# GROUNDWATER IN IGNEOUS, METAMORPHIC, AND SEDIMENTARY ROCKS

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**Keywords:** porosity of natural rocks, scale dependence of hydraulic parameters, hydraulic continuity, rock types, rocks as water receptacles, storage properties, yield properties, water chemical quality

## Contents





## Summary

This article offers a bird's-eye view of the principal features of the storage, yield, flow, and chemical quality of groundwater in igneous, metamorphic, and sedimentary rocks. No detailed presentation of the topic can be given within the space available because the occurrence and flow of groundwater are not dictated solely by the host rock's type: rock structure, topography, climate, crustal stresses, and geological history may modify or even override its influence. The approach taken, therefore, has been to stress the link between the most important hydraulic rock properties—porosity and permeability—and the genetic aspects of individual rock types—such as origin, texture, and mineralogical composition—and provide the reader with a list of relevant major references covering the details.

By way of introduction, two fundamental issues are raised: porosity in natural rocks and regional hydraulic continuity. Criteria for porosity classification, various factors controlling porosity in natural rocks, and important agencies that produce and/or modify porosity are briefly reviewed. Regarding hydraulic continuity it is argued that, over

some scales of space and time, the rock framework allows flow and pressure propagation across any apparently impermeable rock unit.

Section 2 considers groundwater conditions in different rocks, largely as a function of their origins and petrologic properties. Igneous rocks are divided into intrusive (plutonic) and extrusive (volcanic) groups. Because of close similarities in their hydrogeologic characteristics, plutonic and metamorphic rocks are treated together. Sedimentary rocks are divided into unconsolidated sediments and lithified rocks. The first group is further divided into water-laid, aeolian, and ice-related sediments, and the second into clastic sedimentary and carbonate rocks.

The main conclusion to be derived from the review of groundwater conditions in different rock types is that successful hydrogeological evaluations and predictions call for a very thorough knowledge of the rock types, their genesis, and modifying geological factors, as well as the principles of subsurface hydraulics.

## 1. Rocks as Receptacles for Water

### 1.1. Porosity in Natural Rocks

The subsurface space occupied by groundwater consists of voids in the rocks. The volume of voids relative to that of the rocks is expressed by the porosity ratio n, which is defined in Theme 3.01 Biological Science Foundations. Voids in the rocks can be generated and modified by a great variety of geological processes and can be very different in age, shape, and size. Hydraulic communication between them can be good, poor, or non-existent. An awareness of the different processes and factors creating, modifying, and controlling porosity, and their relation to various different rock types, is needed when evaluating hydrogeologic conditions in any given area.

#### 1.1.1. Classification of Porosity

Four important criteria commonly used to classify porosity in natural rocks are:

- relative age
- pore size
- degree of hydraulic communication
- pore-forming features

*Relative age* expresses the time at which the pores were created with respect to the age of the rock. Thus, *original* or *primary porosity* was created simultaneously with, and by the same processes as, the rocks themselves. Examples of this are the open spaces between grains of clastic rocks remaining since the time of deposition, the space between the crystals of plutonic igneous rocks, or the vugs and tunnels in lava flows. *Secondary* or *induced porosity* develops later, due (for instance) to fracturing, solution recrystallization, or the impact of life processes: in other words, after the rocks has formed.

Classification according to *pore size* is based partly on the types of forces able to induce

flows of water through the network of pores. *Crystal lattice porosity* is the space between crystals, and between the layers of clay minerals and micas. *Colloidal porosity* is space between colloid particles of clays. Due to swelling, it may exceed 100% (in other words, the pore volume of the swollen sample may be greater than its original bulk volume). In *microporosity* or *subcapillary porosity* the pore size is less than 0.1 μm. Water is held by adhesion and may be removed by evaporation, but not by gravity. The pore radii of *capillary porosity* are between 0.1 μm and 2.5 mm. In a vertical open tube, water is held by capillary suction above the level to which it would rise under hydrostatic pressure, but part of the water can be drained by gravity: the flow of the water is normally laminar. *Macroporosity* or *supercapillary porosity* embraces pores and/or fractures with diameters in excess of 2.5 mm. Water is not held significantly above hydrostatic level, and eddies and cross-currents—signifying turbulent flow—are common.
Classification according to *hydraulic communication* between the pores recognizes two end-points. In *open* or *effective porosity* the pores are in hydraulic communication, whereas the pores in *closed porosity* materials are isolated. Unfractured pumice is an example of the latter state.

