GEOLOGY OF THE HOST FORMATION FOR THE NEW HYDRAULIC FRACTURING FACILITY AT OAK RIDGE NATIONAL LABORATORY*

C. S. Haase and S. H. Stow
Environmental Sciences Division,
Oak Ridge National Laboratory, P.O. Box X,
Oak Ridge, Tennessee 37831

C. L. Zucker
Department of Geological Sciences,
The University of Tennessee
Knoxville, Tennessee 37996

ABSTRACT

Liquid low-level radioactive wastes are disposed of at Oak Ridge National Laboratory (ORNL) by the hydrofracture process. Wastes are mixed with cement and other additives to form a slurry that is injected into a low permeability shale at 300-m depth. Important properties for a host shale formation at a hydrofracture facility include: (1) predictable fracture behavior, (2) hydrologic isolation, and (3) favorable mineralogy and geochemistry to retard radionuclide migration and enhance grout stability. The stratigraphy, petrology, diagenesis, structural geology, and hydrology of the Pumpkin Valley Shale host formation at the ORNL site are summarized and discussed in light of these three properties. Empirical data from hydrofracture operations at ORNL over the past 25 years suggest that many aspects of the Pumpkin Valley Shale make it favorable for use as a host. This observation agrees with analysis of several aspects of the Pumpkin Valley Shale geology at the ORNL site. Although presently available data suggest that the permeability of the Pumpkin Valley Shale is low and that it should provide sufficient hydrologic isolation, more data are needed to properly evaluate this aspect of host formation performance.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) has disposed of low-level liquid radioactive wastes by a unique technology based on hydraulic fracturing and grout injection for over 20 years [1,2]. In this paper we present a brief overview of the site geology of the hydraulic-fracturing facility at Oak Ridge. Our purpose is to document and to discuss critical aspects of site geology as they relate to the performance and long-term success of the hydraulic-fracturing radioactive waste disposal technology.

Hydraulic Fracturing at ORNL

A detailed description of the ORNL hydraulic-fracturing process appears elsewhere in this volume[3]. A brief description of the process is included here for background purposes. The process is based on the subsurface injection of radioactive waste-bearing grouts into hydraulically fractured intervals of a geological formation selected as a host for the emplaced wastes. At the ORNL site, this host formation, the Pumpkin Valley Shale, occurs at depths between 225 and 340 m in the subsurface. During waste injection, a steel-cased injection well is pressurized with water to initiate a hydraulic fracture within the host formation. After initial fracturing, waste-bearing cementitious grouts are pumped downhole to further propagate the hydraulic fracture. During subsequent pumping, the grout spreads out to form irregularly shaped sheets that typically are 2 to 25 mm thick and extend outward from the injection well for distances of 150 to 200 m. Grout injection occurs from a slot cut near the bottom of the well and several injections may be made from the slot. Subsequent slots are cut at shallower depths so that over the lifetime of the facility, grout sheets will be injected from the bottom to the top of the host formation. Grout injection produces surface uplifts and seismic signals that can be used to determine the orientation of the grout sheet. An analysis of these aspects is found elsewhere in this volume[4].

Host Formation Considerations

After subsurface injection and solidification, the cementitious grout acts, more or less, as a waste package for the radioactive waste. The grout is the primary containment feature of the technology and is responsible for retention and isolation of the radioactive wastes. The role of the host formation is that of an isolation medium for the emplaced wastes. It should isolate the waste-bearing grouts from groundwater, provide a favorable geochemical environment to ensure long-term grout stability, and provide protection against waste migration should the grouts ultimately break down and release their contained radionuclides.

General site selection criteria for a hydrofracture facility are discussed elsewhere[2]. However, because of the site's important role in enhancing and augmenting the isolation and containment functions of the grout, several specific criteria for the evaluation of potential host formations are contained in the general site selection considerations. Such criteria include the evaluation of several properties of the host formation that are regarded as essential. These host formation properties are the ability to (1) hydraulically fracture in a predictable manner, (2) to hydrologically isolate the grout sheets, and (3)

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retard radionuclide migration and promote long-term grout stability. The importance of each of these properties to the successful operation of a hydrofracture facility is briefly discussed below.

To ensure that all injected grout sheets stay within the host formation, it must have properties that result in hydraulic fractures oriented parallel to its top and bottom contacts. Ideally, such fractures should maintain a constant orientation throughout their extent and remain in the particular stratigraphic interval in which they were initiated.

