REGIONAL GEOHYDROLOGIC CONSIDERATIONS IN LLW DISPOSAL SITE SELECTION AND CHARACTERIZATION

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ABSTRACT

In implementation of the Low-level Radioactive Waste Policy Act of 1980, site selection studies for shallow land burial facilities for LLW are needed in geologically very diverse areas of the United States. The basic geohydrologic goals for location of a LLW burial site are (1) that it be in a geologically simple, stable and predictable setting and (2) that subsurface migration of wastes via groundwater be minimized and predictable. The first goal directs the site search toward thick, stable sedimentary formations with simple stratigraphy and homogeneous materials so that site characterization and modeling can be achieved with confidence. The second goal indicates that the burial unit should be substantially above the watertable, or if it is below the watertable, it should have extremly low permeability and good sorptive properties so that migration times are long relative to radioactive decay.

In the humid eastern and midwestern sections of the United States, saturated soil conditions (perched or watertable) are common at shallow depths below the surface. Thus units with low permeability, overlying well-defined bedrock conditions, are most promising. In the more arid west and southwest, unsaturated surface formations with great depth to the watertable are more likely to be found. Under such conditions, significantly more permeable units can prove acceptable for burial, and bedrock structure become less critical when the bedrock is separated form the burial unit by thick, unsaturated strata. The use of sedimentary depositional (facies) models for a particular depositional environment, with existing geologic data, allows the site search to rapidly focus on these more promising areas. The use of facies models for siting in glaciated areas, the Coastal Plain, and the Basin and Range Province in the western U. S. are described.

INTRODUCTION

In light of the the Low Level Radioactive Waste Policy Act of 1980, with its 1986 deadline for the establishment of regional LLW disposal sites, and the related regional compact development efforts, several new low level radioactive waste disposal sites must be brought into operation within the next few years. Guidelines for LLW siting have recently been developed by the NRC and published in 10 CFR Part 61 and related documents[1,2,3,4,5]. This paper presents a geohydrologic perspective on LLW siting, keyed to several of the fundamental site selection requirements listed in 10CFR Part 61, for three very different regions of United States: glaciated areas in the northern part of the country, the Atlantic and Gulf Coastal Plain, and the Basin and Range Province in the western United States. The discussion concentrates on the later steps in LLW site selection, i.e. after the initial regional screening steps have excluded the clearly unfavorable areas for siting within the region of interest (see Alvarado, et al., this volume) and focused the site search on the more promising areas of the region.

Typical geohydrologic conditions in each of the three regions are described through the use of sedimentary depositional, or facies, models. The facies models present a general, simplified picture of the stratigraphic relationships in a particular environment. This paper illustrates how, by using these models and the available geologic information, the most promising conditions for siting can be identified within a generally favorable area before the more costly, time-consuming, and localized site-specific investigations are undertaken. The depositional models are used first as a preventive tool, to help in avoiding geohydrologically complex sites, which at best may be difficult to characterize, and may make the prediction of site performance impossible. Then, once a favorable site has been identified, the models can help to formulate the design of the site characterization study by identifying what materials may be present, their geometry and geohydrologic relationships, and what potential geohydrologic problems may occur in these materials.

10 CFR PART 61 SITE SELECTION CRITERIA

10 CFR Part 61 broadly outlines low level waste disposal site performance objectives and site suitability requirements. The fundamental site performance objective is the protection of

site workers and the general population from exposure to radiation contained at the site, both during site operation and following site closure (Fig. 1). Long-term stability of the site is required to promote this objective, and to minimize the need for active site maintenance during the post-closure period.

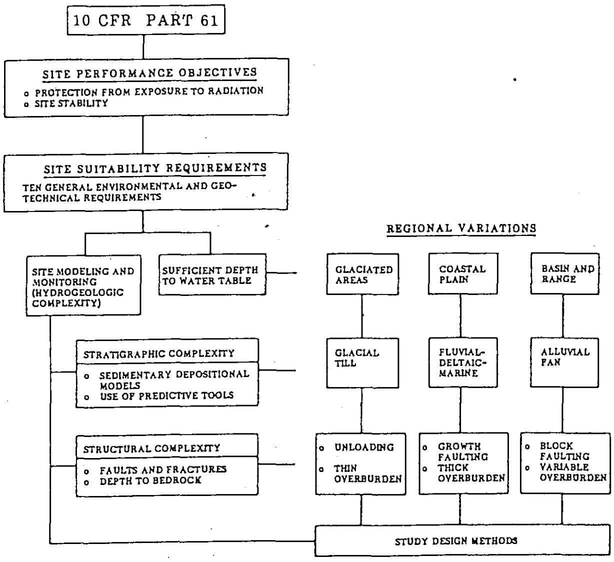

Fig. 1. Geohydrologic site selection requirements of 10 CFR 61, and regional geohydrologic variations discussed in this paper.

