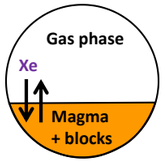
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CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Magmas in nuclear cavities and their potential effects on the source term and its migration

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1. Rationale



Underground nuclear explosions lead to the formation of cavities filled with a complex medium made from **melt** surrounding **blocks** falling from the rubble zone above.

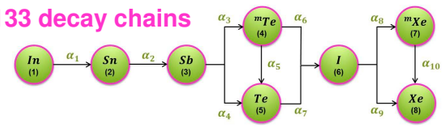
Along the 3 decay chains leading to the **4 xenon isotopes** of interest for the detection and discrimination of underground nuclear explosions, radionuclides can be trapped in the magma.

The transport of the fission products through a complex matrix made of blocks of rocks surrounded in part by some bubble-bearing melt needs to be evaluated in order to determine whether it is likely to diminish the activity or modify the xenon isotope ratios of the source term and the fraction of it that is eventually released to the atmosphere.

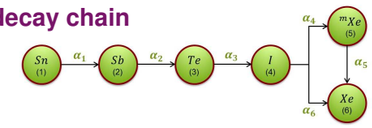


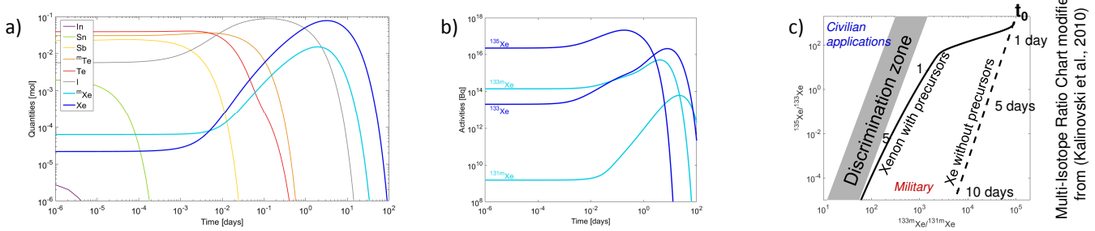
2. Xenon cavity source-term calculations classically do not account for magma

131-133 decay chains



135 decay chain

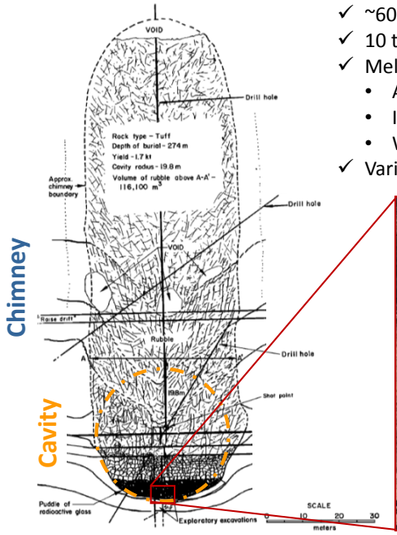




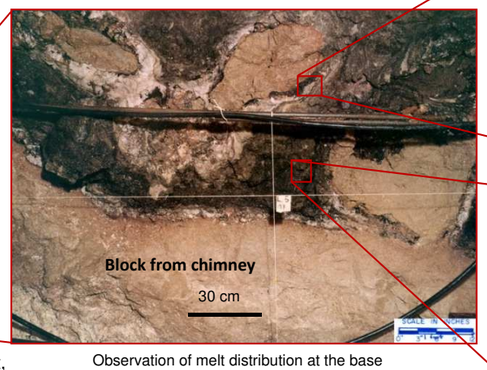
✓ Xe isotope production as a function of time: total inventory in moles (a), in Becquerel (b) and associated isotope ratios (c).

3. Melt is present under various forms in nuclear cavities

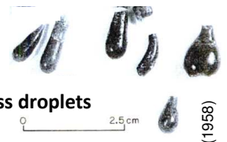
- ✓ ~600,000 kg of melt produced per kt of nuclear energy.
- ✓ 10 to 50 vol.% of former cavity contains melt.
- ✓ Melt observed in various locations:
  - Accumulated in puddle,
  - Injected into fractures,
  - Within partially melted blocks or walls.
- ✓ Various types of melt: massive lava, pumice.

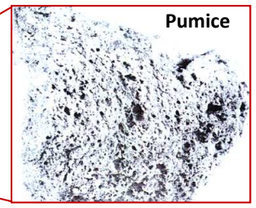


Post-detonation vertical section (Rainier event, 1957), modified from Boardman et al. (1964).

