HYDRAULIC CONTINUITY IN LARGE SEDIMENTARY BASINS[1]

by

József Tóth

Department of Earth and Atmospheric Sciences, University of Alberta
Edmonton, Alberta, Canada T6G 2E3

ABSTRACT: Regional hydraulic continuity is a phenomenological property of the rock framework. This property is quantified as the ratio of an induced change in pore pressure at a point of observation to an inducing change at a point of origin. A subsurface rock body is considered to be hydraulically continuous on a given time scale if a change in pressure at any of its points can cause a change at any other point, within a time interval measurable on the specified time scale. The hydraulically continuous behaviour of the rock framework may be masked in large sedimentary basins by large distances, relatively short periods of observations, and sharp contrasts in flow-sensitive properties of subsurface fluids, such as temperature and chemical composition. Due probably mainly to these masking effects, the concept of "hermetically" sealed hydraulic compartments in the subsurface is still used as a working hypothesis by some earth scientists, particularly in petroleum geology.

That the rock framework is hydraulically continuous has been established independently from both local aquifer studies and regional evaluations of water resources. The principal natural consequences are extensive groundwater flow systems, systematic areal distribution of matter and heat, and hydraulic interdependence of different basinal areas. The recognition of regional hydraulic continuity is, therefore, indispensable for the correct interpretation of numerous natural processes and phenomena, and for the correct modelling and prediction of the effects of stresses imposed on the groundwater regime by nature and man.

RÉSUMÉ: La continuité hydraulique régionale est une propriété phénoménologique des roches magasins. Cette propriété est quantifiée par le rapport entre un changement provoqué dans la pression porale au point d'observation et celui produit au point d'origine. Un ensemble rocheux souterrain est considéré comme étant hydrauliquement continu à une échelle de temps donnée si une variation de pression en l'un de ses points peut provoquer une variation de pression en n'importe quel autre point, dans un intervalle de temps mesurable à l'échelle de temps définie. Le comportement hydrauliquement continu de la roche magasin peut être masqué dans les grands bassins sédimentaires par les grandes distances, par les durées d'observation relativement courtes et par de forts contrastes dans les propriétés des fluides souterrains relatives à l'écoulement, telles que la température et la composition chimique. A cause probablement surtout de ces effets de masque, le concept de compartiments hydrauliques souterrains isolés " hermétiquement " a encore cours comme hypothèse de travail en géosciences, en particulier en géologie pétrolière.

Le fait que la roche magasin soit hydrauliquement continue a été établi de manière indépendante à la fois par des études d'aquifères locaux et par des évaluations régionales de ressources en eau. Les conséquences naturelles principales sont l'existence de systèmes d'écoulements souterrains de grande extension, la répartition systématique de la matière et de la chaleur et l'interdépendance des différents bassins. La mise en évidence de la continuité hydraulique régionale est cependant indispensable à une interprétation correcte des nombreux processus et phénomènes naturels et à une modélisation et à une prédiction convenables des effets des contraintes imposées sur le régime des eaux souterraines par la nature et par l'homme.

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RESUMEN: La continuidad hidráulica regional es una propiedad fenomenológica de los cuerpos rocosos. Esta propiedad se cuantifica como la relación entre el cambio inducido en la presión intersticial en un punto de observación respecto al producido en el punto de origen. Un cuerpo rocoso se considera continuo hidráulicamente a una cierta escala de tiempo, si un cambio de presión en cualquiera de sus puntos puede producir un cambio en cualquier otro punto, en un intervalo de tiempo medible a una escala de tiempo específica. El comportamiento hidráulico continuo de la roca en grandes cuencas sedimentarias puede estar enmascarado por largas distancias, periodos de observación relativamente cortos y por contrastes bruscos en las propiedades de los fluidos que son sensibles al propio flujo, como son temperatura y composición química. Debido probablemente a estos efectos de enmascaramiento, el concepto de compartimentos hidráulicamente "sellados" en el subsuelo se sigue usando como una hipótesis de trabajo, particularmente en geología petrolífera.

El hecho que un cuerpo rocoso sea continuo hidráulicamente se ha establecido independientemente a partir tanto de estudios en acuíferos locales, como de evaluaciones regionales de recursos hidráulicos. Las consecuencias naturales principales son sistemas de flujo de aguas subterráneas extensivos, distribución sistemática de materia y calor e interdependencia hidráulica de las distintas áreas de cuenca. El reconocimiento de la continuidad hidráulica regional es, por tanto, indispensable para la correcta interpretación de numerosos procesos y fenómenos naturales, así como para la correcta modelación y predicción de los efectos de las tensiones impuestas al régimen de flujo por la naturaleza y el hombre.

INTRODUCTION

A topic that is relevant to most of the diverse practical and scientific problems related to groundwater in large sedimentary basins is the question of regional hydraulic continuity of the rock framework. Because of hydraulic continuity: 1) large-scale groundwater flow systems and regionally-extensive patterns of hydrogeologic phenomena develop; 2) the effects of naturally and artificially imposed stresses on the groundwater body occur at great distances and depths; 3) the rate of sustainable water production depends ultimately on some weighted average permeability of all the rocks included in a basin-wide "Representative Elementary Volume," or even on the climate, rather than on the pumped aquifer's transmissivity, T, and storage coefficient, S; or 4) industrial, agricultural, and municipal contaminants may appear at unexpected distances or in unexpected strata. Indeed, one might even argue that the primary, although not necessarily obvious, justification for considering large sedimentary basins as natural units of hydrogeological analysis, and as a subject of discussion, is the fact that their different and often distant regions and depths are linked through a continuous network of voids.

