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In Search of a Nuclear Waste Disposal Site

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ABSTRACT

The choice of a site for high and intermediate level nuclear waste product material disposal in Jordan requires careful consideration of hydrology, hydrogeology, geological materials, seismicity, climate and other geological factors. The purpose of this paper is to explore how these factors in Jordan may affect the ultimate decision on where to site such a facility. Taking these factors into consideration would ensure long-term safety of the environment. Using all of these criteria eliminates many choices, but it does not eliminate all of them.

Available data on Jordan show that there are areas where suitable geological, seismological, hydrogeological and climatological characteristics are to be found. Zeolitic tuff deposits in Tulul-al-Ashaqif area and Muwaqqar formation belt in the east seem to provide a promising start, although further significant research on these areas will be needed.

KEYWORDS: Nuclear wastes, Disposal sites.

INTRODUCTION

Jordan is embarking on an ambitious plan to exploit nuclear energy. Some elements of this plan involve partial completion of the nuclear fuel cycle. This includes uranium mining and enrichment (and obviously utilization), but no transformation, enrichment or disposal plans have been mentioned in the media. While it will be conceivably possible to import enriched uranium in exchange for processed yellow cake, as some reports have suggested, it is not obvious that our partners will be willing to take away the various nuclear waste products resulting from the endeavor. Thus, it may be prudent to consider local disposal sites that may meet internationally recognized requirements for the safe containment of such wastes.

The choice of a nuclear waste disposal site is a difficult one, involving political, logistical as well as environmental considerations. Foremost in the environmental issues is how to prevent the leaching of nuclear fission products into the environment, particularly into groundwater. The choice of the site must be geologically suitable, which means that the geological materials (and the climate) at the site must be conducive to long-term containment of radioactive wastes.

In this paper, some of the most important constraints on choosing a nuclear waste disposal facility in Jordan will be discussed, and some locations that may be geologically suitable for this purpose will be suggested.

Nature of Nuclear Wastes

Nuclear wastes can be classified into low, medium and high level radioactive wastes, depending on the level of radioactivity found in a unit mass of the

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material. Typically, low level radioactive waste consists of disposable medical and laboratory supplies (gloves, vials, towels, syringes and so forth), which are bulky and yet contain minimal amounts of radiation. This type of waste is estimated to consist of 90% of the volume of nuclear waste and only 1% of the total radiation produced. Disposal of this type of waste is a more problematic political issue than a technical one. Intermediate level waste mostly consists of decommissioning wastes as well as resins, chemical sludge and fuel element cladding. Intermediate level waste contains more radioactivity than low level waste, and often requires shielding. This type of waste is often mixed with concrete in order to keep the waste in a stable inert form. By far, the biggest concern lies with high level radioactive waste, which, despite its relatively small volume, contains most of the radioactive products of the process of producing nuclear energy. Herein, focus will be put on the various geological considerations to be taken when choosing a site for intermediate and high level radioactive wastes, with the obvious implication that what is suitable for these types is also suitable for low level waste too.

When fissionable uranium (^{235}U) is split to produce energy, a mixture of waste products (called fission products) is produced along with a number of neutron activation products, particularly transuranides. Many of these products are high level radioactive waste products, and significant care is needed in handling them.

A number of techniques are used to reduce the volume of radioactive waste products that need to be handled. In the case of low level waste, an obvious option is incineration. For high-level waste, reprocessing is sometimes used to reduce the volume and to recover some valuable components of the waste. In the future, some of the more dangerous components of the waste may be destroyed using a process known as transmutation. Reprocessing is a procedure whereby the spent nuclear fuel rods are opened and the unfissioned ^{235}U as well as some of the more useful fission and neutron activation products are removed through various chemical treatments. While reprocessing is a delicate procedure, it results in a substantial reduction in the volume of the waste material as well as a reduction in the cost of producing enriched uranium, since the spent fuel still has higher ^{235}U concentrations than natural uranium ores and contains fissionable plutonium as well. This may be an obstacle to any reprocessing attempts in Jordan, because plutonium can be used in nuclear weapons.

