NUCLEAR FUEL CYCLE TECHNOLOGY AND POLICY PROGRAM

Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes

B. Sapiie
M. J. Driscoll
K. G. Jensen

MIT-NFC-TR-113

January 2010

CANES
Center for Advanced Nuclear Energy Systems
Massachusetts Institute of Technology
Cambridge, MA 02139-4307

ABSTRACT

This report develops and exercises broad-area site selection criteria for deep boreholes suitable for disposal of spent nuclear fuel and/or its separated constituents. Three candidates are examined: a regional site in the Baltic Fennoscandian shield for the fourteen nation European Repository Development Organization (ERDO) group of small European users; an area in the Arabian shield for newly announced reactor programs in several nations of the Middle East; and, following the same theme, a US site in Minnesota based on exploitation of the Canadian Shield. The criteria applied are restricted to technical, geological aspects and do not address the significant sociopolitical constraints faced by all repository programs. It is concluded that the subject sites all pass first-level technical criteria, and would thus be eligible for in-the-field follow-up, if so desired, by the cognizant organizations.

ACKNOWLEDGEMENTS

The lead author, Dr. Benyamin Sapiie, Associate Professor in Structural Geology, is Head of the Computational Geology Laboratory in the Department of Geology Institut Teknologi Bandung. He visited the Center for Advanced Nuclear Energy Systems, Department of Nuclear Science and Engineering (CANES) at MIT during Spring and Fall 2009, which resulted in this report, the second of two.

Support to the lead author was provided by Baruna Nusantara Energy (BNE), an independent Indonesian oil and gas company through Dr. Baldeo Singh and Mr. Yudiana, directors of BNE.

The authors are grateful for the input and support provided by Dr. Charles W. Forsberg, Executive Director of the MIT Nuclear Fuel Cycle Study, and Prof. Mujid S. Kazimi, Director of CANES.

Prof. Jacopo Buongiorno and Jonathan S. Gibbs of the MIT Deep Borehole group provided essential support in several technical and economic areas.

Finally, all concerned are greatly appreciative of the technical guidance provided by Sandia National Laboratories, and for the funding which provided a graduate research assistantship for Kristofer Jensen, who will prepare a separate report on his studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

1.1 Foreword and Objectives

This report updates work at MIT carried out during the latter half of 2009 on the subject of deep borehole disposal of nuclear wastes. In particular, it is a geology-oriented follow-on to Ref(1.1). In this undertaking considerable benefit and impetus were provided by a meeting with a research group from Sandia National Laboratories in August 2009, during which their findings, summarized in Ref(1.2), were presented and discussed. Figure 1.1 from this report shows a generic version of a deep borehole of the type of present interest.

The specific goals of this phase were to sharpen the specifications for sought-for site characteristics, and to broaden our scope to consider applications outside the U.S. It was felt that this was desirable for several reasons. First of all, it is compatible with the National Waste Policy Act (NWPA) of 1982, which states:

> "Sec.233(a) It shall be the policy of the United States to cooperate with and provide technical assistance to non-nuclear weapon states in the field of spent fuel storage and disposal."

To the degree that borehole sites can exploit widely available and similar geological settings, a considerable savings in joint RD&D and licensing expenditures, and a potentially greater assurance of exceptional performance, can be realized.

There are several other reasons for broadening the prospectus:

1. The geographically confined venue for several major users of nuclear power: for example, Taiwan, Japan and Korea. Deep boreholes may well expand the number of acceptable sites for a repository.
2. The prospective entry of many small new users for which a small national repository may suffice. This is especially relevant if spent fuel is reprocessed at large well-safeguarded facilities in a few countries and the waste returned to the originator for ultimate disposal.
3. If a country elects not to reprocess spent fuel, an easy-to-safeguard repository will help assuage concern over control of weapon-usable plutonium.
4. The modular build-as-needed feature of a borehole field, and the widespread availability of oil/gas well drilling services.

1.2 Host Rock Selection

1.2.1 Granite Performance Attributes

Recently published (2009) proceedings of a workshop on crystalline rock suitability for HLW disposal provide a wealth of useful information (1-5). This workshop was sponsored by the OECD's Nuclear Energy Agency (NEA), a group of 28 member countries. Even though the participants limit consideration to shallower (e.g. ~500m) mined repositories, sufficient information is provided to make useful inferences about much deeper (3 – 5 km) boreholes into the same granitic rock. In general one finds that threats to integrity diminish as depth increases. The papers are primarily from Sweden and Finland and their use of the Fennoscandian Shield, and from Japan, dealing with younger granite sites. The first category is directly applicable to our current interest, in Chapter 3, in a Baltic site for the ERDO group of European nations; and the Japanese work gives special attention to volcanoes and seismic events – which (at a considerably reduced level) have some relevance to the Arabian Shield as a candidate site (see Chapter 4). The Fennoscandian work and a Canadian paper consider factors such as glaciation and permafrost effects, which have direct applicability to our use of Minnesota as a U.S. example in Chapter 5.

Some selected commentary gleaned from Ref(1-5) is as follows:

- A 10^6 yr time horizon is deemed appropriate.
- Glacial retreat leads to earthquakes, but not of large magnitude, and the displacement effects decrease with depth.
- The increased hydrostatic head due to glaciers must be considered.
- Low salinity oxygenated surface water will not penetrate deeper than a few hundred meters; similarly for permafrost penetration.
- Keeping 10-20 km from known volcanoes is adequate; but seismic and EM surveys should be done to rule out the presence of hidden magma chambers.
- Salinity should not be too high (TDS≥50g/1) to avoid detrimental effects on buffer clay; but not too low, to reduce colloid formation (> 1 millimolar).

The cited workshop findings strengthen the conviction that continental shields are a very stable platform for hosting HLW disposal facilities, with a very long geological history amenable to confirmatory measurements and modeling.

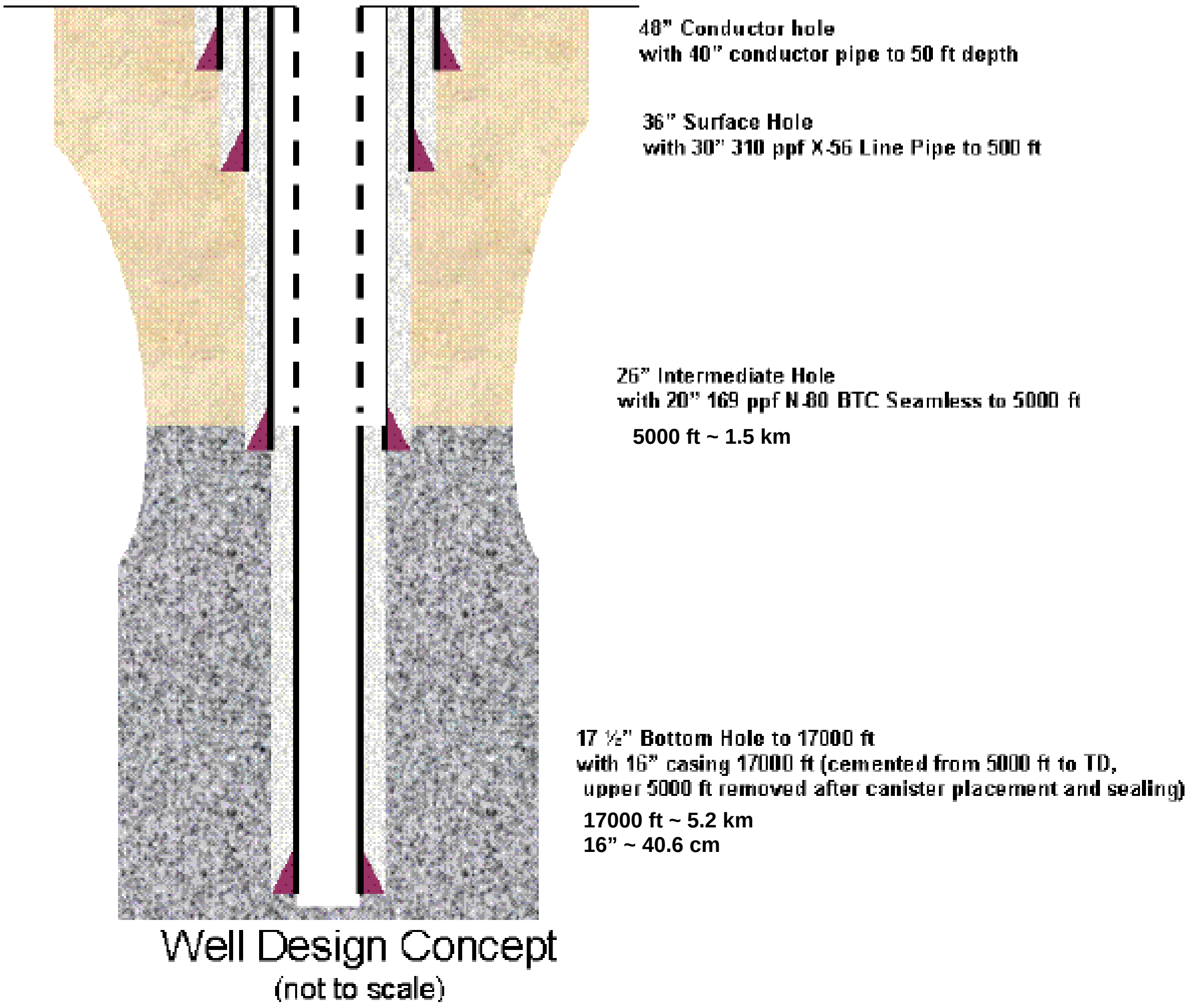


Figure 1.1 Sandia Deep Borehole Design Concept (from Ref 1-2)

1.2.2 Other Host Media

Attention has been confined to granite type rock because of its widespread continental presence (especially if several hundred meters of sedimentary overburden are tolerable) and its superior physical properties: low porosity and permeability, in particular. However, other considerations may lead to a preference for locales in which other media are the dominant stratum. The obvious candidates are salt and clay, both of which have been selected by other countries to host their shallower mined repositories. Salt (dome or bedded) was targeted for seven of the nine sites identified in the early stages of the US program. Furthermore, one can substitute boreholes for mined cavities in virtually all cases, especially now that horizontal drilling technology is so highly developed. The use of boreholes also opens up for consideration hybrid sites in which an impervious upper layer (granite, salt, clay, basalt, lava, etc.) is bored through to provide a seal zone over whatever lies below (subject to the absence of susceptibility to horizontal escape beyond the top cap zone). Salt and clay caps have the advantage of self-sealing, and thus eliminate the need for developing and testing engineered plugs of the type required for hard rock borehole repositories.

We will focus here on granite, but with the understanding that other rock types may also prove to be suitable.

1.3 Summary and Path Forward

Accordingly, a strategy ultimately evolved of focusing on continental shields (large stable expanses of ancient Precambrian granitic rock) as the preferred host medium. This came out of two principal surveys of potential users: an existing community (Chapter 3) of fourteen smaller European users, and a potential future group of nations in the Middle East (Chapter 4). A less intensive search for a parallel U.S. application was made, since earlier work had previously identified the Canadian shield as a promising locus (1-3) (1-4) (Chapter 5).

