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September 5, 2001

Memorandum

To: John Stuckless, USGS, Yucca Mountain Project

From: Roger P. Denlinger, Geophysicist, GD, Cascades Volcano Observatory

Subject: Review of two papers describing possible disruption of a nuclear waste repository at Yucca Mountain by shock waves or pyroclastic debris from a dike intrusion into the repository.

John:

At your request, I have read the following two papers that describe possible disruption of a nuclear waste repository at Yucca Mountain by shock waves and pyroclastic debris during intrusion of a basaltic dike into the repository.

Bokhove, Onno, and Andrew W. Woods, 2001, Explosive magma-air interactions by volatile-rich basaltic melts in a dike-drift geometry.

Woods, Andrew W., Sparks, Steve, Bokhove, Onno, LeJeune, Anne-Marie, Connor, Charles E., Hill, Brittain E., 2001, Modeling magma-drift interactions at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada USA.

Upon reviewing the assumptions and the numerical methodology, I find that the fluid calculations are reasonable, but that the assumptions giving the initial conditions for these calculations are not. In particular, there is no way that fluid pressures of 10 or 20 MPa may be sustained at 200 m depth in a crust with an internal friction angle of 30 to 40 degrees, or equivalently, a limit on the ratio of deviatoric to normal stresses of about 0.6. Frictional faulting of the crust would occur to reduce the fluid pressures, so that the fluid pressure entering the drift would be on the order of 2 MPa. A value of 2 MPa limits the velocities in the analysis to be on the order of 20 m/sec in this 1d linearized analysis, and these speeds do not produce a shock unless the fluid is extremely dense relative to air. Hydrofracture studies (Stock et al., 1985) at Yucca Mountain show that rapid breakdown occurs at pressures of 5 MPa, with sustainable pressures of 3 MPa at depths of 1026 m, five times the confining pressure and depth here. These measurements are consistent with the frictional strength of the crust, and it is this finite strength that makes the initial conditions they postulate improbable.

Stock, J.M., J.H. Healy, S.H. Hickman, and M.D. Zoback, Hydraulic fracturing stress measurements at Yucca Mountain, Nevada, and relationship to the regional stress field, *Journal of Geophysical Research, 90* (B10), 8691-8706, 1985.

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Memorandum

To: John Stuckless, USGS, Yucca Mountain Project

From: Larry G. Mastin, Hydrologist, WRD, Cascades Volcano Observatory

Subject: Review of two papers describing possible disruption of a nuclear waste repository at Yucca Mountain by shock waves or pyroclastic debris from a dike intrusion into the repository.

John:

At your request, I have read the following two papers that describe possible disruption of a nuclear waste repository at Yucca Mountain by shock waves and pyroclastic debris during intrusion of a basaltic dike into the repository.

Bokhove, Onno, and Andrew W. Woods, 2001, Explosive magma-air interactions by volatile-rich basaltic melts in a dike-drift geometry.

Woods, Andrew W., Sparks, Steve, Bokhove, Onno, LeJeune, Anne-Marie, Connor, Charles E., Hill, Brittain E., 2001, Modeling magma-drift interactions at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada USA.

I have reviewed the assumptions and the numerical methodology. The pressures and velocities of shock waves and eruptive debris, presented in these papers seem reasonable given the assumptions used in the models. However neither paper devotes much discussion to the underlying premise, that the onset of a basaltic fissure eruption into a repository will be so impulsive as to generate shock waves. Are there any examples of basaltic fissure eruptions initiating with shock waves?

Shock waves have been described in only a small fraction of all volcanic eruptions, primarily at stratovolcanoes during Vulcanian explosions, as described at Vulcano in 1888-1890 (Mercalli and Sylvestri, 1891); Ngauruhoe in 1975 (Nairn and Self, 1978); Sakurajima during recent decades (Morrissey and Chouet, 1997), and Galeras in the early 1990s (Stix et al., 1997). Such explosions occur at the central vents of stratovolcanoes where gas from a shallow reservoir is funneled through a single conduit, and where gas escape is periodically blocked by solidification of magma (Mercalli and Sylvestri, 1891; Self et al., 1980; Stix et. al., 1997). Shock waves have also been felt or heard at distances of hundreds or thousands of kilometers from massive eruptions such as the lateral blast at Mount St. Helens in 1980 (Lipman and Christiansen, 1981; Kieffer, 1981); and the caldera-forming phases of Krakatau in 1883 (Simkin and Fiske, 1983); and Tambora in 1815 (Stewart, 1820). Some shock waves were recorded during explosions during 1975-76 alkali basalt fissure eruption Tolbachik (Firstov et al., 1983). However I am not aware of any shock waves that have been described during the opening phase of a basaltic fissure eruption; explosive bursts during basaltic eruptions have taken place primarily after the vent was established; this was the case, for example, at Tolbachik (Doubik and Hill, 1999), Haemaey, Etna, and Stromboli (Chouet et al., 1974).

