Final Report of the Igneous Consequences Peer Review Panel

Presented February 2003 in Las Vegas

Summary for NWTRB presented May 14, 2003

by:

Allan M. Rubin
Department of Geosciences
Princeton University
(panel member)

Chapter 1

Introduction

Presented by:

February 2003

J.R. Anthony Pearson

Schlumberger Cambridge Research & Peer Review Chairman

Panel Membership

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- 3 volcanologists
- 1 fluid mechanician
- 1 geomechanician
- (1 risk assessment and nuclear waste expert)

Synopsis of Table 1-1

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- Is conceptual model adequate and comprehensive?
- What level of analysis is sufficient?
- How accurate and reliable can quantitative modeling be?
- What alternatives to modeling are feasible?
- What is the role of analog studies?
- Will uncertainties be quantifiable?

Panel's Perception of Problem

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- Consequences of an igneous event neither clear-cut nor readily quantifiable
- TSPA the crucial outcome of entire investigation

Path Chosen by Panel

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- Concentration on reducing uncertainty where possible
- Restriction of range of magma properties and eruptive scenarios – Chapter 2
- Modeling the mechanics of a rising dike and its interaction with repository – Chapter 3
- Relating waste entrainment to eruptions – Chapter 4

Chapter 2

Volcanological Setting, Eruption Chronology, Magma and Host Rock Properties

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Presented by:

Frank J. Spera
Dept. of Geological Sciences
UC Santa Barbara

'Expected' Characteristics of YMR Eruptions

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"Expectations" drawn from analog eruptions (historical and geological)

- Eruptive Volume ~ 0.01-1 km^3
- Eruptive Duration ~ days, weeks to months. Mass flux range ~10^3 kg/s (mildly effusive lava flows) to ~10^{6*} kg/s (violent Strombolian eruptions with plume heights to 10* km)
- Eruption Chronology: lava/tephra ratios can vary non-monotonically during 'single eruption' made up of discrete eruptive phases

An Illustrative Scenario (others have been considered!)

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- Early eruption along fissure or *en echelon* fissures of length ~ km;
- Vent localizes to fixed location(s) along fissure;
- Cylindrically symmetric conduit flow develops;
- Early cone building stage following by eruption of mildly effusive lava flow(s);
- Variable lava/tephra ratio during course of eruption;
- Phreatomagmatic (magma meets ground water) eruption phases may occur anytime (possible small phase of phreatomagmatism at Lathrop Wells)

Outstanding Volcanological Issues

(sections 2.6.1, 2.6.2 and 2.6.3)

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- Eruptive Volumes, Rates & Recurrence Intervals
  - Volumes of exposed (surface) volcanics are reasonably well know, given geologic vagaries (e.g., loss of distal ash, covering by alluvium, etc)
  - It is unclear whether some eruptive sites with multiple cones of "close" ages represent a single event or several events closely spaced in time
  - Possible buried volcanics in Crater Flat and Amargosa Valley near Yucca Mountain identified in aeromagnetic surveys are not well constrained in age or volume

Further high-resolution geochronology (e.g., 40Ar/39Ar dating) at analog eruptive sites and drilled magnetic anomalies may better constrain eruptive rates

Volatile Content Constraints

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- Thermochemical modeling
- Glass inclusions in phenocrysts
- Order of phenocryst crystallization during magma decompression and cooling

Results

- 2.5 - 4 wt % total volatiles
- H_2O/CO_2 ratio: ~10 - 20
- Magma dynamics controlled by thermodynamic behavior of H_2O; this is known quite well

Magma Properties

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- Illustrative Example of some Magma Properties Figures 2-1a to 2-1g in Chapter 2 of Volume 1
- T = 1150 °C
- 3.8 wt % H_2O + 0.2 wt % CO_2

Figure 2-1c Mass fraction (ϕ) and volume fraction of vapor (θ) for water (Z_{H2O}) and carbon dioxide (Z_{CO2}) content of 3.8 wt % and 0.2 wt %, respectively, at 1150 °C. The magma fragmentation condition is θ_{crit} = 0.7. In this example, the fragmentation pressure is about 20 MPa.