The host formation should have low porosity, contain insignificant quantities of groundwater, and have low permeability. Such properties minimize the quantities of groundwater that could come into contact with the grouts and prevent the outward flow of any fluids introduced during hydraulic fracturing operations.

The mineralogy and geochemistry of the host formation should promote the retention of radionuclides contained in the grout sheets. Clay minerals, such as illite and smectite, that have large capacities to sorb radionuclides should be abundant so that the mineralogy of the host formation will provide adequate retention characteristics for the radionuclides of concern. The geochemical environment within the host formation also must be compatible with the chemical and physical stability of the radionuclide-bearing grouts.

With these considerations as a background, the relevant aspects of the site geology of the ORNL hydraulic-fracturing facility will be summarized in the following sections. Most of the data resulted from an ongoing research project, begun in 1980, to reexamine the interaction between the ORNL facility and the surrounding geological environment. Initial site characterization and preliminary geological investigation occurred 20 to 25 years ago, when the hydraulic-fracturing technology for radioactive waste disposal was initially developed at ORNL[1]. The objective of the current research is to develop a more comprehensive picture of the geohydrological aspects of this unique waste disposal technology.

LOCATION AND GEOLOGIC SETTING

Location and Regional Geological Setting

The ORNL hydraulic-fracturing facility is located in the U. S. Department of Energy's Oak Ridge Reservation in east Tennessee (Fig. 1). The facility is within the city limits of Oak Ridge, Tennessee and is approximately 30 km northwest of Knoxville, Tennessee.

The ORNL site is located in the Valley and Ridge province of the Appalachian orogenic belt (Fig. 1). The Valley and Ridge province in east Tennessee is characterized by a series of regional thrust faults that strike parallel to the borders of the province and extend from Alabama to Virginia. Motion along these thrust faults during the Alleghanian orogeny (230 to 250 My ago) resulted in southeast to northwest crustal shortening of 100 to 150 km[5]. This shortening resulted in the formation of a series of imbricate thrust sheets that repeat a stratigraphic succession consisting of sandstones, shales and limestones as many as 7 times from the southeastern to the northwestern border of the province. Within the sediments on each of the imbricate thrust sheets, a significant amount of small-scale folding and faulting results in a complex structural fabric within all rocks of the Valley and Ridge province.

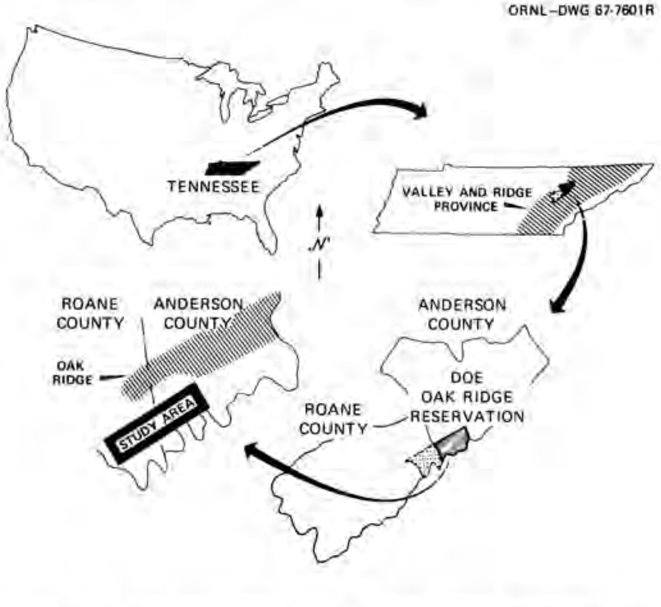

Fig. 1. Location map for the Oak Ridge locality. The ORNL hydrofracture facility is within the study area indicated.

Site Geological Setting

Major geological features of the ORNL hydraulic-fracturing site are summarized in Figs. 2 and 3. The site occurs on the leading edge of the Copper Creek thrust sheet within 1 km of where the fault comes to the surface (Fig. 2). The strike of strata at the site is N 45° to 55° E and the dip of the strata is variable. Within 500 m of the Copper Creek fault trace, dip values range from 45° to 90° to the SE. Further from the fault trace, at the hydrofracture facility, dip values range from 10° to 20° to the SE.