In order to produce volcanic explosions that generate strong shock waves, the host rock containing the magma gas must be strong, brittle (to allow impulsive release), and impermeable. Plugs of solidified magma within well-established eruptive vents seem to fit these requirements; it is not clear that the pyroclastic flow deposits and breccias that compose Yucca Mountain would be sufficiently impermeable, strong, and brittle to produce such explosions, especially with an intruding dike that tends to generate dike-parallel fractures ahead of it as it rises (Delaney et al., 1986).

Volcanic explosions generally expel blocks of both non-juvenile and juvenile origin and highly fragmented juvenile debris of fine average grain size (due to the extensive comminution by internal gas pressure). Do any basaltic deposits in the Yucca Mountain area display such features at the base of their eruptive deposits?

In short, I think that the arguments made in these two papers would be greatly strengthened if the authors (1) could show cases where the impulsive onset to a basaltic fissure eruption has taken place in the manner that they envision, and (2) cite evidence in the deposits of basalts in the Yucca Mountain area for impulsive onsets to such eruptions. Once this is done, the modeling will appear more justified.

Below, I have a few more specific comments regarding the points in these papers:

1) On p. 2 of Woods et al., they assume that magma in the dike will have a pressure of about 10 MPa at 200-300 m depth when it encounters the repository drifts. I estimate it would be perhaps a fourth to half of that. The magma pressure within a rising dike should be somewhat greater than the least compressive horizontal stress magnitude (S_h). Extensive hydraulic fracturing stress measurements at Yucca Mountain (e.g. Stock et al., 1985) suggest that, at a depth of 200-300 m, S_h is probably less than half that of the vertical stress (S_v), which has a gradient of about 20 MPa/km in the uppermost kilometer (Stock et al., 1985). Thus at ~250

m depth, one would expect the magma pressure to be a little greater than S_h=~(1/2)S_v=~2.5 MPa. The excess, or driving pressure required to open and propagate the dike would be on the order of one to a few megapascals (Pollard, 1987), bringing the total pressure to a few to several MPa. The lower pressure should produce shock waves in their model that are somewhat less energetic.

2) On p. 4, Woods et al. assume the magma to be driven upwards by the density difference ρ_h-ρ_m, where ρ_h is the host rock density, which they assume to range from 2400 kg/m3 at the surface to 2940 kg/m3 at the base of the crust, and ρ_m is the magma density, assumed to be about 2600 kg/m3. Extensive density tabulations for Yucca Mountain (Healy et al., 1984; Stock et al., 1984) show that the density in the uppermost few kilometers is closer to 2000 kg/m3 than to their value of 2400. But regardless of this fact, the upward drive of an intruding dike should not be controlled by density contrasts between magma and host rock, but rather by the difference $\rho_m\, g$-dS_h/dz, where dS_h/dz is the gradient in S_h with increasing depth. (e.g. Rubin and Pollard, 1987). In the uppermost few kilometers, the gradient dS_h/dz (from Stock et al., 1985, Fig. 12) is about 20-23 MPa/km, which is substantially less than the vertical gradient pressure gradient (~26 MPa/km) within an unvesiculated magma column. If this is correct, the upward driving force should be *negative*, making one wonder how a dike would manage to propagate to the surface at all in this area.

Incidentally, in comparing the magma density with the average density in the crust, Woods et al. implicitly assume that the dike would extend then entire length from the Earth's surface to the base of the crust. This seems rather unlikely; for reasons of fracture mechanics (e.g. Rubin and Pollard, 1987), most dikes would be expected to be about as high as they are long (in plan view). A dike that has a mapped extent of a few kilometers, for example, would be expected to extend only a few kilometers vertically. This constraint means that the factor that controls upward propagation of a dike would be the difference be $\rho_m\, g$-dS_h/dz, where dSh/dz is the local gradient in least-compressive horizontal stress at a particular depth, rather than an average through the crust.

3) Figure 5a of Woods et al. shows various pressure profiles within the dike-drift system for steady-state eruptions under three different scenarios. It should be pointed out that this result is calculated by assuming a particular conduit geometry and calculating the pressure profile within such a conduit. An alternative way of setting up the model is to specify a pressure profile and to numerically determine the conduit geometry that produces such a profile (see Mastin and Ghiorso, 2000, for details). For flow through a dike, the second scenario would seem more appropriate given the likelihood that internal pressure would be constrained by the magnitude of S_h, plus a driving stress of ~1-4 MPa (Pollard, 1987), whose exact value is related to the shear modulus and fracture toughness of the host rock. On this basis, I would suggest that the pressure profiles given in this figure are not especially meaningful.

4) Neither Woods et al., nor Bokhove and Woods indicate how their calculated pressures and velocities translate into destructive potential to containers. Although the shock waves have high velocities, it seems to me that the greatest destructive potential may lie in the clouds of pyroclastic debris that follow them.

The lateral force on objects within the drift due to shock waves or pyroclastic clouds should proportional to lateral momentum density, ρv, where ρ is the density of the air or gas-ash mixture, and v is its velocity. A pyroclastic cloud with a density of 12 kg/m3 (ten times that of air), traveling at 35 m/s, has the same momentum density as a shock wave of air (ρ=1.2 kg/m3) traveling at 350 m/s.

I hope these comments are useful.

Sincerely,

Larry Mastin

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