Groundwater as a geologic agent: An overview of the causes, processes, and manifestations

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Abstract The objective of the present paper is to show that groundwater is a general geologic agent. This perception could not, and did not, evolve until the system nature of basinal groundwater flow and its properties, geometries, and controlling factors became recognized and understood through the 1960s and 1970s.

The two fundamental causes for groundwater's active role in nature are its ability to interact with the ambient environment and the systematized spatial distribution of its flow. Interaction and flow occur simultaneously at all scales of space and time, although at correspondingly varying rates and intensities. Thus, effects of groundwater flow are created from the land surface to the greatest depths of the porous parts of the Earth's crust, and from a day's length through geologic times. Three main types of interaction between groundwater and environment are identified in this paper, with several special processes for each one, namely: (1) Chemical interaction, with processes of dissolution, hydration, hydrolysis, oxidation-reduction, attack by acids, chemical precipitation, base exchange, sulfate reduction, concentration, and ultrafiltration or osmosis; (2) Physical interaction, with processes of lubrication and pore-pressure modification; and (3) Kinetic interaction, with the transport processes of water, aqueous and nonaqueous matter, and heat. Owing to the transporting ability and spatial patterns of basinal flow, the effects of interaction are cumulative and distributed according to the geometries of the flow systems.

The number and diversity of natural phenomena that are generated by groundwater flow are almost unlimited, due to the fact that the relatively few basic types are modified by some or all of the three components of the hydrogeologic environment: topography, geology, and climate. The six basic groups into which manifestations of groundwater flow have been divided are: (1) Hydrology and hydraulics; (2) Chemistry and mineralogy; (3) Vegetation; (4) Soil and rock mechanics; (5) Geomorphology; and (6) Transport and accumulation. Based on such a diversity of effects and manifestations, it is concluded that groundwater is a general geologic agent.

Résumé L'objectif de ce papier est de montrer que les eaux souterraines sont un agent géologique général. On n'a pas pu avoir conscience de ce rôle avant que la nature en tant que système de l'écoulement souterrain dans les bassins et ses propriétés, ses géométries et ses facteurs de contrôle aient été reconnus et compris au cours des années 60 et 70.

Les deux causes fondamentales du rôle actif des eaux souterraines dans la nature sont leur capacité à interagir avec l'environnement et la distribution spatiale généralisée de leur écoulement. L'interaction et l'écoulement se produisent en même temps à toutes les échelles de temps et d'espace, mais à des taux et à des intensités variables selon les échelles. Ainsi, les écoulements souterrains produisent leurs effets depuis la surface du sol jusqu'aux profondeurs les plus grandes dans les parties poreuses de l'écorce terrestre, et pour des durées qui s'étendent d'une journée jusqu'aux temps géologiques. Trois types principaux d'interaction entre les eaux souterraines et l'environnement sont identifiés dans ce papier, avec plusieurs processus particuliers pour chacun ; ce sont: 1) les interactions chimiques, avec les processus de dissolution, d'hydratation, d'hydrolyse, d'oxydo-réduction, d'attaque acide, de précipitation chimique, d'échange de bases, de réduction des sulfates, de concentration et d'ultrafiltration ou d'osmose, 2) les interactions physiques, avec les processus de lubrification et de modification de pression de pores, et 3) les interactions cinétiques, avec les processus de transport de l'eau, de substances aqueuses et non aqueuses et de chaleur. Grâce à la capacité de transport et à l'organisation spatiale des écoulements dans les bassins, les effets de ces interactions sont cumulatifs et se distribuent en fonction des géométries des systèmes d'écoulement.

Le nombre et la diversité des phénomènes naturels générés par les écoulements souterrains sont presque

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illimités, du fait que les quelques types de base sont modifiés par certaines ou par l'ensemble des trois composantes de l'environnement hydrogéologique: la topographie, la géologie et le climat. Voici les six groupes de base dans lesquels les eaux souterraines se manifestent: 1) l'hydrologie et l'hydraulique, 2) la chimie et la minéralogie, 3) la végétation, 4) le sol et la mécanique des roches, 5) la géomorphologie, et 6) le transport et l'accumulation. En se basant sur une telle variété des effets et des manifestations, on en conclut que les eaux souterraines sont un agent géologique général.

Resumen El objetivo del artículo es mostrar que el agua subterránea es un agente geológico habitual. Esta percepción no se pudo desarrollar hasta que la naturaleza de la hidrogeología de cuenca, sus propiedades, geometría y factores de control no fueron reconocidos y entendidos en las décadas de los 60–70.

Las dos causas fundamentales para el papel activo de las aguas subterráneas en la naturaleza son su capacidad para interactuar con el medio ambiente y la distribución espacial del flujo. Ambas tienen lugar simultáneamente a todas las escalas de espacio y tiempo, aunque con distintas intensidades. Así, el flujo subterráneo tiene lugar desde la superficie hasta a grandes profundidades, y desde escalas de un día hasta tiempos geológicos. En este artículo se identifican tres tipos principales de interacciones entre aguas subterráneas y medio ambiente, con ciertos procesos particulares para cada tipo de interacción: (1) Interacción química, con los procesos de disolución, hidratación, hidrólisis, oxidación-reducción, ataque químico, precipitación, intercambio iónico, reducción de sulfatos, concentración, ultrafiltración y ósmosis; (2) Interacción física, con los procesos de lubrificación y modificación de presiones y (3) Interacción cinética, con los procesos de transporte de agua, materia acuosa y no acuosa y calor. Dadas la capacidad de transporte y las características especiales del flujo en cuencas sedimentarias, los efectos de interacción son acumulativos y se distribuyen de acuerdo con la geometría de los sistemas de flujo.

El número y la diversidad de los fenómenos naturales que se generan mediante flujo subterráneo son prácticamente ilimitados, ya que los tipos básicos se pueden modificar por una o varias de las componentes del medio hidrogeológico: topografía, geología y clima. Los seis grupos básicos en los que se han dividido las manifestaciones de flujo subterráneo son: (1) Hidrología e hidráulica, (2) Química y mineralogía, (3) Vegetación, (4) Mecánica del suelo y de las rocas, (5) Geomorfología y (6) Transporte. Basándose en tan gran diversidad de efectos y manifestaciones se concluye que las aguas subterráneas son un agente geológico habitual.

Key words groundwater flow · geologic agent · hydrochemistry · general hydrogeology

Introduction

This "Theme Issue" of *Hydrogeology Journal* is intended to be an explicit statement of the view that moving groundwater is the common basic cause of a wide variety of natural processes and phenomena and hence it should be regarded as a general geologic agent.