Void spaces of significantly different sizes and characteristics give rise to a number of different *pore-forming features.* The names of these porosity types are mostly self-explanatory, as they give an explicit description of the nature of the feature. Thus, *intercrystalline porosity* consists of void spaces between the basic building blocks of rocks such as crystalline limestones, or igneous and metamorphic rocks created by diagenesis, cooling, or metamorphism. *Intergranular porosity* occurs in clastic rocks such as sandstone, shale, clay, loess, and pyroclasts, and is created during deposition in water or air. *Vuggy porosity* refers to small cavities in a vein or rock created by solution, as in limestones and dolomites, or by the presence of gas bubbles in extrusive igneous rocks, as in pumice and basalt. *Fracture porosity* is void space in faults, cleavages, fractures, and joints that may be caused by tectonic stresses, sediment compaction, dehydration, or diagenesis: it can occur in any type of rock. *Solution porosity* is due to leaching and removal of solid material by formation fluids, primarily water, and can include voids ranging from pinpoint size vugs to karst channels and caves. *Oolitic porosity* refers to the pore space between, or left behind after dissolution by, the small (0.5–1.5 mm) oval-shaped accretions of (mainly) calcite, and occasionally silica, that grow around the nuclei of foreign matter in seawater. Oolites may form massive beds, chiefly of limestone, which can form excellent aquifers or hydrocarbon reservoirs.

### 1.1.2. Factors Controlling Porosity in Natural Rocks

Porosity is a sensitive function of several factors related to the rock and its geological history. The *shape of the rock's constituent particles* affects their arrangement, or packing. Irregular, angular grains result in bridging, and thus looser packing and higher porosity, than more spherical grains. *Sorting* is a measure of grain-size uniformity. Porosity is generally higher in rocks of uniform (i.e. well-sorted) grains than in rocks of poorly-sorted grains. In the latter group, the pore space between the larger grains or rock fragments may be occupied by smaller material, thus reducing the porosity that would exist in the case of better sorting. *Cementation and compaction* after deposition lead to a reduction of the original porosity. Cement material takes up part or all of the pore space (as in sandstones, for example), while compaction deforms the pore space (as in clays). *Solution* generally enlarges pore space by dissolving and removing mineral matter, primarily from evaporites such as limestone, gypsum, and halite, and often results in karst formation. *Fracturing* is one of the most important controls on porosity, both because it can affect any type of rock and because of the high values it can cause. Typical forms of fracture porosity are fault planes, fracture zones, joints, cleating in coal, mylonitic zones, and so on. The *depositional environment* may affect porosity, since sub-aerially deposited rocks such as loess are generally more porous than subaqeous sediments.

### 1.1.3. Agencies Producing and/or Modifying Porosity in Natural Rocks

The above survey of physical features affecting porosity was made from a factual, or static, viewpoint: porosity was considered as a function of the rock's actually existing state. In what follows, emphasis is shifted to the processes—as dynamic agencies—that can cause the porosity of natural rocks, and modify it over time. Eleven such natural processes are identified, as follows.

1. *Processes of sedimentation.* Sedimentation can occur in water and in the atmosphere. Clastic sediments deposited subaqeously tend to have relatively low porosity, due to high agitation during formation and the resulting poor sorting of the grains. Wind-borne sediments however, such as loess or dune sands, are well sorted and consequently more porous. Pore space in carbonates deposited in water occurs between and within fossil shells, carbonate crystals, oolites, and along bedding plains, whereas in reefal carbonates it is primarily space between coral tabulae.

