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STATUS OF EVALUATION OF TUFF IN SOUTHERN NEVADA FOR GEOLOGIC DISPOSAL OF HIGH LEVEL NUCLEAR WASTES*

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INTRODUCTION

One rock type presently being evaluated as a possible disposal medium for nuclear wastes is silicic tuff, a fragmented volcanic rock similar to granite in composition. The purposes of this paper are to discuss the geologic setting of tuff, which locally occurs in great thicknesses in southern Nevada, and to provide a brief overview of some aspects of efforts to evaluate the potential of tuff as a medium for safe geologic disposal of high level radioactive wastes. Emphasis is placed on those factors that might affect site characterization and on preliminary geochemical and material properties data.

SILICIC TUFF: DEFINITION, DESCRIPTION, AND MODES OF OCCURRENCE

Tuff, a volcanic rock composed of particles ejected during volcanic eruption, is deposited by two major mechanisms: aerial settling (air-fall tuff) and ash-flow transport (ash-flow tuff). Ash-flows spread radially from vent areas, driven by gravity, depositing tuff as thick sheets extending laterally as much as several tens of kilometers from the source vents. Tuff within these sheets may "weld" by compaction and cohesion of glassy fragments, in response to the high emplacement temperatures and to lithostatic loads. Due to inherent vertical temperature and pressure gradients in a newly deposited ash-flow sheet, distinct

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zones of welding are often formed, with porosities ranging from near 0% to as much as 50% as a function of the degree of welding. Air-fall tuff is emplaced at relatively low temperatures by deposition of discrete particles, and therefore has high initial porosity. Consequently, air-fall deposits are nonwelded, but may become compacted and indurated with burial.

The mineralogy of tuff is highly variable. Freshly deposited tuff consists of fragmented particles of volcanic glass, in addition to as much as 50 percent crystals and rock fragments. There are two major processes that may affect the mineralogy of tuff after deposition: devitrification of the glass phase and secondary alteration. Devitrification refers to the crystallization of the glass to form alkali feldspars and quartz or cristobalite. Alteration, which leads to the growth of new mineral phases stable at lower temperatures, is a complex process, and often includes changes in the chemical composition of the rock, resulting from ion exchange with percolating fluids. Tuff may alter to various clay or zeolite minerals, depending largely on the chemistry of the rock and of the pore fluids. Zeolites are hydrous Na-K-Ca aluminosilicates and are characterized by a relatively open three-dimensional framework structure. Because of their structure, they lose or gain water reversibly at relatively low temperatures and have a high potential for exchange of certain cations with percolating fluids. In general, air-fall and bedded or reworked tuff, as well as nonwelded to partly welded ash-flow tuff, have high zeolite contents if affected by secondary alteration.

Silicic tuff occurs in large volumes within and adjacent to many large silicic volcanic centers. Typically, individual large-volume eruptions occur in rapid succession, resulting in the formation of numerous thick ash flows over a short time interval. Commonly, as a result of the rapid emptying of the magma chamber underlying the volcanic center, subsidence of a circular central block occurs, forming a collapse depression or caldera. With continued eruption, the caldera may be filled with thousands of feet of ponded tuff (Smith and Bailey, 1968). Consequently, there appear to be two major geologic settings where tuff deposits provide exploration targets for siting of a radioactive waste repository: 1) within collapsed calderas, and 2) within relatively thick ash-flow sheets flanking large volcanic centers. The latter type of occurrence is illustrated at Yucca Mountain, a current exploration area in tuff at the Nevada Test SITE (NTS). Yucca Mountain is located on the south flank of the Timber Mountain-Oasis Valley caldera complex (Byers and others, 1976; Christiansen and others, 1977), and is composed of numerous ash-flow sheets and zones of air-fall tuff, with an aggregate thickness that may exceed 5000 feet.

REGIONAL GEOLOGIC SETTING OF TUFFS IN SOUTHERN NEVADA

Southern Nevada lies within the Great Basin section of the Basin and Range Physiographic Province of the western United States. The Basin and Range is composed of linear, block-faulted mountain ranges, separated by alluvium-filled valleys. The Great Basin is unique in the western United States, in that it is characterized by completely internal surface drainage.