The stratigraphic sequence in the basal portion of the Copper Creek fault block consists of, from top to bottom, the Rome Formation, the Conasauga Group – that includes the host formation, and the Knox Group. The Rome Formation ranges from 100 to 150 m in thickness and consists of massive sandstones, thinly bedded siltstones and laminated shales and mudstones[6]. The Conasauga Group ranges from 550 to 600 m in thickness and consists of six formations, that are, in ascending order, the Pumpkin Valley Shale – the host formation, the Rutledge Limestone, the Rogersville Shale, the Maryville Limestone, the Nolichucky Shale, and the Maynardville Limestone. The clastic-rich formations, including the Pumpkin Valley Shale, consist of thinly bedded siltsones and laminated shales and mudstones. The carbonate-rich formations consist of coarse- to fine-grained limestones, conglomerates, and calcareous siltstones and shales[6]. The Knox Group consists of carbonates, principally dolostone with subordinate amounts of limestone, and locally abundant sandstones. The group has been divided into five formations in the vicinity of the ORNL site and ranges from 600 to 650 m in thickness[7].

Strata in the basal portion of the Copper Creek thrust sheet are characterized by a pervasive structural fabric consisting of multiple joint sets and several generations of small-scale folds and faults[8,9]. Such features are associated with the major episode of thrust faulting that deformed the entire Valley and Ridge province. In addition to these features, several major structural features of the ORNL site are illustrated in Fig. 2. Of importance are several tear faults that cut across the leading edge of the Copper Creek thrust sheet in the immediate vicinity of the ORNL site. The net effect of these faults is to divide the leading edge of the fault block into a series of discrete units that have been translated or rotated with respect to each other. Note the prominent tear fault (Fig. 2) that passes close to the ORNL hydraulic-fracturing facility. Fault strike is generally normal to that of the Copper Creek fault, and fault dip is steep. Motion along the tear faults is complex and is typically a combination of strike- and dip-slip movement. Total displacement along the faults appears to be on the order of several tens of meters. Most tear faults are 1 to 3 km and die out within strata of the Knox Group that crop out to the SE of the ORNL site.

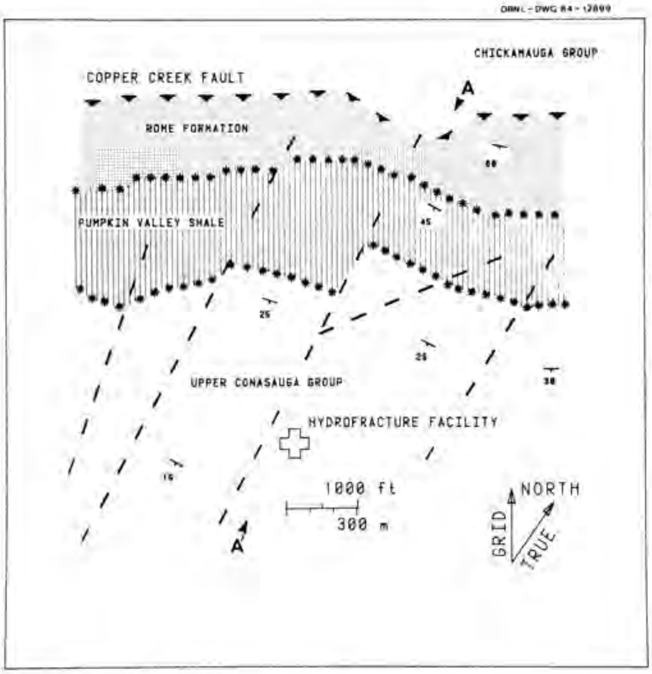

Fig. 2. Site geological map illustrating the major geological structures and outcrop areas for the stratigraphic units on the Copper Creek thrust sheet in the vicinity of the ORNL hydrofracture facility. Lines with teeth mark the trace of the Copper Creek fault. Dashed lines mark the trace of tear faults in the Copper Creek thrust sheet. Dotted lines mark formational contacts. The vertical-ruled area is the outcrop belt of the Pumpkin Valley Shale; because of the SE dip of the formation, it is 230 to 330 m in the subsurface at the hydrofracture facility.

GEOLOGY OF THE PUMPKIN VALLEY SHALE

Stratigraphy

Knowledge of the lateral and vertical distribution of rock types within the Pumpkin Valley Shale is essential to understand local variations in physical, mineralogical, and geochemical properties within the formation. At the ORNL site, the Pumpkin Valley Shale is 105 m thick and can be divided into a siltstone-rich, 45-m-thick lower member and a shale-rich, 60-m-thick upper member[6,10]. The lower contact of the formation is gradational over a 2-m-thick interval into massive to thickly bedded sandstones of the upper Rome Formation. The upper contact of the formation is also gradational over a 3-m-thick interval into limestones and calcareous shales of the Rutledge Limestone. The Pumpkin Valley Shale is composed of several distinct types of mudstones, shales, and siltstones that are common to both members (Fig. 4). The two members differ principally in the relative proportions of the different lithologies, in the character of the interstratification sequences of the different lithologies throughout the member, and in the nature of the primary bedding structures within the constituent lithologies[6,10,11].

