are ingested with lizards — rather than directly from the plant — is supported by observation and by a strong correlation between lizard remains and *Lycium* seeds in the pellets. The seeds in the shrike pellets had a higher germination rate (64%) than those from lizard droppings (50%) or directly from the plant (54%), showing that their experience in passing through two vectors had increased their potential for immediate germination.

Lizards are an effective dispersal system for *Lycium* on Alegranza, but movement of the plant between islands using the lizard as a vector is likely to be rare (although not impossible[5]). Movement of the seeds from lizard to bird, however, presents a range of opportunities for island-dwelling plants, giving them a far greater chance of moving to new islands. Because the seeds are retained in the shrike's gizzard for less than an hour, feeding and flight must follow in rapid succession if dispersal by this means is to be effective. Like so many other events in island biology, given enough time it will probably happen.

The significance of predators as secondary dispersers of fruits and seeds is likely to be limited to specific situations. In Britain, the sparrowhawk (*Accipiter nisus*) is known to exploit situations where flocks of fruit-eating birds are feeding[6]. So, again, the predator could easily ingest seeds with the prey. But the transfer of seeds from one bird to another in this way is unlikely to have much of an effect on seed dispersal. On Alegranza, *Lycium* seeds have also been found in kestrel (*Falco tinunculus*) pellets, but these may have been derived from fruit-eating birds rather than lizards. Only where seed transfer involves increased mobility and range (as in the plant–lizard–bird sequence) will new dimensions of dispersal be opened. Predation can then assume a biogeographically significant role. □

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Geochemistry

Colloidal culprits in contamination

Bruce D. Honeyman

Perhaps nowhere have the details of contaminant transport in groundwater systems been more contentious than in the area of nuclear waste disposal. Over the past decade, the discovery of colloidal forms of actinides, such as plutonium (Pu), has often been at the centre of concern over underground storage of radionuclides. On page 56 of this issue[1] Kersting *et al.* provide an illustration of the striking influence colloids[2] may have on contaminant transport. The authors have studied groundwater migration of Pu from a nuclear detonation site in Nevada. However, the particular significance of their report lies in reinforcing a general awareness of colloid-facilitated contaminant transport.

As late as the early 1980s, a groundwater contaminant was generally assumed to occupy one of two phases: a stationary phase consisting of aquifer solids; and a mobile, aqueous phase that serves as the medium for the movement of dissolved chemical species. In such a system, the rate of contaminant transport depends on the groundwater transport velocity, of course, but also on the distribution of the contaminant between the two phases. The greater the extent to which a contaminant partitions into the immobile phase, the slower its average transport velocity in the ground water (Fig. 1).

The unexpected appearance of low-solubility contaminants some distance from known sources, or sooner than would be expected from their solubility, led to examination of the possible involvement of non-aqueous, mobile colloids in contaminant transport[3]. Invoking colloids to explain such observations gave rise to three-phase models of contaminant transport (Fig. 2, overleaf). The results of Kersting *et al.* reinforce the need for such models. In their work, they use isotopic 'fingerprinting' to demonstrate that Pu, an element with extremely low aqueous solubility (as low as 10^{-17} M, depending on its oxidation state), was transported significant distances through a groundwater system, and they argue that colloidal species were responsible.

Colloid-facilitated transport of contaminants has become a sort of Gordian knot for environmental scientists. Field studies have often been subject to sampling artefacts, such as colloid mobilization through excessive well-pumping rates, and it has been difficult to reconcile field observations with theory and model simulations. (In 1988, a reviewer of a manuscript[4], on which I was an author, implicating a colloidal intermediate in the scavenging of metals in marine systems, complained: "The problem developing in the literature with colloids is that they are blamed or claimed for everything that can't be explained".) Since then, colloid-facilitated contaminant transport has gained broad acceptance. Nonetheless, few studies have unequivocally demonstrated its significance in the field.

