Ground Management Issues of Selected river basins with special reference to Hard Rock Aquifers

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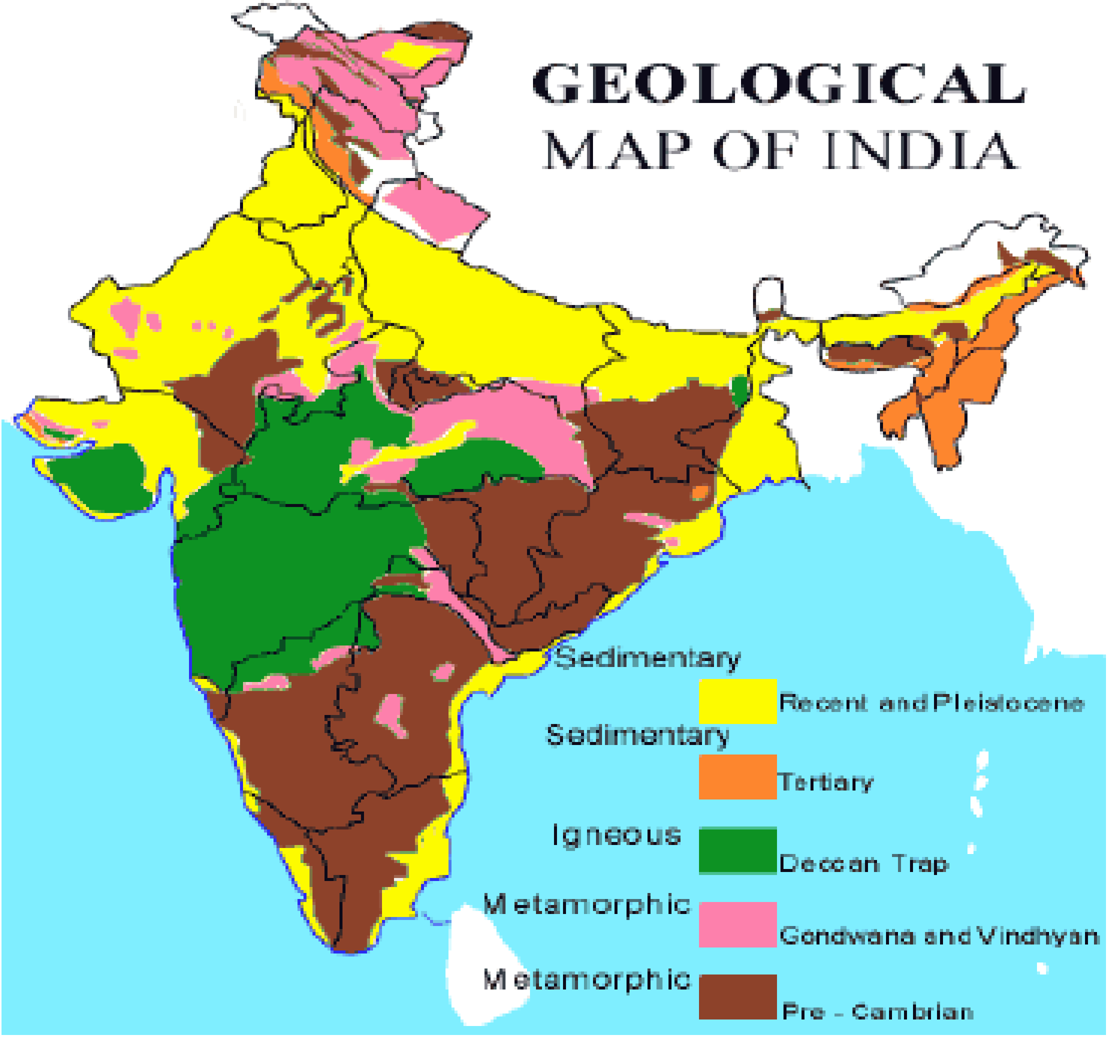
Introduction

It is a known fact that about 65% of the total land area is covered by hard rocks. Both surface and groundwater are to be used conjunctively to meet the water requirements of the area, which often become more acute due to recurring droughts. Due to the wide distribution of hard rocks in Central and Southern India the whole behavior of the nature and hydrologic process varies from other parts of the country due to the unique nature of hard rocks, i.e., **they devoid of primary porosity but have been rendered porous due to weathering and fracturing. The weathering zone is extensive within depths of 10 to 20 m but is localised down below with increase in fracture porosity.** The calcareous members like clay gneisses and marbles have been subjected at places to solution.

Definition of `Hard Rock'

Among the geologist and hydrogeologist, still there is no consensus in defining the **`Hard Rocks'**. In general, Hard Rocks are those geological formations with very low drillability and further, the inter-granular porosity is practically absent. **Larsson et al (1987) defined `hard rocks' as igneous and metamorphic, non-volcanic and non-carbonate rocks.** Recently, **Gustafson (1993) proposed that the term `hard rock' might, from a groundwater exploration point of view, include all rocks without sufficient primary porosity and conductivity for feasible groundwater extraction.**


GEOLOGICAL
MAP OF INDIA
Sedimentary
Recent and Pleistocene
Sedimentary
Tertiary
Igneous
Deccan Trap
Metamorphic
Gondwana and Vindhyan
Metamorphic
Pre - Cambrian

PROBLEMS

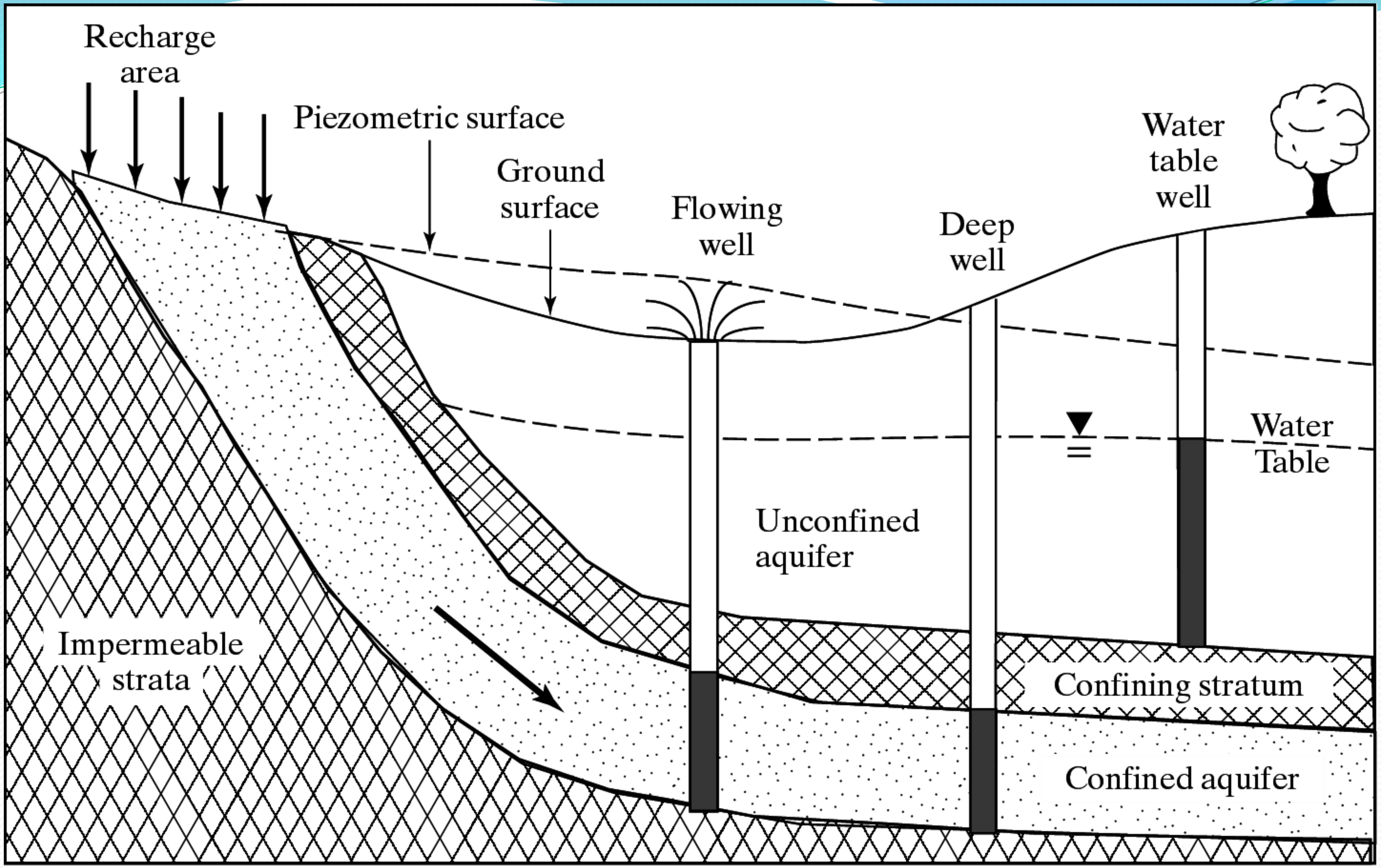
- Groundwater – Quantity and Quality
- Surface and Groundwater Interaction
- Impact of Land use/ Land cover changes on groundwater.

GROUNDWATER AVALABILITY

- The rainfall in the peninsular region varies from 500 mm to about 4000 mm annually.
- Inspite of that, the groundwater availability in the region in dry season is very low.

SURFACE-GROUNDWATER INTERACTION

- Exhibits spatial as well as temporal variations throughout the peninsula.
- Largely depends on the topographic, geological and lithological conditions of the area.



Groundwater System

Components of Groundwater Management

- Sustainable use of ground water
- Preservation of its quality
- Prevention of: groundwater pollution
  groundwater over-use (exploitation)
- Groundwater protection plans
  (as part of environmental protection planning)

Management Issues…

- How long can an aquifer sustain given rate of GW draft?
- What is the safe yield that the aquifer can sustain?
- What is the capture zone of a water well field?
- What can be the pathways of pollutants from wastewater/ leaches from solid waste ?
- What are the chances that the pollutants from such sources would arrive at water supply-wells?
- And how long it may take?
- What should be the size of the protection zone to protect the well fields from pollution?

Groundwater Management:

Role of Models

To answer such *difficult* questions: WE NEED

- Good understanding of the GW systems

- Prediction of the system response to stresses

Best tools available today:

GROUNDWATER MODELS

Groundwater Models

Groundwater Models = Numerical Groundwater Models

Physically founded mathematical models, based on certain simplifying assumptions, derived from Darcy's law and the law of conservation of mass

Simplifications involve:

* Direction of flow
* Geometry of the aquifer
* Heterogeneity or anisotropy
* Contaminant transport mechanisms
* Chemical reactions etc.

Formulation of Groundwater Models

When modelling GW flow, the aim is to predict the GW head distribution in the aquifer under different stress conditions

To use Darcy's law alone to describe GW, we need the heads everywhere in the aquifer . . . . .

Darcy's law gives 3 Eqns. for flow in 3 major directions
But, there are 4 unknowns : 3 components of GW flux + The head

So, we need the flow equation based on the law of conservation of mass

Fractures: Definitions

- **Fracture**: a sub planar **discontinuity** in a rock or soil formed by mechanical stresses.
- **Fault:** a plane of fracture in a rock along which **displacement** has occurred.
- **Joint**: a surface of fracture in a rock, **without displacement** parallel to the fracture, a fracture in a rock along which there has been no movement, in contrast to a fault
- **Aperture:** the distance between the two surfaces of a fracture (the hydraulic conductivity of a fracture is roughly a function of aperture, where the increase of hydraulic conductivity **is proportional to the third power of the aperture**)
- fissure, crack: small and very small fractures..
- Vein: A deposit of foreign minerals within a rock fracture or joint.

