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Assessment of Effectiveness of
Geologic Isolation Systems

Disruptive Event Analysis: Volcanism and Igneous Intrusion

B. M. Crowe
Los Alamos Scientific Laboratory

August 1980

Prepared for the
Office of Nuclear Waste Isolation
under its Contract with the
U.S. Department of Energy

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PREFACE

Associated with commercial nuclear power production in the United States is the generation of potentially hazardous radioactive waste products. The Department of Energy (DOE), through the National Waste Terminal Storage (NWTS) Program and the Office of Nuclear Waste Isolation (ONWI), is seeking to develop nuclear waste isolation systems in geologic formations. These underground waste isolation systems will preclude contact with the biosphere of waste radionuclides in concentrations which are sufficient to cause deleterious impact on humans or their environments. Comprehensive analyses of specific isolation systems are needed to assess the post-closure expectations of the systems. The Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program has been established for developing the capability of making those analyses.

Among the analyses required for the system evaluation is the detailed assessment of the post-closure performance of nuclear waste repositories in geologic formations. This assessment is concerned with aspects of the nuclear program which previously have not been addressed. The nature of the isolation systems (e.g., involving breach scenarios and transport through the geosphere) and the great length of time for which the wastes must be controlled dictate the development, demonstration, and application of novel assessment capabilities. The assessment methodology must be thorough, flexible, objective, and scientifically defensible. Furthermore, the data utilized must be accurate, documented, reproducible, and based on sound scientific principles.

The current scope of AEGIS is limited to long-term, post-closure analyses. It excludes the consideration of processes that are induced by the presence of the wastes, and it excludes the consideration of nuclear waste isolation in media other than geologic formations. The near-field/near-term aspects of geologic repositories are being considered by OWNI/DOE under separate programs. They will be integrated with the AEGIS methodology for the actual site-specific repository safety analyses.

The assessment of repository post-closure has two basic components:

- identification and analyses of breach scenarios and the pattern of events and processes causing each breach;
- identification and analyses of the environmental consequences of radionuclide transport and interactions subsequent to a repository breach.

The Release Scenario task is charged with identifying and analyzing breach scenarios and their associated patterns of events and processes.

The Release Scenario task is concerned with evaluating the geologic system surrounding an underground repository and describing the phenomena which alone or in concert could perturb the system and possibly cause a loss of repository integrity. Output from the Release Scenario task will establish the boundary conditions of the geology and hydrology surrounding the repository at the time of an identified breach. These bounding conditions will be used as input for the consequence analysis task, which will employ sophisticated hydrological transport models to evaluate the movement of radionuclides through the groundwater system to the biosphere.

The Release Scenario task has contracted with a number of consultants to obtain expert scientific opinion about the geologic processes which could affect an underground repository. The consultants were asked to specify processes and events which might affect potential repository sites and, if possible, to give rates and probabilities for those phenomena. The consultants have also been involved with the description of the system interactions and synergisms.

This report contains information obtained by one of the Task 1 consultants during the FY-1978 research effort. The research described in this document is still being pursued. Because of the ongoing nature of the Release Scenario methodology development effort, many of the results and conclusions outlined in this report are subject to change upon completion of additional research and analyses. The information contained in this report is based upon the expert opinion of an individual consultant and should be treated as such.

ABSTRACT

An evaluation is made of the disruptive effects of volcanic activity with respect to long term isolation of radioactive waste through deep geologic storage. Three major questions are considered. First, what is the range of disruption effects of a radioactive waste repository by volcanic activity? Second, is it possible, by selective siting of a repository, to reduce the risk of disruption by future volcanic activity? And third, can the probability of repository disruption by volcanic activity be quantified?

The main variables involved in the evaluation of the consequences of repository disruption by volcanic activity are the geometry of the magma-repository intersection (partly controlled by depth of burial) and the nature of volcanism. Dependent upon these variables, the percentage of disruption of a waste inventory uniformly distributed within a 10 km^2 vault site ranges from less than 10% to as great as 100%. Potential radionuclide dispersal by volcanic transport within the biosphere ranges in distance from several kilometers to global. Risk from the most catastrophic types of eruptions (large volume, explosive silicic eruptions) can be reduced by careful site selection to maximize lag time prior to the onset of activity.

Certain areas or volcanic provinces within the western United States have been sites of significant volcanism within the last 1.5 m.y. These provinces can be designated as high risk areas and should be avoided as potential sites for a radioactive waste repository. Additional consideration needs to be given to future migration or expansion of presently active areas. This consideration is best directed at a site specific level. Examples of projection of future sites of active volcanism are discussed for three areas of the western United States.

Probability calculations require two types of data: a numerical rate or frequency of volcanic activity and a numerical evaluation of the areal extent of volcanic disruption for a designated region. The former is clearly beyond the current state of art in volcanology. The latter can be approximated with

a reasonable degree of satisfaction, but there can be considerable variation depending upon the logic of areal considerations. In this report, simplified probability calculations are attempted for areas of past volcanic activity. The actual numbers are of little value, but they do approximate high risk limits. The probability of volcanic activity for nonvolcanic areas cannot be specified numerically. It must, however, be orders of magnitude less than probabilities for areas of active volcanism.

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ACKNOWLEDGMENTS

Grant Heiken, Los Alamos Scientific Laboratory, prepared the geologic data for the Snake River Plains. Suzzanne Sayer assisted in compiling and evaluating geologic literature for this study. I am grateful to Dan Miller and Don Mullineaux of the U.S. Geologic Survey for thought provoking reviews of the paper.

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INTRODUCTION

Within the last several decades, considerable progress has been made with respect to eruption prediction and hazard assessment of volcanic activity. These efforts have been directed toward several general areas. First, a number of geophysical and geochemical techniques have been used for surveillance and prediction of episodes of volcanic activity at active volcanic cones (Gorshkov 1971, Decker 1973). These techniques are used primarily for short term prediction. They are concerned with obtaining premonitory data (for example, seismic patterns, ground deformation) that provide a basis for predicting impending eruptions. A certain amount of success has been obtained for active volcanoes, where geologic data from previous eruptions can be used to predict future activity (for example, Kilauea Volcano, Hawaii, or Asama Volcano, Japan). Much more difficulty in volcanic prediction is encountered for volcanic events for which little or no historic eruption data are available (for example, the 1973 activity of Mt. Baker or the 1975 activity of La Soufriere de Guadeloupe).

A second area of interest in volcanic prediction is that of risk assessment for nuclear reactor safety. Geologists are concerned with examining the risk of engineering failure of a nuclear reactor facility during its 50-year life span as a result of primary or secondary effects caused by volcanic activity. At present, standard geological procedures for assessing volcanic risk to a reactor facility have not been established. The general procedure in site location is to avoid areas of recent volcanism.

There has also been considerable progress in volcanic-hazard appraisals of active volcanoes located adjacent to populated areas (Crandell 1973, Crandell and Mullineaux 1975; Crandell, Mullineaux and Rubin 1975; Miller et al. 1978). For these studies potential volcanic hazards and affected areas are predicted, based on detailed studies of past activity of a particular volcano. The studies are conducted under the assumption that future volcanism will be similar in scale (generally related to eruption energy) and nature (the type of eruption) to past activity. The results or reliability of predictions are therefore strongly controlled both by the degree of preservation and exposure of deposits from past activity and by the abilities of a geologist to decipher the preserved record.