Nuclear fuel consists of pellets of UO_2 enriched in ^{235}U encased in zirconium alloy casings. In order to ensure maximum stability for long-term storage, high level nuclear waste is typically mixed with borosilicate glass in a process known as vitrification, or is converted into a stable ceramic form. The vitrified radioactive waste is placed in stainless steel drums in preparation for long-term storage.

Optimal Sites for Long-term Storage

A number of conditions need to be met for safe long-term internment of high level nuclear waste. Ideally, these conditions would include the following:

1- A remote area far from residential, touristic, industrial or natural resource sites.
2- Low amounts of rainfall.
3- An area far from groundwater resources.
4- Slow moving groundwater (if any).
5- The presence of natural geologic barriers to the movement of radionuclides that may be leached from the site.
6- Geological stability (far from seismic or volcanic hazards).

Human Geography and Land Use

Most of the population of Jordan lives in the western highlands. The major cities in the country are: Amman, Zarqa, Irbid, As-Salt as well as cities in the southwest (Karak, Ma'an and Aqaba). On the other hand, most of the southern and eastern parts of the country are sparsely populated. Tourism, industry and agriculture follow similar trends.

Climate

As is well known, the climate in Jordan is semi-arid to arid, with most rainfall occurring on the western and northwestern highlands (not coincidentally in the areas of higher population density). The high rainfall areas receive between 300 and 600 mm per year, as opposed to the arid areas to the east and south, which receive as little as 70 mm per year or even lower.

Old Groundwater

Isotopic studies have helped us understand how different regions of the country have different ages and reflect different climatic conditions. Bajjali and Abu-Jaber (2001) have attempted to summarize these variations and their implications. According to the stable and radioisotopic analyses of groundwaters in different areas, it has been determined that some are quite old (>20,000 years). These include Al-Disi waters as well as the waters in Tulul-al-Ashaqif and Al-Hammad basin waters.

The presence of very old water reflects very low recharge rates, so that isotopic signatures of modern rainfall are not reflected on them. Low recharge is a function of both climate (low rainfall) as well as geology (the presence of impermeable horizons that slow the arrival of recharge water to the groundwater table).

In the case of Al-Disi aquifer, there is reasonable evidence to suggest that some recharge is occurring, based on traces of tritium in the groundwater (Salameh and Gedeon, 1999). This is to be expected because the groundwater basin is dominated by permeable sandstone. Therefore, despite the evidence of very low recharge in the area, the valuable non-renewable water resources in the basin would not be adequately protected in the event that hazardous or nuclear wastes are disposed in the area.

On the other hand, Tulul-al-Ashaqif and Al-Hammad basins provide more interesting potential. The groundwater in the area is old, of relatively poor quality and not very abundant. In Tulul-al-Ashaqif basin, thick volcanic flows overly Tertiary limestone and marly marine deposits. The old groundwater in the area is present in both volcanic basalt as well as limestone and marl (Abu-Jaber et al., 1998). Extensive study has shown that recharge in the area is limited to small surficial aquifers confined in alluvial deposits of the area (Abu-Jaber et al., 2003; Al-Qudah and Abu-Jaber, 2009). Evidence shows that the groundwater in the shallow aquifers reacts quickly with the basalt to form an impermeable horizon that precludes further recharge into the deeper groundwater (Kimberley and Abu-Jaber, 2005). In the case of Al-Hammad basin, surface water flows into internal playas, which are filled with fine-grained impermeable sediments. Thus, modern playa deposits as well as impermeable marly limestone formations in the western part of Al-Hammad basin (such as the B5 Wadi Shallalah Formation) preclude any meaningful recharge in this part of the basin. In the eastern part, there is evidence of some recharge into the outcropping Umm Rijam formation, especially near the town of Ruwaishid.