2. *Expansion of gases.* Gases included in lava and mud flows can expand and form cavities varying in size from pinpoint bubbles to tens of millimeters. The voids may be connected to form effective porosity, or may be isolated as in pumice.

3. *Crystallization of igneous rocks.* This produces intercrystalline interstices as seen, for instance, in the weathering processes exhibited by these rocks, indicating the possibility of water penetrating the space between the crystals.

4. *Mechanical disruption.* From a hydrogeological viewpoint this is perhaps the most important agency creating and modifying porosity: any brittle rock, regardless of its density and strength, may become porous and permeable as a result of fracturing, fissuring, and shattering. Natural processes capable of causing mechanical disruptions include:

- tectonism (diastrophism), which may result in faults, fracture zones, shear zones, and folding (producing joints, slickensides, and cleavage);
- landslides and slumping;
- fracturing by processes of flow (as in lavas, earth flows, and mud flows);
- decompaction upon erosional removal of overburden (producing joints, fractures, fissures, and the opening of incipient weaknesses, all of which are particularly common features in material beneath geological unconformities);
- reduction in bulk volume of shales by diagenetic mineral changes coupled with a

loss of water (as in montmorillonite–illite diagenesis); and
- reduction of bulk volume by drying and cooling (as in desiccation polygons and columnar basalts).

5. *Chemical action, solution.* Acids (chiefly carbonic and organic) may dissolve and/or deposit minerals in previously existing pores, thus either increasing or reducing porosity.

6. *Recrystallization, dolomitization, and diagenesis.* Representative examples are the volume shrinkage of ca. 12–13% resulting from the replacement of Ca in $CaCO_3$ by Mg to form $CaMg(CO_3)_2$ in seawater, or the porosity increase in montmorillonite when its Na base is exchanged for the pore-water's Ca.

7. *Cementation.* This may result in 30–40% reduction in porosity and is most important in sandstones and carbonates. The most common cemen materials are silica, carbonate, and clay, as well as heavy hydrocarbons (such as bitumen) in oil sands and oil shales.

8. *Sediment compaction.* This is an effective porosity-reducing process, mainly affecting shales in subsiding deep sedimentary basins. In general, the rate of porosity reduction decreases logarithmically with depth; due to brittleness in the compacted shale, however, development of fracture porosity may reverse the trend below depths of 2–3 km. Clean sands and sandstones are less susceptible to compaction than argillaceous sediments.

9. *Metamorphism.* This process also tends to reduce porosity, due to the high pressures and temperatures associated with it. However, metamorphic rocks such as slate, phyllite, and gneiss may develop mechanical disruptions, providing them with latent porosity which can develop in the event of erosional unloading, weathering, solution, and other processes.

10. *Weathering.* Weathering generally increases porosity in igneous and metamorphic rocks, but reduces it in argillaceous clastics. The process is due to various chemical, biochemical, and physical agents, and high porosity is common at unconformities as a result.

11. *Vital processes.* Biological actions create and increase porosity at shallow depths, and particularly in the soil zone. The most effective processes are penetration by tree roots (leaving vertical openings which are often lined with calcite or other minerals), animal and insect burrowing, and biochemical effects.

### 1.2. The Rock Framework as Regional Flow Medium: Hydraulic Continuity

A fundamental hydrogeologic property of the rock framework is *hydraulic continuity*. A subsurface rock body is considered hydraulically continuous on a given timescale if a change in pore pressure at any point can cause a change in pressure at any other point within an interval of that timescale. Owing to its hydraulic continuity, the rock framework functions as a regional flow medium: groundwater flow can be induced across strata of low permeability, theoretically over infinite distances. However, because the rock is heterogeneous with respect to porosity and permeability, its effective porosity and permeability depend on the position, size, and extent of the flow domain involved (in addition, of course, to the individual porosities and permeabilities of the domain's different constituent rock bodies). It is necessary, therefore, to use values for rock hydraulic properties that characterize the entire domain involved with a given flow problem. A conceptual analysis of the problem of regionalization, or *upscaling*, of porosity is briefly reviewed below.