Because of the long half-lives of some radionuclides, radioactive waste must be kept in isolation for long periods of time. There is considerable variation in the defined time span required for waste isolation; in general, the range is on the order of 10^4 to 10^7 years (Bredehoeft et al. 1978). For this study the conservative time span of 10^6 years has been used. This long time frame raises considerable problems, because geologists have had little experience in making predictions for such a length of time. The primary difficulty is that for most areas there is virtually no data from which to establish rates of volcanism and project these rates for 10^6 years.

Three basic problems are addressed for the disruptive event analysis: first, the range of disruptive consequences of a radioactive waste repository by volcanic activity; second, the possible reduction of risk of disruption by volcanic activity through selective siting of a repository; and third, the quantification of the probability of repository disruption by volcanic activity.

In order to examine these problems, several assumptions are made. It is assumed that the probability of volcanic activity within the eastern United States (east of the Rocky Mountains) is extremely low. Actual values can probably not be specified numerically, but clearly they must be orders of magnitude lower than those for areas west of the Rockies. It is also assumed that a repository site will not be located within the general boundaries of an active volcanic province. An active volcanic province is defined as a region having multiple volcanic centers of Quaternary age ($<1.8 \times 10^6$ yr) and including eruptive activity within the last 10^5 to 5×10^5 yr. This second assumption should result in a significant reduction in the probability of future volcanic activity affecting a repository site. Additionally, the assumption introduces an important concept to the disruptive event analysis--the concept of lag time. Lag time refers to the interval of time between closure of a repository site and disruption of the repository by volcanic activity, with subsequent dispersal of radionuclides to the biosphere. There are two components to lag time; the first component includes the time period from burial of waste until intersection of a repository by volcanic activity, and the second component includes the time period from disruption by volcanic activity until biosphere dispersal of radionuclides. A long lag time prior to disruption of a radioactive waste repository may greatly reduce the consequences of waste dispersal, due to the exponential radioactive decay of waste elements.

POSSIBLE MODES OF DISRUPTION BY VOLCANISM

For the first part of the study, the consequences of direct intersection of a repository by magmatic activity are considered. There are two major variables: depth of intersection of a repository by magmatic activity and type of volcanic activity. The degree of disruption (percentage of repository dispersed) and the potential biosphere pathways created are strongly controlled by the depth of intersection of a repository by magmatic activity. Four general cases are considered:

Case 1:

Injection of magma into or through a waste repository at a shallow depth (<500 m, Figure 1) followed by surface volcanism.

Case 2:

Injection of magma into or through a waste repository at depth (>500 m) followed by surface volcanism (Figure 2).

Case 3:

Injection of magma into or through a repository at depth (>500 m) without surface volcanism (igneous intrusion, Figure 3).

Case 4:

Distant volcanism.

The second major variable is the nature of volcanism. There is a wide range in the character of volcanic eruptions, depending in large part on the composition of the magma. The character of the eruption will strongly control the potential disruption and transport distance of radionuclides. For example,

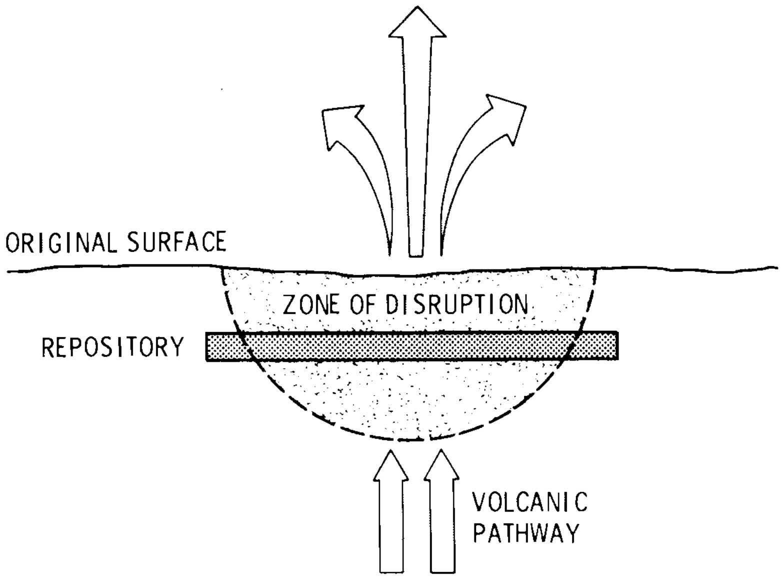

FIGURE 1. Injection of Magma into or Through a Waste Repository at a Shallow Depth (<500 m) Followed by Surface Volcanism

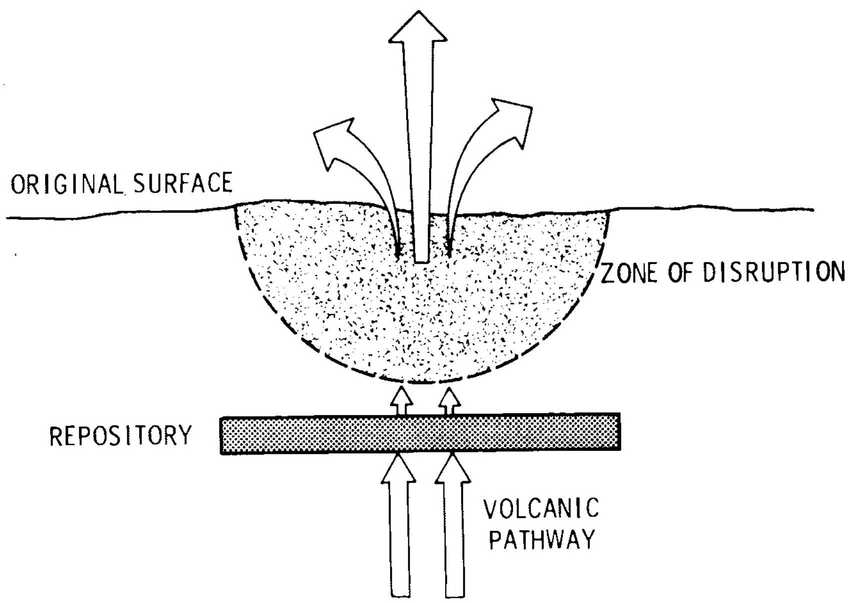

FIGURE 2. Injection of Magma into or Through a Waste Repository at Depth (>500 m) Followed by Surface Volcanism