The geology of Southern Nevada is highly complex. Regional Paleozoic and Mesozoic thrust faulting involved west-to-east movement of up to 40 km along single fault systems, and occurred during three separate time intervals, with deformation generally migrating eastward during successive orogenic events. In Esmeralda and north-central Nye counties, thrust faults date from the Antler orogeny, and are as old as 360 m.y. (Burchfield and Davis, 1975). Central Nye county and western Lincoln county, including the NTS and vicinity, underwent thrusting 205 to 180 m.y.b.p. during an unnamed orogenic event (Burchfiel, Pelton and Sutter, 1970). Much of Lincoln county experienced thrust faulting during the Sevier orogeny, 90-75 m.y. ago (Armstrong, 1968), after which thrust faulting ceased. The combined results of these three periods of faulting was to produce a locally complex substrate upon which tuff was later deposited.

Widespread extensional or normal block faulting began more than 25 m.y. ago in much of the Basin and Range (Crowe, 1978; Livaccari, 1979) giving the region its distinctive physiographic and geologic character. Because this faulting was active both during and after tuff deposition in many areas (Christiansen, et al., 1977), and may involve several hundred meters of vertical offset, it locally complicates the surficial and subsurface distribution of some tuff units. The resulting rapid variations in tuff thickness may complicate detailed site characterization efforts in some tuffs.

Present day seismicity in the Basin and Range is an issue in repository siting activities. Seismicity tends to be concentrated around the margins of the province outside southern Nevada, but also extends along an east-west trend from south-central Nevada into Utah (Suppe, Powell, and Berry, 1975; Smith and Sbar, 1974). While much of the seismicity appears to be related to continued Basin and Range normal faulting, activity along the east-west trend in southern Nevada is apparently due to left-lateral strike-slip faulting. Although general patterns in present-day seismicity are apparent, there are numerous exceptions, i.e., local concentrations of seismic activity that do not occur along well-established trends.

General time-space trends are evident in the distribution of volcanic rocks in Nevada (Steward, Moore, and Zietz, 1977; Steward and Carlson, 1976). These trends are of interest as background data for evaluation of the probability of future volcanism in specific areas. Small volumes of silicic tuff aged 34-43 m.y. are present in the north-central part of the state. Abundant tuffs aged 17-34 m.y. outcrop in a broad band across the central portion of the state. In southern Nye and central Lincoln counties there is abundant tuff aged 6 to 17 m.y. No silicic tuffs younger than 6 m.y. are mapped in Nevada. From this simplified picture, it appears that the distribution of silicic tuff fits a fairly regular time-space pattern in Nevada, and that the likelihood of recurrent silicic volcanism in any specific area would be very slight, especially in the northern part of the state. There are, however, numerous local occurrences of young (i.e., < 6 m.y. in age) basalts in the Basin and Range. These basalts, like the present-day seismicity, tend to be concentrated around the margins of the province (Best and Brimhall, 1974), but there are occurrences within the province interior (Stewart and Carlson, 1976). Some of these basaltic centers are of Quaternary age.

Many data are available on the hydrologic properties of tuff in the vicinity of the NTS (Winograd and Thordarson, 1975). Tuff may be either an aquifer or an aquitard, depending upon its matrix and fracture permeabilities. In general, welded tuff is relatively permeable due to the presence of cooling and/or secondary joints. Nonwelded tuff tends to have low permeability, due to low matrix permeability and wide joint spacing (Smyth and others, in press). The arid to semi-arid Great Basin, including the NTS, is dominated by regional ground water flow systems which generally have long, deep flow paths to discharge areas, low ground water velocities, and flow paths through numerous rock types. The widespread distribution and general hydrologic setting of tuff within the Great Basin provide the potential for siting a waste repository in a region within which ground water would filter through several tens of kilometers of tuff and tuffaceous alluvium before discharging to the biosphere.

GENERAL MEDIA PROPERTIES OF INTEREST

One of the most attractive features of tuff for nuclear waste management is its strong sorption of many radionuclides, which has also been examined for tuffaceous alluvium. Preliminary data (Hoffman and others, 1977; Wolfsberg and others, in press) suggest that average measured cation sorption ratios (batch K_D's) for tuff are distinctly higher than for granite, and comparable to those for argillite. These results also indicate that sorptive properties of tuff for individual radionuclides vary considerably as a function of the amount of unaltered volcanic glass, degree of crystallization, and abundance of alteration minerals, notably zeolites and clays. The inherent mineralogic variability within tuffs encountered along regional flow paths thus would appear to provide strong sorption for a broad range of nuclides.

