CLOUDY with a chance of steaming bombs
Modelling Steaming Surtseyan Ejecta

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Surtseyan Eruptions

- underwater near surface of sea or lake
- water and vesicular magma interact
- lots of steam, cock’s tails, bombs trail steam
- relatively silent
- re-entry of slurry mix
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Magma-water interactions in subaerial volcanism


Peter Kokelaar
Emergent volcanoes are characterized by distinctive steam-explosive activity that results primarily from a bulk interaction between rapidly ascending magma and a highly mobile slurry of clastic material, water, and steam. The water gets into the vent by flooding across or through the top of

- relatively silent
- re-entry of slurry mix

**Magma-water interactions in subaqueous volcanism**


Peter Kokelaar
Tonga
Surfpehu

Surfpehu

A surtseyan eruption on May 8, 1971, from Crater Lake at the summit of Surfpehu volcano in New Zealand ejects a dark column of ash, mud, and steam. Individual ejected blocks can be seen at the margins of the cloud, trailing cockscomb sprays of ash and steam. This type of eruption column is typical of explosions that involve water-magma interaction.

Type/Process: Magma Meets Water
Volcanic Status: Historical
Image Number: 004-019
Photographer: Peter Otway, 1971 (New Zealand Geological Survey)
Summit Elevation: 2797 meters
Latitude/Longitude: 39.28 S / 175.57 E
Timeframe: Last known eruption 1964 or later
Region: New Zealand to Fiji
Ruapehu

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Tonga

Ruapehu
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- Jólnír satellite vent of Surtsey
- Synchrotron X-ray tomography
- Imaging and Medical Beamline (IMBL)
- Australian Synchrotron, Melbourne.
- Entrained clasts rendered blue
- Void space around entrained clasts
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Mathematical Model

Conceptual model:

- spherical ejecta
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Mathematical Model

in vapor region
Mathematical Model

in vapor region

energy conservation

\[
(1 - \phi) \rho_m c_{pm} \frac{\partial T}{\partial t} + \rho_v c_{pv} \left[ \phi \frac{\partial T}{\partial t} + u \cdot \nabla T \right] - \left[ \phi \frac{\partial p}{\partial t} + u \cdot \nabla p \right] = K_e \nabla^2 T.
\]
Mathematical Model

in vapor region

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Drew and Wood, Two Phase Flow Fundamentals, 1985
Mathematical Model

in vapor region

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mass conservation

\[ \phi \frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v u) = 0 \]
Mathematical Model

in vapor region

energy conservation

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(1 - \phi) \rho_m c_{pm} \frac{\partial T}{\partial t} + \rho_v c_{pv} \left[ \phi \frac{\partial T}{\partial t} + u \cdot \nabla T \right] - \left[ \phi \frac{\partial p}{\partial t} + u \cdot \nabla p \right] = K_e \nabla^2 T.
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\[
\phi \frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v u) = 0
\]

momentum (Darcy’s law)

\[
u = -\frac{k}{\mu_v} \nabla p
\]

\[u = \phi v\]
Mathematical Model

in vapor region

energy conservation

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(1 - \phi) \rho_m c_{pm} \frac{\partial T}{\partial t} + \rho_v c_{pv} \left[ \phi \frac{\partial T}{\partial t} + u \cdot \nabla T \right] - \left[ \phi \frac{\partial p}{\partial t} + u \cdot \nabla p \right] = K_e \nabla^2 T.
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momentum (Darcy’s law)

\[
u = -\frac{k}{\mu_v} \nabla p
\]

ideal gas law

\[
\rho_v = \frac{M_v p}{RT}
\]

\[
u = \phi \mathbf{v}
\]
in liquid region

symmetry and low compressibility implies no flow saturated porous medium

\[
\phi \frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l \mathbf{u}_l) = 0
\]

\[
\mathbf{u}_l = -\frac{k}{\mu_l} \nabla p
\]

\[
\rho' c' \frac{\partial T}{\partial t} + \rho_l c_{pl} \mathbf{u}_l \cdot \nabla T - \phi \beta T \frac{\partial p}{\partial t} - \beta T \mathbf{u}_l \cdot \nabla p
\]

\[
= K_{el} \nabla^2 T
\]
at interface

on saturation curve \[ p_{sv} = p_0 e^{\frac{M_v L}{R T_0} \left( \frac{T_s - T_0}{T_s} \right)} \]

transform to a moving frame, integrate mass, energy across flash front:

\[ \phi \rho_s h_{sl} (v - \dot{s}) = \phi \rho_i h_{sl} (v_i - \dot{s}) = [K \nabla T]^+ + \phi (v - v_l)p \]
at interface

on saturation curve \[ p_{sv} = p_0 e^{\frac{M_v L}{RT_0} \left[ \frac{T_s - T_0}{T_s} \right]} \]

transform to a moving frame, integrate mass, energy across flash front:

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\]

boundary and initial conditions

\[ p(R_2) = p_a, \quad \frac{\partial p}{\partial r} = 0 \text{ at } r = 0 \]

initial \( p \) initial T: hot in magma, at boiling in inclusion
\[
\frac{\partial T}{\partial t} = \frac{\epsilon_3}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right), \quad r < s(t),
\]
\[
\dot{s} = \epsilon_4 \rho_s \frac{\partial p}{\partial r} = -\frac{1}{\text{St}} \left[ \frac{\partial T}{\partial r} \right]_+, \quad r = s(t),
\]
\[
p = \exp \left[ H \left( \frac{T - T_0}{T} \right) \right], \quad r = s(t)
\]
\[
\frac{\partial T}{\partial t} = \frac{\delta_5}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right), \quad r > s(t)
\]
\[
p = \rho_s T, \quad r > s(t),
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\[
\frac{\partial \rho_s}{\partial t} = \frac{\epsilon_5}{r^2} \frac{\partial}{\partial r} \left( r^2 \rho_s \frac{\partial p}{\partial r} \right), \quad r > s(t),
\]
\[
T = T_0, \quad r = 1; \quad p = 1, \quad r = 1; \quad \frac{\partial T}{\partial r} = 0, \quad r = 0;
\]
\text{initial conditions} \quad T = T_0, \quad r < s(0); \quad T = 1, \quad r > s(0);
\[
p = 1; \quad s(0) = R_1/R_2 .
\]
\[
\frac{\partial T}{\partial t} = 0.002 \varepsilon_3 \frac{\partial}{r^2 \partial r} \left( r^2 \frac{\partial T}{\partial r} \right), \quad r < s(t),
\]
\[
\dot{s} = \varepsilon_4 \rho_s \frac{\partial p}{\partial r} = -\frac{1}{\text{St}} \left[ \frac{\partial T}{\partial r} \right]^+ , \quad r = s(t),
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p = \exp \left[ H \left( \frac{T - T_0}{T} \right) \right] , \quad r = s(t)
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\frac{\partial T}{\partial t} = \frac{\delta_5}{r^2 \partial r} \left( r^2 \frac{\partial T}{\partial r} \right) , \quad r > s(t)
\]
\[
p = \rho_s T , \quad r > s(t),
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\[
\frac{\partial \rho_s}{\partial t} = \frac{\varepsilon_5}{r^2 \partial r} \left( r^2 \rho_s \frac{\partial p}{\partial r} \right), \quad r > s(t),
\]

Nondimensionalise

reject smallest parameters

initial conditions

\[ T = T_0 , \quad r = 1 ; \quad p = 1 , \quad r = 1 ; \quad \frac{\partial T}{\partial r} = 0 , \quad r = 0 ; \]

\[ T = T_0 , \quad r < s(0) ; \quad T = 1 , \quad r > s(0) ; \]

\[ p = 1 ; \quad s(0) = R_1/R_2 . \]
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\frac{\partial T}{\partial t} = \frac{\varepsilon_3}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right), \quad r < s(t),
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T = T_0, \quad r = 1; \quad p = 1, \quad r = 1; \quad \frac{\partial T}{\partial r} = 0, \quad r = 0;
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Numerical solutions

• boiling driven by magma temperature gradient
Numerical solutions

- boiling driven by magma temperature gradient
- initial gradient infinite
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- boiling driven by magma temperature gradient
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- moving boundary: freeze with Landau transformations
Numerical solutions

- boiling driven by magma temperature gradient
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- moving boundary: freeze with Landau transformations

\[ \zeta = \frac{r}{s} \quad \text{in slurry} \quad \xi = \frac{r - s}{1 - s} \quad \text{in hot magma} \]
Numerical solutions

- boiling driven by magma temperature gradient
- initial gradient infinite
- moving boundary: freeze with Landau transformations

\[ \zeta = \frac{r}{s} \text{ in slurry} \quad \xi = \frac{r - s}{1 - s} \text{ in hot magma} \]

Then use method of lines. Upwind advection terms. Transform to non-uniform mesh, to resolve thermal boundary layer.
Numerical solutions

The key parameters controlling solution behaviour are D and the point source flux E. Typical values for parameters used here are listed in Table (1). Note that as R1 increases, the flux E increases at origin. But dimensionless D also increases as R1 increases, so it is difficult to deduce pressure behaviour at origin.

Numerical solutions reveal an interesting feature - the pressure at the surface of the lapillus quickly equilibrates, as illustrated in Fig. (1). This rapid equilibration is observed over a wide range of parameters.

The rapid stabilisation of pressure at the surface of the lapillus means that the steady-state solution for pressure with the source of vapor never turns off provides a formula for the correct maximum value of pressure achieved there. As a steady state everywhere is not typically achieved by the time t = 1, as is evident in Fig. (1), but if the vapor source were to continue for long enough, steady state would be achieved and the value of pressure at r = ⍟ will be the same since it rapidly reaches its stable value.

1 cm inclusion
10 cm bomb
moving flash front

k is $10^{-14}$ m$^2$
Numerical solutions

The key parameters controlling solution behaviour are $D$ and the point source flux $E$.