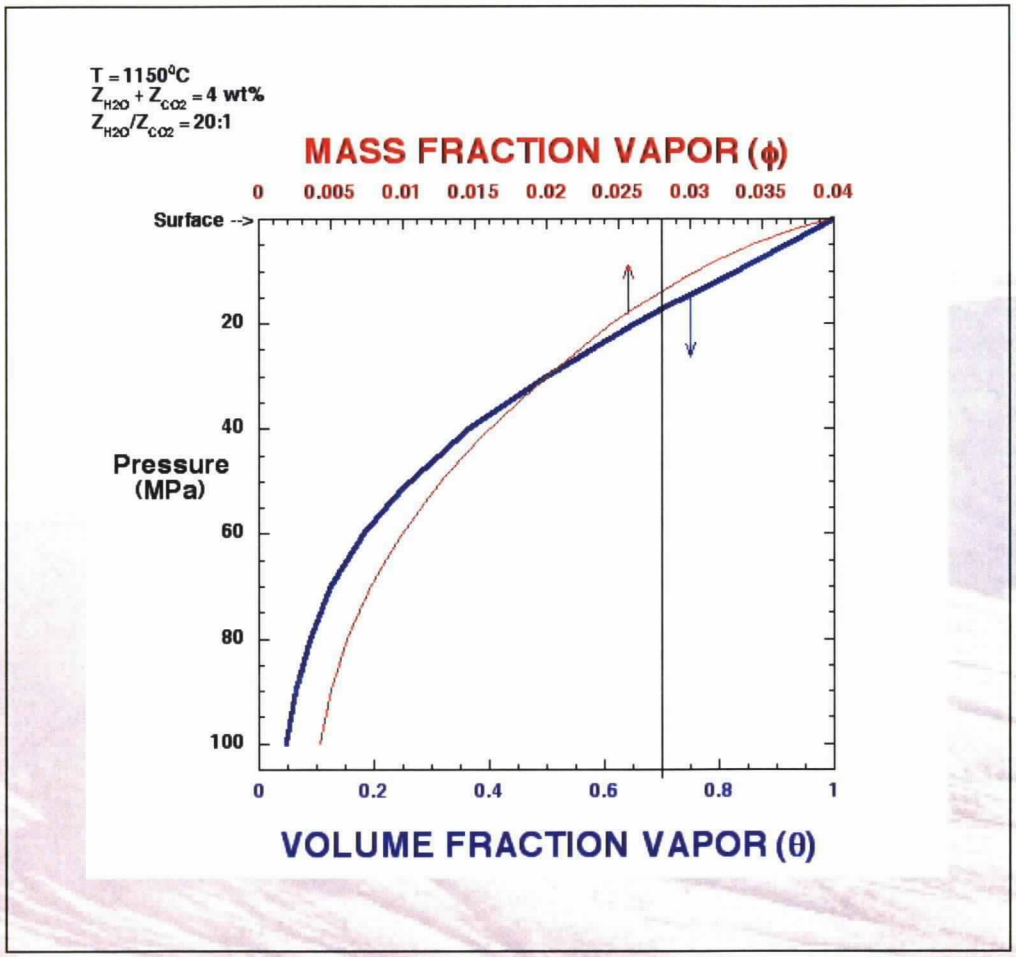
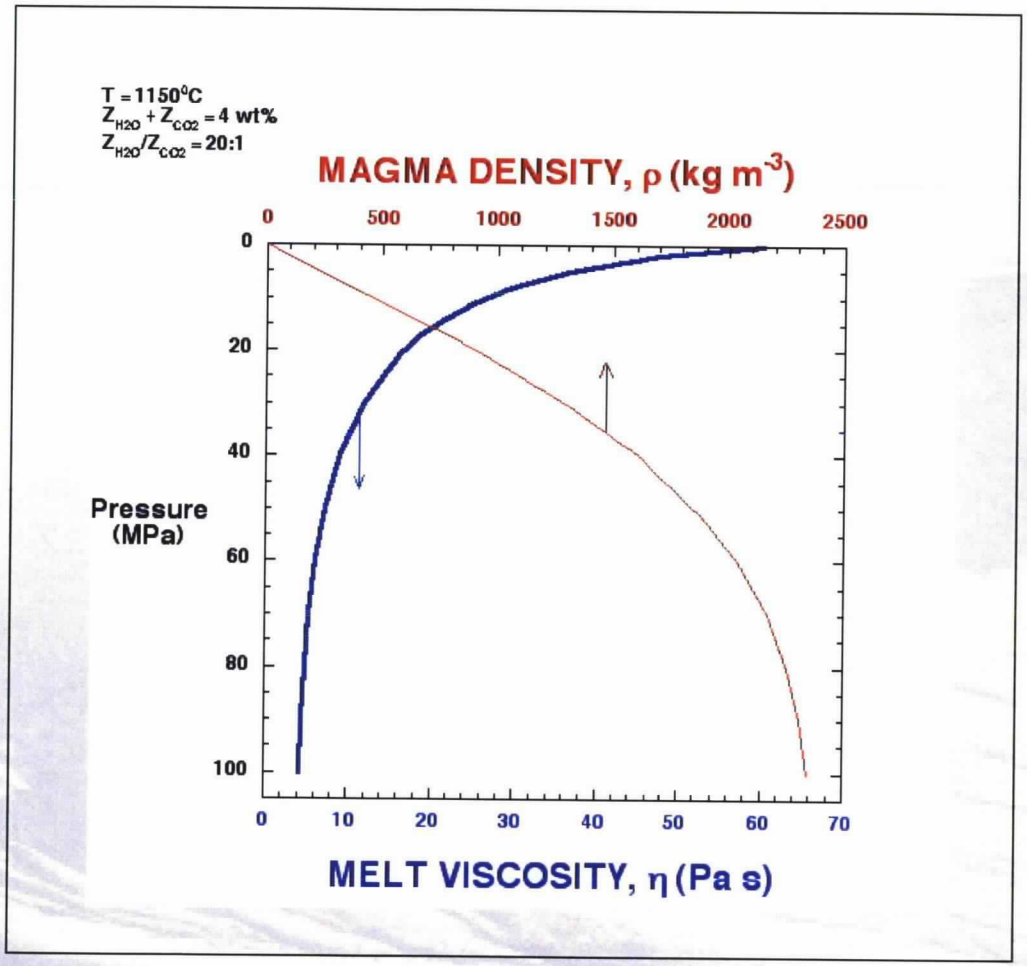


Figure 2-1e Density of magma (ρ) (i.e., two-phase mixture) and shear viscosity of melt (η_m) versus pressure for water (Z_{H2O}) and carbon dioxide (Z_{CO2}) content of 3.8 wt % and 0.2 wt %, respectively, at 1150 °C. (Note that density of magma decreases rapidly upon decompression due to exsolution of volatiles from coexisting melt.)



Fragmentatoin pressure

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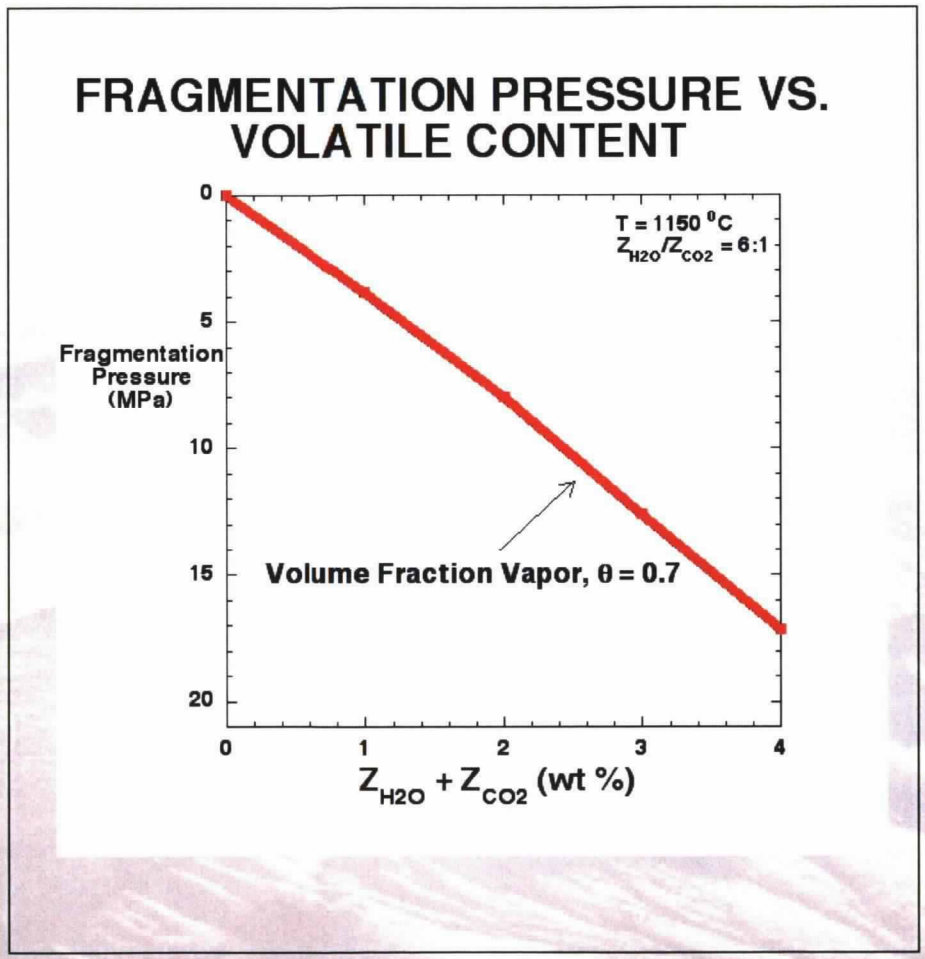

- "Fragmentation" pressure of potassic trachybasalt as a function of volatile content at 1150 °C
- Thermodynamic results are given in terms of pressure

Chapter 3

Interaction between a Dike and the Repository

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Presented by:

Emmanuel Detournay
Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455

Dike Mechanics

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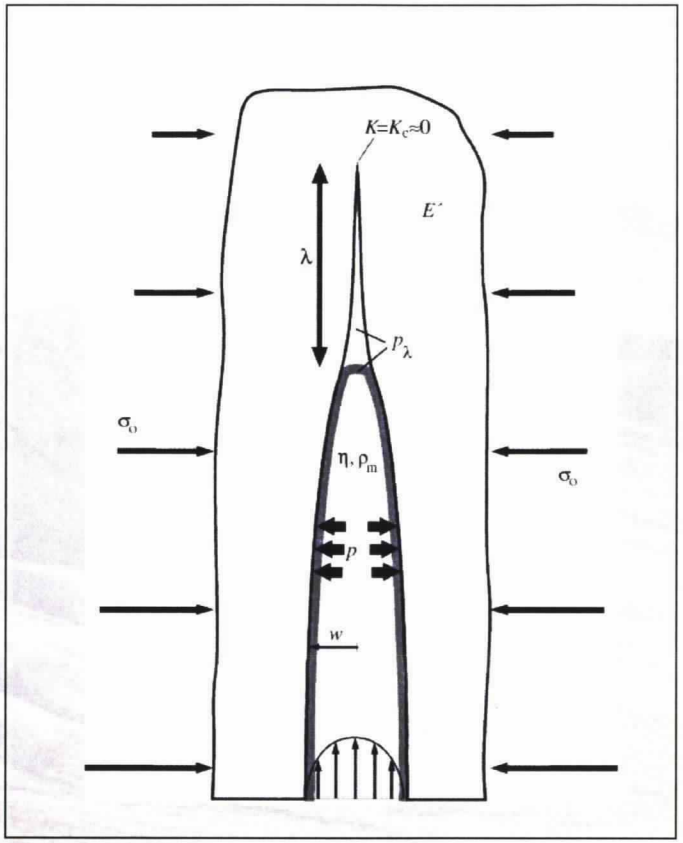
- Features relevant to the dike/repository interaction
  - Existence of a tip cavity
  - Tip cavity pressure?
  - Tip cavity length? (instability - Dike may breach the surface before magma intersects the repository)
  - Magma velocity at front?
  - Dike aperture at front?
  - Pressure gradient behind front?



Tip Cavity

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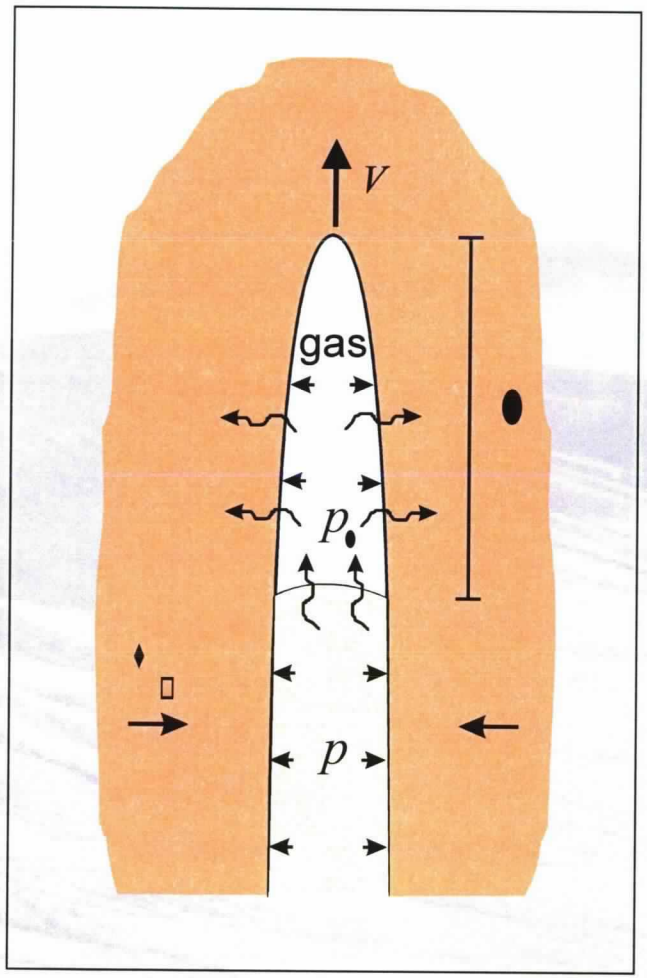
- The tip cavity is the first part of the dike to intersect the drifts
- Cavity Length λ

$$\lambda = \mathrm{O}\,(1\ \mathrm{m}) \text{ if } \sigma_o \sim 10\ \mathrm{MPa},\ p_\lambda \sim 0$$
$$\lambda = \mathrm{O}\,(100\ \mathrm{m}) \text{ if } \sigma_o \sim 3\ \mathrm{MPa},\ p_\lambda \sim 0$$

- Cavity Pressure p_λ
  - Balance between gas inflow and outflow

$$p_\lambda < 1\ \mathrm{MPa}$$



Magma with H_2O and CO_2

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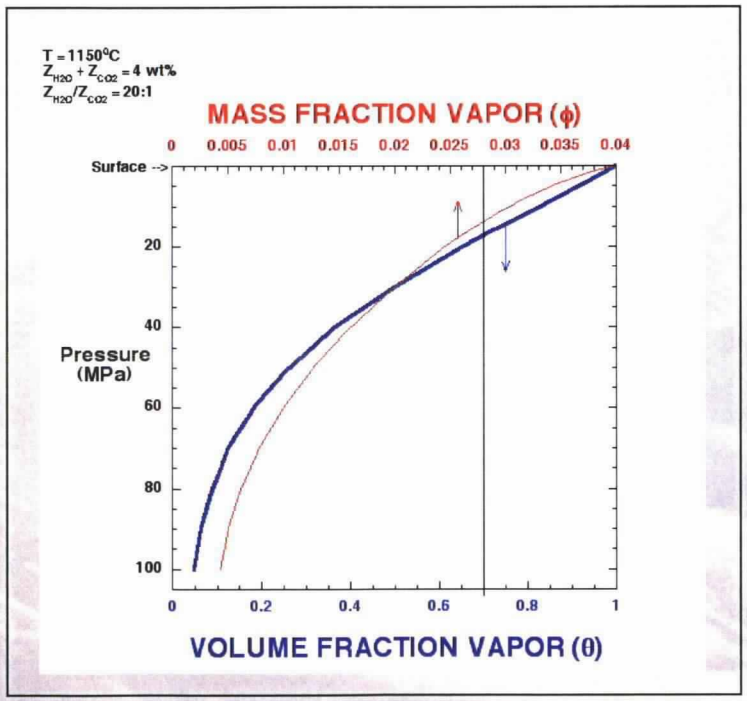
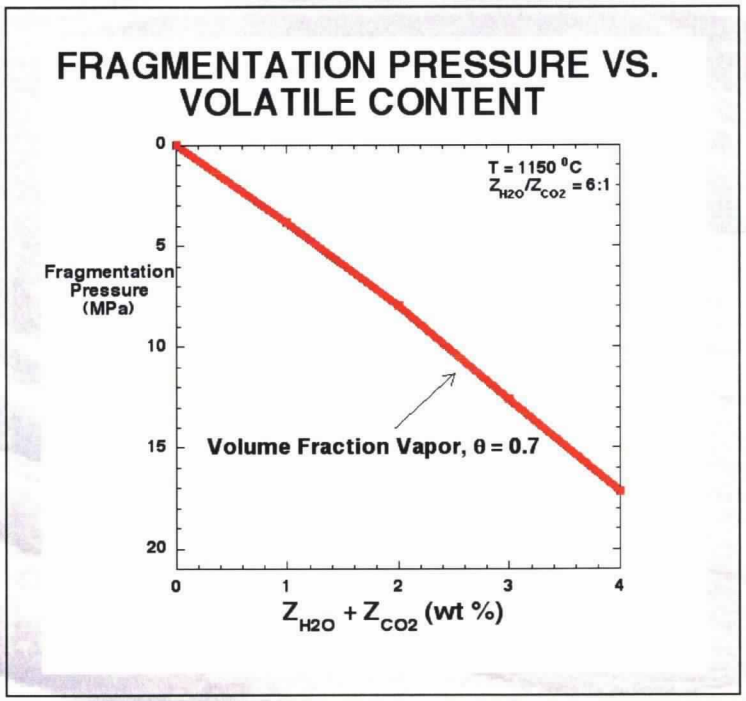
- Consequences:
  - Increasing bubble volume fraction θ during ascent
  - Fragmentation of magma when $\theta \sim 70\%$