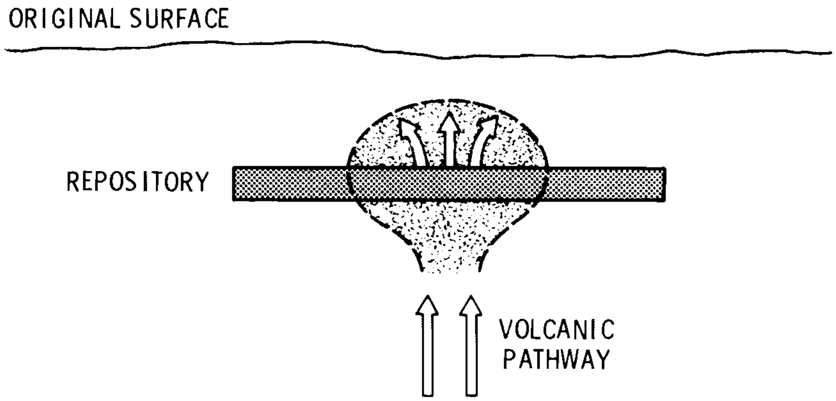

FIGURE 3. Injection of Magma into or Through a Repository at Depth (>500 m) Without Surface Volcanism

relatively "quiet" eruptions typical of the cinder cone building phases of Hawaiian shield volcanoes have a limited disruption and dispersal potential. In contrast, the disruption potential is large for explosive eruptions such as the climactic eruptions of Mt. Mazama approximately 6,600 years ago. These eruptions led to the formation of Crater Lake caldera and deposited measurable quantities of volcanic ash as far as British Columbia, Canada.

There are a variety of classification schemes for the known types of volcanic activity (MacDonald 1973, Walker 1973). Table 1 is a summary of the most commonly used classifications of volcanic eruptions (MacDonald 1973), along with approximations of the total energy released for the respective eruption types (modified from Bullard 1976). This classification illustrates the many types of volcanic activity but is too detailed to systematically apply to the evaulation of possible modes of disruption. Moreover, in many cases, several distinct types of eruptive activity will be exhibited at a single volcano during one eruptive cycle. The most important consideration for the disruptive event analysis is the maximum degree of geologic disruption that could directly or indirectly create biosphere pathways for dispersal of radionuclides. Accordingly, a generalized classification of eruption types is listed in Table 2, along with generalized size parameters for typical volcanic centers.

TABLE 1. Classification of Volcanic Eruptions (after Macdonald 1973)

Eruption Type	Nature of Activity	Nature of Volcanic Centers	Representative Eruptive Energy (Ergs)*
Flood Basalt	Voluminous wide spreading lava flows; minor tephra as spatter and from lava fountaining	Fissure eruptions, broad lava plain, broad low cones	10^{26}
Hawaiian	Thin, extensive lava flows, lava fountaining	Shield volcano	10^{24}
Strombolian	Thicker, less extensive flows, vertical to near vertical fountaining to form cinder accumulations	Cinder Cone	10^{22} to 10^{23}
Vulcanian	Flows absent to thick and stubby, violent ejection of solid or viscous lava fragments	Composite Cone	10^{23} to 10^{24}
Peleean	Domes, thick lava flows, nuee ardente	Dome complexes	10^{23} to 10^{26}
Plinian	Ash flows, copious ejection of air-fall pumice	Caldera	10^{27}
Rhyolitic Flood	Voluminous, wide-spreading ash flows	Large cauldrons, ignimbrite plateau	

*Refers to eruption energy of one eruptive cycle. Energy determined by several techniques. From Bullard (1976).

TABLE 2: Generalized Classification of Volcanic Activity Based on Approximate Magmatic Compositions.

		Major Types	Size Parameters
Basaltic	A.	Strombolian	Height: 100-500 m Width: 300-1000 m Disruption Depth: <200 m
	B.	Phreatomagmatic (Magma-water steam explosions)	Height: 50-200 m Width: 0.3-3 km Disruption Depth: <200 m
Andesitic	A.	Composite Volcano	Height: 0.5-3 km Width: 1 km - 5 km Disruption Depth: 0.5 - 4 km
	B.	Caldera (single center)	Height: 0.5 - 3 km Width: 2 km - 10 km Disruption Depth: 0.5 - 5 km
Silicic	A.	Dome Complex	Height: 0.5 - 2 km Width: 1 km - 10 km Disruption Depth: 0.5 - 4 km
	B.	Large Cauldrons	Height: 1 - 3 km Width: 5 - 30 km Disruption Depth: 1 km-10 km

Case 1

The important boundary condition of Case 1 is that a waste repository is located at a relatively shallow level, so that the vault lies within the zone of near-surface disruption produced by the volcanic activity. It is assumed that the waste is directly incorporated and dispersed by the volcanism. Therefore, the percentage of repository disruption will be a function of the nature of the volcanism. Assuming a 10 km^2 repository, the percentage of waste dispersed will vary from 100% for explosive silicic eruptions to possibly as low as 10% or less for Strombolian eruptions. The biosphere pathways will be determined directly by the volcanic pathways. Therefore, potential transport distances of radionuclides will be controlled by the maximum transport distances of volcanic processes (Table 3). The transport distances of lava flows, lahars, and pyroclastic flows are controlled by the topography; the transport distances of air fall materials are controlled by the wind. The

TABLE 3. Transport Distances - Eruption Types

Magma Type (in order of decreasing frequency)	Lava Flows	Lahars	Pyroclastic Flow	Air Fall
Basaltic "cinder cones"	30 km	5 km		Regional
Basaltic "phreatic"	10 km	5 km	20 km	Global
Andesitic "composite cone"	5-10 km	>65 km	30 km	Global
Silicic "Crater Lake"	5 km	>65 km	>60 km	Global

rates of volcanic transport from intersection of the repository to biosphere dispersal can be considered to be instantaneous (in comparison to the lifetime of the repository).

Case 1:

- Transport distances consist only of range of potential volcanic transport (Table 3)
- Biosphere pathways correspond to volcanic pathways
- Virtually no time lag from onset of volcanism and radionuclide dispersal. Only significant lag time is from time of activation of repository site to onset of volcanism (instantaneous dispersal).
- Incorporation mechanisms
  - I. Explosive disruption of surface to near surface areas
    - A. Limiting boundaries
      1. Vent diameter
         <1 km to >10 km
      2. Depth of explosive vesiculation and incorporation
         <100 m to 4 km
      3. Depth of magma-water contact
         <200 m
      4. Radial fracturing distance (approximately 10 km)
      5. Diameter of surface subsidence (approximately 10 km)

II. Extrusion of lava flows

A. Limiting boundaries

1. Vent structure

   <10 m to <100 m

2. Subsurface dike width

   <1 m to <20 m

3. Magma temperature (country rock thermal effects)

4. Hydrothermal circulation

Case 2

For Case 2, the repository vault is located below the zone of surface disruption. This geometry is realistic only for basaltic volcanism, for which a 500 meter-burial depth would be required to place the vault below probable disruption depths. However, burial depths exceeding 4 to 5 kilometers would be required to achieve this geometry for large andesitic centers and most silicic volcanic centers. For Case 2, it is again assumed that the waste is directly incorporated and dispersed by the magma. However, the percentage of inventory disrupted is greatly reduced over Case 1 and would probably not exceed 25% (assuming a 10 km^2 repository and applying only to basaltic volcanism). Biosphere pathways are again controlled by volcanic pathways with transport distances of Table 3 applicable. Lag time may have two components: lag time from the onset of volcanic intersection of the repository and lag time from the time of repository intersection and surface dispersal. The latter is probably relatively short (months or tens of years) but introduces the possibility of secondary (nonvolcanic) radionuclide transport. However, in all but a few cases, secondary transport should be greatly overshadowed by primary volcanic transport.

