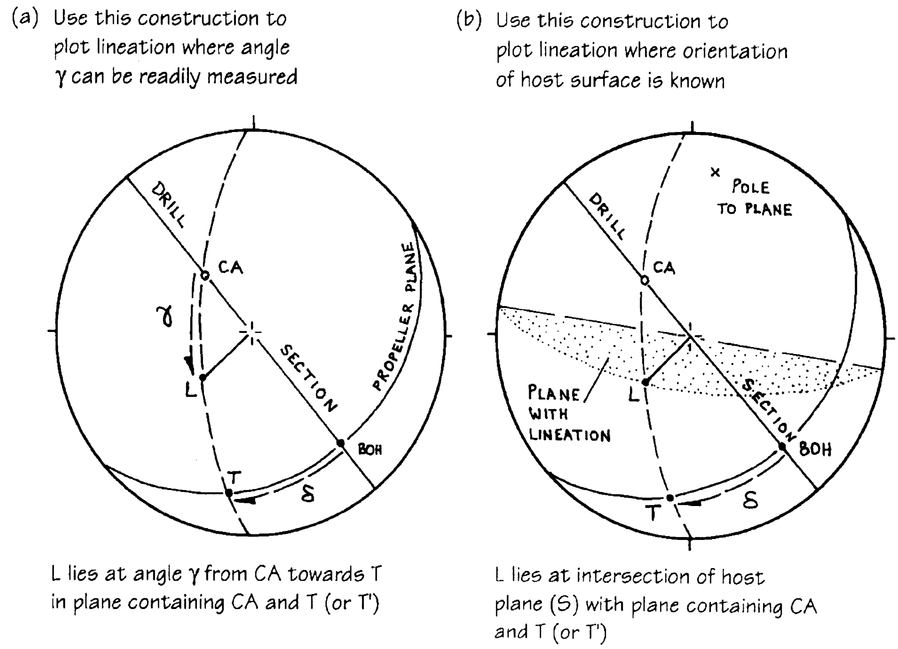


Figure B.8 Using a stereo-net to determine the orientation of a penetrative lineation. Two alternative procedures are illustrated; in the first (B.8a), the angles γ and δ are known; in the second (B.8b), the angle γ is known plus the orientation of a plane within which the lineation lies. In this example, CA is 60° to 320°; δ is 45°; γ is 40°; L is 63° to 234° and the host surface (S) dips 68° to 190°.

manually, this is a non-trivial exercise involving spherical trigonometry, but commercially produced software is available that enables these calculations to be done by computer. The computer does digitally what the stereo-net does graphically, and has the advantage over the stereo-net in being quicker and less tedious when large numbers of α and β angles have to be solved all at once. However, for calculating individual orientations as logging proceeds (the recommended procedure) the computer generally cannot compete in speed or convenience with the stereo-net. Plotting data manually has the added advantage of providing the ideal opportunity for validation of the measurements made on the core.

B.3.4 USING A CORE FRAME

Although geologists are encouraged to master the stereo-net technique, some will prefer to measure the oriented core pieces using a core-orienting frame. Although the core frame is slower and less accurate for measuring the attitudes of structures than the other methods, precise accuracy is seldom necessary and the frame enables some structures to be measured which cannot be measured with the other techniques.

The frame can be invaluable for helping to visualize the meaning of the relationships between structures seen in core and in particular for working out vergences (Figure 4.7). Some features such as non-penetrative linear structures can only be readily measured with the aid of a frame. A frame is also sometimes necessary to distinguish the lower from the upper end of a lineation (T from T′), or the lower end of the long axis of an intersection ellipse from the upper end (E from E′), in order to measure angles in core for stereo-net or mathematical solutions. For that reason, a core frame should always be available when core is to be logged.

