TWO-DIMENSIONAL SIMULATIONS OF EXPLOSIVE ERUPTIONS OF KICK-EM JENNY AND OTHER SUBMARINE VOLCANOS

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ABSTRACT

Kick-em Jenny, in the Eastern Caribbean, is a submerged volcanic cone that has erupted a dozen or more times since its discovery in 1939. The most likely hazard posed by this volcano is to shipping in the immediate vicinity (through volcanic missiles or loss-of-buoyancy), but it is of interest to estimate upper limits on tsunamis that might be produced by a catastrophic explosive eruption. To this end, we have performed two-dimensional simulations of such an event in a geometry resembling that of Kick-em Jenny with our SAGE adaptive mesh Eulerian multifluid compressible hydrocode. We use realistic equations of state for air, water, and basalt, and follow the event from the initial explosive eruption, through the generation of a transient water cavity and the propagation of waves away from the site. We find that even for extremely catastrophic *explosive* eruptions, tsunamis from Kick-em Jenny are unlikely to pose significant danger to nearby islands. For comparison, we have also performed simulations of explosive eruptions at the much larger shield volcano Vailulu'u in the Samoan chain, where the greater energy available can produce a more impressive wave. In general, however, we conclude that explosive eruptions do not couple well to water waves. The waves that are produced from such events are turbulent and highly dissipative, and don't propagate well. This is consistent with what we have found previously in simulations of asteroid-impact generated tsunamis. Non-explosive events, however, such as landslides or gas hydrate releases, do couple well to waves, and our simulations of tsunamis generated by sub-aerial and sub-aqueous landslides demonstrate this.

INTRODUCTION

Water and magma make a highly explosive combination, particularly at water depths less than about 130 meters. The explosive vaporization of water, heated by contact with magma at 1200 C or hotter, produces an instantaneous pressure of ~50 kBar, that can have extremely dangerous consequences. The August 1883 explosion of Krakatau is thought to have been caused by this hydromagmatic mechanism. This event produced tsunami that killed many thousands of people in the near vicinity, and propagated (though much more weakly) around the world.

It is of interest to discuss whether there is a significant danger of tsunami from the submarine volcano Kick-em Jenny in the eastern Caribbean. We conclude here that there is not. The simulations that we have performed, in an axisymmetric geometry resembling Kick-em Jenny, suggest that only for very much more energetic events are significant waves generated, and that even these waves do not propagate as classical tsunami. These results are consistent with conclusions we have drawn from simulations of other explosively-generated waves.

Kick-em Jenny, located 8 km north of the island of Grenada in the volcanic arc of the Lesser Antilles, is one of the most active volcanos in the region. It has erupted a dozen times since 1939, and is a known hazard to shipping, marked on navigation charts. The principal dangers caused by Kick-em Jenny are from volcanic missiles projected to altitudes of a few hundred meters, and from gases emitted into the seawater from the volcano, reducing the density of the water and thereby causing ships to lose buoyancy. No significant tsunami have been observed to arise from these eruptions, which have generally been of magnitude between 0 and 1 on the Volcanic Explosivity Index (VEI) scale (Simkin et al 1981), though there were early reports of minor waves.

Smith and Shepherd (1993, 1995, 1996) investigated the tsunami hazard posed by the Kick-em Jenny volcano. While the top of the volcanic cone is at a depth such that the hydrostatic water pressure confines the explosive effects of the eruption, bathymetric surveys conducted during the 1960s and 1970s led to the impression that the cone was building towards the surface, and therefore might eventually pose a tsunamigenic hazard from the explosive vaporization of sea water in a major eruption. Smith and Shepherd therefore studied this potential hazard by using linear theory to calculate initial amplitudes, dispersion, and propagation, and shoaling, given a spectrum of potential events and their probability. Their worse case scenario included run-ups as high as 46 meters on the northern shore of Grenada for a VEI=6, or Krakatau-like event, considered as potentially likely on a 1000-year scale, or as high as 8 meters for a more realistic, 100-year, VEI=3 event.

This potential threat has recently been downplayed, owing mostly to bathymetry obtained in a March 2002 multi-beam survey (Lindsay, Shepherd, and Wilson, 2005), which was conducted after the publication of the Smith and Shepherd papers. This recent bathymetry suggests that the depth of the Kick-em Jenny summit, now at 185 m, has not significantly diminished since the first report in 1966 of 192 m. The immediate danger from tsunami that might potentially be caused by this volcano is therefore now thought to be insignificant. Nevertheless, it is of interest to study the role of underwater volcanic explosive eruptions in producing tsunami in the general case with particular application to this very interesting case.

