A SIMPLE AND FAST ANALOGUE EXPERIMENT DEVICE TO STUDY MAGMA - CRUST INTERACTIONS ON TERRESTRIAL PLANETS

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Abstract: Understanding the evolution and dynamics underlying caldera collapse is crucial for accurate and scientifically supported geo-hazard prediction of currently inactive calderas. Natural geological examples allow us to study the final product of a caldera collapse, but give little information about the active tectonics during the formation of the caldera. As a result, only modeling experiments are able to cast light into these black boxes. A new caldera collapse analogue experimental device for educational and research was designed at the Washington and Lee University and is presented in this paper. With this new device, we performed three experiments simulating the formation of the intraplate Kilauea Caldera structure. All three experiments are consistent in the initial formation of a central depression, followed by reverse ring-faulting and later normal faulting around the earlier structures. Results obtained from the new device were successful in reproducing the Kilauea Caldera with an analogue model composed of a dry sand as the brittle crust and a with air filled balloon as the magma chamber. The most consistent analogue model suggests a complete eruption and collapse of a 5 km deep (height) and 12 km wide magma chamber as responsible for the formation of the natural caldera. This example, where a natural caldera has been downscaled reproduced, illustrates the great potential of the new device for the study of natural collapse structures on rocky planets.

Keywords: Analogue Experimental Device, Volcanoes, Calderas, Modeling, Collapse

Abstrakt: Um Vorhersagen über mögliche Eruptionen von ruhenden Caldera-Vulkanen treffen zu können ist ein besseres Verständnis der Kollaps Dynamik von Calderas entscheidend. Leider erlaubt die Erforschung natürlicher Calderas dem Geologen ausschließlich einen Überblick über das Endprodukt einer Caldera Eruption.

Modellierungen sind aus diesem Grund wesentlich bei der Erforschung dieses Eruptionstyps. Numerische und/oder analoge Modelle sind geeignet für eine solche Untersuchung. In dieser Arbeit wird ein neues Gerät zur analogen Modelllierung der Kollaps-Dynamik von Caldera-Vulkanen vorgestellt. Die Leistungsfähigkeit des neuen Apparates wird an drei Experimenten aufgezeigt, welche versuchen die Struktur der natürlichen Kilauea Caldera (Hawaii) zu simulieren. Alle Experimente zeigen ein vergleichbares Scenario bei der Entstehung einer Caldera. Erst kommt es zu einer zentralen Absenkung welche gefolgt wird von ringförmigen Aufschiebungen, die dann wiederum eingekreist werden von größeren Abschiebungen. Das erfolgreiche Experiment W&L_RM1 deutet darauf hin, dass die heutige Kilauea Caldera durch die vollständige Eruption und den daraus resultierenden Kollaps einer 5 km tief liegenden Magmakammer mit einem Durchmesser von 12 Kilometer Größe erfolgte. Dieses erfolgreiche Experiment zeigt, dass der neue Modellierungsapparat in der Lage ist, verschiedene Calderen auf der Erde und erdähnlichen Planeten zu simulieren.

1. Introduction

Historically, geology first explored continental ore deposits, the formation of mountains, basins and eventually the deep sea far away from continents. Nearly a half century ago the desire to explore planetary processes beyond our planet was a major motivation for mankind to start visiting our Moon during the Apollo program. However, today our technology allows us to study the geology of our neighbor planets with unmanned space missions and alternative methods have developed to study our solar system planets. Landers, rovers as well as remote sensing are able to provide us with a flood of data from different extraterrestrial objects. Without numerical, theoretical and experimental models, planetary geologists are limited to qualitative descriptions of observations. The science community needs to compare data with theoretical, numerical and analogue models to shed light on the planetary processes responsible for observed, physical-chemical variations within the solar system.

