Postdoc Fellowships for non-EU researchers

Final Report – Dr. Pablo GROSSE

Name	Pablo Grosse
Selection	October 2013
Host institution	Department of Geography, Vrije Universiteit Brussel
Supervisor	Matthieu Kervyn
Period covered by this report	from 01/03/2014 to 30/11/2014
Title	Investigating the shape evolution of Central African volcanoes via morphometric analysis and analogue experiments

1. Introduction and Objectives of the Fellowship

The research project consisted in studying volcano shape evolution using digital elevation models (DEMs) of both analogue experiments and of real volcanoes, with emphasis on the volcanoes of the Central African Virunga Volcanic Province (VVP). It was carried out in support of the BELSPO SSD project GeoRisCA (SD/RI/02A), 'Geo-Risk in Central Africa: integrating multi-hazards and vulnerability to support risk management'. The project was part of an ongoing research effort being carried out since 2009 between P. Grosse and M. Kervyn dedicated to volcano geomorphometry. It was closely aligned with the research orientation of the host unit in general, including the development of a state-of-the-art analogue modelling lab, and with the objectives of the BELSPO-financed GeoRisCA project, as well as with P. Grosse´s research objectives at his home institutions (CONICET and Fundación Miguel Lillo).

The research project aimed at investigating the processes that control volcano shape evolution, with a focus on the VVP volcanoes, through the morphometric analysis of analogue modeling experiments and comparison with natural examples. Thus, the specific objectives were to:

1. Carry out analogue modeling experiments that simulate volcano shape evolutions controlled by processes that operate in the VVP.
2. Construct synthetic DEMs of the experiments and analyze their morphometry in order to define quantitative shape evolution trends for each of the simulated processes.
3. Analyze the morphometry of the VVP volcanoes and compare with the morphometry of the analogue models.
4. Interpret the factors and processes controlling the shapes of the VVP volcanoes.

2. Methodology in a nutshell

The project consisted in three main tasks: (1) analogue experiments; (2) DEM generation of the experimental models; and (3) morphometric analysis of DEMs, both synthetic and of natural examples. The materials and methods used for each of these tasks were the following.

(1) Analogue experiments: experiments were carried out at the analogue modelling lab of the host unit. Models were physically scaled in terms of distance, mass and time. Established laboratory materials were used and their properties (density, cohesion, etc.) were measured. Granular mixtures of fine-grained sand and kaolin were used as analogues of volcanic rock. They were used to construct synthetic volcano edifices and, for some experiments, as basal layers. Volcano growth was simulated depositing loads of granular material from a point source. Synthetic volcano sizes varied between 5 and 20 cm in basal diameter, and 1 and 5 cm in height. For one set of experiments, the growth location was shifted following specific spatial probability density distributions simulating shifts or migrations in vent location with time. In a second set of experiments, a basal plate attached to a step-motor was used to simulate strike-slip displacements and concomitant deformation of an overlying volcano. During this second set of experiments, volcano growth was simulated at a fixed central location but with varying growth rates.

(2) Synthetic DEM generation: during the progression of the experiments, the analogue models were photographed at regular time intervals using four digital cameras positioned at slightly different angles over the experiment, at a distance of approximately 1.5 m. Afterwards, the photographs were used to generate synthetic DEMs of each step of the experimental models by applying the MICMAC digital stereo-photogrammetry software. Outputs were sets of DEMs with 0.2 mm spatial resolution. The raw DEMs were then post-processed (georeferencing, filtering, corrections, etc.) using the ENVI/IDL software.

(3) Morphometric analysis: the synthetic DEMs of the analogue models and DEMs of real volcanoes from the VVP were used to perform detailed morphometric analyses. For the analogue models, the synthetic DEMs generated during the project were used. For the VVP volcanoes, the public-access 90 m spatial resolution SRTM DEM and a high-resolution 5 m DEM of the VVP derived from the TanDEM-X mission and produced by the Royal Museum of Central Africa in the framework of the GeoRisCA project were used. Morphometric parameters were extracted from the DEMs by applying specifically developed IDL-language algorithms: NETVOLC (Euillades et al., 2013), used to automatically calculate the volcano basal outline, and MORVOLC (Grosse et al., 2009, 2012), used to extract a set of morphometric parameters that characterize the volcano edifice in terms of size, plan shape, profile shape and slopes. The output data was assembled in a database and analyzed systematically using MS Excel.

3. Results

3.1. Analogue models

Two sets of experiments were carried out: (1) growth of volcanoes related to shift or migration of vent location; and (2) growth of volcanoes on active strike-slip faults. A total of 120 models were performed. Each model was documented by photographs at predetermined time intervals, with the number of intervals varying between 5 and 35. For each of these intervals, a synthetic DEM was generated using the MICMAC software, giving a total of around 1800 synthetic DEMs.