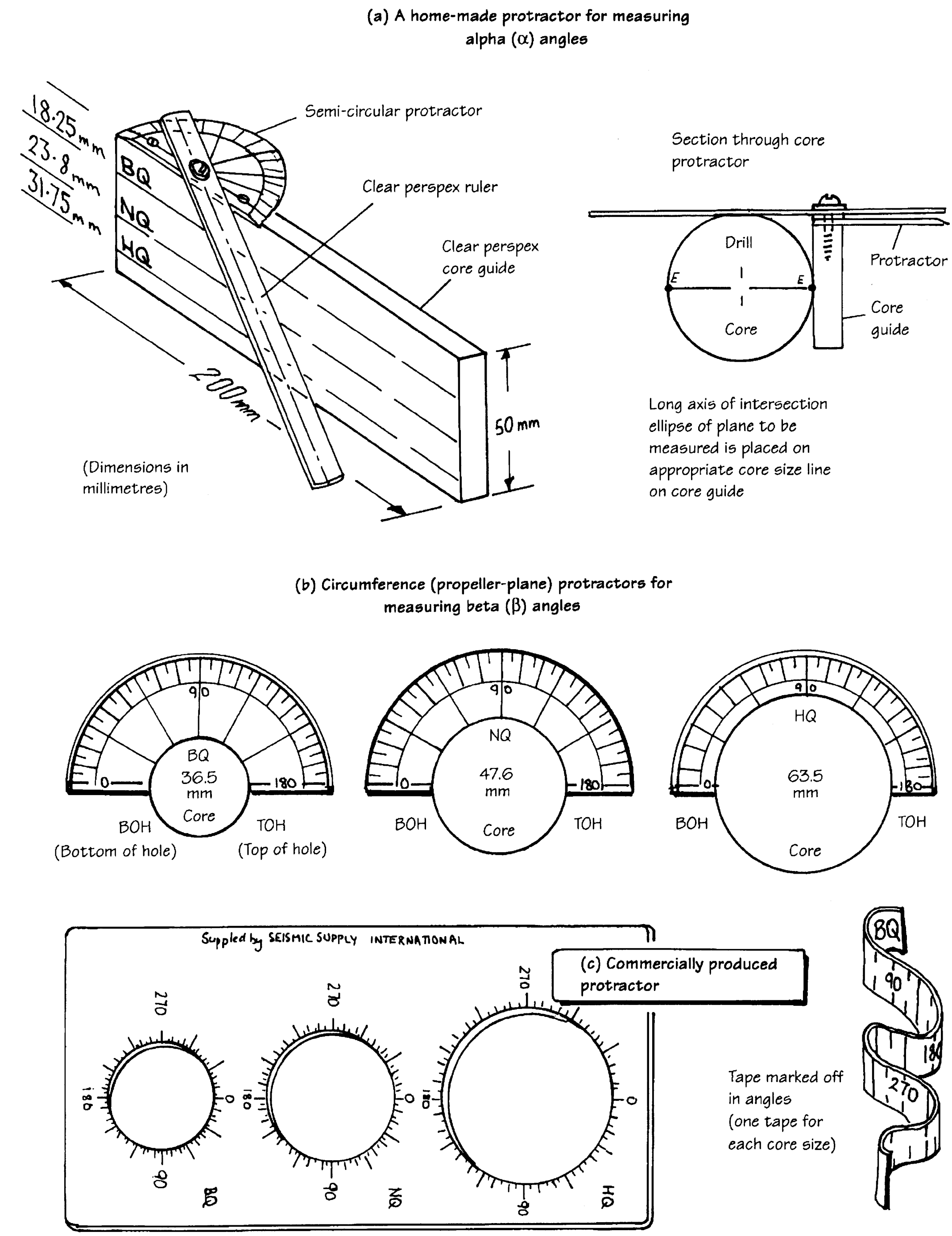


Figure B.9 Some instruments for measuring the attitude of structures in drill core. A simple home-made goniometer such as that illustrated in B.9a greatly facilitates the measurement of α angles. The most efficient circumference goniometers for measuring β angles can be made by cutting standard semi-circular protractors to fit different core sizes (B.9b). Commercially produced circumference protractors are also available (B.9c).

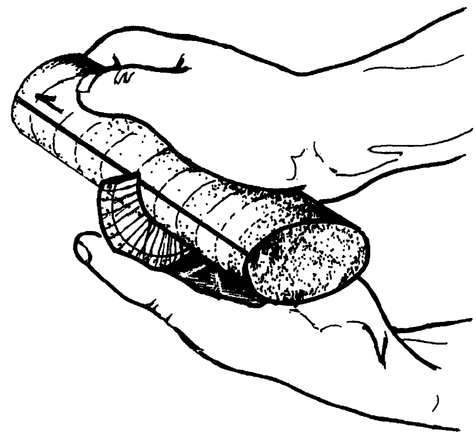


Figure B.10 Using a circumference core protractor to measure a β angle in drill core.

