Review of Shock Wave Models and Igneous Activity

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Overview:

The fluid dynamic models presented by Bokhove and Woods (2001) and Woods et al. (2001) demonstrate the fluid dynamic processes that may occur in the drift during the first minutes after magma enters. Upon entry, the migrating magma generates a pressure wave that propagates through the stagnant air inside the drift. This leading pressure wave travels at a velocity greater than the sound speed of air (340 m/s @ standard conditions, 25°C and 1 bar (0.1 MPa)) and is referred to as a shock wave. The propagating shock wave raises the pressure of the air behind it to a value between 0.1 MPa and the flow pressure of the entering magma (20 MPa) and increases the velocity of air to a value of that of the moving magma. A rarefaction wave is also generated by the inflowing magma and it moves through the magma-filled dike attempting to lower the magma pressure. This pressure wave continues to propagate through the magma until it is dissipated by viscous and other damping forces.

In this idealized 1-dimensional setting, the leading shock wave continues to propagate through the stagnant air until it reaches the end of the drift. At the end of the drift, the shock wave encounters a wall and reflects back into the pressurized moving air; no energy is transmitted through the wall, it is all reflected back into the moving, pressurized air. The reflected shock wave raises the air pressure to a value greater than that of the initial shock wave. When this shock wave encounters the oncoming magma interface, it reflects off the interface but part of its energy will be transmitted through the magma as a shock wave and part will be transmitted back into the pressurized air as second reflected shock wave. The second reflected shock wave will again raise the pressure of air inside the drift. The air pressure inside the drift continues to increase until the magma interface reaches the end of the closed drift and as demonstrated by Bokhove and Woods model (2001), pressures may reach values (5 MPa) 50 times greater than the

initial pressure (0.1 MPa). The shock waves that are transmitted into the magma-filled dike dissipate and do not reflect back into the drift.

How realistic is this model?

The general dynamics of the model are realistic in that if a high-pressure fluid enters a low-pressure fluid a pressure wave will be generated. Whether that pressure wave will be a shock wave or a sound wave depends on the pressure difference between the two fluids and the compressibility of the low-pressure fluid. Air is very compressible and given the initial temperature and pressure of the drift, a shock wave will likely be generated. How pressurized the air in the drift becomes is essentially dependent upon the boundary condition at the end of the drift. A closed drift will enable the shock wave to reflect multiple times before the magma fills the drift. The reflective shock waves pressurize the part of the drift filled with air.

The model is not realistic in its assumption that the walls of the drift will be smooth and uniform in cross-section. The presence of wall irregularities will create friction and will likely lower the air flow pressure behind the shock wave (Anderson, 1984). Any significant change in cross-sectional area of the drift will modify the air pressure behind the shock wave. Increasing the cross-sectional area of the drift will increase the pressure by lowering the air flow velocity (Anderson, 1984). The opposite will happen if the cross-sectional area of the drift is decreased.

Another assumption in the model that is not realistic is the omission of waste packages and their protective materials. The presence of waste packages would provide additional reflective surfaces for the shock wave. The shock wave may propagate over the series of waste packages and reflect off any large surface of a waste package that is not parallel to the flow path of the moving shock wave. Furthermore, the shock wave may be able to lift the coverings or displace the mounted waste packages. This may also happen if the magma intrudes under a waste package instead of an unoccupied region of the drift as assumed in the model.

Strong points of the model:

As previously mentioned, the Bokhove and Woods model (2001) clearly demonstrates the basic fluid dynamics that may occur in the drift during the first minutes after it is breached by magma. The model also demonstrates how the properties of magma affect the amount of energy transmitted into the magma by the rarefaction wave and the transmitted shock wave. In addition, the model illustrates how the air pressure may build inside the drift to up 50 times that of the initial pressure by multiple reflections of the leading shock wave allowed by the closed end of the drift.

Weak points of the model:

There are several weak points in the model that will strongly affect the pressurization of the drift by the shock wave. Firstly, the flow pressure of the magma entering the drift is over-estimated. The model assumes the flow pressure to be equal to the lithostatic pressure plus overpressure totaling 20 MPa. A more realistic flow pressure value would take into consideration the minimum principle stress for the region around the drift. In this case, the flow pressure of magma will be an order of magnitude lower which in turn will lower the overall pressurization inside the drift. This point is in agreement with the review of R. Denlinger of the U.S. Geological Survey.

Secondly, the model assumes 1-dimensional behavior of magma flow and the shock wave inside the drift. This assumption limits the shock wave to be a normal wave propagating perpendicular to the length of the drift. Given the other assumptions that the walls are smooth and uniform in area allows 1-dimensional flow to be valid (Anderson, 1984). To account for irregularities along the walls of the drift and changes in area, a 2- or 3-dimensional model (i.e. Baltrusaitis et al., 1996; Morrissey and Chouet, 1997a) is necessary to estimate the air pressure and true behavior of the shock wave.