Accordingly, we have conducted a series of two-dimensional axisymmetric simulations of explosive underwater volcanic eruptions to study the coupling of these events to the production of water waves.

THE SAGE HYDROCODE

The SAGE hydrocode is a multi-material adaptive-grid Eulerian code with a high-resolution Godunov scheme originally developed by Michael Gittings for Science Applications International (SAIC) and Los Alamos National Laboratory (LANL). It uses continuous adaptive mesh refinement (CAMR), by which we mean that the decision to refine the grid is made cell-by-cell and cycle-by-cycle continuously throughout the problem run. Refinement occurs when gradients in physical properties (density, pressure, temperature, material constitution) exceed user-defined limits, down to a minimum cell-size specified by the user for each material in the problem. With the computing power concentrated on the regions of the problem which require higher resolution, very large computational volumes, and substantial differences in scale, can be simulated at low cost.

SAGE can be run in several modes of geometry and dimensionality, explicitly 1-D Cartesian and spherical, 2-D Cartesian & cylindrical, and 3-D Cartesian. The RAGE code is similar to SAGE but incorporates a separate module for implicit, gray, non-equilibrium radiation diffusion. Both these codes are part of LANL's Crestone project, in turn part of the Department of Energy's program in Advanced Simulation and Computing, or ASC.

Because modern supercomputing is commonly done on machines or machine clusters containing many identical processors, the parallel implementation of the code is supremely important. For portability and scalability, SAGE uses the widely available Message Passing Interface (MPI). Load leveling is accomplished through the use of an adaptive cell pointer list, in which newly created daughter cells are placed immediately after the mother cells. Cells are redistributed among processors at every time step, while keeping mothers and daughters together. If there are a total of M cells and N processors, this techniques gives very nearly M/N cells per processor. As neighbor-cell variables are needed, the MPI gather/scatter routines copy those neighbor variables into local scratch.

In a multi-material code like SAGE, every cell in the computational volume can contain all the materials defined in the problem, each with its own equation of state (and strength model, as appropriate). There are a number of equations of state available, analytical and tabular. In the calculations reported here, we use the LANL SESAME tables for air and basalt, and for water we used a somewhat more sophisticated table (including a good treatment of the vapor dome) from SAIC. For the strength of basalt, we used a simple elastic-plastic model with pressure hardening (with depth) for the basalt.

The boundary conditions we use in these calculations are designed to allow unhindered outflow of waves and material. This is accomplished by the use of "freeze regions" around the edges of the computational box, which are updated normally during the hydrodynamic step, then quietly restored to their initial values of pressure, density, internal energy, and material properties before the next step. This technique has proven to be extremely effective at minimizing the deleterious effect of artificial reflections. But by far the best technique for dealing with unwanted boundary effects is to put the boundaries very far away from the regions of interest or to place the boundary beyond a material interface that truly exists in the problem and might be expected to interact with waves in an appropriate way (i.e. through reflection, transmission, and absorption).

SIMULATIONS OF KICK-EM JENNY

For the sake of simplicity, we perform our simulations in two-dimensions only, ignoring the very real three-dimensional character of the Kick-em Jenny volcano. Its cinder cone is embedded in a horseshoe-shaped slump caused by slope failure from a larger mound to its east. The event that caused this slump must have produced significant tsunami, and we shall argue that the danger from future such slumps is greater than from eruptive events on the cinder cone. The geometry of the slump and other three-dimensional features would provide collimation and amplification of eruptively produced waves that propagate in certain directions while attenuating waves that propagate in other directions. We ignore these effects in order to focus solely on the generative mechanism.

