Particle dynamics class, SMS 618, Emmanuel Boss (last edited on 12/3/2003)
Particles in bed

Properties of sediment beds (based on Boudreau, 1997, Allen, 2001):

Porosity:
Porosity (ϕ) is defined as the fraction of volume of sediment that is occupied by open space (where the pore water is), and is calculated as ϕ= (total volume of voids)/(overall volume of grains+voids). It is a non-dimensional fraction. It equals (1-the fractional volume concentration), the ratio of (total volume of grains)/(overall volume of grains+voids).
Porosity is a function of packing (random vs. organized, loose vs. dense), particle size distribution (sorted vs. wide), particle shapes. The process by which the bed is formed (single grain accumulation vs. a turbidity current coming to a halt), can greatly influence the porosity. When particles settle together they tend to get 'locked' in position and the porosity is therefore high. Single grain deposition will favor a denser packing (lower porosity). Porosity varies from ~0.4 for non-cohesive beds (e.g. sand) to 0.9 for organic rich fluff layers. In muddy (cohesive) beds porosity can be very high (0.8-0.95) for newly deposited material, but decreases a lot as the deposit dewaters with age. Porosity can be measured, for example, by the difference of wet and dry mass of a given volume of sediment.
The closest packing of identical spheres (rhombohedral, see Allen, 2001) has ϕ=0.26, a value rarely approached in nature.

Diffusion in sediment pore water and tortuosity:
Diffusion in sediment-water mixture is slower than in the equivalent volume of water due to the convoluted path that ion/molecules have to follow to circumvent particles.
The diffusion in sediment (D') is related to the diffusion in the water D as follows:

$$D' = D/\theta^2,$$

where θ is the tortuosity (dimensionless).The tortuosity is defined as the ratio of the average incremental pathlength dL that an ion/molecule takes to get to a point at a geometric distance dx in the direction of diffusion, $\theta = dL/dx \geq 1$.
Turtuosity is related to a measured parameter, f, which is obtained by an electric resistivity measurement: f=(bulk sediment specific resistivity)/(resistivity of pore water alone), and to porosity through:

$$\theta^2 = f\phi.$$

Three types of relations have been suggested between tortuosity and porosity:

Archie's law:	$\theta^2=\phi^{1-m}$;	$3\geq m=m(\phi)\geq 2$	($m=2.14\pm0.03$)
Burger-Frieke equation:	$\theta^2=\phi+a(1-\phi)$;		($a=3.8\pm0.1$)
Modified Weissberg relation:	$\theta^2=1-b\,ln(\phi)$;	$2.1\geq b\geq 0.5$	($b=2.0\pm0.1$)

The values in brackets indicate the best-fit values to a literature based dataset obtained by Boudreau, 1997, to data with $1\geq\phi\geq 0.2$.

Permeability: Permeability is a measure of the ease of flow of a fluid through a porous medium. It is based (and computed) using Darcy's law that states that at low Re # the flow rate (Q) through a porous material is linearly proportional to the pressure drop per unit length ($\Delta P/d$) along the flow:

$$Q=-kA\Delta P/\mu d.$$

A is the cross-sectional area and μ the fluid's viscosity. $[k]=m^2$, since k has dimensions of length-squared and since the only length scale is the particles' diameter it makes sense that $k \sim d^2$, where d is the mean diameter of the sediment. It also point to the fact that the fluid is slowed by interaction with the surface areas of particles. For a given porosity there is much more surface area to mud sediments than to sandy sediments. We also expect k to increase with porosity. There is no consensus, however, on how it increases with porosity; Four relations from the literature are (first 3 from Boudreau, 1997):

Carman-Kozeny equation: $k= d^2\phi^3/(1-\phi)^2/180$,
Blake-kozeny equation: $k= d^2\phi^3/(1-\phi)^2/150$,
Rumf-Gupte equation: $k= d^2\phi^{5.5}/5.6$,
Allen (2001): $k= d^2\phi^{4.65}/(1-\phi)/18$.

