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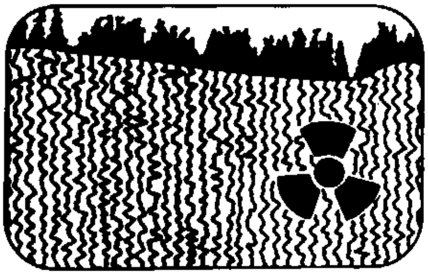

Geophysical Methods and Toxic Waste Disposal

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Introduction

The issues of toxic waste disposal have recently become issues that require a direct geoscience solution. This involves not only the disposing of small amounts of high level nuclear waste, but also the disposal of increasing volumes of chemicals and petrochemicals. The problem is increasing and it has certainly become much more visible in the past few years as various communities and pressure groups demand the right to make the decisions on disposal. Naturally there must be a great effort put into reducing the amount of toxic wastes and putting them into forms that are not readily attacked by subsurface fluids. It is inevitable, nevertheless that disposal of toxic wastes remains a problem of extreme importance and that geoscientists must devise the solutions. The residue is presumably safer placed underground, than dispersed through the atmosphere or into our rivers, lakes and oceans.

There are a variety of geologic environments which have been considered for this purpose. Some workers advocate the use of salt deposits which are present in various parts of Canada. It is important to realize that there is a considerable amount of salt in southern Ontario, the source of much of the waste. Salt is considered desirable because in general it is moisture free and because it flows, it has a self-sealing quality. A second geologic environment, which is the one being considered in the Canadian program, is that of massive Precambrian granite plutons. It is assumed that it will be possible to find plutons which are relatively fracture-free and which therefore will not leak contained fluids, nor will fluids be able to enter a repository in such a pluton. Drilling of sites is under way, but there is considerable doubt as to whether a sufficiently large container without cracks and fractures can be located. Both the salt and the granite option use the same basic philosophy. Locate a mass of rock with essentially no permeability, so that fluids cannot migrate into or out of the repository chosen. This philosophy leads quite simply to a well defined geophysical target. A variant of the above is to consider some of the carbonatite plugs which are found in various places, but are present in many locations in Ontario. These are also old igneous rocks, but tend to be somewhat more ductile and are therefore expected to have fewer fractures than the more brittle granitic rocks. To date there has been no research on the possibility that this type of intrusive may be suitable for a repository.

Various estimates of the fluid-free and fracture-free volume required for a repository have been made, but this requires a knowledge of the permeability of a large volume of granitic rock in situ, a quantity which is presently unknown. Using reasonable values it is felt that a mass which has a high degree of integrity with a volume of about 10 cubic kilometers is the target (Fyfe and Haq, 1979). The repository would then be located in the middle of this volume.

A number of investigators are now considering the possibility that rocks with a maxium permeability and ion exchange capacity might prove to be useful repositories (Bredehoeft *et al.*, 1978). Shales in particular, with a large clay content, might prove to be very useful for trapping migrating fluids either into or out of a repository and they might be chosen, if they will trap many of the harmful species in some preferential manner. Similarly, serpenitite units have been considered useful possibilities since they would tend to hydrate and expand under the influence of fluids and warm temperatures. The geophysical approaches to these types of containers are quite different that those that would be used in studying minimum permeability containers. It is more likely that one would use techniques designed to examine interfacial effects between fluids and rocks.

Characterization of a Rock Mass

A number of physical properties are especially sensitive to the presence of fluids and/or fractures. These techniques would be the ones most likely to yield useful information about the important parameters. The electrical resistivity of rocks ranges typically from 1 ohm-m for brine-saturated units to 100,000 ohm-m or more for very massive and unfractured rock without pore space fluid. For the case of rocks, where the requirement is to contain the fluids or to exclude fluids, the important criteria is to find a block of rock of ten cubic kilometers in which the electrical resistivity is very high, preferably 100,000 ohm-m or more and in which this high resistivity is uniform over the whole volume. Since the electrical currents will move almost exclusively through the fluid phase, this criterion establishes the amount of fluid present and locates fractures with fluid in them. There are regions like this in the Precambrian shield as reported by Strangway (1979), but great care must be taken in mapping such regions. Since electromagnetic propagation through such rocks is relatively unimpeded, there is no difficulty in mapping the properties of such regions to depths of several kilometers, provided there are no conductive clays (as at the Whiteshell Nuclear Reactor site) or extensive faults (as at the Chalk River site). We cannot emphasize too strongly that a suitable container is readily verified and mapped by electromagnetic mapping methods such as the audio magnetotelluric method (Strangway *et al.*, 1980). If it cannot be tested in this way, it is likely to fail the high resistivity criterion and hence be unsuitable.

There are some regions of the Canadian shield where the resistivity appears typically to be even higher than 100,000 ohm-m. The Huronian quartzites in the Sudbury area have such values of resistivity and are therefore low in fluid and very nearly fracture free.