1.4 References for Chapter 1

(1-1) B. Sapiie and M. J. Driscoll, "A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes," MIT-NFC-TR-109, Aug. 2009

(1-2) P. V. Brady et al., "Deep Borehole Disposal of High-Level Radioactive Waste," SAND2009-4401, Aug. 2009

(1-3) K. G. Jensen, M. J. Driscoll, "Siting of a Deep Borehole Repository for High Level Nuclear Waste in the United States," MIT Dept. of Nuclear Science and Engineering, 2008

(1-4) G. Heiken et al., "Disposition of Excess Weapon Plutonium in Deep Boreholes: Site Selection Handbook," LA-13168-MS, Sept. 1996

(1-5) "Stability and Buffering Capacity of the Geosphere for Long-Term Isolation of Radioactive Waste: Applicability to Crystalline Rock," Workshop Proceedings, Manchester UK, Nov. 2007. NEA, 2009

Chapter 2 Generic Site Characteristics

2.1 Foreword

Before proceeding to the discussion of specific examples, a brief review and update of the deep borehole concept version pursued at MIT is in order. Basically it has consistently involved drilling into granitic rock using standard oil/gas/geothermal drilling technology to provide a borehole capable of accommodating canisters holding a single PWR assembly. Depths of several kilometers are the norm.

As described in Refs(2-1), (2-2) and (2-3), all work prior to mid-2009 has been based on vertical holes, and this remains the reference approach. However we will also preview a slant-path version, which may supersede the vertical configuration given further review. Differences are not such that the siting process will be significantly affected.

2.1.1 Vertical Borehole Version

Figure 2.1 and Table 2.1 briefly summarize the reference configuration which the reader should keep in mind in order to understand the material presented in subsequent chapters. It is basically similar to the Swedish version described in Appendix B, and to the concepts studied in the UK.

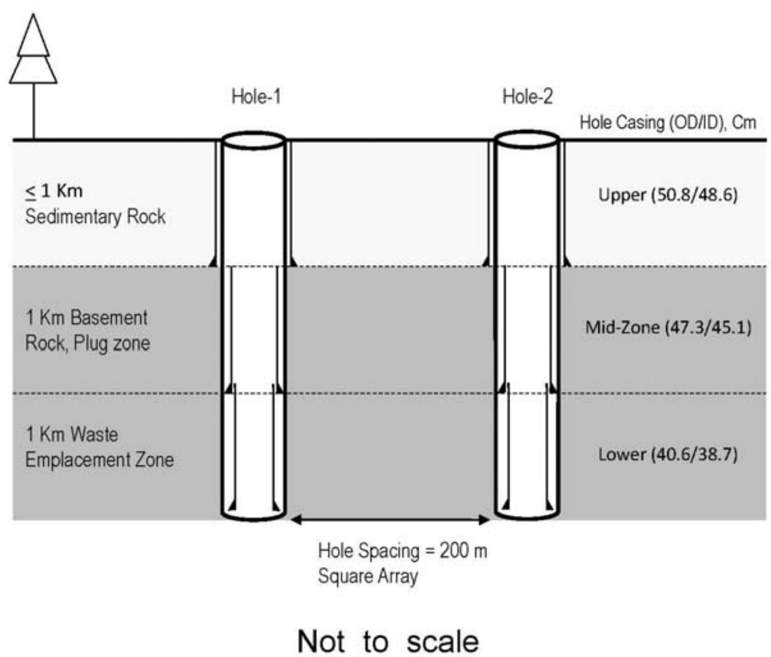


Figure 2.1 Vertical Version of Deep Borehole HLW Disposal Concept

Table 2.1 Basic Technical Features of Vertical Borehole Concept

<u>Waste String "Canister" Casing</u>

34 cm OD, 31.5 cm ID*
5 m length (half of usual 10 m)
Capacity: One PWR Assembly

Weights, kg:	Casing**	600
	Spent Fuel***	700
	Sand Fill	700
	Total	2000

*To accommodate 21.4 cm. width assemblies (30.3 cm diag.)
**Including end plugs
***Of which 500 kg is (as-loaded) heavy metal

<u>Borehole Repository Field</u>

200 Canisters (assemblies) per hole
100 MTHM/Hole (5 reactor years' worth)
Hole Array: 20 x 40 = 800 Holes, i.e. 4 km x 8 km field
Capacity: 80,000 MT (~Yucca Mountain)
Uranium loading: 100 kg/m as waste,
300 kg/m in rock (@ 3 ppm in granite)

2.1.2 Slant-Path Borehole Version

The perfection of horizontal drilling techniques over the past decade suggests it is time to consider this improvement in technology: see Ref(2-4) for a recent industrial example. Accordingly a potential new configuration is previewed in Fig. 2.2: it differs from the earlier all-vertical configuration, see Fig. 2.1, mainly in the change to a slant path at an angle to the vertical for the emplacement zone. The principal advantage is a significant reduction in the self-induced crushing pressure imposed by the stack of canisters. A potential disadvantage is the paucity of larger diameter experience for near-horizontal drilling.

Relaxing the canister weight constraint opens the way to enhancing defense in depth. One can, for example, fill the canister's internal voids with sand or grout to improve crush resistance. A more innovative fill is depleted uranium silicate glass beads, which also inhibits dissolution of UO_2 fuel (2-5).

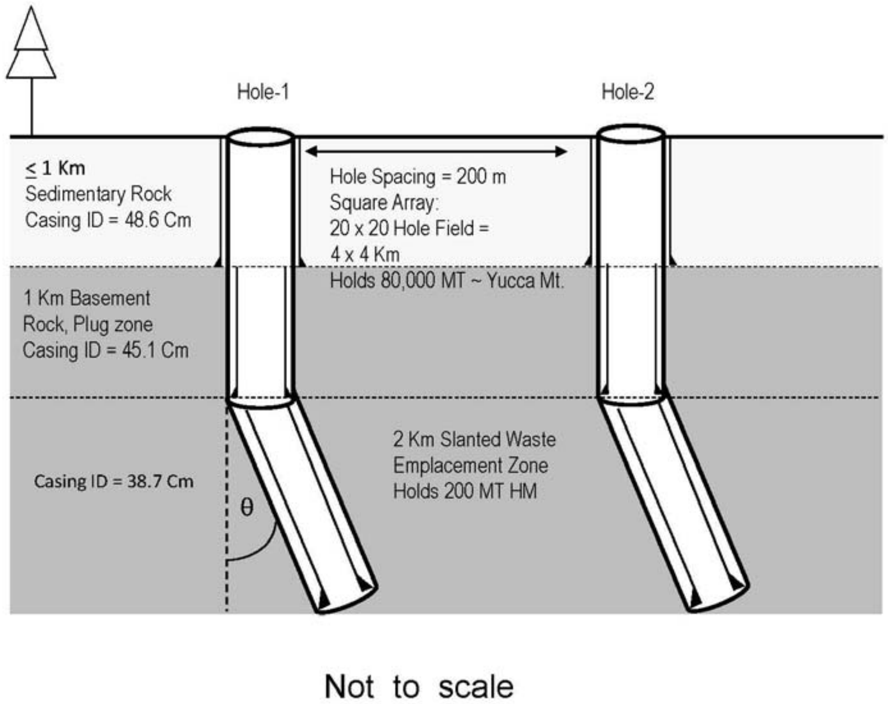
At the cost of increased diameter, one could also adopt the Swedish practice of cladding the steel canister with copper, to enhance corrosion resistance. An alternative or supplement worth considering is lining the canister with a quartz tube. Since granite is roughly 50% quartz and the remainder silicates, any downhole water will be saturated with ions which are in equilibrium with quartz – hence non-corrosive. While quartz is weak in tension, its compressive strength is high: ~1000 MPa, compared to ~30 MPa hydrostatic pressure at a depth of 3 km.

A more exotic alternative would be to melt granite debris generated during drilling to form an obsidian-like glass canister.

Fewer of these special features need be considered when separated reprocessing wastes are dealt with, since their chemical waste forms can be specially and individually tailored to achieve high durability (2-6).

The principal disadvantage of slant path holes is a more difficult loading procedure, since gravity alone is inadequate to propel a canister to hole's end. This will require pushing and wet loading (e.g., in drilling mud) to lubricate the process.

While important, the above issues and options will not be addressed in any detail in the body of this report. They are deferred to a later research agenda, which will be addressed in subsequent technical reports.



Weight borne by bottom canister:

$$WB = N.\ WC \cos\theta$$

where N = number of canisters in emplacement zone

WC = weight per canister

θ = angle with vertical

Let $\theta = 80°$; $\cos\theta = 0.174$

$N = 2000\text{m}/5\text{m} = 400$

$WC = 2000$ kg (casing + fuel + sand fill)

Thus

$WB = 1.4 \times 10^5$ kg

Let $A = 140\ \text{cm}^2$, cross section area of canister tube wall

thus $\sigma = 1000\ \text{kg/cm}^2 = 100$ MPa

compare to 760 MPa yield stress and 3500 MPa to buckle

Figure 2.2 Generic Slanted-Hole Version of a Deep Borehole for HLW Disposal

2.2 Host Rock for Siting of Deep Boreholes

Independent of the type of boreholes in mind (vertical, slanted, multibranch), it is the quality of the host rock which is of paramount concern.

2.2.1 Ideal Sites

This is one in which, in addition to having high quality rock properties at emplacement depth, the granite body (shield, pluton, batholith, massif, etc.) is exposed at the surface, free of appreciable sedimentary overburden. The resulting advantages are:

(a) A shallower emplacement depth is enabled, which will reduce drilling costs.
(b) Reduced total depth reduces the number of casing stages, and thus allows for a larger diameter in the emplacement zone or a smaller hole diameter in each stage, again conferring a savings.
(c) Although significant faulting on a macro scale may be present in the top fifty meters, high interconnected horizontal porosity is absent, which rules out the presence of an aquifer which would attract people, fauna or flora and flood a repository from above with oxygenated water.
(d) Overall the terrain is unattractive for human habitation, agriculture or water supply – which significantly reduces exposure pathways

The principal disadvantages are reduction in the number and areal extent of candidate sites, and the increased likelihood of logistical complications in site development and use. Nevertheless the benefits appear sufficiently compelling to make surficial granite sites a first choice in any vetting process. Hence in our siting studies in Chapters (3), (4) and (5), we will focus on a search for ideal conditions.

2.2.2 Acceptable Generic Sites

A generic site is one that is well-suited to the task at hand and also widely available geographically and geologically.

In general, granitic bedrock overlain by an average (but highly variable) 2 km or so of sedimentary rock is widely present in all continents. This suggests consideration of sites having about one kilometer of sedimentary overburden. Furthermore, we adopt the common practice of designating igneous continental bedrock as “granitic,” even though it may be in its metamorphosed form of gneiss or in its glassy version of a rapidly-cooled rhyolite. The key attribute of all is their exceptionally low permeability with regard to water transport.

Note that disposal into the equally impervious, and more widely prevalent, basalt which underlies oceanic sediment is not considered, principally because of the higher costs in drilling under water and the jurisdictional complexities of international siting. On-land basalts, however, should be considered as an alternative host rock.

2.3 Chapter Summary

The main points to take away from this chapter are the change in reference borehole design to a slant path emplacement zone, and the decision to shift attention to "ideal" sites with exposed granitic bedrock. Thus the uppermost of the three zones in Fig. 2-1 should now be considered as ~50m of weathered/fractured bedrock, with at most a few meters of surface soil.

2.4 References for Chapter 2

(2-1) B. Sapiie and M. J. Driscoll, "A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes," MIT-NFC-TR-109, Aug. 2009

(2-2) C. I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2004

(2-3) W.-S. Kuo, M. J. Driscoll, J. W. Tester, "Reevaluation of the Deep-Drillhole Concept for Disposing of High-Level Nuclear Wastes," *Nuclear Science Journal,* Vol. 32, No. 3, June 1995

(2-4) D. Rotman, "Natural Gas Changes the Energy Map," *Technology Review*, Vol. 112, No. 6, Nov./Dec. 2009

(2-5) C. W. Forsberg et al., "DUSCOBS – A Depleted Uranium Silicate Backfill for Transport, Storage and Disposal of Spent Nuclear Fuel," ORNL/TM-13045, Nov. 1995

(2-6) D. Caurant et al., *Glasses, Glass Ceramics and Ceramics for Immobilization of Highly Radioactive Nuclear Wastes,* Nova Science Publishers, 2009.