This fact, however, is not generally recognized or accepted. In a recent paper, for example, one of today's most eminent petroleum geologists, John M. Hunt (Hunt, 1990) explains petroleum migration and entrapment and several associated pressure, temperature, and mineralogical conditions by invoking hermetically sealed three-dimensional rock compartments. While Hunt's ideas have gained some acceptance, the same processes and phenomena are easily understood on the basis of a hydraulically-continuous rock framework.

It would seem, therefore, that a discussion of the topic is not only appropriate and justified, but may be even needed. In this paper, the concept and the arguments are presented in favour of regional hydraulic continuity, as well as its natural consequences and effects, all in the context of groundwater in large sedimentary basins.

THE CONCEPT OF REGIONAL HYDRAULIC CONTINUITY

Description

Hydraulic continuity is a phenomenological property of the rock framework. This property is characterized quantitatively as the ratio of an induced change in hydraulic head (or pore pressure) to an inducing change of head (pressure). Because pore-pressure changes propagate through the rocks at finite velocities, hydraulic continuity is a relative property that depends on the distance between the points of origin and observation of pressure disturbance as well as on the hydraulic diffusivity (hydraulic conductivity/specific storage) of the rock-fluid system. Consequently, continuity is a function of the scales of both space and time. The concept of hydraulic continuity is particularly useful in characterizing the hydraulic behaviour of heterogeneous rock masses on specified spatial and temporal scales, in general, and on the regional and geological segments of the space- and time-scale spectra, in particular. Thus, a subsurface rock body is considered hydraulically continuous on a given time scale if a change in hydraulic head at any of its points causes a head change at any other point, within a time interval that is measurable on the specified time scale. Regional hydraulic continuity is not a self-evident or easily verifiable property of the rock framework. Large contrasts in permeabilities of contiguous rock bodies may make the less permeable ones appear impervious from conventional types of observations. Pore-pressure responses at various points in the flow region to a pressure change elsewhere may take longer than the time span of observation, thus rendering the rock body, or parts of it, to appear impermeable. Or, where major contrasts in water chemistry, temperature, or other flow-sensitive fluid properties coincide with low-permeability rock boundaries, an impression of hydraulic discontinuity is created or reinforced. It is, therefore, not entirely surprising that the century-long debate about hydraulic continuity, i.e., about the existence of absolutely isolated portions of the rock framework, has not yet been settled. The evolution of the concept and the principal arguments in support of hydraulic continuity are best reviewed by means of a brief historical retrospective.

Evolution

Current understanding of hydraulic continuity has developed independently from two very different, indeed opposite, types of groundwater investigations, namely: aquifer and well hydraulics (local pumping tests), and basin hydraulics (regional water resources).

Hydraulic Continuity Derived from Aquifer Hydraulics

Chamberlain (1885), in his discussion of the "The Requisite and Qualifying Conditions of Artesian Wells," noted that "No stratum is entirely impervious." Nevertheless, all early calculations of flow to wells assumed either a free water table or ideally confined conditions (e.g., Thiem, 1906; Theis, 1935). Hydraulic communication across confining strata was not formally taken into account until Hantush and Jacob (1955) included a "leakage factor" in Theis' nonequilibrium equation: the "ideally confined aquifer" was replaced by the "multiple aquifer." This concept was extended and refined by Neuman and Witherspoon (1971), whose calculations clearly illustrate the time-dependent nature of the hydraulic behaviour of multi-aquifer systems. In figure 1 (Neuman and Witherspoon, 1971, fig. IV-18), the drawdown for "small values of time" in the pumped aquifer of a two-aquifer system is very similar to that in an ideally confined stratum. With time, however, the departure from ideally confined behaviour increases, and at "large values of time" all water is derived through the confining layer from the unpumped aquifer. If pumping were to stop early, the aquifer would be perceived as ideally confined; if only late drawdowns were considered, the aquifer would appear unconfined. These theoretical conclusions were empirically corroborated by a field test (Neuman and Witherspoon, 1972), in which a time lag of approximately 30 days was observed across a shale bed 16 ft in thickness. Consequently, whether System "a" or "b" (fig. 2) will be deemed to be hydraulically continuous depends primarily on the relative lengths of pumping and observation.

Hydraulic Continuity Derived from Basin Hydraulics

In what might be the earliest attempt at explaining petroleum accumulation by cross-formational water flow, Munn (1909) called "imperviousness of strata" a "time-honored delusion." From the 1950's on, regional studies have led increasingly to the conclusion that a quantitative interpretation of long pumping tests, regional pressure patterns, basinal water balances, and large-scale flow models is possible only if regional and cross-formational hydraulic communication is assumed. Walton (1960) observed, for instance, that in the southern Illinois Basin the entire sequence of strata behaves hydraulically as "one aquifer." Kolesov (1965) stated explicitly that thousands of observed pressures in Siberia, Russia, and the Dnieper-Donets basin are easily explained if the "strata are considered one single complex entity hydraulically connected . . ." A group of French hydrogeologists (Albinet and Cottez, 1969; Astié et al., 1969; Margat, 1969) interpreted vertical hydraulic-head differences in various large sedimentary basins (e.g., Paris, W. Africa, Sahara, and Aquitain) as indicating flow between confined aquifers through the intervening aquitards. They argued that if "leakage" can be produced artificially by pumping, it must occur also under natural head differences. By means of a quantitative water-balance model of the Aquitain Basin,