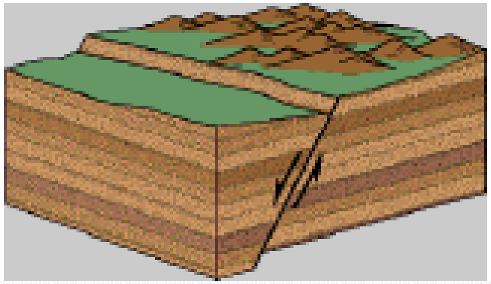
Processes Affecting Hydraulic Properties of Rocks, Summary (1)

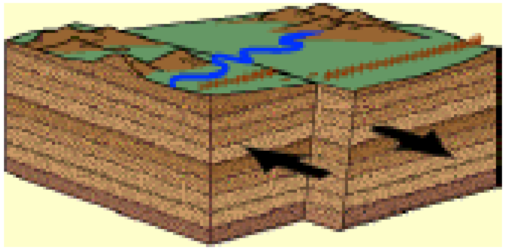
- initial conditions at the time of formation (Sedimentation, Crystallization) = primary properties
- Diagenesis consolidation / lithification = secondary properties:
  - caused by
    - compaction (sediment load, tectonic stress ...)
    - dewatering
    - mineral growth (growth of existing grains)
    - cementation (growth of new minerals)
  - leads to:
    - increase of specific weight
    - decrease of porosity and hydraulic conductivity (storativity, spec. yield)
    - decrease of compressibility
    - increased sensitivity to fracturing (brittleness)

- Weathering / Decomposition = secondary properties
  - caused by:
    - mechanical w. (heat, frost wedging, water)
    - chemical w. (oxidation, hydrolysis etc.)
  - leads to:
    - decrease OR increase of porosity and hydraulic conductivity
    - decrease of stability

Processes Affecting Hydraulic Properties Summary (2)

- fracturing, faulting, folding
  - caused by:
    - global and regional processes: influence of tectonic stress (plate tectonics…)
    - regional: exposure (uplift and erosion)
    - local processes: e.g. caused by gravitational forces at slopes
  - leads to:
    - increase of porosity and hydraulic conductivity (storativity, spec. yield)
    - increase of compressibility
- reverse processes (= closure of fractures)
  - caused by
    - "healing" of fractures: mineral growth in fractures, closure of fractures
    - "sealing" of fractures: fractures that are filled with detritus, weathered material, soil material from the surface
    - closure of fractures by compaction (tectonic, load of the rocks above)
  - leads to:
    - decrease of porosity and hydraulic conductivity (storativity, spec. yield)





Aquifer Characteristics and Well Yields

Barring the volcanic rocks, igneous and metamorphic rocks usually have porosities less than 1%, the voids being minute, generally isolated and inconsequential from a practical point of view. On weathering and fracturing, the rocks acquire higher porosity, which may reach 30% or more in the case of granite, gabbro, basalt and schist in some cases highly weathered granites may attain a porosity as high as 56.6% (Morris and Johnson, 1967). Estimations by various methods show comparatively low values of specific yield, a range of 2-4% being common for granite, gneiss and schist.

Development of Fissures and Joints

In any discussion of the hydrology of fractured crystalline and argillaceous rocks, one must first consider the structural nature of the rock mass. Fractures also called joints, are planes along which stress has caused partial loss of cohesion in the rock. It is relatively smooth planar surface representing a plane of weakness (discontinuity) in the rock. Conventionally, a fracture or joint is defined as a plane where there is hardly any visible movement parallel to the surface of the fracture; otherwise, it is classified as a fault. A fracture is any break in a rock matrix, regardless of its size. Faults are most common in the deformed rock of mountain ranges, suggesting either lengthening or shortening of the crust.

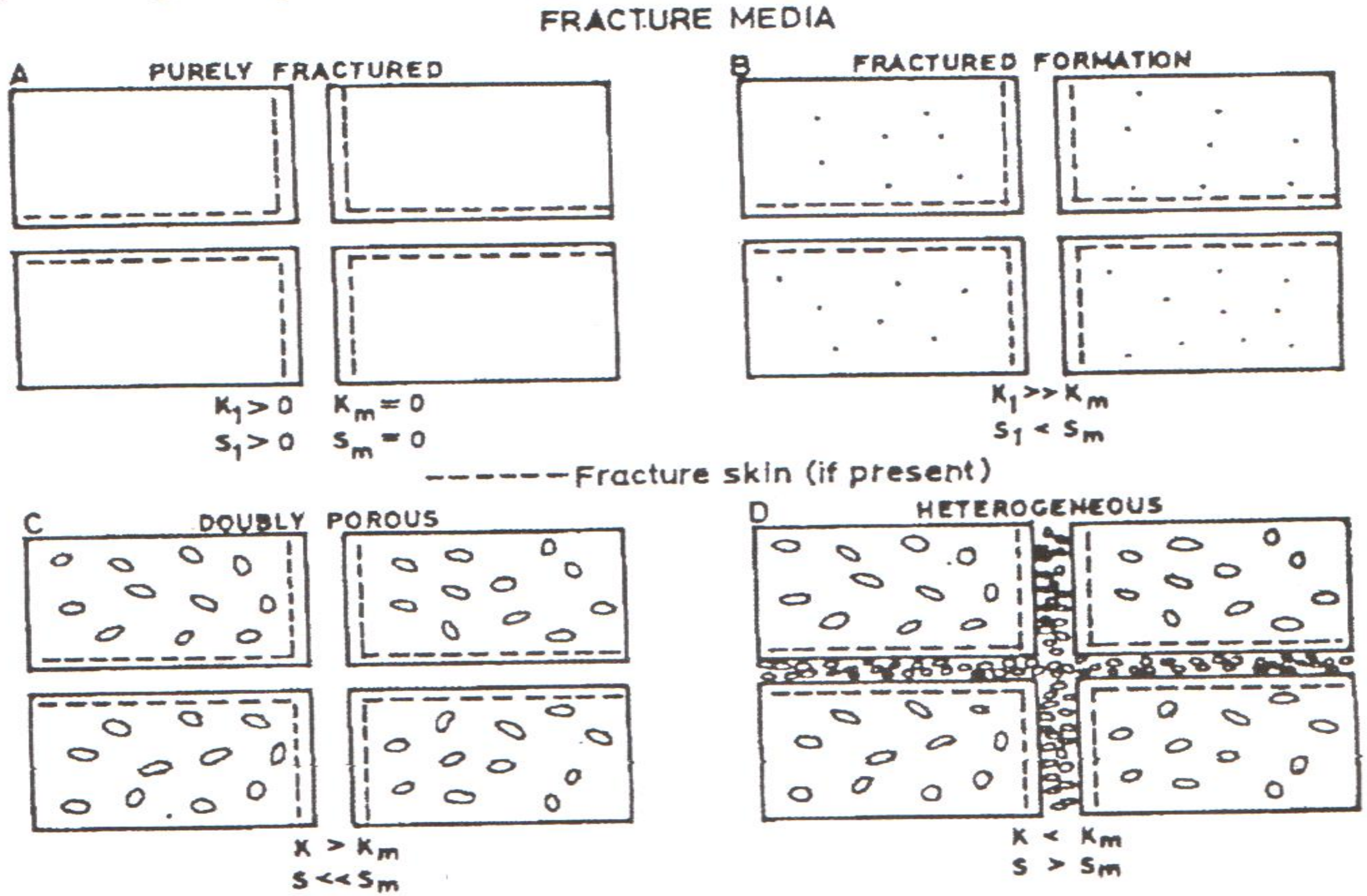


Figure 2. Hydrogeological classification of fractured media (after Streltsova, 1975). K_f and K_m are the hydraulic conductivities of the fractures and the matrix, respectively. S_f and S_m represent the fluid storativities of the fractures and the matrix. A: purely fractured media. B: fractured formation. C: double porosity medium. D: heterogeneous formation. In cases B, C, and D, the fracture coating or "skin" may be hydrogeologically significant.

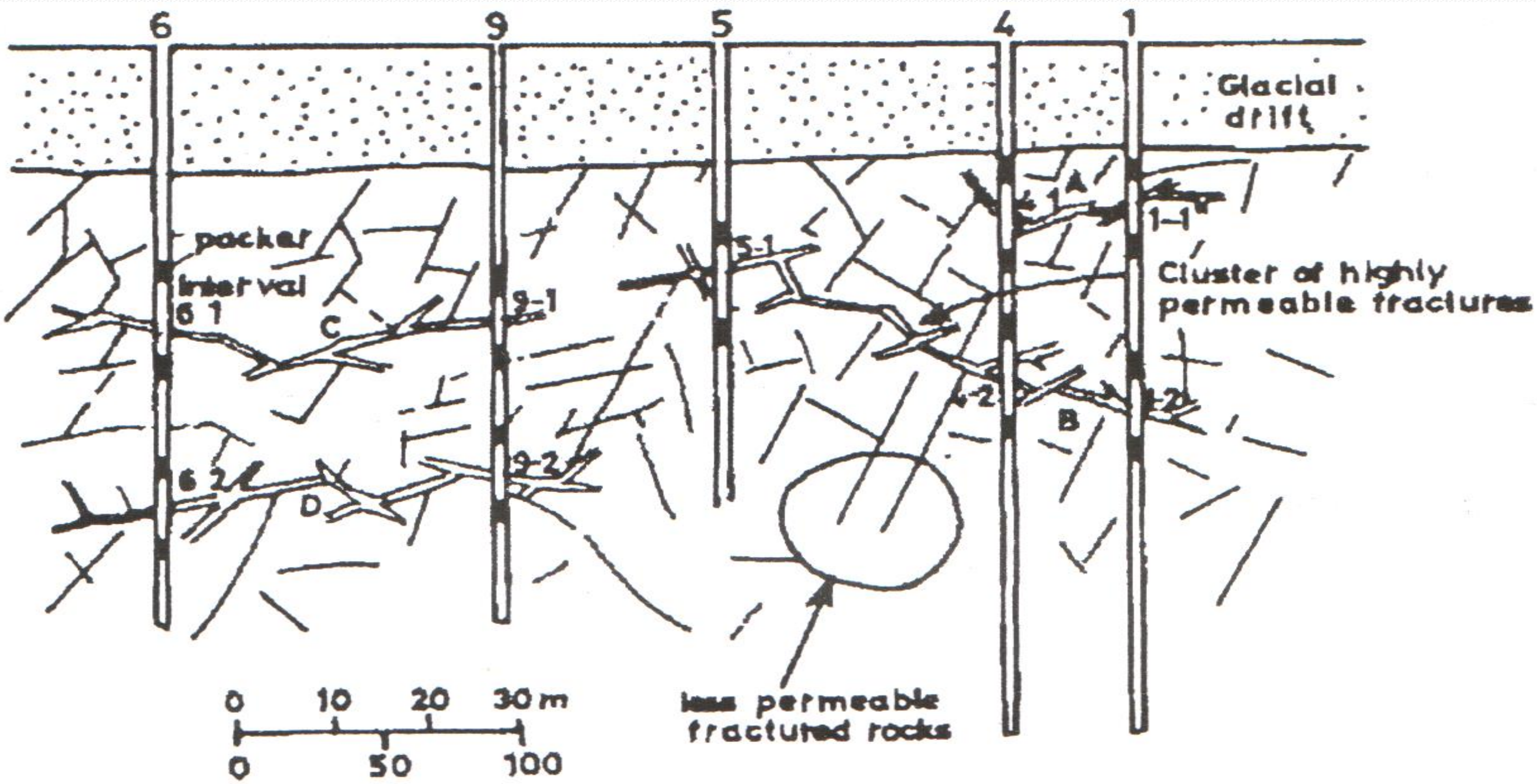


Figure 1. Vertical cross section and conceptual model of the US Geological Survey's fractured rock research site near Mirror Lake, New Hampshire. Four clusters of highly permeable fractures labelled A-D occur in the less permeable fractured rocks. Borehole packers are closed sections (after Rutqvist and Stephansson, 2003).

Fractures and Hydraulic Conductivity

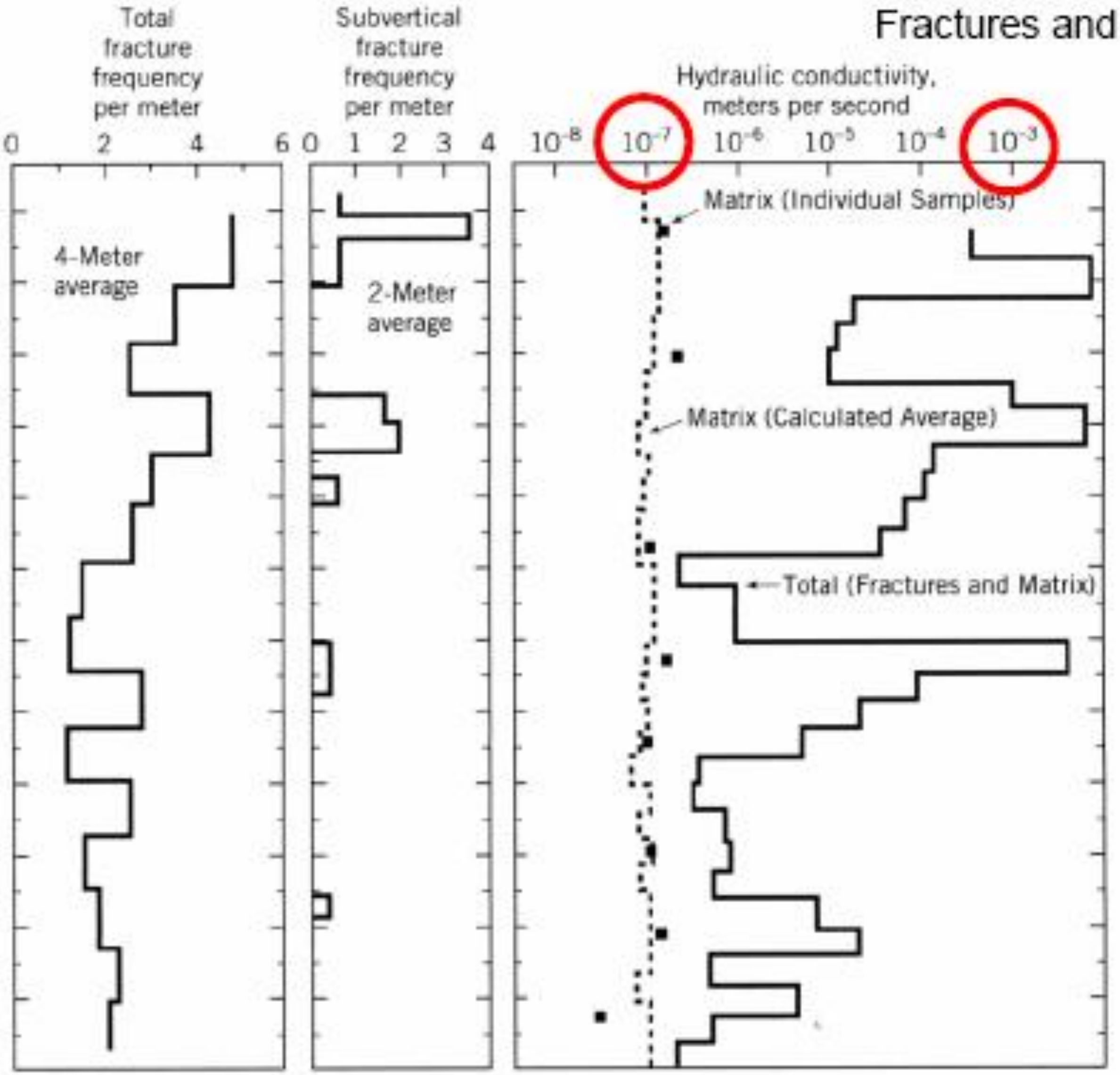


Figure 4.27 Comparison of two measures of fracture frequency and measured hydraulic conductivities as a function of depth (from Francis, 1981).

