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Principles Governing Deep Groundwater Flow [and Discussion]

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Principles governing deep groundwater flow

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In humid regions, deep groundwater flow through rocks, away from major structural discontinuities, is largely controlled by the gross features of the surface elevation and by the general way the hydraulic conductivity decreases with depth. Estimates of the time taken for dissolved radioactive substances to reach the surface, and of the amount of radioactivity released when they do, depend on simple physical mechanisms but are made difficult in practice by the paucity of reliable data. By concentrating on understanding the crucial factors it should be possible to devise indirect techniques that will lead to reliable estimates. One possible example is furnished by regional surveys of groundwater chemistry.

Introduction

For a waste disposal system involving burial in rock, the flow of groundwater is crucial, and it is essential to assess its consequences. This paper aims at isolating simple principles that can guide us in this task. I shall restrict my remarks to the context of the Canadian research programme, which concentrates on disposal deep within the igneous and/or metamorphic Precambrian rocks of the Canadian Shield. I assume that the climate is humid. What I propose would not be greatly changed if the terrain were glaciated, but it would not apply under arid conditions.

Figure 1 indicates the kind of situation I wish to discuss. It represents, in a very idealized way, a vertical section through the rock mass. In the main part of the figure, the horizontal and vertical scales are the same. No attempt has been made to indicate any structural features such as faults or contacts, nor to give any detailed indication of groundwater flow at depths less than 2 km.

I wish to propose the thesis that, at depths of the order represented in the figure, the general character of the flow of groundwater is dominated by the general trend of the surface topography within a few kilometres of the region of interest, combined with a very generalized hypothesis that the hydraulic conductivity of the rock falls off fairly systematically with increasing depth. I contend that, except in their immediate vicinity, variations or fluctuations of structural properties of the rock have only a minor effect on the general character of the flow. This is admittedly a gross simplification, which needs to be applied with considerable caution.

I do not intend here to enter into a detailed account of how these ideas can be applied quantitatively. If one grants the general principle, it becomes reasonable to expect that simplified assumptions about the variation of hydraulic conductivity with depth, and the reasonable boundary condition that the water table is never more than a few metres below the surface, make it possible to estimate the hydraulic potential (closely related to the fluid pressure in the rock interstices).

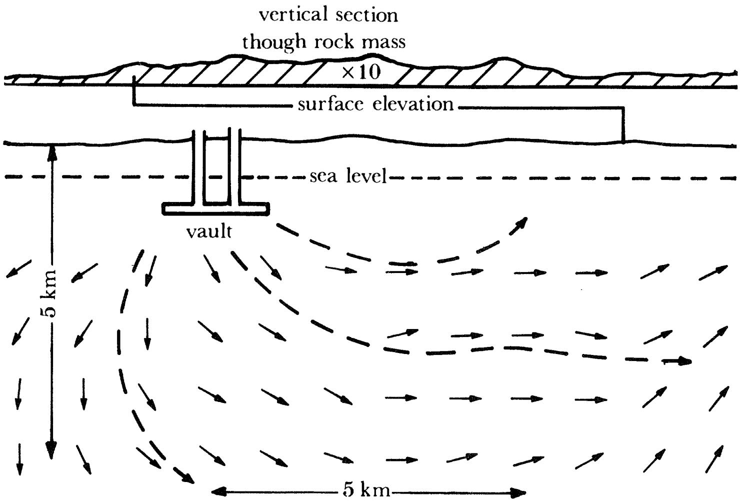

Figure 1. Vertical section through idealized rock mass. The arrows indicate the direction of groundwater flow projected onto the section, without regard to speed of flow, at selected points. Broken lines suggest the projections of flow lines of water emerging from a hypothetical vault.

Figure 1 shows arrows centred on a grid of points. These are meant to indicate the direction of flow of the water in the rock at the designated point, projected onto the vertical section. Such a diagram gives no indication of the speed of the flow, nor of the component of flow perpendicular to the plane of the paper. Figure 1 is based on a model calculation for a real terrain, using a very idealized representation of the rock properties, and I believe that in its important essence, it corresponds to the large-scale pattern of deep groundwater flow.