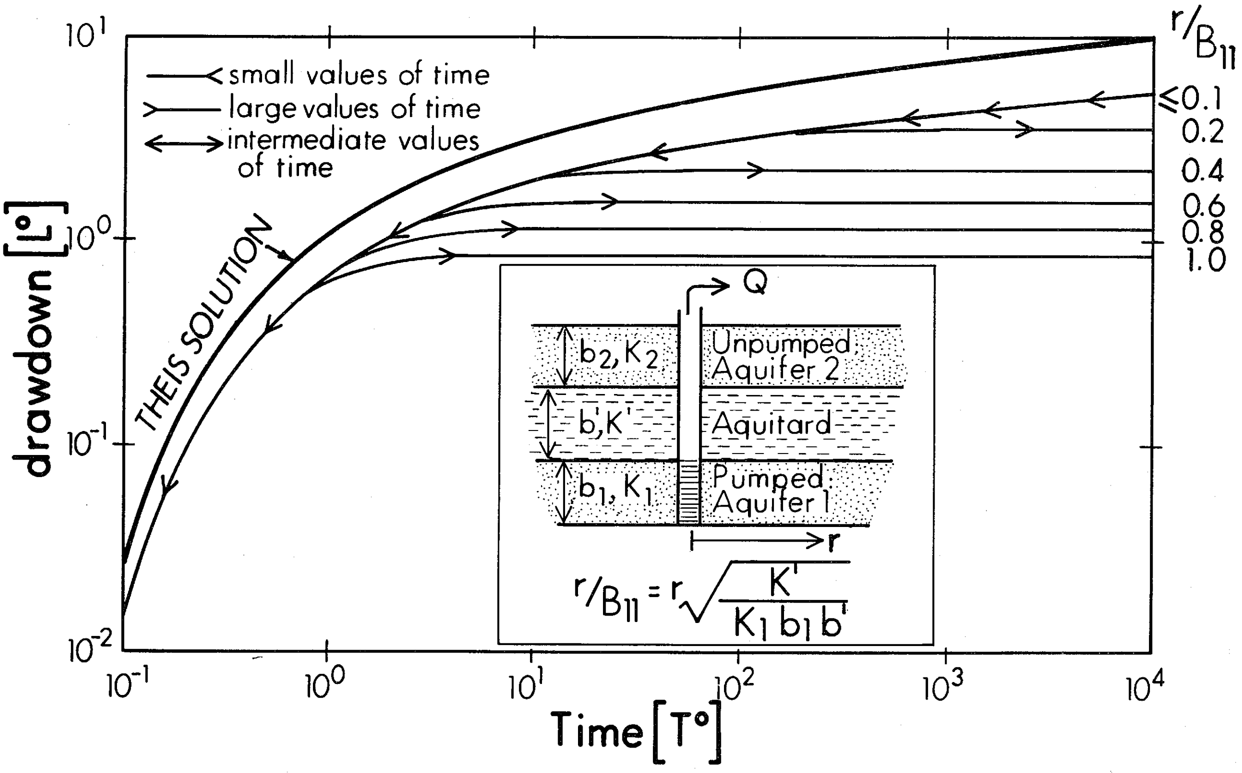

Figure 1. Example of relative hydraulic behavior of confined aquifer as function of time (simplified from Neuman and Witherspoon, 1971, figure IV-18).

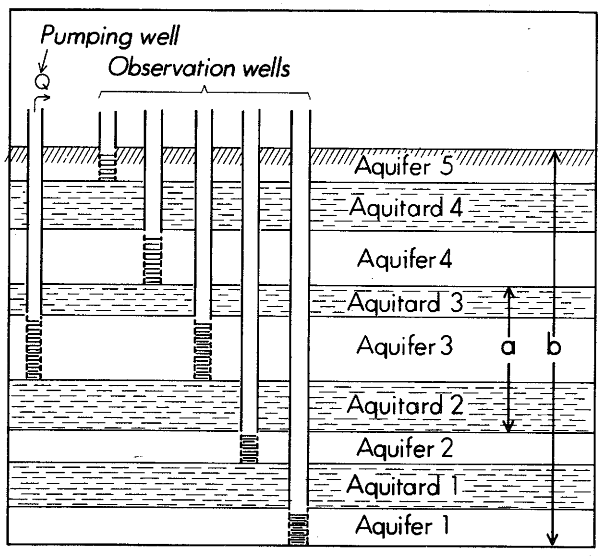

Figure 2. Hydraulic continuity of multiple-aquifer systems "a" and "b", as inferred from short and long pumping tests, respectively.

France, covering an area of over 100,000 km^2, Besbes et al. (1976) verified the hydraulics of "eight main aquifers, which communicate through aquitards. . ." (fig. 3). More recently, Neuzil et al. (1984) showed by numerical simulation that the actual amount and rate of water withdrawal from the Dakota aquifer would be impossible without leakage through the overlying Pierre Shale. The vertical permeability of the shales, however, must be 10 to 1,000 times larger on the regional scale than on the local scale.

Convergence of Transmissivities Derived from Pumping Tests to a Regional Field Value, Cretaceous, Alberta

Transmissivities derived from pumping tests of increasing durations (Tóth, 1966, 1973) approached a value obtained from the annual pattern of regional water-level fluctuations (Tóth, 1968, 1982) in heterogeneous clastic rocks in the Alberta Sedimentary Basin (fig. 4). The convergence of transmissivities to a limiting value suggests that the flow domain sampled by the water withdrawn through individual aquifers is the