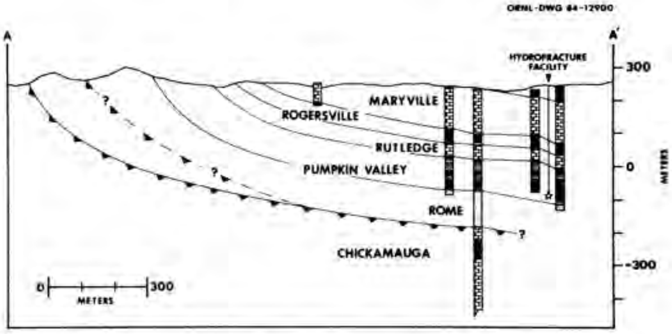

Fig. 3. Cross section along a line between points A and A' in Fig. 2. The subsurface distribution of the Conasauga Group, the Rome Formation, and the Copper Creek fault in the vicinity of the ORNL hydrofracture facility are illustrated.

Based on compositional differences, the lower member of the Pumpkin Valley Shale can be divided into individual stratigraphic intervals that are 0.25 to 3 m thick. Such intervals are complexly interstratified and may be composed of massive mudstones, laminated shales with wavy, discontinuous siltstone stringers, thinly bedded siltstones, or massive, irregularly bedded bioturbated shaly siltstones (Fig. 4). An individual horizon almost always contains several other lithologies in subordinate amounts to the principal one. The stratigraphic intervals appear to be lenticular and do not have great lateral continuity[10,11]. Bedding patterns within the shales vary from planar and continuous to wavy and discontinuous. Some siltstones have thinly bedded, planar, continuous laminations, although most have wavy and discontinuous bedding; cross bedding and current-rippled laminations are locally abundant. Within bioturbated shaly siltstones, churning by bottom-feeding organisms has largely destroyed primary depositional features and produced a homogenized lithology that lacks significant sedimentary structure. Complex interstratification of different lithologies within the lower member of the Pumpkin Valley Shale has produced a highly anisotropic distribution of physical properties within the member[11].

The upper member of the Pumpkin Valley Shale also consists of complexly interstratified, 0.5- to 5-m-thick horizons of massive mudstones, laminated shales, and thinly bedded siltstones and shales with discontinuous siltstone stringers[6,10,11] (Fig. 4). The upper member is similar to the lower member except that it lacks the bioturbated shaly siltstones of the lower member and has a greater abundance of thinly laminated shales. As with the lower member, there is significant compositional variability with statigraphic position. Lateral continuity of beds within the shale-rich horizons appears to be greater than within similar intervals in the lower member. Siltstone-rich horizons, however, are lenticular and lack long-range continuity on the scale of several tens of meters. As in the lower member, the complex interstratification of differing lithologies in the upper member of the Pumpkin Valley Shale has produced a rock unit with an anisotropic distribution of mineralogical, chemical, and physical properties.

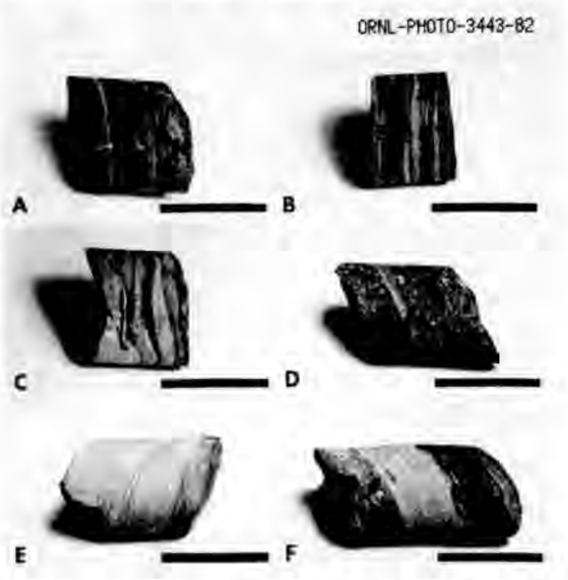

Fig. 4. Photographs illustrating the principal lithologies of the Pumpkin Valley Shale. Bar represents 5 cm in each photograph. (a). Laminated mudstone with discontinuous siltstone stringers. (b). Laminated shale with continuous siltstone stringers. (c). Wavy-bedded, current-rippled siltstone. (d). Bioturbated shaly siltstone. (e). Planar cross-bedded siltstone. (f). Bioturbated shaly siltstone and planar laminated siltstone.