In defining porosity n (Theme 3.01 Biological Science Foundations) the tacit assumption was made that the rock is homogeneous: in other words, that "n" remains constant in one location and is independent of the size of the sampled *control volume* $V_T$. In reality, porosity and other physical properties—such as density, permeability, and strength—vary, and are not uniformly distributed in space. The definition of these properties must therefore be refined to make it applicable to problems of variable domain sizes.

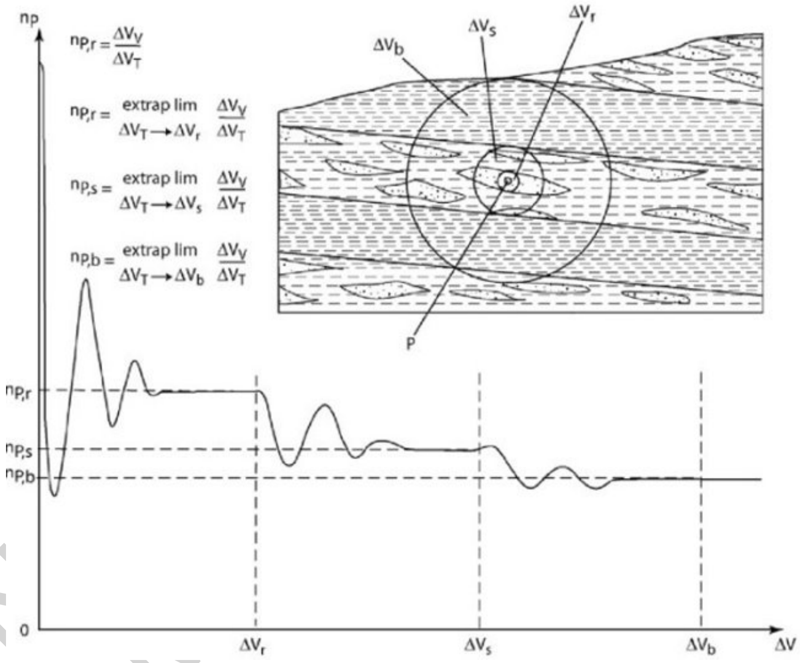


Figure 1. Schematic illustration of calculated rock porosity as a function of the control volume $\Delta V_T$ (after Tóth, 1967, Figure 5)

Consider a point inside a pore between the grains of a sand lens in a lenticular and stratified rock framework of a sedimentary basin (Figure 1). According to the definition

$$n_{P,r} = \frac{\Delta V_v}{\Delta V_T} \tag{1}$$

where $n_{P,r}$ is the porosity of the rock r at point P, $\Delta V_T$ is the total rock volume considered, and $\Delta V_v$ is the pore volume within the rock volume $\Delta V_T$. Porosity in the pore is n = 1 as long as the sampled control volume $\Delta V_T$ also remains within the pore's boundaries. If, however, $\Delta V_T$ is expanded to include a gradually increasing number of the surrounding sand grains and intergranular voids, the curve of the successively calculated values of the function $n_P(\Delta V_T)$ will oscillate, with dampening amplitude. When a sufficient number of grains and pores within the sand lens are included, the ratio of pore volumes to the control volume ceases to change. The porosity of the sand lens is then obtained by extrapolating the constant value of the curve's stable portion back to the n-axis. The porosity equation for the *rock* can then be defined as

$$n_{P,r} = \frac{\text{extrap lim}}{\Delta V_T \rightarrow \Delta V_r} \frac{\Delta V_v}{\Delta V_T} \tag{2}$$

This definition may be extended to include the geologic stratum that contains pockets of different porosities:

$$n_{P,s} = \frac{\text{extrap lim}}{\Delta V_T \rightarrow \Delta V_s} \frac{\Delta V_v}{\Delta V_T} \tag{3}$$

or even further to encompass the drainage basin, where the individual strata are the "microscopic" units:

$$n_{P,b} = \frac{\text{extrap lim}}{\Delta V_T \rightarrow \Delta V_b} \frac{\Delta V_v}{\Delta V_T} \tag{4}$$

Thus, on a local scale (for example, from borehole logs) the rock framework may appear heterogeneous, displaying (for instance) confining layers of low permeability.