The same situation holds with respect to salt horizons as a suitable container. Salt and ice are the two most resistive, naturally occurring materials (apart from lunar materials which have never been exposed to water). This means that natural salt beds often have resistivities of 500,000 ohm-m since all water has been excluded from pores except for that contained in isolated brine pockets which are not interconnected. Geophysical applications that can readily be envisioned make use of electromagnetic radar methods, which will penetrate for several kilometers in such material. Reflections and/or standing wave patterns can be used to map out the geometry of the salt body where it abuts up against more conductive layers as well as to trace markers horizons as has been successfully done in ice - reflections from depths as great as 20,000 feet have been detected. The use of high resolution radar techniques can also be used to detect brine pockets, since these will be very sharp radar targets just like aircraft or rain drops.

High resolution seismic techniques are

also of direct relevance to characterizing a suitable rock mass. Seismic reflection techniques have been notably unsuccessful in Precambrian terrains, because numerous reflectors cause reflections to come from many different places over a wide variety of equal time paths (the multipath problem). In general therefore, geophysicists have been inclined to assume that most of the Precambrian is too fractured to give useful seismic data. It appears, given the requirement of finding ten cubic kilometers of unfractured rock, that seismic reflection techniques operated even from the surface are of special significance. Extensive high resolution, high frequency surveys should be done over potential targets sites since only if they have few reflectors (i.e., fractures) should these sites be considered further.

There are of course many other geophysical techniques available, but most of these, such as magnetics and gravity, will largely be useful for outlining the geometry of the body. Thus, except in a very minor way they do not directly characterize the fluid and/or the fracture content of the potential repository.

At the other extreme of repository type, there is shale with its effective absorbing capacity. This characteristic of shale is well known and has long posed difficulties in geophysical well logging to assess the pore fluid present. Very little work has yet been done to test such a rock for a repository, but such absorbing shales have the characteristic that they are electrically polarizable. This means that they have a frequency-dependent electrical resistivity in the range of a few 10th's to a few 10's of hertz. The commonly used induced polarization method is based on this characteristic. The induced polarization effect is a property of chemical interactions at interfaces and hence is directly related to ion exchange capacity. It would therefore be most useful to examine the induced polarization of any possible geological container both to map out the extent of the unit and to assign it a stopping capacity. It is known for example, that very finely disseminated graphite is one of the most polarizable of naturally occurring materials because of the large effective surface area for stopping the migration of electrochemical species.

Thus geophysical methods can be used to detect optimum sites for toxic waste disposal, since by their very nature, they measure the parameters of most importance - i.e. the lack of fluids in pores, fractures or pockets for repositories designed to hold fluids or the effective stopping power in repositories designed to absorb fluids.

Paleogeophysics - For Determining Long Term Permeability or Temperature History

So far the discussion has focussed entirely on the question of using active or passive methods of characterizing the rock mass or the subsequent fill. In picking a site however, we also have available a number of geophysical methods which measure a parameter that was recorded at some time in the rock's past. If it has remained unchanged for long time periods, these methods can be used to record this fact.

In measuring remanent magnetism, it is often possible to record the field that was present when the sample formed. If it was subsequently reheated to 600°C or more, the magnetization will be completely reset and the rock will record the field corresponding to the time of the heating event. This can clearly detect events that took place in the past few million years. If the heating was only to 200 or 300 °C, or if there was extensive fluid migration and reprecipitation of magnetic phases, the rocks may also be partially remagnetized and hence carry a record of a young field either normal or reversed, but close to the present direction (Beales *et al.*, 1980). Thus the paleomagnetic record is likely to be useful for detecting changes or for indicating very long term stability.

Similarly, a few minerals such as plagioclase are well known to be thermoluminescent. The traps are filled by the natural radiation background over long periods of time. Partial heating, often to only 200°C or so, can completely reset these traps and start the clock running again. It is common for dumped traps to take a million years or more to refill. Thus thermoluminescence can be used as an effective recent geothermometer. If the traps are filled, the samples have been undisturbed for a long time. There are other "clocks" that get reset readily by fairly low temperature annealing. One of these is spontaneous fission tracks which are also sensitive indicators of recent thermal events.

Fluids that are exposed at the surface of the earth will acquire radioactive elements such as C^{14}, Cl^{36}, Be^{10} and Al^{26} with half lives of 5.7×10^{3}, 0.3, 1.6 and 0.7, million years respectively. These are radioactive because of the radiation environment at the surface of the earth and in the atmosphere. Any fluids encountered in the subsurface will contain some of the radioisotopes if they have been exposed to the surface within a few half lives. Some of these methods have been used to determine cosmic ray exposure ages on meteorites and with devices now becoming available it will soon be possible to routinely analyze pore space fluids. (Litherland, 1979).