Petrology

Compositionally, shales and mudstones from throughout the Pumpkin Valley Shale are similar to each other. Both contain 75 to 95% clay-sized material composed of illite/vermiculite + illite ± kaolinite ± chlorite + quartz. The shales typically contain 5 to 25% silt-sized material composed of detrital quartz, plagioclase and potassium feldspars, muscovite, and biotite. The mudstones contain 0 to 5% silt-sized material and have the same clay mineral assemblage as the shales[10,11].

Siltstones of the Pumpkin Valley Shale contain 50 to 99% silt-sized detrital grains of quartz, plagioclase and potassium feldspar, muscovite, biotite, and glauconite pellets. The amount of matrix, or clay-sized material, in siltstones ranges from less than 1 to 50%. This matrix material consists of mixtures of primary clay-sized detrital material, partially recrystallized detrital clays and altered feldspar grains, and clay cements. Siltstones can be differentiated into two types by the amount of matrix material. The most abundant siltstones are subarkosic graywackes that have greater than 10% matrix material. These siltstones are moderately well to poorly sorted with subrounded detrital grains of quartz, plagioclase and potassium feldspar, and trace amounts of muscovite and biotite. They are wavy bedded and current-ripple laminations are locally common. A subordinate amount of Pumpkin Valley Shale siltstones are subarkosic in composition with less than 10% matrix material. These siltstones have equigranular and well sorted detrital grains of quartz and plagioclase and potassium feldspars, and are characterized by planar stratification patterns that locally are cross-bedded.

Knowledge of the mineral assemblages, their distribution, and their variability within the lithologies of the Pumpkin Valley Shale is necessary to characterize the radionuclide sorption and retention capability of the formation. Furthermore, data on the mineralogy and the distribution of mineral components throughout the host formation are needed to evaluate the compatibility of the Pumpkin Valley Shale with the injected grouts and to determine if groundwaters within the formation are compatible with the mineral assemblages present. Lack of such compatibilities could have serious negative consequences for grout stability and the radionuclide retention capability of the formation.

Diagenesis

The nature and character of diagenesis within sedimentary rocks is important because the mineralogy, the porosity and permeability, and the physical properties of sediments can be significantly modified by this recrystallization event. The Pumpkin Valley Shale is no exception: during diagenesis, it experienced various recrystallization reactions that significantly changed its ultimate mineralogical and porosity/permeability characteristics. The nature and the extent of reactions during diagenesis differed within the major rock types of the Pumpkin Valley Shale. In general, the diagenetic episode had three stages: (1) a period of early cementation and occlusion of primary porosity, (2) a subsequent period of grain dissolution and secondary porosity development, and (3) a final period of cementation and occlusion of remaining primary and all secondary porosity[10,11].

All three stages of diagenesis are best developed in the low matrix content siltstones. Early cementation consisted of the development of quartz overgrowths and grain-rimming kaolinite and chlorite cements within intergranular pore spaces. Dissolution of detrital feldspars and, locally, early quartz cement and detrital quartz grains marked the episode of secondary porosity formation. The final diagenetic stage is marked by the occlusion of all remaining intergranular porosity by calcite. Within other lithologies of the Pumpkin Valley Shale, the amount of matrix material determined the extent of diagenetic reaction[10,11]. In siltstones with greater than 10% matrix, diagenesis consisted simply of cementation and porosity occlusion. Secondary porosity formation occurred only locally. Diagenesis within shales and mudstones is characterized by recrystallizt1on of the clay-sized material into patches of coarser-grained illite, kaolinite, or chlorite. Variability in the amounts of primary illite/vermiculite-rich matrix and of secondary illite, kaolinite, and chlorite within shales and mudstones represents different degrees of diagenetic recrystallization[10].

Analysis of diagenetic trends is necessary to determine the ultimate distribution of mineral assemblages and porosity and permeability patterns within the Pumpkin Valley Shale. This analysis of diagenesis also illustrates the importance of understanding the character of the compositional heterogeneity within a formation. The nature of the diagenetic recrystallization within a particular interval of the Pumpkin Valley Shale was controlled by the original composition of that interval. Therefore, knowledge of the original distribution of rock types within the formation would allow predictions to be made about the postdiagenetic distribution of mineral assemblages, porosity and permeability patterns, and physical properties.