Propagation in Impermeable and Permeable Rocks

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- Impermeable Rock (and Slowly Growing Cavity)
  - Tip cavity pressure p_λ = "fragmentation" pressure
  - Model "similar" to incompressible flow model
- Permeable Rock (or Rapidly Growing Cavity)
  - "Incompatibility" between *high* fragmentation pressure (~ 10 MPa) and *low* tip cavity pressure (~ 1 MPa)
  - Gives rise to phenomena that are treated only approximately (and perhaps inadequately) by panel's numerical modeling (e.g., mass acceleration at magma front; two-phase flow in cavity and near magma front; etc.)

Results for one model - carried to instability of tip

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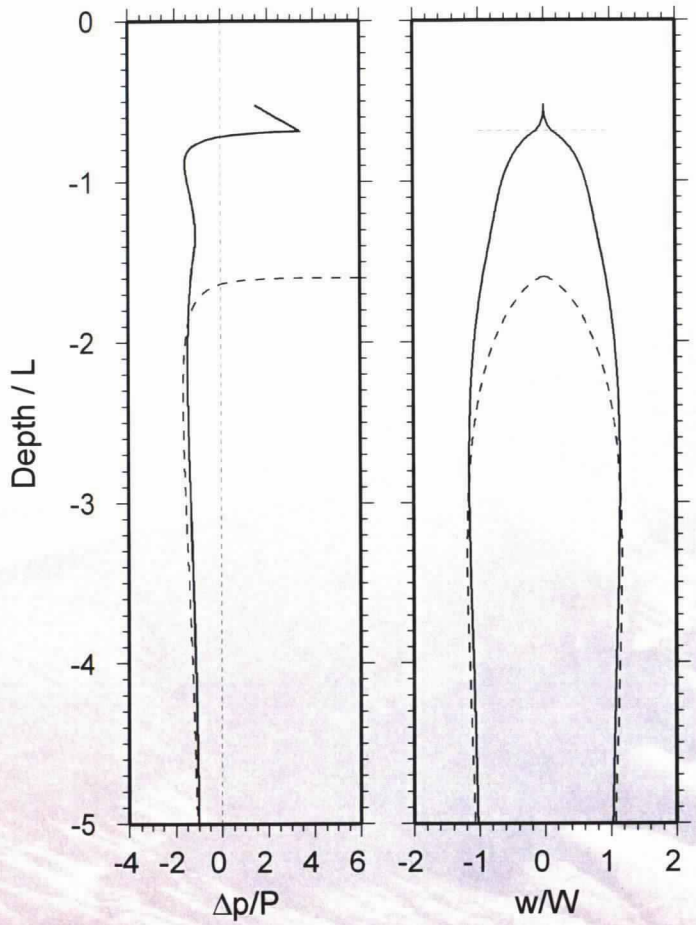
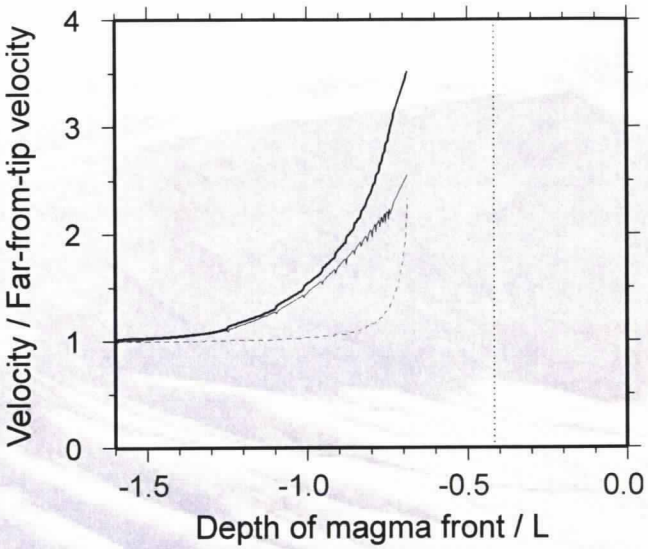


Profile of net pressure and aperture



Velocities vs depth

Interaction Dike/Repository

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- Alteration of the Stress State by Repository
  - Drift Scale
  - Repository Scale
- Drifts act as magma "sinks"
  - Tip progression
- Drifts act as "corridors" for magma flow (*"dog-leg" scenario*)

Influence of Repository on Dike (via Stress Perturbations)

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- Changes in both magnitude and principal directions of stress
- Mechanical stress perturbation
  - Time-independent, localized around drifts
- Thermo-mechanical stress perturbation
  - Time-dependent, drift- or repository-scale
  - Consequences of large horizontal stress (~ 10 MPa)
    - Small cavity length, large magma pressure
    - Reorientation of dike, propagation along bedding planes, sills

Magma Flux into Repository

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- Progression of Dike Tip
- Pyroclastic Flow
  - Woods et al. (2002 scenario: *unrealistic* in view of assumed initial/boundary conditions)
  - "Violence" of initial interaction linked to thermal stress
- Lava Flow
  - Partitioning of magma between flow up the dike and flow along the drifts

Recommendations

- Dike propagation model with compressible flow
  - Gas dynamics
  - Non-trivial state of stress
- Dike propagation after magma enters drifts
  - Tip progression and magma partitioning

Chapter 3, Sections 3.4 and 3.5

The Dogleg Scenario

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Presented by:

Allan M. Rubin
Department of Geosciences
Princeton University

Dogleg Scenarios

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- Initiation of a dogleg requires that the pressure within a drift exceed the normal stress acting to keep potential dogleg fractures closed
- Essentially all the recommendations of the Panel related to assessing dogleg probabilities are aimed at placing more confident bounds on either the drift pressure or expected variations in the normal stress

Factors contributing to normal stress variations:

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1. Topography
2. Inherent variability
3. Dike-induced stresses, including:
   - The parent dike (generally compressive; locally tensile near lateral ends or a subsurface top)
   - Dike-induced normal faulting
   - Dike-induced tensile cracking

Likely stress variations from these processes thought to be no more than ~1-2 MPa (Appendix 3.6)

Factors contributing to normal stress variations (cont'd):

4. Stress perturbations due to the drifts themselves:
   - Tunneling
   - Pressurization by magmatic material
   - Thermal stresses
   - Perturbation to dike-induced stresses

Recommendation: Assess stress perturbations around drifts using 3-D mechanical and thermoelastic models.