Thirdly, the model assumes that the magma entering the drift will remain fluid. The model does not consider heat loss due to expansion of magma and volatiles inside the drift. The magma may cool significantly and freeze upon entering the drift. If this happens, then the initial shock wave may dissipate before reaching the end of the drift because the driving fluid comes to rest. Instead of freezing in place, the magma may fragment upon entering the drift creating a mixture of ash and hot gases. This scenario

may be more dynamic than that of the fluid magma. The ash-gas mixture will enter the drift moving at a higher velocity behind the leading shock wave than the fluid magma (Fisher and Schmincke, 1984). The high speed mixture would contribute to the degradation of the waste packages by pitting and scouring the outer surfaces.

Lastly, the model considers the drift walls to be perfectly rigid neglecting the elasticity of the wall rock. The elasticity of the walls will reduce the pressure behind the shock wave by transmitting some of the energy out of the drift (Chouet, 1986; 1988).

How can the model be changed and what are the effects?

Many of the weak points of the model are related to the assumptions of the drift walls and the assumed value for the pressure of the magma upon entering the drift. If the drift was open ended and a lower flow pressure for the magma were considered in the calculations by Bokhove and Woods (2001), then the model would result in lower pressures inside the drift after the passage of the leading shock wave. These pressures would likely be equal to or lower than the range of principle stresses that the drift could tolerate without fracturing. The effects of the shock wave on the waste packages are not as clearly understood. All the Bokhove and Woods model (2001) can do is estimate a maximum pressure and speed for the shock wave and air flow behind it.

The model also needs to consider how the shock wave will affect the waste packages and coverings, and how it will behave as a 2- or 3-dimensional wave as opposed to the 1-dimensional normal wave considered in the model. Irregularities along the wall, the presence of waste packages, different entry configurations, and an extended pathway to consider the open-ended drift and connection to perimeter drifts will have significant effects of the behavior of the shock wave inside the drift. The wave may not propagate as a simple single wave, it may be a series of oblique shock waves or expansion wave may be generated around the waste packages, which may not increase the pressure behind it as greatly. How these affect the drift and its contents is unknown due to the complex nature of the wave type. Numerical models that are currently available (i.e. Baltrusaitis et al., 1996; Morrissey and Chouet, 1997a, 1997b) can consider these factors and are easily adaptable to the drift scenario.

The Bokhove and Woods model (2001) needs to test other physical conditions or states for the magma in terms of flow behavior as it moves into the drift and how much energy the magma transmits from the shock wave. There are three scenarios that could occur and all would have different consequences on how they would affect the waste packages and the shock wave. If the magma expanded into the drift and froze, then the drift and waste packages would be protected from any additional magma entering the drift. It would also aid in dissipating the shock wave. If the magma expanded into the drift passively as a fluid foam as in the Bokhove and Woods model (2001), then the magma would behave according to their model. If the magma expands into the drift as a mixture of ash and hot gases, then a high speed ash-gas mixture will be flowing behind the leading shock wave. The effects of this mixture on the waste packages will depend on whether the flow is turbulent or laminar. The ash-gas mixture will enhance the leading shock wave and dissipate less energy than in the case of a fluid magma.

To address the review of L. Mastin of the U.S. Geological Survey – he questions whether a shock wave will be generated by a basaltic fissure eruption. Although there is no recorded evidence of shock waves associated with the initiation of a basaltic fissure eruption, a shock wave will occur in the scenario in the Bokhove and Woods model (2001). In their model, a basaltic magma enters the drift with a pressure greater than that of the air inside the drift. The compressibility of air allows a shock wave to develop from the steep pressure gradient between the two fluids. Whereas in the case of a surface fissure eruption, the magma pressure is near atmospheric pressure which would prevent a shock wave from forming.

What can be done to decrease the uncertainty of the model?

The main uncertainty of the model is the behavior of the magma upon entering the drift. To decrease this uncertainty, the model needs to consider heat loss due to the expansion of magma and volatiles and heat loss into the surrounding drift walls. The volatile content of the magma and void ratio would be better constrained by petrologic observations of juvenile materials in samples collected from the most recent eruptions in the area. Fluid inclusions will help determine the volatile content of the magma at depths

< 1 km. The present model considers conservative values and should consider more realistic values and scenarios.

Another uncertainty is the behavior of the shock wave on the contents of the drift. Numerical models or wind tunnel testing could aid in this area using the constraints of air speeds and pressures from the Bokhove and Woods model (2001) with realistic magma flow pressures.

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