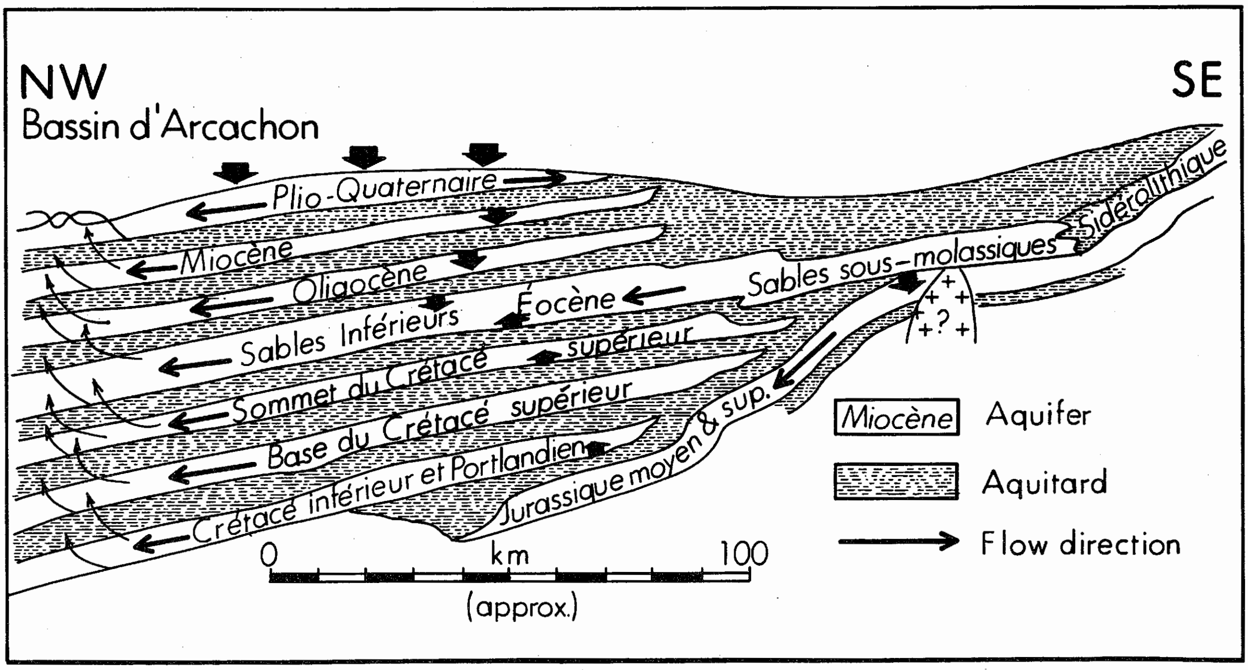

Figure 3. Schematic of multiple-aquifer systems and computed flow rates, Aquitain Basin, France (modified from Besbes et al., 1976).

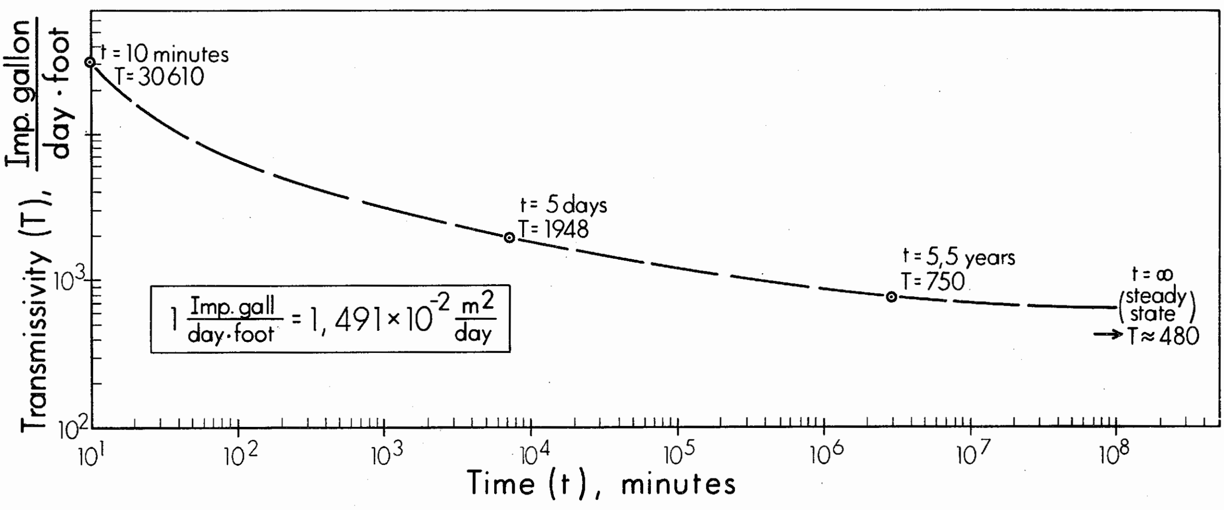

Figure 4. Transmissivities derived from pumping tests of increasing duration and converging toward values obtained from seasonal water-level changes (compiled from Tóth, 1966, 1968, 1973, 1982).

same as the one traversed by regional flow from recharge areas to discharge areas, i.e., that the rock framework is hydraulically continuous.

Additional Arguments in Favour of Regional Hydraulic Continuity

In addition to conclusions reached from aquifer and basin hydraulics, regional hydraulic continuity is also supported by observations of rock-pore sizes and rock-permeabilities.

Rock-pore sizes were estimated by Tissot and Welte (1978) to decrease to an (apparently minimum) value of 1 nm at a depth of 4,000 m, whereas the effective diameter of a water molecule is ≈0.32 nm. Consequently, a water molecule should be able to pass through the intergranular voids of the tightest shales even if two immobile monomolecular water layers are assumed to line the pore walls.

Brace (1980) reported measurable permeability values in any rock type (pure halite being one possible exception) and at any depth accessible by today's drilling technology. In the Swan Hills area of Alberta, Canada, minimum values for vertical hydraulic conductivities of massive clastic and evaporite aquitards were observed by Hitchon et al. (1989) to be about 7 to 9 $\times 10^{-11}$ m/s. Many other examples may be cited for extensive and tight rocks being effectively permeable, whereas not one reliably impermeable formation has yet been identified, to this author's knowledge, in the search for suitable repository sites for radioactive or other long-living hazardous wastes.