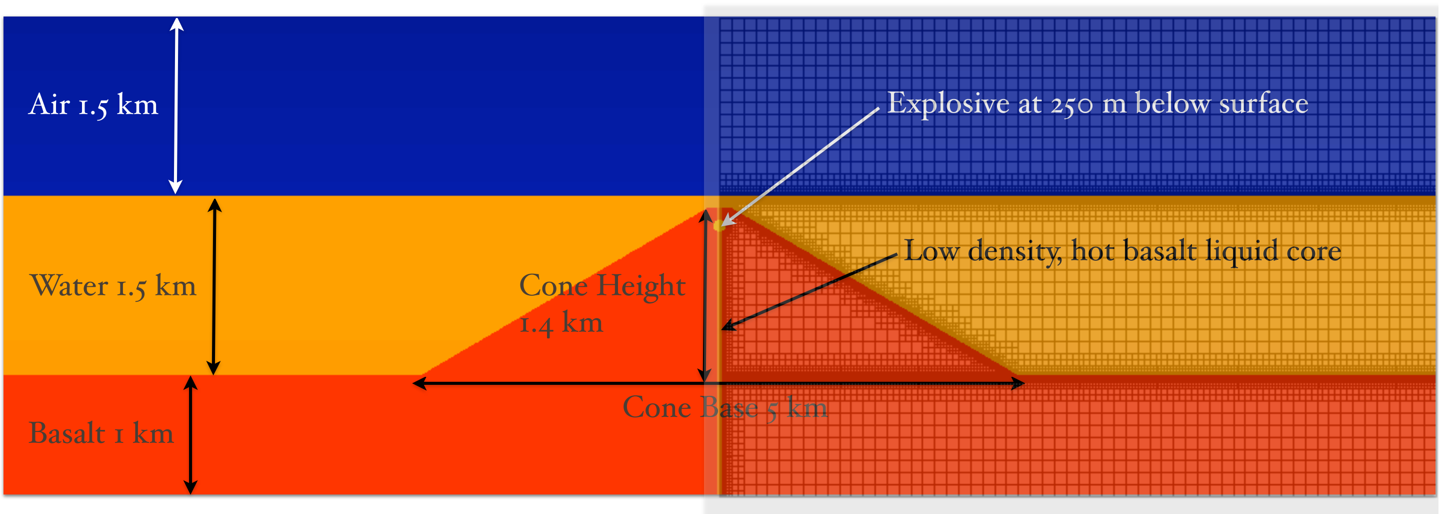

Figure 1. Geometry of SAGE set-up for Kick-em Jenny simulations. Colors indicate density, with red representing the basalt of the crust and cone, orange the water, and blue the air. Dimensions are as indicated, and the diagram is in proportionate scale. On the right we show the initial gridding of the problem as set up by the SAGE code. Before any dynamics have occurred, the grid is refined only at the material interfaces.

Accordingly, we model the volcano as a simple geometrical frustum, with a base of 5 km diameter, a top of 100 m diameter, and a height of 1.4 km (see Fig. 1). The cone has a hot magma core of 20 m diameter. We take the water depth to be 1.5 km, so that the submerged top of the frustum is only 100 m below the water surface, thus significantly shallower than the true cone summit, and above the threshold depth for pressure confinement of a hydromagmatic eruption. We use three materials in the problem, air for the atmosphere, water for the ocean, and basalt for the seafloor, the volcanic cinder cone, and the hot magma core. We use tabular equations of state for these from the LANL Sesame Library except for water, which we take from a high-quality SAIC table. We use a simple elastic-plastic strength model for the solid basalt, and no strength for the magma, water, or air.

To model an explosive eruption, we take the extreme (and admittedly unlikely) case of an instantaneous explosion near the top of the cone. Because we anticipate that the strongest coupling to the water motion will be through the motion of rock, we do not place the explosion at the summit, but some depth (usually 150 m) below the summit.

We present here three sample runs that span the range of interest. The parameters of these runs, and the resulting maximum wave heights are presented in Table I.

We chose these parameters to span a major portion of the range of interest, as an exploration of what waves might possibly be generated by significant explosive eruptions at Kick-em Jenny. Our extrapolated wave heights at 10 km distance are significantly less than reported by Smith and Shepherd (1993).

Table I. Summary of important runs.

run name	VEI	initial source energy (megatons)	wave energy at 60 seconds (megatons)	wave height at 3 km (meters)	extrapolated wave height at 10 km (meters)
kej11	5.5	233	2.11	300	37
kej12	4.5	21.2	0.0254	130	21
kej13	3.7	3.71	0.0078	20	2.7

We illustrate these three runs by showing the final density configuration in Figure 2. The explosive energy is sourced in instantaneously at the beginning of the calculation. A hot crater quickly opens in the basalt, and the explosive vaporization of the water in contact with this crater produces a large transient water cavity. A "debris curtain" or rim wave makes a precursor tsunami that dies off very quickly. The main wave is produced by the collapse of the transient water cavity, and the strong water currents modify the shape of the basalt crater produced in the explosion. The wave that is produced by the cavity collapse is very turbulent and dissipative, and it propagates slowly. When the main wave leaves the computational domain (6 km from the center), we terminate the simulation, though the center is still hot and turbulent.