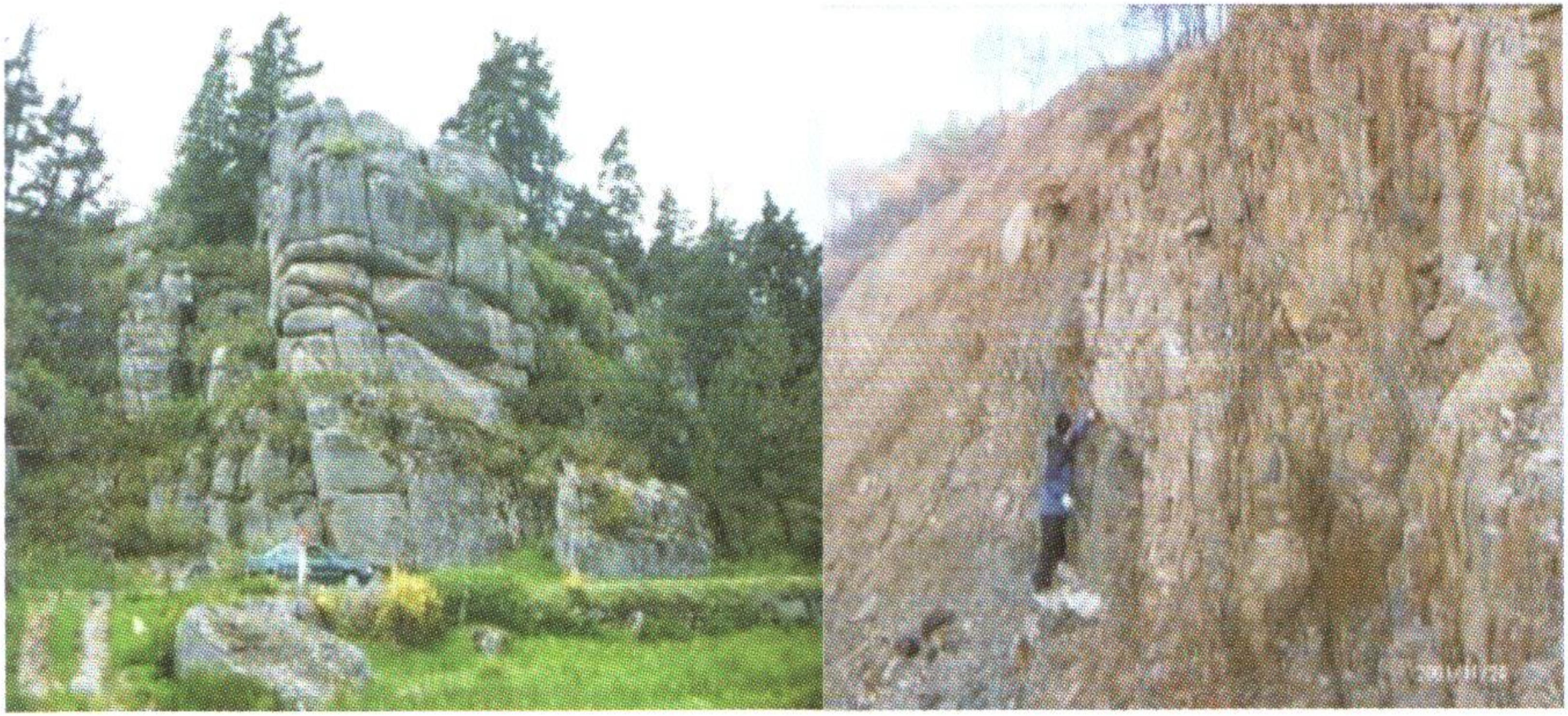


Figure 4. The fissured layer in granites (left: Margeride, Lozère, France)and in metamorphic rocks (right: Gokseong area, South Korea).

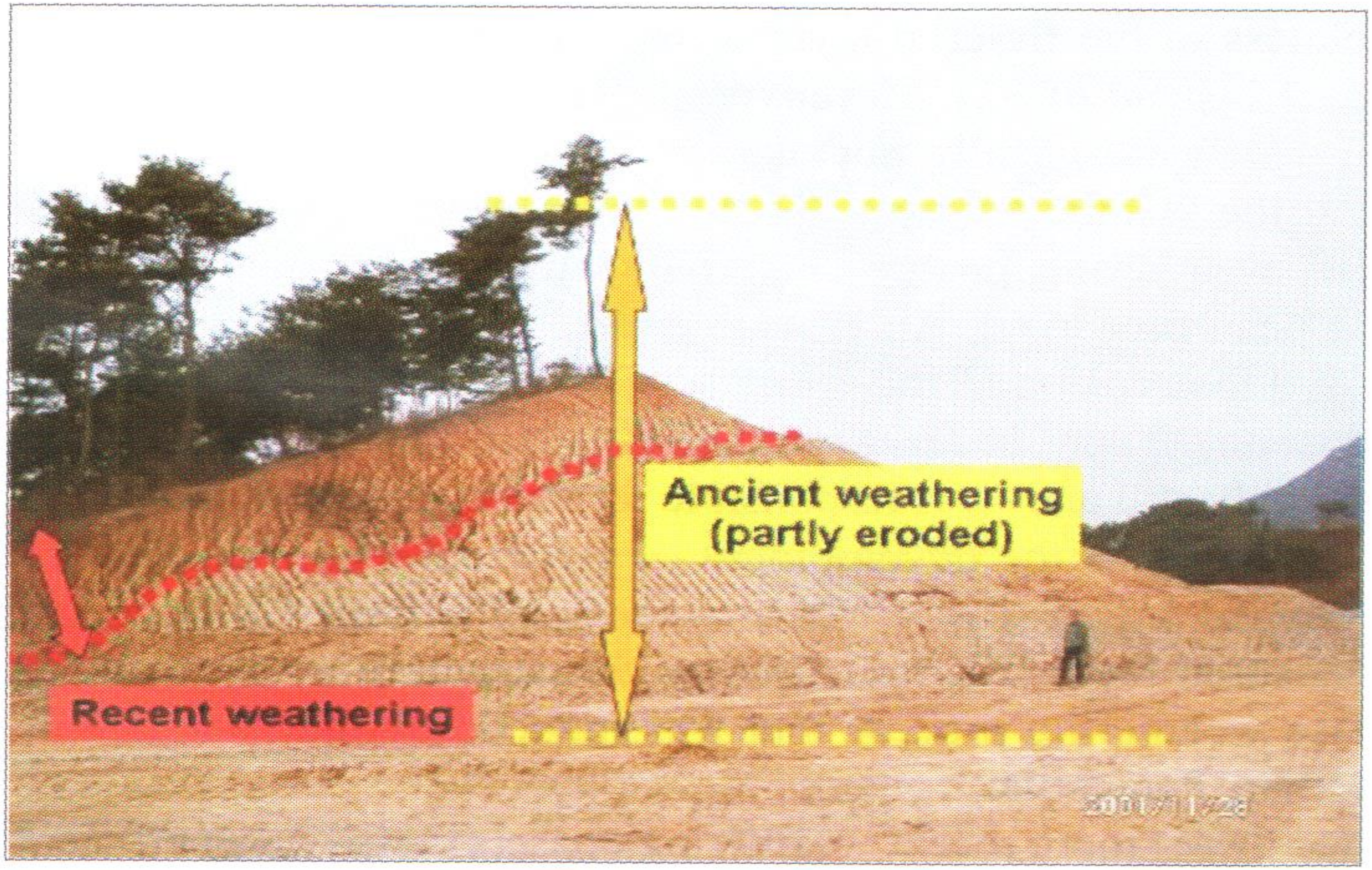


Figure 5. Red recent weathering, related to the present topography, intersecting an old weathering profile (Namwon area, South Korea).

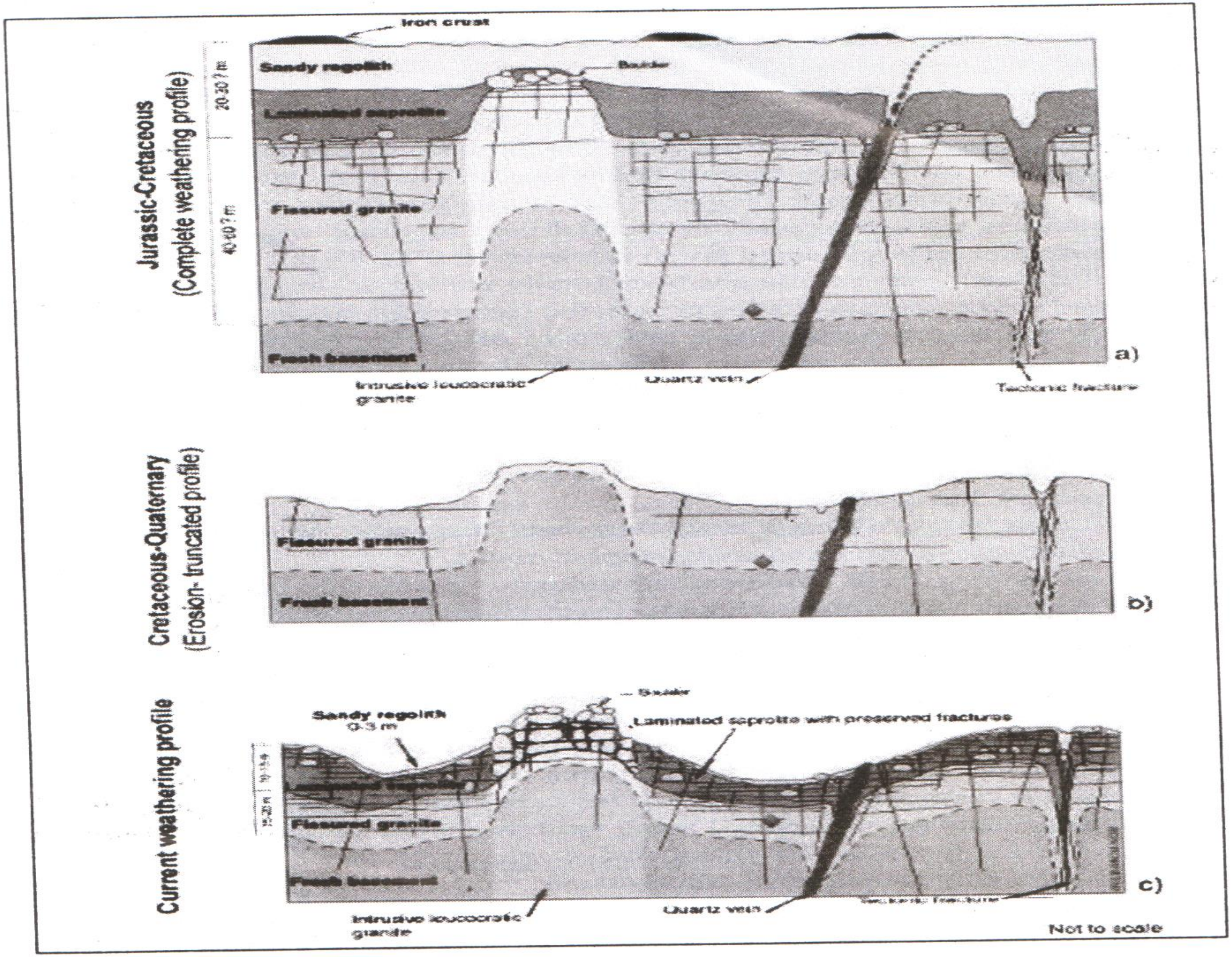


Figure 6. Multiphase weathering conceptual model observed in southern India (vertical scale exaggerated) from Dewandel et al., 2006.