Chapter 3 Regional European Small Users

3.1 Introduction

As noted in Ref(3-1), fourteen European countries have set up a working group to create a European Repository Development Organization (ERDO) as a follow-on to their Strategic Action Plan for Implementation of European Regional Repositories (SAPIERR) Project (3-2). This effort was based on the belief that implementation of a suitable repository would be difficult or impossible in some countries because of challenging geologic conditions, restricted siting options, or high costs (3-1). Table 3.1 summarizes the voluntary group membership as of 2009 and their current commitment to the use of nuclear power, where such information has been made publically available.

Since a 2 x 2 km borehole field could dispose of the high level waste from 16 GWe of reactors over their potential lifetime of 60 years, deep boreholes could clearly be an option of interest. However the SAPIERR Project considered only conventional shallow mined repositories, without identifying a specific geographic locale.

Table 3.1 Small European Users in the SAPIERR/ERDO Group

	In Operation		Total	
Country	#Units	MWe	#Units	MWe
Austria	-			
Bulgaria	2	1906	4	3906
Czech Republic	6	3574	6	3574
Denmark	-			
Estonia	-			
Ireland	-			
Italy	-			
Latvia	-			
Lithuania	1	1185	1	1185
Netherlands	1	485	1	485
Poland	-			
Romania	2	1412	5	3272
Slovakia	4	1705	6	2515
Slovenia	1	666	1	666
TOTALS: 14	17	10,933	24	15,603

Note: Data from *Nuclear News,* Vol. 52, No. 3, March 2009.

3.2 Discussion

It is beyond the scope of this review to repeat the details of the ERDO program, but, as shown in Fig. 3.1, there are large granite massifs: the Bohemian in Germany/Czech Republic/Austria/Poland and the Sila in Southern Italy, which may prove favorable for deep borehole siting in the ERDO region. Fig. 3.1 is from Ref(3-3), a useful up-to-date (2006) review of exposed granite worldwide, showing that there is enough to permit definition of an almost universally applicable generic terrain. Ref(3-3) is mainly concerned with near-surface granite, and it notes that weathering, and faulting as deep as 50 – 100 m is prevalent. Hence it is prudent to begin the borehole plugging zone at a depth of several hundred meters. Figure 3.2 narrows the focus to Europe. Crystalline rocks:, e.g., the Bohemian massif, are of present interest.

International repositories, more broadly conceived, are receiving increased attention of late: Ref(3-4) reports on a generalized approach, with a European case study, and Ref(3-5) suggests that the US could host such an operation. Again, socio-political hurdles appear to be far more daunting than the technical issues. In this regard the deep borehole concept may be more palatable because it can offer an easier to comprehend route to extremely high sequestration assurance.

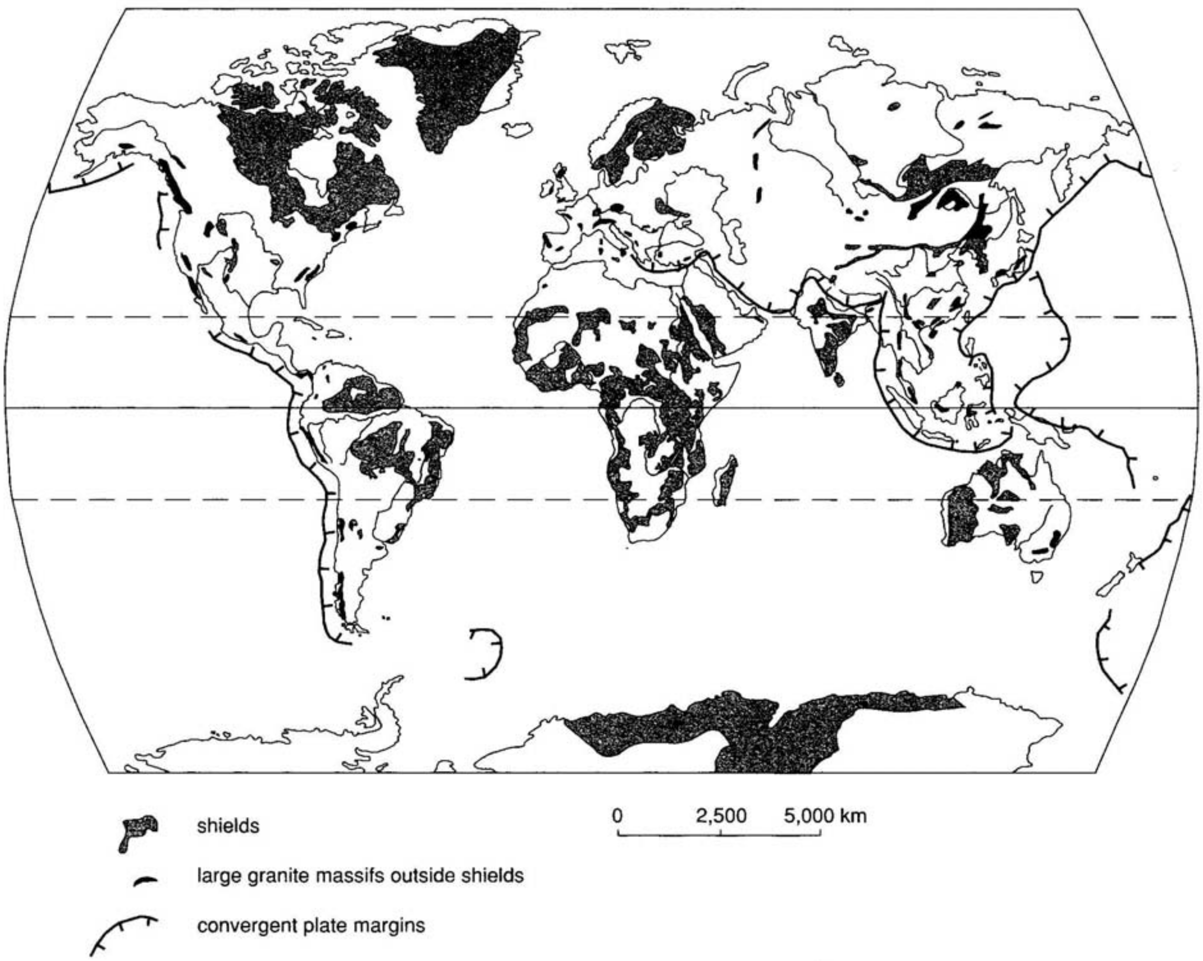


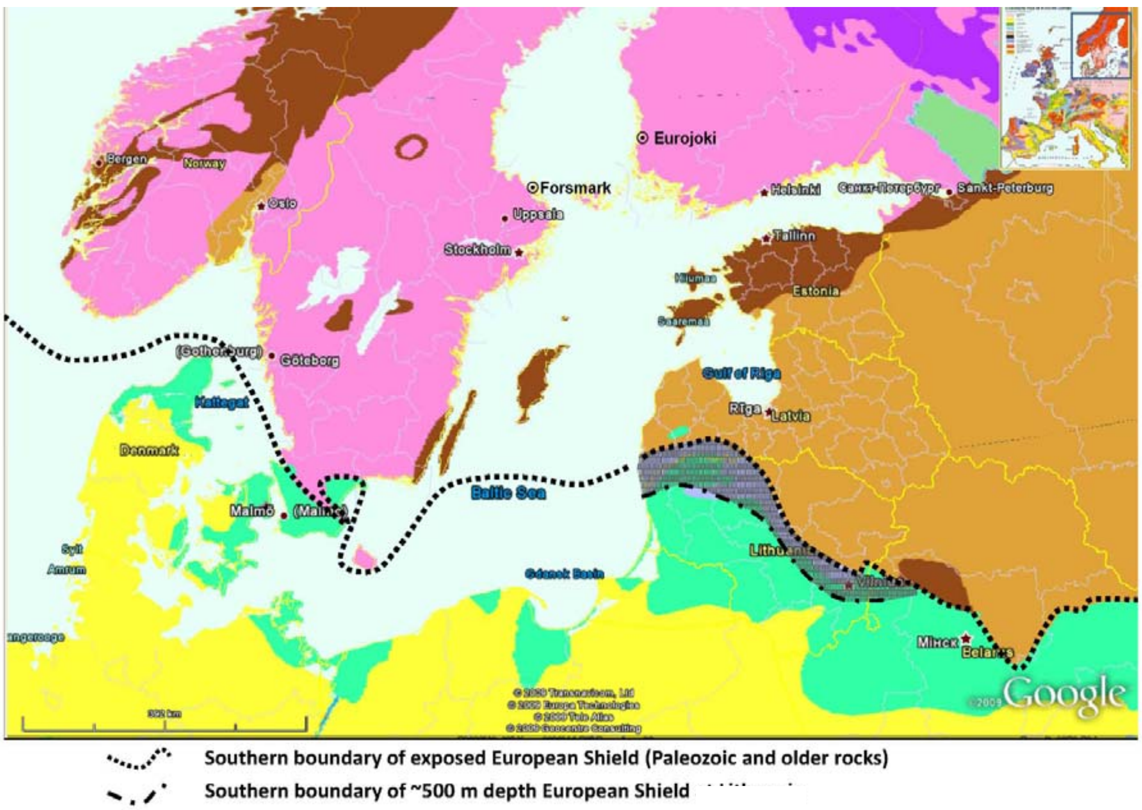
Figure 3.1 Distribution of Granite Shields and Massifs across the World (from Ref [3-3])

Note: Present interest is crystalline rocks
http://www.soton.ac.uk/~imw/jpg/eurogy.jpg [10/21/2009 1:02:48 PM]

Figure 3.2 Crystalline Rock in Europe

3.3 Site Localization for Smaller European Users

The ERDO group have a number of potentially suitable sites for deep borehole waste repositories. As shown in Figs. 3.1 and 3.2, near-surface granite occurs in the Bohemian (Czech Republic) and Sila (Italy) massifs and in the Fennoscandian shield. The last of these is particularly attractive because it provides the host rock for the successfully-sited Swedish repository at Forsmark and the Finnish repository at Olkiluoto/Eurojoki (see Fig. 3.3). Lithuania, Latvia and Estonia are all members of ERDO, and contain northernmost areas of exposed shield and, as one moves a bit further south, areas with a tolerable few hundred meters of sedimentary overburden. See Fig. 3.3. A professor at Tallinn University of Technology in Estonia has recently suggested HLW disposal in a granite mine at Maardu (3-7).



Note Swedish (Forsmark) and Finnish (Eurojoki) Sites in Fennoscandian Shield

Figure 3.3 Sites for Existing and Potential Baltic Repositories

Another possibility would be to drill just offshore in the shallow Baltic Sea (average depth of 55 m) from natural or man-made islands in territorial (rather than international) waters (3-8)(3-9)(3-10). This option could be particularly effective using multibranch wells and reconstituted or reprocessed waste forms. The oil industry has ample experience in drilling from constructed islands (e.g., on the Alaskan North Slope); and as many as a dozen side branches can be drilled from one main vertical shaft.

It is likely that the Bohemian massif will prove less attractive because of the high population density in central Europe. There has also been “massive public opposition” in the past to siting a repository in Bohemia near Pilsen (3-6). The granite in the toe of the boot of Italy (Calabria region) is worth further evaluation, provided that a sufficient distance (e.g., 100 km) is kept from Mount Etna in Sicily. However, there is a legacy of disputation from the aborted attempt to site an intermediate level waste repository at Scanzano (a city in the arch of the boot). Calabria also has a long history of recurrent earthquakes.