Ten environmental and geotechnical site suitability requirements are listed in 10 CFR 61. Two fundamental requirements, that profoundly affect both the site's ability to meet the performance objectives, and our ability to show that the performance objectives will be met, are:

- o The disposal site must provide sufficient depth to the watertable that ground water intrusion, perennial or otherwise, into the waste will not occur (10 CFR61.50.7) (an exception may be considered, discussed below)
- o The disposal site shall be capable of being characterized, modeled, analyzed and monitored (10 CFR61.50.2).

The second criterion implies that the site must be geologically and hydrologically simple. This is required because site selection, characterization and monitoring can only sample a very small portion of the subsurface, yet we must be confident that this sample represents typical conditions of the entire site so that accurate monitoring and predictive modeling programs can be developed. Factors which contribute to geohydrologic complexity include stratigraphic complexity of the burial medium (i.e., variable soils properties, bed thicknesses, etc.) and geologic structural complexity of the site and its environs (such as faulting, subsidence, tectonic activity, etc.). Being able to understand and predict these factors will help both in site selection and characterization.

FACIES MODELS

The geotechnical requirements for a disposal medium for near surface burial of LLW are that the material be relatively homogeneous (i.e. capable of being characterized and modeled) and, from the trench design and operational viewpoint, that it be easily excavatable and have sufficient thickness above bedrock. In other words, the medium should be unconsolidated material that is either formed in place as the bedrock weathers (regolith), or is deposited as transported material. The thickness and characteristics of regolith vary considerably on a very local scale (e.g. from the top to the bottom of a hill) and are difficult to predict regionally. However, the characteristics of transported materials deposited in a particular sedimentary setting can be generally predicted, prior to site-specific, subsurface investigation, using sedimentary depositional (facies) models.

Facies models are generic for a particular sedimentary environment, and are based on many specific geological studies of modern and ancient depositional environments. By analyzing the geometry of the environment, the geologic materials present, and the physical processes that affect the distribution of materials in a particular depositional setting (e.g. glacial, fluvial, marine, etc), a facies model depicts the resulting stratigraphic relationships and properties of materials of the various units in the sedimentary environment (Fig. 2). Of course, the specific, quantitative parameters of each unit's geometry and materials can only be determined by on site investigations. Nevertheless, in application to LLW siting, the use of facies models helps to:

- o Locate the most promising burial materials.
- o Avoid areas with complex or variable geohydrology.
- o Design the site characterization studies based on the expected geometry and characteristics of the materials.

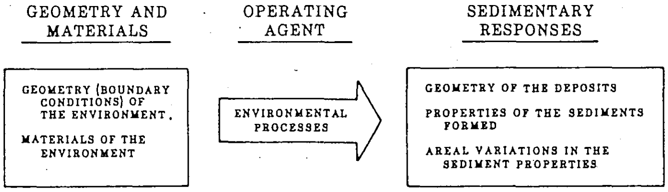

Fig. 2. The facies model approach.

The remainder of this paper will describe the facies models for glacial, coastal plain, and alluvial fan environments, and show how they can be used to effectively focus the site search in each of these areas.

GLACIATED AREAS

Figure 3 depicts the areas covered by glaciers in the United States during the Pleistocene glacial epoch (approximately 1.5 million to 10,000 years ago). It can be seen that glacial material covers large portions of the states in the midwest and northeast regional compacts; glacially-deposited material is thus a likely candidate for LLW siting in these areas[6].

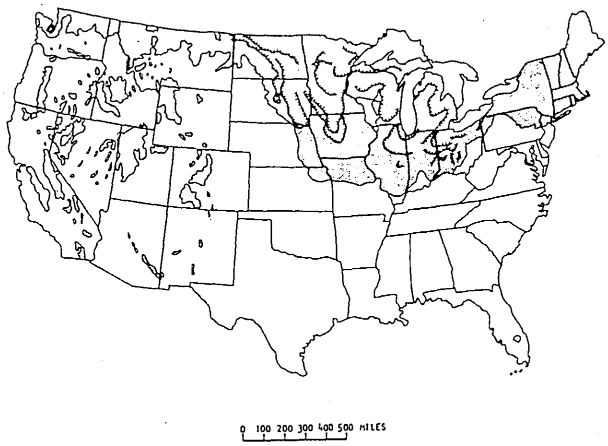

Fig. 3. Distribution of glacial deposits in the United States.