Distance from Groundwater Resources

Somewhat paradoxically, the fewer water resources available to inhabitants, the more valuable they become and the more attention they warrant. In the arid, low-density habitation areas in Jordan, water resources consist of surface water manifestations of groundwater (i.e. the Azraq oasis) as well as groundwater wells exploiting aquifers that extend from Al-Azraq basin in the north to Al-Disi basin in the south. Some of the groundwater in this belt is relatively shallow, of good quality and is currently extensively used for irrigated farming and domestic use. This is true especially regarding the waters of Al-Azraq basin and Al-Disi basin, and somewhat less true regarding the waters of east central Jordan and the northeastern panhandle (Tulul-al-Ashaqif and Al-Hammad basins). Waters in these basins are less extensively used because of lower quality, volume and availability (greater depths).

Geological Hazards

Jordan lies on the boundary between the Arabian and African tectonic plates. This boundary is manifested by the Jordan Rift Valley, which extends from Aqaba in the south to Baqoura in the north. This active plate boundary shows frequent seismic activity as well as an elevated geothermal gradient resulting in a series of hot springs all along the rift. Seismic activity drops significantly as we move away from the rift zone towards the east.

Volcanic activity in Jordan has resulted in basaltic flows in the southern and northeastern parts of the country. Radiometric dating of these flows has shown that the oldest flows are about 30 million years old, while the youngest volcanic eruptions resulted in the tuffaceous (zeolitic) pyroclastic deposits mentioned earlier. The pyroclastic deposits have been dated to be about 100,000 years old, seeming to mark the last episode of volcanism in the country.

It is worth noting that, in general, the older the formation is the longer is the time it has been exposed to tectonic stress. This means that younger deposits would tend to have fewer fractures, faults and joints that may act as conduits for fluid and pollutant movements in the subsurface.

Natural Barriers to Radionuclide Migration

When seeking a nuclear water disposal site, it is advisable to look for material that would retain the most significant radionuclides for the longest time periods in the event of release into the environment. Often, clay deposits are considered suitable for this purpose, although other materials are more desirable.

Upper Cretaceous to Lower Tertiary Marl Deposits

Two thick series of marly limestone deposits occupy significant areas of the eastern and northeastern desert of Jordan: Al-Muwaqqar Chalk Marl Formation (also known as the B3 Formation) and Wadi Shallalah Formation (known as the B5 Formation). Both of these formations consist of thick series of clayey marl and limestone layers, with disseminated chert nodule horizons. From a hydrological perspective, these formations are considered to be aquicludes, lacking water and preventing water movement through them. The presence of illite-smectite clay at concentrations of 30% can be viewed positively in this regard, as they act as barriers to groundwater flow and as absorbants and adsorbants that may further retain radionuclides at the disposal site. The main question related to the use of thick marl sequences as natural barriers to the movement of radionuclides from waste is related to both the movement of water through the sequence as well as the types of water-rock-waste interactions that can be expected. While marl is impermeable, faults and fractures may locally increase permeability and allow for water movement. Clearly, any proposed waste disposal facility must take this into consideration.

Coincidentally, these two formations have locally been metamorphosed at Maqarin on the Yarmouk River in the north and at Khushaym Matruk in the eastern desert. This metamorphism has led to the formation of low pressure high temperature mineral suites consisting of larnite (Ca_2SiO_4), spurrite ($Ca_5(SiO_4)_2(CO_3)$), wollastonite ($CaSiO_3$), ellestadite ($Ca_5(SiO_4,PO_4,SO_4)_3(F,OH,Cl)$), brownmillerite ($Ca_2(Al, Fe)_2O$), periclase ($MgO$), brucite ($Mg(OH)_2$), portlandite ($Ca(OH)_2$), lime ($CaO$) and other calcium aluminosilicate-sulphates and ferrites (Milodowski et al., 2001). Interaction with groundwater at these sights has given researchers a unique insight on how long-term weathering behavior of concrete in these settings will impact the movement of isotopes in cases where nuclear waste is stored.

The interaction of groundwater with these natural cement-like minerals leads to the formation of very high pH water (up to 13), enabling leaching of some metals such as rhenium (which behaves in a similar fashion to ^{99}Tc). Studies have shown that most rhenium becomes retained in fracture deposits near the leaching site (Trotingnon et al., 2006).