Case 2:

- Transport distances include range of volcanic transport and secondary effects (groundwater incorporation, hydrothermal circulation)
- Biosphere pathways include volcanic pathways and secondary pathways (volcanic related fracture systems, hydrothermal circulation)

- Time lag introduced for nonvolcanic transport (rate dependent)
- Incorporation mechanisms

  I. Explosive disruption

  1. Distance between repository and surface volcanism (variable depending upon type of explosive volcanism)
  2. Distance between repository and volcanic fracturing
  3. Diameter of feeding conduits
  4. Distance between repository and "holding" magma chamber.

Case 3

For Case 3, a repository vault is intersected by magma, but the magma is not erupted to the surface. Case 3 deals with igneous intrusion. This case differs greatly from Cases 1 and 2. Biosphere pathways are secondary or non-volcanic, with the possible exception of fluid transport to hot spring or geyser discharge areas. Transport distances are governed by the range of secondary effects such as ground-water or hydrothermal circulation driven by convective heat transfer from the magma body. Both the transport limits and rates are dependent on the respective process; these values were not examined in the study. There are several potential components to lag time:

- Time to the onset of igneous intrusion
- Rates of upward migration of the intrusion following repository intersection
- Time between repository intersection and development of primary or secondary release pathways.

Case 3:

- Transport distances are governed by a range of secondary effects (ground-water disruption, hydrothermal circulation)
- Biosphere pathways are largely secondary. Exceptions include hot spring or geyser areas above shallow magma chambers.

- Potential major time lags have several considerations:
  1. Onset of intrusive "episode"
  2. Rate of upward migration of magma body
  3. Lag between magma-repository intersection and development of release pathways.
- Release pathways
  1. Radial and concentric fracture system produced by domal uplift
  2. Accelerated erosion rates (decrease lag time to repository breach)
  3. Hydrothermal convection system above magma chamber
- Depth of igneous mass (controls uplift effects, temperature contrast with country rock)
- Dimensions of magma body
- Distance from repository
- Residence time as a molten body
  1. Initial temperature
  2. Temperature of country rock
  3. Cooling mechanisms
  4. Mechanisms of heat replacement

<u>Case 4</u>

Case 4 includes distant volcanism, which does not directly intersect a repository site but which may cover the surface overlying the vault with volcanic material (lava flows, pyroclastic flows, tephra, etc.). In Case 4 the effects are entirely secondary and are not examined in detail. Some possible effects include:

- Surface drainage disruption with possible changes in erosion rates
- Modifications of recharge-discharge areas of a ground water system
- Climate changes due to particulate loading of the atmosphere from ash ejected during large explosive eruptions.

Certain types of eruptions, notably large volume eruptions of silicic magma, have extremely large potential for geologic disruption and dispersal of radionuclides, provided that eruption is through or adjacent to a waste repository site. These eruptions are generally characterized by eruption of large volumes of pyroclastic rocks by ash-flow and air-fall mechanisms. Volcanic structures, generally collapse cauldrons which are associated with and produced by these eruptions, have surface dimensions as great as several tens of kilometers. Geologic disruption associated with these eruptions extends to depths of 3 to 5 kilometers and possibly to a depth of 10 kilometers. Consequently, these types of eruptions represent the extreme range of consequences for volcanic risk assessment of long-term geologic storage of radioactive waste. It may be possible to avoid or reduce the probability of occurrence of large volume silicic eruptions at a repository site, because these eruptions are commonly preceded by "precursor" volcanic activity. The duration of this precursor activity may be on the order of less than one to as great as several million years. For example, the Long Valley caldera located in east central California is an elliptical shaped depression with dimensions of 17 by 32 km (Bailey et al. 1976). The caldera was formed 0.7 m.y. ago by the eruption of the Bishop Tuff. The oldest volcanic rocks of the Long Valley magmatic cycle include the rhyolites of Glass Mountain. The oldest date for eruption of these rhyolites is about 2.0 m.y. By recognizing areas that may show evidence of precursor activity to explosive silicic eruptions, one could avoid these areas for siting of a waste repository.

PROJECTION OF FUTURE SITES OF VOLCANISM

The second question addressed in the study is whether the present state of knowledge in volcanology allows identification of future areas of volcanic activity during the next 1 m.y. This question requires a consideration of knowns and unknowns. With respect to knowns, there is a relatively good understanding of the areal distribution and nature of Quaternary volcanism within the western United States. Additionally, some generalizations can be made concerning the geologic setting of certain areas characterized by volcanic activity. For example, there is a recognized global association of areas of active volcanism with subduction zones or zones of plate convergence.

Two major settings of subduction zone volcanism are important: island arcs, in which the volcanic chain is constructed on oceanic crust; and continental arcs, in which the volcanic chain overlies continental crust. With respect to the western United States, the Cascade volcanic chain appears to be a continental arc located east of an inferred, east-dipping, buried, and presently aseismic subduction zone off coastal northern California, Oregon and Washington. Numerous geologists have suggested that the Cenozoic record of volcanism within the Basin and Range Province may reflect the former presence of a subduction zone adjacent to the_coast of the western United States. Volcanic rocks are also found at the oceanic rises. Ocean rises are linear ridges of plate divergence (boundaries along which plates separate) and are generally characterized by active basaltic volcanism. With respect to the western United States, volcanism within the Salton Trough of southernmost California may reflect the onland projection of the East Pacific Rise (Elders et al. 1972, Robinson et al. 1977).

The major unknowns affecting the understanding of volcanism in the western United States are the actual processes of magma generation, magma evolution, and magma migration through the crust to the surface. There are numerous ideas in petrology concerning these problems, but much remains unknown. For example, the heat source or sources for magma generation are poorly known, as are the causative factors triggering episodes of magma generation. The actual details of source rock melting to produce magma are not completely understood, due to the complex, multi-component chemical systems of most magmas and uncertainities with respect to the nature of the source rocks. Furthermore, the hydrodynamics of vertical migration of magma are poorly known, and possible processes of magma evolution are both numerous and vaguely defined. Consequently, without a complete understanding of the processes of magmatism and volcanism, efforts to predict future volcanism are reduced to assessments of past volcanic patterns.