Figure 4 is a simplified schematic diagram of the processes leading to deposition of sediments in a glacial environment. The glacial deposits tend to be quite heterogeneous, on horizontal and vertical scales of as little as tens of feet. The largest volume of glacial sediments is deposited as nonstratified and unsorted glacial till beneath, along the edges of, and in front of the glacial ice. This material consists predominantly of pebble-to boulder-sized rock fragments in a fine-grained (sand to clay) matrix. The thickness of till deposits varies from a few feet to over 600 feet in buried glacial valleys [7]. The average thickness over large areas of the north-central and northeastern states is 50-120 feet[7]. In much of this area, then, sufficient thickness exists for near-surface (20-50 feet) LLW burial.

Although glacial till has a very variable composition and grain size distribution, the fine-grained nature of the matrix in many till deposits, combined with compaction and dewatering by glacial loading, results in very low permeabilities (10^{-6} to 10^{-8} cm/sec). Problems may arise, however, where subglacial streams carrying glacial meltwater cut through the till and deposit higher-permeability channels of sand, silt and gravel. The location of such channels is difficult to predict or determine without extensive subsurface investigation[8] and makes siting in till somewhat more complicated. Nevertheless, thick till deposits, if well characterized, offer good potential for siting.

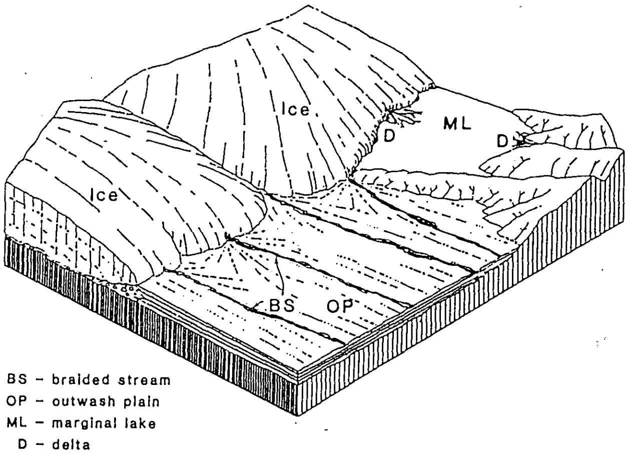

Fig. 4. Simplified diagram of glacial margin depositional environments.

The glacial meltwater streams disgorge onto outwash plains in front of the glacial ice (Fig. 4). The outwash plain is a stratigraphically heterogeneous unit, consisting predominantly of interbedded sand and gravel lenses (the finer materials are usually carried further downstream). This material was deposited by braided streams (i.e., consisting of several interconnected, temporary watercourses) whose channel locations change frequently across the outwash plain. This unit would be very difficult to characterize or model and does not contain materials favorable for LLW siting.

The most homogeneous glacial deposits form in glacial lakes which develop at glacial margins (Fig. 4), and "pluvial lakes", which formed in enclosed basins distant from the glaciers, particularly in the western U.S. (Fig. 3). Pluvial lakes are not directly related to glaciers, but are a result of the glacial climate, having formed as a result of the higher precipitation/evaporation ratio, and therefore greater net moisture supply, during the colder, wetter glacial period. Glacial lake sediments consist primarily of very regular, horizontally layered (varved) silt and clay deposited during annual melt cycles. Pluvial lake sediments also consist of stratified silt and clay, but also contain layers of evaporite salts (halite, borax, etc.) deposited during drier interpluvial periods. The sediment thickness in some of the larger glacial and pluvial lakes reaches several hundred feet, and 30-80 feet of lake sediment is not uncommon, even in the smaller lakes.

The regularity and low permeability of these lake sediments make them among the most attractive glacial units for LLW burial, if they are well-defined to ensure that they do not include coarser delta sediments, which form if a sub-glacial stream empties into a glacial lake. These sediments consist of sands and gravels (fine material is deposited on the glacial lake bed) deposited in steeply dipping and cross-cut beds. These materials are considerably more permeable than the glacial lake sediments. The stratigraphy in these delta units is complex and variable on a small scale; they are difficult to characterize, predict or model, and are not favorable for LLW burial.

