

FLUIDS IN GEOLOGICAL PROCESSES

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Summary

Fluids play an important role in many geological processes. The principal interactions of fluids are: (1) solute transport including chemical processes, (2) formation of ore deposits, (3) heat transport, (4) formation of hydrocarbon deposits, (5) participation of fluids in stability of slopes and tectonic movements including earthquakes. Ground water steady-state flow can be described by the Laplace's Equation, which can be solved for different permeability distributions and boundary conditions. Basic processes of transport in ground water include: advection, diffusion, dispersion, adsorption/retardation, and decay. They are included in the advection-dispersion equation (ADE). Principal geochemical processes include dissolution of gases, precipitation/dissolution of solids, redox reactions, hydrolysis, and cation-exchange. Both transport and geochemical processes can modify concentrations of dissolved solutes and cause processes like soil salinization and formation of brines. Fluid phase play a major role in mobilization, transport and deposition of nearly all types of ores. The aqueous part of ore-bearing fluids usually comes from (1) surface water (including rainwater, lake, river, seawater), (2) deeply penetrating ground water, (3) magmatic water, (4) metamorphic water and (5) highly evolved water of unknown provenance. Salinity of ore-bearing fluids usually varies between ~1 and 60 wt. % of dissolved salts and most of the metals is carried in the form of metal complexes. Heat transport is

strongly affected by heat convection related to the ground water flow, which can change heat pattern compared to no-flow conditions. The tendency for convective heat transport is expressed by the Peclet Number for heat transport. Migration and accumulation of hydrocarbons depends on ground water flow. There is a relation between the dip of stratigraphic boundary of a permeable layer transmitting hydrocarbons and hydraulic gradient, which has to be satisfied to accumulate petrol. Stability of slopes and tectonic movements depend on pore pressure. Increase of pore pressure can decrease the shearing resistance of soil and cause slope failure with resulting landslide. Earthquakes also depend on pore pressure and can be initiated by pore pressure changes.

1. Introduction

This text has the objective to present an overview of the role of fluids in geological processes. We deal exclusively with ground water and related fluids because the role of surface water in geomorphological processes is discussed in specialized chapters.

There are many forms of ground water interactions with natural environment. The principal interactions are: (1) solute transport including chemical processes, (2) formation of ore deposits, (3) heat transport, (4) formation of hydrocarbon deposits, (5) participation of fluids in stability of slopes and tectonic movements including earthquakes. We will discuss each type of interactions separately.

2. Principals of Ground Water Flow and Solute Transport

Ground water movement is described by the *Darcy's Law*, expressed in one of its common forms as

$$v = -\frac{K.I}{n_e} \quad (1)$$

where v is ground water average linear velocity, K is hydraulic conductivity, I is hydraulic gradient and n_e is effective porosity. Negative sign indicates flow from higher hydraulic head point to lower hydraulic head point. *Hydraulic conductivity* k characterizes transmitting properties of porous media and transmitted liquid and is defined for *representative elementary volume (REV)*. The REV is a volume of porous media for which we can define average hydraulic parameters. The size of the REV must be large compared to the scale of microscopic heterogeneity, but small relative to the entire domain of flow. The size of REV varies dramatically, for example, in well sorted coarse sand is about 10^{12} smaller than the minimum REV size needed to represent permeability in a granitic block with fractures about 10 m apart. Steady-state flow in homogeneous porous media ($k = \text{const.}$) is described by *the Laplace's equation*, expressed in two dimensions (2-D) as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \quad (2)$$

where h is hydraulic head. However, a porous media is rarely homogeneous and the effect of variable hydraulic conductivity has to be taken into account. Thus, for determination of flow pattern we need to know hydraulic head distribution, hydraulic conductivity distribution and boundary conditions for investigated system plus the distribution and amount of recharge.

There is a hierarchical set of different flow systems in a regionally unconfined drainage basin. This includes shallow flow system related to local topography, intermediate system, and deep regional system with single recharge and discharge areas.

Basic transport processes in ground water are: (a) advection, (b) molecular diffusion, (c) dispersion, (d) retardation, and (e) decay. *Advection* describes the process when dissolved solids are carried along with the flowing ground water. The mass of solute transported by advection is a function of its concentration in ground water and the quantity of ground water flow. When only advection occurs, then the mass of solute remains in the same stream-tube and there is a sharp boundary between ground water containing the solute and solute-free ground water. Advection is the principal transport process and, thus, the knowledge of ground water flow pattern is the key to the determination of the migration of solutes.