It is noteworthy that Al-Muwaqar Chalk Marl Unit is actually the major target formation for uranium mining in the country, which means that the nuclear fuel cycle may begin and end in the same formation. The fact that uranium is found in the rocks of this formation is an indicator of the retentive qualities these rocks have with regard to uranium.

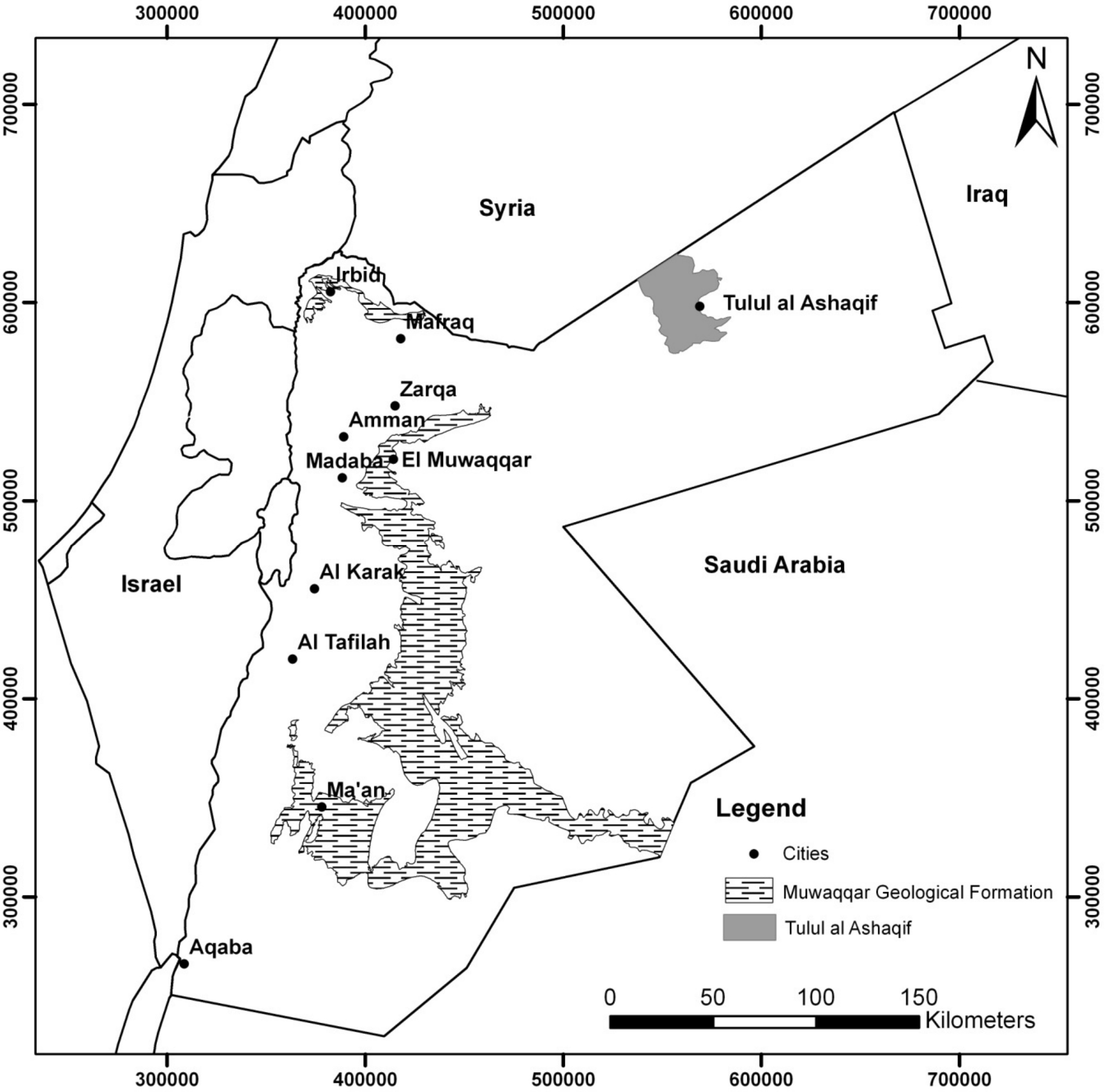

Figure 1: Map showing the locations of Al-Muwaqqar formation outcrops and Tulul-al-Ashaqif highlands in Jordan