3.4 Chapter Summary

This chapter has expanded upon the general theme of adopting crystalline basement/shield rocks (“granite”) as a generic host medium for nuclear high level waste repositories. The 14 (currently) nation ERDO group of small European users was identified as a plausible customer, and based primarily on geology, siting in the Fennoscandian shield was recommended. In this we were strongly influenced by the successful prior siting of shallower mined repositories in this same category of rock in Sweden and Finland, after extensive studies by these two nations. One can regard deep boreholes as slimmer, deeper versions of their facilities. Hence the Baltic nations of Lithuania, Latvia and Estonia (all voluntary members of ERDO) could be potential sites for a deep borehole field repository. Achieving socio-political consensus, as in Sweden and Finland, is, of course, a key requirement.

3.5 References for Chapter 3

(3-1) *Nuclear News*, Vol. 52, No. 4, April 2009

(3-2) N. Chapman et al., “SAPIERR: Possible Options and Scenarios of Regional Disposal and Future Recommendations,” EC/EURATOM, Sept. 30, 2005

(3-3) P. Migon, *Granite Landscapes of the World*, Oxford Univ. Press, 2006

(3-4) N. Chapman, C. McCombie, “Staged Siting Strategy,” *Nuclear Engineering International*, Vol. 53, No. 646, May 2008

(3-5) J. L. Conca, J. Wright, “A Single Global Small-User Nuclear Repository,” *Waste Management 2009*, Phoenix, March 2009

(3-6) “Public Rejects Bohemian Repository,” *Nucl. Eng. Int.*, Vol. 49, No. 595, Feb. 2004

(3-7) *Nuclear Waste News*, Vol. 29, No. 21, p.4, October 26, 2009

(3-8) E. G. Frankel, “The Call of the Islands,” *Technology Review*, Nov./Dec., 1991

(3-9) F.-L. Chen, S.-H. Li, G.-P. Yu, “Preliminary Assessments for Disposal of High-Level Waste within Small Islets,” *Nucl. Tech.*, Vol. 95, No. 1, pp.54-63, July 1991

(3-10) C. W. Forsberg, “An Ocean Island Geological Repository – A Second Generation Option for Disposal of Spent Fuel and High Level Waste,” *Nuclear Technology*, Vol. 101, Jan. 1993

Chapter 4 Middle Eastern New Users

4.1 Introduction

Several countries in the Middle East have recently initiated or rejuvenated plans to build nuclear power reactors: the UAE, Jordan, Saudi Arabia, Egypt, and Turkey. The adjacent nations of Iraq, Syria, Lebanon, Yemen, Kuwait, Oman, Bahrain, and Qatar have no announced power reactor programs at present but are obvious candidates for future participation. These programs will eventually have to deal with high level waste disposal. As will be seen, a regional deep borehole field is a promising approach.

4.2 Discussion

Scrutiny of maps showing geological features (see Fig. 4.1 from Ref[4-1]) immediately calls to attention the Arabian Shield, an exposed outcrop of crystalline Precambrian basement rock in west central Saudi Arabia. It is made up of batholitic granitic intrusions and covers more than 600,000 square kilometers. The Arabian shield has a west-central plateau about 500 km wide which is free of sedimentary rock deposits, and is largely of Precambrian, approximately 700 million years old, igneous or metamorphic rock. Water and population are scarce. The average elevation of this central plateau is about 1200 m, and average thickness about 40 km. The center of the shield has significantly lower earthquake frequency and magnitudes than along its margins (bordering the Red Sea, and especially to the north, in Jordan). Since a borehole field of only 25 km^2 suffices to dispose of HLW from 100 reactors over their useful lifetime of 60 years, it is clear that a selective search for premium sites should prove productive. Figure 4.2 (also from Ref[4-1]) shows a variety of promising localities.

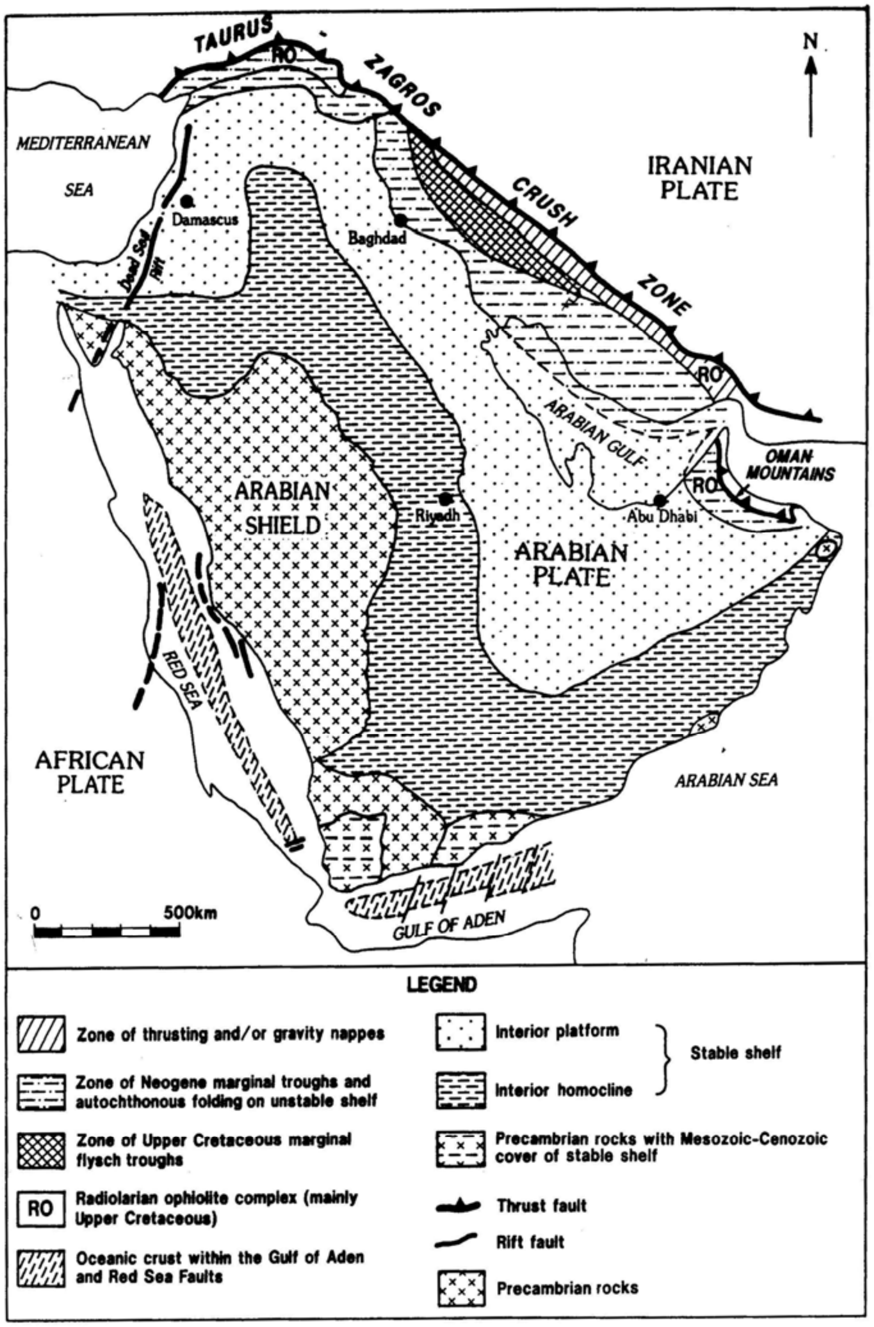


Fig. 4.1 Structural Elements of the Middle East (from Ref[4-1]).

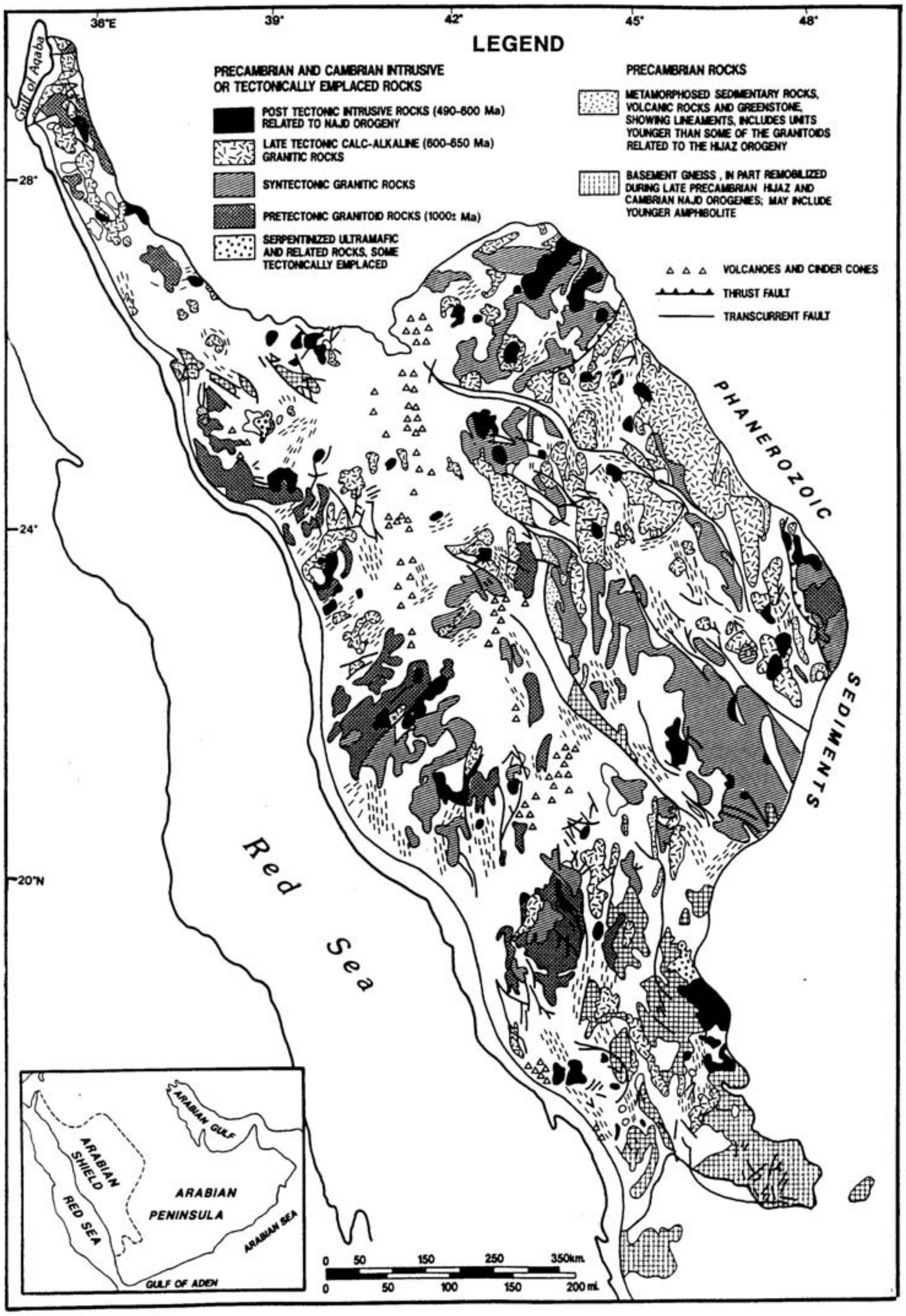


Fig. 4.2 Generalized Geological Map of the Arabian Shield, Western Saudi Arabia (from Ref[4-1])

4.3 Site Localization for Middle East

The objective of the surveys carried out in the present study was to apply available contemporary methodology and information to identify promising locales for future detailed field studies, for example 3D seismic mapping. A variety of atlases proved useful in this regard (4-2) (4-3). For example, based on population density alone [page 64 of Ref (4-2)], most of the smaller nations listed in section 4.1 can be ruled out. The distribution of oil production facilities, [page 80 of Ref (4-2)], delineates areas having thick sedimentary basins, another disqualifying feature. Finally, as shown in Fig. 3.1, only in Saudi Arabia are there granite shields (or massifs). Of particular note are satellite survey photograph compilations such as Ref(4-4), and especially the up-to-date versions which can be accessed via, for example, Google Earth. This extremely useful category of information was not available until even the recent past, and is still being expanded and improved.