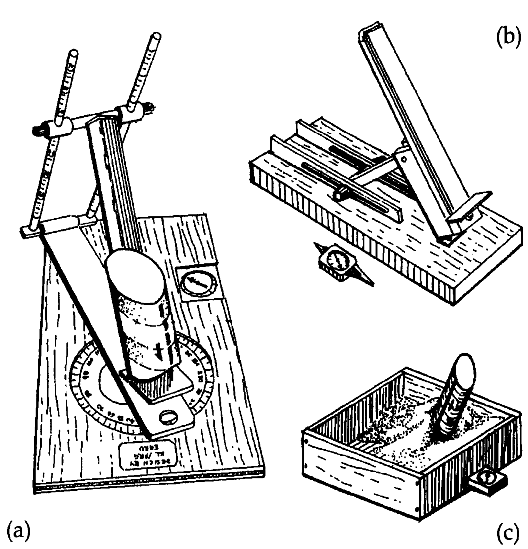


Figure B.11 Examples of core-orienting frames. (a) is a fully featured frame with built-in protractor scales and compass. This model was designed and made by James Cook University of North Queensland. (b) is a home-made frame in wood, designed by the author. It does everything that frame (a) does, but needs to be set using a geologist's compass. (c) is a sand-box – a simple solution, but adequate for measuring planes exposed as the top surface of core (illustrated) or for determining vergences.

With this system, a plane or linear is directly measured with a geologist's compass,[1] after correctly orienting the piece of core in a core-orienting frame or sand-box. Core frames are not easy to find, but a practical basic model, such as that illustrated in Figure B.11b, can be made in wood by anyone with modest workshop skills.

The frame itself is a simple device that enables a piece of core to be set up in exactly the three-dimensional orientation it was in when an integral part of the solid rock. With a piece of core so orientated, it is a relatively simple matter to measure structures within it using a geological compass in exactly the same way that an outcrop would be measured in the field.

For internal surfaces and linear elements that can only be seen as a trace on the surface of the core, it is possible to attach small extension planes or rods to the core with adhesive putty (such as Blu-Tack® or some similar product), and adjust these so that they lie parallel to the internal rock structure (Figure B.12). The extension planes or rods can then be readily measured with a compass and clinometer. Extension planes should be around 60 mm square and can be of any light, non-magnetic material. A piece cut from a disposable plastic food container has been found ideal.

If some dark coloured liquid (such as watered down ink, or food colouring) in a small dropper bottle is kept available, it can be dripped on to the extension plane. The run of liquid down the plane marks the dip direction and so facilitates compass measurement.

Extension rods can be match-sticks, small wooden dowels or brass or aluminium rods. They are attached to the core surface with adhesive putty (one rod is attached to each end of the linear feature to be measured) and oriented by sighting on to the linear from several angles, thus ensuring that the rods lie on a single straight line parallel to the structure (Figure B.12). Since the eye is very efficient at judging the parallelism of lines, extension rods can be positioned very accurately by this technique.

[1] Measurement is probably easiest with a compass that measure dip and dip direction directly, but any geology compass will do.