Zeolitized Pyroclastic Deposits

In the case of Yucca mountain waste repository (Nevada, USA), one of the key factors in considering the site was that the mountain consists of zeolitized welded rhyolitic volcanic tuff. The zeolite in the volcanic tuff has the capacity to retain the most dangerous radionuclides in the waste (^{239}Pu, ^{90}Sr and ^{137}Cs). This is because zeolites are open structure silicates, with large voids in their crystal structures. Thus, the zeolite in the tuff adds protection to the environment because of adsorption and cation exchange capacity characteristics.

Similar zeolitized tuff deposits are found in Al-Azraq basin and in Tulul-al-Ashaqif highlands. These are alteration products of sideromelane present in volcanic tuff in cinder cones that have been estimated to be 100,000 years old. These are currently mined in Al-Aritain, Tell Hassan and Tell Rimah (Nawasreh et al., 2006), all of which are in Al-Azraq basin. Other sites in Tulul-al-Ashaqif highlands are currently being considered, although no tangible steps have been taken in this regard yet.

The deposition and composition of these cinder cones have been studied well in recent years (Ibrahim and Hall, 1996; Al-Malabeh et al., 2003). The mineralogy is of particular interest, especially that of zeoloites. These were first discovered in 1987 by Ibrahim Dwairi and were characterized as being mainly phillipsite ($KCaAl_3Si_5O_{16}$- $6H_2O$). Later work by Ibrahim and Hall (1996) recognized the presence of both chabazite ($CaAl_2Si_4O_{12}$- $6H_2O$) and faujasite ($Na(Na_2,Ca,Mg)_{3.5}(Al_7Si_{17}O_{48})$-$32(H_2O)$ as well.

Ibrahim Dwairi studied these zeolite deposits extensively. Some of his work (Dwairi, 1992) was specifically designed to test the ability of Jordanian zeolitic tuff to retain cesium (and thus ^{137}Cs). His experiments involved comparing Jordanian zeolites with other types, including commercial zeolites from Nevada and California (USA). The results of the study showed that the Jordanian zeolitic deposits are comparable, if not superior, to those from California in this regard, but slightly less exchangeable than the zeolitic tuff deposits from Nevada. The cation exchange capacity of these zeolites for other heavy metals has also been investigated, showing that the Jordanian zeolite effectively removes Pb, Cr, Cu, Zn and Ni from aqueous solutions (Ibrahim, 1991), which suggests that radioisotopes of these and other heavy metals may be effectively immobilized in this matrix.

CAUTIONS AND CONCLUSIONS

A technically sound disposal site will most probably be needed for high and intermediate level radioactive wastes resulting from Jordan's planned nuclear program. Such a site, when chosen, must meet strict standards of environmental safety now and in the future.

Based on what has been presented in this paper, the most promising area would be in one of the zeolitized cinder cones in Tulul-al-Ashaqif area. The area is arid, remote, seismically and volcanically stable, has only small volumes of very old low quality groundwater and contains zeolite that would add a natural entrapment of nuclides that may migrate from the vitrified containers in the future. Attention may also be given to Al-Muwaqqar formation outcrop belt, which has the advantage of being farther from border areas. It also contains abundant clays that would help immobilize any migrating radioisotopes, and is impermeable allowing for the protection of groundwater resources. The general locations are shown in Figure 1.

However, making such a decision should not be taken lightly. Tulul-al-Ashaqif area contains shallow renewable groundwater that needs to be protected. There is evidence that the highlands provide an orographic barrier where rainfall is more abundant than the few measuring stations in the area have suggested. The zeolitic deposits in the area are a natural resource that the present or future generations may need to exploit. The possibility of renewed volcanic activity in the area needs to be investigated. All of these issues and other ones would need to be adequately considered before a site in the area is chosen for such a project. It is worth mentioning that the Yucca Mountain site in the United States underwent over 20 years of extensive environmental investigations to ensure its long-term safety, before the option was abandoned under political pressure.

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