Ground water in hard rocks

Project 8.6 of the
International Hydrological
Programme

Prepared by the
Project Panel,
Ingemar Larsson:
Chairman

Unesco

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Preface

Although the total amount of water on earth is generally assumed to have remained virtually constant, the rapid growth of population, together with the extension of irrigated agriculture and industrial development, are stressing the quantity and quality aspects of the natural system. Because of the increasing problems, man has begun to realize that he can no longer follow a "use and discard" philosophy – either with water resources or any other natural resources. As a result, the need for a consistent policy of rational management of water resources has become evident.

Rational water management, however, should be founded upon a thorough understanding of water availability and movement. Thus, as a contribution to the solution of the world's water problems, Unesco, in 1965, began the first world-wide programme of studies of the hydrological cycle – the International Hydrological Decade (IHD). The research programme was complemented by a major effort in the field of hydrological education and training. The activities undertaken during the Decade proved to be of great interest and value to Member States. By the end of that period, a majority of Unesco's Member States had formed IHD National Committees to carry out relevant national activities and to participate in regional and international co-operation within the IHD programme. The knowledge of the world's water resources had substantially improved. Hydrology became widely recognized as an independent professional option and facilities for the training of hydrologists had been developed.

Conscious of the need to expand upon the efforts initiated during the International Hydrological Decade and, following the recommendations of Member States, Unesco, in 1975, launched a new long-term intergovernmental programme, the International Hydrological Programme (IHP), to follow the Decade.

Although the IHP is basically a scientific and educational programme, Unesco has been aware from the beginning of a need to direct its activities toward the practical solutions of the world's very real water resources problems. Accordingly, and in line with the recommendations of the 1977 United Nations Water Conference, the objectives of the International Hydrological Programme have been gradually expanded in order to cover not only hydrological processes considered in interrelationship with the environment and human activities, but also the scientific aspects of multi-purpose utilization and conservation of water resources to meet the needs of economic and social development. Thus, while maintaining IHP's scientific concept, the objectives have shifted perceptibly towards a multidisciplinary approach to the assessment, planning, and rational management of water resources.

As part of Unesco's contribution to the objectives of the IHP, two publication series are issued: "Studies and Reports in Hydrology" and "Technical Papers in Hydrology." In addition to these publications, and in order to expedite exchange of information in the areas in which it is most needed, works of a preliminary nature are issued in the form of Technical Documents.

The purpose of the continuing series "Studies and Reports in Hydrology" to which this volume belongs, is to present data collected and the main results of hydrological studies, as well as to provide information on hydrological research techniques. The proceedings of symposia are also sometimes included. It is hoped that these volumes will furnish material of both practical and theoretical interest to water resources scientists and also to those involved in water resources assessments and the planning for rational water resources management.

Contents

Foreword

This volume has been prepared within the framework of IHP Project 8.6, "Study of crystalline rock aquifers," one of the major projects of the International Hydrological Programme of UNESCO, (IHP) approved by the Intergovernmental Council of the IHP in April 1975.

The activities of IHP Project 8.6. have included expert panel meetings, publications and seminars. Following several panel meetings and a seminar which was held in September 1977 in Stockholm, Sweden and Cagliari, Sardinia, Italy, a preliminary draft of the present work was prepared and used as a text for an inter-regional seminar held in Coimbatore, India, from 22 November to 20 December 1979. A revised preliminary draft was prepared for the African regional seminar in Arusha, Tanzania, from 14 September to 2 October 1981.

As printed in its present form, it is hoped that the volume will be of interest to a somewhat broader audience, especially in developing countries.

The work is intended primarily to fill a gap in the knowledge of ground-water hydrology. Current manuals and technical books used by geologists, hydrologists and engineers contain relatively little specific information on the subject of the occurrence, exploration and development of ground water in hard rock areas, that is, mainly igneous and metamorphic rocks of the Precambrian shield areas. On the other hand, a vast amount of research, exploration and development have taken place at random all around the world, in the course of the last 10 or 15 years, with variable results.

The purpose of this volume is also to inform water-resources specialists, physical planners, and water-policy decision makers, especially in developing countries, of the possibilities, both real and limited, of finding and developing ground-water resources in what has been previously considered one of the least promising hydrological environments, and to draw their attention to the complexity, sophistication and costs of the technologies involved. Therefore, while most of the material deals with the scientific and technological aspects of the occurrence of ground water in hard rock areas and related exploration and development activities, some planning and economic aspects are also considered.

The volume is the result of the combined efforts of a group of ground-water specialists, and should be regarded as a first co-operative venture in the subject matter. The extensive bibliography which is presented at the end of the volume should not be misleading. The volume is not a mere compilation of existing scientific and technical literature. It is primarily based on the collective field experience of the drafting panel, experience which has been acquired in many parts of the world: Africa, North and South America, the Middle east, Europe (especially Scandinavia), India, Australia and Southeast Asia. On the other hand, the authors do not pretend to present a full picture of the knowledge acquired to date or of the state of the art in exploration and development of ground water in hard rock areas.

The project has benefited from substantial financial and technical support of the Swedish Government, channeled to UNESCO through the Swedish International Development Authority (SIDA).

The volume was prepared by a panel of experts composed of:

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Each of these contributors has dealt with one or more sections of the volume according to his personal specialization and specific professional experience. The entire text, however, has been discussed, analysed, reviewed and finalized through extensive exchange of views, which involved all the experts. Without recognizing any exclusive authorship responsibility it is appropriate to mention that most of the material of some sections was prepared by one author, namely Professor Larsson for Sections 2.1.1, 2.1.2, 2.2.2 and 3.3.2.3; Mr. Campbell for Sections 2.2.3, 3.3.1 to 3.3.7 (excl. 3.3.6.3) and Section 3.3.9; Dr. Dijon for Section 1 and 3.3.2.3; Professor Eriksson for Sections 2.3.1 to 2.3.4, 3.3.2.3 and 3.3.8; Professor Gustafson for Section 3.3.6.3; Dr. Krol for Section 3.2.1 and 3.3.2.3; Professor Parasnis for Section 3.2.2 and 3.3.2.3; Mr. Taylor for Sections 2.1.3, 2.2.1 and 3.3.2.3; and Mr. Thomas for Sections 3.1.1 to 3.1.3. The authors of the case histories in Chapter 4 are identified under each case history.

In addition to the editorial work carried out by the authors, final editing has been performed by Mr. José A. da Costa, Paris, France, and Mr. Åke Nilsson, Royal Institute of Technology, Stockholm, Sweden.

The text was prepared by the authors mainly during 1977-1979 and the list of references and bibliography was completed 1982.

1. Introduction

Over major parts of the earth's surface, igneous and/or metamorphic rocks crop out or lie close to the surface under a thin veneer of surficial deposits; alluvial, glacial, etc. This is the case, in particular, in the vast Precambrian shields of igneous and metamorphic rocks, the very basement of continents, which occur widely in the Western Hemisphere (Canada, Northeastern and Northwestern United States, the Guyana plateau of Brazil), northern Europe (Scandinavia, Russia), Asia (Siberia, Arabian Peninsula, India, Sri Lanka, Southeast Asia, Korea, China), the Pacific region (Australia), and western, central and eastern Africa (see Figure 1.1). Large parts of this geological domain are located in tropical and subtropical regions which are among the least developed in the world. These areas are from ecological and environmental viewpoints among the most fragile parts of the world, with populations which have a prevailing low per capita income. This is especially true of northeastern Brazil, peninsular India, the Red sea region, western Africa from Senegal to Cameroon, and extensive parts of the highlands of central and eastern Africa. The populations concerned are, at least, in the range of 30 million in Latin America, 50 million in Africa and several hundreds of millions in Asia.

One of the primary constraints to economic and social development in these regions of the world is the difficulty encountered in developing reliable water supplies for the populations. In tropical arid regions, surface water is not available on a permanent basis, while in humid regions it is often contaminated with waterborne pathogens. As a result, ground water is, generally, the only permanent and safe source of water. However, the search for ground water and its development in these regions raises a number of problems which until recently were considered almost impossible to solve. As a result, in humid regions the populations have suffered from various diseases related to polluted surface water, while in semi-arid or arid areas land and mineral resources could not be effectively utilized for lack of water. Thus, in western Africa cattle could not be watered; in central Africa large tracts of good "black cotton soil" were not cultivated as populations could not settle owing to the technological difficulties encountered in developing ground water; in eastern Africa the "gum arabic" was not harvested owing to the lack of available water for the workers who would normally be brought in temporarily to collect the gum from the widely scattered Acacia gummifera trees; and economic mineral resources were not developed because of the lack of processing water for meeting the needs of planned mining towns.

Recent breakthroughs have taken place, however, both in the methodology and technology for the exploration and development of ground water in igneous and metamorphic rocks and especially in the rocks of the Precambrian shields. These have raised considerable hopes for the future of these developing regions. The governments of the countries concerned, with the support of the UN family and other multilateral or bilateral development agencies, are engaged in large programmes of ground-water resources development in such regions. This publication is intended to bring to the attention of the broadest possible readership among water specialists the status of knowledge and the state of the art in the ground-water geology and hydrology of igneous and metamorphic rock terrains.

As in the case of any other natural resource, the occurrence and behaviour of ground water in such terrains are related to a number of factors which can be grouped into three broad categories, relating respectively to geology/pedology, morphology and climatology.

Geology is considered here first, as it is often the limiting factor of ground-water occurrence. In general, igneous and metamorphic rocks, especially in the Precambrian shields have virtually no intergranular porosity, and for a long time they have been considered impervious. When galleries and tunnels were first driven into granite mountain masses, geologists and engineers were surprised by the large-yield, high-pressure flows which occurred through fractures. As a matter of fact the knowledge of ground-water hydrology in hard rocks was primarily acquired through studies related to geological engineering. Hard rocks, while mostly solid, non-porous, and absolutely impervious at the scale of a hand sample, can hold water in networks of cracks, joints, fractures or faults or along contacts between rocks of various types, as in the case of dikes and sills. In addition, where exposed under certain climatic conditions, these rocks are subjected to extensive weathering which may create conditions favourable for the infiltration and storage of ground water. Geological conditions may vary from one region to another, as the fracture systems are related to local lithologi-

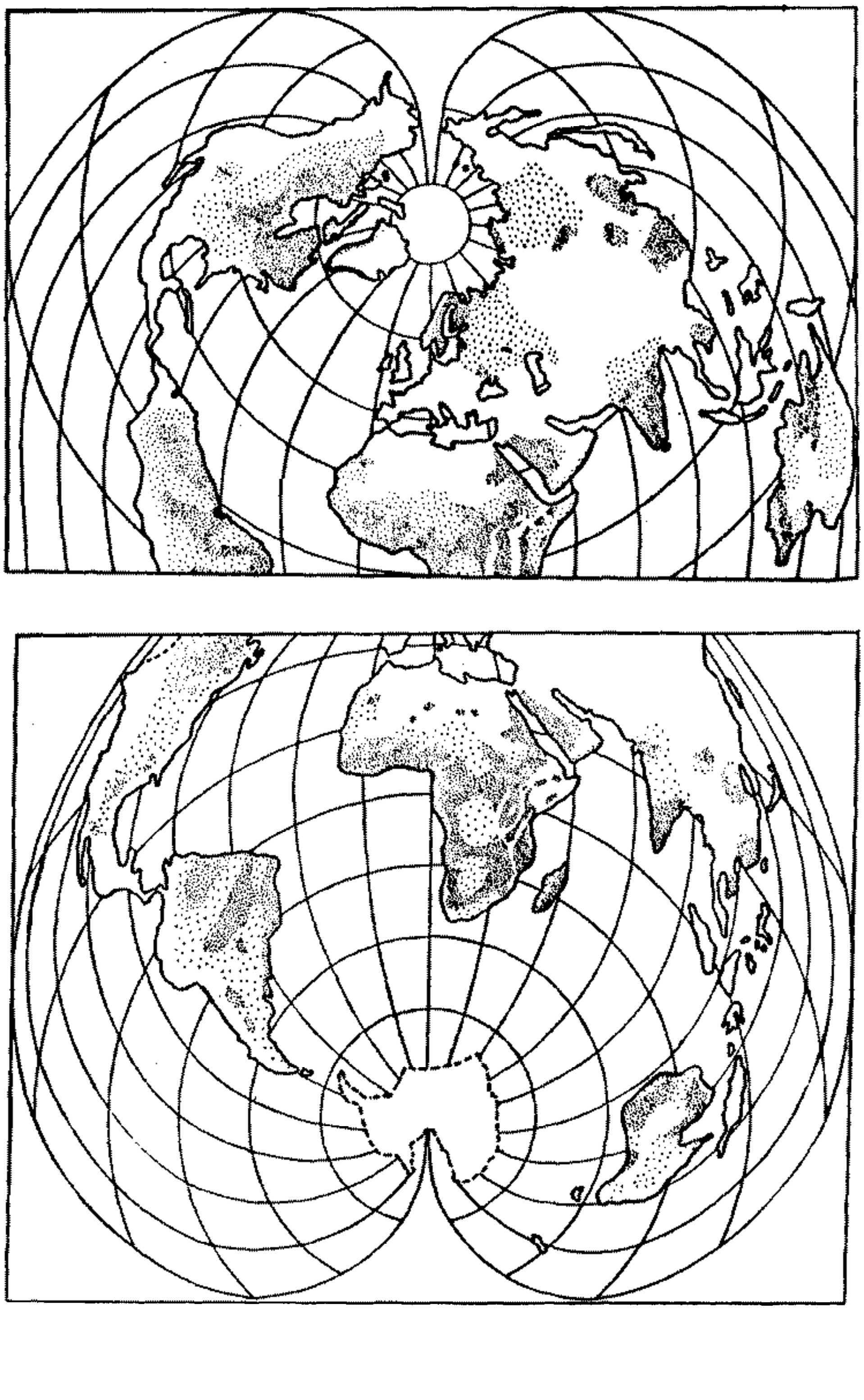


Figure 1.1 Distribution of "shield" areas in the northern and southern hemispheres. Exposures of basement rock heavily stippled, later deposits resting upon basement lightly stippled (King, 1962). (Reprinted by permission.)

cal and structural characteristics while the thickness and nature of the weathered layer is related both to these characteristics as well as to the climatic conditions. Some other factors are not to be overlooked as regards the hydrological behaviour of the weathered layer, as for example the vegetation cover which has an influence on the infiltration and evaporation of ground water. Certain zoological features may also be significant, as for example the occurrence of ant hills, which in ancient India were rightfully considered as ground-water indicators.

Morphological factors are also to be considered. Hard rock terrains often have rather flat topography as a result of their geological history of long periods of erosion. Drainage systems are usually poorly defined, and no substantial runoff is observed. Such conditions are favourable to evaporation. In humid regions, infiltration may take place if soil (pedological) and weathered layer conditions are propitious. In arid regions infiltration can take place only if the drainage pattern allows runoff to occur so that water can accumulate in relatively low, fractured areas where it can percolate into the subsurface ground-water reservoir.

Climatic conditions are extremely important in ground-water occurrence, especially such factors as rainfall and evaporation, which are always to be considered jointly in a given geographical area. This is especially true in many hard rock terrains where geological/pedological conditions are not optimum and where a certain concentration of rainfall within a short span of time, or a certain level of runoff is necessary to offset the effects of evaporation and thus permit some water to infiltrate and recharge the aquifer. On the other hand, evaporation can draw heavily on the ground water stored in the weathered layer. For example, it has been found in several areas of West Africa extending between Mali, Cameroon and Nigeria that the weathered layer over unweathered hard rocks becomes seasonally depleted of ground water at the end of the dry season, if the thickness of that layer is less than 12 to 15 metres.

In fact, ground-water occurrence, availability and quality are related to a complex interaction of all the above factors. A typical case of such interaction is that of some areas of northeastern Brazil. These areas of flat topography are underlain by eroded gneisses and schists which are capped by massive sandstone mesas or plateaus. Rain falling on these elevated sandstone plateaus percolates into fissures and fractures and discharges through freshwater springs located around the edges of the plateaus at the contact of underlying gneisses and schists. In the plains the gneisses and schists themselves contain only small amounts of ground water which is commonly brackish or saline. This particular example illustrates in an obvious manner the direct influence of geology on morphology, morphology on climate, climate on mophology, and geology/morphology/climate on the occurrence and quality of ground water. The basic interaction of these factors in this complex environment is considered in the following chapters, which examine successively the geological, hydrological and hydrochemical characteristics of ground water in hard rocks.

2. Hydrogeology

2.1. *GEOLOGICAL CHARACTERISTICS*

2.1.1 GENERAL AND LOCAL ROCK PARAMETERS

Hard rock terrains comprise a great variety of igneous and metamorphic rocks. But from the hydrological point of view they are rather homogeneous in two respects. They have virtually no primary porosity as do sandstones and other sedimentary rocks. They have a secondary porosity due to fracturing and weathering, which permits the flow and storage of ground water. For some years, hydrogeologists have been using a general term for all these igneous and metamorphic rocks. They call them "hard rocks". The most common hard rocks are gneisses and granites.

Hard rock is a very general and vague term for all kinds of igneous and metamorphic rocks, typical for all shield areas of the earth. In the present work the term is not applied to volcanic or carbonate rocks, even though the latter may be a part of a particular metamorphic suite. The reason for excluding the above mentioned rock types is that they may have a primary porosity, which generally is not present in igneous and metamorphic rocks. Thus, karstic formations and porous layers of volcanic rocks are excluded. Hard rocks are sometimes defined in UN-family publications as "compact, non-carbonate, non-volcanic rocks."

The storage capacity of unweathered hard rocks is restricted to the interconnected system of fractures, joints and fissures in the rock. Such openings are mainly the result of world-wide tectonic phenomena in the earth's crust.

Hard rocks react more or less in a similar fashion to stress, depending on their internal structure. In studying their storage capacity for ground water this behaviour must be taken into consideration.

Weathering processes have considerable influence on the storage capacity of hard rocks. Mechanical disintegration, chemical solution and deposition, and the weathering effects of climate and vegetation bring about local modifications of the primary rock and its fractures. This action can imply either an increase or a decrease of the secondary porosity of the original fracture pattern of the rock. The transition zone between the weathered layer and the underlying fresh rock (see Section 2.1.3.4) can function as a reasonably good aquifer, depending on the porosity of this zone.

2.1.2 UNWEATHERED HARD ROCKS AND FRACTURING

2.1.2.1 *General petrographical properties*

Introduction – The Precambrian shields are among the oldest parts of the earth's crust. They contain hard rocks of different age, grade of metamorphism and structure. Many orogenic movements have affected the shields. Faulting processes have had different influences on the rocks of the shields due to difference in strength of the individual rock type. This difference can easily be seen in the field. Some rock types are extensively fractured; while others are almost undisturbed, even though they belong to the same tectonic environment.

The strength of the rock or its resistance to brittle failure in the crust is rather a complicated matter. Petrographical parameters are involved, that is, grain size, grade of metamorphism, fold structures, direction of fold axis versus stress orientation, etc. These parameters play a dominant role in rock fracturing, and thereby they are indirectly related to the occurrence of ground water in hard rocks. Systematic studies of these parameters and their relation to the occurrence of ground water have not previously been made. The present state of knowledge can be summarized as follows:

Intrusive rocks and fracturing – Fine-grained rocks such as aplites generally show a dense pattern of fractures. In such rocks individual fractures usually are very limited in length. On the other hand, coarse-grained rocks such as granites generally develop fractures tens to hundreds of metres long. These fractures usually are widely spaced. Some rocks such as pegmatites show weak cohesion among the individual crystals. Therefore the rock body is brittle and may fracture easily with applied stress. Depending on the local tectonic framework, granitic rocks may be highly fractured while in the same region basic rocks as diorites and gabbros will be less fractured (Larsson, 1968).

Metamorphic rocks and fracturing – The degree of metamorphism seems to determine the strength of the rock against fracturing. In India characteristic high-grade metamorphic or igneous rocks (e.g. charnockites) show almost no fracturing. Metamorphic rocks of a lower grade on the other hand such as biotite gneisses, which crop out close to charnockite bodies, have normal to heavy fracturing. This seems to be a general condition. Extremely low-grade metamorphic rocks as schists are often heavily fractured.

Folded rocks generally have their own characteristic fracture pattern (see Section 2.1.2.3). But apart from this type of deformation folded gneisses generally have a very sparse post-crystalline fracture pattern. With respect to rock strength, folding seems to provide a kind of "reinforcement" of the rock (Larsson, 1977).

A striking example, illustrating the different fracturing of brittle rocks is shown in Figure 2.1.2.1. Two kinds of rock crop out along the southeastern coast of Sweden. A finegrained gneiss of supercrustal type is surrounded by granitoid rocks in all directions, except to the south (the Baltic).

Figure 2.1.2.1 Tectonic-morphologic map of hard rock area in SE Sweden showing the main tectonic features of the area (modified from Larsson, Lundgren and Wiklander, 1977).

The age of the granites to the east and to the west of the gneiss is about 1430 Ma. (Rb/Sr, Wilson and Sundin, 1979). The gneiss is considerably older than the surrounding granites. The gneiss has been folded several times, about north trending axes.

Later the whole area was deformed in a brittle manner by lateral compression in SSW-NNE direction. On that occasion the surrounding granite rocks were intensively fractured. The gneiss, on the other hand, was almost undisturbed by this action. No conspicuous valleys or major fractures related to this deformation appear in the gneiss, as is generally the case in the surrounding granite rocks (Larsson, Lundgren and Wiklander, 1977).

Therefore the gneiss is considered a competent rock body while the surrounding granite rocks, which are brittle, and therefore incompetent, are highly fractured. The small angle between the fold axis of the gneiss and the direction of maximum compressive stress of the post-folding brittle deformation has probably increased the resistance of the gneiss.

Migmatization in folded rocks with increase of quartz and feldspar generally results in a weakening of the resistance of the rock. This phenomenon is often observed in underground caverns and during the construction of tunnels in hard rocks (Larson, 1977).

2.1.2.2. *Fracture porosity*

To the hydrogeologist the common attribute of hard rocks is the absence of primary porosity. By definition, hard rocks are compact. On the other hand the fracture pattern of the rocks creates a type of porosity which is termed fracture porosity. This means that open fractures lying below the ground-water level can store water (Figure 2.1.2.2).

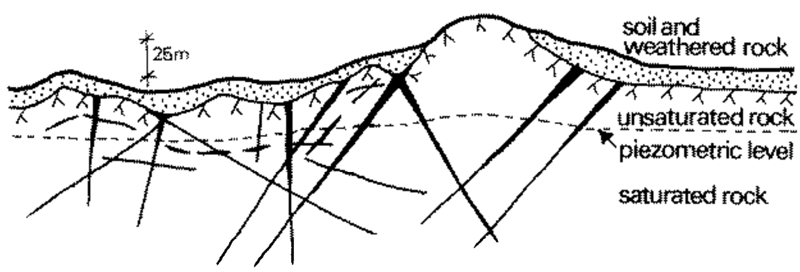


Figure 2.1.2.2 Typical water-bearing fracture zones in hard rock.

2.1.2.3 *Fractures originating from tectonic movements in the earth's crust.*

Introduction – Fairbairn (1949) states that there are two groups of deformation fabrics. One is characterized by solid flow in the broadest meaning of the term. Here, continuity of the rock is retained despite the movements. The other group is characterized by rupture, which destroys the continuity. As a name for the first group Sander (1930) created the term "Teilbewegungen" (componental movements). He defined it as each movement of any element in the rock, where the rock retains its continuity after the deformation and during the period under consideration.

In most rocks these componental movements are correlated to some tectonic pattern shown by grain orientation. These rocks were termed tectonites a number of years ago. This useful term includes many classes of deformed rocks ordinarily described as foliated, slaty, banded or even massive (Fairbairn, 1949).

Lineation and foliation – Most tectonites are characterized by planar and linear elements. Parallel planar elements give rise to foliation. Parallel linear elements show up as lineation (Figure 2.1.2.3). If both foliation and lineation are present, the lineation is invariably parallel to the foliation.

Recognition of essential features of a tectonite is facilitated by the use of fabric axes. Following Sander (1930) these axes are referred to as *a*, *b* and *c*. (Figures 2.1.2.3 and 2.1.2.6). The critical axis *a* denotes the direction of movement or transport. It may be either perpendicular or parallel to lineation. The axis *b* is limited by Sander to parallelism with the fold axis. Axis *c* is perpendicular to *a* and *b*. On a regional scale, these axes may be referred to as tectonic axes.

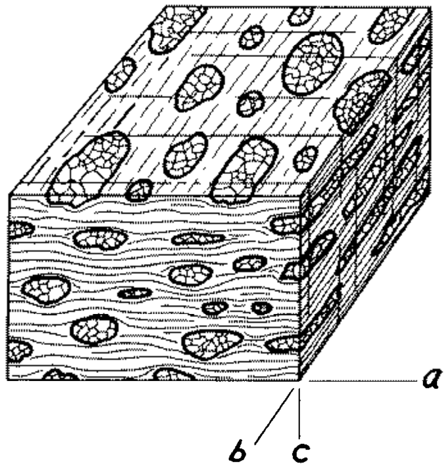
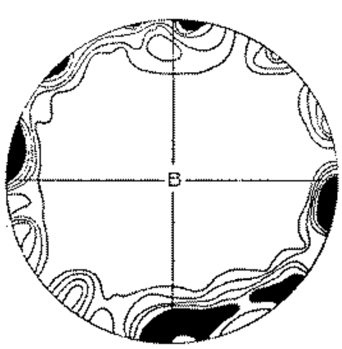


Figure 2.1.2.3 Main features of a tectonite consisting of aggregates of quartz grains enclosed by a "web of mica leaves." (After Fairbairn, 1949).

Figure 2.1.2.3. illustrates the main features of a tectonite consisting of aggregates of quartz grains enclosed by a web of mica leaves. Each quartz nest is a fabric element, or superindividual, and shows dimensional orientation. The grains composing the superindividual show no dimensional orientation but statistical analysis would probably disclose a lattice orientation. This lattice orientation may be referable to a statistical *s*-surface not apparent from inspection of the diagram. Both quartz aggregates and mica define the conspicuous foliation (parallel to the upper face of the block) and lineation (parallel to the axis *b*). The assumed fabric-axis orientation illustrates a common relation to foliation and lineation. Cross fractures parallel to the *ac*-plane are shown as unbroken straight lines perpendicular to *b*. In another common relation *a* is parallel to the lineation and tension fractures are approximately parallel to the new position of the *bc*-plane.

Types of tectonites -- Two main types of tectonites are usually developed in folded rocks. If the lineation is better developed than the foliation, this indicates a rotational movement (internally/externally) of the rock around the *b*-axis (fold axis). The grain fabric is elongated in the direction parallel to the *b*-axis. Joints develop parallel to the *ac*-plane. This type is called *B*-tectonite (Sander, 1948).

If the foliation (schistosity) is predominant and the lineation is weakly developed or absent this indicates a sliding movement (shear) or compression of the fabric. This type is called *s*-tectonite (slip tectonite) (Sander, 1948).



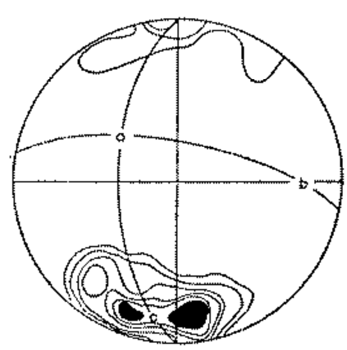


Figure 2.1.2.4 Fabric of an s-tectonite (slip tectonite). Poles of 206 lamellae in a marble from Griesscharte, Hochpfeiler, Tyrol (Knopf and Ingerson, 1938). (Courtesy of the Geological Society of America).

Figure 2.1.2.5 B-tectonite. Poles of 222 muscovite cleavage planes from a fibrous calcareous phyllonite from Brenner, Tyrol. Typical girdle diagram (Knopf and Ingerson, 1938). (Courtesy of the Geological Society of America).

The difference between the two tectonic types is well manifested in the structure of the grain fabrics, above all in that of mica. The characteristic *s*-tectonite has a mica fabric with one single well developed maximum, showing planar control. A typical *B*-tectonite has a mica orientation in a girdle around the *b*-axis, indicating axial control (see Figures 2.1.2.5 and 2.1.2.6).

A generalized sketch of the development of the two tectonic types is shown in Figure 2.1.2.6. (Larsson, 1968). The deformation is considered to have been dominated by slip parallel to the *ab*-plane (left side of the picture). Rotational movements (external and internal) around the *b*-axis have developed lineation parallel to the *b*-axis and tensile fractures parallel to the *ac*-plane (right side of figure 2.1.2.6).

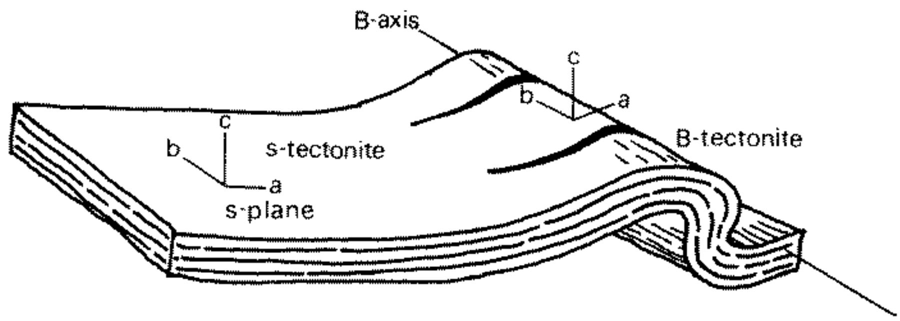


Figure 2.1.2.6 Generalized sketch of the development of *s*- and *B*-tectonites (Larsson, 1968).

Jointing of the *ac*-type (Figure 2.1.2.9) is often shown prominently in aerial photographs as a well-developed pattern of parallel lines which are perpendicular to a fold axis or an intrusive flow structure. Therefore, local variations often occur in their direction. It may be termed the local pattern. This type of tectonite is generally a poor aquifer because of weak interconnection between the joints, even though they may be numerous.

The two tectonite types are frequently developed in gneisses and other metamorphic rocks. They are common in all parts of the crust, in shield areas as well as in younger geologic formations. (Figures 2.1.2.7 and 2.1.2.8).

Figure 2.1.2.7 Road cut in *s*-tectonite gneiss (slip tectonite) in Västergötland, Sweden. No fractures are developed, except parallel to foliation.

Figure 2.1.2.8 *B*-tectonite, coarse gneiss at Stavsnas, Stockholm archipelago. Frequent *ac*-jointing. Fold axis parallel to the coast-line.

In prospecting for ground water in hard rocks, it is important to take these types into consideration. They have special characteristics as rock aquifers, which differ entirely from those of granites. This problem is discussed in Section 2.2.2.

Origin of jointing — The origin of the *ac*-jointing is still a matter of dispute. The character of jointing is obvious. There is no movement between the sides of the *ac*-joints under undisturbed conditions. The most characteristic feature of the *ac*-joints in metamorphic rocks is their "en echelon" layout. That means they usually are not interconnected. They are mostly short, usually less than 10-15 m. At each end they are very narrow but they open up in the middle. This indicates their tensile origin.

Turner (1948) discusses rock behaviour under plastic-viscous deformation and argues that fractures cannot develop during plastic deformation. Rock flow eradicates any previous jointing. Price (1966) states that, at least in metamorphic rocks, joints were formed after the main tectonic compression, at a time when the rocks were no longer plastic. From this statement Price draws the general conclusion that joints in metamorphic rocks develop at higher levels in the crust than those where the rocks underwent tectonic deformation. He suggests that residual stress was modified during uplift and took place in such a way as to result in tension joints. In some cases the stress resulted both in shear and tension joints.

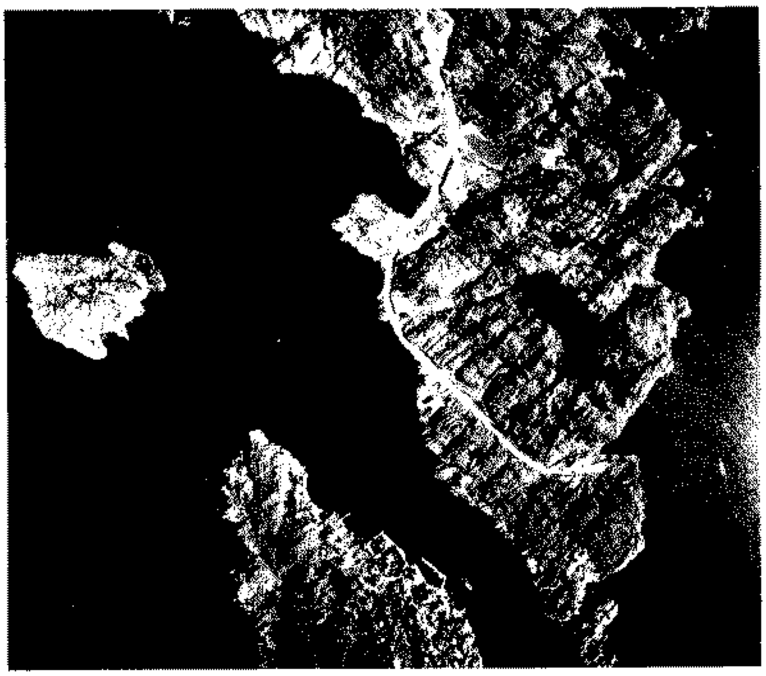


Figure 2.1.2.9 *ac*-jointing in *B*-tectonitegneiss in the island of Björkö, Bohuslan, Sweden. The fold axis strikes mainly NW-SE but is lightly curved. (Reprinted by permission of the Security Officer, National Land Survey of Sweden).

Domes and batholiths — Granite rocks in the form of ring structures are known in many parts of the world. Sorgenfrei (1971) has made an exhaustive study of these rock bodies. Some writers interpret these structures as products of magmatic differentiation. Others believe they are derived from granite magmas. Migmatite belts often surround the granite batholiths. They consist of a mixture of granite and country rock material.

The type of fracturing in these rock bodies has not been studied systematically from the hydrogeologic point of view. In maps and satellite images two types of fractures appear. One is a fracture system that conforms closely to the fringe of the batholith (Figure 2.1.2.10). The other type is a fracture system that conforms to the main tectonic pattern of the area (Figure 2.1.2.11). This indicates that the fracture pattern of the area is younger than the diapir intrusion.

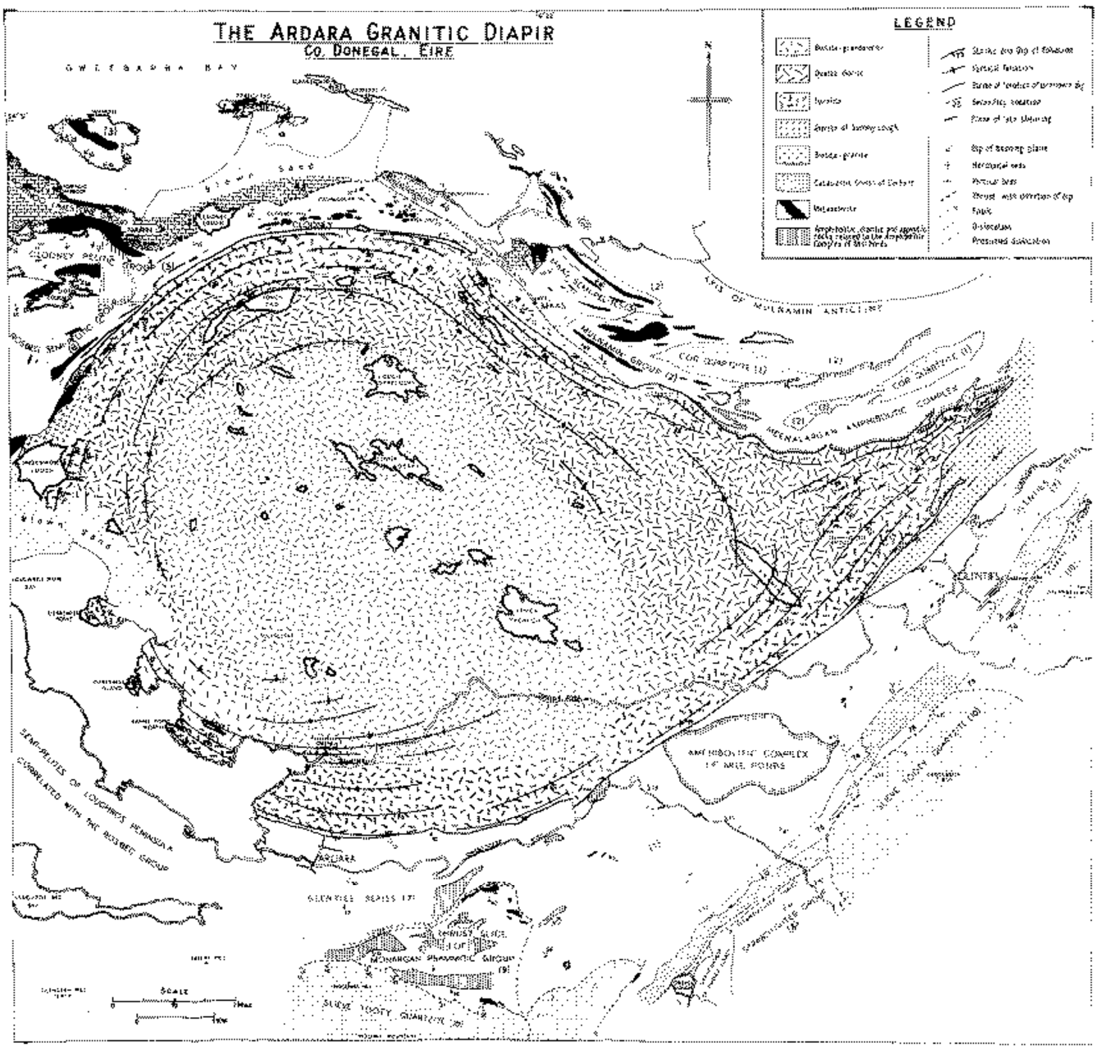


Figure 2.1.2.10 The Ardara Diapir (Akaad, 1957). (Reprinted by permission of Geological Society of London.)

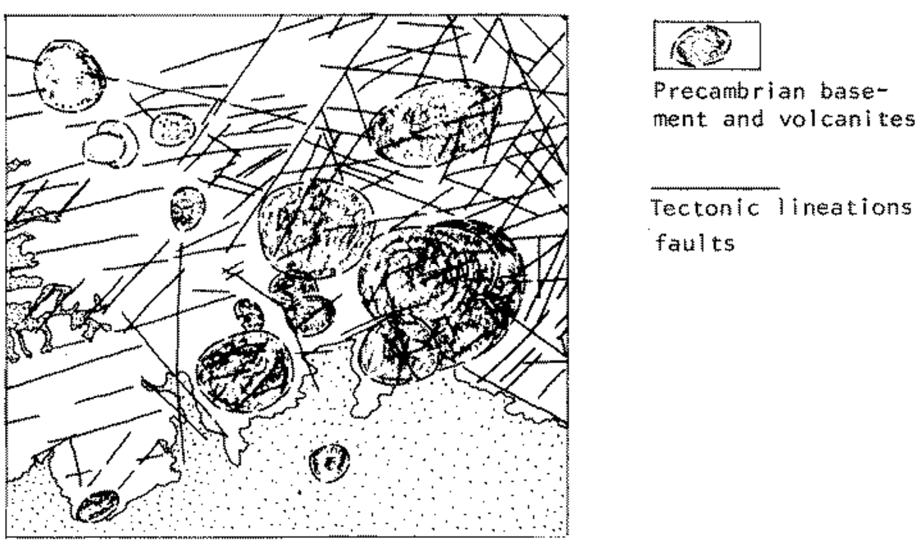


Figure 2.1.2.11 Granite diapirs and ring structures at the southern border of Sahara. (After Sorgenfrei, 1971). (Courtesy of Geological Society of Sweden.)

Fractures developed in consolidated rocks – Tectonic deformations of the crust are created by stress. The brittle rock material reacts in an elastic way up to the moment of failure. Failure means rupture of the rock, which develops a pattern of fractures.

A simple prism of unit cross-sectional area is considered. It is compressed by a force F (Figure 2.1.2.12). The stress σ_z acts on the end surface ABCD (area a). Force F has no component acting parellel to the surface ABCD. Thus it exerts no traction on this end surface. In other words, the shear stress along this plane is zero. By definition, any stress acting perpendicular to a surface along which the shear stress is zero is a principal stress. By convention the z-axis is usually taken vertical.

Other principal stresses may be oriented parallel to the x- and y-axes and would be designated as x and y. If the relative intensities of the principal stresses are known, they may be termed the maximum (or greatest), intermediate and minimum (or least) principal stresses, i.e. σ_1, σ_2 and σ_3 respectively (Price, 1966).

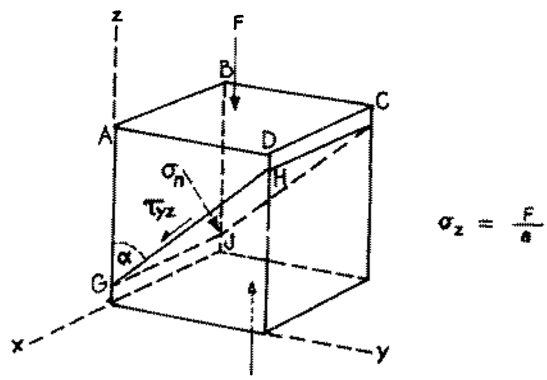


Figure 2.1.2.12 Normal and shear stresses acting on external and internal surfaces of a small unit cube subjected to a compressive force F (adapted from Price, 1966).

Shear fractures are the result of differential movement of rock masses along a plane. They are commonly observed in the field. They can range in length from many kilometres to tiny fractures observable in the hand specimen or under the microscope. If two intersecting shear planes develop under the same stress conditions, they are called conjugate shear fractures (Figure 2.1.2.13).

Price (1966) has shown the relationship of fractures to the axes of principal stress (Figure 2.1.2.14-16).

Case (a) is illustrated in Figure 2.1.2.14. The greatest principlal stress σ_1 is horizontal and the least principal stress σ_3 is vertical. If movement is significant the fractures are termed thrusts (overthrusts). This case is illustrated by the fracturing of a granite area in southeast Sweden. The thrust zones are filled with fault gouge, often granular with relatively high hydraulic conductivity.

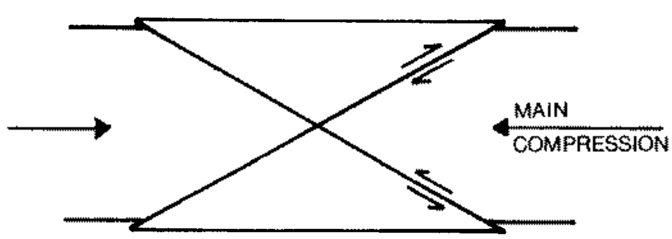


Figure 2.1.2.13 Conjugate shear fractures (after Price, 1966).

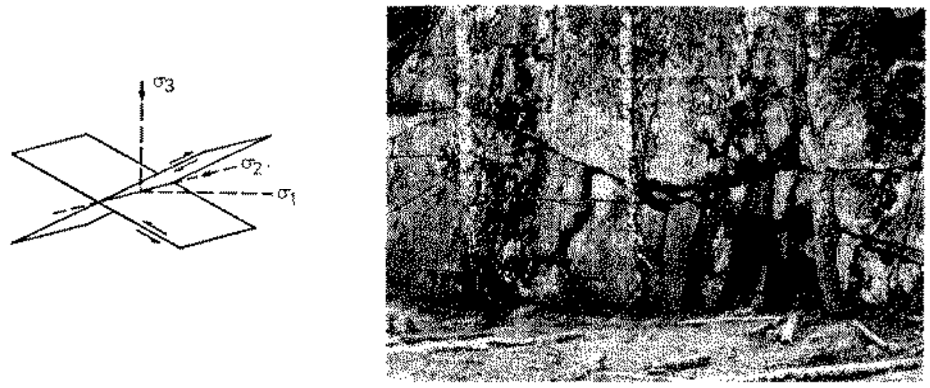


Figure 2.1.2.14 Relationship of fault to axes of principal stress (modified from Price, 1966). (σ_1 -horizontal; σ_3 -vertical.)

Figure 2.1.2.15 illustrates case (b) in which the greatest principal stress σ_1 acts vertically and the least principal stress σ_3 in the horizontal plane. The fractures are termed normal faults. A part of the escarpment of the Vättern graben in south Sweden shows striated normal faults (Figure 2.1.2.15). The total length of the graben is around 140 km.

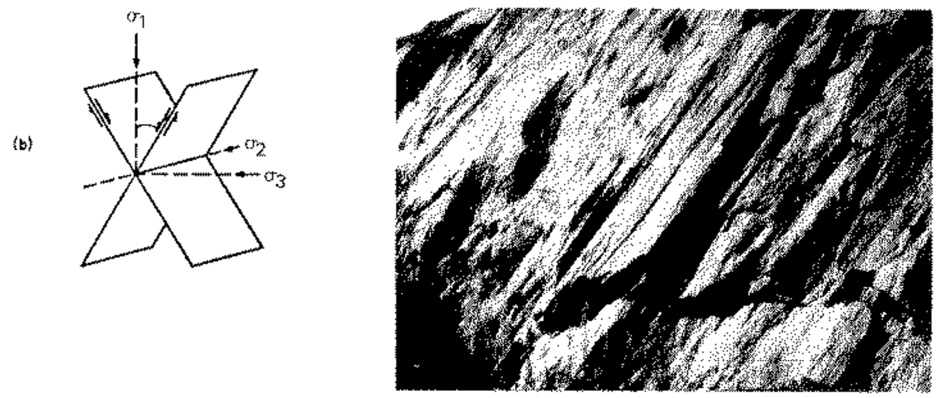


Figure 2.1.2.15 Relationship of faults to axes of principal stress (modified from Price, 1966). (σ_1 -vertical; σ_3 -horizontal.)

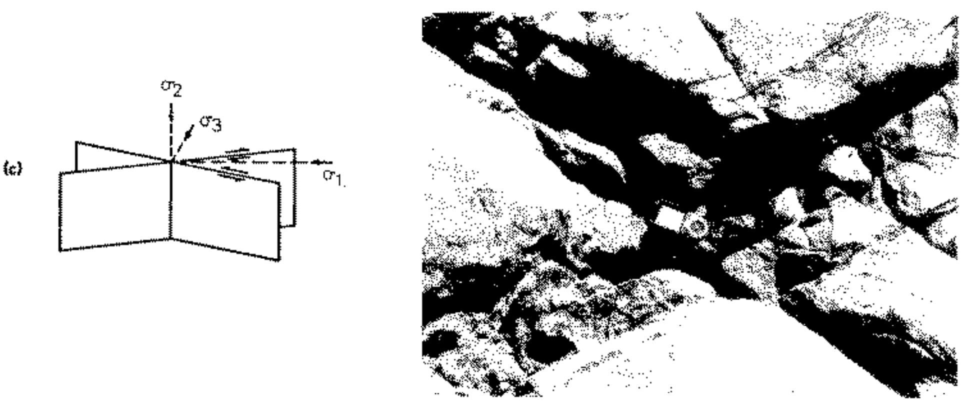


Figure 2.1.2.16 Relationship of faults to axes of principal stress (modified from Price, 1966). (σ_1, σ_3 -horizontal)

Case (c) is shown in Figure 2.1.2.16. Both the greatest and the least principal stresses act in the horizontal plane. The intermediate principal stress acts vertically. This type is illustrated by two intersecting shears in a Rapakivi granite from the islands of Aaland between Finland and Sweden. The photo was taken from above. The compass lies at the intersection of the shear planes (Figure 2.1.2.16).

Figures 2.1.2.17 and 2.1.2.18 show the effects of uniaxial compression tests on rock specimens. Tensile fractures develop parallel to the direction of compression due to parting and dilation perpendicular to compression direction (Romero and Gomez, 1970; Hawkes and Mellor, 1970).

Although longitudinal splitting of test specimens has long been recognized, no satisfactory explanation for the mechanics of the process has been offered (Holzhausen and Johnson, 1972).

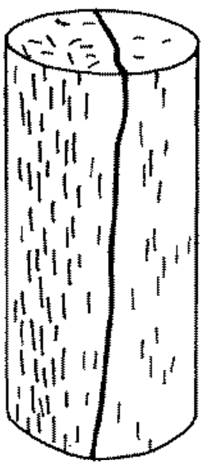


Figure 2.1.2.17 Sketch of failure of rock specimen uniaxially compressed (Holzhausen and Johnson, 1979).

Figure 2.1.2.18 Failure of cylindrical rock specimen under uniaxial compression. Axial cleavage, granite (Hawkes and Mellor, 1970).

Mechanism of dike formation — Larsson (1972) put forward the hypothesis that the findings from laboratory research work on uniaxial compression tests of rock specimens could be applied on a field scale, in dimensions of kilometres instead of centimetres. He suggests that the mechanism of dike formation could be similar to the subaxial splitting of test specimens under uniaxial compression, but of course at another scale.

It is evident that dike formation means tension acting perpendicularly to the dike direction in the crust. As an explanation to this Anderson (1942) suggested a buckling or an arching of the crust, causing vertical fractures through which the magma has come.

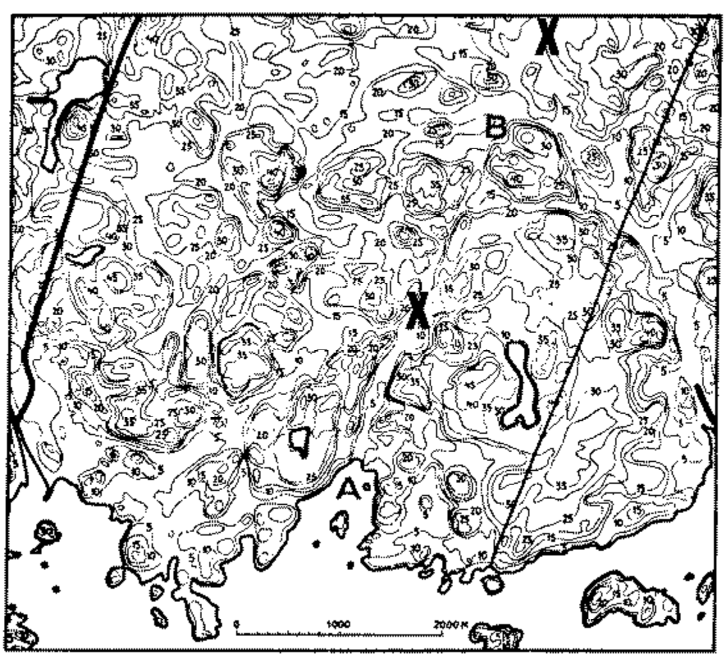


Figure 2.1.2.19 Contour map of southernmost part of the Karlshamn granite area, South Sweden. Black lines = diabase dikes; A — B = tension fracture valley; drilling sites (Larsson; 1972).

Dike formation, as an effect of compressional stress (like subaxial splitting) or tension (or pressure relief) perpendicularly to the maximum stress direction, should open up fractures in the crust, deep enough to reach regions with molten rock. If the dikes are of about equal width along their length, the buckling or arching model seems to be adequate. On the other hand, if the dikes are wide in one end and narrowing towards the other end, the hypothesis of subaxial splitting by compression stress seems more likely. This would indicate a decreasing stress effect corresponding to the narrowing of the dikes.

From the hydrogeological point of view dike formation in the rocks would mean that fractures parallel to the dikes could be tensile, open and therefore potentially water bearing, if they are not filled up with dike material.

The hypothesis was tested out by Larsson (1972) in a granite massif at Karlshamn in southern Sweden. After geophysical exploration, inclined holes were drilled to penetrate fracture zones (valleys, low-velocity zones) parellel to the dike direction and cores were obtained (Figures 2.1.2.19-21).

Examination of the cores and boreholes revealed more or less open fractures at the centre of the valleys at a depth of about 70-90 m, largely filled with sandy material. The total fracture width in the horizontal direction is 2.7 m at one site and at another site it is 2.4 m (Figures 2.1.2.19 and 2.1.2.20).

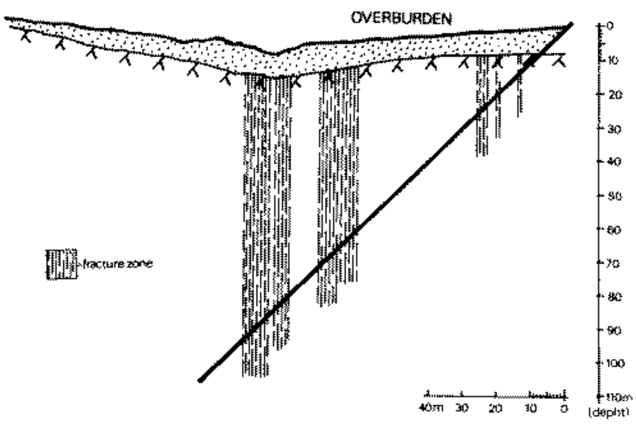


Figure 2.1.2.20 Cross-section of a tension-fracture valley at Hallaryd Karlshamn area. (Modified from Larsson, 1972).

Brittle deformation model – Larsson (1972) suggests that the model of the fracture pattern of the Karlshamn granite in South Sweden (Figure 2.1.2.21) can be applied more or less generally to other similar rocks. In effect the model is a collection of the most usual fractures due to brittle deformation, a kind of catalogue. The model is not the result of one brittle deformation. In the model fractures 1A and 1B indicate a tension (pressure relief). The shears 2A and 2B may belong to this phase of brittle deformation (see also Figure 2.1.2.16). The fractures 3A and 3B probably indicate a later phase of thrusting (see also Figure 2.1.2.14).

The model presupposes an isotropic substratum. The problem of isotropy is to a large extent a matter of scale. A granite sample can be quite an isotropic under the microscope. But in the field, on the scale of square kilometres, the same rock can be considered as an isotropic medium. Therefore, the fracture pattern of the model is assumed to be an adequate response to the applied stress.

Similar investigations were made in a gneiss-granite area about 60 km north of Stockholm. A system of fractures, similar to that of the model in Figure 2.1.2.21 was found. The core drilling revealed that the tensile fractures were filled with a previously unknown diabase, hidden below thick glacial sediments (Larsson, 1972).

The model was also tested on granites in Sardinia. Several systems of fractures, similar to that of the model were observed in hydrogeological investigations. Two of these systems were more closely investigated by geophysical methods and test drilling. A central open, tensile fracture was found in both cases (Figure 2.1.2.22). For further description see Section 2.2.2 and case history, Section 4.6).

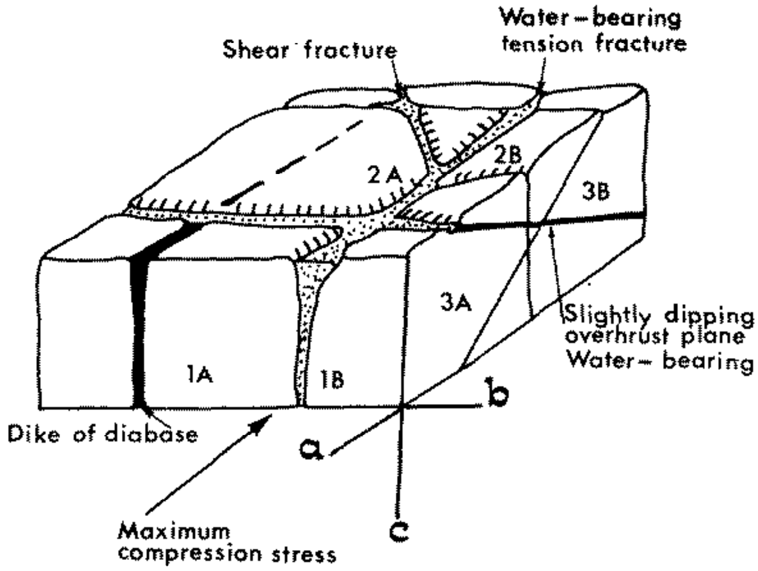


Figure 2.1.2.21 Model of rock fracturing due to brittle deformation (Larsson, 1972).

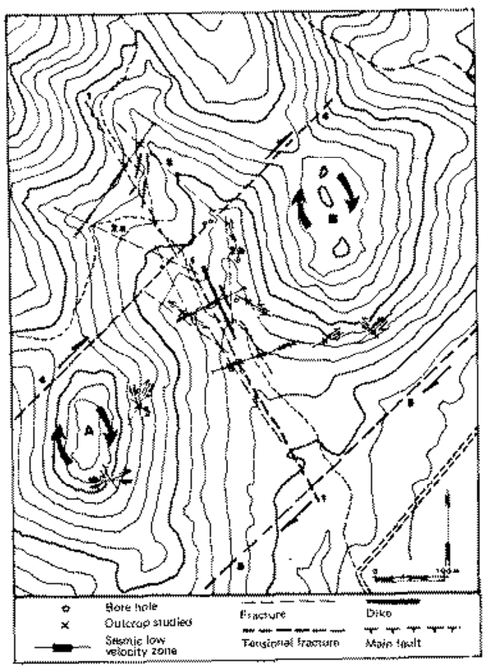


Figure 2.1.2.22 Tectonic sketch map of the Santa Margherita area, southern Sardinia, Italy, showing rotational movements of plinths. (Barrocu and Larsson, 1977).

The main problem for the hydrogeologist undertaking ground-water exploration in hard rock areas is to find a fracture pattern with maximum storage capacity. In this respect the model can be of some use. Where a set of dikes intersects a hard rock area, a fracture pattern like that of the model can be expected. The amount of water stored in the fractures cannot be directly calculated, since there are too many parameters involved. But it is possible to get an idea of the relative water-bearing capacity of the different types of fractures. A model always implies a generalization. This is also valid for the above described Karlshamn model. It is evident that the model must be modified to fit the local conditions. For instance, very often only one of the two shears 2A and 2B (Figure 2.1.2.21) is developed or dominant.

The model is applicable in hard rock areas in connection with dike formation. The topographic expression of the fractures in the model, similar to that depicted in Figure 2.1.2.22, is mostly observed in the transition zone between a mountaineous or hilly inland and a plain in front of it. From the geologic-tectonic point of view this type of tectonics has mostly been found at the boundary of crustal blocks. This is the case in southern Sweden, in the southernmost part of the island of Sardinia and in certain areas in India (see case histories, Sections 4.4 and 4.6).

It is quite clear that the model must not be applied without considering local petrographical and structural conditions. As the model is based in part on the presence of dikes, it is necessary to check if there are several generations of dikes. If there are two generations of dikes in different directions the model is still applicable. However, the model should be regarded as only one of the many tools available to the investigator.

Anisotropic steering – The brittle deformation model, described above, is designed for "isotropic" rocks. Larsson (1967) pointed out that pre-existing anisotropies may cause local deviations from the idealized model. Experience based on examination of outcrops, underground construction of tunnels and rock caverns has strengthened this asumption. Generally, a major anisotropic element in the rock conducts brittle deformation into preferred "tracks." Depending on the orientation of such an element the ideal model (Figure 2.1.2.21) can be distorted. Larsson (1967) suggested the term anisotropic-steering for this effect. Such steering elements can be a well-developed schistosity, slabs of amphibolite, etc (Figure 2.1.2.23).

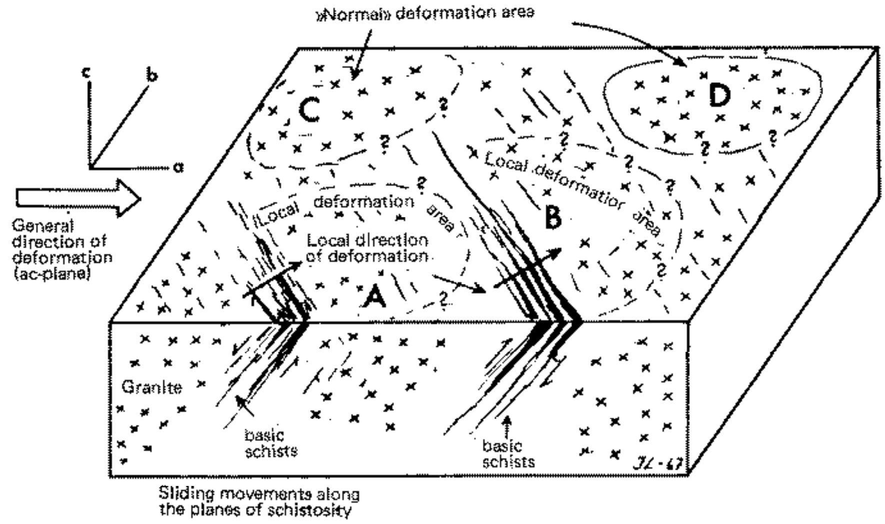


Figure 2.1.2.23 Sketch of anisotropic steering and local deviation of a hypothetical post-crystalline deformation (Larsson, 1967).

The steering effect of the schistosity of a rock is frequently observed in gneisses in Sweden, especially in the Gothenburg area. Figure 2.1.2.24 shows a model (Larsson, 1967) of a gneiss area. The applicability of the model in three dimensions has been tested with good results during construction of numerous tunnels. According to observation it is valid to a depth of 50-60 metres. The model can be applied to areas with a minimum surface of a couple of thousands of square metres. The difference between this model and the previous one is the absence of the main tensile fracture. It seems that the stress has been released in the form of overthrusts and vertical shear fractures. The reasons for this difference are still not clear.

Co-ordinate systems of fabrics and fractures – Two co-ordinate systems have been applied on folded rocks. One relates to grain fabric structures of the rock (plastic deformation) and the other relates to fracture systems in the consolidated rock (brittle deformation). Both are derived from the crystallographic axial system:

1. *Grain fabric co-ordinate system* (plastic deformation, folding). This system has already been shown in Figure 2.1.2.3. According to this system the *ac*-plane is the plane of deformation. The *ab*-plane corresponds to the foliation and the *b*-axis to the lineation. When the *b*-axis becomes an axis of rotation it is designated as *B*-axis (Sander, 1948).

2. *Fracture co-ordinate system, solid state* (brittle deformation). In this system the *ac*-plane (dike) is the plane of deformation. The *a*-axis (Figure 2.1.2.21) corresponds to the direction of maximum compressive stress. The *c*-axis is vertical and the *b*-axis is perpendicular to *a* and *b*. When the *b*-axis becomes a shear axis it is designated as *B*-axis.

In order to avoid confusion in analytical work concerning rock fractures the fabric axes can be written a^1, b^1, c^1. The axes in the fracture co-ordinate system can be denoted a^2, b^2, c^2. This nomenclature of the two-axial systems is usually abbreviated in the following way: a^1c^1 is generally written ac^1 and a^2c^2 is written ac^2, etc. The corresponding indexes (Miller) are h (to a), k (to b) and l (to c). When a plane does not cut an axis, the index is 0 (zero), e.g. $h0l$, $hk0$ (Figure 2.1.2.25).

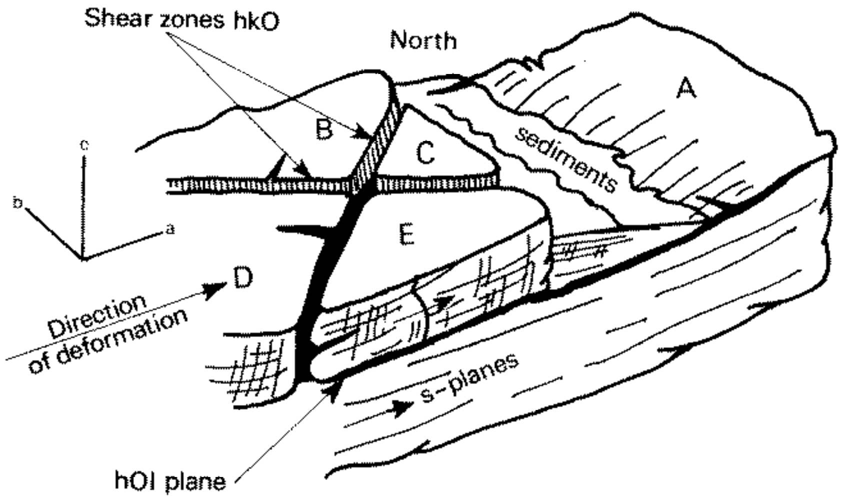


Figure 2.1.2.24 Brittle deformation model, modified by anisotropic steering due to schistosity (modified from Larsson, 1967).

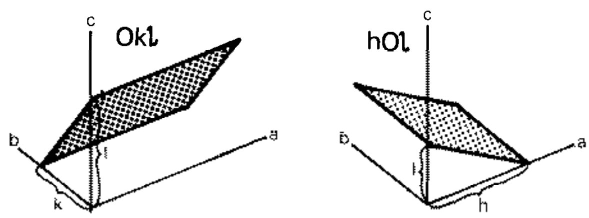


Figure 2.1.2.25 Examples of the use of indexes to define planes in relation to the axes. (Larsson, 1967).

2.1.2.4 *Non-tectonic fractures*

Thermal shrinkage, consolidation of intrusive rock bodies – Hard rocks are frequently cut by dikes, which generally show a fracture pattern quite different from that of the country rock. This phenomenon is generally interpreted as thermal shrinkage. During cooling the dikes fracture due to the contraction of the rock. The fractures thus developed are parallel as well as perpendicular to the long axis of the dikes (Figure 2.1.2.26).

Marginal zones between intrusive rocks and the country rock are often fine-grained due to rapid cooling. This is characteristic of dolerite and aplite dikes. A fine-grained rock is generally more brittle than a coarse-grained one. Therefore, marginal zones are often more fractured than the adjacent rocks.

Sheet jointing (Bankung in German) – Sheet jointing fracturing is common in hard rock areas. It is virtually ubiquitous in intrusive rocks such as granites, granodiorites, etc., which are more or less "isotropic" (in a broad sense). On the other hand sheet jointing is infrequent in anisotropic rocks. In migmatized gneisses and other metamorphic rocks, sheet jointing is fairly common (Figure 2.1.2.27).

The origin of sheet jointing is still a matter of dispute. Some authors consider this type of fracturing to be the result of load release. For example, a granite is consolidated by high loads from the overlying crust. By erosion the granite has reached higher levels. This "upheaval" should mean a change in direction of the principal stresses. During the consolidation the intermediate stress σ_2 could have been vertical. By "upheaval" it has been replaced by the minimum principal stress σ_3. This change should produce the sheet jointing.

Figure 2.1.2.26 Thermal shrinkage in a diabase dike at Karlshamn, southern Sweden. Joints parallel to the longitudinal axis of a dike.

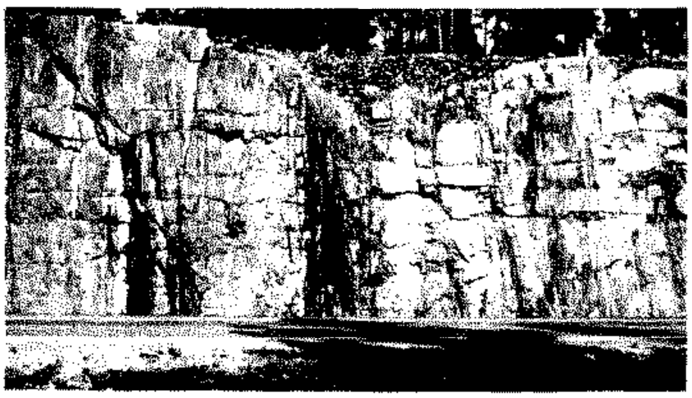


Figure 2.1.2.27 Sheet jointing in a migmatite gneiss at Nacka, Stockholm area, cutting the isoclinal structure of the gneiss.

However, Wolters (1969) gives another explanation. By studying cores from deep drillings he found that temperature changes may be the cause of sheet jointing. A comparison with the effect due to unloading shows that a change in temperature of 100° C brings about strains larger than the erosion of 10 000 m of rock. He found that even in temperate zones, temperature variations between day and night are rather large throughout the year. They result in stresses corresponding to an erosion of several metres. Still more significant is the disintegration due to large daily temperature changes, as for example in the deserts.

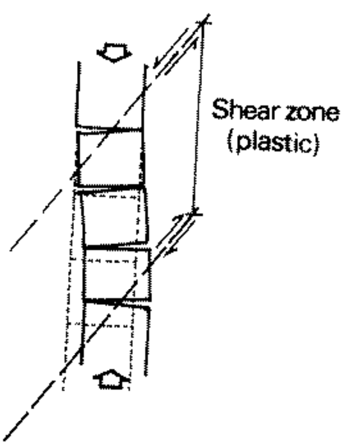


Figure 2.1.2.28 Development of a shear zone by uniaxial compression. (After Lundgren, 1978) (Reprinted by permission.)

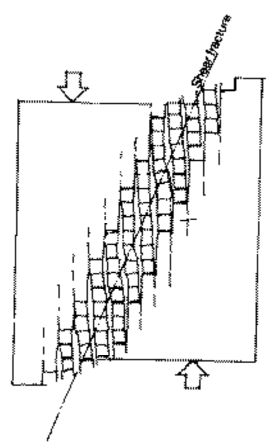


Figure 2.1.2.29 Development of a shear zone (macroscopic scale). (After Lundgren, 1978) (Reprinted by permission.)

2.1.2.5 *Scale of fracture patterns*

The length of fractures in hard rock varies through a wide range from micro fractures in the rock to fractures of continental scale. In considering the micro scale it is apparent that shear fractures are produced by uniaxial compression (Figure 2.1.2.28). The shears originate as tension fractures and propagate into macroscopic shear fractures (Figure 2.1.2.29).

This process has been discussed by Price (1966). The geological significance of the mechanism and the resultant dilation is visualized by Lundgren (1978) (Figures 2.1.2.28 and 2.1.2.29).

Major fracture patterns are often clearly visible in the topography. Aerial photos and satellite imagery are good tools to recognize major structures of the rock (Figures 2.1.2.30 and 2.1.2.31).

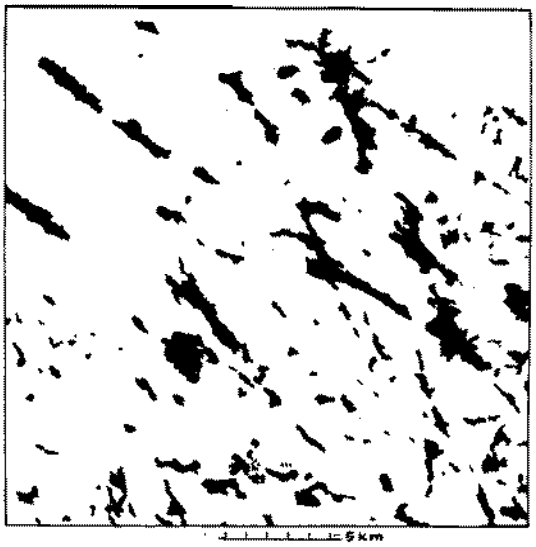


Figure 2.1.2.30 Lake pattern in SE Sweden. Tensile ac^2-fractures have a NW-SE direction. Adherent shear fractures are oriented NNW-SSE. The angle between the two directions is about 30°.

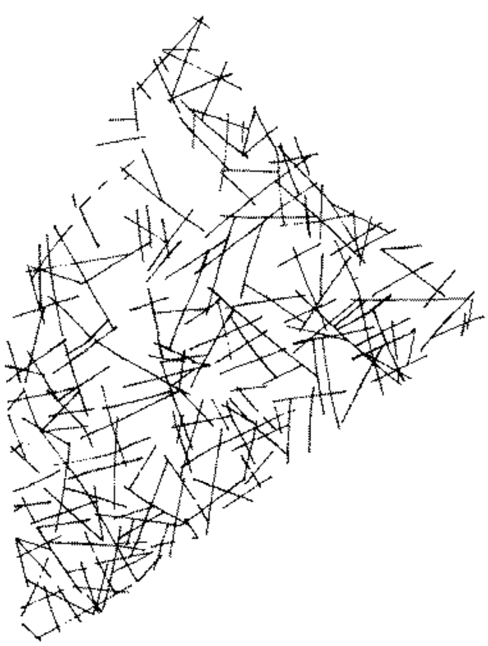


Figure 2.1.2.31 Fracture pattern in granite of Banfora, Upper Volta. (Engalenc, 1978).

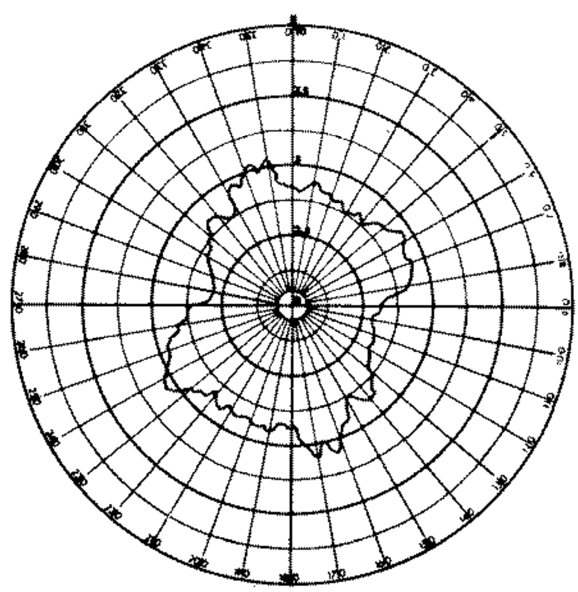


Figure 2.1.2.32 Measurement (stereographic projection) of fracture pattern in Figure 2.1.2.31 (Engalenc, 1978).

2.1.3 WEATHERED HARD ROCKS

2.1.3.1 *General features*

Large regions of the continents and neighbouring islands are directly underlain by extensive batholiths of granite, granodiorite and more mafic igneous rocks or by metamorphic complexes of gneisses, schists, quartzites, slates, phyllites and other metasediments, metavolcanics and associated igneous rocks. In these regions the ground water contained in the surficial weathered layer overlying and derived from these hard rocks commonly in tapped by thousands of wells supplying villages, farms and livestock in rural areas.

Also ground-water discharge from the weathered layer sustains the flow of springs, and in the more humid regions, the dry-period base flow of great numbers of streams. In addition to its function as a container for ground-water storage, the weathered layer also conveys infiltrating water from the land surface to deeper fracture systems in underlying hard rocks. The physical and chemical characteristics of the weathered layer and its potential to absorb infiltrating water and to store and yield it to wells, galleries and springs thus becomes a priority concern in the water economy of these regions.

The weathered layer forms as a result of the interaction between the atmosphere, hydrosphere, biosphere and lithosphere. The weathering processes, which generate the layer, include the disintegration (disaggregation) and the decomposition (chiefly hydrolysis) of original or primary mineral constituents of the host rock as well as the formation (crystallization) of secondary clay mineral products. Weathering occurs in all types of climatic environment; it is most intense in the tropics, where levels of insolation are greatest, and is least intense in the polar regions.

Weathering is dependent on the interplay of numerous factors such as: (1) relative surface area of the rock and its modification by mechanical weathering; (2) relative solubility of the original rock and its weathered products; (3) relief of the land surface; (4) size of the host rock particles; (5) permeability of the rock mass; (6) mineralogic composition of the rock; (7) temperature of the rock; (8) chemical composition and amount of the percolating water active in weathering; (9) position of the water table; (10) distribution and amounts of oxygen, carbon dioxide, nitrogen and other gases active in the system; (11) nature and abundance of macro- and microflora active in the system; and (12) wetting and drying of colloids and salts in the rocks.

2.1.3.2. *Weathering processes*

Weathering processes are commonly grouped in three broad categories: physical or mechanical, chemical and biological. These processes go on simultaneously in virtually all climatic environments, but mechanical weathering is considered to be dominant in cold and arid climates while chemical weathering is dominant in warm and humid climates. Mechanical weathering includes disintegration (disaggregation) of rocks by (1) long-continued diurnal and seasonal changes in temperature (insolation); (2) freezing and thawing of water; (3) crystallization of salts; and (4) growth of plant roots. Chemical weathering includes the mechanisms of hydrolysis, chelation, cation exchange, dialysis, oxidation and reduction, carbonation and hydration. Among these, hydrolysis, with the aid of carbonic acid and CO_2, is probably the dominant mechanism; the others are secondary. Biological weathering includes the activities of microflora (bacteria), macroflora (plants, algae, lichens and mosses), and also earth-worms and burrowing animals.

Mechanical weathering — The various minerals composing hard rocks have different indices of expansion and contraction in response to insolation. For example, the coefficient of expansion of quartz is about twice as great as that of orthoclase. Hornblende lies between these two minerals in its expansion coefficient. Thus rocks which are coarse-grained or porphyritic are more susceptible to weathering by insolation than fine-grained, even-textured rocks, owing in part to unequal expansion of mineral grains.

Part of the process of spheroidal weathering (exfoliation) may be attributed to insolation which is usally accompanied by hydration of the feldspars, micas, amphiboles and pyroxenes. Although most commonly observed in granites, granite gneisses and porphyrites, exfoliation and/or spheroidal weathering is also common in basalts and diabases as well as in some other rock types. Exfoliation occurs on all scales ranging from lamellae or weathering rinds less than a centimetre thick around spheroidal boulders to large exfoliation sheets or domes several tens or scores of metres long and commonly developed on massive homogenous granite and related rocks.

Freezing and thawing of water in temperate and cold climates is a powerful agent for fragmentation of rocks. Water freezing in the capillary pores and diaclases is particularly effective. Thus rocks with numerous diaclases such as phyllites, slates and schists are particularly susceptible to fragmentation.

Crystallization of different salts, (as for example $CaCO_3$ and NaCl in many places and MnO and Fe_2O_3 in some places), upon evaporation of dissolving liquids, is very effective in the fragmentation and comminution of brittle rocks. This process is particularly effective under conditions of alternate wetting and drying.

Chemical weathering – Primary hard rock minerals can be ranked acccording to their susceptibility to attack from oxygen, dissolved carbon dioxide and water. Most of these minerals were formed under temperature and pressure conditions greatly different from those prevailing at the earth's surface. A ranking list of susceptibility to weathering of the more common minerals in hard rocks would be as follows, with olivine the most susceptible and quartz the least:

> olivine > pyroxene > amphiboles (hornblende) > biotite > anorthite > albite > orthoclase > muscovite > quartz.

Ferrous minerals are susceptible to weathering mainly because oxidation of ferrous iron to ferric oxides involves a considerable amount of energy. The crystal lattice hence collapses more or less when ferrous iron is removed. For the feldspars, relatively small variations in crystal stability account for the differences in susceptibility, the major weathering agents being carbon dioxide and water. Quartz is soluble in water but solubility is low and the rate of dissolution very slow.

During weathering the primary minerals are transformed into new secondary minerals which are partly hydrated. These minerals frequently exhibit layered structures and are collectively called layer silicates. They are also known as clay minerals because their mechanical resistance is so low that they are found as extremely small particles.

The typical clay minerals have, in principle, rather simple structures. One can divide then into two groups, the kaolinite type and the montmorillonite types. The kaolinite type consists of a silica tetrahedral layer (each silicon atom being surrounded by four oxygen atoms) joined to an aluminum octahedral layer (each aluminum atom being surrounded by six oxygen atoms). This can be called the Si-Al structure. The layers are loosely attached by molecular forces (van der Waal forces); this accounts for their low mechanical resistance.

The montmorillonite group has as a basic feature a central aluminum octahedral layer joined to silica tetrahedral layers on each side. This can be labelled the Si-Al-Si arrangement. However, substitution has taken place in the layer. In the Si-layers, Si can be substituted for Al leaving a net negative charge which is then compensated by cation charges outside the crystal lattice. In the same way Al can be substituted for Mg or Fe^{2+} in the Al-layer, also creating charges which must be compensated by cations outside the crystal lattice. There is a considerable range in possible substitutions which account for the extraordinary range in chemical composition of the Si-Al-Si layer silicates, the extreme being perhaps illite with extensive substitution.

Compensating cations outside the crystal lattice are sodium, potassium, magnesium or calcium. Of special interest is sodium because of its high hydration which pushes the Si-Al-Si layers apart, accounting thus for the swelling properties of Na-montmorillonite. The other extreme is potassium which, because of its size, is poorly hydrated and therefore helps to join Si-Al-Si layers together, evident particularly in the illites where the joining is so firm as to make exchange of potassium very difficult.

Because of their large specific surface clay minerals retain considerable amounts of adsorbed water, part of which is available to plants. For the Si-Al-Si layers the excess net charges in the crystal lattice make them excellent cation exchangers.

During the transformation of primary rock minerals into clay minerals cations such as sodium, potassium, magnesium and calcium are released and appear partly as bicarbonates in the ground water. In addition, some silicic acid H_2SiO_4, is formed, accounting for the presence of amorphous silica frequently encountered. Although amorphous silica is very much more soluble than quartz, it may precipitate.

The transformation of primary hard rock minerals into layer silicates is enhanced by hydrogen ions, that is, by acids. This can be seen from the reaction:

$$\underset{\text{(albite)}}{2NaAlSi_3O_8} + 2H^+ + 9H_2O \rightarrow \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} + \underset{\text{(silicic acid)}}{4H_4SiO_4} + 2Na^+$$

In the zone of weathering, hydrogen ions are supplied by carbonic acid. The reaction can therefore be called a carbonation and the released sodium appears as bicarbonate. However, since water is used in the reaction it is also a hydration, particularly of the silica but also of the silicates. For ferromagnesian minerals such as biotite, ferrous iron is oxydized to ferric oxides so the reaction is at the same time an oxidation. Near the land surface organic compounds enhance weathering by chelation of cations.

Calcite is common in fractures in hard rocks. It is formed during weathering of primary minerals containing calcium as, for instance, in the reaction:

$$CaAl_2Si_2O_8 + CO_2 + 2H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$$

(anorthite) (calcite) (kaolinite)

The calcite can, later on, be dissolved by carbon dioxide in the reaction:

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$$

(calcite)

Near the land surface the weathering processes depend greatly on the transport of soluble products away from the site. Leaching of soluble compounds becomes important. During strong leaching in hot climates silicic acid will have a high solubility and will be carried away. Under such conditions no layer silicates can be formed. The residues of weathering will be ferric oxides and aluminum oxides, that is, Fe_2O_3 and AlOOH (bauxite). This process leads to lateritic soils.

In cool, humid climates the solubility of silicic acid is less, leaching is therefore less and aluminum can form kaolinite. Under semiarid conditions, leaching is impeded, favouring formation of montmorillinite minerals. It is evident then, that climatic conditions have a considerable influence on the course of chemical weathering in the uppermost portion of the weathered layer. Deeper down, in the fractures of hard rocks, climatic influences decrease, and other factors such as geohydrological conditions will then determine the course of events.

2.1.3.3. *Pedogenic regimes*

Pedogenesis – In any given region the development of the weathered layer profile is closely related to soil formation or pedogenesis, which in turn is related to climate, topographic position and rock type. Among these factors climate can perhaps be considered dominant although, locally, ground-water movement is certainly important, being partly controlled by topography. Synthesizing all the various weathering processes which have been previously discussed, it is possible to identify the following five broad pedogenic regimes: podzolization, laterization, calicification, salination and gleization. The regimes of podzolization, laterization and calcification are generally characterized by a tripartite stratification of the soil profile starting at the land surface with the A horizon, progressing downward to a B horizon and with a C horizon at the base.

Podzolization – The podzol soil type is characteristically developed in cool climates with relatively abundant precipitation, generally in the middle and high latitudes or at high altitude. The coniferous forest trees, typical of this regime, do not require much of the bases (Na, K, Ca and Mg) and hence do not restore any appreciable part of them to the soil through decay of litter. Humic acids from abundant leaf mould leach the upper part of the A horizon of the bases, colloids, Al_2O_3, Fe_2O_3 and clay minerals. The bases are carried down in solution to the C horizon and from there to the ground water and out of the system; the other solutes are precipitated in the B horizon. The lower part of the A horizon – the bleached horizon – consists then, largely of silica (SiO_2).

Laterization – This process is the warm-climate equivalent of podzolization and is also associated with forests and high precipitation. Laterization takes place in equatorial-rainforest, tropical wet-dry, monsoonal and humid subtropical climates. With characteristically thriving bacteria, which destroy dead vegetation as fast as it is produced, there is little or no humus in the soil. Because of the absence of humic acid, Fe_2O_3 and Al_2O_3 are relatively insoluble and accumulate as hydrates in red clays, nodules and rock-like layers (laterite) in the B horizon. Silica (SiO_2) together with the bases (Na, Mg and Ca) are leached down to the C horizon and thence to the ground water and out of the system. In contrast to podzolization clearly distinctive A, B and C horizons are not developed in laterization. Also as clay minerals are virtually absent, the A and B horizons tend to be porous rather than sticky and plastic. Laterization commonly results in low soil fertility because the bases and humus are lacking in the A horizon.

Ground-water recharge and discharge – Podzolization and laterization require strong leaching as a result of downward movement of percolating water. These pedogenic regimes are, therefore, commonly tied to source areas of ground water or perhaps better ground-water recharge areas.

Ground water usually emerges in the lower parts of the terrain as in valleys along river courses. These parts are called ground-water discharge areas and may be permanent or temporary. When the relief of the land is low these ground-water discharge areas may be extensive and the permanent parts will form swamps. Because of evaporation from ground-water discharge areas, dissolved salts will be concentrated in the soil and in the water unless precipitation is high enough to wash them away.

Calcification – In semi-arid climates ground-water discharge may not be visible at the surface as such. However, because of evaporation, a concentration of the salts dissolved in the ground water takes place. This may lead to deposition of salts, particularly of calcium carbonate, below the root zone. Accumulation of easily soluble salts may, nevertheless, be prevented if the climate is alternatively dry and wet seasonally; in this case excess salts are washed out during the wet season. This, however, does not prevent deposition of calcium and carbonate, and the process eventually leads to the formation of calcium carbonate hardpans in the ground-water discharge areas. As the hardpans grow and become impervious the ground-water discharge areas will shift "upstream," hence covering larger and larger areas. This process is called calcification. The calcium carbonate precipitated forms nodules, slabs and layers of caliche, "croûte calcaire" or hardpan in the B horizon.

Salinization – This process is generally associated with semi-arid and desert climates where there is an accumulation of highly soluble salts in the soil profile, again due to ground-water discharge. Salinization profiles occur where there is poor drainage and surface-water runoff accumulates and evaporates. Salinized soils are commonly located in low-lying valley floors, flats and continental interior basins, and in places along arid and semi-arid sea coasts. Sulphates, bicarbonates and chlorides of sodium, potassium, calcium and magnesium are common salts in such soils.

Gleization – This process is associated with poor (but not saline) drainage, cool or cold (tundra) climates, and also bog environments. Commonly, the A horizon is characterized by an accumulation of peat with an acid (low) pH. Below the peat, in a saturated B horizon, occurs the glei, a blue-gray structureless clay resulting from reduction of ferric iron to FeO (ferrous oxide) which imparts a blue-gray colour to the clay.

2.1.3.4 *Weathered layer profile*

Although there is considerable potential range in the thickness, areal extent and physical character of the weathered layer from place to place and region to region, the typical profile, beginning with the fresh host rock at the bottom and progressing downward from the land surface, may be summarized as follows:

Zone (a): Sandy clays or clay sands often concretionary. Generally no more than a few metres thick.

Zone (b): Massive accumulation of secondary minerals (clay) in which some stable primary minerals may be preserved in their original form. Its thickness may reach up to 30 metres. High porosity but low permeability.

Zone (c): Rock which is progressively altered upward to a granular friable layer of disintegrated crystal aggregates and rock fragments. May range in thickness from a few metres to 30 metres.

Zone (d): Fractures and fissured rock. May range from a few tens to several scores of metres in thickness. Low porosity but moderate permeability of fracture system.

In most places zone (a) is essentially a continuum with the C horizon of the soil profile. The B horizon is commonly the most compact part of the soil profile and is the locus of most intensive deposition of nodules and/or layers of ferruginous and/or aluminous laterites in humid and subhumid tropical environments (laterization pedogenic regime). Where the climate is semi-arid or wet-dry tropical (calcification pedogenic regime) the B horizon is the locus of deposition of nodules and/or layers of calcium carbonate known locally as kankar, caliche, croûte calcaire, calcrete or hardpan, indicating at least temporary ground-water discharge. With advanced laterization or calcification, as may occur in the old age cycle of geomorphic evolution, laterite or calcrete duricrusts may take over most of the B and C horizons of the soil profile and may attain thicknesses ranging from a few metres to as much as 15 metres. In some transitional climatic environments it is possible to find both laterization and calcification regimes co-existing in the same general region, as for example in parts of western and southern India.