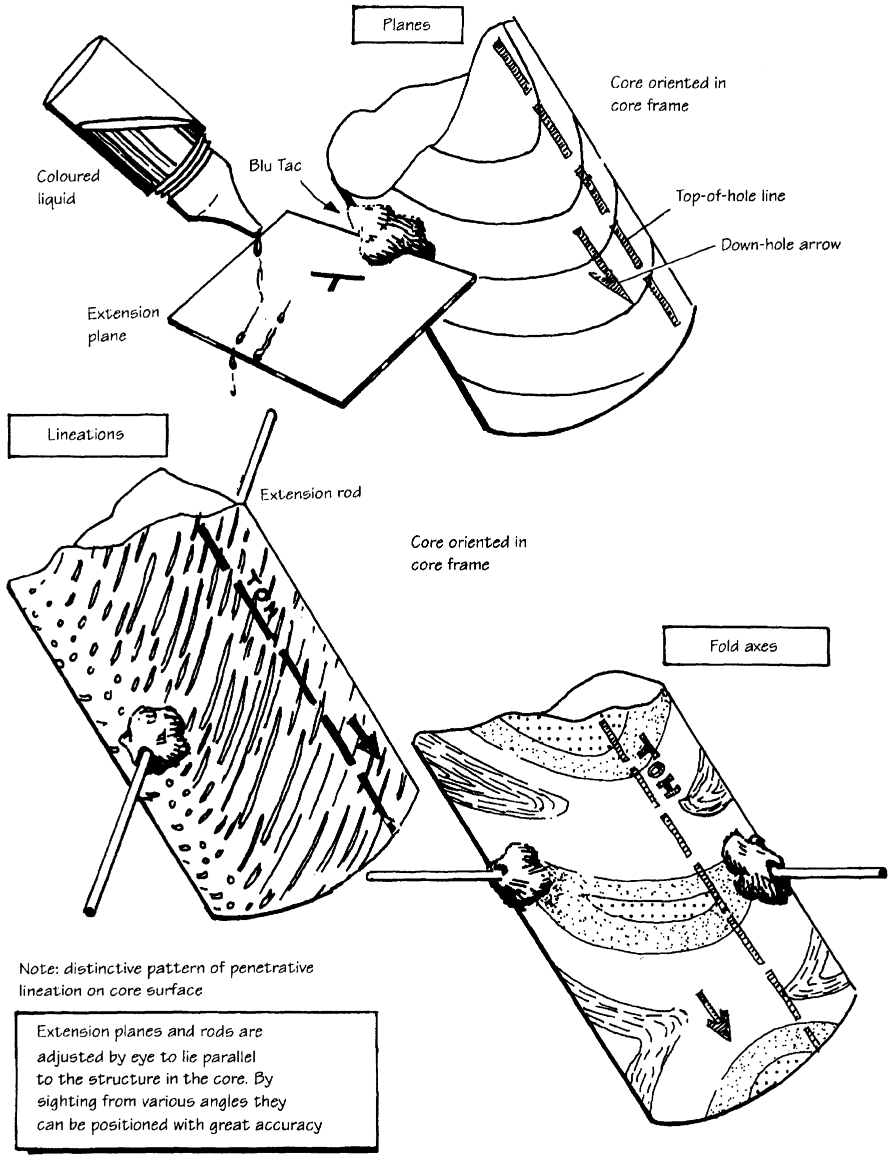


Figure B.12 Using extension planes and rods as an aid to measuring internal planes and linear features of oriented drill core. Measurement is made with a geologist's compass on core pieces set up in a core frame.

APPENDIX C PRACTICAL FIELD TECHNIQUES

C.1 CHOOSING THE RIGHT COMPASS

Great precision is not generally necessary when measuring geological structures in the field and most available geological compasses will do the job adequately. However, when choosing a compass for field work, look for the following features:

- An efficient damping system for the compass needle. An oil-filled compass provides the most efficient type of damping system.
- An adjustable compass card which can be set to compensate for magnetic declination or the orientation of a local grid.
- A compact and lightweight body.
- An ability to take measurements on small or inaccessible surfaces, including underlays. This is an important requirement in mine mapping.
- An ability to take accurate survey bearings.
- Not too expensive.

Needless to say, no single geological compass currently available meets all these requirements. In particular, geological compasses are generally not sufficiently accurate for taking the bearings necessary in surveying. To solve this problem, the author carries two compasses in the field: a relatively cheap general-purpose geological compass (a Brunton® or a Silva®), and a lightweight, compact, specialist compass designed for taking bearings (a Suunto®).

Compass needles rotate so as to line up with the lines of force of the earth's magnetic field. The north-pointing end of the needle thus tends to dip below the horizontal in the northern hemisphere and above the horizontal in the southern hemisphere. Compass makers compensate for this effect by weighting the needle to enable it to lie approximately horizontal in mid-latitude areas. Different compasses are manufactured for northern and southern hemispheres. Compasses designed for the northern hemisphere are difficult to use in the southern hemisphere and vice versa. Mid-latitude compasses work adequately in tropical areas but may need to be tilted slightly to keep the needle swinging freely in the compass case.

C.2 MEASURING THE STRIKE AND DIP OF PLANES

Every geologist knows how to do this, but it may be worth while setting down a few helpful tips.

The most representative strike is obtained by sighting along a line of outcrop thus averaging the strike over that distance (Figure C.1). Be careful, when doing this, to ensure that the line of sight is horizontal (however, any tilt on the compass sufficient to make the strike measurement substantially in error will also trap the compass needle against the face glass and so alert you to the problem).

