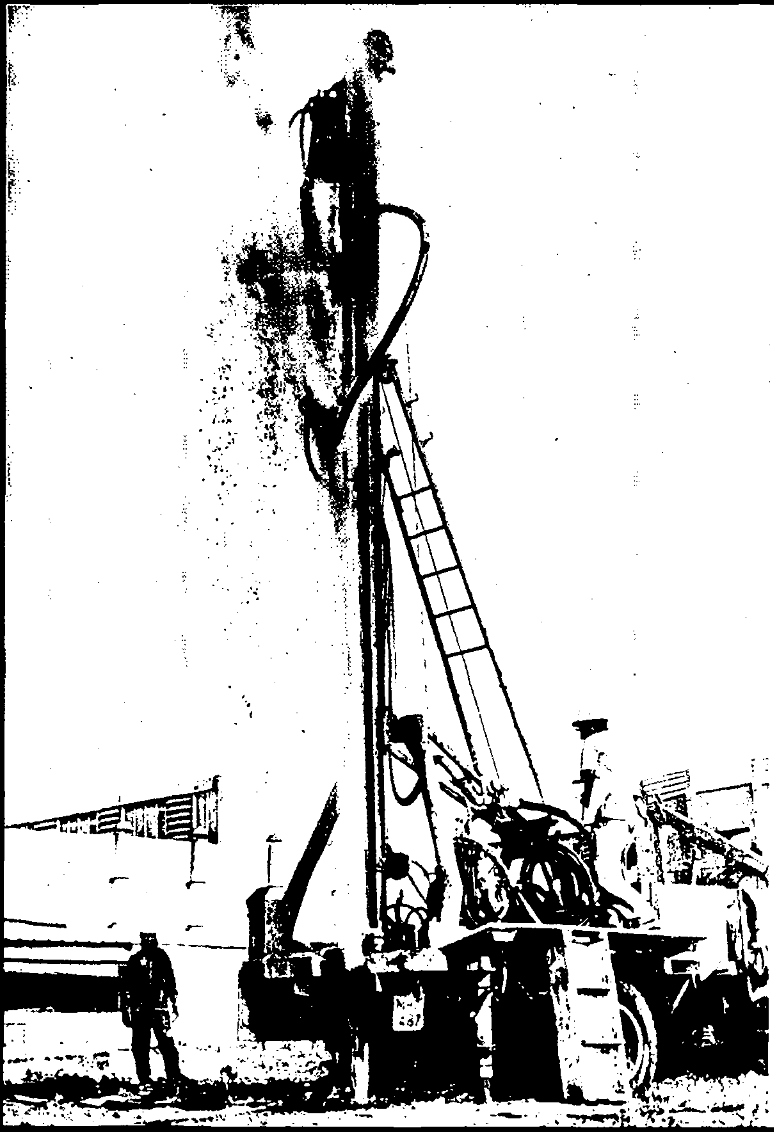
mining and construction methods

Ground water utilization in hard rocks



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Ground water utilization in hard rocks

by Per Fredrik Tröften

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CONTENTS

Page
Abstract 3
1. Introduction 3
2. Consumption of water 4
3. Availability of water 4
4. Utilization of surface water 5
5. Ground water 7
6. Ground water utilization 8
7. Ground water in non-indurated sediments 8
8. Ground water in consolidated formations 9
9. Occurrence of ground water in hard rocks 10
10. Occurrence of ground water in glaciated hard-rock areas 11
11. Hydrogeological analysis of a hard-rock area 12
12. Geophysical investigations 17
13. Test drilling 20
14. Subsurface investigations 20
15. Hydrogeological rules of thumb for the water well driller 24
16. Various types of drilling methods 25
17. Development procedures of a ready drilled well 30
18. Some considerations on pump installation as related to the yield of the well 30
19. Atlas Copco's water well drilling equipment for hard-rock formations . . . 33
20. References 39
21. Glossary 41

ABSTRACT

Atlas Copco have developed a method intended for drilling water wells, primarily in hard-rock formations, which under ideal conditions has proved its ability to produce one well in one day at a reported total cost as low as Rs. 15.52 per foot. (1 Indian Rupee = 0.55 Swedish Krona = US $ 0.13).

New tools have been designed to assist the water well driller in overcoming his traditional problems, notably those encountered while drilling through collapsible overburden and rock formations.

Scientific and technical factors relevant to ground water utilization in hard-rock areas are reviewed, resulting in the presentation of a list of demands which should be satisfied by the designer of a water well drilling rig.

In order to make the contents of the paper accessable to a broader selection of readers, a glossary covering most of the scientific and technical terms and expressions is included.

Most claims and achievements presented in the paper will be found documented in the enclosed list of references (page 39), the numbers of which are indicated within brackets.

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1. INTRODUCTION

Next to air, water can be considered as life's most basic requirement.

Without water, no life can originate and the pattern and obtainable levels of life's development will largely depend upon the quantity, quality and variations in the supply of water made available to the species.

The intercourse between these parameters and the openings and limitations to development which they present, can be as conclusively established whether the object under study is a simple botanical sample or the most highly developed creature on Earth: Homo Sapiens.

An equation with the latter entered as biological parameter will be inherent with the greatest possibilities of variation because of the capability which this species possesses to more independently affect the process and since this capability, due to a complex pattern of reasons, is utilized to such a varying degree.

Water supply systems of all kinds are, therefore, found throughout the world, from women carrying the day's consumption on their heads from a simple pot hole in a dried-out river, no more sophisticated in design than the ones dug up by elephants (Fig. 1), to TVA's elaborate system of dams and distributing canals, from marvellously arched Roman aqueducts still in use to water-carrying donkeys trotting alongside the ruins of the same (Fig. 2).

At the same time as bedouins herd their camels and sheep from oasis to oasis and eskimos melt their drinking water from snow, airplanes spread out rain-triggering crystals in the sky while nuclear desalting plants below convert sea-water to potable water.

And as starkly as the systems differ in technical standard, just as stark is the contrast in the types of society which grow up around them with, sadly and as usual, the developing countries being the ones which most strongly suffer from the lack of adequate water supplies.

Fig. 1. Woman carrying water in India

Fig. 2. Donkey carrying water in Mexico

2. CONSUMPTION OF WATER

According to German calculations (1), normal consumption of water for personal use is around 50 liters (11 Imp. gal.) per person and day.

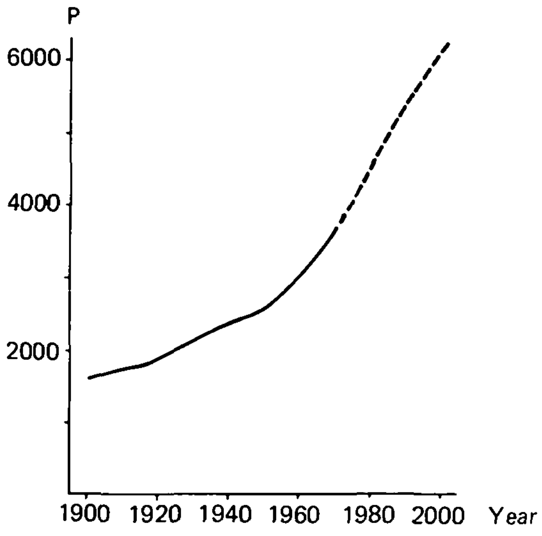
For emergency situations 16 liters (3.5 Imp.gal.) is considered to be sufficient while the absolute minimum consumption in air-raid shelters can be pressed down to 6 liters (1.3 Imp.gal.) per person and day according to the following break-up:

2 liters (0.44 Imp.gal.) for drinking and cooking purposes
1 liter (0.22 Imp.gal.) for sanitary use
2 liters (0.44 Imp.gal.) for water closet
1 liter (0.22 Imp.gal.) in reserve

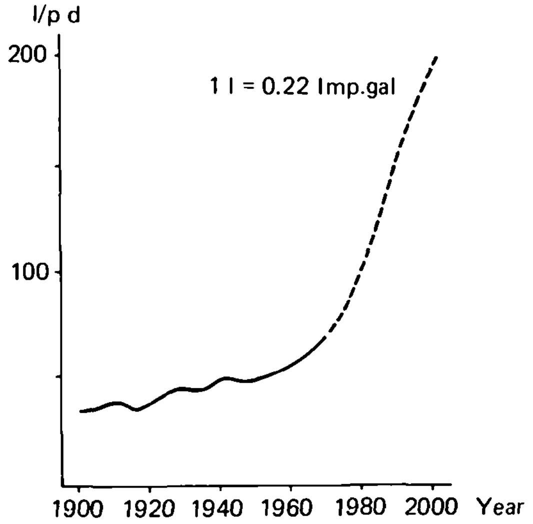
Under favourable climatical conditions, a person will require 1.5–2 liters (0.33–0.44 Imp.gal.) of water per day only to compensate for losses through urination, perspiration and respiration, and this amount rises strongly with heat and dryness. At 32°C (90°F), thus, from 6 to 12 liters (1.3–2.6 Imp.gal.) will be required for survival, depending upon the dryness of the air.

Even though many people on earth periodically will have to live with supplies close to those listed above, the average national consumption figures are very much higher. This is primarily due to the great consumption of certain industries. One single Swedish paper factory can, thus, consume more water than the entire city of Stockholm, and a dairy or a brewery will use from 5 to 10 times more water than the volume of their end products (2).

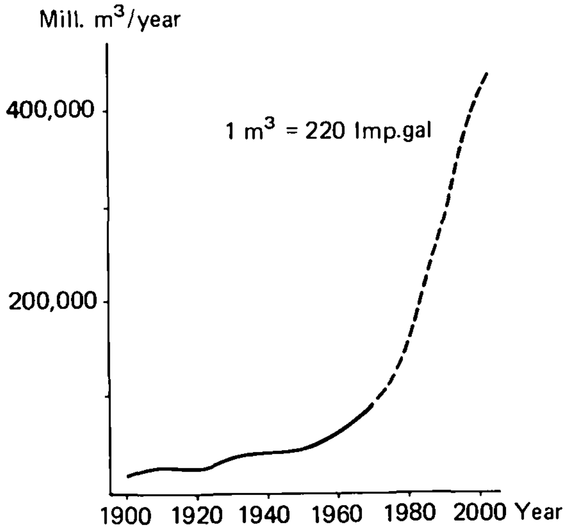
And as industry, irrigation and public installations of all kinds develop with ever increasing speed, all available statistics and forecasts on the world's consumption of water reveal a similar staggering and not unexpected upward trend (Fig. 3).



a) The population of the world in millions (p)



b) Specific water consumption in litres per person and day (l/p d)



c) The world's total individual water consumption in million m^3 per year

Fig. 3. Statistics and forecast of the world's individual water consumption

3. AVAILABILITY OF WATER

97% of all water on earth is confined to the oceans while only the remaining 3% occurs as sweet water. Of this sweet water, 77% is tied up in polar ice covers and glaciers, 22% flows slowly toward the sea as ground water, 0.4% is found in lakes, 0.04% in streams and 0.043% in the atmosphere (3).

At first glance, these figures look quite alarming, especially in view of the great consumption of water which is forecasted for the future (Fig. 3).

Out of the estimated 36,000 km^3 ($3x10^{10}$ acre-feet) of water which is annually discharged into the sea by all rivers on earth, however, no more than 2% is utilized for communities, industry, power and cooling and only 6% is being collected and stored in artificial dams. The enormous ground water deposits, which constitute over 96% of all fluid fresh water appearing at a given time on earth, equalling an estimated quantity of 10 million km^3 (8x10^{12} acre-feet) (4), is but negligibly made use of and the ice deposits not at all.

Rather than being a question of quantity in an absolute sense, the real problems are found in the discordance between location of resources and consumers, pollution and, maybe most important of all, lack of funds, technical know-how and time to enable man to avail himself of and maintain these resources, which are often so close at hand.

While Europe and Asia, thus, have 72% of the world's population, they hold only 27% of its water resources, and presently more than 20% of all water discharged by the world's rivers is being polluted (3).

4. UTILIZATION OF SURFACE WATER

The simplest way to utilize surface water is to carry it from a river or a lake to site of consumption by some means of transportation: a donkey, a truck, a ditch or a hose.

Since, however, so many rivers in the temperate and tropical zones have a tendency to dry out periodically, man soon started to construct barrages across them at the same time as transport systems of higher capacity were designed: aqueducts, canals, pipelines, tunnels. Part of the water thus arrested is often made use of for production of electric power with subsequent distribution of discharge water to irrigated fields, and the possibility opened to conserve and tap river water at will presents the hydraulical engineer with a reliable tool for the execution of flood control. Other important side effects of arresting and harnessing surface water flows are decreased soil erosion and an elevated ground water table, the main reasons behind the elaborate toil laid down on the construction of the earth's millions of acres of paddy fields.

Artificial collection and storage systems are found in all sizes and stages of sophistication, from primitive log barrages directing brook water into wooden troughs as motive power for medieval water mills to the incredibly massive dams and power plants which can be considered as the economic backbone of many a nation.

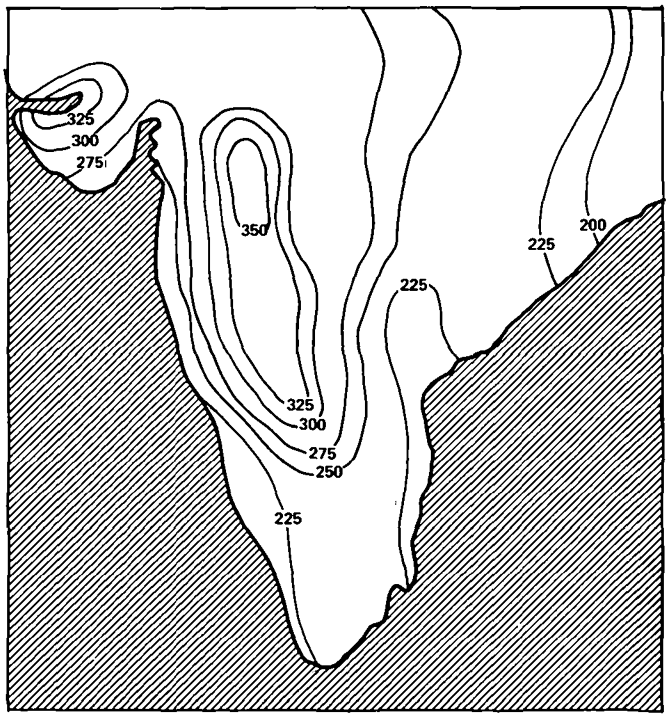
Utilization of surface water has, however, a number of inherent disadvantages:

a) **Evaporation**, which in hot and arid areas can be very high (Fig. 4). (5). A "tank" (small dam) of the size of a tennis court (260 m^2 = 2800 sq.ft.), which is very common in India, will, if situated in an area of highest evaporation rate, suffer a loss of 910,000 liters (200,000 Imp.gal) of water per year, a quantity which incidentally, corresponds to no more than 10 days continuous pumping of an average well drilled in the Sholapur region (6), and since these tanks are quite shallow, they generally dry out completely during the dry season, which is not the case with tube wells.

   Knowing that the average rainfall of India is only 115 centimeters (45") per year, one may jump to the impossible conclusion that a greater quantity of water evaporates into the atmosphere than precipitates out of it, which of course is not the case. The picture is bad enough, though. Of India's estimated total rainfall of 3,700 km^3 (3x10^9 acre-feet), one third is lost through evaporation. (7).

   A sizeable portion of the great quantities of water stored in dams throughout the world is, thus, lost through evaporation, a problem where an attempted solution is to cover the surface with oils or plastic materials of various kinds.

b) **Silting**. Most rivers in the arid zones carry immense quantities of sediments with them to the sea. The water of the Euphrates, thus, has a concentration of suspended material as high as 1%, corresponding to a sediment transportation of 40 tons per second. (8).



1 cm = 0.4 in.

Fig. 4. India. Annual Pan Evaporation in centimeters at 28°C (82.4°F)

from Krishna Rao (5)

When such water comes to rest in a dam, much of this silt will settle out and eventually fill up the whole reservoir (Fig. 5). This problem is particularily severe in the case of small dams. The Matumbulu reservoir near Dodoma in Tanzania which, when it was built, could store 360,000 m^3 ($3x10^{11}$ acre-feet) of water, was filled with 180,000 m^3 ($1.5x10^{11}$ acre-feet) of sediments after only 7 years. (9).

Other problems connected with the de-silting of river water are: decreased natural fertilization of the river banks, greater erosion of the river course downstream of the dam, changes in the ground water level – elevation upstream of the dam and lowering downstream, and hydrochemical disbalance in the deltas with resulting increased marine erosion (10).

c) **The fact that irrigation can be contrived only downstream of the dams**, areas which often already are the most properous ones of the region. Great distributing systems have, furthermore, to be constructed to transport the water to the fields, with additional losses in evaporation and leakage. Such leakages will result in an elevation of the ground water table which, if carried too far, will be very damaging to the vegetation. In the states of Punjab and Haryana, over 1 million hectares (2.7 mill acres) have been destroyed by "land cancer", (11), an area exceeding Norway's total cultivated land by 10%! (44).

Water carried in irrigation canals is, furthermore, not suitable for drinking water purposes, so that problem is still there, even in irrigated areas.

d) **Risk of spillover or total collapse of the dam construction in connection with natural catastrophes, such as earthquakes.** The Langarone landslide in Italy on the 9th of October 1963 and the earthquake in Peru on the 31st of May 1970 are proof that this danger actually does exist (12). (Fig. 6).

e) A much smaller problem, but still an annoying one, is the risk of **freezing pipe lines** in cold countries (13). The water pipes will here have to be dug down deep and in some areas, like on Greenland, will even have to be covered with expensive insulation against loss of heat. Public water supply systems in arctic and subarctic rural areas, where the distance between the consumers moreover often is great, will be very costly.

f) The greatest problem connected with utilization of surface water is, however, the **great capital investment** required and the **long time** it takes before the systems can be put to use.

10 years can be considered as reasonable for completing a major dam in a developing country, and only during the coming decade, WHO's Regional Office for South-East Asia estimates that the rural population of Ceylon, India, Indonesia, Nepal and Thailand will increase by 142 million people (14).

In spite of the listed disadvantages, surface water will of course be collected and made use of at an increasing pace in the future, and the necessity for massive investments in this field is undisputable.

1 km = 0.62 mile
1 m = 3.28 ft.

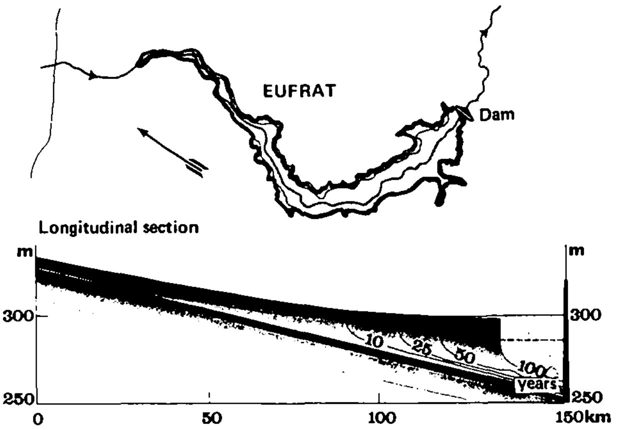


Fig. 5. Probable fill-up of a dam in Syria. Sedimentation rate in 1960 = 90 million tons

from Sundborg (8)

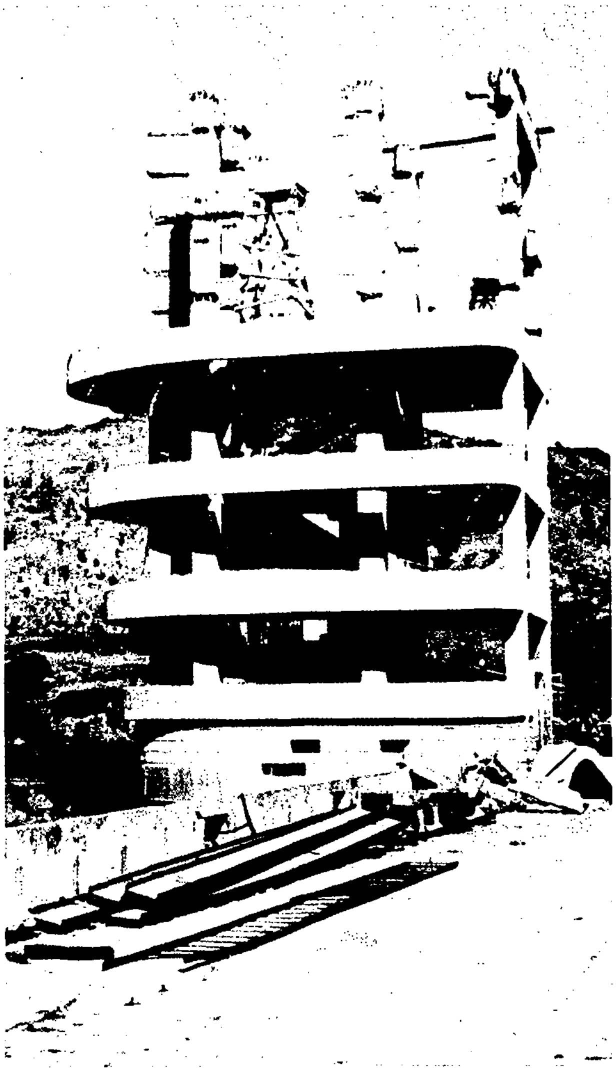


Fig. 6. Collapsed control tower of the Koyna Dam of India, damaged by earthquake in December 1967

• 5. GROUND WATER

Fig. 7 gives a simplified picture of the hydrologic cycle.

The oceans are the immense reservoirs from which all water originates and to which all water again returns. Water evaporates from the surface of the oceans and the vapour is transported by the winds toward the continents where it condenses to clouds and eventually falls to the earth as precipitation. Part of this water evaporates again while the remainder flows back to the sea, through rivers and through the ground.

The ratio between evaporation, surface and underground run-off is governed by climate, topography and the composition of the ground and will, thus, show great variations from area to area.

In India an estimated 33% of the total rain fall evaporates immediately and goes back to the atmosphere while the surface run-off is in the order of 45%. Of the remaining 22% some portion gets absorbed in the upper soil layers and also evaporates, leaving between 10 and 20 % as contribution to the groundwater storage. (7).

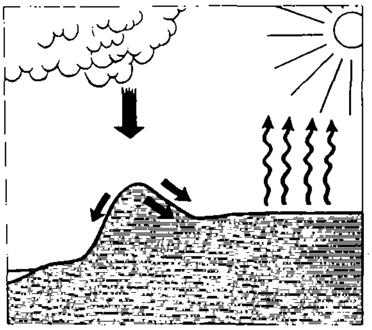


Fig. 7. The hydrologic cycle

Total storage, annual contribution to the storage and speed of the ground water flow vary, however, widely from region to region. While the rate of flow will be highest in the Himalayas, with its steep hydraulic gradients, the huge masses of alluvial material of the Ganges and Indus Basins will hold most of the water, with the hardrock areas of peninsular India in an intermediate position, both with regard to storage and flow. (Fig. 8).