2.1.3.5. *Extent and thickness of the weathered layer*

To contain significant aquifers with exploitable ground water the weathered layer must attain a minimal areal extent and thickness and have sufficient porositiy and permeability to store water and to yield it to wells from season to season and from year to year. Extensive and thick weathered layers are likely to contain the most viable and productive aquifers. Thin weathered layers may contain no significant aquifers or, at best, intermittent ground-water bodies which do not persist through long dry periods. Locally, however, even relatively thin weathered layers may sustain perennial aquifers, provided there is prevailing high recharge, either natural or artificial. In some irrigated areas of India, for example, return seepage from irrigation plus natural recharge sustain wells in weathered layers only 5 to 7 m thick. In most places, however, weathered layers less than 10 m thick do not generally contain exploitable aquifers. Even where the weathered layer is of maximal thickness (as much as 50 to 70 m or even more in some places in the humid tropics) only 10 to 15 % of the total thickness may contain materials sufficiently permeable to yield water to wells.

Many productive wells, where ground water is developed for rural water supply, livestock or small-scale irrigation, tap aquifers in zone (c) of the weathered profile which averages about 10 to 20 m in thickness. Where the weathered layers are thin or absent, ground water occurs in the fracture systems of zone (d) and must be sought by drilling to tap these systems. Even thin weathered layers perform the important function of absorbing infiltrating rainfall and transmitting it to deeper fracture systems. Indeed, in many situations it is possible for a well to tap water both from the weathered layer and from a deeper underlying fracture system. Such a well has the possibility of drawing on deeper ground water stored in the fracture system, when that in the weathered layer becomes depleted during dry cycles.

The thickness of the weathered layer and the presence of permeable zones in it depend on the interplay of a number of factors, among which are climate, topographic position, mineralogic composition and lithologic texture, and the distribution and spacing of the fracture system in the host rock.

The thickest weathered layers generally develop in subhumid and humid tropic regions where vegetative cover is relatively dense and annual rainfall exceeds 1,000 mm. In the eastern districts of the Upper Region of Ghana, for example, the weathered layer averages about 65 m in thickness and in places along major faults it is as much as 135 m thick. This area lies in the Guinea savannah belt of West Africa where the average annual rainfall ranges from about 1,000 to 1,150 mm. Similar conditions are reported in neighbouring parts of Ivory Coast, Upper Volta, Togo and Benin.

Relatively thick weathered layers may also be found in regions which are now essentially semi-arid. In low-latitude steppes of Rajasthan in western India, for example, the weathered layers are as much as 25 to 30 m thick in areas where the annual rainfall is now only 380 to 460 mm. (Taylor, Roy and Sett, 1955). Under somewhat higher rainfall conditions, in Sudan and Nigeria, the weathered layers are reported in places to attain a thickness of 50 m. The development of such thick weathered layers is believed to have occurred during warm pluvial cycles of the Pleistocene epoch.

Thick weathered layers in parts of the semi-arid Sudan savannah and Sahelian steppe regions of western and central Africa may also be relics from earlier pluvial cycles of the Pleistocene or even more remote Tertiary time. Estimates of the thickness of weathered layers tapped by wells, as reported in a number of African countries, are shown in Table 2.1.3.1 and in countries of the Western Hemisphere and Asia in Table 2.1.3.2. (See also Tables 2.2.3.1 and 2.2.3.2). (Some of the exceptionally thick weathered layers reported may not be related to meteoric factors but rather to tectonization and hydrothermal alteration).

Relatively thick weathered layers are also developed in certain hard-rock terrains of the eastern United States, southern Europe, eastern Asia and southern South America that are now in temperate climatic zones. These areas all lie beyond the limits of Pleistocene glaciation where erosion has progressed to the mature or late mature stage of the geomorphic cycle. These weathered layers may have been developing since late Pliocene times with weathering possibly accelerated during the warm interglacials of the Pleistocene epoch.

Topography and stage of geomorphic evolution are important with respect to the development of areally extensive weathered layers (Cotton, 1948; King, 1962). These are commonly most extensive and thickest in erosional peneplains of low relief at or near base level where local relief is only a few metres and the slope of the land surface is less than 10 per cent. Such peneplains cover thousands of square kilometres in the hard-rock terrains of Uruguay and Brazil; Sub-saharan Africa; peninsular India; and parts of Australia. Erosional residuals as inselbergs ("morros" in Brazil), sugar loaves, whalebacks, tors and kopjes commonly take up perhaps 15 to 20 per cent of the gross area of these terrains in the old-age stage of the geomorphic cycle but as much as 50 per cent or more in the late mature stage. The residuals are generally devoid of weathered layers and fresh rock crops out at the surface.

Table 2.1.3.1 Typical yields reported from wells tapping weathered hard rocks in Africa (after United Nations, 1973).

Country	Province or area	Rock types	Yield per well (m^3/h)	Remarks
Angola	Catuiti	Granites	3 to 30	
Botswana		Granites, gneisses and schists	0.5 to 10	
Central African Republic		Gneisses schists and quartzites	0.5 to 5	Of 400 dug wells put down during 1967-69 to depths of 3 to 15 m, 90 % were productive in the weathered layer above the basement.
Benin	Central Region	Granite gneisses, mica schists	1 to 4	
Dem. Rep. of Congo (Zaire)	Orientale	Gneiss, schist and quartzites	1 to 8	Wells 25 to 100 m deep. Spec. capacity 0.4 to 3.6 $m^3/h/m$.
Ethiopia	Sidamo	Granite, gneiss and schist	Low	Weathered layers, poorly developed. Yields from fractured zones low and water often of poor quality.
Ghana	Accra plains	Gr., gn., qtz., biotite schist	0.5 to 11	
	Upper and Northern Regs.	Granite	0.4 to 24	Range in 280 wells averaging 34 m deep.
Ivory Coast	Western Region	Granite	2 to 5	Wells 10 to 15 m deep.
Mozambique	Central and northern region	Granites, ortho-gneisses, para-gneisses	4 to 12	Weathered layer thick and fairly permeable.
		Ferromagnesian paragneisses	low	Weathered layer clayey and barren.
South Africa	Precambrian basement area	Granite gneisses and schists	0.5 to 10	Weathered layer 30 to 150 m thick. Detected by electrical resistivity surveys. About 50 % of the boreholes in the country tap water in the weathered layer.
Zimbabwe	Central area			
Sudan	Southern Kordofan	Granite, gneiss, schist	0.5 to 6	Weathered layer 10 to 50 m thick.
Swaziland	Central area	Granite gneiss	0.5 to 6	Weathered layer 10 to 30 m thick.

Table 2.1.3.2 Typical yields reported from wells tapping weathered hard rocks in the Western Hemisphere and India.

Country	Province or area	Rock types	Yield per well (m^3/h)	Remarks
United States	Piedmont region South-western states	Gneiss and schist most common with some granite and other intrusive rocks	3 to 10 occasionally 2à or more	Weathered layer ranges from 15 to 30 m thick. Most wells tapping weathered layer are less than 45 m deep. Water generally contains less than 500 mg/l.
Brazil	Semi-arid region (North-east)	Granites, gneisses, schists and other metamorphic and igneous rocks	0.3 to 8	Weathered layer ranges from 5 to 10 m thick. Wells range from 20 to 40 m deep. Water commonly contains more than 3000 mg/l. Spec. cap. 0.1 to 1.0 $m^3/h/m$.
	Humid region	d:o	0.5 to 15 average 6	Weathered layer ranges from 10 to 20 m thick. Wells range from 10 to 30 m deep. Water commonly contains less than 1000 mg/l. Spec. cap. 0.2 to 4 $m^3/h/m$.
Uruguay	South	Granites, gneisses, metamorphics	0.2 to 8 average 5	Wells tapping weathered layer range from 20 to 40 m deep. Spec. cap. 0.1 to 1.8 $m^3/h/m$.
India	Semi-arid region (Rajasthan)	Granite	0.9 to 2.8	Wells tap weathered layer which is 12 to 25 m thick. Water is brackish to sightly saline.
		Slates	0.6 to 4.0 aver. 2.2	
	Sub-humid region (Karnataka)	Granite	0.5 to 15 aver. 3.2	Wells tap weathered layer at depths generally less than 15 m.
		Cordierite, hornblend and biotite gneiss		D:o
		Crystalline schist	D:o	D:o
		Clayey schist and phyllite	Low	Weathered layer clayey with poor aquifers.

Major inselbergs and whalebacks may rise as much as 100 to 500 m above surrounding lowland plains. Tors and kopjes, which are minor topographic features, generally form low rocky knobs only a few metres or a few tens of metres above the plains. The inselberg-and-plains topography (Bornhardt, 1900) is quite common in the hard-rock terrains previously mentioned and occurs in tropical and subtropical climates ranging from humid to arid. Although the development of this type of topography has been attributed exclusively to geomorphic processes operative in the savannah or steppe climate, it is also found in humid tropical and subtropical hard-rock terrains.

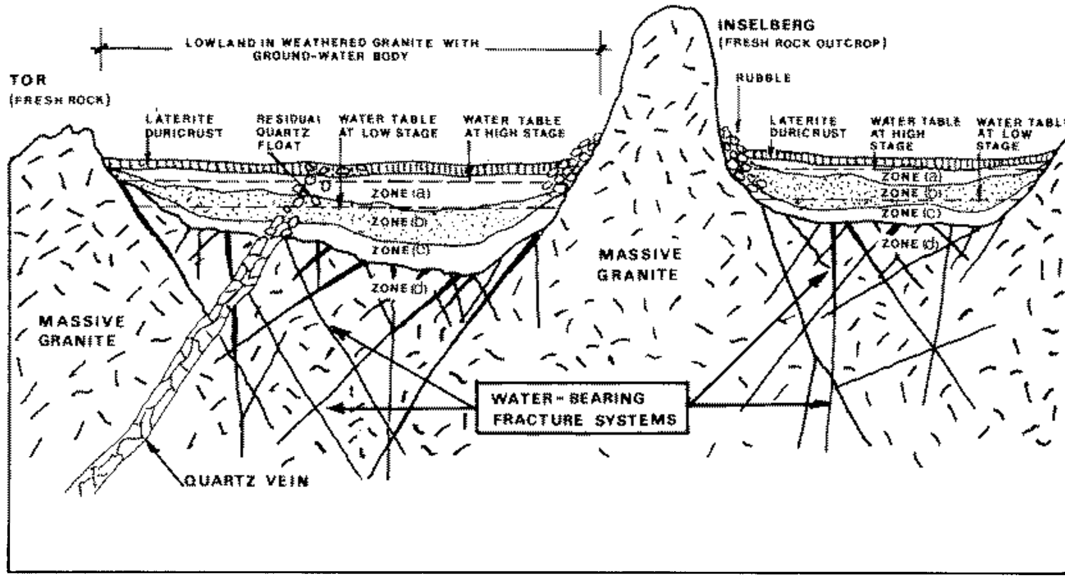


Figure 2.1.3.1 Sketch of lowlands of weathered granite forming ground-water bodies and separated by uplands of unweathered, massive granite. Laterite duricrust: Hard ferruginous carapace passing downward into ferruginous clays and ferruginous concretions.
Zone (a): Sandy clays and clayey sands. Commonly concretionary and kaolinitic. High porosity but low permeability.
Zone (b): Altered massive clays, commonly plastic, in which stable primary minerals may be preserved in their original form. High porosity but low permeability.
Zone (c): Rock progressively altered upward to a granular, friable layer of disintegrated crystal aggregates and rock fragments. Low porosity but appreciable permeability.
Zone (d): Fresh fractured rock with water-bearing fractures.

A somewhat idealized cross-section through a hard-rock terrain of inselberg-and-plains topography is shown in Figure 2.1.3.1. As noted in this sketch the weathered layer profile is developed only in the lowland plains between bare erosional residuals (inselbergs, tors, etc.). Although a laterite duricrust is indicated on this sketch, it might even be totally missing or, under drier conditions, substituted for a calcrete or silcrete duricrust. Laterites, which are now found in regions with low-latitude steppe or semi-desert climates, may be relics from early pluvial cycles of the Pleistocene. The configuration of some typical inselberg-and-plains terrains for several regions in Africa and India are shown in Figures 2.1.3.2 - 2.1.3.7.

The relative areal extent of the lowland plains versus that of the residual uplands (inselbergs) depend chiefly on the stage of the geomorphic evolution of the region. Rejuvenated and uplifted peneplains under active erosion may have the earlier developed weathered layers partly or completely stripped away. Such rejuvenated peneplains occur in parts of northeastern Brazil and southern Africa.

Elsewhere erosion may have progressed only moderately leaving extensive tabular residuals capped by laterite (or silcrete and calcrete) duricrusts which protect the soft underlying zones (a) and (b) of the weathered layer on hard rock terrains. Such tabular residuals, often hundreds of square kilometres in areal extent, are common in Upper Volta and neighbouring parts of Mali and Niger as well as in Sudan and parts of India and Australia.

The mineralogic composition and lithologic texture of the host rock also play important roles in the development of the weathered layer. These are commonly thickest and contain the most permeable (c) zones on coarse-grained salic rocks such as granites; granodiorites, and orthogneisses. Among all the various categories of hard rock terrains the granite, granodiorites and orthogneisses generally seem to have the greatest susceptibility to deep weathering (as much as 100 m deep in places). Also in these quartz-rich rocks zone (c) layers are commonly thicker and more permeable than in mafic rock terrains. In large and extensive granite batholiths which have been subject to prolonged weathering, zone (c) may range from 10 to 30 m in thickness.

All other factors being equal the finer-grained rocks are less susceptible to weathering than the coarse-grained ones. In the inselberg-and-plains terrains of northwest India, for example, fine-grained granites commonly form inselbergs or

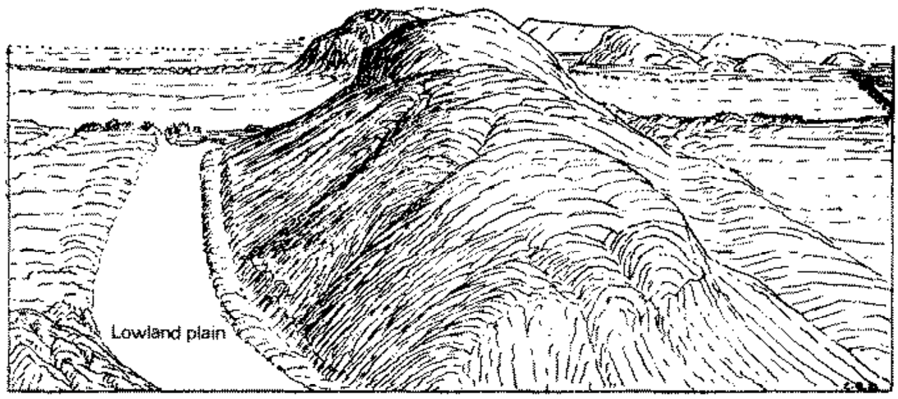


Figure 2.1.3.2 A group of inselbergs traversed by the Kistna River at the base of the Eastern Ghats. (Modified from Cotton, 1948)

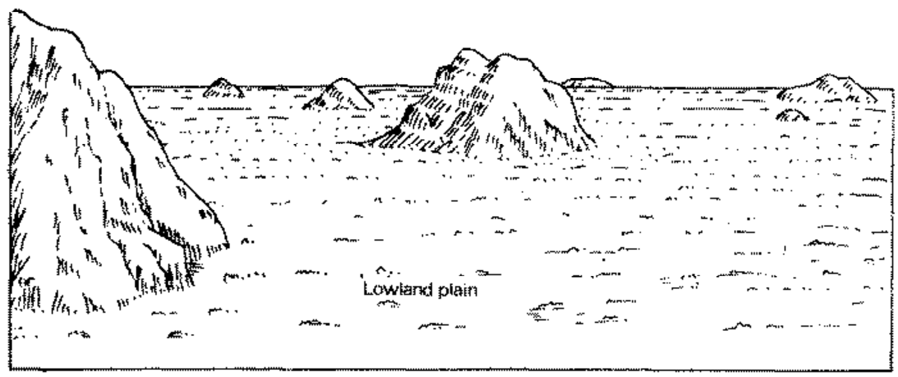


Figure 2.1.3.3 The "inselberg landscape" of Mossamedes; South-west Africa. (Modified from Cotton, 1948).

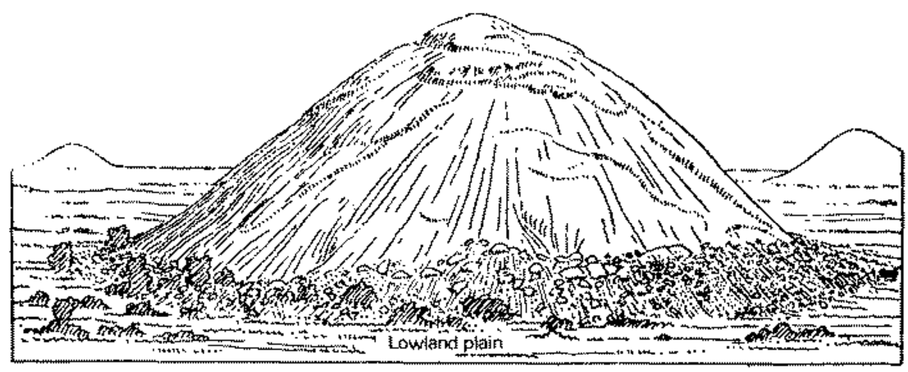


Figure 2.1.3.4 An inselberg of granite in the Kilba Hills, Northern Nigeria. (Modified from Cotton, 1948)

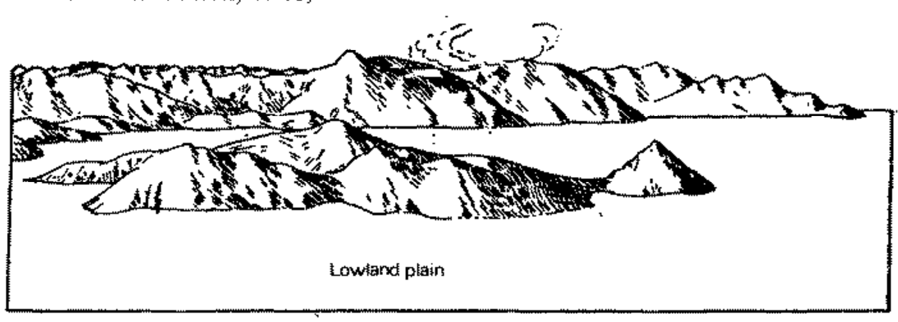


Figure 2.1.3.5 Mature savana landscape at the western side of the Alantika Mountains Adamawa, W. Africa. (Modified from Cotton, 1948)

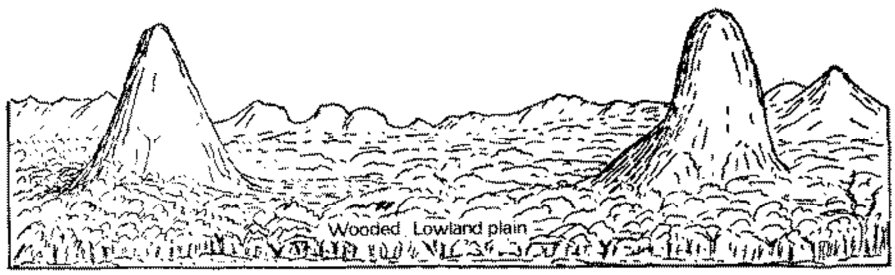


Figure 2.1.3.6 Sugarloaves of the Ribawe inselberg group, Mozambique. (Modified from Cotton, 1948)

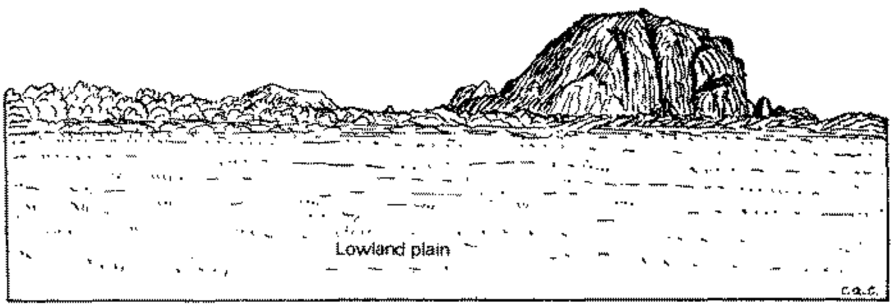


Figure 2.1.3.7 An inselberg at Krishnagiri, Madras, India, on granite-gneiss errain. (Modified from Cotton, 1948)

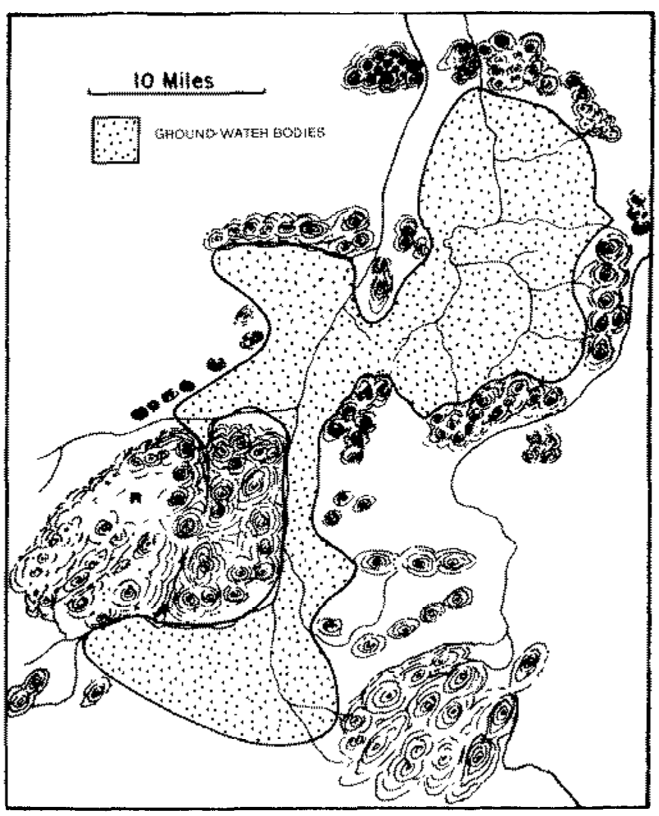


Figure 2.1.3.8 Development of ground-water bodies in an inselberg-and-plains. (After Holmes, 1918) (Reprinted by permission of Geological Society of London).

erosional residuals of unweathered rock and subjacent coarse-grained granites beneath lowland plains are weathered to depths of 30 m or more. When developed on mafic rocks such as diorites, gabbros, diabases and dolerites, the weathered layer may be thick but the (c) zones tend to be clayey and poorly permeable. Among the metamorphic rocks in hard rock terrains, quartz mica schists and thin-bedded quartzites may develop fairly permeable (c) zones in the weathered layer. These zones are seldom more than 5 to 10 m thick in contrast with those in the granites. Massive quartzites, however, commonly resist weathering and form linear inselberg ridges rising above lowlands of other weathered rocks. On some metamorphic rocks of stable mineral composition such as slates, phyllites and argilaceous schists, weathered layers may be thin or absent, even when these rocks underlie extensive peneplains in climates otherwise favourable for deep weathering.

The spacing and distribution of fracture systems in the host rock are also highly important factors in the development of the weathered layer. In granite and other salic rock terrains, for example, where the fracture systems are closely spaced (a few metres or less) weathering agents may penetrate deeply into the host rock to form thick weathered layers with permeable (c) zones. On the other hand, the massive and poorly fractured granite resists weathering and forms erosional residuals which may rise from a few metres to 100 m or more above intervening lowlands of deeply weathered rock. By this action discrete ground-water bodies are formed in the weathered layers of the lowland areas separated by unweathered uplands of fresh rock. These relations are shown schematically in Figure 2.1.3.1.

Ground-water bodies may also potentially occur in all the weathered-rock lowland plains shown in Figures 2.1.3.2 - 2.1.3.7. Typical ground-water bodies in an inselberg-and-plains terrain including the Ribawe Range (R) and Nrassi Basin (N) in Central Mozambique are shown in Figure 2.1.3.8.

2.2 *HYDROLOGICAL GHARACTERISTICS*

2.2.1. GENERAL FEATURES

Ground water moves and is stored in hard rock terrains in relatively open systems of fractures in unweathered rock and also in pervious zones of the surficial weathered rock layer. Where the weathered layer is thin or absent, as may be the case in upland or mountainous regions of active erosion, virtually all ground-water movement and storage occurs in open fractures. Also in such regions surface drainage networks are commonly aligned along the fracture system in the underlying rock (Figure 2.2.2.7). Relatively little recharge to ground water in such fractures takes place by direct infiltration from rainfall. Rather, recharge occurs chiefly by infiltration from streams where these cross or closely follow open fracture traces. Percolating water moves down the hydraulic gradient through open fracture systems and discharges through springs at points where the traces of closed clay-filled fractures intersect stream channels or where masses of impervious unfractured rock interrupt the continuity of open fracture systems.

Where thick weathered layers are well developed, as is commonly the case in lowland peneplains, virtually all percolating water must necessarily move through the weathered layer before it can enter deeper fracture systems in the unweathered rock. Thus, shallow ground water is commonly stored transiently in the weathered layer, chiefly in the zones (c) and (b) previously described (2.1.3.1). This ground water generally forms a continuum with that stored in the deeper fracture systems of the host rock, that is, in zone (d).

In contrast to the host rock, virtually all the alteration products of the weathered layer have appreciable interstitial porosity. This is important from a hydrological standpoint. Generally, the total porosity of zone (b), previously described, is relatively high — of the order of 40 to 50 per cent. However, because most of the pore spaces are very small, the hydraulic conductivity is often quite low probably in the range of 10^{-5} to 10^{-8} cm/s. Porosity decreases with depth in the weathered profile, but at the same time the hydraulic conductivity may increase to the range of 10^{-2} to 10^{-3} cm/s. Zone (c), for example, is commonly the most permeable part of the weathered profile.

Ground-water bodies occurring in lowland areas of weathered hard rock tend to be relatively small, with surface areas ranging from a few tens to a few hundred square kilometres. Many such bodies are contiguous with the valleys of fairly large through-flowing streams which may be either ephemeral or perennial. Other basins may lie in systems of interior drainage with a central discharge sump or pan. Within any given surface drainage system there may be several independent ground-water systems developed in lowlands of weathered rocks. Moreover, even beneath peneplains of relatively large areal extent and seeming continuity, subsurface interruptions or discontinuities of unweathered and unfractured rock may occur. These divide the weathered rock, as well as contiguous underlying fracture systems, into fairly small "cells" each of which functions as an independent hydrologic unit in so far as the recharge and discharge of shallow ground water and the areal distribution of water quality are concerned (see Section 2.3.4.1).

Ground water stored in the weathered layer is intermittently replenished by direct infiltration from rainfall as well as by indirect infiltration from influent (losing) streams. As most weathered layers tend to be discontinuous both laterally and vertically, virtually all recharge is of local origin and not supplied by some distant source. Much infiltrating water after passing through the soil profile (and any laterite or calcrete duricrust that may be present) is intermittently stored in zone (b) which has high porosity but low permeability. This water drains slowly into zone (c) and thence into underlying fracture systems of zone (d).

The amount of water available to recharge ground water in hard rock terrains of low relief depends on the annual total rainfall; the intensity and duration of individual rainstorms; and the evaporation which is a function of latitude (or insolation), altitude and temperature.

Where rainfall exceeds 1 000 to 1 200 mm per year, as in low-latitude wet savannahs, equatorial and tropical rain-forests, rainfall generally exceeds potential evaporation most of the year. Under these conditions, a large part of the precipitation, perhaps as much as 20 to 30 per cent, can percolate down to the aquifer during the course of the year.

Where the annual rainfall is less than 200 mm, as in arid climates, the central factor in recharge is the intensity and duration of individual rainstorms. Thus, even where potential evaporation exceeds rainfall most of the time, recharge occurs in sporadic events during which there is an excess of rainfall over evaporation over a span of several days or more, allowing time for infiltration to occur. Recharge also takes place chiefly by infiltration from streams rather than directly from rainfall. Such recharge events may be widely spaced in time and several years or decades may pass between recharge events.

Where rainfall is between 250 mm and 1 000 mm, as in the low latitude steppes and dry savannahs, the decisive factor is potential evaporation, as rainfall is more evenly distributed over time. Even during the rainy season, with variable rainfall distribution from year to year, evaporation may still be significant. A highly variable residual amount of water is generally available each year for recharge and/or runoff. During long dry seasons, which may last 3 to 6 months, there are considerable evaporation losses from shallow ground-water and surface-water bodies.

Because of the low overall permeability of the weathered layer, the range between the high and low stages of the ground-water level can be quite large. Commonly, at high stages, the water level may rise to within 2 or 3 m of the land surface and then, with declining stages reach lows of as much as 10 to 15 m or more below land surface. In areas where the annual rainfall exceeds about 600 mm the water level commonly fluctuates seasonally entirely within the weathered layer. On the other hand, where rainfall is less than 600 mm annually, the weathered layer, especially where it is relatively thin, may be seasonally dewatered when the water level declines into zone (d).

The response of the ground-water level in the weathered layer to recharge events is also quite rapid. Water-level rises of several metres are commonly observed in wells within periods of a few days to a week following such events. Subsequent water-level declines during dry cycles are generally more gradual and prolonged. Probably the decline is gradual because much natural discharge from the weathered layer takes place through slow dissipation by evaporation from the upper part of zone (b) rather than by more rapid outflow from springs. These, in fact, are rather uncommon in weathered rock terrains of low relief where annual rainfall is less than 600 mm. Most ground-water discharge in such areas takes place through direct evaporation from the capillary fringe or through vegetation where the fringe is within the limits of root penetration.

Where the rainfall is greater than about 600 mm but less than about 1 000 mm, zone (b) may be seasonally dewatered during long dry periods. In this case the depletion curve of the declining water level tends to flatten markedly and stabilize when the water level reaches zone (c), which has a much higher permeability and specific yield than zone (b). Although most groundwater discharge still takes place by evaporation, temporary springs may discharge to surface streams or sumps (pans) during and following periods of high rainfall.

Where rainfall exceeds 1 000 mm annually and is fairly well distributed throughout the year, the water level may fluctuate through a range of only a few metres and remain near the land surface through most of the year. Also zones (b) and (c) of the weathered layer remain continuously saturated. There is, however, active transpiration of ground water by vegetative cover, and springs rising from the weathered layer feed the flow of perennial streams.

2.2.2 HYDROLOGICAL SIGNIFICANCE OF FRACTURES

If the weathered layer with its special hydrologic characteristics is omitted from consideration, it can be stated that the storage capacity of hard rock aquifers depends on the fracture porosity. This is a general characteristic, similarly developed in all hard rock terrains. This characteristic is modified by weathering processes and influenced by the hydraulic properties of any material filling the fractures. The two last-named factors are, to a great degree, influenced by local conditions of geology, topography and climate.

The storage capacity of hard rocks depends on the relative degree of fracturing the specific rock type will permit. Thus, we can discern a selective storage capacity. In analysing this characteristic the authors have used the convenient field terms — "dry rock" or "tough rock," "soft rock" and "brittle rock" — defined as follows:

"Dry rock" or "tough rock": (competent)
Massive rock with low frequency of fractures. Low storage capacity. "Tough" should indicate that rock bodies of this kind can transfer stress in the crust to neighbouring rock bodies, without being fractured themselves (such as icebergs crushing weaker ice sheets).

"Soft rock": (incompetent)
Mainly slightly metamorphosed schists, with low resistance to brittle deformation. Often heavily crushed into breccias and mylonites. Fractures generally covered with slickensides (chlorite, etc.). Generally low storage capacity (see Section 4.1.2)

"Brittle rock": (incompetent)
Mainly acid intrusive rocks such as granite (batholith, etc.) with well-developed fracture patterns. The most typical brittle rock is aplite. Good to high storage capacity.

It is emphasized that these terms are to be applied only on a megascopic scale.

2.2.2.1 *Characteristic storage capacity of different types of rocks*

Acid intrusive rocks such as granites, granodiorites, aplites, quartzporphyries and pegmatites, have a high storage capacity, as they are brittle rocks from a hydrogeological point of view. Fine-grained rocks are generally good aquifers. They have a characteristic type of narrowly spaced fractures. Granite areas, on the other hand, often show a fracture pattern which divides plateau-like granite areas into a mosaic of plinths (Figure 2.2.2.1).

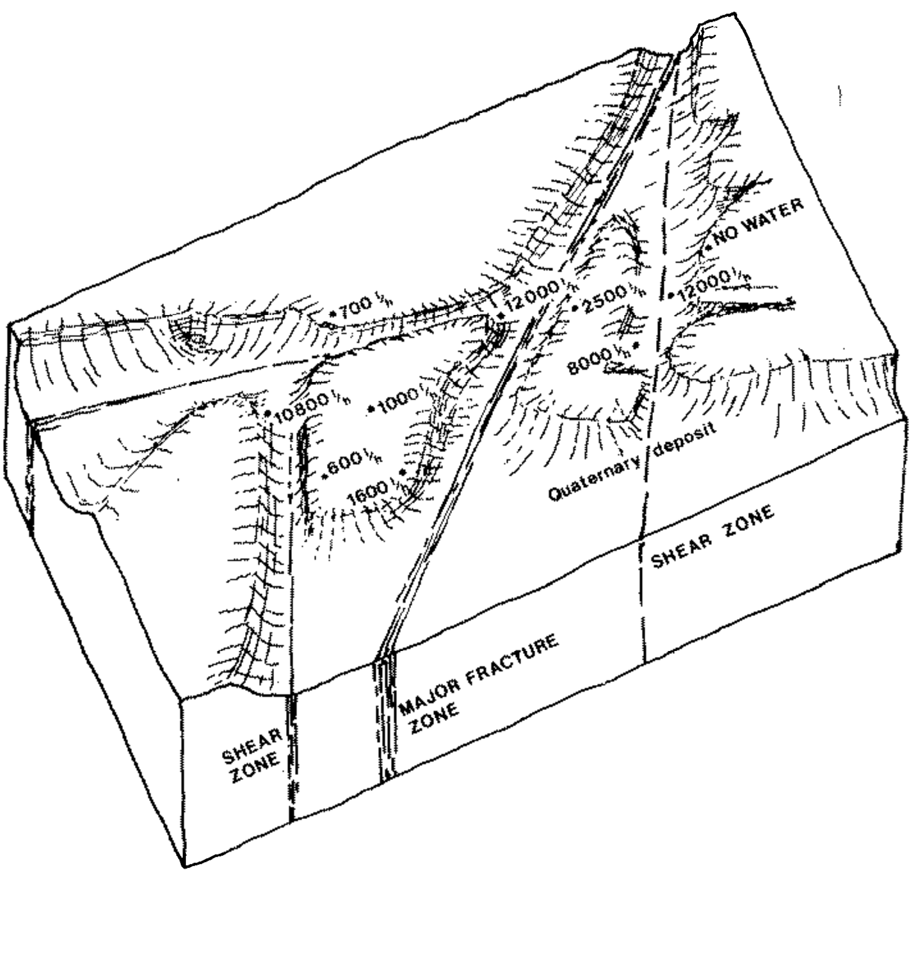


Figure 2.2.2.1 Block diagram showing plintns in a gneiss-granite area in southern Sweden. Yields of drilled wells given in litres per hour (after Larsson, 1963).

Inside the plinths the rock is very little fractured and has, therefore, low storage capacity. This relation is well illustrated in Figure 2.2.2.1 which shows the yield of a number of drilled wells in a gneiss-granite area in southern Sweden (Larsson, 1963). It should be mentioned that the yields shown in the figure were not obtained by conventional pumping tests. They are approximate yields furnished by the driller on completion of well construction. In spite of this lack of precision the differences between yields inside the plinths and those of wells in the fracture zones are quite apparent.

Pegmatite intrusions are generally very brittle and therefore highly permeable. The vital point is the grain size. The more coarse-grained, the more brittle is the pegmatite. The more brittle the rock, the bigger is the potential yield of ground water, assuming recharge has been effective.

Basic intrusive rocks such as diorites and gabbros have in general low storage capacity. Basic rocks can be considered in field terms as tough rocks and, therefore, they are poor aquifers.

Basic dikes constitute rather poor aquifers because of the weak interconnection between the dike and the country rock. However, the boundary zone between the dike and the country rock often contains open fractures with high storage capacity. This characteristic usually results from thermal shrinkage at the time of cooling of the dike; consequently open spaces develop between the dike and the country rock. The fine-grained boundary zone between the two rocks generally is more fractured than the interior part of the dike.

Dikes have another characteristic that may have local importance for ground water. They commonly act as subterranean dams, dividing the rock into separate hydraulic units. If a mountain slope is cut by a set of dikes trending more or less parallel to the contour lines, the dikes will have a damming effect on the ground-water flow, causing the development of springs (Figure 2.2.2.2).

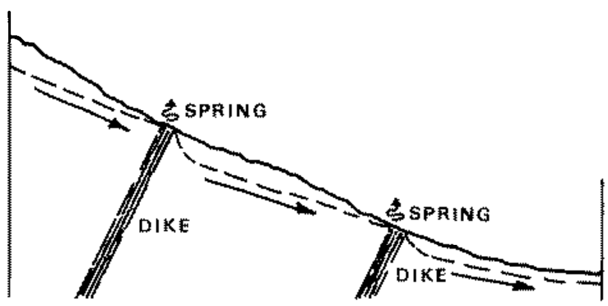


Figure 2.2.2.2 Damming effect of dikes at the side of a mountain.

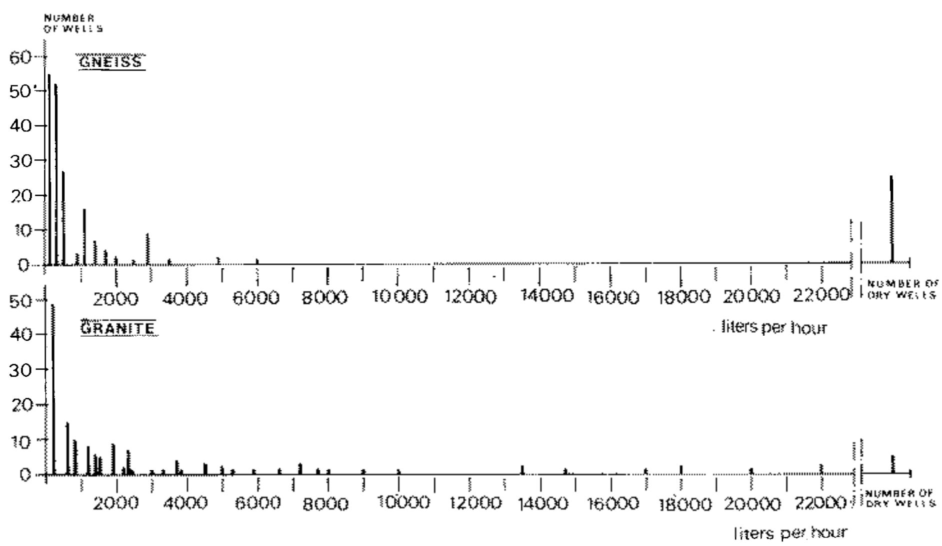


Figure 2.2.2.3 Yields of wells, drilled in a granite area and in a gneiss area in Sweden (after Larsson, 1977). (Reprinted by permission of Swedish Association for Water Hygiene).

Metamorphic rocks – Metamorphic rocks, on the whole, can be considered to have low storage capacity in comparison with intrusive rocks. This is shown in Figure 2.2.2.3 in which the yields of wells drilled in granite and in gneiss are compared. Characteristically, in a sample of 205 wells drilled in gneiss, 25, or 12 per cent, were dry. In the granite, on the other hand, 170 wells were drilled and only five, that is, 3 per cent, were dry.

Strongly folded gneissic areas usually are very poor aquifers. This type of rock is often capable of resisting crustal stresses and is usually less fractured. Migmatite zones, on the other hand, can be quite promising. They behave more or less like granites.

High metamorphic rocks generally are very compact. Fractures are very sparse. The rock is almost impervious and usually a poor aquifer. The rock can act as a barrier, preventing ground water in recharge areas from reaching the zones of high permeability where ground-water exploitation may be feasible. Furthermore it is characteristic that in gneiss areas most of the wells yield less than 2 m^3/h and seldom more than 6 m^3/h. In granite areas many wells have low yields, probably because they have been located in solid plinths. On the other hand, some wells have yields of up to 20 m^3/h most likely because they penetrate fracture zones.

2.2.2.2 *Characteristic storage capacity of different types of fractures*

Introduction – From the hydrogeological point of view three main types of fractures can be identified in hard rocks:

1. *Tensile joints* (ac^1-jointing) related to plastic deformation (Figures 2.1.2.6; 2.1.2.8 and 2.1.2.9).

2. *Tensile fractures* (ac^2-fractures) related to brittle deformation (Figures 2.1.2.18-2.1.2.22).

3. *Shear fractures* (*hk0, h0l*) related to brittle deformation.

Tensile joints (ac^1) – The characteristic layout "en échelon" of the ac^1-joints has already been described in Section 2.1.2.3. This design, with weak interconnections between the separate fractures, results in very low storage capacity. The network of ac^1-joints implies a weakness of the rock in the ac^1-plane. That means that later brittle deformations can have "used" this plane of weakness at stress release. This is illustrated in Figure 2.2.2.4.

The hydraulic conductivity of such a fracture zone can be considerable. In the case illustrated the fracture probably contains saline water from the Baltic Sea. Because of the weak interconnection, even between regenerated joints/fractures, described above, this kind of rock can be classified as a poor aquifer.

Tensile fractures (ac^2) – This type of fracture generally has a high storage capacity, because of its tensile origin. Such fractures function as large drain pipes collecting water from minor fractures belonging to the same fracture system. In Figures 2.1.2.19 and 2.1.2.22 some examples are shown. The geology of the tensile fracture zone depicted in Figure 2.1.2.19 has been discussed in Section 2.1.2. In the two boreholes (x on the map) a yield of about 10 l/s was obtained with a breakdown of 60 m. The precipitation in the area is about 500 mm and the annual evapotranspiration is about 400-500 mm.

A granite area on the south coast of the island of Sardinia is shown in Figure 2.1.2.22. The main brittle fracture pattern is quite similar to that of the model of Figure 2.1.2.21. A major tensile fracture zone, parallel to a set of lamprophyre dikes has been opened up in the rock. The direction of this deformation is about SE-NW. Shear fractures of different order are developed around the central tensile fracture direction. (Barrocu and Larsson, 1977)

Based on hydrological investigations, test drilling and pumping tests carried out in all types of fractures, the storage capacity of the whole fracture system was calculated. Assuming that all fractures have a minimum depth of 10 m, a fracture volume of 0.6 % of the rock volume was calculated to be open for recharge and discharge. If this fracture system would be sealed off at the outlet a quantity of about 30.000 m^3 of ground water could be stored. This is rather a reasonable quantity as the feeding surface basin only is 0.4 km^2. In areas with short rainy seasons and fitting tectonics in the rock, this type of underground storage could be useful to take into consideration at regional and local water resource planning. (Rosén, 1977. See Section 4.5.11.)

Shear fractures (hk0, h0l) – The development of shear fractures has already been discussed in Section 2.1. The storage capacity of shear fractures is a very complex phenomenon. It seems that most, if not all shear fractures are tightly compressed by residual stresses. However, as seen from Figure 2.2.5 heavy fracturing of hard rocks commonly is followed by

Figure 2.2.2.4 B-tectonite type of granite-gneiss. Stavsnas area, archipelago of Stockholm. Frequent ac^1-jointing in the rock. Secondary generation of joints to a fracture zone (lower part of the wooden steps).

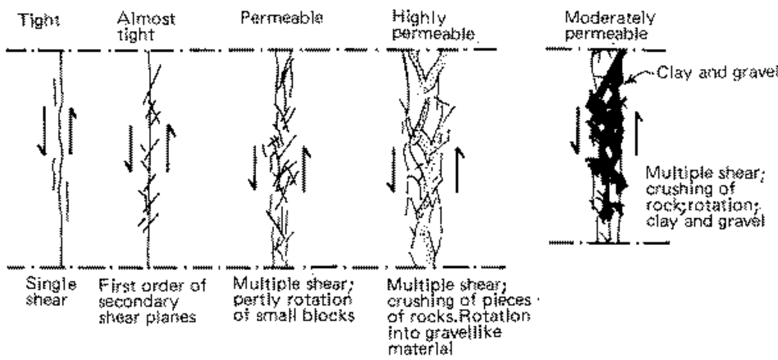


Figure 2.2.2.5 Different stages in the development of shear fractures and permeability.

intense weathering (clays, smectites). The chemistry of the rocks plays a predominant role in this process (Section 2.1.3).

Slightly dipping shears and thrust faults hold a unique role with respect to water yield as they generally have a high storage capacity. Clay weathering affects this type of shear as it affects all other shears. However, in hard rocks, gravel fillings have been observed in thrust faults more frequently than in vertical or sub-vertical shears. The reason is unknown. Thrust faults usually have a good connection with the land surface thanks to their inclined position (Figure 2.2.2.6). At the construction of underground caverns and tunnels this type of fracture is considered hazardous due to the risk of sudden influx of water along these fractures.

If two or more thrust faults cut each other, an axis of intersection develops which can act as an effective drain pipe (see right side of the block in Figure 2.1.2.21).

Hydrogeologists in China have found that fracture planes of tensile, tenso-shear and shear origin are good for water collection while compressive fracture planes act as aquicludes (Fei Jin, 1980).

Avias (1967, 1975, 1977) stresses the importance of tensile fractures ("decompressive") for the storage capacity of a rock aquifer. He also emphasizes the importance of recognizing the hydrogeological effects of superimposing a later brittle deformation on a pre-existing one with secondary opening or closing of older fracture systems.

Interconnection of fractures – The importance of good interconnection between the fractures in hard rock aquifers for storativity has previously been pointed out in Section 2.1. Highly fractured rocks may be treated in hydrological computations in a similar way as porous media. In rocks with fracture patterns more distantly spaced the storage capacity of individual fractures plays a more predominant role. According to the general definition (see definition of joint/fault system in the Appendix) a fracture system consists of two or more sets of fractures with a characteristic pattern. This means that all fractures in a system have developed under the same stress regime. They are syn-tectonic. The fracture pattern in Figure 2.2.2.7 is such a system (see also Figure 2.1.2.22). Therefore a fracture system roughly corresponds to a hydraulic system in the rock. A rock which has been exposed to a two-phase brittle deformation can also constitute one hydraulic system if there is a good connection between the two fracture systems (see Figure 2.1.2.21).

Figure 2.2.2.6 Road cutting in thrust fault in gneiss-granite, Stockholm. The fault zone is about 0.2 m thick and consists of gravelly, crushed rock. High storativity. Note the seepage of water on the left side of the picture (black colour of the rock).

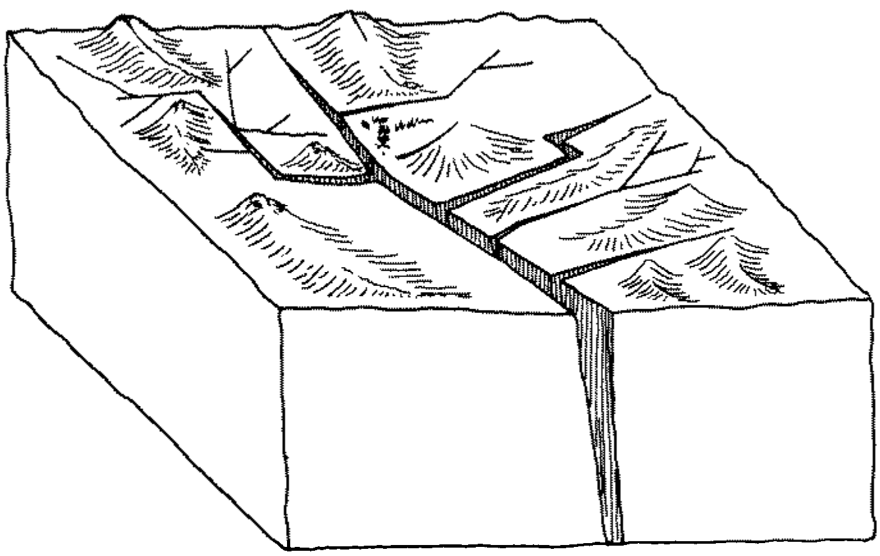


Figure 2.2.2.7 Idealized fracture system due to brittle deformation.

2.2.3 WATER-BEARING CAPACITY AND WELL YIELD

2.2.3.1 *Introduction*

The site-specific occurrence of ground water in hard rocks is often difficult to predict. The ground-water production potential from such rocks is considered to be generally low, but production can vary from very low (or nil) to very high sustained production rates, that is, greater than 68 m^3/hr (Ellis, 1909; Stewart, 1962 b). Limited and incomplete knowledge of those geological conditions that have combined to yield ground water at relatively high production rates have been major constraints to cost-effective ground-water exploration and development in such rocks.

Table 2.2.3.1 Reported yields from wells in hard rocks of Africa (United Nations, 1973)

Country	Average rainfall (mm)	Province or area	Rock types	Yield per well (m^3/h)	Well depth (m)	Remarks
Angola	1000	South Catuiti	Metamorphics Weathered tectonized granites	0.6 (aver.) 3 to 30		Fracture yields up to 80 m^3/h
Botswana	100-250		Granites, gneisses and schists	0.4 to 10		Under exceptionally favorable geological conditions
Central African Republic	800-1400		Gneisses, schists and quartzites	0.5 to 5	3-15	Of 400 dug wells put down during 1967-69 90 % were productive in the weathered layer above the basement.
Benin	750-1250	Central region	Granite gneisses, mica schists	1-4		
Ethiopia	1000-2000	Sidamo	Granite, gneiss and schist	Low		Weathered layers poorly developed. Yields from fractured zones low and water often of poor quality.
Ghana	750-2000	Accra plains Upper and northern regions	Gr., gn., qtz. and biotite schist Granite	0.5-11 0.4-24	34 (aver.)	Depth based on 280 wells.
Ivory Coast	1000-2000	Western Region	Granite	2 to 5	10-15	
Malawi	800-1500		Biotite gneiss Gneiss w/dolerites Graphite gneisses Gneiss (basal complex) Weathered zone of gneiss	5 0.5 4 1.2-3.6 1.2-5	60 (aver.) 30 " 45 " 25-40 25-40	Avg. 1.8 m^3/h Avg. 3.5 m^3/h
Mozambique	500	General	Orthogneiss, granite and paragneiss	4-8		w/"thick" surface weathered layer (10-25 m^3/h reported)
Zimbabwe	300-1200	Central area				
Sudan	20-500	Southern Kordofan	Granite, gneiss, schist	0.5-6		Weathered layer 10 to 50 m thick
South Africa	400-1500	Precambrian Basement area	Granite gneisses and schists	0.5-10		Weathered layer 30 to 150 m thick. Detected by electrical resistivity surveys. About 50 % of the bore-holes in the country tap water in weathered layer.
Swaziland	500-1750	Central area	Granite gneiss	2 to 8	20-30	Weathered layer 10 to 30 m thick.
Togo	1000	Dapango Kande Dahomeyan	Granite-gneiss Schists Gneiss, granite and migmatites	3-175 .5-1 .25-.50	0-8 0-11 0-20	Drawdown: 6-18 m Artesian in part
Uganda	1000	General	Granite gneiss	.2-2	30-100	
Upper Volta	400-1000	General	Granite gneiss and schists	.2-2		$3m^3/h$ reported maximum
Zaire	1500-2000	Orientale Maniema Bas-Congo	Weathered zone in Precambrian basement " " " "	1-8 1-8 1-8	25-100 40-100	0.2 to 2 specific yield l/s/m "
Zambia	500-1500	Kalomo-Choma Munali Pass Copper Belt	Weathered granite-gneiss, quartz veins and pegmatites Biotite schist Quartz veins Schist	3-5.5 1-2 1-2 1-2	35	Quartz veins have slight head (yield up to 11 m^3/h)

Table 2.2.3.2 Reported yields from wells in hard rocks of the Western hemisphere, India and Korea (after United Nations, 1973).

Country	Average rainfall (mm)	Province or area	Rock types	Yield per well (m^3/h)	Well depth (m)	Remarks
Brazil	300	Semi-arid region (Northeast)	Granite, gneiss, schists and other metamorphic and igneous rocks	0.3-8 (aver. 4)	20-40	Weathered layer ranges from 5 to 10 m thick. Water commonly contains more than 3000 mg/l. Spec. cap. 0.1 to 1.0 $m^3/h/m$.
	2000	Humid region (South and South-central		0.5-20 (aver. 4)	10-30	Weathered layer ranges from 10 to 20 m thick. Water commonly contains less than 1000 mg/l. Spec. cap. 0.2 to 4 $m^3/h/m$.
Canada	750-1200	General	Gneiss Granite	1.0-3.0	30	Depths greater than 30 m commonly produce saline water.
India	700	Semi-arid region (Rajasthan)	Granite	0.9-2.8	20-40	Wells tap weathered layer which is 12 to 25 m thick. Water brackish to slightly saline.
			Slates	0.6-4.0 (aver. 2.2)		
	1500	Sub-humid region (Karnataka)	Granite	0.15-15 (aver. 3.2)	13	Wells tap weathered layer at depths generally less than 15 m.
			Cordiarite, hornblende and biotite gneiss	0.3-10 (aver. 3.2)		-"-
			Crystalline schist	"		-"-
			Clayey schist and phyllite	Low		Weathered layer clayey with poor aquifers.
Korea	1100-1300	General	Granite	12.2 (aver.)	74 (aver.)	Yield range: 0.2-34 (39 wells) Well depth range: 30-200 m
			Schist	7.0 (aver.)	97 (aver.)	Yield range: 0.6-17 (22 wells) Well depth range: 30-146 m
			Gneiss	5.3 (aver.)	88 (aver.)	Yield range: 0.5-21 (16 wells) Well depth range: 42-135 m
United States	500-1000	Piedmont region; Southeastern states	Gneiss and schist most common with some granite and other intrusive rocks	3 to 10 occasionally 20 or more (>180)	40-50	Weathered layer ranges from 15 to 30 m thick. Water generally contains less than 500 mg/l.
		New England Connecticut	Granite	2.6 (aver.)	44 (aver.)	Based on 217 wells
			Gneiss	2.4 "	40 "	Based on 261 wells
			Schist	3.1 "	44 "	Based on 63 wells
		New Jersey	Biotite gneiss	2.2 "	37 "	Based on 29 wells
			Granite (Hornblende)	2.1 "	48 "	Based on 81 wells
			Pyroxeus Granite and gneiss	1.9 "	47 "	Based on 162 wells
			Amphibolite	1.5 "	49 "	Based on 31 wells
			Quartz Diorite gneiss	1.4 "	71 "	Based on 31 wells
Uruguay	1000-2000	South	Granite, gneiss metamorphics	0.2 to 8 (aver. 5)	20-40	Sp. cap.: 0.1 to 1.8 $m^3/h/m$.

The pressing need for obtaining even a limited water supply (less than 1 gpm, or 0.2 m^3/h) has prompted random drilling, augmented occasionally by preliminary geological evaluations. Drilling has been conducted in many areas underlain by hard rocks, and voluminous data resulting from such drilling indicate a broad range in the productivity of such rocks. In Brazil, for example, approximately 63 per cent of the country is underlain by igneous and metamorphic rocks. Rebouças (1978) reports that approximately 15,000 wells have been drilled in fractured crystalline rocks, of which 92 per cent were considered successful. Many such wells have been in use for more than 30 years. The average specific capacity of the successful wells is 0.1 $m^3/h/m$ of drawdown which is consistent with previous investigations conducted in other countries (see Figures 2.2.4.3 - 2.2.4.15). A 60 metre depth limitation was suggested as a maximum economic drilling depth. This principle is followed in many countries.

2.2.3.2 *Typical well yields in hard rock areas*

Typical well yields in hard rock areas of Africa, India, Korea and parts of the Western Hemisphere are indicated in Tables 2.2.3.1 and 2.2.3.2. When significant production was encountered, the geological conditions (fractures, joints, faults, etc.) that permitted such productivity were considered too complex to be evaluated quickly and were considered simply a matter of good fortune. The general impression was that such productivity could not have been forecast because of the complexity of the geological conditions. However, the type of systematic investigations discussed in the present work demonstrates that the regional and local structural history of igneous and metamorphic rocks in selected regions, combined with various surface geophysical and geochemical techniques, can serve to identify permeable zones potentially capable of significant ground-water production.

These methods could increase the rate of success and consequently the cost effectiveness of such programmes. The ramifications of the investigations discussed in the present work are significant in that vast areas of the earth's surface are underlain directly by hard rocks.

2.2.3.3 *Types of fractures*

Unweathered hard rocks generally have porosity of less than one per cent (Davis and DeWiest, 1966) and frequently this is discontinuous or ineffective pore space. Their permeability is therefore low as well.

Fracturing, either associated with regional deformation as discussed in Section 2.1.2, or weathering (Section 2.1.3) may create significant porosity and permeability in these rocks and is alone responsible for their ground-water potential. Based on investigations in the United States, the frequency of occurrence of fractures in crystalline rocks has generally been found to decrease with depth (Davis and DeWiest, 1966; Davis and Turk, 1964; Landers and Turk, 1973; and Legrand, 1967). However, underground mines have encountered heavy flows of ground water hundreds of metres beneath the surface, indicating that some fractures extend to great depths ((Hurr and Richards, 1966; Snow, 1968a, 1968b; Wahlström and Horback, 1962). Robinson (1976) suggests that two zones are present, that is, an active and an underlying passive zone. Therefore two types of fractures have been combined in previous evaluation programmes of ground-water productivity in ingneous and metamorphic rocks: (1) fractures related to weathering and unloading, and (2) fractures related to regional tectonics. Marine (1966, 1967) has also noted two types of fractures in hard rocks of Georgia, that is, "fine" and "open" fractures.

The direction of ground-water movement in saturated fractures is frequently difficult to establish because of the nature of these openings and their possible relationship to fracture pattern in general.

It should be emphasized that igneous and metamorphic rocks having a hard crystalline texture in the outcrop do not always extend into the subsurface in the same condition. A variety of structural and compositional differences of the

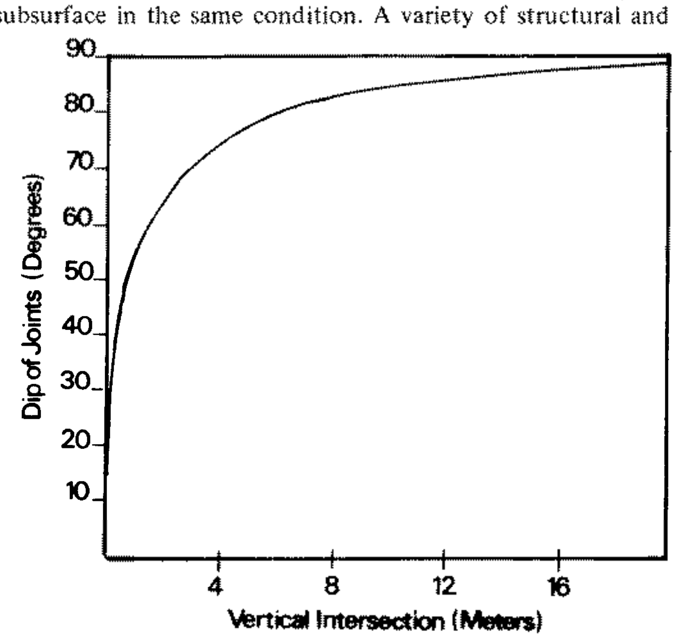


Figure 2.2.3.1 Vertical intersection of joints for various dips (Karanth, 1973). Horizontal spacing of joints is assumed to be 1 metre.

rock appear at depth. These differences are generally associated with structural features such as faults, or other chemical or contact features which can occur between two rock units of dissimilar composition. Since secondary mechanical disintegration produced by tectonic phenomena, horizontal or sub-horizontal sheet-jointing produced by unloading, and chemical decomposition produced by diagenetic alteration are associated with such factors, the result may be permeable zones ranging from a few centimetres to a few metres in thickness (Jahns, 1943; LeGrand, 1949 and 1952; Reed et al., 1963). However, Lachenbruch (1961) indicates that many joints or fractures caused by tension at or near the ground surface die out rapidly with increasing depth. This is apparently related to unloading and is a near-surface phenomenon to which most occurrences of ground water in igneous and metamorphic rocks have been related.

For a given spacing of fractures, the probability of intersecting a fracture while drilling a well decreases with the increase in fracture dip magnitude, being maximum in rocks with sheet fractures and minimum in vertically fractured rock (Karanth, 1973). The chances of intersecting fractures decrease rapidly when the fracture dip exceeds 70° (Figure 2.2.3.1). To optimize well yield, drilling, ideally, should be at right angles to the attitude of the principal fracture system in the area of the greatest fracture frequency.

2.2.3.4 *Effect of fracturing on ground-water production*

In order to evaluate the effect of near-surface fracturing on ground-water production, welldepth relationships are here reviewed for a number of rock types and locations in the United States and Korea. Davis and Turk (1964) present the results of an evaluation of productivity from granite and schist in the eastern United States; granodiorite or closely related igneous rocks in the Sierra Nevada area of California; amphibolite and granite from injection tests at the Oroville dam site and other sites in California; and for wells in miscellaneous metamorphic and igneous rocks in California (Figures 2.2.3.2 - 2.2.3.6). Summers (1972) also presents similar data for wells in a variety of rock types from a 15.5 km^2 area in the Rotschild region of Wisconsin which includes nepheline syenite, quartz syenite, granite, gabbro-diorite, "greenstone," felsite, schist and rhyolite. (See Figure 2.2.3.7 and 2.2.3.8.)

2.2.3.5 *Relationship between well yield and well depth*

Figures 2.2.3.2 to 2.2.3.6 show the relationship between well yield per unit length of well penetration in the aquifer, or the water injection rate per vertical unit length of well as functions of well depth. All the graphs shown indicate that production generally decreases with depth. It should be noted that the scatter of the points plotted is large and may be due to one or more of the following reasons:
(1) number of fractures penetrated by the individual wells;
(2) differences in the type of fractures encountered;
(3) inaccurately reported data;
(4) variations in rock type.

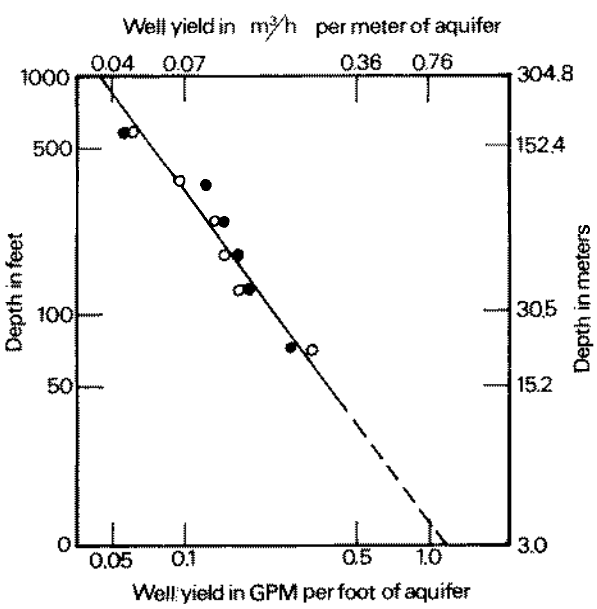


Figure 2.2.3.2 Yield of wells in crystalline (hard rocks of eastern United States. Open circles represent mean yields in granite rocks for 814 wells. Black dots represent yields in schistose rocks for 1522 wells. (Modified after Davis and Turk, 1964.)

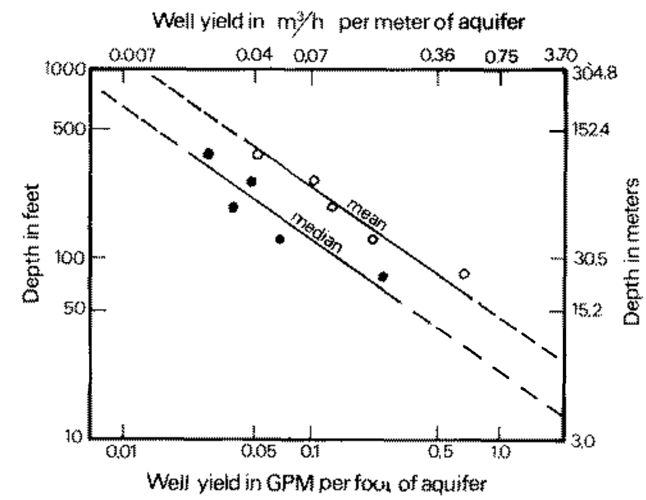


Figure 2.2.3.3 Yield of wells in crystalline (hard) rock of Sierra Nevada, California. Open Circles represent mean yields. Black circles represent median yields both in granodiorites or related rocks (modified after Davis and Turk, 1964).

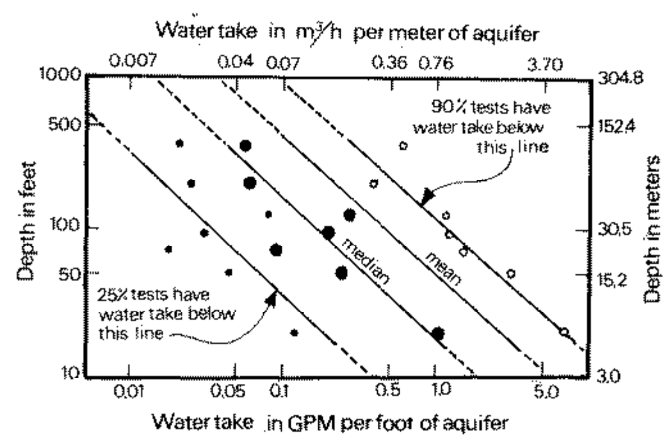


Figure 2.2.3.4 Water injection data from Oroville Dam site, California. Based on results of 385 injection tests in amphibolite or related rocks (modified after Davis and Turk, 1964).

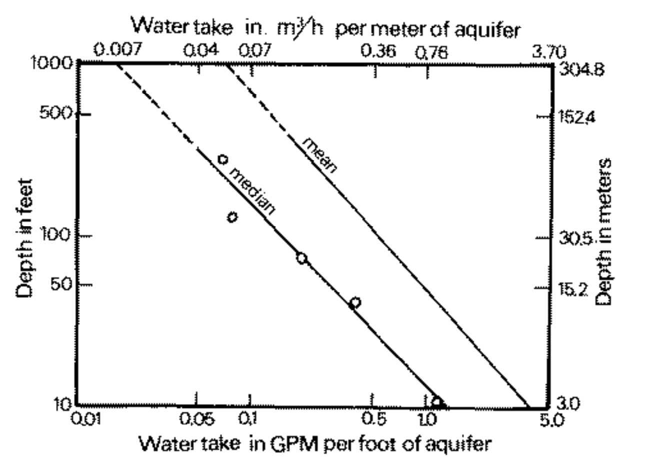


Figure 2.2.3.5 Water injection data from California. Based on results of 412 injection tests in granitic rocks (modified after Davis and Turk, 1964).

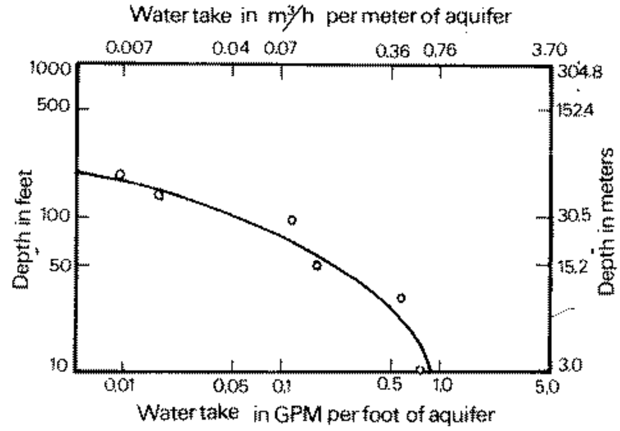


Figure 2.2.3.6 Water injection data from California. Based on results of 494 injection tests in serpentine, slate, phyllite, gabbro and other miscellaneous rock types (modified after Davis and Turk, 1964).

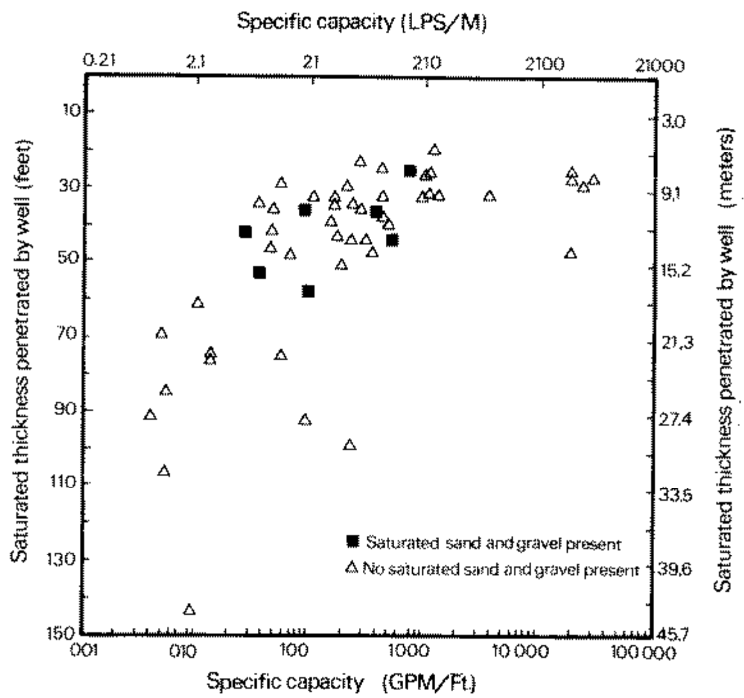


Figure 2.2.3.7 Yield of wells versus depth below water table in crystalline (hard) rocks of Wisconsin. Based on individual yields of 50 wells in nepheline syenite, quartz syenite, granite, gabbro-diorite, felsite, schist, rhyolite and related rocks (modified after Summers, 1972a).

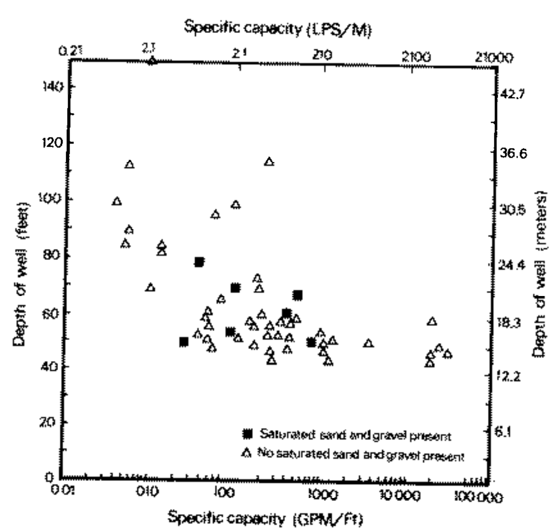


Figure 2.2.3.8 Yield of wells versus depth of well in crystalline (hard) rocks of Wisconsin. Rock type same as in Figure 2.2.3.7 (modified after Summers, 1972a).

2.2.3.6 *Effect of rock type*

The effect of the rock type on the relationship between well yield and well depth in the Llano area of Texas is shown in Figure 2.2.3.9. A comparison of the well yield and well depth in granite rocks in other regions of the United States is shown in Figure 2.2.3.10. In the former graph, the overlying weathered material ("grus") is shown to be a significant contributor. In the latter, the plot of the Llano area declines more rapidly with depth than the plots of the other regions. Landers and Turk (1973) suggest that climate may have a significant role in the occurence of ground water in crystalline rocks. Different rates of formation of weathered material (grus) may be related to rainfall (Bannermann, 1973). The Llano area has the driest climate followed by the Sierra Nevada and eastern United States (see Figure 2.2.3.10). The effects of climate on ground water have been discussed earlier in Section 2.1.3.

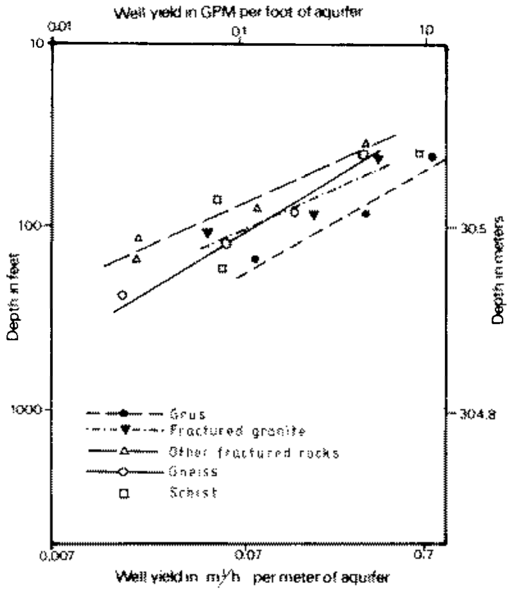


Figure 2.2.3.9 **Yield of wells versus depth of well in crystalline rocks of the Llano area, Texas. Based on 848 wells in grus, granite, gneiss, schist and other fractured rocks (modified after Landers and Turk, 1973).**

Callahan and Choi (1973) present a comprehensive review of a drilling programme in crystalline rocks, undertaken in Korea during the period 1966-1971. Figures 2.2.3.1 - 2.2.3.14 summarise the result of that programme.

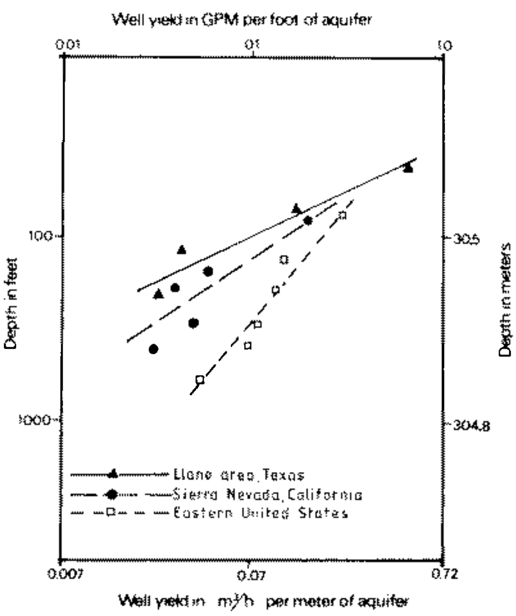


Figure 2.2.3.10 Yield of wells versus depth of well in granitic rock aquifers of various regions in the United States (modified after Landers and Turk, 1973).

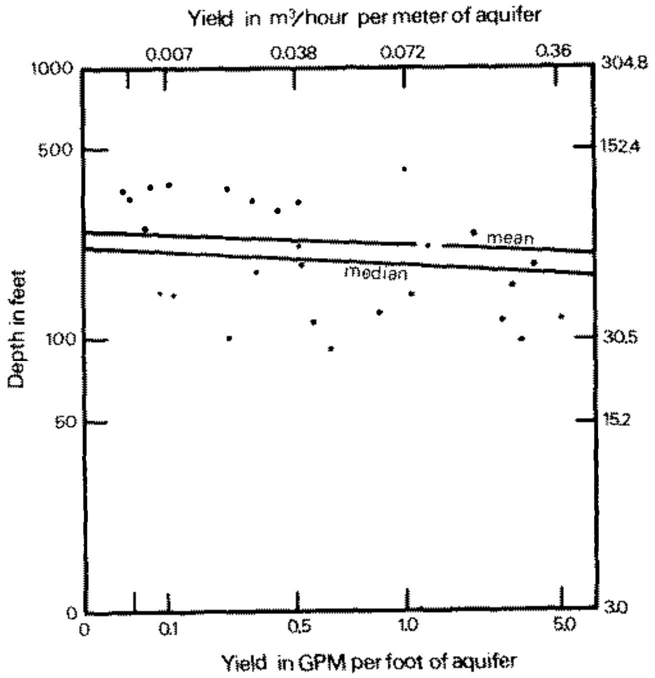


Figure 2.2.3.11 Yield of wells versus depth in granitic rock in Korea. Based on 28 wells (after Callahan and Choi, 1973).

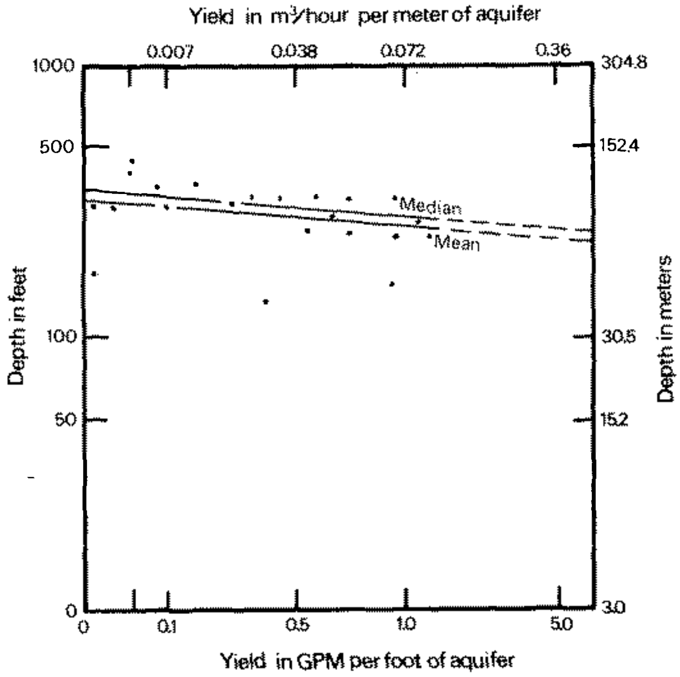


Figure 2.2.3.12 Yield of wells versus depth in gneiss of Korea. Based on 22 wells (after Callahan and Choi, 1973).

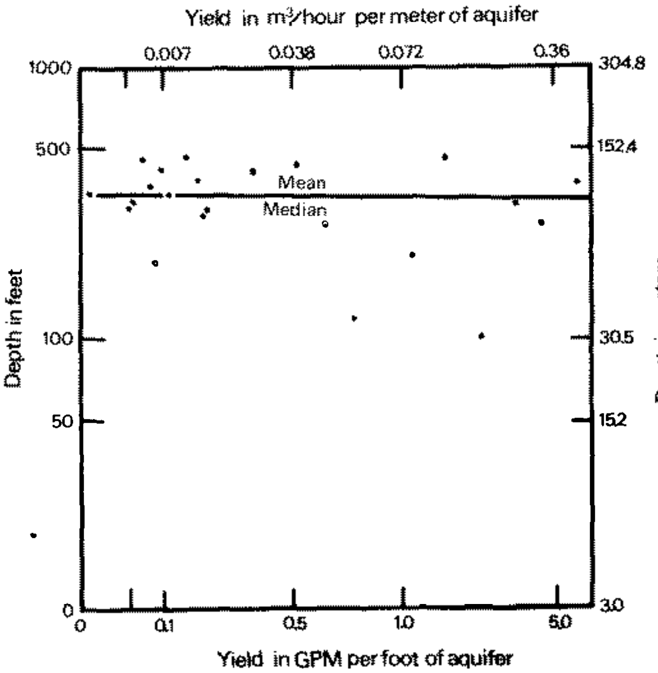


Figure 2.2.3.13 Yield of wells versus depth in schist of Korea. Based on 22 wells (after Callahan and Choi, 1973).

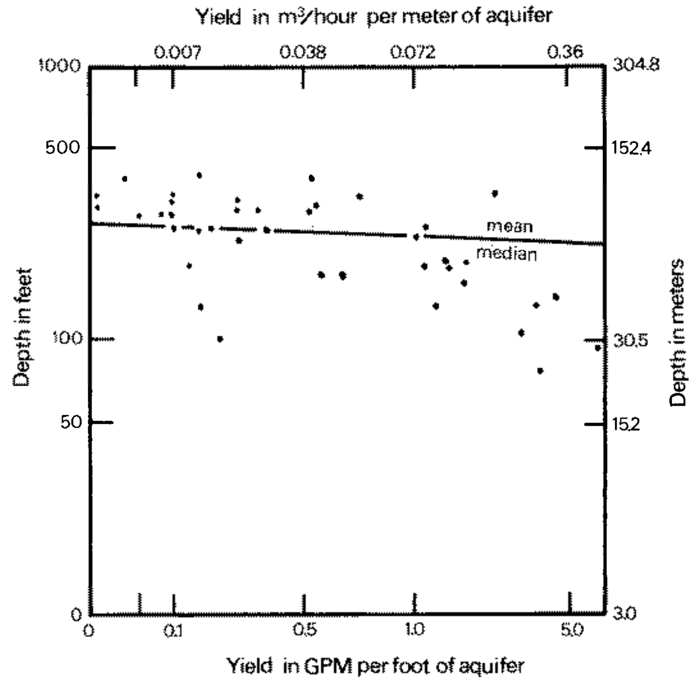


Figure 2.2.3.14 Yield of wells versus depth in miscellaneous rock types (andesite, rhyolite, metaquartzite, gneiss, schist, granite-mixed zones). Based on 41 wells (after Callahan and Choi, 1973).

2.2.3.7 *Occurrence of ground water in hard rocks in various countries*

A comprehensive evaluation of the productivity of igneous and metamorphic rock aquifers in the State of Mysore, India, was conducted by Krupandi et al. (1973). In Africa, Faillace (1973) reports on an investigation involving metamorphic rocks of the Karamoja District, Uganda. Burdzhanadze et al. (1970) provide information on the water-bearing capacity of crystalline rocks of the Soviet Union. Beyer (1968) and Larsson (1968, 1972) report on the occurrence of ground water in Sweden. Filho et al. (1966) discuss ground water occurrence in Brazil. In the United States, Clapp (1911), Mundorff (1948), LeGrand (1949), Baker (1957), Sever (1964), James (1967), May and Thomas (1968), Stewart (1971), Nutter (1974), Floyd and Peace (1974) and Caswell (1979) report on ground water in igneous and metamorphic rocks in various regions in relation to well yield.

2.3 *HYDROCHEMICAL CHARACTERISTICS*

2.3.1 ORIGIN OF CHEMICAL COMPONENTS

2.3.1.1 *Main chemical elements*

The major dissolved components in ground water are positive ions of sodium (Na^+), potassium (K^+), magnesium (mg^{2+}), calcium (Ca^{2+}) and negative ions of chloride (Cl^-), sulphate ($So_4{}^{2-}$); nitrate ($No_3{}^-$), bicarbonate ($HCO_3{}^-$), and silicid acid (H_4SiO_4). In addition there may be varying levels of ammonium ($NH_4{}^+$) and fluoride ions (F^-). Ground water may also contain dissolved oxygen. When oxygen is absent the water most likely contains ferrous iron (Fe^{2+}), divalent manganese (Mn^{2+}), and ammonium ions (NH^{4+}).

Two of the elements, nitrogen and carbon, are of atmospheric origin although they both can be stored in the root zone in appreciable quantities. Carbon, as carbon dioxide, is found in the gas phase of the unsaturated zone, with partial pressure far exceeding that of carbon dioxide in the atmosphere. The reason for this is the high rate of production of carbon dioxide in the root zone by roots and living organisms. Molecular nitrogen may be "fixed" in the soil, that is, converted into organically-bound nitrogen which, when released, appears as nitrate ions or, under reducing conditions, as ammonium ions.

The chloride content of unweathered, hard rocks is usually very low. Hence, practically all the chloride dissolved in ground water comes from external sources. One important source is chloride of marine origin dissolved in rain or deposited as microscopic particles (condensation nuclei) from the atmosphere. Another source which is most important in densely populated areas is chloride in form of human and animal waste.

As to the rest of major ions, they are, by and large, derived from common minerals by weathering, as described later. An exception may be sulphur in sulphate ($SO_4{}^{2-}$) which hardly can come from weathering of igneous rocks. The geochemistry of sulphur is still incompletely known, although quantitatively this ion is strongly involved in biological processes.

2.3.1.2 *Minor chemical elements*

This group is made up of heavy metals as well as non-metals in trace concentrations. Most of them originate from minerals in the rocks. A few, such as iodine and bromine, are most likely of marine origin, and are like chloride deposited by precipitation from the atmosphere.

2.3.2 CHANGES IN CHEMICAL COMPOSITION

2.3.2.1 *Changes at the surface*

Components dissolved in precipitation are in general already enriched at the soil surface because of evaporation of part of the precipitation. Other processes occur at the soil surface; for example, absorption of gaseous inorganic compounds such as sulphur dioxide and ammonia. The sulphur dioxide is in general oxidized to sulphuric acid thus increasing the sulphate concentration. Ammonia may also escape if slightly acid precipitation, containing ammonium, is turned alkaline at the soil surface due to the presence of calcium carbonate. Decomposing litter on the soil surface releases cations and anions but these may also be taken up by plant roots already near the surface. The more important processes seem to take place at deeper levels.

2.3.2.2 *Changes in the root zone*

It is generally recognized that three processes occurring in the root zone affect chemical composition. The first process is loss of soil water due to evaporation which increases concentration of dissolved components in the soil water. This is no doubt the process which has perhaps the strongest influence on the overall salt content of ground water, particularly of sodium chloride.

The second process, often referred to as important for the composition of soil water, is ion exchange in the root zone. This is not always the case because when a steady-state condition is reached, and it has to be reached sooner or later, ion exchange between the percolating soil water and the ion exchange complex becomes ineffective. In this connection it should be mentioned that considerable transport of some elements from the root zone to the vegetation takes place, although it is compensated by the return of these elements in litter fall. On a long-term basis a complete balance is maintained, as long as no human intervention takes place.

The third process is that characterized as weathering, although it is probably more appropriate to speak about mineral transformation, since new minerals may appear in the process (see Section 2.1.3.2). Mineral tansformation equilibria are treated quite extensively in the literature and the reader is referred to textbooks such as "Aquatic Chemistry" by Stumm and Morgan (1970) and specialized papers by Garrels (1967); Paces (1972a and b, 1973); Jacks (1973a and b); Tardy and Garrels (1974).

2.3.2.3 *Chemical reactions and equilibria in the unsaturated zone*

The unsaturated zone is in direct contact with the oxygen and carbon dioxide of the air. Reactions, hence, proceed under practically constant oxygen and carbon dioxide pressures. A suitable example demonstrating the course of chemical weathering is the breakdown of anorthite. It is found that this mineral is absolutely unstable under present environmental conditions. This means that it can never reach an equilibrium with any secondary mineral before it is completely transformed. The same seems to be true also for the biotite under conditions prevailing in the unsaturated zone. It is likely to be true also for primary minerals like hornblende and other ferromagnesian minerals, whereas soda and potash feldspars and muscovite seem to be able to attain chemical equilibria with secondary minerals.

Anorthite, for example, essentially breaks down according to the reaction:

$$\underset{\text{(anorthite)}}{CaAl_2Si_2O_8}\ (c) + 2CO_2\ (g) + 2H_2O\ (l) \Leftrightarrow Ca^{2+}\ (aq) + 2HCO_3^-\ (aq) + \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH_4)}\ (c)$$

where (c) = crystalline; (g) = gas; (l) = liquid; (aq) = water.

The carbon dioxide and water supply the hydrogen ions necessary for the reaction. An important part of the reaction is also hydration.

The reaction above is written in such a form that kaolinite is formed. Initially, one may suspect that a somewhat disordered form of aluminum silicate is formed, later crystallizing into kaolinite. As kaolinite may not be stable, this process has to be investigated further. There are at least two things that can happen. One is the following:

$$Al_2Si_2O_5(OH)_4\ (c) + 3H_2O\ (l) \Leftrightarrow 2AlO.OH\ (c) + 2H_4SiO_4\ (aq)$$

that is, a simple hydrolisis. From the thermodynamic data given, the equilibrium constant for this reaction can be computed. When equilibrium is attained, the following results:

$$p[H_4SiO_4] = 4.07$$

where p = -log pH

which means that the concentration of dissolved SiO_2 in the water is 5.1 mg/l. If the silica concentration is maintained below this value, Kaolinite will dissolve. Hence, under strong leaching conditions, such as those which can occur in the uppermost part of the soil under humid conditions, silica concentrations may become so low that the only thing left will be aluminum oxide in the form AlO.OH, the major ingredient in bauxite. Under drier conditions the silica concentration in water will be higher, preventing a breakdown of kaolinite.