Material properties data on tuffs are limited. In general, welded tuff has a critical strength ($16-20 \times 10^3$ psi) roughly half that of granite or basalt, while nonwelded tuffs are appreciably weaker ($C_o \sim 6 \times 10^3$ psi). Preliminary ambient-pressure data indicate that linear thermal expansion of non-glassy tuffs with less than about 25% porosity is both porosity and rate-independent. Variable contents of layer silicate minerals and cristobalite cause second order variations, depending on local solid and fluid confining pressures. An approximate average α_L between ambient conditions and 300°C is 12.3×10^{-6} ($°C^{-1}$) for welded tuffs. Expansion of nonwelded tuffs (i.e., those with greater than about 25% porosity) appears to be more complex, due to variable contents of expandable clay and/or hydrated glass, both of which contract upon dehydration (Lappin, 1979).

One-dimensional thermal modeling of the effects of disposal of a variety of heat-producing wastes in a simulation of the layered tuff stratigraphy at Yucca Mountain has recently been completed (Bulmer, 1978). The model assumes uniformly distributed horizontally-planar heat production at varying depths below the contact between the Prow Pass and Bullfrog Members of the Crater Flat Tuff, which occurs at a depth of 711 m. Since it is one-dimensional the model is applicable only for distances greater than about 10 m above the heat-producing horizon. Additionally, it is assumed that all waste was emplaced instantaneously, and the heat-producing zone was perfectly back-filled. The occurrence of boiling at the contact between the heat-producing zone and the overlying rock which is approximately equivalent to a position 10 m above canistered waste, was used as a limit to acceptable power densities. Results indicate the complex interplay of several variables. If it is assumed that the effective in situ fluid pressure is approximately 1 atmosphere, then emplacement of either conventional 10-year-old HLW or 10-year-old UO_2 spent fuel at an initial power density of as little as 50 kW/acre would generally lead to far-field boiling. This assignment of fluid pressure is equivalent to assuming: 1) that the tuff is infinitely permeable on the time scale of in situ heating; and 2) that the repository is above the water table. An alternative set of assumptions is that the rocks surrounding a repository are totally impermeable and have zero tensile strength in situ. Under these conditions, large-scale boiling would not begin until the fluid pressure in heated areas was approximately equal to the lithostatic pressure, plus compressional thermomechanical stresses, if any. Calculations occur for areal power loadings of at least 150 kW/acre. An intermediate assumption is that the in situ boiling temperature above a back-filled repository would be defined by the height of standing water between the repository and the local water table. This is equivalent to assuming that the in situ permeability is sufficient to maintain communication with the overlying column of water at all times. Under this assumption, maximum allowable power densities calculated range from 130 to 175 kW/acre for HLW and 115 to 145 kW/acre for $SF(UO_2)$, depending upon the assigned initial geothermal heat flux. In the case of Yucca Mountain, with a measured geothermal flux of approximately 1.6 $\mu cal/cm^2$ sec (Sass, et al., 1971), calculated allowable loadings at a depth of 860 m are 165 kW/acre for HLW and 140 kW/acre for $SF(UO_2)$, using the stated criterion of far-field boiling as a limit.

In reality, it is expected that an unspecified volume of rock in the vicinity of emplaced canisters would be able to vent directly into the underground workings during the operational phase of a repository, and that contained water would boil under an effective fluid pressure approaching 1 atmosphere. Outside the area of major compressive thermal stresses, it is reasonable to assume that equilibrium between the water in a given volume of rock and that in the overlying column of water would be maintained. It is not clear whether or not compressive thermomechanical stresses in the vicinity of a repository would be sufficient to reduce effective in situ permeabilities to near zero within any appreciable volume of rock.

CONCLUSIONS

Siliceous tuff in southern Nevada occurs in a complex and locally active geological environment. Regional thrust faulting, Basin and Range faulting, and present-day seismicity complicate exploration and site characterization activities. The inherent variability of tuff and the complexity of caldera complexes also complicate siting efforts, but may serve to enhance long-term containment. Time-space trends of silicic volcanism are moderately well-established, while those of recent basaltic volcanism are not. At present, the final consequences for repository siting of the geologic complexities described in this paper are not known. Evidence from laboratory cation exchange (K_D) measurements indicate that tuff and tuffaceous alluvium can serve as effective natural barriers to migration of radionuclides. This fact, coupled with multiple hydrologic barriers and long flow paths, as in the vicinity of the Nevada Test Site, might well result in tuff being a suitable medium for the safe long-term geologic disposal of nuclear wastes. Preliminary thermal modeling indicates the strong influence of varying assumptions regarding in situ fluid pressures and geothermal heat flux on acceptable initial areal power loadings.

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