Similarly, where a dipping bed is exposed on a vertical or near-vertical surface, the most representative dip is obtained by sighting the clinometer on that surface from a distance and so averaging the dip over the area of the outcrop (Figures C.2 and C.3). This technique is only accurate if the sighting is made while looking along strike – otherwise an apparent dip is obtained. An apparent dip is always less than the true dip.

Figure C.1 Sighting with a compass along an outcrop to obtain the averaged strike direction. Caution – the line of sight must be horizontal.

When measuring a plane with a small surface area, the plane can be extended to permit measurement by laying the surface of a notebook or map-board against the surface and then measuring the attitude of the extension plane so formed.

Determining the dip direction of small or awkwardly positioned planes can be difficult. A trickle of water down the surface of the plane can often solve this problem – heroic measures are not necessary here if a small dropper bottle of coloured liquid is kept handy in the field kit.

When measuring orientation on the underside of a plane, particularly when looking up at that plane (a problem that often arises in mine mapping), the use of a Silva® geological compass is invaluable as its compass needle can be sighted from below as well as from above, and the bezel can be rotated to record the position of the needle. For that reason, the Silva® has some advantages over other types of compass for mine mapping. Some specialist geological compasses (such as the Freiberg® geologists' compass or the Cocla™ compass by Breithaupt Kassel®) will also measure on an underlay, but these compasses are larger and often cannot fit into a confined space. They are also much more expensive.

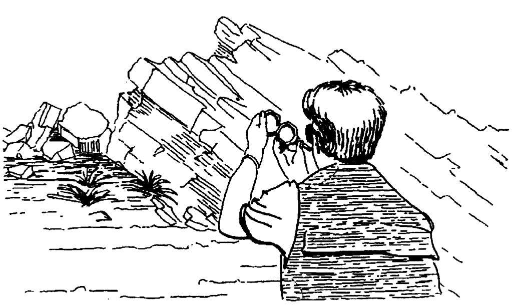


Figure C.2 Sighting with a geological compass along the strike of an outcrop to obtain the average dip of beds exposed on vertical surfaces. Caution – the line of sight must be parallel to the strike.

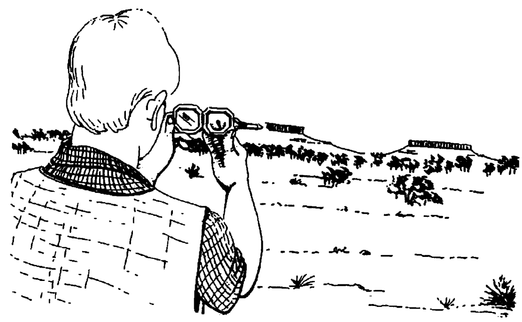


Figure C.3 Measuring the dip of beds on a distant mesa by sighting along strike.

Some recent models of geological compass, such as the Tectronic™ made by Breithaupt Kassel®, offer automatic electronic measurement of dip and dip direction. The measurements can then be stored in the instrument memory against keyed-in code numbers, or displayed on a liquid crystal display. This instrument would be valuable in applications where large numbers of orientation measurements need to be taken (e.g. some specialist structural or geotechnical applications), but they are very expensive; for most applications, the traditional low-tech geologists', compass will do everything that the field geologist requires.

C.3 MEASURING LINEAR FEATURES

Measurable linear features encountered in rocks can be fold axes, elongate boudins, mullions, preferred mineral elongations, elongated clasts, slickenlines or the intersection of two surfaces (e.g. bedding and cleavage). All these will be collectively referred to as linears. Linears are important and provide vital clues towards unravelling geology and mineralization in deformed rocks. Linears are easy to measure and record and this should be done routinely when field mapping or logging drill core.

In the author's experience, many geologists are not quite sure how to measure and record lineations, hence the following detailed description. It is based on the use of a Brunton® compass but other geological compasses can be used. However, the slotted and horizontally extendable sight on the Brunton® makes the procedure particularly easy.

Linear features within a rock are defined geometrically either by their trend and plunge, or, if they lie upon the surface of a plane, by their pitch upon that plane. These terms are defined on the block diagram of Figure C.4. The pitch will only define the absolute orientation of a linear if the attitude of the plane on which the pitch is measured is also known. Given either of the two sets of measurements, the other can be calculated mathematically or by stereo-net. For general mapping purposes it is usually more useful to measure and record the trend and plunge of the structure.