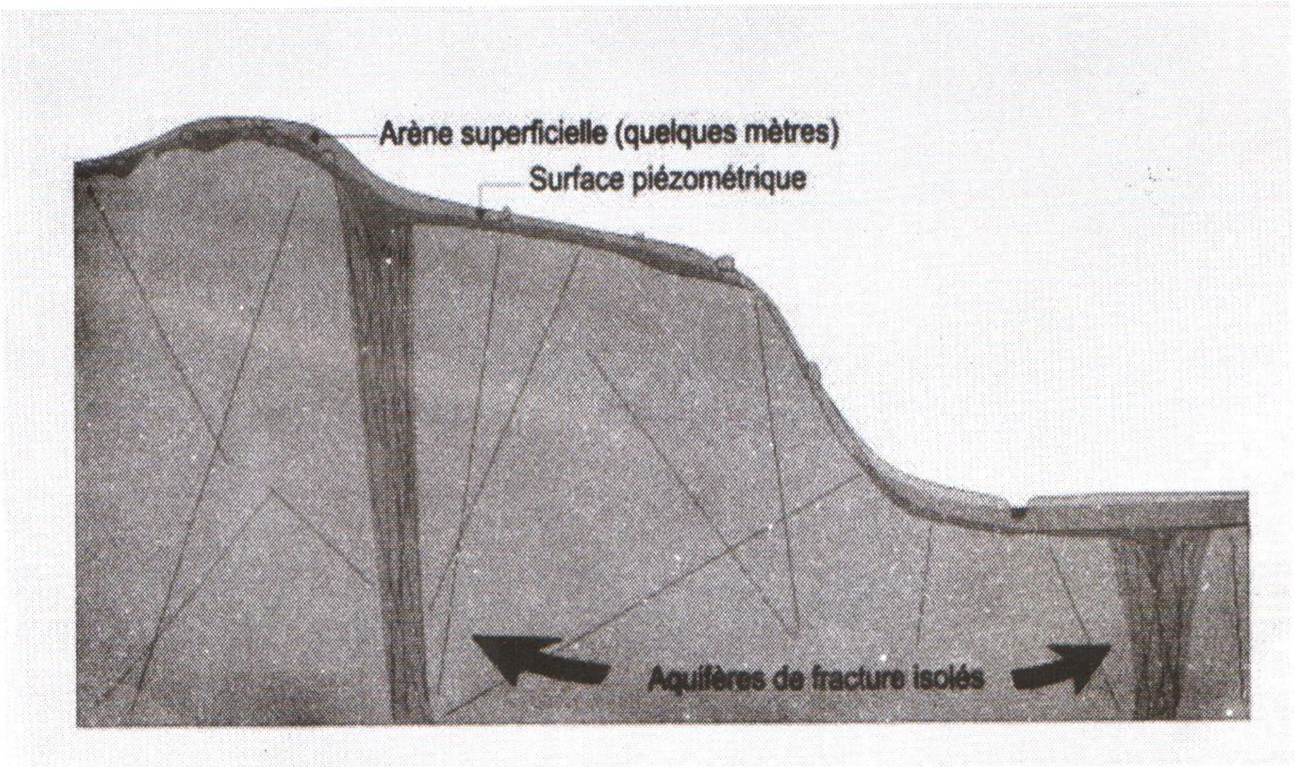


Figure 1. The classical concept of discontinuous aquifer [translation - upto bottom: superficial and consolidated weathering cover (a few metres), piezometric level, aquifers in isolated fractures].

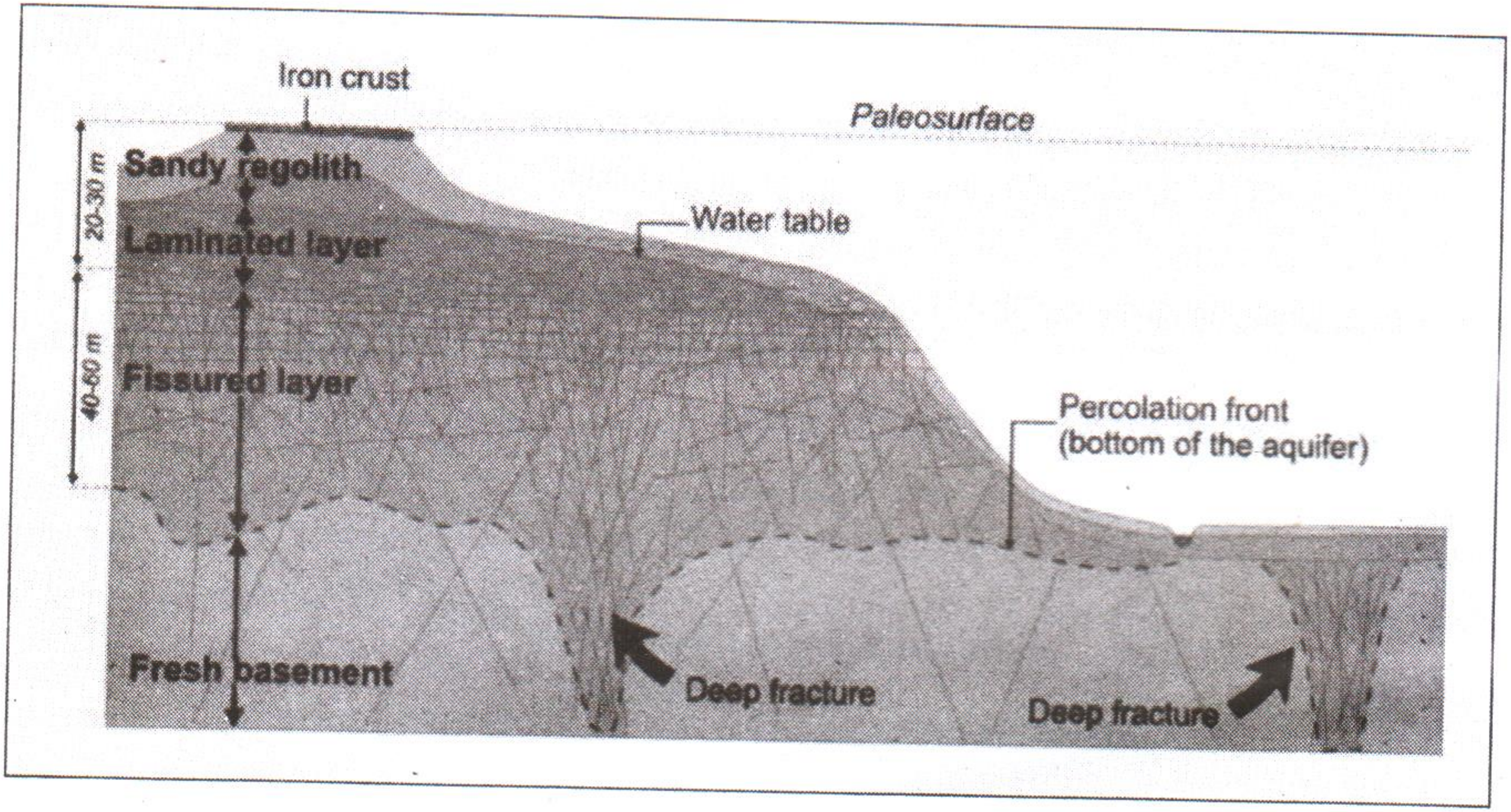


Figure 2. Stratiform conceptual model of the structure and the hydrogeological properties of hard rock aquifers (after Wyns et al., 2004).

Interaction of two Processes: Jointing and Weathering

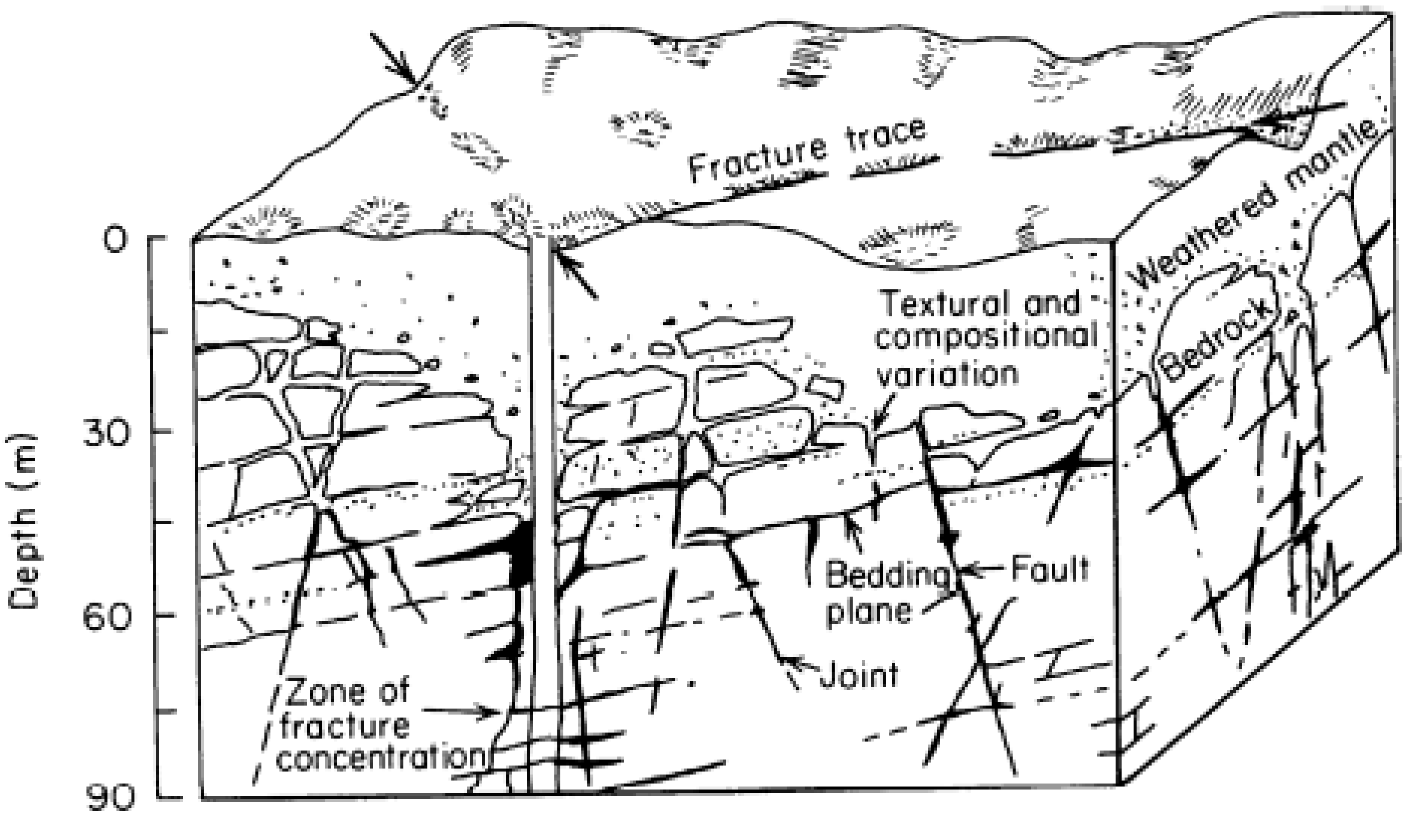
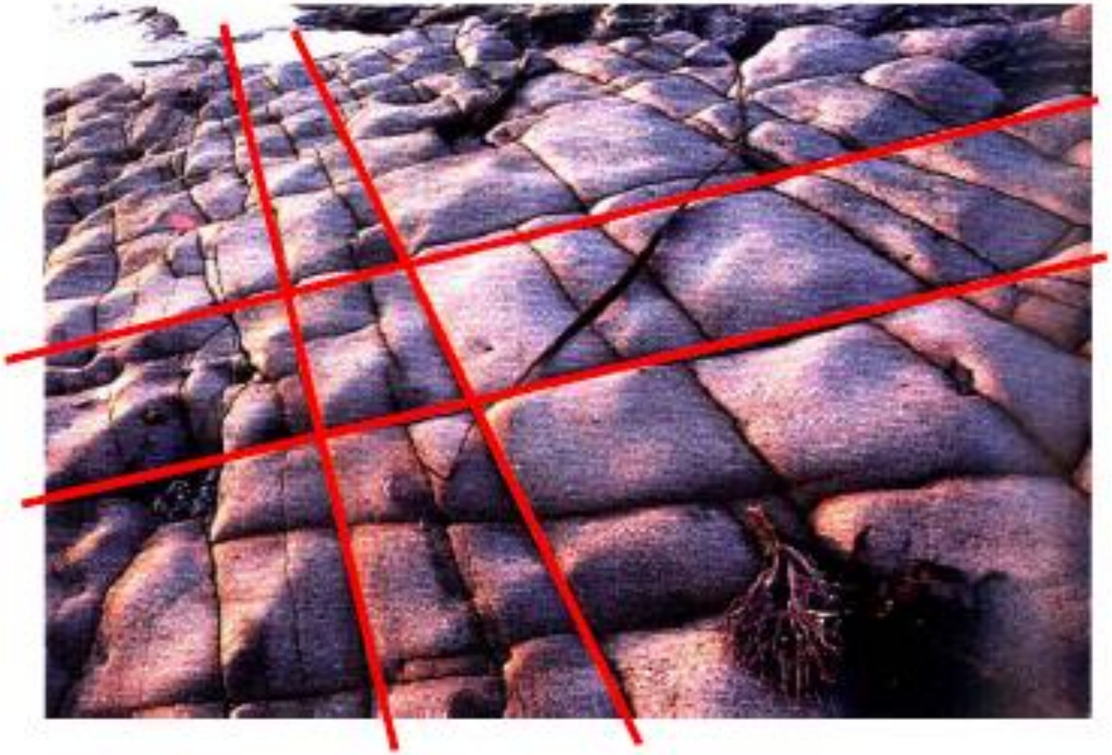