Structural Fabric

Deformation features associated with major tectonic events of the Alleghanian orogeny are ubiquitous in the Pumpkin Valley Shale. Joint sets, fractures, folds, and faults occur throughout the Pumpkin Valley Shale[6,8,9]. Because such features can produce significant amounts of secondary fracture porosity and permeability within a formation, detailed knowledge of such features is essential to understanding their potentially large impact on subsurface hydrology and flow patterns. Furthermore, folds and faults may have an influence on the orientation of induced hydraulic fractures and injected grout sheets. Evaluation of these factors requires a detailed knowledge of the structural fabric of the Pumpkin Valley Shale at the ORNL site.

At least two and, locally, as many as four joint sets have been identified within the Pumpkin Valley Shale[9]. All of these can be related to major structures, such as the Copper Creek thrust fault or specific folding events. Within a particular interval, joint spacing, length, and density is a complex function of lithology and bed thickness. Futhermore, although joint sets show fairly constant orientations with respect to major structures, specific joint sets exhibit significant variability within lateral distances of several hundreds of meters. Joints within siltstone-rich lithologies are commonly filled with secondary carbonates (see Fig. 5), although locally such joints may be unfilled. Joints within mudstones and shales are frequently unfilled. The vertical and lateral continuity of joints is limited by the complex interstratification patterns with the Pumpkin Valley Shale. Single joints rarely cut more than several adjacent beds and typically die out at siltstone/mudstone contacts. Because of the generally lenticular nature of many bedforms within the Pumpkin Valley Shale, the lateral continuity of a particular joint does not exceed several tens of meters[9].

Fig. 5. Drill core sample of planar laminated siltstone from the Pumpkin Valley Shale illustrating abundant jointing. Note that joints are filled with secondary calcite.

Small-scale fractures within the siltstone-rich intervals of the Pumpkin Valley Shale are abundant. At least two generations of cross-cutting fractures can be identified in drill core[6]. As with the joints, fractures are most numerous within siltstones; although locally, mudstones and shales contain significant concentrations of fractures. Most fractures are filled with secondary carbonate minerals; at relatively shallow depths, however, many fractures are unfilled or only partially filled and sealed[6,9].

Small-scale folds and faults are common throughout much of the Pumpkin Valley Shale. Folds have amplitudes of 0.5 to 3 m and are tight, occasionally being isoclinal. Many folds are associated with small-scale faults that occur throughout the Pumpkin Valley Shale. Such fault zones are 0.1 to 3 m thick and typically have nearly vertical dips, although lower angle faults have been observed[6,9].

Hydrology

The hydrologic properties of the Pumpkin Valley Shale at the ORNL site are important because the formation must isolate the injected grout sheets from contact with groundwater. Hydrologic isolation requires that small quantities of groundwater are present in the host formation and that groundwater move through the formation slowly and in small volumes: that is, the formation must have low porosity and permeability, and hydrologic heads within the formation must be low.

The hydrology of the ORNL hydraulic-fracturing facility site is complex and not understood in detail. Available data suggest that the subsurface groundwater regime consists of a shallow, freshwater system and a deep, saline system[12]. In general, the permeability of the Conasauga Group is low and flow directions for much of the shallow groundwater system are influenced by structural fabric elements, such as joints and fractures[9,13,14]. The shallow groundwater system at the site extends to depths of 60 to 150 m. Groundwater within this system is fresh, with TDS values less than 5000 ppm. Within the upper portions of the zone of shallow fresh groundwater, at depths less than 50 m, the weathered portions of Conasauga Group strata contain moderate amounts of groundwater. Below this depth, borehole geophysical logs suggest that fresh groundwater is increasingly confined to fracture and fault zones. At present, little is known about the behavior of groundwater at the bottom of the shallow zone.

The nature of the deep, saline groundwater system within the lower portions of the strata of the Conasauga Group is not known. Waters within this deeper system appear to be high-TDS fluids (see Table I) with chloride concentrations ranging from 100,000 to 120,000 ppm[15]. Because of the dramatic compositional differences between shallow and deep groundwaters, the deep system is thought to be largely separate from the shallow system. Details of possible coupling between the two systems are not known. By analogy with the shallow groundwater system, it is hypothesized that flow directions of the deep system are largely controlled by the fracture permeability related to structural fabric elements. No data are available at present on the formation pressures or hydrologic heads associated with the Pumpkin Valley Shale or adjacent formations in the deep subsurface. Currently, research is in progress to make such determinations within the Pumpkin Valley Shale.