The recommended field procedure for measuring lineations is as follows:

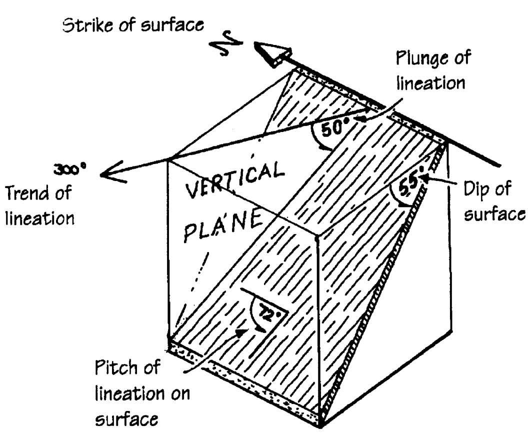


Figure C.4 An explanation of the terms 'pitch' and 'plunge' of linear features.

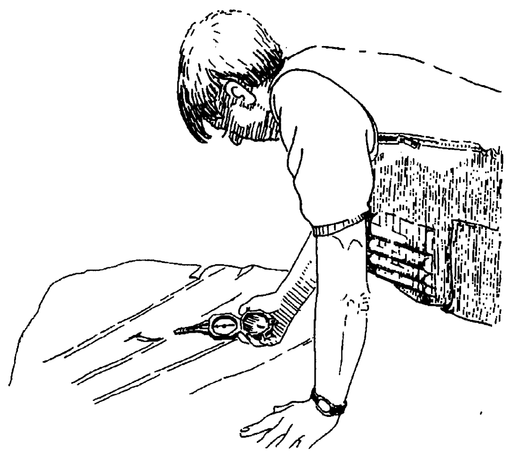


Figure C.5 Measuring the trend of a lineation with a Brunton® compass.

Figure C.6 Measuring the plunge of a lineation with a Brunton® compass.

- If the linear to be measured is not clear in the rock, mark it with a felt-tip pen, or lay a pencil along it, before making the measurement.
- Hold an open Brunton®[1] compass horizontally above the linear with the slotted sighting bar horizontally extended (Figure C.5). Sight vertically down on to the linear through the slot in the sighter, rotating the compass in the horizontal plane so that sighter bar and linear are

[1] The Freiberg® structural geology compass will measure trend and plunge of lineation directly.

aligned. Use the thickness of the sighter bar to judge whether the view is vertical down on to the linear (when the view is from above, the edge of the bar – its thickness – cannot be seen). Record the bearing on the compass card – this is the trend of the linear feature.

- Next, lay the long edge of the open compass against the linear and, holding the compass body vertically, measure the angle that the linear makes with the horizontal (Figure C.6). This angle is the plunge of the lineation.
- The orientation of the linear feature is recorded on to the map using an arrow pointing to the direction of trend, and a number indicating the amount of plunge. Different types of arrow can be used for different types of lineation.

APPENDIX D
SUGGESTED FURTHER READING

GENERAL

Berkman, D.A. (Compiler) (1991) *Field Geologists' Manual*, 3rd edn, The Australasian Institute of Mining and Metallurgy, Melbourne, Monograph No. 9.
A general reference and an invaluable source of the thousand and one useful facts and figures that every field geologist will at some time need

Peters, W.C. (1987) *Exploration and Mining Geology*, 2nd edn, Wiley, NY, 685 pp.

Reedman, J.H. (1979) *Techniques in Mineral Exploration*, Applied Science Publishers, London, 533 pp.
Excellent detailed texts on the practical field aspects of exploration geology

CHAPTER 1

Guilbert, J.M. and Park, C.F. Jr (1986) *The Geology of Ore Deposits*, W.H. Freeman, NY, 985 pp.
A comprehensive and well-written text on the geology of ore deposits

Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. and Duke, J.M. (eds), (1993) *Mineral Deposit Modelling*, Geological Association of Canada, Special Paper 40, 798 pp.
An excellent and up-to-date compendium on ore deposit models and their use in developing conceptual exploration strategies

CHAPTER 2

Australian Institute of Mining and Metallurgy, Melbourne (1990) *Geological Aspects of the Discovery of some Important Mineral Deposits in Australia*, Monograph Series 17, 503pp.
Casa histories of geological aspects of mineral discovery

