EXPERIMENTS ON EXPLOSIVE BASIC AND ULTRABASIC, ULTRAMAFIC, AND CARBONATITIC VOLCANISM.

Lorenz[1], V.; Zimanowski[1], B. and Fröhlich[2], G.

(1) Institut für Geologie, Universität Würzburg, Pleicherwall 1, D-8700 Würzburg, FRG; (2) IKE, Universität Stuttgart, Pfaffenwaldring 31, D-7000 Stuttgart 81, FRG.

Until recently, explosive volcanism of basic, ultrabasic, ultramafic, and carbonatitic magmas leading to the formation of maars and diatremes has been considered to be the result of near-surface depressurization of the respective magmas and the consequent intensive unmixing of large amounts of volatile phases. During the last twenty years, the study of active and fossil rhyolitic to basaltic volcanoes has shown, however, that phreatomagmatic explosions, i.e. thermal explosions, are much more widespread than previously thought and are the result of a near-surface interaction of rising magma and surface water or groundwater. As the Earth has a hydrosphere consisting of widespread surface water bodies (sea, lakes, rivers) and groundwater (pore or joint water) magma rising to theEarth's surface, with a high probability, has to rise not only through parts of the lithosphere but also into or through the hydrosphere. Thus, there is a high probability that contact with the hydrosphere may result in phreatomagmatic explosions. From the study of maars and diatremes it has also been shown, that every magma type reaching the Earth's surface may get involved in phreatomagmatic explosions if the hydrologic environment is suitable. As long as magma rises to near-surface levels (no matter what its chemistry) and contacts groundwater or surface water in suitable quantities, phreatomagmatic explosions will follow each other rapidly and the respective maar-diatreme volcano will grow in size, i.e. in diameter ,depth, and thickness of its tephra-ring.

Many aspects of the tephra deposits and the features of maars and diatremes indicative of a phreatomagmatic origin have been discussed already. Very important aspects are the scarcity or lack of vesicles in the juvenile pyroclasts, the blocky to spherical shapes of these clasts, and their grainsize variation from fine ash to lapilli size. Another important aspect is the large proportion of country rock clasts in the tephra reaching 80 - 90 % and indicating explosive fragmentation in the root zone of the respective diatreme, i.e. in the transition zone between a 1 - 2 m thick feeder-dike and the conical-shaped diatreme.

Maars and diatremes of basic, ultrabasic, ultramafic, and carbonatitic magmas in most aspects do not differ very much between each other neither do they differ in respect to maars and diatremes associated with more silica-rich magmas. Type of alteration and type of country rock clasts including deep seated xenoliths are variables, depending on the particular chemistry and depth of origin of the magma involved and on the particular country rocks surrounding the diatreme. In addition the amount of water involved in the individual explosions is dependant on the local hydrogeological situation.

One particular aspect where there is a difference between most acid to basic magmas and ultrabasic, ultramafic, and carbonatitic magmas concerns the shape of ash grains and lapilli. Only the latter magma types contain a significant amount of spherical ash grains and spherical lapilli indicative of low viscosity and consequent influence of surface tension. Sofar very little is known about the actual physical processes leading to and causing phreatomagmatic explosions.
Unknown are:

Relative and absolute quantities of magma and water which interact explosively, or participate "passively" in the explosions.

Maximum pressures reached during the explosive process.

Energy balances of the thermal explosion process.

Fragmentation processes of the magma prior, during and after the explosion.
Fragmentation processes in the surrounding country rocks.

Thermal explosions (including the natural phreatomagmatic explosions) can evolve If a sufficiently hot melt and water mix mechanically and form an igniteable mixture (i.e. coarse fragmentation). The temperature contrast between the hot and the cool liquid results in formation of insulating vapour films ("Leidenfrost effect"). Pressure pulses or other hydrodynamic events in the system can destabilize these vapour films. The consequent collapse of the vapour films (resulting in a so-called direct contact) in combination with an extremely fast enlargement of the heat transfering surface of the melt (i.e. fine fragmentation) results in fast heat transfer from the melt to the water. The water consequently gets superheated and transformed into steam. As the heat transfer happens much faster (about one magnitude) than the vapourization, the water vapourizes "coherently" (i.e. nearly completely and homogeneously), thus resulting in an explosive expansion of highly pressurized steam to ambient pressure.

Numerous experiments were carried out on metal melts and some on thermite melts interacting with water (e.g. Fröhlich, 1987; Wohletz & McQueen, 1984) with only the latter undertaken in respect to phreatomagmatic volcanism. In 1987 an experimental set-up for studies of explosive interaction between water and basic, ultrabasic, ultramafic, carbonate, and carbonatitic melts was constructed by an interdisciplinary research group at the IKE laboratories in Stuttgart. Aim of the project was **not** to build a "mini volcano" but to produce igniteable mixtures of water and hot melt on a small scale in order to investigate basic physical aspects.