Following this generic approach, plausible reasons can be advanced for eventual selection of a site within a 30 km radius of Khaybar (see Map, Fig. 4.3 from Ref [4-2]), which is about 150 km northwest of Medina on the road to Tabuk. Table 4.1 summarizes some of the factors leading to this down selection.

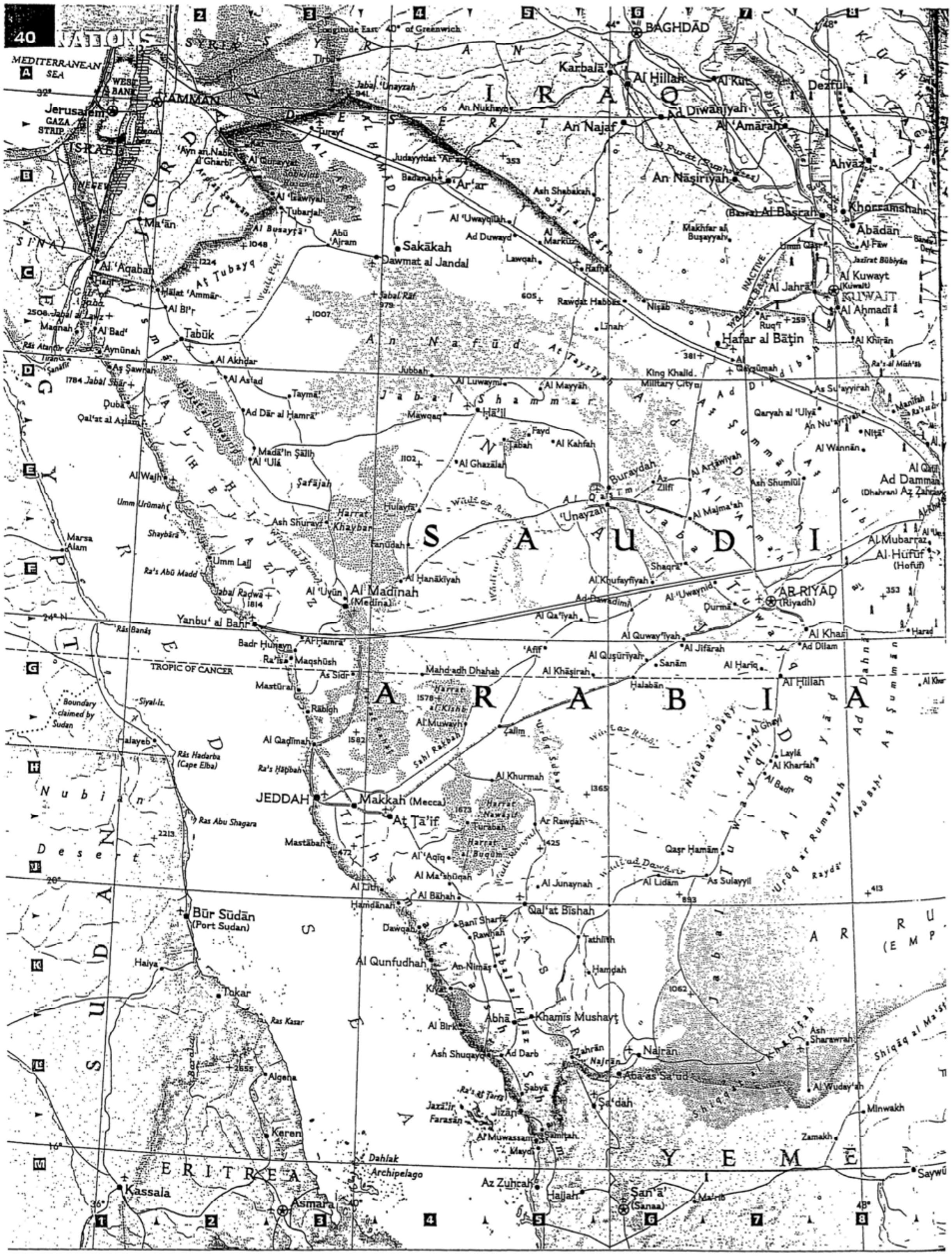


Fig. 4.3 Map of Saudi Arabia (from Ref[4-2])

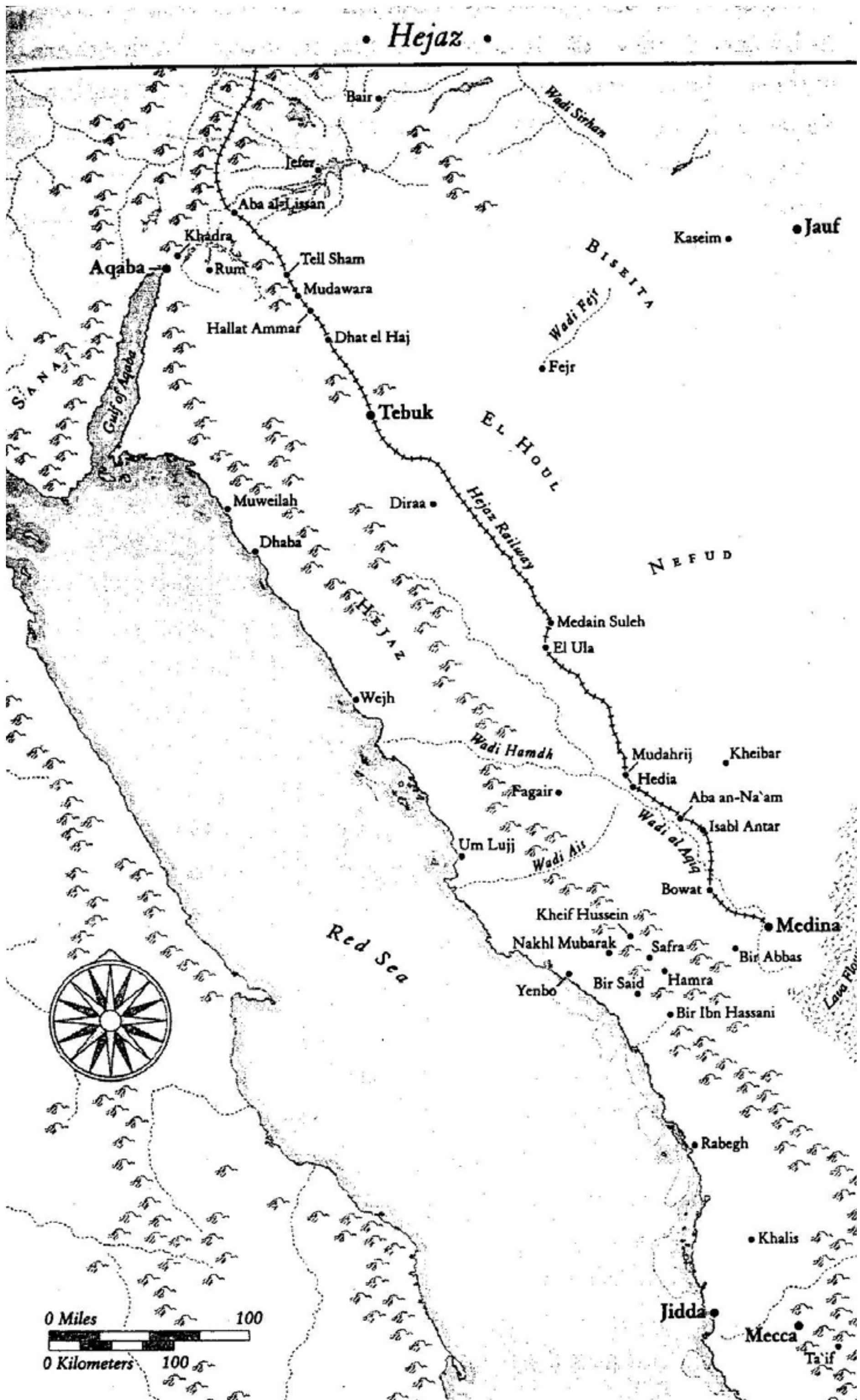


Figure 4.4 Route of Defunct Hejaz Railroad (from Ref[4-6])