That groundwater plays an active role in certain geologic processes has been recognized in numerous subdisciplines for a long time. The generality of this role, however, was not realized until the underlying common cause – regional, or basinal, groundwater flow – itself was sufficiently understood in the 1960s and 1970s to allow, and indeed to stimulate, dedicated studies of its broader ramifications. Even during this period, the generalization of groundwater's role in nature was hindered by at least two factors. First, the diversity of natural phenomena generated by groundwater flow effectively conceals the likelihood of one single common cause. Second, a lack of understanding, or even awareness, of regional groundwater hydraulics by specialists of the various subdisciplines prevents them from recognizing the cause-and-effect relation between basinal groundwater flow and the particular phenomena that they may be studying. By way of illustrating the difficulty of discovering a common origin, suffice it only to list such diverse, and indeed in some cases disparate, natural phenomena generated and/or fundamentally shaped by groundwater flow as: soil salinization, continental salt deposits, regional patterns of groundwater's chemical composition, soil liquefaction, gullying, landslides, ice fields, geysers, positive and negative geothermal anomalies, lake eutrophication, stream base-flow characteristics, bog- vs. fen-type wetlands, type and quality of plant cover, taliks in permafrost, roll-front and tabular uranium deposits, dolomitization of limestones, karst morphology, diagenesis of certain clay minerals, some sulfide-ore deposits, and certain types of hydrocarbon accumulations.

Examples of major works that focus on specific geologic processes while recognizing the role played by groundwater include: Back (1966); Boelter and Verry (1977); Deere and Patton (1971); de Vries (1974); Domenico and Palciauscas (1973); Fogg and Kreitler (1982); Galloway (1978); Garven (1989); Garven et al. (1993); Gerrard (1981); LaFleur (1984); Macumber (1991); Stuyfzand (1993): Wallick (1981); Williams (1970); Yaalon (1963); and Zaruba and Mencl (1969).

On the other hand, attempts at advancing the notion/concept of groundwater as a general geologic agent by focussing on its multifarious effects in nature are exemplified by: Back et al. (1988); Deutscher Verband (1987); Domenico and Schwartz (1997); Engelen and Jones (1986); Engelen and Kloosterman (1996); Freeze and Cherry (1979); Ingebritsen and Sanford (1998); Ortega and Farvolden (1989); and Tóth (1966, 1971, 1972, and 1984).

The recogniton of moving groundwater as a common cause of such a diversity of geologic effects was not possible until the system-nature of its regional flow distribution had been understood. A period of conscious efforts began in the early 1960s to model, observe, and evaluate basin-scale flow of groundwater and the factors controlling it. Initially, attention was directed at small basins and gravity-driven flow (Tóth 1962, 1963; Freeze and Witherspoon 1967). The essential results, which are relevant also in the present context, were the recognition that in topography-controlled flow regimes, groundwater moves in systems of predictable patterns and that various identifiable natural phenomena are regularly associated with different segments of the flow systems (Astié et al. 1969; Williams 1968, 1970; Freeze 1969; Mifflin 1968). The scope of investigations was expanded later to extensive and deep basins. These studies have revealed or confirmed (1) the hydraulically continuous nature of the rock framework, which facilitates large-scale cross-formational flow systems; (2) time lags in the adjustments of flow patterns to changing boundary conditions, ranging on the time spectrum from the human to the geological scales; and (3) the multiplicity of possible flow-inducing energy sources. It has also become obvious that, although in many respects different from their small-basin counterparts, a wide variety of geologic phenomena is associated with the large-scale flow systems (Bethke 1985; Bredehoeft and Hanshaw 1968; Erdélyi 1976; Goff and Williams 1987; Neuman and Witherspoon 1971; Neuzil and Pollock 1983; Neuzil et al. 1984; Parnell 1994; Tóth 1978; Tóth and Corbet 1986; Tóth and Millar 1983).

In brief, the recognition of the system-nature of subsurface water flow on broad spectra of space and time has provided a unifying theoretical background for the study and understanding of a wide range of natural processes and phenomena and has thus shown flowing groundwater to be a general geologic agent. The illustration of this conclusion is the prime objective of this paper and, indeed, of the present volume.

Specifically, the objective of this volume is to consolidate the notion of groundwater as a geologic agent and to emplace it firmly into the ranks of such geologic forces as surface water, wind, and ice. To this end, a collection of articles has been assembled that deal with widely different aspects of regional groundwater flow and of its geologic effects.

The present paper, on the other hand, attempts to give an overview of the basic causes, principal processes, and diverse manifestations in nature of regional groundwater flow, thus to demonstrate the common genetic background of apparently unrelated geologic phenomena. This summary overview is based on, and is limited to, effects of gravity-driven flow, because particular cause-and-effect relations have been most extensively ascertained for these situations. Conclusions pertaining to other types of cases are presented in the respective individual cases.

The Basic Causes

Two fundamental causes are responsible for groundwater's geologic agency, namely: (1) interaction between water and its ambient environment, and (2) systematized and hierarchical flow paths. The water's interaction with its surroundings generates various natural processes, products, and conditions. Flow systems, on the other hand, function as mechanisms of transport and distribution of those effects into regular spatial patterns within the basinal flow domain. In basins where groundwater flow is controlled by the topography, the spatial distribution patterns of groundwater's effects are functionally related to identifiable and characteristic segments of the flow systems. Such a relation makes correlation between cause (groundwater flow) and effect (natural conditions and phenomena) feasible and verifiable, and it is used as the chief argument in limiting the scope of this paper to that of gravity flow.

Interaction between Groundwater and its Environment

Interaction between groundwater and its natural environment occurs in different forms and is driven by the various components and attributes of the two respective systems seeking equilibration. For the purposes of this paper, three main types of interaction between groundwater and its hydrogeologic environment are identified, namely: chemical, physical, and kinetic. The tendency toward equilibration between different systems, i.e., seeking a state of minimum free energy, whether they be chemical, mechanical, kinetic, or thermal, is a basic law of nature and is accomplished through various natural processes. As a result of such natural processes (reviewed below), water moving through the subsurface can: (1) mobilize and deposit matter and heat; (2) transport matter and heat; (3) lubricate discontinuity surfaces in the rock framework: and (4) generate and modify pore pressures.

These activities of groundwater produce various in-situ effects, the nature of which depends on the chemical, physical, and hydro-kinetic conditions of a particular locality. In regions of high chemical and thermal energy, minerals are added to the water by dissolution, oxidation, attack by acids, and other processes. Relatively high mechanical energy causes the water to move away from a site, possibly carrying with it dissolved mineral matter and heat, thus rendering the locality a source of minerals, water, and heat. Conversely, in regions of low chemical, thermal, and kinetic energy, the water tends to converge and possibly leave the subsurface domain by discharging onto the land surface, stream bed, or lake bottom; precipitate mineral matter; and lose heat. Collectively, the diverse manifestations resulting from the interaction of groundwater with its environment at a given locality may be called the in-situ environmental effects of groundwater.