This paper presents a new analogue modeling device able to simulate different physical parameters related to the emplacement of magmas within the crust of rocky planets. In addition, first results modeled for the Kilauea Caldera with this new device are presented to show the full capability of this tool. Valuable analogue models are representatively downscaled and consist of material with similar to identical rheological properties as their natural equivalent. Most available models do not focus on crust-magma interactions within different tectonic environments, but focus either on the tectonic setting or magmatic structures within a stable craton. However, because volcanism generally occurs in active tectonic regions, the presented device is able to combine successfully both modeling approaches. Despite many years of research on caldera systems on Earth, our understanding of the formation of these volcanic structures is rather limited (Lavallee *et al.*, 2004). Similar caldera

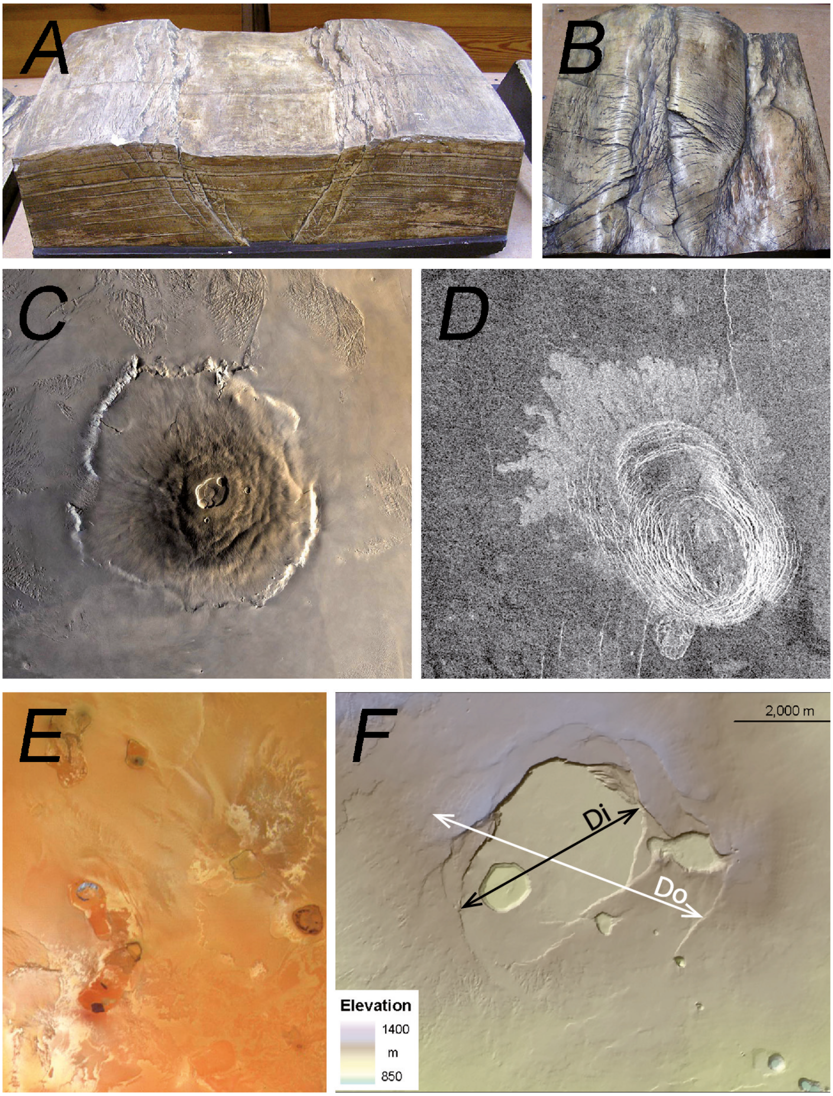

Fig. 1: *A) Extensional tectonic analogue model from* Cloos *1929 B) Variscan model Rhenish shield and the Rhine Graben from* Cloos *1929. (Both pictures are taken from the DFG-Project: "Universitätssammlungen in Deutschland", results of which are available under: http://www.universitaetssammlungen.de/dokumentation. C) The Caldera of Olympus Mons on Mars (Viking Mission, NASA). D) The Sachs Patera Caldera on Venus (Magellan Mission, NASA). E) Calderas on Jupiter satellite Io (Voyager Mission, NASA). F) Digital elevation model (DEM) of the Kilauea Caldera.*

structures have been observed on all rocky planets of our solar system (Fig. 1C-F). As a result, processes related to caldera formation might play an important role in the evolution of a planet, despite the present rare occurrence of these violent eruptions on Earth. Modeling the parameters responsible for the development of calderas has the potential to cast new light on intrinsic caldera processes active on all rocky planets. Geophysical, geochemical and petrological investigations are restricted to calderas on Earth and their results might be overprinted by geodynamics limited to the Earth (e.g. plate tectonics).