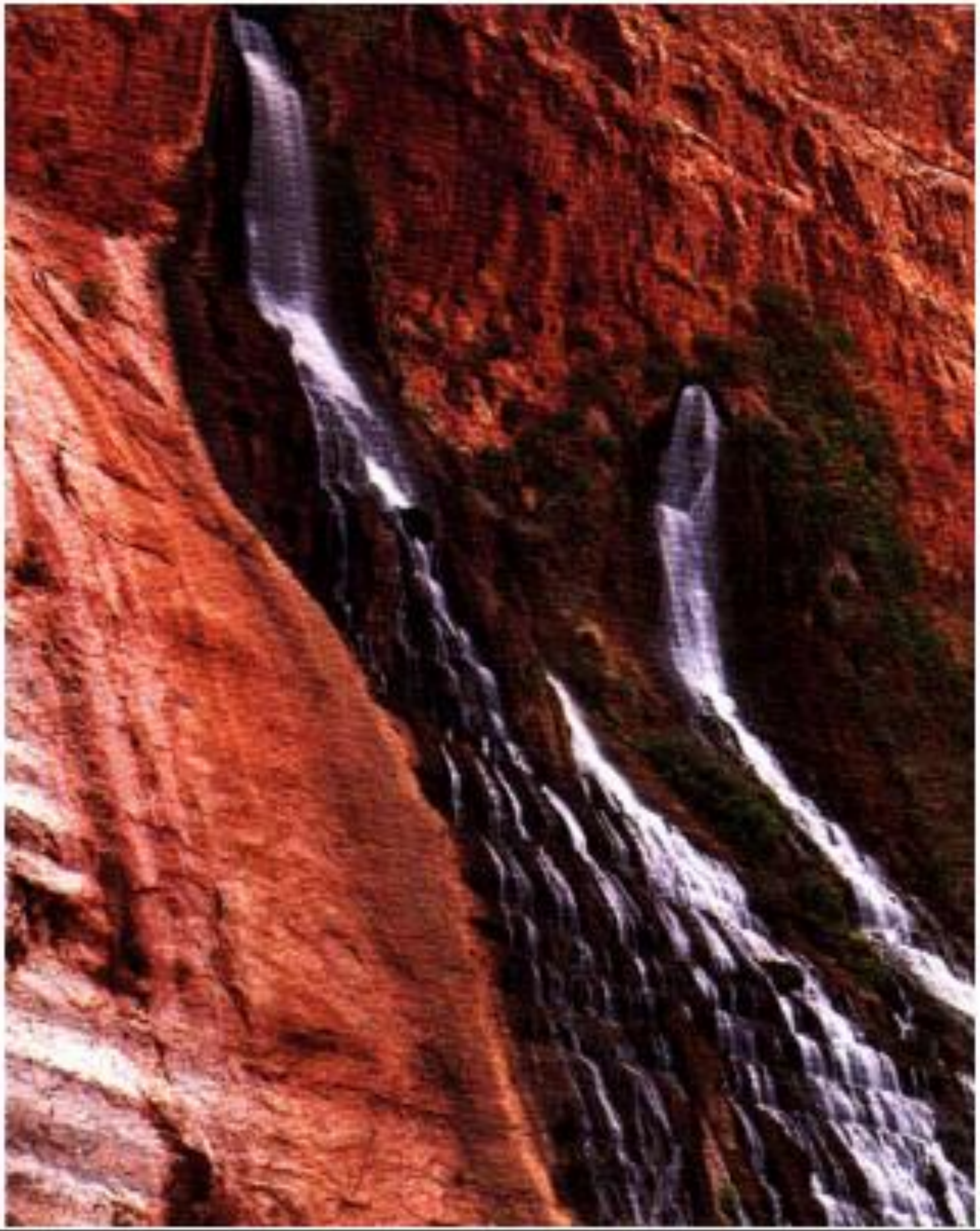
Figure 4.8 Occurrence of permeability zones in fractured carbonate rock. Highest well yields occur in fracture intersection zones (after Lattman and Parizek, 1964).

Freeze&Cherry

Fractures in a Granite: Joints



Systematic Joints



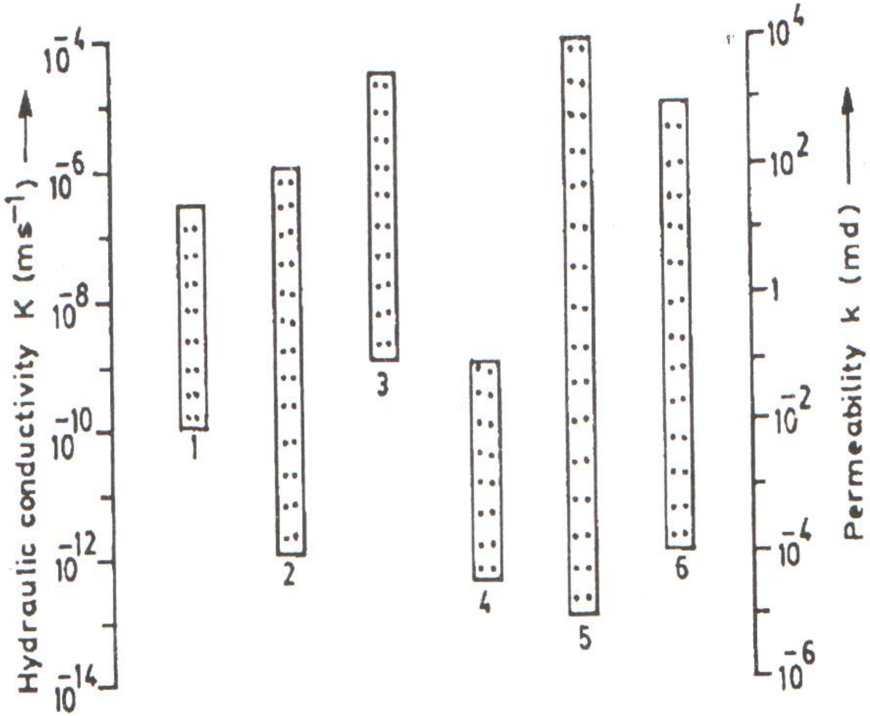


Figure 4. Range of hydraulic conductivity (K) and permeability (k) in some crystalline rocks estimated from in situ borehole tests (based on data from Brace, 1984; Black, 1987). 1. Granite batholith, Monticello, SC, USA; 2. Altnabreac, Scotland; 3. Carynnen, Cornwall, UK; 4. HDR, Cornwall, UK; 5. Deep drilling in northern Switzerland; 6. Four sites in Sweden.

Sediments	Specific Yield (%)
Clay	1-10
Sand	10-30
Gravel	15-30
Sand and Gravel	15-25
Sandstone	5-15
Shale	0.5-5
Limestone	0.5-5

Specific Storage (S_s): ***Specific storage*** is the amount of water stored or expelled by the compressibility of the mineral skeleton and pore water per unit volume of a confined aquifer and per unit change in head. Specific storage has a dimensions of (1/L) and has value on the order of 10^{-3}.

Storativity or storage coefficient (S) of a confined aquifer is the product of the specific storage (S_s) and the aquifer thickness (b). The storativity of most confined aquifers is between 10^{-3} and 10^{-5}. The storativity for an unconfined aquifer is usually taken to be equal to the specific yield. The specific yield of most alluvial aquifers is between 10 to 30 percent.

Transmissivity of the aquifer is the flow capacity of an aquifer per unit width under unit hydraulic gradient.

In aquifers containing large diameter solution openings, coarse gravel, rock-fills, and also in the immediate vicinity of a gravel packed well, flow is no longer laminar due to high gradient and exhibit nonlinear relationship between the velocity and hydraulic gradient.

Methods of estimating Hydraulic Properties of rocks

Hydraulic properties of rock materials can be estimated by several techniques in the laboratory and in the field. The values obtained in the laboratory are not truly representative of the formation. However, the advantage of laboratory methods is that they are much less expensive and less time consuming. Laboratory methods are based on both indirect and direct methods.

In unconsolidated material, hydraulic conductivity can be determined from grain-size analysis. The hydraulic conductivity of unconsolidated material is found to be related empirically to grain-size distribution by a number of investigators. Hazen, as far back as 1893, developed the empirical relationship between hydraulic conductivity (K) and effective diameter (de)

Hydrogeological Investigations Carried out

In general the groundwater potential of hard rocks is poor, through relatively high yields may be obtained in restricted locations under favourable circumstances of topography and rainfall. The zone and the frequency of openings in fractured rocks are normally restricted to shallow depth resulting in low void ratio and hydraulic conductivity. Exceptionally carbonate rocks develop solution channeling with high hydraulic conductivity and yield, particularly in zone of past and present water table fluctuations. The drainage d3eveloped in individual lava flows during intertrappean periods give rise to productive zones, under favourable conditions of topography with high conductivity and yield.

The hydrology and groundwater resources in Deccan Traps have explained by many hydrologists. As per the wok done by State Department of Mines and Geology, Karnataka (1975), the black trap is hard, compact and is traversed by joints in shallow depth. **Joints had persisted only upto 10 - 15 m depth.** Beyond this depth, the rock becomes more and more compact and presence of such massive variety of trap was noticed approximately from 630.6 m contour and below. Weathering extended hardly 0.5 to 1.0 m depth. The depth for the water in the well varied from 2 to 10 m. While, the pink trap appeared to be better aquifer. They are weathered to an average depth of 12 to 15 m and were having more blowholes and amygdoloidal structures which were filled by secondary minerals like zoeolites and silica. More of fractures and fissures were noticed which helps to retain water percolation, after rainfall. Pink t raps are seen at an approximate altitude of 660.6 to 675 m above M.S.L. and extended approximately upto 630 m contour. The depth of water table in such formation varied form 6 to 12 m depending upon the topography.

In the Deccan trap, the ground water occurs under water table conditions in weathered and jointed traps, and under confined conditions in the zeolitic and vesicular traps wherever they are overlain by hard traps. Depth of weathering in general varied from 2 m to 18 m. **Wells ranged in depth from 3.7 to 17.8 m bgl and depth to water table ranged from 1.10 to 16.2 m bgl. The yield of dug wells ranged from 20 cu. m / day to 250 cu. m /day for the pumping period of 2 to 8 hrs.** Wells in valleys nearer to nalas and in zeolitic traps yielded better. The inflow rate varies from 0.58 lpm / sq. m to 1.2 lpm / sq. m for recuperation period varies from 1380 minutes to 1175 minutes and in vesicular trap the inflow rates of 1.1 lpm / sq. m to 1.2 lpm / sq. m for recuperation period of 70 minutes and 1260 lpm. The transmissivity figures obtained by the Pappodopulos and Cooper method ranges from 21.5 sq. m /day to 150 sq. m /day.The specific capacity of the wells ranges from 2.42 to 19.13 cu. m /h/m and unit specific capacity in the range of 0.039 to 0.1995 cu. m /h/m. Deccan trap does not contribute appreciably to tube well yield, and the contained water can be tapped only by constructing large-diameter well. In most cases, this zone is entirely shut off by the lining in a tube well..