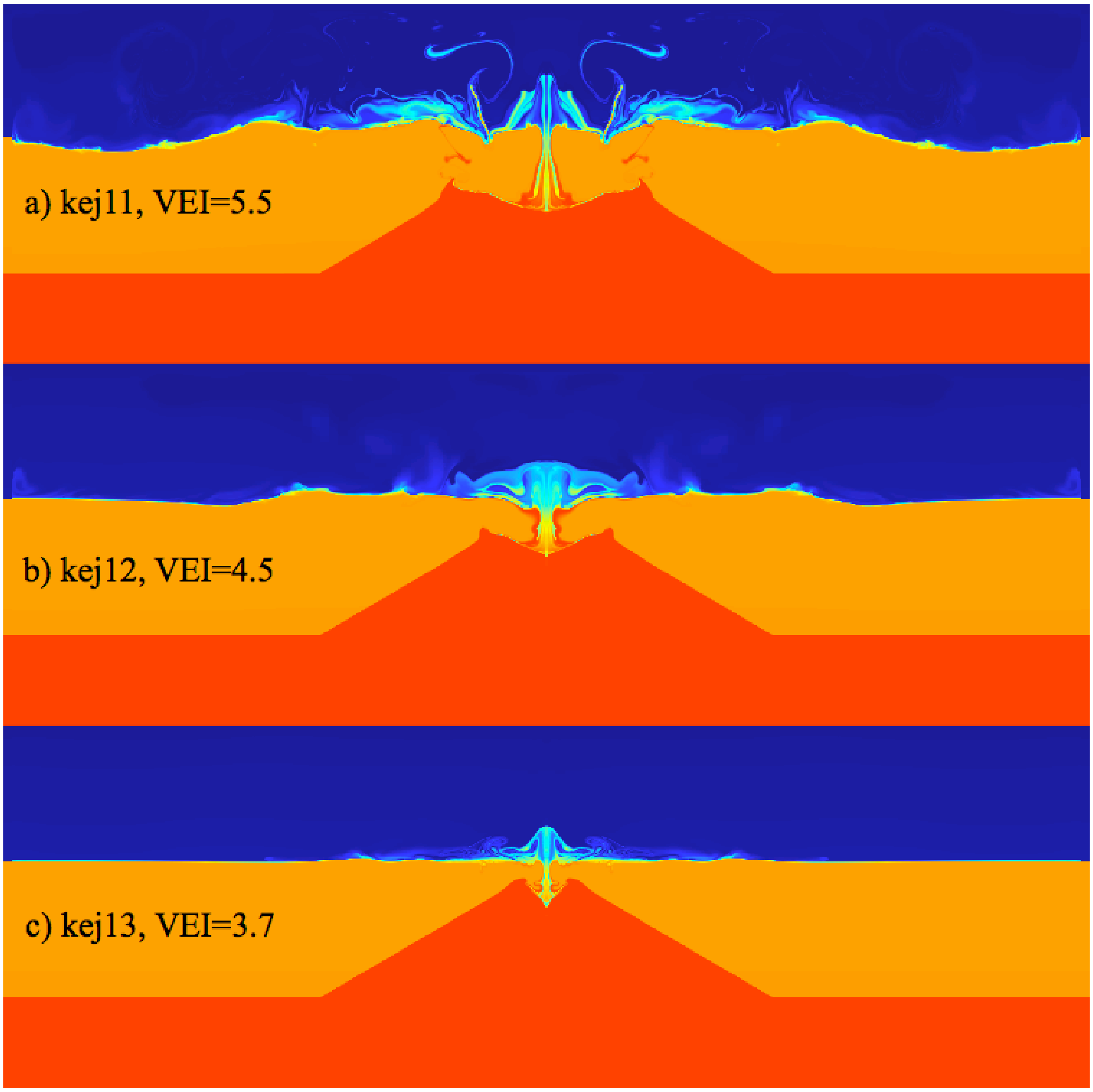

Figure 2. Final wave profiles for the three representative runs.

This relative inefficiency of coupling for explosive energy deposition is similar to the inefficiency we have previously found for coupling of asteroid impacts to tsunami wave energy. In the latter case we have found that impact-generated waves decline rather more steeply with distance than waves from seismic or landslide events, and their speeds and wavelengths are correspondingly lower (Gisler et al. 2002).

The coupling of source energy to eventual wave energy is much less efficient in the explosive release case that we are considering here than it is for slower mechanisms of energy release. As seen in Table I, only 2% of the source energy for run kej13 goes into the wave, reducing to < 1% for the most energetic run, kej11. The kinetic energy histories for the principal components of the simulation are shown in Figure 3 for the middle run of Table 1. Much more of the initial source energy is transformed directly into the internal energies of the various components, and mainly goes into the vaporization of water and the melting of basalt.

