CHAPTER I

DISRUPTIVE EVENT ANALYSIS: VOLCANISM AND IGNEOUS INTRUSION

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Three basic topics 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 the 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 examining these topics, several assumptions are made. The probability of volcanic activity within the eastern United States (east of the Rocky Mountains) is assumed to be extremely low. Actual values can probably not be specified numerically but must be orders of magnitude lower than those for areas west of the Rockies. Another assumption is 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 (less than 1.8×10^6 yr) and including some eruptive activity within the last 10^5 to 5×10^5 years. Avoidance of areas of active volcanism for repository siting should result in a significant reduction in the probability of repository disruption by future volcanic activity.

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: type of volcanic activity and depth of intersection of a repository by magmatic activity.

The first 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.

The depth and geometry of intersection of a repository by magmatic activity strongly controls the degree of disruption (percentage of repository dispersed) and the potential biosphere pathways created. Four general cases are considered:

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

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

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

Case 4: Distant volcanism.

Case 1

The important boundary condition of Case 1 is that the 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. The waste is assumed to be 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 as low as 10% or less for Strombolian (cinder cone) eruptions. Potential transport distances of radionuclides will be controlled by the maximum transport distances of volcanic processes. Furthermore, the rates of volcanic transport of radionuclides to the biosphere following repository intersection can be considered to be instantaneous (in comparison to the lifetime of the repository).

Case 2

For Case 2, the repository vault is located below the zone of surface disruption. This geometry is realistic only for basaltic volcanism. A

500 meter-burial depth would place the vault below probable disruption depths for basaltic eruptions. However, burial depths exceeding 4 to 5 kilometers would be required to achieve this geometry for large andesitic centers and most silicic volcanic centers. As in Case 1, the waste is assumed to be directly incorporated and dispersed by the magma. However, the percentage of inventory disrupted is much less than for Case 1 (for basaltic eruptions) and would probably not exceed 25% (assuming a 10 km^2 repository). Potential transport distances of radionuclides will be controlled by the maximum transport distances of volcanic processes.

Case 3

For Case 3, a repository vault is intersected by magma, but the magma is not erupted to the surface. Case 3 involves intrusive, not extrusive, activity. This case differs greatly from Cases 1 and 2. Pathways to the biosphere are secondary or nonvolcanic, 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. Lag time (the interval of time between repository intersection and development of primary or secondary release pathways) has a major role in this case.

Case 4

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

- surface drainage disruption with possible changes in erosion rates
- modificatons of recharge-discharge areas of a ground water system
- climate changes resulting from particulate loading of the atmosphere from ash ejected during large explosive eruptions.

PROJECTION OF FUTURE SITES OF VOLCANISM

The second topic addressed in this study is the possible reduction of risk through selective siting of a repository. Selective siting involves identification of future areas of volcanic activity, based on the present state of knowledge in volcanology.

Volcanism occurs primarily at subduction zones and oceanic rises. 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 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.

Distinct concentrations of volcanic rock within zones or volcanic provinces are noted. These volcanic provinces can qualitatively be viewed as high risk zones and can thereby be avoided for siting of a radioactive waste repository. High risk zones must additionally be evaluated with respect to future migration or expansion of areas of volcanism within the next 1 m.y. The degree of geologic detail required to extrapolate future volcanism from past volcanic activity 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 Salton Trough is a zone of high heat flow and Quaternary volcanism. Tectonic studies of the trough indicate that it is lengthening to the northwest at a rate on the order of 5 cm/yr. 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 chain of large andesitic volcanic centers and associated basaltic volcanic centers. It extends from northern California into British Columbia. The presence of this probable 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. The magnitude of the activity is difficult to predict, however, due to the lack of geologic information concerning the behavior of subduction related volcanism as the rise approaches the continent.

Wasatch Front - Basin Range Volcanism

Late Cenozoic alkalic basalts are found along the east boundary of the Basin and Range Province in northwesternmost Arizona and southwesternmost Utah. Based on an analysis of K-Ar dates, an apparent eastward migration of basaltic volcanism at the rate of approximately 1 cm/yr is suggested. Projection of these patterns, which are recorded for rocks ranging in age from 7.0 m.y. to less than 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 Generalizatons

- Basalt is widely distributed and is the most abundant magma composition 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 correlation between the type of geologic province and the nature of the associated volcanism. For example, continental arcs are generally characterized by the development of andesitic cones, and oceanic rises by volcanism.
- Basaltic volcanism can occur within areas where there would be little or no compelling geologic evidence to expect volcanism.
- 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, 2.0, 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 topic to be addressed is the quantification of the probability of repository disruption by volcanic activity.