Diffusion is a transport process based on the concentration gradient, which takes place even in stagnating ground water. The process is also called molecular diffusion and is caused by random motion of solute molecules due to their kinetic energy. Stationary diffusive flux in one dimension is described by the first Fick's Law,

$$J = -D_d \frac{dC}{dx} \quad (3)$$

where D_d is diffusion coefficient for porous media, C is concentration of a solute and x is a distance.

Dispersion is a spreading of solutes due to the heterogeneity of permeability in porous media. The heterogeneity occurs at microscopic scale (velocity of flow is higher in large pores and in the middle of pores), mesoscopic scale (for example, due to less permeable lenses of clay in a sandy aquifer), and at macroscopic and megascopic scales (permeability differences between different layers and different geological formations in a regional flow system). Because of the heterogeneity, ground water carrying solute is not traveling at the same velocity as the average linear velocity of ground water flow, and mixing takes place along flow path. This mixing is called mechanical dispersion and has 3 components called *dispersivities*: longitudinal dispersivity in the direction of flow, transverse horizontal dispersivity in horizontal direction perpendicular to the ground water flow, and transverse vertical dispersivity in vertical direction perpendicular to the ground water flow. Both diffusion and mechanical dispersion are coupled in a parameter called *hydrodynamic dispersion coefficient*, D .

Retardation is related to *adsorption* of a solute on solid phase. Adsorbed solute travels slower compared to the average linear velocity of ground water flow. The most common description of the adsorption process is by *the linear adsorption isotherm* K_d , defined as

the slope of graph adsorbed solute S vs. concentration of solute in water C . The relation between the *retardation coefficient* R and the linear adsorption isotherm K_d is

$$R = \frac{v_w}{v_s} = 1 + \frac{\rho_b}{n} \cdot K_d \quad (4)$$

where v_w is ground water flow velocity, v_s is velocity of solute transport, ρ_b is bulk density of solid phase (adsorbed), and n is porosity. When retardation coefficient R is equal, for example, to 4.0, then the velocity of advective solute transport is four times slower than the ground water flow velocity. There are more complex isotherms, including the Freundlich isotherm and the Langmuir isotherm, which can be used to determine the retardation factor.

Decay of a solute (for example, dissolved organic matter) is decomposition of dissolved solute in time, which can generally be described as first order kinetic process, expressed as

$$\frac{dC}{dt} = -\lambda \cdot C \quad (5)$$

where C is concentration, t is time, and λ is a *decay constant* related to *half-life* by relation $\ln 2 / t_{1/2} = \lambda$, where $t_{1/2}$ is half-life. Some processes can be described by kinetics of different orders (zero order kinetics, second order kinetics).

All above mentioned processes are included in *the advection-dispersion equation (ADE)* of transport which includes retardation and decay. One-dimensional form of the equation is

$$\frac{D}{R} \cdot \frac{\partial^2 C}{\partial x^2} - \frac{v}{R} \cdot \frac{\partial C}{\partial x} - \lambda \cdot C \pm W = \frac{\partial C}{\partial t} \quad (6)$$

First term is dispersion term, second term is advection term, third term is decay term, fourth term is chemical reaction term, and fifth term at the right side of the equation is concentration term. The chemical term W is source/sink term for solutes generated by geochemical reactions discussed in the next section. The equation, including its 2-D and 3-D forms, can be solved both analytically and numerically for different boundary conditions. However, in majority of solutions complex geochemical processes are not included and coupled transport/geochemical models are in the stage of development.

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Biographical Sketches

Ondřej Šrůček received his M.Sc. in 1984 in geological engineering in 1984 at the Technical University of Mining in Ostrava, Czechoslovakia, M.Sc. in in hydrogeology in 1993 at the University of Waterloo in Waterloo, Ontario, Canada, and Ph.D. in contaminant geochemistry in 1997 at the Université Laval, Ste Foy, Québec, Canada. He teaches contaminant hydrogeology and geochemistry courses at Universidade de Sao Paulo, Sao Paulo, Brazil, Pontificia Universidade Catolica, Rio de Janeiro, Brazil, and Charles University, Prague, Czech Republic. He is member of the Groundwater Arsenic Research Group (GARG) at the Royal Institute of Technology, Stockholm, Sweden. He was consultant for contaminant hydrogeology and geochemistry including mining wastes, contamination by metals and chlorinated organics and petroleum products in Algeria, Bangladesh, Bolivia, Brazil, Canada, Chile, Czech Republic, India, Peru, and Spain.

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