CONSEQUENCES OF REGIONAL HYDRAULIC CONTINUITY

The natural consequences of hydraulic continuity of the rock framework are divided into three categories: 1) Development of regionally extensive groundwater flow systems; 2) Systematic areal distribution of matter and heat; and 3) Hydraulic interdependence of different basinal areas.

Regionally Extensive Groundwater Flow Systems

The basic form of regionally extensive steady-state flow systems facilitated by hydraulic continuity develops in the "Unit Basin." Such a basin is a symmetrical topographic depression with linearly sloping flanks and a homogeneous rock framework (fig.

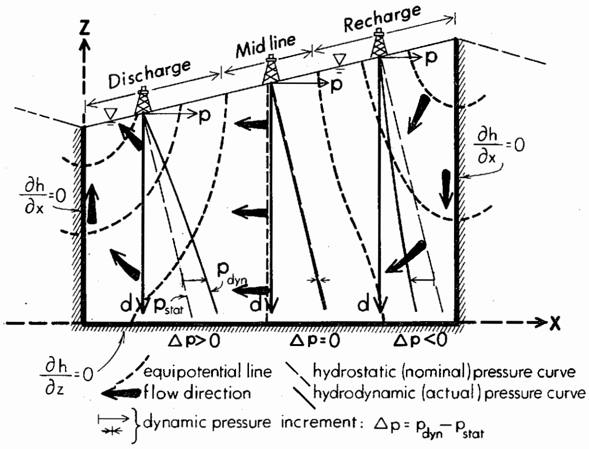

Figure 5. The "Unit Basin," showing patterns of fluid potential, pore pressure, and flow.

5). Three distinctly different groundwater flow regimes occur in the basin, namely the recharge, midline and discharge regions. These regions are characterized by descending, lateral and ascending flow, respectively, as well as by the associated patterns of pore-pressure, hydraulic-head and vertical-pressure gradients. The closest natural equivalents of the Unit Basin are intermontane valleys and closed lake basins (e.g., Issar and Rosenthal, 1968; Mifflin, 1968; Ortega and Farvolden, 1989; Tóth and Otto, 1989). In regions with substantial local topography, such as high-relief platforms and foreland basins, *composite flow patterns* develop. These patterns are considered to be topographically modified versions of the Unit-Basin flow system. In such basins, three types of flow system are recognized: local, intermediate, and regional (fig. 6). Composite patterns are characterized by laterally alternating recharge-discharge regions, contiguity of hydraulically similar regions of flow systems of different order, vertical superposition of different types of flow regimes, and stagnation points (e.g., Erdélyi, 1976; Astié et al., 1969).

Low-permeability strata may modify basinal pore-pressure patterns to a degree that the erroneous impression of hydraulic discontinuity is created. The apparent discontinuity suggested by the p(d) curves in figure 7 is due to a lack of pressure measurements in the aquitard, rather than to a lack of flow through it.

A similar hiatus in observed pressure values can, of course, lead to similarly erroneous conclusions regarding hydraulic continuity also in non-

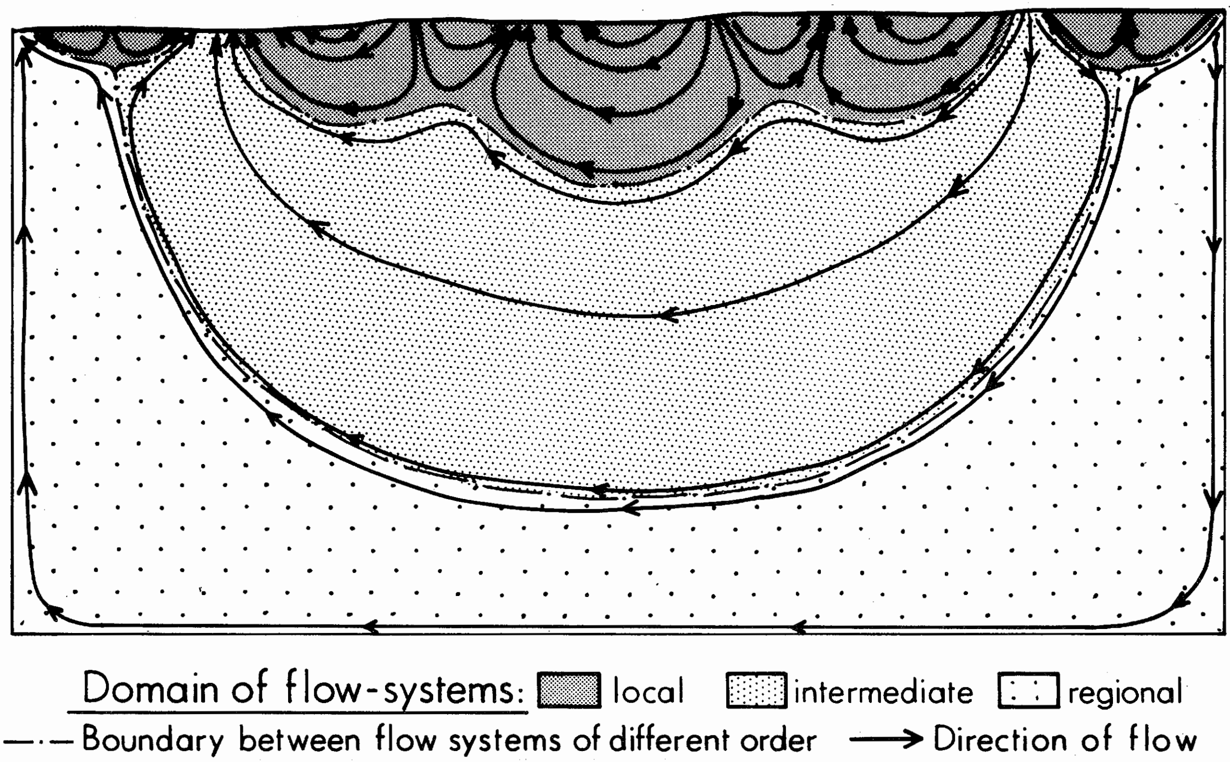

Figure 6. Composite basin with homogeneous rock framework, showing flow-system types (modified from Tóth, 1963).

gravity-driven hydraulic regimes. Such may be the case in the compactional water systems of subsiding basins, such as, the Gulf of Mexico.