Figure 4 shows the distribution of Quaternary volcanic rocks in the western United States (modified from Suppe and others, 1975). The most immediate conclusion that can be derived from the map is that there are distinct concentrations of volcanic rocks within zones or volcanic provinces. These

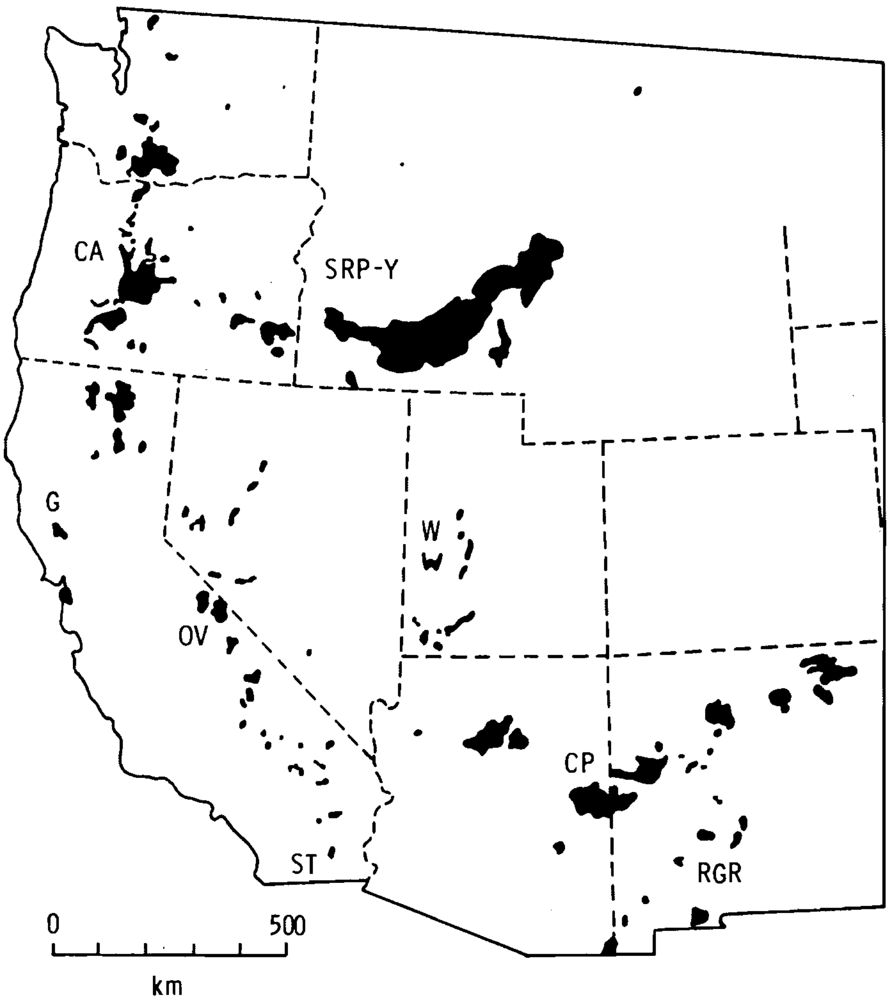

FIGURE 4. Distribution Map of Quaternary Volcanism in the Western United States (after Suppe et al. 1975).

CA: High Cascade Volcanic Field
SRP-Y: Snake River Plain-Yellowstone Province
G: Geysers Volcanic Province
OV: Owens Valley Volcanic Province
ST: Salton Trough Volcanic Province
W: Wasatch Volcanic Province
CP: Colorado Plateau Province
RGR: Rio Grande Rift Province

provinces are labeled on the map and are briefly described in the figure caption. The volcanic provinces can qualitatively be viewed as high risk zones and can be avoided for siting of a radioactive waste repository. This avoidance would reduce the probability of disruption of a repository by volcanic activity. Actual recognition of a designated high risk zone can best be determined at a site specific level. However, at a generic level, conservative boundaries can be drawn around the identified Quaternary volcanic provinces, and these areas should be considered unsuitable for siting of a radioactive waste repository. Note that Figure 4 is considered preliminary. The data base used to construct the figure needs to be refined and updated before it can be rigorously applied to identification of unsuitable areas for repository siting.

Additionally, the "high risk" volcanic zones or areas must be evaluated with respect to future migration or expansion of areas of volcanism within the next 1 m.y. There is a wealth of geologic models that attempt to explain the distribution of Cenozoic volcanism within the western United States. These models can, in some cases, be used to predict areas of future volcanic activity. However, rather than true predictions, the models offer projections of past volcanic patterns, under the assumption that future volcanic activity will be similar to that of the past. Furthermore, the degree of geologic detail required to make "projections" is beyond the scope of this paper and is best directed at a site specific level. However, to illustrate the application of possible techniques to volcanic projections, three general areas are described in the following sections.

Salton Trough

The Mexicali-Imperial Valley, located in southernmost California and Mexico, is a broad structural trough (commonly referred to as the Salton Trough) that appears to be the onland northern extension of the Gulf of California. The area is cross-cut by northwest trending faults apparently related to the San Andreas fault system and probably connecting sections of the East Pacific Rise. The actual rise segments lie deeply buried beneath the thick sedimentary fill of the trough (Elders et al. 1972). The Salton Trough is a zone of high heat flow and Quaternary volcanism. Surface volcanic rocks include the Buttes rhyolite domes located at the south end of the Salton Sea and the dacitic volcano of Cerro Prieto, south of Mexicali (Robinson et al. 1977). Inclusions of basalt are present within the other, more silicic, volcanic rocks (Robinson et al. 1977), and basaltic dikes cutting sedimentary rocks have been noted in drill holes within the trough (Griscom and Muffler 1971). The presence of these rocks suggests that the Salton Trough is an area of Quaternary bimodal basalt-rhyolite volcanism. Tectonic studies of the trough indicate that it is lengthening to the northwest at a rate on the order of 5 cm/year (Elders et al. 1972). Consequent with the northwestward lengthening of the trough, it is likely that there will be continued and perhaps significant northwestward migration of volcanism within the area during the next 1 m.y.

High Cascade Range

The High Cascade Range is formed by a linear array of large andesitic volcanic centers and associated basaltic volcanism (McBirney et al. 1974) extending from northern California into British Columbia. The presence of the continental volcanic arc is commonly attributed to the presence of an inferred, east-dipping, aseismic subduction zone concealed beneath marine sediments off the coast of the Pacific Northwest. Based upon this assumption, the Cascade chain should continue to exhibit active volcanism in the future. However, the magnitude of the activity is difficult to predict, due to the lack of geologic information concerning the behavior of subduction related volcanism as the rise approaches the continent. Two possible future volcanic trends can be considered. First, the existing southern boundary of the Cascade chain and the inferred subduction zone is Mt. Lassen volcano, which lies on line with the landward projection of the intersection of the inferred subduction system, the Gorda rise, and the San Andreas Fault. This intersection or triple point is currently migrating northeastward; consequently, there may be a waning of volcanism within the southern Cascades during the next 1 m.y. Second, MacLeod et al. (1976) have documented a monotonic, westward decrease in age of Neogene rhyolite domes in southeastern Oregon. The youngest dated volcanic rocks (<1 m.y.) are present within the area of Newberry caldera, closely adjacent to the High Cascade Range. Available data suggest a westward age decrease of about 1 cm/yr for younger domes (<5 m.y.). Furthermore, data indicate that there may have been a recent (<2 m.y.) increase in the rate of progression (MacLeod et al. 1976, p. 468). The projected intersection of this zone with the High Cascade Range suggests that the area of intersection could be the site of significant volcanic activity during the succeeding 1 m.y.