The latter may then be transformed into montmorillonite through a reaction like:

$$0.8Al_2Si_2O_5(OH)_4\ (c) + 0.2Ca^{2+}\ (aq) + 0.4Mg^{2+}\ (aq) + 1.2HCO_3^-\ (aq) + 2.4SiO_2\ (amorphous) \Longleftrightarrow$$

$$Ca_{0.2}(Mg_{0.4}Al_{1.6})Si_4O_{10}(OH)_2 + 1.2CO_2\ (g) + 1.2H_2O\ (l)$$

This requires, of course, more silica than can be supplied by anorthite. However, minerals like albite and microcline contain excess silica for this purpose. Some magnesium is also required and this can be supplied from the weathering of minerals such as biotite, hornblende or olivine. It can be seen from the reaction above that the carbon dioxide pressure becomes important. If calcium is released from anorthite the carbon dioxide pressure will also determine if precipitation of calcite will take place. There are also other reactions to consider, such as the equilibrium between feldspars, kaolinite and montmorillonite.

The process of chemical weathering in the unsaturated zone can be summarized by considering two different climatological environments:

(a) In humid climates, with high percolation rates, primary minerals break down more or less completely leaving a residue of quartz, hydrous ferric oxide, and hydrous aluminum oxide. The hydrous ferric oxide may be dehydrated to Fe_2O_3 giving the soil a deep red colour. Because of strong leaching practically no other secondary minerals are formed, and a laterization of the uppermost part of the weathered layer results. In cooler climates enough silica could be retained to allow for the formation of kaolinite except near the surface. The weathering type is podzolization.

(b) Under semi-arid conditions leaching is low and, hence, concentrations of soluble constituents are high. Primary minerals are transformed into ferric oxide, kaolinite and montmorillonite. Also calcium carbonate may be formed.

The stability conditions for kaolinite-montmorillonite are illustrated in Figure 2.3.2.1, which shows a so-called phase

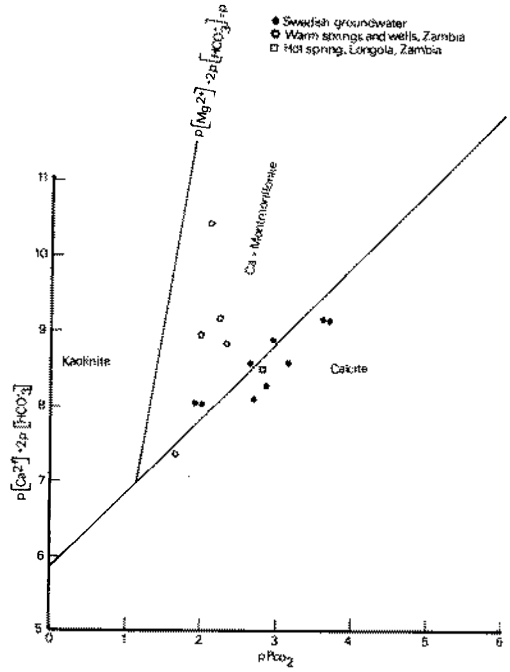


Figure 2.3.2.1 Phase diagram of calcium carbonate potential with respect to the partial pressure of carbon dioxide.

diagram constructed on the assumption that the solution is saturated with respect to amorphous silica (Tardy and Garrels, 1974). The ordinate is $p|Ca^{2+}| + 2p|HCO_3^-|$ which can be called the calcium bicarbonate potential. On the abscissa the negative logarithm at the partial pressure of carbon dioxide is used as a variable. The phase boundaries are outlined.

Of particular interest is the phase boundary between kaolinite and calcium montmorillonite which depends on the $p|Mg^{2+}| + 2p|HCO_3^-|$, that is, the magnesium bicarbonate potential. It is, however, seen that high values of the partial pressure of carbon dioxide favour kaolinite formation. In the figure some analyses are entered admittedly from deep ground water showing that both calcite saturation and equilibrium with montmorillonite are obtained for some of the samples.

The concentration level which can be reached in the unsaturated zone can be illustrated with anorthite. The reaction shown earlier produces two bicarbonate ions for each calcium ion. At equilibrium with calcite, the equation of the calcite saturation line in Figure 2.3.2.1 is:

$$p[Ca^{2-}] + 2p[HCO_3^-] = 5.86 + pP_{CO_2}$$

or if rewritten: $$[Ca^{2+}]\,[HCO_3^-] = 10^{-5.86} \cdot P^2_{CO_2}$$

Approximately $[HCO_3^-] \approx 2\,[Ca^{2+}]$ is obtained so that:

$$[Ca^{2+}]^3 = 0.5 \times 10^{-5.86} \times P_{CO_2}$$

or $$[Ca^{2+}] = 0.0088 \times P^{1/3}_{CO_2}$$

from which the following concentrations (not corrected for activity coefficients) are obtained (Table 2.3.2.1):

Table 2.3.2.1. Concentration of calcium ions and bicarbonate ions in equilibrium in calcite in the unsaturated zone, at different carbon dioxide pressures (when weathering has taken place).

P_{CO_2}	3.10^{-4}	10^{-3}	3.10^{-3}	10^{-2}	3.10^{-2}	atm
Ca^{2+}	18.8	28.0	40.5	60.3	87.2	mg/1
HCO_3^-	57	85	123	184	266	"
pH	8.33	7.98	7.67	7.32	7.00	"

The range in carbon dioxide pressures as well as the range in concentrations are realistic. The maintenance of steady carbon dioxide pressures in the unsaturated zone is evidently of great importance. One can also compute the pH values at equilibrium as shown on the last line of Table 2.3.2.1. Also these fall in the range frequently encountered in ground water.

As for the weathering of iron-bearing minerals, ferrous iron is oxidized to ferric iron, forming oxides. It is thus retained along with other secondary minerals.

Where the water table in fractured hard-rock aquifers is at some depth, physico-chemical conditions in the unsaturated zone with regard to carbon dioxide and oxygen do not differ from those occurring near the surface. Reactions occur on the walls of fractures and fissures.

In thick unsaturated zones, gradients of weathering appear. As water moves downward it comes closer and closer to some mineral equilibrium. At some point secondary minerals start to form, arresting the weathering of primary minerals. Since pH also increases, reaction rates slow down. Some reactions will, however, continue at a reduced rate. Anorthite would still tend to be transformed into, particularly, montmorillonite and the calcium released will be precipitated as calcite.

2.3.2.4 *Reactions in the saturated zone*

In the saturated zone the water is cut off from fresh supplies of carbon dioxide and oxygen. This sets a limit on how far weathering can proceed. If weathering in the unsaturated zone is relatively intense not much will happen in the saturated zone. This can be demonstrated by considering a rather extreme case.

Assume that no weathering has taken place in the unsaturated zone because of a ground-water level which is close to the surface. The amount of carbon dioxide dissolved will depend on the partial pressure in the saturated zone. Assume a partial pressure of 10^{-2} atm of carbon dioxide. This will give a concentration of carbon dioxide in water of 0.33 mmol/l or 14.5 mg/l CO_2 at 25° C. It is apparent that this can match about 6 mg/l of Ca^{2+} as bicarbonate in solution. This is the maximum concentration of calcium, through weathering of anorthite, which conceivably can be found under the conditions outlined, and is about 10 per cent of that which could conceivably be found if weathering had taken place in the unsaturated zone. Hence, not much can happen in the unsaturated zone. In fact, because of some further silicate weathering precipitation of calcium carbonate may occur, partly because the pH must inevitably rise unless the system is buffered by bicarbonate obtained in the unsaturated zone.

As for weathering of ferromagnesian minerals, oxygen is of essential interest since it will enhance the weathering process by oxidizing the ferrous iron inside the minerals. This will effectively remove all oxygen from solution. The ferrous iron and manganese can appear in solution, provided the pH is not too high.

From the previous discussions there are strong indications that the greatest change in the chemical composition of percolating water takes place in the unsaturated zone, particularly where it is thick and well developed. Where the unsaturated zone is thin, chemical weathering in the saturated zone will still not add much. There are, however, possibilities for ferrous iron and manganese to enter the water (Eriksson and Khunakasem, 1968).

2.3.3. OTHER ASPECTS

2.3.3.1 *Use of environmental isotopes*

In recent years much valuable information on origin and storage has been obtained from studies of the distribution of the stable isotopes of hydrogen and oxygen in ground water. The usefulness of those depend on systematic variations in the isotope ratios in precipitation with season, latitude, distance to the oceans, and altitude. The altitude variation is particularly valuable since it is of such magnitude that differences of 200 m in altitude can easily be detected using modern mass-spectometric equipment. Through such studies it has been possible, in a number of cases, to establish the altitude within a basin at which the ground water occurring lower in the basin originated. This may be of great value particularly for testing hypotheses on long-distance ground-water transfer due to specific tectonic patterns.

The use of stable isotopes in ground-water exploration programmes must be planned at an early stage in the programme so that the background variation in rainfall is well established. Stable isotope ratios have also been used to identify bodies of "fossil" ground water, dating back to some earlier pluvial period. This application can, of course, be of great interest in ground-water development schemes in hard rock areas.

Turnover rates of ground water can be assessed if storage and age of the water are known. Age determinations of ground water in sedimentary rocks have been carried out quite extensively using carbon-14 data on the dissolved inorganic carbon in water. Interpretation of data are, however, not always easy. In sedimentary rocks dissolution of old carbonate tends to dilute also the modern carbonate giving apparent ages which may be far in excess of the real ones. It is possible to correct for this in sedimentary rocks when the old carbonate is of marine origin, utilizing information on the stable isotope carbon-13 in the water. However, in hard rocks the carbonate is ulikely to be of marine origin. Hence carbon-13 will not give any information on the influence of dissolved old carbonate in the carbon-14 content of water.

The possibility cannot be excluded that long-term fluctuations in climate cause long-term fluctuations in precipitation and dissolution of carbonate in the fractures of hard rocks. If so, there does not seem to be any really reliable way to correct apparent carbon-14 ages. Only carbon-14 assays of samples taken in the direction of ground-water movement can give reliable age estimates.

Fritz et al. (1979) and Back and Hanshaw (1965) provide detailed information on the use of isotopes in ground-water investigations.

2.3.3.2 *Chloride concentration patterns in ground water*

Information on ground-water regimes can be obtained from analysis of chloride in ground water. As pointed out earlier, hard rock weathering hardly contributes to the chloride concentration in ground water. The source of chloride is thus usually the soil surface aided entirely by precipitation, at least in areas of low population density. In this case the addition rate can be fairly well estimated from rain-water analysis or estimated from the large-scale pattern of distribution of deposition of chloride, at present obtainable through the WMO background air pollution network. Hence, variations in chloride concentrations reflect the recharge rates at the point of origin. Within a large basin it is worthwhile to collect such data systematically. Careful analysis of these data may reveal significant variations in recharge within the basin.

There are, of course, difficulties and complications involved in such applications. In permanent ground-water discharge areas where evaporation is strong enough to prevent water from appearing at the surface, elevated concentrations of chloride are formed. However, in this case concentrations of other constituents, such as nitrate and bicarbonate will also be high. If the chloride concentration is elevated while the concentrations of bicarbonate and nitrate are normal, the higher chloride concentration must be due to addition of salt, not to evaporation. The interpretation of chloride concentration data thus requires that proper concepts and models of ground-water movement be used. In fact, the distribution of chloride concentrations can be used to test such models.

2.3.3.3 *Saline and brackish waters in hard rocks*

The occurrence of brackish waters in hard rocks is, in general, difficult to predict. There are, however, possibilities for interpretation, provided the geologic history of the region is reasonably known, particularly with respect to its previous submergence beneath the sea. There is one means of identifying whether the salts are of terrestrial or marine origin. Marine sulphate has a stable isotope composition which differs appreciably from terrestrial sulphur, which is biologically influenced. Hence the sulphur-34/sulphur-32 ratio can be valuable for assessing the origin of the salts.

If brackish water occurs in patches one can suspect local enrichment of salts during a previous dry period far back in time. In addition, the ground-water circulation must be extremely local, that is, water in one set of fractures does not connect with that in other sets. Under such conditions pumping may cause a decrease in salinity with time, as fresh water replaces the old water.

In coastal hard rock areas deep fractures may extend below sea level and be connected with sea water. Under normal recharge conditions fresh water will keep the sea water at greater depth. This depth can be approximately estimated from the hydrostatic head of the fresh water in the fractures and the difference in density between fresh and sea water. If fresh water is pumped from such fractures the ground-water level will decline and the sea-water interface will move inland and upwards. There is thus a risk that the extracted water may turn salty if the pumpage is great enough. The risk has to be judged in the light of the tectonic patterns prevailing in the region.

2.3.4 ADEQUACY OF WATER QUALITY AND POSSIBLE PROBLEMS

2.3.4.1 *Areal characteristics of ground-water quality*

In hard rock terrains the chemical quality of ground water tends to be quite variable from place to place and even from season to season. This results in part from the compartmentalisation of hard rock areas into discrete ground-water basins or "cells" each of which may have an independent recharge-discharge regime. Ground-water quality tends to be best in regions where seasonal recharge from rainfall is appreciable and there is active ground-water circulation (including spring discharge). Conversely, the quality tends to be poor where recharge is small or sporadic and evaporation rates are high, concentrating and accumulating salts in the residual ground water. Commonly in the semi-arid and arid regions of the tropics and subtropics, where the annual rainfall is less than about 600 mm, the ground water in hard rock terrains is often of poor quality with total dissolved solids greater than 3 000 mg/l. Water containing from 3 000 to 5 000 mg/l of dissolved salts may still be usable for livestock and for irrigation of salt-tolerant crops which are dependent on rainfall. Such conditions are common in the semi-arid regions of southern Angola and northeastern Brazil and in the steppes of central Sudan and western India.

Where the annual rainfall is from about 600 to 1 000 mm, as in the savannah regions of the tropics, the quality of the ground water in hard rock terrains is generally good to fair, that is, with a range of about 500 to 3 000 mg/l of total dissolved solids. In the tropical rainforest and equatorial regions where annual rainfall exceeds 1 000 mm the ground water is generally of good to excellent quality with total dissolved solids less than 500 mg/l, as in southwestern Nigeria, Ghana and Ivory Coast. This is also often the case with ground water even in more humid climates (LeGrand, 1958).

Locally, even within the same climatic belt, there can be considerable variations in water quality in hard rocks from one point to another. These variations can be attributed to different rates of recharge and discharge within neighbouring ground-water "cells," and to local chemical differences in the host rock and its weathered products. It is not unusual to find 4- or even 5-fold differences in total dissolved solids concentration in the water from adjacent "cells." Also within the same ground-water basin, recharge areas tend to have lower salinity than discharge areas, where salts are concentrated by evaporation. In many closed basins, in semi-arid or arid regions, the water may contain 10 000 mg/l or more of total dissolved solids and hence be so saline as to be unusable.

2.3.4.2 *Fluoride concentration*

Various water-quality criteria for domestic water supplies set an upper limit of allowable concentrations of fluoride (expressed as F) ranging from 0.6 to 1.7 mg/l (WHO, 1971). In some regions, particularly in hard rock areas, it is difficult to fulfill these requirements, and provisional criteria are used allowing much higher concentrations. Fluoride is found in many common primary minerals such as biotite and others and is released fairly easily by hydration. However, in the presence of calcium ions, its concentration will be limited by the solubility of calcium fluoride, CaF_2. This is set by:

$$p|Ca^{2+}| + 2p|F^-| = 11.0$$

$$\text{so that: } p|F^-| = 5.5 - 0.5\, p|Ca^{2+}|$$

At saturation the fluoride concentration will decrease with increasing calcium concentration. The following computed set of data illustrates this:

Ca^{2+}	mg/l	10	20	30	40	50	60	70
F	mg/l	3.8	2.7	2.2	1.9	1.7	1.6	1.4

These figures are probably minimal figures. It is, however, interesting to note that, in the range of calcium concentration normally found in ground water, fluoride concentrations will mostly exceed the WHO limit recommended. It should be noted, however, that high calcium concentrations favour low fluoride concentrations. Moreover, the calcium concentrations will depend probably more on the physical conditions in the unsaturated zone than on the mineral composition of the rocks.

2.3.4.3 *Nitrate concentration*

Alarming concentrations of nitrate in ground water have been reported in recent years from many parts of the world. It is quite evident that nitrate originates in soils to which it is added partly by biological fixation of atmospheric nitrogen, partly by man-made fixed nitrogen from fertilisers and organic waste. Not all added nitrogen goes into ground water. Moreover, denitrification processes, which are quantitatively poorly known, decrease the amounts of nitrates. The optimal conditions for denitrification are not known. The high nitrate concentrations sometimes found in semi-arid areas are puzzling and may be due to extensive growth of vegetables.

In temperate regions the source of high nitrate concentrations in ground water is no doubt excessive fertilizer applications. The nitrate moves downward at about the same rate as infiltrating water percolates down to the water table. The considerable time lag confuses the effect of changes in fertilizer applications. It may be necessary to consider water quality in the unsaturated zone to assess future changes in nitrate concentrations in the ground water.

2.3.4.4. *Iron and manganese concentration*

As pointed out in Section 2.3.2.4, iron and manganese are likely to appear in old ground water from which all oxygen has been extracted by ferro-manganesian minerals. The concentrations of iron and manganese depend, however, also on the pH and on the bicarbonate concentration. In a "normal" bicarbonate water of pH around 8 the iron concentration rarely exceeds 0.5 mg/l.

2.3.4.5 *Aggressive water*

When the carbon dioxide partial pressure in the water is high and the pH below 7, the water is said to be aggressive, i.e. tends to attack metals (such as metal pipes). The reason for occurrence of such water is lack of easily weathered minerals in the rocks or inadequate time of contact between the water and the rock material. The high carbon dioxide pressure normally originates in the root zone.

3. Investigation, assessment and development

3.1 *INTRODUCTION*

3.1.1. DIFFERENT LEVELS OF INVESTIGATION

Ideally ground-water development should be preceeded by proper investigation and assessment. The reader will be aware of areas where ground water has been developed without any assessment or evaluation. The surprising fact is that, in many cases, ground-water development has been satisfactory in spite of the lack of data and lack of scientific inquiry. When a given area is first developed and when the ground-water extractions are small in comparison to the total resources, no harm is done.

As **extractions** become greater in comparison to the resources, and as the local economy becomes more dependent on an assured ground-water supply, investigation and assessment become more important. When the water extractions equal or exceed the resources, the effect on the local economy may become serious if adequate precautions are not taken.

The relatively low permeability and storage capacity of hard rocks, in a sense, limit the amount of ground water which can be extracted from them, even in very humid areas. Moreover, as rainfall decreases, permissible extraction rates may become very small. In arid regions, however, even small amounts of ground water may be of important socio-economic value and therefore warrant careful investigation and assessment.

Investigation and assessment can be undertaken at various levels of detail and/or intensity. Reconnaissance investigations usually are carried out in a short span of time with only limited use of more costly techniques, and may only provide a preliminary assessment of resources. Detailed investigations generally will require more time (depending on size of area, data available, etc.) and may require geophysics and some test drilling. Major ground-water development may require large scale investments in a short period of time in detailed design and feasibility studies. Detailed studies will also be needed for specific problems such as pollution, engineering construction, legal problems, etc. Such detailed studies may require highly sophisticated exploration techniques and use of models. In practice, however, these various levels of study tend to overlap.

3.1.2 RELATION BETWEEN PURPOSE OF STUDY AND FUNDING

Funding is usually one of the constraints to the level of study and to the extent of development of ground water. Generally, reconnaissance studies tend to be the least costly, and detailed feasibility and design studies the most costly. Ground-water development is usually carried out over extended periods of time but is normally phased or staged. Thus when funding for reconnaissance studies, some provision may be made to include limited ground-water exploitation which later provides data for further refinement of resource estimates and for decisions on expanded exploitation.

In some developing countries basic materials such as topographic maps and aerial photographs at an appropriate scale may not be available. The lack of such materials may increase the costs of reconnaissance investigations considerably more than in countries where they are already available.

Where ground water has a very high value, as for a major industry or a large town, funds will often be available for more sophisticated studies. In contrast, in many countries an individual landowner or a small village will generally have very limited funds, and exploration methods to be used have to be simplified accordingly.

In most hard rock areas water development is, by the nature of the rocks, limited in each well to relatively small yields. Therefore, investigation and assessment, if done for the government, will usually be carried out over relatively large areas and will provide guidelines for pinpointing the most likely areas for detailed work. The detailed site work may or may not include geophysics, airphoto interpretation, etc., depending on funds available.

In summary, the selection of methods for investigation and assessment of ground water in hard rock areas may not be under control of the technical staff if funds are limited. However, the selection of methods is important at the funding stage. Such is the emphasis of this Section.

3.1.3 EVALUATION AND SELECTION OF METHODS

Hydrogeology is based on science but its application is an art, and the evaluation of which methods to use is perhaps more art than science. As discussed above, financing may place very strict limits on the choice of techniques. While experience and an open mind are required, it is obvious, that the least time and money consuming techniques should be used first. Interpretation of geomorphic and geological features on available maps, aerial photographs and Landsat (ERTS) imagery is the most reasonable first step, followed by field reconnaissance and further map interpretation. In deeply weathered areas or areas covered by shallow surficial deposits, obviously favourable zones may be tested and perhaps extended by geophysical methods. Normally, results of geophysical methods are analysed using all available surface outcrop and subsurface data.

A common problem arises in the areas with no outcrops and where there are no wells against which to calibrate the interpretation of geophysical investigations. Where possible, the best way to approach this problem is to start a test drilling programme to obtain some subsurface data, then to carry out the geophysical studies to decide on the remaining drilling programme. Ideally the geophysics should be re-interpreted after completion of the drilling programme and, perhaps after some years, again interpreted when more data are available and before more geophysical programmes are planned. In effect, then, ground-water exploration is carried forward by an alternate use of geophysics and test drilling together with geological interpretations.

3.2 *INVESTIGATION OF GROUND WATER*

3.2.1 REMOTE SENSING TECHNIQUES

3.2.1.1 *Remote sensing systems*

Introduction — Remote sensing has become an indispensable tool in many types of surveys, including exploration programmes in igneous and metamorphic rock areas. The use of remote sensing methods has a number of advantages over the traditional field survey. It reduces considerably the amount of field surveys and can be executed under more agreable conditions. It enables also the investigator to study at the same time the surroundings of the area of interest for important information which otherwise should be beyond his field of observation.

Remote sensing comprises a number of techniques for identifying phenomena existing on the earth's surface at the time of recording. It makes use of the characteristics of the electromagnetic spectrum by recording the reflected energy from the objects at the surface of the earth. The reflected energy may come either from an artificial source (e.g. radar) or from the sun. The photographic system and the scanning system use the sun as energy source: the former records the energy reflected from the target or object while the latter records the reflectance as well as the heat radiation emitted by the objects (Figure 3.2.1.1).

Within the scope of the present work only the application of aerial photography and multispectral scanning will be discussed. However, other techniques can also be valuable tools: Radar and especially thermal-infrared scanning may become, in the future, very promising tools for identifying directly hydrogeological features. (Ellyet and Pratt, 1975.)

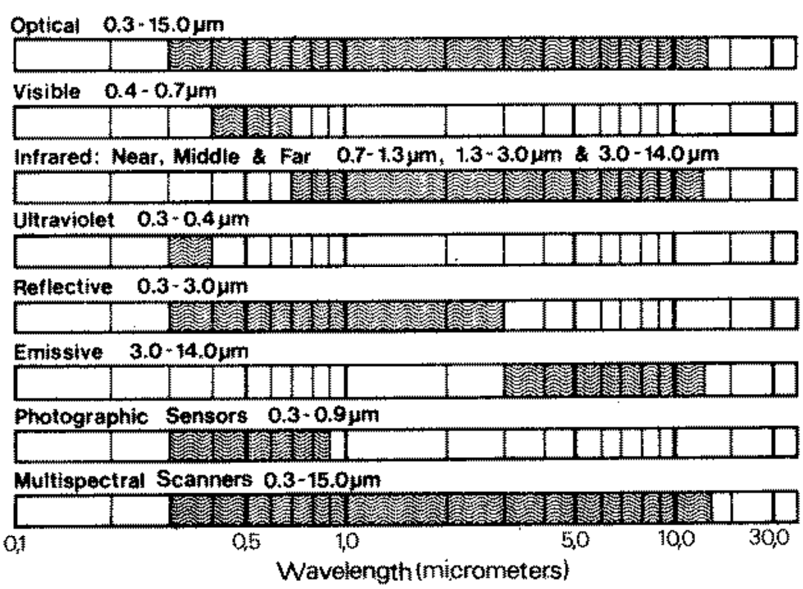


Figure 3.2.1.1 Wavelength ranges in the passive system.

Photographic system – The photographic system (0.3 - 0.9 micron) uses radiation from the sun as a light source. It covers the visible wavelength range and a little beyond it on both sides (Figure 3.2.1.1). In the conventional black and white (panchromatic) photography, filters are used to absorb parts of the visible light. As haze light falls in the shorter wavelength range, ultraviolet and blue are usually filtered out. Also longer wavelengths are sometimes cut out by filters.

Black and white infrared films contain an emulsion sensitive to radiant energy extending beyond the visible range into the near-infrared part. Filters are used to absorb wavelength smaller than 0.7 micron whilst transmitting only red and infrared. An advantage of this film type is its haze penetration capability and its ability to delineate sharply open water bodies.

Experiments (Holz, 1973) show that white light is built up by different colours (Figure 3.2.1.2), and that any colour can be obtained by matching certain proportions of red, green and blue (primary colours). A mixture of these three colours will produce white. Complementary colours are those which, when mixed together, produce a grey tone. Complementary to blue is yellow, to green is magenta and to red is cyan. When they are all mixed together they produce black.

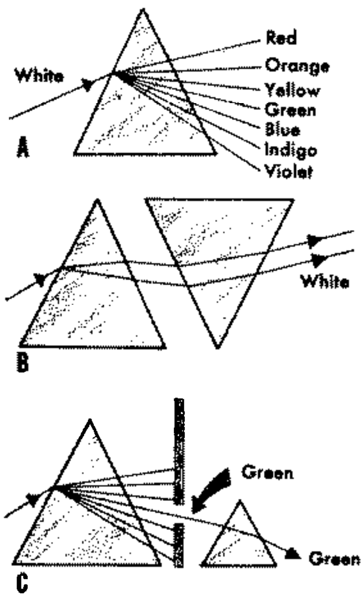


Figure 3.2.1.2 White light is built up by different colours (from Holz, 1973).

The primary and complementary colours and their combinations are used in colour films, false-colour films, in colour composites, in diazo's etc. The advantage of colour over grey tone is that is provides additional information. It may give either direct indications of the nature of the area under investigation through a characteristic colour, or a better differentiation between areas that might appear to be similar in black-and-white photography. However, the image quality of colour films is not always as good as black-and-white because of haze influence and decrease in sharpness at the boundaries.

As the same camera equipment is required for panchromatic film, colour photos and black-and-white infrared films, the higher costs of colour photography are caused more by the organizational aspects and the time spent waiting for good atmospheric conditions than by film costs.

Table 3.2.1.1 Comparison of colours on normal colour and infrared colour films.

Topic	Normal colour film	Infrared colour film
Clear water	Bluish green	Dark blue to black
Silty water	Light green	Light blue
Healthy deciduous vegetation	Green	Red magenta
Needle-type vegetation	Green	Brownish red to purple
Stressed vegetation	Yellow-green	Dark red to cyan
Wet soil	Darker shade of colour	Distinct dark
Red rocks	Red	Yellowish

Colour infrared (false colour) is obtained by a colour shift: in normal colour films the emulsion layers are sensitive to blue, green and red; in colour infrared films they are sensitive to green, red and infrared. Interpretation of this type of photograph does not differ in essence from that of the panchromatic or colour type except for their specific colour characteristics. A good understanding of the colour triangle (Reeves et al. 1975); Sabins, 1978) is however necessary. Table 3.2.1.1 shows a comparison between the colours of a normal colour film product and those of false colour.

In multi-band photography a number of photographs are taken simultaneously, each with a different film-filter combination, in order to record separately specific parts of the spectral reflections.

Scanning system – Multispectral scanning (MSS) may cover a part of the photographic range (Figure 3.2.1.1) but its recording system is not photographic. Figure 3.2.1.3 shows the functioning of the multispectral scanning system. Multispectral scanners are capable of collecting data both in the visible portion of the spectrum and beyond it. The scanner uses a series of detectors, each sensitive to a preselected band of a certain part of thè visible and near-infrared portion of the spectrum. The ground surface is scanned in successive strips as the platform is passing over the area. The MSS system in the satellite-Landsat uses electro-optical instruments sensing simultaneously in a number of bands of the spectrum (colour resolution). As in Landsat I and II, Landsat III collects data separately at wavelengths of 0.5 - 0.6 microns (band 4, green), 0.6 - 0.7 microns (band 5, red), 0.7 - 0.8 microns (band 6, near-infrared) and 0.8 - 1.1 microns (band 7, near-infrared). It carries also an additional band (band 8) responding to thermal-infrared radiation.

The energy reflected from and emitted by the observed objects is picked up in successive scan lines by rotating mirrors and is recorded on tape. The scanning direction is perpendicular to the direction of the platform motion. The scan lines are later framed to form imagery resembling a photograph.

The spatial resolution (the smallest element recorded) is, at present, about 80 m x 60 m; and a Landsat image covers about 185 x 185 km. Once every 18 days the orbiting Landsat satellite (Figure 3.2.1.4) covers each feature on the earth's surface (time resolution).

Figure 3.2.1.5 shows the spectral reflectance percentage for certain types of soil, water and vegetation within a certain wavelength reach. It shows that Landsat band 7 gives the highest absorption for water (black) and the highest reflection for vegetation (light grey). (See image 1 b and 1 c .) The opposite is valid for band 5 (see Image 1 a).

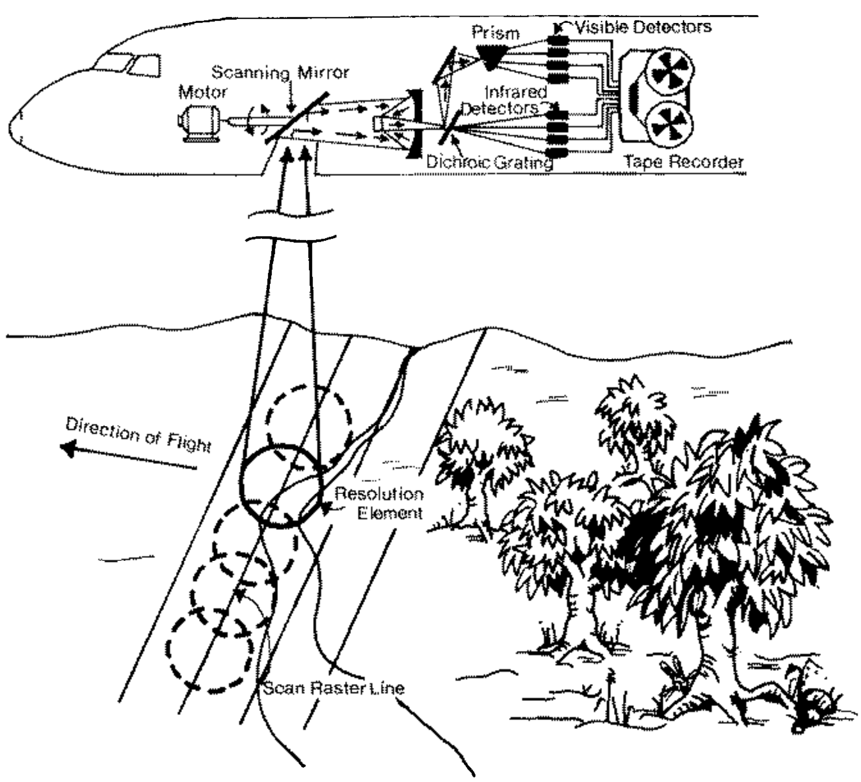


Figure 3.2.1.3 Multispectral scanner system (adapted from Lindenlaub, 1976).

Digital image processing – Although research in digital image processing is still in its infancy this process may render, in the future, the possibility of obtaining more detailed information from Landsat images, as computer-compatible tapes embrace a much larger range of radiance levels than the human eye can differentiate on paper prints (about 10 grey tone levels). With this process, image enhancement, data compression and reduction can be performed, thus offering a possibility of producing imagery which best suits the purpose of the interpreter. (Donker and Mulder, 1977.)

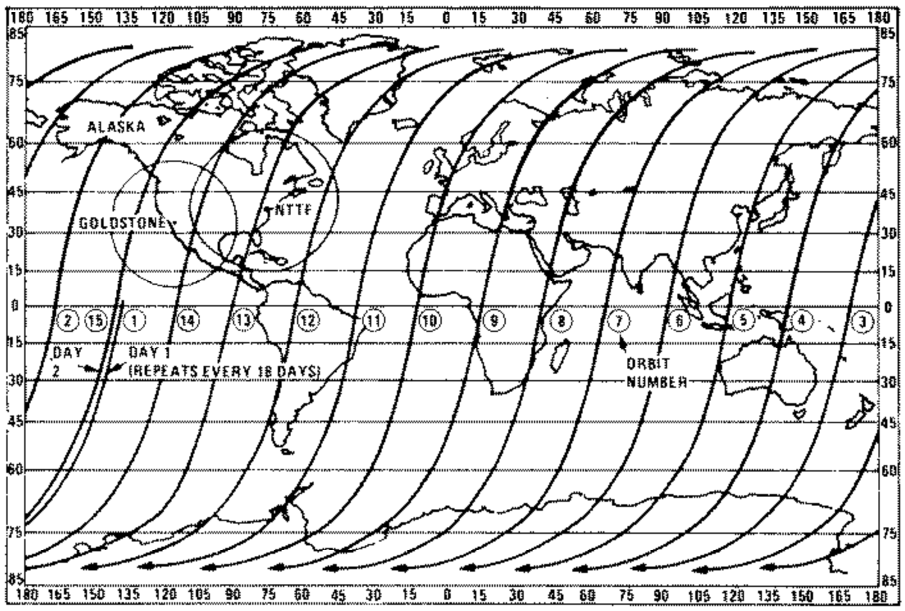


Figure 3.2.1.4 Successive orbital paths of the Landsat satellite. (Adapted from U.S. Geological Survey, 1979.)

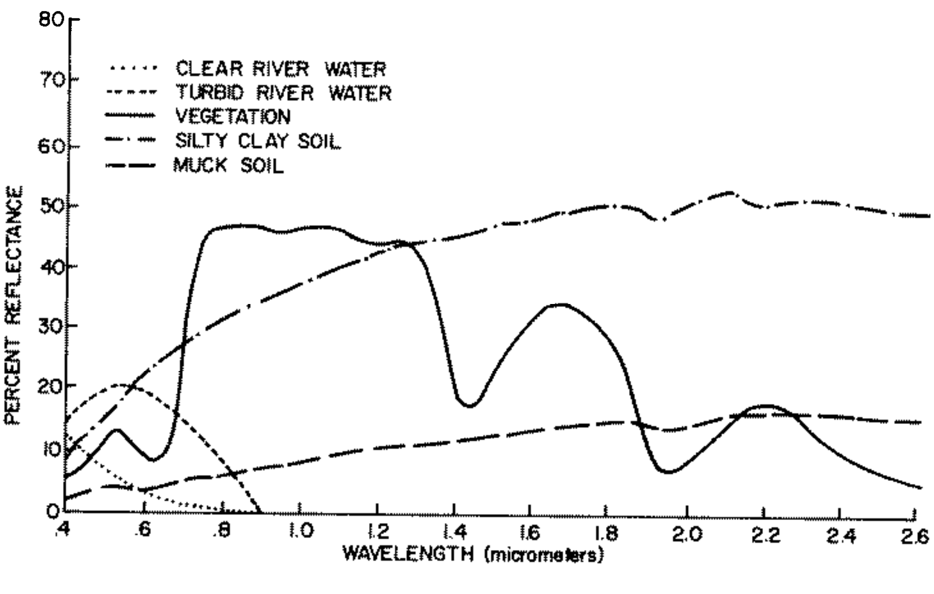


Figure 3.2.1.5 Spectral reflectance of basic cover types (after Lindenlaub, 1976).

3.2.1.2 *Photographic interpretation*

Introduction – While photogrammetry is the science of obtaining reliable measurements by means of photographs, interpretation is defined as an act of examining photographic images for the purpose of identifying objects and geological features and judging their significance. It is a performance in which several processes are involved, which can be summarized in the sequence of observation, identification by recognition, analysis of the elements in relation to their environment, and conclusions based on knowledge and experience. The performance is affected by the image characteristics: photographic tone of the object, pattern, shape and texture.

Image characteristics – Photographic tone depends on light reflectivity which in turn depends on the location of an object with respect to the sun (Ray, 1960). As the measurement of tone is relative, without an absolute scale, tonal variations are only comparable within sets of stereo pairs. The difference in tone between the object and the surroundings and the sharpness of the boundary are aids in detecting and identifying objects. In general a light tone indicates well-drained coarse material (e.g. sand); a dark tone may indicate a high soil-moisture content, a high organic content, basic rock type, certain colours (e.g. red). An irregular and indistinct boundary between light and dark tone may indicate a gradual change in soil-moisture content, and a sharp boundary a well-defined one between two different materials.

Another image characteristic is pattern, which indicates a repetition in tone or texture of detectable features that may be related to geology, vegetation, land use, etc. Very often, however, it is used in relation to drainage. As drainage is very sensitive to changes in rock resistance and to strike and dip, changes in drainage pattern may be indicative of variations in character of rocks, of the presence of geological structures, etc. Drainage patterns and their significance have been described by many authors (Howard, 1967; Lueder, 1959; Miller and Miller, 1961; Strandberg, 1967; Way, 1972).

The density of drainage – fine, medium or coarse textured – is indicative of resistance and permeability: a coarse-textured drainage pattern suggests relatively resistant material which is permeable and a fine-textured pattern soft and impermeable material, that is, arenaceous versus argillaceous rocks.

Shape is defined as the recognition element in the landform of which the identification is subject to the imagination of the interpreter: a mountainridge, a river, a volcano will be identified as such by most of the interpreters; however, unfamiliarity with certain terrains may lead to the wrong interpretation.

Texture is defined as the frequency of change and arrangement of tones (Reeves et al, 1975). Descriptive adjectives are: smooth, rippled, mottled, fine, medium and coarse. Texture is associated with tone, pattern, shape and size. It is used for an aggregate of features too small to be clearly distinguished individually, but also for the density of drainage, for topographic description, etc. (Ray, 1960.)

Observation, division and classification of land forms – The first stage in photo interpretation is a phase of observation; division and classification of land forms in the terrain on the basis of topographic expression and changes in tone and texture. Such land forms represent morphologic units – e.g. valleys, flood plains, tablelands, hilly areas – which are surface expressions to be analysed and evaluated for their meaning in the specific field of discipline in which the study is undertaken.

In this stage of photo interpretation certain morpho-hydrologic units will be recognized (marshes, inundated areas, areas of potential infiltration, basins). The combination of elements which has caused such units can be complex in nature. They can be of geological, climatological, pedological or vegetational origin, and have to be studied and analysed in the following phase for the understanding of present and past conditions (e.g. karstic phenomena in an arid environment).

In areas where the geological conditions are closely reflected in morphological expressions of rock types and structures, geological features such as strike ridges, lithological boundaries, fault scarps and lava flows may be recognized and identified with certainty. In areas with poor exposures the relation between geology and morphology may be less clear and other indications may have to be used (drainage, vegetation changes, etc.).

Little difficulty will, in general, be met in separating consolidated from unconsolidated material; greater difficulty may be experienced in distinguishing the different lithologic units within the main groups. Close integration of photo interpretation and field survey becomes increasingly necessary as the difficulties in interpretation are greater.

Photo characteristics of unconsolidated material – Sand and clay may often show different photographic tones, the former being relatively light and the latter dark. Drainage patterns on sandy soil are generally less dense than on clay and may even be completely absent. Permeability is a dominating factor in drainage density. Cross-sections of drainage channels show the connection between form and material: steep gully faces in cohesive sediments, and more gently sloping faces in the case of non-cohesive material. Sand dunes have a bright tone on photographs. Due to rapid internal drainage any sign of surface runoff may be missing.

Recognition of landforms and knowledge of the processes involved in their development enables the interpreter, during his survey for ground water, to draw already some preliminary conclusions about the possibilities of the existence of potential aquifers and of the quality of ground water. For example, a mottled texture may be indicative of salinization in the case of a fine-grained soil.

Photo characteristics of sedimentary rocks – Sedimentary rocks are generally characterized by stratification due to their origin. The stratification is emphasized by variations in resistance to erosion. Differences in resistance between individual beds are often reflected in the morphology showing valleys following less resistant beds. Even where the morphological expression is obscure, bedding may still be traced by banding due to variations in vegetation, tone or texture.

Shale and fine-grained sedimentary rocks tend to show relatively dark photographic tones, finer textured drainage and relatively closely and irregularly spaced fractures, while coarser-grained clastic rocks tend to have lighter tones, coarser drainage texture and relatively widely and regularly spaced fractures. The lithologic characteristics and the direction of dip of the layers are frequently reflected in the drainage pattern. In the analysis of landforms the drainage pattern is an indispensable tool. In a flat terrain the drainage will show a dendritic pattern, in which the density will generally increase in proportion to the decrease in permeability of the rock; but the density will also depend on the resistance of the rocks.

Carbonate rocks under arid conditions are sometimes difficult to differentiate from sandstones. Both may show sharp bluffs and a drainage pattern influenced by the fracture system. Sometimes remnants of karst features from a past humid period may be observed on aerial photographs.

Photo characteristics of hard rocks – The landforms of extrusive igneous rocks show rather distinct features: craters, lava flows, tuff plains, dikes, etc. Basaltic lava shows, in general, a dark phototone; sometimes columnar jointing may be observed. Pyroclastic materials show features resembling arenaceous material: fine to coarse grained, brecciated, bedding, etc. A fine dendritic drainage pattern commonly develops in this material. As tuff erodes quickly a tuff landscape is characterized by a highly dissected topography.

Granitic rock types show in general a rounded to gently rolling topography under humid conditions, with a dendritic drainage pattern. Under arid and semi-arid conditions the topography may show sharp, angular forms, sometimes smoothed by continuous erosion. Independently from climatic and erosional influences this type of rock has an homogeneous appearance and shows a characteristic criss-cross fracturing. This fracturing is often reflected in the main drainage lines, especially where the soil cover is thin or absent (see Images 2 and 3). The phototone is light to medium grey with a tendency to be brighter in the more arid regions. Fractures, accumulating soil and soil moisture tend to be dark.

Depressions formed by weathering and fractures are potential sources of ground water in granitic and gneissic rocks. Depressions can often be recognized on aerial photographs by their topographic position and by higher density of vegetation. Fractures are often indicated by lineations on the photographs; these lineations may be formed by trees.

Outcrops of basic igneous or metamorphic rocks are rare over large areas in comparison with acidic types. Occurrences of small intrusive outcrops are usually of basic composition.

Lines of trees in semi-arid regions may indicate the presence of a dike as the weathered contact between dike and adjacent rock may contain moisture. Acidic dikes tend to be more resistant to erosion than the basic types. Dikes may form ridges in the landscape, when the adjacent rocks are softer, or trenches when they are harder. Sometimes a dike may change from a ridge into a trench, probably due to changes in composition of the dike material (see Images 4 and 5).

Intensely metamorphosed rocks are difficult to distinguish from igneous rocks on aerial photographs but sometimes a vague banding may indicate a sedimentary origin of the rock. Lower grade metamorphic rocks of sedimentary origin may show characteristics similar to those of sedimentary rocks. Increase in metamorphism tends to diminish the difference in resistance between sedimentary rocks, while foliation and cleavage may change completely the appearance of the rock.

Quartzite is, under various climatic conditions, a resistant rock, well expressed in the topography by its rounded or sharp hills and ridges. The drainage pattern is coarse, due to the resistance of the rock against erosion, and it is controlled by fractures.

Gneisses are more resistant than slates and schists, but often less than granite and quartzite. The topographical expression in gneiss is similar to the features of granite regions. Banding can sometimes be recognized on aerial photographs. The drainage pattern is angular and dendritic (see Image 6).

Schists have a low resistance. The drainage pattern in this type of rock is rather dense and dendritic.

Linear features – Linear features on aerial photographs can have various origins: geological (such as fractures, faults, dykes), vegetational (rows of trees), man made (roads, canals, fences), etc.. On satellite imageries lineations may also indicate the presence of folds, escarpments, sand dunes, etc..

Fractures can be an aid in distinguishing between rock types. In igneous rocks fractures may be irregularly spaced in a criss-cross pattern, while widely spaced lineations at right angles to a pronounced topographic trend may be indicative of metamorphic rocks. These lineations commonly represent cross-fractures, the influence of which is reflected in the abrupt changes in drainage and in the development of tributary streams (Ray, 1960).

In flat-lying sedimentary rocks, fractures are often steep and regularly spaced, giving a blocky appearance to the topography. Sometimes linear features can be observed also in unconsolidated material. If the material is cohesive (clay) their presence can be explained by a possible relationship to fractures in the underlying rocks. Reeves et al. (1955) suggest that the presence of this type of linear fractures in sand may be caused by increased downward seepage of moisture over fractures in underlying rock or by upward welling from fractures.

When displacement can be observed in key beds along linear features, faulting has occurred. High-angle faults, normal faults (dipping plane $> 45°$) usually appear on aerial photographs as straight or slightly curved lines. Strongly curving lines or irregular traces indicate low-angle faults (thrust faults). When no displacement along a linear fracture can be observed or deduced, it is difficult to determine without field check whether the lineations are due to faulting or to the presence of other types of fractures, dikes, etc. The presence of faults may be deduced from certain phenomena such as morphologic alignments (lakes, depressions and saddles), abrupt ending of resistant beds, sudden changes in strike or dip, fault scarps, repetition of absence of beds and straight sections in river-courses. Convergence of evidence may lead to a conclusion.

3.2.1.3 *Applications*

Aerial photographs versus satellite imagery – As ground-water occurrence cannot be observed directly on the surface of the earth, aerial photo interpretation makes use of information obtained from studying the geology, morphology and vegetation in the area under investigation. The combined information is analysed for indications of potential ground-water occurrence.

Aerial photographs have the best spatial resolution, but they have the disadvantage of being the product of one single recording, rendering a snapshot with a static impression of dynamique processes.

Observation through satellite recording may partly compensate this inconvenience because of the possibility of sequential recording (time resolution – 18 days) which permits to observe seasonal variations within the region, such as variations in extension of inundated or marshy areas, in river discharges and in spring flow. The information thus obtained is used in the interpretation process. The synoptic view of large regions rendered by satellite images (area covered about 185 x 185 km) makes them particularly valuable for recognizing indications of large-scale features and patterns. Summarizing, one could say that aerial photographs show mainly the details of surface phenomena and satellite images their relation to regional features and their variation in time.

The availability of satellite images enables the interpreter to economize on survey time by selecting or rejecting areas in a first reconnaissance survey of large regions with scanty information. In a second phase, more detailed study of selected areas by means of aerial photographs should be carried out, supplemented with field checks and field observations. Aerial photographs are useful tools for information on the accessibility of the terrain. In the next phase, geophysical investigations and drilling operation may be carried out in the areas selected during previous phases.

Some examples of interpretation of aerial photographs and satellite imagery are given below. The reader is referred to the images contained in the back cover pouch and the overlays accompanying some of them for additional information and for the explanation of the symbols.

Image 7 is a satellite image of the Amadeus Basin (Australia), on which a number of synclinal and anticlinal structures can be recognized. Even indications of possible faults may be inferred from the presence of certain lineations, morphological features and changes in structural trends.

Image 8 shows some of these features on an aerial photograph of a part of the same area: an anticline in which a valley is situated on a less resistant layer (probably shale filled with gravel and sand), drainage outlets through narrow gorges in the adjacent sandstone, wide fractures in the synclinal structures, etc.

Landsat Image 9 shows the confluence of the Benue and Gongola rivers in Nigeria. The lighter tone along the Gongola and the downstream part of river Hawal probably indicates sedimentary rocks (Bima sandstone). Farther to the east, along these two rivers, granitic rocks occur in which can be observed a number of lineations which are large fractures, some clearly running in a NE-SW direction, others NNE-SSW. The northeast corner of Image 9 shows another granitic area with many large fractures in several directions, separated from the granitic area in the west by a wide zone (tens of kilometres) of rangeland with grass-burning practice (black tone).

Images 2 and 10 are aerial photographs of parts of this region. They show clearly many fractures and some dikes which are not apparent in Image 9.

In Image 2 both the "plastic deformation" phase (see Section 2.1.2.3) and the "brittle deformation" phase can be observed (see overlay of Image 2). In the fracture pattern the very fine but persistent fracture set (1) is interpreted as probably *ac'* (related to the plastic deformation) perpendicular to an old fold axis and/or intrusion. The aquifer prospects are poor in this area (cf. Section 2.2.2.2). The area covered by the photograph could be divided into a number of plinths: A, B, C, D (cf. Figure 2.2.2.1). Inside these plinths very little ground water can be expected. The fractures bordering these plinths may, however, yield reasonable quantities of water. Plinth A for instance represents a poor aquifer, but the fracture sets (2), (3) and (4) around it may act as drain pipes. The fracture pattern of the "brittle deformation" phase contains here different types of fractures: tensile and shear (see Section 2.1.2.3). The tensile fractures are expected to be wide, long and winding. The shears are in general tight and very straight. These characteristics can be used in aerial photo interpretation criteria for the classification of fractures.

Taking as an example Image 2, the following may be observed:

Fracture set (2): Some of the fractures of this set are clearly cut off by another set of fractures: plinth B was moved to the north in relation to plinths C and D due to the shearing influence of set (3).

Fracture set (3): From the above it can be concluded that this set has a shearing character (Section 2.2.2.2) and must therefore be considered to be rather tight with poor ground-water potentials.

Fracture set (4): seems to have a tensile character and should therefore be open. However, a more detailed geological study would be required.

Additional geological study is also required for determining the age sequence among the various fracture sets. The fracture of set (2) between plinths B, C and D are blocked due to the shearing effect of set (3) which is diminishing the drainage area of each fracture of set (2). This should be taken into account when considering where the most promising areas for ground-water development (α and β).

In the area covered by Image 10 fractured granitic rocks are cut by some dikes forming ridges (see overlay).

Fracture set (1) probably has a tensile character in view of its position in relation to dikes. Fracture set (2) could belong either to a shearing set or to a tensile set. In the former case dilatation should be observed along set (2) and, if not present, which seems to be the case here, another phase of brittleness must be considered. The width of the valleys belonging to set (2) observed on the aerial photographs already suggests tensile character. Just outside the area of the photo coverage a dike system parallel to set (2) is present (not shown here) which seems to point to a tensile character of set (2). Set (3) belongs probably to a shearing set.

Unlike in the Amadeus Basin Image (Image 7), it is rather difficult to locate on the Nigeria Image (Image 9) the areas covered by the aerial photographs (Images 2 and 10). In Image 9 well expressed large-scale topographic features – such as folding and block faulting – are missing, and easily recognizable river courses are absent. This shows that the presence of important structural indications of potential ground-water occurrence cannot always be recognized on satellite images, especially when the morphologic expressions of the geological structures are relatively small, the tone difference between rock types indistinct and the variations in dip of layers minimal (Moore and Deutsch, 1975).

3.2.2 GEOPHYSICAL TECHNIQUES

3.2.2.1 *Scope of geophysical techniques*

In contrast to sedimentary terrains where ground water is to be found typically in the pores of horizontal strata of rocks like sandstone or in the interstitial spaces of deposits like sand lenses, in hard-rock terrains ground water occurs in fractures, fissures, crushed zones and joints. The object of geophysical exploration is to locate such features. Generally, the overburden, which may consist of transported material or the products of in-situ weathering of the underlying rock, is of small thickness so that the water-bearing systems of hard-rock areas commonly lie at shallow depth in contrast to the aquifers of sedimentary terrains which may lie at as much as a hundred metres or more. If the loose overburden is unusually thick, geophysical methods may be needed for finding its thickness apart from locating fractures, joints, etc. in the bedrock.

The geophysical properties of water-bearing zones (electrical resistivity, seismic velocity, average density, etc.) depend, among other factors, on the degree of fracturing, the mode of ground-water occurrence and the dissolved salts. In many cases water-bearing fractures can be located indirectly by detecting features, e. g. diabase dikes, associated with them. The geophysical techniques to be used for ground-water prospecting in hard rock areas must be selected with these different aspects in mind (Shiftan, 1967).

Although numerous publications are available on general geophysical techniques, only a few treat the topic with special emphasis on hard-rock areas and associated conditions. Considerable information can be obtained, for example, from publications relating to geophysical mineral exploration and mining in hard-rock areas (e. g. Parasnis, 1966).

Experiences in geophysical applications under hydrogeological conditions ranging from the weathered zone and buried valleys to exposed crystalline rocks are presented in the following selected references as supplemental support to field geophysical operations: Barham, 1973; Birch, 1976; Blankennagel, 1968; Carpenter and Bassarab, 1964; Frischknecht and Ekren, 1961; Kelly, 1977; Leaman, 1973; Patra and Sanyal, 1973; Schwartz and McClymont, 1977; Stewart, 1980; Verma et al., 1980; Wachs et al., 1979; Weibenger et al., 1956; Strange, 1967; Keller, 1967; Brown, 1967; Joiner et al., 1968.

3.2.2.2 *Airborne geophysical techniques*

General – As has been previously discussed in this text lineaments in hard rock areas can be mapped by remote sensing techniques involving study of satellite or high-altitude photographs of an area (cf. chapter 3.2.1). It is a matter of semantics whether airborne geophysical techniques should also be called remote-sensing techniques or not, but because they are much older than photogeology, it is better to categorize airborne geophysical techniques separately. Also, the aim of airborne geophysical techniques, like that of other geophysical techniques, is to study quantitatively a definite physical property, in contrast to the remote-sensing techniques previously described in this volume where no definite physical property is involved and hardly any quantitative determination is aimed at or possible.

The object of airborne work is to cover large regions in a relatively short time to distinguish the areas of primary interest from those that appear unpromising as far as ground-water occurrence is concerned. Several factors should be kept in mind in this connection. First, the equipment for airborne work (the aircraft itself, the measuring, recording and data processing instruments, navigational aids, etc.) is highly sophisticated. Second, the personnel for airborne work must be specially trained and experienced and usually it is only possible to hire such personnel from specialized contracting agencies or firms. Third, the processing and analysis of airborne data needs considerable experience.

All these and other factors like the availability of suitably situated airfields, mobilizing costs, etc. tend to make airborne techniques a capital-intensive operation that can only pay off if the areas to be covered are sufficiently large. In such favourable cases, however, airborne work is incomparably cheaper per line or square kilometre investigated than ground-based work. Airborne techniques are thus at their best advantage in extensive, virgin territories. Where relatively small areas are to be explored or where problems of local interest are involved ground work may be preferable.

An advantage of airborne work, that should not be lost sight of, is that airborne measurements can be made over areas that may be inaccessible to ground parties or at least with very difficult access. However, as far as ground-water prospecting is concerned this advantage will generally be in theory only, because such areas are unlikely to be inhabited.

Airborne geophysical techniques comprise magnetic, electromagnetic and radioactivity measurements. Because radioactive radiations are completely absorbed by any appreciable overburden and because radioactivity is not a phenomenon characteristic of the water-bearing systems of hard rocks, as such, the radioactivity techniques, whether airborne or ground based are not of relevance in the present connection. That is not to say that the phenomenon of radioactivity cannot be exploited in other ways in ground water study, for example, for following the movement of ground water. Although helicopters can be used and may, in fact, be the only means of airborne work in some areas, most airborne geophysical operations are carried out using fixed-wing aircraft. This is because the payload of small helicopters is much less than that of fixed-wing aircraft and their range is also smaller with the result that the overall survey speed is also slower.

In a typical airborne operation the aircraft with the instrumentation may be flown at a ground clearance of 70-150 m following the terrain. A typical measurement profile may be 30- 50 km long and the spacing between profiles 400 m to 1 km for reconnaissance surveys and 100 to 400 m if detailed surveys are desired. Navigation can be carried out by means of airphoto strips on which the survey lines have been previously drawn. This is possible if airphotos are available and the terrain has sufficiently numerous recognizable features. Otherwise a camera can be installed in the aircraft and the film exposures synchronized with the geophysical records. If the terrain is featureless, as is often the case in tropical areas of dense jungles, it may be necessary to use other navigational methods such as a Doppler navigation, Decca or Omega systems based on radio transmission or specially set up radio systems. Navigation by means of satellites is not possible in airborne geophysical work as it is in shipborne work.

In all airborne work the data of measurements must be recorded continuously during flight. In modern equipment the data are recorded on magnetic tape but it is customary to have a simultaneous chart-recording for monitoring. After processing of the data the final results are often presented as contoured maps of, say, the magnetic intensity or as "indication maps" on which only the promising indications are plotted. A prospective client should insist on the former type of maps as they represent the primary data, the interpretation of which (indication maps) may be open to discussion.

Although quantitative estimates of depth, dip, thickness and other geometrical parametres of rock masses can be made from airborne results, it is not always worthwhile to devote excessive effort to such calculations because the prime task of airborne measurements is a rapid location of interesting areas. It is not advisable to base drilling decisions in ground-water prospecting on the basis of airborne indications or calculations alone because uncertainties of the order of several tens of metres or up to even a hundred metres in the position of the indication exist due to imperfections in maps and navigational errors. Airborne indications should always be checked on the ground before drilling is undertaken.

Magnetic measurements – The earth is surrounded by a magnetic field that can be thought of as a flux. The flux density, or the intensity of the field, is not the same everywhere on the earth. Certain features, such as diabase dikes, sometimes produce a strong increase or decrease in the normal geomagnetic flux density. This topic will be discussed in more detail in connection with ground methods. It is sufficient to note here that the magnetic method is based on detecting the variations in the flux density of the earth's magnetic field.

Magnetic measurements in geophysical work are made by instruments called magnetometers. The sensor element of a magnetometer is usually installed in the rear of the aircraft or on a "Stinger" protruding from the rear. The magnetometer most commonly employed in modern airborne work is the proton free-precession magnetometer, often called the proton magnetometer for short. This instrument depends for its action on the phenomenon that the magnetic moments of protons (hydrogen nuclei) in say, a bottle of water or kerosene, can gyrate around the earth's magnetic flux-density vector under certain conditions and the speed of their gyration provides a measure of the flux density of the field in which they gyrate. It is important to realize that the proton magnetometer measures only the magnitude of the earth's total magnetic flux-density but does not give its direction. Such measurements are therefore called total-intensity measurements. Although the proton magnetometer is the most commonly used instrument in present-day airborne geomagnetic work, some surveys are carried out using a so-called flux-gate magnetometer. Unlike the proton magnetometer the airborne flux-gate does not measure the actual magnitude of the earth's total flux-density but only the variations in it from a set value which is the undisturbed flux-density within the area of measurement.

Fracture zones due to tectonic processes may show up on aeromagnetic maps as distortions in what otherwise appears to be a more or less regular anomaly pattern. More commonly, however, they appear with distinctive long anomalies. It is most important to remember that zones of crushed rock may show up as minima in magnetic intensity, rather than maxima, that is, negative anomalies in relation to the surrounding rock. The reason is that tectonic processes often destroy the magnetic properties of what was once fresh magnetic rock (see Figure 3.2.2.1).
Here a long, northwest-southeast trending zone of magnetic minimum is marked by two arrows. Another zone trending northeast-southwest seems also to show up and is marked at its one end by an arrow in the upper right hand corner.

Even when the rocks of an area are weakly magnetic it may be possible to delineate sufficiently wide fracture zones from small magnetic anomalies. This requires, however, very accurate measurements and is more an object for ground work.

Electromagnetic continuous wave techniques – When electromagnetic waves, for example radio waves, impinge on a subsurface conductor like a water-bearing fissure, they induce electric currents in it. The electromagnetic techniques

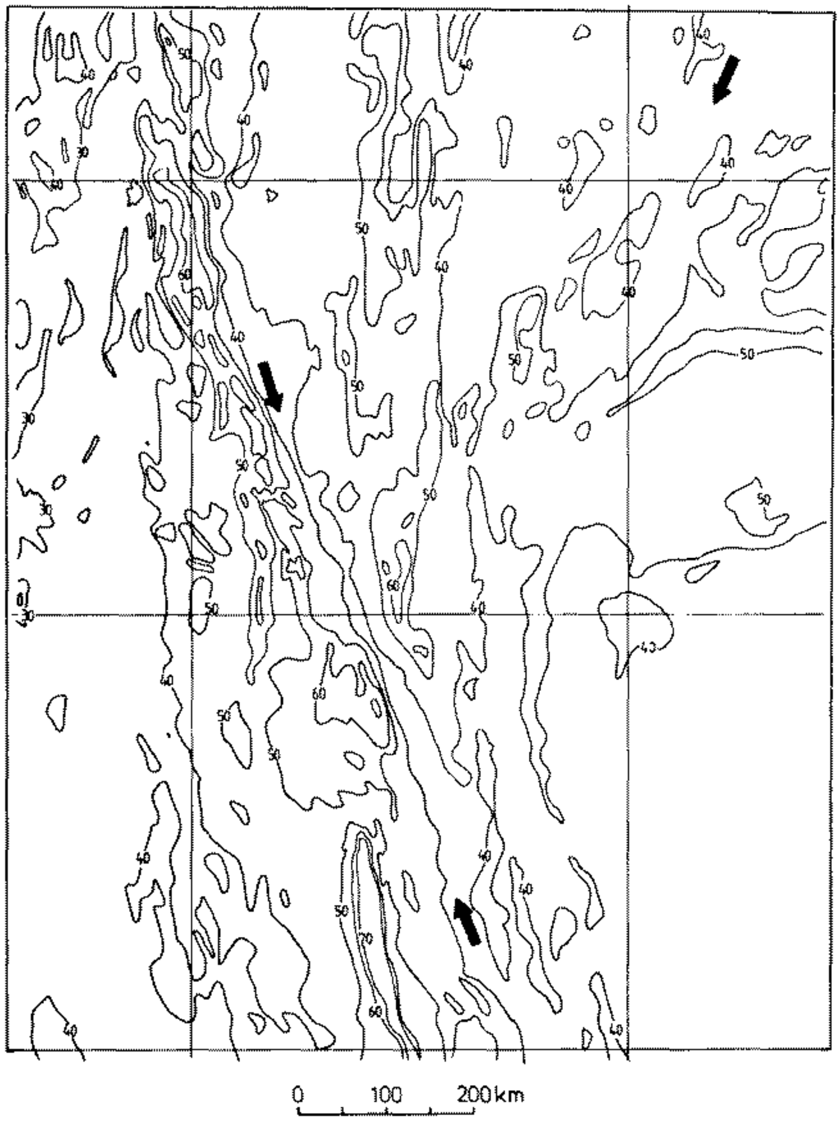


Figure 3.2.2.1 Negative magnetic anomaly zones (marked by arrows) in the Jäckvik area in northern Sweden, indicating fractures. Airborne measurements (flight height 35 m) of total intensity. Contours in microtesla. (Courtesy Geological Survey of Sweden.)

depend on measuring the secondary electromagnetic field produced by the induced currents in the subsurface conductor. The typical set-up for electromagnetic measurements is then a transmitter of the waves and a receiver. Electromagnetic waves have a wavelength that is related to the frequency f of the waves and their velocity c by the simple relation $f\lambda = c$. In air, c is approximately 300,000 km/s so that a wave of frequency, say 3,000 cycles per second (= 3000 Hertz, Hz) will have a wavelength of 100 km in air. A wave of frequency 15 kHz will have an air wavelength of 20 km.

There are two principal types of electromagnetic prospecting methods, namely, the near-field methods and the far-field methods. In the near-field methods the distance between the transmitter and receiver is much smaller than the wavelength. In the far-field methods the receiver is separated from the transmitter by a distance which is much larger than a wavelength, even as much as 100-200 times a wavelength.

In the airborne near-field methods both the transmitter and the receiver will be typically carried on the aircraft, or the transmitter may be in the aircraft and the receiver ("bird") may be trailing behind on a cable. Several different airborne electromagnetic prospecting systems, that is, transmitter-receiver arrangements, are available. A few will be briefly described here.

In the wing-tip system the transmitter is a coil mounted on one wing-tip with the axis in the flight direction. The receiver is a similar coil mounted on the other wing-tip. The system is flown approximately perpendicular to the presumed strike of geological conductors. When the primary field of the transmitter is subtracted from the measured field at the receiver we obtain the secondary field produced by subsurface conductors. Very similar are the helicopter systems in which the transmitter and receiver are often mounted coaxially on a boom hanging below the helicopter. In the wing-tip and helicopter systems it is usual to measure the so-called in-phase (or real) as well as the out-of-phase (or "imaginary" or quadrature) component of the secondary field. These two components can be looked upon respectively, although not in the strict sense, as measures of the strength of the field and the time lag of the secondary field behind the primary field. It is customary to express the magnitude of either component as parts per million (ppm) of the magnitude of the primary field at the receiver.

In the trailing-bird systems it is only possible to measure the time lag of the received field in relation to the primary field. The lag is often expressed in degrees, the convention being that 360 degrees correspond to a lag of one period of the wave. (The period (seconds) of a wave is the reciprocal of the frequency). Note that degrees in this sense do not refer to the orientation or inclination of the field but to a time lag. The airborne and ground electromagnetic prospecting systems using the near-field operate typically on frequencies between 500 Hz and 10 000 Hz.

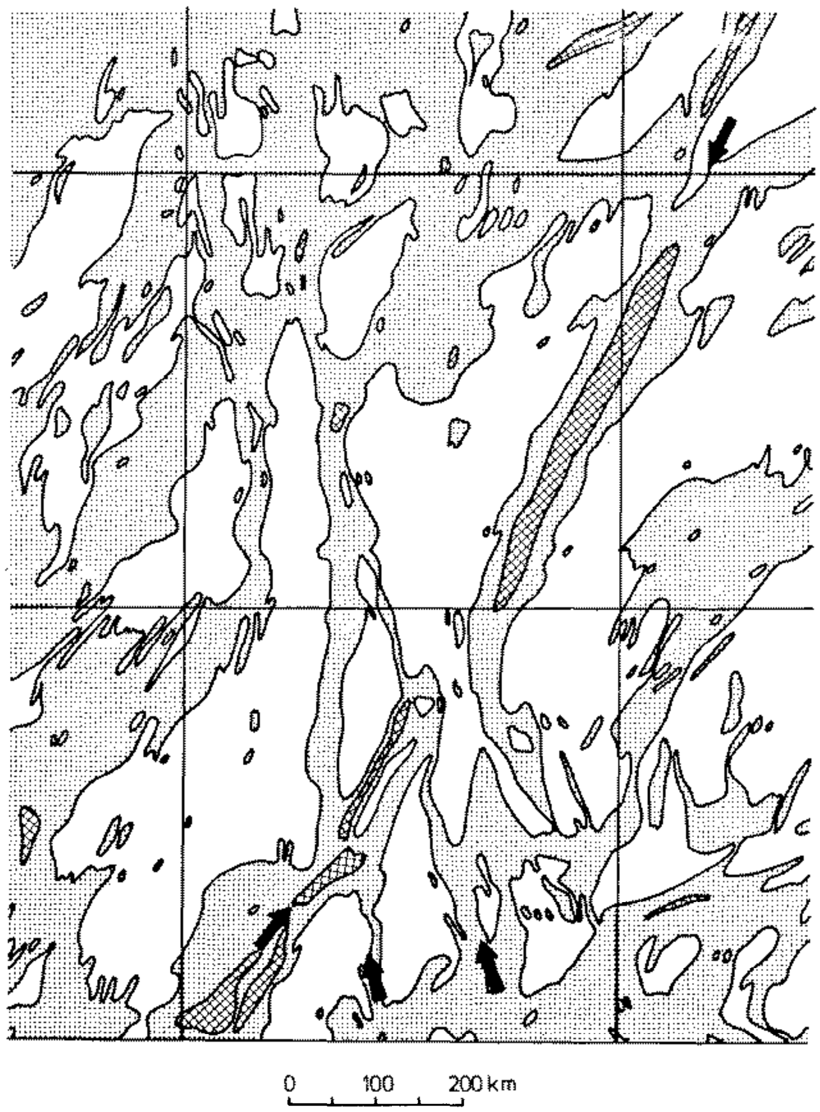


Figure 3.2.2.2 VLF electromagnetic map showing electrically conducting water-bearing zone in the area of Figure 3.2.2.1. Airborne measurements (flight height 35 m). Transmitter GBR (16 kHz). (Courtesy Geological Survey of Sweden.)

The far-field methods measure the field of distant transmitters. Powerful transmitters for long-distance communication have been set up in different parts of the world. These operate on frequencies in the band 15-30 kHz which are very low compared to the frequencies of ordinary radio transmissions (e. g. long-wave radio, about 200 kHz). The transmitters are therefore called Very Low Frequency (VLF) transmitters although it is obvious that their frequencies are, in fact, much higher than those used typically in the near-field electromagnetic methods of prospecting. One airborne VLF method, the Radiophase, is based on detecting the electrical field of the VLF waves but the magnetic field can also be measured. Although commercial VLF prospecting systems at present make use of the global transmitters mentioned above, relatively low power local transmitters for far-field prospecting are also coming into use.

An aerial VLF survey on 16 kc/s of the area in Figure 3.2.2.1 is shown in Figure 3.2.2.2. The stipled areas show the maxima in the total VLF field. The northwest-southeast magnetic zone does not show up very clearly on this VLF picture. On the other hand the northeast-southwest (now marked with two arrows at the two ends) trending zone gives a very strong VLF field anomaly. This difference is almost certainly due to the difference in the electric conductivity of the two zones. As the conductivity depends in turn on water content we may surmise that the latter zone contains far more water than the former making it a much better electric conductor. A combination of two geophysical methods enables us to discriminate between two different presumed fracture zones.

Induced pulse transient method – The methods described in the previous sections operate on continuous waves. An airborne method known as Induced Pulse Transient (INPUT) uses, on the other hand, a succession of "momentary" pulses in the transmitter as the excitation source. A transient pulse creates transient currents in subsurface conductors which decay at a rate depending, among other factors, on the quality of the conductor. The better the conductor the slower is the decay. The field at the receiver is measured in between two pulse transmissions. It is, of course, a gradually decaying field and its strength is sampled at several different instants (channels) during the decay.

Indications with INPUT surveys are often displayed on maps in the form of small circles which are appropriately hatched to show the channel up to which the signal at the point in question persisted.

An advantage of INPUT is that is is possible to create very powerful transient pulses and therefore excite deeper lying conductors to a sufficient degree.

3.2.2.3 *Ground geophysical techniques*

Magnetic measurements – Fractures and fissure systems in hard rock areas are often found to be associated with dikes that intrude the country rock. The intensity of magnetization of some types of dike, for example diabase or amphibolite dikes, may differ considerably from the magnetization of the surrounding rock, in which case anomalies can be observed in the local geomagnetic field and the intensity of the earth's field might be locally changed considerably. Depending on the attitude of the dike and the direction of magnetization the change may be an increase or decrease in the normal magnetic intensity of the area. Dikes may be discovered or, if already known at some point, can be followed and mapped in detail by systematic magnetic measurements. Unfractured, tight dikes need often to be located because they act as dams for the flow of ground water. In other cases fracture zones may be associated with dikes.

The magnetic method depends on detecting the deviation (anomalies) in the earth's magnetic flux density. The vector of the earth's magnetic flux density of field is completely specified at any point by its "elements," the horizontal intensity H, the declination D of H, east or west of true north and the vertical intensity Z.

The departures of H, Z, D or T (the total field) from their normal undisturbed values in an area are called anomalies and denoted by ΔH, ΔZ, ΔD, ΔT respectively. It is not possible to say from the start what the normal values of these elements in an area are. They are determined at the end of a survey from a study of all the values at the different measurement points.

Magnetic measurements on ground are carried out by means of portable magnetometers. If the value of an element of the magnetic field at any point is determined as a difference from its value at a suitable chosen base point, the measurements are called relative determinations. This was more or less the sole procedure until recently, and in it readings of the deflection of a pivoted or a wire-suspended magnetic needle formed the basis of observations. Nowadays, however, magnetic measurements are mostly carried out as absolute determinations of the total-field intensity (by a proton magnetometer) or of the vertical field intensity (by a fluxgate magnetometer).

Magnetometer observations must be corrected for the diurnal variations of the earth's magnetic field. Besides the diurnal variation, magnetic storms (sudden and violent variations in the geomagnetic field) also affect magnetometer readings but there is no satisfactory method of correcting for them. The safest course is to discontinue the field measurements and resume them when the storm is over. A trained observer can easily detect the signs of an approaching magnetic storm during a survey, as the readings of the magnetometer start to fluctuate rather violently.

Magnetic dikes (diabase, gabbro, amphibolite, etc.) may occur as relatively thin dikes or as broad magnetic zones. The anomalies of these two types are different and it is therefore essential to be familiar with some type curves. A magnetic zone or dike is considered as broad when its horizontal dimensions are large compared with the depth to the top surface. The magnetic anomaly over such a zone has a characteristic shape. It is nearly constant above the central portions of the zone but falls sharply across the edges. If the walls of the zone have a vertical or steep dip the anomaly above the edges is almost exactly half that at the centre. The boundaries of a broad magnetic zone can therefore be located relatively easily in many cases from the magnetic anomalies. If there is a flatter dip the anomalies may not fall as sharply on the hanging wall side as on the footwall one, and the corresponding edge may be difficult to locate.

Figure 3.2.2.3 shows a set of ΔZ profiles across long, broad dikes or magnetic zones, each having a width equal to 16 times the depth of the upper surface and striking east-west. It is assumed that the net magnetization is in the direction of the component of the earth's total field in the plane of the figure. The upper set of profiles is therefore valid north of the magnetic equator, the lower set at and south of it. In the lower set is also shown the case when the magnetization of the zone is entirely horizontal (curves 1). It should be particularly noted that even for this case there is a strong peak-to-peak ΔZ anomaly. The reader should guard against the fallacious statement sometimes made that vertical intensity anomalies are non-existent or negligible in low magnetic latitudes or that horizontal ones are negligible in high magnetic latitudes.

The anomalies of relatively thin dikes are shown in Figure 3.2.2.4. An example of ground magnetic anomalies obtained on dikes is shown later in Figure 3.2.2.9.

Self-potential methods – An electrical voltage difference exists, in general, between two points in the ground due to natural electric currents. Such differences, called self-potentials (SP) are generally fairly low, a few tens of millivolt, but do sometimes attain values as large as hundreds of millivolt. Dikes composed of weathered or crushed rock containing water often show SP values of the order of a hundred millivolt. It should be remembered that even small values of SP less than, say, 20 millivolt can reveal fissures and fractures if systematic SP maps are prepared over an area. The SP method is an extremely cheap and easy method to use. Unfortunately its applicability is limited to areas with fairly shallow overburden, not more than, say 10-20 metres, and often less if the overburden has a high electrical conductivity.

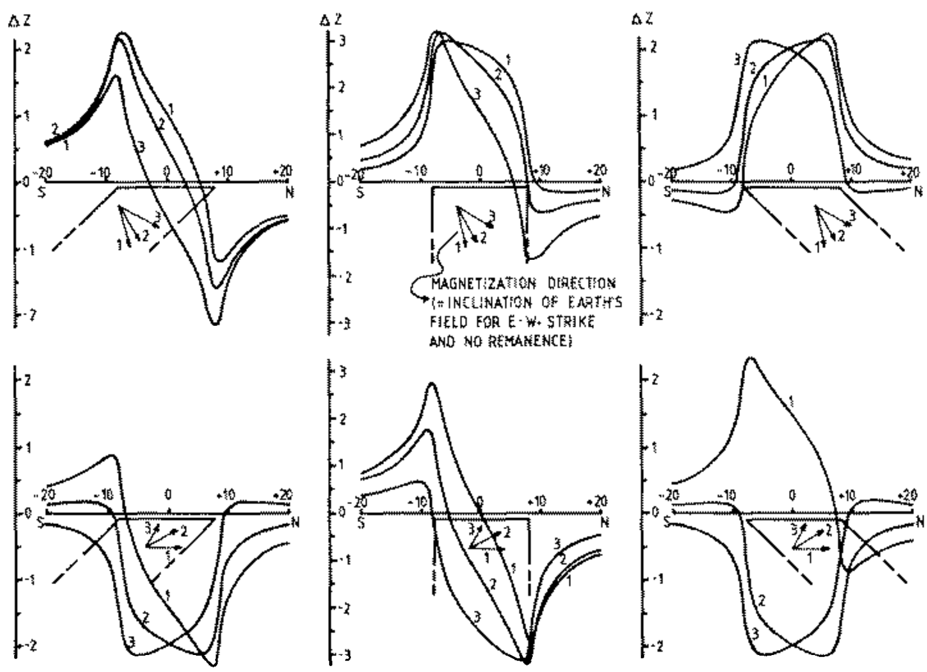


Figure 3.2.2.3 Type curves of vertical intensity magnetic anomalies over a broad zone (width = 16 times depth to upper face) for different magnetization directions (Parasnis, 1966). (Reprinted by permission of Elsevier Publishing Co.)

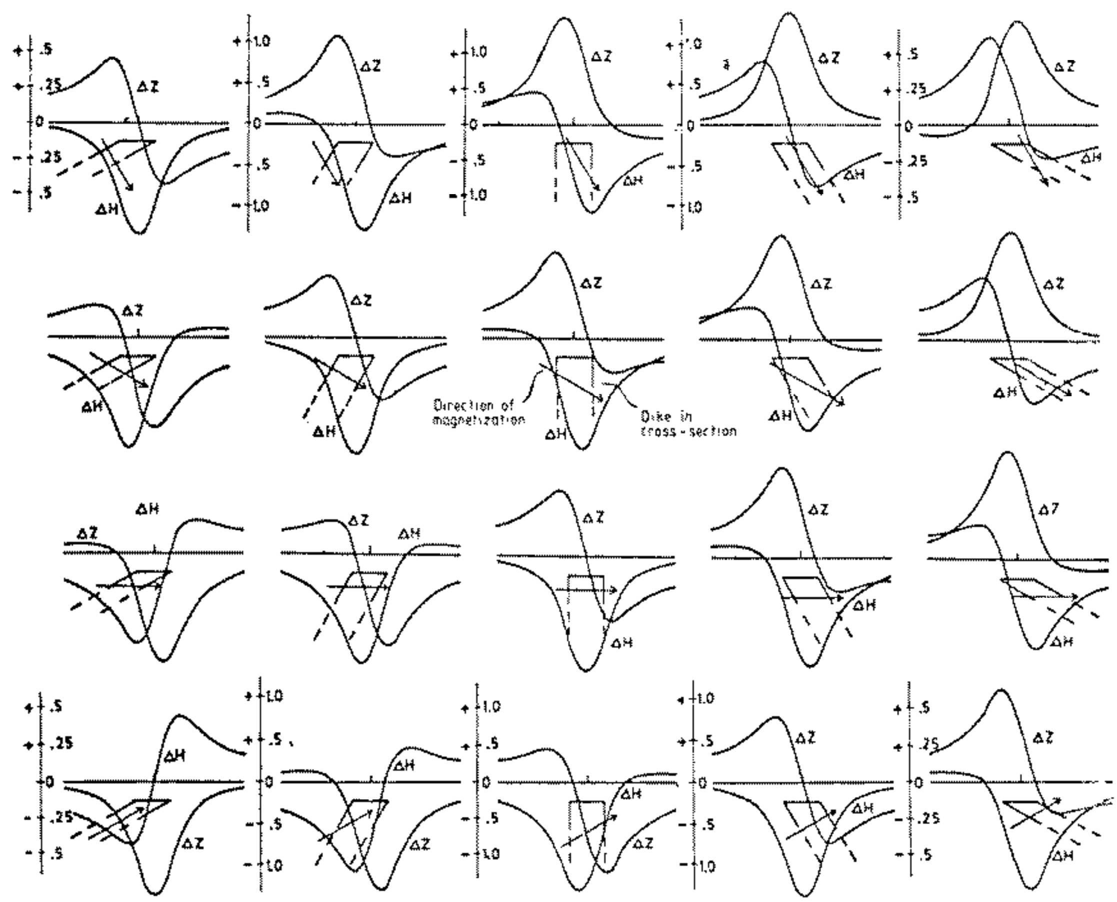


Figure 3.2.2.4 Type curves of vertical and horizontal magnetic anomalies over a thin dike for different magnetization directions.

The apparatus required for SP measurements is essentially simple and comprises only: (a) electrodes, (b) cable, and (c) voltmeter. SP outfits are also commercially available.

Self-potentials are measured by connecting the potential electrodes (preferably non-polarizable ones) to a sensitive voltmeter.

Two alternative procedures can be used for SP surveys. In the first of these, one electrode is kept fixed at a base station while the other electrode, together with the cable reel and the voltmeter, is carried to different points as the cable is laid off, and the electric potential of each point with respect to the base is read on the voltmeter. The zero or normal level of the self-potentials is determined in essentially the same manner as the zero in magnetic work, that is, by an inspection of all the observed SP values in the area.

In the second, and less frequently used, procedure of SP surveys, the two electrodes have a constant mutual separattion s, say, of 10-50 m and they are advanced together along the line of measurements in steps equal to the mutual separation so that the rear electrode (1) each time occupies the position previously occupied by the front electrode (2). If the potential difference between the electrodes is $\Delta_2 - \Delta_1$, then $(\Delta_2 - \Delta_1)/s$ is approximately the gradient of the potential or the electric field (volt per metre) at the point midway between the electrodes.

It should be noted that water-bearing fractures will be indicated by maxima or minima in SP values only while using the first procedure of measuring self potentials described above. In the second procedure, namely gradient measurements, the SP profiles will have an inflection point above the fracture zone.

Figure 3.2.2.5 shows the results of an SP survey using the first of the procedures mentioned above. A zone of fractured rocks occurs in this area and it is evident from the lower part of the figure in particular that an anomaly of as much as -50 mV is produced on the ground due to it. An example where the SP anomalies correlate with overburden thickness in a qualitative way appears in Figure 3.2.2.9.

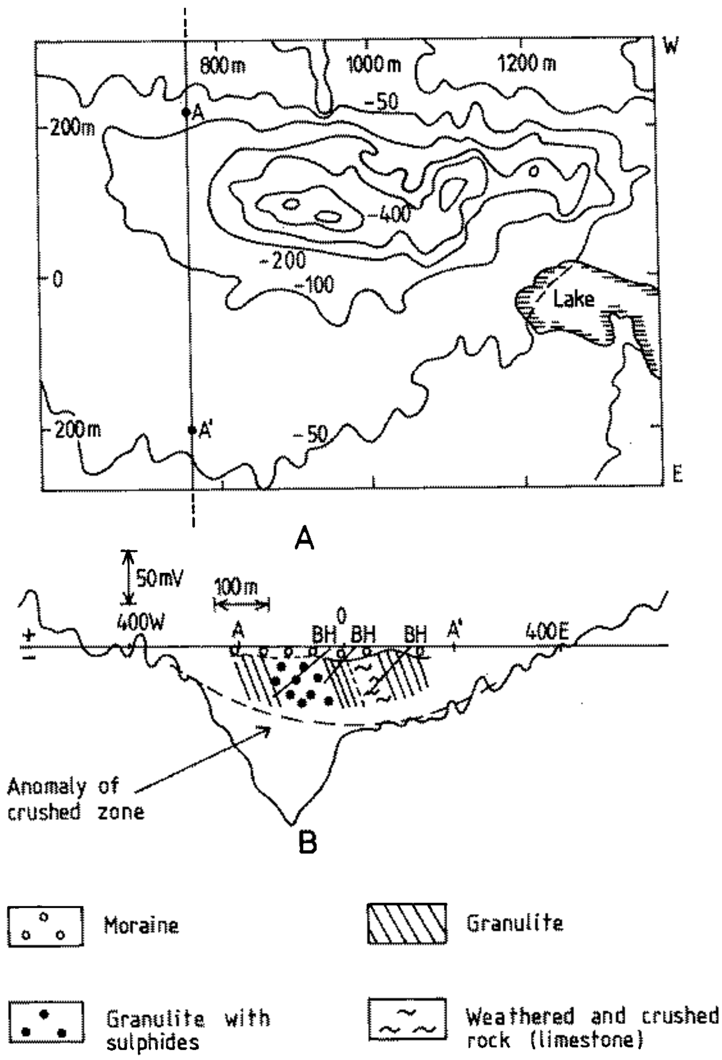


Figure 3.2.2.5 SP measurements showing anomalies over a crushed zone superimposed by anomalies due to sulphide mineralization (Parasnis, 1966). (Reprinted by permission of Elsevier Publishing Co.).

Electrical resistivity methods – Water-bearing fractures in hard rock are often better electrical conductors than the surrounding rock and can be detected by electrical mapping described below. This is not so difficult if the overburden is uniform and fairly highly resistive from the electrical point of view, but often the ground section is electrically more complicated.

In a typical tropical hardrock terrain it may be somewhat as follows: First there may be a top layer of transported or in-situ dry soil covering the water-bearing but unsaturated part of the highly weathered zone of the underlying rock. This top layer is more or less a composite layer having a resistivity of 10 to 50 Ωm (ohm-metres) depending upon the local conditions controlling clay and moisture contents. The second layer may consist of the water-saturated part of the weathered zone, and the fractured and jointed zone that gradually merges with the bedrock. This layer is less resistive than the first layer and will, typically, show resistivities of 10-20 Ωm. At the bottom there will be fresh bedrock having a resistivity of 400-1000 Ωm or more, and it may contain vertical or dipping fractures and fissures of varying width. Basic intrusive rocks, if present, will also show high resistivity of this order.

With such a complicated section it is useful to be able to identify the various layers and their thickness as well as to determine the depth of the fresh rock, before drilling is undertaken. Electrical measurements can be used towards this purpose as will be seen below.

Electrical methods include those in which an electric current is sent into the ground, and the resulting distribution of potentials is mapped by means of a pair of electrodes driven into the ground and connected to a sensitive voltmeter. Electrical methods can be employed only if a satisfactory electrical contact with the ground can be attained and not, for example, in regions with non-conducting surface formations like dry rocks, frozen ground etc. When the positions of the points at which the current enters and leaves the ground are known, it is possible to calculate the potentials, and the paths which the current would take if the ground were homogeneous. Inhomogeneities such as electrically better or worse conducting bodies (e. g. fractures or dikes) are inferred from the fact that they deflect the current and distort the normal potentials.

If a subsurface body is a better electrical conductor than the surrounding ground, more current will flow through this body than through the rest of the ground. The current paths and the equipotentials are then distorted in the neighbourhood of the body, but also at some distance from it. The result is that the voltages in an area above the body tend to be more uniform than in the absence of the body. On the periphery of this area, on the other hand, the voltage difference between any two points is increased above its undisturbed value. When the body is a poorer conductor than the host rock the current trends to avoid it and the voltage difference between any two points above the body is increased while that in the peripherical regions is decreased.

As the electrical anomalies of subsurface conductors depend upon the electric resistivity contrast between them, it is desirable to have an idea of the resistivities of rocks within a survey area. The electrical resistivity of rocks and minerals is an extremely variable property and depends on a number of factors. The resistivity in situ of crystalline rocks such as granulite, granite and diorite is largely dependent upon water in the fissures and fractures. Similarly, the porosity, the degree of saturation and the nature of poro-electrolytes governs the resistivity of rocks like sandstone and limestone. Generally speaking, hard rocks are poor conductors of electricity and, if compact, have resistivities of the order of thousands of ohm-metres but with normal systems of fissures and pores, hard rocks in tropical areas generally have resistivities of the order of hundreds to a thousand ohm-metres. Zones of crushed and badly fractured rocks may on the other hand sometimes have resistivities as low as 1-2 Ωm. Again, some clay as well as water-logged soils and sedimentary rocks like chalk and marls may also possess very low resistivities of the order of 1-20 Ω m.