This brief description of glacially-deposited materials shows that such deposits can be quite variable, and emphasizes the need for detailed geologic mapping when siting in this environment. Fortunately, much detailed mapping of glacial deposits in the northern U.S. has been done by glacial geologists. Using the facies approach and available maps, the search for potential LLW burial sites would be focused on more promising units such as thicker till deposits and glacial or pluvial lake deposits, while avoiding the less favorable units.

During the Pleistocene glacial period there were several glacial advances and retreats. Stratigraphic complexity can be introduced if the LLW burial zone includes two different glacial tills, because they are usually separated by an erosion surface or soil zone which developed between the glacial advances (Fig. 5). These zones may have high permeability and different materials properties, which cause complexity in characterization or modeling, and provide undesireable characterisitcs for LLW burial. Using regional maps of glacial deposits, the site search can be focused on areas that have thicker deposits laid down during a single glacial advance.

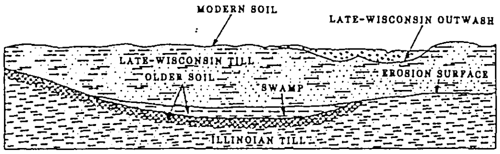

Fig. 5. Possible stratigraphic relationships at the contact of two glacial till deposits.

Potential structural complexity in glaciated areas includes small scale folding and faulting of the glacial deposits caused by differential settling or compaction, and a more regional phenomenon known as glacial-isostatic deformation, which may have led to fracturing of the glacial deposits and the underlying bedrock. Simply stated, glacial-isostatic deformation is displacement of upper mantle material and depression of the Earth's crust under the massive load of glacial ice. With deglaciation, the displaced mantle material flows back and the crust rebounds to approximately its previous elevation. The amount of crustal downwarping and subsequent rebound can reach as much as 1500 feet or more at the centers of the ancient ice masses (in northeastern Canada and Scandinavia). In the northern U.S., deformation of up to 300 feet occurred[7,9]. This deformation may have reactivated older faults and zones of crustal weakness, caused faulting and fracturing due to differential movement of more or less brittle rock formations, and caused fracturing of the glacial deposits. Study of glacier-related faulting is a more site-specific issue, but may lead to greater complexity in siting in glacial deposits.

A second issue of structural complexity is introduced by the fact that glacial deposits are generally shallow (50-120 feet) and directly overlie bedrock. In this situation, the structure of the bedrock must be examined, since leachate from LLW burial trenches would not have far to migrate to reach bedrock, and could then move rapidly through faults and fractures (related to glacial deformation or created by earlier tectonic stress) in the bedrock.

The depth to groundwater, on a regional scale, can be judged by the amount of precipitation, evaporation, and the surface sedimentary materials in the region. Figure 6 shows the mean annual precipitation in the United States. The glaciated areas have moderate precipitation, relatively lower evaporation rates because of colder temperatures and, as described above, generally fine-grained and impermeable surface materials. These characteristics lead to generally shallow depths to the watertable (10-50 feet). This is important to consider, because 10 CFR 61 does allow LLW burial below the watertable "if it can be conclusively shown that disposal characteristics will result in molecular diffusion being the predominant means of radionuclide movement . . . . " (10 CFR 61.50.7). Clearly, the discussion above shows the variability of glacial deposits, and emphasizes the need for detailed site characterization, particularly if burial is to be below the watertable as may be the case in the northern and northeastern U. S.

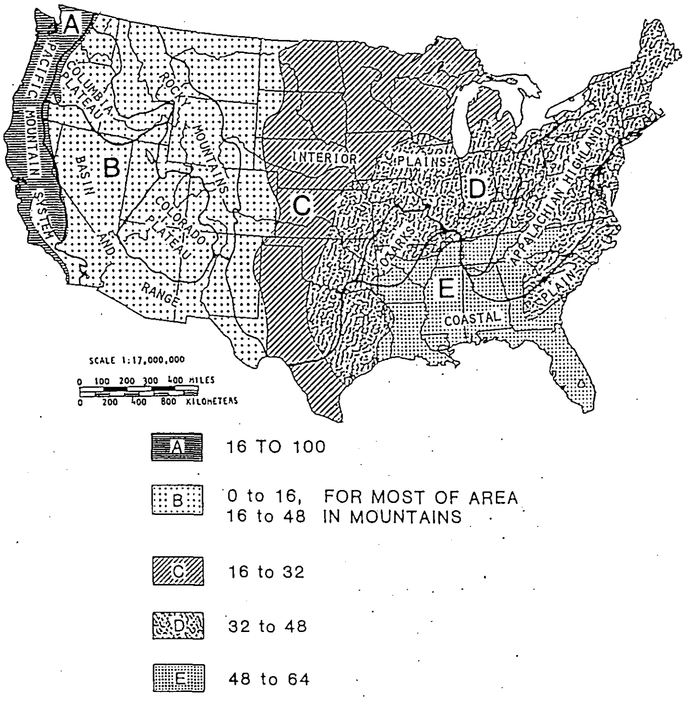

Figure 6. Mean annual total precipitation (inches) in the United States.