Wasatch Front-Basin Range Vocanism

Best and Brimhall (1974) have described late Cenozoic alkalic basalts along the east boundary of the Basin and Range Province in northwesternmost Arizona and southwesternmost Utah. Based on an analysis of K-Ar dates, they suggest an apparent eastward migration of basaltic volcanism at the rate of approximately 1 cm/yr. Projection of these patterns, which are recorded for rocks ranging in age from 7.0 m.y. to <1.0 m.y., suggests that basaltic volcanism may encroach in an eastward direction onto the Colorado Plateau within the next 1 m.y.

Regional Generalizations

A third important consideration for the subject of qualitative risk evaluation is an examination of the types of volcanism expected within volcanic provinces of the western United States. As noted in a previous section, the nature of volcanic activity strongly controls the range of consequences of a repository breach. There have not been systematic attempts to characterize the frequency of occurrence of the various types of volcanic activity. However, some generalizations can be made using a qualitative data base:

- Basalt is the most broadly distributed and most frequent of magma compositions in the geologic record. Consequently, the most frequent eruption types are likely to be Strombolian and/or Phreatomagmatic (cinder cones--maar volcanoes).
- There is a strong correspondence between the type of geologic province and the nature of associated volcanism. For example, continental arcs such as the High Cascade Range are generally characterized by the development of relatively large andesitic volcanoes which are usually separated and surrounded by areas of basaltic volcanism. Some areas, such as the Salton Trough and fringing areas of the

Colorado Plateau (San Francisco and Mt. Taylor volcanic fields), are characterized by predominantly bimodal basalt-rhyolite volcanism.

- Basaltic volcanism can occur within areas where there would be little or no compelling geologic evidence to expect volcanism. For example, relatively young basaltic cones and associated lava flows are present within areas of the Mojave Desert in California and southern Arizona. These sites are not associated with a recognized volcanic province.

- During the last 2 m.y. there were at least seven major explosive silicic eruptions within the western United States, including Crater Lake caldera (6,600 years), Yellowstone caldera (three eruptions, 20, 1.2 and 0.6 m.y.), Valles caldera (two eruptions, 1.4 and 1.1 m.y.), and Long Valley caldera (0.7 m.y.). As much as several hundred km^3 of magma were extruded during some of these eruptions. Consequently, the effects of similar future eruptions on climate and/or surface erosion rates could be substantial. Based on this past record, it is likely that the western United States will experience one and possibly several eruptions of this type during the next 1 m.y.

PROBABILITY CALCULATIONS

The third and final question to be addressed is whether the probability of repository disruption by volcanic activity can be quantified.

To calculate, or more properly, to approximate the numerical probability of volcanic activity within a million year time span requires two types of data. First, a rate or frequency of activity needs to be established for a designated area. Second, the disruption effects for an individual episode of volcanism need to be determined for a designated area. The latter determination, as will be shown in the following sections, can probably be approximated with a reasonable degree of satisfaction. There can, however, be major variations depending both upon the logic scheme for establishing disruption effects and upon the size of the area chosen for the calculations. The first requirement, that of establishing a representative rate of volcanism, is clearly well beyond the current state-of-the-art in volcanology. The major problem is that there is an absence of numerical data concerning rates of volcanism for all but a few areas of the world. These areas are restricted to active volcanic regions, which by definition will not be considered for location of a repository site.

However, in order to evaluate the risk of disruption of a repository by volcanic activity, some effort at probability calculations may be worthwhile. A number of insights into the magnitude of the problem become apparent from the exercise. The actual numbers have little meaning, but the procedures are of interest. Since "rates" of volcanism can only be attempted for active volcanic provinces, the argument can be made that resulting probabilities for nonvolcanic areas must be orders of magnitude less than those calculated for currently active areas. This argument at least provides some basis for final risk evaluation.

There have been some attempts in the geological literature to calculate the probability of volcanic activity. Logan and Berbano (1977) considered volcanic probabilities for the WIPP (Waste Isolation Pilot Plant) in southeastern New Mexico. The WIPP site is located within the Delaware Basin, an area with no preserved record of volcanism since Permian time, which ended approximately 200×10^6 years ago. (Logan and Berbano 1977; note, however, that the basin is cut by dikes dated at about 30 m.y.). Logan and Berbano (1977) establish a rate of volcanism of:

$$1 \text{ event in } 200 \times 10^6 \text{ years} = 5.0 \times 10^{-9} \text{ events/year.} \qquad \text{(Rate)}$$

Assuming a 10 km^2 waste repository, an area of the Delaware Basin of 3.1×10^4 km^2, and a volcanic effect zone of 50.3 km^2 (Logan and Berbano, 1977, Figure 9), the resulting probability is:

$$P = (5.0 \times 10^{-9}/\text{yr})(50.3 \text{ km}^2/3.10 \times 10^4 \text{ km}^2)$$

$$= \underline{\underline{8.1 \times 10^{-12}/\text{yr}}}.$$

The major limitation of this calculation is the logic of using a rate of volcanism of 1 event in 200 million years. Moreover, the size of the disruptive zone is somewhat large, though not significant in the calculation.

Smith (1974) determined a global rate of production of a new volcano to be about 1 in 20 years. He chose the average height of a volcano to be about 430 m and assumed that the disruption zone is approximately 5 times the height or 2,150 m. Assuming a 10 km^2 circular repository:

$$P = \frac{(1.8\ km + 2.15\ km/2)^2}{(20)\ 5.1 \times 10^8\ km^2}$$

$$= \underline{\underline{2.5 \times 10^{-9}/yr}}$$

where $5.1 \times 10^8\ km^2$ is the surface area of the earth and 1.8 km is the repository radius. Further, Smith assumed that the rate of occurrence of volcanism in continental areas is approximately 1/28 of the average earth's surface. This assumption leads to a corrected probability of volcanism:

$$\underline{\underline{P = 8.9 \times 10^{-11}/yr}}.$$

The bounding limitation of this approach, as noted in the previous section, is that the rate of volcanism is strongly areally dependent.

For this study, probability calculations for several selected areas have been "determined". The derived numbers are of little value except that they are established for areas of active volcanism, and the probability of volcanic activity for nonvolcanic areas has to be substantially less. The emphasis in the section is not on the actual numbers but on the calculation procedures.