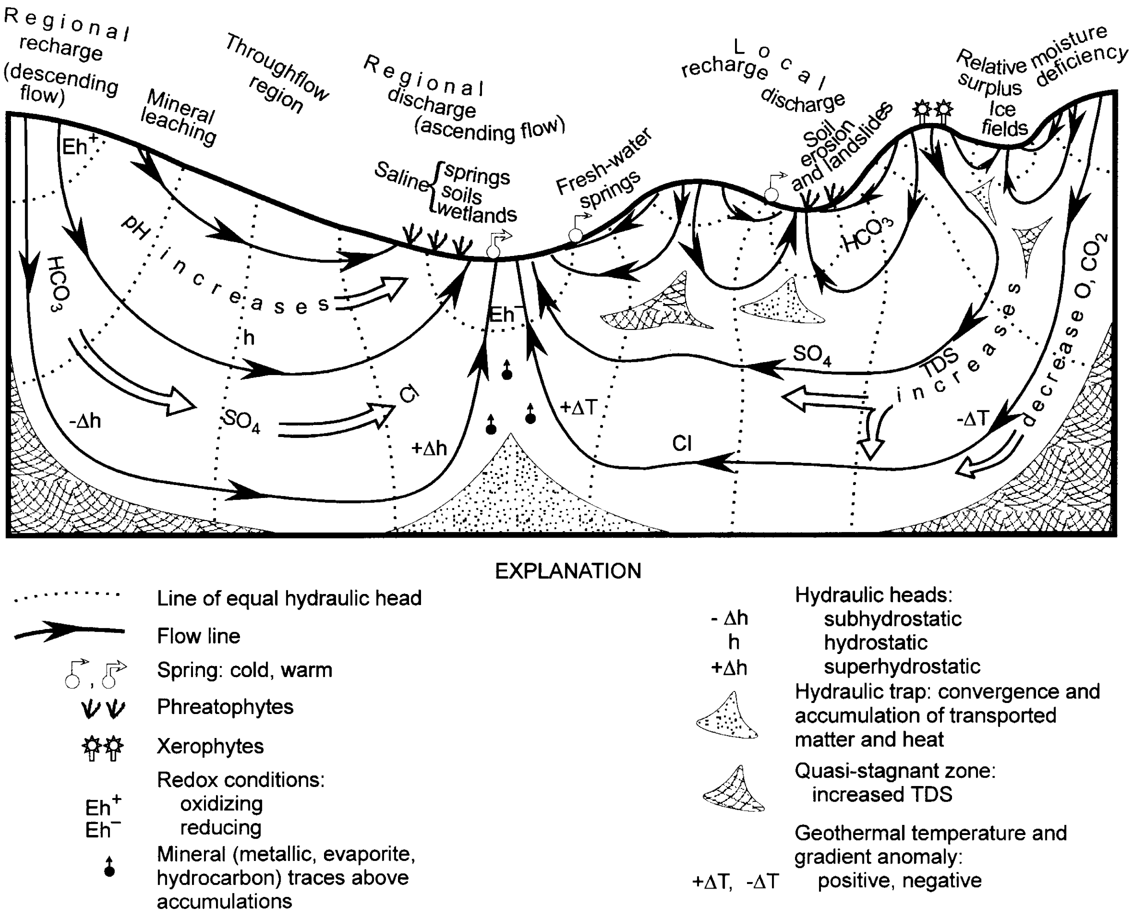
Flow: A Systematic Transport and Distribution Mechanism

In-situ environmental processes alone are normally not sufficient to render groundwater a significant geologic agent, because most of them are self-limiting in time and/or randomly scattered in space. To develop, most geologic phenomena, such as mineral deposits, geothermal anomalies, and wetlands, need the effects of processes produced by disequilibria to accumulate over sufficiently long periods of time and/or to concentrate within relatively small rock volumes or areas from more extensive source regions. Other phenomena, such as vegetation patterns, soil- and rock-mechanical instability, ice development, etc., are secondary effects consequent upon the primary processes.

The only mechanism capable of producing and maintaining the required disequilibrium conditions for such a wide range of natural phenomena is the regional, or basinal, flow of groundwater. The individual systems of groundwater flow may be compared to conveyor belts, with their source regions viewed as the areas of mobilization and loading, and their terminal regions as the areas of delivery and deposition. The middle segments function chiefly as relatively stable environments of mass and energy transfer.

A schematic overview of groundwater flow distribution and some typical hydrogeologic conditions and natural phenomena associated with it in a gravity-flow environment is presented in *Figure 1*. The figure shows an idealized basin with one single flow system of the left-hand side flank of insignificant local relief, and a hierarchical set of local, intermediate and regional flow systems of the right flank of composite topography. Each flow system, regardless of its hierarchical position, has an area of origin or recharge, an area of throughflow or transfer, and one of termination or discharge. In the recharge areas, the hydraulic heads, representing the water's mechanical energy, are relatively high and decrease with increasing depth; water flow is downward and divergent. In discharge areas, the energy and flow conditions are reversed: hydraulic heads are low and increase downward, resulting in converging and ascending water flow. In the areas of throughflow, the water's mechanical energy is largely invariant with depth (the isolines of hydraulic heads are subvertical) and, consequently, flow is chiefly lateral. The flow systems operate as conveyor belts which effectively interact with their ambient environment. The interaction produces in-situ environmental effects,

Figure 1 Effects and manifestations of gravity-driven flow in a regionally unconfined drainage basin. (Modified from Tóth 1980, Figure 10)



with the flow serving as the mechanism for mobilization, transport (distribution), and accumulation.

Typical environmental effects and conditions resulting from the action of groundwater moving in basinal gravity-flow systems are illustrated in *Figure 1* and include: (1) sub-, normal-, and super-hydrostatic hydraulic heads at depth in the direction of flow from recharge, to discharge areas, respectively; (2) relatively dry surface-water and soil-moisture conditions (negative water balance) in recharge areas, and water surplus (positive water balance), possibly resulting in wetlands, in discharge areas; these conditions are expressed in comparison to an average water balance in the basin, which would result solely from precipitation and evapotranspiration; (3) systematic changes in the water's anion facies, from HCO_3 through SO_4 to Cl, both along flow systems and with depth; (4) chemically leached soils and near-surface rocks in areas of inflow, but increased salt contents possibly amounting to salt-affected soils or even commercial salt deposits at flow-system terminuses; (5) saline marshes in situations where wetland conditions and intensive salt supply coincide; (6) negative and positive anomalies of geothermal heat and geothermal gradients beneath areas of descending and ascending flows, respectively; (7) chemically oxidizing and reducing conditions in the near-surface environment of recharge and discharge areas, respectively; (8) identifiable response in the type and quality of the vegetation cover to the contrasting nutrient and moisture conditions generated by the inflow and outflow of groundwater at flow-system extremities; (9) increased vulnerability of the land surface to soil- and rock-mechanical failures (such as soil erosion, slumping, quick grounds, and landslides) in areas of discharge, possibly developing into major geomorphologic features, such as gullying and stream meanders; (10) accumulation of transported mineral matter such as metallic ions (uranium, sulfides), hydrocarbons, and anthropogenic contaminants, primarily in regions of converging flow paths (hydraulic traps) or in regions where the fluid potential is minimum with respect to a transported immiscible fluid (oil, gas), e.g., at grain-size boundaries or in rocks of adsorptive minerals.