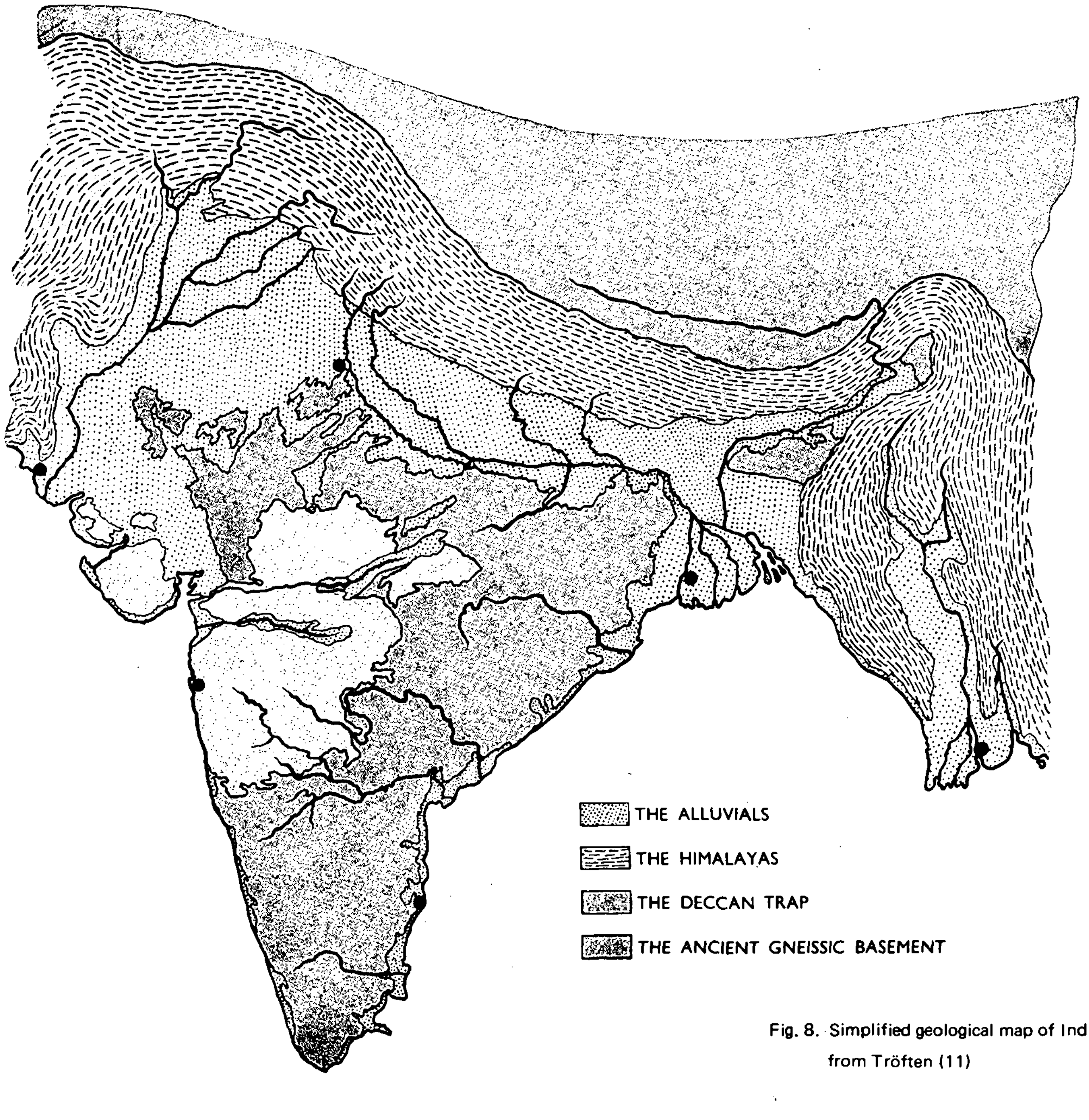


Fig. 8. Simplified geological map of India from Tröften (11)

6. GROUND WATER UTILIZATION

As should have been realized by now, the ground water resources of the world are of immense proportions and the logical question then arises, to what extent this water is made use of.

The answers contrast starkly depending upon what country one looks at.

While the entire water supply of Copenhagen is based on ground water, hardly one single tube well will be found in the city of Bombay, and whereas in the US an estimated 770,000 new wells were drilled in 1970, (Fig. 9), bringing the total number of wells close to 15 millions, (Fig. 10), wells drilled in a country like Morocco can be counted with two digits.

Why is this so?

We believe it is primarily a question of equipment and methods, which are either too primitive to produce appreciable results or too expensive and complicated to buy and maintain for countries with a low technical tradition.

One also has to admit that hydrogeological understanding, particularily when it comes to the occurrence and extraction of water in hard rocks, has just recently started to attract international attention.

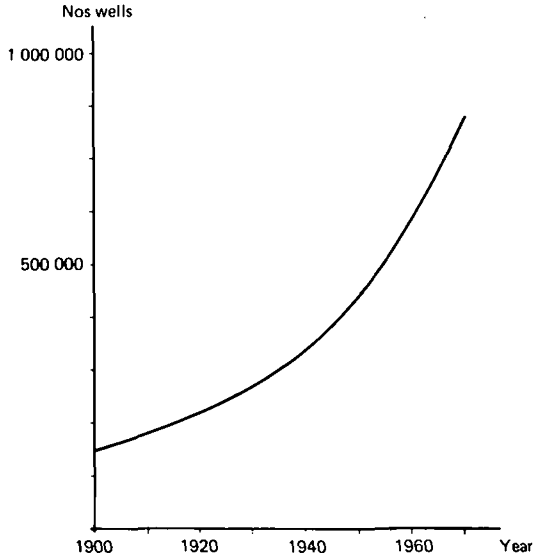


Fig. 9. New water wells drilled in the United States. Compiled from publications nos.: 15 to 20

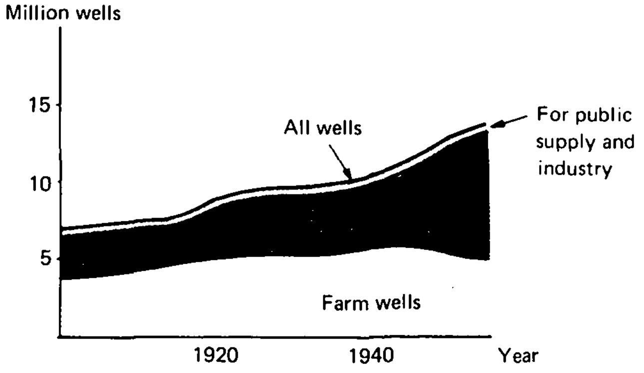


Fig. 10. Accumulated water wells in the United States from Picton (21)

7. GROUND WATER IN NON-INDURATED SEDIMENTS

The by far greatest quantities of ground water will be found stored in recent geological formations, characterized as they are by their high porosity and waterholding capacities.

Such formations are primarily located in the coastal area, in the big planes along major rivers and to landscapes of mild topography, like Central Europe and the midwestern states of the US.

Since the majority of the population has settled in such areas and the geological formations are often easy to drill, it is only natural that ground water extraction, both in the past and today, is most extensively carried out here.

To the developing countries these formations are particularily appealing because of the uncomplicated drilling procedure and simple equipment required. Most countries will, accordingly, be in a position to manufacture their own rigs for drilling such types of holes and will not have to spend their costly foreign exchange on the purchase of equipment and technical know-how.

Many unconsolidated sedimentary formations may, however, contain boulders which, depending upon their hardness, shape, size and numbers, will present various problems to conventional drilling methods.

Most difficult to penetrate are the heavy glacial drifts of the northern countries but sediments with encumbering drilling characteristics are also found in the south. Most notable are mountain pediments and alluvial deposits in areas of high to moderate topographical relief with eolian deposits containing boulders produced by spheroidal weathering as a more exotic, but still very annoying type of formation to encounter (Fig. 11). Lots of technical development is, therefore, called for in order to arrive at fast and troublefree drilling techniques which will be applicable in all kinds of loose sediments.

Fig. 11. Boulder-containing alluvial deposit between Toluca and Mexico City

8. GROUND WATER IN CONSOLIDATED FORMATIONS

A very great proportion of the land surface of the world will have hard rocks exposed or covered with only thin layers of soft deposits.

Yields from sedimentary rocks, which are the most common ones, will be in the order of 1/10 of what can be extracted from non-indurated sediments, with 10,000 liters (2,200 Imp.gal.) per hour as an expected high average (22), while wells drilled in igneous and metamorphic rocks, with constitute some 20% of the land surface of the world, will produce much smaller quantities (Fig. 12).

Why is it then that Atlas Copco have concentrated their efforts on developing prospecting and drilling equipment for this latter type of formation, which from a hydrogeological point of view is the least favourable?

The main reason lies in the fact that Sweden is a typical hard-rock country with approx. 75% of her geological formations being of Precambrian age (23). Based on her ancient traditions in the mining field and over 80 years of experience from drilling for water in metamorphic rocks (24), it is only natural that much of her expertise even to-day will be focused on overcoming problems related to this material.

Apart from adhering to the proverb that "the cobbler is not to go beyond his last", other factors point to the correctness of concentrating our efforts to the field of hard-rock hydrogeology:

a) If we take a country like India, we see that 70% of her area is underlaid by hard-rock (Fig. 8) and since no suitable drilling equipment was at hand, little could be done to provide the teeming millions of people living in these areas with water. The picture is the same in most other dry countries: Africa, Brazil, the Middle East. (25).

b) Because of the strong weathering in these regions, good agricultural soil is quickly produced which, coupled with the favourable climatical conditions they enjoy, have a phenomenal growing capacity.

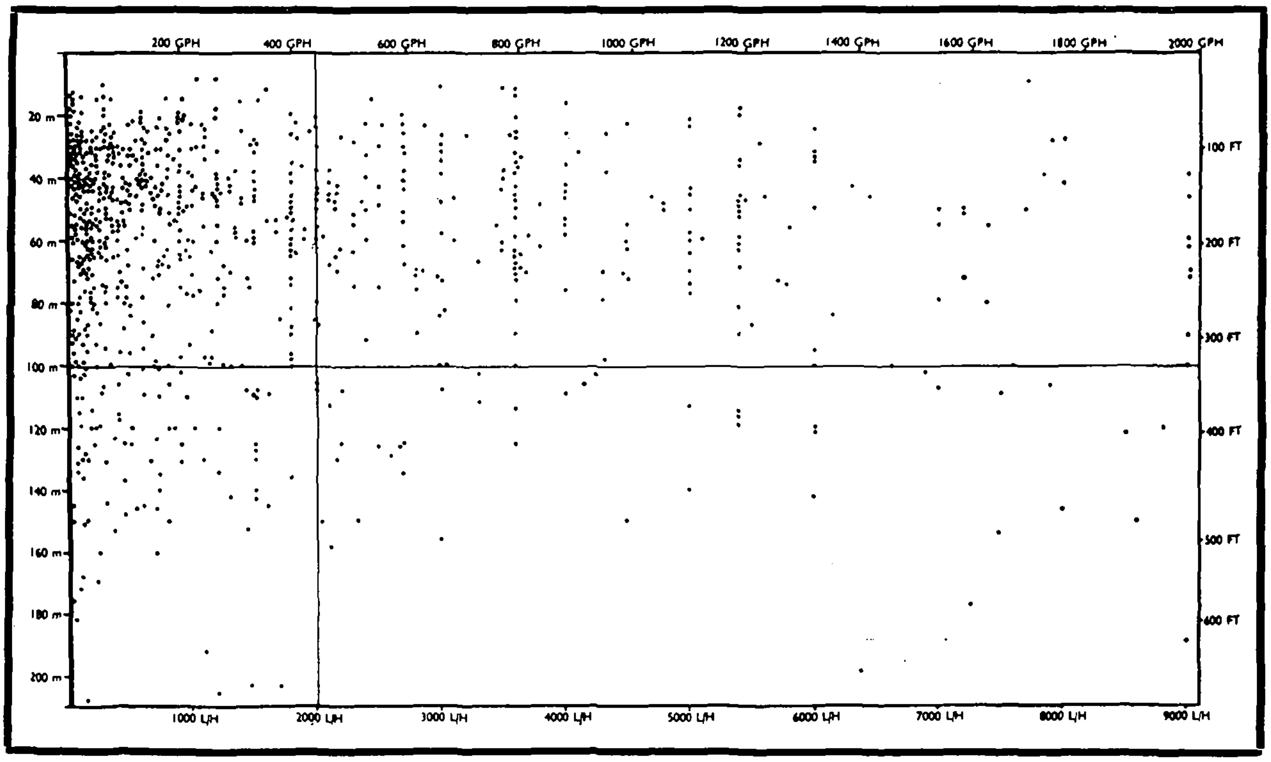
c) Sparsely populated as these areas are, they represent tempting possibilities for absorbing the surplus population of the crowded lowlands.

d) The hard-rock areas of the developing countries contain, therefore, great economic, strategic and political potentials, if only they can be provided with acceptable living conditions, and water is one of the basic needs in this context.

e) A company striving to develop efficient unconventional equipment for ground water utilization in hard rocks will, therefore, create a new and rapidly expanding market.

f) Through our technical development it has been found that certain of the solutions arrived at can also be made use of to overcome problems related to other types of formations, such as the ones previously described in chapter 7 "Ground water in non-indurated sediments" and possibly also the particular difficulties faced when drilling in karst (26).

g) And as will soon be seen, the yields of wells drilled in hard-rock areas can be considerably improved if modern hydrogeological surveys and analyses are carried out prior to locating the wells.



L/H = liters per hour
GpH = Imp.gal per hour

Fig. 12. Yield plotted against depth for 818 water wells drilled in igneous and metamorphic rocks in Sweden from Tröften (11)

9. OCCURRENCE OF GROUND WATER IN HARD ROCKS

It can be stated as a general rule that it will not be the solid particles building up a geological formation which contain the water, but the pores, fissures and voids which separate them.

The porosity, and thereby, the water-holding capacity of a sediment can, therefore, be very high (Fig. 13), whereas the same material, while being compressed and melted together to metamorphic rocks, gradually looses this original characteristic.

Solid pieces of most igneous and metamorphic rocks will exhibit porosities of less than 1% and the few pores that are present are so small and so completely separated from each other that permeability can be regarded as zero for all practical purposes.

Appreciable porosities and permeabilities are, however, developed when such rocks are exposed to fracturing and weathering and they will, furthermore and particularily in the tropics, be covered with thick layers of residual soil.

The formation of this residual soil is accelerated by the presence of the surfacial fracture system which will be produced by tensions set up as overlying material is removed by erosion (27). (Fig. 14).

This tectonic fracture system will provide access for infiltrating ground water, which in hot countries will be particularily aggressive, leading to a rapid further decomposition of the broken up rocks, eventually to soil. No strict boundaries can be drawn between the soil and the parent rock but the weathering effect in India is on an average noted down to between 10 and 30 meters (30–90 feet).

The residual soil, which gradually goes over to solid rock as one goes down, has hydrogeological properties akin to alluvial and colluvial deposits (22) and will, accordingly, present a great contribution to the ground water resources in the hard-rock areas of the south (Fig. 15).

In the State of Mysore, which is predominantly underlaid by hard rocks, thus, between 10,000 and 20,000 liters of ground water per day and hectare land (1/2 to 1 million Imp.gal. per day and square mile) are estimated as extractable and wells drilled there will on average yield between 3,500 and 4,500 liters (800–1,000 Imp.gal) per hour with exceptionally high rates of success – as high as 91% reported by Sholapur Well Service (6).

It is only natural then that water well drilling in Indian hard-rock areas will be primarily directed to the extraction of the water contained in the surfacial fracture zone. When a well enters solid rock, therefore, drilling will go on for only a few more meters and since the weathered zone is shallow, the wells will also be shallow. 41 m (134 feet) is, thus, reported as the average depth of the wells drilled during 1971 in the Sholapur region.

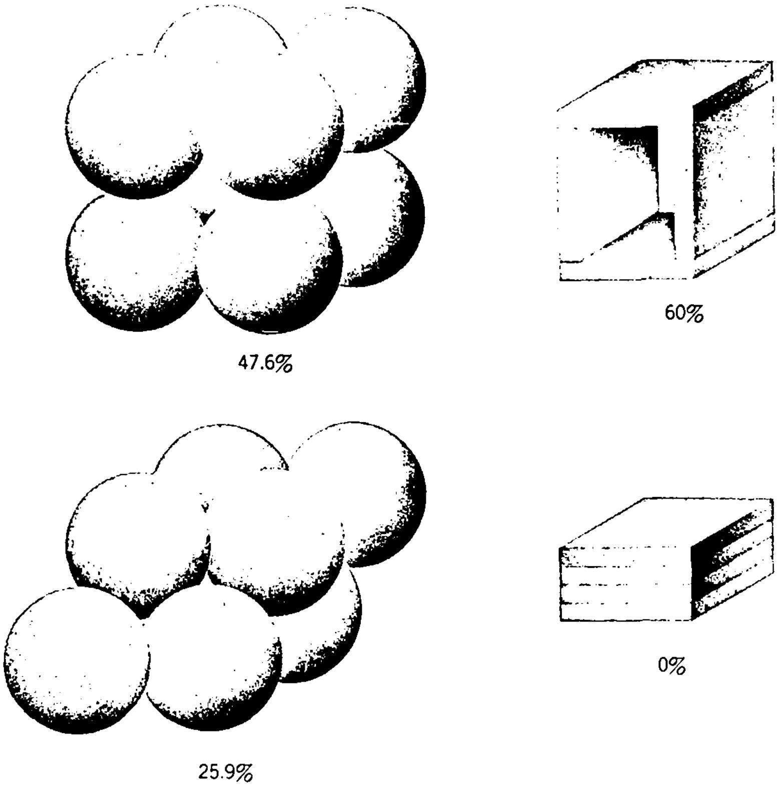


Fig. 13. Open and close packing of spherical and tabular particles. Figures indicate max. and min. porosities for stable configurations of the particles

from Davis and DeWiest (22)

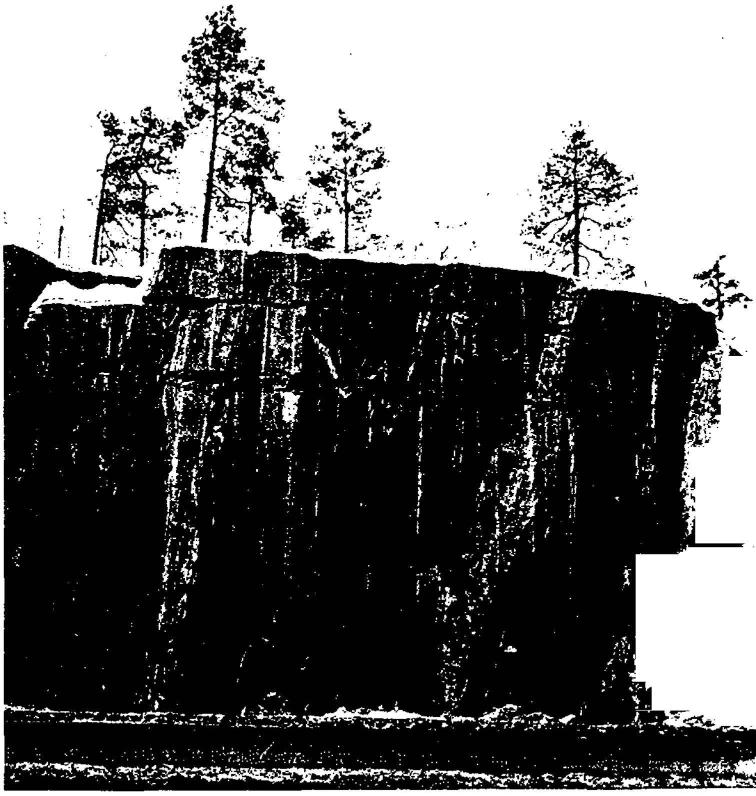


Fig. 14. Horizontal tensional fractures formed by stresses set up by erosional unloading.
Fisksätra, 10 km south-east of Stockholm

Formation	Porosity	Water-holding capacity	
		liters per m^3	Imp. gallons per cu.ft.
Soils	50 %	500	3.0
Clays	45 %	450	2.8
Sands and gravel	40 –30 %	400 to 300	2.5 to 1.8
Completely decomposed rock	40 –30 %	400 to 300	2.5 to 1.8
Highly decomposed rock	24 –16 %	240 to 160	1.5 to 1.0
Greatly weathered rock	16 – 4 %	160 to 40	1.0 to 0.25
Slightly weathered rock	3.0– 1.5 %	30 to 15	0.18 to 0.1
Fresh rock	0.3– 0.05 %	3 to 0.5	0.018 to 0.003

Fig. 15. Porosities of various formations in the State of Mysore, India

from Radhakrishna (7)

10. OCCURRENCE OF GROUND WATER IN GLACIATED HARD-ROCK AREAS

Due to her mild topography and the absence of glacial activity, weathering has been permitted to proceed for hundreds of million of years in peninsular India without serious erosional disturbances. The above described residual soil deposits are the end products of this process and due to their favourable hydrogeological properties and their great distribution, satisfactory results will be obtained even if the location of the wells is made at random.

In the northern countries, however, the major part of this soft cover has been bulldozed away by repeated glaciations, leaving behind only the roots of the surfacial fracture system.

Drilling at random, which is quite common also in Sweden since the majority of wells are sunk only to meet the modest water consumption of summer houses, will, therefore, generally result in very low yields (Fig. 12).

The figure shows, however, that many wells even here produce considerable amounts of water and this is partially due to chance and partially due to the results of geologic surveys carried out for customers requiring more water than what the vacationer will be content with.

Igneous and metamorphic rocks must, accordingly, also without the weathered capping, allow considerable quantities of water to infiltrate and travel underground.

The origin of these properties is, as said above, tectonical stresses, but now much more forceful ones, which have broken up the earth's crust to greater depths.

The logical prescription for obtaining good yields from one's wells should then be first to look for fractures in the terrain and thereafter mount the drill rig so that a maximum number of them will be penetrated by the bore hole.

Unfortunately is it, however, so that the earth has been made subject to many different types of stresses and each type is possessed with its own very special capacity to break the ground in different ways. The chronological order in which the various stresses are applied will decide which one of the subsequently applied will dominate, and the picture is further disturbed by the differences there are in the petrographic fabric of the rocks, meaning that two rocks will yield in a different manner even if they are subject to one and the same type of stress.

An area which possesses a rich lithology and which has undergone a long and complicated tectonic history may, therefore, exhibit a highly confusing congestion of fractures (Fig. 16): some will be open and some will be tight, some will be long and others short and some will have a tendency to interconnect with each other, while others may prefer to develop as more defined, independent cracks.

Fig. 16. Heavily fractured granite. Monte Limbara, Sardinia

And when the tectonic process has finally come to rest, the permeability of the various fracture systems may be further enhanced or abridged through chemical activities, erosion and depositions of various types of quaternary deposits.

From a hydrogeological point of view, the following system should be ideal: open and long fractures interconnected with each other to form a continuous channelway, preferably leading from higher to lower ground and which, in the area of infiltration, should be located to topographical depressions filled up with porous quaternary material. One will also have to see that the plumbing system is not polluted or invaded by seawater. Nor should it traverse highly soluble rocks which may bring the salt content of the water above accepted levels.

It will naturally be quite difficult to find out by visual judgement only which of the fractures appearing on a drill site will belong to such a system and which ones will not. This can only be achieved through a more or less thorough hydrogeological survey.

11. HYDROGEOLOGICAL ANALYSIS OF A HARD-ROCK AREA

Supposing that regional geological maps are available, representative areas of some 5 to 10 km^2 (1.9–3.8 sq.miles) in size are chosen for more detailed studies. Lithologic mapping and plotting of fractures, which comes first, is most rapidly and conveniently done by photo interpretation followed by traverses on the ground.

The next step will be to give the various fracture systems their tectonic identities, i.e., find out what type of stresses was responsible for the formation of what type of fracture system, and the first major division one will have to make is to sort out those fractures formed by plastic deformation from those formed by ruptural (29).

a) **Plastic deformation**

This type of deformation belongs to the orogenic phase, when the rocks were ductile and tended to yield to the stresses by folding rather than faulting. Major fractures are, therefore, rarely developed during this deformation.

Fig. 17 shows, however, that cracks, which undoubtedly must have some connection with the folding, nevertheless are found. These cracks, which lie in planes perpendicular to the fold-axis, are formed by later tensional stresses and will be open. It would, therefore, be logical to conclude that they should be good collectors of ground water.

Since, however, the cracks are confined to the folds only, they will soon wedge out, and since they occur so strictly in one plane only (the ac-plane), they will not be interconnected with each other either (Fig. 19). Such cracks will, therefore, have small volumes, and water stored in them will be stagnant. In spite of their promising appearance, therefore, a driller who choses to sink his wells in this system will experience very poor results.

Due to the strict geometrical relationship between the orientation of these cracks and the fold-axis (normal to each other), they can be identified and excluded by establishing the direction of the fold-axis of the area. This easily done through photo interpretation and petrographic studies.