COASTAL PLAIN

The Atlantic and Gulf Coastal Plains extend from southern New England to Texas, and include not only the present coastal areas, but broad inland areas which lay in a coastal environment during previous geologic periods (Fig. 7).

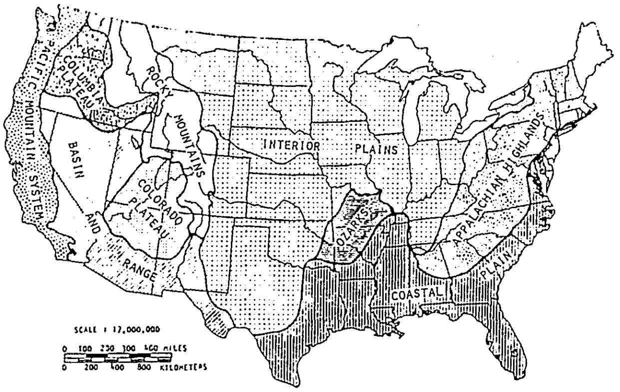

Fig. 7. Major physiographic regions of the United States.

The facies model for this region is the fluvial-deltaic-nearshore marine model. Figure 8 is a simplified cross-section of the coastal depositional system, showing the relatively thinner fluvial (river) deposits, thickening delta muds containing large bodies of "delta front" sands, and the thick prodelta silt and clays. Figure 9 is a map view of a typical delta system, showing also the strandplain (beach) and lagoon environments which develop laterally to the delta. This figure also illustrates typical electic logs from borings through the various units, which demonstrate the relative homogeneity of the units (when the e-log trace on either side of the center line kicks away from the centerline, this indicates sandier materials). The characteristics and suitability of of each of these units for LLW burial, and use of this facies model in site selection, will be discussed below.

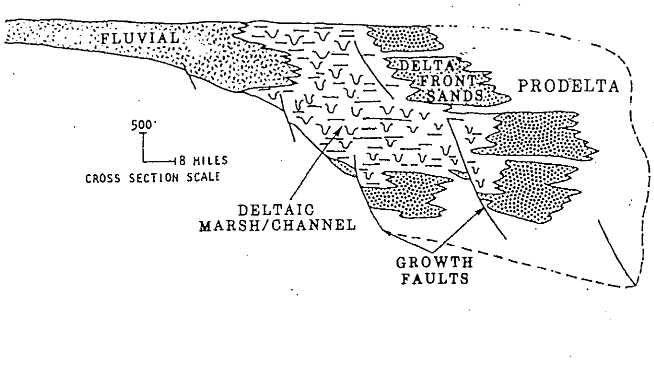

Fig. 8. Fluvial-deltaic facies model.

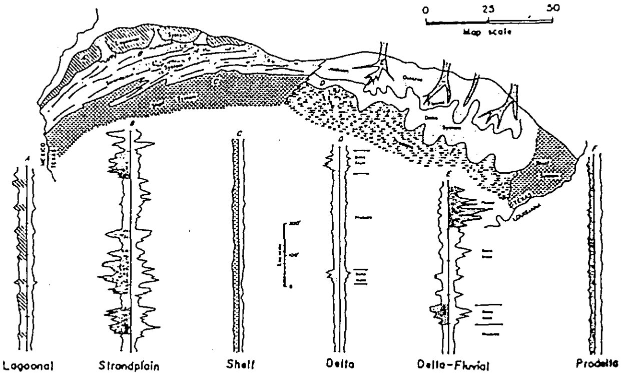

Fig. 9. Depositional environments of the Jackson Group (Eocene), Texas, with representative borehole electric logs (Source: reference No. 10).