Owing to hydraulic continuity, basinal pore pressures adjust to changing boundary conditions albeit, perhaps, with a time lag. The process may result in the development of *heterochronous flow fields* (fig. 8), and the adjustment was estimated to take approximately 4 Ma through a shale stratum 480 m in thickness in northern Alberta (fig. 9) (Tóth and Millar, 1983).

Systematic Distribution of Matter and Heat: The Geologic Agency of Groundwater

Moving groundwater interacts with its environment through a variety of physical, chemical, and mechanical processes. Groundwater mobilizes, transports, and deposits matter and heat, modifies pore pressures, and lubricates fracture planes and soil grains. The effects of these processes are different, or even opposite, in the high-energy recharge and the low-energy discharge areas. Oxidation, dissolution, moisture deficiency, removal of matter, subhydrostatic pressures, and low temperatures are common in the former, whereas opposite conditions characterize the latter (Tóth, 1984). An important aspect of the geologic agency of groundwater is that its manifestations occur simultaneously in any size and any order of flow systems, as well as at any depth and any time scale (fig. 10). The diversity of groundwater-generated field features is increased by the effects of local environments. For instance, just a simple excess of water in a discharge area can result in springs, seeps, soil creep, quick sand, ice mounds, fens, and so on, depending on the climatic, soil and topographic conditions. In the deeper subsurface and on the scale of geologic time, hydraulic continuity facilitates the development of extensive flow systems. In combination with other requisite conditions, such flow systems may become effective transport mechanisms in the generation of various types of metallic ore deposits (Galloway and Hobday, 1983; Baskov, 1987; Garven et al., 1993), petroleum accumulations (Tóth, 1988; Wells, 1988), and geothermal heat anomalies (Smith and Chapman, 1983; Beck et al., 1989). Table 1

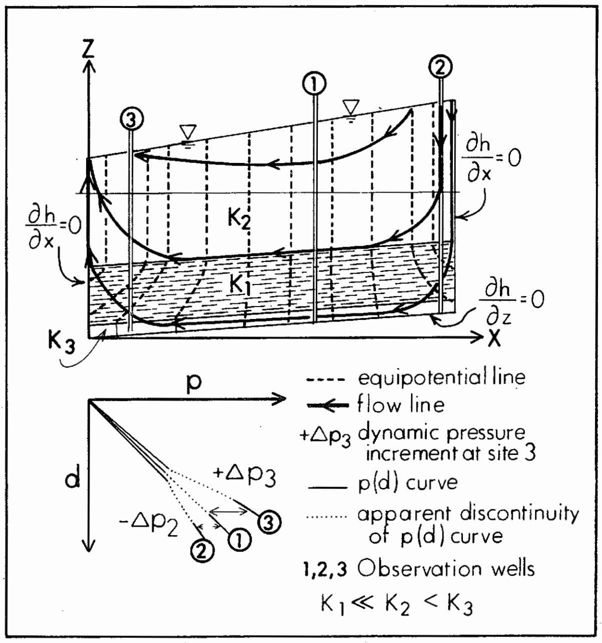

Figure 7. Simple basin with regional aquitard, showing patterns of fluid potential, pore pressure and flow (modified from Tóth, 1978).

summarizes the major groups of groundwater-generated field phenomena (Tóth, 1984).

Hydraulic Interdependence of Different Basinal Regions and Hydrologic Components

An important consequence of hydraulic continuity is the propagation of hydraulic stresses imposed on the groundwater body to distant geographic regions, to unexpected depths and strata, for great lengths of time, or in unexpected forms. As an example, figure 11 presents the theoretical response of various water-balance components to pumping in a regionally unconfined basin (Freeze, 1971). The effects most relevant in the present context are the unexpected decline in natural recharge at time = t_4, and the conversion of former discharge areas into recharge areas (between t_3 and t_4) upon extended pumping.

In the case of a real example, pumping in the Kanto groundwater basin for the city of Tokyo affects groundwater levels in a radius of over 100 km and has caused land subsidence in excess of 4 m at places (Nirei and Furuno, 1986). In the design of repositories for radioactive wastes, changes in pore-pressure fields must be considered for thousands of years after possible changes in boundary conditions, and oil fields may be re-migrated by changes in natural flow-field boundaries (fig. 8) (Tuan and Chao, 1968), or by pumping in apparently unconnected locations (Hubbert, 1953).

CONCLUSIONS

From a hydrogeological viewpoint, a large sedimentary basin is defined as an extensive structural depression of the Earth's crust filled with sedimentary rocks and including several drainage basins. Owing partly to large possible contrasts in rock permeabilities, sharply differing groundwater conditions may develop in different regions and/or depths of these basins. In addition to variations in pressure, temperature, and chemistry, different sources of fluid potentials may even exist, such as gravity, compression, compaction, dilation, thermal, and chemical.