The above examples pertain to gravity-driven systems of groundwater flow. However, similar natural effects can be generated by flow due to other sources of energy, namely: sediment compaction; tectonic compression; thermal convection; buoyancy; dehydration of minerals as, for instance, gypsum; and osmosis. The history, geometry, and geologic effects of the nongravitational flow systems are much less tractable and, therefore, not yet amenable to systematic and generalized discussions. Some outstanding examples of particular cases are represented by Berry (1973); Bethke (1989); Hanor (1987); Harrison and Summa (1991); and Oliver (1986).

Ubiquity and Simultaneity

The key element in creating such a diversity in groundwater's geologic effects is its being active over broad spectra of space and time. Water permeates the entire porous section of Earth's upper crust through regionally cross-formational communication, and it may penetrate to depths of 15–20 km. Throughout this depth range, water is in continual motion, although at vastly different rates, possibly ranging from more than 10^{-3} m/s near the surface to less than 10^{-12}–10^{-14} m/s at depth. Also, the stability of individual flow systems is a function of depth and/or lateral position within the flow domain. Flow paths near the land surface and/or in unconfined domains adjust to changes in boundary conditions more readily than at great depths or in confined situations. Geologic effects requiring long-term permanency for their creation are therefore less likely to develop at shallow depths.

Groundwater interacts with its environment at all depths and at all times. Owing, however, to the vastly different conditions, different reactive matter, different processes and different flow rates prevailing at different locations and depths of the flow regime, the rates and products of interaction between water and its environment will also be fundamentally different, although generated simultaneously and by the same agent: moving groundwater.

The Main Processes

Three types of disequilibrium conditions are identified in the previous section as the primary causes for groundwater's geologic agency, namely: chemical, physical, and kinetic. The disequilibria tend to be reduced in nature through numerous and different processes, of which a brief, annotated enumeration is presented in this section. Their detailed discussion is unwarranted in the present paper as they are all processes and material interactions dealt with in the present context by various works and they are well known from basic science (Freeze and Cherry 1979; Domenico and Schwartz 1997; Fetter 1994).

Chemical Processes

Dissolution is one of the most generally effective processes in groundwater chemistry and could be considered as the first step in the water's chemical evolution. It affects both gases and solids. Typical regions of gas dissolution by groundwater are the soil zone, unsaturated or vadose zone, and zones of oil and gas accumulations. Gases commonly interacting with groundwater include N_2, Ar, O_2, H_2, He, CO_2, NH_3, CH_4, and H_2S. Dissolution of gases may render the water weakly acidic, i.e., chemically aggressive. The degree of dissolution depends on the solubility of the minerals, the antecedent concentration of the water, and the pressure and temperature of the locality. Rocks that are most soluble include limestone ($CaCO_3$), dolomite ($CaMgCO_3$), gypsum ($CaSO_4$), halite (NaCl), and sylvite (KCl); these also serve as the principal source for Ca, Mg, Na, K, CO_3, SO_4, and Cl in groundwater. Silicates and other so-called "insoluble rocks" also are soluble to some degree under certain chemical conditions and yield the minor or trace constituents in groundwater.

Hydration is the penetration of water into the crystal lattice of minerals or the attachment of water molecules to the ions of dissolved salts. It is a common process in the evolution of groundwater's chemical composition and plays an important part, among others, as the first step in the weathering of minerals as, for instance, anhydrite to gypsum or biotite to vermiculite.

Hydrolysis is defined as the reaction of any substance with water. More strictly, hydrolysis is the reaction of an ion with water to form an associated species plus H^+ or OH^-. Hydrolysis of cations produces slightly acidic solutions according to the general equation $M^+ + H_2O \rightleftharpoons MOH + H^+$, whereas anion hydrolysis results in a basic solution $X^- + H_2O \rightleftharpoons HX + OH^-$. Hydrolysis is an effective process only if (1) some of the produced ions are removed from the solution, or (2) others that are required for the hydrolysis are added to the solution. Otherwise, chemical equilibrium, thus cessation of dissolution, occurs.

Oxidation-reduction reactions are chemical reactions in which electrons are transferred from one atom to another. The process of oxidation is the result of a loss of free electrons by the substance being oxidized, whereas reduction is the gain of free electrons by the reduced substance. Oxidation and reduction must occur together and also compensate each other. Oxidation, as a process of modifying water quality, is most important in the vadose zone, where there is a copious supply of O_2 from the air and from CO_2. Below the water table in the saturated zone, water is rapidly depleted in O_2. Also, the solubility of O_2 in water is low (6.6 cm^3/L at 20 °C), in contrast to solubility in air (200 cm^3/L at 20 °C). Consequently, the importance of oxidation also decreases rapidly with depth. Typical and important oxidation processes include the oxidation of sulfides, producing Fe_2O_3, H_2SO_4, and CO_2, with the acids attacking carbonates; magnetite, producing limonite; and organic matter, such as lignite, coal, and bitumen, producing CO_2. Reduction also is important in organic deposits, which constitute reducing chemical environments. In these cases, oxygen may be obtained from oxides, sulfates, nitrates as well as nitrites, and from various gases. As a result, ionic species may be generated, including H_2, H_2S, CH_4, and other hydrocarbons, and S^{2-}, $NO^-{}_2$, $NH^+{}_4$, Fe^{2+}, and Mn^{2+}. Some metallic compounds, such as UO_2 (pitchblende), are chemically stable in reducing environments and may be trapped there to form deposits.

Direct *attack by acids* on the rock framework contributal to the chemical evolution of groundwater. The most commonly occuring of these acids are carbon dioxide (CO_2), nitric acid (NO_2), sulfuric acid (H_2SO_4), and various organic (humic, fulvic) acids.

Chemical precipitation of mineral matter dissolved in groundwater may occur for several reasons, including (1) reaction with ions from the solid framework to form insoluble precipitates, such as the formation of fluorspar (CaF_2) by the reaction of fluoride in water with calcium of the country rock; (2) changes in pressure and temperature affecting the solubility of certain chemical constituents in water, as in the precipitation of calcareous tufa ($CaCO_3$) around the orifices of springs due to the release of dissolved CO_2 upon pressure decrease, or the deposition of silica (SiO_2) from hot springs owing to a drop in temperature; and (3) oxidation of dissolved matter exposed to air resulting in components of decreased solubility, such as the precipitation of ferric hydroxide ($Fe(OH)_3$) from waters containing ferrous iron ($Fe(OH)_2$) in solution.

Base exchange, or ion exchange, is the process in which ions and molecules adsorbed on the surfaces of solid substances by physical or chemical forces (van der Waals attraction and "chemisorption," respectively) are exchanged for ions in the water. The most important substances capable of ion exchange are clay minerals, such as kaolinite, montmorillonite, illite, chlorite, vermiculite and zeolite, ferric oxide, and organic matter, mainly because they form colloids of large surface areas. An important example of base exchange is the replacement of Na by Ca and/or Mg in bentonite, resulting in a natural softening of the water by enrichment in Na, on the one hand, and increased porosity and permeability of the newly-formed Ca- and/or Mg-based clay mineral.