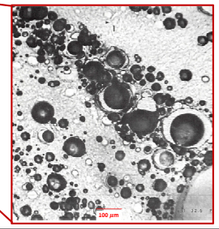


Observation of melt distribution at the base of the cavity made by the Rainier event (picture as given in Kersting & Smith, 2006)





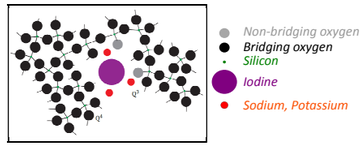
Kennedy & Higgins(1958)



Piwinskii et al. (1983)

4. Radionuclides from the cavity source-term interact with magma to a great extent

- ✓ ~ 10 % of magma directly condensed from the gas phase in the nuclear cavity: radionuclides likely to co-precipitate.
- ✓ Magma droplets dripping from cavity roof may potentially scavenge the radionuclide source-term, especially the compatible and refractory ones.
- ✓ Vesicular lava (pumice) and bubble-bearing glass are likely hosts for volatile radionuclides.
- ✓ Iodine, the precursor of xenon, has a high solubility in magma, of the order of 0.1 to 1 wt.% depending on the magma composition (Cicconi et al., 2019a, b), while iodine contributed from nuclear explosions is at most ~1 ppb.

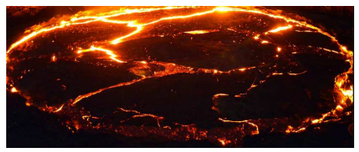


- ✓ Iodine is well incorporated in melts due to monocations (modified from Grousset, 2016).

5. What are the processes likely to control the release of radionuclides out of the magma?

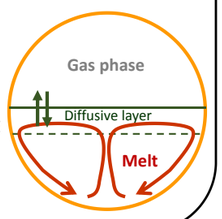
- ✓ Thermal convection of the magma associated with chemical diffusion of radionuclides toward the gas phase?
- ✓ Bubble transport across magma carrying radionuclides to the gas phase?
- ✓ Roof collapse? Blocks of rocks surrounded by magma are an additional source of volatiles (H_2O, CO_2) that may create porosity and provide a carrier gas for radionuclides to escape.

6. Convection coupled with chemical diffusion too weak to bring radionuclides back to the gas phase



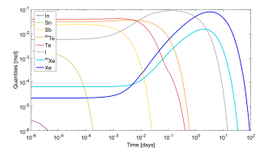
Erta Ale lava lake

- ✓ Assuming heat flow and melt properties analogous to volcanic lava lakes,
- ✓ Calculating the Rayleigh number (Carrigan, 1987) shows that **thermally-driven** flow coupled with **chemical diffusion** is not effective for transporting even xenon across the melt zone to the overlying vapor phase.

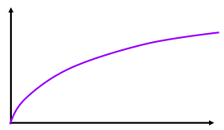


7. Xenon cavity source-term may be controlled by transport through complex media made of melt, vesicles and blocks

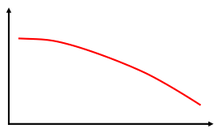
- ✓ **Radionuclide production** in melt



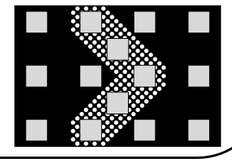
- ✓ **Radionuclide diffusion** toward vesicular pathways



- ✓ **Temperature evolution** of the melt with time



- ➢ Gas transport model in idealized **rubble + melt +** vesicles



8. Conclusion

- ✓ Melt in nuclear cavity likely to control part of radionuclide inventory released to the atmosphere.
- ✓ Transport by diffusion and advection through complex media made of melt, vesicles and rock blocks must be taking into account.



- ✓ Experiments in progress indicate devolatilization of some minerals in rocks falling into melt zone feeds bubbles which define a pathway to the overlying vapor.

References: Boardman, C.R., Rabb, D.D., McArthur, R.D., 1964. Responses of four rock mediums to contained nuclear explosions. Journal of Geophysical Research 69(16): 3457-3469. Carrigan, C.R., 1987. The magmatic Rayleigh number and time dependent convection in cooling lava lakes. Geophysical Research Letters, 14(9): 915-918. Cicconi, M.R., Pili, E., Grousset, L., Florian, P., Bouillard, J. C., Vantelon, D., Neuville, D. R., 2019. Iodine solubility and speciation in glasses. Scientific Reports, 9(1): 7758. Cicconi, M.R., Pili, E., Grousset, L., Neuville, D.R., 2019. The Influence of Glass Composition on Iodine Solubility. MRS Advances, 4(17-18): 971-979. Grousset, L., 2016. Incorporation of iodine into melt silicates (in French). Ph. D. Thesis, Institut de Physique du Globe, Paris, 218 pp. Kalinowski, M.B. et al., 2010. Discrimination of Nuclear Explosions against Civilian Sources Based on Atmospheric Xenon Isotopic Activity Ratios. Pure and Applied Geophysics, 167(4-5): 517-539. Kennedy, G.C., Higgins, G.H., 1958. Temperatures and pressures associated with the cavity produced by the Rainier event, University of California, Radiation Laboratory. Kersting, A.B., Smith, D.K., 2006. Observation of Nuclear Explosive Melt Glass Textures and Surface Areas, Lawrence Livermore National Laboratory. Piwinskii, A., Ryerson, F., Beiriger, W., 1983. A chemical investigation of glass produced by underground nuclear explosions. In: Olsen, C.W. (Editor), Second symposium on containment of nuclear explosions. Lawrence Livermore National Laboratory, pp. 323-367.

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