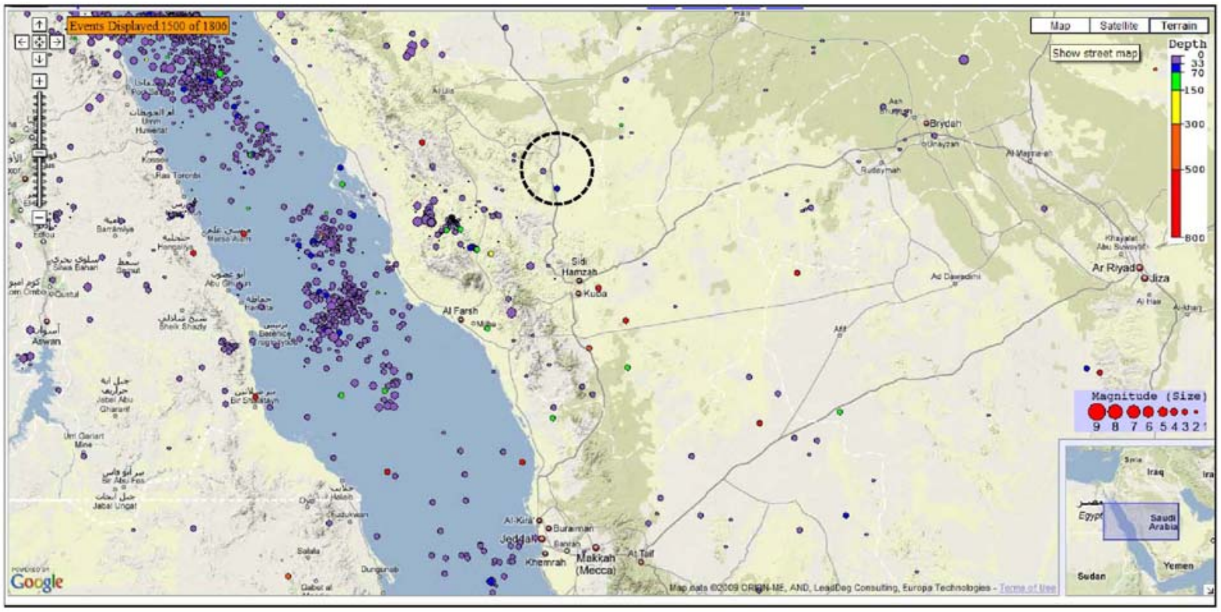


Figure 4.5 Earthquake Distribution of Saudi Arabian Shield

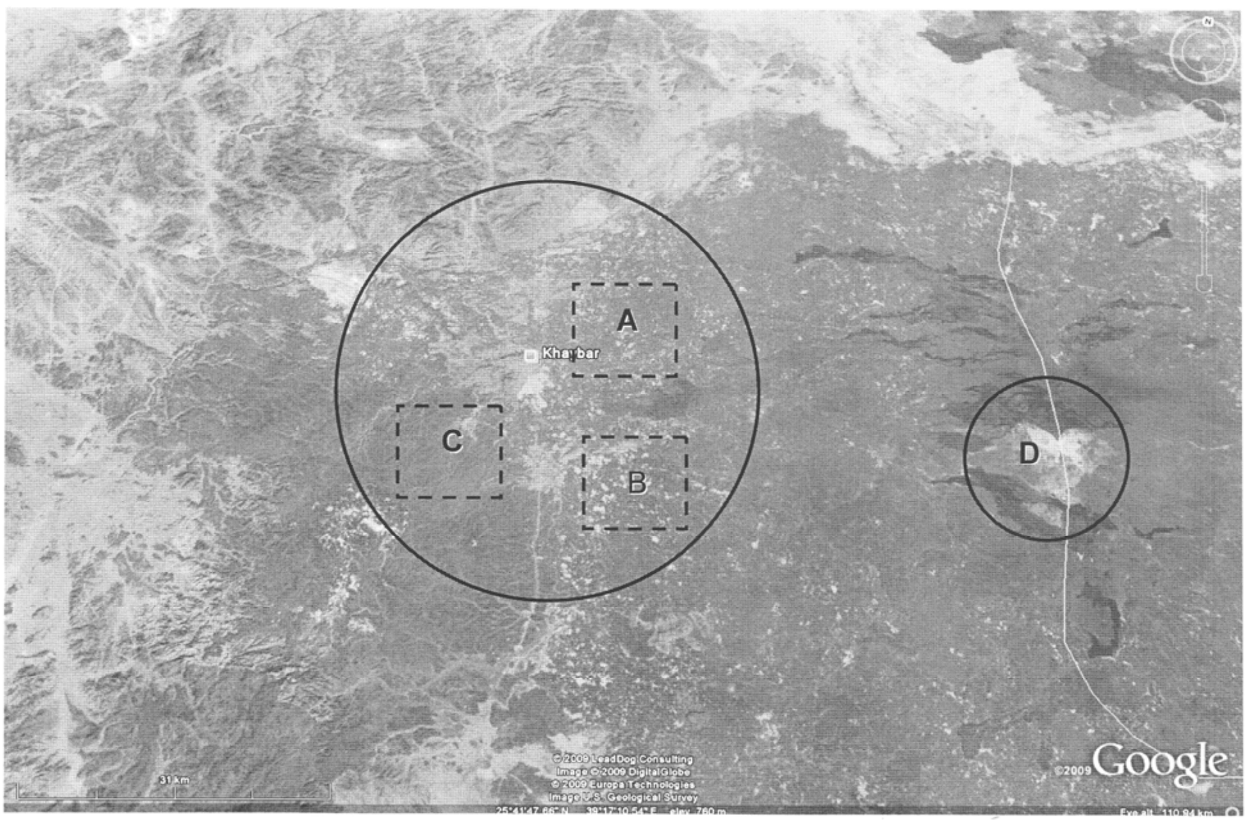


Figure 4.6 Satellite View of Khaybar Region 25° 41’ 47.66” N, 39° 17’ 10.54 E

74 m

Khaybar at 25 48' N, 39 12' E

Figure 4.7 Closeup of Region of Interest: Note Scale.

Table 4.1 Factors Favoring Khaybar-Centered Siting of Deep Borehole HLW Disposal Field

- Availability of exposed Precambrian basement rock of the Arabian shield: The only such area in the territory of potential Middle-Eastern users (see Fig. 4.1)
- Subzones have:
  - Limited or no groundwater
  - No oases or surface water
  - No large wadi (normally dry stream beds)
  - Average precipitation <1 cm/month
  - Mean population <1 person/km^2
- Area has access via a modern industrial seaport on the Red Sea at Yanbu, and existing roads to near Medina, then north to Khaybar
- No oil or gas fields
- Area is centered comfortably east of the coastal mountains and west of an inactive cluster of volcanic cinder cones
- No important archeological or cultural sites: about 150 km south of Madain Salah and 150 km north of Medina
- Area bounded on the west by the now defunct Hejaz (Hijaz: i.e., "barrier") railroad Western Province track route – which attests to the presence of benign topography to its east [see Fig. 4.4 and refs(4-6) and (4-8)]
- Low earthquake frequency and magnitude (two events, M<3) – see Fig. 4.5

As noted earlier, satellite images are of considerable use. Figure 4.6 shows several possible sites (A, B, C) within a ~30 km radius of “Khaybar” (variously described as a town or district (harrat) in the Medina Administrative Area). The map also shows an area of volcanic cinder cones (D) about 100 km to the east. Figure 4.7 shows a closeup.

While only on-site exploration and detailed seismic imaging, followed by drilling of a test borehole, can confirm site suitability, the region identified here appears to be one promising candidate of many possibilities.

4.4 Chapter Summary

In this brief chapter, a hypothetical group of new users in the Middle-East were identified as prime candidates for forming a collaborative to emulate the ERDO group in siting a regional repository. Geology alone prompted immediate interest in the Precambrian rocks of the Arabian shield. While many other criteria must eventually be sorted through, low population density is another compelling motivation for starting with a location in the Khaybar region as a likely candidate.

4.5 References for Chapter 4

(4-1) A. S. Alsharhan, A. E. M. Nairn, *Sedimentary Basins and Petroleum Geology of the Middle East*, Elsevier, 1997

(4-2) *Atlas of the Middle East*, National Geographic, Washington DC, 2003

(4-3) *Saudi Aramco and Its World, Revised Edition*, 1995. Saudi Aramco, Dhahran

(4-4) *Satellite Atlas of the World*, Oxford University Press, 2004

(4-5) G. Robison, *Arab Gulf States,* 2nd Edition, Lonely Planet Publications, 1996

(4-6) R. Florence, *Lawrence and Aaronsohn,* Viking, 2007

(4-7) Saudi Geological Survey, www.SGS.ORG.SA

(4-8) J. Barr, *Setting the Desert on Fire,* W. W. Norton & Co., 2008

Chapter 5 A U.S. Example

5.1 Introduction

Although considerable prior work has been done on siting boreholes in the continental U.S. (5-1) (5-2), a brief re-visit is in order to apply a process parallel to that employed in earlier chapters for screening of European and Middle Eastern sites. Specifically, a narrower focus on emplacement in continental shield host rock, and a preference for "ideal" sites in which the Precambrian rock is exposed at (or very near) the surface, is applied.

5.2 Discussion

Figure 5.1 shows the exposed extent of the Canadian Shield in North America. Because of convenient access to the Canadian Shield, northeastern Minnesota deserves further scrutiny. The map in Fig. 5.2 focuses on a triangular area about 250 km on a side defined by route 61 north from Duluth along Lake Superior, route 53 north from Duluth to International Falls, and the Canadian border. Good access by water is available and shipping terminals and railroads devoted to iron ore transport are also close by. Hence we have not looked into similar terrain further west.

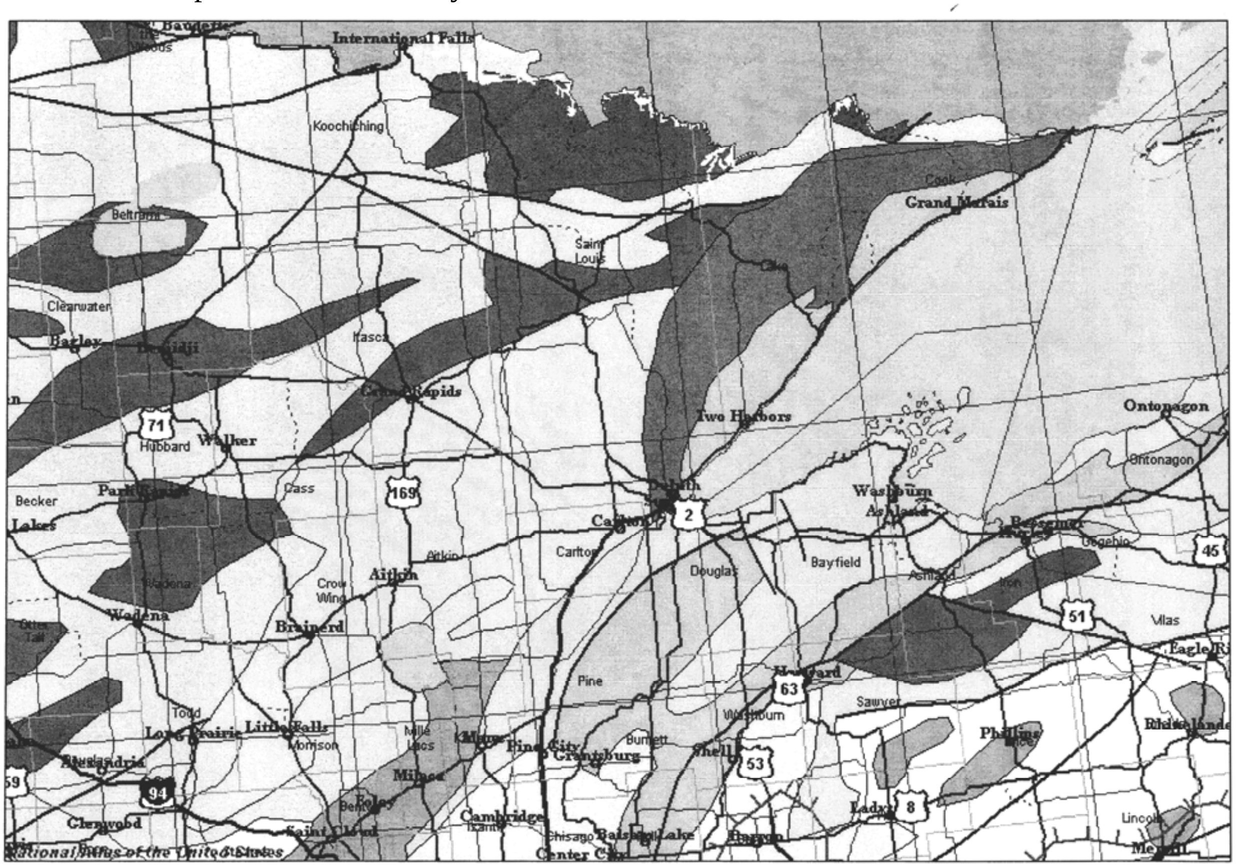


Fig. 5.1 Exposed Shield Areas in Minnesota (Dark Grey) (from Ref [5-3])