High Cascade Range

The U.S. Geological Survey has conducted volcanic-hazards appraisals for volcanic centers within the High Cascade Range (Crandell and Mullineaux 1975). Detailed studies at individual volcanic centers have revealed considerable information on the past behavior of these andesitic centers. From the data, Crandell and Mullineaux (1975) have suggested an average eruption rate of at least one volcanic eruption within the Cascade Range per century. This rate applies to a period of about 12,000 yr, which is slightly more than 1% of a million year time span. With the invalid assumption that this rate of volcanism applies for the succeeding 10^6 years, the rate of future volcanism is:

1 Eruptive Event/Century = 10^{-2} Events per year. (Rate)

The area of the Cascade Range is approximately 1.1×10^5 km^2. The zone of disruption beneath an andesitic cone can be approximated as the area of the cross-section of the underlying magma chamber. Relatively complete data on the size of a magma chamber for an andesitic volcano exists for the Avachisky Volcano. Geophysical data indicate the present of a magma chamber at a depth of 1.5 to 4 km with an average radius (high temperature part) of 3.6 km (Fedstove et al. 1975). The cross-sectional area of the magma chamber, assuming a circular body, would be about 41 km^2, and this area is inferred to correspond to the size of the disruption zone beneath an andesitic volcano. Because the area of the volcanic disruption zone is greater than the area of a repository, disruption of a repository does not require direct waste-magma intersection. The repository area can be represented as a circle of dimensions πr^2 = 10 km^2. The worst case intersection of a repository by a zone of disruption produced by an andesitic magma chamber can be defined by drawing the circumference of the magma chamber tangential to the circumference of the repository. This geometry defines a larger disruption zone with a radius Rz = r + 2rm where r is the radius of the repository and rm is the radius of the magma chamber. For the Cascade example:

$$\begin{aligned} Rz &= r + 2rm \\ &= 1.8 \text{ km} + 2\ (3.6 \text{ km}) \\ &= 9 \text{ km}. \end{aligned}$$

The area ratio A therefore is:

$$\begin{aligned} A &= \frac{\pi r^2}{1.1 \times 10^5 \text{ km}^2} \\ &= \frac{254 \text{ km}^2}{1.1 \times 10^5 \text{ km}^2} \\ &= 2.3 \times 10^{-3} \end{aligned}$$

and the Cascade probability calculation becomes:

$$P = (10^{-2}/y)\ (2.3 \times 10^{-3})$$
$$= 2.3 \times 10^{-5}/y.$$

Snake River Plain

The Snake River Plain is an elongate valley of southern Idaho characterized by extensive Quaternary volcanism. Several approaches were chosen for volcanic probability calculations. Kuntz (1977) has studied in detail a 750 km^2 area of the Snake River Plain and established a recurrence interval for volcanism of one eruption per 10,000 yrs:

$$= 1.0 \times 10^{4} \text{ Events per year.} \qquad \text{(Rate)}$$

Two values are used for the disruption area. The first is the volcanic effect zone of 50.3 km^2 from Logan and Berbano (1977), and the second is a more realistic value obtained by assuming deep burial of waste (>500 m) within an area of predominantly basaltic volcanism. Geologic studies have shown that basaltic cones are generally fed by relatively narrow dikes (<10 m). At depth, the size of the area of disruption from a 10 m feeder dike is considered to be approximately 2.1 km^2 (assuming a 10 meter dike with an additional 100 meter disruption zone adjacent to each margin and a lateral extent equal to the maximum repository width or 10 km). This area is smaller by slightly less than a factor of 5 than an assumed 10 km^2 repository, and therefore the repository area is used to define the area ratio.

$$P = (1.0 \times 10^{-4}/yr)(50.3\ km^2/750\ km^2)$$ CASE ONE: Large Disruption Zone

$$= \underline{\underline{6.7 \times 10^{-6}/yr}};$$

$$P = (1.0 \times 10^{-4}/yr)(10\ km^2/750\ km^2)$$ CASE TWO: Small Disruption Zone

$$= \underline{\underline{1.3 \times 10^{-6}/yr}}.$$

As a second approach, a vent count of Holocene centers (10,000 years old) for a selected 2.6×10^4 km^2 area (Figures 5 and 6) was completed. Eighty-five vents were counted, yielding a rate of :

8.5×10^{-3} events per year (Rate)

assuming each vent can be counted as one event (clearly invalid). Making the same assumptions concerning the disruption zone as were made in the previous section yields two cases:

$P = (8.5 \times 10^{-3}/yr)(50.3\ km^2/2.6 \times 10^4\ km^2)$ CASE ONE: Large Disruption Zone

$= \underline{\underline{1.6 \times 10^{-5}/yr}};$

$P = (8.5 \times 10^{-3} yr)(10\ km^2/2.6 \times 10^4)$ CASE TWO: Small Disruption Zone

$= \underline{\underline{3.3 \times 10^{-6}/yr}}.$

As a final approach the dike surface area was calculated for 85 events in 10,000 years. Making the same areal assumptions for the dike area and disruption zone as were made in the previous section (2.1 km^2) yields the following rate:

$= (85\ \text{events})(2.1\ km^2)$ per 10,000 years

$= 1.8 \times 10^{-2}\ km^2$ events per year. (Rate)

Using this approach, the probability is:

$P = (1.8 \times 10^{-2})(10\ km^2/2.6 \times 10^4\ km^2)$

$= \underline{\underline{6.9 \times 10^{-6}/year}}.$

DISCUSSION

This paper represents a "first stab" at assessing the threat posed by volcanic activity to the long-term geologic storage of radioactive waste. The approach taken is general and represents a necessarily oversimplified view of volcanic hazards. The general cases that are considered in the worst case