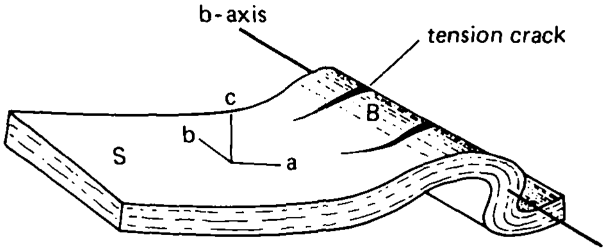


Fig. 17. Generalized sketch showing planar (S) and axial (B) deformation resulting from stresses acting on a plastic rock body.
Stress direction is parallell to the a-axis.
b-axis is the fold-axis.

from Larsson (29)

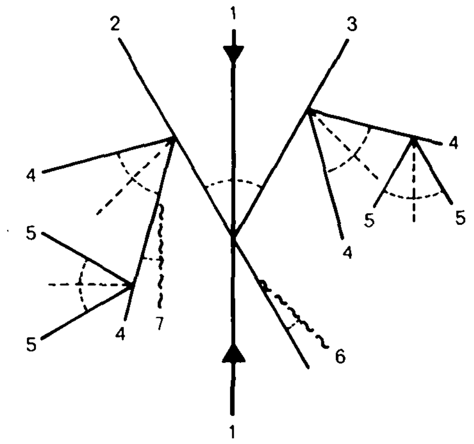
Fig. 18. Planar (S) and axial (B) plastic deformation of quartz-banded iron ore from Sydvaranger, North Norway. The tension cracks shown on Fig. 17 is the feature responsible for the nice cleavage surface of this hand specimen.

b) **Ruptural deformation**

After having gone through an orogeny, the rocks will be more homogeneous and more brittle than before. They will, therefore, now tend to yield to stresses in a

Fig. 19. Fracture patterns appearing in the Bohus granite of Western Sweden.
The strictly parallel fractures running in WNW-ly direction are the unfavourable tension cracks which have originated during plastic deformation.
The great NNE-ly running valley is a major *tensional ruptural fracture*.
The NW-ly running smaller valleys are first order shear zones

from Larsson (33)



1. Primary stress direction, parallel to which major tensional fractures may develop
2. Primary first order wrench fault (shear zone)
3. *Complementary first order wrench fault*
4. Second order wrench fault
5. Third order wrench fault
6. Second order drag fold
7. Third order drag fold

Angles are 30, resp. 15 degrees

Fig. 20. Different fractures formed in an isotropic body under compression

from Moody and Hill (30)

ruptural manner and the fracture pattern will, depending upon the degree of isotropy which the rocks have attained more or less closely follow those arrived at through theoretical calculations and model studies (31).

Ruptural deformation does, however, not necessarily mean that the permeability of a rock will be indiscriminately improved. Only those fractures formed, or later reactivated, by tensional stresses, will be open, whereas those formed under compression will be tight and impermeable.

Fig. 20 shows that most of the fractures will be compressional (shear zones and drag folds) and Fig. 21 confirms that these fractures will predominate in the field.

Fig. 21. Aerial view of a comparatively isotropic arcosite body in Repparfjord, North Norway.

The major fracture running 45^{o} upwards to the left is parallel to the primary stress direction, i.e. tensional.

Note the close relationship to the theoretical pattern shown on Fig. 20

The confusing picture arrived at when all the ruptural fractures are superimposed upon those already existing from the plastic deformation phase (Fig. 19) suggests that a hydrogeological analysis based on plotting of fractures on aerial photos only will be meaningless.

Information on the regional tectonic trend coupled with morphological investigations and studies of representative fractures on the ground will, however, dissect the picture and eventually lead to what we are looking for: the few really big water storing fractures which, as we will now understand, are the tensional ones.

The primary stress direction can be detected by striations on overthrust planes. Fractures parallel to these striations should, accordingly, be termed favourable. If some of them, furthermore, are found to be filled with diabase, it should be taken as additional proof of this direction being of a tensional, i.e. open nature.

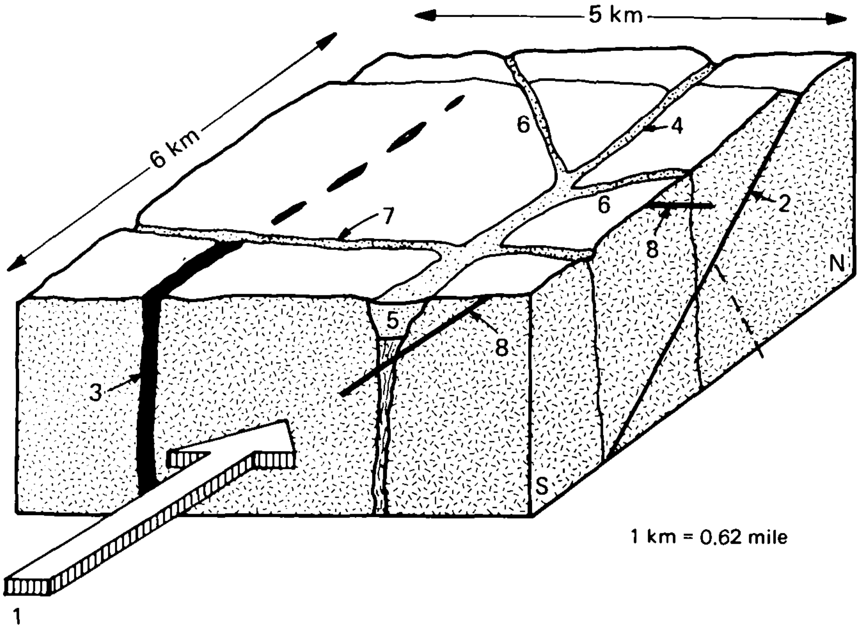
If on the other hand, the fracture looks like the one depicted in Fig. 22, the system to which it belongs can be immediately discarded – it is a typical compressional shear fracture.

Major tension fractures will also be revealed by topographic depressions which can be very pronounced and run through the area in straight lines for several miles.

Fig. 22. Typical shear fracture, Altenes, North Norway.

The surface of the fracture is covered by a thick layer of brown slickensides.

The horizontal striations reveal direction of movement, which is 30° to the primary stress direction.



1. Primary stress direction
2. Overthrust plane
3. Diabase dyke
4. Major tensional fracture
5. Quaternary deposits
6. First order shear zone
7. Local fracture system parallel to cracks formed under the plastic deformation phase. Does not belong to the pure ruptural model shown in Fig. 20
8. Test holes (note that they are drilled with oblique angles)

Fig. 23. Deformation model of post-orogenic ruptural deformations in the quasi-isotropic Karlshamn granite of southeastern Sweden.

The model is believed to represent an area of 20 x 30 km.

from Larsson (31)

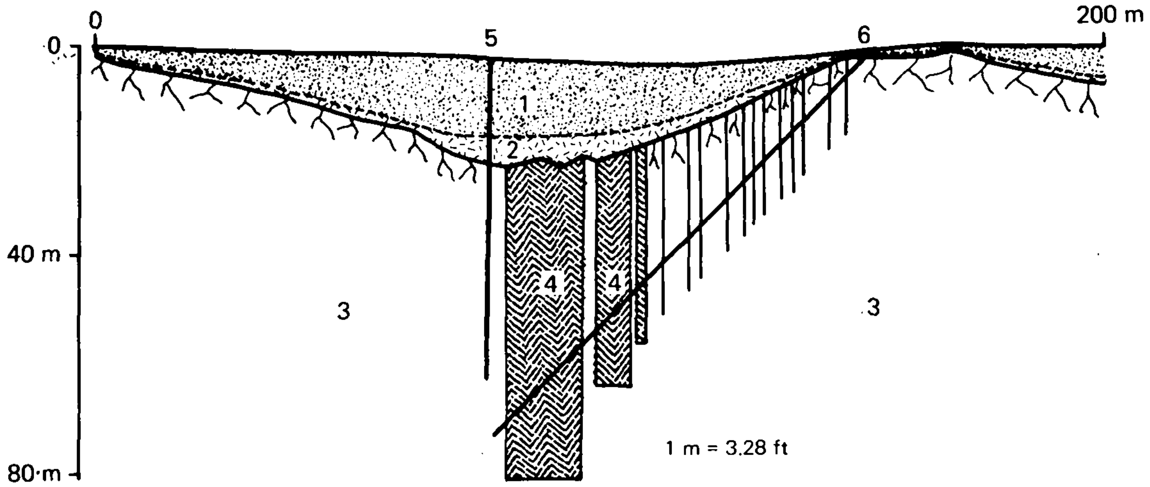
Geophysical instruments will be helpful tools for the geologist in these deductions. Seismic surveys will give depth to bedrock, composition of the overburden and confirm that rocks underlying a suspected valley have been broken up in an open manner, electric resistivity measurements will give another check on depth to bedrock and can also, under favourable conditions, directly indicate presence of water-bearing formations while magnetic anomalies will reveal the presence of magnetite-bearing diabases. See the following chapter.

After all the surveys have been carried out in the type areas, deformation models are designed which will be representative for the conditions prevailing in the surrounding region (Fig. 23).

Two test holes drilled on the model shown (Fig. 24) gave yields as presented in Fig. 25.

As can be seen, the quality of the well sunk through the tensional fracture far surpasses the one sunk through the shear zone.

Further to the north of Sweden, the same general picture prevails as was found in the Karlshamn region.



1. Clay
2. Gravel
3. Solid granite
4. Tensional fracture zone
5. Old well yielding very little water
6. Test hole yielding 9.7 liters (2.13 Imp.gal) per second

Fig. 24. Test drilling through the major tensional fracture appearing in Fig. 23

from Larsson (31)

Hole through	Yields			Drawdown	Specific yields	
	liters/sec	= liters/hour	= Imp.gal/hour		l/sec/m	= Imp.gal/min/ft
Tension fracture	9.7	= 35,000	= 7,700	60 m = 197 ft	0.16	= 0.65
Shear zone	0.04	= 144	= 32	30 m = 98 ft	0.0013	= 0.0054

Fig. 25. Test pumping results from the model shown on Fig. 23

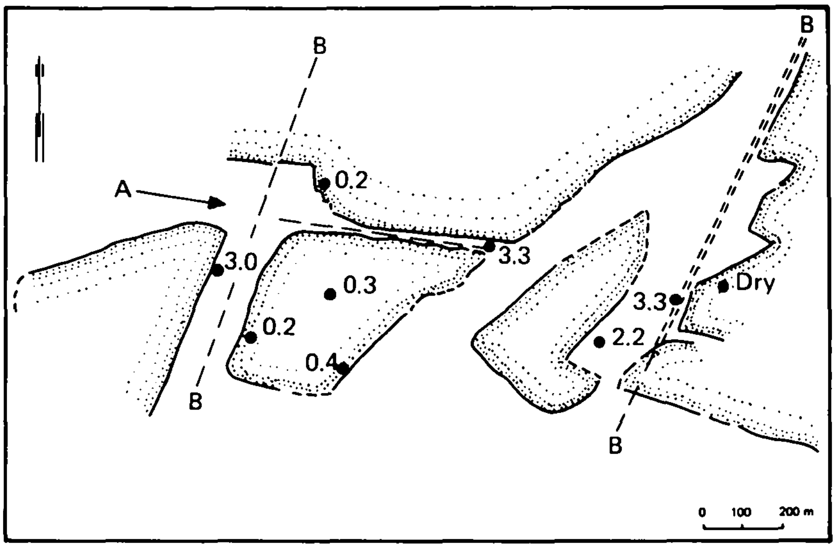
from Larsson (31)

In many places it has, however, been found that even shear zones will deliver appreciable amounts of water which they, according to theory, should not (Fig. 26).

The explanation may be that which was found in an area investigated near Vallentuna, 30 km north of Stockholm (Fig. 27). Here, the good yield of the well sunk through the shear zone was found to be due to late tectonic rotation between the "plinths", resulting in an opening of the already formed, tight shear zones.

A section of a shear zone which is thus refractured, will be more vulnerable to erosion and would be expected to be located to topographical depressions in the terrain.

In an area where no scientific research has been carried out and the morphology is as presented in Fig. 28, thus, it will be safer for the driller to sink his wells between exposed hillocks rather than in them.



A = primary stress direction
B = known shear zones

1 liter = 0.22 Imp.gal

Fig. 26. Tectonic-morphological sketch of an area 50 km north of Gothenburg, Sweden showing the contrast between the yields of wells sunk in solid, undeformed, "plinths" and that of wells sunk between such "plinths".

Good yields, given in liters per second, are obtained both in the tensional and the compressional valleys.

from Larsson (32)

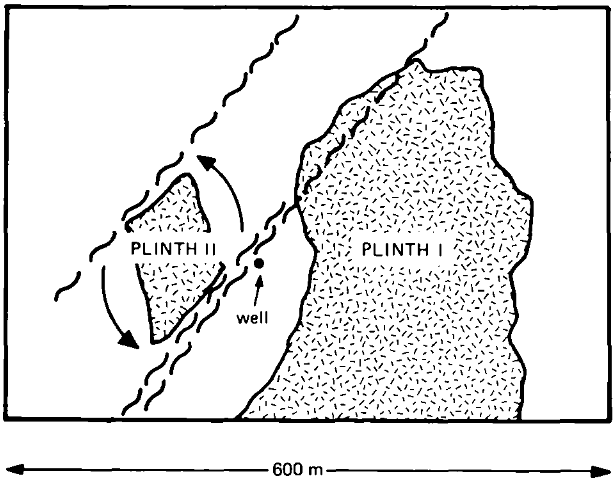


Fig. 27. Shear zone at Bergby, Uppland, Sweden yielding abnormally high quantities of water.

"Plinth" II has rotated in relation to "Plinth" I, whereby the earlier-formed, tight shear zone has been opened.

Yield of the well: 7–8 liters (1.5–1.8 Imp.gal) per second

from Larsson (32)

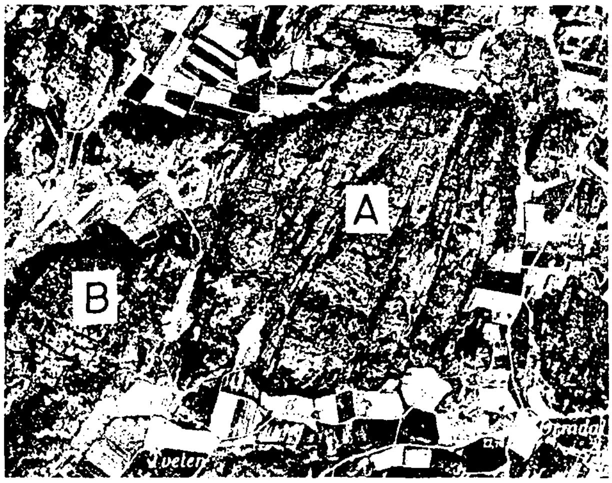


Fig. 28. Typical morphological picture of the lowlands of Central Sweden.

A and B are so called "plinths", slabs of compact, undeformed metamorphic rock. Fractures, which may or may not be favourable, are located under the fields between them.

from Larsson (32)

12. GEOPHYSICAL INVESTIGATIONS

As already mentioned, geophysical surveys will provide information which may be very valuable to the hydrogeologist in his interpretations. Such surveys refer to scientific measurements of physical properties of the earth's crust, with the intention of detecting differences in the same, which may be interpreted in terms of geologic structure, rock type and porosity, water content and quality.

Like the above-described tectonic studies, however, geophysical measurements will, particularly in hard-rock formations, only seldom give a direct confirmation of the presence of drinkable water in pumpable quantities. What they produce are only additional bits and pieces of information which, when interpreted together with the geological observations in an integrated manner, will lead to recommendations for drilling a well at such a location and in such a direction that its chances of yielding potable water in adequate quantities are considerably improved. (34).

The three ground survey methods which are generally used for water prospecting are: seismic refraction, electric resistivity and, in specific areas, the magnetic method.

Airborne and drill hole geophysical surveys may also be used in regional and detailed water resources investigations.

Loess	300– 600 meters per second
Clays	1000–2500 meters per second
Moraine above water table	500–1200 meters per second
Moraine below water table	1800–2700 meters per second
Gneiss	3500–7500 meters per second
Granite	4750–6000 meters per second
Gabbro	6450–6700 meters per second
Eclogite	8000 meters per second

Fig. 29. Typical velocities of compresional waves in different materials

1 meter = 3.28 ft

a) The seismic refraction method

This method involves the creation of a small shock at the earth's surface by means of a heavy sledge or a small dynamite charge and measuring the time required for the resulting shock wave to travel known distances.

Seismometers, also known as geophones, are spaced in a line from the shock point at fixed intervals. They receive the shock wave, convert the vibrations into electric impulses which are fed into a recording oscillograph, which automatically records the instant of firing and the various first arrivals of the shock wave.

The travel time of a wave depends upon the media through which it passes; velocities are greatest in solid igneous rocks and least in unconsolidated material (Fig. 29). If the profile crosses a rock body with a different density than the surrounding rock, it will be detected by the difference in lateral velocity recorded over the body. Fracture zones, having marked lower velocities than the unfractured rock, will be detected in the same way.

Since the waves expand as a sphere outward from the shock point, they will also travel down into the ground. Seismic waves, following the same laws of propagation as light rays, may therefore be reflected or refracted at any interface where a velocity change occurs.

For water exploration, where only moderate depths are involved, it is the refraction technique which is in use. The times taken for the wave to travel down to a refracting interface, along the interface and up again to the geophone, are used to compute the depths to this interface and/or the composition of the material covering it.

Fig. 30 shows the type of cross-sections which can be drawn from the various recordings made. It is beyond doubt that this information will be of very great value to the hydrogeologist.

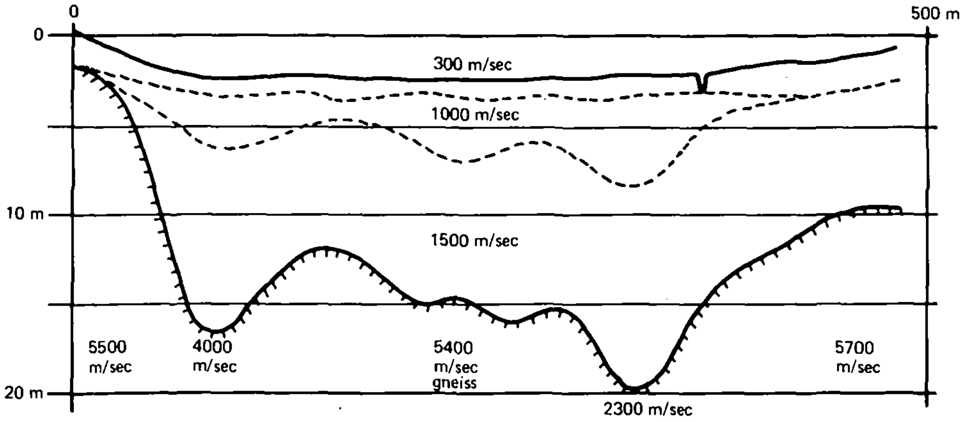


Fig. 30. Seismic cross-section of a valley suspected to have been formed by tensional fractures.

Two highly fractured zones are indicated in the otherwise undeformed gneiss.

The velocities recorded in the overburden suggests an upward successtion of moraine, clay and loess.

simplified from Larsson (33)

Electric resistivity in ohm-meters

Gneiss	1×10^3 – 7×10^4
Moraine	1×10^2 – 2×10^3
Sandstone	1×10^2 – 3×10^2
Clays	1×10^1 – 1×10^2
Water for human uses (0.25% salt)	1.80
Water for irrigation (0.70% salt)	0.65
Sea water	0.20

Fig. 31. The magnitude of electric resistivities in ohm-meters of different materials

Even though seismic instruments, despite their relatively high cost, are simple to use, considerable experience is needed for accurate interpretation of the measuring results. Seismic surveys are, therefore, mainly made use of for detailed studies over limited type areas.

b) The electric resistivity method

The electrical resistivity of a rock formation limits the amount of current passing through the formation when an electrical potential is applied. (34). It may be defined as the resistence in ohms between opposite faces of a unit cube of the material. If a material of resistance R has a cross-sectional area A and a length, L, then its resistivity can be expressed as

$$p = \frac{RA}{L}$$

In the metric system, units of resistivity are ohm-m²/m, or simply ohm-meter.

Resistivities of rock formations vary over a wide range, depending upon the material, density, porosity, pore size and shape, water content and quality, and temperature. There are no fixed limits for resistivities of various rocks but the magnitudes are as shown in Fig. 31.

In relatively porous formations, the resistivity is controlled more by the content and quality of water within the formation than by the resistivity of the (dry) formation itself. In aquifers composed of unconsolidated materials, such as the residual soil covers in the tropic countries, electric measurement can, therefore, directly indicate presence and quality of water, (Fig. 32), which is not possible when dealing with true hard-rock ground water deposits. Here, the greatest value of the method lies in its capacity to measure depth to bedrock in a simpler way than with seismic instruments.

c) The magnetic method

Measurements of variations of the earth's magnetic field are probably the most rapid, uncomplicated and inexpensive geophysical observation to make (22).

The intensity of either the total field or its vertical or horizontal components, can be recorded with a magnetometer, which may be designed according to the suspension or torsion wire, the fluxgate or the proton precession systems.

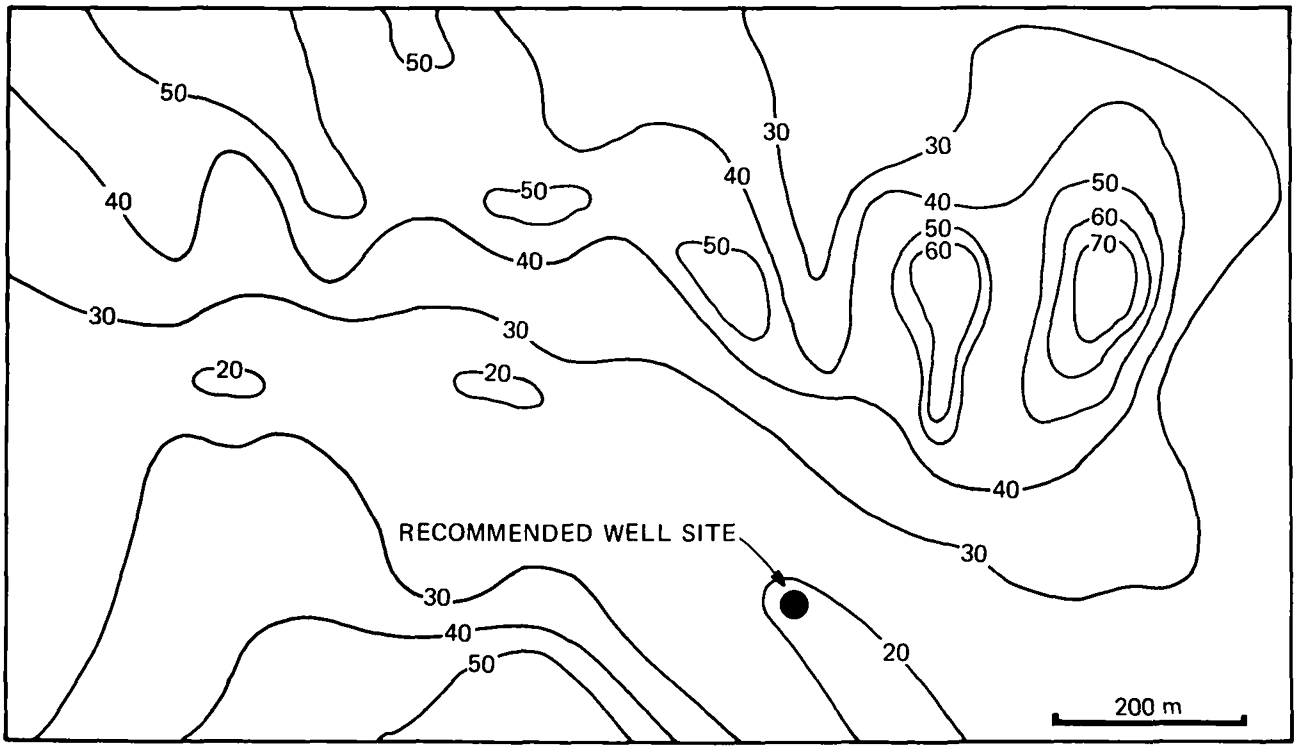


Fig. 32. Apparent resistivity contour map of the Jallapally Area, Andhra Pradesh, India

Contour interval: 10 ohm-meter

Survey carried out by the National Geophysical Research Institute, Hyderabad

from Tröften (11)

Magnetite ore	7.1×10^4	$-\ 14.2\times10^6$
Pyrrhotite	10^4	$-\ 25.0\times10^4$
Diabase	6.3×10^2	$-\ 25.0\times10^4$
Gneiss	0	$-\ 3300$
Granite	0	$-\ 65$

Fig. 33. Magnetic volume susceptibility, $k\times10^6$ (SI) of different rocks

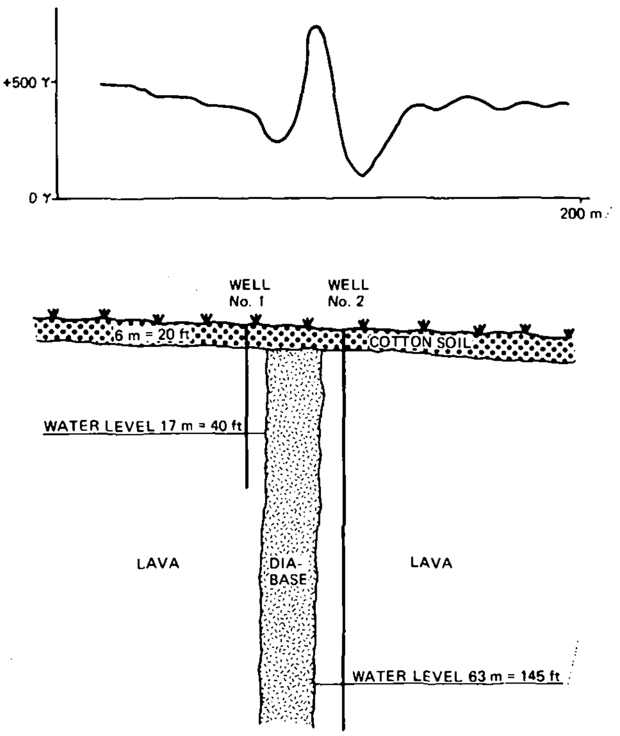


Fig. 34. Magnetic survey at Atlas Copco's factory in Poona, India.