The chemistry of groundwater within the Pumpkin Valley Shale is complex. Analysis of water from wells finished within the interval of the Pumpkin Valley Shale and the two overlying formations (the Rutledge Limestone and the Rogersville Shale – total combined thickness of 70 m) indicated that the groundwaters are high-chloride brines (see Table I)[12,15]. Research in progress is intended to better characterize such waters and to determine the stratigraphic variability of groundwater within the Pumpkin Valley Shale.

TABLE I

Chemical Data for Deep Groundwater

Component	Samples from Borehole S400 (μg/ml exept where noted)	
	960*	120**
pH (pH units)	5.1	7.0
Na	36400	900
K	137	8.2
Ca	10000	85.5
Mg	2070	13.8
Sr	952	1.6
Ba	94	0.5
Fe	65	0.4
Mn	44	0.3
Cl	100000	1200
Br	550	7
SO4	<40	100
NO3	<40	<4
Alkalinity	0	603
Conductivity (μmhos/cm)	156400	5020

* Saline, deep groundwater sample from 293 m.
** Fresh, shallow groundwater sample from 37.6 m.

At depths greater than 200 m, the Pumpkin Valley Shale appears to have low permeabilities. Laboratory measurements from drill core samples indicate exceedingly low permeability values in the range of 0.0003 to 0.00003 md[1]. Research in progress will determine permeability values by in situ methods for specific stratigraphic intervals of the Pumpkin Valley Shale. Porosity values determined by laboratory measurements on core samples range from ~1.0 to 3.0%[1]. Such values are consistent with the range of values determined by petrographic study of thin sections from siltstones.

PERFORMANCE OF THE PUMPKIN VALLEY SHALE AS A HOST FORMATION

Hydraulic-Fracture Orientation

The orientation of hydraulic fractures and injection grout sheets has been determined by core drilling, gamma-ray logging in observation wells, and measurement of surface deformation patterns associated with grout injection[1,4]. The results indicate that the Pumpkin Valley Shale hydraulically fractures in a consistent manner and that such fractures typically occur along, or parallel to, bedding planes. Because of the relatively shallow dip of the Pumpkin Valley Shale at the ORNL site, such fracturing behavior results in a near-horizontal orientation for injected grout sheets. Results from an extensive core drilling of experimental injections indicate that structures such as folds and faults have only localized influence on grout sheet orientation[1]. Typically, grout sheets remained within 4 m of the stratigraphic interval in which they were injected. Such observations suggest that the complex structural fabric of the Pumpkin Valley Shale, which could produce erratic fracture orientation, does not play a significant role in determining fracture behavior of the formation at the ORNL site.

Grout sheet orientations have been determined for operational hydrofracture injections making use of gamma-ray logging in a network of cased observation wells in the immediate vicinity of the new hydrofracture facility[3]. Data from 13 injections obtained by this technique at the new ORNL hydrofracture facility suggest that grout sheets have an essentially horizontal orientation near the facility[16]. Similar results were obtained for 25 injections at a previous facility located within 250 m of the new facility[1,17,18,19].

Research reported elsewhere in this volume[4] has addressed the problem of determining the orientation of the entire grout sheet through analysis of surface deformation associated with the injection. Preliminary results from this research also suggest that grout sheet orientation is nearly horizontal and that grout sheet orientation remains constant throughout the course of an injection.

The data gathered over the past 25 years indicate that grout sheets injected into hydraulic fractures within the Pumpkin Valley Shale have a consistent and predictable orientation and that they remain in the intended host formation. The Pumpkin Valley Shale rates highly, with respect to the "predictable fracture behavior" consideration discussed in the Introduction.

Hydrologic Isolation

The hydrologic properties of the Pumpkin Valley Shale appear to be favorable to the "hydrologic isolation" considerations discussed in the introduction. Laboratory-determined porosity and permeabilities fall within a range that would indicate water movement through the rock matrix of the Pumpkin Valley Shale should be very slow, on the order of a few meters in 100 y.