3.1.1. Volcano growth and shape evolution related to vent distribution

For this set of experiments, each model volcano was grown within a 28 x 28 cm area. For each model, individual growth steps consisted in the deposition of 10 cm^3 of granular material from a point-source within a fixed 9 x 9 grid (i.e. a total of 81 possible deposition locations). The number of growth steps per model (i.e. number of depositions) varied from 27 to 81. The deposition location within the 9 x 9 grid (i.e. the volcano growth location) at each growth step was determined following different probability density distributions (Fig. 1A): fixed-location (i.e. deposition always from the same location), completely random (i.e. same probability in every location of the 9 x 9 grid), linear with equal probability (i.e. equal probability restricted to one line of the grid), linear with increasing probability towards center, radial with increasing probability towards center. For the latter two types of distributions, three different probability functions were applied to simulate different degrees of probability increase towards the center (from weaker to stronger): linear, power-law and logarithmic.

The resulting models thus simulate the growth and morphology of several types of volcanoes (Fig. 1A, B), including simple symmetrical cones, cone fields, linear ridges, twin edifices, complex massifs, etc. Analysis of the DEM-derived morphometric parameters allows to characterize the morphometry of each type of growth evolution and to quantitatively link the resulting morphologies to the number and location of vents and to the proportion of growth at each vent (Fig. 2). Ongoing comparison with the morphometry of real volcanoes will give information on the vent distribution and growth evolution of the natural examples.