Factors controlling the drift pressure

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General considerations:

I. Cannot exceed the pressure at the parent dike/drift intersection (for cases worthy of attention)

II. Depends upon whether the magmatic material is a:

- Lava flow
- Pyroclastic flow

III. Depends upon whether the parent dike (and/or conduit) is:

- Venting (or propagating)
- Blocked

Lava Flows

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Once the drift fills, the pressure quickly equilibrates to that at the dike/drift intersection

Given expected variations in the normal stress, it is plausible that the magma pressure can open a dogleg. BUT:

- It is very difficult to start a dike in a cold rock (Appendix 3.4)
- The resulting eruption is likely to be effusive, with perhaps less waste material entering the biosphere

Pyroclastic Flows

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- The pressure in the tip cavity must be substantially less than the dike-normal stress, or the tip will propagate dynamically to the surface.
- Once a dike and/or cylindrical conduit to the surface is established, pressures at a few hundred meters depth can reach a few MPa, if flow in the vent is "choked"
- If the parent dike/conduit system becomes blocked by faulting/freezing, it is the consensus of the Panel that as the pressure increases the most likely outcome is that the obstruction will fail before a dogleg initiates. If such an obstruction does not fail, the host rock appears to be sufficiently permeable that for reasonable mass fluxes large pressures are not reached prior to the drifts filling with pyroclastic material (Appendix 3.8).

Hot versus cold design

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- Cold design is likely to decrease the explosivity of the initial dike/drift interaction
- Once the drifts fill (fairly quickly), thermal stresses associated with hot design are more "favorable" for preventing egress of magmatic material from drifts

Given the low probability of an initial "shock wave", the latter consideration is likely to be the more important

Additional benefit: Possibility of deflecting or locally "shutting down" dike by large thermal stresses.

Potential pitfall: Increased likelihood of sill intrusion along a bedding plane that cuts drifts (motivation for alternate design?)

Summary Recommendations

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Normal stress on potential dogleg fractures:

- Numerical evaluation using expected sources of stress and 3-D elastic and thermoelastic models.

Magma flows:

- 3-D mechanical codes incorporating incompressible flow in elastic crack/drift system, to evaluate (1) level of magma in dike at the time the drifts fill, and (2) partitioning of magma up the dike vs up the dogleg fracture (ignores thermal death issue)

Summary Recommendations

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Pyroclastic flows:

- Use 2-D (possibly 3-D) numerical models of hydrodynamic flows as dike intersects drifts, using 2-D dike propagation codes as a guide for the boundary conditions at the drift intersection.
- Assess any lingering issues concerning gas diffusion into the host rock

"Big picture":

- Incorporate dogleg probability estimates into TSPA to assess large-scale engineering options (backfill or no backfill of drifts; orientation of drifts relative to most likely dike orientation)

Eruption and Waste Entrainment

Larry G. Mastin
U.S. Geological Survey

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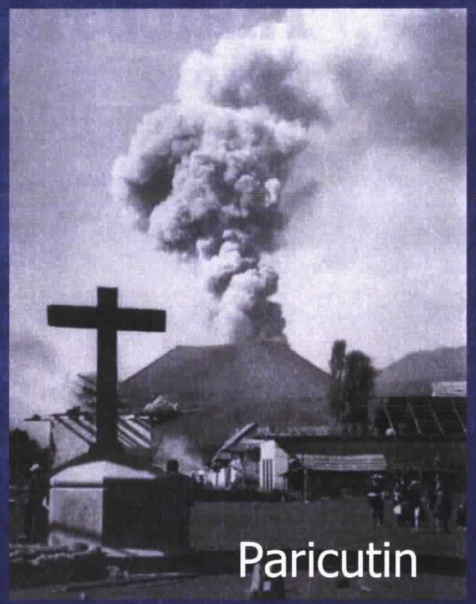
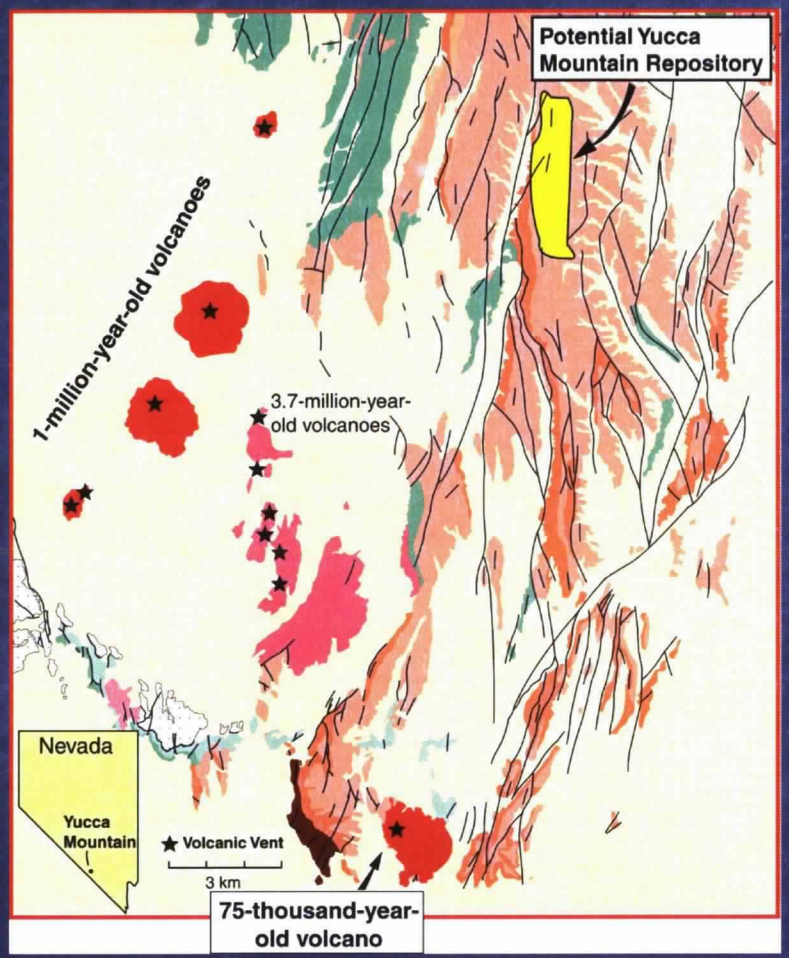
Conceptual Model

- Based on past events in Yucca Mountain region
- and on historical analogs





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Main eruptive characteristics