Two closely spaced tube wells struck water at greatly differing depths.

Interpretation: A diabase dyke cuts the lava and acts as a natural dam in the ground.

The largest natural anomalies are caused by the presence of magnetite, either in rock or in placer deposits. Depending upon the content of magnetite in a rock or an alluvium, these formations will exhibit more or less marked differences in magnetic properties, wherefore they may be separated from each other by magnetic measurements (Fig. 33).

If the formations, in addition to differences in content of magnetite also contain different hydrogeological properties such as susceptibility to crack (quartzite) versus tendency to yield to the stresses in a plastic way (gabbro), the advantage of magnetic surveys become obvious.

Geological maps, which are the basis of the stocktaking of all natural resources can, thus, be constructed even in areas where the rocks are completely covered by overburden.

Since the magnetometer, furthermore, is probably the simplest and least expensive of all geophysical instruments, every field geologist should have such an instrument in his pocket.

Figs. 34 and 35 exemplify how puzzling hydrogeological problems can rapidly be solved with the help of a simple pocket magnetometer.

For further information on geophysical instruments, operation and interpretation procedures, the reader is invited to contact our subsidiary Atlas Copco ABEM AB, Box 200 86, S-161 20 Bromma, Sweden.

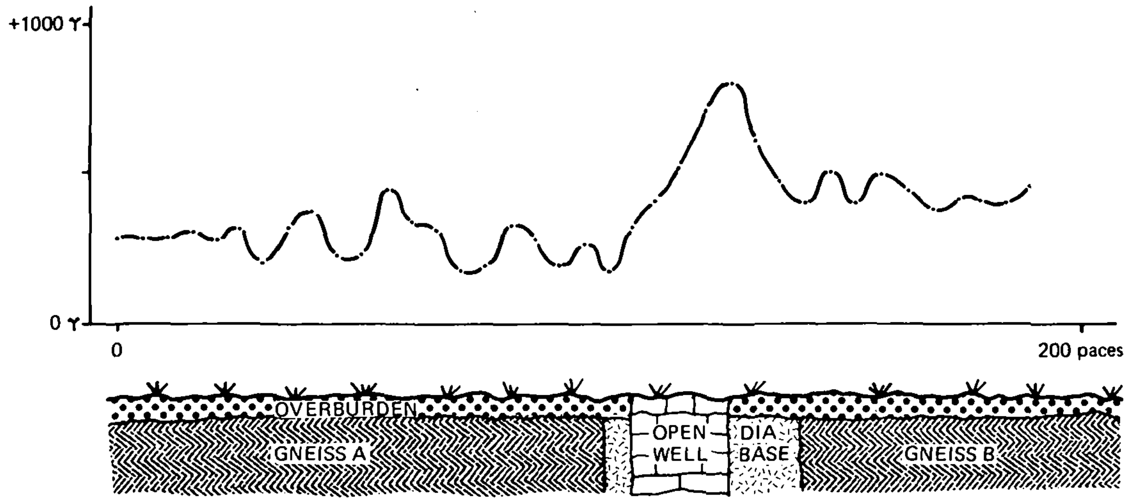


Fig. 35. Magnetic survey over an open well near Hyderabad, India.

This well was almost dry even though another well situated 50 m to the left gave good water. The survey reveals that the well was sunk in an impermeable diabase dyke.

Differences in petrology between the two gneisses could not be established by macroscopic examination. Gneiss B contains, however, more magnetite than Gneiss A. Test drillings would confirm whether they also differ in hydrogeological respects.

13. TEST DRILLING

No sensible hydrogeologist will, on the basis of individual geological and geophysical observations alone, or even on an integrated interpretation of the same, preemptorily claim that water in a given quantity and a given quality is to be found underground at a given location.

As is the case in mineral exploration, a final confirmation or refutation of one's interpretations can only be achieved through a physical investigation of the actual deposit; one will have to drill down to the location which one has predicted will or will not carry water, measure the flow of the water, in quantity as well as in direction, and collect samples for chemical and biochemical analyses.

The more numerous and complicated the hydrogeological parameters become, the greater becomes the need for such dissections, and the more extensive the ground one wants to cover with greater accuracy, the more penetrations will be called for.

Test drilling is, however, unfortunately regarded as an "unproductive" type of investment and will no doubt continue to be considered as such. The test rig and its accessories must, therefore, be designed so that the drilling will be inexpensive at the same time as it fulfils all other requirements which are characteristic for this type of scientific investigations: be able to drill at high speed (speed is inverse to cost, incidentally), have the ability to drill holes of different diameters in all directions and through all kinds of formations, ensuring that the hole will truly reflect the hydrogeological conditions of the ground, have good terrain properties and be simple to operate.

It should also be equipped with accessories for carrying out various types of subsurface investigations which will be described in the next chapter.

Also, since an intelligent water well driller is expected to occasionally carry out test drillings on his own behalf or may accept contracts on scientific research projects, it would be a great advantage if his production drill were designed in such a way that it, with few and rapid modifications, could be converted to a test drilling rig.

The fact that Atlas Copco have incorporated these demands into their water well drilling method is considered by the author as one of its more important advantages.

14. SUBSURFACE INVESTIGATIONS

Geology is the science which treats of the origin, history, and structure of the earth, as recorded in the rocks, together with the forces and processes now operating to further modify them (35). It is, accordingly, a four-dimensional affair composed of the three vectors of space + time.

One advantage of the test hole is that the third dimension, the vertical, has thereby been opened for direct investigations. These may be of various kinds and will all contribute to a better understanding of the geological conditions beneath.

Below are listed some such subsurface investigations with a direct relationship to hard-rock conditions.

a) Rock sampling

The core or the fragments of rocks drilled out of the hole represent valuable material for geological mapping. This material should, therefore, be collected and shipped to some governmental archive for storage.

Only few countries, like Denmark, have, however, taken legal steps to make such procedure compulsary. As a matter of fact, in many countries is it not even required to report the location of the wells.

b) Logging

As the water can not flow through the rock proper but only through cracks in it, it becomes important to have all cracks recorded, the permeable ones as well as the impermeable.

1) Local increases in diameter of a bore hole will indicate the location of a fracture, but not conclusively so. Molds of fragments which have been loosened by the drill bit will produce a similar feature.
2) If there is a difference in the salt content of the water of the well and that of the surrounding ground, an electric potential will be set up. This potential, the self potential as it is called, will vary along the walls of the bore hole with tops at locations where water flows into it through cracks.
3) Differences in temperature of the water in a well will indicate that water flows into it or out of it through cracks.
4) Differences in electric conductivity of the water in a well will indicate the interface between stagnant (old) and flowing (new) water.

At the Royal Institute of Technology, Department of Land Improvement and Drainage, Stockholm, a sond has been designed which measures and records these parameters simultaneously as it is lowered into the hole (36). (Fig. 36). By studying such records, the population and nature of fractures in the ground can be interpreted. Fig. 37 indicates, e.g., an active fracture at 50 meters depth whereas the hydraulic activity of the bigger fracture located at 55 meters depth, is lower.

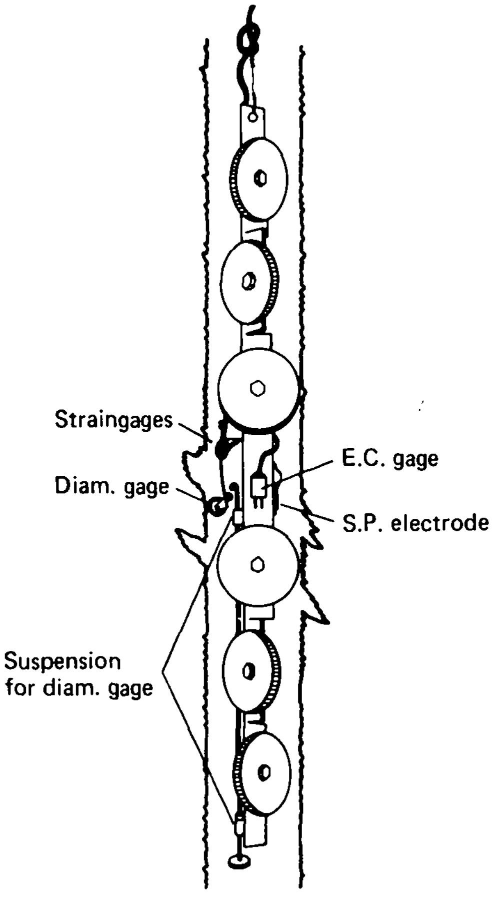
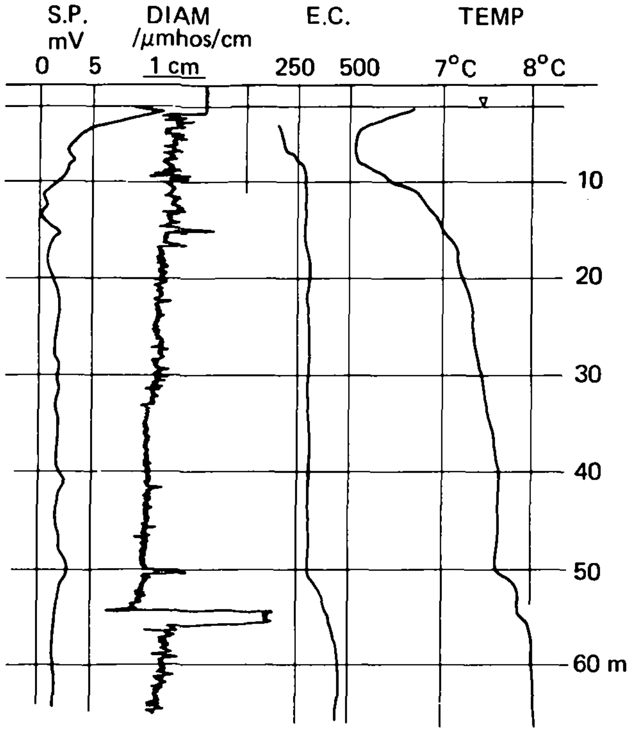


Fig. 36. Sond for well logging

from Jacks (36)



1 m = 3.28 ft
1 cm = 0.4 in.

Fig. 37. Log from a well

From left to right: variations in self potential, diameter, electric conductivity and temperature

from Jacks (36)

c) **Keeping a drilling record**

The net penetration speed of a drill should, in theory, decrease gradually as the hole gets deeper (Fig. 38). This is due to:

1) gradual blunting of the drill bit,
2) increased strain on the mechanism which rotates the drill string,
3) increased resistance against transporting the flushing medium down to the bottom of the hole,
4) increased resistance against transporting the drilled-out material up and out of the hole,
5) decreased ability of the flushing medium to keep the bottom of the hole clean, and,
6) when the drill is a "top hammer", less percussive energy reaching the drill bit due to losses in the increasing numbers of couplings connecting the drill rods together.

The net penetration speed curve of one hole will, however, seldom be that even (Fig. 39).

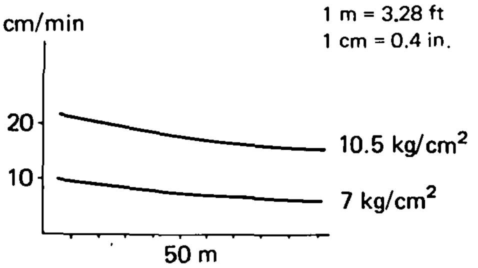


Fig. 38. Average net penetration speed of water wells drilled in Svionian gneisses around Stockholm with Atlas Copco DTH-hammer COP 4.

Bit diameter: 115 mm (4 1/2 inch)
Air pressure: 7 and 10.5 kg/cm^2 (100 and 150 psi)

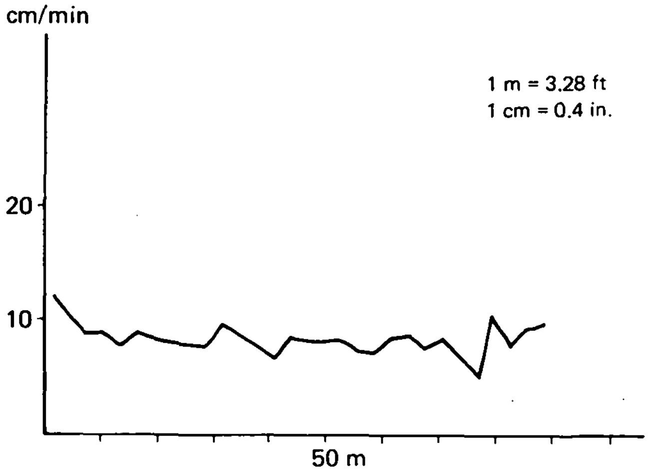


Fig. 39. Net penetration speed of one water well drilled in Svionian gneiss near Stockholm with Atlas Copco DTH-hammer COP 4

Bit diameter: 115 mm (4 1/2 inch)
Air pressure: 7 kg/cm^2 (100 psi)

Local decreases in penetration speed may be due to the encounter of harder rock bodies in the hole (Fig. 40), flushing problems, etc., while increases will generally reflect the opposite. A formation revealed by an increased penetration speed may be a softer rock body or a fracture zone.

What often happens in practice is that the penetration speed will suffer a drop when the drill bit starts to break into a water-bearing fracture zone, whereafter it will increase to above normal, as happened at 75 meters depth in the hole depicted in Fig. 39.

The explanation of this phenomenon is that the small quantities of water which start to seep into the hole when the fracture zone is encountered, will clot the cuttings together into a paste which will be difficult to blow out of the hole. When the bit has penetrated deeper into the fracture zone, more water will stream in, will dilute the paste and bring flushing back to normal. The fact that the penetration speed now is **above** normal is due to the easier drilling characteristics of the fractured rock.

An intelligent driller will notice such changes in penetration speed and will be acquainted with their causes. He will, thus, make his own geological interpretations which will be helpful, above all, in making the decision at what depth he should consider his well finished.

Variations in penetration speed are in fact a geophysical phenomenon which should be recorded and mailed to some governmental archive for filing.

d) Water sampling

Measurements of self potential and electric conductivity are strictly speaking measurements of chemical properties. True chemical analyses carried out on collected water samples may yield additional information on the nature of the water and its flow (36).

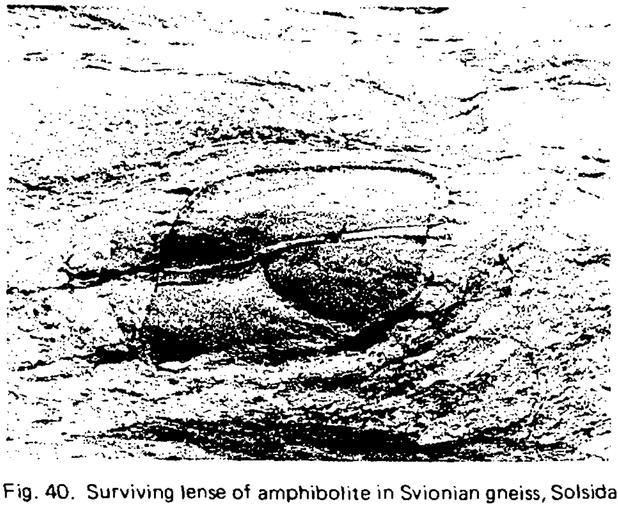


Fig. 40. Surviving lense of amphibolite in Svionian gneiss, Solsidan, 15 km south-east of Stockholm.

When the drill bit reaches such a body, the net penetration speed will increase or decrease depending upon the relative drillability of the two rock types.

Recently infiltrated atmospheric water, which has a low pH value, will be slowly neutralized by reactions with the silicates of the rock. By measuring the pH of the well water, thus, one will get an idea of its age. High iron content indicates a high ground water table or infiltration from lakes whereas high sodium content in salt well water suggests that the contamination may be due to infiltration from the sea. High contents of calcium and magnesium, on the other hand, suggest lithologic contamination, i.e., that the water is old and stagnant.

e) Test pumping

From a practical as well as from a scientific point of view test pumping is, perhaps, the most important and at the same time the least complicated subsurface investigation to carry out.

To the geologist it will give information on the rate of flow through the fractures cut and the customer will know what pump he should install.

It is, however, important that this test is done in such a way that it truly reflects the drainage into the well, and one error commonly committed is that the pumping is not carried out over a sufficiently long period of time (37).

If the capacity of the test pump is low and the ground water magazine is large, it may take a long time before the ground water level is affected to such an extent that correct conclusions can be drawn as to the size of the deposit.

It is also very incorrect to place a sign of equation between the quantities of water which a well is able to produce and the yielding capacity of the deposit as a whole.

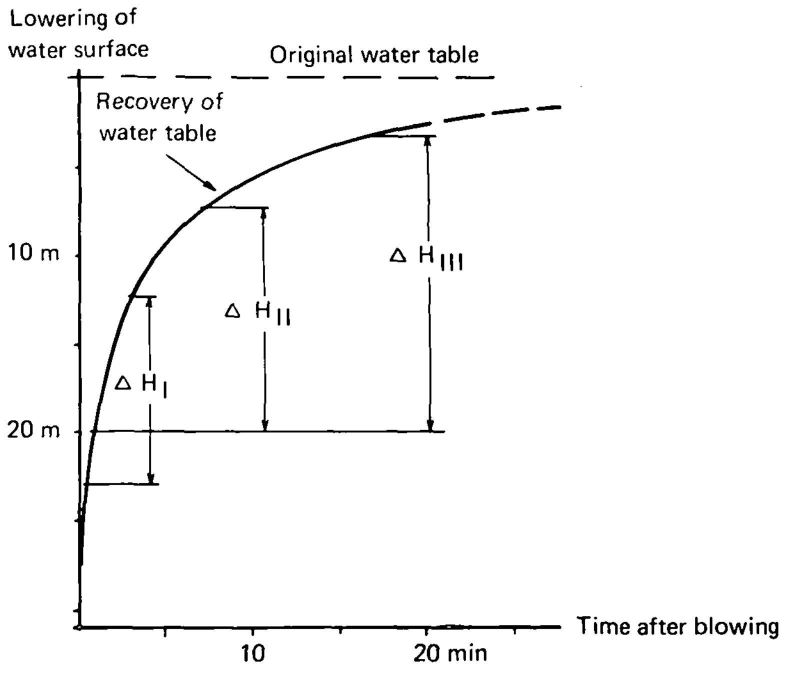
To arrive at correct answers as to the size and yield capacity of the water deposit, the test pumping has to be done over a sufficiently long period of time with a sufficiently strong pump.

Mode of procedure has also to be paid close attention to.

The method often employed by small contractors is to blow the well clean of water with compressed air, lower a float into it and measure how high the well is filled with water by a given time.

Since the volume per meter of the hole is known, the recorded time can be converted to yield per time unit.

Fig. 41 shows, however, that great variations in yield will be arrived at, depending upon what measuring period one makes use of.



Procedure	Measure period	Recovery time	ΔH	Volume	Estimated yield
I	0.5 to 4 min	3.5 min	10.5 m (34 ft)	10.5x8 l	1440 l/h (315 Imp.gal/h)
II	1 to 7 min	6.0 min	12.7 m (42 ft)	12.7x8 l	1002 l/h (220 Imp.gal/h)
III	1 to 16 min	15.0 min	16.7 m (55 ft)	16.7x8 l	540 l/h (120 Imp.gal/h)

Fig. 41. Varying results obtained when estimating the yield of a well by blowing it with air and measuring time of recovery.

Well diameter = 100 mm (4"); volume of 1 m (3.28 ft) hole = 8 liters (1.7 Imp.gal)

from Möller (37)

Even if a standardized procedure were employed, the method would nevertheless give unreliable results since it does not comply with any hydraulic law governing the flow of water from a formation and into a well.

"Varied test pumping" is an appealing method due to the reasonably reliable results obtained only after one day of test pumping.

Since modern rigs under favourable conditions may be in a position to drill a well during the same time, the drilling and test pumping teams will be able to work in good concert with one another. How this method functions will be understood by examining Fig. 42. The well is test pumped for a couple of hours at three different capacities: 3, 5.5 and 7 liters per second. The diagram shows that the drawdown rapidly increases at pumping rates above approx. 6 liters per second. To take out more water than that will not pay off since a production pump able to overcome the rapidly increasing head will have to be chosen, and the cost of such a pump will not be in economical relationship to the additional small quantities of water it will bring out of the well.

6 liters per second was therefore decided to be the working yield of the well. (37).

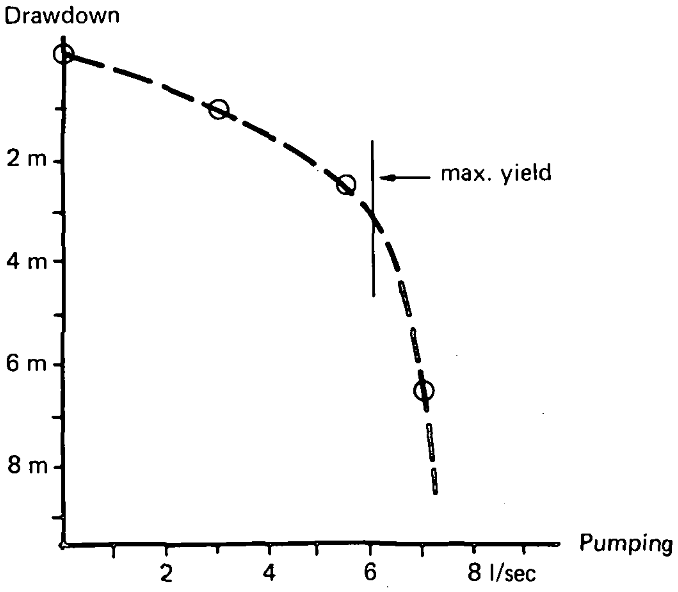


Fig. 42. Calculation of max. yield of a well by varied test pumping

from Möller (37)

1 m = 3.28 ft
1 l = 0.22 Imp. gal

15. HYDROGEOLOGICAL RULES OF THUMB FOR THE WATER WELL DRILLER

From the foregoing it should be evident that hydrogeological surveys and interpretations in hard-rock areas should enable the driller to locate his wells so that highly improved yields are obtained. It is, however, also evident that each and every well cannot be made the object of such comprehensive investigations as described above.