None of these has been well established for $\phi \geq 0.8$. In addition, comparison of these formulations suggests large differences, as well as a large dynamic range (Fig. 1):

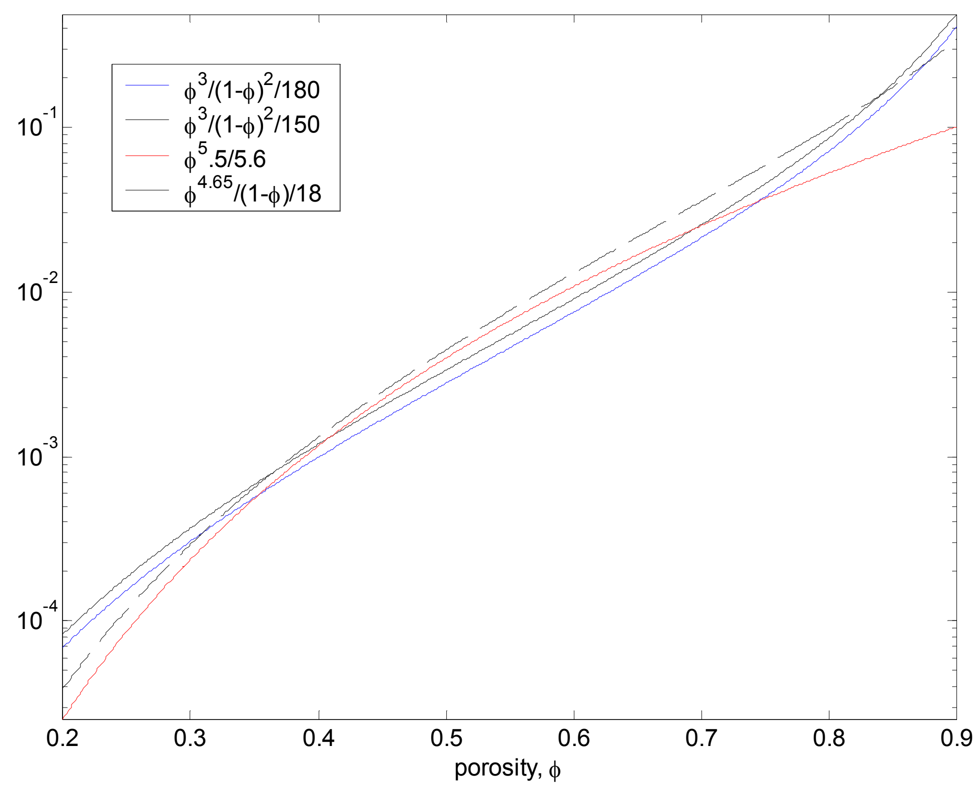

Fig. 1. Comparison of four different relationships between permeability and porosity.

Given that there is likely to be an inverse correlation between mean diameter and porosity in sediments the dynamic range in permeability is likely to be smaller than suggested by Fig. 1.

Liquidization: fluidization and liquefaction.
Fluidization occurs when an upward stream of water is applied to a suspension of particles such that the suspension settling velocity matches the upward stream velocity (e.g. the suspension stays put). Large upward discharges are not necessary to fluidize natural sediments as their (hindered) settling is slow.
Porous, liquid filled, sediments can become liquefied by application of an impulsive or cyclic force (e.g. earthquack, large waves from storm) that dislodges particles from touching each other thus changing rapidly the properties of the sediment (the pressure field changes rapidly as the weight of the sediment contributes to the pressure, through the weight of the suspension, when they are suspended but not when they are supported by each other, Fig. 2). A sediment bed that behaves as a solid when shear is applied to it flows like a liquid following such liquefaction. Parameters that contribute to liquefaction are: 1. high disturbing force, 2. cyclic forcing, 3. high porosity, 4. a grain size towards fine sands, 5. little confining pressure (shallow burial), 6. recent deposition.
Once liquefied the horizontal variations in pressure between the liquefied sediment and nearby water can force the lateral movement of the suspension.