On a regional scale, however, large parts of entire drainage basins may behave as homogeneous units, with their groundwater regimes exhibiting unconfined characteristics. The possible average water-flow rates through the domains of differing effective porosity (or permeability) will also be different.

The ultimate value will be controlled by the effective properties of the entire basin. An example of the effect of control-volume size on regional flow rates, and thus on potentially sustainable production rates, is shown by the variation of transmissivity values derived from pumping tests of different duration, combined with a groundwater balance determined from observed seasonal changes of groundwater in regional recharge and discharge areas (Figure 2).

The gradual decrease in transmissivity values is attributed to the increasing ratios of shale to sandstone in the Upper Cretaceous clastic sediments of Central Alberta, Canada, as the affected flow domain expands with increasing length of production.

A plausible limiting value for transmissivity is obtained from natural water-level fluctuations that reflect the rate of regional flow traversing the basin, thus sampling its entire rock framework.

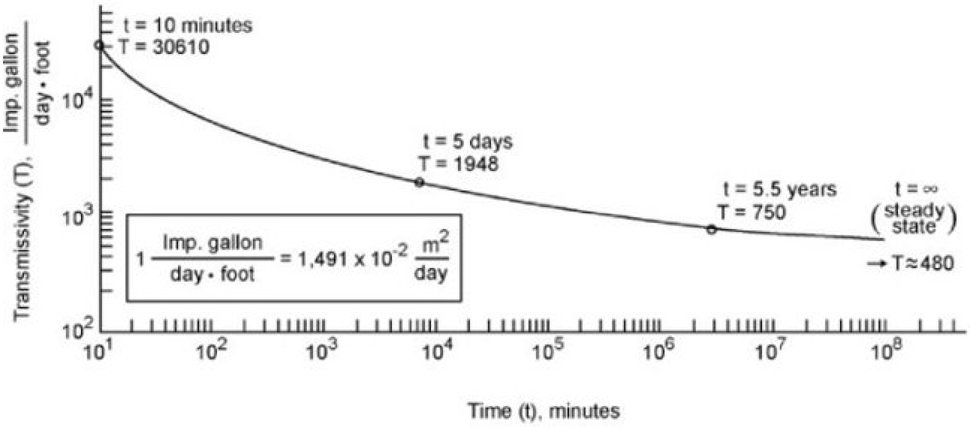


Figure 2. Transmissivities derived from pumping tests of increasing duration, and converging toward values obtained from basin-wide seasonal water-level fluctuations in a shale/sandstone rock framework (after Tóth, 1995, Figure 4)

A trend of scale-dependent hydraulic conductivities, in complete contrast to that described above, is shown in Figure 3. In this case, empirically determined hydraulic conductivity values increase with increasing control-volume sizes, ranging from laboratory hand specimens, through rock volumes sampled by conventional (i.e. relatively short-term) pumping tests, to entire basins controlling the discharge of major springs. The explanation offered for the trend is that the physical nature of permeability changes from the pores and microfractures of the laboratory samples, through their effects combined with those of fracture zones and faults in pumping tests, to the wide open channels of the basin's karst systems.