In order to model physical processes responsible for the development of these magma-crust interaction structures, we present a new analogue-modeling device designed and build at the Washington and Lee University. The analogue modeling results illustrate the great potential of this new device in planetary geology to shed light on the geodynamic history of rocky planets.

2. Calderas

Collapse calderas were defined by Williams (1941) as subcircular collapse structures formed during volcanic eruptions, whose diameter exceeds that of explosive vents and craters. Calderas and caldera complexes are also observed on most rocky planets. On Earth such calderas are known in all plate tectonic environments: Calderas are reported within extensional systems from the East Pacific Rise Mid-ocean ridge (Fornari *et al.*, 1984) and continental rifts like the East African Rift (Acocella *et al.*, 2002), as well as at convergent plate boundaries such as the well-known caldera, Crater Lake, Oregon, USA (Bacon, 1983). As a result, caldera formation is independent of plate tectonics and it might be helpful to review fundamental formation processes on planets where no plate tectonic process and/or water erosion might mask the essential caldera dynamics. Cole *et al.* (2005) pointed out that it is only in the last 25 years that geophysical, geological and analogue modeling data have provided a better understanding of the 3-dimensional structure and probable caldera collapse dynamics. The dynamics of caldera formation is based on the evacuation of large magma volumes from a magma chamber and the subsequent collapse of the now destabilized chamber roof (Fig. 2). Calderas are of economic interest as these structures have not only a high potential for electrical power generation, with geothermal energy, but also caldera ring faults are sites of ore mineralization (e.g. Lipman, 1992).

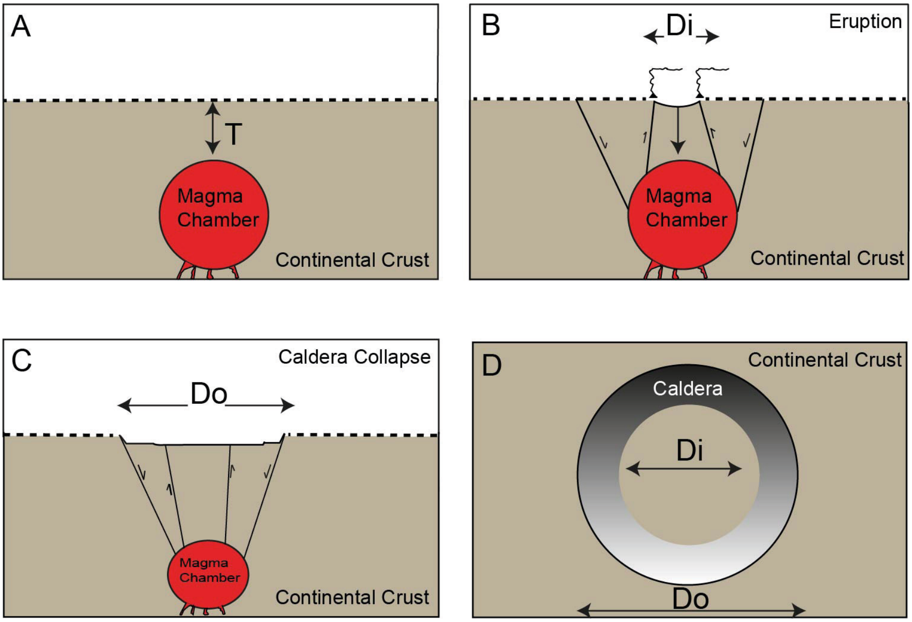

Fig. 2: *Schematic illustration of a caldera collapse. A) Initial magma chamber within the continental crust. B) Evacuation of the magma chamber and subsequent instability of the magma chamber roof. C) Cross section of a caldera after the final collapse. D) Caldera top view similar to the pictures on Fig. 1.*

3. **Analogue modeling**

Analogue modeling in Earth sciences consists of a scale simulation of a natural process (Acocella, 2008). Analogue modeling has been used for two centuries to study large scale structural evolution within compressional and/or extensional settings. While pioneering work with tectonic sandboxes was limited to a few scientists, geodynamic analogue modeling boomed after the introduction of the plate tectonic concept. One of the early "temples" of analogue modeling was in the first decades of the 19th century the University of Bonn, where Hans Cloos developed the analogous modeling of tectonic structures to an internationally admired perfectionism (cf. Fig. 1A,B). Created mostly with clayey material, the resulting model structures resembled natural forms in all details. Mostly his case studies are famous extensional (e. g. graben) or compressional (folds in parts of the variscan orogeny) structures. (*"Die Analyse der Bewegungsvorgänge im Modell gibt der .... großtektonischen Synthese ein Mittel in die Hand, zahlreiche Probleme der Gebirgsbildung einer Lösung ein Stück näher zu bringen*") (Cloos, 1929). Some of his best facsimile analogue experiment examples of European regions have been presented in his publication of 1929 (Fig. 1A, 1B).