In actual practice the procedure is that the formulas arrived at in the type areas are projected to the regions they are believed to represent. As one moves away from one such type area, thus, the rules become increasingly more unreliable.

The ideal scientific support to the water well drilling industry would then be that an evenly distributed net of type areas were laid out and national maps prepared on which would be found outlined what regions the type areas represented.

At least as far as hard-rock hydrogeology is concerned, such maps are, however, virutally non-existant.
The water well driller will have to lay out his work according to certain rules of thumb, based on his own experience and what he may extract from scientific sources.

With the present knowledge of the hydrogeological conditions of the igneous and metamorphic formations of Sweden, a driller operating in this theater should observe the following broad guidelines:

a) Build up a library of topographical and geological maps and, preferably also, aerial photographs. If it is found that such a file will be too costly, the material can be borrowed. Find out where.

b) Before signing a contract, study this material and establish the pattern of valleys and fractures of the area. Find out how previously drilled wells in the area perform. Walk around a little on the ground.

   1) If open fractures are found, check on the aerial photos whether they, or fractures parallel to them, soon wedge out or whether they are long and interconnected. The former system should be discharged regardless of how promising it looks.

   2) If no pronounced fracture system is found on the hillock where the client may happen to want the well drilled, study the nature of the topographic depressions in the surroundings.

   3) Broad, regionally straight but locally irregular valleys should be given first choice.

   4) Where such valleys don't exist, choose locations in tight valleys where these are intersected by other valleys or long, pronounced fractures.

   5) If the fractures are found to dip at low angles or they are suspected to be broad, crushed-up zones, the well may be drilled vertical.

   6) If the fracture is an individual, steeply dipping one, intersect it with an inclined hole.

   7) Close to the coastline, be aware of the danger of infiltrating sea water, especially if great quantities are to be extracted from the well.

   8) In an unpromising area, don't believe that the problems will be solved simply by drilling deeper holes. At best, one may only strike fossile sea water. (See Fig. 70.)

   9) If the client wants more water than what, say a 4" or an even smaller pump can deliver, interpret the ground's potential for draining more water than that into the well. Since the discharge into the well will not appreciably increase by increasing the diameter of the well only, it may be better economy to sink several small-diameter wells rather than one large-diameter well.

   10) Where the presence of diabase dykes is marked on the geological map, try to locate them in the field, eventually with a pocket magnetometer. In areas of high relief, locate the well uphill of the dyke rather than downhill of it.

   11) If the picture arrived at is confusing, it may pay off to drill a test hole.

   12) Try to convince the client that it will be more profitable to sink the well at a favourable location farther away from his site of consumption rather than at an unfavourable location close to it.

   13) Don't be scared of the listed recommendations. They are easier to master than may appear at first glance.

c) A very good suggestion is to establish a good personal relation with scientific institutions engaged in the field of hydrogeology and water supply, and don't be bashful; the scientist will be as happy to share your practical experience as you will be at benefitting from his academic knowledge.

d) When sufficiently many people of various background but that one interest in common — supply of water from underground — come together, the time will be ripe for establishing a water well association. Then, and only then, can all information be systematically collected and distributed to the benefit of all parties involved.

e) And finally, a word from the supplier.

Water wells are often asked for in places and in geological formations which makes this kind of drilling quite different from drilling for mining and construction purposes.

While the layout of drilling patterns for the mining and the civil engineering field strives at simplifying the drilling procedure, the water wells actually aim at the most difficult conditions: the most highly fractured portions of the rock, which contain the best possibilities of holding water. And these locations are often placed far away from even the simplest service facilities, may be difficult to reach and are, on top of it all, most often buried beneath the thickest layers of overburden.

See to, therefore, that an equipment is chosen which simplifies and speeds up the work at the same time as reliable service can be counted on, regardless of where the drilling is carried out. The relation between investment and production rate must finally be so that the best economic return is obtained.

Atlas Copco, being well informed about the various demands in this field as they differ from place to place throughout the world, have tried to direct the design of their water well drilling equipment so that it will satisfy most of our prospective clients.

16. VARIOUS TYPES OF DRILLING METHODS

The following principal methods are available for drilling for water in various formations:

a. Cable tool percussion drilling

b. Calyx or steel shot drilling

c. Core drilling with diamond or tungsten carbide set drill bits

d. Rotary drilling with tri-cone rock roller bits

e. Pneumatic percussion drilling

No generally valid answer can be given to the question of which method is best, as each method contains both advantageous and disadvantageous features compared to the others. The factors at work here are the type of rocks and water-bearing stratum, depth to the ground water level, volume of the desired water supply, diameter of the well, costs, etc.

In this chapter the discussion will focus on methods for drilling in consolidated formations only. (38).

a. **Cable tool percussion drilling** (Fig. 43)

Cable tool percussion drilling is a very old method, the use of which can be dated to more than 1000 years ago in China. The principle is unchanged today even though the tools are vastly improved.

The method consists of lifting and then dropping a heavy chisel which crushes the rock and thus works its way down into the formation. The method is most suitable in consolidated material, but can also be employed in loose formations if casing tubes are driven down at the same time to prevent the hole from collapsing.

This drilling method is practicable in both small and large holes and depths of 300 to 500 meters (1000 to 1650 ft) are not uncommon.

The advantage of the method is primarily that the equipment is relatively inexpensive, the disadvantage, that it is slow and requires a certain access to water, especially when drilling above the ground water level.

In addition, a rather large crew is needed to operate the rig when drilling with heavy equipment to great depths.

Cable tool drilling may be considered suitable in exceptionally hard rock formations and where great depths are asked for. In addition, there should be as little overburden as possible.

The suitability of the method in developing countries is open to discussion. Here it is often required to drill a large number of wells as quickly as possible and since the drilling speed, as noted, is very low, approx. 1/10 to 1/20 of the speed of a modern compressed air drill, the method has, despite its low cost, often a very limited value.

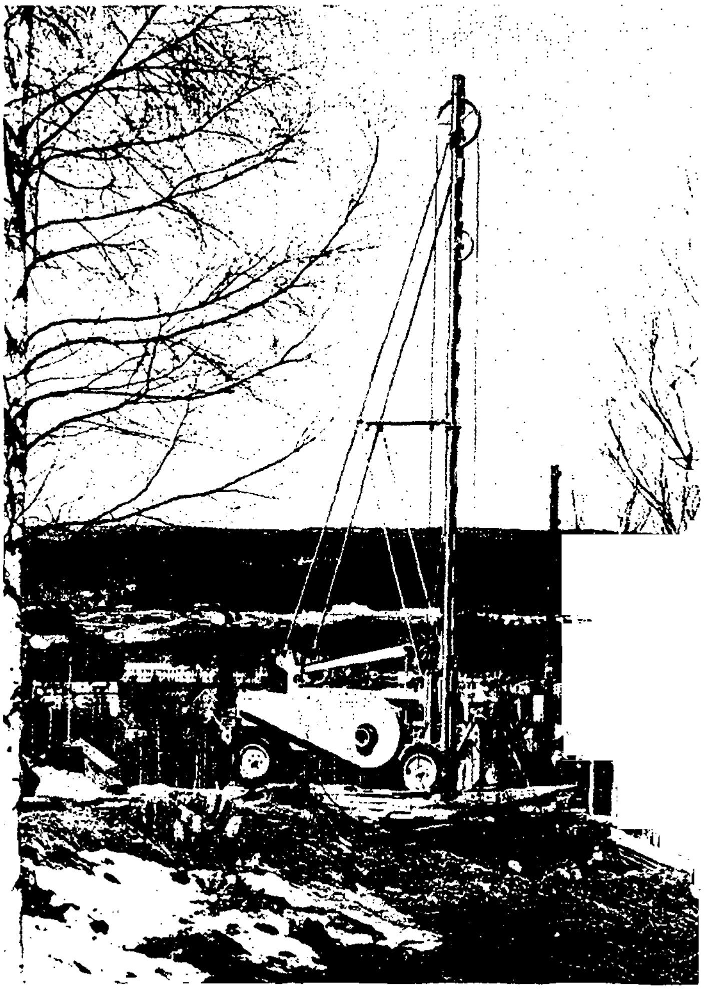


Fig. 43. Cable tool rig drilling for water near Linköping, Sweden

b. **Calyx drilling** (Fig. 44)

This very simple drilling method consists in principle of adding steel shot to the flushing water while rotating a crude core barrel and thus working one's way down into the rock. The advantage of the method is that the rig is inexpensive, the disadvantage primarily the need for water for flushing and powerful pumps for circulating it. In addition the drilling rate is very slow, often even lower than what is obtained with cable tool percussion machines.

c. **Core drilling** (Fig. 45)

This method finds its principal use in mineral prospecting where the object is to recover whole rock samples for petrological examination and analysis. The diameter of the holes will be small, in most cases from 36 to 100 mm (1 1/2 to 4").

The method must, at its present stage of development, be considered too expensive and slow for drilling of ordinary water wells from the surface.

The unconventional contractor should, however, not overlook the possibility of employing modern core drilling machines for well constructions in confined spaces such as air-raid shelters (1) or cellars in cold countries. If such wells are drilled in an upward direction, there will be no need for installing a pump, and by avoiding long and costly pipe lines from surface drilled wells, the total price of the system may be competitive.

d. **Rotary drilling**

This method is suitable for drilling in loose sediments and not too highly metamorphosed rocks. The drilling principle is that an abrasing and crushing roller bit grinds down or breaks up the formation while the disintegrated material is removed from the hole by a continuous circulation of flushing fluid.

Rotary drilling is suitable for both deep and large diameter holes and is, for example, clearly superior to cable tool percussion drilling in loose soil strata and soft rock types. For drilling in hard rocks, gneiss, granite, etc., it will be less suitable as a very high feed force is required, usually 10 tons or more.

The need for great quantities of water for flushing is particularily annoying in dry areas (Fig. 46) and since the rig is most often both large and heavy, its terrain properties will be limited (Fig. 47).

e. **Pneumatic percussion drilling** (Fig. 48)

This rapidly expanding drilling method is most valuable when drilling in hard rocks which constitute a very large portion of the earth's surface and for which, hitherto, no really satisfactory method has been at hand. The overburden, even if it is of the collapsible type, presents no problem as the method is based on the simultaneous drilling and inserting of casing tubes down to and even into the bedrock.

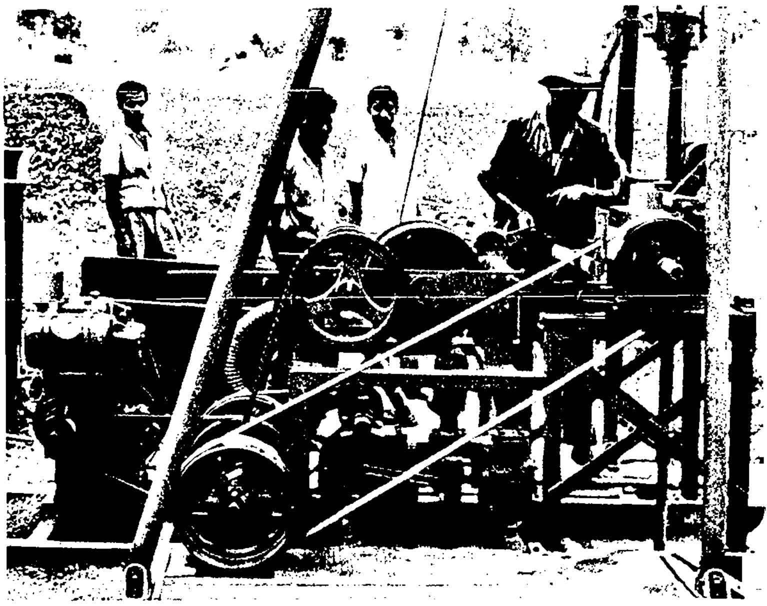


Fig. 44. Locally manufactured Calyx rig drilling for water in India

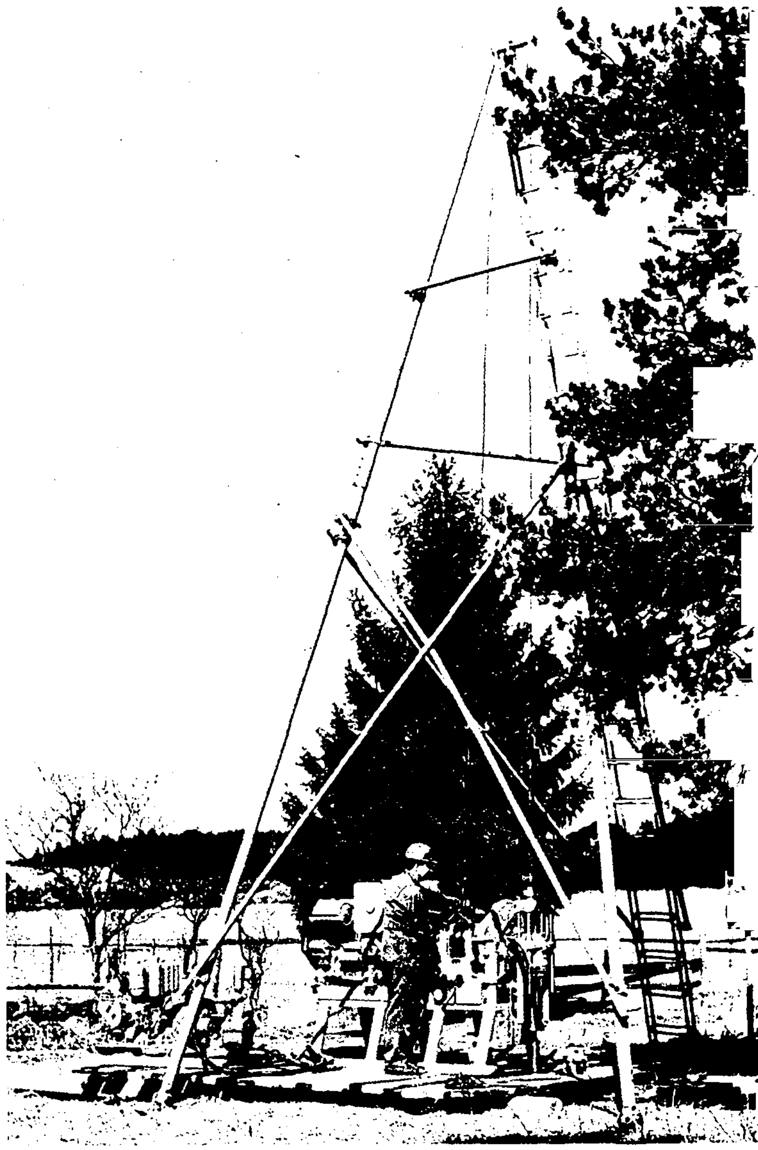


Fig. 45. Diamond core drill

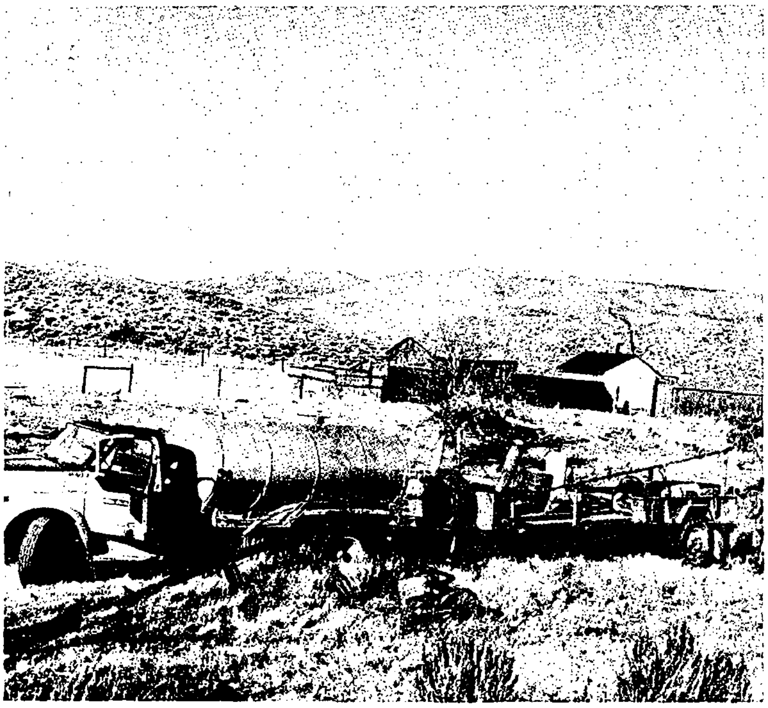


Fig. 46. Supporting vehicles of a rotary rig unit, Wyoming, USA

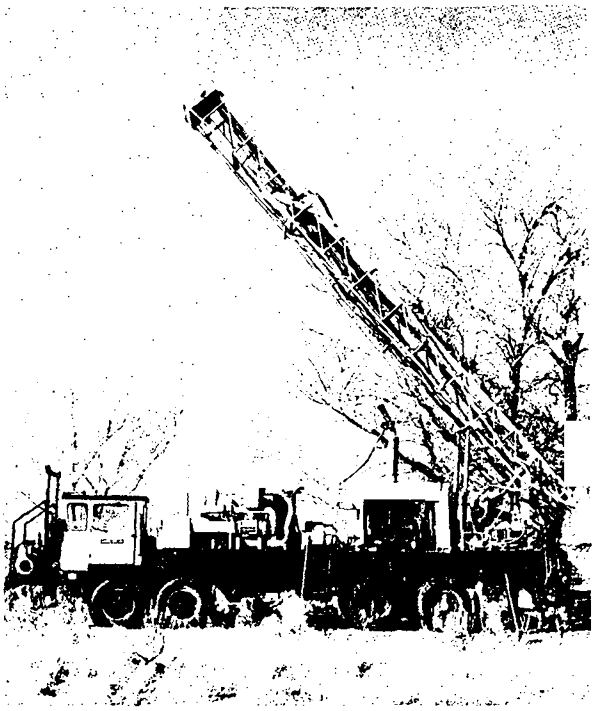


Fig. 47. Rotary rig

Mast in the process of being erected to drilling position, Wyoming, USA

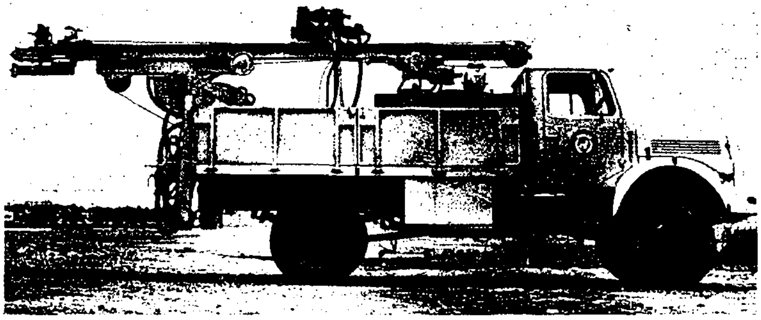
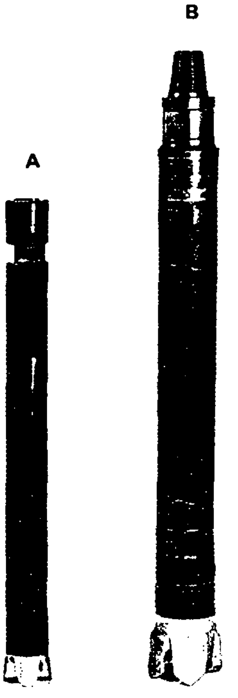


Fig. 48. Atlas Copco's water well drilling rig Aquadrill, fitted with top hammer and mounted on Indian truck



Hole diameters in mm (in.)	
COP 4	105 (4 1/8), 110 (4 5/16), 115 (4 1/2), and 140 (5 1/2) for casing
COP 6	152 (6), 156 (6 1/8), 158 (6 1/4), 165 (6 1/2), and 203 (8) for casing

Fig. 49. Atlas Copco's DTH-hammers COP 4 (A) and COP 6 (B).

The principle of drilling is basically as follows:

A cemented carbide tipped drill bit, either of four point or button design, receives strong and rapid strokes from a pneumatically powered rock drill at the same time as it is turned with a speed of between 20 and 50 r.p.m.

Each strike will chip away pieces of solid rock at the bottom of the hole and they will immediately be carried away and out of the hole by the flushing medium (air, water, mud or foam), which is administred to the drill string at the surface and emerging out of the bit through a number of flushing holes.

The rock drill can be either a top hammer (Fig. 48) or a down-the-hole hammer, called DTH for short (Fig. 49).

The former, which has a separate rotation motor built onto it and is attached to the chain feed of the rig works, as the name implies, on top of the drill string; in the latter system the drill and the rotation motor are separated. Here, only the rotation motor is attached to the feed while the drill is of so small diameter that it can follow the bit as it excavates its way into the ground.

The principle differences between the two systems are that:

a) while the DTH drill bit always is connected directly to the hammer and thus receives a constant percussive energy, the distance between the bit and the top hammer will increase as the hole gets deeper resulting in a gradual decrease in received energy due to losses, primarily over the couplings. Compare Figs. 38, 39, 70 and 71 with Figs. 60 and 63.

b) the top hammer requires extra air for flushing in addition to that which is consumed by the drill, while in the DTH system the exhaust air from the hammer is made direct use of for flushing. The DTH hammer will, thus, need a smaller compressor than a top hammer to drill a hole of the same diameter. On the other hand water flushing will not be possible with the DTH.

c) as the drill string between the rotation motor and the DTH hammer is not required to transmit the violent impact energy of the hammer, which is directly coupled to the bit, it can be made up of tubes with large diameters and still be relatively thin walled. This gives the DTH method better flushing characteristics than conventional top hammer drilling, where the string is made up of rods with a much smaller diameter than the bit.

d) while the top hammer cannot be expected to drill holes of more than 5" diameter with satisfactory penetration, the DTH hammer cannot drill holes with diameters less than the diameter of the hammer, restricting its use for exploration purposes.

Which of the two systems to choose depends on various factors. A decision will have to be made from case to case.

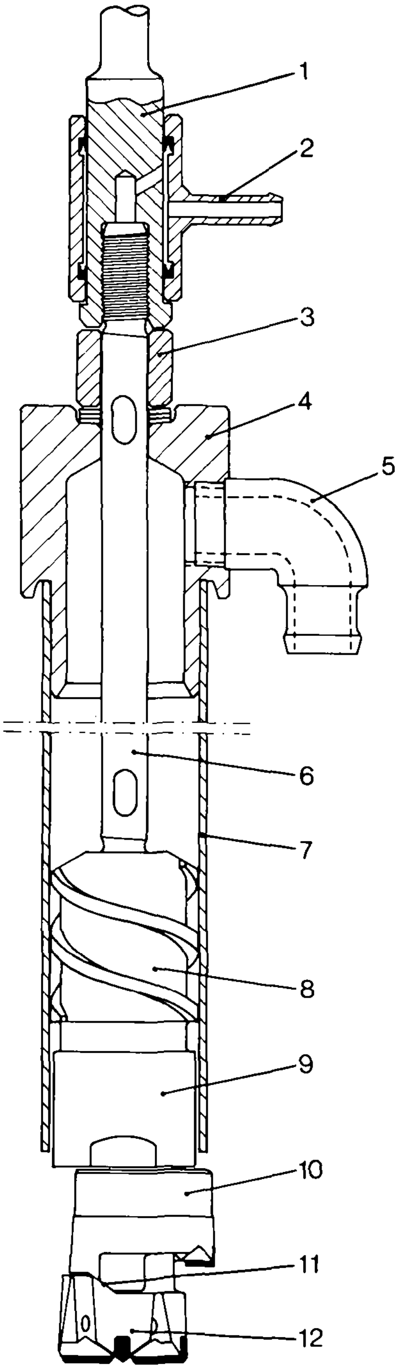
Overburden drilling with the eccentric bit

One of the greatest advantages of the pneumatic percussion method developed by Atlas Copco is the eccentric bit, an accessory which permits casing tubes to be emplaced through overburden of any kind simultaneously with the drilling.