Intensive exploratory drilling in igneous and other hard rock in parts of peninsular India have showed that the openings at greater depth, becomes less pronounced and less abundant and in some cases they are not favourable for movement of ground water . Relatively higher yields from hard rocks are obtained within 40 to 50 m. Depth from surface. Optimum depth drilling beyond which is normally not warranted is about 100 meters while rock type is commonly of secondary importance to the control of weathering and structure. The geometry of the fracture or joint sets is determined by the types of the rock and the stress to which they have been subjected, besides the effect of weathering and relief which makes the void space constituting the system progressively larger on approaching the surface. The topographic conditions and the rainfall regime maintain a high level of saturation in the hard rocks. Thus topographic lows and high rainfall will offer better advantage, although latter factors are insufficient to ensure favourable conditions. Every situation must be considered in the light of the relative influence of the controlling factors. Nevertheless, the water table and the top of the flow system will show generally sympathetic relationship to the topography. The degree of sympathy will be governed by the hydraulic conductivity, the closer water table and topography relationship.

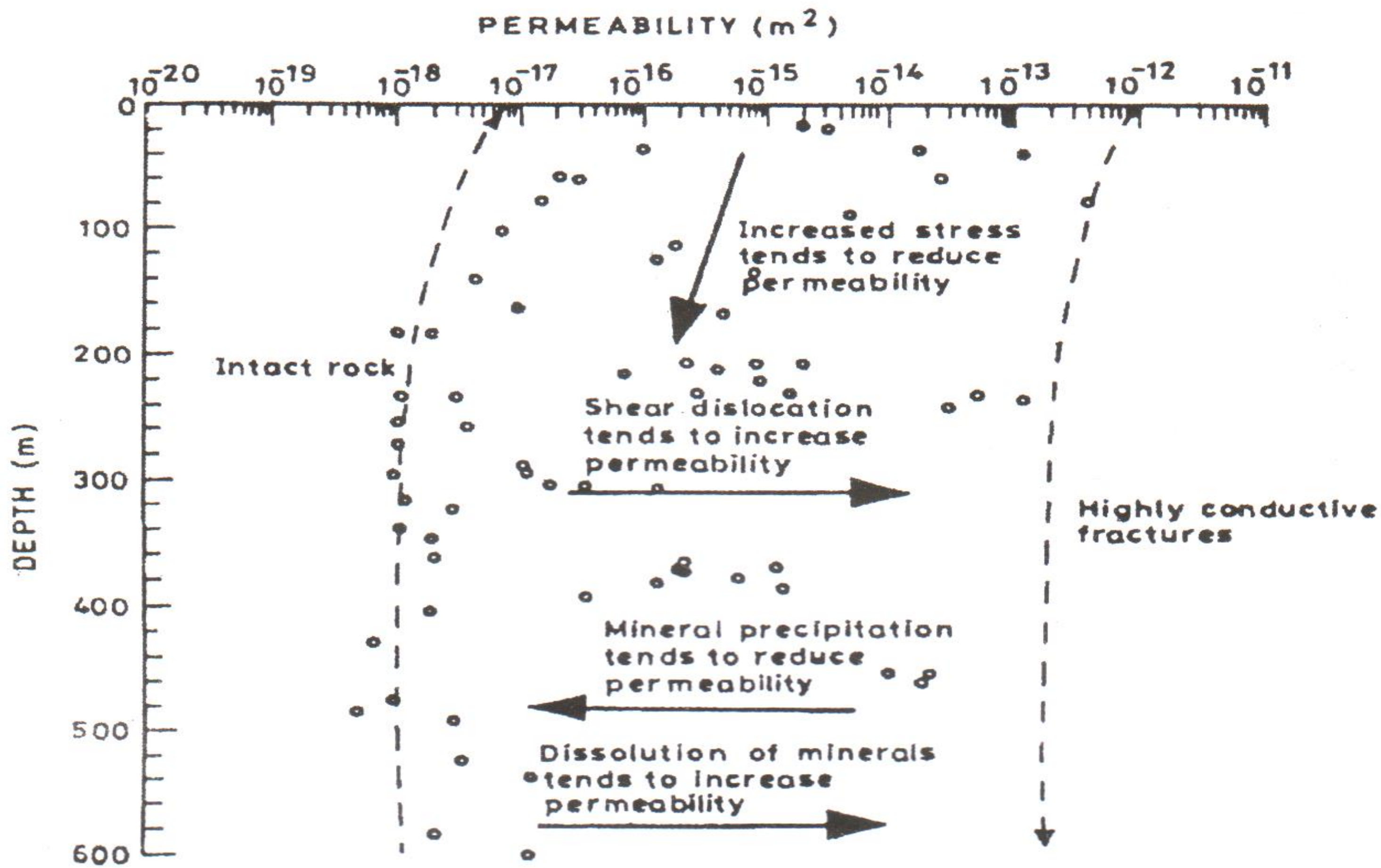


Figure 5. Permeability estimated from short-term well tests in fractured crystalline rocks of Sweden (after Rutquist and Stephansson, 2003)

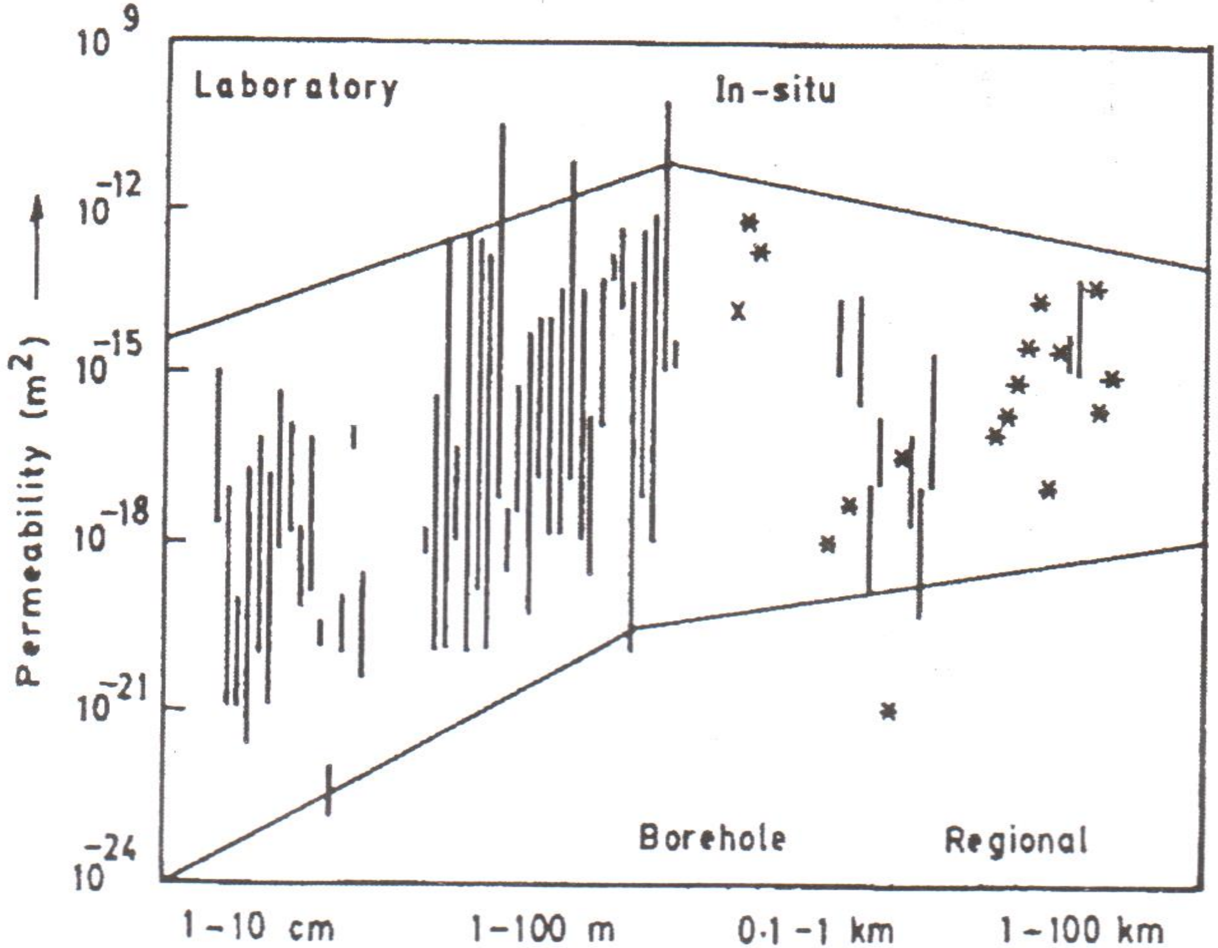


Figure 6. Variation in permeability values of crystalline rocks as a function of scale of measurement. Bars mark the permeability range based on several reported values, and stars represent single values (after Clauser, 1992).

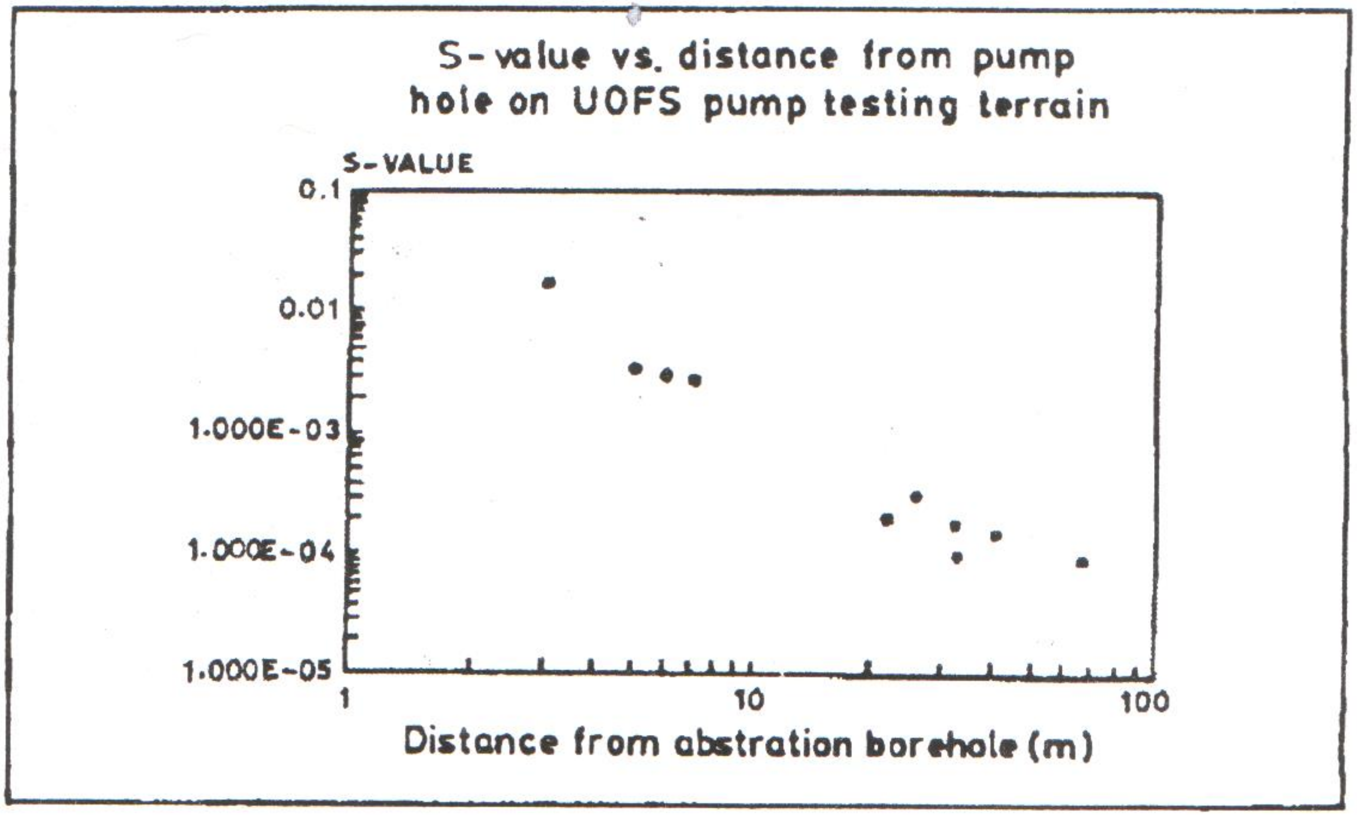


Figure 7. Variation of estimated *S*-values in relation to the distance between the observation and pumping borehole as obtained in the fractured-rock aquifer on the University of the Orange Free State (UOFS) campus (after Lloyd, 1999).