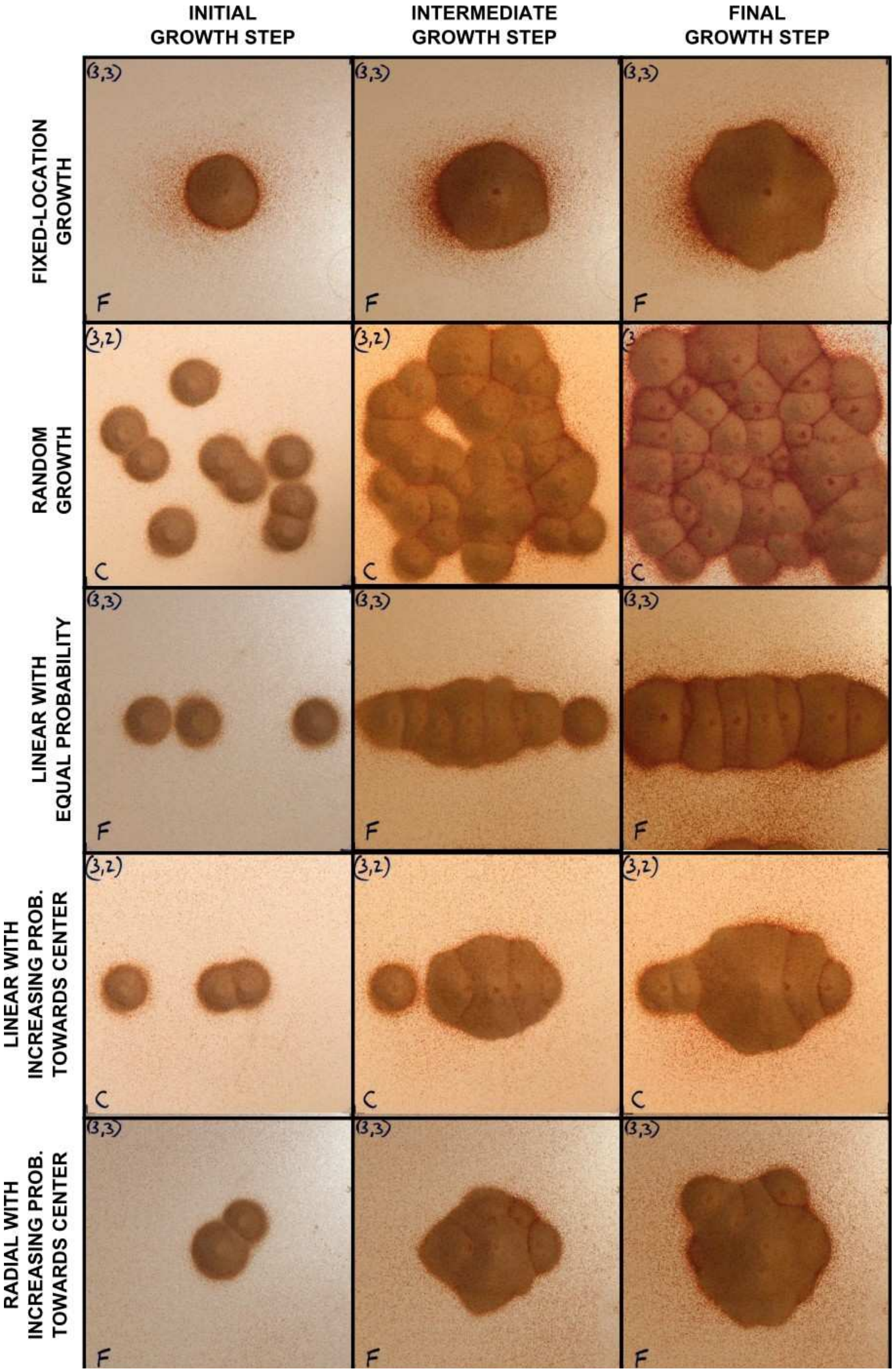

Fig. 1A: Photographs of 5 models exemplifying the different growth distributions at 3 growth steps (each photograph spans 28 cm).

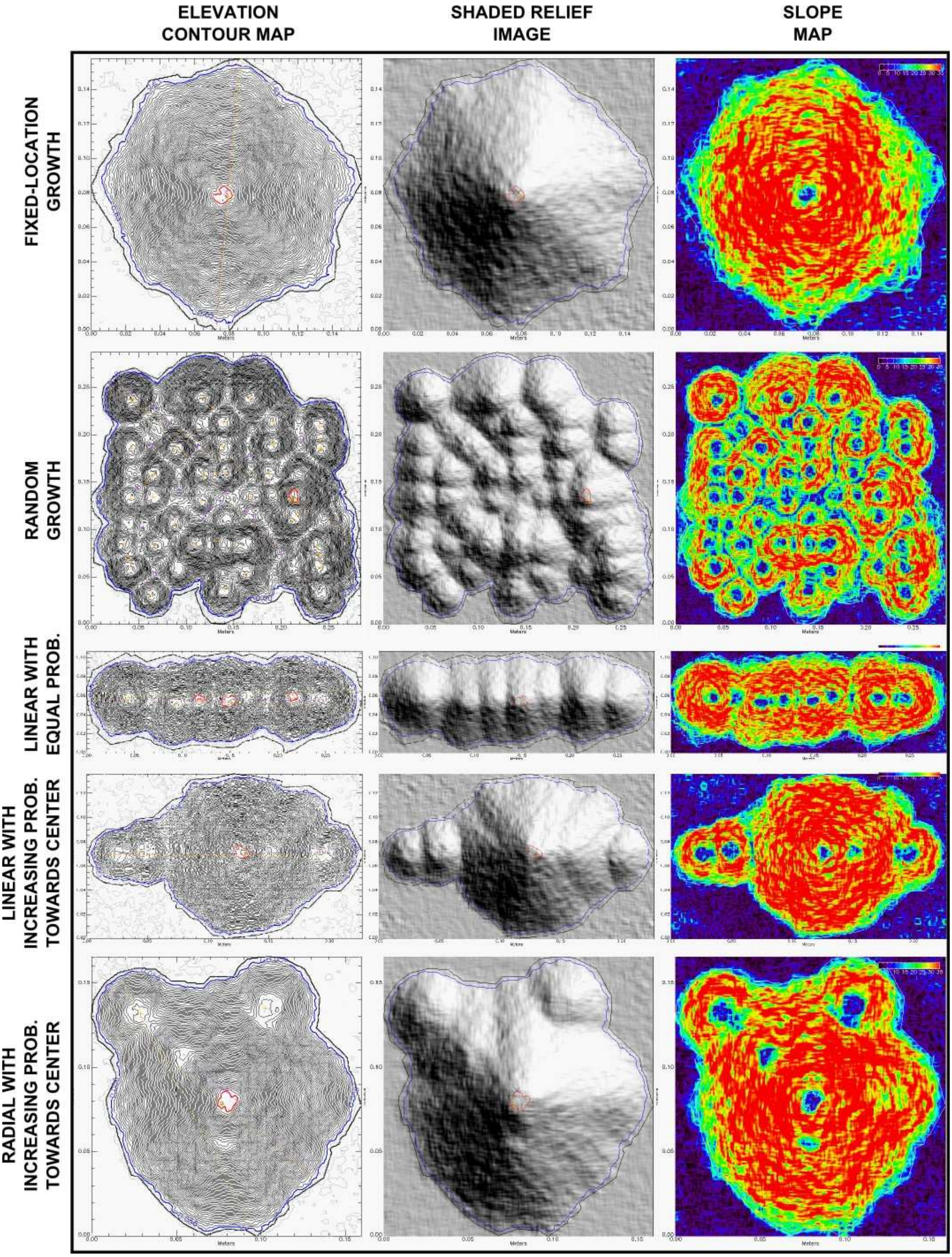

Fig. 1B: DEM-derived images of the final step of the models shown in Fig. 1A (scale varies).