The principle is as follows (see Fig. 50):

At the bottom of the drill string is a cemented carbide set drill bit, the pilot bit, to which the impact and rotation is transmitted. Immediately above this bit is a reamer with cemented carbide set cutting edges. With normal drilling rotation the reamer will swing out eccentrically and cut a hole which is of larger diameter than the pilot bit, allowing the casing tubes which enclose the drill string to enter into the hole at the same pace as the drilling proceeds.

Since no external obstructions can be tolerated on the string of casing tubes, they will have to be flush-jointed with male and female threads or, preferably, by welding. (Figs. 51, 52 and 53).



1. Shank adapter
2. Separate flushing device
3. Distance ring
4. Driving and centering head
5. Outlet for cuttings
6. Extension rods
7. Casing tube
8. Guide part of centering guide
9. Strainer part of centering guide
10. Reamer
11. Stop lugs
12. Pilot bit

Fig. 50. Sandvik Coromant Eccentric Bit for drilling and simultaneous emplacement of casing tube through collapsible overburden

The cuttings are flushed up between the drill string and the casing tubes. To make this effective and also prevent the formation of large amounts of dust, methods for metering foam-producing chemicals into the flushing air have been developed. (Fig. 54).

After the casing tube has been drilled down sufficiently deep into solid rock, the drill string is given a brief turn in the direction opposite to that of drilling causing the reamer, which is in an eccentric position during drilling, to be drawn into the diameter range of the pilot bit. The drill string with the eccentric bit can then be taken up while the casing tube remains in place as protection against collapse of the hole walls.

The eccentric bit is removed and drilling continues in solid rock with a standard rock drilling drill bit.

The principal advantage of the pneumatic percussion method is its speed. Drilling down to 100 meters (328 ft) in gneiss or granite usually only takes 1–2 days. Furthermore, the drill is very light compared to rotary and cable tool machines and the demand for good roads is not so great. As water is not required for flushing, the method is especially well suited for areas poor in water.

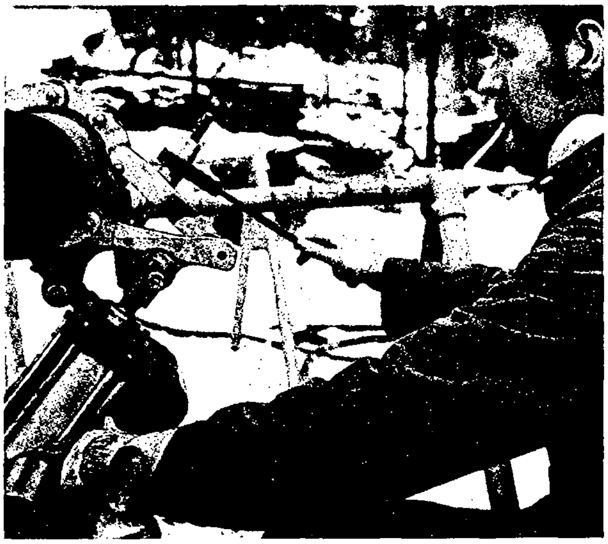


Fig. 51. Semi-automatic, pneumatic tube cutter ensuring a perfect 90° cut, a prerequisite for easy and safe welding

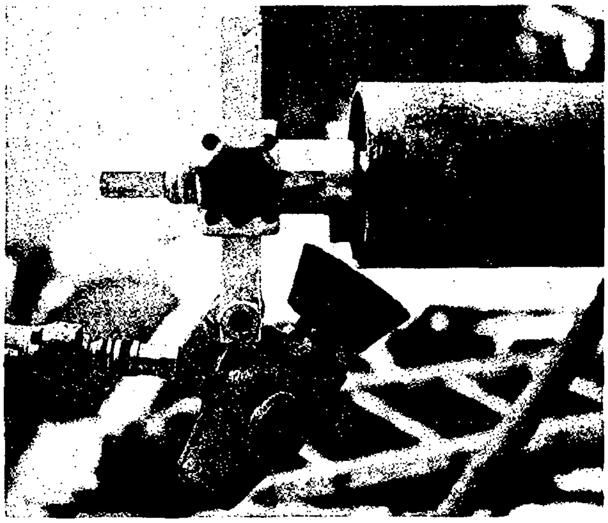


Fig. 52. Semi-automatic, pneumatic chamfering tool

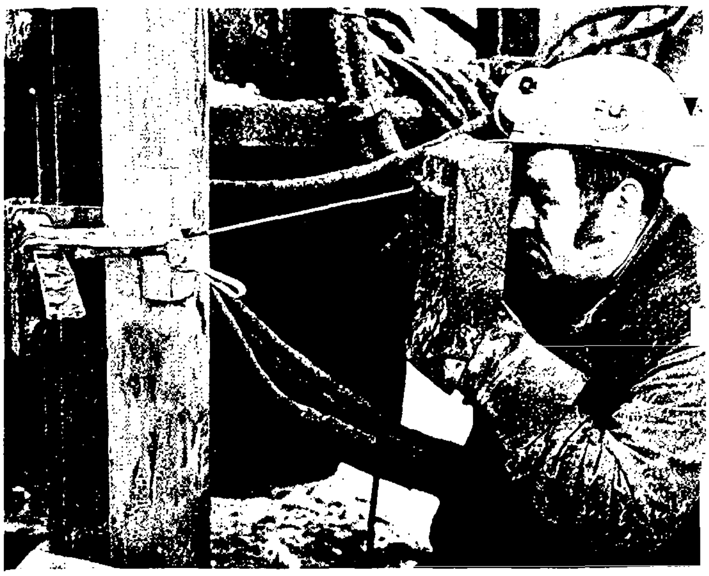


Fig. 53. Welding of casing tubes

Electric welding, employing a small, portable petrol-driven welding set as power aggregate, is much easier to perform than gas welding

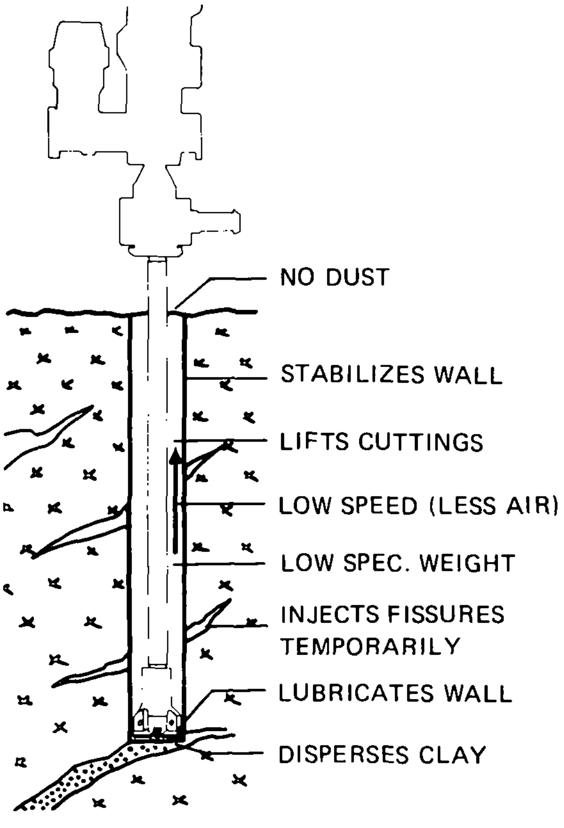


Fig. 54. Advantages of foam flushing

17. DEVELOPMENT PROCEDURE FOR A READY DRILLED WELL

As opposed to wells drilled in alluvial formations, the development required for wells drilled in hard rocks is simple and is essentially restricted to preventing contaminated surface water from entering into the well and cleaning the well before the production pump is installed.

a. Sealing

Usually the casing tube is driven 1 to 3 meters (3–10 ft) into the rock and then sealed before the actual drilling in rock begins. For the sealing between the tube and rock to be effective an easy-flowing quick-setting cement solution is poured into the tube and forced out in the cracks and cavities between the casing and the drilled hole, e.g., with compressed air. When the cement has hardened, drilling can continue in the solid rock. (38).

Another procedure is, that after the casing tube has been emplaced well into bedrock, a hole of 120 mm (4 3/4") diameter is drilled some 5 to 15 meters (15–45 ft) further down. A 110x120 mm (4 5/16"x 4 3/4") plastic tube is then inserted and cut a few centimeters above the top of the steel tube.

During the actual well drilling, which in this case will be performed with a standard 110 mm (4 5/16") well drilling bit, this plastic tube will be "forged" tightly against the hole wall while cuttings forced into it both from below and from above, will further add to the sealing.

No time-consuming cement grouting will then be required and the well will be protected against contamination by the rusting steel casing.

Which wells require such sealing and how elaborately it must be carried out depends on the geological situation in the vicinity of the well. If the material is loose and permeable, e.g., sand or gravel, the sealing will of course have to be carried out with great precision while, if the bottom layer consists of thick, dense clay, the need for exactitude will be less.

The sanitary conditions in the neighbourhood of the well also play a large role as does the depth of the ground water level.

Because of the complexity of these factors no strict rules can be established. The question of sealing must be decided on from case to case. A qualified well driller is usually able to decide on the basis of his experience. (38).

b. Cleaning

When the well is finished, some cuttings will be left at the bottom and along the walls of the hole. Some will also have been deposited in the water bearing fractures and be an obstruction to the water flowing freely into the well. This material should therefore be removed before the production pump is installed.

It can be done either by means of blowing the water out of the well with compressed air several times, pumping the well intermittently with, e.g., a high capacity air lift and/or raise and drop a heavy cylinder of steel in the well repeatedly.

This mechanical washing and the water which gushes into the emptied well will remove the cuttings from the fractures so that the well can be delivered to the client with its full capacity and with a correct pump installed.

18. SOME CONSIDERATIONS ON PUMP INSTALLATION AS RELATED TO THE YIELD OF THE WELL

The aim of ground water utilization is to seek for, go down to and bring up ground water for various uses at the surface. The well is, therefore, not finished before it has been fitted with a production pump.

Depending upon the quantities of water supposed to be lifted, along with several other factors, one of the following pumps will be installed: hand pump, suction, ejector, air-lift, submersible or turbine pump, and the choice of motive force will be as diverse: muscle power, wind, compressed air, electricity, petrol or diesel oil.

A description of these various pumps and how they are to be installed can be had from any pump dealer, including Atlas Copco's Pump Department. In this paper, we will dwell only on the question of what hole diameter the well should be drilled with.

From the geological explanation given above, we will understand that it is the nature of the formation which governs the quantities of water which will drain into a well and we are also informed that the hard-rock formations which we have concentrated on in this paper, will yield smaller quantities than un-consolidated material.

Disregarding the few really high yields which can be obtained on exceptionally favourable locations, the overwhelming majority of wells sunk in hard-rock formations will give less than the 7–10,000 liters (1,500–2,200 Imp. gallons) per hour, which can be raised with a 4" submersible pump.

Why then drill such wells larger than 4" in diameter?

The reply one always gets is "I want a big well, for a big hole will naturally give more water than a small one, won't it?", yes one often hears "doubling the diameter of the well will double its yield", or more reasonably, "doubling the circumference will double the yield".

And it is true enough, a larger size well will produce more water than a small one but not by far as much as generally believed. Let's, to straighten out this issue, have a look at what the relationship between yield and well diameter actually is.

The basic formula for well discharge, related to water table conditions, not artesian conditions, is given in Fig. 55.

$$Q = N \frac{P\,(H^2 - h^2)}{\log R/r}$$

where

Q is the yield of the well
P is the permeability of the formation
H is the original height of water in the well
h is the height of water while pumping
R is the radius of the cone of depression
r is the radius of the well
N is a numerical constant depending on units

Fig. 55. Basic formula for well discharge for water table conditions

from Johnson (4)

How does now the radius of the well affect the yield?

If all the terms in this formula are kept constant, it can be written as shown on Fig. 57, and if we calculate the yield of a 4" well and compare it with that of an 8" well, selecting R = 100 meters (330 ft) which is a typical value for water table conditions, we find to our surprise that the yield of the 8" well will, theoretically, increase with 10% only.

The same relationship is maintained when doubling the sizes even of larger diameter wells, as can be seen from Fig. 58.

One should, maybe, here mention that when drilling in highly porous formations, where the permeability will be very high and one, thus, would suspect that the increase in yield should be higher than the above 10%, also the radius of the cone of depression will increase so that no dramatic increase in yield will be achieved even here (Fig. 56).

One also has to mention that the formulas presented pertain only to alluvial conditions, where the water flows in a comparatively homogeneous manner through porous layers, meaning that, above all, P can be reasonably well measured. In hard rocks, where the water flows through cracks and fissures with all kinds of apertures and restrictions, it will be very difficult to establish a reliable value for the permeability.

Even though we, for crystalline conditions, cannot have our claims confirmed by straight discharge formulas, practical experience says that also here, the principle will apply, that an increase in well diameter will not substantially increase the yield of the well.

In accordance with our philosophy, which is based on the principle of not investing more time and money in a well than is absolutely necessary, and knowing that the cost of drilling an 8" well will be many times that of drilling a 4" well we, therefore, advocate that the diameter of a well, especially in hard rocks, should be kept at a minimum.

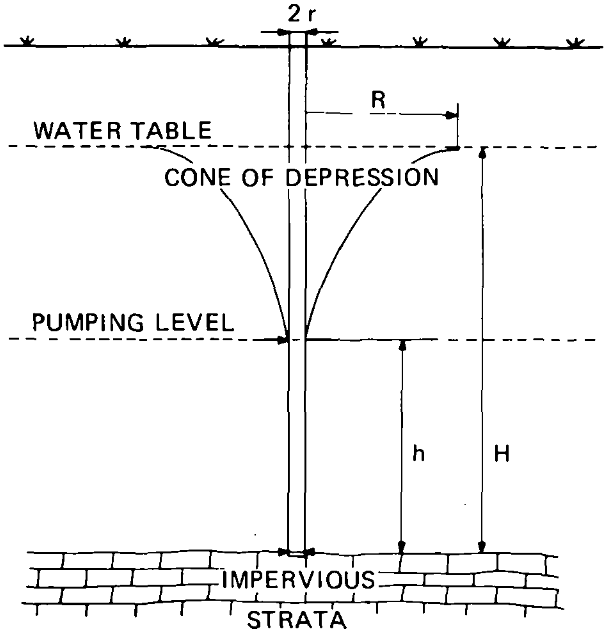


Fig. 56. Diagram of water-table well showing the significance of the various terms used in the formula presented in Fig. 55

from Johnson (4)

$$Q = \frac{K}{\log R/r}$$

Fig. 57. The formula presented in Fig. 55 with all terms other than the well radius (r) kept constant

from Johnson (4)

Well Diameters						
6"	12"	18"	24"	30"	36"	48"
100	110	117	122	127	131	137
–	100	106	111	116	119	125
–	–	100	104	108	112	117
–	–	–	100	104	107	112
–	–	–	–	100	103	108
–	–	–	–	–	100	105

Fig. 58. Index table

Well diameter versus yield in %

from Johnson (4)

Types of wells drilled	Nos. wells	%	Qty. water required	%
Municipal or water district supply	6,979	2.1	large	7.7
Industrial plant supply	5,550	1.7	large	
Farm irrigation supply	12,615	3.9	large	
Private home and livestock supply	282,284	87.2	small	89.6
Shallow well-sprinkler, recreation supply, etc. well points	3,578	1.1	small	
Air conditioning supply	4,208	1.3	small	
Waste disposal wells	240	<0.1		
Other types	8,454	2.6	?	

Fig. 59. Types of water wells drilled in USA.

Note that close to 90% of the clients require small quantities of water

from Drew (41)

Why is it then so difficult to convince the conventional man, who has never heard of a well below 6" in diameter, that drilling with these large sizes often will give him unnecessarily expensive water?

It is partly because of the above explained misunderstandings with regard to yield versus diameter, but also due to the fact that with conventional drilling methods, small diameter holes are so difficult to drill.

To take a cable tool rig, the greater the weight of the chisel, i.e., the bigger it is, the better penetration one gets, while those using rotary rigs will know that the bearings of a tri-cone rock roller bit smaller than 6" diameter won't stand up to the great feed force required in harder formations. The rotary driller will also have experienced that his hole will have a tendency to "cork-screw", meaning that he will have to drill the hole with a much greater diameter than the pump, just in order to get the latter inserted. Even the so far comparatively few drillers who have chosen to rely on compressed air have, up to recently, found DTH hammers smaller than 6" weak in percussion and too delicate in design, a situation which, however, now has been corrected with the introduction of our DTH-hammer COP 4.

A water well will, thus, in the mind of the conventional man – driller and water consuming client alike – simply be a hole in the ground of 6" diameter or more, even though the theoretical decline in yield if the well were drilled with 4" diameter, would amount to no more than 5%.

The only restriction on reducing the well diameters, the way we see it, will be the restrictions in having a sufficiently large pump installed, and as already stated, 4" submersible pumps have capacities of 7–10,000 l/h. (1,500–2,200 Imp.gal.). Only in such areas where this yield will be substantially exceeded, do we see a reason to drill wells larger than 4" in diameter – provided the client really needs that much water.

A wicked suspicion, arises namely, that people often ask for more water than what they actually need (Fig. 59).

For the supply of small quantities of drinking water, which can be raised with ejectors, air-lifts or hand pumps, we feel that one should even consider smaller wells than 4", not only because of the higher penetration speed and the consequent better economy (Fig. 60), but also due to the fact that drilling a hole with smaller diameter is so much simpler to carry out.

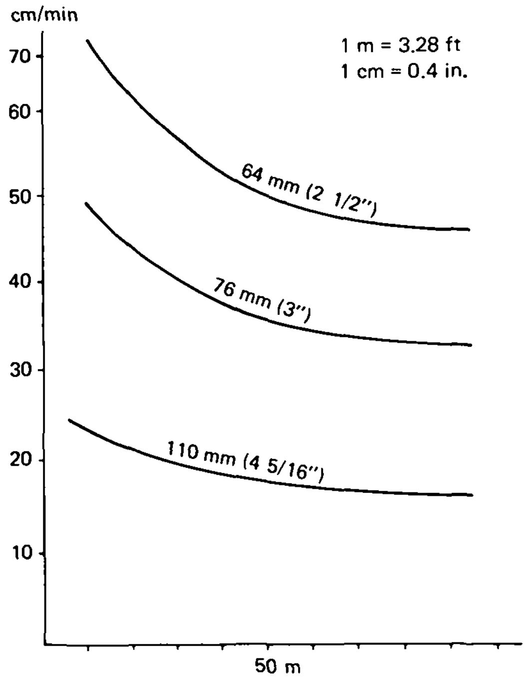


Fig. 60. Difference in net penetration speed of Atlas Copco Aquadrill, fitted with top hammer BBE 57 as related to bit diameter.

Local variations are evened out.

The lowest curve is based on drilling records of 52 wells drilled in Vasa Län, Finland.

Rock type:	Svionian gneiss
Air pressure:	7 kg/cm^2 (100 psi)
Direction:	Vertical

19. ATLAS COPCO WATER WELL DRILLING EQUIPMENT

Aquadrill (Fig. 61) and ROC 601 (Fig. 62), along with their accessories and tools for water well drilling, are primarily intended for production of wells in hard-rock formations. In designing this equipment we have taken into consideration and have tried to satisfy most of the practical and scientific demands presented in the previous chapters of this paper.

These demands can be summerized as follows:

a) high drilling speed

b) low drilling costs

c) trouble-free drilling

d) drilling through all kinds of formations

e) drilling in all directions, even upwards

f) drilling with all relevant diameters from 64 mm (2 1/2") up to and above 165 mm (6 1/2")

g) depth capacity must cover the bulk of hard-rock wells drilled

h) low price

i) low weight

j) good cross-country mobility

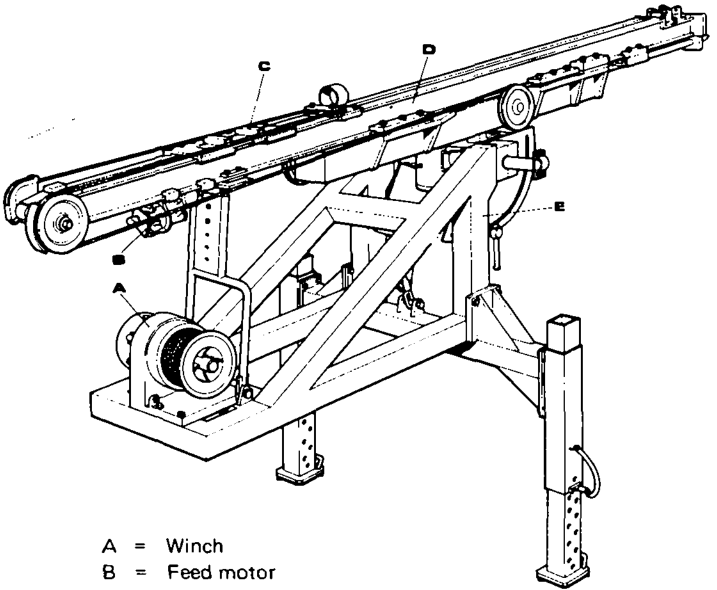
k) simplicity in design

l) only one source of motive power

m) easy servicing

n) easy to convert from production into test drilling rig

o) assistance from the supplier regarding accessories



A = Winch
B = Feed motor
C = Cradle for mounting of:
1. Top hammer BBE 57
2. Rotation unit BBR 4 for DTH hammer COP 4
3. Rotation unit BBR 6 for DTH hammer COP 6
D = Chain feed
E = Frame for mounting on truck, trailer or the like

Fig. 61. Atlas Copco's water well drilling rig Aquadrill

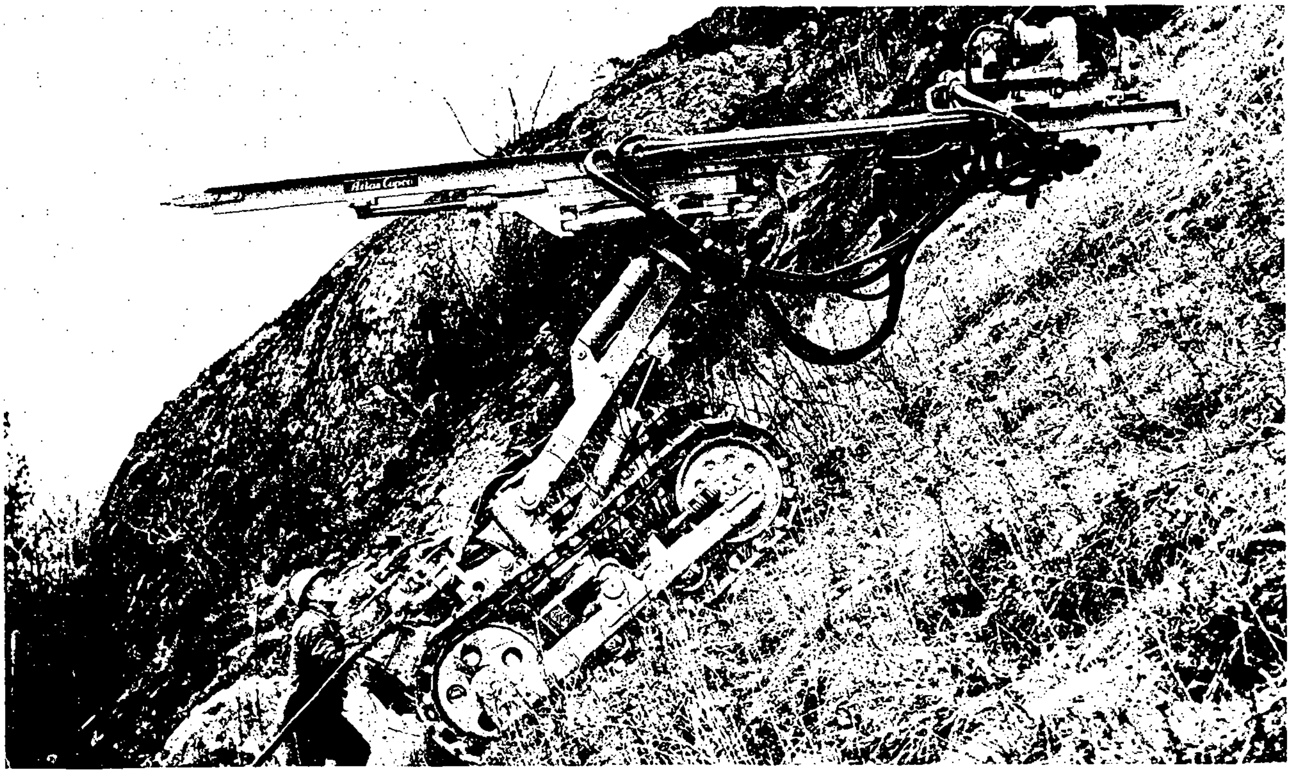


Fig. 62. Atlas Copco Crawler Rig ROC 601 fitted with top hammer BBE 57 and the same type of feed as found on Aquadrill

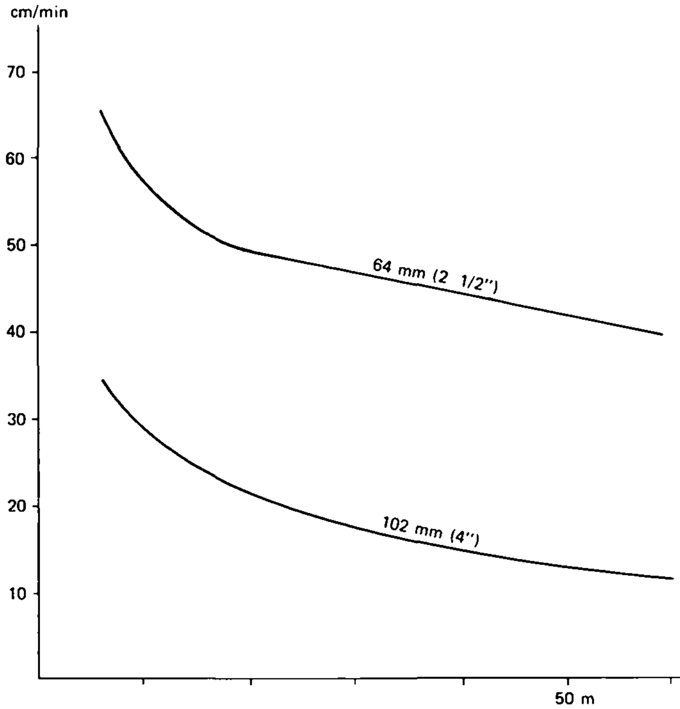


Fig. 63. Net penetration speeds recorded by Sholapur Well Service, India. Local variations are evened out.