Also indicated on figure 1 is a hypothetical disposal vault. This has been sited where it is in relation to the flow pattern to illustrate what I believe should be an important site selection criterion, namely that groundwater flowing in the vicinity of the vault should be flowing away from the surface, so that it has a long distance to travel before eventually reaching the biosphere. The flow paths of groundwater that has passed through, or near, the vault are roughly suggested. The correspondence is vague, since the flow paths will in general move out of the depicted section, and will tend to bypass the apparent upward-moving column suggested by the projection.

TRANSIT TIMES

In assessing the performance of a disposal system it is very important to have a credible estimate of the time it will take for water to travel from the neighbourhood of the vault to the biosphere. Although there are many difficulties in the way of achieving this, some simple principles can be invoked.

Figure 2 shows a greatly idealized microscopic section through a sample of rock, and it attempts to indicate that the flow occurs within connected, crack-like channels of very variable apertures. In reality, the variations and fluctuations in scale, length and aperture will be much greater than indicated in figure 2. However, the flow is controlled by two very simple physical principles. The first relates to what drives and what impedes the flow. Two important driving influences can be discerned: one is the force of gravity, which acts in a vertical direction; the

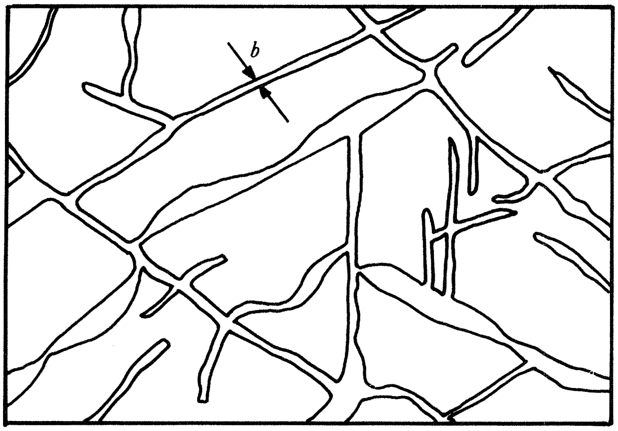

FIGURE 2. Idealized microscopic section through the rock, showing channels through which water flows. The scale is arbitrary; *b* defines the 'aperture' of the indicated channel.

other is the pressure difference between one end of a channel and the other, which acts roughly parallel to the channel walls. These cause the fluid to try to move. In hydrogeological theory the two influences are combined into the concept of hydraulic potential, or of hydraulic head. The fluid tries to move from regions of higher to regions of lower hydraulic potential or head. The counteracting retarding influence is the effect of viscosity, which ensures that the mean flow velocity is proportional to the (negative) gradient of the hydraulic head, parallel to the length of the channel. The factor of proportionality depends on the aperture of the channel, illustratively denoted by b in figure 2 for one particular channel. The physical laws governing this type of flow are very well established, and basically very simple. For a single uniform channel of length L and aperture b, the mean time, T, taken by a particle of fluid to travel from one end of the channel to the other is

$$T = 12\mu L/\alpha\rho g b^2. \tag{1}$$

Here α is the gradient of hydraulic head, often referred to as the hydraulic gradient; μ is the coefficient of dynamic viscosity; ρ is the density of the fluid, and g is the acceleration of gravity.

The other important physical principle is the conservation of matter, which in the present context asserts that what flows into the system either flows out again, or else gets stored. In the present discussion I shall limit the argument to steady-state conditions, so that storage is ignored. But if glacial rebound is an important consideration, as it well may be, one will have to be more circumspect.

The interplay between the driving effect of a hydraulic gradient and the regulating effect of conservation of matter gives rise to a complicated adjustment of the distribution of flow. At first sight one might have imagined from (1) that the presence of a wide channel would have given rise to a rapid transit. But this would require the supply of a large flux of water at the entrance, and a corresponding large drainage at the exit end, which the system cannot provide. The result is a reduction of the hydraulic gradient, α, to match the available supply and drainage. Paradoxically, this results in a lengthening of the transit time.