Certainly nature has been most cooperative in storing fluids that originate from the time of formation of the rocks or shortly after. Many minerals contain fluid inclusions. These were trapped when the mineral formed and by examining the vapour bubble found in some of these, we can even record the temperature of formation, not to mention analyze the composition of these juvenile fluids. If reheating had been great, many of these which formed at 100 to 300°C would have been destroyed. They are thus also sensitive indicators of the history of the rock and prove that rocks can be effective fluid containers.

Of course oil reservoirs leak some gas hydrates to the surface although the amounts over geological time are small if there is still a reservoir. Sometimes, they can lead to small gas bubbles trapped at the base of permafrost. The presence of trapped gas in gas reservoirs suggests that permeabilities in cap rocks are very small indeed. Similar brine pockets in salt that are dated at several hundred million years, suggest that the seal is very effective and the permeability very small.

In Situ Studies

It would be useful to drill an array of holes beyond the limits of the proposed geological barrier. These holes would be used to further test the volume of rock believed to be fracture and fluid free. This is logical because the very act of drilling or mining at a pilot test will, by definition, be done at a pilot site believed to be suitable for mining. Hence, it is desirable to further test it from the subsurface before mining. It is essential to characterize the region surrounding the potential repository. Does it in turn have fractures or pore fluids or brine pockets? The use of high frequency electrical (radar or radio) methods from drill hole to drill hole or from drill hole to surface are especially useful - if there are no return signals except at large ranges, the region is suitable. If there are reflectors present, it will be possible to map these out to ranges of two or three kilometers. Experiments of this type have already been done in salt and potash mines, but there are no reported examples in highly resistive granite intrusives. If they are not resistive and hence not transparent to high frequencies, they are however not of further interest in any case. Similarly high frequency acoustical mapping, in effect using a lower frequency version of ultrasonic flow detectors, will similarly be extremely useful for characterizing the potential repository in situ.

Once the repository has been mined out a series of in situ tests should be done to again test the integrity of the geological container. At this stage of testing the cavity, a number of other useful techniques in addition to electromagnetic and seismic might be applied. These could include nuclear mapping for water content, or electrical resistivity measurement, or even dielectric constants to measure in situ water in the cavity walls. If the cavity is designed to exploit the absorptive properties of shale, the induced polarization method can be used to test the stopping power.

It cannot be emphasized too strongly, that if the rock unit is to behave as one of the barriers to fluid intake or escape, that geophysical methods of characterizing the volume surrounding the cavity both before and after mining seem ideally suited and essential.

Characterization of Barriers and Trailing

An area of geophysical testing that has so far not even been contemplated to this writer's knowledge, is one that would involve testing of the barriers that were artificially emplaced. For example, it is common to see discussions of a barrier add within the cavity which serves the purpose of absorbing fluids. Bentonite clay is frequently mentioned. In situ testing methods could well be used to test the integrity of such barriers. Again, induced polarization could be used to measure the in situ stopping power and the packing factor thus testing quite effectively the integrity of this barrier. Similarly if toxic wastes are stored in surface ponds or tailings dumps, the use of electrical and seismic methods could be used to test and monitor the barrier.

Long Term Monitoring

Having developed such a repository it will be necessary to conduct long term monitoring to ensure that the barriers are not being subsequently breached. Naturally we would contend that if the repository is located in the center of a 10 km^3 volume of perfectly impermeable rock or perfectly absorbing clay that there should be no danger. Nevertheless, it would be advisable to have monitors. These would presumably be ones in which the detection of small rock displacements or fluid flows could be detected. An array of drill holes at the edge of the 10 km^3 would not interfere with the integrity of the geological barrier (perhaps the same ones as used before mining). These could be arrays of passive seismometers listening at high frequencies for microseisms and searching for unusual patterns. If the site has been chosen to be free of residual earth stress, these microseisms might reflect actual fluid movement as reported by Fletcher and Sykes (1977) in connection with fluid pumping in New York State. Otherwise, they might reflect spalling just as one sees in mines. Electrical resistivity arrays monitored at regular intervals would be very sensitive indicators of fluid movements. Sensors of this type, with the bulk of the instrumentation at surface, could be effectively used and a preprogrammed sequence of commands could be set up to routinely interrogate the subsurface drill hole sensors and telemeter the data back to a central receiving station. Such listening posts are routinely used for example at the sea bottom.

The question of long-term monitoring needs much more thought and debate but many possibilities exist.

Comment

Concepts for geophysical techniques to be used in the toxic waste disposal problem seem to be limited only by imagination and experience. The problem is well defined, but to date there has been no serious effort made in the Canadian program to solicit concepts and ideas and to seek proposals for promising avenues to be developed. It is unfortunate that those agencies in Canada which are charged with the responsibility for toxic waste disposal have not yet seen fit to solicit ideas and information on possible techniques and to fund the most promising of these.

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