In the geological literature, some attempts have been made to calculate the probability of volcanic activity. The following numbers have little meaning, but the procedures are of interest. Consider 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 the end of Permian time (approximately 200 x 10^6 years ago).

One event in 200 x 10^6 years equals 5.0 x 10^{-9} events/year. Using this rate of volcanism, and assuming a 10 km^2 waste repository, the Delaware Basin area of 3.1 x 10^4 km^2, and a volcanic effect zone of 50.3 km^2, the resulting probability, P, of volcanic activity is:

$$P = (5.0 \times 10^{-9}/yr)(50.3\ km^2/3.10 \times 10^4\ km^2)$$
$$= \underline{8.1 \times 10^{-12}/yr}.$$

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

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

High Cascade Range

Geologic studies of large composite cones within the Cascade Range suggest an average eruption rate of one eruption per century for the volcanic chain. Geophysical data for a representative composite cone suggest the presence of a magma chamber at a depth of 1.5 to 4 km with an average radius (high temperature part) of 3.6 km. Such dimensions yield a disruption zone of about 22 km^2. This number can be expanded by considering various geometric configurations of intersection of a repository by the disruption zone, but maximum variation is on the order of a factor of three.

Using a rate of volcanism of 10^{-2} events/year, a 66 km^2 disruptive zone, and an area of 1.1 x 10^5 km^2 for the Cascades, the probability, P, of volcanic activity is:

$$P = (10^{-2}/yr)(66\ km^2/1.1 \times 10^5\ km^2)$$
$$= \underline{6.0 \times 10^{-6}/yr}.$$

Snake River Plain

The Snake River Plain is an elongate valley in southern Idaho characterized by extensive Quaternary volcanism. A 750 km^2 area of the Snake River Plain has been studied in detail, resulting in establishment of a recurrence interval for volcanism of one eruption per 10,000 yrs.

Two values are used for the disruption area. The first value is the volcanic effect zone of 50.3 km^2, and the second is a more realistic value assuming deep burial of waste (>500 m). Geologic studies have shown that basaltic cones are generally fed by relatively narrow dikes (<10 m wide) and consequently, disruption at depth from a 10 m wide feeder dike is considered to be approximately 2.1 km^2 (assuming a 10 meter wide 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). Thus, for each case the probability of volcanic activity, P, is:

$P = (1.0 \times 10^{-4}/yr)(50.3\ km^2/750\ km^2)$ CASE ONE: <u>Large Disruption Zone</u>
$= \underline{6.7 \times 10^{-6}/yr}$;
$P = (1.0 \times 10^{-4}/yr)(2.1\ km^2/750\ km^2)$ CASE TWO: <u>Small Disruption Zone</u>
$= \underline{2.3 \times 10^{-7}/yr}$.

As a second approach, a vent count of Holocene (<10,000 yrs old) volcanic centers for a selected $2.6 \times 10^4\ km^2$ area was completed. Eighty-five vents were counted, yielding a rate of:

$$8.5 \times 10^{-3} \text{ events per year}$$

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

CASE ONE: <u>Large Disruption Zone</u>

$$P = (8.5 \times 10^{-3}/yr)(50.3\ km^2/2.6 \times 10^4\ km^2)$$
$$= \underline{1.6 \times 10^{-5}/yr};$$

CASE TWO: Small Disruption Zone

$$P = (8.5 \times 10^{-3}/yr)(2.1\ km^2/2.6 \times 10^4\ km^2)$$
$$= \underline{6.7 \times 10^{-7}/yr}.$$

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

$$= (85\ \text{events})(2.1\ km^2)\ \text{per}\ 10{,}000\ \text{yrs}$$
$$= 1.8 \times 10^{-2}\ km^2\ \text{events per year}.$$
$$P = (1.8 \times 10^{-2})(10\ km^2/2.6 \times 10^4\ km^2)$$
$$= \underline{6.9 \times 10^{-6}/yr}.$$