If we now extend the interpretation of (1) from a simple uniform channel of length L to a long tortuous flow path on the scale of figure 1, and now interpret L to mean the length of the macroscopic path; and T to be the total transit time, we can still use (1) if we introduce the notion of an 'effective hydraulic gradient' and an 'effective channel aperture'.

The effective gradient is not too difficult to assess. It will not differ greatly from the general trend of the topography (usually between 10^{-3} and 10^{-2}). The estimation of the effective aperture, however, even if one had detailed information about the distribution of crack apertures, is still a matter of very considerable difficulty. All the other factors on the right side of (1) can be estimated without very great uncertainty. Their product can be relied upon to within a factor of 10 either way. The factor b^2 in the denominator, on the other hand, is a source of uncertainty. Measurements carried out on core samples (Chernis 1981) suggest that the rock is permeated by microcracks whose apertures fall mainly in the range from 0.1 to 5 μm. With values of the other parameters suggested by figure 1, this suggests transit times in the range from a few thousand years to millions of years.

While this is to some extent reassuring, it indicates that further systematic work on basic understanding of fluid transport in real rock is very necessary.

It will be noticed that (1) makes no mention of either 'porosity' or of hydraulic conductivity, which are normally used as the basis of hydrogeological calculations. If one looks at the conventional calculations one sees that the two latter parameters enter as their ratio into the expression for the transit time, and that if one attempts to make an estimate of the hydraulic conductivity from first principles, the two approaches are roughly equivalent. What (1) has achieved is to bypass a lot of complicated reasoning. It focuses our attention on the necessity of devising a reliable rationale for assessing 'effective aperture' in the context of a real rock mass under the conditions that prevail at the depth of a disposal vault.

The argument I have used relies heavily on the notion that channels of large aperture are ineffective carriers of fluid because of limited access. This argument breaks down if there are large-scale zones of connected wide channels connecting the deep rock with the surface. It must be emphasized that such zones probably exist in the neighbourhood of all major structural faults, and their effects have to be studied as well. It should be pointed out, however, that such pathways will only bring contaminated water to the surface if the hydraulic head at the vault is higher than at some points of the nearby surface, which in turn can only occur if there is access from other, higher, points to the vault through similar zones.

Release to the biosphere

In addition to an assessment of the transit time, we also need some qualitative information about where the contaminated water is going to emerge, and a quantitative description of how much water, with what concentration of radioactive contamination. I shall restrict myself here to the qualitative aspects of this question, and only in very broad outline. Other papers in this symposium have dealt with many of the quantitative aspects above.

Figure 1 suggests that contaminated water will mainly emerge in regions of major groundwater discharge, and so probably will find its way into the major river systems and thence to the oceans. This is an aspect of the whole waste disposal problem that requires much more careful study, particularly at the theoretical level. It does raise the general question of whether it is very useful at present to extend detailed modelling of future biological consequences much further, in view of the very considerable uncertainties regarding the characterization of the regions where the contaminated water will actually emerge.

POSSIBLE EXPERIMENTAL CHECKS

We still have much to learn about deep flow in rocks like those of the Canadian Shield. Although a great deal of effort has been devoted to understanding very deep flow in oil-bearing formations, there has been very little incentive to study the particular conditions of the Canadian Shield from the point of view of water flow. The Swedish nuclear fuel waste management programme has resulted in much valuable information concerning the trend of hydraulic conductivity with increasing depth in the Scandinavian Shield (Carlsson *et al.* 1983), which is presumably rather similar in many of its characteristics. Similar measurements are available from the Canadian programme (Davison 1981). The extension of such measurements to depths in excess of 1 km strains existing techniques to the limit because the quantities being measured are so small. There is in addition the difficulty that what is being probed in deep borehole measurements is not the properties of the rock mass some distance away from a repository, but of rock that has been profoundly modified by stress release during drilling. The development of experimental techniques to overcome these difficulties is urgently required, but no early breakthrough seems likely.