Reduction of sulfate is due mainly to bacteria and contact with organic matter (coal, lignite, petroleum) and results in the removal of sulfates from the transporting groundwater. One example is the reaction of sulfate water in contact with methane: $CaSO_4 + CH_4 \rightleftharpoons CaS + CO_2 + 2H_2O$; $CaS + 2CO_2 + 2H_2O \rightleftharpoons H_2S + Ca(HCO_3)_2$.

Concentration of the total dissolved solids (TDS) content in groundwater may be effected also by evaporation of water and solution of mineral matter, in addition to various chemical reactions indicated earlier. Concentration by evaporation is operative mainly in the soil-moisture zone and between rainfall events. In this zone, owing to evaporation of earlier rain water, salt concentration increases and the dissolved salts are washed down to the water table by subsequent rains. The higher the temperatures and the longer the periods between rainfall events, the higher is the degree of salt concentration in the groundwater. On the discharge ends of flow systems, concentration by evaporation may lead to soil salinization and/or the formation of continental salt deposits as the transported salts precipitate from the groundwater upon emerging at the land surface (Jankowski and Jacobson 1989; Macumber 1991; Tóth 1971; Wallick 1981; Williams 1970).

Concentration by solution may also be an important hydrochemical process in the subsurface. The maximum concentration attainable by this process is limited by the chemical equilibrium between the rock and water. If, however, there is a sufficiently long time for the water to dissolve mineral matter, a very small amount of soluble minerals in the rocks will result in relatively high water salinity. For instance, in leached clays with a NaCl concentration of 1–2%, a density of 2.2, and porosity 40%, water in equilibrium with the rock will contain 13.2–26.4 g/L of NaCl.

Ultrafiltration by shale membranes is thought to be a possible mechanism for increasing ionic concentrations in groundwater. The hypothesis postulates that compacted clays and shales may perform as imperfect semipermeable membranes through which water molecules are forced by differences in hydraulic heads. The ions of chemical species are left behind, thus increasing the salt concentration on the high pressure side of the argillaceous beds. The process is probably not as prevalent and general in nature as its original proponent thought (Berry 1969).

Physical Processes

Lubrication by water of discontinuity boundaries in the rock framework, such as grain surfaces in soils and in unconsolidated sediments or fracture and fault planes in indurated rocks, reduces friction and enhances the effects of shear stresses, possibly acting upon the discontinuities. As a consequence, shear movements of soil and rock material can be induced along the discontinuities, ranging in magnitude from minor rearrangement of mineral grains, as in compaction, to major land slides and earthquakes. The process is particularly effective in regions where large variations in precipitation cause large fluctuations in the water table (Deere and Patton 1971). The effect is further magnified by high or increased pore pressures (neutral stresses) that help to reduce frictional resistance to shear displacement. Relatively high or increased pore pressures are natural attributes to the discharge segments of groundwater flow systems.

Pore-pressure modification, as compared to hydrostatic values for given depths below the water table, can have various causes, with widely ranging geological consequences. Reductions or increases in pore pressures, with respect to either space or time, affect the types, rates, and directions of chemical reactions, the solubility of gases, gas-saturation levels in subsurface fluids, and the strength and even the integrity of rocks (Domenico and Schwartz 1997; Freeze and Cherry 1979; Gretener 1981; Hubbert and Rubey 1959; Tóth and Millar 1983).

Modification of pore pressures by gravity-flow systems is a dynamic effect. It changes systematically from negative through zero to positive in recharge, throughflow, and discharge areas, respectively, (*Figure 1;* Tóth 1978). Based on Terzaghi's (1925) theory of stress relations in saturated rocks, these changes lead to increases in effective stresses, i.e., to increased strength, in soils and unconsolidated rocks in recharge areas, while reducing the effective stress, i.e., the strength, at a system's discharge end. The result is an increased vulnerability of the land surface to soil erosion, landslides and other forms of mass wasting in discharge regions, and a relative increase in the stability of hill slopes, river banks and various positive geomorphologic features in areas of recharge.

Kinetic or Transport Processes

The *transport of water* itself in flow systems is groundwater's most fundamental process in playing its role as a geologic agent. In addition to its functions as a medium of transport and a reactive agent in the subsurface environment, water is also a component of that environment as well as of the hydrosphere of the land surface. By means of the systematized flow paths, the water masses are regularly distributed in a gravitational flow domain and thus effect regionally contrasting moisture conditions between the regions of inflow and outflow. The process may be viewed as the subsurface portion of the hydrologic cycle and, as such, a key element in the areal distribution of water bodies, their chemical characteristics, the type and magnitude of water-table fluctuations, and the many far-reaching ecological ramifications linked to these conditions.

The *transport of aqueous and nonaqueous matter* in and by groundwater flow systems also is fundamental among the subsurface geologic processes. A wide variety of matter in many different forms is transported by groundwater flow, including aqueous solutions of organic and inorganic ions; particulate matter in colloidal form or larger size suspended grains; gases as bubbles or in solution; globules, micelles, or ionic solutions of liquid hydrocarbons; and viruses and bacteria. The importance of transport of these matters by groundwater derives from the cumulative effects of the sustained processes resulting in the leaching and removing of minerals from soils and rocks, carrying nutrients to surface-water bodies, building and remigrating deposits of metallic and nonmetallic minerals and hydrocarbons, causing water washing and biodegradation of ore deposits and oil accumulations, and concentrating contaminants at fluid-dynamically suitable subsurface locations.

Heat transport by moving groundwater is one of the most visible and most well understood geologic processes in the subsurface (Beck et al. 1989; Romijn et al. 1985; Rybach 1985; Smith and Chapman 1983). Water can contain, and thus transport, heat because of its specific heat capacity, $r_w C_w$, where r_w is the water's density and C_w is its specific heat. If a temperature difference exists, i.e., thermal disequilibrium, between the water and its ambient environment, heat is induced to flow in the direction of the lower temperature. The rate of heat transfer depends on numerous factors, including the thermodynamic properties of the saturated rock framework and of the water, the temperature difference between the water and the environment, and the rate of the water flow. The greater the rate of heat exchange the faster the temperature difference (the temperature anomaly) is reduced between the water and the environment.

The rate of heat exchange between moving groundwater and the rock framework is essentially the result of a competition between the dissipation of heat by conduction, on the one hand, and the advective removal of heat by the water's flow, on the other. This competition is expressed quantitatively by the Péclet Number, P_e:

$$P_e = \frac{n \rho_w C_w}{(\rho_m C_m)} \cdot \frac{qD}{k_m}$$

where n is porosity of the rock; ρ_w, ρ_m are density of water and saturated medium, respectively; q is specific volume discharge; D is flow-path length; $k_m = l_m/\rho_m C_m$ is thermal diffusivity, in which l_m is thermal conductivity and $\rho_m C_m$ is specific-heat capacity of the saturated porous medium. In cases where $P_e < 1$, for instance due to slow flow, dissipation by heat dominates and temperature differences between water and rock equilibrate. If, however, $P_e > 1$, then advection, i.e., transport of heat by moving groundwater, prevails over the tendency for equilibration, and temperature anomalies are created and/or maintained. The process is enhanced by highly permeable discontinuities such as faults, fracture zones, cavities, and solution channels, which are often major attributes in the formation of hot springs, hydrothermal ore deposits, or other types of geothermal anomalies.