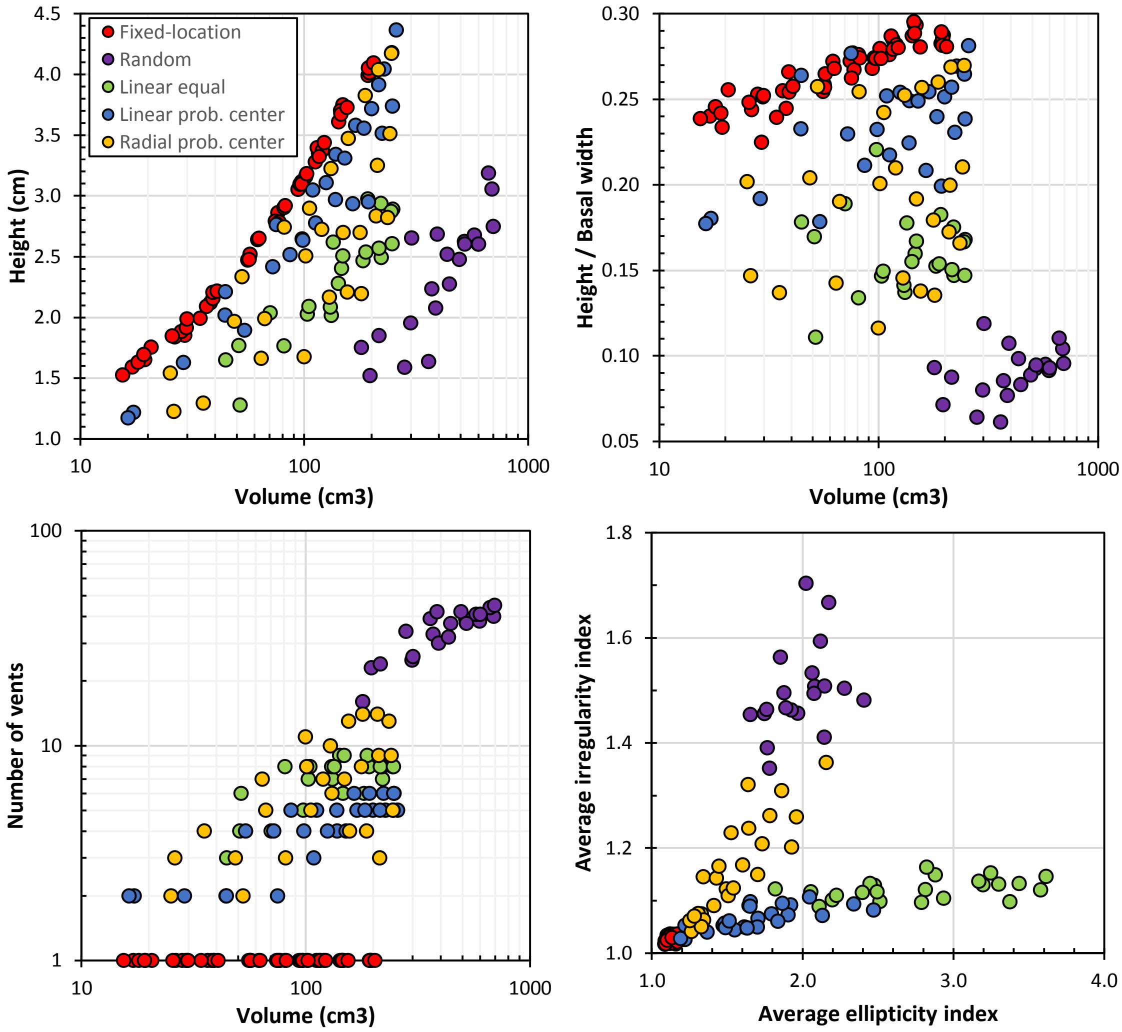

Fig. 2: X-Y plots of synthetic DEM-derived morphometric parameters for selected models with different growth distributions.