Barnes, J.W. (1995) *Basic Geological Mapping*, 3rd edn, Wiley, NY, 133 pp.
A practical coverage of field geological mapping techniques

Drury, S.A. (1993) *Image Interpretation in Geology*, 2nd edn, Chapman & Hall, London, 304 pp.
A superbly illustrated and up-to-date book on all aspects of image interpretation including aerial photography, satellite reflectance imagery and radar imagery

Hancock, P.L. (1985) Brittle Microtectonics: Principles and Practice. *Journal of Structural Geology*, **7**, pp. 437–57.
The recognition and interpretation of sense of movement indicators in brittle fracture zones

Hanmer, S. and Passchier, C. (1991) *Shear Sense Indicators: A Review*, Geological Survey of Canada (Ottawa) Paper 90–17, 72 pp.
On the recognition and interpretation of sense of movement indicators in shear zones

Hobbs, B., Means, W. and Williams, P. (1976) *An Outline of Structural Geology*, Wiley, NY, 571 pp.
A general text on structural geology, relatively cheap, and written by experienced field geologists. In the author's opinion, it is still one of the best texts in the field.

Hutchinson, R.W. and Grauch, R.A. (eds) (1991) *Historical Perspectives of Genetic Concepts and Case Histories of Famous Discoveries*. Economic Geology Monograph 8.
Case histories of geological aspects of mineral discovery

Marshak, S. and Mitra, G. (1987) *Basic Methods in Structural Geology*, Prentice-Hall, NY.
A good treatment of the philosophy of geological mapping

McClay, K. (1987) *The Mapping of Geological Structure*, published for the Geological Society of London by Halstead Press, London.
On the field observation and use of ductile deformation structures

Petit, J.P. (1987) Criteria for the Sense of Movement on Fault Surfaces in Brittle Rocks. *Journal of Structural Geology*, **9**, 597–608.
The recognition and interpretation of sense of movement indicators in brittle fracture zones

Smith, R.E. (1987) Using Lateritic Surfaces to Advantage in Mineral Exploration. *Proceedings of Exploration '87: Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater*. Ontario Geological Survey, Special Volume, Toronto.
On using maps of the regolith to control geochemical mineral exploration

Turcote, D.L. (1992) *Fractals and Chaos in Geology and Geophysics*, Cambridge University Press, NY, 221 pp.
A detailed discussion of some of the applications of chaos theory in geology

CHAPTER 3

Annels, A.E. (1991) *Mineral Deposit Evaluation: A Practical Approach*, Chapman & Hall, London, 456 pp.
A comprehensive and up-to-date coverage of all aspects of the evaluation of mineral deposits, with an emphasis on advanced exploration projects and ore deposits

CHAPTER 4

Barnes, J.F.H. (1987) *Practical Methods of Drill Hole Sampling*, Australian Institute of Geoscientists Bulletin No. 7 – Meaningful Sampling in Gold Exploration.

Barnes, J. (1989) *RAB Drilling – Secret Weapon*. Resource Service Group Pty Ltd, Resource Review, October, pp. 5–7.
RAB and RC drilling and sampling techniques in mineral exploration

Blackbourne, G.A. (1990) *Cores and Core Logging for Geologists*, Whittle's Publishing, Caithness, Scotland, 113 pp.
Comprehensive coverage of drilling techniques

Hartley, J.S. (1994) *Drilling: Tools And Program Management*, A.A. Balkema, Rotterdam, 150 pp.
Good discussion of the management of drilling programmes and directional control of diamond drill holes

McPhie, J., Doyle, M. and Allen, R. (1993) *Volcanic Textures*, published by the University of Tasmania.
An example (p. 13) of graphical scale logging in volcanic rocks (and many other good and useful things besides)

CHAPTER 5

MacDonald, E.H. (1983) *Alluvial Mining: The Geology, Technology and Economics of Placers*, Chapman & Hall, London, 508 pp.
Detailed information on the geology and exploration of unconsolidated placer deposits

CHAPTER 6

Drury, S.A. (1990) *A Guide to Remote Sensing*, Oxford University Press, London, 243 pp.
Detailed treatments of remote sensing technology