Rock drill: Top hammer BBE 51
Rock type: Deccan Trap lava
Air pressure: 7 kg/cm^2 (100 psi) 1 m = 3.28 ft
Direction: Vertical 1 cm = 0.4 in.

To have all these demands satisfied by one single machine is, of course, an impossibility, and for this reason our designers have solved the problem with another line of reasoning.

The tool which actually does the job is the drilling machine with its feed and in-hole equipment. The remaining items are only to be considered as supporting elements, no less important for that sake but more readily adaptable to changes in design and mounting to allow the major tool to perform in such a way that it satisfies the water well driller's wishes and demands.

Three such major tools were found to be particularily applicable each with their own specific characteristics but all well tried standard machines:

1) The top hammer BBE 57
2) The DTH hammer COP 4
3) The DTH hammer COP 6

In Fig. 61 is shown the standard Aquadrill, where the major tool is supported by a frame which can be bolted to a truck, a trailer or a cradle (Fig. 48). This is the most common mounting while others, like ROC 601, shown on Fig. 62, will be chosen by a driller who wants extreme cross-country mobility and full freedom to direct his holes in any direction.

Apart from these two properties, the performance will be the same.

The difference between the top hammer and the down-the-hole techniques is already described under Chapter 16 e), so let us straight away see how the Aquadrill and the ROC 601 fulfil the above listed demands.

a) **Speed**

The same high net penetration speeds reported from Sweden are obtained also in India (Fig. 63).

Under the climatical, technical and business conditions prevailing in Sweden, 2.5 wells, on an average of 60 meters (197 ft) depth per five working days week can be considered normal performance.

In India, where the wells are shorter, the working week longer and drilling can go on at the same pace on large government drill schemes the year around, one will come closer to the theoretical possibility which is claimed in the abstract of this paper: One well per day. (Fig. 64, 65, 66).

The best report, as concerns numbers of wells produced, has been received from the Hiriyur taluk of the State of Mysore. During the month of December 1971, 22 wells were drilled with Aquadrill fitted with top hammer BBE 57. Average depth of these wells was 23.2 meters (75.9 ft) and the wells yielded in average 3,400 liters (748 Imp.gal.) of water per hour.

The monthly total of 510 meters (1,670 ft) corresponds well with the average result obtained by Sholapur Wells Service during the year of 1971 (6):

16 wells, in average 41 meters (134 ft) deep per month, totalling 656 meters (2,144 ft). Average yield at Sholapur was 3,800 liters (838 Imp.gal.) per hour.

b) **Cost**

An indication of direct drilling costs under Indian conditions is given in Fig. 67, while Swamy (39) reports the following total cost, overhead included:

for Aquadrill fitted with top hammer
BBE 57: .... Rs. 19.36 per foot

for Aquadrill fitted with DTH hammer
COP 4: .... Rs. 15.52 per foot

A competing rotary rig fitted with tri-cone rock roller bits for overburden drilling and 6" DTH-hammer for rock drilling came to ..... Rs. 31.76 per foot.

Since the conditions vary so widely from country to country and total cost is calculated in so many different ways, the reader is advised to exercise the necessary caution if he wants to transfer these Indian figures to his own territory.

Fig. 68 elucidates, however, that in whatever way one wants to calculate, a fast machine will come out with a much lower total cost per well than can be achieved with, e.g., a "cheap" cable tool rig.

15 m (50 ft)	–	5.0 hours	
18 m (60 ft)	–	3.0 "	
18 m (60 ft)	–	4.5 "	
22 m (75 ft)	–	3.5 "	
22 m (75 ft)	–	4.0 "	
23 m (77 ft)	–	4.5 "	
24 m (80 ft)	–	5.5 "	
27 m (90 ft)	–	4.5 "	
27 m (90 ft)	–	5.0 "	
28 m (92 ft)	–	5.0 "	
29 m (94 ft)	–	4.5 "	
32 m (106 ft)	–	2.4 "	*)
33 m (110 ft)	–	6.5 "	
37 m (122 ft)	–	3.0 "	*)
50 m (165 ft)	–	15.0 "	
62 m (202 ft)	–	13.5 "	

*) abnormally good result

Insertion of casing included

Rock drill: Atlas Copco top hammer BBE 51
Rock type: Deccan Trap lava
Air pressure: 7 kg/cm^2 (100 psi)
Direction: Vertical

Fig. 64. Gross drilling time recorded by Sholapur Well Service, India

Average depth – 28.21 meters (92.5 ft) per well
Average time – 8.18 hours per well
Average time – 3.44 meters (11.3 ft) per hour

286.58 hours – 35.82 eight hour shifts
Theoretically – **1 well per shift**

Fig. 65. Gross time taken for drilling 35 wells in the state of Andhra Pradesh, India with Atlas Copco Aquadrill fitted with top hammer BBE 57: 987.25 meters (3,239 ft) in 286.58 hours.

Note! The figures include only time taken for actually drilling the well

Average depth – 30.30 meters (99.4 ft) per well
Average time – 11.37 hours per well
Average time – 2.66 meters (8.7 ft) per hour

352.66 hours – 44.08 eight hour shifts
Theoretically – **0.7 wells per shift**

Fig. 66. Gross time taken for drilling 31 wells in the State of Andhra Pradesh, India with Atlas Copco Aquadrill fitted with DTH hammer COP 4: 939.39 meters (3082 ft) in 352.66 hours.

Note! The figures include only time taken for actually drilling the well

With Atlas Copco Aquadrill fitted with top hammer BBE 57:

November 1970 December 1970	Rs. 6.60 per foot

With Atlas Copco Aquadrill fitted with DTH hammer COP 4:

December 1970	Rs. 7.80 per foot
January 1971	Rs. 8.40 per foot
February 1971	Rs. 6.67 per foot

Fig. 67. Figures on direct drilling cost reported from the State of Andhra Pradesh

Note! Overhead is not included

1 Rupee = S.kr. 0.55 = US $ 0.13

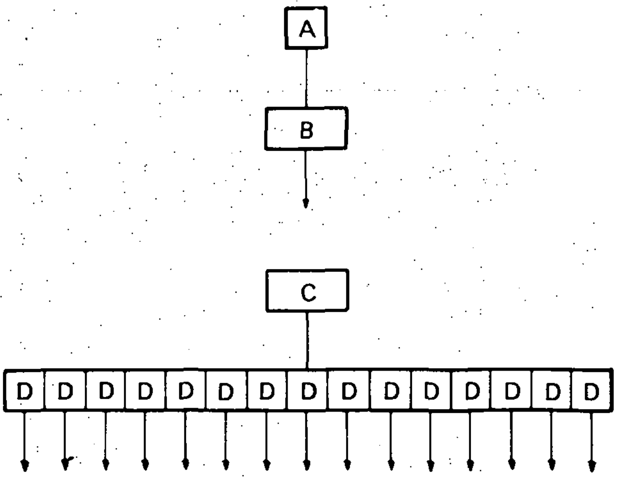


Fig. 68. Diagram showing the influence of drilling speed on total cost of one well

Condition: the "fast machine" will produce 15 wells in the same time as a cable tool rig will produce one

A = Overhead cost for keeping one cable tool rig running
B = Direct cost for drilling one well with a cable tool rig
C = Overhead cost for keeping one fast machine running
D = Direct cost for drilling one well with a fast machine
D = 1/2 B under Swedish conditions
C will presumably be higher than A but will not by far increase in direct proportion with the number of wells drilled

Total cost for drilling one well with a cable tool rig: A + B
Total cost for drilling one well with a fast machine: 1/15 C + 1/2 B

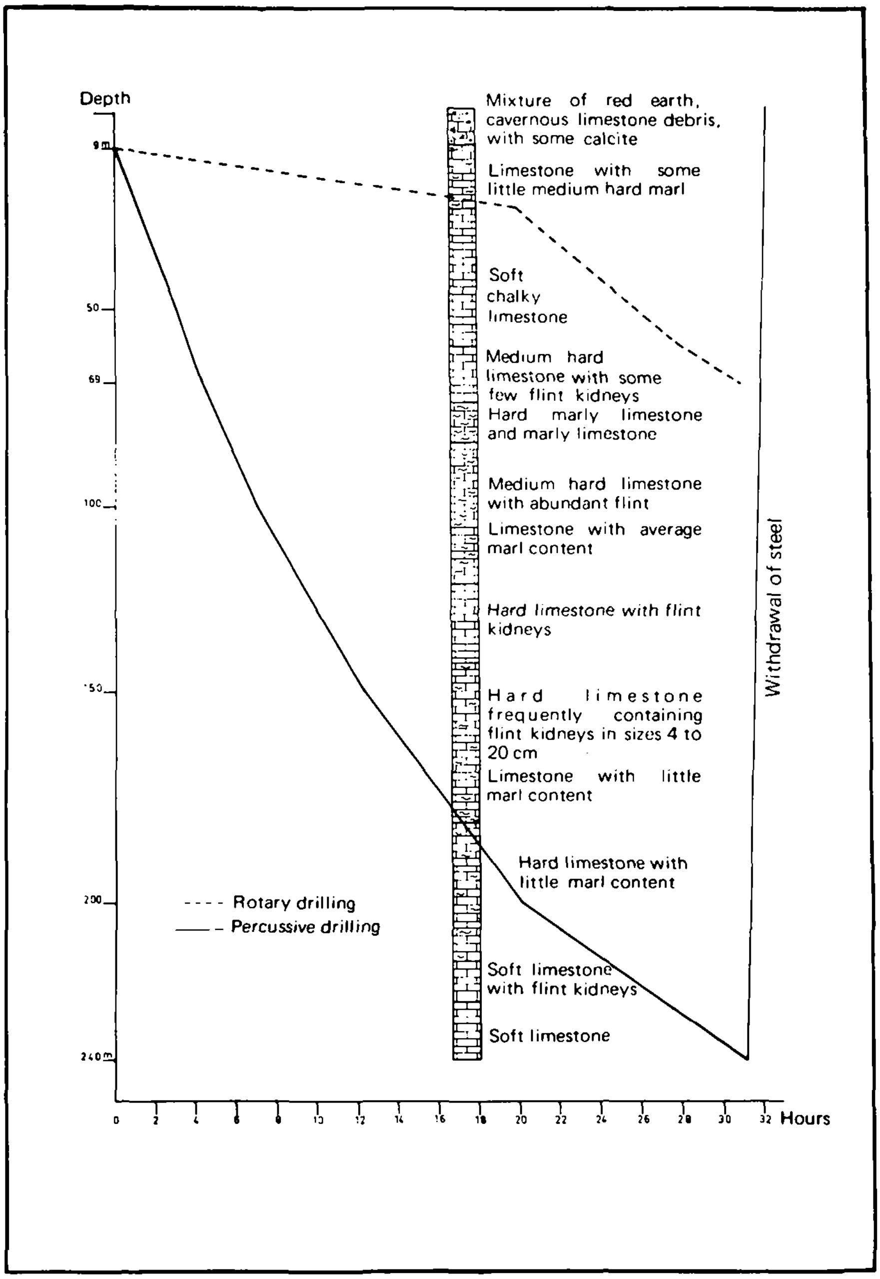


Fig. 69. Time taken to drill a 64 mm (2 1/2") test hole with Atlas Copco top hammer BBE 53 at the Meyfedoun dam site, Lebanon.

Water flushing and absolutely impervious rocks is the reason why this exceptional *result was obtained.*

from MCT (40)

c) Drilling problems

The reported performances indicate that most of the traditional drilling problems must have been solved by our method.

d) Drilling in various formations

The overburden is the most notable problem which the conventional water well driller is faced with. With the introduction of our eccentric bit, overburden drilling can now be done in any kind of formation as easily and safely as drilling in the rock.

e) Hole directions

Aquadrill can drill holes with up to 60° angle dip. ROC 601 can drill in all directions.

f) Hole diameters

When using the top hammer, holes between 64 mm (2 1/2") and 127 mm (5") can be drilled by simply changing the drill bit.

The DTH hammer COP 4 will drill holes between 102 mm (4") and 127 mm (5"); COP 6 between 152 mm (6") and 203 mm (8").

g) **Hole depth**

The deepest 110 mm (4 5/16") well drilled with top hammer BBE 57 is 145 meters (475 ft), 70 meters (230 ft), though, considered to be its economic depth.

The deepest test hole known to the author to have been drilled with BBE 53, (a top hammer fitted with two rotation motors) is a 240 meters (788 ft) deep 64 mm (2 1/2") diameter hole in Lebanon (40). (Fig. 69).

DTH-hammer COP 4 has drilled 115 mm (4 1/2") holes to 200 meters (656 ft) (Fig. 70); COP 6 152 mm (6") holes beyond 100 meters (328 ft) (Fig. 71).

Comparing these performances with the depths actually drilled by the water well drilling industry (Fig. 72), one will see that our rigs have an adequate depth capacity.

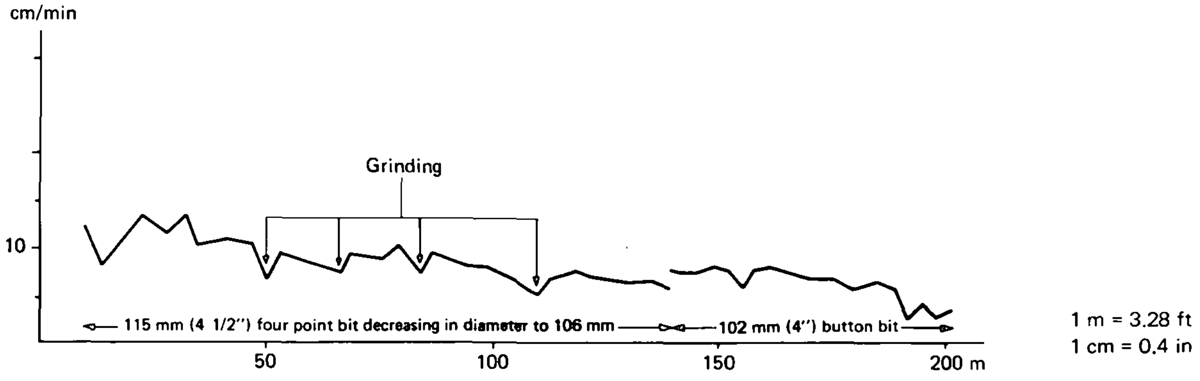


Fig. 70. Net penetration speeds of a water well drilled at Stavsnäs, 30 km east of Stockholm with Atlas Copco DTH hammer COP 4

Rock type:	Massif Svionian gneissgranite
Bit diameters:	115 mm (4 1/2"), 102 mm (4")
Air pressure:	7 kg/cm^2 (100 psi)
Direction:	Vertical

The variations are partially due to variations in rock hardness and partially due to grinding.

From a drilling point of view, the conditions at this site were particularily favourable as the hole was completely dry down to 188 meters depth. The sharp drop in penetration speed here was due to small quantities of water starting to seep into the hole.

This water was salty, probably fossile sea water, The well was with other words a failure. No sense drilling so deep holes in these formations.(42).

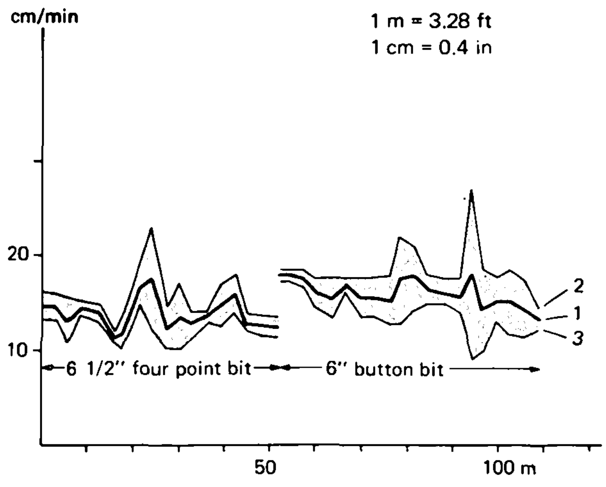
Fig. 71. Net penetration speeds of two water wells drilled at Järna, 40 km south-west of Stockholm with Atlas Copco DTH hammer COP 6 mounted on ROC 601 equipped with extra winch

Rock type:	Soft, mica-rich Svionian gneiss
Bit diameters:	165 mm (6 1/2"), 152 mm (6")
Air pressure:	7 kg/cm^2 (100 psi)
Direction:	Vertical
Curve no. 1:	Average
Curve no. 2:	Max. recorded
Curve no. 3:	Min. recorded

The variations are partially due to variations in rock hardness and partially due to grinding.

Laboratory tests have shown that COP 6 and COP 4 have the same net penetration speeds in the same rock types. The high speeds obtained in this hole as compared with the 4"/4 1/2" holes shown on Figs. 38, 39 and 70, are due to the soft characteristics of the gneiss at Järna.

The hammer, the bits and the accessories of COP 6 are more expensive than the COP 4 equipment. Since net penetration speed furthermore constitute only a comparatively small percentage of total time taken, a hole drilled with COP 6 will be more expensive than one drilled with COP 4.



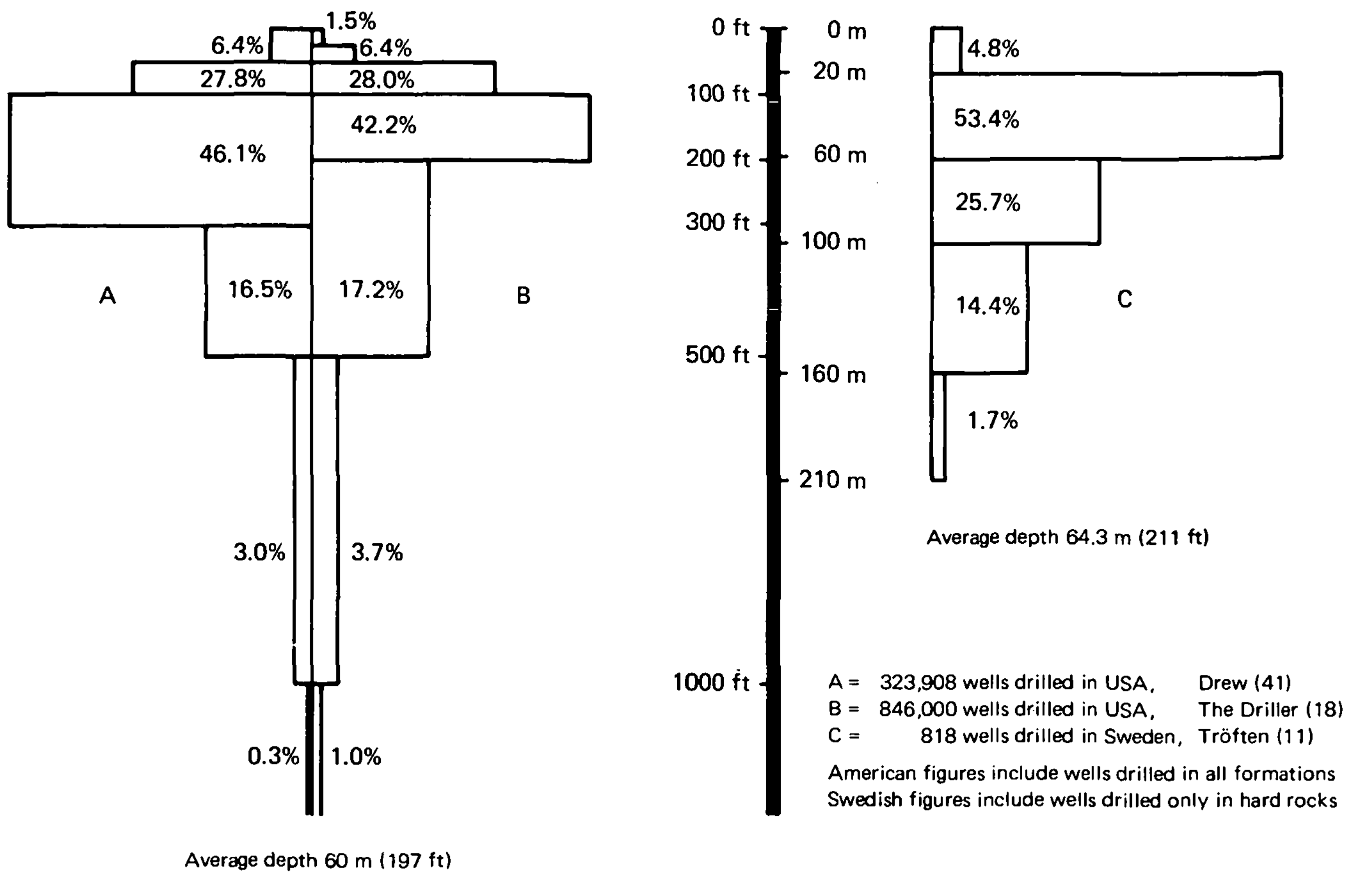


Fig. 72. Distribution of depths of wells drilled in USA and Sweden

h) Price

Depending upon freight, customs, licence and other local expenses, purchase prices will naturally change from country to country.

If a comparison is made under the same fiscal conditions, however, one will find that the price of Aquadrill will range between 25–40 % of that of a rotary rig with a competitive technical performance.

i) Weight

	kg	lbs
Aquadrill		
fitted with DTH-hammer COP 4	1,810	3,990
Compressor VT 6 Fd	1,570	3,460
	3,380	7,450
+ the weight of a 5 ton truck ~	3,000	6,600
Aquadrill		
fitted with top hammer BBE 57	2,200	4,850
Compressor PR 600 Gd	2,670	5,880
	4,870	10,730
+ the weight of a 5 ton truck ~	3,000	6,600
Crawler rig ROC 601	4,380	9,650
Compressor PR 600 Gd	2,670	5,880
	7,050	15,530

These are very much lower than the weights of competing rotary rigs.

j) Mobility

If a winch is mounted to the crawler rig ROC 601 it can negotiate almost vertical cliffs (Fig. 62).