- Alkali basalt (1-4 wt% volatiles)
- Monogenetic cinder cone-type
  - Duration: days to >15 years (Wood, 1980)
- Eruptive style
  - Strombolian (cinder-cone forming)
  - Lava flows
  - Violent Strombolian (Plume heights to several kilometers; tephra over $>10^2$ km^2)

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Panel Conclusion on Conceptual Model

- Model is realistic
- Assumption of violent Strombolian (VS) activity is conservative, possibly realistic based on evidence for VS activity at Lathrop Wells and at historical eruptions (Paricutin, Cerro Negro)

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Modes of waste transport to inhabited areas

- Atmospheric dispersal (tephra)
- Surface wind & water transport following eruptions
- Groundwater transport following eruptions

Our expertise qualifies us to evaluate primarily mode (1), and aspects of waste and drift damage that affect mode (3)

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Most Important Quantifiable Parameters

- Number of canisters entrained in waste
- Percentage of waste that escapes from canisters
- Grain size distribution of waste
- Areal distribution of tephra

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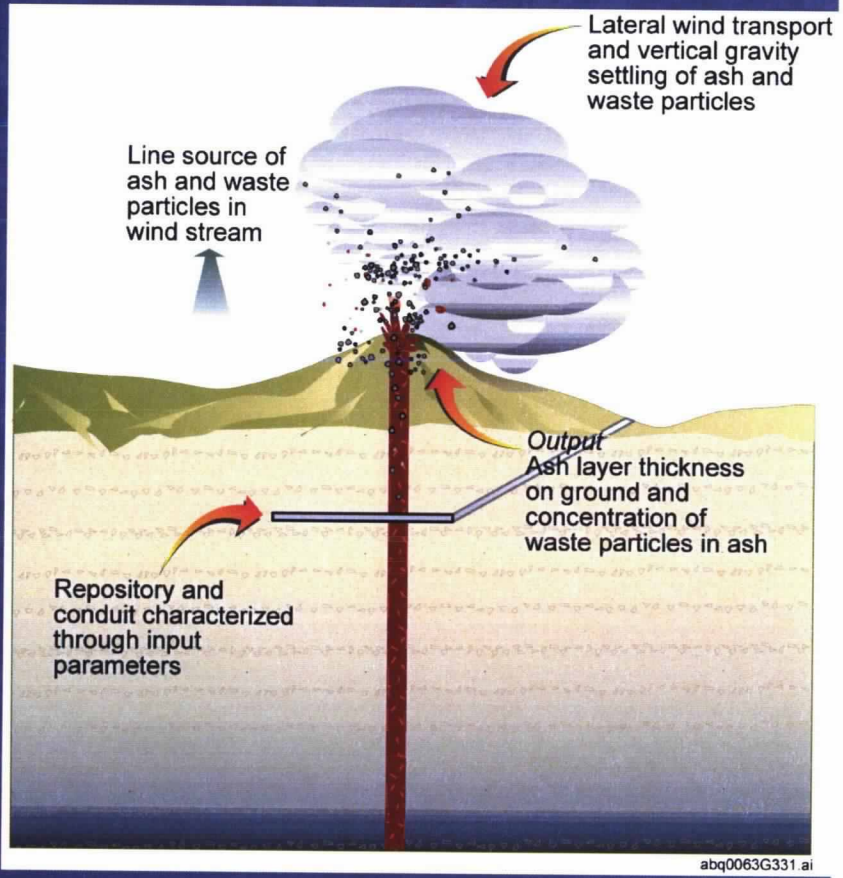
Number of waste canisters entrained: TSPA assumptions

- Entrainment primarily by engulfment in vertical conduits
- Number of entrained canisters depends on
  - Conduit diameter
  - Number of conduits



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Number of conduits

- One to a few (<5)

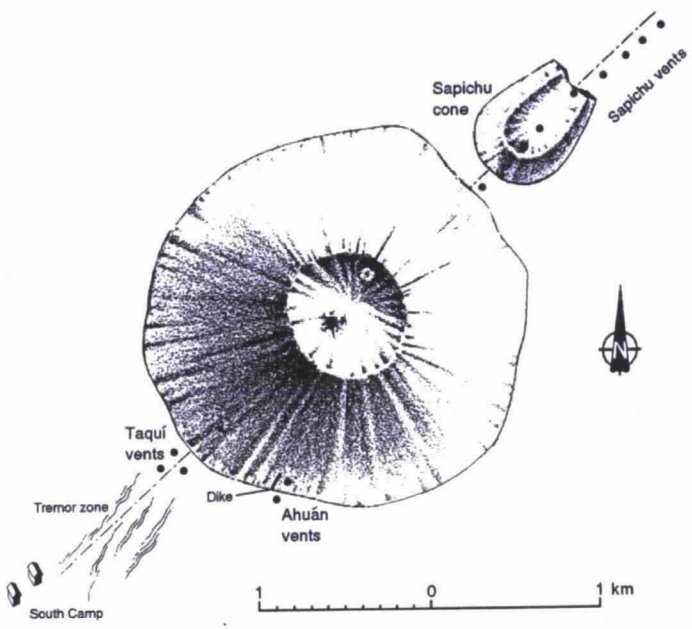
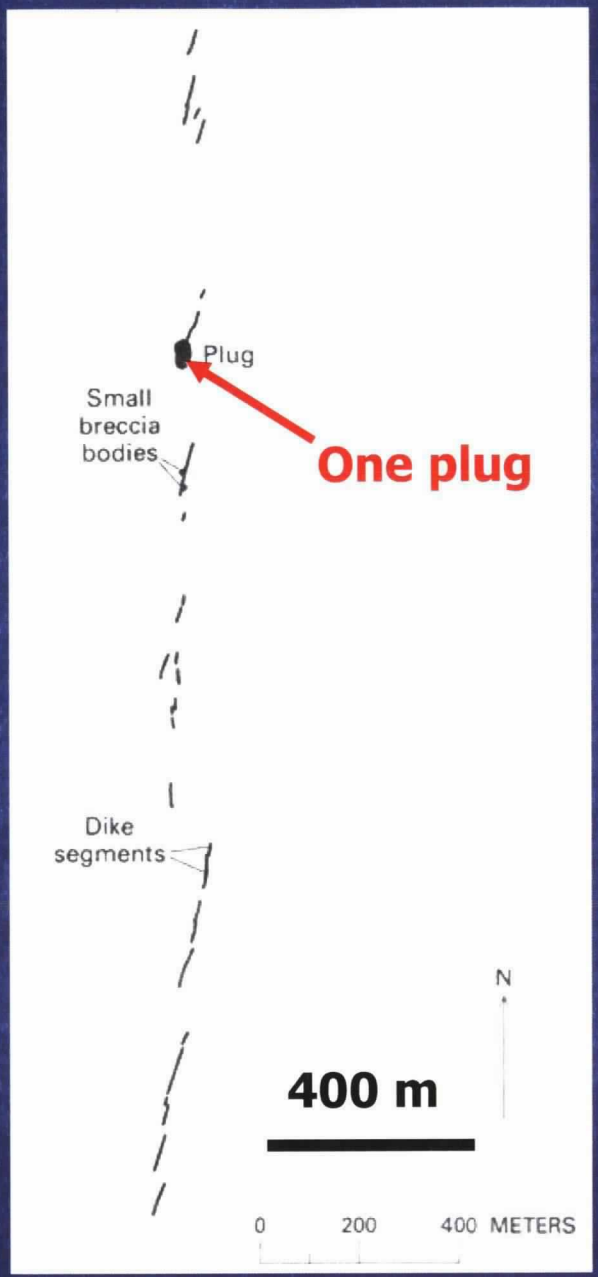


Fig. 74. Parícutin volcano, showing the vents of 1943-44.