The pioneer work of Cloos already illustrated, the advantages of analogue modeling including the possibility to study the evolution of a defined tectonic setting within 3 dimensions. Boundary conditions of experiments can be set according to the needs of the study. The major kinematic and mechanical boundary conditions of tectonic sandbox experiments consist of convergent or divergent settings where material between two plates is deformed relative to the motion of both plates. In addition to these tectonic "sandboxes," in the last 10 years various sets of analogue models have been described (Acocella, 2008; Marti *et al.*, 2008) to study caldera architecture and development due to underpressure or overpressure collapse. Simulating analogue calderas has the potential to shed light on the mechanism of collapse, define the mode of deformation and the importance of the different parameters of the system. The basic concept of these experiments includes a systematic change in the rate of each parameter, while keeping the other parameters stable. Analogue caldera collapse experiments are, in contrast to numerical models, particularly suitable to study fault developments during the deformation process. Acocella (2007) concluded that underpressure experiments reveal consistent scenarios for caldera formation, but limitations include the inability to simulate temperature gradient within the experiments.

4. Materials, scaling and the new device

In order to simulate the natural process, the sandbox experiment must be scaled geometrically, kinematically and dynamically to the full-scale situation using the principles of physical similarity (Hubbert, 1937). However, in many geological questions the appropriate scaling relationships between the involved physical and chemical variables are unknown. Painstaking scaling always involves the rheological parameters of the materials employed and the system dimensions. In analogue caldera experiments the continental crust is usually simulated by sand, flour or clay (Acocella, 2007). The length ratio is often as high as 10^{-5} to 10^{-6} implying that 1 cm in the model simulates 1 to 10 km in nature. Intrinsic constitutive properties, such as cohesion and the internal friction angle must be scaled so that the non-dimensional shear strength of the model and nature are equal. The stress ratio between analogue models and natural prototypes is approximately 5×10^{-6} ($\sigma' = \rho' g' L'$) with a length ratio of $L' \sim 10^{-5}$, a density ratio of $\rho' \sim 0.5$ and the gravity ratio $g' = 1$ in our experiments. Assuming a Mohr-Coulomb criterion the cohesion c' has the dimensions of stress, and with average continental crustal rock cohesion $c \sim 10^7$ Pa requires an analogue material with a $c \sim 50$ Pa. A suitable material to fulfill this physical precondition is dry quartz sand with a similar low cohesion ($2 < c < 40$ Pa). In addition well-sorted and rounded dry beach sand (containing small proportions of carbonate) can be added to simulate local compositional bedrock heterogeneities. Alternate materials such as clay or flour have 1 to 3 magnitude greater cohesion and are therefore less ideal analogues for continental crust. Other materials have also been reported to simulate magma within these analogue models. Marti *et al.* (1994) used air, while Kennedy *et al.* (2004) choose water and Roche *et al*. (2000) used silicone to simulate magma interacting with the continental crust. The obvious difference between these materials is their variation in viscosity. The viscosity of magma is also quite variable and is controlled by various interconnected factors as composition, temperature and crystal content. The presence of crystals, high silicate and low temperature make magma more viscous. Over time the viscosity in a magma chamber increases. In analogue models silicone is used to simulate highly viscous, evolved magmas, whereas water and air are good analogues for mafic magmas. Due to the fact that basaltic magmas on Mars and Venus are very primitive, we selected air as the most appropriate analogue for the melts to simulate extraterrestrial calderas. In addition, such a system allows simulating terrestrial mafic basaltic caldera complexes. The caldera collapse-modeling box used in this study comprises a rigid tank with two movable upper walls and can be filled to different depths with dry sand (Fig. 3A). With these movable walls, we are able to simulate magma crust interactions under compressional or extensional settings. However, for these first experiments we studied a within plate tectonic setting with no movements along the walls. A hole on the base of one of the two fixed walls enabled an inflatable chamber (an elastic balloon) to be connected via a small diameter, rigid hose to a valve and an air compressor. The balloon was inflated to a defined size (volume). This balloon was then covered with an additional layer of sand of a specific thickness (e.g. 5 cm). A spherical balloon was always used to be consistent with a traditional simple isotropic magma chamber model. Deflation of the balloon was performed at different “eruption” speeds by regulation of the valve. Edge effects were kept to a minimum by using a large tank (1 m x 0.8 m x 0.4 m) and a balloon with a maximum diameter of 25 cm. Experimental results are compared with observed data from the Kilauea Caldera to determine if the new sandbox is able to perform representative experiments. We used experiments to simulate the magma-crust interactions at the Kilauea Caldera due to its geological location atop of a huge seamount, which can be considered as an Earth analogue for volcanic systems like Olympus Mons on Mars. Analogous to Hawaii, volcanism on Mars and Venus is generally linked to postulated hot spot activity on these planets (Widdowson, 2003).