The experimental set-up was called TEE-HAUS (**T**hermal **E**xplosion **E**xperiment House). In this TEE-Haus thermal explosions are generated by the injection of several ml (0.5 to 10 ml) of water into 150 ml of melt. Inductive heating of a crucible (steel or metal ceramics: 5 cm internal diameter, 7.5 cm in depth) to temperatures between 740 - 1800°C is used to melt mixtures of carbonates (Na, K, Ca carbonates) or granulates of volcanic rocks of basic, ultrabasic, or ultramafic composition. Explosions are either triggered by the injection pressure of the water (in case of carbonate melts) or by the impact of a metal object of 0.5 g mass and approx. 8 J kinetic energy (in case of silicate melts). Measurements of explosion intensity, ejection velocity, water mass and water injection velocity, control of melt composition and temperature, adjustment of injection geometry and strength of trigger pulse, video and high speed film documentation of the explosions were performed. The fragments derived from the silicate or carbonate melt of each run were collected and analyzed for their grain size distribution and shape.

In excess of 500 experiments were performed between 1988 and 1991 on carbonate (50/50 % Na_2CO_3/K_2CO_3) and carbonatite (a simplified artificial Lengaite) melts as well as on Tertiary olivine melilitite (ultramafic) from the Swabian Alb, Tertiary olivine tholeiite (basic) from the Vogelsberg, Quaternary nephelinite and basanite (ultrabasic) from the West Eifel and Permian basaltic andesite from Palatinate (all samples from areas within Germany). During these experiments thermal explosions were observed with all the melts used. The explosions generated inside the crucible exerted repulsion forces to the crucible between several 1000 and 23 000 N. These ranges were found in the carbonate experiments where no external trigger was applied, as well as in the silicate experiments where an external trigger force of approx. 400 N (vertical force component) was applied. One of the most important results of the experimental work is the determination of the magnitude of the trigger pulse for the ignition of phreatomagmatic explosions. Pressure waves of that intensity (8 J) certainly are abundant at active volcanic sites, caused e.g. by volcanic tremor, pressure pulses of the rising magma, or other seismic events. The ejection velocity was found to be in a range between 200 and 400 m s^{-1}. Explosion energy values up to 500 J were calculated. The maximum explosion pressure was calculated in the range between 10 and 100 MPa.

In case of experiments with vesicular melts irrespective of their chemical composition, the presence of many non-condensible gas bubbles obviously hinders or even prevents the ignition of a thermal explosion (Zimanowski et al., 1991). A probable explanation for this phenonemon is the damping of the trigger pulse (shock wave) due to the compressability of the gas bubbles: If the volume ratio of gas bubbles to liquid phase exceeds a yet unknown limit the trigger pulse is damped below the minimum level for destabilizing the vapour films.

Mass ratios of the respective amounts of water and melt which interacted thermally (so-called interactive masses) were determined between 1 : 10 and 1: 30. Thus, only a small part of the 150 ml of melt interacted thermally with injected water causing the explosion whereas the larger part of the melt was ejected passively from the crucible.Different fragmentation processes result in specific grain size and grain shape populations that can be distinguished from each other. Particles resulting from the fine fragmentation process that precedes and causes the thermal explosion are characterized by angular to subrounded shapes and grain sizes ranging from 20 µm to 180 µm. Due to the mechanism of formation the interactive fragments are characterized by an extremely high cooling rate, therefore, the resulting particles consist of highly unordered glass and have an extremely large surface area. In natural pyroclastic deposits such particles probably will loose their characteristics in short time because of alteration. The majority of the experimentally produced fragments, i.e. the fragments ejected passively, form during the expansion of the generated steam by stimulated Taylor instability wave growth, stripped-off Helmholtz instability waves and free air fragmentation. As the cooling rate of these fragments is distinctly lower than that of the "interactive" fragments, they are still liquid once they formed and, therefore, the shape is characterized by the effects of viscosity and surface tension in respect to the chemical composition of the melt. In natural ultrabasic, ultramafic, and carbonatitic phreatomagmatic volcanism a large proportion of the ash grains and lapilli as well as the bombs show a spherical shape, often display internal layering (lapilli, bombs), contain xenocrysts or xenoliths derived from country rocks (surrounding the diatreme), or contain juvenile clasts which formed penecontemperaneously. Those accretionary features as well as frequent concentrically oriented flow textures demonstrate the liquid state of these fragments after their formation. The results of the experiments suggest, that the pyroclasts described above are related to phreatomagmatic explosions but are not diagnostic to the process of explosive interaction of magma and water itself.

The experimentally produced explosive mixture (igniteable mixture) represents a small geometric element that most probably also occurs during phreatomagmatic events in nature. The behaviour of large scale explosive mixtures of water and magma can be modelled by combination of many small elements, but may require additional scaling factors (e.g. geometric damping or thermal detonation mechanisms). The determined magnitude of energy and pressure pulses in the experiments, however, demonstrates that the mechanism of thermal explosion is suitable to explain large scale fragmentation in diatreme root zones and thus formation of maars and diatremes.

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