Manifestations

The geologic agency of moving groundwater is most plausibly revealed by the numerous and diverse effects and manifestations resulting from the various flow-driven chemical, physical, and kinetic processes. Nontheless, in spite of their great number and diversity, all groundwater-induced natural phenomena comprise a relatively small number of basic types, with variations within each type being due to the local characteristics of the "hydrogeologic environment."

The Hydrogeologic Environment

The "hydrogeologic environment" is a conceptual system of those morphologic, geologic, and climatologic parameters that determine the principal attributes of the "groundwater regime" in a given area (Tóth 1970). The six main attributes, or parameters of the groundwater regime are: (1) water content of the rocks; (2) geometry of the flow systems; (3) specific volume discharge; (4) chemical composition of the water; (5) temperature; and (6) the variations of all these parameters with respect to time.

The parameters of the groundwater regime are controlled by the three components of the hydrogeologic environment, namely the topography, geology, and climate. In turn, the environmental components are made up of various parameters, such as: for topography, the size and shape of topographic depressions and prominences, and orientation and frequency of geomorphic features; for geology, soluble mineral content, configuration of lithological and structural features of different permeabilities, e.g., stratification, lenticularity, faulting, fractures, karst, and degree of anisotropy; and for climate, temperature, amount, type, and seasonal variation of precipitation and potential evaporation.

The controlling effect of the hydrogeologic environment on the groundwater regime is easily seen when the roles of the individual components are considered. The climatologic factors determine the amounts and distribution of the water supplied to any region. Topography determines the amount of energy available to the water for motion at any given point in a drainage basin, i.e., the topographic relief determines the distribution of the flow-inducing energy for the water and shapes the boundaries of the flow domain. Finally, geology provides the conduit system for water movement, which controls the possible amounts, rates, and patterns of flow, and the distribution and amount of stored water. Geology also determines the chemical constituents and may contribute local or regional sources of energy by, for instance, compaction, compression, or heat.

The various environmental parameters can combine in nature in a virtually unlimited number of ways, each of them modifying a groundwater-related basic process or phenomenon in a different way. For instance, soil-mechanical effects of discharging groundwater may be manifest simply by liquefaction (quick sand, quick clay) in a flat, plains region; by soil creep, slumping, and landslides in hills and mountains; or ice mounds and frost heaving under cold climates. Discharging spring water at the end of a simple flow system is cold and fresh, hot or saline, depending on whether the system is shallow in a cold climate, passes by a subsurface heat source, or across beds of evaporites. Tree types, characteristic of groundwater discharge areas are, among others, willow, alder, and tamarack in cold climates; birch, poplar, and oak in temperate regions; and palms in dry tropics.

Types

In order to facilitate an overview and thereby to enhance an appreciation of the common origin of the mulitude of groundwater-generated and environmentally-modified effects and manifestations, it is expedient to group them into a few basic types. Six such types are defined for the present purpose (Tóth 1984), as discussed below. The ,main factor in the formation of all phenomena within each of these types is the effect of groundwater itself. Several levels of further divisions can be made in each case until individual effects and manifestations of groundwater flow are identified as shaped by the hydrogeologic environments of particular localities. By way of illustration, some examples are presented for each of the main types of natural phenomena below.

Hydrology and hydraulics

Two important hydraulic phenomena associated with the gravity-induced basinal flow of groundwater are the areally systematic orientation of the flow's vertical components, and the relief-dependent depth of the phreatic belt (annual fluctuation of the water table). Flow is generally descending under positive morphological features, whereas it is ascending beneath topographic depressions *(Figure 1)*. Also, the water table is at a greater depth and its annual fluctuation is greater in recharge areas than in discharge areas (Fogg and Kreitler 1982; Freeze 1969; Meyboom et al. 1966; Mifflin 1968; Tóth 1984, Figure 22). Although the type of these conditions is topography dependent, their magnitude, intensity, and areal extent are strongly affected by the regional climate.

An important hydrologic consequence of basinal flow distribution is the regionally contrasting near-surface and soil-moisture conditions. In general, moisture conditions are deficient in recharge areas and excessive in discharge areas as compared with the throughflow regions, i.e., with regions without groundwater recharge or discharge. Depending on the climate and geology, deviations from a neutral water balance may be manifest by imperceptible amounts of, and differences in, soil moisture, to striking contrasts between parched recharge areas and marshy lowlands. Boelter and Verry (1977) present an illustrative case from Minnesota, USA, of steady and high annual surface runoff from a groundwater fen (discharge position) versus a high variation and low rate of runoff from a perched bog (recharge position) of similar areal extent. Tóth (1984) shows a relatively dry cashew plantation in a high recharge area of permeable Permian sandstone at Neyvely, Tamil Nadu, India, contrasting sharply with the paddy fields and flowing wells in the self-sustained marshes of the flow system's discharge terminus, approximately 15 km away. Moisture contrasts of this nature appear to be directly proportional to the rock's permeability. In sand dunes, for instance, high permeability allows ponded water to collect from groundwater discharge only tens or hundreds of metres from dune tops with deep water tables and possibly ,arid surface conditions.

Chemistry and mineralogy

Regional groundwater flow can have many different, significant, and visible effects on the chemistry and mineralogy of the rocks and water at and beneath the land surface. Typically, total dissolved solids (TDS) content increases, the anionic facies of groundwater changes from bicarbonate through sulfate to chloride, carbon dioxide and free oxygen decrease, redox potential changes from positive to negative, and the pH from acidic to basic, in the direction of flow and with increasing depth (*Figure 1*; Back 1966; Chebotarev 1955; Domenico and Schwartz 1997; Jankowski and Jacobson 1989; Sastre Merlin 1978). Due partially to these conditons, dissolution and leaching of minerals dominate in intake areas, whereas deposition and accumulation characterize discharge regions. Salts, such as $NaSO_4$, NaCl, $Ca(SO_4)_2$, and $CaCO_3$, that are brought to the land surface may be retained in the soils to cause salinization or accumulate possibly to form commercial deposits, such as sodium sulfate, halite, gypsum, and calcareous tufa (Macumber 1991; Yaalon 1963). Weathering, dissolution, cementation, and diagenesis of a wide range of rocks and minerals are natural manifestations of groundwater's chemical activity.

A well studied example is a $NaSO_4$ deposit, 15–25 m thick, in Alberta, Canada. This deposit has accumulated from groundwater discharge in a closed topographic depression since the last glaciation, approximately 10,000 yBP (Wallick 1981).