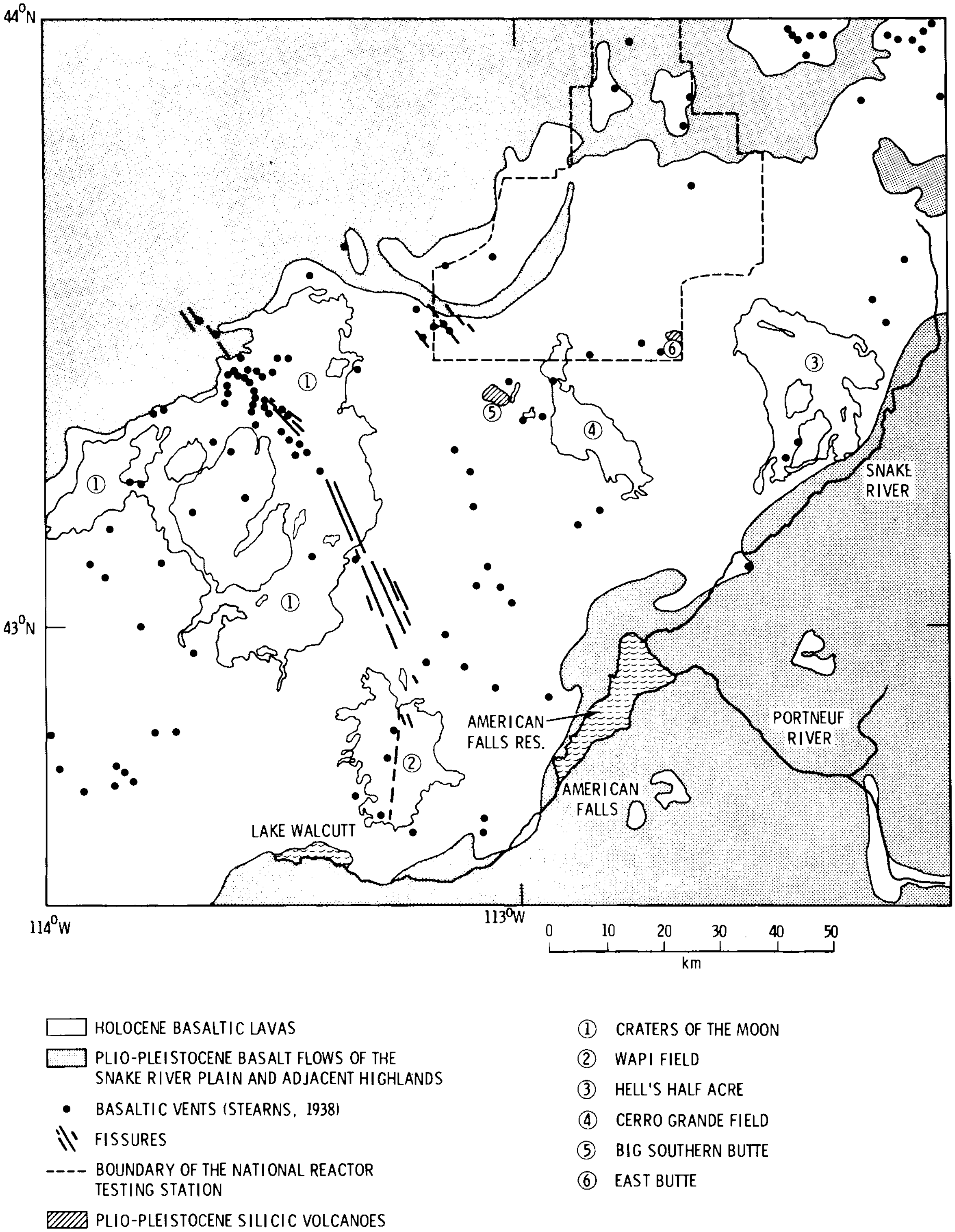

FIGURE 5. Northeastern Segment of the Snake River Plain. Boxed area outlined by dashed lines was examined for the probability calculations.

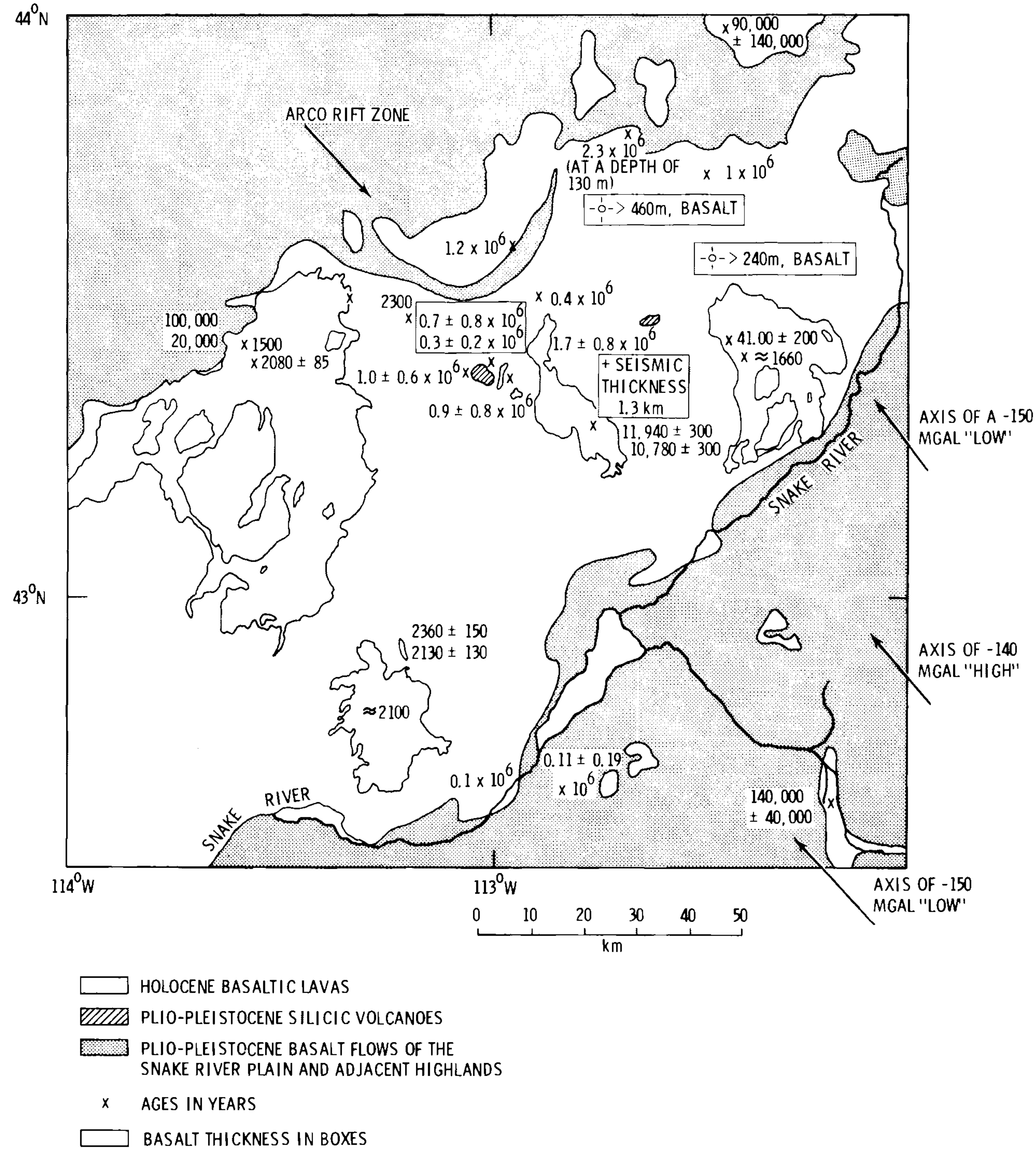

FIGURE 6. Geology of the Area of the Snake River Plain Examined for the Probability Calculations

scenario are unacceptably simplified. Volcanoes are extremely complicated and unpredictable; there are many areas of unknown with respect to geologic understanding of volcanic activity. Accordingly, the disruptive effects and potential dispersal of radionuclides by volcanic activity described in the paper are preliminary and need to be continually revised, both in the degree of detail of evaluation and with respect to coupling with other nonvolcanic transport mechanisms. Assessment of past volcanic patterns for future predictions is best approached on a site specific level. This approach provides two advantages. First, considerably more detailed geologic studies of a smaller area can be undertaken to specifically gather data on past volcanic patterns. This data can be used to attempt to establish rates of volcanism and to more clearly define areas for which these rates may apply. Second, the past behavior of eruptive activity of ancient volcanoes within a specified area can be studied. This kind of investigation should allow a clearer definition of the types of volcanic activity to be expected within an area and may both limit and focus volcanic consequence analyses. Finally, there is an inherent danger in specifying probability calculations for volcanic activity numerically. The numbers could be used out of context to either justify or attack the degree of risk associated with geologic disposal of radioactive waste. Clearly, the approaches used for probability calculations with respect to volcanic activity are highly speculative. Assumptions are necessarily numerous and the approaches are oversimplified; both are difficult to defend, scientifically, at this stage.

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