Fluvial deposits are relatively thinner than deltaic units, but may reach thicknesses of several hundred feet. They consist primarily of well-sorted, relatively permeable river channel sands, bedload gravels, and overbank (floodplain) silts and clays. In general, channel deposits are volumetrically greater than overbank deposits. Furthermore, the river channels migrate across the floodplain, cutting through and eroding older channel and overbank deposits to replace them with younger channel deposits. The three-dimensional zonation in a fluvial system thus consists of a complex of horizontally and vertically interfingering channel sand and overbank mud deposits. Electric log E in Fig. 9 demonstrates this heterogeneity. On a regional basis, the varability of these deposits makes it difficult to focus the site search on a particular area. On a site-specific basis, it may be possible to identify floodplain deposits of sufficient thickness, homogeneity, and area for development of a LLW disposal site. However, the complex stratigraphy of fluvial deposits will make site characterization, modeling and monitoring difficult and costly. These units are thus not favorable for LLW siting.

Deltas are one of the major depocenters for sedimentary materials (the others being enclosed terrestrial basins and deep marine basins). As illustrated in Figs. 8 and 9, deltaic deposits are generally much thicker and more widespread than fluvial deposits. The major deltaic units are thick delta-front sands, deposited where rivers disgorge into the sea, with adjacent and enclosing silt and clay marsh and swamp deposits, cut by sandy distributary channels (Fig. 8). As shown in Fig. 8, deltaic deposition is cyclic, with sand bodies deposited en echelon vertically and laterally as the areas of deposition migrate across the delta plain. Although delta-front sands may be several hundred feet thick, they commonly reach 20-80 feet in thickness (see electric logs D and E, Fig. 9), at which point the area of active deposition switches to another part of the delta. The relatively high permeability and downdip hydraulic continuity of delta-front sand units make then unfavorable for siting. Deltaic marsh and swamp deposits, consisting predominantly of clays with large amounts of organic material and lignite, have characteristically lower permeabilities and may be sufficiently thick and widespread to offer good potential for locating LLW burial sites. However, as mentioned above, these units are irregularly cut by sand-filled distributary channels leading from the main river channels, which may make site characterization and modeling more complicated, and provide higher-permeability conduits for leachate migration.

Thick units of prodelta silts and clays (reaching several thousand feet) are deposited seaward of the delta front (Figs. 8 and 9). The prodelta unit is the most homogeneous and widespread of all delta environments (see electric log F, Fig. 9), and provides the most favorable conditions for site characterization and modeling. Continental shelf sediments are similarly thick, fine-grained and homogeneous (see electric log C, Fig. 9), and provide excellent conditions for site characterization and modeling. The prodelta and shelf sediments are however, among the most impermeable units, and sites in these materials would have to be carefully designed and maintained to avoid the accumulation of water in trenches.

Strandplain deposits, as shown by electric log B in Fig. 9, tend to be very heterogeneous on a vertical scale of tens of feet. These units consist of complexly interfingered beach or dune sands and marsh or tidal flat silts and muds, cut by tidal channels; they would be difficult to characterize and model, and do not present good siting potential. Lagoon deposits are more regular and fine-grained (see electric log A, Fig. 9), and present some of the better opportunities for siting, being thicker and homogeneous, but not as tightly impermeable as prodelta and shelf sediments.

In summary, using the facies analysis approach for the coastal plain region with available geologic mapping and other data will direct the site search to the more promising formations (lagoon, prodelta and shelf environments) and avoid the potentially complex units. It should be noted that Fig. 9 depicts a 40 million year old coastal system located in south-central Texas. If the LLW site search included this area, using the information published on the system[10] would rapidly focus the siting study on the most promising areas.

Potential structural complexity in the coastal plain is introduced by the presence of growth faults, which develop in the lower sections of the thick deltaic deposits through compression and slumping of the sediments caused by the mass of material above (Fig. 8). These faults can propagate to the surface, and in older deposits, be exposed at the surface by erosion of overlying materials. In some areas the distribution of growth faults has been well mapped during exploration for oil and gas. In any case, the potential presence of such faults is a site-specific issue which would have to be studied at that level of detail. Bedrock structure in the coastal plain is much less important for site selection, characterization and modeling than, for instance, in glaciated areas, because of the greater thickness of sedimentary materials through which leachate would have for migrate before reaching the bedrock.

As noted before, the depth to the watertable depends on the ratio of rainfall to evaporation, and the permeability of surface material. Figure 6 shows that mean annual precipitation varies widely across the coastal plain, from very high rainfall in the humid southeast to semiarid conditions in the southwest. In the southeast, the watertable may be only a few feet to tens of feet below the surface. In this area, if burial was to be below the watertable, the very impermeable shelf and prodelta clays are clearly the units of choice. In the drier parts of the coastal plain, however, depths to the watertable may be several hundred feet, and large areas of delta plain, lagoonal, prodelta or shelf deposits may be favorable for siting.