Figure 2 compares two- and three-phase contaminant transport models. Figure 2a shows a low-solubility contaminant distributed between an aqueous phase and immobile aquifer solids (the macroparticles). Colloidal materials can increase the apparent solubility of low-solubility contaminants (Fig. 2b) if those contaminants strongly associate with the colloids and the colloids minimally interact with the stationary macroparticle phase. Because colloid groundwater concentrations are typically quite low, the contaminants most likely to be transported by colloidal materials are of extremely low solubility and strongly partition to mobile non-aqueous phase materials. In this respect, Pu is an ideal candidate; others include pesticides (for instance, DDT and dieldrin), polynuclear aromatic hydrocarbons, other light actinides (for example, thorium) and many transition metals (such as cobalt).

Groundwater colloids originate from two sources[5]: through mobilization of existing colloid-sized (1 nm to 1 μm) materials in aquifer systems following chemical pertur-

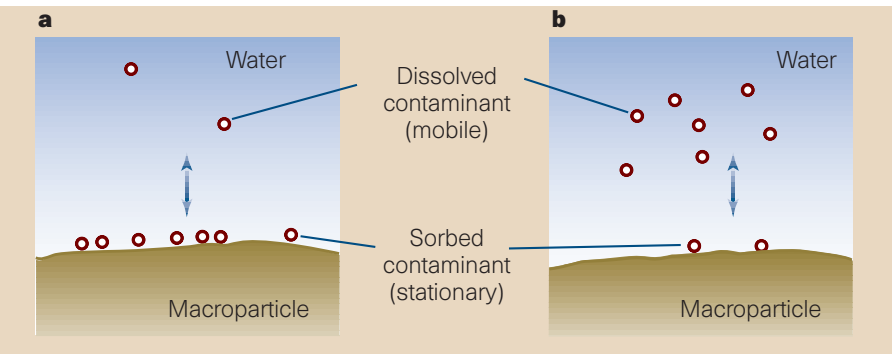


Figure 1 **Contaminant transport in a simple two-phase groundwater system.** a, **High sorption, and therefore low contaminant solubility;** b, **low sorption, high contaminant solubility. Macroparticles are the stationary components of a groundwater aquifer and include clays, metal oxides such as quartz, and particulate organic matter. The extent to which contaminant molecules are sorpted to macroparticles (by adsorption, surface precipitation or absorption) regulates the rate of contaminant transfer through groundwater systems for a given water velocity.**

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100 YEARS AGO

The native arithmetic of Murray Island, Torres Strait, is described by the Rev. A. E. Hunt in the latest *Journal* (New Series, vol. I Nos. 1 and 2) of the Anthropological Institute. The only native numerals are netat (one) and neis (two). Higher numbers would be described either by reduplication, as neis netat, literally, two-one for three; neis-i-neis, or two-two for four, &c., or by reference to some part of the body. By the latter method a total of thirty-one could be counted. The counting commenced at the little finger of the left-hand, thence counting the digits, wrist, elbow, armpit, shoulder, hollow above the clavicle, thorax and thence in reverse order down the right arm, ending with little finger or right hand. This gives twenty-one. The toes are then resorted to, and these give ten more. Beyond this number the term gaire (many) would be used. English numerals are now in general use in the Islands.
From *Nature* 5 January 1899.

50 YEARS AGO

Fertilized mouse ova have been cultivated *in vitro*, and their development filmed, by Friedrich-Freska and Kuhl, who used as medium a clot of guinea pig plasma and mouse embryo extract containing segments of Fallopian tube. Like Chang, I have been working on ovum culture with a view to transplantation of ova. Chang has used rabbits, with serum as a culture medium; I have chosen to use mice, as more readily available, and because (like most domestic animals) they have naked eggs. Seeking a medium readily prepared in large quantities, I have tried saline hen-egg extracts. The procedure adopted revealed an unanticipated difference between the viabilities of two-cell and later tubal stages; eight-cell ova survived and developed in culture, whereas two-cell ova did not. ... A few became blastocysts either completely separated from the zona, or spherical and still half-enclosed in the split and distended membrane. ... A physiological difference between two-cell and eight-cell stages seems clearly established; the reason for the difference remains obscure. The result recalls a similar one of Chang's, namely, survival of morulae, but not two-cell ova, when transplanted into the rabbit uterus, though both survived when cultivated in serum.
From *Nature* 1 January 1949.