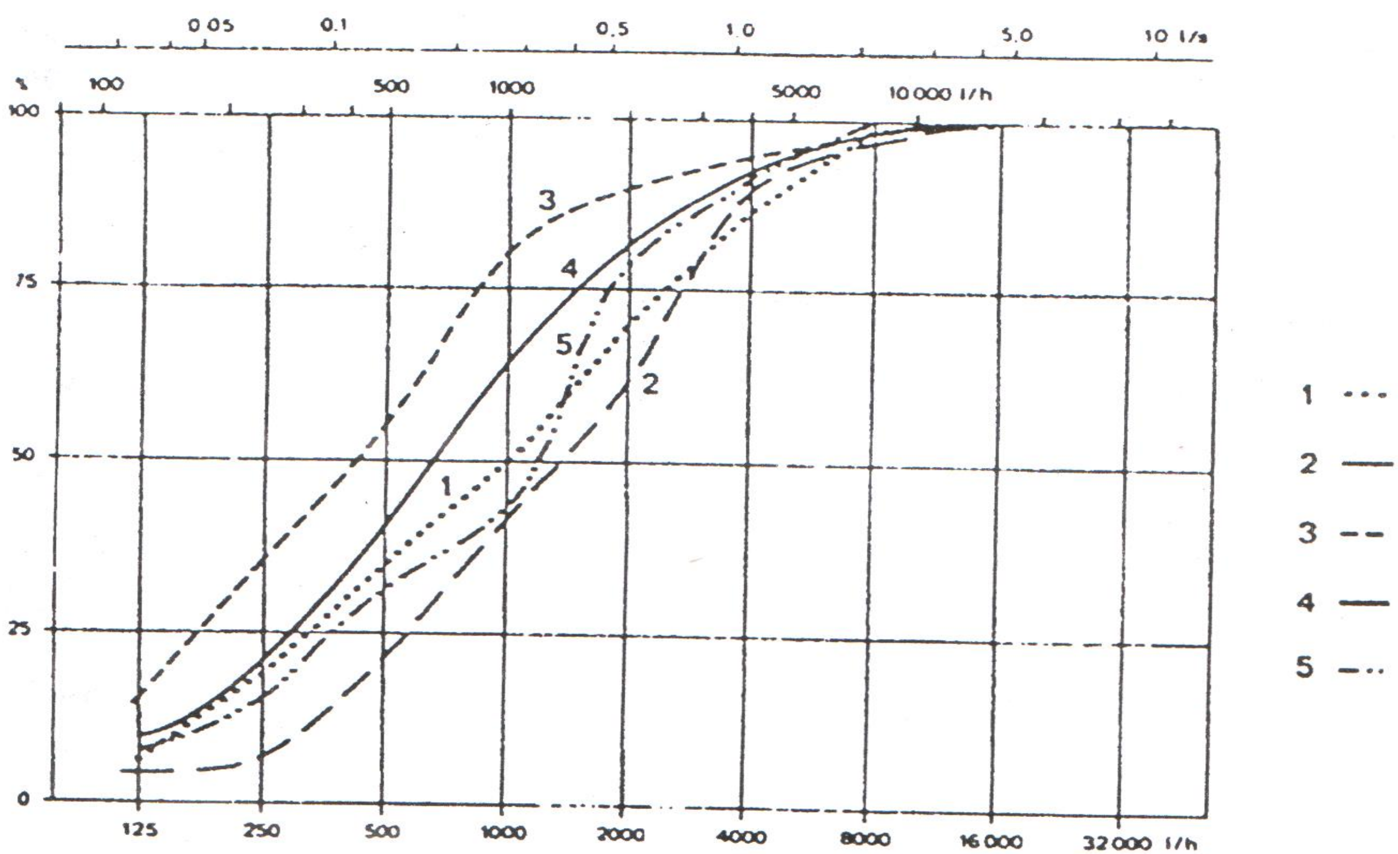


Figure 8. Distribution of well yields for different rock types in the Central Scandinavian area (after Banks et al., 1996) 1: syn-orogenic granites. 2: post-orogenic granite. 3: post-orogenic gabbros and dolerites. 4: gneisses. 5: Caledonian mica schists.

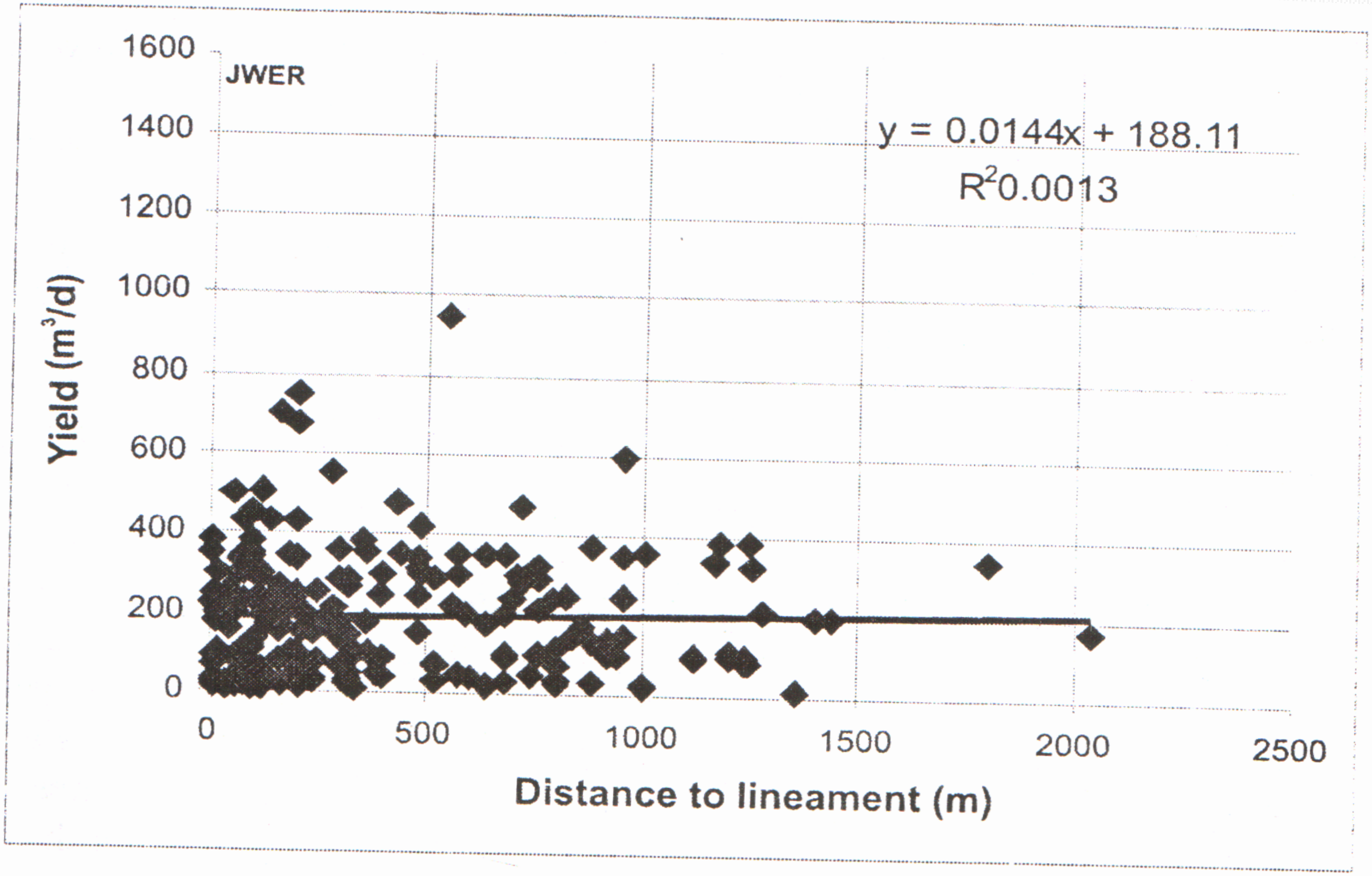


Figure 7. Example of the distribution of well yields as a function of the distance to lineaments (from Cho et al., 2003).

Dug well used for Irrigation

Photograph-6 Dumpsite of animal waste close to the well (Konaval galli.)

Mapping Regional Flow Systems

- **Hydrostratigraphy**
- **Hydrogeological Cross Sections**
- **Potentiometric Surfaces**
- **Water Table Maps**
- **Recharge & Discharge Areas**
- **Surface Water Interactions**

Definition

Hydrostratigraphy is the identification of mappable units on the basis of hydraulic properties aquifer/aquitard) that have considerable lateral extent and that also form a geologic framework for a reasonably distinct hydrogeologic system.

Hydrostratigraphy

Stratigraphic	Lithologic	Hydrostratigraphic
Surficial Deposits	Clay	Surficial Aquitard
Floral Fm	Sand	Floral Aquifer
	Till	Floral Aquitard
Empress Gp	Sand & Gravel	Empress Aquifer
Bearpaw Fm	Shale / Mudstone	Bedrock Aquitard

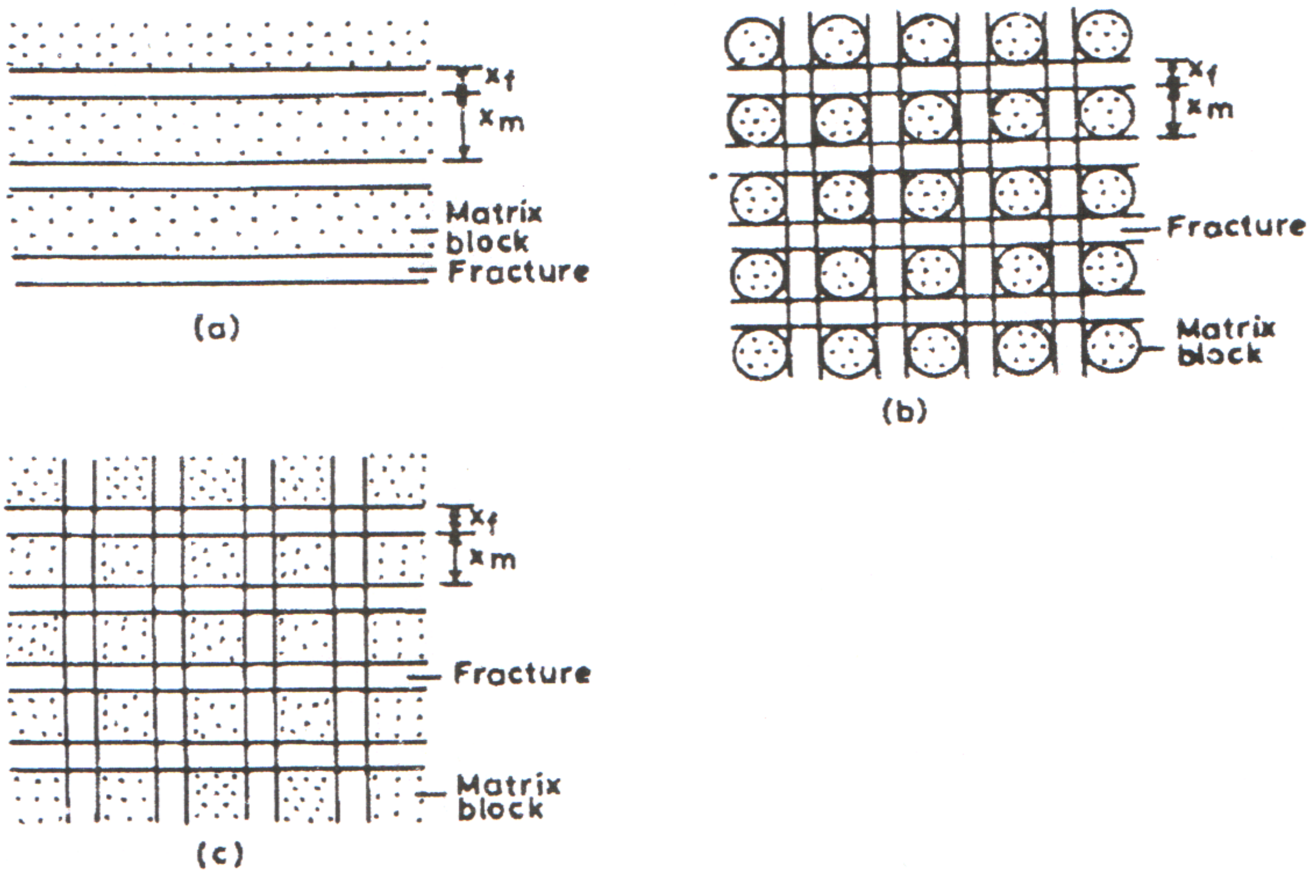


Figure 3. Types of double porosity aquifers: (a) Horizontal fractures and matrix blocks; (b) Spherical matrix blocks, and (c) Cubical matrix blocks.

GROUNDWATER MODEL

- A groundwater flow simulation model was prepared for the Bellary nala and Malaprabha sub-basin.

- Processing MODFLOW for windows (PMWIN) v8.04 was used.