BASIN AND RANGE

The Basin and Range Province extends from southern Oregon to west Texas (Fig. 7). The alluvial fan facies model used for this region applies in some part also to the intermontane basins and valleys of the Colorado Plateau and the Rocky Mountains.

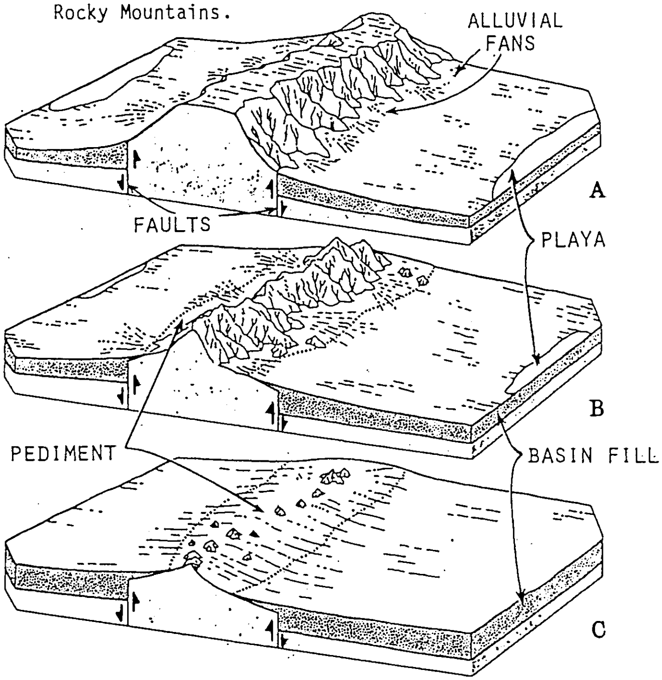

Fig. 10. Sequence of alluvial basin development in the Basin and Range Province.

Figure 10 illustrates the sequence in the development of basin fill deposits. The mountain ranges are initially uplifted by block faulting, with downfaulted basins flanking them. In the early stages of erosion, coarse-grained, relatively small and heterogeneous alluvial fans develop at the base of these mountains (Fig. 10A). As the mountains are further eroded, the fans extend into, and begin to fill, the basins (Fig. 10B). After a long period of erosion, only remnants of the mountain peaks remain, and the basins contain thick sequences of alluvial fill (Fig. 10C). Areas in this final stage of erosion and basin fill, containing the thickest sedimentary wedge, are the most promising for LLW siting in this physiographic region. The pediment area, where the overburden is not very thick and still undergoing downslope transport, and areas immediately adjacent to the block faulting, which may still be active and may provide conduits for groundwater migration, should be avoided.

Figure 11 gives a more detailed view of the alluvial fan model. The thickest sedimentary deposits are adjacent to the uplifted block, but this is also the coarsest-grained material, consisting for the most part of gravel. This is also an area of recharge of groundwater, which flows off the elevated mountain block and infiltrates deep into the basin sediments through the permeable gravel deposits. The fan material becomes finer toward the center of the basin (Fig. 11), but the total thickness decreases somewhat, and at the center of the basin, the potential for flash flooding increases. The most promising areas for siting in this sedimentary environment would be in the silt-sand or silt-clay units, but away from the interfingering sand-gravel or sand-clay interfaces. The generally thick nature of alluvial fill materials makes bedrock structure and potential migration pathways through bedrock less important in this region.

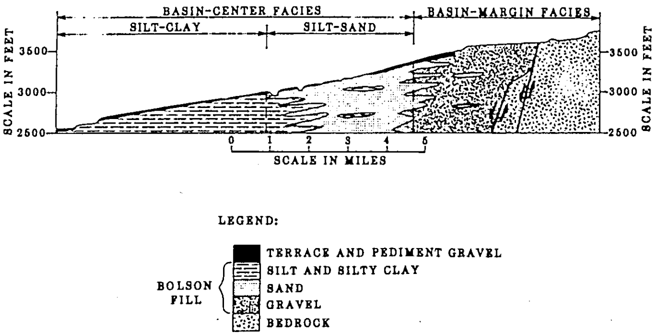

Fig. 11. Alluvial fan facies model (Source: reference No.11).