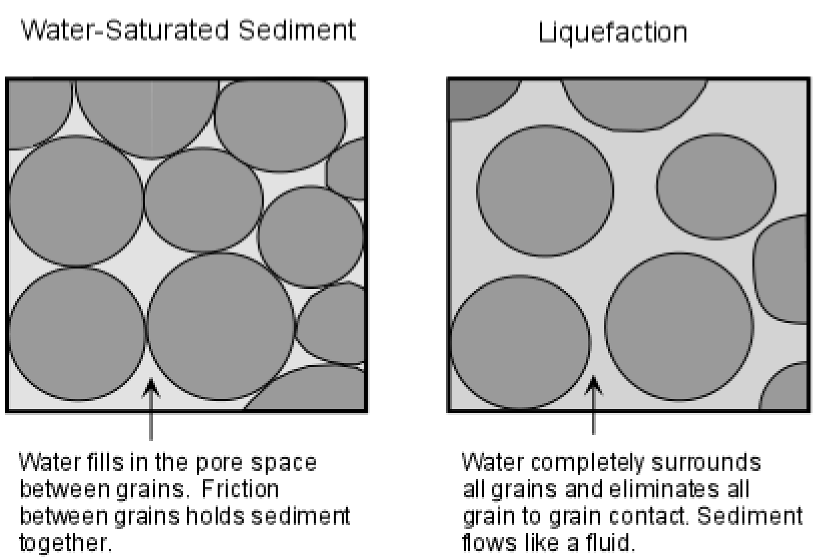

Figure 2. Liquefaction. From: earthsci.org/teacher/basicgeol/ earthq/earthq.html

Mechanisms for enhancement in exchange of ions/molecules/small-particles between bed and overlying waters in permeable sediments:
Huettel and Webster (2001) identify a series of mechanisms that can lead to enhanced exchange of solutes (and small particles) between bed and overlying fluid (in all cases transports were found to be proportional with permeability and inversely proportional to viscosity):

1. Steady flow over bed with isolated permeable obstruction: details of penetration are closely linked to the topography with downwelling in the front of the obstruction and upwelling in its lee.
2. Steady flow over ripples and dunes: large downwelling regions over upstream face of the ripples and concentrated upwelling near the trough.
3. Steady flow over rough topography (as above).
4. Steady flow above bed with horizontally varying permeability: divergence of horizontal flow due to changes in permeability force vertical velocities.
5. Steady flow above smooth porous beds: When $\phi>0.75$, flow above bed induces a slip flow at a thin layer near the surface of the bed (Brinkman layer). Interaction with grains enhances the vertical and horizontal diffusion.
6. Wave-induced flow over flat bed: time dependent variation in pressure at sediment-water interface forces time dependent flows in sediment. Waves force rotational motion within the sediment which enhances dispersion.
7. Shear dispersion (due to waves or with steady flow): Shear within pores (between wall of pore and center) stretches elements of fluid enhancing diffusion.
8. Waves over rippled bed: similar to the steady flow above, but with oscillatory current.
9. Pore water exchange in beaches: As waves and tides rise and fall, water fill and drains out of beach interstices.
10. Density driven convection: when water overlying the sediment is heavier than pore water, gravity will work to exchange the two fluids (or in the least enhance diffusion between them).

Another mechanism which dominates the exchange in weakly permeable sediments is bio-turbation (see Boudreau, 1997, and The Benthic Boundary Layer, 2001).

Useful references:

Allen, J. R. L., 2001. Physical Sedimentology, Blackburn Press, 272pp.

Boudreau, B. P., 1997. Diagenetic Models and their implementation. Springer, 414pp.

The Benthic Boundary Layer, 2001, edited by B. P. Boudreau and B. B. Jorgensen, Oxford University Press.