Aquadrill mounted on a four-wheel drive truck will reach all normal drill sites.

k) Simplicity in design

Setting up the Aquadrill in drilling position is done in 5 minutes time by means of a wire system powered by the winch and the feed motor. No hydraulic system, thus, to maintain under the primitive conditions which most water well drillers are working under.

On the ROC 601, the chain feed is directed into position by means of hydraulic cylinders of the same design as those used in earth-moving equipment.

l) Motive power

All mounting and operational procedures (apart from directing the chain feed of ROC 601) are powered by one single motive force: compressed air.

m) Service

Aquadrill is composed of standard Atlas Copco machine elements, well known to our great international staff of drill masters as well as to a great number of drillers throughout the world.

n) **Test drilling**

To change Aquadrill fitted with top hammer BBE 57 and ROC 601 into a test drilling machine is done simply by exchanging the well drilling bit with a smaller diameter bit. Even coring can be done with a specially made left hand threaded core barrel.

o) **Accessories**

Atlas Copco manufacture and supply geophysical instruments, auger and core drilling equipment, test pumping sets, production pumps and a great variety of tools.

We are also well acquainted with scientific institutions who will be helpful in supplying equipment and know-how for more esoteric investigations, which don't fall directly into our line of business.

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21. GLOSSARY

A

Acre

A measure of land. 1 acre = 0.4 hectare (ha).
1 hectare = 10,000 m^2

Acre-foot

(Irrigation Engineering.) A volume of water equal to the volume of a prism one foot high with a base one acre in area. 43,560 cubic feet = 1,233.5 cubic meters.

Aerial photo interpretation

See Photo interpretation

Air lift

A pumping method based on the principle of transmitting compressed air down to and injecting it into the bottom portion of a tube inserted in a well. The air bubbles will bring down the specific weight of the water within the tube whereby it will be pressed up by the heavier water outside the tube.

Airborne geophysical survey

Use of geophysical instruments in helicopters or fixed wing airplanes to enable electric, magnetic, radiometric and other measurements to be carried out more rapidly and over greater areas.

Alluvial

An adjective denoting material transported by running water. A general term for all detrital deposits resulting from the operations of modern rivers, thus including the sediments laid down in river-beds, flood-plains, lakes, fans at the foot of mountain slopes and estuaries.

Amphibolite

A general designation for coarsely grained igneous rocks or metamorphic rocks entirely or almost entirely composed of amphiboles. Amphibole = group of bisilicate minerals whose chief rock-making member is hornblende.

Anomaly

The deviation of physical and chemical properties from normal (that is caused by the presence of subsurface deposits when these are searched for by geophysical and geochemical methods).

Arcosite

A sand or sandstone composed of mineral fragments derived from decayed granite. A large part of the component grains are quartz and feldspar.

Aquifer

Geologic formation having structures that permit appreciable quantities of water to move through it under ordinary field conditions. Literally meaning: water-bearing.

Artesian

Ground water confined under pressure greater than atmospheric by overlying, relatively impervious strata. Orginally the term referred to a well containing water with so high pressure that it rises up to the surface. The term drives from the French province of Artois, where the first such well was drilled in 1750.

Atmospheric water

Rain

Auger

An in-hole equipment consisting of a drill bit (head) attached to an extendable drill rod with spiral-shaped flights welded to it, giving it the appearance of a cork screw or a meat grinder. When rotated, the bit will dig out the material of the formation while the flights will transport it up and out of the hole.

Augite

The most common rock-making pyroxene; a mineral of higher grade of metamorphism than amphibole.

B

Basalt

An igneous rock of volcanic character, composed chiefly of plagioclase feldspar and pyroxene. It is usually fine-grained and black and is generally applied to lava flows.

Basic rock

Igneous rock having a relatively low percentage of silica, usually below 52%

Bedrock

Any solid rock underlying the overburden

Bit

See Drill bit

Button bit

Drill bit for percussive drilling with a number of cylindrical-shaped tungsten carbide inserts at the face. The steel of the bit body is supposed to wear away at the same rate as the tungsten carbide, leaving the inserts always protruding. A button bit will, thus, be self-grinding. Even though button bits may have a slower net penetration speed in certain formations than a four point bit, the total time taken for drilling the hole may be less since the bit does not need to be taken up for grinding. Since time taken for a round trip will increase with the depth of the hole, it is customary to exchange the four point bit by a button bit after the hole has been drilled to a certain depth. See Figs. 70 and 71.

C

Casing tube

Steel or plastic tube inserted into a well to prevent its walls from collapsing as well as to prevent contaminated surface water from draining into the well.

Cemented carbide

Slugs or inserts of this very hard material are mounted in the face of drill bits acting as the cutting edge of the bit.

Centrifugal pump

A pump based on the principle of lifting a fluid by centrifugal force, employing impellers on a rotating shaft to give the fluid this force.

Chain feed

Feeding mechanism by which the up-and-down movements of the drill string are controlled by a link chain running on sprocket gears.

Chamfering tool

A grinding tool for producing an angled phase on e.g. a cut casing tube.

Clay

An earthy material which is usually plastic when wet but becomes hard and stone-like when baked or fired.

Colluvial

An adjective from the latin word colluvies (mixture) denoting the heterogeneous aggregates of rock detritus, such as talus and avelanches, resulting from the transporting action of gravity.

Cone of depression

See Fig. 56.

Consolidate

To unite or press a loose material into a compact mass.

Core

A cylindrical sample of rock produced by an annular (hollow) drill bit.

Core barrel

A length of tubing coupled between the drill bit and the drill rod string. It carries and contains the core produced during drilling until it can be raised to the surface.

Country rock

A general mass of adjacent rock as distinguished from that that of a dyke, vein or lode.

Crystal

A body, generally solid, but not necessarily so, whose component atoms are arranged in definite space lattices, crystal faces being a commonly developed outward expression of the periodic arrangement of atoms.

Crystalline rock

A rock composed of closely fitting mineral crystals as contrasted with one made up of cemented grains of sand and other material. In this paper having the same meaning as igneous and metamorphic rock.

Crystallinity

A term applied to the degree of crystallization exhibited by an igneous rock, expressed by terms such as **holocrystalline** (completely made up of crystals), **hypocrystalline** (partly made up of crystals and partly of glass), **holohyaline** (wholly glass), etc.

Cuttings

Rock particles loosened at the bottom of a bore hole by the abrasive or percussive action of a drill bit.

D

Deccan Trap lava

A huge sheet of lava of presumed Carboniferous age (approx. 350 mill. years old) having originally covered the greater part of India. The term trap is Swedish (trappa = a stair) and has been applied to basaltic rocks whose outcrops gave rise to a terraced type of landscape.

Diabase

A basic igneous rock usually occurring in dykes or intrusive sheet, composed essentially of plagioclase feldspar and augite. The plagioclase forms lath-shaped crystals lying in all directions giving the rock a very high mechanical strength.

Dip

The angle of a slope, a rock stratum, a fracture or a bore hole as measured from the horizontal plane.

Down-the-hole hammer

For short also called DTH hammer. A rock drill which is mounted directly to the drill bit and is of so small size that it can follow the bit down into the hole as it is being drilled.

Drag fold

Minor folding is apt to occur in connection with major folding or thrusting. It is produced by the shearing stresses set up by the relative movements of beds along bedding planes or of rock masses against rock masses. The smaller folds thus produced are called drag folds.

Drawdown

When a well is pumped, water is removed from the aquifer surrounding the well whereby the water table will be lowered. The drawdown at a given point is the distance the water level is lowered. See Fig. 56.

Drillability

The relative speed at which a material may be penetrated by a drill bit.

Drill bit

One of a number of different types of detachable cutting tools used to cut a circular hole in rock, wood, metal, etc.

Drill hole geophysical survey

Use of geophysical instruments so designed that they can be lowered into drill holes. Also called logging or sonding.

Drill string

The assemblage of drill rods, coupling sleeves, core barrel, drill bit, etc. in a bore hole which is connected to and rotated by the drill rig at the surface.

DTH hammer

See Down-the-hole hammer.

Ductile

Capable of being drawn out or hammered thin. Syn. plastic.

Dyke (Dike)

A wall-like intrusion of igneous rock which cuts across the bedding or other layered structure of the country rock. The thickness is narrow in proportion to the two other dimensions.

E

Eclogite

One of the most strongly metamorphosed rocks known. The overall reduction in volume to transform basalt to eclogite is from 100 to about 85, with corresponding increase in density.

Ejector pump

Also known as jet pump. Water under pressure is pumped down to the bottom portion of a tube inserted in a well and discharged into the tube through a nozzle. The pressure of the outside water at a point right before the nozzle will decrease, whereby it will be sucked into the tube and be transported up to the surface.

Electric conductivity

Quality or power of conducting or transmitting electric current.

Electric potential

The force which enables electric current to overcome electric resistivity and travel from one point to another.

Endogenetic

A term applied to geological processes originating within the earth and to rocks, ore deposits and land-forms which owe their origin to such processes . Contrasted with exogenetic.

Eolian

Derived from Eolus (the god of winds). Pertaining to characteristics of, produced or deposited by or derived from the action of wind, such as the sands or other loose material found in deserts and along shores.

Erosion

All processes by which earthy matter or rock is loosened and removed from one place to another.

Erosional unloading

Removal of material by erosion resulting in the uplift of the underlying rocks. The tensions thus set up will produce a surfacial fracture system, which is often flat-lying with curved surfaces.

Evaporation

The process by which molecules of water at the surface of water or moist soil acquire enough energy to escape the liquid state and pass into the gaseous state. See transpiration and evapo-transpiration.

Evapo-transpiration

Combined loss of water from the earth's surface through evaporation and transpiration.

Exogenetic

A term applied to geological processes originating at or near the surface of the earth and to rocks, ore deposits and land-forms which owe their origin to such processes. Contrasted with endogenetic.

F

Fabric

The part of a texture which depends upon the shapes and arrangement of the constituents of a rock; texture being considered as a function of crystallinity, granularity and fabric.

Faulting

The movement which produces relative displacement along a fracture.

Fauna

An assemblage of animal forms living in a given place and a given time.

Feldspar

A group of minerals composed of aluminium silicates with either potassium, sodium, calcium or barium or a mixture of these. Feldspar is found in practically all igneous rocks.

Flush coupled

Two tubes jointed with a coupling which has the same outside diameter as the tube.

Flush-jointed

Tubes coupled together in such a manner that the outer and inner diameter over the joint are the same as that of the tube.

Flushing medium

Water, mud, air or foam used to flush drilled-out material out of the hole.

Flux

The rate of flow of energy, across or through a surface.

Fluxgate

A magnetometer system where use is made of the fact that magnetic fields will induce a high flux density in certain types of material. If a coil is wound around such a material, the voltage induced in this coil will be proportional to the strength of the magnetic field.

Fold axis

See Fig. 17.

Folding

Deformation of rocks causing bending.

Formation (geological)

A large and persistent stratum of some one kind of rock. Set of strata possessing a common suite of lithological and/or faunal characteristics. Also loosely employed for any local, more or less related group of rocks.

Four point bit

Drill bit for percussive drilling with four sharpened rectangular-shaped tungsten carbide slugs inserted at the face. When the inserts become blunted, the bit has to be taken out of the hole for grinding.

Fossile water

Incorrect term for old, stagnant water.

G

Gabbro

Igneous rock of the same mineralogical composition as diabase but occurring in larger bodies and lacking the inter-laced texture of diabase. Gabbro is ductile and possesses a high mechanical strength and does, thus, not readily break up.

Geology

The science which treats of the origin, history and structure of the earth as recorded in the rocks together with the forces and processes now operating to further modify them.

Geophysics

The science that uses the application of physical properties such as electricity, magnetism, gravity, etc. in a detailed study of the composition of the earth's crust.

Glacial

In geology, pertaining to characteristics of, produced or deposited by or derived from a glacier.

Glacial drift

Unstratified or roughly stratified masses of sand, gravel, clay and boulders which have been transported by glaciers.

Glaciation

Period during which the earth's surface has been made subject to glacial activity.

Gneiss

A foliated or banded crystalline rock in which granular minerals, lenticles or bands alternate with schistose minerals, lenticles or bands. A highly metamorphic rock having the minerals arranged in more or less massive bands or layers. The term, like schist, has a loose geological usage.

Granite

A comparatively coarsely crystalline igneous rock consisting essentially of quartz and alkali feldspars with some dark minerals as accessories.

Granularity

One of the features involved in the conception of **texture;** the effect due to the magnitude of the constituent crystals.

Gross drilling time

Total time taken from a drill hole is started until it is finished.

Ground water

Without further specification; water occupying all voids within a geologic formation. In a practice; water of appreciable quantities infiltrating into, travelling through and being stored in the ground.

Ground water level

Same as ground water table. The level below which all voids of the rock or soil, down to unknown depth, are full of water.

H

Hard rock

Popular term used to distinguish igneous rocks and indurated sediments from unconsolidated formations.

Hard-rock

Adjective of the same.

Head

1. The height of a fluid column, usually water, which maintains a pressure on a surface, the amount of the pressure being directly proportional to the depth of the fluid standing above the point at which the pressure is taken.
2. A drill bit.

Hornblende

A variety of the mineral amphibole; a normal metasilicate of calcium, magnesium, iron and manganese.

Hydraulics

The branch of science or of engineering which treats of water or other liquids in motion, its action, the machinery for conducting or raising it, its use in driving machinery, etc.

Hydrogeology

The science which treats of the occurrence, distribution and movement of water below the surface of the earth.

Hydrologic cycle

See Fig. 7.

I

Igneous rocks

Rock which have solidified or crystallized from a hot fluid mass called a magma. Also rocks formed from material blown out of volcanic vents or poured out with water as mud and consolidate somewhat as sediments, e.g., tuff. Igneous rocks that have cooled deep in the earth, such as granites, are usually very compact and have an extremely low porosity.

Indurate

Harden; applied to rocks or loose deposits hardened by heat, pressure and the action of some ingredient not commonly contained in the rock referred to.

In-hole equipment

Also down-the-hole equipment. Any equipment used inside the bore hole below its collar at the surface.

Irrigation

Artificial watering of farm land by canals, ditches, flooding, sprinklers, etc.

Isotropic

Having the same properties in all directions.

K

Karst

Derived from the district of Karst at the eastern coast of the Adriatic, a landscape marked by sink holes, interspersed with abrupt ridges and irregular protuberant rocks and by caverns and underground streams.

L

Lateral

Directed towards or coming from the side.

Lava

Igneous rock that has been poured out upon the surface and there has solidified, usually in sheets.

Lithology

From the Greek word "lithos" meaning stone. The branch of geology that deals with the origin and properties of rocks.

Lode

See Vein.

Loess

A widespread deposit of silt or marl, buff or brownish coloured, porous but coherent.

M

Magnetic field

The field of force that surrounds a magnet. The earth has its own magnetic field which can be measured in terms of total, vertical or horizontal intensity at any given point.

Magnetic susceptibility

A measure of the intensity of magnetization induced in a body when emplaced in a magnetic field.

Magnetite

Iron oxide Fe_3O_4. Possesses a high magnetic susceptibility.

Marine erosion

Erosion by the action of the sea.

Marl

Calcareous clay.

Metamorphism

The sum of the thermo-dynamic processes of endogenetic origin which cause the transformation of a rock into a well characterized new type by more or less thourough recrystallization and change of texture and structure, with or without the introduction of new material.

Mica

A hydrous silicate having a very fine basal cleavage that renders it capable of being split into thin, tough, transparent plates.

Mineral

A body produced by the processes of inorganic nature, having a definite chemical composition. If formed under favourable conditions, a certain molecular structure will be exhibited in its crystalline form and other physical properties. In miner's parlance: any inorganic substances which can be extracted from the earth for profit whether it be solid, as rock, clay, ore and coal, or fluid, as mineral water, petroleum and gas.

Moraine

An accumulation of earth, stones, etc. carried and finally deposited by a glacier.

Morphology

The branch of geology that treats of the external structure of rocks in relation to the development of forms or topographic features produced by erosion.

Mountain pediment

A plain which lies at the foot of mountains in an arid region. The name is applied because the plain appears to be a pediment upon which the mountain stands. A mountain pediment is formed by the erosion and deposition of streams.

Mud

A mixture of water or oil with special clay like bentonite and sometimes other materials used as a drill-circulation liquid.

N

Net penetration speed

Time taken for drilling a hole over a given length. Other works than actual drilling are excluded, such as adding new drill rods, changing drill bit, etc.

Non-indurated

Not hardened. See Indurate.

O

Orogeny

The process of mountain building.

Oscillograph

A recording device in which miniature mirror galvanometers under high intensity light source are used to register electric inputs on photographic paper.

Overburden

Clay, sand, boulders and other unconsolidated material overlying bedrock.

Overthrust

The lateral thrusting of a mass of rock over or upon other rocks along a thrust fault.

P

Paddy field

A field in which rice is grown.

Pan evaporation

Evaporation from an unstirred container kept at constant temperature.

Parent rock

Rock from which a formation is derived.

Pediment

See Mountain pediment.

Percussion

Act of striking, beating.

Permeability

of a porous medium refers to the ease with which a fluid will pass through it.

Petrography

A general term for the systematic description of rocks, based on observations in the field, on hand specimens and on thin sections. **Petrography** is thus wider in its scope then **lithology** but more restriced than **petrology**, which implies interpretation as well as description.

Petrology

A general term for the study by all available methods of the natural history of rocks, including their origins, present conditions, alterations and decay.

pH

A symbol denoting acidity and alkalinity of a material. pH values run from 0 to 14; 7 indicating neutrality, numbers less than 7 increasing acidity and numbers greater than 7 increasing alkalinity.

Photo interpretation

Examination of aerial photographs or mosaics by stereoscopic or other methods in order to detect and analyze geological features not easily observable from the ground.

Placer deposit

A mass of gravel, sand or similar material resulting from the crumbling and erosion of solid rocks and containing particles or nuggets of gold, platinum, tin or other, generally heavy, minerals, that have been derived from rocks or veins.

Plagioclase

A group of feldspars containing sodium and calcium in various proportions.

Plinth

Slab of compact, undeformed metamorphic rock divided from other plinths by fracture zones.

Pneumatics

The branch of physics treating of the mechanical properties of air and other gases.

Pores

The open spaces or voids between the individual grains of a rock or a soil.

Porosity

The property of a rock or a soil in containing interstices; can be quantitatively expressed as the ratio of the aggregate volume of its interstices to its total volume.

Potable water

Drinkable water.

Precambrian

A general term for all time and for all rocks formed prior to the Cambrian (approx. 550 million years ago). As a general rule Precambrian rocks are highly metamorphosed.

Proton precession

A magnetometer system where the deflecting element is a proton rich fluid (water or kerosene) arond which a coil is wound. When current is sent through the coil, the protons line themselves up in one direction. When the current is removed, the protons start to precess (rotate) at a frequency directly proportional to the intensity of the earth's magnetic field at that location. This frequency can now be measured.

Q

Quartz

Crystallized silicon dioxide SiO_2.

Quartzite

Metamorphic rock produced by a recrystallization of a quartz sandstone under heat and pressure.

Quasi-isotropic

Close to isotropic

Quaternary

The latest period of geologic time, the time of extensive glaciation on the northern hemisphere. Quaternary deposits are widespread at the surface but usually patchy and of slight depth. They are of course highly unconsolidated.

R

Recent

The later of the two geologic epochs comprised in the Quaternary period; same as Holocene.

Residual soil

The soil accumulated in place as a result of the weathering of the rock below and from which the more soluble rock material has been leached out. Residual soil has not been transported.

Rock drill

A machine used to drill holes in rock. The term is most commonly used for percussive machines.

Roller bit

Also known as rock roller bit or tri-cone rock roller bit. See the latter.

Round trip

The process of pulling the drill string from a bore hole, performing an operation on the string (such as changing bit, emptying core barrel, etc.) and then returning the drill string into the bore hole.

Rural

Designating or pertaining to country people or country occupations, especially related to agriculture.

S

Sandstone

Consolidated rock composed of sand grains cemented together.

Schist

A loose geological term used to define those foliated metamorphic rocks whose individual folia are mineralogically alike and whose principal minerals are so large as to be visible to the naked eye.

Sediment

In the singular the word is usually applied to material in suspension in water or recently deposited from suspension. In the plural, the word is applied to all kinds of deposits from the waters of streams, lakes or seas, and in a more general sense also to *material* deposited *by the* action of wind and ice. Such deposits that have been consolidated are generally referred to as sedimentary rocks.

Self potential

The natural voltage differences of ground currents which are caused by chemical reactions in or between subsurface structures. These voltages are seldom larger than ± 1 volt.

Shear zone

A clean cut in the rock along which the two parts of the rock have moved past each other without separation. A product of compressional stress.

Silica

An oxide of silicon: SiO_2

Silt

Loose sedimentary material, rock particles less than 1/16 millimeter in diameter, suspended in water or deposited out of water.

Slickensides

Polished and grooved surfaces caused by one mass of rock in the earth's crust sliding past another under compression.

Spheroidal weathering

When water penetrates the joints of well-jointed rocks which are readily decomposed, the depth of decay is greater at the corners of the blocks than along its flat surfaces resulting in the block becoming transformed into an *onion-like structure covered by concentric shells of* rusty and dotted residual material.

Stress

The combination of an external force applied to a body and the cohesive strength or molecular resistance opposing this force.

Structure

A term applied (a) to morphological features of rocks due to fractures and (b) to the appearance of a heterogeneous rock in which the texture and composition of neighbouring parts differ from one another.

Submersible pump

A centrifugal pump directly coupled to an electric motor which can operate submerged in water. The unit has a diameter less than that of the well, allowing it to be lowered into the well. See Turbine pump.

Suspension wire

A magnetometer system where the magnet is suspended by two wires. For a reading an internal compensating magnet is used and at the instant of reading, the wires are not under torsion.

Svionian

The oldest known orogeny of Precambrian Sweden.

T

Taluk

A subdivision of an Indian revenue district. The area may be in the order of 1,000 to 3,000 km^2, population from 200,000 to 1 million.

Tectonic

Pertaining to the rock structures and external forms resulting from the deformation of the earth's crust.

Tension

A system of forces tending to draw apart the parts of a body combined with an equal and opposite system of resisting forces of cohesion holding the parts of the body together.

Texture

The appearance, megascopic or microscopic, of a rock, due to the degree of crystallization (**crystallinity**), the size of the crystals (**granularity**) and the shape and interrelations of the crystals or the constituents (**fabric**).

Top hammer

A rock drill which works on top of a drill string, at the bottom of which a drill bit is attached. As the top hammer cannot enter into the hole, the distance between it and the bit will increase as the hole becomes deeper.

Torsion wire

A magnetometer system where the magnet is held between two wires that are mechanically turned for a reading. At the instant of reading, the wires are under torsion.

Transpiration

The process by which plants loose water to the atmosphere.

Tri-cone rock roller bit

A drill bit consisting of a shank with three toothed, circular or cone-shaped cutter parts affixed to the head of the bit in such a manner that the cutters roll as the bit is rotated.

Tube well

A well having a tubular shape, i.e., its length is great in proportion to its diameter. Opposed to an open, dug well.

Tuff

Cemented volcanic ash.

Turbine pump

A centrifugal pump powered by a prime mover (motor) mounted at surface and to which the pump is coupled by a rotating shaft. See Submersible pump.

TVA

Tennessee Valley Authority, a famous American development project based on harnessing the water resources of the region.

U

Un-consolidated

See Consolidate

V

Vein

An irregular sinuous igneous injection or a tabular body of rock formed by depositions from solutions rich in water or other volatile substances.

W

Water table

See Ground water level.

Water table conditions

Ground water that is in direct contact vertically with the atmosphere through open spaces in permeable material.

Weathering

All physical and chemical changes produced in rocks at or near the surface by atmospheric agents which result in more or less complete disintegration and decomposition of the rock.

Y

Yield

Quantity of water per time unit produced by a well or a formation.

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