From the stand point of groundwater, this region is probably the most favorable, because the very low precipitation and high evaporation rates, combined with generally coarser-grained materials, lead to depths to the watertable of several hundred to a thousand or more feet. Although some alluvial basins do contain locally important aquifers, they are located at considerable depth below the ground surface. As with all other potential LLW burial environments, it is important to be able to model the groundwater system in these materials in order to show that the potential for aquifer contamination by leachate migration does not exist.

Using the alluvial fan model, and identifying the source area for the alluvial materials, the areas of block faulting, and the horizontal extent of the alluvial fill, allows the site search to focus on the more favorable units in this region.

SUMMARY

10 CFR 61 lists several requirements for LLW disposal site selection that deal with depth to the watertable and the geohydrologic simplicity of potential sites, as related to site characterization, modeling, and monitoring. Since geologic and hydrologic conditions are distinctly different in various regions of the United States, no single set of specific geotechnical parameters can be defined to ensure that all potential sites meet the siting requirements in a uniform manner. Rather, each potential site will rely on a combination of interactive geohydrologic characteristics specific to that site which allow it to meet the site performance objectives.

Although no generic, "ideal LLW disposal site" can be defined that applies to all parts of the United States, each region of the country is characterized by certain typical sedimentary depositional environments which developed in response to the geologic and climatologic history of the region. These environments can be broadly characterized by sedimentary facies models, which define the types of materials and spatial relationships to be expected in that environment. This paper has briefly described the facies models for three very different regions of the United States - glaciated areas, the Coastal Plain, and the Basin and Range Province - and shown how, using these models in conjunction with available geologic data, the search for suitable LLW disposal sites can be rapidly focused on areas having the strongest siting potential. To meet the 10 CFR 61 requirements, such areas would provide:

- a relatively homogenous burial medium,
- adequate depth to the watertable and to bedrock, and
- structural simplicity.

REFERENCES

1. Nuclear Regulatory Commission, "Licensing Requirements for Land Disposal of Radioactive Waste", 10 CFR Part 61, 1982.

2. Nuclear Regulatory Commision, "Standard Format and Content of Environmental Reports for Near-Surface Disposal of Radioactive Waste", Regulatory Guide 4.18, 33 pp., 1983.

3. Siefken, D., Pangburn, G. Pennifill, R., and Starmer, R. J., "Site Suitability, Selection and Characterization"; Branch Technical Position, Low Level Waste Licensing Branch, NUREG-0902, 26 pp., 1982.

4. Lutton, R.J., Malone, P.G. Meade, R.B., and Patrick, D.M.." Parameters for Characterizing Sites for Disposal of Low-level Radioactive Waste", NUREG/CR-2700, Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, 1982.

5. Lutton, R.J., Butler, D.K., Meade, R.B. Patrick, DM, Strong, A.B., and Taylor , H.M. Jr., "Tests for Evaluating Sites for Disposal of Low-level Radioactive Waste", NUREG/CR-3038, Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, 1982.

6. Witzig, W.F. Dorsife, W.P. and Clemente, F.P. (eds.), Low-level Radioactive Waste Disposal Siting: A Social and Technical Plan for Pennsylvania; Institute for Research on Land and Water Resources, The Pennsylvania State University, prepared for EG & G Idaho, Inc., under contract No. DE-AC07-761D01570, U. S. Dept. of Energy.

7. Flint, R. F., Glacial and Quaternary Geology, John Wiley and Sons, Inc. New York, 892 pp., 1971.

8. Foster, J. B.,"Lessons Learned in a Hydrogeological Case Study at Sheffield, Illinois", in Symposium on Low-Level Waste Disposal: Site Characterization and Monitoring, NUREG/CP-0028, Vol.2.

9. King, P.B., "Tectonics of Quaternary Time in Middle North America", in The Quaternary of the United States, H.E. Wright and D.G. Frey, eds., Princeton University Press, Princeton, N.J., pp. 831-870, 1965.

10. Fisher, W.L., Proctor, C.V. Jr., Galloway, W.E., and Nagle, J.S.," Depositional Systems in the Jackson Group of Texas -- Their Relationship to Oil, Gas and Uranium," Geology Circular 70-4, Bureau of Economic Geology, University of Texas, Austin, Texas, 27 pp., 1970.

11. Groat, C.G., "Presidio Bolson, Trans-Pecos Texas and Adjacent Mexico; Geology of a Desert Basin Aquifer System", Report of Investigations No. 76, Bureau of Economic Geology, University of Texas, Austin, Texas, 46 pp., 1972.