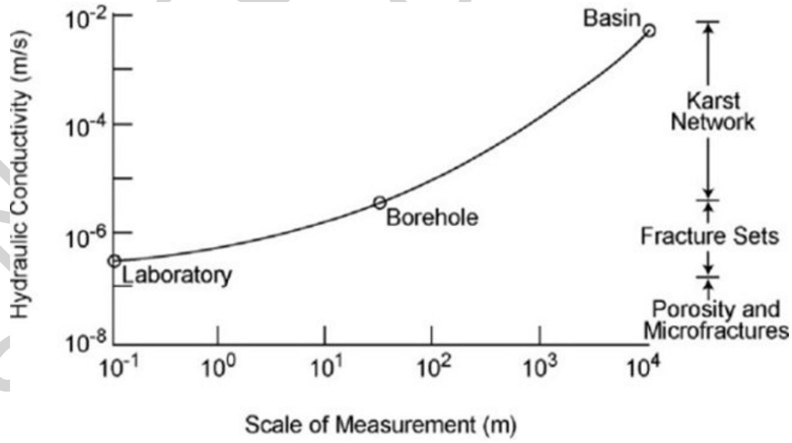


Figure 3. Schematic representation of the effects of scale on typical hydraulic conductivities of carbonate rocks (after Király, 1975, Figure 19)

Regional hydraulic continuity of the rock framework may remain unrecognized because the time over which an observable pore-pressure change (induced, for example, by pumping, seasonal changes in the water table, erosional lowering of the land surface, sediment compaction, or other factors) unfolds is longer than the duration of observation. One study considered the time interval involved in seeing the effect of a fall in the water table to be transmitted vertically down across a permeability-stratified rock framework to a point at a depth of approximately 1500 m, for varying permeability combinations. Hydraulic conductivities of two major aquitards (Hydrogeologic Units 2 and 4) were varied by five and three orders of magnitudes, respectively ($K_2$: $10^{-9}$–$10^{-14}$; $K_4$: $10^{-9}$–$10^{-11}$ m s$^{-1}$), and the time between the pressure change's first appearance and total adjustment was measured. The results showed the times required for a 50% hydraulic head adjustment at the basal point P to vary from approximately $1.5\times10^3$ to $3\times10^7$ years. Adjustment of the flow field to a transient field of fluid potential delays the appearance of various natural effects and processes associated with basinal groundwater flow patterns even further.

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**Biographical Sketch**

**József Tóth**, Professor Emeritus at the University of Alberta, studied exploration geophysics at the School of Mining and Geodesy of Sopron in his native Hungary. He fled that country from the invading troops of the Soviet Union in 1956, resumed his studies, and obtained a Ph.D. in hydrogeology in 1965 at the State University of Utrecht, the Netherlands. He moved to Canada in 1960 and worked at the Alberta Research Council for 20 years, the last 12 of them as Head of the Groundwater Department. He formulated, directed, and administered the scientific and technical activities of the Department, including a 10-year-long hydrogeological mapping program covering the entire Province of Alberta (660 000 km$^2$). He became the Council's first Research Fellow in 1980. That year he joined the Department of Geology (Department of Earth and Atmospheric Sciences since 1995), University of Alberta. He worked and lectured in over 15 different countries, and was the Hydrogeologist Member on the Technical Advisory Committee of Canada's Nuclear Fuel Waste Management Program for 11 years.

Tóth's research interests center on the theoretical and applied aspects, and natural manifestations, of regional groundwater flow, as reflected by over 80 publications that he has authored or co-authored. He was the first recipient of the O.E. Meinzer Award of the Geological Society of America for "Distinguished Contribution to Hydrogeology" in 1965; 34 years later he received the International Association of Hydrogeologists' "President's Award 1999," which is "presented annually to a senior hydrogeologist who has made outstanding contributions to the advancement of hydrogeology," and was the recipient of the "Prix Robert R.N. Farvolden Award" of the Hydrogeology Division of the Canadian Geotechnical Society in 2002, presented annually "…for outstanding contributions to the disciplines of earth science and engineering that emphasize the role or importance of groundwater." Several of his concepts and ideas concerning basinal groundwater flow are applied to problems involving water resources, soil salinization, slope stability, strata-bound ore genesis, lakes and wetlands, radioactive waste disposal, and petroleum migration and exploration. His current research is focused on groundwater flow and its effects in the Pannonian Basin, Hungary.