Paricutin cones, 1944



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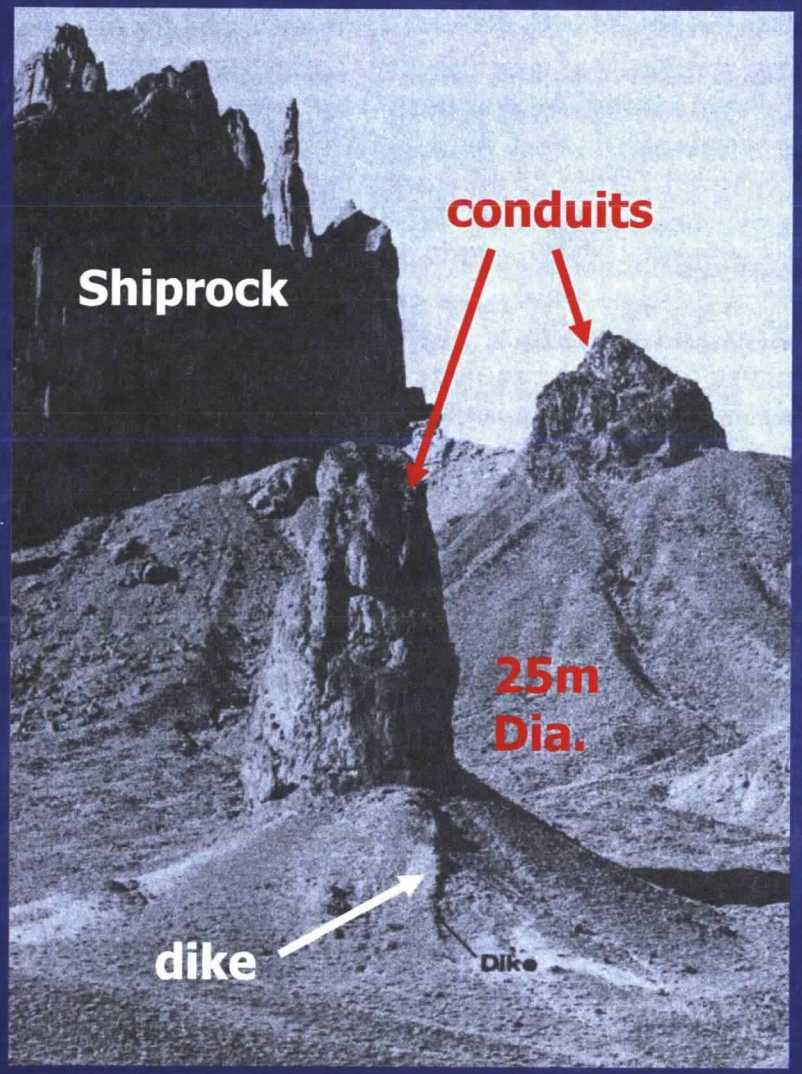
Conduit diameter

- TSPA assumes 15-150 m
- appears consistent with the few available observations
- We encourage additional field study



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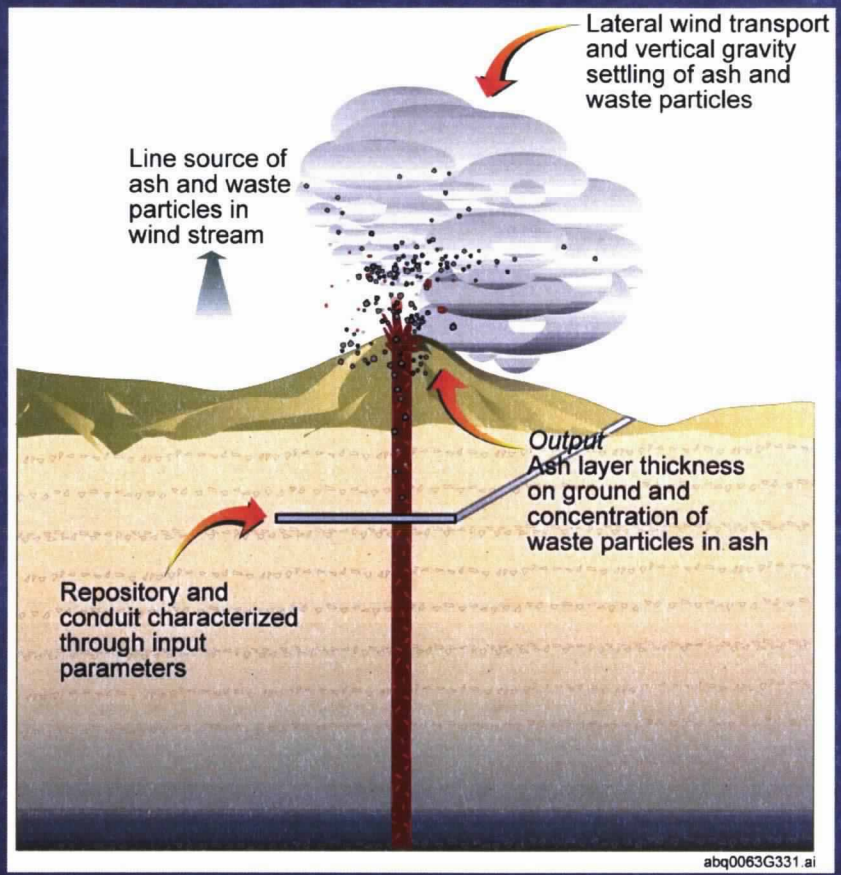
"Typical" Number of canisters entrained