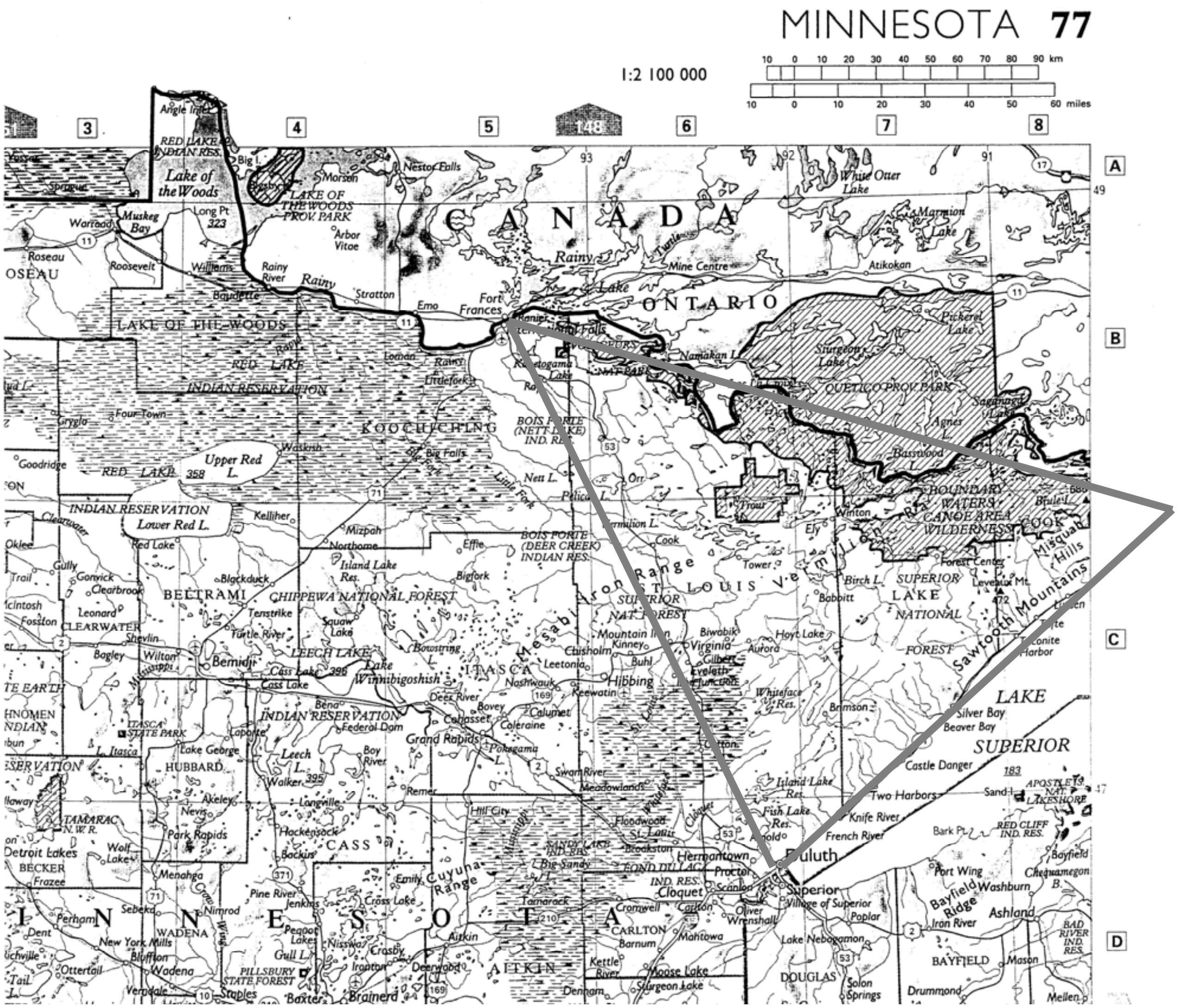


Fig. 5.2 Potential Region for a Borehole Field in Minnesota (from Ref[5-4])

US CANDIDATE - NORTHERN MINNESOTA

Fig. 5.3 Satellite Image of "Arrowhead" Region of Minnesota (from Ref[5-5])

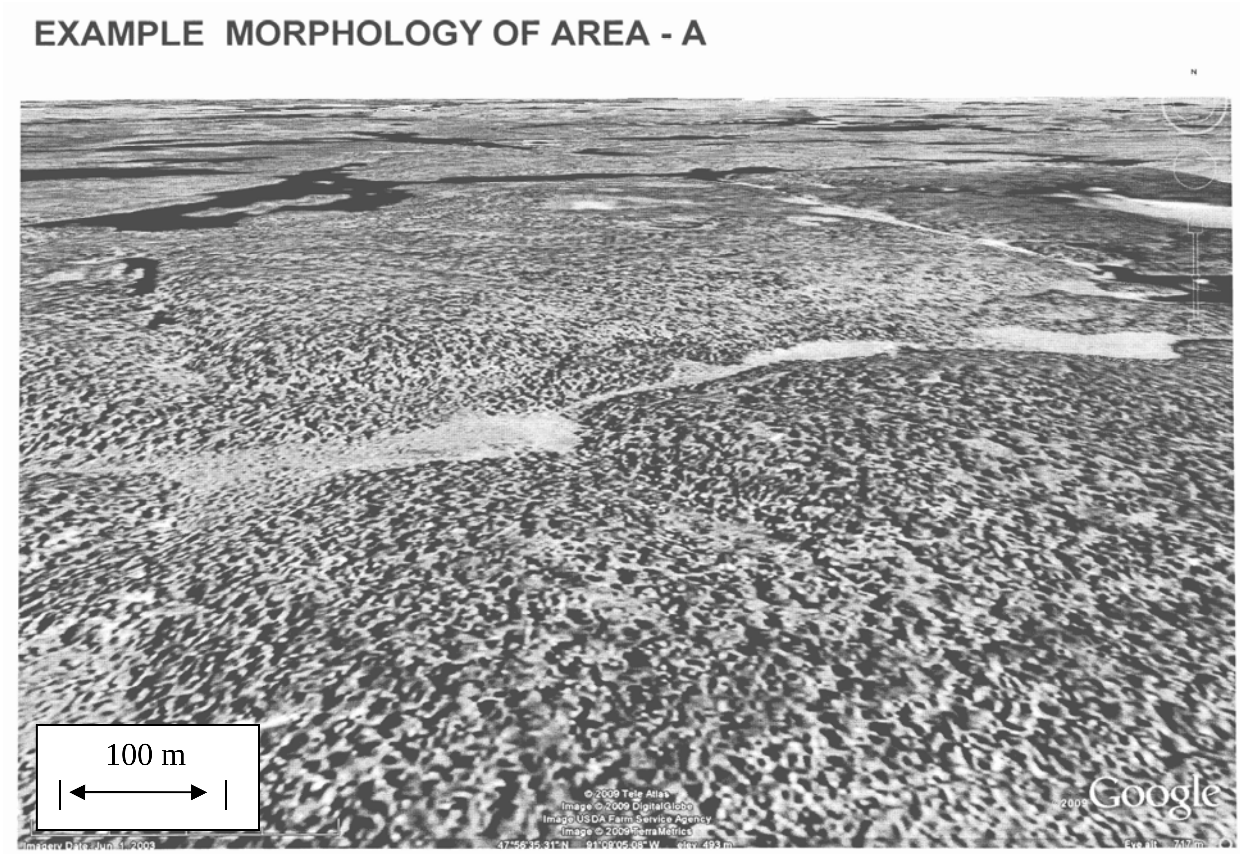


Fig. 5.4 Satellite Image of Representative Subregion: Note Scale (from Ref[5-5])

Figures 5.3 and 5.4 show satellite images of a promising subregion. Complicating factors are the forestation, a scattering of lakes, parks and the proximity of the Canadian border. However, an area less than 1% of that delineated would suffice for the present application.

A further advantage of emplacement in Canadian Shield rock is the synergism it provides with the Canadian waste disposal program, and with the recent study of the Canadian program by the US National Association of Regulatory Utility Commissioners (NARUC) (5-8).

The most important geophysical issue is the abundance of surface water, both in the form of precipitation and subsequent ponding. In this regard, conditions are roughly similar to siting in the Fennoscandian shield, and starkly different than those on the extremely arid Arabian shield. Where surficial water is abundant, more attention must be paid to plugging the uppermost zone of the borehole, to prevent flooding from above, and an attack on plug integrity from above in the high-integrity plug seal zone. Even so, reducing total hole depth by up to a kilometer will still yield a considerable net economic savings.

5.3 Chapter Summary

As an exercise, an exposed shield host rock area has been identified in the U.S., which is at least superficially similar to the examples in Chapters 3 and 4 of Northern European and Arabian sites. The process has been limited to far-field assessment; clearly all three focal areas will need on-site evaluation, including seismic tomography and drilling of diagnostic holes.

It is appropriate to end here by repeating the disclaimer that our concern has been primarily with targeting locations having very high quality deep rock and a minimal overburden. The multitude of socio-political factors involved in final site selection have been largely discounted. In Minnesota, as elsewhere, there is an organized opposition effort to activities involving the back end of the nuclear fuel cycle (5-6). Fortunately, the deep borehole approach, in its more generic embodiment, is applicable, as noted by Gibb, "to a substantial portion of the continental crust." (5-6) Reference (5-2) explores the issue of ubiquity in much more detail.

5.4 References for Chapter 5

(5-1) G. Heiken et al., "Disposition of Excess Weapon Plutonium in Deep Boreholes: Site Selection Handbook," LA-13168-MS, Sept. 1996

(5-2) K. G. Jensen, "Siting of a Deep Borehole Repository for High Level Nuclear Waste in the United States," MIT MSRP Project Report, 2008

(5-3) USGS

(5-4) *Firefly Atlas of North America: United States, Canada and Mexico,* Firefly Books, 2006

(5-5) Google Earth

(5-6) Waste Management Briefs: "Sixteen Minnesota Groups Opposed to Spent Fuel Recycling," *Nuclear News,* Vol. 52, No. 12, Nov. 2009, p.83

(5-7) F. G. F. Gibb et al., "A model for heat flow in deep borehole disposals of high level nuclear waste," *Journal of Geophysical Research,* Vol. 113, 2008

(5-8) "Regulators Study Canadian Model as Way to Site Nuclear Waste Repository," *Nuclear Waste News,* Vol. 29, No. 15, July 28, 2009

Chapter 6: Summary, Conclusions and Recommendations

6.1 Summary and Conclusions

This report has been concerned with demonstrating the widespread applicability of the deep borehole approach, even if one confines attention to the "ideal" host rock, namely exposed continental shield bedrock. This reduces entrance zone thickness, hence borehole length and cost. It has attempted to do this by a descriptive review of three cases of practical interest: Baltic region siting in the Fennoscandian shield for use by an existing 14 nation small European community organization; Arabian Shield siting for a potential group of newly-interested middle-eastern nations; and a Canadian shield site in Minnesota for the U.S.

It is concluded that the three sites examined are sufficiently promising to warrant further more detailed review. On a technical basis, the biggest site-to-site difference is the wide spectrum of ambient freshwater: ranging from extreme aridity in Saudi Arabia to Minnesota and Lithuania, which have many lakes (6-3). Since conditions several kilometers deep determine borehole repository performance, these surficial differences can be accommodated.

A potential future change in borehole configuration from prior work at MIT is the use of a slant-path emplacement zone (~60° - 80° from the vertical) to alleviate crushing by the canister stack. However, differences from the reference vertical version are not such that the siting process would be significantly affected.

6.2 Recommendations

Based on the findings of this survey of potential sites for deep borehole HLW repositories, it is concluded that the results are sufficiently promising to proceed further along these lines. Specifically:

(1) Additional geological information should be compiled on the three sites identified in this report: Arabia/Baltic/Minnesota. In addition, sociopolitical constraints on siting must be accommodated – an aspect only superficially addressed in this report.
(2) The scope of site surveying should be extended to other regions. The present survey was limited to the Northern Hemisphere; but, as shown in Fig. 3.1, there are significant granitic shields in South America, Africa, and Australia. This work can build upon the investigation by Pangea Resources, which identified promising locales in Argentina, southern Africa, western China, and especially Australia (6-4).
(3) For the U.S. a broader selection of sites should be identified by relaxing the criterion of minimal sedimentary overburden above the basement bedrock.
(4) Key technical issues must be addressed, the highest priority being water transport in granitic bedrock, and borehole plugging.
(5) Closer collaboration with advanced drilling RD&D for geothermal applications. As noted in Ref(6-1), ARPA-E is sponsoring development of a hybrid thermal-mechanical drill for "quickly cutting through ultra-hard rock." Air drilling is an already available alternative used for about 30% of terrestrial oil and gas well drilling (6-2).