Typical values for parameters used here are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_c$</td>
<td>$2 \times 10^6$</td>
<td>Pa</td>
</tr>
<tr>
<td>$h v_l$</td>
<td>$2 \times 10^6$</td>
<td>J/kg</td>
</tr>
<tr>
<td>$k$</td>
<td>$10^{14}$</td>
<td>m$^2$/K</td>
</tr>
<tr>
<td>$\mu v_l$</td>
<td>$3 \times 10^5$</td>
<td>Pa.s</td>
</tr>
<tr>
<td>$M$</td>
<td>$1.8 \times 10^3$</td>
<td>kg/mol</td>
</tr>
<tr>
<td>$R$</td>
<td>$8.314$</td>
<td>J/K/mol</td>
</tr>
<tr>
<td>$T_m$</td>
<td>$1300$</td>
<td>K</td>
</tr>
<tr>
<td>$T_0$</td>
<td>$300$</td>
<td>K</td>
</tr>
<tr>
<td>$m$</td>
<td>$0.4$</td>
<td></td>
</tr>
<tr>
<td>$R_1$</td>
<td>$0.001$</td>
<td>m</td>
</tr>
<tr>
<td>$R_2$</td>
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As $R_1$ increases, the flux $E$ increases at origin. But dimensionless diusivity $D$ also increases as $R_1$ increases, so it is difficult to deduce pressure behaviour at origin.

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P rise: steam flux prescribed
P fall: T gradient easing off
P fall: decreasing slurry area
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P fall: T gradient easing off
P fall: decreasing slurry area

T~1.0 in magma
T~0.3 at flash
initial T gradient: unbounded?
numerical convergence
varying smallest mesh size and # mesh points

Figure 8: The maximum pressure at the flashing front, and the time at which this maximum is achieved, versus mesh size, with different lines for different total numbers of mesh points. Pressure is dimensionless, but is effectively in bars. The initial conditions are step functions in temperature and pressure. The smallest mesh size is initially set to the dimensionless value $r = 10^{-4}$, then divided by the values 4, 16, 64, 256, and 1024. The number of mesh points varies from 200 to 3200 in the magma, with values in the slurry set to half of the magma values. The maximum pressure increases as mesh size decreases, and as the number of mesh points increases. Parameter values are as listed in Table (1), except that here $k = 10^{12}$. 
numerical convergence
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Figure 8: The maximum pressure at the flashing front, and the time at which this maximum is achieved, versus mesh size, with different lines for different total numbers of mesh points. Pressure is dimensionless, but is effectively in bars. The initial conditions are step functions in temperature and pressure. The smallest mesh size is initially set to the dimensionless value \( r = 10^{4} \), then divided by the values 4, 16, 64, 256, and 1024. The number of mesh points varies from 200 to 3200 in the magma, with values in the slurry set to half of the magma values. The maximum pressure increases as mesh size decreases, and as the number of mesh points increases. Parameter values are as listed in Table (1), except that here \( k = 10^{12} \).
The model equations in the new coordinates become (dropping the subscript on and in the surrounding magma,
the chain rule says that in the slurry,
correspond to the now stationary flashing front.
so that both regions are transformed to the region \[0 \leq r \leq s \]
and in the hot magma and vapour region we use a radial coordinate
In the slurry, we use the new radial coordinate
Numerical solutions are helped by freezing the moving boundary
4 Freezing the moving boundary
front is at
Figure 2: Simulated temperatures (symbols) in the slurry inclusion, and in the
magma, plotted against the similarity variable
\[ T_{\text{magma}} = \left(1 - T_f\right) \text{erf} \left( \frac{\sigma}{2\sqrt{t}} \right) + T_f \]
Data - bomb samples

The resulting maximum pressures simulated are given in Fig. (12) versus permeability, together with a horizontal dashed line at a typical value for tensile strength of rock at 20 bara. The implication of these results is that Surtseyan bombs with permeability less than about $10^{-12.5}$ should fragment due to the pressures developed at very small times due to flashing of liquid in the enclosed slurry. This is broadly consistent with the measured values of permeability in intact bombs shown in Fig. (11), which all lie at or above this value of permeability.

The other parameter of importance is the ratio of the size $R_1$ of the slurry inclusion to the size $R_2$ of the magma bomb containing it. The sensitivity of the maximum pressure to varying sizes is explored in the simulated results shown in Fig. (13). These results indicate that the simulated maximum pressures are not very sensitive to the size of the inclusion, with variations $\pm 2$ bars, compared to variations of 4-8 bars as the permeabilities and porosities are varied. Furthermore, it is only the very smallest of inclusions that give clear reductions in the maximum pressure.
Data - bomb samples

The maximum pressure simulated, using $\log k = 6.33\phi - 14.1$
Data - bomb samples

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References

Conclusions

Hunga Tonga
Before & After
Conclusions

Numerics and asymptotics

=> fragmentation criterion
Conclusions

 numerics and asymptotics

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pressure, temperature:
different timescales
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initial T gradient is unbounded,
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pressure, temperature:

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hope to use steady state pressure solution to
bound the maximum pressure
Thank you!