Evaluation of the total permeability of the Pumpkin Valley Shale must include not only the primary permeability associated with the rock matrix – discussed above – but also any secondary permeability associated with fractures and joints. This important aspect of permeability within the Pumpkin Valley Shale has not been adequately evaluated. The pervasive structural fabric of the formation can produce a significant fracture permeability that can not be fully characterized by laboratory measurements on core samples. For example, joint and fracture set spacings could be larger than core sample dimensions, making the contribution of joints and fractures to total rock permeabilty difficult to determine. Furthermore, folds and faults could produce local zones of greatly increased permeability that would not be adequately sampled by drill core material. *Total permeability* values for 30-m-long intervals of Conasauga Group strata overlying the Pumpkin Valley Shale have been determined from pressure decay measurements in boreholes. The values are similar to those determined by laboratory measurements[16]. However, such measurements were not carefully controlled and the potential influence of fracture permeability on the total permeability of the formation has not been rigorously evaluated. Research in progress includes in situ hydrologic measurements that will allow such an evaluation to be made.

The high-chloride groundwater indicates that fluids within the Pumpkin Valley Shale are not linked directly to the shallow fresh water-bearing groundwater system overlying the host formation at the ORNL site. This is a positive aspect because it suggests the lack of effective communication between shallow and deep groundwater systems, and, hence, good isolation for the deep groundwater immediately surrounding the injected grouts.

The overall assessment of the "hydrologic isolation" property for the Pumpkin Valley Shale hydrology at the ORNL site shows that several aspects need further clarification. The formation has the low permeability, but the possible localized effects of structural features needs to be clarified.

Radionuclide Retention and Favorable Geochemical Environment

The clay mineralogy of the Pumpkin Valley Shale is relatively simple and the assemblage of clay minerals present throughout the formation is constant. Such a feature has both positive and negative consequences for the suitability of the formation as a host for injected grout sheets. The illite and illite/vermiculite content of the Pumpkin Valley Shale can be as high as 80%, and because these clay minerals have high sorption properties for ^{137}Cs, the Pumpkin Valley Shale is extremely efficient in sorbing and retaining this radionuclide[1]. This fact is essential to the ORNL facility because ^{137}Cs is a major component of ORNL wastes. Available data indicate, however, that the mineralogical composition of the Pumpkin Valley Shale is much less favorable for sorption and retention of ^{90}Sr, which is also a major component of ORNL waste[20]. Under ambient geochemical conditions, the illite and illite/vermiculite in the Pumpkin Valley Shale are inefficient in retaining ^{90}Sr, and no other mineralogical constituent of the formation is an effective sorption agent for this radionuclide.

The Pumpkin Valley Shale gets mixed ratings with respect to the "efficient sorption and retention" consideration discussed in the introduction. Because of its high illite and illite/vermiculite content, the formation is very effective in retaining one major waste component. However, because of the lack of other clays, such as smectites, the Pumpkin Valley Shale is much less effective at retaining other important waste components. Increased mineralogical diversity would be desirable.

Another aspect is that the host formation provide a favorable geochemical environment for the injected grout. The high-chloride waters within the Pumpkin Valley Shale may have potentially negative effects on the long-term stability of the waste-bearing grouts. Evaluation of such factors is in progrss at ORNL.

SUMMARY

Empirical data gathered largely from operational experience over the past 25 years at the ORNL site suggest that the Pumpkin Valley Shale has many of the necessary attributes required of a successful host formation. The formation fractures in a regular fashion so that injected grout sheets have predictable orientations and remain within the stratigraphic extent of the formation. Available data suggest that the formation has low intrinsic permeability. The ambient groundwater in the formation is saline and therefore not in rapid communication with overlying freshwater groundwater systems. The mineralogy of the formation is an efficient sorption agent for some radionuclides, especially ^{137}Cs, that comprise the ORNL waste.

Several aspects of Pumpkin Valley Shale hydrology at the ORNL site need additional research. Principal among these is determination of the potential effect of structural features on permeability within the formation. Rocks with generally low permeability are difficult to characterize, and research is under way to address this issue more completely. The geochemistry of the high-chloride formation water of the Pumpkin Valley Shale is under study to determine the age and origin of these waters and to determine the nature of their interaction with the overlying freshwater groundwater system.

Research on the characterization of groundwater chemistry and on the in situ determination of the hydrologic characteristics will continue for the next several years to further determine the behavior of the Pumpkin Valley Shale as a host formation. The long term goals of this research are to provide a rigorous scientific understanding for the large amount of empirical data derived from hydrofracture operations at the ORNL site over the past 25 years and to further clarify the role of the host formation to the long term success of the hydrofracture process.

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