Drury, S.A. (1993) *Image Interpretation in Geology*, 2nd edn, Chapman & Hall, London, 304 pp.
A superbly illustrated and up-to-date book on all aspects of image interpretation including aerial photography, satellite reflectance imagery and radar imagery

Gupta, R.P. (1990) *Remote Sensing Geology*, Springer-Verlag, NY, 356 pp.
Detailed treatments of remote sensing technology

Kosko, B. (1993) *Fuzzy Thinking – The New Science of Fuzzy Logic*. Hyperian Press, NY, 318 pp.
A good introduction to fuzzy logic

Sharma, P.V. (1986) *Geophysical Methods in Geology*, Elsevier, NY, 428 pp.
Details on geophysical techniques used in mineral exploration

Smith, R.E. (1987) Using Lateritic Surfaces to Advantage in Mineral Exploration. *Proceedings of Exploration '87: Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater*. Ontario Geological Survey, Special Volume, Toronto.
On using maps of the regolith to control geochemical mineral exploration

Telford, W.M., Geldart, L.P. and Sheriff, R.E. (1990) *Applied Geophysics*, 2nd edn, Cambridge University Press, NY, 770 pp.
Details on geophysical techniques used in mineral exploration

Handbook of Exploration Geochemistry, Elsevier, NY.

1. Fletcher, W.K. (1981) *Analytical Methods in Exploration Geochemistry*, 255 pp.
2. Howarth, R.J. (ed.) (1983) *Statistics and Data Analysis in Geochemical Prospecting*, 437 pp.
3. Govett, G.J.S. (1983) *Rock Geochemistry in Mineral Exploration*, 461 pp.
4. Butt, C.R.M. and Zeegers, H. (1992) *Regolith Exploration Geochemistry in Tropical and Subtropical Terrains*, 607 pp.
5. Kauranne, K., Salimen, R. and Eriksson, K. (eds) (1992) *Regolith Exploration Geochemistry in Arctic and Temperate Terrains*, 443 pp.
6. Hale, M. and Plant, J.A. (1994) *Drainage Geochemistry*, 766 pp.
A recent and exhaustive treatment of the theory and practice of mineral exploration geochemistry

REFERENCES

Annels, A.E. and Hellewell, E.G. (1988) The orientation of bedding, veins and joints in core; a new method and case history. *International Journal of Mining and Geological Engineering*, **5**(3), 307–20.

Baumer, A. and Fraser, R.B. (1975) Panguna porphyry copper deposit, Papua New Guinea, in *Economic Geology of Australia and Papua New Guinea I – Metals*, (ed. C.L. Knight), The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 855–66.

Gresham, J.J. (1991) The discovery of the Kambalda nickel deposits, Western Australia. *Economic Geology Monograph*, **8**, 286–8.

Handley, G.A. and Henry, D.D. (1990) Porgera Gold Deposit, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*, (ed. F.E. Hughes), The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 1073–7.

Izawa, E., Urashima Y., Ibaraki, K. *et al.* (1990) The Hishikari gold deposit: high grade epithermal veins in quaternary volcanics of southern Kyushu, Japan. *Journal of Geochemical Exploration*, **36**, 1–56.

Koehler, G.F. and Tikkanen, G.D. (1991) Red Dog, Alaska: Discovery and definition of a major zinc–lead–silver deposit. *Economic Geology Monograph*, **8**, 268–74.

Moyle A.J., Doyle B.J., Hoogvliet, H. and Ware, A.R. (1990) Ladolam Gold Deposit, Lihir Island, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*, (ed. F.E. Hughes), The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 1793–1805.

Reeve, J.S., Cross, K.C., Smith, R.N. and Oreskes, N. (1990) Olympic Dam copper–uranium–silver deposit, in *Geology of the Mineral Deposits of Australia and Papua New Guinea*, (ed. F.E. Hughes), The Australasian Institute of Mining and Metallurgy, pp. 1009–35.

Sales, R.H. (1913) Ore deposits at Butte, Montana. *Transactions of the American Institute of Mining Engineering*, **46**, 1523–1626.

Van Leeuwen, T.M. (1994) 25 years of mineral exploration and discovery in Indonesia. *Journal of Geochemical Exploration*, **50**, 13–90.

Young, L. (1989) Geology and genesis of the Red Dog deposit, Western Brooks Range, Alaska. *CIM Bulletin*, **82**, 57–67.

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