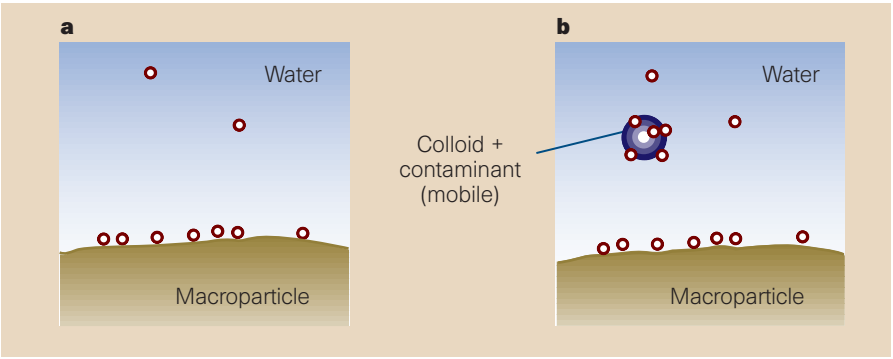


Figure 2 **Comparison of generalized two- and three-phase groundwater systems.** a, **Two-phase;** b, **three-phase. The third phase in** b **is a colloid or microparticle, shown here with contaminant molecules sorbed to it, thus making them mobile. Colloidal material is usually chemically similar to the stationary macroparticle phase.**

bations or changes in flow velocity from pumping, and through *in situ* precipitation of supersaturated mineral phases. Colloids are removed from the aqueous phase by deposition on stationary macroparticles; it is the efficiency of deposition that regulates the facilitation of contaminant transport[6].

Kersting and colleagues' analysis[1] of colloids isolated from pumped ground water clearly identified the source of the Pu as a single underground nuclear test site, the test well and detonation site being 1.3 km apart. The elimination of other detonation cavities and contamination as the source of Pu makes it evident that the Pu has been transported through the ground water by some process.

As delineated by Ryan and Elimelech[5], however, three conditions must be met for defensible evidence that colloids have transported contaminants: first, colloids must be present; second, contaminants must associate with them; and third, the colloid–contaminant combination must move through the aquifer. The results of Kersting *et al.* qualitatively meet the first two conditions. But, as the authors point out, the possibility of sampling artefacts meant that they could not quantify some of the parameters needed for supporting the detailed assessment of colloid-facilitated Pu transport in their study. That is, the third condition has not been rigorously met. Nevertheless, their work clearly shows that a low-solubility contaminant travelled some way from the source, perhaps at or near the local groundwater flow velocity ($1-80\ \mathrm{m\,yr^{-1}}$).

Has the Gordian knot been cut? No, I do not think so, although a good slice has been taken out of it. The fundamental difficulty remains the gap between field observations and expectations based on bench-scale experiments and theory. For example, according to classical filtration theory, colloid transport should be relatively limited (tens of metres[7] or less under typical subsurface conditions). Advances in incorporating[8] macroparticle chemical heterogeneity and site blockage into models have helped to narrow the gap, but it nonetheless remains wide.

The trouble with most field studies is that the systems are difficult to manipulate, and are often too large and heterogeneous to characterize accurately. There is a great need to develop meso-scale experimental systems (several metres to more than ten metres) for the careful evaluation of the effects of system heterogeneity on colloid transport and the testing of methods for scaling up from the bench to the field.

Given that the work by Kersting *et al.* shows that Pu may be transported considerable distances through groundwater systems, can one conclude that the colloidal transport of actinides provides a significant exposure pathway from nuclear testing and waste sites? Not really. The very properties of compounds that make them good candidates for colloid-facilitated transport — low solubility and high particle reactivity — limit the amount of contaminant that can be transported: colloids are both the means and the bottleneck. But we need to know more. T. H. Huxley[9] had it that "It is the customary fate of new truths to begin as heresies and to end as superstitions [dogma]". In its evolution from heresy to dogma, colloid-facilitated contaminant transport has become a perceived truth, widely recognized, but rarely understood in detail. □

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