Vegetation

The vegetation cover of a locality may be directly or indirectly affected, and in certain cases controlled, by groundwater flow through its effects on the area's soil moisture and salinity. Both the type and quality of the plants are sensitive to groundwater conditions and each site, with different combinations of moisture and salinity (and climate), has a characteristic climax association of herbaceous and woody plants. Because most plants can tolerate a certain range of salinity and moisture, it is their associations rather than the individual species that reflect the groundwater regime. Climax associations in the relatively moisture-deficient recharge areas thrive on soil moisture that would not sustain their discharge-area counterparts. The major types of plants reflecting extreme dry, average, and wet conditions are called xerophytes, mesophytes, and phreatophytes, respectively; salt-tolerant plants are the halophytes. Studies that show the effects of different groundwater flow conditions on plant associations are exemplified by Leskiw (1971); Engelen and Kloosterman (1996); Sastre Merlin (1978); and Tóth (1972). Although it does not invoke the flow-sytem concept explicitly, the "Guidebook for determining the lithological composition of surface deposits and depth of occurrence of ground waters," by Vereiskii and Vostokova (1966), uses a detailed, flora-style presentation of herbs, shrubs, and trees, and occasionally flow arrows, to indicate relations among conditions of soil type, topography, and water-table depth. The relationships are shown in such a way that they can, today, be interpreted in terms of hydraulic regions (recharge, discharge) of flow systems.

Soil and rock mechanics

Soil- and rock-mechanical manifestations of groundwater's geologic agency include moisture-weakened soft soils, liquefied quick ground, and mud flows and landslides. In cases where they are due to groundwater, these phenomena occur mainly in discharge areas. Here, flow-induced increases in pore pressures reduce the effective stresses between the soil's grains, whereas relatively high water levels enhance lubrication. In combination, the two factors tend to diminish the soil's or rock's shear strength and increase their vulnerability to erosion and mass wasting. The actual form of the basically weakened soil- or rock-mechanical conditions depends largely on the, hydrogeologic environment in which they occur. Soft, marshy grounds, often combined with phreatophytic vegetation and soil salinization, cover extensive areas in low-lying plains or bottoms of mountain valleys with relatively homogeneous near-surface soil/rock material (Angelus 1996; Clissold 1967; Srisuk 1994; Tóth 1966). Liquefied conditions of limited areal extent (quick sand, quick clay, "soap holes," "mud volcanoes," "pimple mounds") may be generated in the above situations, in which localized, relatively highly permeable lenticular heterogeneities focus upward flow through reduced cross sections in the rock. This phenomenon is known to occur in flood plains; valley bottoms; sea-side beaches and lake shores; desert wadis; in mines and wells; and under dams, dykes, and levees (piping), in which cases they are known to be possible causes of destructive floods. Significantly, their discharge water is usually fresh in mountainous regions, whereas the water can be highly saline in plains (Farvolden 1961; Ihrig 1966; Tóth 1972, 1984).

In environments where slopes are dominant components of the morphology, the groundwater-weakened state of the geologic materials may be manifest by creeps, slumping, mudflows, landslides, and other forms of mass movements. Owing to the generally high intensity, small dimensions and shallowness of the flow systems, high water salinity is ,not normally associated in these environments, but excessive moisture is a common attribute (Cherry et al. 1972; Freeze and Cherry 1979; Zaruba and Mencl 1969; Deere and Patton 1971).

Geomorphology

The geomorphologic manifestations of groundwater's activities range from the obvious and well known to the masked and unrecognized. Karst development in limestone, gypsum, and halite has long since been attributed to the action of groundwater. The effects of flow systems and their dynamics, distribution, and patterns on the evolution, depth, and geometry of karst caves, sink holes, and channels, as well as on karst-water chemistry, have been extensively studied and reported on (Bedinger 1967; LaFleur 1984; Paloc and Back 1992).

The genetic link between geysers and groundwater flow systems also is well understood, although less widely recognized. In discussions of the workings of geysers, attention is usually focussed on the "plumbing" systems and heat source. Although both of these attributes are indespensable components of a geyser-producing hydrogeological environment, their principal role is to turn an otherwise regular discharge of gravity-flow systems of cold water into spectacularly functioning hot-water springs. In general, geysers and geyser basins epitomize the many-faceted geologic effects of moving ,groundwater. In addition to their environmentally generated cyclic discharge of hot water, other manifestations in common association with geysers are positive water balance, saline soils, mineral deposits, phreatophytic vegetation, quick ground, and other groundwater-induced soil- and/or rock-mechanical phenomena.

Groundwater-induced soil- and/or rock-mechanical weaknesses and, consequently, increased erodibility, often grow into major geomorphologic features. Such features include (1) headward erosion from springs or quick ground, possibly developing into gullies and stream valleys; (2) asymmetrically sloping banks or valley flanks on opposite sides of consequent streams (streams running parallel to the strike of regional slopes), with the upslope bank being flatter and concave because of increased erosion and weakening due to the discharge of groundwater received from the higher ground (Vanden Berg 1969); (3) stream-bank erosion, possibly resulting in lateral translation and concave bending of the thalweg toward the weakened area (Clissold 1967); and (4) mud flows and landslides, induced and/or enhanced by groundwater discharge, which may leave permanent effects on the shapes of hills and mountains and may accumulate into mounds of debris, dam streams, and otherwise modify the landscape, particularly if occurring repeatedly.

Perhaps the least generally appreciated geomorphologic manifestations of groundwater flow are due to its discharge in cold weather or cold climates, namely the various forms of soil-mechanical and ice phenomena. Ice accumulates commonly in the winter and cold climates in discharge areas, even where all available water is used up by evapotranspiration in the summer time. The continual discharge of relatively warm groundwater is often marked by soft, yellowish slush at the contact between the ice and mineral soil. On flat terrains, the ice accumulates as extensive fields, whereas in situations where discharge is concentrated either by topographic features or geologic inhomogeneities, ice mounds may form.

Frost heaving and frost mounds constitute a soil-mechanical group of cold weather/climate manifestations of groundwater flow (Holmes et al. 1968; Mackay 1978; McGinnis and Jensen 1971). The heaving, mounding and possibly fracturing of the ground is due to the gradual growth of frozen groundwater masses, made possible by the continual supply of additional water at the discharge ends of flow systems. Damage to highway pavements in Illinois and Alberta is reported by Williams (1970) and Tóth (1984), respectively, and ice-mound formation is attributed to groundwater discharge in permafrost regions by Müller (1947).

In a prairie environment of Alberta, Canada, a seasonal "frost blister," or "frost mound," approximately 1.5 m high and 20 m in diameter, starts to rise from the flat bottom of a spring-eroded circular depression each fall after ground frost blocks the continued discharge of groundwater through the spring's orifice and its surroundings. Throughout the winter, mounting pore pressure and a growing ice lens keep lifting the ground surface until the spring thaw breaks the frost seal and melts the ice lens. By the end of April, the ground sinks back to its original flat and level position, the previously open tension cracks heal, and water with increased salinity discharges through the crater-like collapsed apex of the former mound. This annual cycle has been observed for several decades (Tóth 1972, 1984).