Three different experimental designs were performed with this modeling device. The experiments are pure collapse experiments without any replenishment of the magma reservoir. Experimental parameters are reported within Table 1. No extensional or compressional stresses have been applied to the system under investigation during these experiments. Experiment W&L_RM1 consisted of a ca. 12 cm diameter air chamber buried beneath a 5 cm sand layer. The balloon was evacuated within 60 seconds simulating an intensive and strong eruption. During experiment W&L_RM2 lower eruption rates were simulated, by using a somewhat larger (14 cm diameter) magma chamber, which was totally deflated within 120 seconds. The last reported experiment W&L_RM3, had the biggest magma chamber (20 cm) which was emptied to a size of 5 cm diameter within 60 seconds.

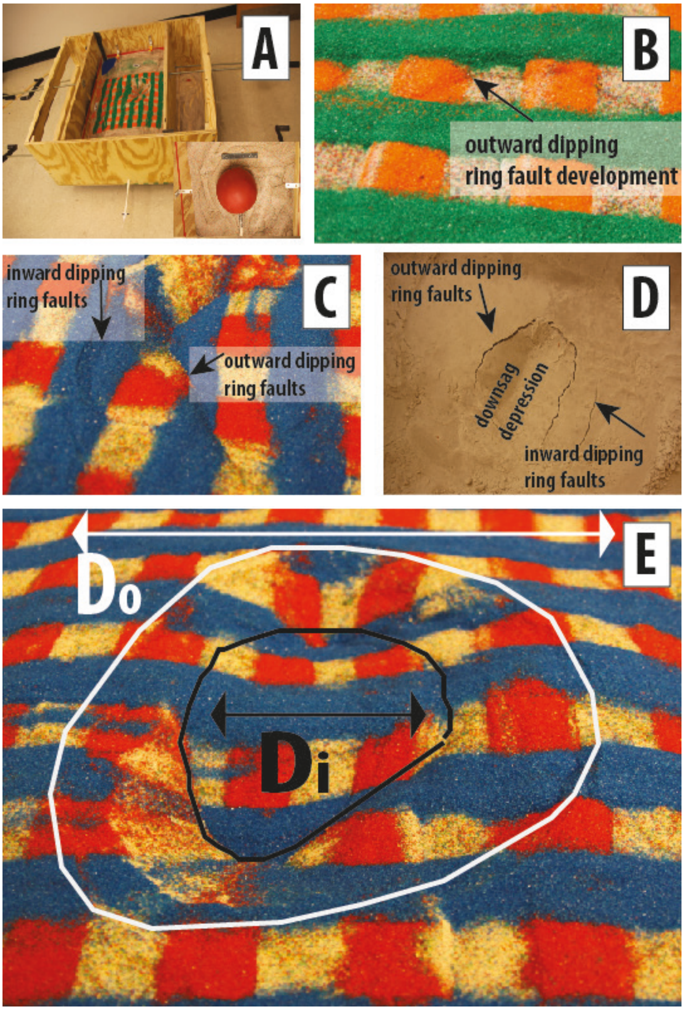

Fig. 3: *Experimental results. A) The presented new analogue modeling device showing the movable side walls, the air inlet and the air-balloon. B) In all experiments after 4 seconds of air evacuation, we are able to witness first visible fractures, which in W&L_RM3 are the outward dipping ring faults around the central depression. C) Only in a later stage do we observe the formation of inward dipping normal faults around the outward dipping ring fault system. D) Experiment W&L_RM2 after 25 seconds showing the central depression and the outward dipping ring faults and the initiation of the inward dipping ring fault system. E) Final experiment W&L_RM1 after 60 seconds showing the inner and outer depression diameter and the above in 3B to 3D described characteristic fractures.*