The varied groundwater conditions observed in large sedimentary basins have been interpreted traditionally to indicate hydraulic separation, or even complete isolation, of parts of the rock framework. Gradually, this thinking is giving way to the view that the rock framework is hydraulically continuous.

According to this view, a subsurface rock body is considered hydraulically continuous on a given time scale if a change in hydraulic head (or pore pressure) at any point can cause a head change at any of its other points within a time interval measurable on the specified time scale. This phenomenological property of the rock framework is, therefore, dependent on the chosen scales of space and time.

The most fundamental consequence of regional "leakage" is that large-scale flow systems develop that are adjusted or are in the process of adjustment to boundaries of maximum and minimum fluid potentials. The boundaries may be formed by topographic highs or lows, extensive surface-water bodies, compressional or compactional pressure maxima, or dilatational pressure troughs. The flow systems themselves function as conveyor belts and effect systematic distribution of heat and matter within the basins. Thus, they make groundwater an effective, indeed powerful, geologic agent.

Groundwater is active simultaneously on different scales of space and time. The effects of moving groundwater are varied and environmentally modified. They include, for instance, regionally contrasting soil-moisture conditions; various soil and rock mechanical phenomena, such as liquefaction and land

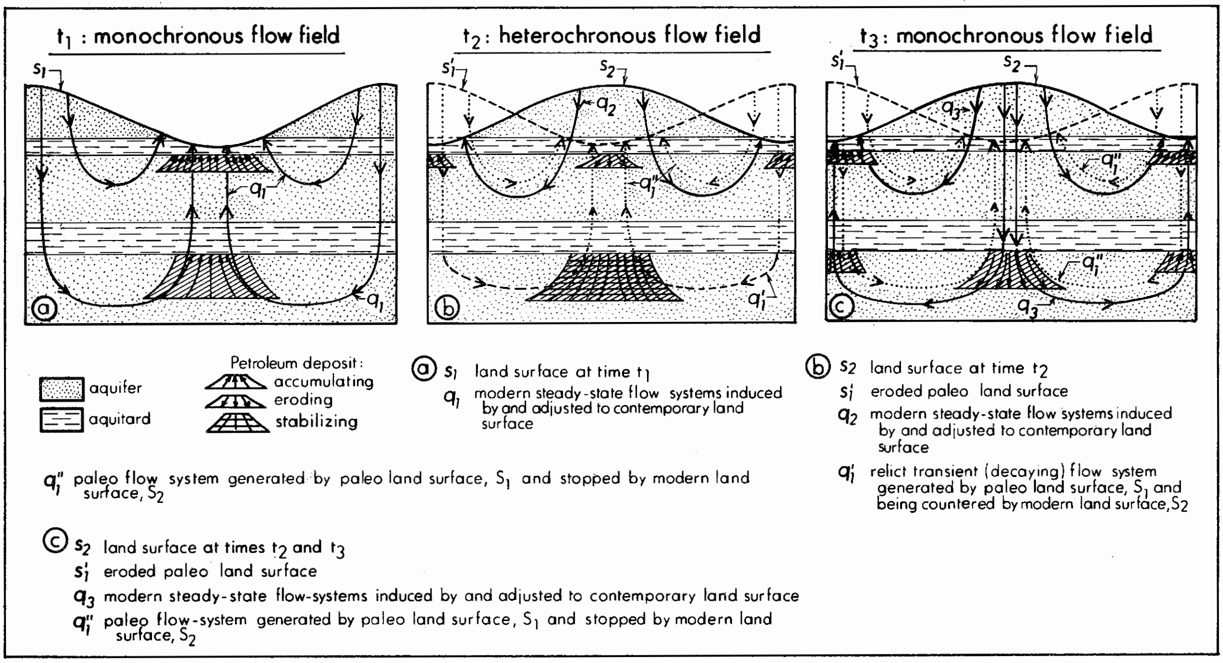

Figure 8. Conceptual illustration of delayed adjustment of flow systems and petroleum deposits upon a change in topography.

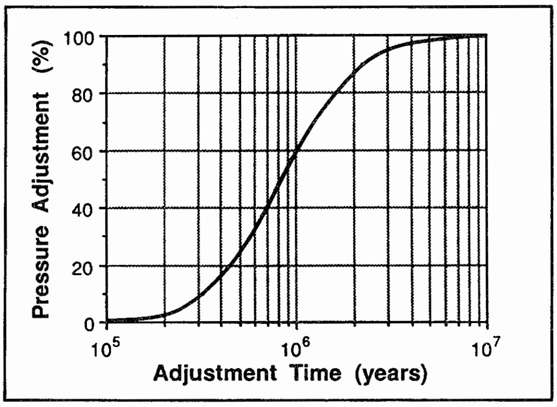

Figure 9. Calculated pressure-adjustment times across 480 m of shale of $K = 5 \times 10^{-13}$ m/s in response to stepwise change in elevation of the water table, Alberta Basin, Canada (modified from Tóth and Millar, 1983).

slides; wetland development and effects on the baseflow of rivers; regular patterns of groundwater chemistry; geothermal anomalies; diagenetic changes of minerals; soil salinization; migration and accumulation of various metallic minerals and petroleum; and generation of certain physical and chemical signatures that indicate the presence of those accumulations.