- Assuming
  - 1 conduit,
  - 50 m diameter, centered on a drift
  - 3 additional canisters on either side

total=~16 canisters



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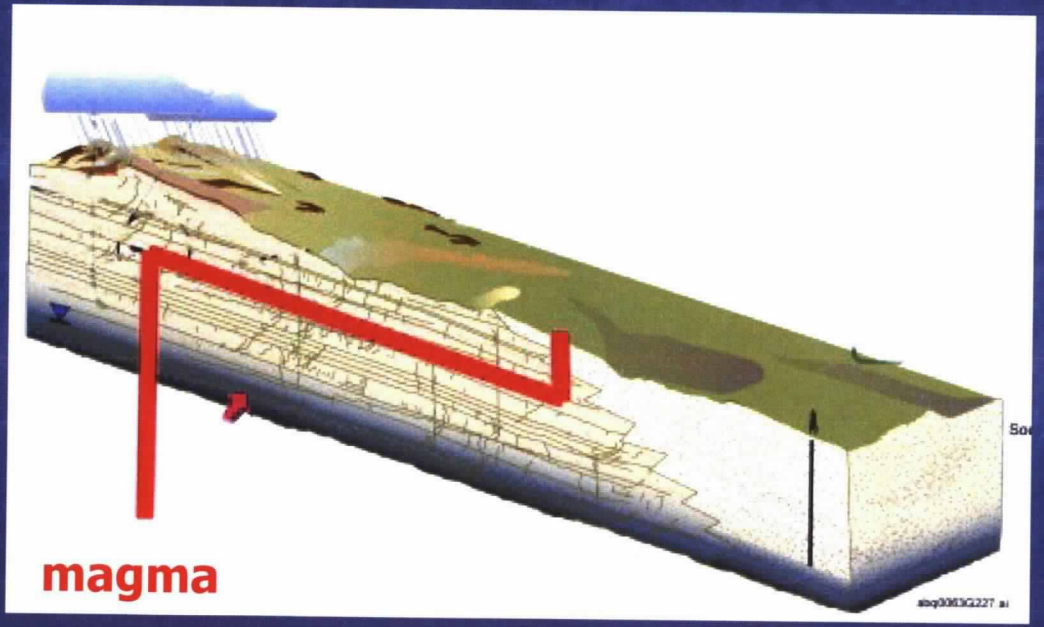
Number of canisters entrained in a "typical" dogleg

- Assume one drift
- 700 m long (half of avg. drift length)
- 5.6 m per canister (including separation)

~130 additional canisters



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Effects of dogleg

- ~10x more canisters entrained in a typical dogleg than a typical "normal" event
- If the dogleg scenario is at least 10x less likely to occur, then the risk (probability*consequences) may not differ significantly from that of a "normal" scenario
- Is a dogleg probability <0.1 that of a "normal" eruption scenario? Our considerations suggest it is, but we recommend more work to explore this.

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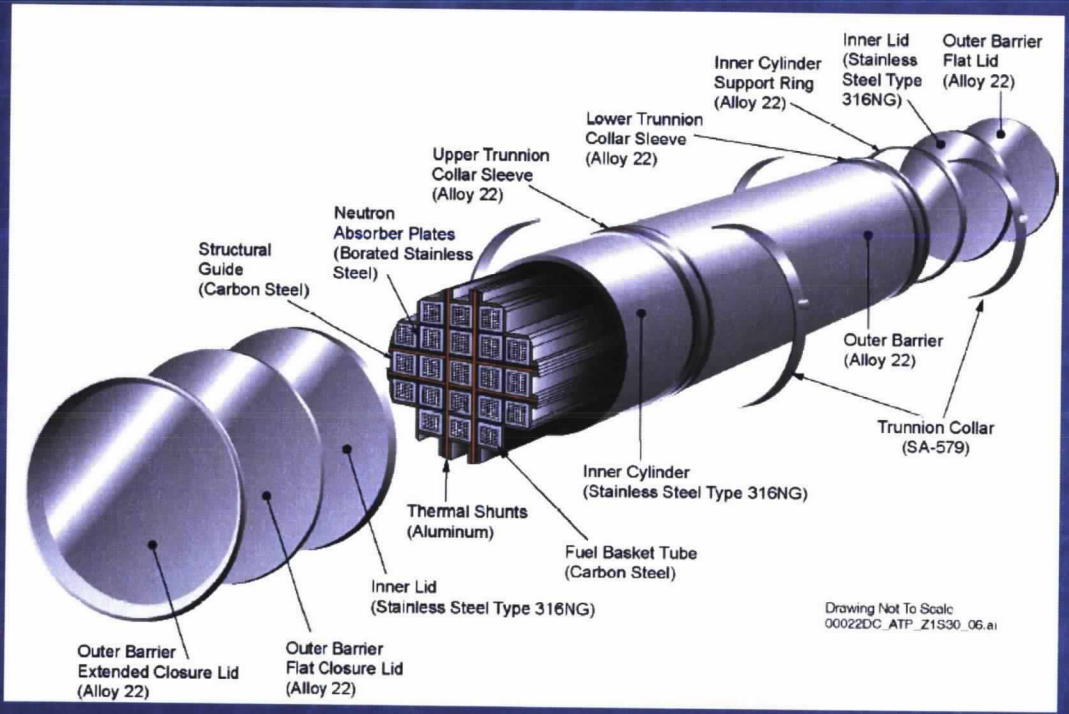
Fraction of waste that escapes containers

- TSPA assumes that all waste in entrained packages escapes and mixes with surrounding magma
- Assumption is highly conservative, based on lack of knowledge of Alloy 22 and its response to corrosion and damage at magmatic temperature



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Uncertainty

•*Factor*	•*Uncertainty*
•Probability that a dike will erupt once it reaches the repository	•10^0
•Number of waste packages entrained in a conduit	•10^2
•Fraction of waste in each package that is entrained into erupted material	•10^2
•Grain size of entrained waste	•10^2
•Fraction of erupted waste that is entrained in a violent Strombolian phase	•10^0
•Areal distribution of VS* tephra sheet(s)	•10^1

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**Violent Strombolian*

Summary

- All values appear realistic or conservative given a "standard" vertical intrusion
- Greatest uncertainty lies in
  - fraction waste that may escape canisters
  - Average grain size of entrained waste
- Factors with greatest uncertainty require additional expertise

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Recommendations

- Plausibility of dogleg scenario best studied using numerical & theoretical treatment
- Waste escape & disaggregation require
  - Experiments carefully designed by engineers & volcanologists
  - Close collaboration with scientists (e.g. USGS) who work on active flows (e.g. Kilauea)

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Chapter 5

Conclusions and *Recommendations*

Presented by:

February 2003

J.R. Anthony Pearson

Schlumberger Cambridge Research & Peer Review Chairman

Conclusions and *Recommendations*

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1) Overall model is adequate
   - No satisfactory mechanistic explanation of eruptive sequences is available or likely to be so in immediate future
   - Independent additive contributions to dosage from aerial and groundwater routes is an acceptable approach for TSPA

2) Characterization of possible YM event by previous "local" events is justifiable
   - *Refinement by high-resolution geochronology recommended*

Conclusions and *Recommendations*

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3) Quantitative assessment of rate and type of flow into drifts (in an igneous event) is inadequate and could be improved
   - *Detailed proposals given for modeling work*
   - *Proposals imply large-scale computing; software and resources are available*
   - *Close collaboration within a team essential*

Conclusions and *Recommendations*

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4) Neither the probability of a dog-leg flowing to the surface, nor its nature, has been quantified so far
   - *Recommend that resolving this be a primary objective of proposals in 3 above*

5) Current estimates for release of HLW into biosphere are conservative except for neglect of dog-leg scenario. It is UNLIKELY that range provided in TSPA will have to change when this quantified

Conclusions and *Recommendations*

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6) *Recommend experimental studies on*
   - *transition from bubbly to pyroclastic flow*
   - *chemical and mechanical damage to canisters*
   - *disaggregation of waste pellets in pyroclastic flows*

7) *Repository design could usefully be revisited (e.g., backfill option; drift orientation; engineering of drifts so as to not cross lithologic boundaries)*