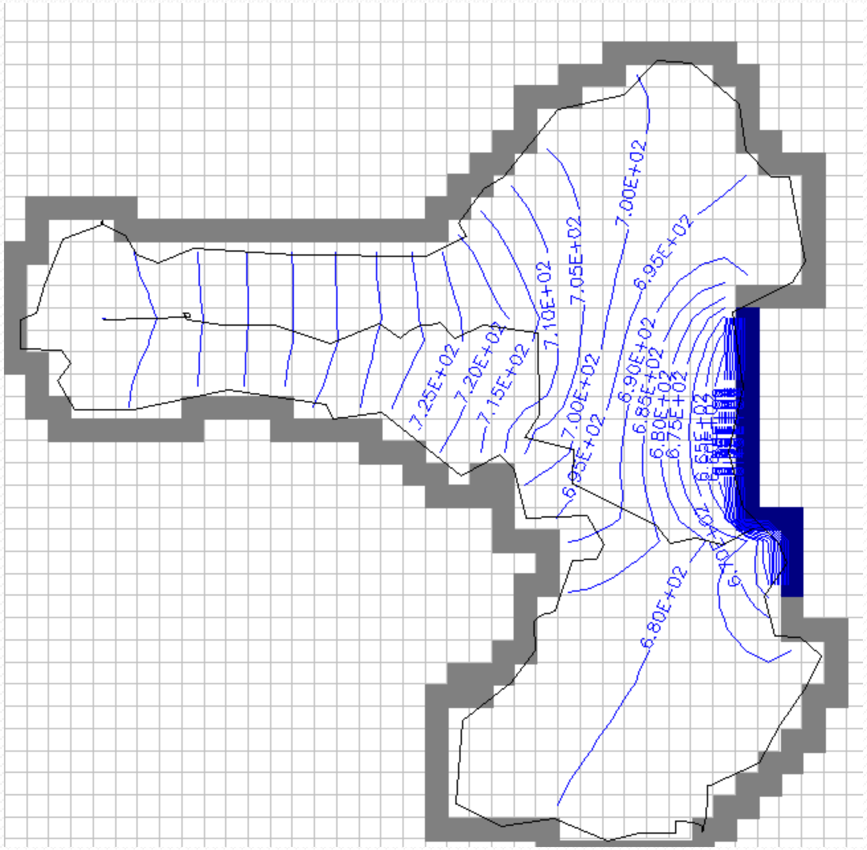
MODEL

- For the Malaprabha sub-basin, models were prepared for different heads above the riverbed; viz. 0.1m, 0.5m, 1.0m & 1.5m.

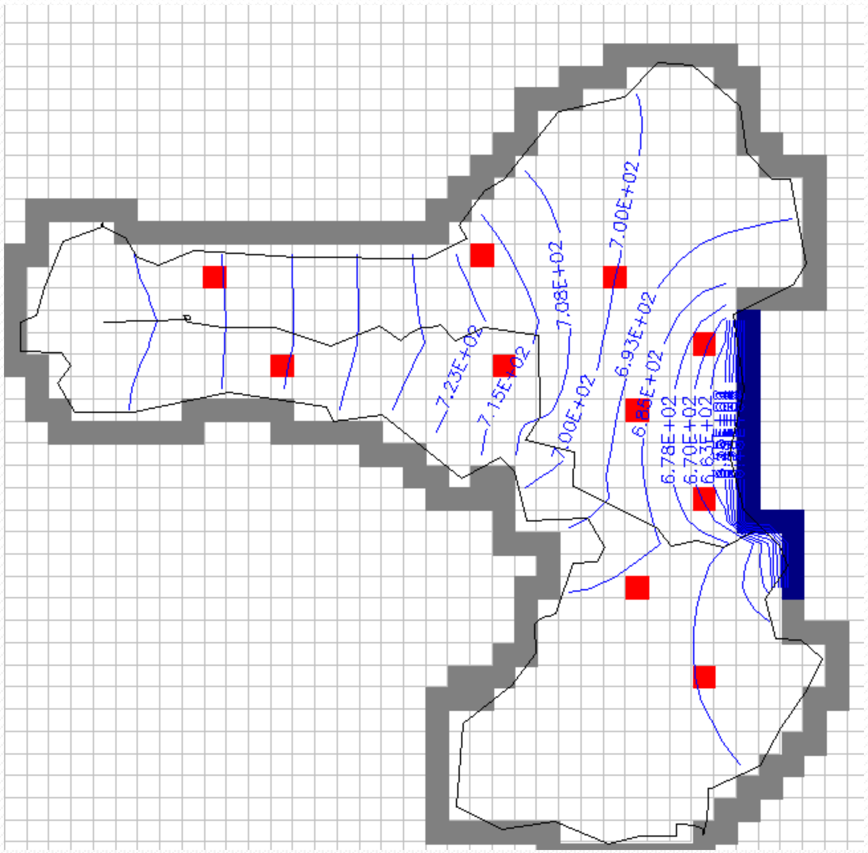
- For Bellary nala catchment, separate models were prepared for wet and dry season. Another model for prepared for the entire year.

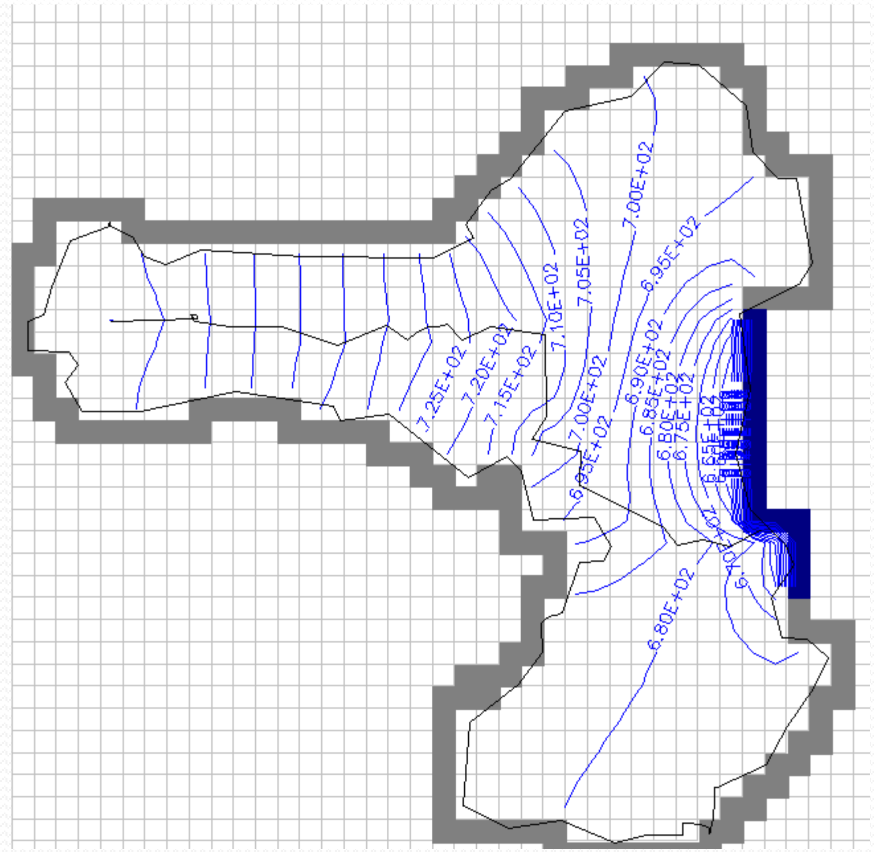
RESULTS

- The groundwater contours for Malaprabha sub-basin are shown in the figure.



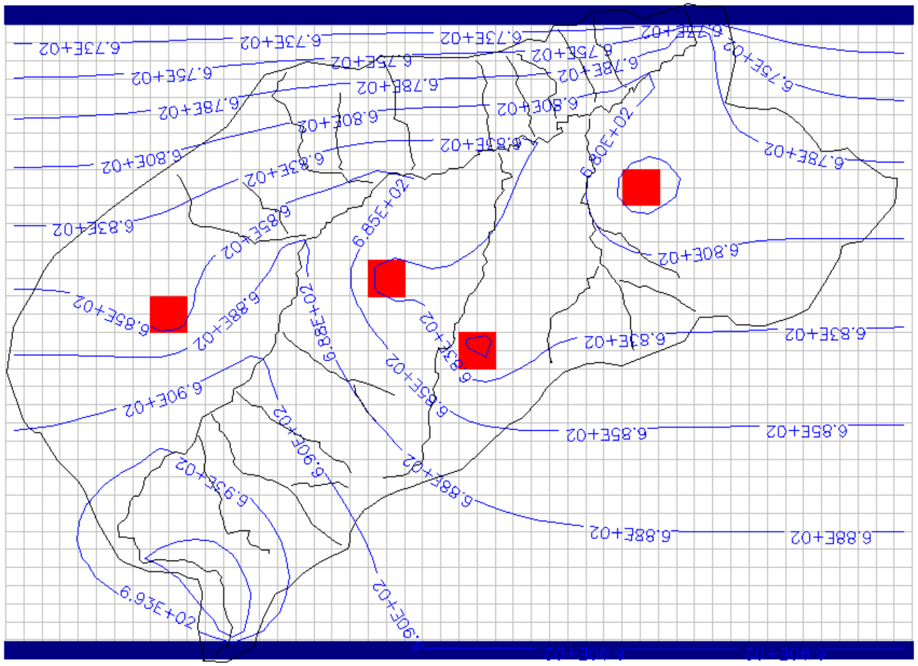
MALAPRABHA SUB-BASIN



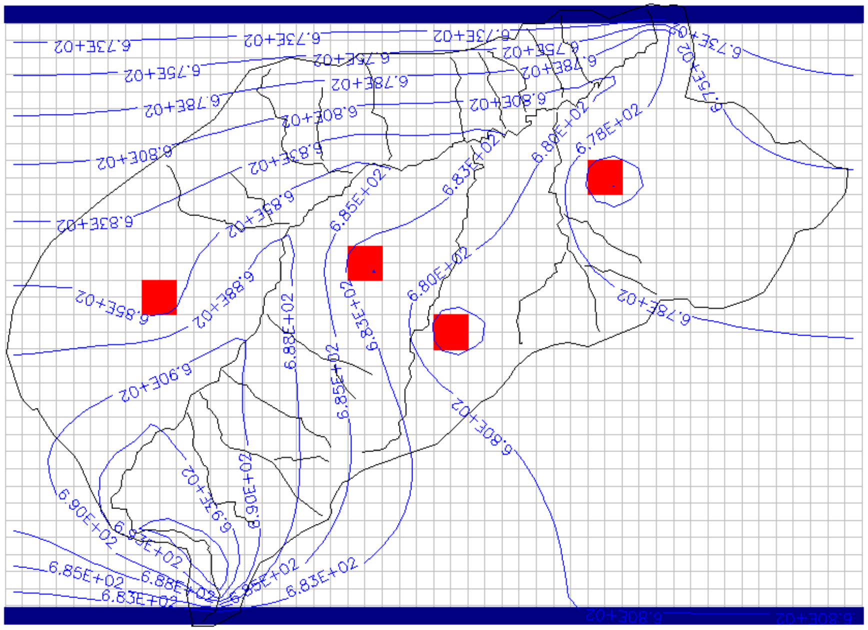


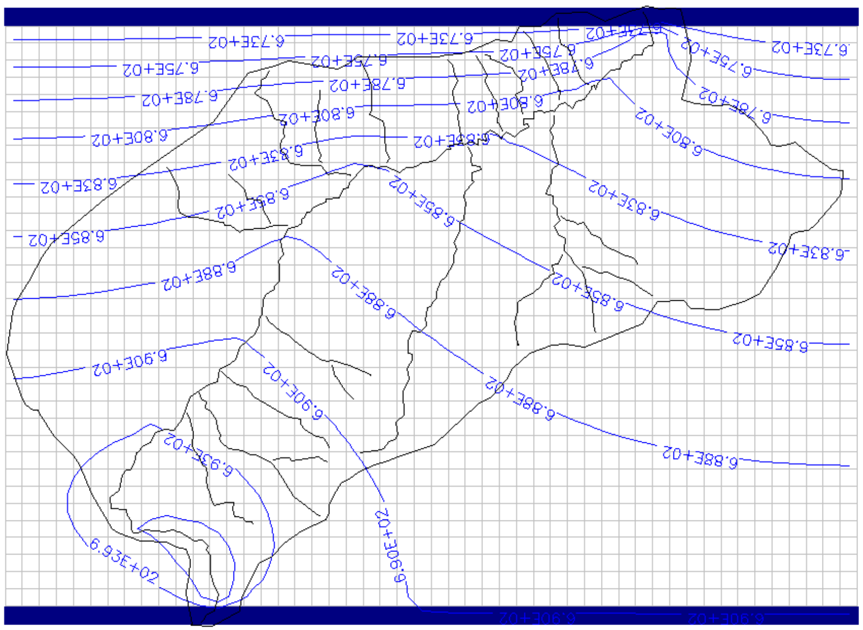
RESULTS

- The groundwater contours for the Bellary nala catchment are shown in the figure.



BELLARY NALA CATCHMENT





CONCLUSIONS

- It is found that in the **Malaprabha** sub-basin there is no significant influence of river recharge to the aquifers.
- In the entire above generated scenario, water level remained almost similar.
- However, a small shift in the flow pattern was observed.

CONCLUSIONS

- In the catchment of **Bellary nala,** the model demonstrated the interaction of surface water with ground water.

- There is a problem of mixing of waste water with groundwater in many parts of Belgaum city.