Transport and accumulation

The transport and accumulation role of groundwater is manifest in nature by a broad range of diverse, sometimes spectacular and sometimes economically important phenomena, which include geothermal temperature patterns; sedimentary sulfide ores; roll-front and tabular uranium deposits; hydrocarbon accumulations, halos, and seeps; and eutrophication of surface-water bodies.

Moving groundwater can create a systematic pattern of heat distribution in a basin owing to its ability, as explained above, to exchange heat with its ambient environment. As a result, descending cold waters reduce the temperatures and temperature gradients in recharge areas below the values that would be due solely to the conductive dissipation of geothermal heat. Conversely, ascending warm waters cause positive anomalies of geothermal heat and gradients in the discharge areas *(Figure 1)*. Flow-induced geothermal anomalies can be accentuated by increased flow rates through highly permeable fault zones and bedding plains, often leading to the development of naturally occurring thermal mineral springs. Geothermal effects of flowing groundwater are well studied and well documented as, for instance, in Beck et al. (1989); Bethke (1985); Deming et al. (1992); Romijn et al. (1985); Rybach (1985); Smith and Chapman (1983).

Mississipi Valley-type ore deposits are considered by various researchers to be the result of the mobilization, transport, and accumulation of metal ions by regional groundwater flow (Baskov 1987; Garven et al. 1993, 1999). According to these hypotheses, metal ions travel in sulfate brines that are reduced in discharge areas by sulfate-reducing bacteria, and reaction with H_2S and/or organic matter, such as coal, peat, and methane.

Theories based generally on the above processes have been advanced to explain the origin of roll-front and tabular type uranium deposits (Butler 1970; Galloway 1978; Raffensperger and Garven 1995a, 1995b; Sanford 1994). The key element in these processes is the transport of metals by groundwater flow from oxidizing recharge regions, where uraninite is highly soluble, to the reducing discharge environment, where it will precipitate. Changing geometries of the flow systems may result in remigration of previously formed deposits.

Certain types and many specific cases of petroleum (oil, gas) accumulations around the world have been attributed to the effect of basinal groundwater flow by numerous authors (Harrison and Summa 1991; Hodgson 1980; Hubbert 1953; Munn 1909; Rich 1921; Sanford 1995; Tóth 1980, 1988; Verwij 1993). According to the "Hydraulic theory of petroleum migration" (Tóth 1980), hydrocarbons can be mobilized in mature source rocks or carrier beds by groundwater flow and advected by its systems toward discharge areas in any of several different forms, such as bubbles, globules, stringers, ionic solution, emulsion, and micelles. En route to a region of flow convergence, the concentration of hydrocarbons increases. Entrapment, thus local accumulation, can be caused by minimum fluid potentials for petroleum, mechanical screening by pore-size reduction, and capillary pressure ,barriers (Hubbert 1953; Tóth 1988). The effectiveness of the latter two mechanisms is augmented by growing particle sizes of the transported hydrocarbons. Such growths are enhanced by the rapidly decreasing temperatures and pressures of the ascending waters in discharge areas. Regional discharge areas represent, therefore, ideal conditions for entrapment and are, indeed, the sites of many large petroleum deposits (Bars et al. 1961; Chiarelli 1973; Deming et al. 1992; Hitchon and Hays 1971; Tóth 1980; Wells 1988).

Hydrocarbon particles that escape entrapment may continue their surfaceward migration and may form concentration anomalies in groundwater, soil gas, plant tissue, sea-bottom sediments, saturated pools as halos, seeps, or springs. During their migration, the hydrocarbons cause chemical reduction in the traversed column of earth material. The affected subsurface environment is called the "geochemical chimney," and it is used extensively in geochemical exploration for petroleum (Schumacher and Abrams 1996). The less-than-expected effectiveness of geochemical exploration has been attributed to a lack of understanding of regional groundwater flow by the exploration community (Tóth 1996).

One possible cause of eutrophication of surface-water bodies is the transport of plant nutrients by groundwater into lakes. Shaw et al. ,(1990) show that phosphorus and nitrogen, derived from fertilizers and lake-side cottage cesspools, are transported by groundwater flow systems and discharged over large portions of lake bottoms, causing anomalously rich growths of aquatic plants. Eutrophication, in such cases, is a manifestation of groundwater's geologic agency.

Summary and Conclusions

The intent of the present "Theme Issue" of *Hydrogeology Journal* is to focus attention on groundwater in its role as a general geologic agent. The objective is sought by approaching the topic from two opposite directions. One of these directions is represented by a collection of several papers, each discussing particular types, aspects, and causes of groundwater's geologic agency. The other direction is represented by this paper, which provides a summary overview of those types and instances of natural processes and phenomena that have been recognized as manifestations of that agency.

In a way, this dual approach to reach the goal mimics the actual historical evolution of the notion of groundwater as a geologic agent. Before the regional patterns and properties of basinal groundwater flow were recognized and clarified during the 1960s and 1970s, the genetic links between a great number and variety of natural phenomena generated by groundwater flow could not be, and were not, appreciated. The various topical papers in this volume describe flowing groundwater as the generator of particular geologic phenomena in considerable detail. The present paper, on the other hand, highlights groundwater as the common generator of those and even some other natural phenomena by means of an overview.

Two causes are considered in this paper as basic to groundwater's role as a geologic agent: interaction between the water and its ambient environment, and systematized and hierachical flow paths. The interactions between water and environment generate various processes, products, and conditions. The systematized flow paths, or flow sytems, on the other hand, result in a basin-wide self organization of those effects of interaction.

Ten chemical, two physical, and three kinetic processes are recognized through which interaction between groundwater and its environment, as well as organized distribution of effects, take place. These processes are the following: (1) Chemical processes, including dissolution, hydration, hydrolysis, oxidation-reduction, attack by acids, chemical precipitation, base exchange, sulfate reduction, concentration, and ultrafiltration or osmosis; (2) Physical processes, including lubrication and pore-pressure modification; and (3) Kinetic processes, including the transports of water, aqueous and nonaqueous matter, and heat. Owing to the transporting ability and spatial patterns of basinal flow, the effects of interaction are cumulative and distributed according to the geometries of the flow systems.

The results of these processes are manifest by a great variety of natural phenomena. Although the number and diversity of these manifestations are great, they can be considered as environmentally modified versions of six basic types: (1) hydrology and hydraulics, (2) chemistry and mineralogy, (3) vegetation, (4) soil and rock mechanics, (5) geomorphology, and (6) transport and accumulation.

In essence, the general effects of groundwater's geologic agency are phenomena of depletion and accretion of water, metallic and nonmetallic solids, hydrocarbons, and heat; soil- and rock-mechanical instabilities, possibly developing into geomorphological features; diagenetic mineral changes; changes in the vegetation cover; eutrophication of surface-water bodies; and systematic areal distribution or self organization.

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