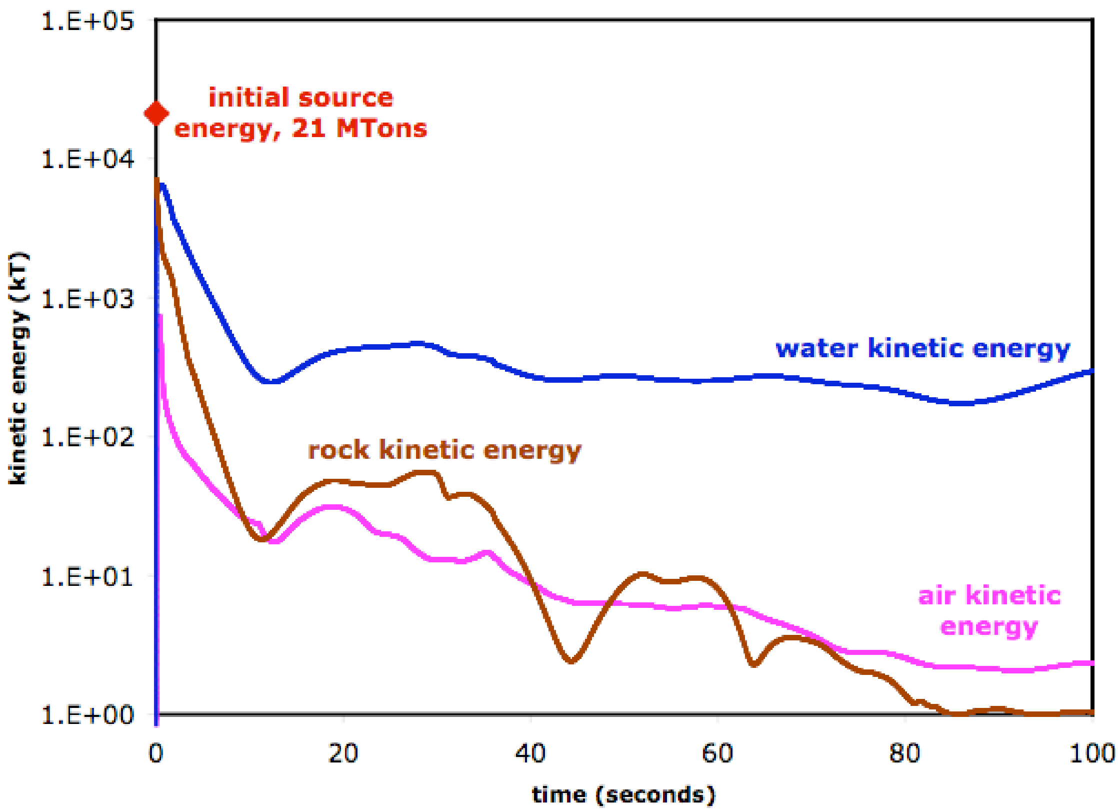

Figure 3. History of material kinetic energies for our run kej11, with an initial explosive energy of 21 MTons.

For comparison, we have performed simulations of underwater and subaerial granular basalt landslide events with free energy ~20 MTons, comparable to our kej12 explosive eruption simulation, and find in these cases coupling efficiencies (source potential energy to water kinetic energy) of 15% to 25% depending on the circumstances.

We also performed simulations of explosive eruptions on the massive shield volcano Vailulu'u, at the end of the Samoan chain. While such eruptions are even less likely in that case than in the case of Kick-em Jenny, we thought it useful to examine a case that was larger in dimension and energy availability. In that case also we find that the coupling to water waves is in general of very poor efficiency. However, if we artificially weaken the strength parameters for basalt so that the rock deformation is substantially greater than in the nominal case, the coupling efficiency, wave heights, and consequently the wave kinetic energy are considerably enhanced. In the extreme we get a coupling efficiency of 25%.

We conclude that the efficient production of a tsunami requires a disturbance that covers a substantial distance or lasts a considerable time. Earthquakes or long-runout landslides, or more generally a movement of the seafloor or a pressure pulse communicated by the seafloor, produce tsunamis efficiently. Explosions or impacts do not couple to water motion as efficiently as do slower motions of rock.

Specifically, the tsunami danger from explosive eruptions of Kick-em Jenny is much less important than the danger that might result from a slope failure at that volcano, similar to that which caused the horseshoe-shape cleft in which the volcano currently nestles.

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