The apparatus required for electrical prospecting need not be complicated unless a number of refinements like automatic controls are desired. In fact, very satisfactory electric surveys can often be carried out with the simple equipment consisting of high-tension dry batteries as the source of electric current, four metal stakes, two as current electrodes and two as voltage probes, a milliameter, a voltmeter and a sufficient length of well-insulated cable. The current electrodes may be round stainless steel rods, about 70 cm long, with a provision (like a clip) for fastening the uncovered end of the cable leading to the battery. A satisfactory electrical contact will usually be obtained in reasonably moist ground if the rods are driven about 10-20 cm in the ground. In dry ground an unsatisfactory contact can some-

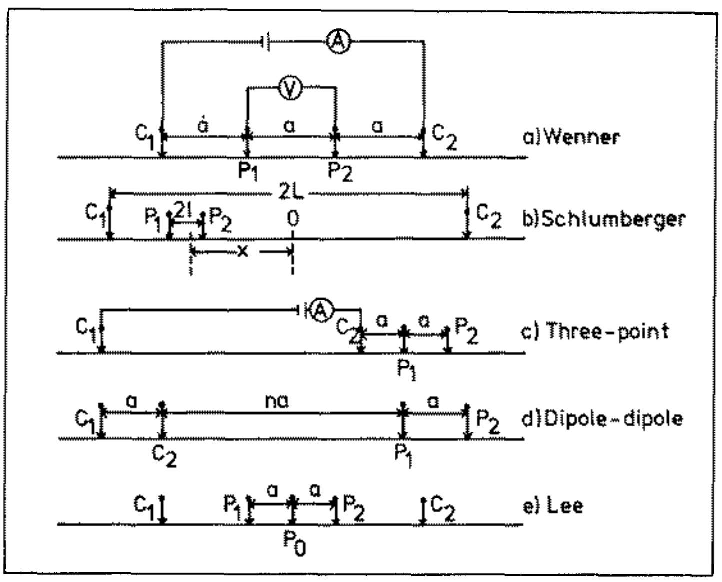


Figure 3.2.2.6 A few different electrode configurations. C_1, C_2 are current electrodes. P_1, P_2 are potential probes.

times be improved by watering the electrodes. The potential electrodes, usually called probes, can also be made of stainless steel rods but non-polarizable electrodes of the Cu-CuSo$_4$ type are preferable. A shallow hole is first scooped out in the ground and the electrodes pushed into it for contact. The voltage (ΔV) created between the probes when a current (I) flows through the earth must be corrected for any self-potential difference that may be present between the probes due to natural electric currents.

The results of a geoelectrical survey are usually expressed in terms of a parameter called the apparent resistivity, denoted by ρ_a. Maps of ρ_a values obtained with a particular electrode configuration can be prepared and contoured. Often the ρ_a values are plotted as profiles as well. The concept of apparent resistivity is a central feature of the earth resistivity method of prospecting.

In a general sort of way low values of the apparent resistivity suggest the occurrence of relatively good electrical conductors and high values that of relatively poor ones, but a measured value of the apparent resistivity at a point must not be directly associated with the electric resistivity of the ground immediately below the point.

A large number of different electrode configurations have been proposed and used in geoelectrical measurements of which some are shown in Figure 3.2.2.6. All the electrodes are assumed here to be point electrodes such as are furnished by metal spikes or polygonal patterns of small dimensions fashioned out of bare copper wire pegged to the ground. From the viewpoint of routine field work, only collinear arrays like those shown here are of importance but we could also use, say, square or rectangular configurations with the electrodes at the four corners. However, the field routine will be cumbersome with such configurations.

The special features of the various configurations shown are briefly described as follows: In the Wenner array, one of the first to be proposed, the separations between adjacent electrodes are equal to each other and the apparent resistivity is given by:

$$\rho_a = 2\pi a \frac{\Delta V}{I} \tag{3. 2. 1}$$

where a is the uniform separation. In the (generalized) Schlumberger or gradient array the distance ($2l$) between the potential probes is small compared with the distance (2L) between the current electrodes. If the probes are sufficiently far from either current electrode, say, at least 10 times the distance $2l$, the apparent resistivity may be calculated from the formula:

$$\rho_a = \frac{\pi}{2l} \cdot \frac{(L^2 - x^2)^2}{L^2 + x^2} \cdot \frac{\Delta V}{I} \tag{3. 2. 2}$$

where x is the distance of the observation point (the point midway between the probes), to the centre 0 of the line $C_1 C_2$.

In the three-point system one of the current electrodes is kept fixed at a very large distance from the remaining three, which have a uniform separation a. As the potential due to the fixed electrode is practically zero at the probes, the configuration is essentially a three electrode system. It is often used for drill-hole measurements. The apparent resistivity is given by:

$$\rho_a = 4\pi a \cdot \frac{\Delta V}{I} \tag{3. 2. 3}$$

In the so-called dipole-dipole system the potential probes are outside the current electrodes, each pair having a constant mutual separation a. If the distance between the two pairs is relatively large, the current source may be treated as an electric dipole. For the apparent resistivity we have:

$$\rho_a = \pi n(n+1) \cdot (n+2) a \cdot \frac{\Delta V}{I} \tag{3. 2, 4}$$

where na is the distance between the two innermost electrodes, one current and the other potential. The voltage difference ΔV is considered positive when P_2 is at a higher potential.

The Lee configuration employs five electrodes, the outer two being the current and the inner three the potential electrodes. Two of the potential electrodes are located as in the Wenner array so that they divide the line $C_1 C_2$ into three equal segments, each of length a, while the third potential electrode is placed at the centre of the configuration. From the voltage differences ΔV_1 and ΔV_2 between the central electrode and each of the other two potential electrodes we obtain two apparent resistivities given by:

$$\rho_{a1} = 4\pi a \cdot \frac{\Delta V_1}{I} \qquad \rho_{a2} = 4\pi a \cdot \frac{\Delta V_2}{I} \tag{3. 2. 5}$$

These are said to "belong" to the respective halves of space on either side of the partitioning plane, a somewhat loose usage that has little theoretical justification.

Of these various configurations the Wenner and the Schlumberger are by far the two most commonly employed. The present tendency, moreover, favours the Schlumberger configuration rather than the Wenner. The Schlumberger configuration has decided advantages in the theoretical computation of apparent resistivity curves. Besides, it is also more convenient from the operational point of view.

Electric sounding – Resistivity surveys are carried out using one or both of two distinct procedures known as electrical sounding and electrical mapping. These are more or less complementary to each other. Electrical sounding, or vertical electric sounding (VES), as it is often called, is based on the fact that the fraction of the electric current injected into the ground penetrating below a given depth increases with the separation of the current electrodes. Thus, as the current electrode separation is increased the electric potential distribution on the surface should be affected relatively more by deep-lying inhomogeneities.

In sounding with the Wenner configuration the separation a is increased in steps by moving each of the four electrodes outwards from the centre ("the sounding point") and taking a series of readings with different separations.

In using the Schlumberger sounding method the potential probes are kept fixed at the centre of the line $C_1 C_2$ while the current electrodes are moved symmetrically outwards in steps. Since only two electrodes are moved, the field routine with the Schlumberger procedure is much more convenient than that with the Wenner one. Furthermore, as the potential electrodes are kept fixed, the effect of local shallow resistivity inhomogeneities in their vicinity (due to soil, weathering, etc.) is constant for all observations.

The first step in the interpretation of sounding observations is to prepare a graph in which the calculated apparent resistivities are plotted as ordinates. In Wenner measurements it is customary to plot the electrode interval a as the abscissa while in Schlumberger measurements half the current electrode separation is chosen for this purpose.

The problem of interpreting electric sounding curves is one of the most intricate ones in the whole of applied geophysics and the reader should constantly guard against any simple rules of thumb in this respect. Unless one has considerable experience in the interpretation of these curves, all that can reasonably be inferred from a cursory study of them is the existence or otherwise of a good or bad conductor at some depth. In relatively simple cases involving only two or three layers, a fairly satisfactory picture of the stratification can often be deduced by means of standard curves, but as a rule computer based procedures are needed.

Electrical mapping – The object of electrical mapping is to detect lateral variations in the resistivity of the ground. Any of the electrode configurations shown in Figure 3.3.2.6 can be used, but as before we shall here confine attention to the Wenner and Schlumberger arrays only. In Wenner mapping the configuration of four electrodes with an interval of, say 20 m, is moved as a whole in suitable steps (5 or 10 m) along a line of measurement. Each electrode is then advanced through the same distance. At the end of the line the array is transferred on the adjacent line and so on until the area to be investigated has been covered in this zig-zag fashion. The apparent resistivity value in each position of the array is supposed to "belong" to the centre of the configuration and is plotted against its coordinate in preparing a map of apparent resistivities. Lines of equal resistivity are then drawn on this map at suitable intervals.

In the (modified) Schlumberger mapping procedure (or the gradient mapping method), the current electrodes are kept fixed at a relatively large distance from each other, say a few hundred metres, and the potential probes with a small separation (5-10 m) are moved between them. The apparent resistivity is calculated from Formula 3.2.1 and a map is prepared by plotting it against the position of the point midway between the potential probes.

There is yet another mapping procedure which is also called the Schlumberger procedure. In this, the current electrodes are kept at a moderately large distance from each other, say 50 m, and the probes are situated midway between them at a small distance from each other, say 5 m. The entire assembly is moved along a line, as in the Wenner method, from "point to point" by advancing each of the electrodes through the same distance.

Figure 3.2.2.7 is a map of apparent electric resistivity on which fracture systems and a couple of fracture zones (areas of low resistivity, stipled in the figure) can be located. Figure 3.2.2.8 shows resistivity profiles across some wide fracture zones showing the drop in resistivity values due to the electric conductivity of water in the zones. These are obtained by the gradient method.

Another example of resistivity mapping (Wenner configuration) in combination with magnetic and SP measurements is shown in Figure 3.2.2.9. The resistivity curves follow the bedrock surface rather well, low values corresponding to relatively thicker overburden and high values to ridges. The SP values are low but the trough in the centre seems to be indicated by the values between -20 and -30 mV between the coordinates 260 and 370 m.

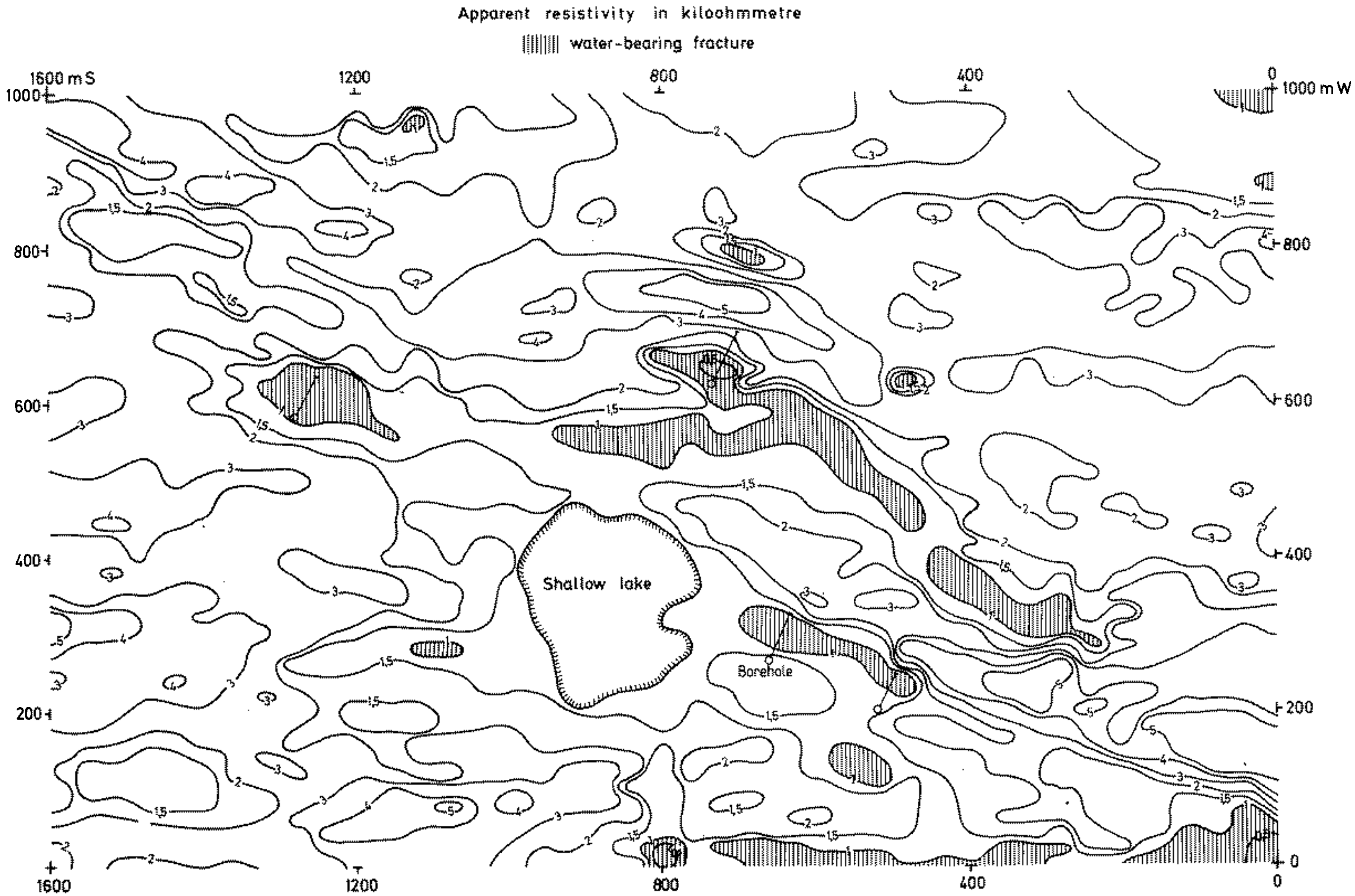


Figure 3.2.2.8 Apparent resistivity profiles showing low values of resistivity over steeply dipping broad fractures (Parasnis, 1965).

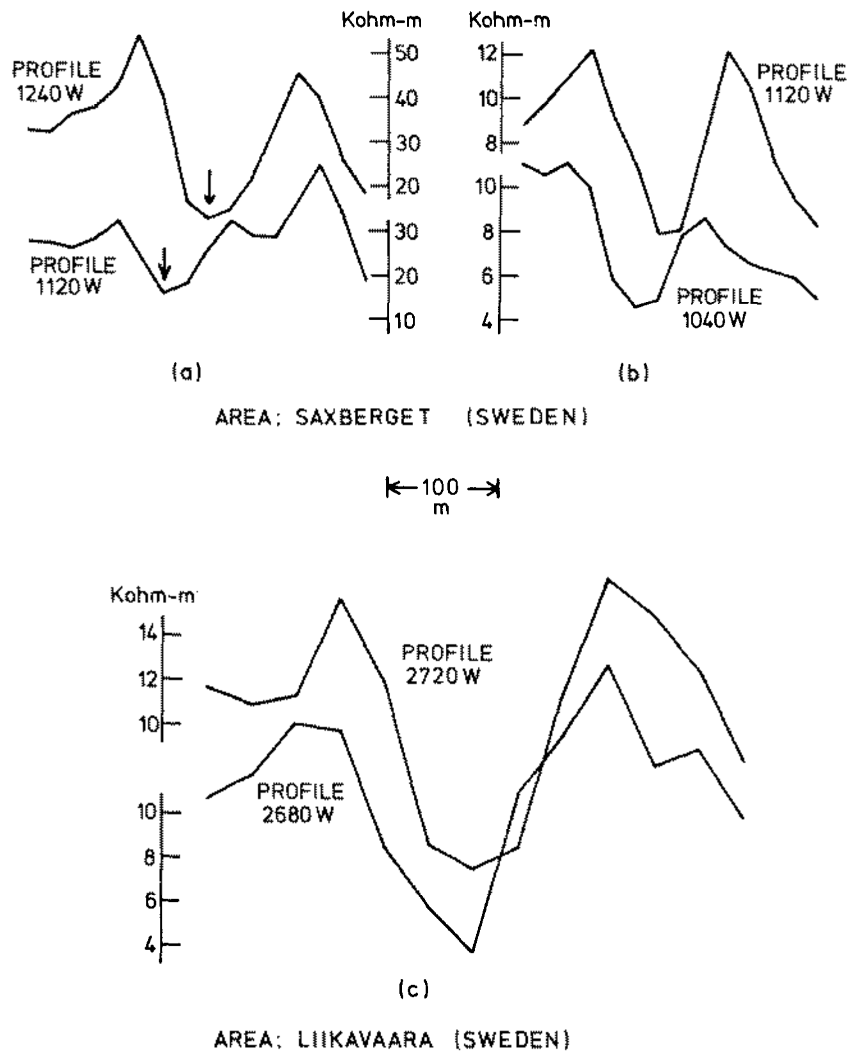


Figure 3.2.2.8 Apparent resistivity profiles showing low values of resistivity over steeply dipping broad fractures (Parasnis, 1965).

Electromagnetic methods – As in the case of airborne electromagnetic work there are near-field as well as far-field ground electromagnetic methods (EM). The near-field methods can be divided into the "moving source, receiver" and the "fixed source, moving receiver" types. The source in the far-field methods is fixed.

A common outfit in the moving source-receiver type is the so-called horizontal-loop system in which the transmitter and receiver loops (about 70 cm im diameter) are horizontal and co-planar. They are held at a specified separation, say 40 m, and the system is moved as a whole in the direction of the transmitter-receiver line, which is perpendicular to the geological strike. The anomalies in the real (in-phase) and imaginary (out-of-phase) components of the received field are measured in percent of the primary field at the receiver. (For meaning of these terms reference should be made to the section on airborne electromagnetic methods). These systems are generally operated on frequencies between about a few hundred cycles per second and, say 1,000 cycles per second.

It can be shown from electromagnetic theory that the in-phase component due to the secondary field of poor conductors is weak while the out-of-phase component is relatively strong. As water-bearing fractures are poor electrical conductors, they are located more frequently by means of anomalies in the out-of-phase component rather than those in the in-phase one.

The example in Figure 3.2.2.10 where a long fracture zone was detected by a horizontal-loop EM survey illustrates the advantage of measuring the out-of-phase component very well. It should be observed that the readings are plotted against the midpoint of the line joining the two loops, and a minimum in the measured readings is obtained when the loops straddle the conductor. In other moving source receiver arrangements an inflection point may instead be observed with the receiver or the transmitter directly above the fracture.

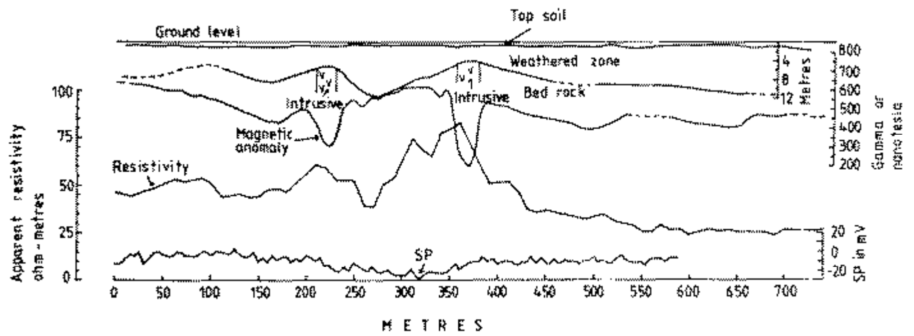


Figure 3.2.2.9 A geological and geophysical section showing comparison of various geophysical results (after Sapathy and Kanungo, 1975).' (Courtesy European Association of Exploration Geophysicists.)

Other moving source-receiver systems measure the inclination of the resultant field rather than the components mentioned above. Thus, in one version, the transmitter loop is held with its axis horizontal and pointing towards the receiver, and the inclination of the receiver-coil axis that gives a zero signal in the receiver is determined by gently rocking the coil "back and forth" making the receiver-loop axis nod, so to speak, towards or away from the transmitter. The loops (at a specified distance from each other, say 40 m) are moved together in steps along a line perpendicular to the presumed fracture. When the measured tilts are plotted as a profile a conductor will be located below the inflection point of the curve. There are several modes of operating such "tilt-angle" systems.

In the fixed source methods the source, usually a large rectangular or circular loop, or a long grounded cable, carrying an oscillating current, is fixed. The receiver arrangement is mobile and, as in the moving source-receiver methods, either the in-phase and out-of-phase components of the field can be measured along a line or, alternatively, the tilt of the field can be measured. In the Turam version of the fixed-source method two receiver coils are employed to obtain a measure of the gradient of the secondary electro-magnetic field. In most instances when the fixed-source method is used to detect poor conductors like water-bearing fractures, it will be found that the anomalies are enhanced when a grounded cable is used instead of insulated loops, which is therefore to be preferred when poor conductors like water-bearing fissures and fractures are the object of exploration.

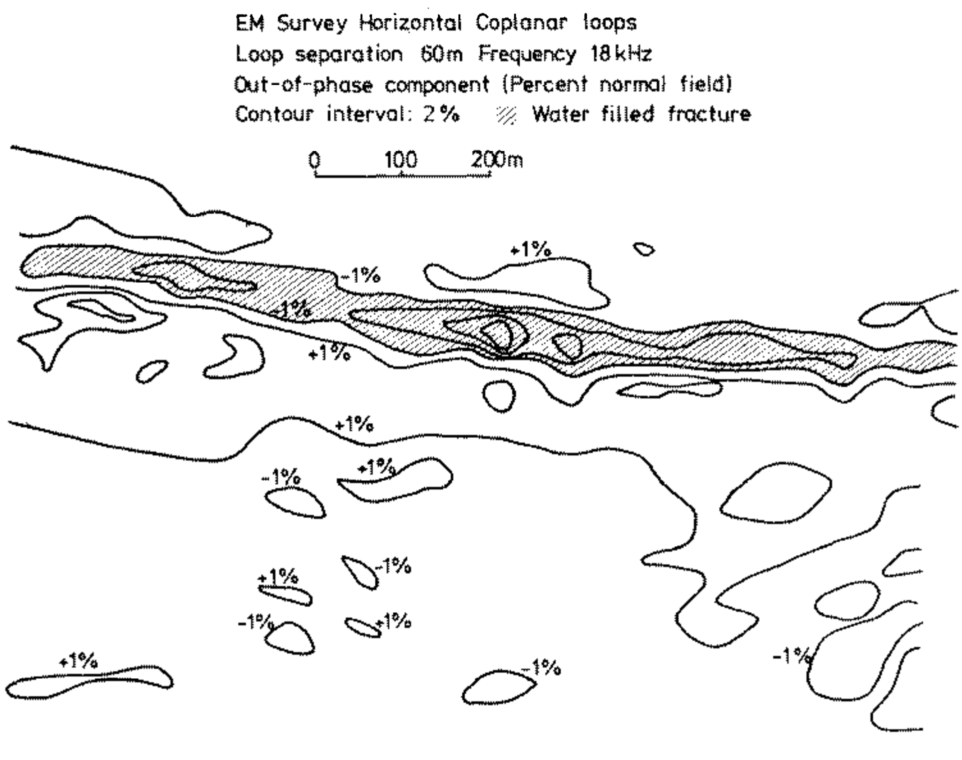


Figure 3.2.2.10 Out-of-phase or imaginary component of the electromagnetic field showing delineation of water-filled fracture.

Following this brief survey of the near-field methods the far-field VLF methods of electromagnetic prospecting can be discussed. As in the case of airborne VLF work, either the electric or the magnetic field may be used but as most surveys at present are carried out using the magnetic component of the field of a distant transmitter, attention will be directed to this so-called H-mode VLF method.

Powerful radio transmitters set up for the purpose of military communication in different parts of the world radiate unmodulated carrier waves, either continuously or with Morse code signals, on frequencies in the band 15-25 kHz. In radio technology, these frequencies are called very low frequencies (VLF) since the carrier frequency of ordinary long wave radio programmes is more than ten times as much. However, in the context of geophysical methods, where frequencies down to 100 Hz are used, the designation VLF is a misnomer. Some examples of VLF transmitters with their codes and frequencies are: NAA, Cutler, U.S.A., 17.8 kHz, 1MW; GBR, Rugby, United Kingdom, 16.0 kHz, 500 kW; ROR, U.S.S.R., 17.0 kHz, 315 kW; NWC, North West Cape, Australia, 15.5 kHz, 1MW.

Measurements in the VLF method essentially involve the determination of the tilt of the electromagnetic field vector. A coil tuned to the frequency of the selected VLF station, and connected to a signal detector, is held with its axis horizontal and turned until a minimum signal is obtained. It is then turned through 90°, the axis continuing to be horizontal, and finally it is tilted around its horizontal diameter until a minimum signal is obtained and the tilt of the coil noted. In this position the magnetic vector lies in the plane of the coil. Figure 3.2.2.11 shows a ground VLF profile across two several kilometres long, parallel conductors. For comparison the results of a moving source-receiver survey along the same profil are also shown. The lower part of the figure shows the construction of the resultant field *R* from the primary VLF field *H'* and the secondary field *S* of the conductor. The tilt-angle θ is upwards on one side of the conductor and downwards on the other side.

Finally, before leaving the electromagnetic methods two further points should be noted. First, the anomaly amplitude in the electromagnetic field increases with frequency so that if poor conductors like water-bearing fissures are being sought it is advantageous to use a fairly high frequency. However, high frequencies are damped more than low frequencies by a conductive overburden so that a limit is often set in any area to the maximum frequency that can be meaningfully used. There are no general rules for the selection of a frequency and it is advisable to carry out trial measurements with a few different frequencies from low to high. Many commercial EM outfits operate on two frequen-

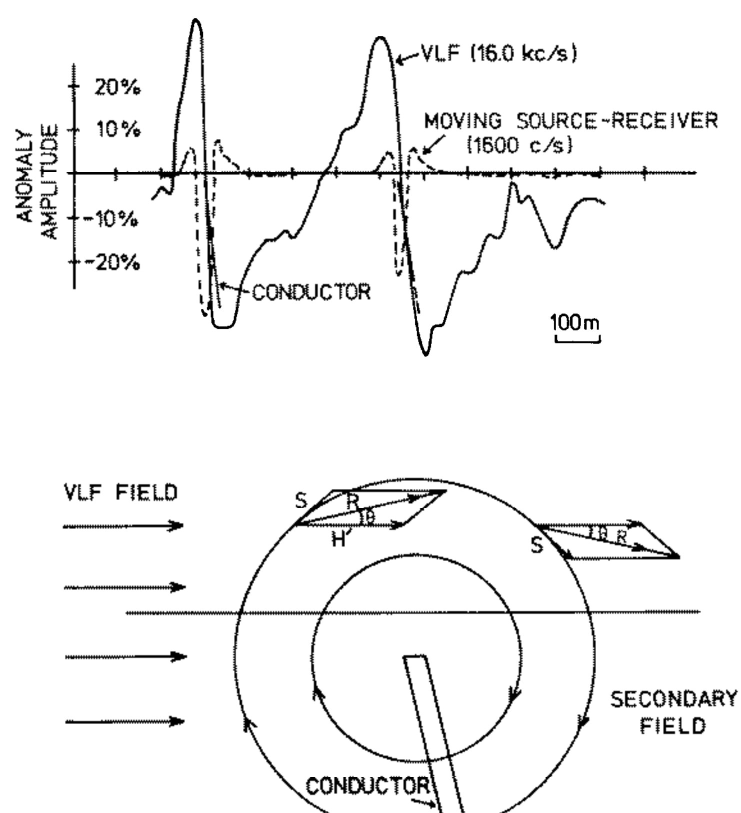


Figure 3.2.2.11 VLF tilt-angle anomalies on a steeply dipping conductor (Parasnis, 1979).

cies and there are also multi-frequency outfits. The second point is that the thickness of a fracture or a fissure is not a very critical factor for the strength of EM anomalies. Even a very thin fracture, say 1 m, will produce quite as strong an anomaly as a very broad fracture provided the conductivity of the connate water it contains is sufficiently high. This is in marked contrast to the resistivity methods described earlier which are not sensitive to thin conductors. On the other hand the resistivity methods need a relatively small contrast between the electric conductivity of a fracture and the surrounding rock before the former shows up in the measurements whereas the EM methods need a fairly high conductivity in the fracture.

Seismic methods — If the fracturing in a broad zone is very intense the zone becomes a more or less homogeneous or quasi-homogeneous feature with characteristic physical properties of its own. For example, the velocity of seismic waves is generally much reduced within such a zone in comparison to the velocity in fresh hard rock and the zone can be mapped by determining the velocities of seismic waves along suitable profiles in the area of interest. The method used for the purpose is the refraction method. Its use is not limited to the detection of fracture zones only but can be extended to hard rocks. The seismic refraction method depends on the fact that the velocities of seismic waves in different rocks are different.

The most common method of generating seismic waves is to explode dynamite charges. The method has the advantage that the required energy can always be obtained by the use of a sufficient amount of explosive. Moreover, provided proper precautions are taken, explosives are convenient to handle. The disadvantage of explosives is that there is always an inherent danger of injury to personnel and damage to property so that very rigorous safety precautions must be taken. Other ways of producing seismic waves have been tried, for example, hammer blows or powerful electric sparks, but the energies obtained by them are not always sufficient for deep investigations. However, for shallow investigations, in particular, the hammer seismograph outfits seem to be well adapted.

Seismic waves are detected by geophones the most common types of which are the electromagnetic ones. A coil attached to a frame is placed between the poles of a magnet which, in turn, is suspended by leaf springs. The frame is in firm contact with a closed tight housing provided with a spike or blade for driving the geophone in the ground. The coil moves with the ground while the magnet remains virtually stationary on account of its large inertia, and the relative movement of the two produces an electrical oscillating voltage. The voltage from the geophone is amplified, filtered suitably depending upon the frequencies in the ground motion to be registered, and fed into the recorder where it sets a tiny galvanometer into oscillations. A mirror carried by the galvanometer reflects a light beam on to a moving recording film where the seismic waves are thus ultimately recorded. The hammer seismograph displays are nowadays often on CRO-screens.

When seismic waves pass from one medium to another in which they have a different velocity they are refracted. The law of refraction is simple. If the ray incident on the interface between two media makes an angle i_1 with the normal to the interface, the refracted ray in the adjoining medium makes an angle i_2 with the normal (Figure 3.2.2.12) and:

$$\frac{\sin i_2}{\sin i_1} = \frac{V_2}{V_1}$$

where V_1 and V_2 are the seismic velocities in the two media. If V_2 is greater than V_1 we have $\sin i_2 > \sin i_1$ and therefore $i_2 > i_1$. Thus, the refracted ray in this case makes a larger angle with the normal, that is, a smaller angle with the interface than the incident ray. If the incident ray makes a particular angle i_c such that:

$$\sin i_c = \frac{V_1}{V_2}$$

$\sin i_2 = 1$ so that $i_2 = 90°$. In this case the refracted ray travels along the interface and the angle of incidence is called the critical angle.

Now consider an overburden of thickness h resting on a substratum having a greater seismic velocity (Figure 3.2.2.12). A critically incident ray will be refracted so that it travels along the line AB_1B_2 .... along the interface, but at various points such as B_1, B_2, etc., its energy re-emerges in the upper medium, along rays making angles ic with the normals at these points. These rays reach the surface of the ground at points G_1, G_2, ... etc.

If a number of geophones are placed along a straight line from the shot, the first ray to arrive at the nearer geophones will be the direct ray travelling along the surface. However, at the more distant geophones the first ray to arrive will be the refracted ray because it travels part of the path with the higher velocity V_2 and overtakes the direct ray.

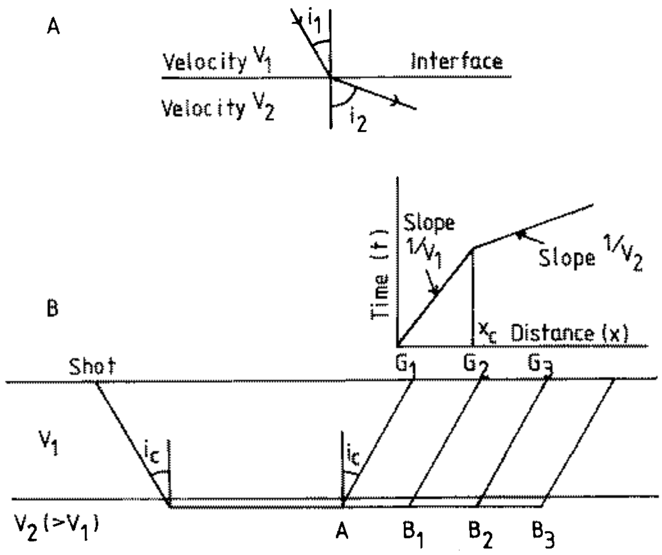


Figure 3.2.2.12 Refraction of seismic rays and a theoretical time-distance graph of first arrivals.

Therefore, if the first arrival times are plotted against the distance from the shot, the first few arrival times will fall on one straight line and the rest on another straight line, the slopes of the lines depending upon the velocities V_1 and V_2. In fact the reciprocals of the slopes are equal to the respective velocities as indicated in Figure 3.2.2.12.

If the interface between the upper layer and the substratum is not horizontal like the ground surface, but makes an angle θ with it, the slope of the second segment will not be the same when the shot is placed on the up-dip side and the geophone set-up on the down-dip side, as in the reverse case. Therefore, the two apparent velocities V_d and V_u, in shooting down-dip and up-dip respectively, will be obtained. The slope of the first segment ($1/V_1$) giving the upper-layer velocity is the same for both shootings.

It can be proved that:

$$V_2 = \frac{2V_d \cdot V_u}{V_d + V_u} \cos \theta$$

If the dip is small, as it often is in practice, $\cos \theta = 1$ and the following may be written:

$$V_2 = \frac{2V_d \cdot V_u}{V_d + V_u} = \frac{V_d \cdot V_u}{(V_d + V_u)/2}$$

This gives the following simple easy-to-remember rule:

The true bedrock velocity is very nearly equal to the product of the up-dip and down-dip velocities divided by their mean, if dips are small. There is one slight snag in this rule in that for certain dips the apparent down-dip velocity can be infinite which shows up as horizontal time-distance segments on the graph. It can be shown that for this particular case the true velocity is simply twice the up-dip velocity.

If there is a fixed geophone set-up and two sufficiently distant shots are fired, one on each side of the set-up, two time-distance graphs are obtained, each corresponding to the passage of the seismic waves along the bedrock surface, provided the shots are sufficiently distant. If the true velocity in the bedrock is determined for successive graph segments in the manner indicated above, a zone of significantly low velocity will show up immediately. An example of the detection of a fracture zone in this way is shown in Figure 3.2.2.13 while Figure 3.2.2.14 shows how the water table as well as vertical fractured zones can be delineated by a study of the changes in seismic velocities, see also page 97 for more details of the procedure.

Finally it should be noted that the seismic method is much more expensive and time-consuming than the electrical and electromagnetic methods. There are, however, situations in which the latter methods cannot be used because of artificial conductors like pipes, buried electric cables, grounded wire hedges, railway tracks, etc. which completely vitiate the electrical measurements. A seismic survey may then be the only one of two alternatives for detecting fracture zones, the other being gravity measurements which are described in the following section.

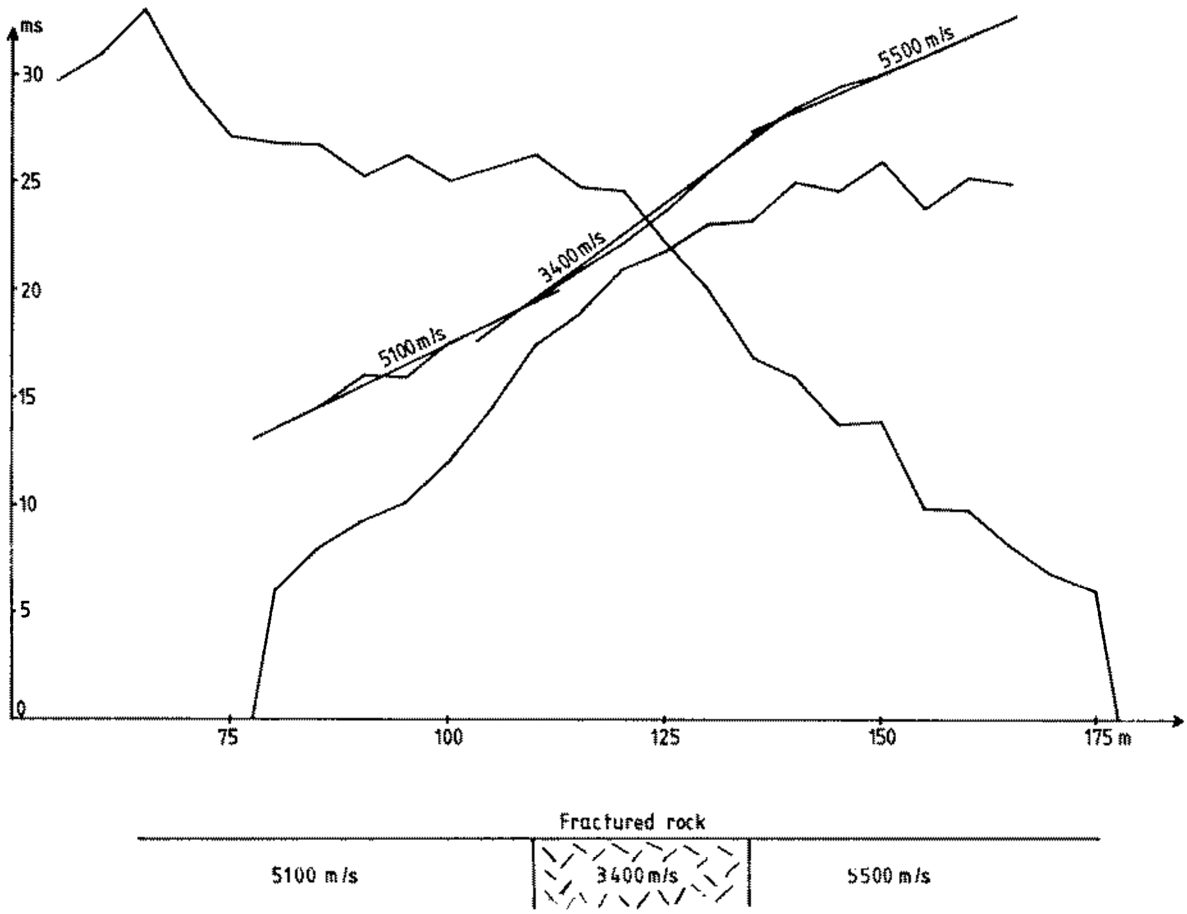


Figure 3.2.2.13 Seismic refraction profile showing low-velocity zone due to fractured rock.

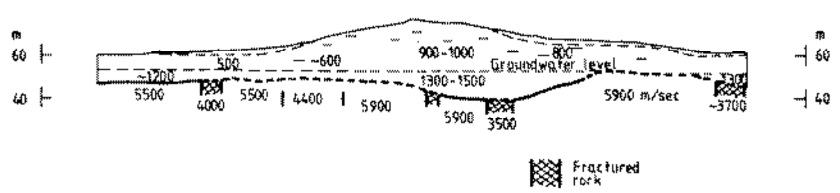


Figure 3.2.2.14 Cross-section of the Badelunda Esker, Västeras, Sweden, showing fracture zones determined by seismic refraction (Hasselström, 1969). (Reprinted by permission of Elsevier Publishing Co.).

Gravity methods – The average density of broad zones of fractured rock is lower than that of compact hard rock so that such zones produce a local decrease in the gravitational attraction of the earth. Very sensitive instruments (gravimeters) are needed to detect such a decrease which is generally of the order of a fraction of one part in a million.

Corrections for the relative latitudes and altitudes of the measurement stations must be applied before the small gravity anomalies are detected. The relative altitudes must be known to better than a few centimetres. If the topography is very irregular, corrections are also needed for the attraction of topographic irregularities. Furthermore, the lateral variations in the overburden density must be small if they are not to mask the anomalies of fracture zones buried underneath.

For all these reasons the gravity method is of extremely limited application in the routine mapping of fracture zones. It is a relatively expensive method since it also requires a levelling survey and a rather close spacing of stations. It is, however, possible to obtain quite clear indications of fracture zones under favourable circumstances as shown by the example in Figure 3.2.2.15 where, in fact, the gravity indication is clearer than the resistivity one.

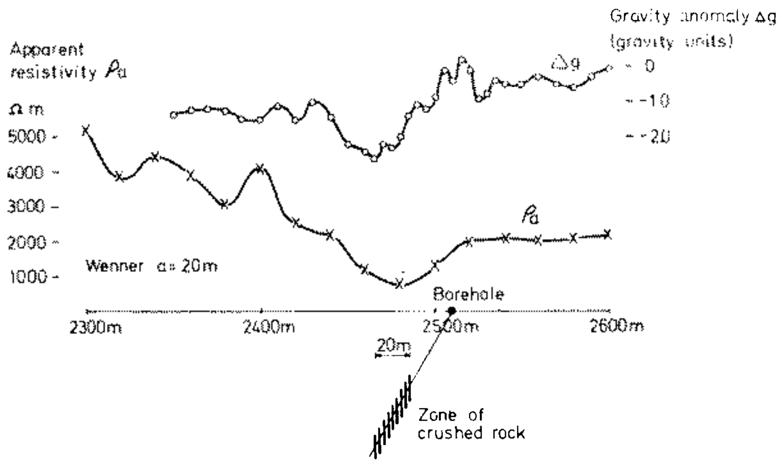


Figure 3.2.2.15 Profile showing gravity and resistivity lows due to a zone of crushed rock.

Well-logging techniques — Geophysical measurements of various kinds can be made in drill holes. This topic is discussed later in Section 3.3.5.2 dealing with drilling methods and investigations in drilled wells.

Swedish "Mean minus T" method of mapping fracture zones by seismic refraction — Two *sufficiently distant* shots from opposite sides are recorded at a series of geophones in between. If T_1 and T_2 are the times of first arrivals at a particular geophone from shot 1 and 2 respectively, half the difference $(T_1 - T_2)/2 = \Delta T/2$ is plotted at the position of that geophone from an arbitrary time line. The difference may be positive or negative and is, of course, plotted accordingly (see Figure 3.2.2.16). Velocities of seismic waves over different parts of the profile can be deduced from the segments of the time-distance graphs thus obtained. A significantly low velocity indicates a fracture zone. The limits of the zone are approximately at the intersection of the segments corresponding to the low-velocity zone and the high-velocity fresh rock on either side.

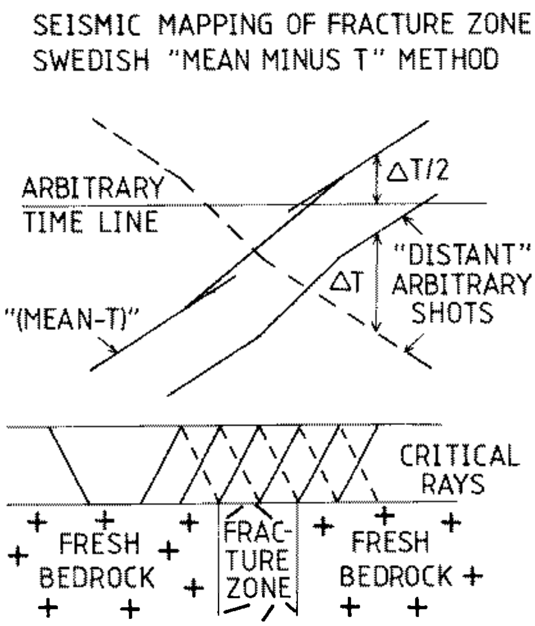


Figure 3.2.2.16 "Mean minus T" method.

3.3 *ASSESSMENT AND DEVELOPMENT OF GROUND WATER*

3.3.1 INTRODUCTION

Steady increase in population in many developing countries has generated a strong demand for water in general and for ground water in particular, especially in hard rock areas. Current master plans for rural water-supplies make provisions on the basis of a minimum of one well for 500 to 1,000 inhabitants (United Nations, 1973 b). This is considered a critical minimum below which high rates of migration will be experienced, further stressing urbanized areas. The water supply required under such critical conditions is approximately 10 litres per capita per day, supplied by wells; one or more wells would be required to produce 25 m^3/day for a village of 1,000 inhabitants only. Adding village requirements for 500 head of livestock, a ground-water supply of 50 m^3/day becomes the critical minimum water supply for the village. Of course, supply requirements would increase linearly with population increase.

It was estimated that for the period 1973-1978, tropical Africa would require a minimum of 150,000 wells. During the same period India required 200,000 wells (United Nations, 1973 b). In countries such as Ghana, the Sudan and the United Republic of Tanzania, the need was estimated at several thousand wells per year, but budgeting and technical limitations have allowed only a fraction of this number of wells to be constructed. This is a widespread problem of critical proportions in most hard rock areas.

Although the solution to such problems is complex, based on a preliminary worldwide review of potential well yield in hard rocks (see Section 2.2.4) and considering the widespread lack of funds and technical expertise, a significant part of the solution to water supply requirements in many remote areas is the construction of dug wells with the construction of drilled wells as emergency support. Dug wells, if sited on the basis of the best available geological techniques, can meet requirements in areas with apparent low ground-water potential (GWP). Although the increase in need has far outstripped the potential construction rate of dug wells, such wells are, and will remain in the foreseeable future, the most economically and socially practical source of water in hard rock areas.

In such areas, drilled wells, although relatively expensive at present, serve two roles: the first is to meet emergency requirements, since they can be drilled in a matter of a day or two – as opposed to a month or more to construct a 30 meter-deep dug well. The second role is to promote rapid development of an area to assist in producing cash crops and industrial products (mining and small industry), which in turn increases the region's wealth. When a region begins to generate cash income, labour-intensive activities (i.e. dug wells) become less attractive and capital becomes available for capital-intensive activities (e.g. drilled wells, mining) which further enhance economies of scale and, subsequently, the standard of living.

It is apparent that both dug wells and drilled wells must play their particular role in hard rock areas, especially those areas with low ground-water potential (relative to sedimentary basins where ground-water potential is generally high).

The weathered layer, where it is sufficiently thick and permanently within the zone of saturation, provides the chief source of ground water for hundreds of thousands of large-diameter dug wells in tropical, subtropical and many temperate-climate regions of the world. There are also many thousands of small diameter (4-6 inches) drilled wells (tubewells) which tap water in the weathered layer. In most places, the laterite duricrust (zone *d*) is seldom permanently water-bearing (see Section 2.1.3.4). Locally, however, the laterite can yield as much as 30 m^3/h to open, unlined wells when it is temporarily saturated during high stages of the water table. Zone (*b*), (Figure 2.1.3.1) which has high porosity but low permeability generally yields no more than a few hundred litres per day to wells. Moreover, during dug well excavation when zone (*b*) is saturated it may be unstable and cave readily. Such problems are reported to be common in the Sudano-Sahelian belt south of the Sahara.

Consequently, it is generally desirable to construct the dug wells toward the end of the dry season when zone (*b*) is sufficiently dewatered so that it stands up well in the walls of the well excavation. Zone (*c*), on the other hand, with relatively low porosity but appreciable permeability generally stands up fairly well in excavations and, where saturated, can be tapped by dug wells or galleries. In most wells, concrete or masonry curbing is necessary to provide support for the weathered rock. Such curbing is commonly perforated in the zone of the saturated rock. The yields obtained by wells from Zone (*c*) generally range from a few hundred litres per hour to a few cubic metres per hour.

3.3.1.1. *Dug wells*

Hand dug (traditional) wells — In western and central Africa dug wells of both traditional and more recent modern construction are widely used for village and livestock water supply in hard rock terrains. The traditional wells are generally dug by simple hand excavation techniques using a pulley or windlass with buckets and hand lines for removal of soil and hard rock (Figure 3.3.1.1). Such wells have been dug to depths of as much as 65 metres or more. Many are unlined, except for a surface curbing, and as much as 5 metres or more in diameter. They seldom penetrate more than a few metres below the water table, and often go dry with the decline of the water table in the dry season. Figure 3.3.1.2 shows a large capacity skin "bucket" used for lifting water. It is constructed so that it can lie flat on the bottom of the well during periods of low water table. The wells are subject to gross polution and occasionally cave in, endangering the lives of local herds and farmers. Although there are still many thousands of such wells in use in West Africa, they are gradually being abandoned in favour of modern open dug wells and of drilled wells.

Figure 3.3.1.1 Women drawing water from a traditional hand-dug well lined with bent branches to retard or prevent caving. The hole is circular, and about one metre in diameter. Note that the well mouth is reduced in size by rectangularly-placed logs, notched by many passages of bucket ropes. Some wells of similar construction are about 0.80 metre across. Buckets are constructed of circular-cut skins attached to strings, a design permitting them to lie flat on the bottom of the well.

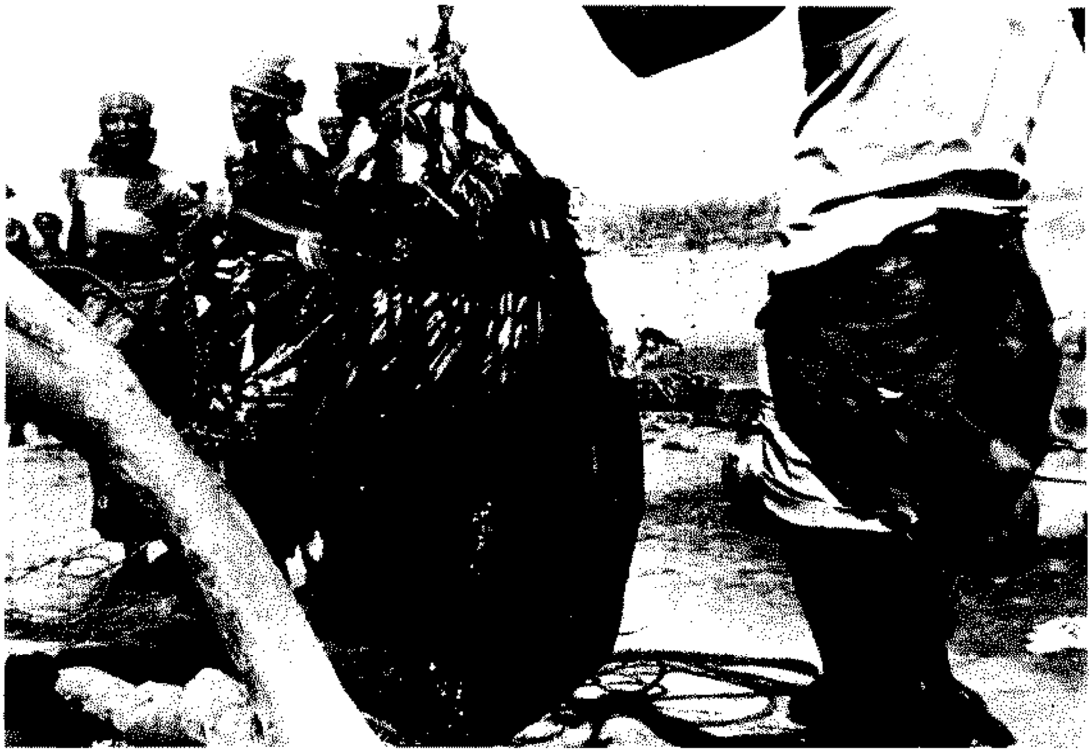


Figure 3.3.1.2 A large capacity skin "bucket" used for hauling water. This utensil is constructed so that it can lie flat on the bottom of a well. This universally-adapted design permits water recovery when the level is low as in the dry season when the water table falls.

Modern dug wells – These wells use the "sinking shoe" method of construction. Considerable mechanical equipment including derricks, air compressors, jack hammers, explosives and sinking pumps is used as well as a large component of hand labour. Concrete rings 2.0 to 1.6 m in diameter are placed in the excavated hole near the surface, reducing to 1.6 to 1.0 m perforated rings in the water-bearing zone. The perforated rings are generally gravel packed to prevent the finer aquifer materials from entering the well (Section 3.3.3.1). The lowermost ring is provided with a sinking shoe, and concrete rings are poured and added to the top of the perforated section as the well is deepened. About two months overall is required for the construction of a modern open well – about 0.3 to 0.5 metres per day. Virtually all modern dug wells require one or more deepenings before a viable water supply can be assured through the dry season. To insure an adequate supply, the open wells must extend at least 2 metres below the lowest seasonal level of the water table. Modern open dug wells tapping the weathered layer of hard rock terrains in West Africa range from about 5 to 50 m in depth and average about 15 m. It is estimated that several tens of thousands of such wells are presently in operation in West Africa.

The prevailing rationale for the modern open dug well in West Africa is the provision of relatively clean water for basic village use and a well from which water can be withdrawn by hand line and bucket with minimum maintenance requirements (see Figure 3.3.1.3). (Steel rollers or pulleys are commonly set in the surface raised curbing about 0.8 m above ground level to facilitate lifting water.) The yields obtained from modern open dug wells in hard rock terrain range from about 0.5 m^3/h to 10 m^3/h and average 2 m^3/h. Also well yields tend to fluctuate seasonally. For example, a well which produces 5 m^3/h during the rainy season may produce only 1 m^3/h at the end of the dry season. In hard rock terrains, moreover, about 10 to 15 per cent provide very meager supplies and only about 75 to 80 per cent can be considered adequate to provide a small village supply.

Modern dug wells provided with covers for sanitary protection and equipped with hand pumps for water extraction have been attempted in several West African countries but have not been generally viable, except locally where regularly maintained by concerned volunteer, charitable or religious groups. In the absence of maintenance, the pumps fail, the covers are broken and water continues to be drawn by the villagers by hand line and bucket. Until the pump maintenance problem can be resolved it will be necessary to continue to rely on modern open dug wells for basic village and livestock water supply.

In the Precambrian shield of central and southern India there are an estimated 35 million open dug wells which obtain water, mainly for irrigation, from the weathered layer at depths generally less than 20 m. (Ramakrishna et al., 1978; Rao et al., 1975; Romani, 1973). While yields of as much as 15 m^3/h have been recorded from indidivual wells, the average recoverable volume of water per well is about 3 m^3/h. The wells of square or rectangular outline are commonly of large diameter, that is about 10 to 15 m, and occasionally as much as 20 m. The uppermost 5 m or so of the well is usually lined with masonry curbing but the lower part of the well is unlined. Such a well can thus accumulate a large volume of water in "tank" storage.

The irrigation wells, fitted with mechanical pumps, are not all pumped daily but rather intermittently at about 50 to 100 m^3/h until tank storage is exhausted. In this way relatively large volumes of water can be delivered to irrigated fields with minimum transit losses. It is usually necessary, however, to wait 20 to 36 hours after each pumping cycle for the well to recover fully. Where water is drawn from the wells for irrigation with water wheels or leather bags (motes) using bullocks or camels for power, the constant rates of withdrawal range from about 0.5 to 3 m^3/h.

With the exception of India there is little record of extensive use of dug wells for irrigation in weathered hard rock terrains. In most parts of Africa and eastern South America and elsewhere, dug wells tapping the weathered layer are used almost exclusively for village, domestic and livestock water supplies or occasionally for small subsistence gardens.

Figure 3.3.1.3 Work in progress on a 1.5 m diameter hand-dug water well about 150 km NE of Niamey near Filingue, Niger. Access is accomplished by a hand, windlass-controlled, steel cable and iron bucket. The hole is excavated slightly wider than the diameter of a collapsible, circular metal mould one metre high. The space behind the mould is filled with gravel-bearing cement. After drying for about 24 hours, the mould is unbuckled and digging continues for another metre. Progress is slow and rarely exceeds 1 m per working day. This hole, proposed as a cistern, will be sunk slightly below the piezometric level in an adjoining well drilled to an artesian aquifer. Through a horizontal connection the cistern will then be continually supplied. This innovation is locally termed a "forage-puits."

Mechanically-excavated wells — In addition to the prevailing modern open dug well, which requires a large component of hand labour, mechanical boring equipment is currently being used to construct large diameter (0.8 to 1.0 m) wells for village supply in the weathered layers of hard rock terrains of West Africa. This method, which has been used with some success in the Ivory Coast, Togo and Upper Volta is limited to soft ground with some cohesion. It is useful, however, for reconnaissance as well as production.

The laterite duricrust of zone (*a*) (Figure 2.1.3.1) can generally be penetrated with no problems. Also because of the rapidity of construction, the fluid or soupy clay layers of zone (*b*) can be controlled with the working casing, where not too thick. The method does not lend itself to penetration very far into zone (*d*). Thus, the effective depth limit of most wells constructed by this method is 25 m.

Three reconnaissance holes or one production well can be constructed in one day. (A modern dug well in West Africa may take as long as 2 months or more to complete). The yields of large diameter bored wells are reported to be in the range of those of modern open dug wells, that is 0.5 m^3/h to 10 m^3/h with an average of about 2 m^3/h.

3.3.1.2 *Drilled wells*

Vertical wells – Small diameter drilled wells equipped with hand pumps are increasingly being used in the hard rock terrains of Korea, Malaysia, Thailand, India, Sri Lanka, West Africa and Brazil for village water supply. (The relative merits and disadvantages of dug wells and drilled wells are given in Table 3.3.1.1, which was developed for India where both kinds of wells are utilized in the same hard rock terrains). (See also Figure 3.3.9.4).

At present many thousands of such small diameter wells in use in hard rock terrains are reported in India, about 9 000 in Ghana, more than 2 000 in Nigeria and about 2 000 in Ivory Coast. (All these village well and hand pump projects are supported by central, regional or state government agencies).

A minimum diameter of about 4 1/2 inches is required for installation of a hand pump in a drilled well with a nominal capacity of 1.5 m^3/h. In some areas polyvinyl chloride (PVC) casing and screens are used for surface casing, but steel casing may be required for deeper wells or where casing driving is required.

Until recent years most small diameter (5-8 inches) wells in hard rock terrains were constructed by conventional rotary or percussion drilling rigs. The rotary rigs with rock bits operate quite satisfactorily except in very hard rock. Percussion drilling is well adapted to hard rock terrain but the drilling rate may be low if hard rock is encountered. In softer rock a well 50 m deep can be completed in a week, but if hard rock is encountered a month or more may be required to complete the well.

Table 3.3.1.1 Relative merits of dug wells versus drilled wells in hard rock terrains based on experience in peninsular India.

Dug wells	Drilled wells
1. Difficult to protect against pollution.	Easy to protect against pollution.
2. May require as much as 6 months to construct a single well 15 to 20 m deep and 10 to 15 m in diameter. Labor-intensive system.	With a down-the-hole air hammer drill it is possible to construct a 6-inch well 40 to 60 m deep in a day or two. By the cable tool percussion rig 40 to 60 days might be required for a well of this depth. Capital intensive system.
3. Pumping costs per unit volume of water are low because water is pumped from storage in the well and drawdown cannot exceed well depth.	Pumping costs per unit volume of water are high because of high lifts.
4. Wells can be pumped intermittently by centrifugal pumps, which are cheap and easy to maintain, at rates of 50 to 100 m^3/h even though average inflows are only 3.2 m^3/h.	Wells require submersible pumps which are costly and more difficult to maintain. Wells can be pumped constantly but only at rates which average 3.0 m^3/h.
5. Water can be delivered intensively to irrigated land without surface storage.	Water cannot be delivered intensively to irrigated land without surface storage.
6. Centrifugal pumps can be electric or diesel powered.	Submersible pumps require electric power.
7. Well can occupy as much as 0.2 ha of agricultural land.	Well occupies very little land.
8. Wells may go dry during prolonged dry cycles.	Wells are less affected by seasonal fluctuations of water levels and consequently more reliable during dry cycles.
9. More desirable for irrigation use under prevailing economic conditions.	More desirable for small municipal and village water supplies under prevailing economic conditions.
10. Hand or mechanical construction.	Drilling equipment must be imported.

The down-the-hole air hammer drill has been introduced into West Africa in recent years and is already widely used in Brazil, India and elsewhere. This drilling method is particularly well-suited to hard rock terrains, because of the rapidity of penetration (up to 60 m per day for a 5-inch hole) and of indications given of water productivity from the fractures of zone (d). Although rotary and percussion rigs are still widely used, the down-the-hole air hammer rig is gaining increasing favour. Small-diameter drilled wells are utilized mostly for small municipal and rural water supplies and livestock as yields are generally considered too small for irrigation.

Drilled wells, of course, have the advantage of being able to draw on a somewhat greater thickness of water-bearing material in the weathered layer than dug wells, particularly where the weathered layer is more than 30 m thick. Drilled wells, however, tapping water in the weathered layer only, have yields which are commonly in the range of 0.4 to 7 m^3/h or about the same as the modern open dug wells of West Africa. In some places, as is reported in Benin, Togo and Ghana, problems are encountered in developing water from drilled wells tapping water in the weathered layer because zone (*b*) contains a saturated layer of kaolinitic "porridge." When penetrated by the drill this layer tends to cave and flow into the well. This layer is usually contained, however, by setting blank casing opposite the saturated layer of "porridge" and slotted pipe with gravel packing in the firmer underlying material of zone (c).

Some hydrogeologists suggest, however, that drilled wells, in which the weathered layer is cased off completely and the deeper part of the well left open in the fracture system of zone (*d*) below the weathered layer, function effectively to draw water from both systems. When a well so constructed is pumped more or less continuously, water from the weathered layer, within the cone of influence of the well, eventually drains into the fracture system and is recovered. It is true that drilled wells, which draw from the fracture system of zone (d), generally have somewhat higher yields than those which tap only the water in the weathered zone. Also the yields of such wells tend to be more stable and less subject to seasonal variations in recharge.

Horizontal wells – Horizontal wells are occasionally drilled in areas of high relief to tap vertical bedding planes or fracture zones, ground water trapped behind dikes or other impermeable vertical boundaries, or ground water above an impermeable, outcropping bed (Figure 3.3.1.4). Hillside seeps or small springs are often good indicators of ground water behind dikes or above restricting beds.

Horizontal wells are drilled with specially designed rotary equipment and are cased and screened as needed (Campbell and Lehr, 1973 b, Summers, 1976 b and U. S. Bur. Mines, 1971). These wells are free-flowing, so that they must be equipped with a valve or other flow control device as their outlet. Such wells should be constructed with some downward slope into the hill to avoid the possible development of negative pressures at the intake of the wells. In Arizona and elsewhere, horizontal wells were drilled 12 to 82 metres (average 38 m) into weathered zones, through highly fractured soft rocks, and through quartz dikes. Well yields ranged from 10 to 50 m^3/d.

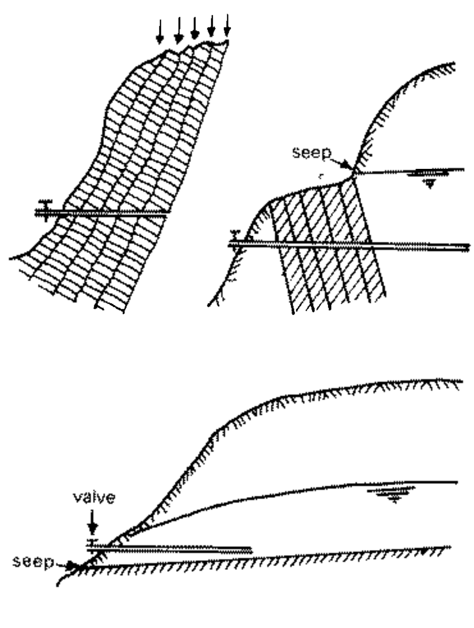


Figure 3.3.1.4 Horizontal wells to tap water from vertical fracture zones (top left), from behind impermeable dikes (top right), and from above an impermeable zone.

Combined wells – Given favourable geologic conditions, two types of "combined" wells may be possible. The first involves drilling a deep well in an area where a high piezometric surface (artesian conditions) can be expected. Satellite dug wells (or cisterns) are constructed nearby to intersect the piezometric surface encountered in the "mother" well. Piping is laid from the central well to each of the satellite wells below the piezometric surface, thereby allowing for the automatic transfer of water to satellite wells for storage. Of course, special geological conditions are necessary but effective variations of this approach have considerable potential, especially in hard rocks with moderate to high relief. This type of well is known in West Africa as a "forage-puits."

The second type of a combined well design is of the "well within a well" variety. This new application involves an existing traditional or open dug well which is deepened via a small diameter drilled well. A temporary platform is built over the dug well for the drilling rig. After completion of the drilled well, a handpump is installed in it and the dug well is fitted with a removable cover. If the handpump fails, the cover over the dug well can be removed by the local inhabitants so that water can be temporarily drawn from the dug well by hand line and bucket. After the hand pump is repaired and the dug well chlorinated, the cover is replaced. The installation is then ready for normal hand pump operation.

Another variation of the same design involves drilling a small diameter well, and then constructing a cement-lined cistern or storage well around the casing of the small diameter well (Figure 3.3.1.5). The water in the storage well can be either withdrawn by pumping or by hand, using a skin bucket. Water can also be pumped from the fracture zone when the need arises to fill the storage well.

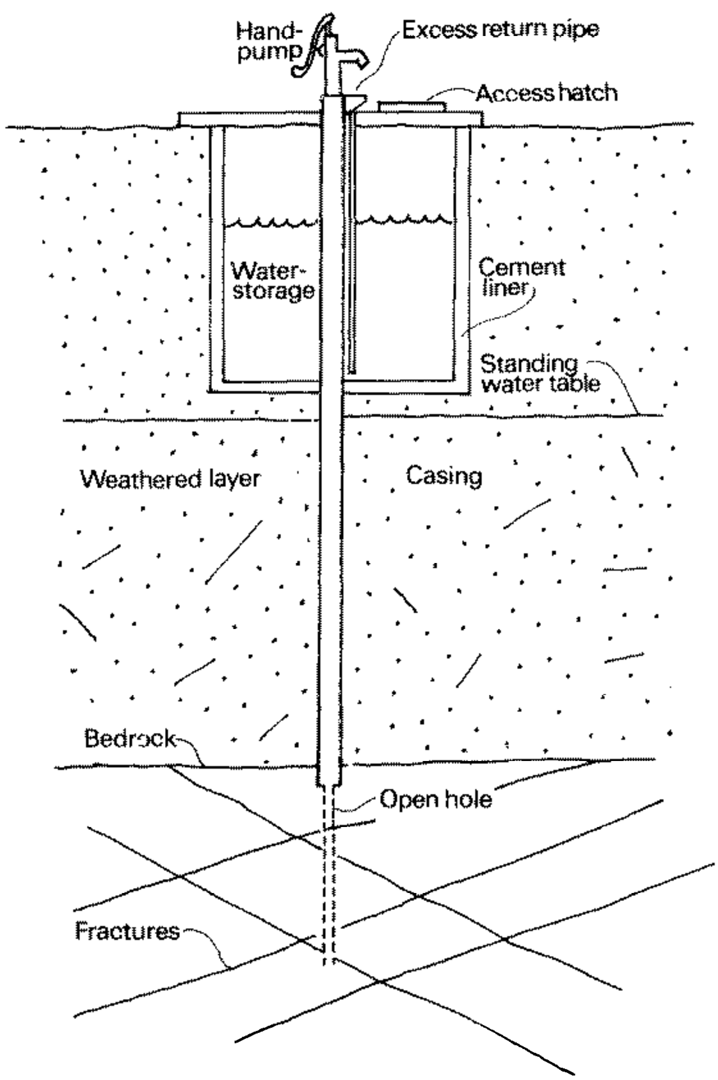


Figure 3.3.1.5 Storage well fitted with hand pump.

3.3.2 EXPLORATION STRATEGIES

3.3.2.1 *Introduction*

In many cases in hard rock areas where applicable geological information is either lacking or of limited value, the problem is one of locating a sufficiently permeable fracture system and/or sufficiently weathered zone to provide the desired water supply. Where such features are visible, even over a limited distance, standard geologic or photogeologic methods are the most effective and often the least costly way to extrapolate existing data. Where such features are obscured it is necessary to develop an alternate exploration approach and the concepts of exploration theory may provide guidance.

Buried, near-surface fractured systems fortunately tend to be linear. If tectonic analyses and photographic interpretation have been successful, the likely direction and extent of the fractures may be predicted. Linear exploration then can be applied to predict the location of the fractures where they are not visible. If, however, the fractures are not linear or their orientations are unknown, a different kind of exploration approach is required, which may simply be a series of equally spaced lines forming a grid to be used as a basis for test drilling locations.

Helweg (1976, 1977), Turk (1977) and Thomas (1978) provide interesting examples of exploration techniques, which are directly applicable to some hard rock exploration programs. Exploration literature (Stone, 1975) emphasizes the importance of the approach. The sensitivity of the exploration method is particularly important in relation to the size of the feature being sought. The simplest example would be exploration for a small vertical fracture. A number of vertical boreholes drilled in a row would theoretically be required to find the fracture, which is a costly approach. If the drill holes were slanted or even horizontal (drilled from an existing shaft or into the side of a hill) the likelihood of finding the fracture would be increased (see Section 3.3.4).

The electrical conductivity of the vertical fracture may be detected by suitable geophysical means over a much wider zone than the fracture itself. The same may be true of its electromagnetic properties. The geophysical methods therefore have a larger area of detection than a vertical drill hole.

For a wider fracture zone, the problem would be in localizing the most fractured portion. This could be detected by a surface resistivity profile, for example the highest apparent conductance (see Section 3.2.2.3). If the zone is fairly wide, a continuous line of profiles may be costly and "adaptive search" techniques may substantially reduce costs.

Such techniques are potentially cost effective for those situations where a single optimum can be detected. Suppose, however, that an area being studied has no indication on photographs or Landsat imagery of fractures or fracture systems. The area may be too large to extrapolate fracture patterns from outcrop areas and existing well data may not be close to the area of interest. In such a case, geophysical surveys that detect depth of weathering may provide clues to underlying fracture patterns. If it is suspected, however, that the weathered layer is of variable thickness, the grid drilling programme is the only alternative. Grid exploration can be carried out in a variety of patterns and generally is considered to be more efficient for most geologic situations than random exploration, wherein blind reconnaissance drilling is conducted.

The most useful approach is to start with a very widely spaced grid and make the grid spacing progressively smaller in selected areas as knowledge of the area improves. Once the areas have been roughly delineated the "adaptive" techniques may be used.

It should be emphasized that the above strategies are useful only when detailed geological information is lacking or of limited application. Such strategies may improve the success rate of a limited exploration programme where success is related only to random chances. As previously discussed in this text, the value of establishing an acceptable geological base, either through geological, geomorphological and/or geophysical investigations, is mandatory in any attempts to optimize ground water exploration and development programmes in igneous and metamorphic rocks.

3.3.2.2 *Standard field exploration techniques*

Recharge of all fractures with ground water is made via some communication with either a surface or near-surface recharge area (saturated weathered layer). If the fractures can be recognized at the surface, they can be mapped and their structural setting can be used to predict the location of these zones at various depths (see previous chapters of this text and Setzer, 1966). Based on an examination of outcrops, topographic expressions (especially stream patterns), vegetation changes and the location of springs, it has been generally feasible to map potential water-bearing zones in various parts of the world. (Blanchet, 1957; Boyer and McQueen, 1964; Florquist, 1973; Lattman and Parizek, 1964).

Special attention should be given to the following geologic and physiographic features:

1) Major and minor fracture zones or lineations and zones of brecciation.

2) Persistent topographic troughs or ridges that do not conform to the regional trends

3) Contact zones between two or more rock types.

4) Features such as pegmatites, dikes which frequently contain kaolinized zones of low permeability or highly fractured zones of high permeability.

5) Float or detrital material such as feldspar, graphic granite, epidote and other minerals also suggest faulting where in-situ outcrops are masked by overburden or soil cover.

In recent years, surface geophysics (resistivity and seismics) have been used in identifying permeable zones in deep igneous and metamorphic rocks. After interpretation of surface geology has been made and structural relationships have been postulated, many variations in geophysical equipment are available that can aid in pin-pointing drilling sites. Further discussions of the role of geophysics in ground-water exploration are made in Section 3.2.2 and previously in this Section.

As has been discussed in this Section and in other sections of this work, ground water occurs in residual soils (grus, saprolite, "kaolinitic porridge," regolith, etc.), underlying weathered rock, and in fractures or faults in the deeper bedrock. Verly little ground water, however, is obtained from depths greater than a hundred metres, unless regional structural conditions suggest major fractures and open faults at depth (LeGrand, 1954; Mundorff, 1948; Robinson, 1976). Depending on the need, in many areas, a yield from an individual well of one gallon per minute per foot drawdown (or 0.21 litres per second per metre drawdown) is well received and appreciated (Krupanidhi et al., 1973). Igneous and metamorphic rock lie at or near the surface in approximately 20 per cent of the world's land surface. In remote villages and habitations with no ready access to surface-water supplies, even low ground-water yields assume critical importance.

In certain circumstances, well-site locations must be selected without benefit of detailed geological, structural and geophysical investigations. Under these conditions, the best available semi-quantitative techniques must be employed. It should be emphasized that the success rate of such techniques would be lower than when more complete geological data are available. LeGrand (1967) has developed a field technique for limited exploration programmes. Although many factors determine well yield, two field conditions serve to augment preliminary geological information in selecting a drilling site. These factors are: 1) topography and 2) "soil" or weathered layer thickness. The latter factor could be estimated by simple geomorphological interpretations and/or by surface resistivity surveys. The LeGrand technique is based on the observation that high yield wells are common where thick residual soils or weathered layers and relatively low topographic areas are combined, and that low yield wells are common where thin soils, or weathered layers and hilltops are combined.

To emphasize the relative chances of success in any particular site, a relative rating value can be developed by assessing the topography and assigning points to the particular surface conditions (Table 3.3.2.1).

Table 3.3.2.1 Rating value and topographic conditions for use in well-site location (from LeGrand, 1967).

Points	Topography
0	Steep ridge top
2	Upland steep slope
4	Pronounced rounded upland
5	Midpoint ridge slope
7	Gentle upland slope
8	Broad flat upland
9	Lower part of upland slope
12	Valley bottom or flood plain
15	Draw in narrow catchment area
18	Draw in large catchment area

A similar approach is made to assess the extent of soil cover or weathered layer (Figure 3.3.2.1). The total points are then used to estimate the per cent chance of success of a particular drilling operation for a well to yield a specified production rate (Table 3.3.2.2). It should be noted that this technique was originally developed for an area in North Carolina (USA) having an annual rainfall exceeding 1200 mm. The data and the implications based thereon should be applicable only to areas with similar rainfall. However, in areas with far less rainfall and different geological conditions, a similar approach could be developed based on local data, assuming general tectonic and other factors are incorporated.

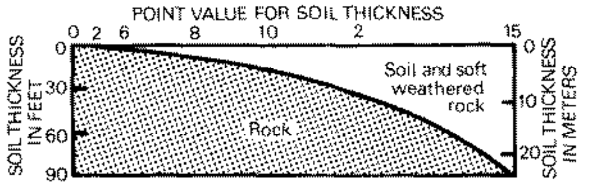


Figure 3.3.2.1 Rating value and topographic conditions for use in well-site location (from LeGrand, 1967).

Table 3.3.2.2 Use of numerical rating of well site to estimate the per cent chance of success of a well relative to possible production rate. Assumption: 1) maximum well depth of 300 feet (91.5 metres) or maximum drawdown of 200 feet (61 metres); 2) no interference. (After LeGrand, 1967.)

Total points of a site	Average yield (l/s)	Chance of success, in per cent, for a well to yield at least: (in m^3/h)				
		0.68	2.27	5.69	11.34	17.03
5	0.47	48	18	6	2	-
6	0.58	50	20	7	3	-
7	0.68	55	25	8	3	-
8	0.90	55	30	11	3	-
9	1.15	60	35	12	4	-
10	1.37	65	40	15	5	-
11	1.58	70	43	19	7	-
12	2.05	73	43	22	10	-
13	2.48	77	50	26	12	-
14	2.74	80	52	30	14	-
15	3.17	83	54	33	16	-
16	3.64	85	57	36	18	-
17	3.85	86	60	40	20	12
18	4.54	87	63	45	24	15
19	5.22	88	66	50	25	18
20	5.90	89	70	52	27	20
21	6.37	90	72	54	30	22
22	7.06	91	74	56	35	24
23	7.74	92	76	58	38	26
24	8.39	93	78	60	40	29
25	8.86	93	80	62	43	32
26	9.32	93	81	64	46	36
27	9.76	94	82	66	48	40
28	10.22	95	83	68	50	42
29	10.44	95	84	71	53	44
30	11.34	96	87	73	56	47
30	11.34	97	91	75	60	50

Figure 3.3.2.2 is a graphical representation of the probability of certain yield using the LeGrand technique (LeGrand, 1967). It should be emphasized that the numerical rating system was not intended to be precise, but similar results would be expected from a number of investigators. As the knowledge of the geological and structural conditions improves in any area, specific target zones can be evaluated without recourse to general exploration guides, although the results of one should support the other. This approach could be useful as a first approximation when other, more detailed geological investigations, as discussed previously in this text, are not available.

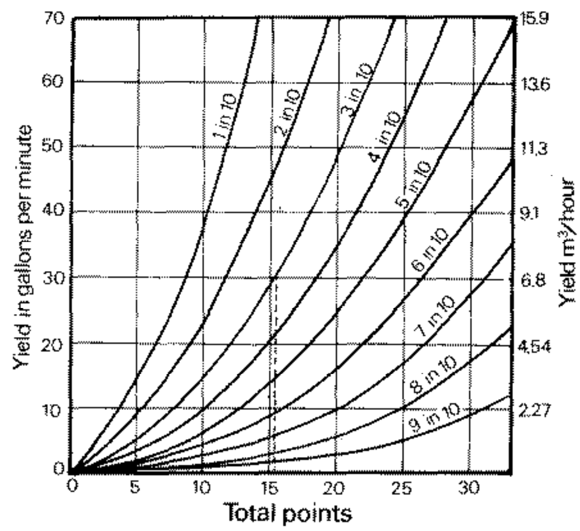


Figure 3.3.2.2 Probability of obtaining a certain well yield having various total point ratings (from LeGrand, 1967).

Example: A site with 26 points has 3 chances in 10 of yielding at least 30 gallons per minute (6.8 m^3/h) and 6 chances in 10 of yielding 10 gallons per minute (2.27 m^3/h)..

3.3.2.3 *Integrated plan of action*

Introduction — As discussed in detail in previous sections of this work the use of photogeological, structural, hydrological and geophysical information will reduce uncertainty in any ground-water exploration programme. The more detailed geological information is developed, the more cost effective programmes can become. This can be accomplished if systematic procedures are employed that utilize all existing data initially, followed by implementation of appropriate techniques of investigation (see Figure 3.3.2.3).

It is a general rule, accepted by photogeologists, geophysicists and hydrogeologists that the evidence for indirect observation and measurement obtained from remote-sensing techniques requires ground control. This is especially true for photogeological and airborne geophysical investigations. Such control can be carried out in two different ways. The first is that each observation from such indirect surveys is checked on the ground, one by one. This is an expensive and time-consuming approach. Therefore, systematic control is more desirable and appropriate. This means that samples of individual characteristic patterns or sets of objectives, found by indirect observation, are identified in relation to the group-set. If such a group-set, supported by selected ground control, seems to be statistically homogeneous, indirect mapping of geological features can be conducted with confidence.

Phase I — Investigations: Data evaluation and integration — For exploration programmes in hard rock areas, topographical, geomorphological, geological and hydrological maps are valuable tools. Usually not all of these are available. By the use of remote sensing, a good deal of such shortage can be overcome (see Section 3.2.1).

Phase I is usually divided into an initial stage, without field work, and a subsequent stage with field work. These stages can be summarized as follows:

A. *Inventory stage without field work*

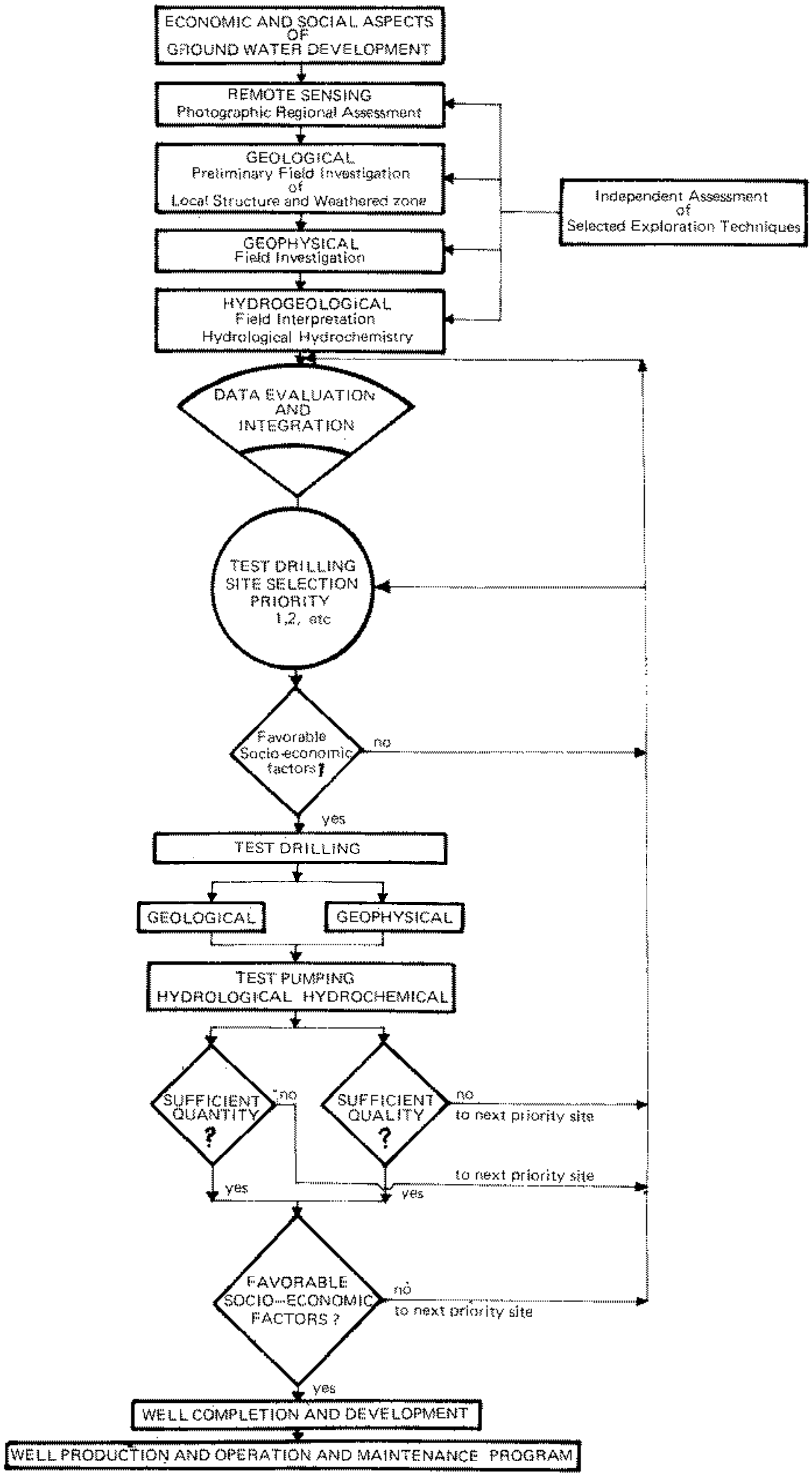
1. Collection of all available data concerned (literature, geological, hydrological and agricultural maps; maps of boreholes, wells, population density, etc.).

2. Remote sensing (see Section 3.2.1).

3. Assessment of the results of 1. and 2., above. Decisions made about necessary field control, field work, etc.

B. *Inventory stage with field work*

1. Field control of remote sensing.



THE SYSTEMATICS OF GROUND-WATER EXPLORATION AND DEVELOPMENT IN HARD ROCKS

Figure 3.3.2.3 The systematics of ground-water exploration and development in hard rocks.

a) Field control of extent of major rock types in the actual area of interest. Correlation (preliminary) with potential yield of wells. Control of storage capacity in different rocks.

b) Field control of the distribution of major fractures; control of dike patterns. Regional extension of different fracture types (plastic or brittle deformation, see Section 2.2.2.2).

c) Field control of different types of major deposits of unconsolidated sediments. Correlation with potential yields of wells. Preliminary delineation of basins, aquifers and structural phenomena.

2. Field studies of the tectonic pattern of the area.

(In connection with B.1.b above.) Hypotheses on plastic and brittle deformation of the rocks. Tensile overthrust and shear fractures. Hypotheses on storage capacity of different fracture types.

3. Geophysical control of tectonic analysis.

(See B.2, above.) Width of fractures. Control of pegmatite frequency.

4. Field studies of water quality.

Areas with slow ground-water circulation. Occurrence of saline waters.

Phase II – Investigations: Social and geological assessment – For planning purposes it is necessary to identify the critical parameters present in the area of interest. One or more of the following topics of consideration may have a special impact on which potential well locations are drilled and which wells are completed for water supply for the local population:

1. Density of population. Urban areas.

2. Social aspects. Water requirements.

3. Geology, tectonics and morphology.

4. Hydrology, hydrogeology and hydrochemistry.

In some cases social requirements may outweigh favourable geological conditions or proximity to a site having the best ground-water potential. In other cases geological conditions may outweigh social convenience. A compromise is usually sought in an attempt to meet both the requirements. In some cases, however, compromises are not available and either social or geological requirements will prevail.

The integration of all these factors will determine the most suitable area for ground-water exploration.

Phase III – Ground-water development – The ground-water development phase begins after most of the investigations described above have been made. Certain decisions, however, are often made as the drilling programme proceeds. The actual volumetric availability of ground water and associated quality, combined with economic considerations regarding well design, pumping and associated transportation systems, if applicable, may play significant roles in establishing the final well locations.

3.3.2.4 *Application of the integrated approach*

An example for a hypothetical region has been constructed to demonstrate the systematic application and integration required in applying the various techniques discussed in this text.

Assessment procedure – The assessment procedure is illustrated in Figures 3.3.2.4 to 3.3.2.11 which depict a series of fictional schematic maps of the hypothetical region. It is assumed that previous investigations concerning regional population density and water requirements have produced the data shown on Figures 3.3.2.4 and 3.3.2.5.