On the other hand, the simple-minded ideas that I am advocating here do make certain predictions of a general nature, which are capable of being checked by rather simple indirect means. Figure 3 illustrates one of the points I wish to bring out. Figure 3 is like figure 1, but on a still smaller scale, and covers a greater depth to bring out the point in question. Like figure 1 it is based on a simplified model calculation of the same general terrain, but it now concentrates on a region to the left of that shown in figure 1. The point marked S is in a region of stagnant flow, around which the directions of flow get reversed. Some flow paths that emerge towards the surface having passed slightly to the left and below S had their earlier history in very deep rock on the left side of the figure. Other flow paths that emerge close by, having passed slightly to the right and above S, on the other hand, have had quite a different history, having entered the rock quite nearby, and never having penetrated very deep. Nevertheless, these two flow paths lie close together once they have managed to get away from the stagnation region, and their flow velocities will be very similar. Their early origins, however, are very

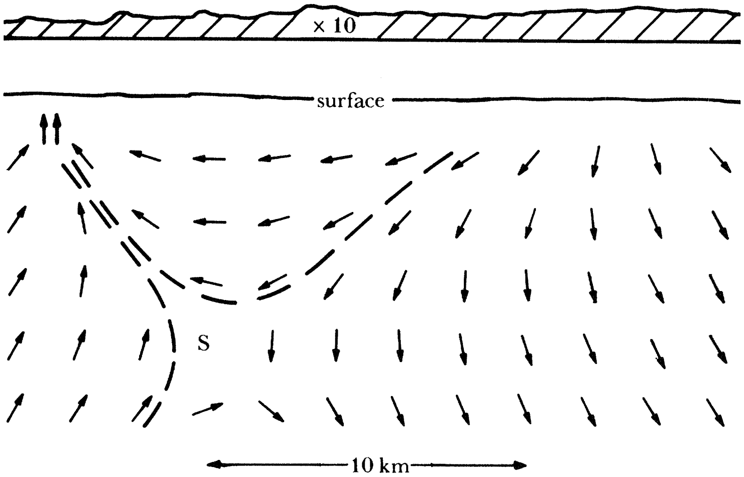

FIGURE 3. A vertical section through idealized rock mass, showing a stagnation point, S. Arrows as in figure 1. The broken lines suggest projections of flow lines that emerge close together but have had very different early histories.

different indeed, and one must expect that the dissolved solids that they have picked up on their journey will be very different. Indeed, one would expect that the fluid to the left would be a rather concentrated brine, whereas the fluid to the right would be a rather fresh, bicarbonate-type, groundwater. Such simple-minded theoretical predictions will of course be seriously modified by the effect of local geological features. A more careful consideration of the situation suggests, however, that there should be easily detectable differences in the chemical composition of water emerging in quite close proximity.

Such chemical differences are known to occur. One fairly spectacular example in Nature is the occurrence of 'salt licks', where highly saline water oozes up in quite a small area. I would suggest that a systematic programme of chemical mapping of groundwater (after taking necessary precautions to avoid contamination by surface water) could check the predictions outlined earlier, in their general aspects. Should they be vindicated, one could then proceed to refine the starting assumptions. If, on the other hand, they are not confirmed, one should still be able to learn a good deal from the nature of the discrepancies.

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Discussion

A. S. LAUGHTON, F.R.S. (*Institute of Oceanographic Sciences, Wormley, U.K.*). Both Professor Pryce and Dr Rae have referred to the need for natural analogues of deep groundwater flow. It may be worth considering the situation of the crystalline rocks of the ocean basement. At the mid-ocean ridges these are exposed to the ocean and there is good evidence for the circulation of sea water to depths of about 5 km. As the rocks move away from the spreading centre and progressively get covered by sediments the convective circulation within the fractured crystalline crust continues and can be observed by the variations in heat flow through the sediments of the ocean floor. Thus there is a mechanism for understanding the gross properties of convective groundwater flow through these crystalline rocks. Although it is clear that the behaviour of the oceanic rocks is different from those of continental granite masses there may be some useful pointers from studying this phenomenon.

M. H. L. PRYCE. I fully agree with Dr Laughton.