Experiment	T cm	t s	R	Di cm	Do cm	Di/Do	T/Di	Material "erupted"
W&L_RM1	5	60	0,43	6,5	11,5	0,57	0,77	1
W&L_RM2	5	120	0,36	6	14	0,46	0,83	1
W&L_RM3	5	60	0,36	9,5	14	0,68	0,53	3/4
Natural Caldera	km			km	km			
Kilauea	3	?	0,43	4	7	0,57	0,75	?

Table 1. *Initial experimental parameters and the measured / calculated results. Di represents the average inner depression diameter; Do the average diameter of the outer depression and T the sand layer thickness above the air filled balloon. The roof ratio R (e.g.* Roche *et al. 2000) is calculated as the ratio T/Do. The variable t represents the eruption time.*

5. Caldera collapse experiment results and observations

In contrast to far-field extensional stress produced graben structures - compare the Rheingraben structure from the Cloos experiment on figure 2B - which have all inwards to the rift axis dipping normal faults, Caldera collapse fault patterns are much more complex. The geodynamic history of all three experimentally modeled calderas started with the initial development of a depression. In all three simulations we always observed two sets of ring fault assemblies developing around the central downsag depression (Fig. 2, 3). Figures 2B, 3B and 3C show the initial outward dipping reverse ring faults and forming the inner ringfault system. Figures 2C and 3C illustrate the later emerging inward dipping ring fault system, which is surrounding the inner ringfault system.

These ring fault patterns are known and it is widely accepted, that geographic relations between those structures can be used for comparison and evaluation of different natural calderas (e.g. Acocella *et al.*, 2001). In analogy to the classical caldera collapse papers (e.g. Acocella *et al.*, 2001) we measured on our analogue models the inner depression diameter of the calderas (Di), the diameter of the outer depression (Do) and the sand layer thickness (T) above the balloon “magma” chamber (cf. Fig. 2). Acocella *et al*. (2001) further suggested that the ratios relationships Di/Do and T/Di form analogue collapse experiments are a good verification of the model. The collapse type of a caldera depends on the roof ratio R (e.g. Roche *et al.*, 2000), which can be calculated as the ratio T/Do. In general a low roof aspect ratio (<1) means a symmetric large-scale caldera, while a high roof aspect ratio represents a more funnel-like system. The measured results for these parameters of the performed three experiments are reported in Table 1.

In our experiments, the average diameter of this inner outward dipping ring fault system was measured and is reported in table 2 as Di. In contrast, the later-formed outer ring fault system (Do in table 1) dips inward. Because none of these rings were formed by a single fault in our experiments, we call them ring fault systems. The faults generally start to develop in the central part of the fault and move outwards. While this central part of the fault evolves rather linear, both ends are bending towards the circular structure of the developing caldera. The final faults are interconnected at their ends to form a circular pattern.

6. Discussion

The mechanism of caldera formation is subject of much debate (Belousov *et al.*, 2005). Most researchers believe that the principal process for the formation of calderas is a catastrophic collapse of the magma chamber roof (Lipman, 1997). However, the exact dynamics behind this process is less obvious. Our initial studies show that analogue sandbox models are a valuable tool to investigate the dynamics behind the calderas because, such experiments are fast, inexpensive and highly educative. Furthermore these analogue experiments provide first order observations on caldera mechanisms that could neither be done from a natural caldera eruption due to large dimensions and the volcanic plume over the erupting center.

A comparison of geometric parameters from the analogue calderas with data for the Kilauea Caldera illustrates their potential use as analogues. The parameters used are listed in Table 1. The comparison of these geometric measurements from the Kilauea Caldera (Acocella *et al.*, 2001) with the data (Di/Do and T/Di) from our analogue modeling experiments shows good agreement (Fig. 4). Actually the experimental setup W&L_RM1 reproduced the Kilauea Caldera values within the measurement accuracy.