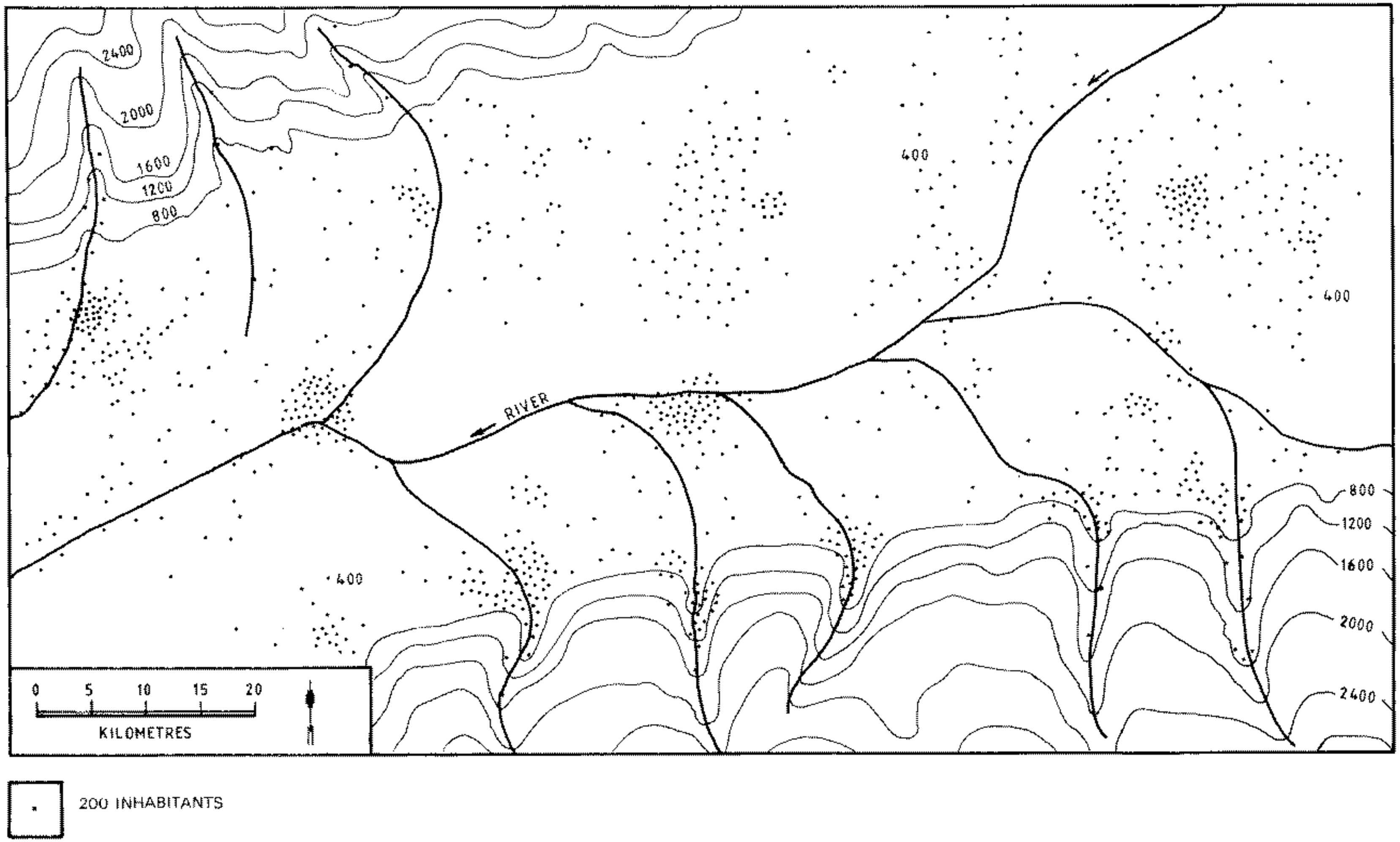


Figure 3.3.2.4 Regional density of population

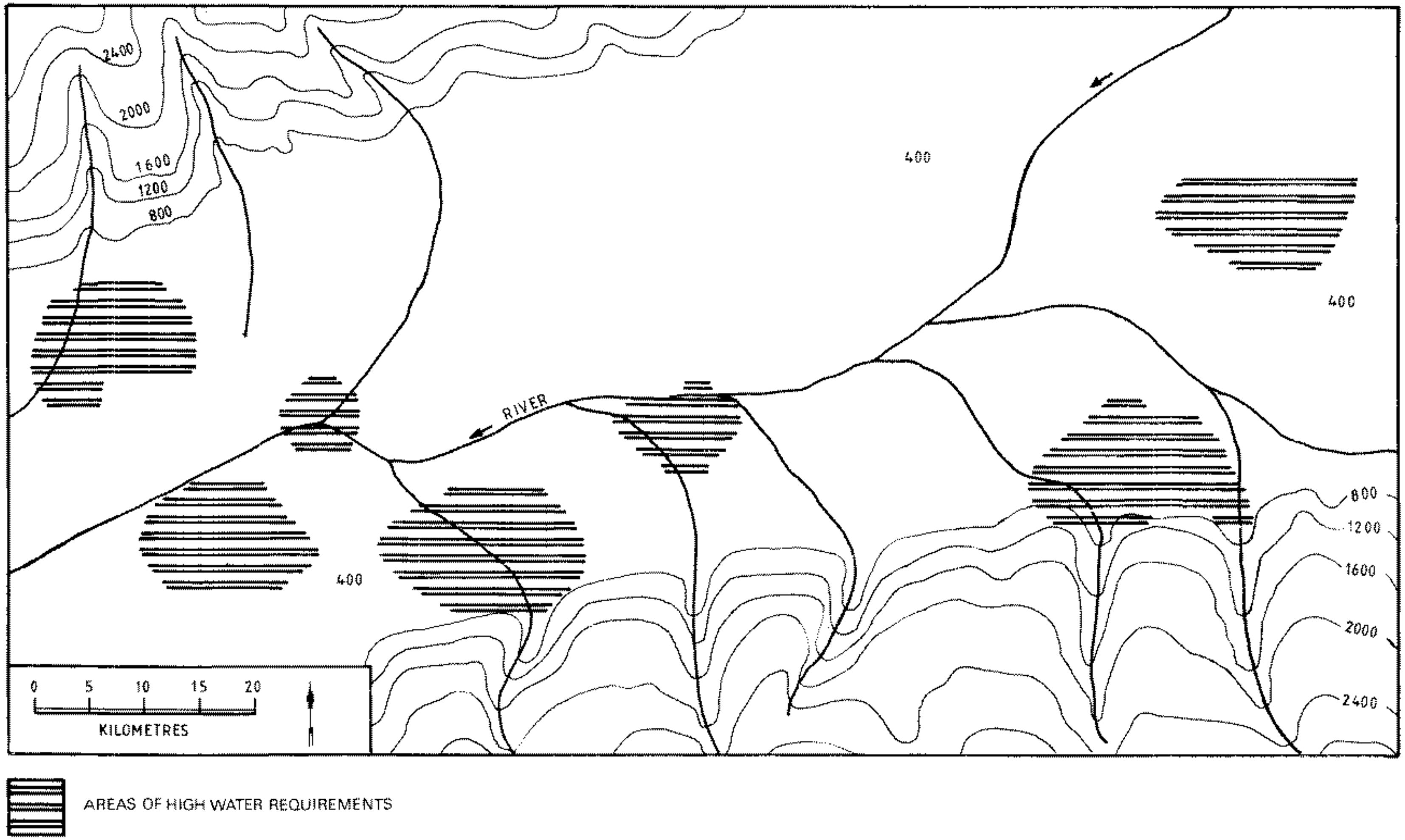


Figure 3.3.2.5 Regional water requirements

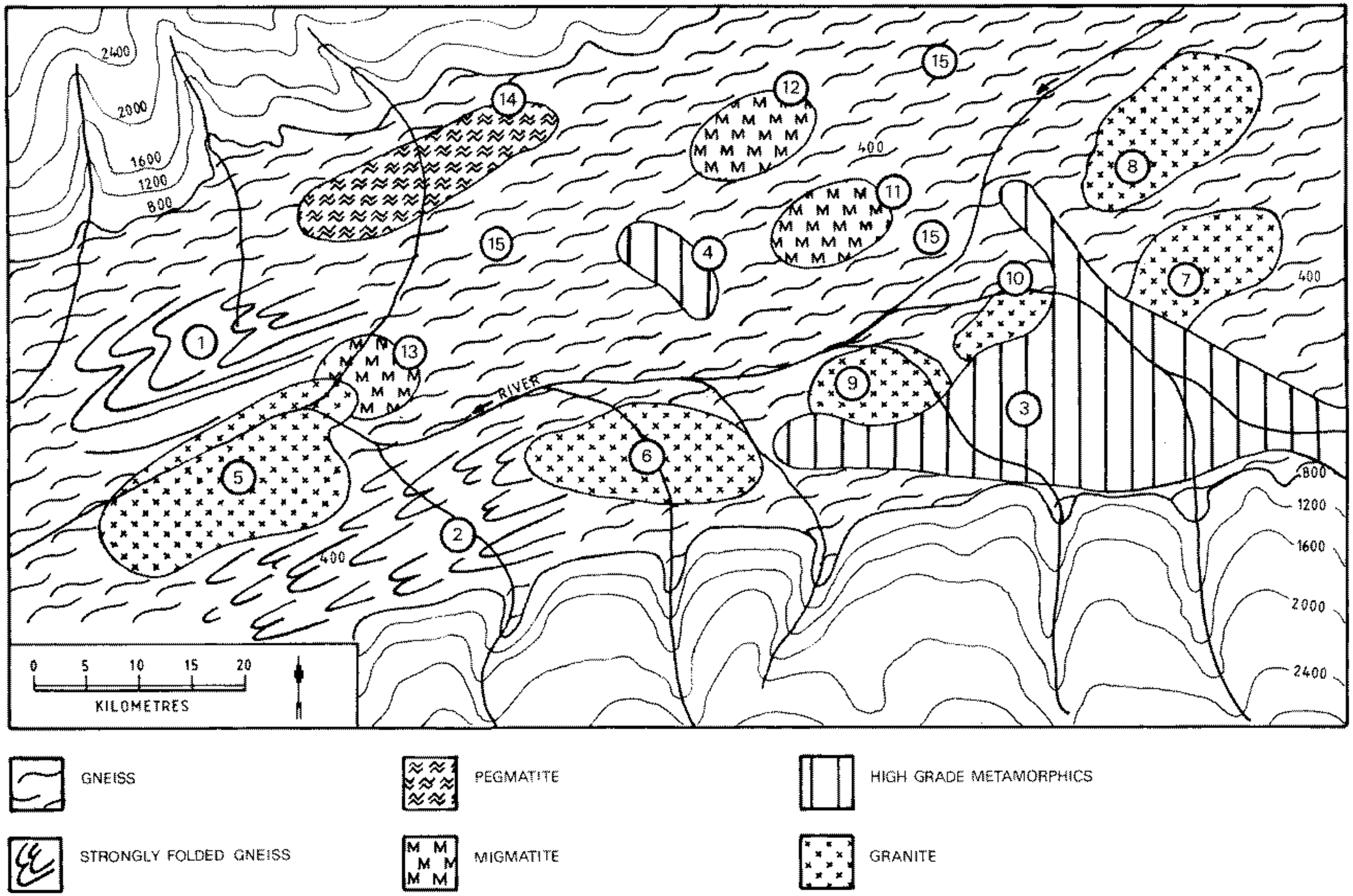


Figure 3.3.2.6 Regional geology

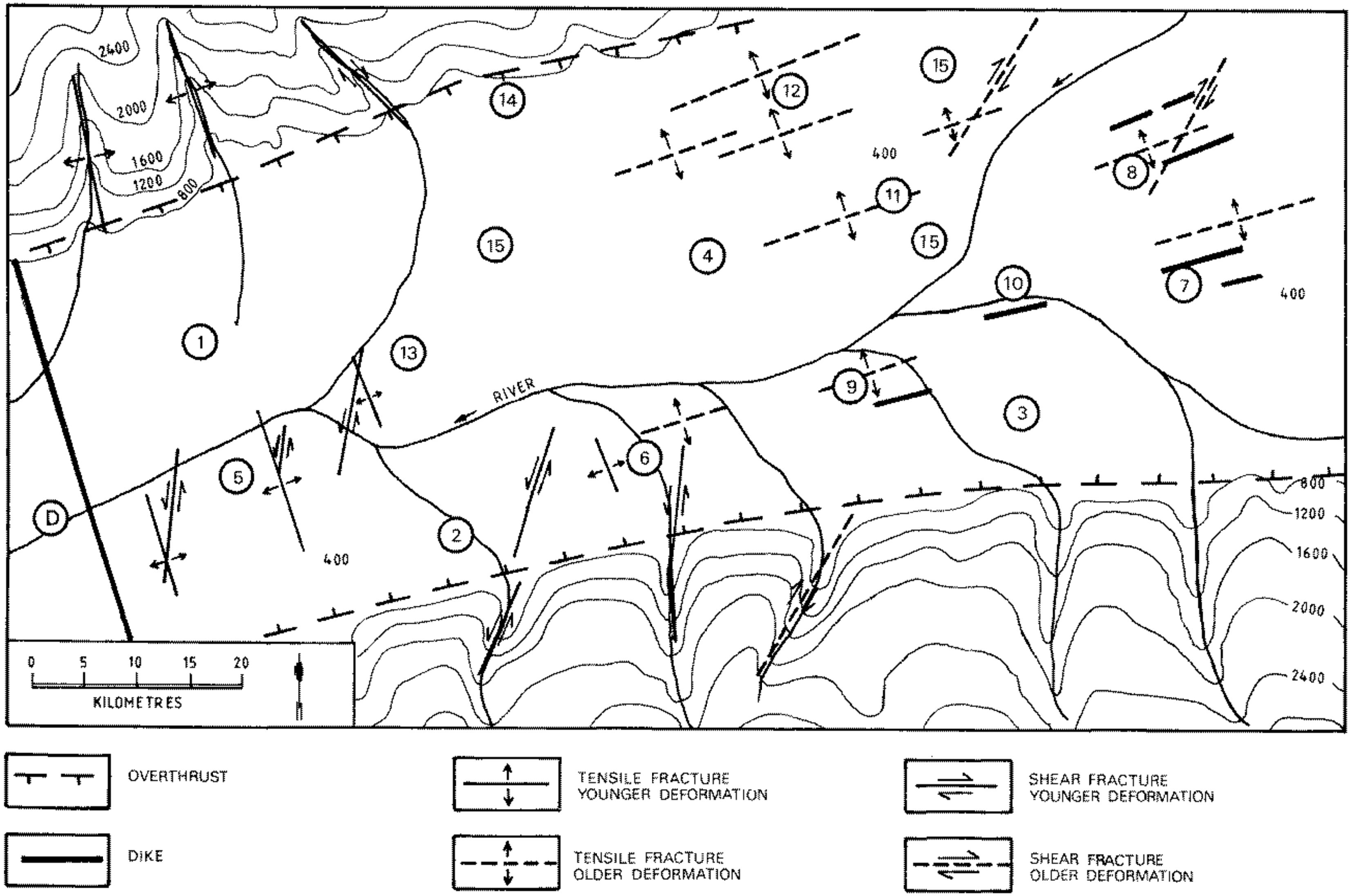


Figure 3.3.27 Regional fracture pattern (structural setting)

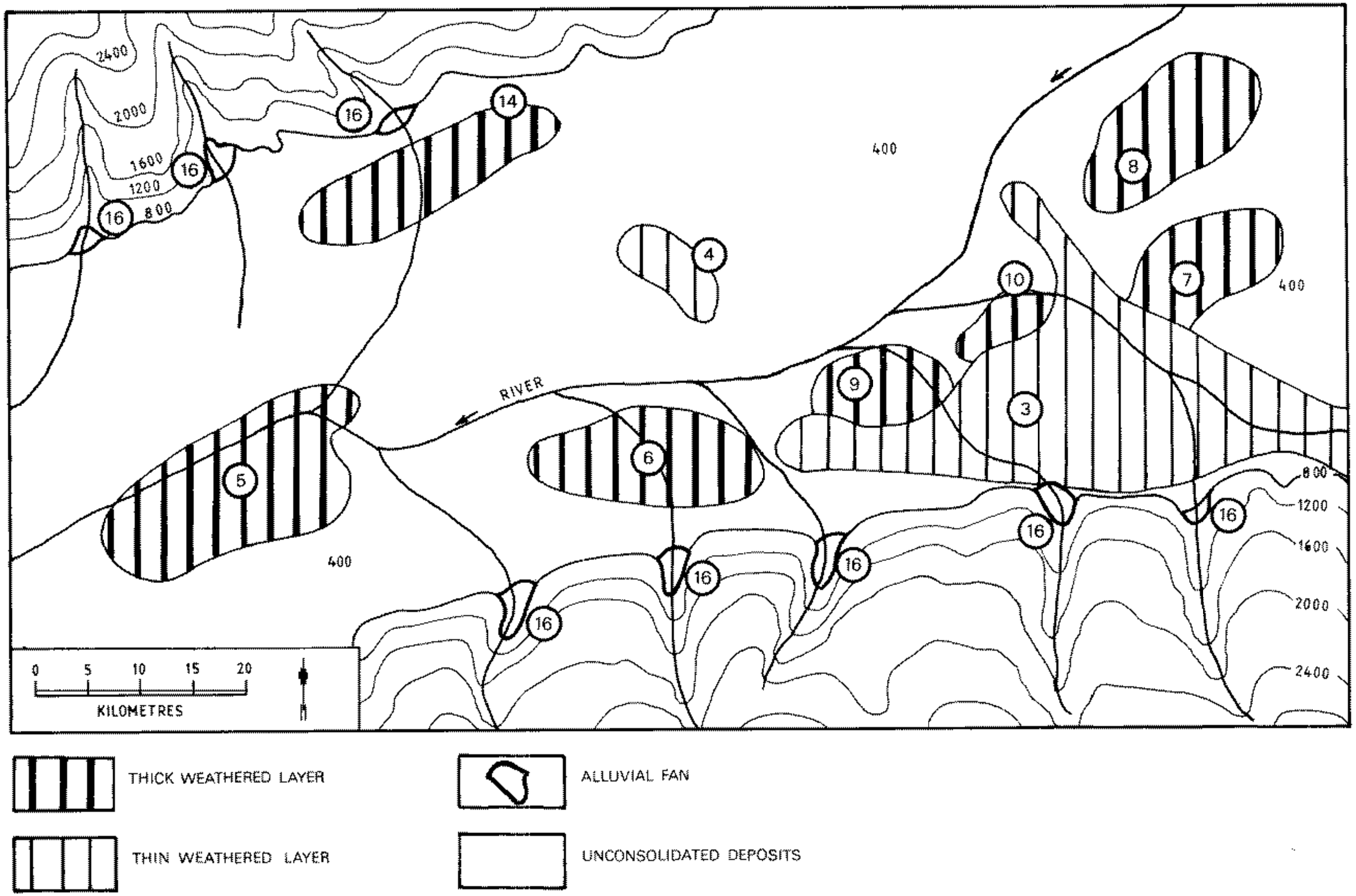


Figure 3.3.2.8 Significant unconsolidated deposits and weathered layer

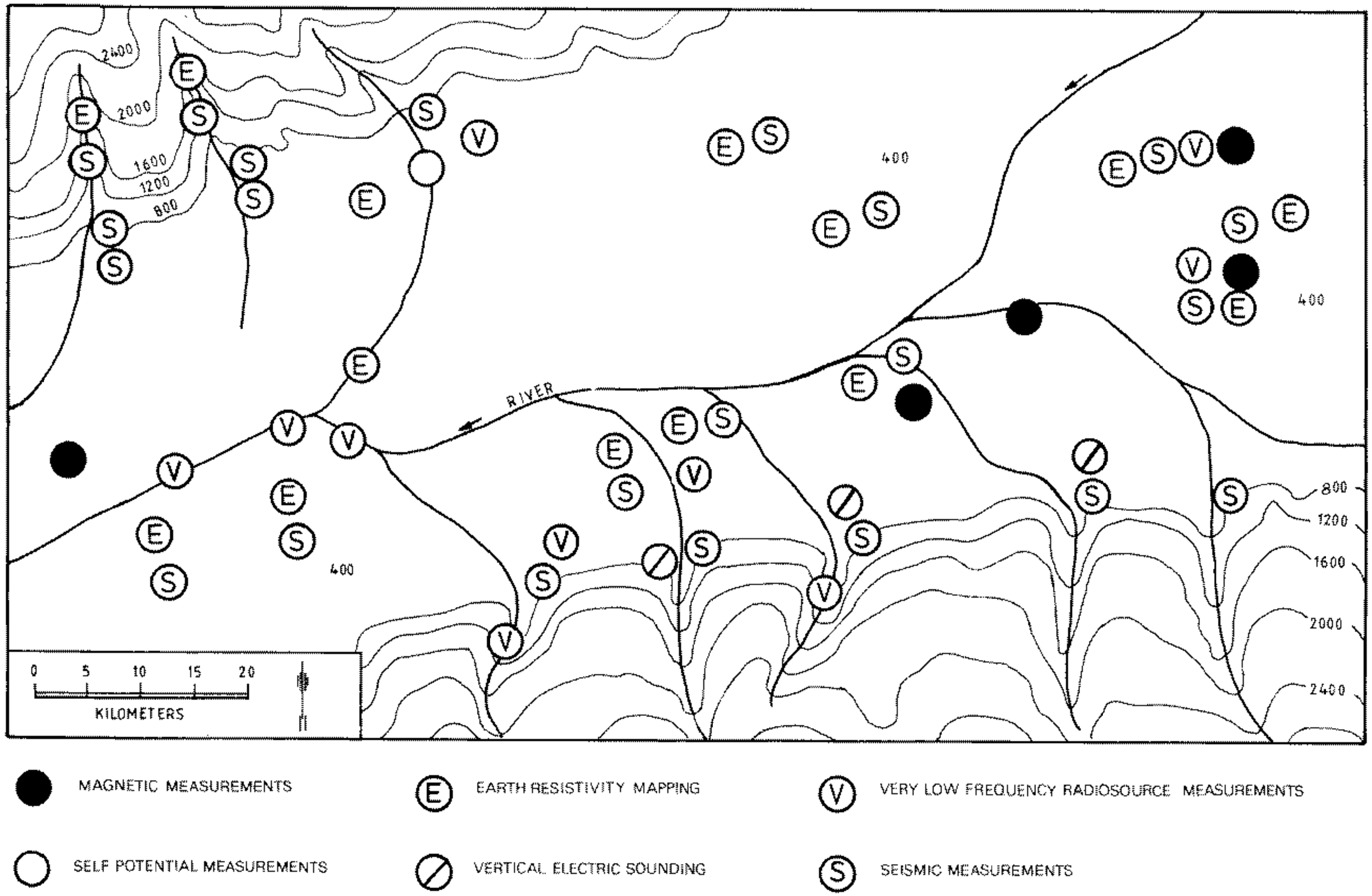


Figure 3.3.2.9 Surface geophysical investigations

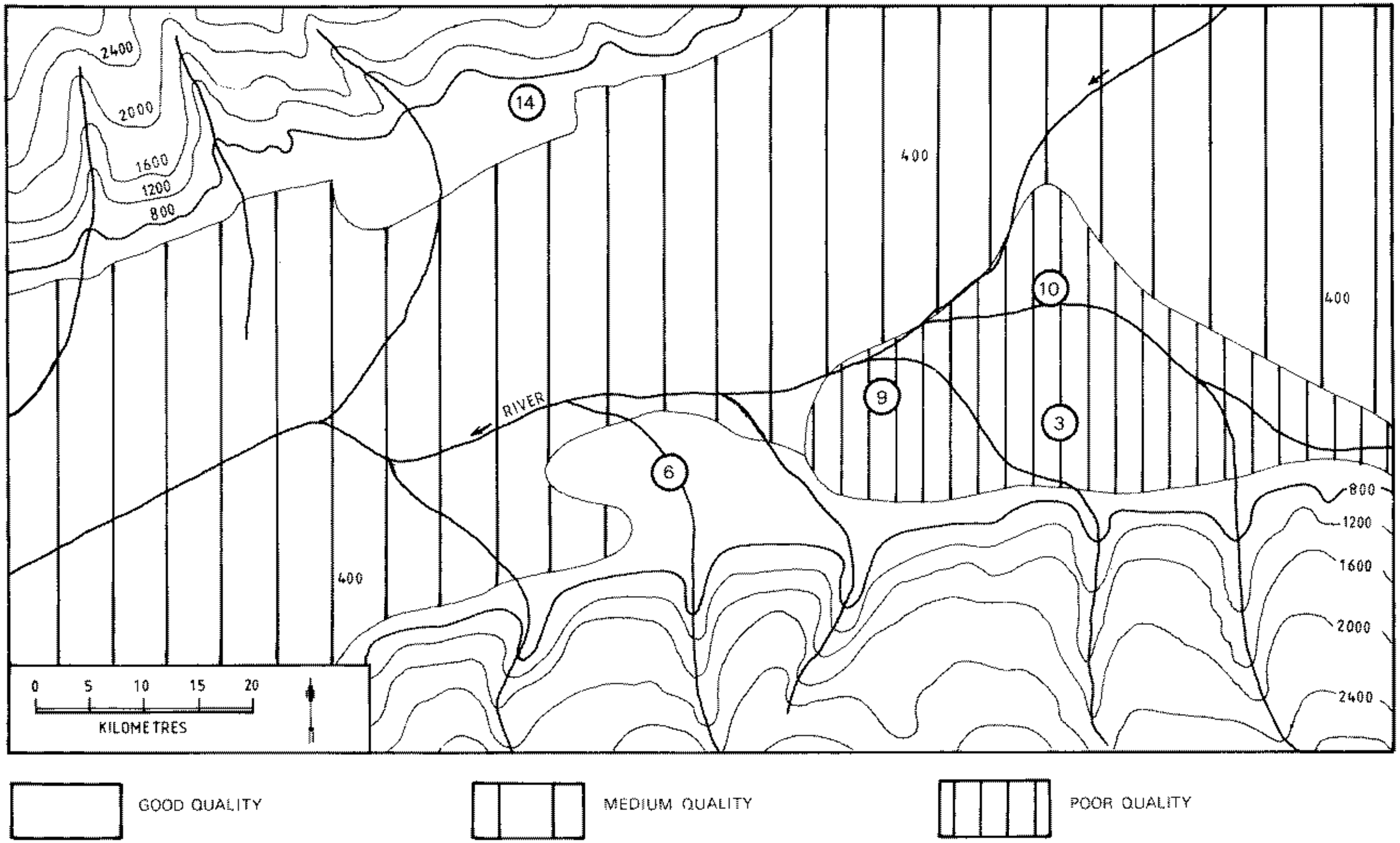


Figure 3.3.2.10 Water quality

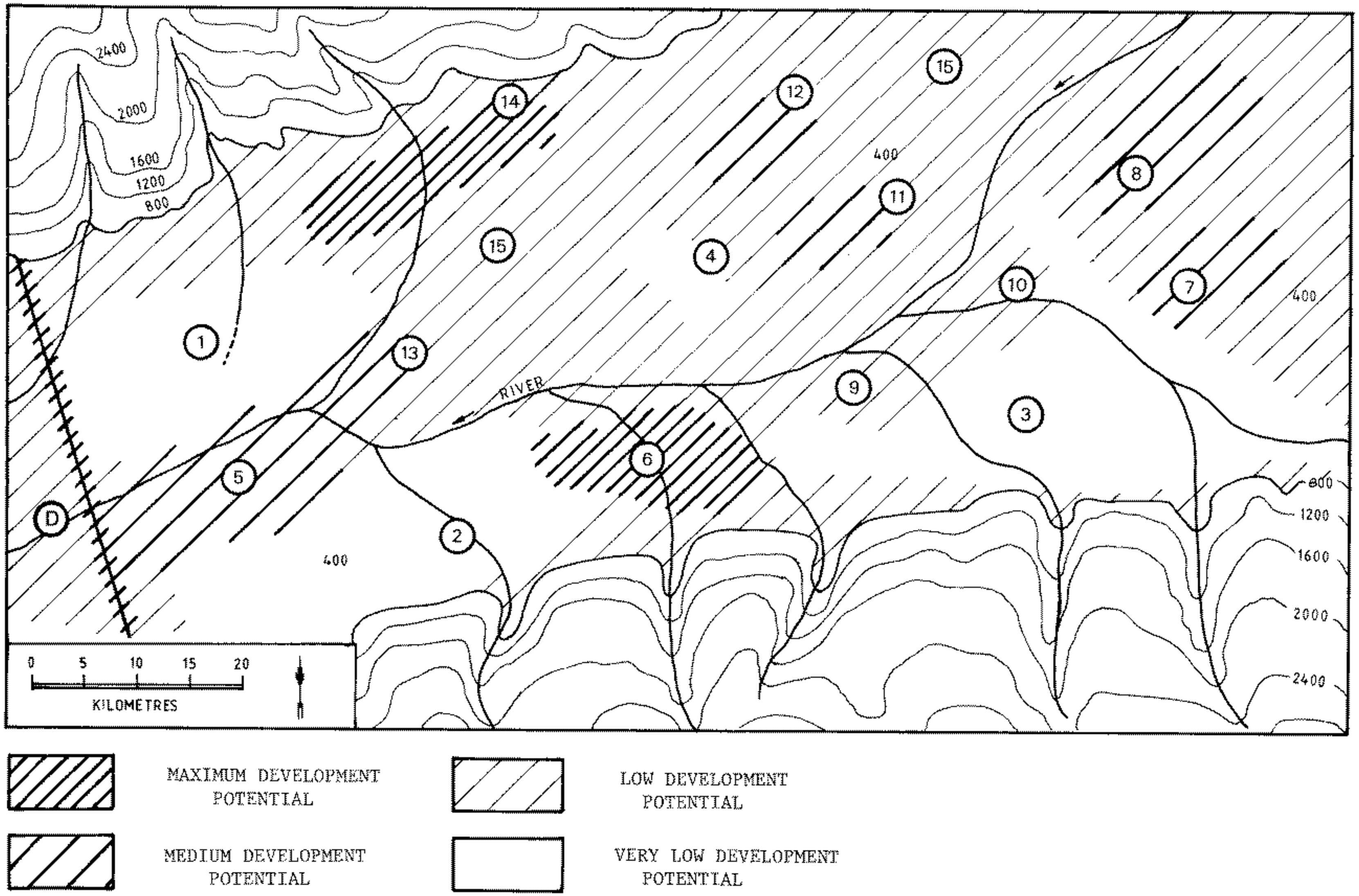


Figure 3.3.2.11 Ground-water development potential

The hypothetical region with an area of about 9000 km^2 is situated between latitude 10° to 12° North. It is a plain, surrounded by mountains rising more than 2000 metres above the plain. The rainfall in the plain is about 400 to 500 mm per year. Rainfall in the mountains is about 2000 mm per year. The climate is of the monsoon type with rainy seasons twice a year.

Regional geology – Figure 3.3.2.6 illustrates the regional geology of the area, developed from geological maps, satellite imagery and aerial photographs with some field checks.

The formations are all of Precambrian age except the dikes which are mostly Tertiary. The major part of the region is underlain by different kinds of gneissic rocks. Some of them are strongly folded. A series of highly metamorphic rocks, generally called charnockites, extends across the eastern part of the area. The gneisses have been intruded by a series of granites, in association with migmatites and pegmatites.

Areas (5), (6), (7) and (8) are estimated to contain good aquifers. Areas (1), (2), (3) and (4) appear to be rather unfavourable. Areas (3) and (4) are probably tight without major fractures. Area (3) prevents infiltration from the mountains in the south into the otherwise favourable areas (9) and (10). Because of the anticipated unfavourable ground-water conditions in the hard rocks of area (3), the alternative of using canals or pipelines should be taken into consideration.

Areas (11), (12) and (13) appear to have good aquifers. Area (14), in the pegmatite zone, appears to have a good potential; the aquifers, however, may be rather limited in area. Area (15) comprises the normal types of gneissic rock in the region. This formation may be only a marginal aquifer. The ortho-types will probably have higher yield than the para-types.

Regional structure setting – Figure 3.3.2.7 illustrates the regional structural setting of fracture patterns. The region has been exposed to two major brittle deformations (see Section 2.1). The oldest one has a direction of about NE-SW and the younger one has a NW-SE direction. The oldest one dominates the eastern part of the region while the younger one is more apparent in the western part.

In Section (2.2.2.1) the general ground-water storage characteristics of different rock types were discussed. A brief synopsis is given here:

1) Granites and pegmatites can in general be classified as potentially good aquifers.

2) Migmatites can be good aquifers locally, depending on the intensity of the migmatization process. Intensive migmatization produces a brittle rock.

3) High-grade metamorphics and strongly folded gneisses, especially of sedimentary origin, are generally poor aquifers.

During the first deformation periods, the stresses which produced these fracture systems, have caused a preferred orientation of the open tensile fractures in the NE-SW direction. In connection with this, shear fractures appeared. However, while causing tensile fractures in the NW-SE direction, the younger deformation may have caused a closing of the older tensile fractures (NE-SW). As a result of this process possibly some of the originally tight shears may have been opened.

In the granite area (5) two well-developed tensile fractures cut the rock. A set of shear fractures approximately in the N-S direction probably causes an increase in the drainage effect of the tensile fractures. Intersections between shear and tensile fractures appear to be excellent sites for locating wells. The granite areas (6), (7), (8), (9) and (10) have tensile fractures with a NE-SW direction. The gneiss area (15) is only moderately fractured. In the strongly folded gneiss and in the metamorphic rocks the fracturing is poorly developed. The pegmatite are (14), has intense fracturing.

In summary, it can be recommended that:

a) Tensile fractures, which are the main "drains" of the aquifers, should be located.

b) Test wells should be drilled at the intersection between tensile fractures and other fractures.

c) Major (hol)-planes (slightly dipping overthrust planes) which often provide the largest infiltration into the rock, should also be taken into consideration.

d) Topographical conditions should be evaluated to determine the possible direction of ground-water flow in the fractures.

Unconsolidated deposits — Figure 3.3.2.8 illustrates the surficial geology (unconsolidated deposits) of the "hypothetical region." Ground water in the region may occur in two types of surficial formations: (i) alluvial deposits along the borders of the mountains and in the low plain; and (ii) areas of deeply weathered rocks. Alluvial fans occur along the borders of the mountain ranges. These fans may contain water in their deepest parts. However, it is also possible that the alluvial fan deposits may lie above the zone of saturation in weathered and/or fractured rocks. In such case the alluvial fans may serve chiefly as infiltration areas for surface-water runoff which can recharge ground-water bodies in underlying hard rocks.

Areas of deeply weathered rock are likely to be present where the granite areas (5), (6), (7), (8), (9) and (10), and pegmatite area (14) occur. These areas may contain significant amounts of ground water in the weathered layer as well as in underlying fractures. The weathered layers, where sufficiently thick, could be tapped for ground water by dug wells. Recharge would be particularly favourable in area (6) which would receive inflow from the alluvial fan to the south as well as the stream flowing in the area in the S-N direction.

Geophysical investigations — Figure 3.3.2.9 illustrates the geophysical investigations which should be carried out in order to clarify further features in Figures 3.3.2.6 to 3.3.2.8. Fractured pegmatites in area (14), at the foot of the northern hills, may be expected to be water bearing.

The electrical resistivity of the fractured zone can be expected to be low in comparison to that of the surrounding rocks. A resistivity traverse, or a VLF traverse across the area of the pegmatite, will enable a delineation of the boundaries of the zone. If the overburden is thin, the simple and inexpensive self-potential method may also give a clear indication of these boundaries. The tension fractures in migmatite rocks, areas (11), (12), (13), trending NE-SW, may contain sufficient water or moisture to give a clear resistivity indication but the values of the resistivities here may not be as low as in the water-bearing fractured pegmatites. Resistivity values may be correlated with the degree of fracturing and hence migmatization.

Seismic mapping of velocities may sometimes give clearer indications of tension fractures than resistivity surveys. Shear fractures are very difficult to locate by geophysical means. Another possible method that can sometimes be used with success is the Very Low Frequency (VLF) method using distant radio transmitters. Magnetic measurements are often able to detect the diabase dikes and show their location, dip, width, etc. Therefore, magnetic profiles should be recommended if the presence of such dikes is suspected as in the northeast and southwest parts of the region.

If a large-scale regional geophysical survey of the area were contemplated in order to delineate the geology in more detail, one should start with a reconnaissance magnetic survey with a line spacing of about 1 km and a point spacing of 100 km. Detailed surveys in limited parts of the region should be planned after the results of the reconnaissance survey have been studied.

The thickness of alluvial fans can be assessed by vertical electrical soundings or by seismic refraction measurements. The former are preferable if the material is not too coarse and if it contains moisture.

Water quality and recharge — Figure 3.3.2.10 illustrates what the interpretation of water quality data would suggest concerning recharge areas, potential areas with water of good quality and potential areas with water of poor quality.

The surface drainage system indicates two features concerning the recharge:

a) Considerable infiltration of water takes place in the alluvial fans bordering the plain (16). This water will directly recharge the pegmatite area (14) and the granite area (6).

b) Aquifers in the other areas will be recharged directly by precipitation and by infiltration from the perennial rivers.

Water quality in the rock aquifers is expected to be best in area (14) and also in area (6) where infiltration takes place. In the remaining areas the mineral content of the ground water will be considerably higher since the surface water is concentrated by evaporation and enriched in nitrates and chlorides by return waters from agricultural areas. The water quality is expected to be particularly poor in area (3) and adjacent subareas (9) and (10). In the overburden, water quality will in general be best along the edges of the plain and least satisfactory in the central parts. Under prevailing climatic conditions, hardpans are expected to be found in the central part of the valley.

Ground-water development potential — Figure 3.3.2.11, which illustrates the ground-water development potential of the various areas, is based on all photogeological, geological, geophysical and water-quality interpretations made in this "hypothetical region."

The following is a summary of results with recommendation for ground-water development in selected areas.

The fracture systems and weathered layers in the granite areas will probably provide the best yields to wells of any of the geologic units in the map area. Recharge conditions and therefore the viability of the aquifers are probably most favourable in areas (5), (6), (7) and (8), because they may receive infiltration from the runoff of streams rising in the southern hills (areas (5) and (6)) or from the north (areas (7) and (8)).

Areas (9) and (10) probably receive recharge only from local precipitation as they are cut off from percolation from hill streams by a large impervious mass of high metamorphic rock (3). The contact zones of the granite intrusives with neighbouring folded gneisses should be studied for evidence of fracturing and higher storage capacity favourable for the siting of deeper boreholes. Shallow dug wells located in the lower parts of granite areas may provide good supplies from thick weathered layers of granite regolith.

The high metamorphic rock is probably very compact with few fractures and virtually impervious weathered layer containing shallow ground water. The position of area (3) close to the southern hills provides favourable recharge conditions for infiltration from runoff originating in the hills. Also reservoirs could be built in the hills to store surface water for conveyance by canal to irrigate area (3). The return seepage as a result of irrigation would recharge the weathered layer and the water could be recovered by pumping from shallow wells. Area (4) is manifestly unfavourable for ground water.

The pegmatites are commonly brittle rocks with considerable storage capacity. This characteristic together with the location of the pegmatite (area (14)) close to recharge sources in the northern hills suggest that this pegmatite may be worthy of exploration by test drilling. The large dike (D) in the western part of the region may contain water in fractures along the contacts with the country rock (folded gneiss). Also as the dike extends into the southern hills, conditions are favourable for infiltration from streams and percolation of ground water along these fractures into the lowlands where it may be tapped by boreholes.

The strongly folded gneiss is likely to contain few fractures capable of yielding significant quantities of water to deeper boreholes. The migmatite bodies (11), (12) and (13) however, are likely to be more fractured, with higher storage capacity and with fair promise of higher yields to wells. A weathered layer of some appreciable thickness and lateral continuity may overlie unweathered gneiss and migmatite in the lowland. This layer probably has considerable storage capacity and is worthy of close examination for its ground-water development potential using shallow dug wells. Recharge conditions are relatively favourable for direct recharge from precipitation as well as indirectly from surface runoff.

After the favourable areas have been located (Figure 3.3.2.11) a socio-economic decision is required on which areas are to receive detailed attention for ground-water development. These decisions can be supported by comparing Figures 3.3.2.4 and 3.3.2.5 with Figure 3.3.2.11. It is apparent that some areas are presently underdeveloped with only limited population (see area (14) in Figure 3.3.2.4). Other areas that are presently populated have a very low ground-water potential (see area (4) in Figure 3.3.2.4).

The final decisions on well-site locations within previously defined favourable areas will be made on the basis of socio-economic factors and are, therefore, beyond the scope of this work. Once decisions are made, test drilling and well construction can begin.

3.3.3 CONSTRUCTION METHODS AND POTENTIAL GROUND-WATER DEVELOPMENT

Well design and construction in igneous and metamorphic rocks are generally simple for both drilled and dug wells. If a well is expected to encounter massive rock with a few significant fractures, there is no need for casing or well support. Certain zones which are known to cave (overburden material) or contain abundant fine-grained material in the fractures, require casing and perhaps screens. Often cemented surface casing or support linings are required to act as sanitary protection and seal the ground surface around the well to prevent fluid communication with the water-bearing zones. The part of the well above ground commonly attracts a variety of visitors, some of which leave unpleasant and toxic by-products behind, which could infiltrate around the well casing and eventually contaminate the water supply.

3.3.3.1 *Dug wells*

Dug well design is especially simple. Excavation can be accomplished by hand or by mechanical means and is carried to the well's total depth before the permanent lining or concrete casing is installed (e.g., Rao et al., 1975). In the event soft or caving material is encountered, temporary steel lining is installed. Figures 3.3.3.1, 3.3.3.2 and 3.3.3.3 illustrates the design features of the so-called "modern" dug wells of Africa. Figures 3.3.3.2 and 3.3.3.3 show the partly screened bottom section that is set opposite the producing interval. In some instances, gravel packing between the outside of the bottom section and the formation is undertaken, but in most cases this is not done and significant production is lost.

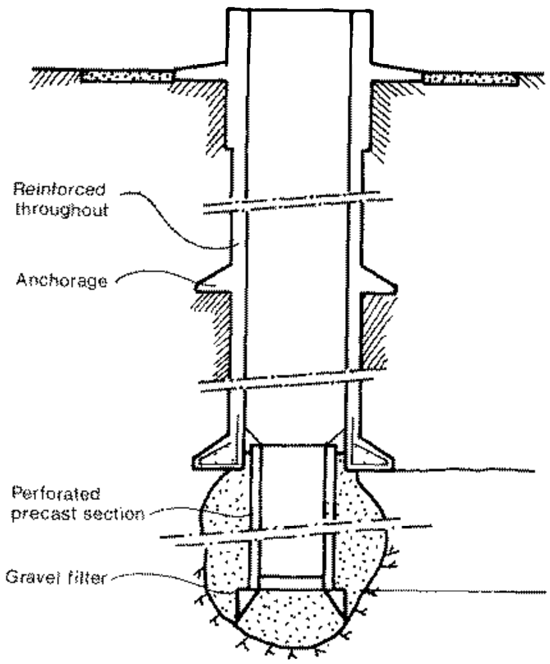


Figure 3.3.3.1 Typical "modern" dug well design (after Bierschenk, 1968).

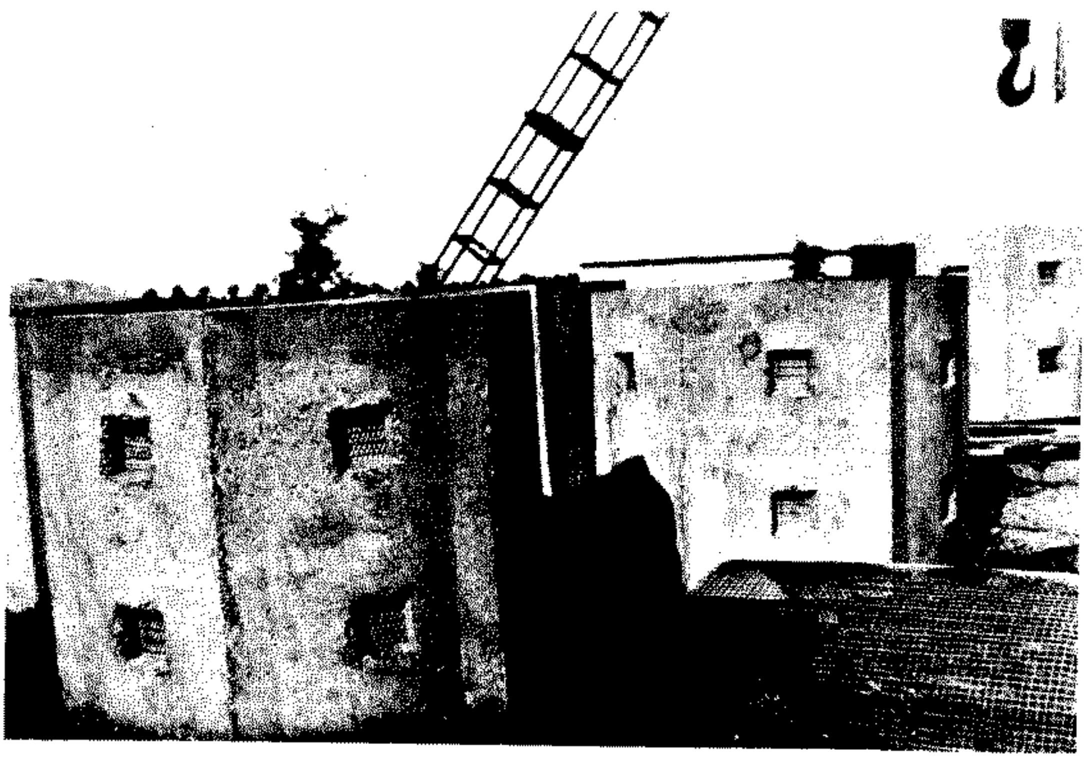


Figure 3.3.3.2 Construction and installation of well "screen" in mechanically-excavated dug well.

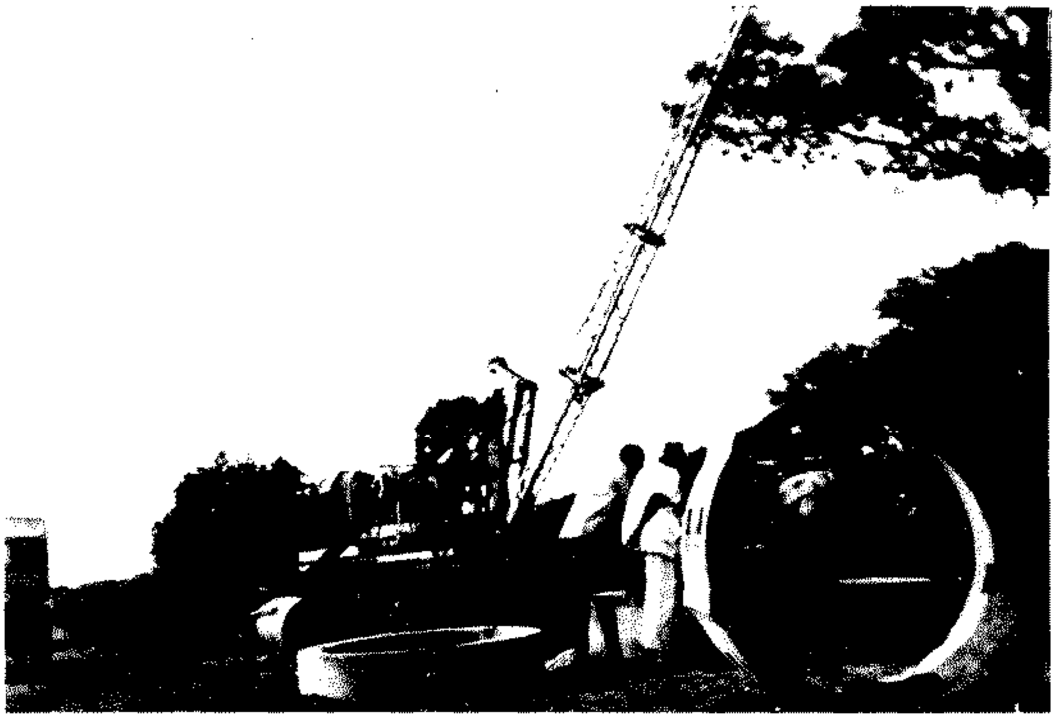


Figure 3.3.3.3 Twelve 10.8 x 10.8 cm stainless steel screen insets occupy approximately 4 per cent of the surface of the 1.0 to 1.4 m diameter reinforced-concrete ring placed opposite the producing interval at the bottom of cement-lined wells.

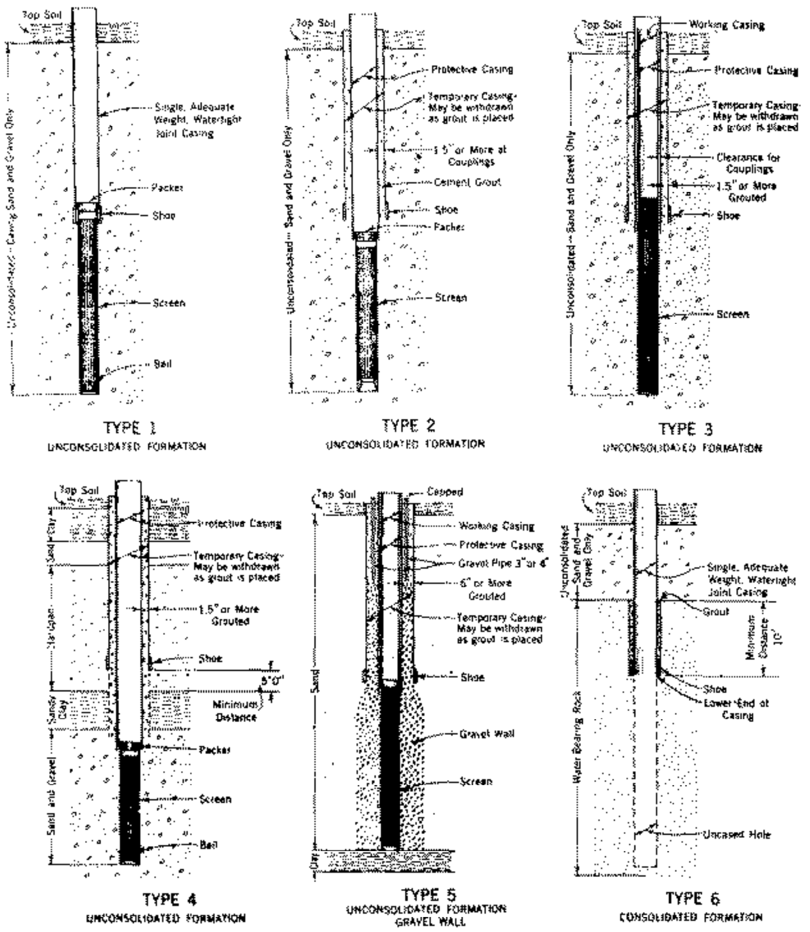


Figure 3.3.3.4 Typical well designs for unconsolidated and consolidated rocks — types 1 through 6 (Amer. Water Works Assoc., 1966).

3.3.3.2 *Drilled wells*

Figures 3.3.3.4 and 3.3.3.5 are typical variations of drilled-well design. Each borehole requires individual attention with respect to its particular geological characteristics, and each well should be designed to meet the specific conditions encountered.

With drainage from overlying material (saprolite, "grus," negolith, "kaolinic porridge"), special well design may be necessary (Bannerman, 1973). One such well design is adopted for conditions at the zone between the overburden and bedrock. Gravel packing is employed to support the saprolite zone and permit flow of water from both zones of the weathered layer (Figure 3.3.3.6).

Well design should also include consideration of contamination, either natural or man-induced. Casing (and cementing) may be required to protect one water-bearing zone from an upper zone that is in communication with a surface source of pollution (Figure 3.3.3.7). Casing only to the "bedrock" may allow contaminants to enter the well through a complex of interconnected fractures at depth in the well (Figure 3.3.3.7).

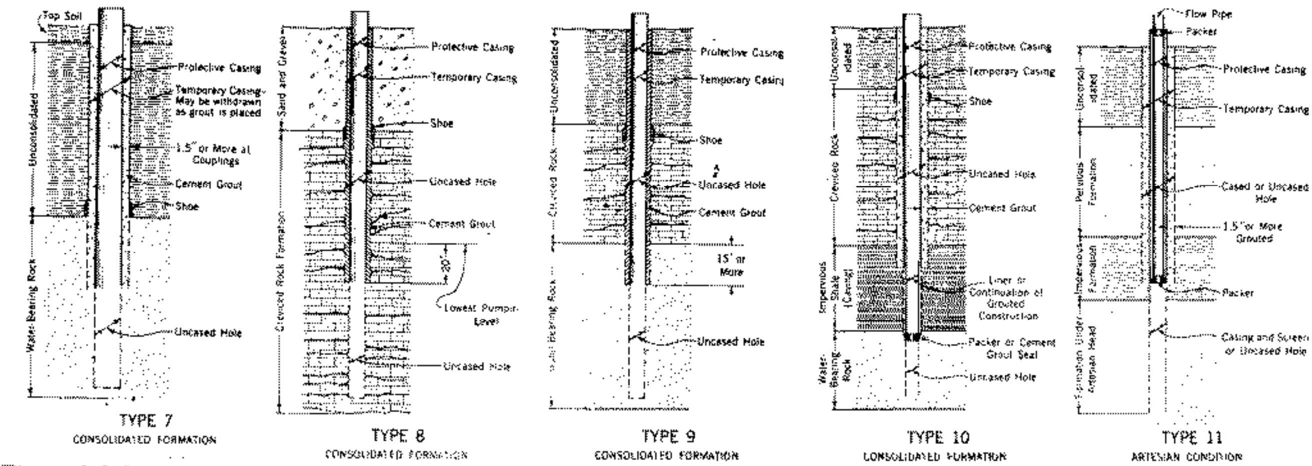


Figure 3.3.3.5 Typical well designs for unconsolidated and consolidated rocks — types 7 through 11 (Amer. Water Works Assoc., 1966).

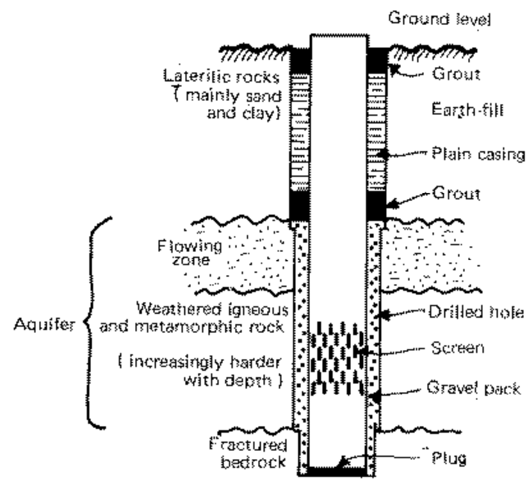


Figure 3.3.3.6 Well design and incorporating gravel packing in contact between weathered and non weathered zone (from Bannerman, 1973). (Reprinted by permission of Water Well Journal Publishing Co. Copyright 1964, world wide rights reserved.)

It is good practice to obtain water samples from each water-bearing zone penetrated as drilling proceeds. Identification of unpotable zones can usually be accomplished by sampling and can indicate the intervals that may require casing and cementing (see Section 2.3.3.3).

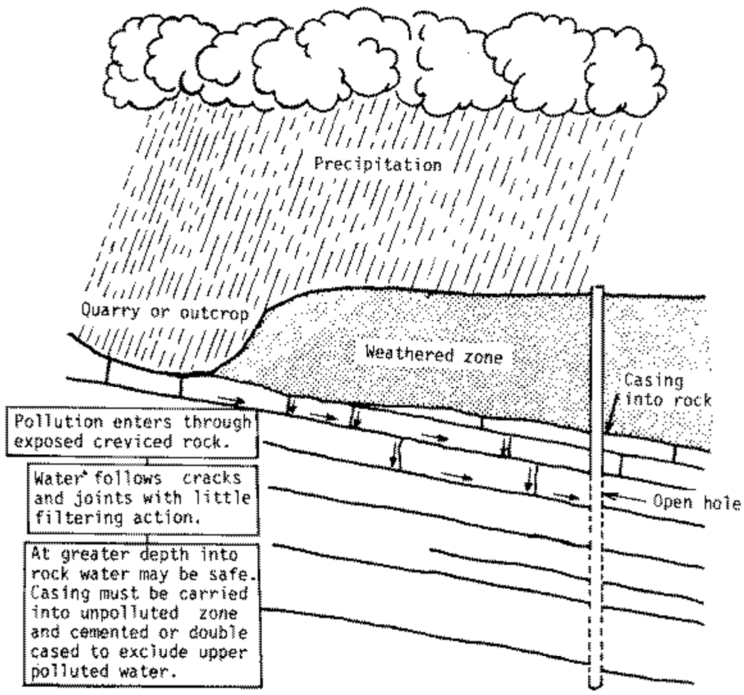


Figure 3.3.3.7 Mechanism of potential well contamination via deep, interconnected fracture systems.

3.3.4 DRILLING METHODS

Percussion and rotary-percussion drilling methods are generally the most applicable techniques for drilling in igneous and metamorphic rocks. If a significant thickness of granular or other overburden materials is present, a combination of methods can be effective, although not very practical. Cable-tool, hydraulic-rotary percussion and air-rotary percussion (down-the-hole air hammer) and foam drilling modifications are the most common types of equipment in use today for such rock types (see Figure 3.3.4.1 and Section 3.3.1.2).

The cable tool drills by lifting and dropping a string of tools suspended on a cable (Mills, 1952). A heavy-duty bit at the lower end of the tool string strikes the bottom of the hole, crushing and breaking the formation material. In consolidated rock, open holes can be drilled, but in overlying unconsolidated materials casing must be driven down the hole during drilling. In some cases of unstable fractured rock, casing follows as drilling proceeds. Bailing of broken rock fragments must then be undertaken periodically (Campbell and Lehr, 1973a; U. S. Dept. of Army, 1965).

The major advantages of the cable-tool method over other systems drilling in similar rock types are as follows:

1) Low initial equipment cost
2) Low daily operating cost
3) Low transportation cost
4) Low rig-up time
5) Drilling rates comparable to standard rotary in hard rocks at shallow depths
6) Very good samples are recovered
7) Very effective identification of water-bearing zones
8) No circulation system required
9) Minimum contamination of water-bearing zones

The major disadvantages of the cable-tool methods are:

1) Limited penetration rate (labour-intensive)
2) Limited depth capability
3) Lack of control over fluid flow from penetrated formations
4) Lack of control over borehole stability
5) Frequent drill-line failures
6) Need for experienced drilling personnel.

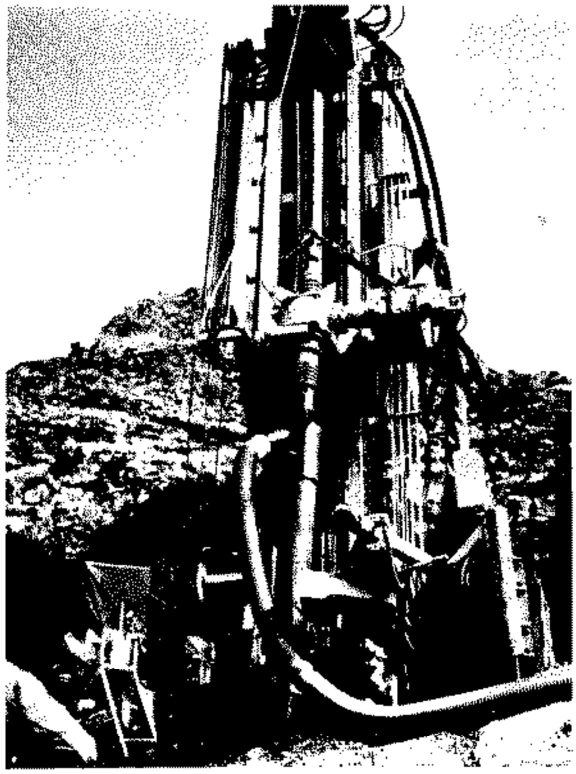


Figure 3.3.4.1 Rotary percussion drilling rig deployed in the Santa Margherita area during the Sardinia project (Larsson et al., 1974).

Given experienced drilling personnel and sufficient time and maintenance (parts) support, the cable-tool method offers distinct advantages in remote areas. One cable-tool rig can drill approximately 20-40 wells/year (60 metres total depth each and 220 working days/year).

In rotary-percussion drilling, developed as a variation of the standard mud rotary, the main source of energy for breaking hard rock is obtained from a percussion machine connected either directly to the bit or to long drill rods with carbide tips (Berube, 1973). The former is commonly called a down-the-hole hammer (Singh, 1979; Herbert, 1975). This technique can control excessive ground-water influx by incorporating foam (Figure 3.3.4.2). The major advantages of the rotary-percussion drilling method are as follows:

1) High penetration rate (labour-time non-intensive)
2) Excellent depth capability
3) Good control of fluid flows
4) Good control of borehole stability
5) Combination drilling (unconsolidated and consolidated formations)
6) No special circulation monitor required unless special additives are required
7) Minimum damage to water-bearing zones
8) Low rig-up time
9) Good samples recovered
10) Effective identification of water-bearing zones

The major disadvantages are:

1) Medium to high equipment cost
2) Medium to high operating costs
3) Medium transportation costs – heavy duty, truck-mounted rig
4) Need for experienced drilling personnel.

Given experienced drilling personnel and maintenance (parts) support the rotary percussion method can drill a minimum of 150-175 wells/year (60 metres of total depth and 220 work days per year). This method could conservatively offer 200 per cent more wells per year than the cable-tool method and therein lies the disadvantage of the cable-tool method when compared to the rotary-percussion method. The longhole, hydraulic mining-type percussion drilling method has many of the same advantages and disadvantages as the cable-tool method (Fairhurst and Lacabanne, 1966) although it is in widespread use in some countries (Beyer, 1968).

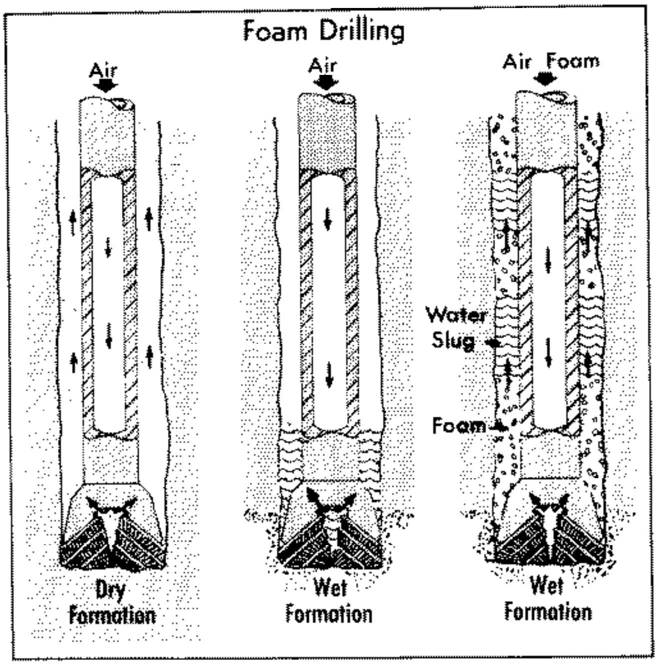


Figure 3.3.4.2 Air drilling incorporating foam and "slug flow" to assist in removing cuttings from the borehole (after Murray and Eckel, Oil and Gas Journal, Feb. 20, 1961).

3.3.5 GEOLOGICAL INTERPRETATION OF TEST DRILLING INFORMATION

3.3.5.1 *Introduction*

After the results of the various geological and geophysical techniques have been integrated and assessed as completely as possible, their collective input expresses, in map form, the hydro-geological conditions anticipated in the subsurface. However, it should be noted that the above mentioned techniques usually do not produce unique solutions, that being the nature of the science of geology and of the subscience of hydrogeology in particular. Of all the physical sciences, geology is the most subjective, relying, to an uncomfortable extent at times, on probabilities and on relative degrees of accuracy of subsurface geological data and related hydrological conditions.

In the past, the exploration for ground water in igneous and metamorphic rocks has been considered a matter of chance. As has been discussed previously in this text, the first steps have been taken in applying systematic procedures to locating useable quantities of ground water in such rocks without resorting to random, costly or unnecessary drilling (Campbell, 1979a).

The ultimate test of any integrated geological interpretation, whether it be designed to locate a specific mineral or ground water is to drill into the subsurface, testing the third dimension. In test drilling, site selection assumes significant importance, an was discussed in Section 3.3.2.3, which was devoted to an integrated survey of a hypothetical area incorporating all of the techniques discussed in this text into a project approach.

Exploration money must be spent on the basis of the best available geological information. Nevertheless chance still plays a dominant role because, although one site may appear to be better than another, any choice is one more level of subjective interpretation which is based on previous subjective interpretations involved in each of the exploration techniques employed.

Test drilling sites are usually selected according to relative priorities, the highest priority site being the one area where all geological information suggests the greatest chance of encountering significant and useful ground-water production. Of course, significant production in one region may not be significant or useful production in another. This depends on what volumes are required and for what use the produced water is intended. Furthermore, significant production may be possible but the pumping depths may, and often are, excessive, resulting in high drilling costs per well during construction and/or high pumping costs (energy requirements) during the anticipated operational life of the particular well.

Added to these considerations is the anticipated quality of ground water which also plays a role in well site selection (see Section 3.3.8.1).

After test drilling has been completed, it is at this point in the exploration programme that geological considerations must be combined with socio-economic considerations. Each region must define the degree to which the latter will direct the former. Figure 3.3.2.4 in Section 3.3.2.3 (integrated plan of action), illustrates the general systematic procedures involved in ground-water exploration and development programmes in hard rock regions and the critical local socio-economic factors play both at the beginning and end of such programmes.

Once the test drilling site has been selected its geographic location must be fixed within reasonable limits, which are controlled by the complexity of the local geological picture. As subsurface information is generated by the test drilling so must its location be known in order to augment previously developed structural, surface, geophysical and hydrogeological interpretations.

3.3.5.2 *Direct subsurface geological information*

Both rotary and percussion drilled boreholes produce cuttings, the size of which in terms of geological interpretation depends on: 1) the type of drilling rig employed, 2) the type of drilling bit used, 3) the type of rock penetrated and, 4) the penetration rate (Campbell and Lehr, 1973 a). Size of cuttings is important because the smaller the chip size the less geological information is available on the rock type encountered, which as discussed in Sections 2.2.4, 3.3.2.2 and 3.3.4, has important ramifications on well yields.

There are two basic sources of direct geological information made available during test drilling programmes. One is from the driller in the form of a driller's log. Most good drillers will make any reasonable type of log desired. Usually this is limited to: 1) a basic geological log, incorporating generalized rock types ("hard" rock, granite, schist, gneiss, etc.), 2) a penetration rate log, in terms of rate of penetration over a general time period, and 3) a water influx log, with notations concerning the depths at which ground-water influx was noted (and often a crude estimate of the influx capacity).

The second source of direct subsurface information comes from the well-site geologist charged with obtaining all information possible during the test drilling programme. It is his responsibility to prepare a detailed geological log from the cuttings as drilling proceeds. This function is often filled by young geologists with considerable knowledge of geology of igneous and metamorphic rocks. A good rapport between the drilller and the geologist is mandatory to ensure that good, reliable data are obtained. The driller, who is usually engaged by senior level geological personnel, should be clearly instructed that the well-site geologist will make all field decisions affecting the driller's operations. Older drillers and young geologists often do not communicate well, especially if both are of different national backgrounds. It behooves the well-site geologist to be in communication or have clear policies established with his supervisor, usually a senior geologist, on major decisions, such as total well depth, rig location, length of drilling day, drilling break periods, driller's sampling procedures, drilling penetration rates etc.

As cuttings are produced, whether via air drilling, mud drilling or percussion, they should be considered a valuable source of information for the present project but also for future geological investigations in mineral exploration. Cuttings should be taken for review at no greater than 1.5 metre intervals, with special care exercised in monitoring drill cutting returns for thin quartz zones or other intervals that may be of vital importance to the local geological interpretations. The well-site geologist should, therefore, be well versed on all geological information developed previously to ensure full integration of data. If storage facilities are available, all cuttings, including the upper soil or alluvium zones should be bagged and clearly tagged for well identification, depth of sample, date, keyed to the geological log prepared and returned to the office for storage and later evaluation, if required. Where storage facilities do not exist or when logistics do not permit sample transfer, one method commonly employed for field storage of cuttings is to: 1) select a standard distance and direction from the rig, 2) dig shallow depressions (usually 20 per row representing 30 metres, and 3) cover via a thin layer of protective soil, each marked by a rock so that parallel rows of rocks will mark the site of well samples for future explorationists.

Good office records are necessary in such programmes. It is often advisable to prepare a brief summary of each well along with the geological log which includes notations on sample locations, storage sites, etc., for future reference. A significant part of the value to the respective country of each test drilling programme completed is in the future use of the data generated, either for the present ground-water project, future ground-water projects, or for future mineral exploration programmes.

Although there are many types of standardized geological logging procedures, the key to the effectiveness of such is in their uniformity. Rock units observed in outcrop during the project's previous field reconnaissance should be clearly defined according to the standard rock nomenclature used or developed in cooperation with the professional staff of the host country. Standardization is always a problem but can be solved by preplanning and by cooperation between field personnel and between multinational groups, although vigorous national preferences exist. Under such conditions a dual system could be functional as long as specific definitions are exchanged early in the project (see Unesco, 1978).

Other areas relating to uniformity of geological descriptions involve similar subjective qualities such as rock colour. In such a case, colour charts are useful for standardization purposes. The Geological Society of America has published a comprehensive colour-numbered code system which could be adapted to a wide variety of regional conditions. As long as one shade of a colour can be assigned a number, the chances are good that the same colour can be reported by others, except for those who wear sunglasses during the preparation of the geological log.

In addition to drill cuttings, cores are another source of direct subsurface geological information. Although useful, cores are relatively expensive and are obtained only when outcrop data are scarce or when additional information is required for a particular rock type or a particular structural setting. Such cores should never be discarded for obvious reasons. Again, standard procedures should be developed regarding core descriptions, packaging, marking, orienting, etc. It is often advisable to take field photographs of the cores with proper labeling to ensure that a record is retained of the physical appearance, texture; colour etc., in the event the core is lost, which is not an uncommon occurrence.

A secondary source of potentially important geological data is the surface geology within a radius of a few hundred metres around the drilling rig. The well-site geologist should make detailed surveys of this area, with special emphasis on surface water courses, outcrops of bedrock and of overlying granular material and its composition, texture and relationship with bedrock. Of course, although his principal responsibility centers on the drill rig, many occasions will arise when rig repairs, or other short down-time periods will allow for such excursions and which may result in significant observations that may affect the success of the project.

Much of the information obtained from drill cuttings and/or cores helps to calibrate the indirect subsurface geological information obtained during borehole geophysical logging. Although direct geological information is useful, only a small part of the rock units drilled can be observed. Indirect information contributes additional, worthwhile data not available otherwise to the well-site geologist.

3.3.5.3 *Indirect subsurface geological information - Well logging*

Introduction — Geophysical measurements of various kinds can be made in drill holes and have been extensively used in sedimentary areas for stratigraphic correlation, study of aquifer characteristics, moisture estimates, etc. (Campbell and Lehr, 1973). Most of these techniques need elaborate corrections if reliable results are to be obtained. In sedimentary areas the geophysical well logging is usually supplemented by caliper logging that measures the diameter of the hole continuously along its length. All such techniques can be adapted to hard rock areas but their scope is somewhat different and in many cases more limited.

A number of down-hole devices are available to assist the well-site geologists in characterizing the subsurface geology and water-bearing zones. The logs produced have been useful in clarifying local structural interpretations and in monitoring the behaviour of the ground-water system (Bardhan, 1973; Zublin, 1964; Keys, 1968; Pirson, 1970; Emerson and Webster, 1970).

A standard logging programme may consist of a caliper log, a spontaneous potential (S.P.) log, a resistivity log, a temperature log, and a natural gamma log. Other logs may be used to meet special requirements. It should be noted that with the exception of the natural gamma log, logging is possible only in an open hole, before casing or liners are installed. Unfortunately, many holes cave severely and casing must be installed to keep the hole open. If logging is attempted in an unstable uncased hole, the down-hole logging tool may become stuck forever.

The cost of a standard bore-hole logging programme in comparison with the cost of drilling is so small that every effort should be made to include a basic logging programme as an integral part of all drilling programmes (Linck, 1963).

Spontaneous potential logging — The simplest log is the self-potential or S.P. log that charts the electric potential of points in the hole with respect to a fixed point of the surface. If the hole is waterfilled the log is simply taken by lowering a lead electrode down the hole. Characteristic changes of electrical potential on the continuously recorded S.P. curve will generally indicate fissures and fractures. However, in holes in hard rock not all fissures and fractures will corelate with S.P. anomalies.

In hard rock regions, the usefulness of the S.P. log lies in defining differences in content of electrolytes of the ground water. In one well, the ground water in an upper fracture may be substantially different in its ionic make-up than another at greater depth, which may indicate a lack of communication between the two, separate recharge sources, different residence time, etc. (see Figure 3.3.5.1).

Resistivity logging – The single-point log can be obtained either by measuring the contact resistance of a spring-loaded electrode pressed against the hole wall or by the variations in the current that can pass through the electrode into the surrounding rock when a constant voltage is applied between it and a fixed electrode that is usually placed on the ground. An example of a single-point resistance log is shown in Figure 3.3.5.1 (Patten and Bennett, 1963).

In multi-electrode logging a set of four electrodes, two current and two potential ones, rigidly built into a sonde or probe, is lowered into the hole and the apparent resistivity (see Section 3.2.2.3) measured by the arrangement can be recorded continuously. Depending on the relative spread of the electrodes one speaks of long or short resistivity probes. A long resistivity probe will smooth out the numerous minor variations of resistivity while the short one will be more useful if resolution is the prime consideration. As with the S.P. log the most valuable information that can be obtained from resistivity logs concerns the presence of fissures and cracks (Guyod, 1966; Keller, 1967).

Electrical conductivity logging – The electrical conductivity of fresh water is extremely sensitive to small amounts of dissolved solids and therefore it is often more useful to express the results of electrical logs in terms of the conductivity rather than the resistivity. Although the conductivity is, numerically, simply the reciprocal of the resistivity, a conductivity log may show greater resolution within the sections of a hole that have low electrical resistance, and can therefore reveal the presence of ground water more easily than the resistivity log (Blankennagel, 1968).

Natural gamma logging – Natural gamma logging, in which the gamma radiation of the rock is recorded by lowering a scintillation counter in the hole, is also found useful for the information it may give not only about fissures and fractures but also about dikes (Patten and Bennett, 1963). Two characteristics can be determined from the natural gamma log. First, the log exhibits a record of the natural gamma emission from hard rocks. In fracture zones of possible

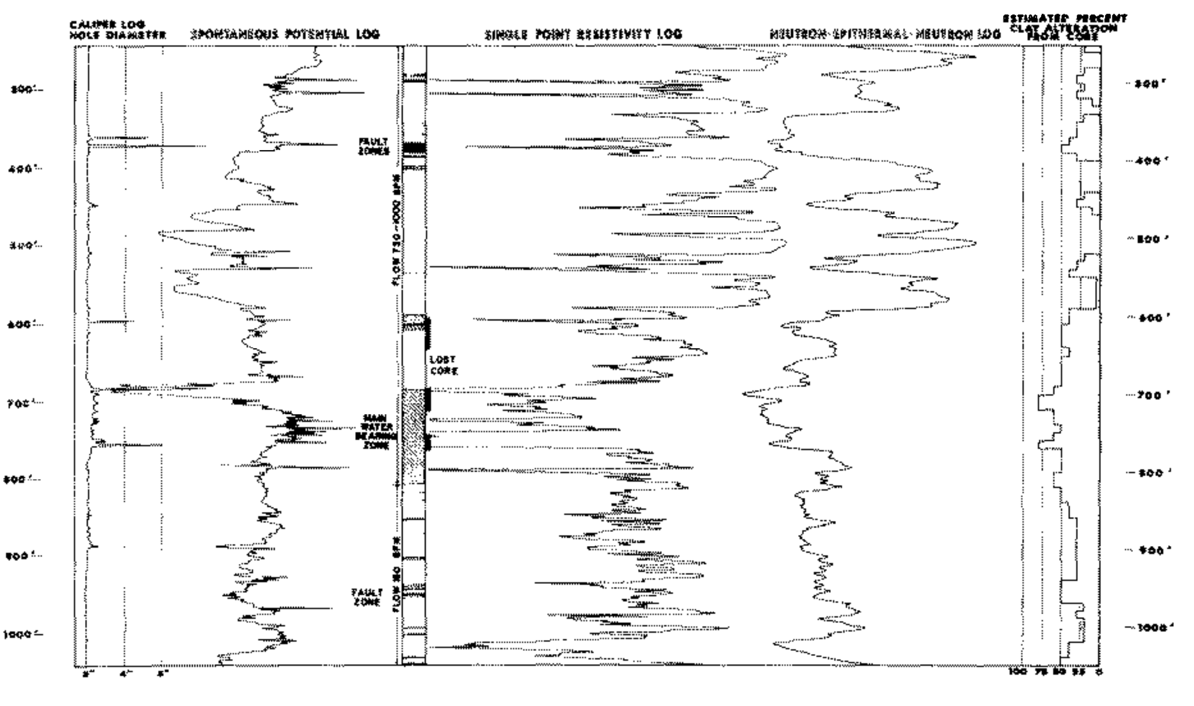


Figure 3.3.5.1 Caliper, SP, resistivity and neutron-neutron logs, Clear Creek, Colorado (Keys, 1970). (Courtesy Geological Survey of Canada).

permeability, a distinctive curve may be produced. If compared to the well-site geologist's log, important information can be gained. Secondly, the gamma log can be used to identify fluid migration behind casing (Killiow, 1966).

The use of the gamma log is also instrumental in conducting "in-hole" tracer tests (Marine, 1980).

Neutron logging – In the neutron logging a neutron source is lowered in the hole to induce artificial radioactivity in the rocks. A detector placed at some distance from the source and appropriately shielded from its direct radiation measures the induced radioactivity as the source-detector system is lowered slowly in the hole. A relatively slow velocity is essential to induce radioactivity in the rock. Depending on whether the secondary neutron radiation or the gamma radiation emitted by the rock is measured, there are neutron-neutron or neutron-gamma logs (International Atomic Energy Agency, 1971).

One important characteristic of radioactivity logs is that they can be obtained in cased as well as uncased holes since neutrons or gamma rays can penetrate through the casing.

Caliper logging – There are numerous types of caliper logging devices available. The design usually involves a 3-arm or 3-wheel mechanical device that responds to changes in the borehole diameter. Such changes, if abrupt, indicate open faults filled with granular material, fracture zones, or contacts between two rock units of different composition which may serve as a significant water-bearing zone. Figure 3.3.5.1 indicates the usefulness of the caliper log in identifying water-bearing zones at depth in a massive granite of Colorado. Note the rate of production from the main water-bearing zone.

Temperature logging – A temperature log, combined with a conductivity log, can indicate if there is water movement within the borehole or across it via intersected fractures. In temperature logging, the temperatures in a hole can be measured either by thermistor or resistance sensors. In water-filled holes it is frequently possible to detect the fissures and cracks where water is percolating from or into the surrounding rock, by characteristic temperature changes (Keys and Brown, 1978). It should be remembered, however, that for meaningful temperature logs to be obtained convection must be absent in the air and water in the well (Blankennagel, 1968; Trainer, 1968).

Well log applications – Considerable experience has been gained in logging of hard rock regions in Sweden. Houtkamp and Jacks (1972) present an excellent review of geohydrologic well-logging techniques in the Precambrian rocks of Sweden. Houtkamp (1977) reports on the logging programme conducted during hydrogeological investigations in Sardinia. Keys (1967) summarizes the work carried out by the U.S. Geological Survey on borehole geophysics as applied to ground water and mining exploration.

In Sweden, the standard set of logs employed consists of the caliper (called the diameter log), the S.P. log, the electrical conductivity log (E.C.) and the temperature log. In one application, illustrated in Figure 3.3.5.2, the caliper log indicates a number of fractures. A major fracture is suggested at a depth of approximately 52 metres. Based on the shape of the temperature and electrical conductivity curves, it can be concluded that there is movement of water within the well. There is a slight increase of salinity (see E.C. log curves) toward the bottom of the well due to weathering reactions and ionic equilibrium.

In Figure 3.3.5.3, however, a substantial increase in salinity at depth has been related to retention of sea-water dating from the Pleistocene. It has been suggested that flushing of the major fracture by meteoric water has been very slow, even after the region experienced tectonic uplift (Houtkamp and Jacks, 1972).

It is interesting to note the temperature curves of Figures 3.3.5.2 and 3.3.5.3. The effects of surface recharge into the slightly weathered and highly fractured zones (due to unloading, weathering, frost-heaving, etc.) are evident. As discussed in Section 2.2.4, it is these shallow zones that have been extensively drilled and have produced limited, although highly variable, volumes of ground water. This has resulted in the general impression that "fracture intensity decreases with depth."

As emphasized throughout this text, the target of this collective investigation focuses on fractures that are related to regional and local tectonics and for major fracture zones within economic depth (see Figures 3.3.5.2 and 3.3.5.3). If the structural geology can be sufficiently defined and if socio-economic factors are favourable, the search for useable ground water can be extended to depths greater than those previously assumed to be economic. The success rate will also improve incrementally as the knowledge of the local conditions of igneous and metamorphic rocks improves with time and effort.

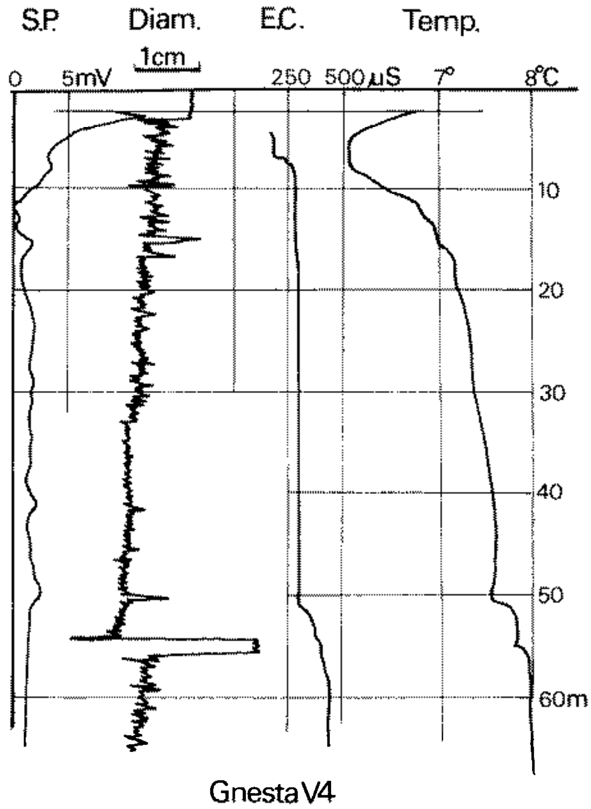


Figure 3.3.5.2 S.P., caliper conductivity and temperature logs from well near Stockholm, Sweden (Houtkamp and Jacks, 1972).

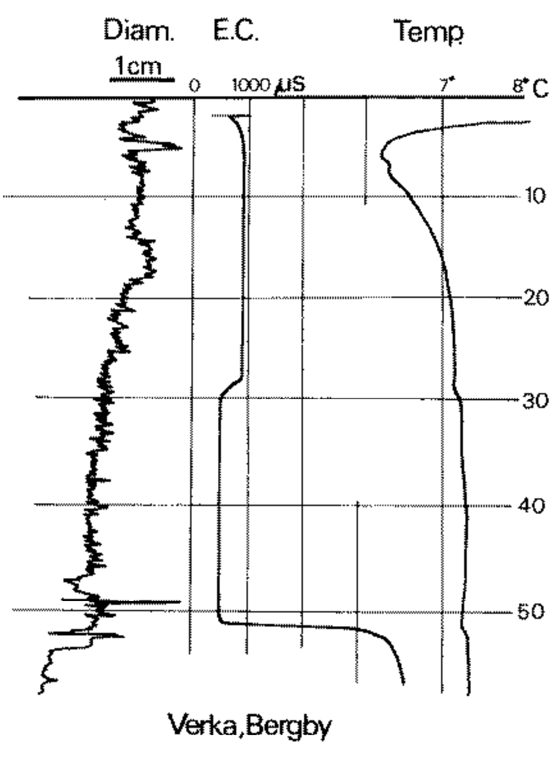


Figure 3.3.5.3 Caliper, conductivity and temperature logs near Stockholm, Sweden (Houtkamp and Jacks, 1972).

by sliding planes. The sites of highly permeable slide planes are marked by increases in hole diameter and increased drilling penetration rates. By contrast, Well 302 was drilled on an auchthonous block nearby, and the logs indicate only a few individual fractures. Well 310, located in a valley where recharge is available, and intercepting shallow, open fractures had a capacity of approximately three times that of Well 302 (Houtkamp and Jacks, 1972).

Other types of logs – There are a few other types of logs that may be useful in exploration and development programmes. For example, the gamma-gamma or density log may be useful in determining zones of relatively low density which may indicate zones of high permeability (fractures) or contact zones. The neutron-neutron log may also be useful in determining recharge areas (see Keys, 1967). Down-hole current (or velocity) testing may be useful in determining location of flow among a complex of indicated fractures (Leve, 1964; Blankennagel, 1968). One of the most useful yet seldom employed down-hole tools is of the visual variety. In the form of either closed circuit television (Zemanek et. al., 1969) or stereo photographs, such equipment is especially effective in observing, although indirectly, the face of the subsurface formations. Rock units and fractures can be identified and their characteristics can be recorded and made a part of the well-site geologist's log. Such equipment also can be used after the well has been completed to ensure that proper construction has been achieved, that is, after casing, screens, etc. have been installed. The effects of corrosion or other well damage also can be observed directly in older wells. This information is useful for the planning of well maintenance operations (see Figure 3.3.5.5).

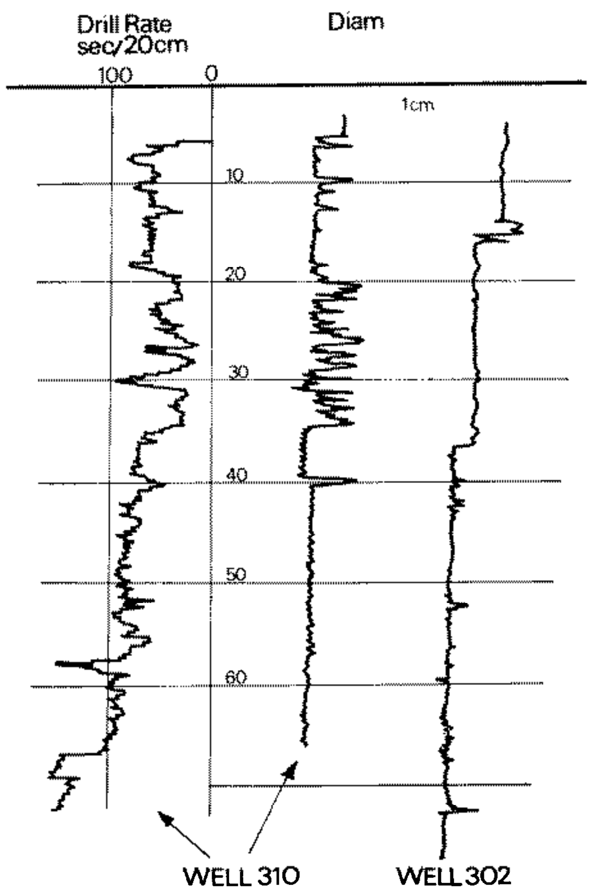


Figure 3.3.5.4 Caliper and penetration rate logs for Wells 310 and 302 near Angered, Götheburg, Sweden (Houtkamp and Jacks, 1972).

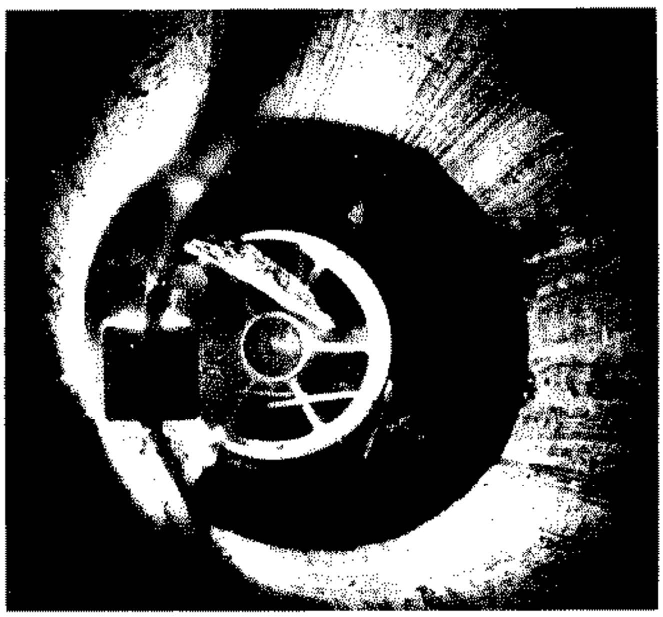


Figure 3.3.5.5 Down-hole photograph showing 8-inch pump bowls in 16-inch casing (Jensen and Ray, 1964).

3.3.6 AQUIFER TESTING AND HYDRAULICS

3.3.6.1 *Introduction*

After the well has been drilled or dug to the desired depth, which may only be to the maximum economic limit suggested by the investigations previously discussed, and after the well has been pumped for a period to remove all fine-grained material created by the drilling process, or hand cleaned if dug by hand, pump testing is undertaken. Proper testing can provide good information about the well yield, aquifer properties and boundaries, and makes possible the prediction of future well capacities. The basic procedures associated with well-pump tests are discussed in Section 3.3.6.3 and include the following considerations:

1) Monitor static-water level several days before pump testing is to begin.