Perhaps the most challenging and rewarding task of the hydrogeologist is the selection of the appropriate scales of space and time for a particular problem. For example, the hydraulic engineer may easily overestimate the sustainable yield of a highly permeable aquifer by not recognizing that the ultimate constraint on production is the regional transmissivity or even annual precipitation. Conversely, pumpage required to keep an open-cast mine dry might be underestimated based on the pumped aquifer's transmissivity and storativity, if leakage through apparently impermeable aquitards is ignored, but which could be recognized by regional flow studies. Or, the impermeable boundary, which the reservoir engineer rightly assumes for the purpose of production-rate calculations to envelop a

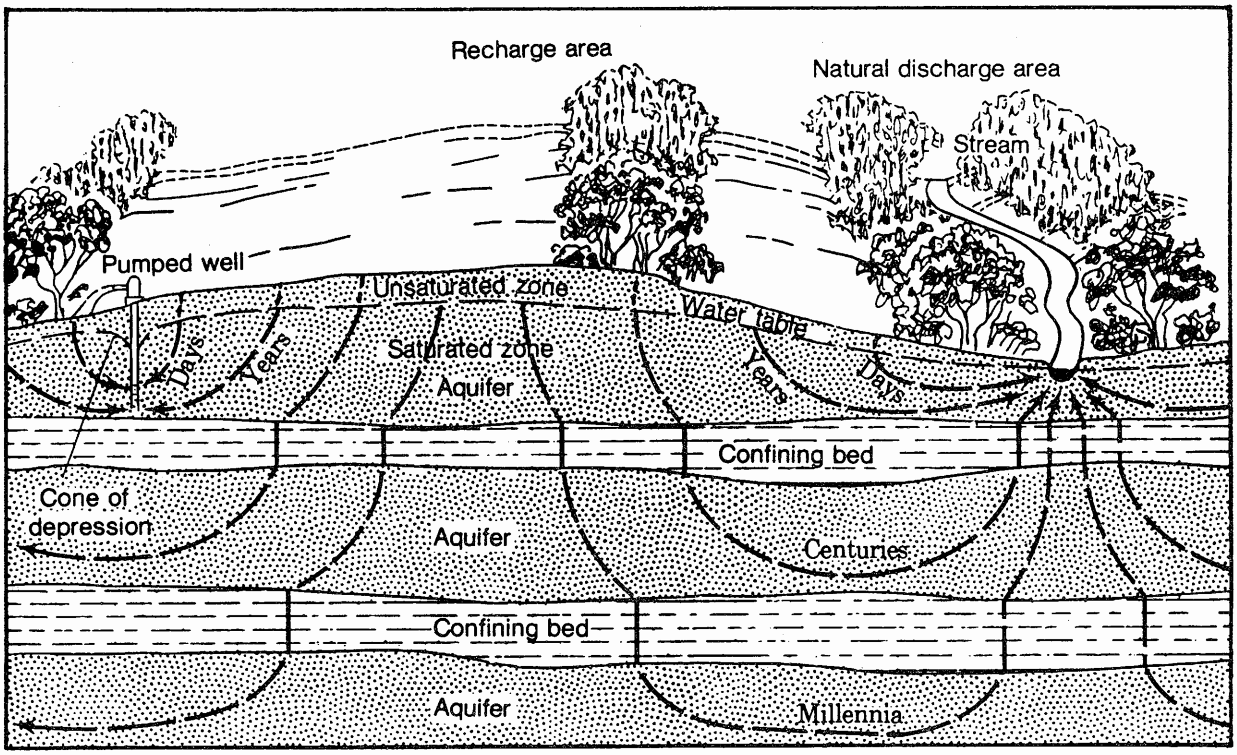

Figure 10. Simultaneous groundwater flow on different time scales.

Table 1. Natural phenomena related to basinal flow of groundwater.

Natural Phenomena	
1. *Hydrology and hydraulics* ● Local water balance ● Regionally contrasting moisture conditions	4. *Soil and rock mechanics* ● Liquefaction (quick sand) ● Slope stability
2. *Chemistry and mineralogy* ● Patterns of water salinity and isotope distribution ● Soil salinization and continental salt deposits ● Weathering, dissolution, cementation, diagenesis	5. *Geomorphology* ● Erodibility ● Karst ● Geysers and mud volcanoes ● Frost mounds, ice fields
3. *Vegetation* ● Type of plant associations ● Quality	6. *Transport and accumulation* ● Temperature patterns ● Sedimentary sulphide ores ● Uranium ● Hydrocarbon deposits, halos, and oil seeps

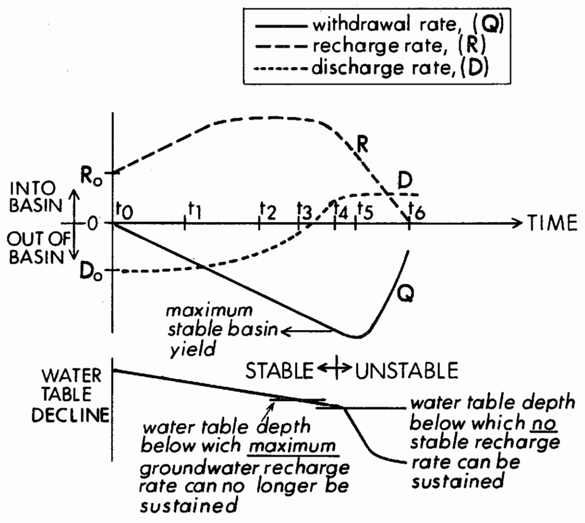

Figure 11. Schematic diagram of transient relations between rates of recharge, discharge, and water withdrawal (modified from Freeze, 1971, figure 11).

lenticular accumulation of hydrocarbons, must surely be considered permeable on the timescale of petroleum migration for the lens to be targeted by the explorationist as a prospective play.

In summary, the correct interpretation and utilization of the great number of groundwater-related processes and phenomena and the correct modeling and prediction of the effects of stresses imposed upon the groundwater regime in large sedimentary basins, i.e., the correct practice of hydrogeology, require the recognition and taking into account of that fundamental property of the rock framework, hydraulic continuity.

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