The comparison of the experimental results with the natural equivalent shows, that the presented analogue modeling device is a valuable tool to study collapsed calderas on Earth and other rocky planets, and the substitution of an air balloon for silicone simplifies the experimental setup. In contrast to sophisticated setups with fluid pipes etc. the used system was due to its simplistic construction less liable to break down. Furthermore for educative purposes the new device could even be used in the field and in classroom to show students caldera evolutions.

The development of different ringfault systems has been discussed in the past. Acocella (2007) pointed out, that the amount of faults would be a consequence on the upper geometry of the deflating magma chamber. He further stated that a flat magma chamber would generally result in a single ring fault pair, while a domed magma chamber roof could generate further ring fault pair systems due to strain accumulation at points of maximum curvature (e.g. Geyer & Marti, 2014). However our models did not show significant additional ring fault pairs compared to the main pair.

The fact that our experiments do not show the from Acocella (2007) proposed expected multiple would be a great further research topic to study with this new device, as the geometry of a magma chamber during analogue experiments is after Acocella (2007), intrinsically linked to the magma analogue, e.g. air, or silicon. Therefore after his hypothesis, the development of different ring fault patterns of natural Calderas should be related to the magma viscosity. And this hypothesis could be tested with experiments with different balloon types.

As extraterrestrial calderas are much larger than the ones on Earth, we aimed for low aspect ratios within our experiments. The huge diameters (600-1000 km) of calderas on Venus have even been used to question the volcanic nature of these structures (Hamilton, 2007). Analogue modeling with a device such as the one presented in this paper would be able to test this hypothesis, after further downscaling of the experiments.

Potential improvements for the analogue-modeling device include two acrylic glass walls for the fixed walls to be able to observe ongoing deformations in an extensional or compression setting. For caldera formation studies acrylic glass walls would not be of a great help, as due to the scaling, the caldera deformation structures should not interact with the walls of the device.

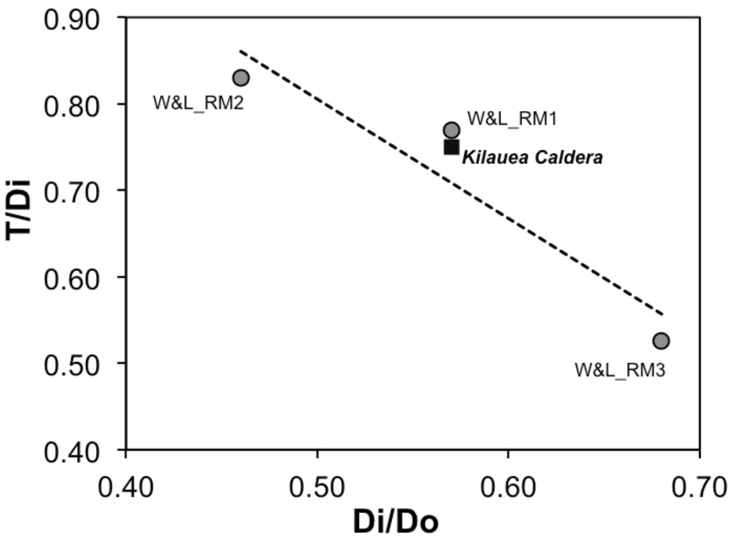

Fig. 4: *Relationships between the ratios Di/Do and T/Di with Di representing the inner depression diameter, Do the diameter of the outer depression and T the thickness above the chamber. These structural parameters from the experiments are compared with the corresponding data from the Kilauea Caldera.*

7. Conclusions

1. Similar experiments have been produced with silicone as magma analogue, however these setups are much more complicated and sophisticated. As a result, this new and easy system with an air balloon is a cheap and simple alternative.
2. It has been illustrated with a model for the Kilauea Caldera, that the presented analogue modeling device is able to perform state of the art caldera collapse simulations.
3. Caldera collapse dynamics studies with analogue models should not only be restricted to calderas on Earth as extraterrestrial Calderas processes might not be overprinted by weathering and/or plate tectonics.
4. In synthesis, our experiments illustrate that a caldera collapse is initially dominated by a downsag depression followed by outward dipping ring faults and later the development of inward dipping ring fault systems.
5. The presented analogue-modeling device is a great teaching help, where students can individually make some hands-on modeling research projects without previous experience in numerical programming.

8. Acknowledgments

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