2) Measure pumping discharge at different rates, usually by increasing steps.

3) Record drawdown associated with discharge.

4) Test should be of sufficient duration to show a definitive response in the nearest observation well.

5) Well discharge should be removed from the area so that it cannot return to the subsurface and disturb the test.

6) Record recovery accurately, especially as the recovery level approaches the original static level.

3.3.6.2 *Practical considerations*

Aquifer tests in igneous and metamorphic rocks are commonly not considered to be subject to the general interpretations and procedures used in porous media such as sandstone, sand and gravel, etc. (United Nations, 1967). Although such general physical conditions as a cone of depression and cone of pressure relief are apparent during pumping in igneous and metamorphic rocks, the yield of all wells in such rock is obtained by drawing water from saturated and interconnected fractures and related permeable zones (see Section 2.2.3). The approximate relationship of drawdown to yield in the hard rock region of the southeastern United States is shown in Figure 3.3.6.1.

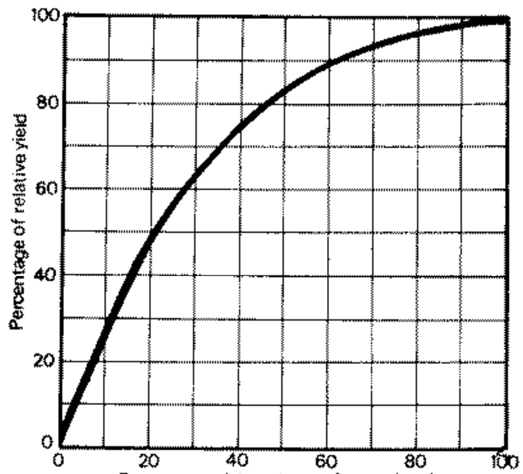


Figure 3.3.6.1 Approximate relationship between per cent of well yield and per cent of drawdown. Example: A yield of 80 per cent results in a drawdown of only 40 per cent (from LeGrand, 1967).

The percentage of relative yield is not directly proportional to the percentage of drawdown during pumping tests; the highest percentage of yield is reached before the highest percentage of drawdown. As an example of this relationship between yield and drawdown, a well 67 m deep has a static water level of 6 m below the surface. In the example (Figure 3.3.6.2), the well yields 9 m^3/h with a pumping level at a depth of nearly 67 m; if the pump were set at 37 m (50 per cent of drawdown or approximately half of the thickness of the water), approximately 8.2 m^3/h or 90 per cent of the relative yield could be obtained. It is uneconomical to lower the drawdown to a position near the bottom of the well unless the yield is so low that even the water stored in the well is required. The difference in power costs between the two pumping levels could be substantial over the life of the well.

The common method of determining well productivity is to measure the drawdown in the well at various pumping rates over a specified period of time. The effect of pumping on a nearby observation well would also assist in determining the extent of interfracture communication in the area, although it should be noted that such communication is not always apparent. Observation wells in hard rock areas are often of little value because the two well system may be tapping two fracture zones which are not hydraulically connected. A plot of drawdown versus time is made during the pumping test (as well as recovery time after pumping ceased). From these data specific capacity (per unit of drawdown) can be assessed based on the following relationship:

$$\text{Specific capacity} = \frac{\text{Rate of discharge } (m^3/h)}{\text{Drawdown } (m)}$$

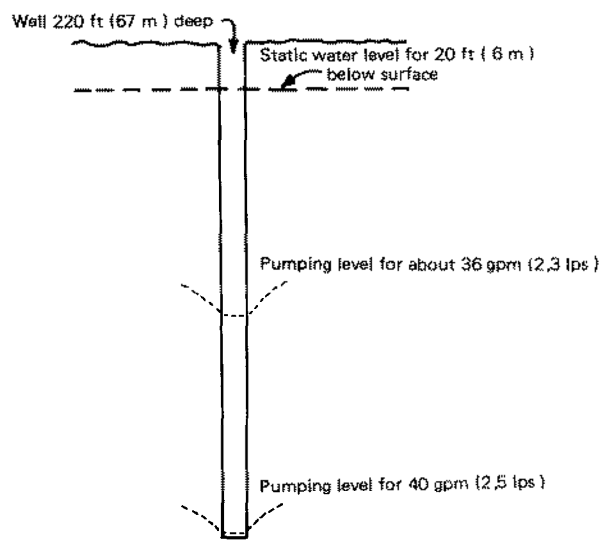


Figure 3.3.6.2 Yield of a hypothetical well at two different pumping rates (from LeGrand, 1967).

It should be apparent that the various combinations of fracture location, fracture width, fracture content (fine-grained material), and amount of ground water in storage in the vicinity of the well can result in almost any type of drawdown curve. As discussed in Section 3.3.6.3, a number of reviews of the hydraulics of wells in fractured, jointed, and related rocks have appeared in the literature (Lewis and Burgy, 1963, 1964; Moore, 1973; Zdankus, 1975). Figure 3.3.6.3 illustrates a few cases or typical drawdown curves for selected geological conditions. In each well having encountered a water-bearing zone there exists a pumping rate wherein drawdown will stabilize at a specific discharge rate, and thereby the well will be characterized by its long-term calculated specific capacity. If the particular well has a very low or a very high specific capacity both are difficult to evaluate without the proper pumping equipment. Usually, the range of well yields is known and the appropriate pumps are available.

In evaluating drawdown curves, a feature that is very common in wells drawing from fracture systems is a high or moderate initial yield that decreases rapidly with time. The cause is usually insufficient storage of ground water in the vicinity of the well. Davis and DeWiest (1966), suggest that wells should be located so that they can draw water from overlying weathered layers or from saturated alluvium or colluvium because these materials contain from twenty to forty times the water per unit volume that is contained in the unweathered crystalline rock. A well location within influence of a perennial stream to prevent depletion and dewatering of the fracture system is also suggested, if contamination is not a potential problem. However, as is usually the case, such "soil" cover and weathered layers as well as significant surface recharge may not be available in certain areas of hard rock regions. The importance of the overburden as a source of recharge is clearly shown in the LeGrand field method of well-site selection discussed elsewhere in this work (see Section 3.3.2.2).

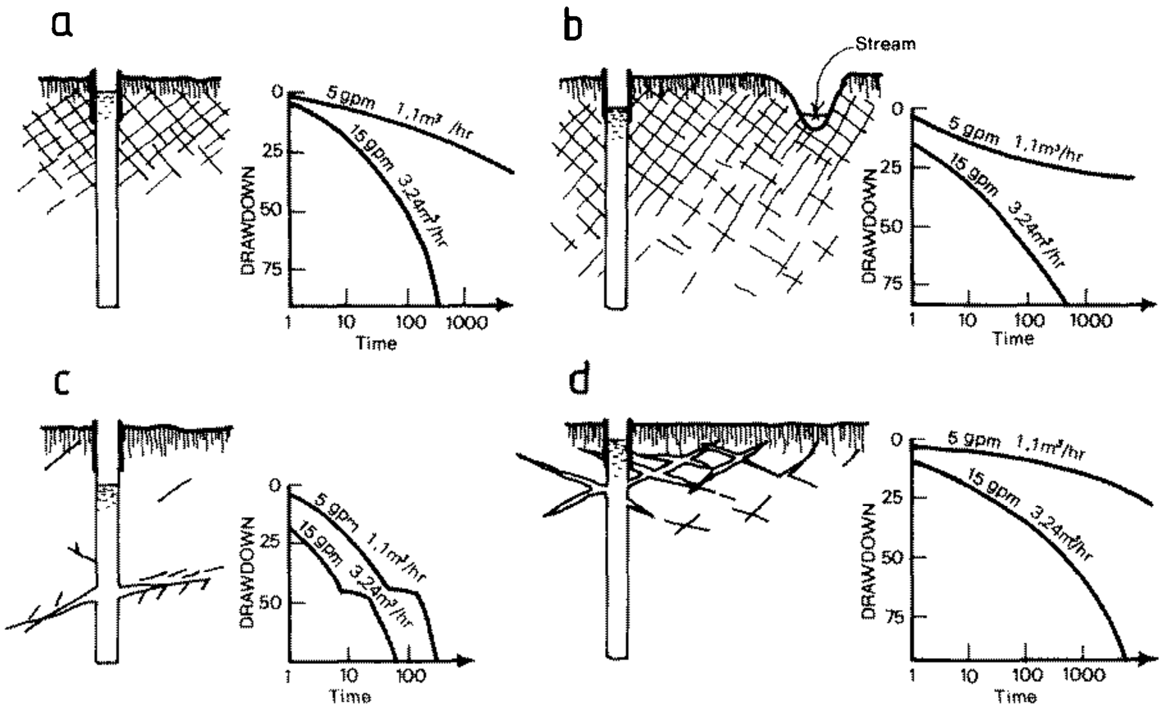


Figure 3.3.6.3 Hypothetical drawdown curves for wells in fractured crystalline rock at various pumping rates, a) Production from small, near-surface fractures; b) Production from extensive and widespread fracture system; c) Production from large but limited fractures that drain overlying weathered rock or soil (modified from Davis and DeWiest, 1966).

Figure 3.3.6.4 shows a few additional typical drawdown curves. Figure 3.3.6.4A shows the response related to pumping in fractured rock that may have several levels of open, saturated fractures. Figure 3.3.6.4B illustrates the typical case where fracture filling material is released during pumping causing minor rises in pumping levels. If this well had been pumped initially at a high rate for the development purpose of removing fine materials loosely held within the fractures, the well's yield might have been increased significantly by increasing communication between a greater number of fractures than may have existed before such development pumping. One indication of such effectiveness is that excessive turbidity may be temporarily evident in the discharge.

Figures 3.3.6.4C and 3.3.6.4D illustrate the typical effects of an impermeable boundary and a recharge boundary, respectively. In the former case an abrupt decrease in the drawdown is shown while in the latter the drawdown stabilizes as the cone of depression (or pressure relief) reaches a surface water body and begins to draw from it. It should be also noted that this type of drawdown curve may also be symptomatic of the recycling of water discharged from the tested well itself and which has reentered the fracture system from above. Of course, there may be many other drawdown curve shapes and other interpretations of the drawdown curves than those presented herein. For this reason it should be stressed that caution is required in conducting and evaluating pumping tests. A short-term test should never be the basis for determining the long-range potential of a ground-water reservoir.

The well discharge rate can be measured in a number of ways, that is with pitot tubes, full flow pipe discharge, orifice plates and totalizing water flow-rate meters. For low-rate flows the pitot tube method is the most practical. For medium rates of flow the full-flow pipe discharge measurement method is an acceptable method and for high rates of flow, the orifice-plate method is in common use.

Figures 3.3.6.5 and 3.3.6.6 are useful for field applications dealing with various flow rates from horizontal and vertical discharge pipes. It should be noted that the equations given will yield only approximate values of flow. Flow through pipe is affected by "friction" loss. The magnitude of such loss depends on pipe diameter and velocity of flow. The discharge rates indicated in Figures 3.3.6.5 and 3.3.6.6 have been adjusted individually for "friction" loss, while the generalized equations given for unspecified pipe diameters do not include specific factors which allow for losses. However, for the vertical-flow equation (Figure 3.3.6.6) an average factor (C) which includes friction and expansion/contraction losses has been given.

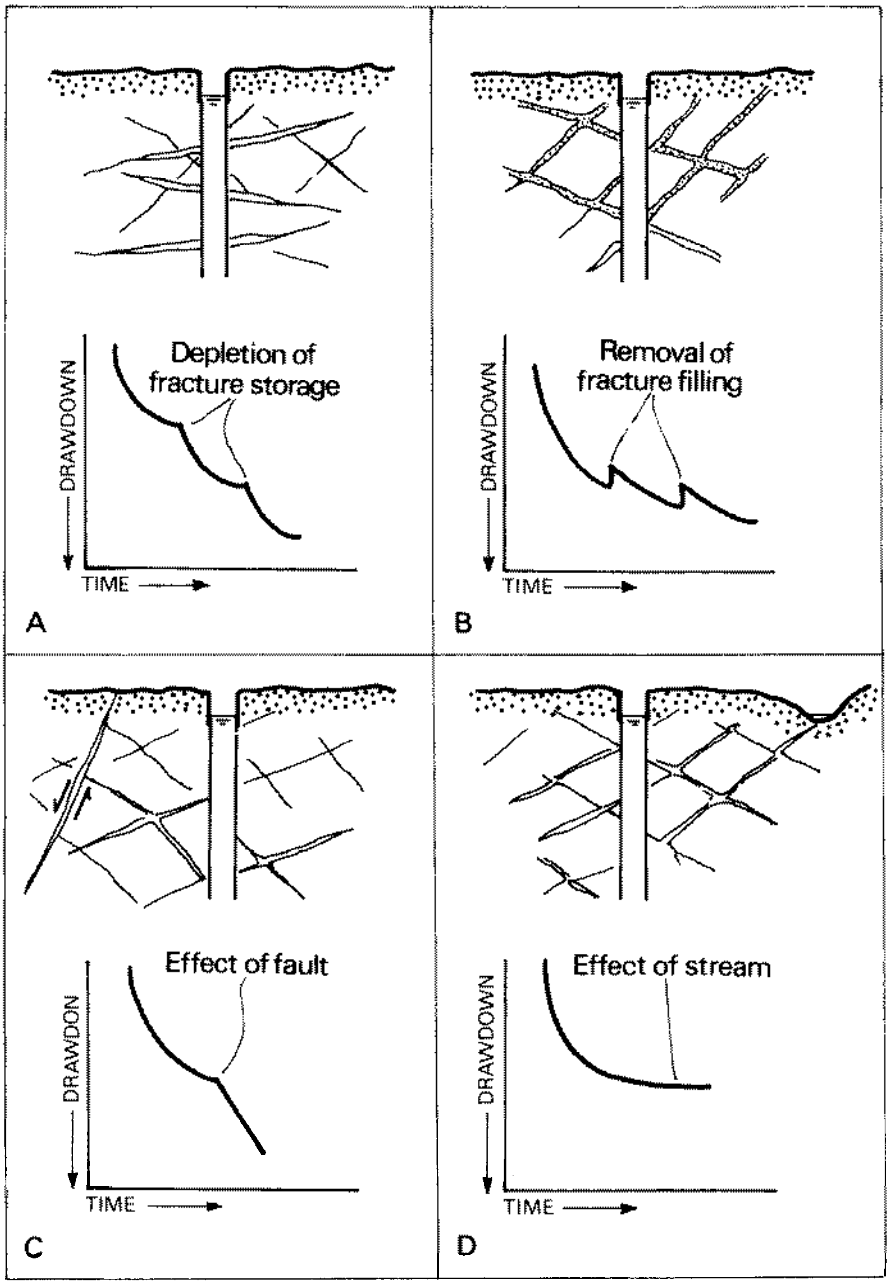
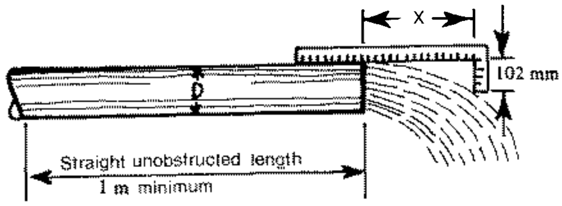


Figure 3.3.6.4 Hypothetical drawdown curves for wells in fractured crystalline rocks in response to fracture characteristics and local structure.

A) Production from large but limited fractures
B) Production from large fractures partially filled with fine-grained material
C) Production from large fractures with tight fault zone as an impermeable boundary
D) Production from large fractures with a nearby source of recharge from a surface source.
(From Davis and DeWiest, 1966) (Reprinted by permission of John Wiley & Sons).



Discharge Rate (litres per second)

Horizontal distance x (mm)	Nominal pipe diameter (inches)				
	1	1 1/4	1 1/2	2	2 1/2
100	0.4	0.7	0.9	1.5	2.1
125	0.5	0.8	1.1	1.8	2.6
150	0.6	1.0	1.3	2.2	3.1
175	0.7	1.1	1.6	2.6	3.7
200	0.8	1.3	1.8	2.9	4.2
225	0.9	1.5	2.0	3.3	4.7
250	1.0	1.6	2.2	3.7	5.2
275	1.0	1.8	2.4	4.0	5.8
300	1.1	2.0	2.7	4.4	6.3
325	1.2	2.1	2.9	4.8	6.8
350	1.3	2.3	3.1	5.1	7.3
375	1.4	2.4	3.3	5.5	7.8
400	1.5	2.6	3.6	5.9	8.4

Figure 3.3.6.5 Estimates of well discharges from horizontal pipe flowing full.

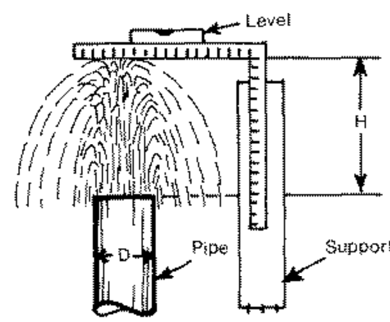
General horizontal flow equation for a pipe diameter not given in the table:

$$Q\ (l/s) = (3.43).(10^{-3})\ .\ D^2 x$$

where:

D = Inside pipe diameter (in.)

x = Length of horizontal flow (mm) for drop of 102 mm (4 in.)



Standard steel pipe (inches)

NOM. D	I.D.
1	1.105
1 1/4	1.38
1 1/2	1.61
2	2.07
2 1/2	2.47
3	3.07
4	4.03

General vertical flow equation for a pipe diameter not given in the table:

$$Q\ (l/s) = (6.45).(10^2)\ .\ CD^2 . H^{1/2}$$

Where:

C = Constant (use 0.92)

D = Internal diameter of pipe (inches)

H = Height of flow (mm)

Discharge rate (litres per second)

Height, H (mm)	Nominal pipe diameter (inches)		
	2	3	4
50	2.0	4.3	7.4
75	2.4	5.3	9.1
100	2.8	6.1	10.5
150	3.4	7.4	12.8
200	3.9	8.6	14.8
250	4.4	9.6	16.6
300	4.8	10.5	18.1
350	5.2	11.4	19.6
400	5.5	12.2	21.0
450	5.9	12.9	22.2
500	6.2	13.6	23.4
550	6.5	14.3	24.6
600	6.8	14.9	25.7

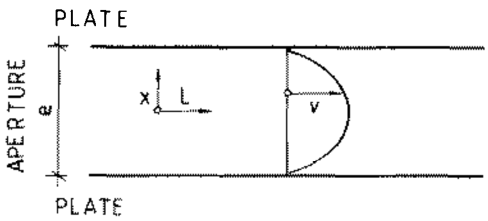
Figure 3.3.6.6 Estimates of well discharges from a full vertical pipe.

3.3.6.3 *Pump tests in theory and practice*

The fractured crystalline bedrock is a medium for ground-water flow that is very different from the porous, homogenous media for which all well test formulae were developed (Bianchi and Snow, 1969). This section is an introduction to the hydraulic properties of fractured bedrock and to the performance and evaluation of pump tests.

Laminar flow in one fracture

Viscous flow between two parallel plates are normally described as a Hele-Shaw flow (see Figure 3.3.6.7).



$$v = -\frac{\partial p}{\partial L} \cdot \frac{1}{8\mu} (e^2 - 4x^2) \text{ or}$$

$$v = -\frac{\partial h}{\partial L} \cdot \frac{\rho g}{\mu} \cdot \frac{(e^2 - 4x^2)}{8}$$

Where p is pressure, h piezometric head, ρ fluid density, g gravity acceleration and μ viscosity. v, e, x, L are defined by the figure.

Figure 3.3.6.7 Model of flow between two parallel plates.

In reality, fracture surfaces are neither smooth nor parallel, but as a first approximation and in order to evaluate some of the more important properties, the above model will serve as a guide to the discussions herein. References to other models can be found in Section 6.

If the velocity equation is integrated, the following is obtained:

$$e \cdot q = \int_{-e/2}^{e/2} v \cdot dx = -\frac{\partial h}{\partial L} \cdot \frac{\rho g}{\mu} \cdot \frac{e^3}{12} \qquad (3.3.1)$$

The analogy with Darcy's law is obvious since it states:

$$q = -\frac{\partial h}{\partial L} \cdot K \qquad (3.3.2)$$

The hydraulic conductivity of the fracture and fracture permeability can therefore be defined as:

$$K_f = \frac{\rho g}{\mu} \cdot \frac{e^2}{12} \qquad (3.3.3) \qquad\qquad k_f = \frac{e^2}{12} \qquad (3.3.4)$$

Furthermore, the fracture transmissivity can be defined as:

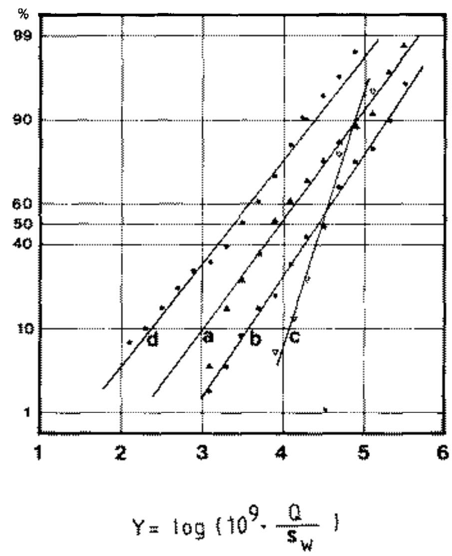
$$T_f = \frac{\rho g}{\mu} \cdot \frac{e^3}{12} \qquad (3.3.5)$$

The hydraulic system

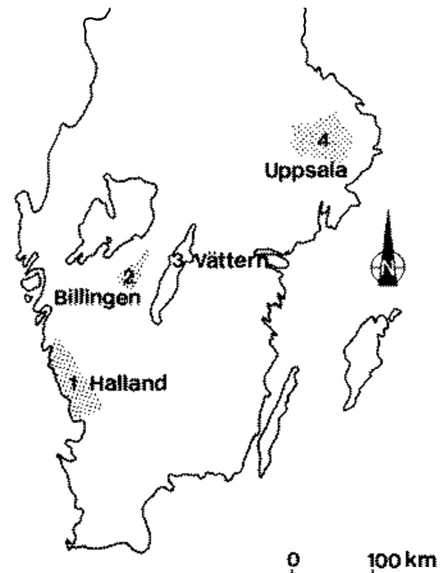
When modeling the hydraulic system of a fractured bedrock, one of two approaches can be made. The first approach (discrete approach) treats a group of fractures as a system of conduits. The second approach (continuum approach) attempts to establish some volume where the properties of the different fractures and the influence of their directions average out, making it possible to treat the flow analytically.

The first approach requires the use of computers and extensive knowledge of the fractures and their properties, e.g. see Wilson (1970); Wilson and Witherspoon (1970, 1974); Witherspoon et al. (1979 a,b.); Gringarten and Witherspoon (1972); Mathews and Russel (1967). Other aspects of the discrete approach are treated by Kazemi (1969), Freeman and Natanson (1959), Zheltov (1961), Parsons (1966), Gringarten and Ramey (1974), Gringarten (1974, 1975) and Boulton and Streltsova (1977 a,b; 1978 a,b), Streltsova Adams (1978), Coale and Witherspoon (1979), and Gringarten (1982). The continuum approach may be applied with analytical mathematical methods. Therefore the conditions will be investigated which make such an approach applicable.

Various investigations (e.g. Carlsson and Carlsted, 1976) have shown that the specific capacities of wells in different types of crystalline bedrock are lognormally distributed (see Figure 3.3.6.8.). On the basis that specific capacity is closely related to aquifer transmissivity, this suggests a lognormal distribution of T and T_f.



Relative cumulative frequences of the Y-values from crystalline bedrock (a = gneisses of Halland, b = gneisses of the Billingen area, c = granites west of lake Vättern, d = granites of the Uppsala area), Q = pumping capacity, s_w = drawdown.



Map of Southern Sweden showing the areas from which data have been used for calculation of permeability and transmissivity in the bedrock.

Figure 3.3.6.8 Specific capacities of wells in different areas of southern Sweden (Carlsson & Carlstedt, 1976).

When applying the continuum approach to a fractured bedrock the size of the representative volume element can be estimated in the following manner: For a well penetrating m fractures, the probable transmissivity will be:

$$T = m \cdot \bar{T}_f = m \cdot e^{\mu_x + \sigma_x^2/2} \qquad (3.3.6)$$

Where μ_x and σ_x are the mean and the standard deviations of the logarithms of the fracture transmissivities, $x = \ln T_f$. It can also be shown that for large values of $t = (x - \mu_x)/\sigma_x$, the following relationship applies:

$$F(t) = 1 - \frac{1}{t} \cdot \frac{1}{\sqrt{2\pi}} \cdot e^{-t^2/2} \approx 1 - \frac{1}{m} \qquad (3.3.7)$$

If Q(t) denotes the ratio between the probable transmissivity of the largest fracture and the sum of transmissivities of all fractures in the system, equations (3.3.6) and (3.3.7) give:

$$\varphi(t) = \frac{T_{f,max}}{m \cdot \bar{T}_f} = \frac{e^{\mu_x + t\sigma_x}}{m \cdot e^{\mu_x + \sigma_x^2/2}} = \frac{1}{t\sqrt{2\pi}} \cdot e^{-(t-\sigma_x)^2/2} \qquad (3.3.8)$$

A graph of Q(t) is given in Figure 3.3.6.9.

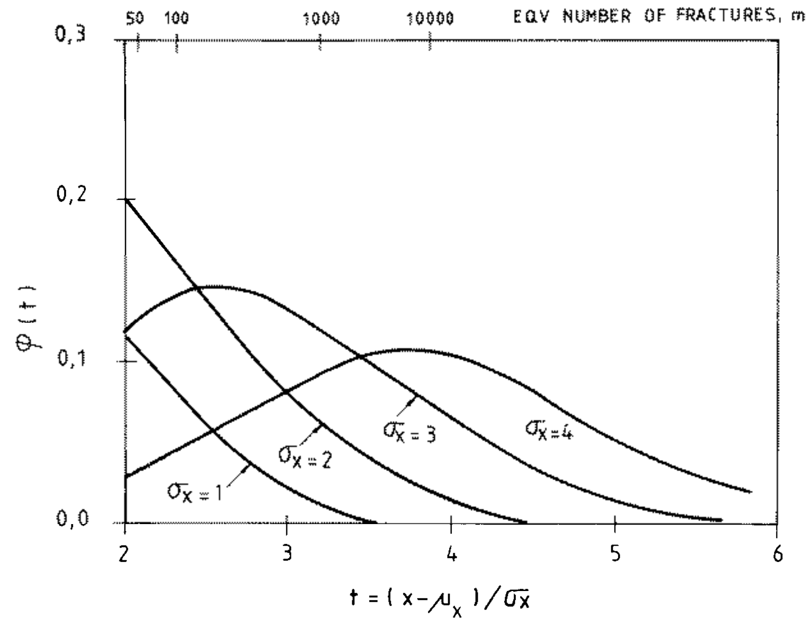


Figure 3.3.6.9 Ratio between maximum and total fracture transmissivity.

One definition of the representative volume element is that the value of Q(t) is close to zero. This means that no fracture alone can govern the flow through the element. This also suggests that according to graph of Q(t) the size is determined by the number of fractures and the value of σ_x. Investigations in the crystalline rocks of Sweden indicate a range of σ_x from 1 to 4 (Carlsson, Gustafsson, unpublished material), or that the representative volume should contain at least 1000 fractures and probably several magnitudes more. This suggests that the continuum approach normally is not applicable to the rock system as a whole but to local structures, single fractures or fracture groups. Therefore, a pump test in a fractured bedrock only evaluates the hydraulic system of the fractures intersecting the well.

Basic equations

As suggested above, a pump test of a well in such rocks involves only the major fractures, which usually occur in the form of a planar structure with an arbitrary direction. The flow in the plane will be radial to the well if the major contribution is in and parallel to the plane. Furthermore, if it is assumed that the sum of the fracture transmissivities equals a total transmissivity, T, and that the volume of water released from storage in the fractures is proportional to the decline in head and unit area of the conductor, then the following relationship would apply: V = (s)(S)(A).

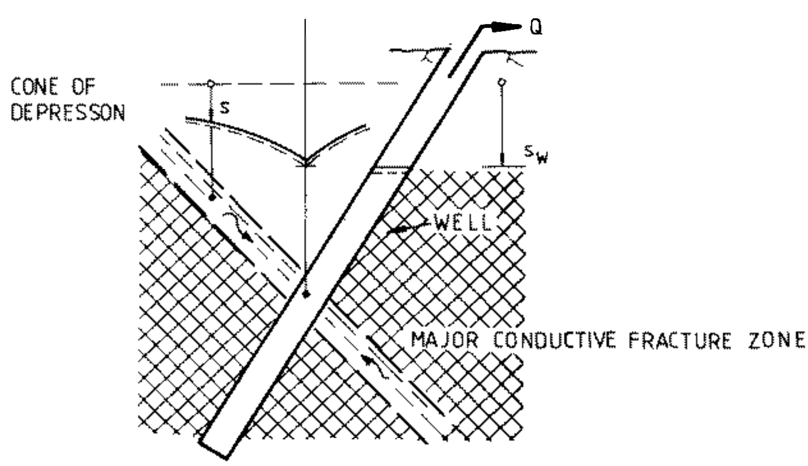


Figure 3.3.6.10 Pump test in a fracture zone.

For a well of small diameter, this condition leads to the differential equation:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial r} \tag{3.3.9}$$

Finally, the well-known Theis solution is applied for constant pumping capacity (Theis, 1935) or:

$$h_0 - h = s = \frac{Q}{2\pi T} \cdot W(u) \tag{3.3.9a}$$

$$u = \frac{r^2 S}{4Tt} \tag{3.3.9b}$$

$$W(u) = \int_u^{\infty} \frac{e^{-x}}{x}\,dx = -0,5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \ldots \tag{3.3.9c}$$

Dimensionless parameters

In the oil industry, where the use of interference pump tests is an exception, many solutions for one well tests have been published (Earlougher, 1977). In the simplest cases, such as the above Theis solution, they are, of course, identical to the ones normally used in hydrogeology. However, there also exist solutions for complicated geometries in proximity to the well which can be used for evaluating pump test data in a fractured bedrock (see Section 3.3.6.4: Field Applications).

In the papers published in the oil industry, the solutions normally are given in dimensionless form. The dimensionless parameter is defined in such a manner that it is directly proportional to the real one and that the real parameter can be expressed as the product of a transformation constant and the dimensionless parameter:

$$\eta \cdot c_\eta = y \tag{3.3.10}$$

In the following, the dimensionless parameter is denoted with the normal parameter corresponding to the Greek letter and the transformation constant with an indexed C. In the equations (3.3.9 a-c), there are several different parameters for which the following dimensionless forms are defined:

$$\sigma \cdot \frac{Q}{2\pi T} = s \tag{3.3.11}$$

$$\Theta \cdot \frac{r_\omega^2 S}{T} = s \tag{3.3.12}$$

$$\rho \cdot r_\omega = r \tag{3.3.13}$$

For the pumping well, $r = r_w$, the Theis well equation can be rewritten:

$$s_w = \frac{Q}{2\pi T} \cdot \sigma_w \tag{3.3.14a}$$

$$\sigma_w = \frac{1}{2} W(1/4\Theta) \approx \frac{1}{2}(0{,}8091 + \ln \Theta) \tag{3.3.14b}$$

$$\Theta = \frac{Tt}{r_\omega^2 S} \tag{3.3.14c}$$

Evaluation of the hydraulic parameters

To determine the hydraulic properties of the fracture system, two approaches can be employed. If the equations (3.3.11) and (3.3.12) are transformed logarithmically, the following forms are obtained:

$$\log s = \log C_\sigma + \log \sigma \qquad (3.3.15a)$$

$$\log t = \log C_\theta + \log \Theta \qquad (3.3.15b)$$

It is thus possible to graphically determine the relationship between the real and dimensionless parameters in a logarithmic diagram (see Figure 3.3.6.11).

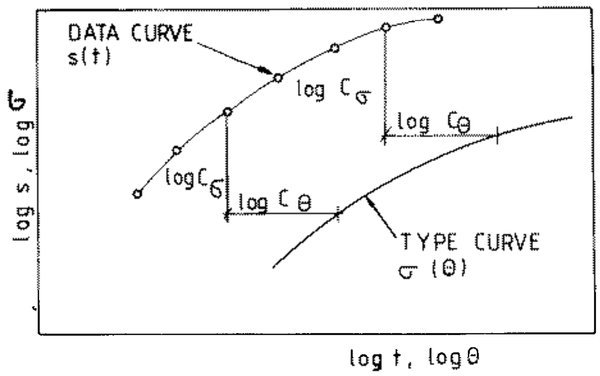
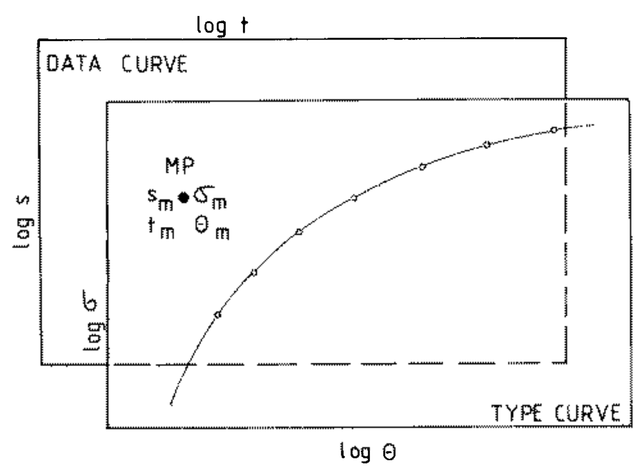


Figure 3.3.6.11 The relationship between the type curve and the data curve.

Thus, the type curve, $\sigma(\theta)$, has the same form as the data curve, s(t) and that they are connected by linear transformations by the distance log C_σ and log C_θ. If these are known, T and S can be determined. In practice, the type curve and the data curve are plotted on separate papers and fitted over one another (see figure 3.3.6.12). For any common point (i.e., matchpoint) in the two coordinate systems, the relationships given in the graphs are valid.



$$T = \frac{Q}{2\pi} \cdot \frac{\sigma_m}{s_m}$$

$$S = \frac{T}{r_w^2} \cdot \frac{t_m}{\Theta_m}$$

Figure 3.3.6.12 Curve fitting.

The other approach to evaluating the hydraulic parameters employs the logarithmic approximation of the dimensionless drawdown equation (3.3.14b). When plotted on a semi-logarithmic diagram, drawdown data form a straight line, provided that the pump test is of sufficient duration (see Figure 3.3.6.13).

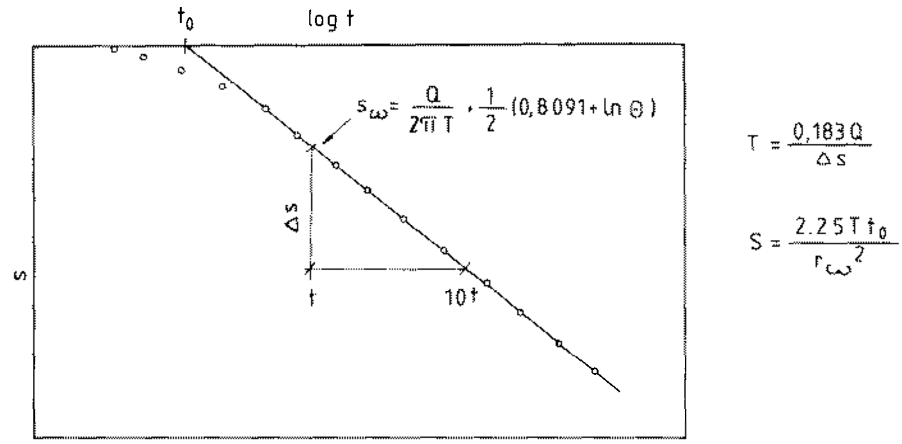


Figure 3.3.6.13 Drawdown data plotted in a semi-logarithmic diagram.

If the increase of the drawdown experienced during the period t to 10t is calculated, the following is obtained:

$$s_{10t} - s_t = \Delta s = \frac{Q}{2\pi T} \cdot \frac{1}{2}(0.8091 + \ln 10\Theta - 0.8091 - \ln \Theta) \tag{3.3.16a}$$

$$\text{Or}: T = \frac{0.183\,Q}{\Delta s} \tag{3.3.16b}$$

Therefore, at zero drawdown the following approximations are derived:

$$0.8091 + \ln \Theta_0 = 0 \;\; ; \;\; \Theta_0 = \frac{T t_0}{r_\omega^2 S} = e^{-0.8091} \tag{3.3.17a}$$

$$\text{Or}: \;\; S = \frac{2.25\,T\,t_0}{r_\omega^2} \tag{3.3.17b}$$

Skin Effects

The Theis well function is based on small diameter well data and linesource solution, that encompasses to all water-bearing zones in the formation. In reality, however, many of the zones may be totally or partially plugged or, in some cases in a fractured bedrock, the fractures that supply water to the well may have a considerably larger hydraulic conductivity than the gross transmissivity of the conductive structure. Both these two irregularities may be modified by employing a skin factor (see Figure 3.3.6.14).

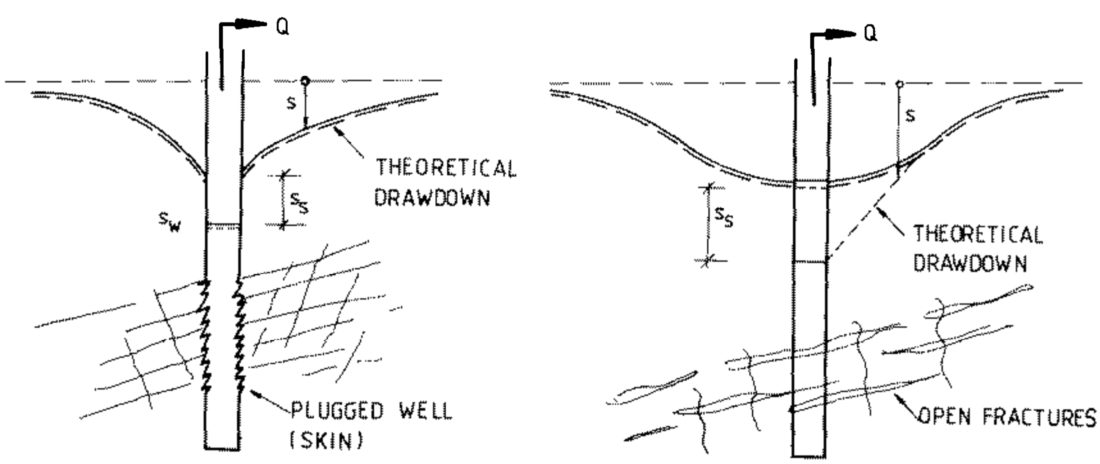


Figure 3.3.6.14 Positive and negative skin.

If the plugged zone or the extension of the open fractures are small compared to the size of the conductor, and if no storage is involved and the drawdown correction, s_s, is constant in time, and if the flow is laminar relative to the pumping rate, the skin effect factor is then defined as follows:

$$\zeta \cdot \frac{Q}{2\pi T} = s_s \tag{3.3.18}$$

The drawdown in the well may therefore be calculated as follows:

$$s_w = \frac{Q}{2\pi T}(\sigma + \zeta) \tag{3.3.19}$$

The effective well radius, i.e. the radius of a nonplugged well with the same drawdown as the real one, may be defined as:

$$r_{wf} = r_w \cdot e^{-\zeta} \tag{3.3.20}$$

This relationship holds both for positive and negative skin factors. Ramey (1982) presents a review of the well-loss function and related skin effects.

Well bore storage

Some water is stored in the well, and when pumping starts most of the water is taken from the well and not from the aquifer (see Figure 3.3.6.15).

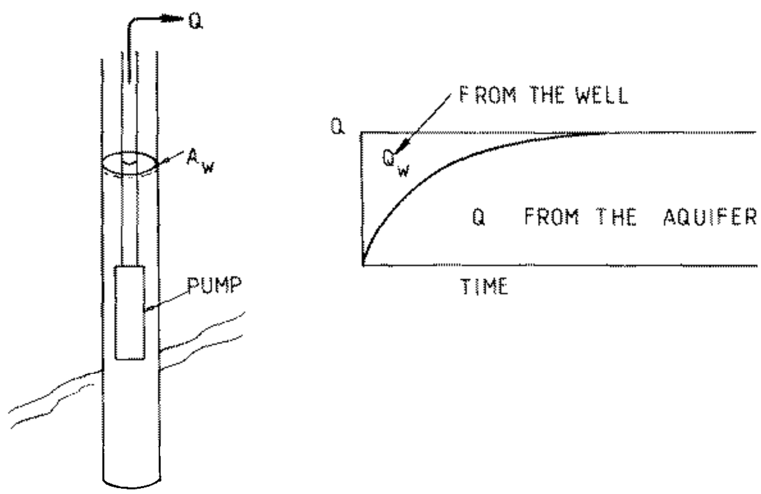


Figure 3.3.6.15 Well bore storage.

The water stored in the well equals the area minus tubing, etc. A_w, multiplied by the drawdown. The dimensionless well bore storage coefficient is defined by:

$$\gamma \cdot 2\pi S r_w^2 = A_w \tag{3.3.21}$$

For very short times, the drawdown is:

$$s_w = \frac{Q \cdot t}{A_w} = \frac{Q \cdot t}{\gamma \cdot 2\pi S r_w^2} = \frac{Q}{2\pi T} \cdot \frac{Tt}{r_w^2 S} \cdot \frac{1}{\gamma} \tag{3.3.22}$$

$$\text{OR}: \sigma = \theta/\gamma \tag{3.3.23}$$

This suggests that drawdown data for very short times appear as a straight line with the slope 1:1 in a logarithmic diagram. For long times, when the effect of well bore storage is negligible, the data plot approaches the Theis curve.

Dimensionless drawdown with well bore storage and skin effect factors

A hydraulic system that incorporates well bore storage and skin effect factors is a fairly complicated drawdown function for transient conditions. However, this type of system has been thoroughly treated by Agarwal et al. (1970). They have shown that the dimensionless drawdown can be represented as a function of θ, ζ and γ.

$$\sigma = \sigma(\theta, \zeta, \gamma) \tag{3.3.24}$$

A graph of this set of functions, in the form of logarithmic data curves, is presented in Figure 3.3.6.16.

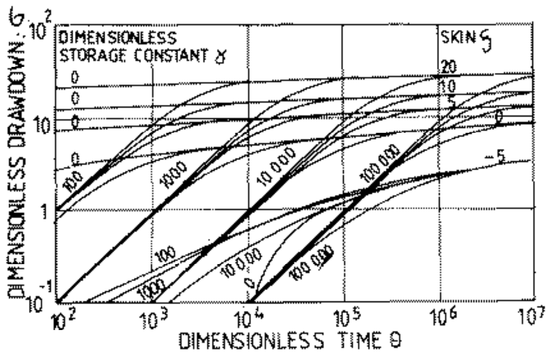


Figure 3.3.6.16 Dimensionless drawdown with skin effect and well bore storage (Agarwal et al., 1970.)

These type curves may be used for the evaluation by curve fitting in the same manner as previously discussed. It is also possible to use a semi-logarithmic plot of drawdown data (see Figure 3.3.6.17).

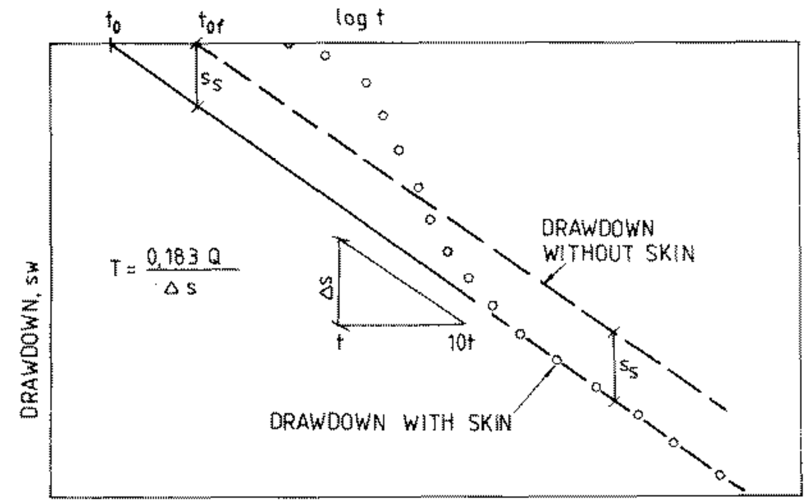


Figure 3.3.6.17 Semi-logarithmic plot of drawdown with skin effect.

As discussed previously, with the addition of the skin effect factor a constant additional drawdown, (s_s) is produced. This does not change the slope of the linear part of the curve and its application nevertheless results in the following familiar equation:

$$T = \frac{0,183Q}{\Delta s} \tag{3.3.25}$$

If the additional drawdown were known, the skin factor could be calculated. However, if a reasonable estimate of the storage coefficient is available, the skin factor can be established by calculating the intersection point between the drawdown line without skin effects and the zero drawdown axis, or as follows:

$$t_{0f} = \frac{S\, r_w^2}{2.25\, T} \tag{3.3.26}$$

From Figure 3.3.6.17 it follows that:

$$s_s = \Delta s \cdot \log t_{0f} / t_0 \tag{3.3.27}$$

When equations (3.3.25) and (3.3.27) are combined, the following result:

$$\zeta = \frac{s_s \cdot 2\pi T}{Q} = \Delta s \cdot \log t_{0f}/t_0 \cdot \frac{2\pi \cdot 0.183}{\Delta s} \tag{3.3.28a}$$

Evaluation procedure

In order to determine the hydraulic properties from a set of drawdown data, it is suitable to begin by plotting data in both logarithmic and semi-logarithmic diagrams (see Figure 3.3.6.18).

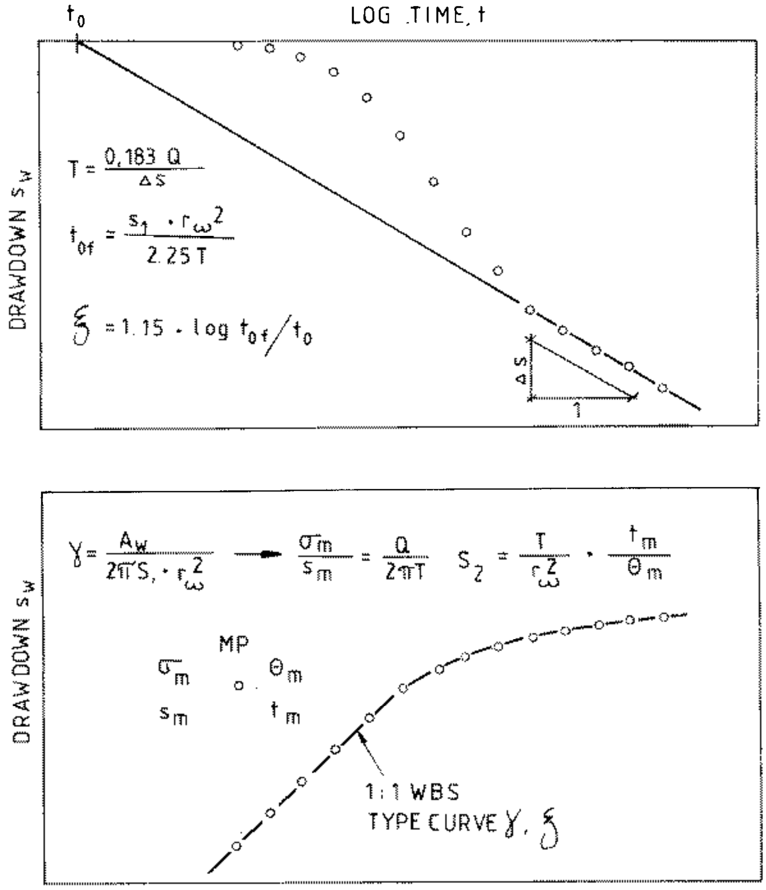


Figure 3.3.6.18 Evaluation of the hydraulic parameters.

The next step is to estimate the storage coefficient. For a fractured bedrock, this value must be based on experience in the specific geographic area. From the semilog plot, the transmissivity and skin factor are evaluated according to the procedures illustrated in Figure 3.3.6.18.

The next stage is to use the type curves given in Figure 3.3.6.16 and the logarithmic plot. It should be noted that the vertical position of the matchpoint is located by the previously obtained value of transmissivity.

The estimate of the storage coefficient also produces the value of γ and a preliminary value of ζ is obtained from the linlog plot. However, a new value of the storage coefficient remains to be determined. If this value differs significantly from the preliminary value, the above procedure is repeated. Thus an iterative procedure produces successively better approximations of the hydraulic parameters of the fracture system tapped by the well.

Field measurements

A successful evaluation of pump test data provides not just a functional knowledge of the use of type curves and equations but is equally important in assessing the quality of the data that are analyzed. This means that special care should be exercised in performing the pump test in the field. For example, constant and steady pumping are necessities because interruptions and variable production may make a proper evaluation impossible. Water-level measurements in the production well and surrounding observation wells, if available, can be made with an electric or acoustic device. (Campbell and Lehr, 1973a.)

Before the pumping starts, several measurements should be made in order to determine the standing water level. When pumping, the time schedule for water-level measurements should follow a geometric series, since the drawdown functions approach logarithmic functions. The following program is recommended:

At rest level: then: every 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 minutes, and then: every 12, 14, 16, 18, 20, 25, 30, 45, 60, 90, 120, 150, 180 minutes, and then: every 4, 6, 8, 10, 12, 16, 20, 24, 30, 36, 48 hours, and then the following days: morning, noon and evening.

During the test, records should be kept of the water level, time of the measurement, pumping rate and any other factors that may affect the test data. When the test is stopped, the same program of measurements should be implemented in order to obtain reliable recovery data. It should be noted that recovery data are influenced by the drawdown trend that normally is still in effect at the end of the test. The situation is illustrated in Figure 3.3.6.19.

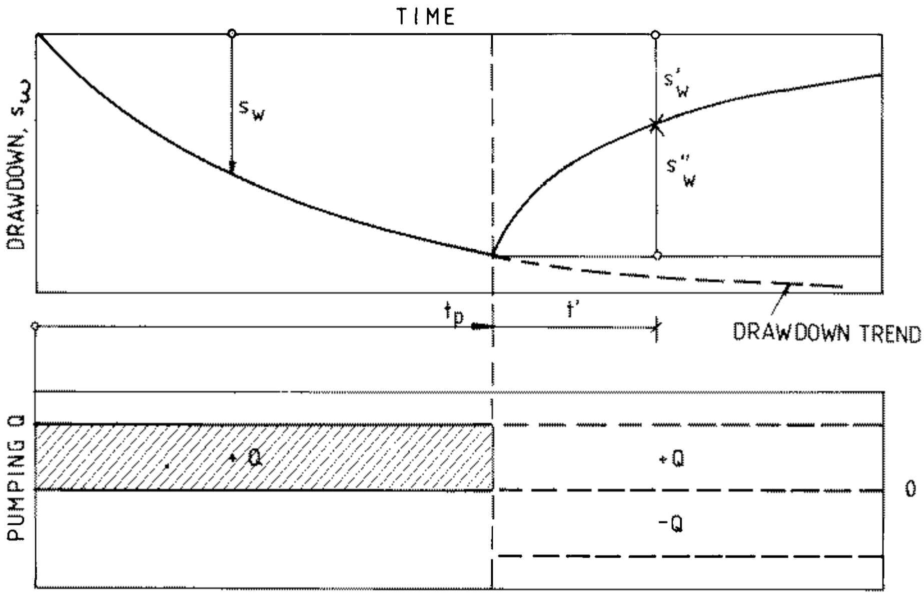


Figure 3.3.6.19 Drawdown and recovery.

However, if the shut down of the test is simulated with a continuation of pumping from the well and an initiation of injection of the same amount of water into the well, the result will be zero production and a recovery of the water level. This recovery will be:

$$s''_w = \frac{Q}{2\pi T}\left[\sigma(\theta') - (\sigma(\theta_p + \theta') - \sigma(\theta_p))\right] \tag{3.3.29}$$

$$\text{Where: } \theta' = \frac{T\,t'}{r_\omega^2\,S}\;;\; \theta_p + \theta' = \frac{T(t_p + t')}{r_\omega^2\,S}\;;\; \theta_p = \frac{T\,t_p}{r_\omega^2\,S} \tag{3.3.30}$$

If the logarithmic approximation of the dimensionless drawdown (3.3.14b) is used, the following is obtained:

$$s''_\omega = \frac{Q}{2\pi T}\left(0.8091 + \ln \frac{T}{r_\omega^2 S} \cdot \frac{t_p \cdot t'}{t_p + t'}\right) \tag{3.3.31}$$

Thus, the use of an adjusted recovery time makes it possible to use the same methods as for calculating drawdown, i.e.:

$$t'' = \frac{t_p \cdot t'}{t_p + t'} \tag{3.3.32}$$

Furthermore, for short recovery times $t'' \approx t'$. It is obvious that t'' never can grow larger than t_p. This is consistent because otherwise it would be possible to gain more data from a recovery period than from pumping. In some cases, the use of recovery data will be helpful in determining the reliability of production data.

Well yield

It is normally not possible to determine the ultimate yield of a well by a short pumping test. The reason for this is that the long-term capacity is affected by climatic variations, interference from other wells, etc. This suggests that the yield from a well or group of wells must be calculated on the basis of long-term observations.

The short-term pump test can, however, provide data for the calculation of the preliminary yield of the well, and together with data from other wells provide information for use in regional analysis.

In evaluating the qualitative features of the data curves of figure 3.3.6.20, these curves can be subdivided into three main parts which are influenced by:

1) The well
2) The fractures surrounding the well
3) The boundary conditions

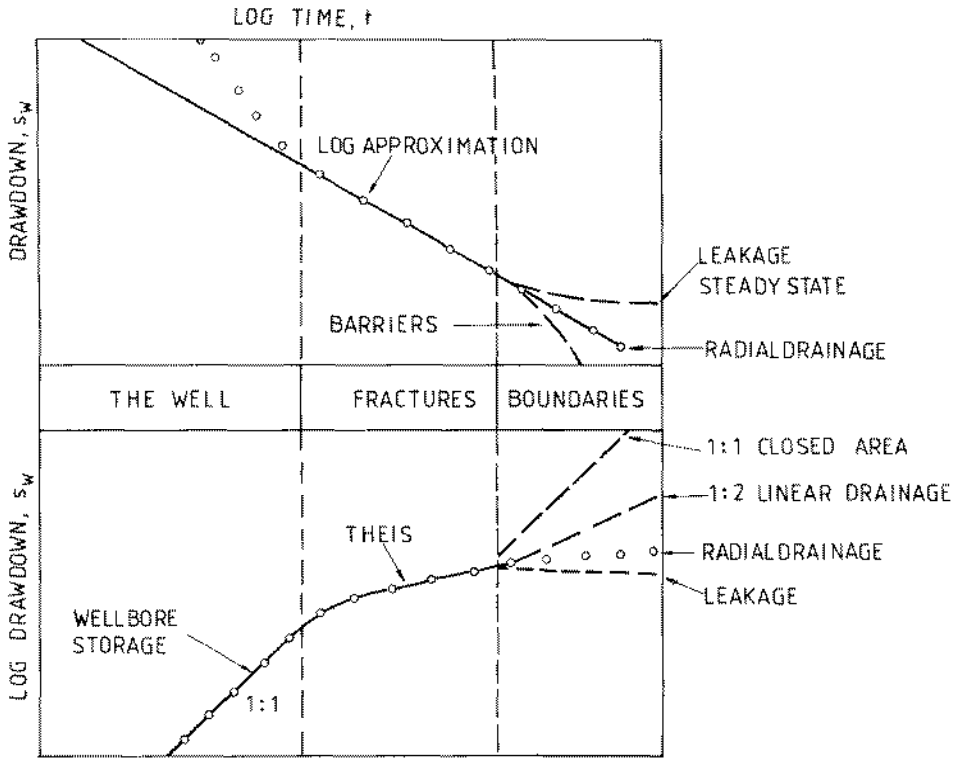


Figure 3.3.6.20 Data curves at different boundary conditions.

The straight line of the log approximation is easily recognized in the semilog plot. If the curve turns upward it indicates leakage to the aquifer and that the drawdown approaches a steady state.

For the radial drainage and the steady state cases, a preliminary yield may be derived by the Thiem equation:

$$Q = \frac{s_w \cdot 2\pi T}{(\ln R_0/r_w + \zeta)} \qquad (3.3.33)$$

In this equation, the transmissivity, T, and the skin factor, ζ, are determined by the pump test. The influence radius may be determined by the test results, but an estimated value based on experience may suffice, since the logfunction grows very slowly in the range $Ro/r_w > 1000$. The drawdown, s_w, applied in the equation should not exceed 50 percent of the possible drawdown in the well.

If there are hydraulic barriers in the system they show up clearly in the semilog plot. In the log-log plot, the type of barrier system is generally indicated by the slope of the later part of the data curve. A 1:2 slope usually indicates a linear drainage and a 1:1 slope a drainage area that is closed on all sides. In both these cases, continued pumping would be advisable until recharge or leakage effects produce a steady state condition, on the basis of which the yield could be calculated. If that is not possible a very conservative estimate of the yield could be made by utilizing equation (3.3.33).

3.3.6.4 *Field applications*

The theoretical aspects of aquifer testing have been discussed in previous sections. When conducting field tests in any specific project, however, local geologic and economic conditions play important roles in the design of the aquifer testing programme. Although local experience is a guide, interregional transfer of experiences and techniques is very constructive and, in many cases, reduces duplication of effort.

Various testing procedures for ground-water production from igneous and metamorphic aquifers in specific field applications are presented in the following summary reference list:

General:	Davis and Turk, 1964
	Webster et al., 1970
	Kiraly, 1971
	Maini and Norrishad, 1973
	Palmquist and Duba, 1974
	Kelly and Anderson, 1980
Australia	Lawrence, 1973
Benin	Lelong, 1963
Brazil	Floyd and Peace, 1974
	Rebouças, 1975a, 1975b, 1976, 1978
Ghana	Bannerman, 1973
India	Krupanidhi et al., 1973
	Limayer and Limaye, 1973
	Romani, 1973
	Radhakrishna and Venkateswarlu, 1980
Korea	Callahan and Choi, 1973
Sardinia	Barrocu and Larsson, 1977
Soviet Union	Zdankus, 1973, 1975
Sweden	Larsson, 1954, 1968, 1977
	Carlsson and Carlstedt, 1976
	Carlsson and Olsson, 1977a
	Carlsson and Olsson, 1977b
	Carlsson and Olsson, 1977c
	Larsson et al., 1977
	Carlsson and Ejdeling, 1979
	Olsson, 1979
Uganda	Faillace, 1973
United States	James, 1967
	Landers and Turk, 1973
	LeGrand, 1954, 1967
	Lewis and Burgy, 1964
	Sever, 1964
	Summers, 1972
	Walby et al., 1979
Upper Volta	Bierschenk, 1968
	Bize, 1966
West Africa	Archambault, 1960
	Biscaldi, 1967; 1968a, b
	Biscaldi and Derek, 1967
	Bize, 1966
	Bourgeois, 1978
	Bourgeap, 1976
	Mathiez et Huet, 1968
	Plote, 1968

3.3.7 WELL EFFICIENCY

In practice the efficiency of a well is the ratio of yield per unit drawdown actually obtained to that theoretically possible. In other words well efficiency is usually considered high in wells drawing from porous media (sand, sandstone, etc.) where entrance velocities of ground water into the well through the screen, slot, or other openings in the casing or liner are less than 0.15 metres per second. Since all flow to wells penetrating fractured rocks will usually be derived from specific fractures, very high entrance velocities may be inherent and unavoidable in such wells, unless the wells are gravel-packed which will tend to reduce entrance velocities. If numerous fractures have been intersected by the well, gravel-packing may not be advisable because the economic gain in well efficiency may not be sufficient to offset the additional cost of gravel packing. Thus, economic evaluations should always be made before the well design has been finalized. Bierschenk (1963 and 1964) presents information on calculating well efficiency under porous media conditions.

To reduce gross well inefficiencies, attempts should be made to eliminate cascading of ground water into the well from fractures above the normal pumping level (Figure 3.3.7.1). When such cascading occurs, drawdown will increase and additional pump lift and wasted energy will result. The oxidation (rusting) potential will also be increased in that part of the metallic structure between the static water level and the normal pumping level.

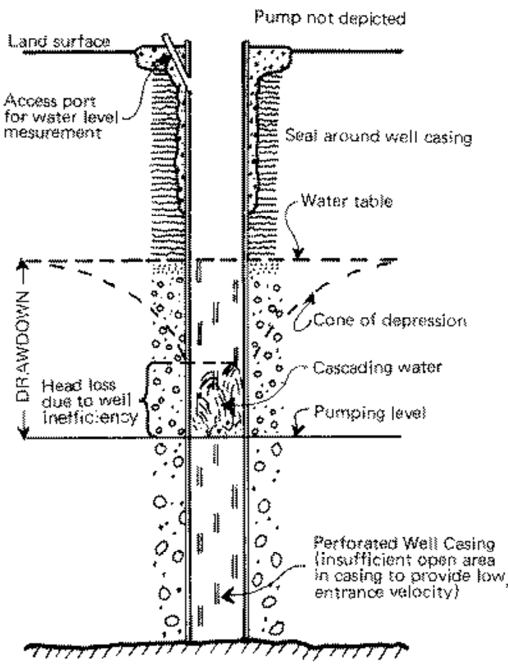


Figure 3.3.7.1 Typical improper well design allowing cascading above pumping level and head loss.

Uhl and Sharma (1978) conducted an evaluation of numerous pumping tests from the Satpura Hill Region of Central India. They observed that well losses were significant for the majority of the wells tested. This assumed particular importance for both low and high capacity wells with limited available drawdown. A direct relationship was observed between percent decrease in specific capacity and well loss, while there was no apparent relationship between transmissivity and the proportion of drawdown due to well losses. Furthermore, they suggested that if a significant portion of well loss occurs in the aquifer adjacent to the pumped well the magnitude of well loss may be related to the number, orientation and nature of the fractures encountered, and to non-Darcian or turbulent (cascading) flow into the well. To control the loss in efficiency attributed to turbulent flow into the well, they advised gravel packing the well. Any practical well design that promotes laminar flow into the well should be sought.

To increase well efficiency, a minimum drawdown can be obtained by:

1) Reducing the pumping rate.

2) Distributing the pumping load from one high-capacity well among several wells or a cluster of low-capacity wells.

3) Setting up a periodic maintenance programme for all wells in the system.

Other methods designed to improve well efficiency have been attempted. For example, blasting of consolidated sandstone has been found to increase specific capacity (Campbell and Lehr, 1973b). However, the method may be of limited value for increasing specific capacity in igneous and metamorphic rocks (Faillace, 1973).

Hydraulic fracturing techniques that show promise have been developed in Sweden and in the United States (Müllern and Eriksson, 1977; Stewart, 1974) although the same general principle applied elsewhere in the world has not produced favourable results (Stewart, 1974). A method for improving the yield of dug wells is presented by Uhl (1980).

3.3.8 HYDROLOGICAL INTERPRETATION OF HYDROCHEMICAL INFORMATION

The chemical composition of ground water reflects, to a considerable extent, the various processes which have taken place during the stay of water in the grounds. Insofar as these processes reflect hydrological variables (ground-water flow characteristics) analysis of hydrochemical data should reveal information on those variables. Conversely, such information can be used to predict changes in water quality due to withdrawal of ground water.

3.3.8.1 *Water chemistry in relation to ground-water flow*

In the discussion under Section 2.3 it was pointed out that oxygen conditions in the unsaturated zone could be critical for occurrence of iron and manganese in ground water. A high water table in a recharge area will, in general, mean that ground water becomes depleted of oxygen. During flow through fractures iron-containing minerals attacked by the carbon dioxide dissolved in the water will be set free. The solubility of carbon dioxide will, however, be limited by the possible precipitation of siderite.

The important reaction in this case is:

$$Fe^{2+}\ (aq) + HCO_3^-\ (aq) \leftrightarrow FeCO_3\ (c) + H^+\ (aq)$$

with the equilibrium equation:

$$pH = 0.37 + p\,Fe^{2+} + p\,HCO_3^-$$

From this equation the equilibrium concentrations of ferrous iron at various pH-values and bicarbonate concentrations can be computed (Table 3.3.8.1).

Table 3.3.8.1 Ferrous iron concentrations in mg/l in presence of siderite, at various pH values and bicarbonate concentrations.

HCO_3 (mg/l)	pH				
	6	6.5	7	7 5	8
50	97.1	30.7	9.7	3.1	1.0
100	48.5	15.3	4.8	1.5	0.5
150	32.4	10.2	3.2	1.0	0.3
200	24.2	7.7	2.4	0.8	0.2
250	19.4	6.1	1.9	0.6	0.2

In practice the ferrous-iron concentration will be higher since the figures are strictly computed on basis of activities. However, they may be of help in judging the importance of water-logged recharge areas. When the unsaturated zone is well-aerated, one should not expect any ferrous iron or manganese.

Even if a constant vertical bulk average concentration of a given substance in the ground water is assumed, one can still expect changes in this concentration along the flow direction. These changes depend on the balance of water and dissolved substances at the surface.

Assuming parallel flow and denoting by Q ground-water flow per unit width perpendicular to the flow, and by F that of dissolved salt (e.g. chloride), the continuity equations can be written:

$$\frac{dQ}{dx} = R \qquad \frac{dF}{dx} = D$$

where R is the recharge of water from the surface and D is the rate of deposition of the dissolved substance under consideration, the direction of flow being in the x-direction. If F = Q·C, where C is the concentration of the added substance, the second equation can be written:

$$\frac{d(QC)}{dx} = D$$

from which:

$$Q = \frac{1}{C} \int_0^L D dx$$

Hence the ground-water flow rate at a point will be the sum of the deposited salt (e.g. chloride) from the ground-water divide along the flow direction divided by the concentration of salt at that point.

These equations were actually used by Eriksson and Khunakasem (1968) for computing the recharge pattern in parts of Israel. Knowing D and R will make it possible to make forecasts of changes in concentration along the direction of flow. Similar equations can be applied to ground-water flow into dug wells and in densely populated areas where deposition of chloride on the surface is high.

3.3.8.2 *Effects of long-term pumping*

It has often been noted that long-term systematic changes in hydrochemistry of water take place in production wells. Salinity increase with time is often noted, sometimes so large as to make the water unfit for the intended use. In theory it should always be possible to trace the origin of the changes and, consequently, to forecast these properly. However, the information necessary to enable to make predictions is often missing. Since the flow pattern to a pumped well can be reconstructed in fair detail one needs obviously also information on the salinity distribution within the aquifer.

There are a few cases which are simple enough for prediction of future changes. The simplest is, perhaps, where the well is located in an area where diffuse ground-water discharge takes place. This may be evidenced, for example, by hard-pans of calcium carbonate. An enrichment of salts may have taken place in the past due to evaporation of ground water. On pumping, the whole flow pattern changes drastically and the more saline water may eventually be drawn to the well.

It may take some time before such a change is noticed. In such a case, the best evidence of shallow ground water, particularly in a densely populated agricultural area such as a valley, would be the presence of chloride and nitrate.

Another simple case is where sea-water residues or even sea water underlies the aquifer being pumped. Pumping essentially depletes the fresh water so that the saline boundary moves upward. Dynamically it can be shown that this boundary is most affected just below the well. Numerous examples of such cases exist in coastal aquifers. In such cases, however, the chemistry of the water will indicate its origin.

Changes in ferrous iron content also occur whenever recharge conditions in an area are favourable for formation of such local ground-water bodies. Again, a careful study of the area prior to ground-water withdrawal will aid in estimating the possibility of such changes.

3.3.8.3 *Pollution aspects*

It is well recognized that water in village wells is frequently more saline than water from wells outside the village. One can, for predictive purposes, knowing the hydrogeology, apply mass balance principles once salt deposition rates at the surface are known.

In agriculture, addition of nitrogen fertilizers in excess of that required by plants will in general cause a change in nitrate concentration of ground water with time. There will, however, be a time lag before the effects are noted. The time lag will depend to a large extent on the thickness of the unsaturated zone and water content at "field capacity." The latter may be of the order of up to a few hundred millimetres of water per metre depth.

It is known that in the vertical movement of this water surprisingly little longitudinal dispersion is noted. During recharge, the water front in the unsaturated zone is literally pressed down, the rate of vertical movement depending on the "field capacity" and on the recharge rate. Fairly extensive investigations using tracer techniques, intended for determination of natural recharge rates, give varying velocities, all depending on the local water balance. Movement of up to one metre per year has been noted but much lower velocities may occur under semi-arid conditions. The time lag before pollutants such as nitrate reach the ground water depends largely on the local recharge rate and depth to the water. Time lags of years can be foreseen in many areas.

There are numerous examples from alluvial areas with well-developed irrigation systems where salinization of soils has taken place in the absence of adequate drainage. For the solution of the problem, including the long term effects of irrigation, an assessment of the salt balance and proper knowledge of the hydrogeological conditions are required. The reader is referred to the literature concerning this problem, for example Bower and Maasland, 1963; Bower et al., 1968; Brown et al., 1974; Horsby 1973; King and Hanks, 1973; McLin and Gehlar, 1977; Oster and Rhoades, 1975; Pratt et al., 1977; Raats, 1974; Rhoades et al., 1973; Yaron et al., 1973.

In areas where significant mineralization is known (mining districts), or suspected (areas having experienced mineral exploration programmes) toxic elements may be present in the ground-water system and may constitute a health hazard (Cannon and Hopps, 1971; Edwards, 1975; Hadley and Snow, 1974; Singer, 1973; and Todd and McNulty, 1976).

After a well has been developed and completed, it should be chlorinated to remove any bacteria that may have been introduced during the drilling process (via the drilling fluids) or that may have been present on any equipment that has been used down the hole.

Table 3.3.8.2 Chlorine compound required to dose 31 m of water-filled well at 50 ppm (modified from U.S. E.P.A. 1975).

Well characteristics		Chlorine Compounds		
Casing Diameter (in)	Volume (31 m) (l)	70 % HTH Perchloron, etc. (Dry weight)* (g)	25 % Chloride of lime (Dry weight)* (g)	5.25 % Purex Chlorox, etc., (Liquid measure)(ml)
2	62	7	14	5
4	247	28	57	59
6	556	57	114	591
8	988	85	199	1 005
10	1 545	114	312	1 656
12	2 224	170	454	2 367
16	3 954	284	795	3 285
20	6 178	454	1 362	6 321
24	8 896	681	1 816	8 819

Note: Liquid sodium hypochlorite in a 12 per cent solution is often sold for water and waste-water treatment plant use, as a commercial bleach. Utilizing a solution of this nature would call for a liquid measure equal to one-half the volumes presented in the last column.

* Where a dry chemical is used, it should be mixed with water to form a chlorine solution prior to placing it in the well.

Table 3.3.8.2 indicates the typical application of chlorine compounds required to eliminate harmful bacteria. It should be noted that local health department personnel should supervise this operation to ensure proper chlorination of the water supply.

3.3.9 SOCIO-ECONOMIC FACTORS

3.3.9.1 *Introduction*

In the evaluation of ground-water development costs in hard rock areas, the following main sources of cost are to be considered: 1) geological, hydrological, and geophysical investigations; 2) well construction; 3) pumping installations and 4) operation and maintenance.

Whether for the development of ground water or mineral resources, programme costs are linked to social needs. Rural water and mineral development programmes have been considered by many countries in a variety of ways (Campbell and Lehr, 1973 b, 1974, 1975; Unesco, 1975, 1977; United Nations, 1970, 1975).

3.3.9.2 *Cost of exploration*

The costs of geological, hydrological and geophysical investigations vary widely, depending upon the geographical conditions, the accessibility of the resource in hard rock areas, the areal extent, the nature of the geological formations within the area of interest and the techniques and methods employed. DeWilliam (1967) presents a detailed discussion of cost parameters in hard rock drilling.

The cost of a preliminary survey involving only field reconnaissance and the interpretation of aerial photographs is in the range of a few tens of dollars per square kilometre, while more detailed investigations involving geophysical exploration and reconnaissance drilling could reach several hundreds of dollars per square kilometre.

The cost of a subcontracted geophysical team (one geophysicist, two operators and the rental of seismic or resistivity equipment) can range as high as $15 000 to $20 000 per month; the cost of siting only a few wells for a tropical village in Africa may be relatively high. However, a systematic, long-term programme resulting in the selection of a number of well sites would be economically advantageous on a per site basis. A review made recently of many of the United Nations's ground-water programmes illustrates the diversity of such programmes (United Nations, 1979).

The cost of a reconnaissance exploration drilling programme involving many wells would normally be in the range of \$40 - \$70 per metre for 4 1/2 -inch casing (mobilization and demobilization, tests and all other costs included), \$80 - \$110 per metre for 6-inch casing and \$110 - \$160 per metre for 8-inch casing.

The smaller the number of wells drilled, the higher the cost for each well. This is an example of the lack of economies involved in limited scale operations. For instance for drilling one hole with 6-inch casing in West Africa, the price in 1971 went up to \$250 per metre. In a desert region of East Africa, for some 25 fully-equipped boreholes located some distance apart, 150 metres deep, with 8-inch to 10-inch casing, including the testing of several aquifers, the cost ranged from \$135 - \$175 per metre.

In general, international drilling operations are costly and therefore capital intensive. This is due to high and increasing costs and increasing selling prices worldwide for drilling equipment, vehicles, supplies and competent expatriate drilling personnel. Basic costs, however, can be estimated. For example, in 1973, drilling costs within the United States could be calculated on the basis of \$1.40 per inch diameter per foot of well depth. For example a 60 metres deep well sold for \$1.650, not including pump. In 1975, with the effects of inflation considered, the same well would cost the buyer \$2.700, (that is, \$7.50 per inch diameter per metre depth or \$2.29 per inch per foot depth). Costs in 1980 were in excess of \$4.000. This was equivalent to \$11.11 per metre for a 6-inch well drilled to 60 metres (or \$3.39 per inch per foot depth).

To these costs must be added mobilization, tests and other related costs. Figure 3.3.9.1 illustrates typical costs for 4.5- and 6-inch wells drilled within the United States in 1969, 1975 and 1980; this shows the significant increase in cost due to inflation in drilling costs and cost of materials.

For international operations personnel costs assume major proportions and result in approximately 300 per cent add-on costs. In addition, the lack of permanent demand for drilling services must be taken into account. Thus, even if a large number of wells are drilled and completed, the cost per metre is approximately three times the cost within the contractor's home country.

Usually only very large international drilling programmes are economically feasible, i.e. with a unit cost of drilling below about \$70.00 per metre. On the international scene, drilling services are very much in demand. Therefore, drilling contractors structure their prices so that more profit can be made internationally than in the home country. If this were not the inducement, drilling companies would not consider the inherent risks of working in often difficult foreign environments and under hazardous conditions. However, home government subsidies can reduce costs for international operations.

However, it has been reported that even when the volume of work is significant, local drilling companies may have higher costs than companies selected from the international scene (United Nations, 1973 b). In a number of countries, government drilling units often have low productivity in terms of metres drilled (1/2 to 1/5 the total average of all drilling programmes).

The situation can be improved if the units are operated at optimum efficiency, that is 2-3 shifts per day; a bonus is given for drilling above a minimum; unsatisfactory personnel are discharged and a swift procedure for the acquisition of equipment and supplies is used. In some cases, the introduction of a United Nations Technical Assistance component or private consultant into a national drilling organization has contributed significantly to an increase of the drilling output and, therefore, to a reduction of unit costs (in a further attempt to realize economies of scale).

High well-construction costs represent a major apparent limiting factor to ground-water development in crystalline rock areas, since such construction is capital intensive. When capital is available for drilling, exploration programmes must be designed in such a manner that the relative hydrogeological potential can be systematically and cost effectively evaluated, thus reducing to a minimum the risk of unsuccessful drilling programmes in igneous and metamorphic rocks.

In addition, whenever possible, once the ground-water potential has been generally established via comprehensive hydrogeological evaluations, well-construction operations should be conducted on a large scale, multi-well basis, if the need exists. Small scale drilling programmes result in escalated unit prices. Furthermore, as discussed previously, well design should be based on the specific, local geological requirements.

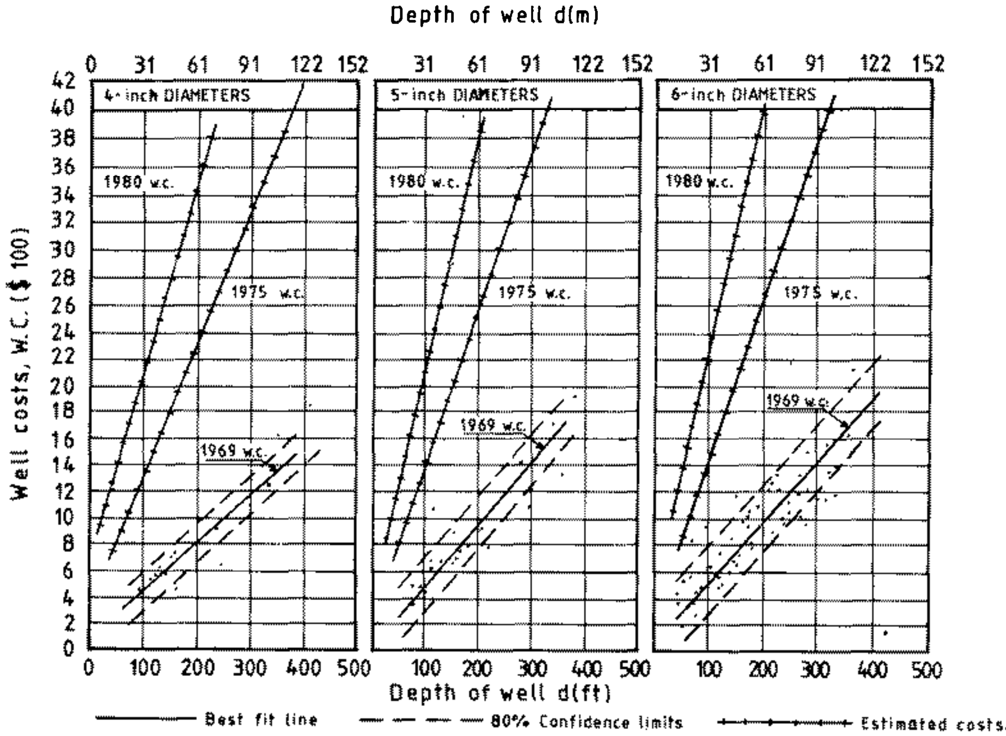


Figure 3.3.9.1. Cost of 4-, 5-, and 6-inch wells in consolidated rock (modified from Gibb, 1971). (Updated to 1980 status; well costs includes cost of drilling, casing and raising installation but does not include pumps, etc.)

3.3.9.3 *Equipment longevity*

The service life of equipment will depend on how much it is used, how well it is maintained and how it responds to the effects of stress imposed by such environmental factors as corrosive water and soils, temperature extremes and humidity. Under extremely corrosive conditions, for example, submersible pumps have been known to fail in six months, while the same model pump operated nearby in a more benign environment may last 10 or 15 years, or more. In addition, there will be obvious trade-offs between the cost of premium materials and construction practices, installation and maintenance on the one hand and equipment longevity on the other. With such uncertainties in mind, average service lifetimes of major components of water systems are summarized in Table 3.3.9.1.

A graph which shows the percentage of units of a particular type of component which is still working after a certain number of years is called a survivor curve (Figure 3.3.9.2).

Table 3.3.9.1 Average service lifetimes of major components of water systems (after Campbell and Lehr, 1974).

Well		
	Casing, metal	10-50 years
	Casing, plastic	25-75 "
	Screen, metal	4-50 "
	Screen, plastic	4-75 "
	Pump, submersible	1-15 "
	Pump, jet	1-15 "
	Pump, turbine	7-20 "
Storage tanks		
	Hydropneumatic	30-50 years
	Elevated/Standpipes, metal	30-50 "
	Elevated/Standpipes, concrete	30-50 "

Ground storage, metal	25-50 "
Ground storage, concrete	40-60 "
Reservoir liners	10-15 "
Transmission systems	
Pumps, auxiliary	7-15 years
Mains, plastic	40-75 "
Distribution systems	
Pumps, auxiliary	7-15 years
Mains, plastic	25-50 "
Water meters	7-10 "
Treatment systems	
Sand filters	30-40 years
Greensand filters	30-40 "
Zeolite softeners	15-30 "
Disinfection devices	
Gas chlorinators	7-10 years
Hypochlorinators, liquid	7-10 "
Hypochlorinators, dry chemical	7-15 "
Ozonators	5-10 "
General use equipment	
Laboratory instrumentation	3-10 years
Service vehicles	3-5 "
Dumper/Tank trucks	5-10 "
Automatic controls	5-20 "

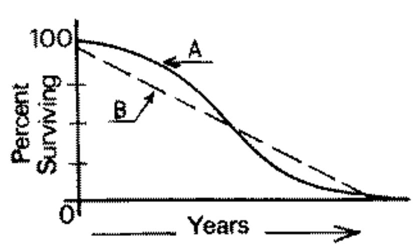


Figure 3.3.9.2 Examples of survivor curves (Campbell and Lehr, 1974).

Survivor curve A depicts a group of units of which very few fail after a number of years, after which most experience failure in the next few years. Curve B represents a situation wherein a constant number of units fail every year. The units of equipment represented by curves A and B have both about the same average service life (mean time before failure) but the occurrence of the failure represented by B is rarely observed. However, in many of the highy capacity well systems, an awareness of such failure characteristics is not taken into account in the operation programme. In effect many systems have, in the past, incorporated straight-line failure rates. Because of lack of early failure, operations and management budgets were not maintained. When failures began to occur rapidly over a short period of time, funds were not available and the system failed. Some components must be replaced on a regular basis under a preventive maintenance programme and adequate operations and management budgets must be maintained.

3.3.9.4 *Ground-water systems cost analysis*

The economics of well systems and their cost effectiveness depend almost exclusively on the success of the exploration programme and well depth. If the rate of success in locating desirable quantities of ground water in igneous and metamorphic rocks could be improved, the cost effectiveness of ground-water exploration and development programmes would be significantly raised above present levels. The present work is devoted to improving the success rate of ground-water exploration and development programmes in hard rock areas, which also includes production from the shallow weathered zone, often overlying igneous and metamorphic rocks.

Present approaches to the economics of exploration and development in crystalline rocks emphasize the role of well depth as the controlling economic factor. As Section 3.3.9.2 indicates, most of the economic evaluations are based on the assumption that the ground-water productivity of wells diminishes with depth. Drilling and material costs, and personnel costs are also directly related to the depth of a particular well. The drilling method employed dictates personnel costs, that is the time required to drill a well to a given depth (cable-tool versus air rotary percussion). The cost of casing for a given well is depth dependent, as is the cost of casing installation.

The type of casing used (plastic versus steel) will affect ease of transport, resistance to corrosion and/or incrustation and relative purchase costs (Smith, 1969; Am. Sooc. Test. Mtls., 1976). Pumping costs are also depth dependent. Therefore, the unit cost of ground-water extraction increases with depth, even assuming that water-bearing zones at depth could be located with a higher success rate than generally at present (Campbell, 1979 b).

If unit drilling costs could be minimized, as in a large programme, such costs would tend to offset the costs associated with increased depths. It should be clearly noted, however, that the cost of ground water to the consumer (private or government agency) will vary according to the inherent local geological conditions. Management aspirations of standardizing ground-water costs in a region of vastly differing geological conditions are presently and will remain futile.

Optimizing costs by considerations of appropriate well design, cost-effective drilling, pumping equipment selection and effective operation and maintenance programmes would be a worthwhile pursuit in maintaining sound ground-water exploration, development and operations and management programmes.

In a cost analysis of ground-water exploitation systems not only is minimizing well depth important to cost-effectiveness, but maximizing well efficiency must also be included as a significant economic factor that directly affects system costs. Well losses can be reduced by adjustments in either well design or operation, but losses due to aquifer factors can not usually be improved. However, some attempts have been made along these lines, (Stewart, 1974 and Mullern and Eriksson, 1977) (see Section 3.3.7). Well efficiency can be improved by pumping at rates less than maximum capacity, by pumping over longer periods (and implicitly using surface storage facilities) and by spreading the required water volume over more than one well in one area.

Before a decision is made all alternatives should be considered: surface water versus ground water; high-capacity well systems or multiple or "cluster" well systems versus dug wells. The selection of the appropriate water source or method of extraction is often complex, involving not only basic economic considerations but also social considerations. Based on economics, the cost of water for supplying the needs of a small village would be low if dug wells were constructed by local labour without concern for the construction time required, often up to 3 months or more. However, and not considering vulnerability of pollution inherent with dug wells, drilled wells, which can produce higher yields than dug wells, offer economic advantages. A summary of system alternatives is given in Figure 3.3.9.3.

SYSTEM ALTERNATIVES

A. TAP & TREAT RAW SURFACE WATER
e.g., small surface reservoir, river, etc.

B. PURCHASE OF TREATED SURFACE OR GROUND WATER
e.g., extension of existing water lines, etc.

C. CONSTRUCTION OF A SINGLE HIGH-CAPACITY WELL SYSTEM
e.g., one well, central treatment plant, extensive distribution system.

D. CONSTRUCTION OF MULTIPLE OR "CLUSTER" WELL SYSTEM
e.g., more than one well, additional treatment plants, less extensive distribution systems.

Figure 3.3.9.3 Water systems alternatives (from Campbell and Lehr, 1975).

For example, construction costs in India vary significantly throughout the country, depending upon the local geology, e.g., sand and gravel, consolidated sedimentary (sandstone and limestone), basalt (Deccan Traps) and, of course, igneous and metamorphic rocks. A recent estimate (Allison, pers. com.) of costs for drilled wells and dug wells in the crystalline areas of Southern India (see Figure 3.3.9.4) favours drilled wells over dug wells. In India, the construction of dug wells has become a capital-intensive activity and a highly mechanical endeavour. Wells are urgently needed throughout India and, in an attempt to reduce the construction time involved in dug wells, quarrying equipment and blasting have replaced labour-intensive methods of construction.

Such new methods can reduce construction time by 50 per cent and more. However, when comparing alternative approaches, dug wells no longer have an economic advantage over drilled wells, especially in areas where ground-water levels are deep (greater than 10 metres). However, in the absence of readily available drilling equipment, dug wells will remain an expedient although cost-ineffective alternative for water supply development in India. In Africa, labour-intensive methods are still employed because capital is not available and inexpensive labour is plentiful. As the general economy of Africa expands, dug wells will be replaced by drilled wells as required by basic economics.

The next decision that must be made concerns the type of drilled well to be constructed. This decision also involves strong socio-economic factors, e.g. population density, water usage, ground-water availability and distance to end users. Often, social patterns must be interrupted by relocating villages and agricultural activities to new areas where adequate water supplies can be developed. This not only meets social needs, but also increases the cost-effectiveness of local, state or federal governments' water supply development programmes.