A potential source of future siting-related geological information is the OneGeology project initiated in 2008, a global project sponsored by UNESCO, the British Geological Survey and others from eighty-plus nations. Its long-term goal is to map out the Earth's underlying topology.

Finally, note should be taken of a parallel report under preparation: "A Framework for Performance Assessment and Licensing of Deep Borehole Repositories," by K. G. Jensen et al., MIT-NFC-TR-(TBA), Jan. 2010. Also worth noting is the MIT Naval/Nuclear Engineer Thesis research underway by J. S. Gibbs, preliminarily titled "Feasibility of Horizontal Emplacement in Very Deep Borehole Disposal of Nuclear Waste." Publication is projected for June 2010. This project includes development of an in-house, non-proprietary, drilling cost code which can deal with vertical, slant-path, and multi-branch boreholes as a function of depth and diameter.

6.3 References for Chapter 6

(6-1) "US Bets Big on Renewable Energy," *New Scientist*, p.24, Vol. 204, No. 2735, Nov. 21, 2009.

(6-2) W. C. Lyons et al., *Air and Gas Drilling Manual, 3rd Edition*, Elsevier, 2009.

(6-3) G. McLachlan, *Lithuania; The Bradt Travel Guide, 4th Edition*, April 2005, p. 5.

(6-4) *International Nuclear Waste Disposal Concepts*, World Nuclear Association, Nov. 2009

Appendix A Long Term Borehole Host Rock Environment

There are two aspects of the host rock which bear on borehole performance in the very long term.

The first is rock water content. If one considers a borehole field with spacing of 200 m, and rock having 0.1 vol. % water-filled porosity, then per meter of depth there are some 40 m^3 of water per m. An empty borehole having an 0.5 m diameter has a floodable volume of 0.2 m^3/m, and a hole with waste in place, a factor of on the order of ten less. Thus based only on a mass/volume basis it is easy to postulate that flooding would eventually occur. It may be possible to show that the radial temperature (hence water vapor) gradient works, via thermal diffusion, against this early-on, until decay heat has significantly died away. Nevertheless, ultimately, it is probably not possible to assure a dry hole ad infinitum. This suggests evaluation of a strategy in which the hole is initially flooded with water containing a high concentration of dissolved corrosion inhibitor (e.g., sodium tetraborate @ 3.2g/100 cc H_2O or trisodium phosphate @ 14.5g/100 cc H_2O or sodium chromate @ 87.6g/100 cc H_2O). Should the emplacement zone dry out subsequently, the solids would remain to dissolve in any future flooding episodes. These additives will also create a toxic environment which prevents microbial corrosion.

The use of borax (sodium tetraborate with ten waters of hydration) also provides a neutron poison to provide even larger margins against criticality: 1 g/100 cc of sodium tetraborate provides about 2000 ppm boron – enough to reduce multiplication factor by 20%.

One important caveat is in order: dissolved solids at too high a level can degrade the performance of bentonite. Less than 5000 ppm TDS is recommended when bentonite is used as drilling mud, and less than 500 is preferable.

The water has two beneficial contributions: its high "salinity" protects against vertical convection: at 200°C pure water density decreases by only 0.12 g/100 cc per °C. Its presence also greatly increases the effective thermal conductivity in the canister-to-liner and liner-to-rock wall gaps, due to small convection cells: Measurements in a mockup at MIT showed a k, W/m°K, some 35 times higher than air and 7 times higher than a variety of "sand" fills (A-1). We are also currently investigating a simple loading procedure in which canisters are dropped into a flooded borehole. The terminal velocity is predicted to be a tolerable 2 mph.

The major unknown at present is the consequence of water radiolysis, either in added or naturally-occurring water, or in water bound in cement or rock.

The second factor is host rock uranium content. Per meter a 200 x 200 m horizontal section contains about 10^8 kg rock/m, hence 400 kgU/m if the granite contains 4 ppm U(A-2): About four times the uranium mass per meter inside a canister. Thus over a very long time span, the canister's uranium series decay products will not add significantly to the pre-existing inventory.

References for Appendix A

(A-1) S. Shaikh, "Effective Thermal Conductivity Measurements Relevant to Deep Borehole Nuclear Waste Disposal," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Jan. 2007

(A-2) M. Eisenbud, *Environmental Radioactivity from Natural, Industrial, and Military Sources*, Academic Press, 1987

Appendix B   Borehole Plugging Options

Assuming maintenance of bedrock integrity, the most vulnerable feature of the deep borehole concept is the plug employed to seal the holes. Our reference design is the “parfait” layer approach – bentonite / asphalt / concrete – proposed as a defense-in-depth system by Swedish borehole investigators: See Fig. B.1 from Ref (B-1). Given its importance, alternative or additional methods are worth evaluation.

Some possibilities include:

(a) Molten granite (B-2)

Ground-up granite produced in the drilling process is available at the site, and is an obviously good geochemical match to the host rock. An electrical heater (e.g., of tungsten) can be used to melt the granite “sand” in situ. Similar technology has been developed and tested for use as a drill on extra-terrestrial bodies.

(b) A thermit reaction (B-3)

A mixture of finely divided aluminum and iron oxide has long been used for in situ welding – e.g., of train rails.

The easily ignited spontaneous reaction is:

$$3Fe_3O_4 + 8A1 \rightarrow 4A1_2O_3 + 9Fe$$

The reaction produces about two-thirds its weight of molten iron under a layer of molten slag, both at about 2800°C.

This approach may be able to melt the adjacent steel liner, and thereby create a direct bond with the rock hole wall.

It may also be possible to use Si powder in place of Al, to produce molten SiO_2, a principal constituent of granite.

(c) Molten Sulfur

Sulfur (melting point = 113°C) may be a useful replacement for asphalt, or an additional upper layer. Most metal sulfides have extremely small solubility product constants, which may help retain escaping fission products.

(d) Specialty Cements, Grouts, Concretes

Although suitable materials have already been formulated and tested for plugging / backfill applications, the scientific basis for specific applications – targeted concretes is in a rapidly evolving phase. For example, in October 2009 MIT established an industry-supported Concrete Sustainability Hub. Its participants will be a valuable resource for the MIT borehole researchers.

For each of the final plug designs a comprehensive performance assessment will be needed. Prior experience from the Sandia Borehole Plugging Program (BHP) should provide a useful starting point (B-4). Reference (B-5), also by Sandia, has a detailed discussion of their assessment of borehole plugging concepts – which has much in common with the Swedish approach. Also germane is actual operational experience with the Waste Isolation Pilot Plant (WIPP), which on March 26, 2009 marked its tenth year of operations (B-6).

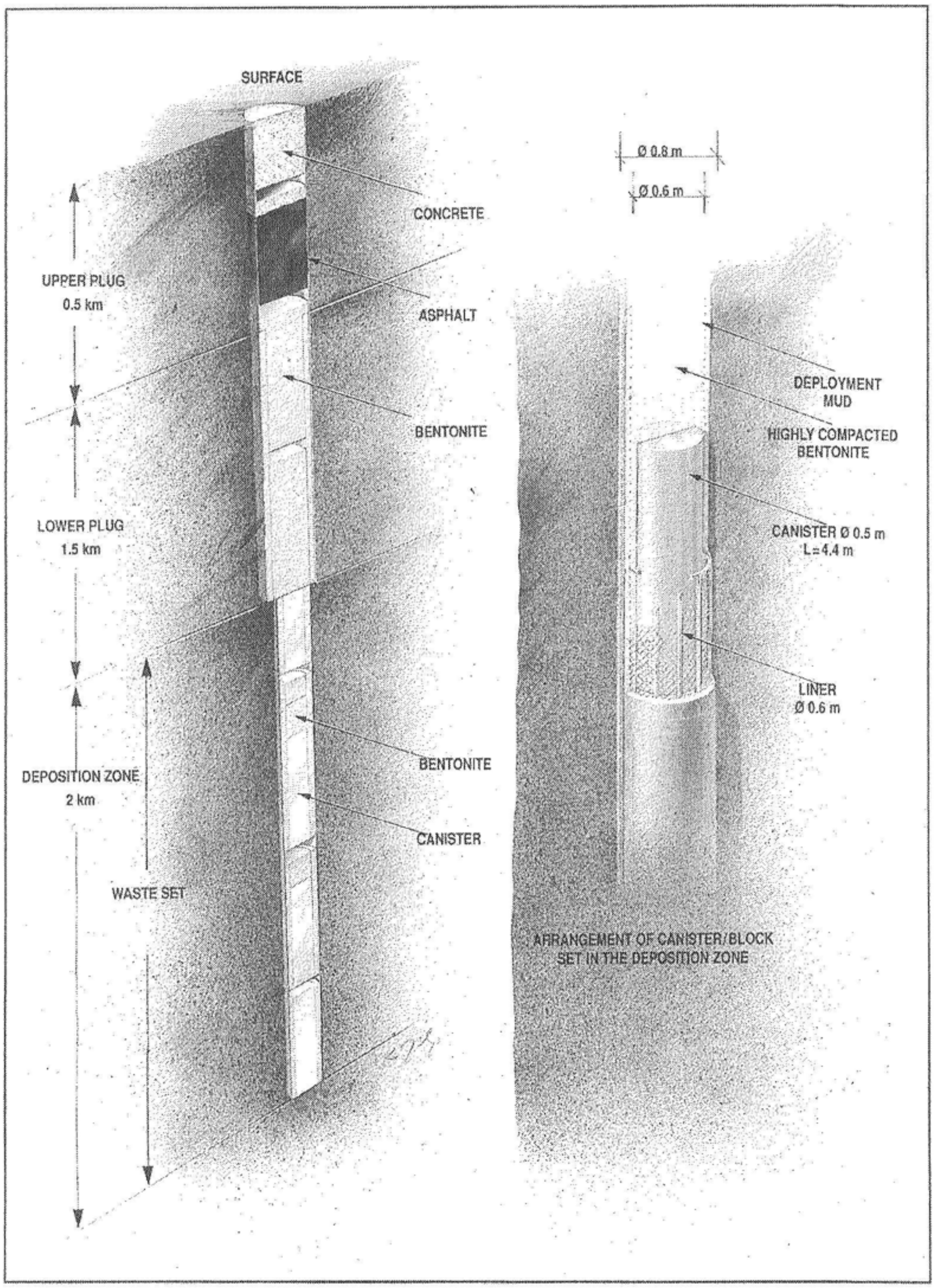


Figure B.1 Swedish Borehole Concept Showing Plug Design Features (from Ref[B-1]).

References for Appendix B

(B-1) SKB Technical Report No. 93-04, "Project on Alternative Systems Study (PASS), Final Report: Appendix 4," Oct. 1992.

(B-2) F.G.F. Gibb et al., "Modeling Temperature Distribution around Very Deep Borehole Disposals of HLW." *Nuclear Technology,* Vol. 163, July 2008.

(B-3) Aluminothermic (Thermit) Welding," in *Mechanical Engineer's Handbook, 6th Ed.*, T. Baumeister, ed., McGraw-Hill, 1958.

(B-4) C.L. Christensen, E.W. Peterson, "Field-Test Programs of Borehole Plugs in Southeastern New Mexico," in *The Technology of High-Level Nuclear Waste Disposal*, Vol. 1, 1981. DOE / TIC-4621.

(B-5) P. V. Brady et al., "Deep Borehole Disposal of High-Level Radioactive Waste," SAND2009-4401, Aug. 2009

(B-6) Radwaste Solutions, WIPP@10 (11 articles), Vol. 16, No. 3, May/June 2009