Davis and Turk (1964) made an economic analysis that produced a graphic comparison between costs for purchased water and ground water from wells in crystalline rocks (Figure 3.3.9.5). Although the costs were derived more than 15 years ago, the approach is nonetheless still applicable today. The important assumptions used in generating the curves shown in the figure were:

1) Well construction cost = \$ 10.00/foot (\$ 32.8/metre)

2) Power cost = 2 U.S. cents/foot (6.6. cents/metre)

3) Interest rate = 6 %

4) Well life = 30 years

5) Average depth to water table = 30 feet (9.2 metres)

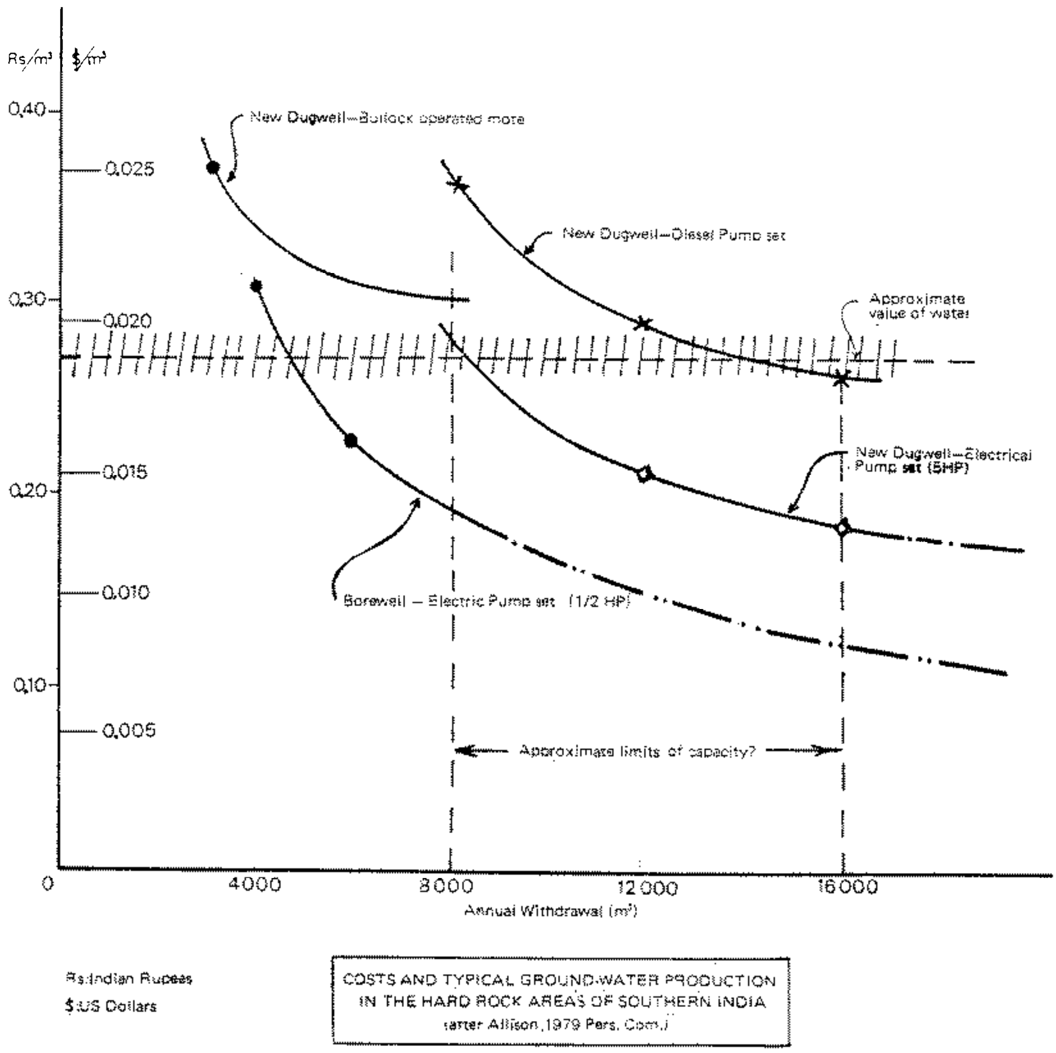


Figure 3.3.9.4 Costs and typical ground-water production in hard rock areas of southern India (after Allison,1979, pers. com.).

The first step in an economic analysis is to compare the cost of developing ground water with the cost of water from other sources. They suggest that although different curves should be constructed for the specific area of interest because of variations in economic and geologic factors, the general shape of all curves using the approach is probably quite similar.

In Figure 3.3.9.5 a fixed unit cost has been assumed for water from sources other than wells. The straight lines show the cost of various amounts of water per unit time for different unit charges. It can be observed that, under the assumed conditions, water derived from wells is more expensive than other water on a 1.3 cents per cubic metre basis, but it is less expensive than other water at 13.2 cents per cubic metre. Between these extremes, the choice should be based on a study of economic factors.

The approach of Davis and Turk (1964) can be used to assist in determining the optimum economic depth of wells. For example, a local government has a choice of either constructing a large number of wells (drilled or dug) or importing water from outside the area of interest at a fixed rate of 5.3 U.S. cents per cubic metre. From the mean curve in Figure 3.3.9.5 it is indicated that ground water will be cheaper only if the depths of wells are generally less than 100 metres.

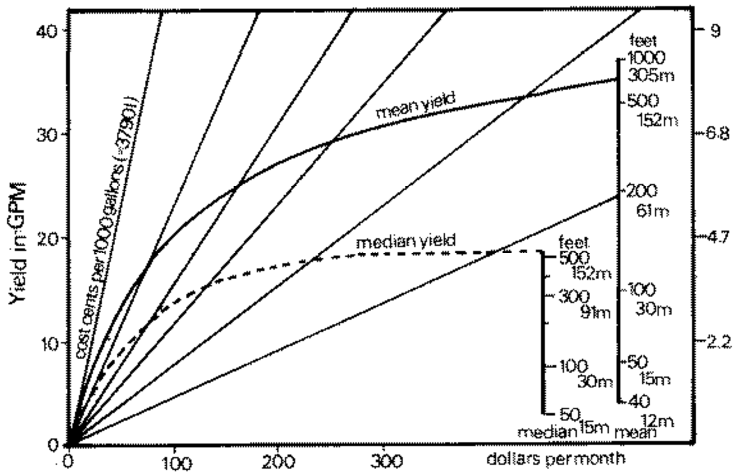


Figure 3.3.9.5 Comparison between costs of developing ground water in crystalline rocks and purchase of municipal water in the eastern United States (after Davis and Turk, 1964).

The maximum economic advantage is gained for each well at the withdrawal rate which gives the greatest horizontal separation between the mean yield curve and the 20 per cent line. The indicated withdrawal or pumping rate is approximately 4.3 m^3/h which can be obtained at a depth of about 45 m, the optimum depth under the given assumptions. This example is correct only if a large number of wells are to be constructed. In such case, a few wells which have high yields will compensate for the wells which are failures or which produce only a small volume.

On the other hand, if a single well is to be constructed, the most likely, or median yield is of most interest. As an example, if a very small industry requires 4.5 m^3/h, the median yield curve indicates that it is unlikely that this amount of water can be obtained from a single well at a reasonable cost. Using the previously discussed LeGrand method of estimating success rate, only one chance in four exists for obtaining the desired water from a single well (see Section 3.3.2.2). A very good chance exists, however, for the development of the required water volume from 5 wells having depths ranging from 12 to 24 metres. The projected cost of this water is less than 3.4 U.S. cents per cubic metre. Of the five wells constructed, one would probably be a failure, three might produce 0.5 m^3/h each and the other well might produce 3.4 m^3/h. The collective production would be 4.9 m^3/h; the average or mean yield yould be 0.97 m^3/h; but most likely, the median yield of a single well would be only 0.5 m^3/h.

The analytical approach discussed consists of a total system cost comparison of all elements within each alternative under review (Figure 3.3.9.6), which also includes the relative economic effects of well efficiency and operation and maintenance.

Often, the comparative review is reduced to a selection between a central well or high-capacity system and a low capacity "cluster" well system (Figure 3.3.9.7). The latter system is usually favoured under certain rural conditions on the basis of the factors previously discussed that involve well efficiency and cost effectiveness (Campbell and Lehr, 1973, 1975; Campbell and Goldstein, 1975).

Ideally, if the total systems cost ratio (C_R) is one or less, the central system would be the best design for the particular project area (see Figure 3.3.9.7).

TOTAL SYSTEM COST COMPARISONS

$S_R = P_W + T_{CR} + D_{CR} + O_{CR} + M_{CR}$ = RAW SURFACE WATER SYSTEM

$S_T = P_P + D_{CE} + M_{CE}$ = PURCHASED WATER SYSTEM

$S_C = W_{CC} + T_{CC} + D_{CC} + O_{CC} + M_{CC}$ = HIGH CAPACITY WELL SYSTEM

$S_W = \sum_{i=1}^{n} W_{CM_i} + T_{CM_i} + D_{CM_i} + O_{CM_i} + M_{CM_i}$ = MEDIUM–LOW CAPACITY WELL SYSTEM

where:

S_R, S_T, S_C, S_M = TOTAL COST OF SYSTEM OVER PROJECT LIFE

P_W = PUMPING PLANT CONSTRUCTION COST

P_P = PURCHASED WATER COST ESTIMATION OVER PROJECT LIFE

T_{CR}, T_{CC}, T_{CM} = TREATMENT PLANT CONSTRUCTION COST

$D_{CE}, D_{CR}, D_{CC}, D_{CM}$ = DISTRIBUTION SYSTEM CONSTRUCTION COST

W_{CC}, W_{CM} = WELL SYSTEM(S) CONSTRUCTION COST

O_{CR}, O_{CC}, O_{CM} = SYSTEM(S) OPERATION COST OVER PROJECT LIFE

$M_{CE}, M_{CR}, M_{CC}, M_{CM}$ = SYSTEM(S) MAINTENANCE COST OVER PROJECT LIFE

Figure 3.3.9.6 Total water systems comparisons (after Campbell and Lehr, 1975).

$$\frac{S_C}{S_M} = C_R$$

or:

$$\frac{W_{CC} + T_{CC} + D_{CC} + O_{CC} + M_{CC}}{\sum_{i=1}^{n} W_{CM_i} + T_{CM_i} + D_{CM_i} + O_{CM_i} + M_{CM_i}} = C_R$$

where: C_R = TOTAL SYSTEM COST RATIO

S_C = TOTAL SYSTEM COST OF HIGH CAPACITY OR CENTRAL WELL SYSTEM

S_M = TOTAL SYSTEM COST OF MEDIUM LOW CAPACITY OR MULTIPLE WELL SYSTEM

Figure 3.3.9.7 Comparative cost analysis of a central well system and a cluster well system (after Campbell and Lehr, 1975).

3.3.9.5 *Low-capacity systems*

Economic evaluations should cover every conceivable aspect of water development from optimizing exploration techniques through well construction, to pumping systems and irrigation practices. Although the latter is beyond the scope of the topics discussed here, pumping systems, in terms of energy and equipment costs, are one of the key focal points of all ground-water development programmes. Technological advances are being made that may reduce the present difficulties of the many small farmers and isolated villages that do not have sufficient electricity to operate pumps. (Allison, pers. com.)

Many areas in India, and elsewhere in the world, experience extended dry seasons during which the climate is sufficient for more than one crop. Financial resources, however, for energy and for appropriately sized pumping units are not available to the many small farmers. Small vertical turbine pumps, electrically driven by inexpensive solar cell arrays or semi-conductor devices, may be available in the near future. Such systems could allow the small farmer to develop more than one cash crop per year and small industries could develop in isolated areas.

It should be noted that low cost solar micro-pump systems now appear to be a manufacturing and industrial development task. The systems are no longer a research item of academic curiosity. Such technological development must be monitored closely for potential widespread application to ground-water programmes. In many areas where ground water occurs only in igneous and metamorphic rocks, the climate is either semi-arid or a desert of the low latitudes. Many such areas are characterized by many hours of sunlight during the year. Solar-generated electrical pump systems should prove to be useful in such areas, thereby reducing significantly the cost of pumping including both the costs associated with energy requirements and the costs of low-capacity pumping equipment (Campbell, 1979 b).

The initial high cost of construction of wells remains a formidable barrier to the development of many rural areas worldwide. A commitment to future technological development, combined with cooperative geopolitical efforts, will serve to meet the needs of mankind, hopefully in the foreseeable future.

3.3.9.6 *Test drilling philosophy*

The desirability of adequate test drilling is well founded in cost analysis (Cederström, 1973). It should be noted, however, that indiscriminate drilling should not be undertaken blindly in the hope of developing higher yield wells than those obtained in a minimum drilling programme. An expansion of the initial programme should be based on the following considerations:

1) The initial programme of a few wells indicates that average yields for the rock type have not been obtained (based on past experience).
2) Favourable areas are present and have not been tested (geological interpretation).

To reinforce the above concepts regarding the low cost of test drilling, assume that a low-capacity water supply is imperative in a particularly unfavourable igneous and metamorphic rock area. Figure 3.3.9.8 indicates that capital cost and cost per cubic metres where 10 test holes were drilled and one or more of these were completed as production wells yielding 16.9 m^3/h.

The cost of a 120 metre test hole is assumed to be U.S. $2,700, and the cost of a completed well is U.S. $ 11,914 less U.S. $ 2,700, or about U.S. $ 9,200. Where only one of the 10 test wells can be completed as a producing well with a yield of 16.9 m^3/h the cost of water at the well head is about 2.9 U.S. cents per cubic metre. When two wells out of 10 are successful, the cost per cubic metre is about 1.8 cents. It should be noted that only small reductions in cost per cubic metre are achieved as the success rate rises from four successful wells out of 10 test holes to the point where all holes are capable of being completed as producers. This relationship shows rather clearly that only moderate success in test drilling is necessary to obtain a ground-water supply at a reasonable cost; or conversely, the "value" of drilling "extra" test holes is small where a moderate success is finally achieved. Each unsuccessful test hole drilled adds 21 mills to the cost per cubic metre to the water eventually produced from one well pumping at a rate of 16.9 m^3/h about 60 per cent of the time. Cost would also be somewhat less if test holes were abandoned as non-productive at depths of 75-100 metres.

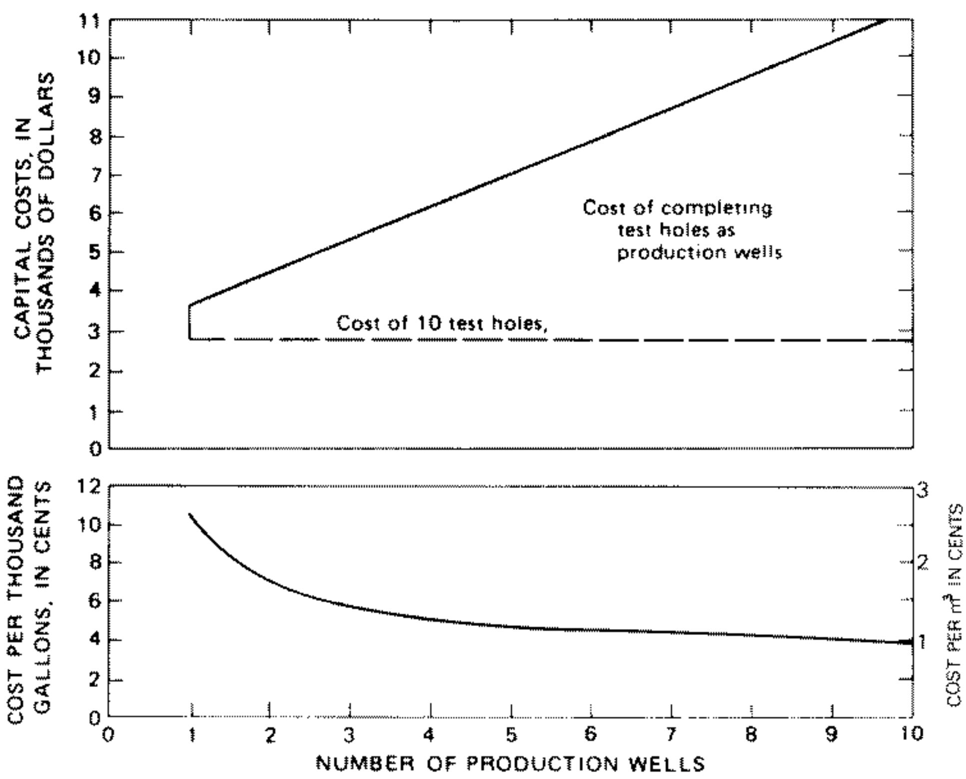


Figure 3.3.9.8 Cost of water where one or more of 10 test holes are completed as producing wells, each yielding 75 gpm (16.9 m^3/h) (from Cedestrom, 1973).

In the final analysis, if only 30 per cent of a region's future dry holes (insignificant production) could be converted to useful production wells as a result of incorporation of more effective methods of well-site selection than presently employed, the value of such systematic techniques would be apparent. It is toward this goal than the integrated approach, discussed at length in this text, is presently directed. The approach is not necessarily the ultimate solution, but it will serve as a firm step in the proper direction of decreasing present costs of ground-water exploration and development. Refinements will no doubt evolve from diligent geological work in the field and in the laboratories throughout t! world within countries wherein ground water is mostly available from igneous and metamorphic rocks.

3.3.9.7 *Well abandonment*

Unsealed abandoned wells and test holes are a hazard to health and safety, and to the preservation of ground-water resources, even in more remote areas. The sealing of such wells and holes presents a number of problems, the character of which depends upon the type of construction of the well, the geological formations encountered and the hydrologic conditions (U.S. Environmental Protection Agency, 1975). The objectives of sealing an abandoned well or test holes are:

1) Elimination of a physical hazard.
2) Prevention of ground-water contamination.
3) Conservation of yield and maintenance of hydrostatic head of the aquifers.
4) Prevention of the intermingling of desirable and undesirable water.

Three basic types of seals – distinguished by their function – are used. They apply to both dug wells and drilled wells. They are:

1) Permanent bridge-seal: the deepest cement seal to be placed in a borehole. This seal serves two purposes: it forms a permanent bridge below which considerable unfilled hole may remain and upon which fill material can be safely deposited; and it seals upper aquifers from any aquifer that may exist below the point of sealing (Figure 3.3.9.9).
2) Intermediate seal: this seal is placed between water-bearing formations which have, or are believed to have, different static heads. Its function is to prevent the inter-aquifer transfer of ground water (Figure 3.3.9.10).
3) Uppermost aquifer seal: this seal is placed immediately above the uppermost aquifer penetrated by the borehole. Its function is to seal out water from the surface and from shallow formations (Figure 3.3.9.11). However, each abandonment effort should be considered as an individual problem and methods and materials should be selected only after detailed study of both construction and geohydrology.

It should be emphasized that the abandonment procedures described above would be costly to implement in certain remote areas. However, such abandoned wells (dug wells especially) are serious hazards to children. In addition, such abandoned wells are often used as waste disposal sites and should therefore be securely covered. In the event of polluted wells, sealing or filling of such wells would be particularly advisable.

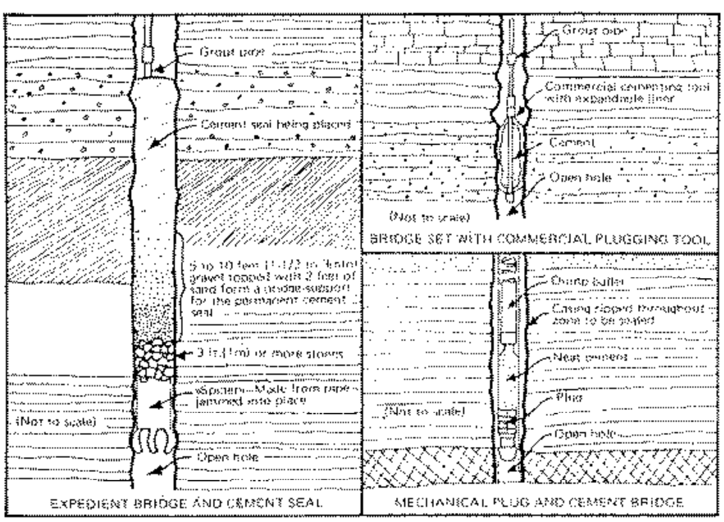


Figure 3.3.9.9 Well abandonment incorporating permanent bridge seals (from U.S. Environmental Protection Agency, 1975).

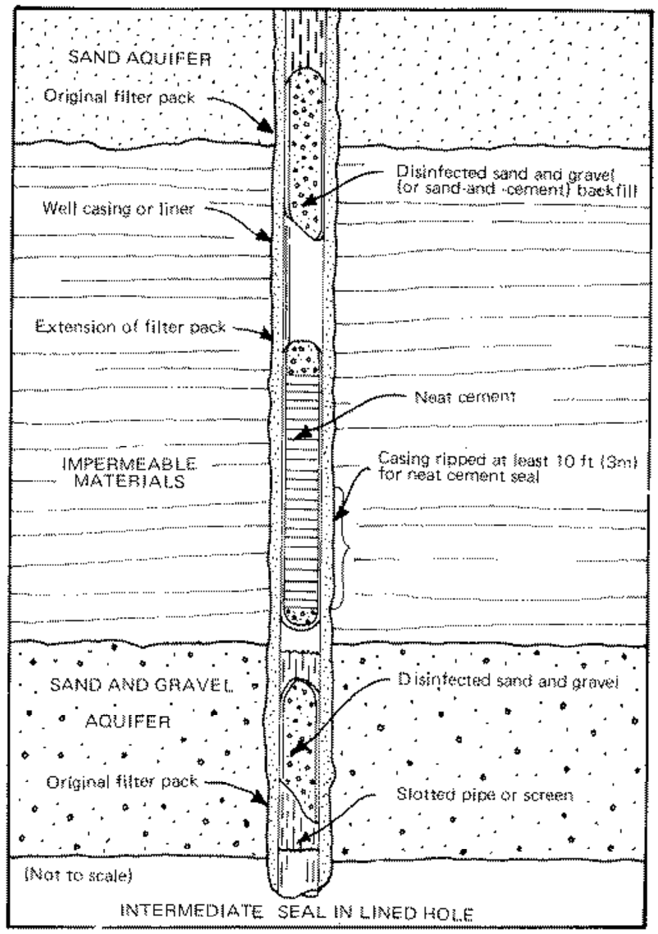


Figure 3.3.9.10 Well abandonment incorporating intermediate seals (from U.S. Environmental Protection Agency, 1975).

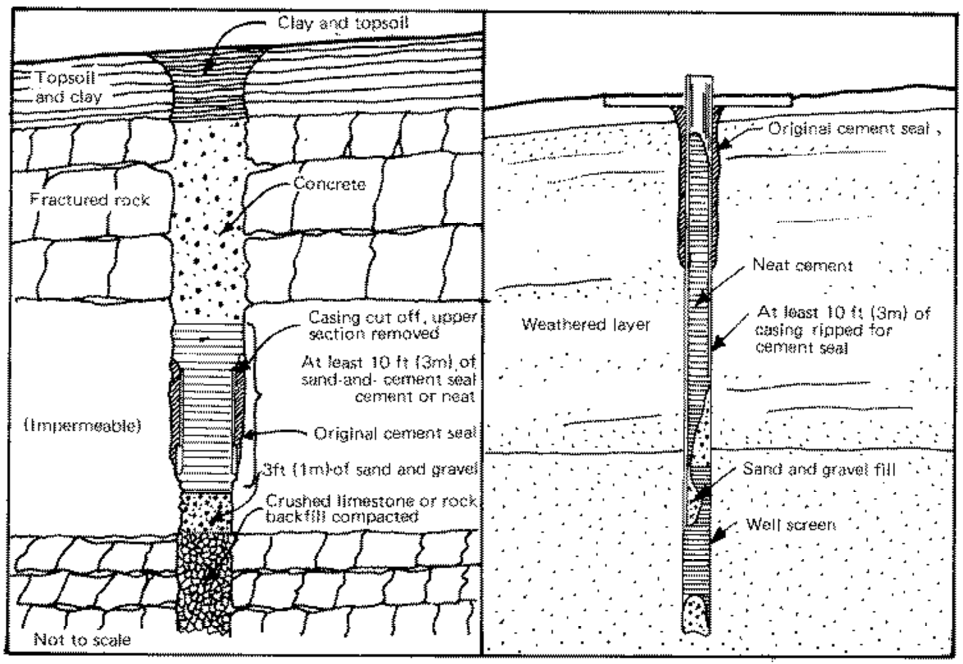


Figure 3.3.9.11 Well abandonment and sealing of uppermost aquifer (from U.S. Environmental Protection Agency, 1975).

4. Case histories

In this chapter, six brief case histories are presented summarizing the results of ground-water investigations or regional reconnaissance in specific hard rock areas of Brazil, Cameroon, India, Sardinia and Uganda, respectively. All these studies point up the close inter-relationships that exist between climate, rainfall, recharge rate, topographic position, rock type and geologic structure in influencing the rate of yield and water quality of a well tapping a hard rock aquifer. The studies also emphasize the need for an integrated knowledge of these variables in the optimum selection of sites for the drilling and construction of production wells.

4.1. *GROUND-WATER DEVELOPMENT IN UPPER PRECAMBRIAN METAMORPHIC ROCKS OF THE ALTO RIO PARAGUAI BASIN, MATO GROSSO, BRAZIL*

by George C. Taylor, Jr.*

4.1.1 INTRODUCTION

The Alto Rio Paraguai basin covers an area of about 496 000 km^2 in southwestern Brazil and eastern Bolivia (Figure 4.1.1). The climate is humid sub-tropical with an annual rainfall ranging from 1 300 to 1 800 mm. Rainfall may occur during any month of the year but is generally greatest during the hot season (December, January and February), and least during the cool season (June, July and August).

The central part of the basin is occupied by a great alluvial lowland which covers an area of some 168 000 km^2. This lowland known as the Pantanal extends some 450 km from north to south and 270 km from east to west. To the north of the lowland in the Cuiabá region and also to the south of the Miranda region are extensive gently sloping peneplains underlain directly by metamorphic rocks of the upper Precambrian Cuiabá Series. These rocks form part of the north-south Paraguai-Araguaia geosynclinal belt (Figure 4.1.2). The Cuiabá rocks include mica schists and phyllites predominantly but also some quartzites, slates, greywakes, tillites and meta-conglomerates in isoclinal folds, locally intruded by granite plutons. In most places the Cuiabá rocks are deeply weathered and outcrops are rare.

In recent years there has been a considerable amount of drilling activity in both Cuiabá and Miranda regions using both percussion and down-the-hole air hammer rigs. Wells have been put down for government installations and also for small municipalities, industries and ranches (fazendas). The sites for virtually all these wells were selected at random with little or no consideration given to geological criteria. It is thus interesting to review the results.

4.1.2 CUIABA REGION

In this region there are many privately-owned shallow dug wells which tap water in weathered Cuiabá rocks at depths ranging from 10 to 25 m. Such wells are used chiefly for domestic purposes, for watering household gardens and fruit trees, and for livestock. The static water levels in such wells are commonly in the range of 5 to 15 below land surface and the wells are equipped with hand pumps or small centrifugal diesel sets. The yields obtained from such dug wells are generally in the range of about 0.5 to 2.0 m^3/h. Owing to high rainfall and good recharge, dug wells in this region seldom fail in the dry season.

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There are some 15 drilled wells in and near the city of Cuiabá for which records are available. These wells are drilled in diameters of 152, 203 and 254 mm and range from 65 to 300 m in depth. Three of the wells produced less than 1.0 m^3/h and were considered unsuccessful. The 12 successful wells produced yields ranging from 1.0 to 12.0 m^3/h with an average of 6.3 m^3/h. The successful wells ranged from 96 to 210 m in depth; the average depth was 135 m.

Three successful wells 128, 121 and 120 m deep, and 152 mm in diameter were drilled in the vicinity of Coxipo da Ponte in mica schists. The wells produced respectively 5.2, 6.0 and 6.0 m^3/h with drawdowns of 36.5, 40.0, and 9.0 m, respectively. The specific capacities were thus 0.14, 0.12 and 0.67 m^3/h. The static water levels were 11.5, 12.0 and 16.0 m, respectively, below land surface. All these wells penetrated through a surficial weathered layer of red to yellow clay 5 to 8 m thick. This layer is in turn underlain by a layer 7 to 12 m thick of decomposed schist, then followed by compact mica schist cut by quartz veins to the well bottoms. Water was encountered at several points in each well down to depths of 121 m. These points correspond to the interesection of the well holes with quartz veins which transect the schists.

Six wells were recently (1976) drilled for the new Centro Politico Administrativo (CPA) de Mato Grosso da Norte, southeast of Cuiabá. The wells average about 120 m in depth with static water levels at about 10 to 15 m and pumping levels 50 to 75 m below land surface. The yields are reported to range from 3 to 5 m^3/h. The wells are pumped either by air lift or by electrical submersible pump. Well no. CPA 6 which is typical of this group has about 5 m of 254 mm surface casing then 203 mm casing to a depth of 32 m. Below 32 m the well has a diameter of 152 mm open hole, and at the bottom of the well, 120 mm. At the time of well completion in 1976 the static water level was at 16.0 m below land surface. After test pumping the well for 48 hours by electrical submersible pump at a rate of 3.16 m^3/h the pumping level was 51.4 m. The drawdown was thus 35.4 m and the specific capacity 0.09 $m^3/h/m$.

The well encountered the following lithologic sequence: 0 - 20 m, weathered yellow phyllite; 30 - 32 m, soft gray phyllite; 70 - 120 m, hard light-gray fine grained quartzite. The bulk of the water tapped by the CPA wells is apparently stored in fractures in quartzite. Little or no water was encountered in the phyllites.

Among the 15 wells drilled in or near the city of Cuiabá the three unsuccessful wells were reported to have penetrated only phyllites. Also in two other wells which were only marginally successful, phyllites predominate in the well sections. One of these drilled at the National Space Research Institute (INPE) reached a depth of 300 m. The well passed through the following: 0 - 4 m, micaceous clayly silt; 4 - 47 m, weathered phyllite; 47 - 300 m, gray phyllite with some intercalated white and yellow quartzite. Water was reportedly encountered at 46.5 m (at the base of the weathered layer) and also at 250 and 255 m apparently in beds of quartzite. The well, with a static level of 27.0 m below land surface, has a drawdown of 118 m when pumped at 2.0 m^3/h. The other well drilled at a military installation near Cuiabá reached a depth of 200 m and encountered the following: 0 - 15 m, residual clay; 15 - 200 m, phyllite alternating with calcareous schist by quartz veins and with some quartzite. Some water was found at 114.5 m, apparently in quartzite. With a static water level 25 m below land surface the well yields 1.0 m^3/h with a drawdown of 75 m. The specific capacity is thus only 0.01 $m^3/h/m$.

Elsewhere in the Cuiabá region four wells have been drilled in the interbedded schists and phyllites and/or slates in and near Acorizal. One of these wells, which was 41 m deep yielded only 0.72 m^3/h and was abandoned as unsuccessful. The other three wells, all tapping water in schists, are 240, 53 and 122 m deep. The yields obtained were 8.7, 16.0 and 5.0 m^3/h, respectively. The 53 m well which provides drinking water for Acorizal, has a static water level 6.2 m below land surface and a drawdown of 17.4 m when pumping at 16.0 m^3/h. The specific capacity is thus 1.0 $m^3/h/m$ which is comparatively high for a well drawing water from schist.

Near the city of Poconé situated near the northern edge of the Pantanal some eight wells 203 to 152 mm in diameter have been drilled in metamorphic rocks of the Cuiabá series, which appear to be predominantly schists near the city. The well depth ranges from 120 to 185 m and averages 138 m. The yields obtained from the wells range from 6.0 to 30 m^3/h and average 14.4 m^3/h.

Seven wells have been drilled in Cuiabá rocks in or near Varzea Grande. These range from 80 to 180 m in depth and average 129 m depth. The yields range from 4.5 to 12.0 m^3/h and average 8.7 m^3/h. One well at Santo Antonio do Leverger was drilled to a depth of 145 m and yields 25 m^3/h. Another well at Nossa Senhora do Livramento was drilled to a depth of 145 m and yields 25 m^3/h. Another well at Nossa Senhora do Livramento was drilled to a depth of 119 m in phyllites but as it produced only 0.6 m^3/h it was abandoned.

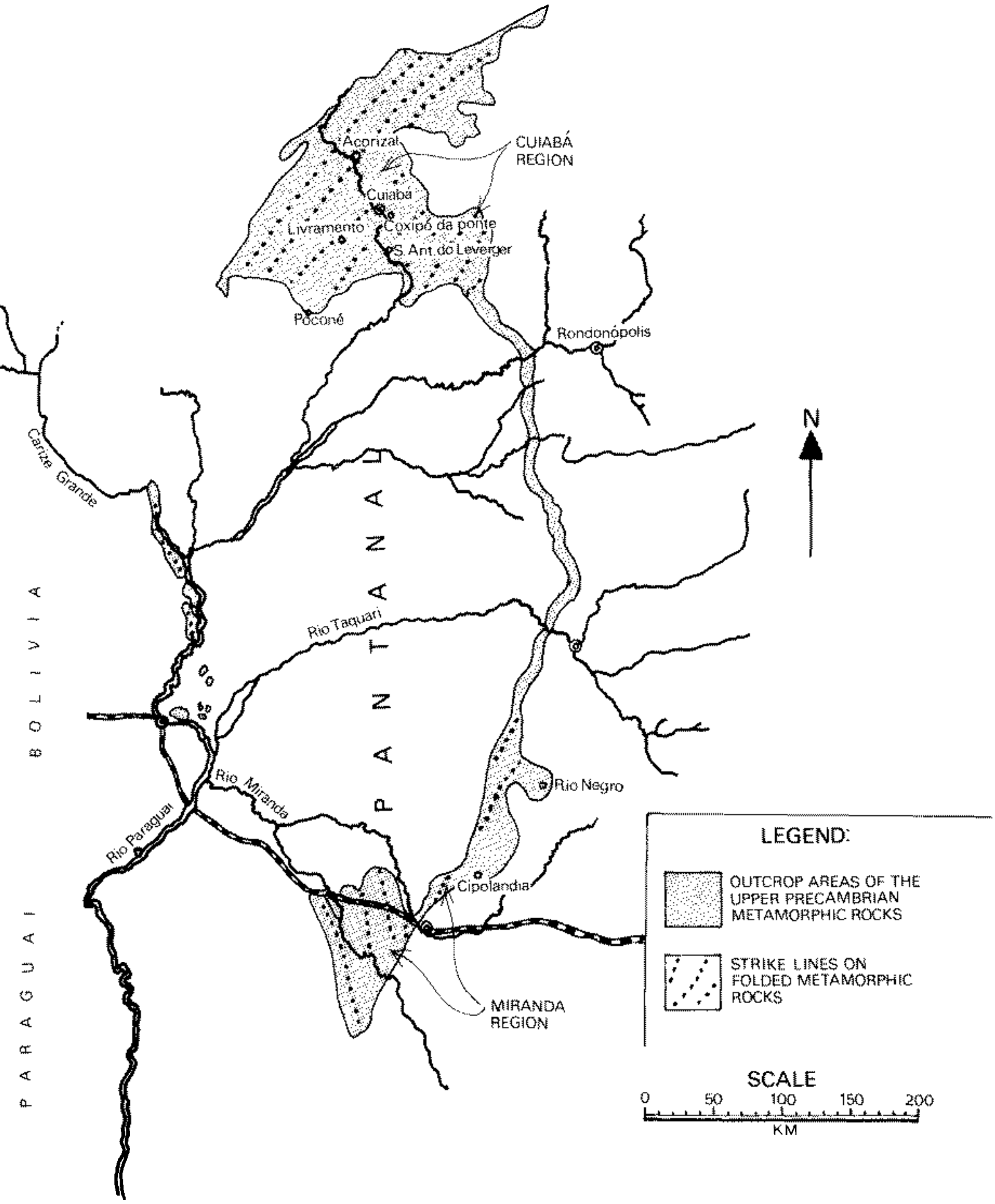

Figure 4.1.1. Map of the Alto Rio Paraguai Basin, Mato Gross, Brazil, showing outcrop areas (shaded) of the Upper Precambrian metamorphic rocks.

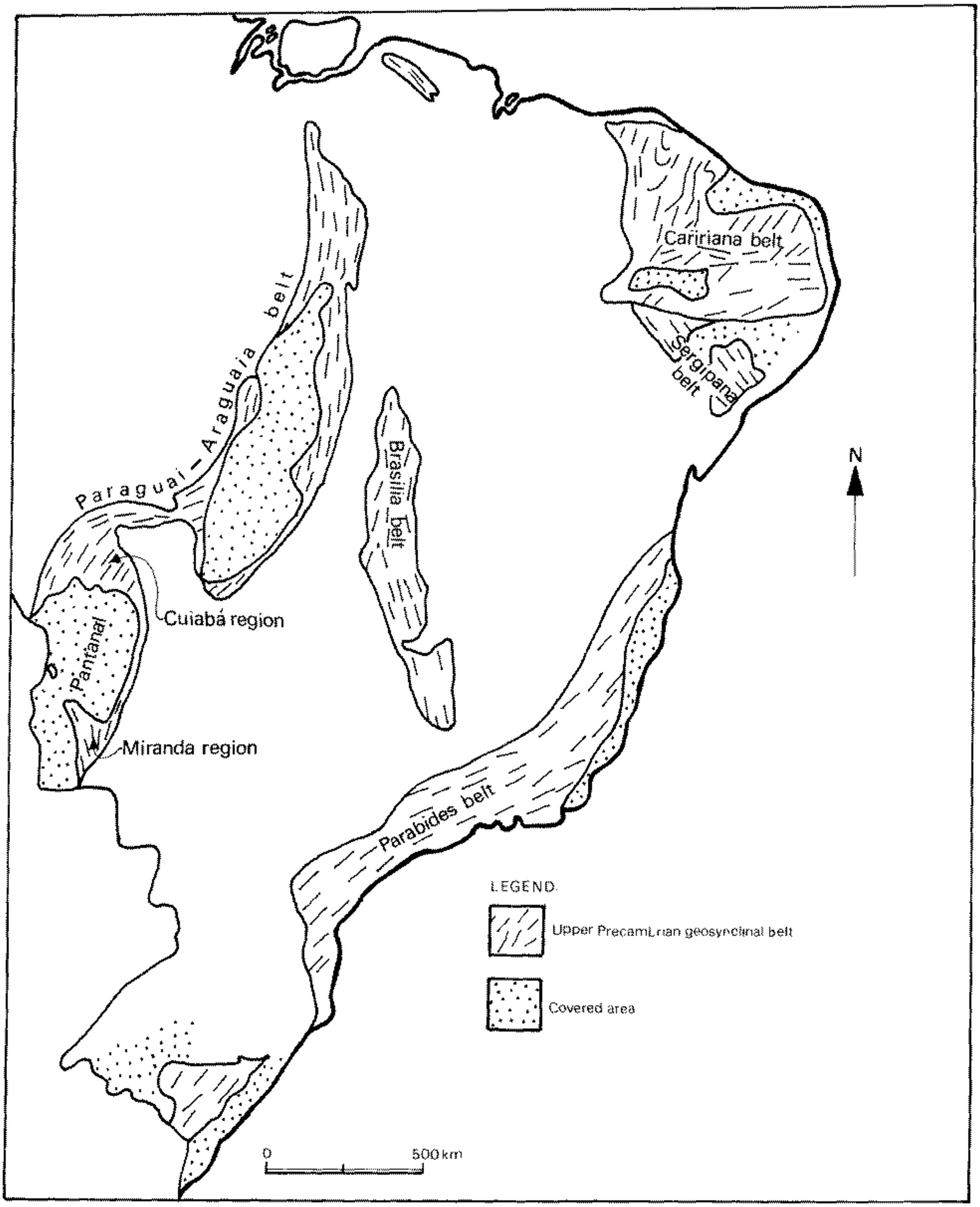

Figure 4.1.2 Sketch map of Brazil showing location of Upper Precambrian Geosynclinal belts (adapted from Rebouças, 1973).

4.1.3 MIRANDA REGION

There are many shallow dug wells in this region with characteristics similar to those of the Cuiabá region. In or near the city of Miranda three wells were drilled to depths of 140, 170 and 200 m in interbedded schists and phyllites. The yields were 1.2, 3.0 and 1.3 m^3/h, respectively.

Elsewhere in this region seven wells were drilled during 1976 for which records are available. These are either 152 mm or 203 mm in diameter and range from 107 to 200 m in depth. Two of the wells were drilled entirely in phyllites and produced little or no water. Among the five successful wells, yields ranged from 2.9 to 6.0 m^3/h. All these wells tap water in schist or in schist with some quartzite and metaconglomerate. The most productive of these wells is located near Rio Negro. This well is cased with 305 mm pipe to a depth of 42 m and then is 152 open hole below. The following geologic sequence was encountered: 0 - 6 m, residual clays, 6 - 33 m, altered quartz mica schist; 33 - 110 m, quartz mica schist with quartz veins. The static water level in the well was at 19 m below land surface when the well was drilled. The drawdown was 30.0 m when the well was pumped at 6.0 m^3/h. This performance is comparable to the better wells tapping schist with quartz veins in the Cuiabá region.

Another well also near Rio Negro encountered the following sequence: 0 - 15 m, silty sandy clay; 15 - 21 m, sandy clay with quartz pebbles; 21 - 34 m, clay; 34 - 38 m, sandy gravel; 38 - 112 m, phyllite; 112 - 200 m, quartz mica schist. The surficial deposits were cased off when the 152 mm blank pipe was set at 68.5 m. The well apparently draws most of the water from the open hole section between 68.5 and 150 m. Three yield tests were made when the well was 106, 150 and 200 m deep. The yield of the well increased from 1.4 m^3/h at 106 m to 3.25 m^3/h at 150 m but no increase occured below a depth of 150 m. The drawdown was 59.2 m when the well was pumped at 3.25 m^3/h. The specific capacity was thus 0.05 $m^3/h/m$.

A well drilled in 1976 near Cipolandia was cased to 56.3 m with 305 mm pipe and then is 152 mm open hole to a depth of 153 m. The following sequence was encountered: 0 - 13 m, residual sandy clay; 13 - 39 m, metaconglomerate with flat pebbles of quartzite and quartz; 39 - 153 m, quartz mica schist. With a static level at 21.8 m below land surface the drawdown was 40.2 m when the well was pumped at 5.1 m^3/h. The specific capacity was thus 0.13 $m^3/h/m$.

4.1.4 WATER QUALITY

Field tests of the chemical quality of the ground water from metamorphic rocks in the Cuiaba region indicate a total dissolved content of about 100 to 350 mg/l near Cuiabá and Coxipo; 150 to 450 mg/l near Acorizal; and 50 to 300 mg/l near Poconé. In the Miranda region total dissolved solids near the city of Miranda range from about 150 to 450 mg/l; about 300 to 500 mg/l near Cipolandia; and 250 to 350 mg/l near Rio Negro. The chemical quality of water in rocks of the Cuiabá series thus appears to be good to excellent in the Alto Rio Paraguai basin.

4.1.5 CONCLUSIONS

The results of random drilling in the Cuiabá rocks of the Alto Rio Paraguai region point up the importance of application of geologic criteria to the selection of appropriate sites for the drilling of supply wells. By application of such criteria the failure rate could probably be reduced from the present 30 to 40 per cent to 20 per cent or less with substantial savings in drilling costs. From the previous discussions it is evident that wells drilled in belts of phyllite are generally unsuccessful, that is, such wells commonly yield less than 1.0 m^3/h with specific capacities in the range of only 0.01 to 0.03 $m^3/h/m$. On the other hand, wells drilled in belts of schist; quartzite and metaconglomerate generally produce substantially higher yields commonly in the range of 2 to 15 m^3/h with specific capacities of 0.10 to 1.0 $m^3/h/m$ or more than 10 times greater than those wells in phyllites.

It is also noted that some wells have been drilled in belts of phyllite to depths as great as 200 to 300 m apparently in blind hopes of obtaining greater yields than those encountered at shallower depth. The results have been uniformly disappointing. On the other hand, wells drilled in belts of schist, quartzite and/or metaconglomerate have generally been unsuccessful in obtaining yields of 2 m^3/h or greater with specific capacities of 0.10 $m^3/h/m$ or greater at depths of less than 150 m. Careful geologic mapping and stratigraphic study of Cuiabá metamorphic sequence together with analysis of existing hydrogeologic data would greatly increase the probability of success as well as reduce the cost of unproductive drilling. The same principles would apply in similar metamorphic rock terrains elsewhere in Brazil as well as in other areas of the world.

4.1.6 OTHER AREAS OF UPPER PRECAMBRIAN METAMORPHIC ROCKS

There are four other geosynclinal belts in Brazil with rock associations similar to those of the Cuiabá series and of similar age to the Paraguai-Araguaia geosyncline (Figure 4.1.2). These include (1) the Brasilia belt trending north-south with Brasilia at its center; (2) the Caririana belt covering an extensive area in northeastern Brazil; (3) the Sergipiana belt also in the northeast; and (4) the Parabides belt which trends northeast-southwest from the State of Espirito Santo do Uruguay.

In all these belts the occurrence of ground water is analogous to that in the Paraguai-Araguaia belt. The schists, especially where numerous quartz veins are present, the quartzites, and the metaconglomerates are the most productive aquifers. The phyllites, slates and grey-wackes are the poorest aquifers and in many places are totally non-productive. Well yields are generally highest in the upper Precambrian metamorphic rocks of the humid regions, all other factors being equal. This comes about because of higher rates of natural recharge and replenishment of ground-water storage. For example, the sustained yields of wells in these rocks in semi-arid northeastern Brazil are reported to be, on the average, only about half of those in the humid Alto Rio Paraguai basin.

The rate of recharge also appears to have a marked effect on the salinity of water in the upper Precambrian rocks. The total dissolved solids in both the shallow and deep ground water in these rocks is generally less than 300 mg/l in the Alto Rio Paraguai basin so the water is usable for virtually all normal human requirements. On the other hand, ground water in the upper Precambrian rocks of northeastern Brazil commonly contains more than 4 000 mg/l of total dissolved solids and in places more than 10 000 mg/l. Water of this quality is, of course, only marginally useful, chiefly for the watering of livestock.

4.2 *GROUND-WATER EXPLORATION IN PRECAMBRIAN ROCKS OF NORTHERN CAMEROON*

by Robert Dijon*

4.2.1 INTRODUCTION

During 1972-78 hydrogeological investigations were carried out by UN/UNDP in a 30 000 km^2 region of northern Cameroon, lying south of Lake Chad and north of 8° north latitude (Figure 4.2.1). The climate of the region is Sudanian with mean annual temperatures ranging from 28° to 32° C and mean annual rainfall, from 1 400 mm in the south to 600 mm in the north. Virtually all rainfall occurs during the period April through October followed by a 5 to 6 month dry season. The vegetation is typical wooded grassland of the Sudan savannah.

4.2.2 GEOLOGY

Four geomorphic areas are represented in the region. The Mandara Mountains, which are formed of Tertiary volcanic rocks, rise to altitudes of 1 000 to 1 500 m in the east-central part of the region. To the north and northwest is the alluvial plain of the Lake Chad basin underlain by Plio-Pleistocene fluvial and lacustrine sediments 100 to 300 m thick resting on Precambrian basement rocks. In the south-central part of the region is the eastward extension of the Benoué sedimentary basin filled with sandstones and shales of Cretaceous age. Lying adjacent to all the above mentioned geomorphic areas are extensive upland plains underlain by thin alluvial and aeolian deposits or weathered layers resting on Precambrian basement rocks. Hydrogeological investigation were carried out only in Precambrian areas, hence post-Cambrian rocks are not described here.

The Precambrian rocks include a wide variety of mesozonal migmatized anatectic granite, anatectic gneiss, migmatite with associated quartzite as well as mesozonal non-magmatic gneiss, amphibolite, soapstone, mica schist, leptynolites, quartzite and amphibole schist.

Epimetamorphic schist, quartzite, mica schist and rhyolite also occur. Plutonic rocks include alkali-calcic granite, gabbro, biotite and amphibole granite, and riebeckite. Volcanic trachyte and andesite are also present as are dikes of microgranite, pegmatite and quartz. The belt of mesozonal metamorphic rocks trend ENE-WSW with dips commonly in the range of 40° to 60° and in places vertical. The metamorphic rocks were originally predominantly argillaceous sediments with some sand deposited in a Precambrian geosynclinal basin then metamorphosed and intruded by syntectonic granite plutons. The epizonal rocks whose dips range from 25° to 40° seem to belong to a later sedimentary and metamorphic cycle.

4.2.3 THE WEATHERED LAYER

Test drilling and related field studies revealed that the Precambrian rocks are commonly covered with a weathered layer whose lithologic character varies somewhat with that of the underlaying host rock. The following sequence is generally found from the land surface downward:

a) Hard laterite. May be fractured and locally water-bearing.

b) Lateritic sandy clay. Generally impervious and not water-bearing.

c) Kaolinitic clay. Generally impervious and not water-bearing.

d) Granite grus. Commonly forms a productive aquifer. The grus is generally finer textured above the gneisses and coarser textured above the migmatites and anatexites. Concentrations of very coarse sandy grus are associated with porphyritic granites and pegmatite veins. (Where epizonal rocks, especially schist, are present this zone of the weathered layer is practically impervious). The yields of hand-dug, traditional wells tapping water in this zone are almost always less than 2 m^3/h and generally less than 1 m^3/h. Hydraulic conductivity values are in the range of 10^{-5} to 10^{-6} m/s.

e) Basement rock. Deeply weathered.

f) Basement rock. Slightly weathered. In both (e) and (f) the structure of the rock has been preserved while the texture has been altered. Downward the alteration of the rock is progressively less, being limited to some fractures and minor diaclases. Both the (e) and (f) zones have appreciable permeability. On the average the (f) zone is about 8 m thick. The (e) and (f) zones over epizonal rocks tend to be rather thin. On the other hand, weathering reaches great depths in areas of vertical schistosity.

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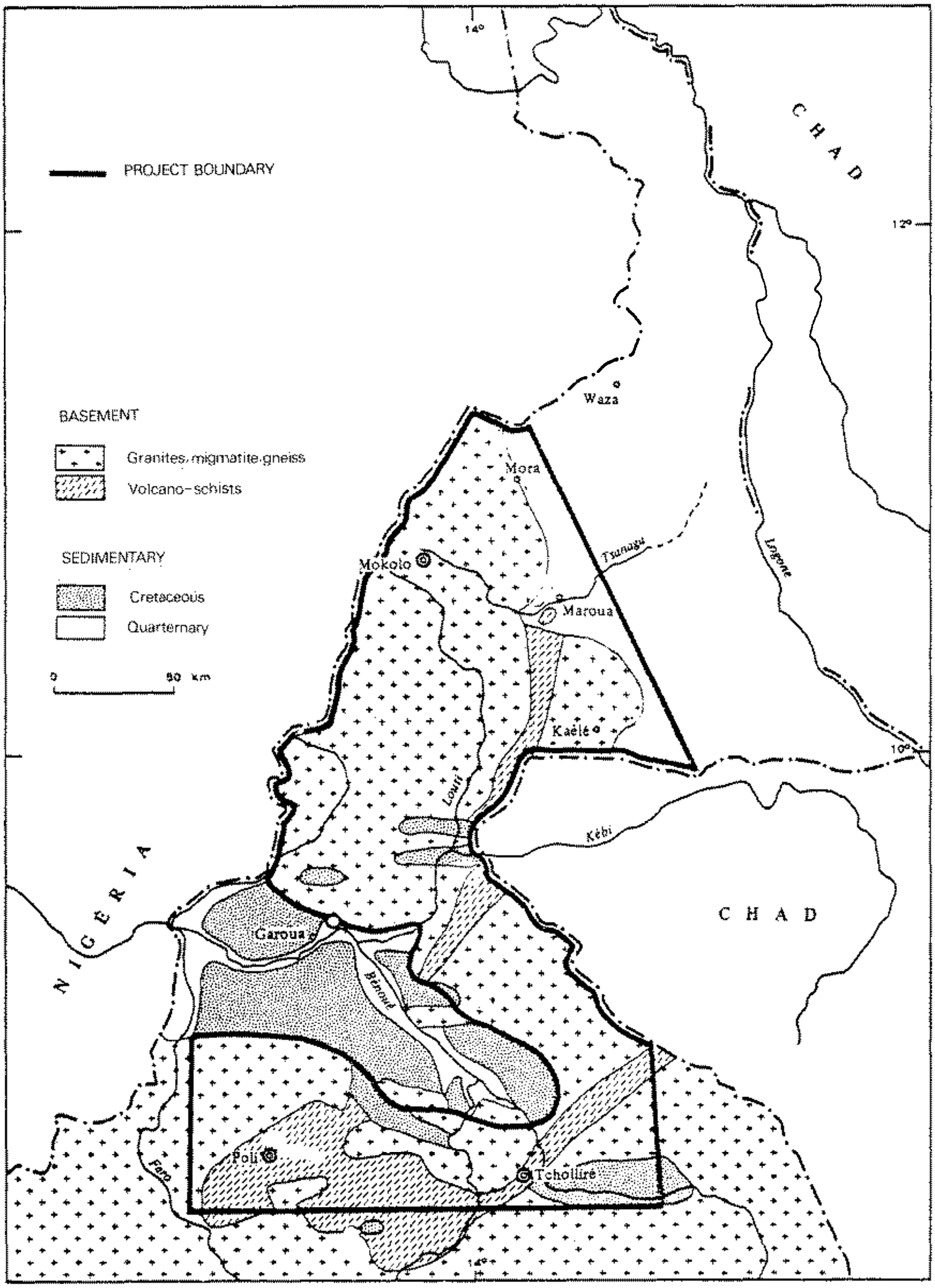

Figure 4.2.1 Cameroon. Location of project area.

g) Unaltered basement rock. Some permeability in fractures but in places these are closed and clogged with clay.

The weathered layer is thickest along the strike of major fractures, which correspond to topographic lows and the hydrographic network. In these lows conditions are favourable for ground water recharge, and most of the more productive wells in the region are located in them. During the rainy season the ground water level commonly rises almost to the land surface in low areas, but during the dry season declines 8 to 10 m into zones (e) and (f). South of the 1 200 mm isohyet the weathered layer is considerably thicker than to the north and conditions are more favourable for recharge by rainfall penetration and infiltration from runoff.

4.2.4 WATER QUALITY

The chemical quality of the ground water is generally good with total dissolved solids averaging 400 mg/l in granite, with prevailingly calcium bicarbonate type water; 300 to 500 mg/l in migmatite, 600 to 1 000 mg/l in syenite, with mixed calcium bicarbonate, sodium sulphate and chloride type waters; and an average 400 mg/l in alluvium and eluvium.

4.2.5 RESULTS OF EXPLORATORY WORK

The general objectives of exploration were to determine the availability of ground water in Precambrian hard rock areas and to provide water supplies for newly created villages in cotton producing areas. Investigatory work during 1972-75 included: photogeologic and hydrogeologic field studies for construction of a geological map, scale 1:200 000; a water quality survey; a field inventory of 374 water points; petrographic studies of 79 rock samples; geophysical studies with 3 146 measurements along 157 km of resistivity profiles, 536 electrical soundings, and 100 refraction-seismic bases of 110 or 220 m; and drilling of 25 exploration boreholes for a total of 720 m of hole.

Some of the exploratory wells (depths 15 to 30 m) drilled in 1972-75 proved productive with yields up to 2 m^3/h in fractured and weathered granite gneiss; 20 to 50 m^3/h in sandy layers overlying granite or schist bedrock; 1 m^3/h in weathered gneiss overlying schist with quartz and pegmatite veins; and 1.5 m^3/h in highly weathered granite. During a subsequent drilling campaign in 1975-78 some 98 boreholes were drilled to depths of 35 to 40 m and of these 53 proved to be productive. The yields obtained from fissured rocks ranged from 0.2 to 0.5 m^3/h and, exceptionally, yields ranging from 2 to 5 m^3/h were obtained. The boreholes tapping weathered rock obtained yields ranging from 0.5 to 4.0 m^3/h and exceptionally, 10 to 15 m^3/h.

4.3 *GROUND-WATER UTILIZATION IN HARD ROCK AQUIFERS OF THE PALI REGION, JODHPUR DIVISION, RAJASTHAN, INDIA*

by George C. Taylor, Jr.*

4.3.1 INTRODUCTION

The Pali region covers about 6 500 km^2 in northwestern India with a hot, semi-arid, savannah-type climate characteristic of the low-latitude steppes of the world. The average annual rainfall is about 430 to 450 mm, virtually all of which falls during the southwest monsoon from June to September.

Most of the Pali region is an almost level to gently undulating erosional plain (peneplain) cut on hard rocks and interrupted from place to place by isolated buttes, rocky tors and short ridges which are essentially inselbergs or erosional residuals. The general elevation of the plain is about 320 m above sea level in the southeast, about 275 m in the east and northeast, and about 180 m on the west. The highest point in the region is 570 m above sea level. The entire region is drained by the Luni River and its tributaries, all of which are ephemeral streams.

4.3.2 HYDROLOGY

In the Pali region surficial Quaternary deposits rest on a basement of early Precambrian metamorphic rocks and middle Precambrian intrusive and volcanic rocks. The basement rocks, however, lie at or near the surface in most of the region (Figure 4.3.1).

The oldest of the rock groups are the Aravalli slates of early Precambrian age. These rocks were originally mostly argillaceous sediments with minor arenaceous beds which on metamorphism have yielded slates with some phyllites and schists and, locally, quartzites. The Aravalli rocks have been moderately to intensely folded along axes striking northeast to north-north-east. Vertical dips are often observed in small outcrops, and dips greater than 50° are common, suggesting isoclinical folding and possibly overturning in some areas.

Ground water in the slates is stored in bedding planes and in slaty and fracture cleavage planes. The behaviour of open dug wells in these rocks suggests that the bulk of available ground water circulates in a zone about 10 to 15 m thick below the water table. Among some 82 dug wells observed in Aravalli rocks, yields range from 0.63 to 4.2 m^3/h and average 2.2 m^3/h. The total dissolved solids content of the water ranges from about 1 000 to 8 000 mg/l and averages about 3 000 mg/l.

Intrusive into the Aravalli rocks is a large batholithic mass of the Jalor (Siwana) granite of middle Precambrian age. The granite occurs in two varieties, a pink felsic type and a gray or greenish gray-mafic type. Both varieties are generally non-porphyritic and non-foliated and are commonly medium to coarse-grained. Vertical fracture sets are generally well-developed in the granites, with one set striking northeast and another north-northwest to north-west. These fracture sets are commonly spaced at intervals of about 1 to 3 m, where they can be observed in large-diameter open wells. Horizontal sheeting subparallel to the land surface is also common in some areas. The weathered layer in the granite terrains is commonly from 0.9 to 2.9 m^3/h thick but in places reaches a thickness of 25 to 30 m.

Ground water in the granites is stored and circulates chiefly in the weathered layer and through underlying fracture sets, sheeting and other minor partings. The most active ground-water circulation probably occurs in the zone extending downward from the water table for about 15 to 20 m. The yield of a well in the granites depends on the number, width and spacing of fractures and/or the relative thickness and permeability of the weathered layer below the water table. The observed yields of 88 open wells tapping water in granite range from 0.9 to 2.9 m^3/h and averaged 1.8 m^3/h. The dissolved solids content of the water in the granites averages about 3 500 mg/l with a range from about 1 000 to 10 000 mg/l. The average yield from the granites was somewhat lower and the average salinity somewhat higher than that from the Aravalli slates.

Associated with the Jalor intrusives, possibly as a late phase of the same period of magmatic activity, are the felsic lavas and pyroclastics of the Malanie volcanics. These rocks are predominantly rhyolite lava flows of porphyritic to glossy texture, interbedded with vitrified tuffs and breccias. Locally lava flows of intermediate to mafic composition are present. For the most parts the Malani rocks are highly indurated and relatively impervious. However, some ground water circulates through the rocks along bedding planes, joints, sheeting and other secondary tabular partings. The bedding planes generally strike north to northwest and dip to the west at about 15 to 30 degrees. North of the Luni River two sets of vertical joints are commonly present. One set strikes about north to northeast and the other at right angles. The spacing of these joints is generally less than 60 cm. Strong vertical sheeting has been observed in some outcrops, although it is not common.

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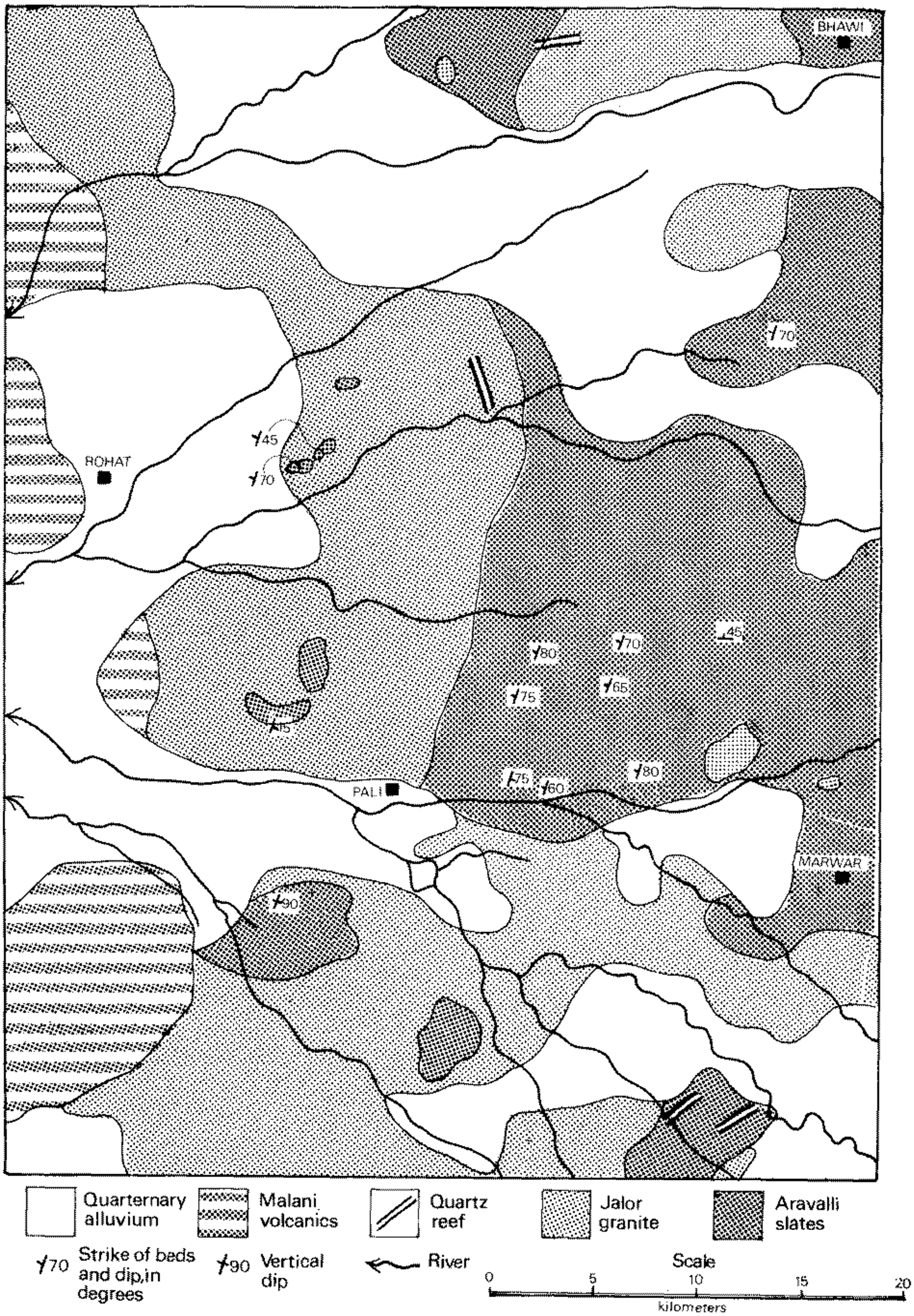

Figure 4.3.1 Geological sketch map of the Pali region, Jodhpur Division, Western Rajasthan.

The yield of a well in the Malani volcanics depends chiefly on the number and width of partings encountered by the well section below the water table. Near the land surface joints and other secondary partings may be fairly numerous and closely spaced. Moreover, by weathering processes, these have generally widened so that percolation of water is faciliated. With increasing depth the partings tend to close and disappear so that deep percolation of water is retarded. Below depths of about 50 m the Malani rocks generally do not appear to contain significant water-bearing horizons. The yields obtained from individual dug wells in the Malani rocks of the Pali region are generally less than 70 m^3/d (2.9 m^3/h). The total dissolved solids content of the water ranges from about 1 000 to 10 000 mg/l and averages about 4 000 mg/l).

4.3.3 WATER QUALITY

Partial chemical analyses indicate that chloride concentration generally exceeds 700 mg/l so that most well waters of the Pali region have a perceptibily to strongly salty taste. Carbonates are generally absent or are present only as traces. Bicarbonates, however, are on the average the second most abundant of the anionic constituents. They are generally present in concentrations ranging from about 400 to 900 mg/l. Sulphates, which are the third most abundant of the anions, are generally present in slightly less concentration than bicarbonates. The pH values of most of the well waters lie between limits of 7.3 to 8.3 indicating that a slight alkalinity generally prevails in the ground water.

The moderate to high salinity which characterizes the ground water of the Pali region as well as much of western Rajasthan is a relatively common phenomenon in semi-arid hard rock regions of the world. Factors which apparently influence relative ground-water salinity are: (1) the net balance between annual evaporation, precipitation, infiltration and runoff; (2) the rate of local rock weathering with resultant formation of water-soluble salts from the decomposition products; (3) the rate at which salts are transported into the region by streams, winds and rains and deposited in the soil; (4) the balance between the rate of ground-water flow and the rate of salt accumulation in the ground-water body from infiltrating water.

The average potential evaporation is of the order of 2 500 mm annually in the Pali region, but the average annual precipitation is only about 430 mm. Thus, in years of normal or below normal precipitation, infiltration may be small or negligible, evaporation is high and surface runoff is low. Consequently, those soluble salts which have been formed by the weathering of local rocks or which have been transported into the region by streams, winds and rains, tend to accumulate in the soil. In subsequent years of higher rainfall a part of the accumulated salts may be dissolved and carried out of the region by surface runoff. At the same time, however, considerable amounts of salts are leached from the soil by infiltrating waters which percolate down to the zone of saturation. Increases ranging from few tens to several hundred milligrams per litre in total dissolved solids content have been observed from one year to the next in many wells of the region. On the other hand, salinity decreases of comparable magnitude have been observed in other wells. These differences from place to place in the region emphasize the local nature of changes in dissolved solids concentrations in the ground water caused by infiltration. Where salts are available in the soil for dissolution by infiltrating water, increases in local ground-water salinity result, but where such salts are not available the infiltrating water tends to reduce ground-water salinity by dilution.

Owing to the relatively low permeability of the rocks of the Pali region, ground-water circulation is generally slow. Thus the salts dissolved in the ground water are only gradually returned to the surface in areas of ground-water discharge along the principal ephemeral streams of the regions. As a consequence of the balance between the rate of salt accumulation and the rate of ground-water circulation and discharge, the net salinity of the ground water remains generally high. However, marked changes in salinity may occur from year to year as a result of shifts in this balance. A lower salinity, which generally characterizes the water of the south-eastern part of the Pali region, is attributed to a more active ground-water circulation resulting from higher water-table gradients and somewhat higher average rainfall which prevail in this area. Consequently, the balance between the rate of salt accumulation and ground-water circulation favours a lower salinity. Other factors affecting salinity are seepage from saliferous human and animal waste and salts accumulated in irrigated fields that may locally increase ground-water salinity and seepage from surface-water tanks that locally decrease normal salinity.

4.3.4 GROUND-WATER UTILIZATION

About 90 per cent of the open wells in the granite and slate terrains of the Pali region range from 10 to 25 m in depth with the water table lying from about 5 to 20 m below land surface. About 75 per cent of the open wells are from 2.5 to 3.5 m in diameter with the largest in the region about 8 m in diameter. Most wells are curbed with stone masonry in surficial unconsolidated materials, but are "openhole" in rock. The wells are commonly pumped by bullocks and "mote" (leather bag) or by Persian water wheels. Centrifugal pumps powered by electric or diesel motors are also used. Drilled wells of 6 to 8-inch diameter have been put down to depths of as much as 75 m at a few places but have not encountered significantly larger quantities of water than those obtainable from the dug wells.

There are about 2 500 wells in the Pali region of which about 80 per cent are used intermittently for irrigation of areas of 1 to 2 hectares per well. Salt-resistant varieties of wheat and millet are the chief crops irrigated. Generally, these crops are sown and germinated in the fresh-water soil moisture derived from rains of the southwest monsoon. The crops are then brought to maturity by irrigation with brackish to slightly saline ground water.

A given plot of land can be irrigated year after year only if monsoon rains are effective in leaching away salts accumulated in the soil from the previous season's irrigation. At best, only one crop a year can be grown on a given plot of land where the ground water is used for irrigation. In some areas the salinity of the water is so high that a cultivated plot must lie fallow for from 2 to 4 years after one cropping to permit adequate leaching away by monsoon rains of the accumulated salt. Where such practice is required one well may be used to irrigate 3 or 4 adjacent plots of land. In many areas in the west and northwest of the region the salinity is so high that the water cannot be safely used for irrigation or any other beneficial purpose. However, in the southeast part of the region ground-water salinity is within the tolerance limits of common vegetable crops.

A number of shallow tanks have been created by construction of low dams across ephemeral streams of the region to store surface-water runoff of the southwest monsoon. The stored water is customarily used for gravity irrigation of small plots of land downstream from the dams during the early part of the dry season. Wells are also dug in and around the margins of the tanks. Wells of this type are fed wholly or in part by fresh-water seepage from the tanks mixed in greater or less degree with the normal brackish to saline ground water of the area.

Commonly, when surface storage in the tanks is depleted, salt-sensitive fresh vegetables such as tomatoes, onions, carrots, peppers, egg plant and potatoes are planted in the moist ground of beds of the tanks and then irrigated to maturity with the relatively fresh water drawn from the tank-fed wells. Such tank-fed wells also provide the bulk of the water consumed by the rural population for domestic purposes. The surface-water seepage of the tanks thus provides a local source of fresh-water recharge which mitigates the normal salinity of the ground water which might otherwise be unusable.

4.4 *GROUND-WATER POTENTIAL OF HARD ROCK AREAS IN THE NOYIL, AMARAVATI AND PONNANI BASINS, SOUTH INDIA*

by B. K. Baweja* and K. C. B. Raju**

4.4.1 INTRODUCTION

A multidisciplinary water-balance project was undertaken in the Noyil, Vattamalaikarai and Ponnani river basins by the Central Ground Water Board, with the assistance of the Swedish International Development Authority (SIDA). The objective of the project was to determine the quantitative potential of ground water in this hard rock area with a view to planning its development and management on a long term basis and on sound scientific lines. In addition, the project would evolve and standardize norms, procedures and methodology which can be applied in other areas having similar hydrogeological and hydrological settings. Due to shortage of space the present report does not cover all project activities; emphasis has been put on investigations of hard rock aquifers.

The project covered an area of 8 150 km^2 in the districts of Coimbatore and Trichirapallin in Tamil Nadu State and Palghat and Trichur districts in Kerala State (see Figure 4.4.1). It comprised the entire drainage basin of the Noyil river (3 510 km^2), the upper reaches of the Ponnani river (4 140 km^2) and the complete drainage basin of the Vattamalaikarai (500 km^2), a tributary of the Amaravati river. The Noyil and Vattamalaikarai river flow eastwards joining the Bay of Bengal, and the Ponnani river flows westwards to join the Arabian Sea.

The area is more or less a plain country bounded by the mountain chains of the western ghats, namely the Nilgiris on the north and north-west and the Palani and the Anamalai hills on the south. The trends of these hills ranges vary from ENE-WSW to E-W and their peaks range in altitude from 1 600 to 2 000 m above mean sea level. The plain in between which covers the major part of the area has an altitude of 200 - 400 m. A gap between the two mountain chains in the west has a very large influence on the climatic regime of the eastern plain, as the southwest monsoon winds enter the plain through this gap. The hydrological and meteorological characteristics of the region are summerized in Figure 4.4.1.

There is a great variation in the annual precipitation both in relative and absolute figures. On the plains of Tamil Nadu average annual rainfall varies between 835 mm and 400 mm and most of it is received during the north-east monsoon, the wettest month being October and the driest being February. On the plains of Kerala part, the annual average rainfall varies from 2 000 mm to 1 000 mm and most of it is received during south-west monsoon, the wettest month being July and the driest being January.

4.4.2 GEOLOGY

A consolidated geological map was compiled on the basis of various unpublished maps produced by the Geological Survey of India (Figure 4.4.2). Additional large-scale geological mapping was carried out in critical areas. Ground checks in soil covered areas were performed in the course of the inventory of existing wells.

The photogeological interpretation was made from contact prints of aerial photographs at an approximate scale of 1:65 000. Emphasis was given, during the study, to the structural features, as the lithological units exhibiting contrasting photo characteristics are limited. The morphological units also have a very low relief due to the thick weathered cover. The data from aerial photographs and Landsat imageries with field evidences were transferred to a base map at the scale 1:253 440 to compile the lineament map of the project area.

The project area is underlain by a wide range of rock types which have been metamorphosed under granulite and amphibolite facies. The main rock types are hornblende-biotite gneiss, garnet-sillimanite gneiss, charnockite and granite. Thin bands of calc-granulites and associated crystalline limestones occur interbanded with garnet-sillimanite gneiss along the hill ranges south of Coimbatore. Bands of magnetite-quartzite ranging in width from a few metres to as much as 100 m occur within the hornblende-biotite gneiss in the central and eastern parts of the area. Other minor rock types include various ultrabasic, basic and acid intrusive bodies such as pyroxenite, pyroxene granulite, amphibolite, dolerite, pegmatite and quartz veins. All the major rock types encountered in the area show moderate to well pronounced vertical to sub-vertical gneissic foliation. The gneissic foliation is very clear in hornblende-biotite gneiss.

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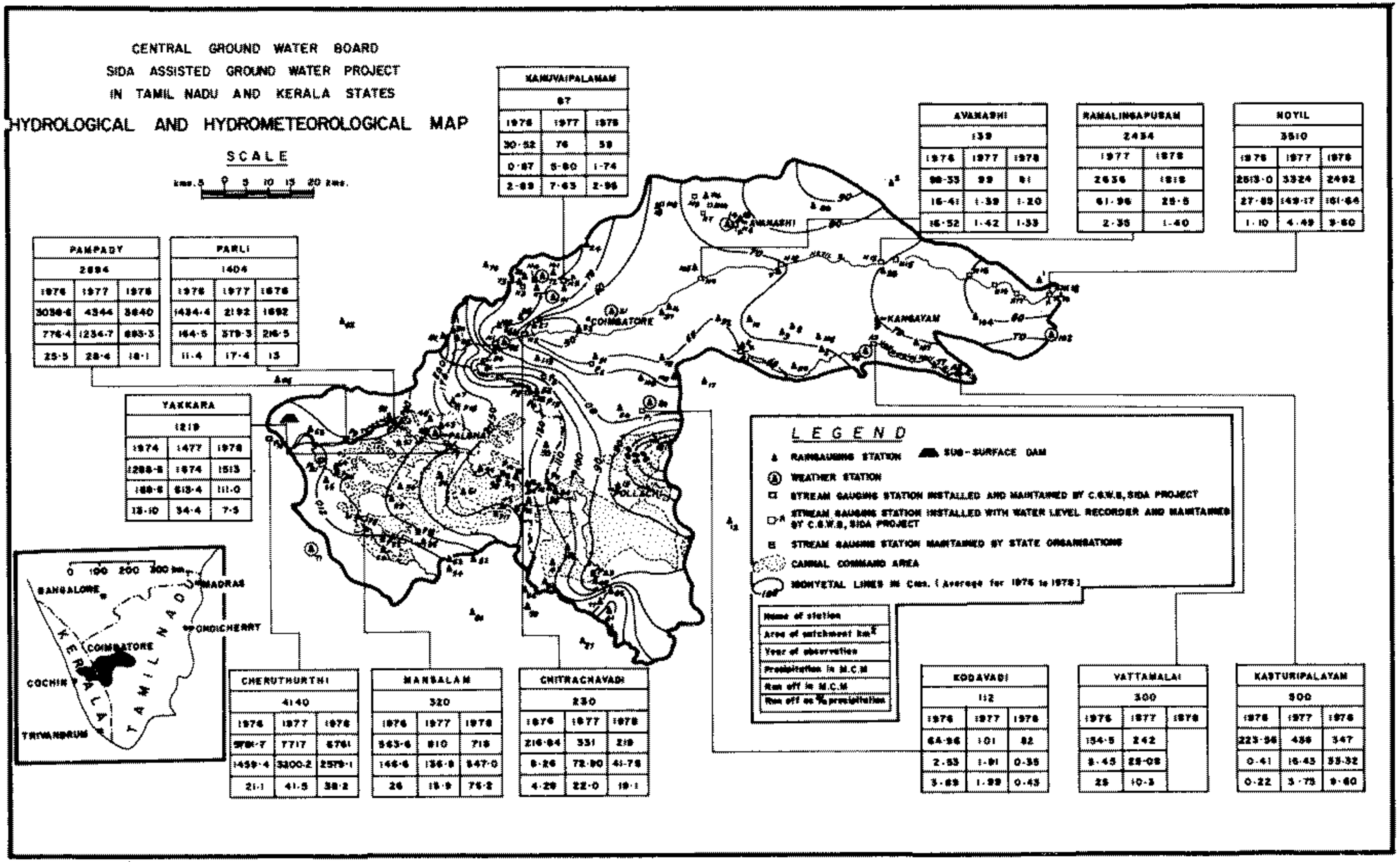


Figure 4.4.1 Hydrological and hydrometereological map of the project area.

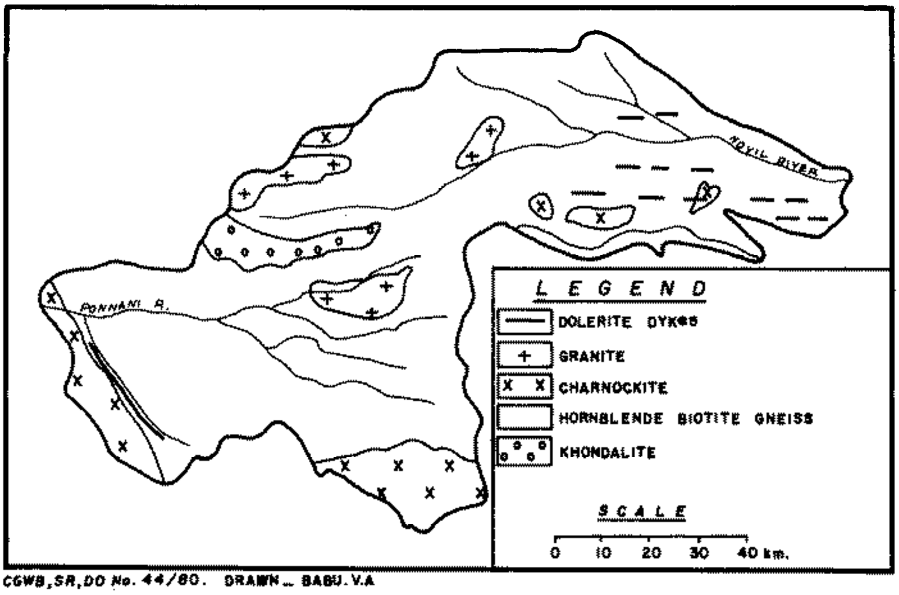


Figure 4.4.2 Geological map of the project area.

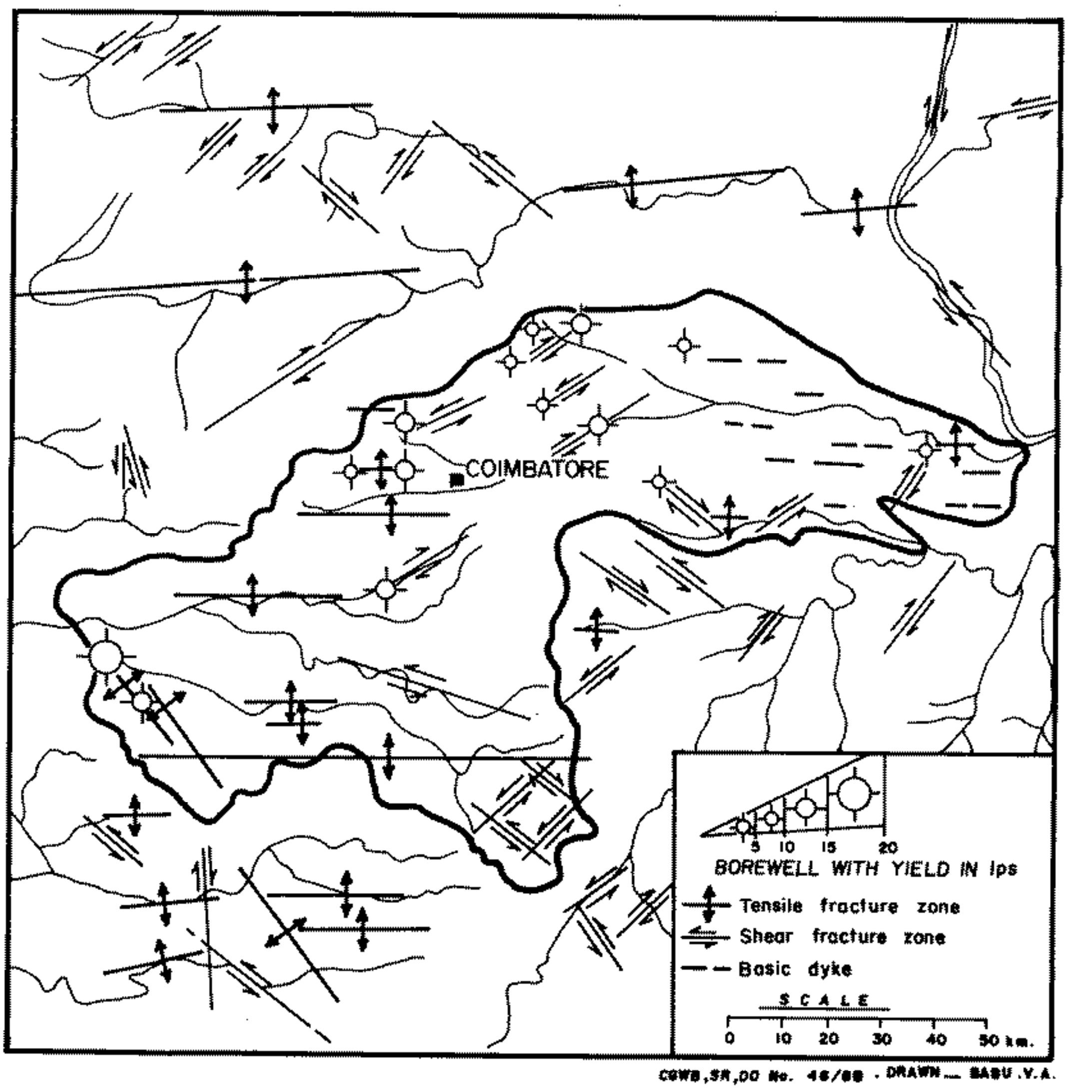


Figure 4.4.3 Regional tectonic map.

4.4.3 TECTONICS

Joints parallel to foliation are very common in almost all rock types. However, the density of these joints is comparatively less in charnockite than in gneiss. Sheet joints are common in granites as well as in charnockite, but they become widely spaced, tight and infrequent in depth as can be observed in quarries and well sections. Joints perpendicular to the fold axes were observed in areas where the rocks are strongly folded as in the crystalline limestones and calc-granulites around Madukkarai. These joints are syntectonic to grain fabric and fold axes. They were developed during regional folding and metamorphism of the rocks.

Apart from these joints which were developed during plastic deformation, the area is marked by vertical to sub-vertical deep seated fractures which occur as long, narrow zones (lineaments) in the basement rocks. These zones were located from aerial photographs and Landsat imagery and a regional fracture pattern map was prepared (Figure 4.4.3). This map indicates that the fractures are connected to brittle deformation – which appears to be posterior to the main period of folding and regional metamorphism – as they develop uniformly over long distances irrespective of metamorphic structures and fold axes. The age of the fractures is unknown. They have possibly been derived from several periods of tectonic activity.

Over a major part of the project area a set of fracture zones with E-W, ENE-WSW and WNW-ESE trends is intense and persistent. These fracture zones control more or less the major drainage pattern in the area. In the southwestern part of the area, another set of fracture zones with N-S, NNW-SSE and NW-SE trends were observed. This set appears to be younger, as displacement of the first set of fractures by the second was often observed.

In the course of detailed geological and hydrogeological studies it was observed that unmetamorphosed basic dikes invariably occur trending either in E-W or NNW-SSE direction, i.e. parallel to two of the six major fracture directions observed in the area. Geophysical surveys carried out across fracture zones with these directions indicate that they are generally wide and composed of multiple fractures separated by thin plinths of massive rock. On the other hand, the fracture zones trending ENE-WSW, WNW-ESE, N-S and NW-SE were found to be highly crushed and often weathered to greater depths. Slickensides are very common in the fractures, indicating movements along the fracture planes. These zones have much lower resistivity values than the E-W and NNW-SSE fracture zones.

In the charnokite hill ranges in the northwest and all along the Anamalai hill range forming the southern boundary of the project area, well developed overthrust planes, with low to moderate dips towards the east and the west were observed.

By analysing systematically the regional pattern and taking into consideration the above mentioned field evidence, the following tectonic history of the area was inferred:

1) Folding and regional metamorphism of a variety of rocks of sedimentary and igneous origin by N-S compression, resulting in the formation of E-W trending isoclinal folds, and metamorphism under amphibolite-granulite facies conditions.

2) Brittle deformation of the solid rocks by E-W compression, resulting in the formation of E-W tensile fractures and ENE-WSE and WNW-ESE shear fractures all over the area.

3) Second phase of brittle deformation probably connected to west coast faulting, affecting only the southwestern parts of the area with the formation of NNW-SSE trending tensile fractures and N-S and NW-SE trending shear fractures.

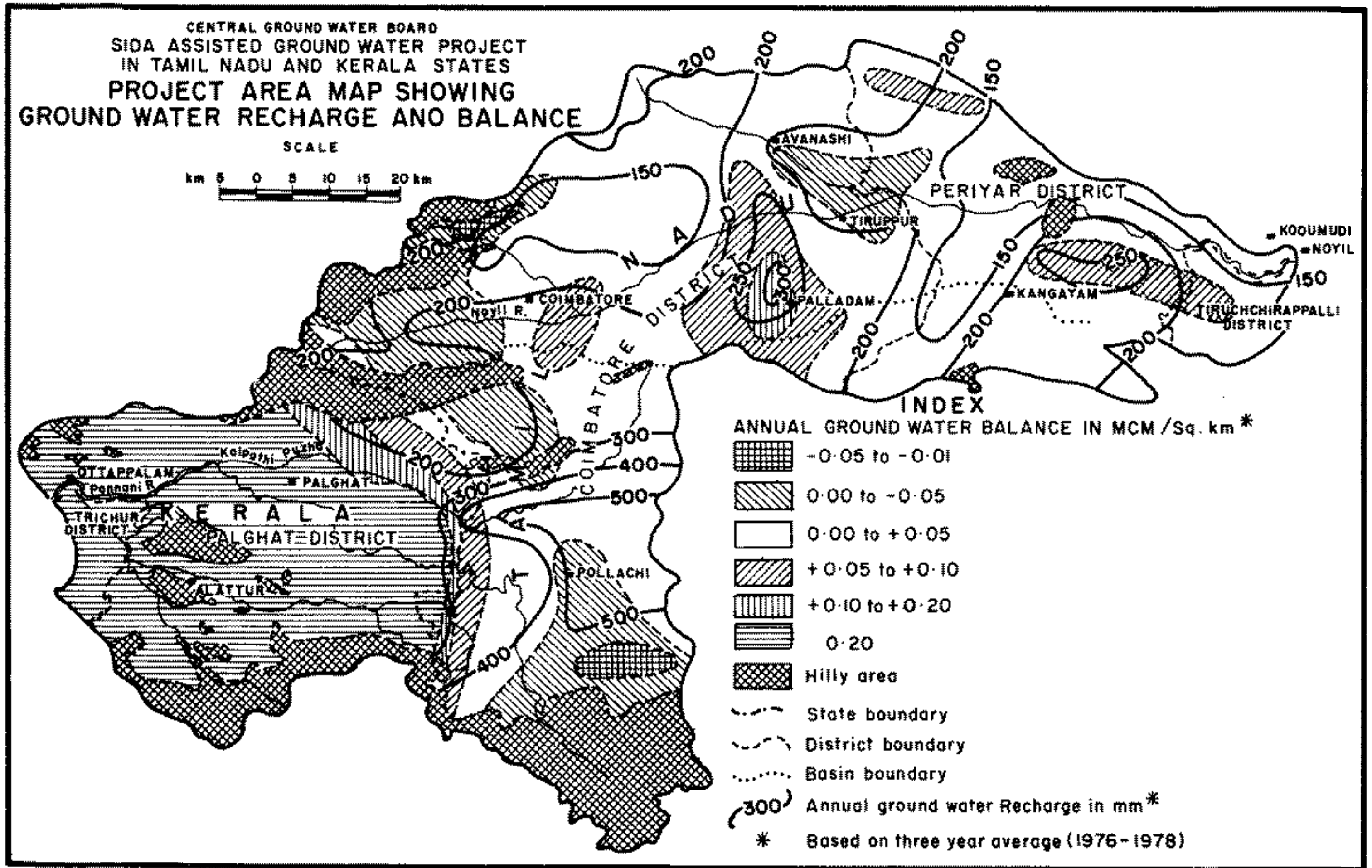
4.4.4 HYDROGEOLOGY

The hydrogeological studies aimed at determining the water-bearing and water-yielding properties of the various rock types encountered in the area, defining the ground-water flow system, locating and delineating the major aquifers and their recharge and discharge areas and to evaluate their hydraulic properties.

The computed status of recharge and ground-water balance is shown in Figure 4.4.4.

The methodology developed for locating sites for exploratory drilling can be summarized as follows:

1. Studying the geology, structure and ground-water conditions of the area by systematic hydrogeological surveys.
2. Studying aerial photographs and Landsat imagery to locate possible lineaments.
3. Ground checking of these lineaments and eliminating those which, due to local geological and hydrogeological conditions, are not suitable for further exploration.
4. Demarcating suitable areas and delineating traverse lines for surface-geophysical surveys.
5. Employing appropriate surface-geophysical methods to pinpoint suitable drilling sites.



CGWB, SR, D.O. No. 50/80. Delt – K.R.RAO.

Figure 4.4.4 Computed status of recharge and ground-water balance.

Of the 53 exploratory wells drilled, one was abandoned at a depth of 23 m due to large cavities and boulders with limestone. The maximum depth drilled was 304 m. Six wells were drilled in the granulitic area tapping crystalline limestones and calc-granulites and the remaining were drilled in granite areas. The following table gives the yield ranges of the wells:

Number	Well yield range (m^3/h)
10	5
5	5-10
13	10-20
9	20-30
6	30-40
3	40-50
2	50-60
4	80-90

The specific capacity of the wells ranges from 0.03 - 30.7 $m^3/h/m$. The aquifer transmissivity ranges from 0.62 - 535 m^3/d and the storage coefficient from 2.1 x 10 to 1.13 x 10. The aquifer parameters were evaluated by means of standard methods, i.e. Theis, Jacob and Boulton.

The yield of the wells drilled in the tensile fracture zones varies from 7.2 - 90 m^3/h while for those located in the shear fractures it ranges from 4.3 - 52.6 m^3/h. Wells located at a distance from the tectonic fractures have low yields ranging from 0.7 - 16.6 m^3/h (Figure 4.4.5).

The yields of wells located in the tensile fractures, are higher than those of wells located in shear fractures. However, wells located in shear fractures also give moderate yields, indicating that the shear fractures have been opened up due to later deformation, thus forming potential aquifers.

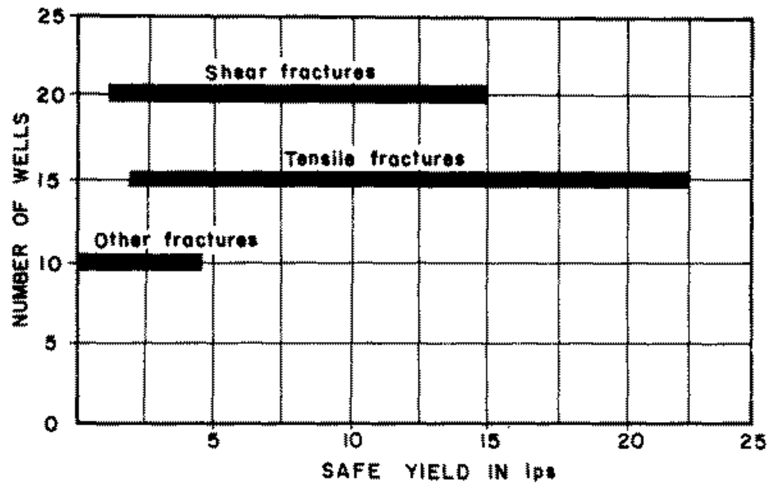


Figure 4.4.5 Yield of wells drilled in different fracture zones.

4.4.5 TECTONIC MODEL OF THE CHINNATADAGAM BASIN

The Chinnatadagam basin is a small natural drainage basin in the northwestern corner of the project area. The basin is surrounded by hill ranges on all sides except towards the east and it has a well defined watershed boundary. The drainage is from west to east.

The northern hill ranges are made up of charnockite, while the hill range on the southern side of the valley consists of granite. The central part of the basin is underlain by well foliated hornblende-biotite gneiss. Outwash material derived from the hill ranges has been deposited in the central part of the basin in the form of colluvial deposits, the thickness of which exceeds 80 m in the centre of the valley.

Outcrops of an umetamorphosed dolerite dike of about 30 m width, trending E-W, are found in the western part of the valley. This dike appears to be continuous in the east, below the colluvial cover. Seismic and resistivity surveys carried out in the basin indicate the existence of deep, E-W trending channels, cutting the basement rock in the central parts of the valley.

A prominent fracture zone with an ENE-WSW trend was located by interpretation of air-photos and satellite imagery in the southwestern part of the basin, close to the contact zone between granite and gneiss. At this locality the rocks are highly crushed with well developed slickensides indicating shearing. In the northern charnockite hill ranges and, to a less extent, in the granite hills in the south, well developed overthrust planes, dipping in moderate angles towards east and west were noticed.

Based on this field evidence, a tectonic model of the Chinnatadagam basin was constructed (Figure 4.4.6).

The basement rocks in the area have been subjected to tectonic compression in an E-W direction after they have attained solid state by regional metamorphism. The compression has produced an E-W trending set of parallel open

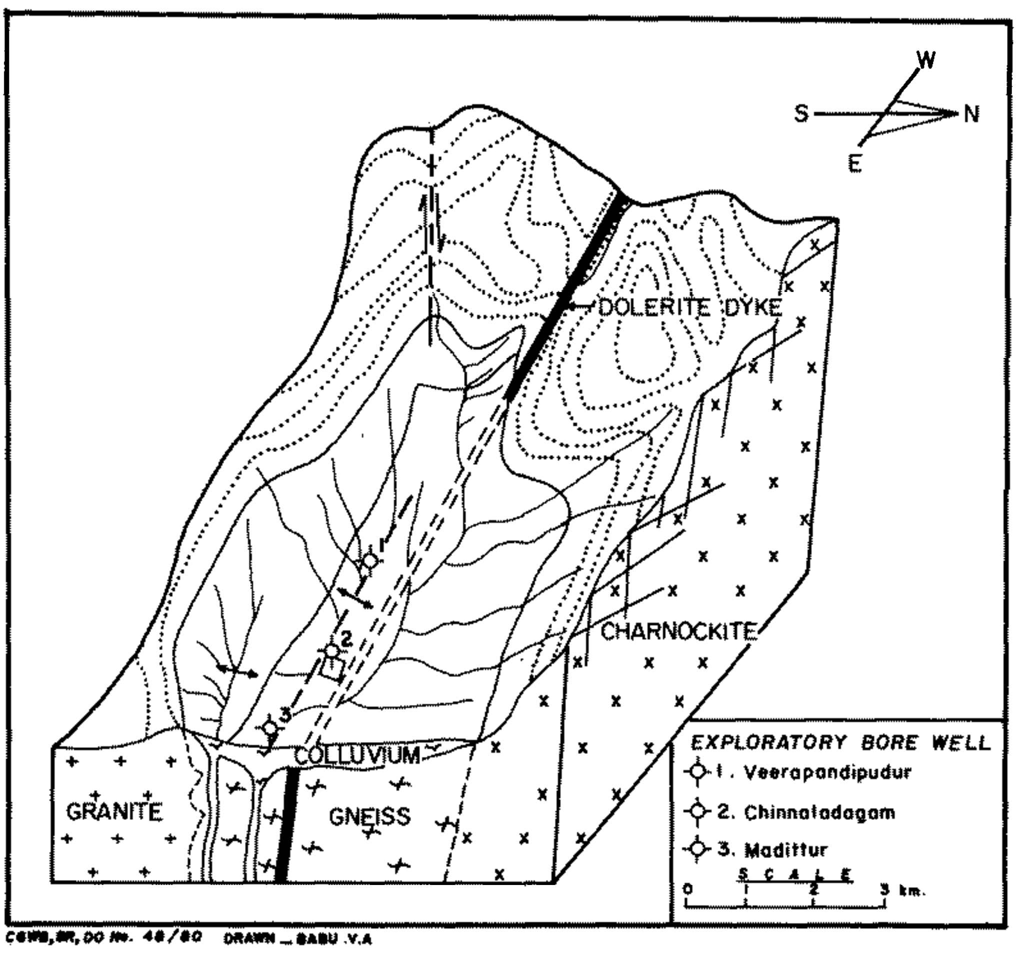


Figure 4.4.6 Tectonic model of Chinnatadagam basin.

tensile fractures, one of which is filled by the dolerite dike. The same compression has also produced the ENE-WSW shear fracture as well as the overthrusts.

Three of the exploratory wells drilled in the area are located in one of the E-W trending open tensile fracture zones. All these wells, which tap mainly the fracture zones occurring below the colluvial cover, have given high yields indicating the openness of the fractures. When water was pumped from well no. 3 during drilling operations, the water level in the open well no. 1, at a distance of about 3 km, showed appreciable fluctuations, indicating an hydraulic connection along the open tensile fracture. This means that the open tensile fractures act as subterranean channels in the basement rocks, storing and transmitting large quantities of water.

4.4.6 GEOPHYSICS

The surface geophysical methods employed, included seismic, resistivity and magnetic methods, while the geophysical logging comprised electrical, radiation and caliper logging. The resistivity surveys were used on a larger scale than the seismic surveys. AC Aquameter and DC Terrameter were used in these surveys.

4.4.7 HYDROCHEMICAL INVESTIGATIONS

To determine the suitability of ground water for domestic, agricultural and industrial use, to locate areas of probable contamination, and to study the genetic character of ground water in the project area, water samples were collected twice a year from 260 observation wells, and from 190 wells in the detailed study basins. Water samples were also collected during drilling and pumping tests. In addition, surface runoff samples and samples of rain water and atmospheric dust were taken.

The results of the analysis of the pre- and post-monsoon samples show that the mineralisation of the water generally does not show wide variation. However, variation in the individual ions can be noticed. In general, ground water in the

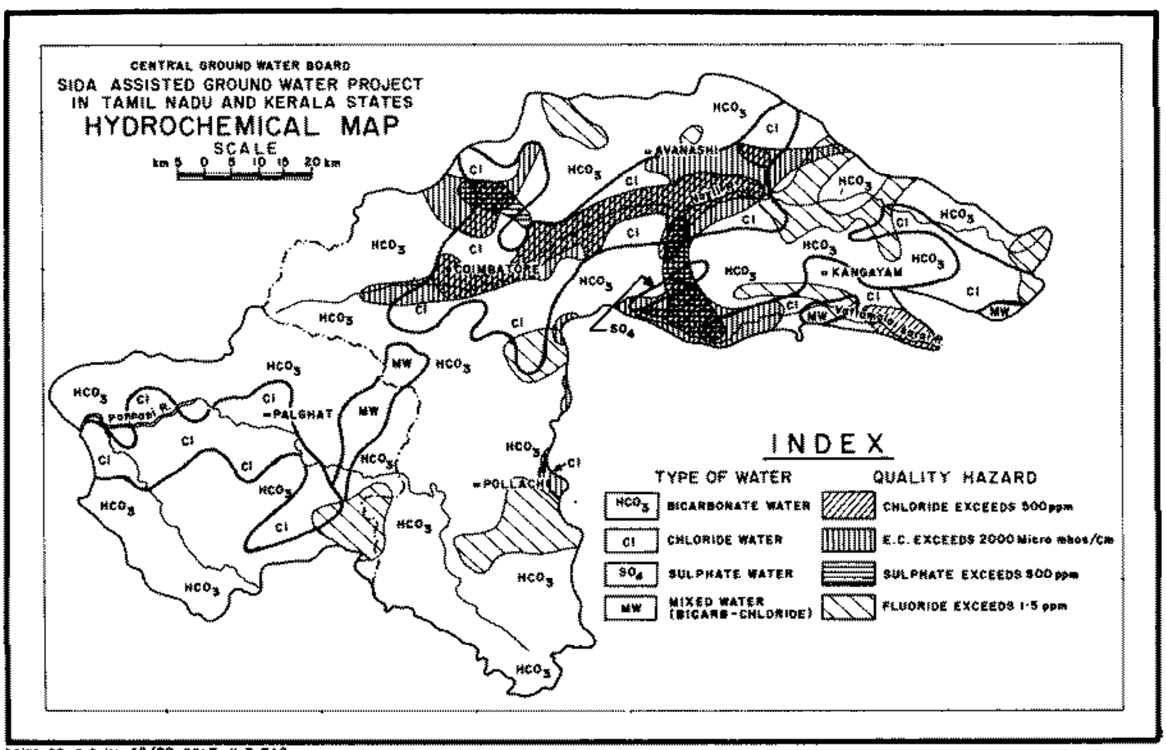


Figure 4.4.7 Hydrochemical map of project area.

Noyil and the Vattamalaikarai basins has a nitrate content in excess of the permissible limit of 50 ppm and also a higher content of salt and fluoride than ground water in the Ponnani basin. About 500 samples collected from observation wells during 1977 show that the content of trace elements present fall within the permissible limits for drinking water. The genetic characteristics and type of ground water are to be studied after completion of the analyses.

Water samples collected during pumping tests in 53 exploratory wells and about 200 samples collected during drilling have been analysed. The results show that the water generally is good for general use, except at a few localities. Some of the water samples have moderate hardness and moderate chloride content. Sulphate and nitrate concentrations are usually low. The water appears to be of bicarbonate and/or chloride type.

In order to find out the origin of deep ground water in the Chinnatadagam basin, 6 samples were analysed for ^{18}O. The results indicate a variation of $\delta^{18}O$ from -5.17 to -7.37 in relation to the reference standard SMOW and this can hardly be explained entirely by origin from rainfall at different elevations. The low depletion values may be due to enrichment of surface water. Hence, it was decided to collect samples for tritium and ^{14}C analysis, from a close network of wells, to asssess the origin and age of the ground water. The results are still awaited.

As a part of a salt balance study, samples are being analysed and the results will be used to compute the salt carried during flood discharges. In order to assess the amounts of salt transported through dust in the atmosphere and dissolved in rain water, four strategic stations coinciding with the four meteorology stations were established in the area. Periodic collection of samples of atmospheric dust and rainwater was made for chemical analysis to determine the sodium and chloride content.

Chemical analysis of water samples from certain areas have shown a fluoride content above the permissible limits for drinking water (Figure 4.4.7). Laboratory studies have shown that the high fluoride content in some areas is genetically related to the occurrence of soluble fluoride present in the form of the calcareous precipitate called "kankar." Such occurrence seems to be connected with slightly alkaline soils.

An experiment was carried out to study the effect on fluoride content of gypsum powder sprinkled around two wells in a village where four wells have been subjected to periodic studies of fluoride behaviour. The results indicate some lowering of fluoride concentrations in these two wells. However, a final conclusion may only be reached after observations have been carried out over a longer period of time.

4.4.8 SUB-SURFACE DAM

Ground water which is under the influence of a hydraulic gradient is under continuous motion from higher to lower levels through the aquifer. Like surface water flowing in a river, ground-water flow can be arrested by building an impervious wall or dike across the flow direction. Such sub-surface dams are feasible in narrow valleys with bedrock at shallow depth. The dike need not be thick and there is no need for any buttress as the passive earth pressure of the soil will compensate the water pressure. Various materials such as clay, tarred felt or polythene sheets can be used besides brick and concrete depending on the local conditions and availability. The underground structure need not project above the surface but can be finished at a depth of 1 m below land surface.

A 140 m long dike was constructed in the Palghat district, using brick, tarred felt and polythene sheets in different sections (Figure 4.4.8). The excavation, the construction of the dike and of the jack well and infiltration wells took 3 months to complete. The total cost was US $ 8 000. The water arrested by the dike can be used for irrigation of an area of 6 hectares, thus making it possible to grow a second crop of paddy and a third crop of black gram.

4.4.9 CONCLUSIONS

1. A methodology was evolved for ground-water exploration in hard rock areas by integrating photogeological, geological, hydrogeological and geophysical surveys. The selection of the exploratory-well sites was based on the methodology developed. Out of 53 exploratory wells drilled, 40 wells yield more than 10 m^3/h and the specific capacity ranges from 2.83 - 1 086 l pm/m drawdown.

2. Various parameters of the water balance were estimated using data from a network of observation stations.

3. An analysis of water level data from a network of observation stations has indicated that except for a small area in Chinnatadagam and the area around Coimbatore, there is no evidence of overdraft which would warrant arresting further ground-water development.

4. Recharge to ground water from rainfall and canal flow over the basin was estimated. It was found that the recharge ranges from 5.7 per cent in the Kerala part of the Ponnani basin to 12.2 per cent in the eastern parts of the Noyil basin. The net recharge to ground water was found to be low in areas where the ground-water development is negligible. This

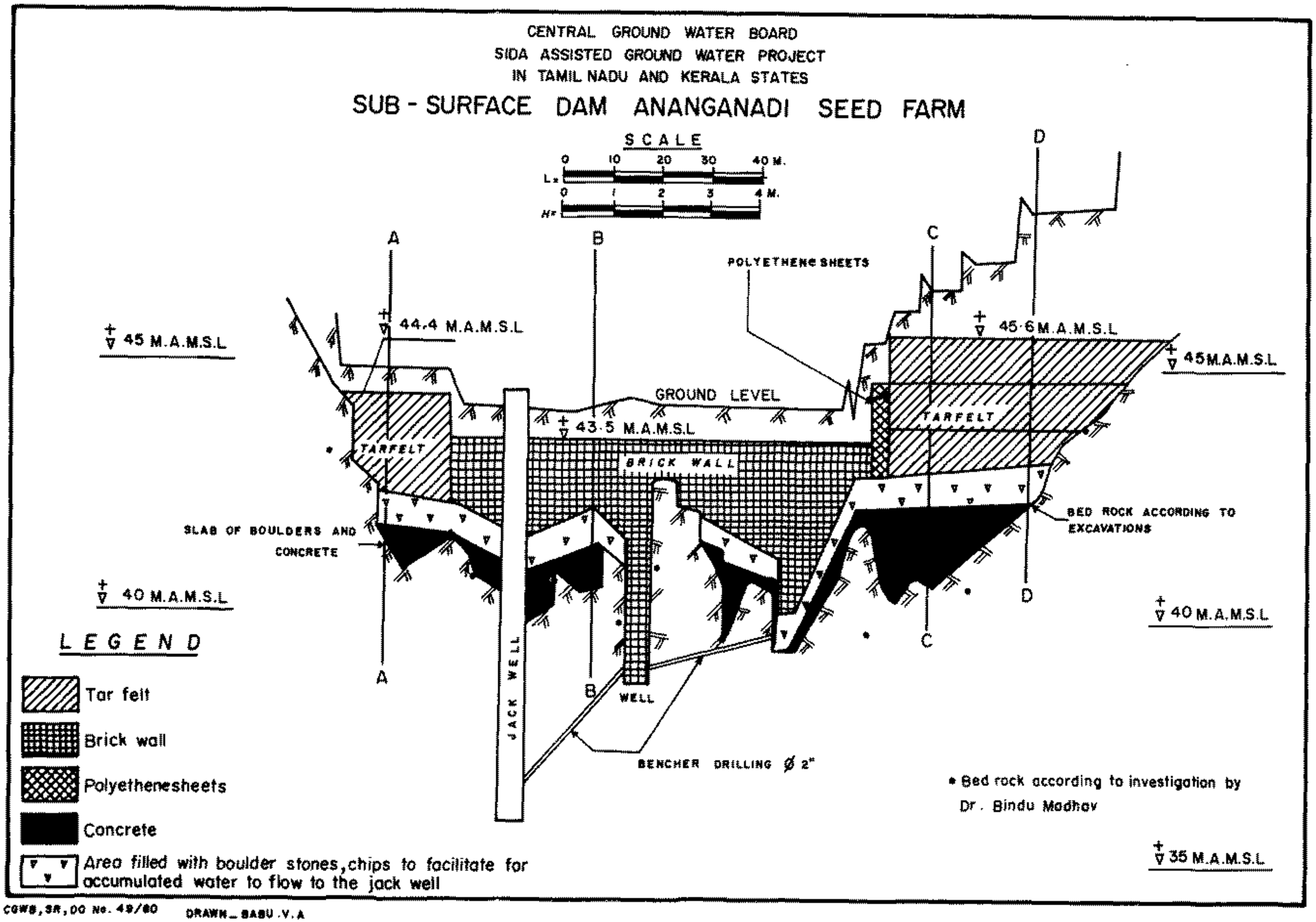


Figure 4.4.8 Sub-surface dam.

indicates that the ground-water reservoir gets fully saturated at the onset of the monsoon, allowing most of the precipitation to leave the area as surface runoff. Such areas have high potential for further ground-water development.

5. Fractured rock aquifers were located at depths of more than 150 to 200 m in hard rock areas. The geometry of the aquifers and the ground-water flow system in them were defined.

6. An experiment of arrest of ground-water runoff by constructing a sub-surface dike was carried out.

7, Areas with poor ground-water quality and hence of limited suitability for domestic and agricultural use were identified. Experiments on the causes of high salinity and excess of fluoride were carried out and remedial measures for arresting deterioration of the chemical quality of the ground water were suggested.

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The complete list of references used in this case history is given in:

Baweja, B. K.; Raju, K. C. B. 1980. A case history of ground water potential of hard rock areas in Noyil, Amaravati and Ponnani Basins, South India. Report to the Central Ground Water Board, New Delhi.

4.5 *GROUND-WATER INVESTIGATIONS IN A GRANITE AREA OF SARDINIA, ITALY*

by Ingemar Larsson*

4.5.1 INTRODUCTION

The present case history is a condensation of a scientific report on "Geohydrological investigation of ground water in granite rocks in Sardinia" (Barrocu and Larsson, 1977). The investigations were carried out between 1975 and 1977 by a team of scientists from the Department of Land Improvement and Drainage, Royal Institute of Technology, Stockholm and from the Department of Applied Geology, Faculty of Engineering, University of Cagliari, Italy.

The purpose of the investigations was to study the storage capacity of a fracture pattern of a typical drainage basin in a granite terrain. The hydraulic conductivity of different types of fractures (tensile and shear) and of fractures of different orders were investigated by means of an exhaustive drilling and test-pumping programme. A rough estimate of the effective fracture porosity of the rock (storage capacity) was made.

The studies of ground water in fractured rocks were limited to granite areas, which occupy half of the northern part of the island. In the southern part only minor areas are granitic. The research team studied several areas, whose names are shown in Figure 4.5.1. The present case history, however, is limited to the Santa Margherita area.

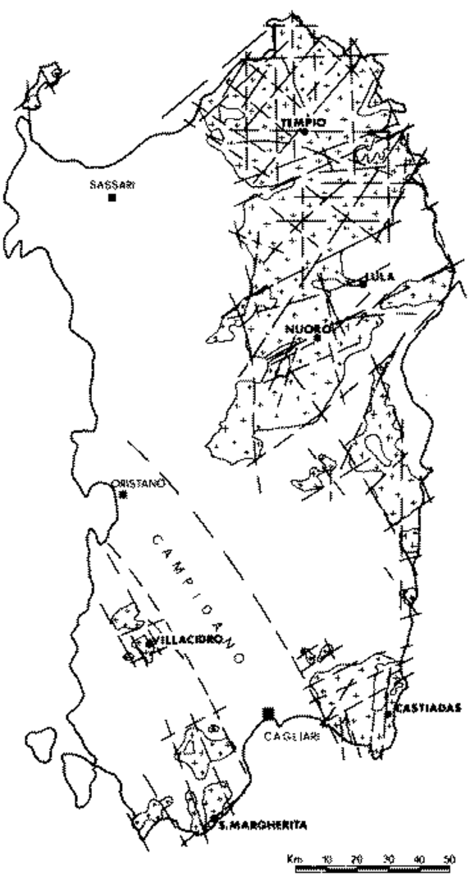

Figure 4.5.1 Geotectonic sketch map of granite areas of Sardinia (Barrocu and Larsson, 1977).

4.5.2. PLAN OF ACTION

The hydrogeological and hydrological investigations at Santa Margherita followed more or less a standard model of investigation, as follows:

1. Supplementary land surveying. Contour mapping using aerial photographs and stereo plotter.
2. Setting up of rain gauges. Construction of runoff stations.

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3. Regional geological mapping. Petrology of the main rocks.
4. Tectonic studies. Plastic deformation of the rocks (folding). Brittle deformation, rock fracturing.
5. Investigation of soils and weathered rocks.
6. Establishment of general working hypothesis for the rock fracturing of the area.
7. Geophyisical control of the tectonic hypothesis by magnetic, geoelectric and seismic surveys.
8. Adjustment of the tectonic hypothesis according to the results of the geophysical investigations.
9. Planning of drilling scheme aiming at:
   a. investigating the hydraulic conductivity of different types of fractures (tensile and shear).
   b. investigating the storage capacity of the two sub-basins, upper and lower. The upper is mainly controlled by shear fracture zones. The lower is controlled by an open tensile fracture and a shear zone.
10. Drilling of wells for pumping tests and for observation of ground-water levels.
11. Test pumping.
12. Computation of storage capacity of sub-basins and of total basin.

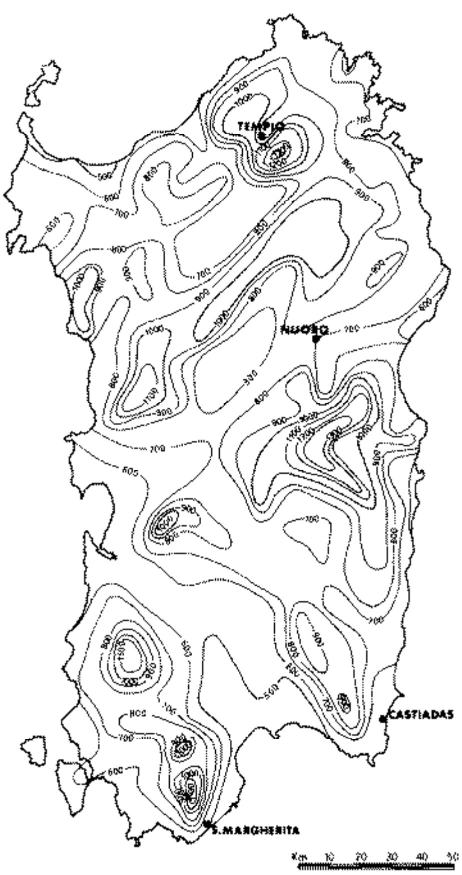

Figure 4.5.2 Annual rainfall in Sardinia, in mm (1921-1960). (From Puddu, 1977.) (Reprinted by permission.)

4.5.3 HYDROLOGY

Precipitation in Sardinia is rather unevenly distributed geographically (Figure 4.5.2). In the mountains the rainfall exceeds 1 000 mm/year, while in the deep valleys, in rain shadow, it barely reaches half that amount. In the Santa Margherita area the rainfall does not exceed 500 mm/year.

The runoff in Sardinia is generally low or nil, especially in small basins. Exceptionally, however, the flow rate during floods may reach values of several $m^3/s/km^2$. In the areas studied measuring weirs and rain gauges were installed (Figure

4.5.3).

The total area of the Santa Margherita basin is 0.45 km^2. Two sub-basins are found within this area, an upper basin with an area of 0.34 km^2 and a lower basin with 0.11 km^2. In each of the two sub-basins runoff gauging stations have been installed.

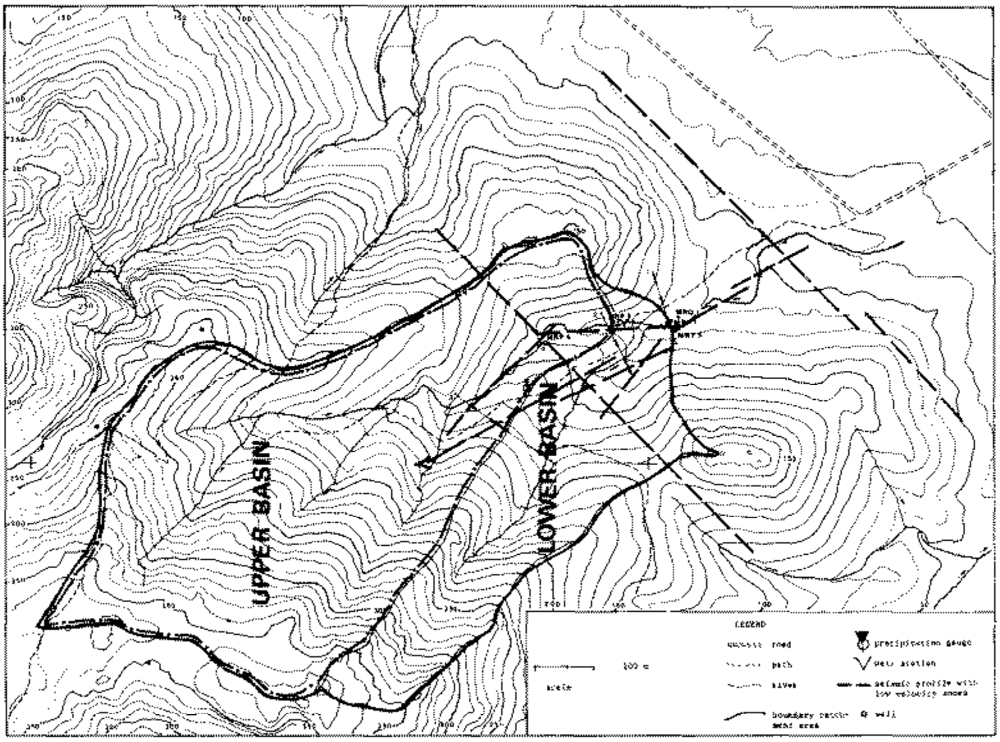

Figure 4.5.3 The Santa Margherita basin.

4.5.4 TOPOGRAPHY

The Santa Margherita area is situated on the coast of the Mediterranean Sea, in the SW part of Sardinia, where the highland ends against a narrow coastal plain. The slopes of the highland are cut by several short ephemeral streams, draining small basins. The hydrogeology of one of these small basins was studied in detail. In the present case history only some of the methods and results from this work are described.

4.5.5 GEOLOGY AND TECTONICS

In order to investigate adequately the occurrence of ground water in fractured igneous and metamorphic rocks it is very important to find out the general tectonic history of the region on a large scale, before the detailed study of the actual area begins. Such a general study must include the epochs of folding as well as those of brittle deformation.

Only through such a procedure will the hydrogeologist be able to analyse the fracture pattern of the rock in order to separate open, tensile fractures in the rock from closed, impervious ones. This procedure was used in the present investigation.

4.5.6 GENERAL STRUCTURE

The islands of Corsica and Sardinia are described as remnants of the original continental crust which constituted the floor of the Tethys sea after the Hercynian orogeny (van Bemmelen, 1972). In Mid-Cenozoic geodynamic processes occurred, during which Central Europe was affected by compressional stresses from SE towards NW.

These movements occurred along two major shear zones, which traversed Europe in a NW-SE direction. The westernmost of these fracture zones is considered to have extended from the Bay of Biscay to the southern margin of the British

Isles and Ireland. The zone farthest east was traced from Ukrania through Poland, the Baltic Sea and the southern tip of Sweden towards NW between Denmark and Norway. Through this mega-tectonic process the southern coast of France was pulled towards the NW for hundreds of kilometres.

This pull towards NW developed two major graben systems in the western Mediterranean. One of these, the Campidano graben, cuts the island of Sardinia into two blocks. Different kinds of volcanic activities in the graben show that this structure was opened up by compressional stress in the NW-SE direction during which tension (pressure relief) developed perpendicularly to the direction of compression, that is, in the SW-NE direction (Figure 4.5.1), (van Bemmelen, 1972).

This mega-tectonic pattern must, of course, be reflected on minor scale in the "local" tectonic pattern of the rocks. Swarms of dikes, parallel to the Campidano graben and therefore also parallel to the direction of the mega-tectonic deformation, intersect the southern part of the island. This is a striking proof that the mega-tectonic pattern also has had a strong influence on the local fracture pattern.

4.5.7 LOCAL STRUCTURE

The dominant rocks in the Santa Margherita area are coarse-grained granites of two varieties, one porphyritic and the other an even-grained type. Locally, veins or slabs of aplite appear. It was observed that the aplites are more fractured than the granite. Dikes of lamprophyre intersect the granite, striking NW (Figure 4.5.3). They generally have a width of 1 to 6 m. They are mostly vertical or subvertical. All the rocks are strongly weathered in flat areas to about 10 - 12 m. In fractured zones more than 40 m of weathered rock were observed in well drilling.

4.5.8 PLASTIC DEFORMATION

During the granite intrusion a sort of axiality was developed, striking NW. This axiality has not been observed macroscopically; it is hypothetically assumed in view of the rock fracture pattern with a typically tensile character. This kind of fracture pattern generally appears perpendicularly to a fold axis or an intrusion axiality.

The characteristic feature of these fractures is that they are rarely interconnected. They usually are very short, are open in the middle and narrow towards the ends. Because of this characteristic they have a very low ground-water storage capacity in spite of their high frequency of occurrence. Rocks with these kinds of fractures are generally poor aquifers.

It should be noted, however, that this fracture pattern creates a general weakness in the rock strength in a certain direction – in this case in a NE-SW direction – which can be "used" by later deformations. They are termed ac^1-planes and are observed as a weak pattern in a NE-SW direction. (Cf. Section 2.1.2.)

4.5.9 BRITTLE DEFORMATION

It has already been stated that the mega-tectonic processes in SW Sardinia must have been reflected in the "local" tectonic pattern. Swarms of dikes which are developed parallel to the Campidano graben indicate deep local fracturing of the crust. The actual drainage basin under investigation is also intersected by a set of dikes.

The bottom of the main valley is cut by a wide fracture zone, 1 - 1 (Figures 4.5.3 and 4.5.4). This fracture is hypothetically considered to be an open tensile-fracture zone. Minor fracture zones, 2a, 2b and 3 are considered to be shears, syntectonic to the tensile zone.

Two parallel major fault lines (normal faults) intersect the mountainous inland, which slopes in a step-like manner towards the sea (Figure 4.5.3). Between the two faults two major blocks A and B are situated. They have been formed by erosion concentrated along the surrounding fault lines.

In outcrops around the blocks typical shear fractures with slickensides are arranged in a clockwise manner, especially around the black B. These structures indicate that the blocks probably have been rotated slightly clockwise by shearing effects. The movement has possibly taken place on deep flat-lying overthrusts.

The tectonic model of the basin is quite similar to Larsson's model described in Section 2.1.2.3. The hypothetical fracture pattern was clearly confirmed by seismic investigations. Low-velocity zones (Figure 4.5.3) apparently correspond to the fracture zones in the rocks. According to the tectonic model the central tensile fracture – if not filled by a dike – was considered to be an open fracture. Unfortunately it was impossible to carry out a magnetic survey owing to the presence of a high tension power line which crossed the basin.

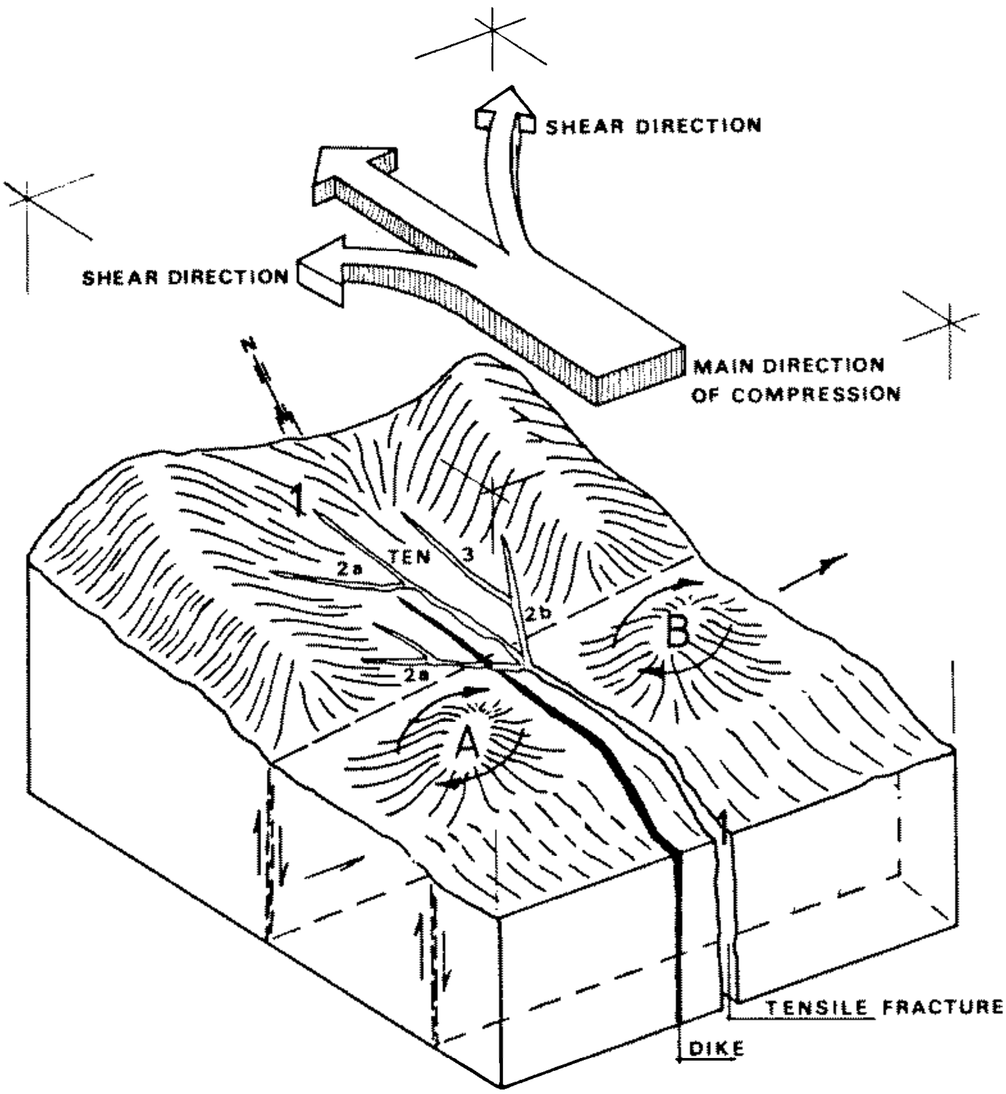

Figure 4.5.4 Block diagram illustrating the fracture pattern of the Santa Margherita area.

The shears 2a and 2b are considered to be somewhat closed, as it is normal with shears. The assumed rotation of the tectonic blocks A and B may have either closed or opened the shears. Shear 2b is considered to have remained closed after the rotation, while the two 2a shears should have been opened to some extent. This problem is again discussed in the Section on hydrologic analysis.

As a working hypothesis the ground water in the basin was considered to be collected in the smaller fractures, fed into the main tensile fracture 1 - 1, and thence drained into the sea. At the constriction between the two blocks, the subsurface drainage was considered to be concentrated (Figure 4.5.4).

4.5.10 HYPOTHETICAL "ANATOMY" OF THE FRACTURE PATTERN OF THE BASIN

On the basis of the tectonic investigations and geophysical control, the fracture pattern of the basin could be described as follows (see Figure 4.5.3).

1. The fracture zone 1 - 1 is considered to be an open (tensile) fracture zone, which collects the subsurface water from the whole basin. The constriction between the two tectonic blocks A and B is considered to be the best place for drilling a production well.

2. The two 2a shears are considered originally to have been closed, being typical shears. The assumed clockwise rotation of the blocks A and B seems to have opened these shears to some extent.
3. The shear 2b is considered to have stayed closed due to the above mentioned rotation.
4. The fracture zone 3 although also a shear diverges in direction from the general shear direction (WNW - ESE, and N - S). Its connection to the other fractures is not quite clear.

4.5.11 WELL DRILLING AND PUMPING TESTS

The test drilling programme was planned with the purpose of testing the hypothetical tectonic prediction of the storage capacity in the different types of fractures and to obtain a quantitative measure for the "gross storage capacity" of the whole fracture system (Rosén, 1977).

In accordance with these considerations a well, MRP-5, was drilled in the assumed tensile fracture. The well was sited in the constriction between the two tectonic blocks, A and B. Close to the well two other boreholes, MRP-1a and 1b, were also drilled. MRP-1a unfortunately collapsed, due to the heavy fracturing of the rock.

Two additional wells, MRP-2 and MRP-3, were drilled in the shear fractures. The following discharge rates were obtained during test pumping of these wells:

	MRP-5	Shear-2b MRP-2	Shear-2a (north) MRP-3
Tensile fracture	1.5 m^3/h	–	–
Shear fractures	–	0.03 m^3/h	0.14 m^3/h

These results illustrate very well the contrast in the storage capacity between tensile and shear fractures. Furthermore, the relatively low yield (0.03 m^3/h) of well MRP-2 as contrasted with the relatively high yield (0.14 m^3/h) of MRP-3 gives additional support to the rotation hypothesis described above.

Another way of studying the difference in storage capacity between tensile and shear fracture zones was made possible by the occurrence of a heavy rainstorm. On one occasion, during the pumping period, 61.8 mm of rain was recorded during 5 hours on the basin. The rate of runoff measured in the upper basin was 79 m^3/h. During the same period the runoff from the lower basin was measured at 90 m^3/h. The upper basin had a specific runoff of only 2.1 $m^3/s.ha$ (Figure 4.5.3). This indicates that the lower basin produced considerably less water per unit area of catchment as surface runoff than the upper basin. The reason for this difference is probably that tensile fractures control the lower basin. This means high rate of infiltration into the open fractures. The upper basin, on the other hand, is controlled by shear fractures which permit considerably less infiltration. Therefore the upper basin had a higher rate of runoff during the rain storm.

Some interesting observations have been made regarding the drawdown curves obtained in the test pumping of the wells. At first the wide fracture zones were emptied. In the undisturbed state the ground-water level in these fractures is relatively high. During pumping the water level dropped sharply to a lower level which is sustained by the narrow fractures. This "two-step" type of drawdown is frequently observed.

On the basis of these pumping tests a calculation has been made of the total fracture volume of the drainage basins. The specific storage capacity (ratio storage capacity/fracture depth) of the wide fracture zones of the area was found to be 600 m^3/m of fracture depth. The corresponding volume for the narrow fractures was found to be 2 000 m^3/m of fracture depth. That means that the wide fractures represent 11 per cent of the total fracture volume and the narrow ones 89 per cent.

If the average depth of the fractures in the area (45 ha) is considered to be a minimum of 10 m, the total fracture volume in the area should be around 30 000 m^3, that is 0.6 % of the rock volume. This estimate of a minimum depth of 10 m is very conservative. In effect, in several wells drilled in the area, wide as well as narrow fractures have been found at depths of 50 metres or more. Therefore a total fracture storage of about 50 000 m^3 seems reasonable.

4.5.12 CONCLUSIONS

The results of this type of investigation of the storage capacity of the fracture system of an area can be extrapolated to neighbouring areas. By using photogeological methods the fracture patterns of other areas with a similar type of tectonics can be studied. Tensile and shear fractures can be identified and by careful comparison with the characteristics of the "master area" rough calculations can be made of the potential storage capacity of larger areas. However, disturbing phenomena, such as changes in rock-fracture type, etc., must be taken into consideration.

The next step in the application of this kind of technology would be to seal off the fractures "downstream" by a subsurface dam thereby considerably increasing the ground-water storage in the area (cf. Case history 4.4).

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4.6. *GROUND-WATER DEVELOPMENT IN PRECAMBRIAN ROCKS OF THE KARAMOJA DISTRICT, UGANDA*

by Robert Dijon*

4.6.1 INTRODUCTION

The Karamoja District in northeastern Uganda covers an area of about 25 000 km^2 to the north of Lake Victoria. Most of the region is part of an extensive featureless plain bordered by hills with Cenozoic volcanoes to the east along the Kenya frontier. The plain, which is dissected by incised river channels, has a general altitude of about 1 500 m above sea level. The annual rainfall in the region ranges from 1 200 mm in the south to 500 mm in the north with an average of about 800 mm. It is estimated that about 90 per cent of the annual rainfall is lost by evapotranspiration. The rainy season extends from April to August.

4.6.2 GEOLOGY

With the exception of the volcanic areas, the region is underlain by Precambrian metamorphic rocks which include acid gneiss, hornblende, biotite gneiss and granulite quartzite. In most places these are deeply weathered and locally are covered with thin alluvial deposits in river valleys and in small alluvial fans.

4.6.3 RESULTS OF EXPLORATORY WORK

A hydrogeological investigation of the Precambrian areas of the Karamoja District was undertaken by UN/UNDP to locate sources of ground water for newly created villages and also where possible, small-scale irrigation. The work included a field hydrogeological reconnaissance; an inventory of water wells and ground-water levels, water temperature and water-quality measurements; photointerpretation of features of hydrogeologic interest such as faults, crushed zones, alluvial fans, drainage patterns and alluvial valleys; and geophysical investigations using electrical resistivity profiling and sounding and seismic refraction methods. In addition to the above, 92 wells were drilled by cable-tool rigs to an average depth of 122 m and finished with 6-inch casing. Most wells penetrated at least 30 m into unweathered bedrock. Some wells were blasted to test the feasibility of increasing well yields. Pumping tests were carried out by bailer and cylinder pump. Where yields exceeded 5 m^3/h pumping tests were continued for 24 hours or more.

The pumping tests indicate, on the average, individual well yields of a few cubic metres per day when equilibrium pumping levels are reached. Commonly, however, pumping levels decline by steps as successively deeper fractures are dewatered during pumping cycles of 24 hours or more. Statistical studies indicate that the likelihood of encountering water-bearing fractures decreases rapidly with depth and that the optimum yields and specific capacities are obtained from wells with depths ranging from 45 to 80 metres. The relationships of depths, yield and specific capacity among 92 6-inch wells are shown in the following table:

No. of wells	Depths m	Average yield m^3/h	Average specific capacity m^3/h/m drawdown
10	15- 45	6.1	3.6
24	45- 80	12.2	4.3
14	80-100	7.9	1.8
38	100-140	4.0	1.08
6	140-150	2.0	0.18

It was also found that the productivity of a well is related to its geomorphic setting as follows:

Flat valley with well defined valley bottom: 14 wells drilled of which 13 were productive with an average yield of 14.4 m^3/h.

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Alluvial cover over Precambrian rock adjacent to a stream channel: 45 wells drilled of which 39 were productive with an average yield of 7.2 m^3/h.

Open flat plain or gently sloping pediment: 11 wells were drilled of which 8 were productive with an average yield of 3.6 m^3/h.

Transition pediment between hills and flat plain: 14 wells were drilled of which 8 were productive with an average yield of 2.5 m^3/h.

Divide in hilly area: 8 wells were drilled of which 2 were productive with an average yield of 1.8 m^3/h.

5. Conclusions

In spite of the fact that hard rocks generally have a smaller storage capacity than granular formations, ground water can be found almost everywhere in hard rock areas, provided recharge is adequate.

Ground-water yields in hard rock areas are usually suitable for the supply of villages, farms and livestock in rural areas. However, except in monsoon areas, the yields are seldom sufficient for irrigation purposes.

In the previous chapters the great variations in the occurrence of ground water in hard rocks and its dependence on a large number of parameters have been described. Emphasis has also been put on the complexity, diversity and sophistication of the technologies and methodologies utilized in the exploration and development of ground water in hard rock areas.

It has to be borne in mind that the majority of hard rock areas of the world are situated in tropical regions which coincidentally are among the least developed. While the technological tools are ready for use, many countries do not have either the financial resources to acquire the necessary equipment and to operate it, or the qualified personnel to handle it.

It is therefore necessary to develop a strategy for the exploration and development of ground water in hard-rock areas including the determination of the most durable, efficient and economical means for the siting, construction and exploitation of wells in such areas.

This strategy includes:

1. Defining and assessing the parameters which determine the storage capacity of hard rock aquifers.
2. Making proper use of ground-water exploration methods and using them in a step-like manner (cf. Section 3.3.2) starting with simple methods in the beginning and proceeding to more sophisticated ones as the need arises.
3. Initiating as soon as possible in the course of the investigation process a preliminary assessment of the potential ground-water resources of the area in question. Whenever the amount of ground water available is judged insufficient to furnish the required supply, consideration should be given to alternate sources of supply such as surface water transported overland by canals or pipe lines. Expensive hydrogeological investigations would not be required in such cases.
4. Finding short-cuts in the process of determining favourable sites for wells. To that effect, it is necessary to maximize the use of satellite imagery and air photographs through the use of adequate interpretation methods focusing upon structural and geomorphological features.
5. Limiting costly field surveys to an acceptable minimum. In particular, it is felt that determination of site-type catagories on the basis of geomorphological and geological criteria may enable optimization of the use of geophysics.
6. Using appropriate drilling technologies and limiting exploratory drilling to geologically appropriate locations and by optimizing borehole diameter, depths, and materials selection (e.g. casing, screens, etc.).
7. Assessing the ground-water potential of the aquifers in a realistic manner, through pumping tests adequately planned and organized, using appropriate equipment and computation methods and taking into account the heterogeneity and anisotropy of hard rock aquifers. It is important to note that, in a number of cases, the storage capacity of hard rock aquifers is limited and the ground-water reserve may be exhausted after a short dry period. Therefore it is necessary to analyse the climatic and hydrologic data as recharge through rainfall and runoff can only produce infiltration during a a few days in a short rainy season each year. It may also happen that water quality will deteriorate with time if pumping rates are too high.
8. Selecting the well-construction and water-extraction methods most appropriate for such terrains, taking into account their cost, the skills of local personnel, the scale and logistics of the operation, the local traditions and the sociological factors. In particular, a choice will have to be made between the digging of large diameter wells, and the drilling of tubewells.

The hydrogeology of hard rocks is a young science. As yet, many scientific tools are missing for proper qualitative as well as quantitative calculations concerning hard rock aquifers. The aim of the present work is to show the more basic tools for a proper understanding of the problem of ground water in hard rocks.

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To attain these goals it is essential that the countries concerned develop a co-operative effort especially in the field of exchange and pooling of information, technology and expertise.

The United Nations Action Plan for Technical Co-operation between Developing Countries (Buenos Aires Conference of December 1978) provides an adequate framework for such action.

Among the 38 recommendations of the Action Plan, the following (summarized) should be mentioned as being particularly relevant to the material dealt with in this work:

(1) Every country should identify its potential (knowledge, know-how, equipment, etc.), facilitate the exchange of expertise through proper policies and regulations and establish proper machinery to that effect.

(2) National information gathering, processing, and dissemination organizations and national centres for research should be strengthened.

(3) Developing countries should exchange information in science and technology and develop technical co-operation between themselves by means of professional and technical organizations, public or private national corporations and institutions.

(4) Information and education programmes should be strengthened.

(5) Other recommendations deal with measures to be taken at the sub-regional and inter-regional levels. They point out needs for the strengthening of the institutions at that level; the identification and execution of operations, the development of new ties between the countries and the support to research and training centres.

(6) Finally, several recommendations deal with measures to be taken at the international level as regards the exchange of experience, technical co-operation, dissemination of information, special measures for economically or geographically disadvantaged countries, roles of the organizations of the U.N. system and support of developed countries.

(7) Keeping the above framework in mind, it would be desirable, as regards the subject of ground-water exploration and development in hard rock areas, to ensure that an appropriate body would collect, analyse and process all the information available on:

1. Past, on-going and anticipated project results and evaluations in the form of case studies;
2. Information, expertise and equipment available in the countries.

(8) A co-operative effort should be organized, if justified and requested, by a number of countries for an inter-regional operation which would deal with ground-water exploration and development in selected areas of several countries. U.N. agencies and other organizations might be involved in such a venture.

Last but not least, it has to be emphasized that the use of methodologies and technologies will be of little or no benefit (perhaps even detrimental) if technical personnel with adequate training are not available, if water ownership, development and use is not covered by proper legislation and regulation, or if the necessary technical services for ground-water exploration and development have not been established or have not been provided with means of action and authority in their field of competence. In this respect, agencies of the U.N. family may be able to assist national and regional operations aimed at the strengthening of the pertinent activities as regards the exploration and development of ground water in hard-rock areas.

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Appendix

SELECTED HYDROGEOLOGIC TERMINOLOGY

Anisotropic steering	Anisotropical structures (anisotropies) in the rock like schistosity, inclusions and fractures which can deviate or "steer" the direction of fractures subsequently developed.
Anisotropy	Having different properties in different directions.
Bedding	Applies to rocks resulting from consolidation of sediments and exhibiting surfaces of separation (bedding planes) between layers of the same or different materials, e.g. shale, siltstone, sandstone, limestone, etc.
Bedrock	The more or less continuous body of rock which underlies the overburden soils.
Brittle deformation	Process of brittle rupture of rocks in contrast to plastic deformation (folding).
Brittle fracture	Sudden failure with complete loss of cohesion across a plane.
Cleavage	The tendency to cleave or split along definite parallel planes, which may be highly inclined to the bedding. It is a secondary structure and is ordinarily accompanied by at least some recrystallinization of the rock.
Cohesion	Shear resistance at zero normal stress. (An equivalent term in rock mechanics is intrinsic shear strength.)
Comminution	The reduction of a substance to a fine powder; pulverization; **trituration**.
Compressive stress	Normal stress tending to shorten the body in the direction in which it acts.
Conjugate joints (faults)	Two sets of joints (faults) that are formed under the same stress conditions (usually shear pairs).
Crack	A small fracture, i.e. small with respect to the scale of the feature in which it occurs.
Deformation	A change in shape or size of a solid body.
Degree of saturation	The extent or degree to which the voids in rock contain fluid (water, gas or oil). Usually expressed in per cent related to total void or pore space.
Dip	The angle at which a stratum or other planar feature is inclined from the horizontal.
Discontinuity surface	Any surface across which some property for a rock mass is discontinuous. This includes fracture surfaces, weakness planes, and bedding planes but the term should not be restricted only to mechanical continuity.
Displacement	A change in position of a material point.
Distortion	A change in shape of a solid body.
Elasticity	Property of material which returns to its original form or condition after the applied force is removed.
Elastic limit	Point on stress/strain curve at which transition from elastic to inelastic behaviour takes place.

Fabric	The orientation in space of the elements composing the rock substance.
Failure	In rocks, failure means exceeding of maximum strength of the rock or exceeding the stress or strain requirement of a specific design.
Fault	A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture. (This displacement may be of a few centimetres or many kilometres). (See also joint fault set and joint fault system).
Fault breccia	The assemblage of broken rock fragments frequently found along faults. The fragments may vary in size from inches to feet.
Fault gouge	A clay-like material occurring between the walls of a fault as a result of the movement along the fault surfaces.
Fissure	A gapped fracture.
Fold	A bend in the strata or another planar structure within the rock mass.
Foliation	The somewhat laminated structure resulting from segregation of different minerals into layers parallel to the schistosity.
Fracture	The general term for any mechanical discontinuity in the rock; it is, therefore, the collective term for joints, faults, cracks, etc.
Fracture pattern	Spatial arrangement of a group of fracture surfaces.
Homogeneity	Having the same properties at all points.
Hydraulic conductivity	A unit describing quantitatively the ability of a material to transmit water under pressure. If a medium is isotropic and homogeneous, the medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of water at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path.
Hydraulic gradient	The change in static head per unit of distance in a given direction, that of maximum rate of decrease in head if not specified otherwise.
Isotropy	Having same properties in all directions.
Joint	A break of geological origin in the continuity of a body of rock occurring either singly, or more frequently in a set or system, but not attended by a visible movement parallel to the surface of discontinuity.
Joint diagram	A diagram constructed by accurately plotting the strike and dip of joints to illustrate the geometrical relationship of the joints within a specified area of geologic investigation.
Joint (fault) set	A group of more or less parallel joints (faults).
Joint (fault) system	A system consisting of two or more joint (fault) sets or any group of joints (faults) with a characteristic pattern, e.g. radiating, concentric, etc.
Joint pattern	A group of joints which form a characteristic geometrical relationship, and which can vary considerably from one location to another within the same geologic formation.
Land subsidence	Sinking or settlement of the land surface, due to diverse causes and generally occurring on a large scale. Usually subsidence refers to the vertical downward movement of land surface following subsoils fluid removal. The term does not include landslides which have large-scale horizontal displacements, or settlements of artificial fills.
Leaching	The removal through solution of the soluble salts from the upper soil zone by percolating waters.
Lineation	The parallel orientation of structural features that are lines rather than planes; some examples are parallel orientation of the long dimensions of minerals; long axes of pebbles; striae on slickensides; and cleavage-bedding plane intersections.

Moisture content	The percentage by weight of water contained in the pore space of a given volume of rock or porous medium with respect to the weight of the solid material.
Mylonite	A microscopic breccia with flow structure formed in fault zones.
Outcrop	The exposure of the bedrock at the surface of the ground.
Overburden	The loose soil, sand, silt or clay that overlies bedrock. In some usages it refers to all material overlying the point of interest (e.g. a tunnel crown), also the total cover of soil and rock overlying an underground excavation.
Perched water table	Unconfined ground water separated from an underlying body or ground water by unsaturated soil or rock. It may be either permanent or temporary.
Percolation	Movement in laminar flow under hydrostatic pressure of water through the interconnected, saturated interstices of rock or soil, excluding movement through large openings such as caves and solution channels.
Permeability	The ability of a material to transmit a fluid under pressure. Quantitatively it has been expressed in numerous ways, such as the darcy. (Cf. intrinsic permeability, hydraulic conductivity.)
Piezometric surface	See potentiometric surface
Plane of weakness	Surface or narrow zone with a shear (or tensile) strength lower than that of the surrounding material.
Porosity	The ratio of the aggregate volume of voids or interstices, whether they are connected or isolated in a rock or soil to its total volume.
Porosity, effective	The amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices.
Potentiometric surface	A surface which represents the static head. (Replaces the term piezometric surface.) As related to an aquifer it is defined by the levels to which water will rise in tightly cased wells.
Rupture	That stage in the development of a fracture where instability occurs. It is not recommended that the term rupture be used in rock mechanics as a synonym for fracture.
Schistosity	The variety of foliation that occurs in the coarser-grained metamorphic rocks and is generally the result of the parallel arrangement of platy and ellipsoidal mineral grains within the rock substance.
Seepage	The infiltration or percolation of water through rock or soil to or from the surface. The term seepage is usually restricted to the very slow movement of ground water.
Seepage force	The frictional drag of water flowing through voids or interstices in rock causing an increase in the intergranular pressure, i.e. the hydraulic force per unit volume of rock or soil which results from the flow of water and which acts in the direction of flow.
Shear plane	A plane along which failure of material occurs by shearing.
Shear stress	Stress directed parallel to the surface element across which it acts.
Sheet jointing	Fracturing of tensile character, mostly in granitoide rocks, parallel to the land surface. Sheet jointing is developed either by load release or temperature differences.
Slickenside	The polished and striated surface that results from friction along a fault plane or other movement surfaces in a rock mass.
Sliding	Relative displacement of two bodies along a surface, without loss of contact between the bodies.
Storage coefficient	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In a confined aquifer the water derived from storage with decline in head comes from an expansion of

the water and compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined aquifer the amount of water so released or accepted is generally negligible compared to the amount involved in gravity drainage or filling of pores; hence, in an unconfined aquifer the storage coefficient is virtually equal to the specific yield.

Strength	Maximum stress which a material can resist without failing for any given type of loading.
Stress	Force acting across a given surface element, divided by the area of the element.
Strike	The direction or azimuth of a horizontal line in the plane of an inclined stratum, joint, fault, cleavage plane or other planar feature within a rock mass.
Structure	One of the larger features of a rock mass, like bedding, foliation, jointing, cleavage or brecciation; also the sum total of such features as contrasted with texture. Also, in a broader sense, it refers to the structural features of an area such as anticlines or synclines.
Texture	The arrangement in space of the components of a rock body and of the boundaries between these components.
Thickness	The perpendicular distance between bounding surfaces such as bedding or foliation planes of a rock.
Transmissivity	The rate at which water at the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Though spoken of as a property of the aquifer, it embodies also the saturated thickness and the properties of the contained liquid. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.
Uniaxial (unconfined) compression	Compression caused by the application of normal stress in a single direction.
Uniaxial state of stress	State of stress in which two of the three principle stresses are zero.
Uplift	The hydrostatic force of water exerted on or underneath a structure tending to cause a displacement of the structure.
Weathering	The process of disintegration and decomposition as a consequence of exposure to the atmosphere, to chemical action and to the action of frost, water and heat.

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Subject Index

GROUND WATER IN HARD ROCKS

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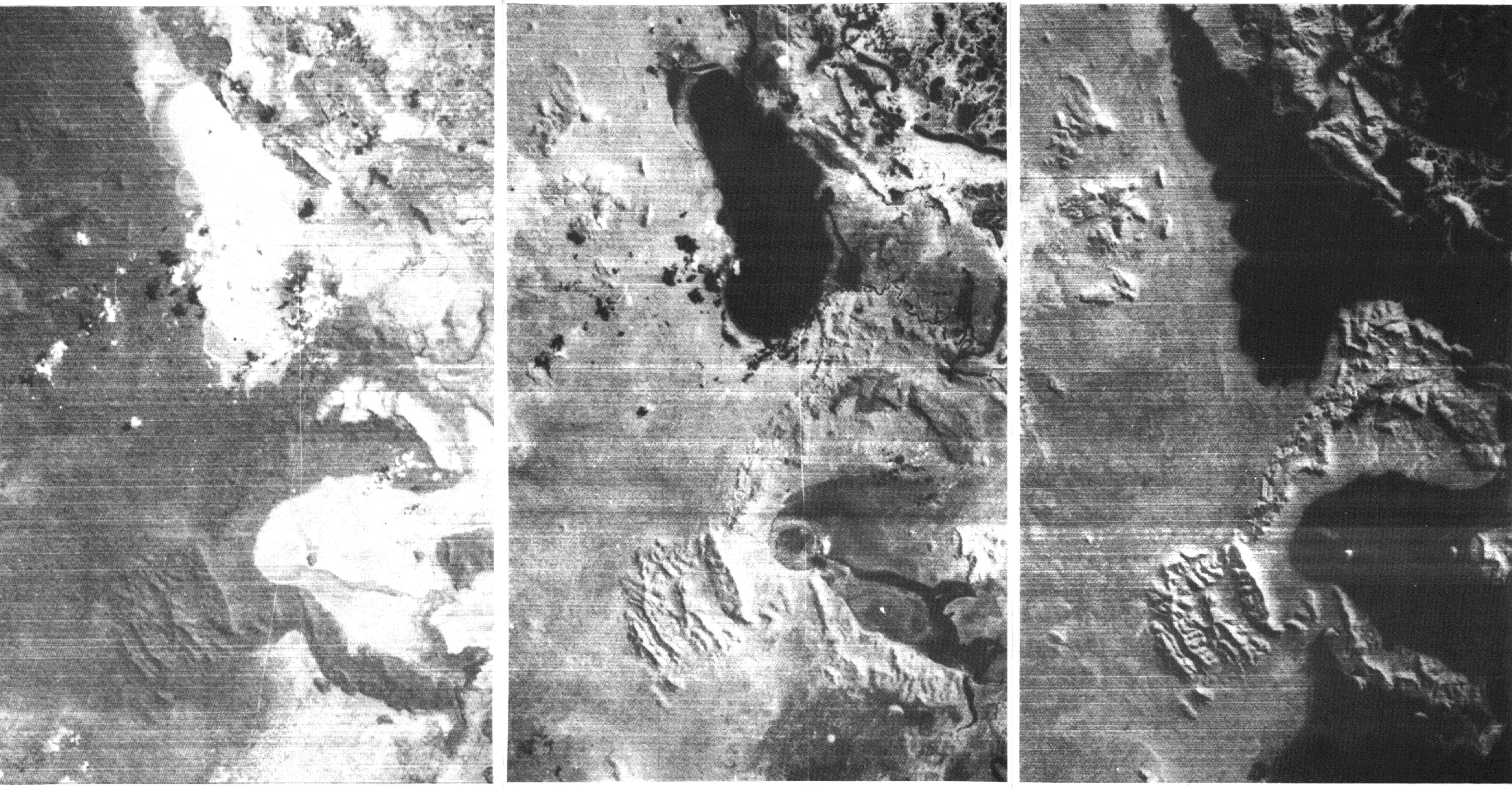
For use with section 3.2.1., Remote sensing techniques, pp. 71-78



(a) (b) (c)

Image 1. Enlargement from 1:1,000,000 to 1:250,000 of Landsat imagery of the Upper Paraguay river. Image (a) - band 5; Image (b) - band 7, of the same date, in the dry period. Image (c) - band 7, during flooding. Image (a) shows, with a darker grey tone, the forest-covered area west of the lakes; the lakes and the humid soil have a light tone. Image (b) shows, in the upper right corner, the Paraguay river (black tone) and Lake Mandiore; two large depressions (dark grey tone) occur in the southeast corner in which the soils are very wet. Image (c) shows the flooding of the Paraguay river, the extension of Lake Mandiore towards the north and towards the Paraguay river and the flooding of the two depressions in the southeast corner.

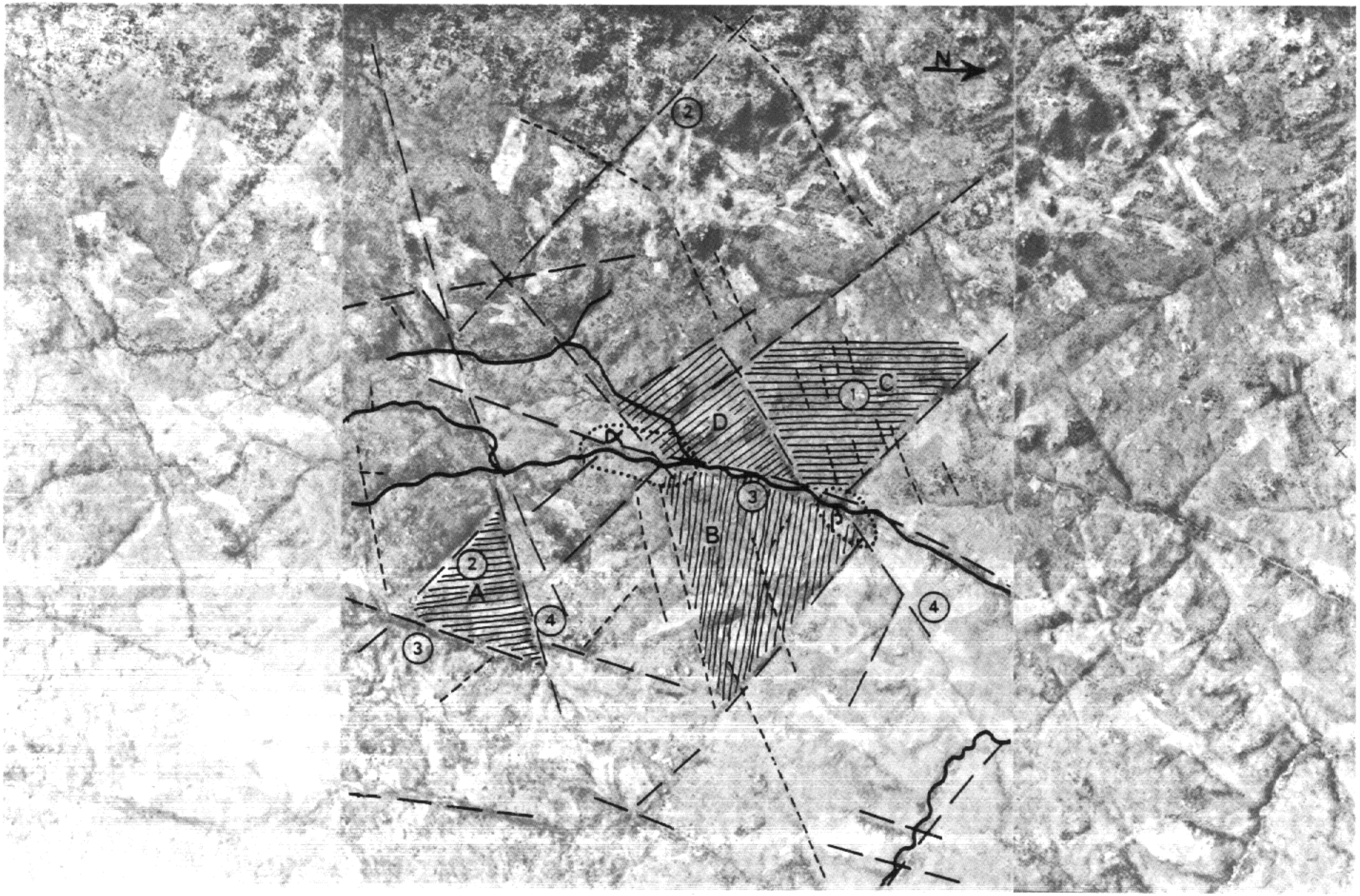


Image 2. Aerial photograph triplet of area in northeast Nigeria (approximate scale 1:40,000). Criss-cross jointing in granite rock, reflected in the directions of the main drainage lines.

An ac - pattern runs WSW-ESE (see (1) in overlay). A tensile pattern runs NW-SE and NE-SW (see (2) and (4) in overlay) and shears and sub-shears in NNE-SSW direction (see (3) in overlay). Fracture set (1) probably is not water-bearing; (2) and (4) are probably open (tensile) fractures and water-bearing; (3) is probably tight (shear), in general closed and not water-bearing. See also text on page 78.

Overlay to image 2 (center panel) — —— **Major fracture** - - - - **Minor fracture**

Image 3. Aerial photograph of fault basement rocks of the Canadian Shield. The axes of the lakes and the drainage are strongly controled by fracture lines in which one direction (NW-SE) is predominating. The rocks with a lighter tone are a granitic variety and those with a darker tone, basic (see overlay).

Overlay to image 3

v v v — dark grey tone material (basic rocks)

L — lakes

- - - — fractures and faults

Image 4. Stereo triplet showing intrusive body of granite (light-tone) in highly metamorphic folded basement rocks (medium tone). Most fracture lines have been intruded by dikes. The aplitic and pegmatite dikes show light phototone and relatively strong relief; the basic show darker tone (see overlay).

Overlay to image 4 (center panel)

- joints and fractures
- boundary, supposed one between rock units
- very light toned igneous rock forming irregular bodies with high relief, jointing rather dense probably pegmatite bodies and crack fillings
- aplitic dikes
- foliation
- bedding trace
- fracture fillings of dark material, diabase dikes
- light toned rock, joint pattern not very well developed, granite dome
- medium gray toned, foliated rocks with well developed jointing in different directions
- light gray semirounded bodies probably an older tonalitic rock

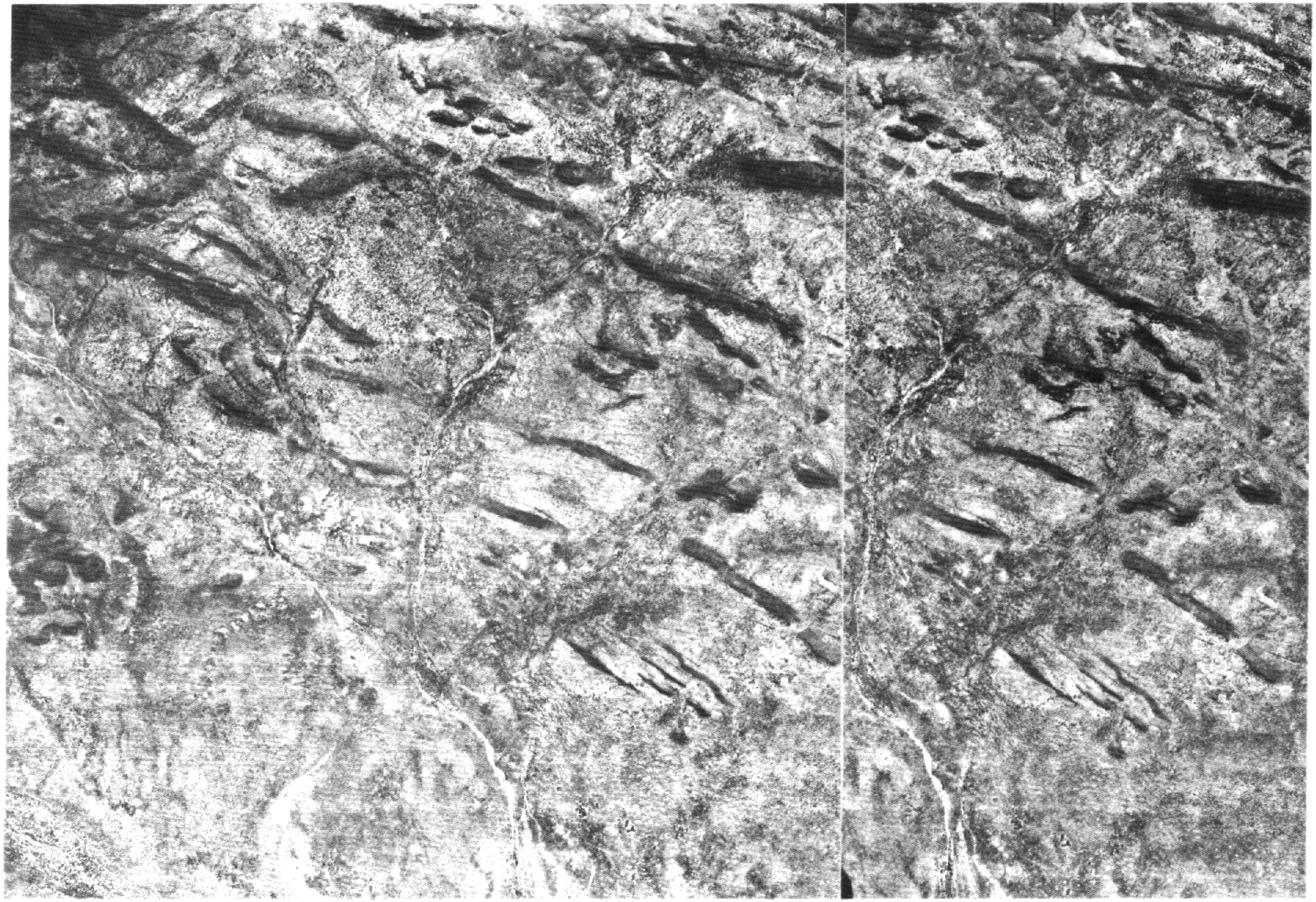


Image 5. Stereo pair showing swarms of basic dikes (very dark tones) in batholith. The dikes form here low ridges. Difference in texture and form may indicate different types of basic rocks.

Image 6. Stereo pair showing a biotite-hornblende gneiss in Tanzania. The strike directions of the gneissic bands can be recognized even when covered with bush. The drainage reflects partly the fractures but also the strike directions of gneiss bands (see overlay). Approximate scale 1:40,000.

Overlay to image 6 (center panel)

---- **fracture** | **drainage** | **strike direction of gneissic bands**

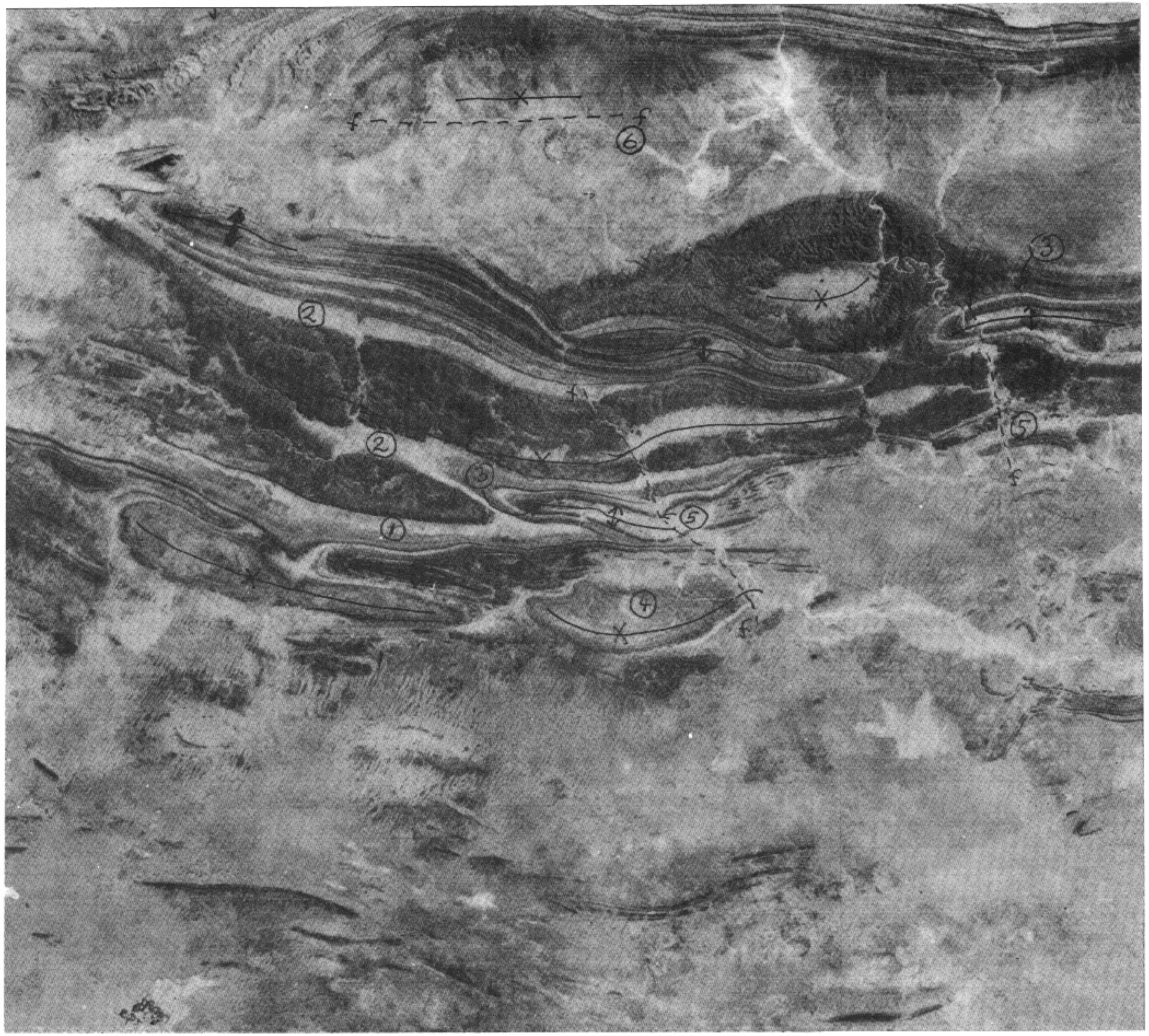


Image 7. Landsat image (band 7) of Amadeus Basin (Australia) showing clearly anticlinal and synclinal structures. (1) indentations in sedimentary rock suggesting the presence of fractures; (2) valleys; (3) valley formed by erosion of a less resistant layer; (4) sediment-filled depressions with drainage outlet; (5) interrupted outcrop indicating possible faults; (6) northern limb of a large synclinal structure with some distortion in the west side; the absence of the southern limb suggests the possibility of a fault. Scale 1:1,000,000.

Image 8. Stereo triplet, approximate scale 1:50,000, showing a part of the area covered by the Landsat image of Amadeus Basin, Australia (Image 7). (1) fractures in sandstone syncline; (2) alluvial fan; (3) gravel sediment in valley formed by erosion of out-cropping shale; (4) drainage outlet of this valley; (5) change in river course possibly caused by a structural phenomenon in the subsurface. Notice fracture-drainage on both sides (5a).

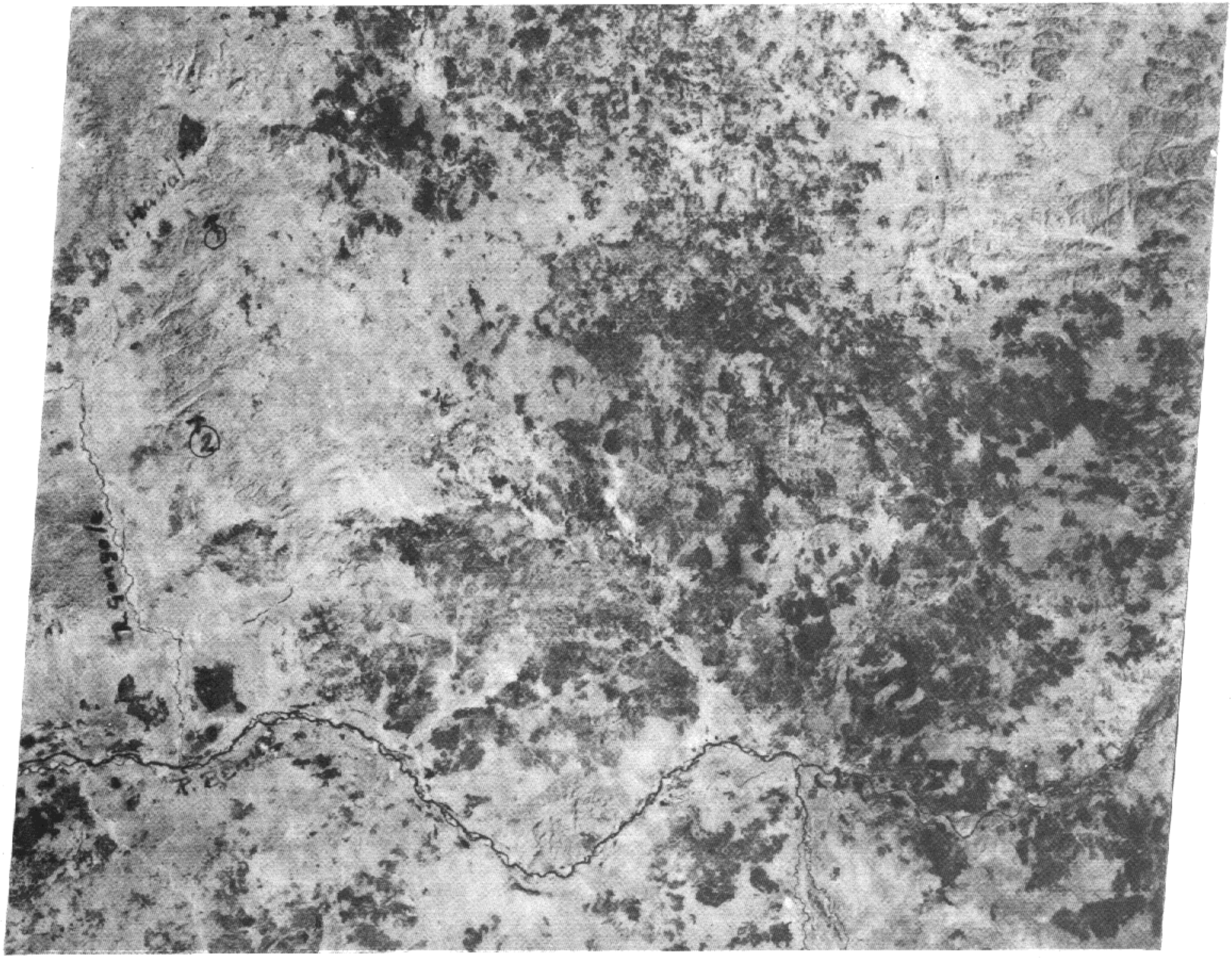


Image 9. Landsat imagery of northeast Nigeria, band 7. The rivers Benue and Gongola carry water which can be seen in black tone. The Hawal river has a light tone, thus probably dry near the surface.

It is rather difficult to locate Image 2 (1) and Image 10 (2) and in particular the features occurring in that image.

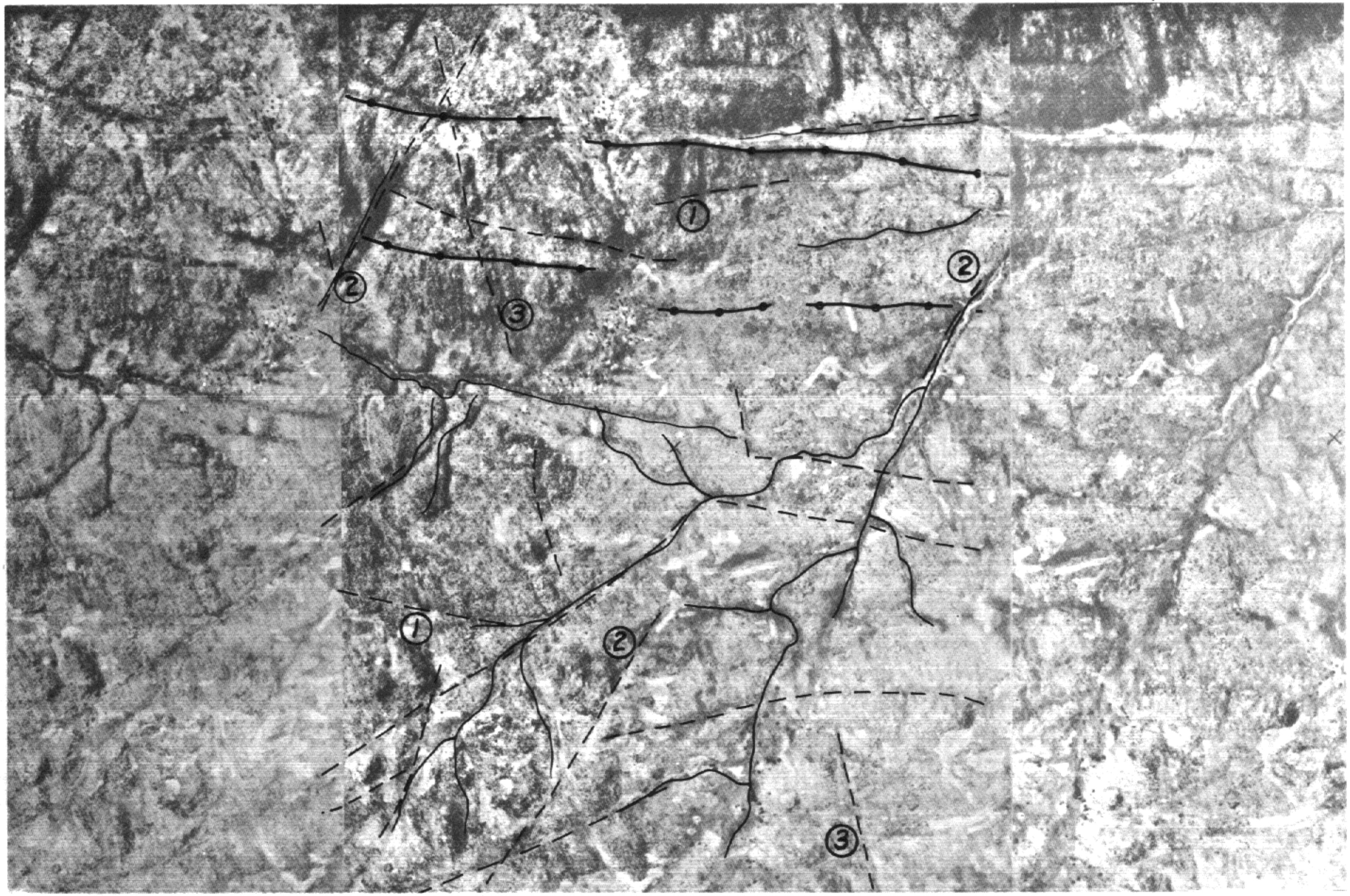


Image 10. Aerial photograph triplet of area in northeast Nigeria (cf. zone 2 on Image (9)). Fractured granite rocks with some dikes forming ridges. Fracture sets (1) and (2) probably with tensile character; set (3) probably shearing. See also text page 78.

Overlay to image 10 (center panel)

– – – fractures

•—• dykes