3.1.2. Volcano growth and shape evolution related to strike-slip deformation

In this set of experiments, the location of cone growth by the deposition of granular material was kept fixed on a point over the trace of the active strike-slip fault. Each experiment lasted 64 minutes. The strike-slip velocity was maintained constant at 3.9 cm/hr; thus total fault displacement for all experiments was 4.2 cm. The volumes and time intervals of granular material deposition were varied in order to simulate a wide range of growth rate-deformation rate ratios (Fig. 3) and resulting morphologies (Fig. 4). Deposited volumes varied between 1 and 512 cm^3, and time intervals between depositions were either 8, 16, 32 or 64 minutes (i.e. depositions were performed 1, 2, 4 or 8 times during the course of the 64 minute experiment). Total deposited volumes (i.e. final volcano volume) varied between 8 and 512 cm^3, giving deposition rates (i.e. volcano growth rates) between 7.5 and 480 cm^3/hr. For comparison, two endmember-type models were also run: progressive growth without deformation (i.e. no displacement along the fault), and initial growth followed only by deformation (i.e. no further growth during displacement along the fault).

In nature, the displacement velocity of active strike-slip faults can vary from around 1 mm/yr to up to 50 mm/yr. Composite arc volcanoes have life-spans between 0.1 to 1.3 Ma and overall growth rates in the order of 0.01 to 1 km^3/ky, commonly consisting of short growth spurts with rate roughly one order of magnitude greater (i.e. 0.1 to 10 km^3/ky) spaced between periods of relative quiescence.

Considering a model/nature length ratio of 1 cm = 0.8 km, and assuming that the experiment spans an average lifetime of a volcano, that is, that the 64 minutes of the experiment is equivalent to circa 0.5 Ma (i.e. a model/nature time ratio of 1 hr = 0.47 Ma), the total model fault displacement of 4.2 cm, equivalent to 3.3 km in nature, corresponds to a strike-slip velocity of 6.7 mm/yr, within the range of observed velocities in nature. Furthermore, the model/nature length ratio of 1 cm = 0.8 km equates to a volume ratio of 1 cm^3 = 0.512 km^3. Thus, the final model volumes of 8 to 512 cm^3 are equivalent to 4 to 260 km^3, well within the range of composite volcano volumes, and, considering the model/nature time ratio of 1 hr = 0.47 Ma, the overall model growth rates between 7.5 and 480 cm^3/hr are equivalent to natural growth rates of 0.008 to 0.52 km^3/ky.

The resulting models show a wide spectrum of morphologies (Fig. 4) spanning between the two endmember-types of pure growth and pure deformation. Deformation of the cone caused by the strike-slip fault is reflected in two main features: elongation of the whole edifice at a small angle to the trace of the fault, and formation of a graben structure in the summit region (Fig. 4). These two features are progressively less visible as the growth rate increases (i.e. as the number of growth steps increases) (Fig. 4). Ongoing analysis of the synthetic DEMs allows to characterize the morphometric evolution of the modelled volcanoes for different growth rate-deformation rate ratios, and in particular to establish the threshold where deformation becomes visible in the morphometry of the volcano. Furthermore, comparison of the results with the morphometry of real volcanoes that have known underlying strike-slip faults should give insights into the dynamics of growth and deformation at these volcanoes.

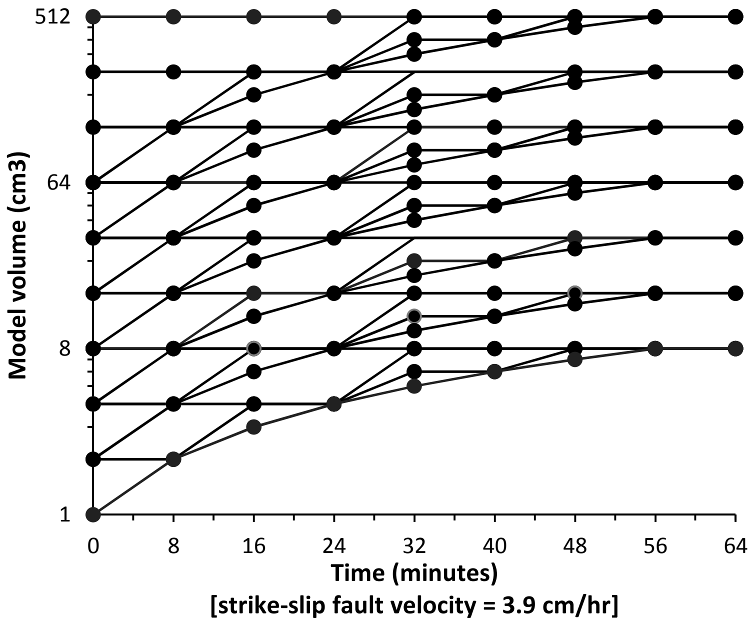

Fig. 3: X-Y plot illustrating the growth paths (in terms of volume) with time for all models.

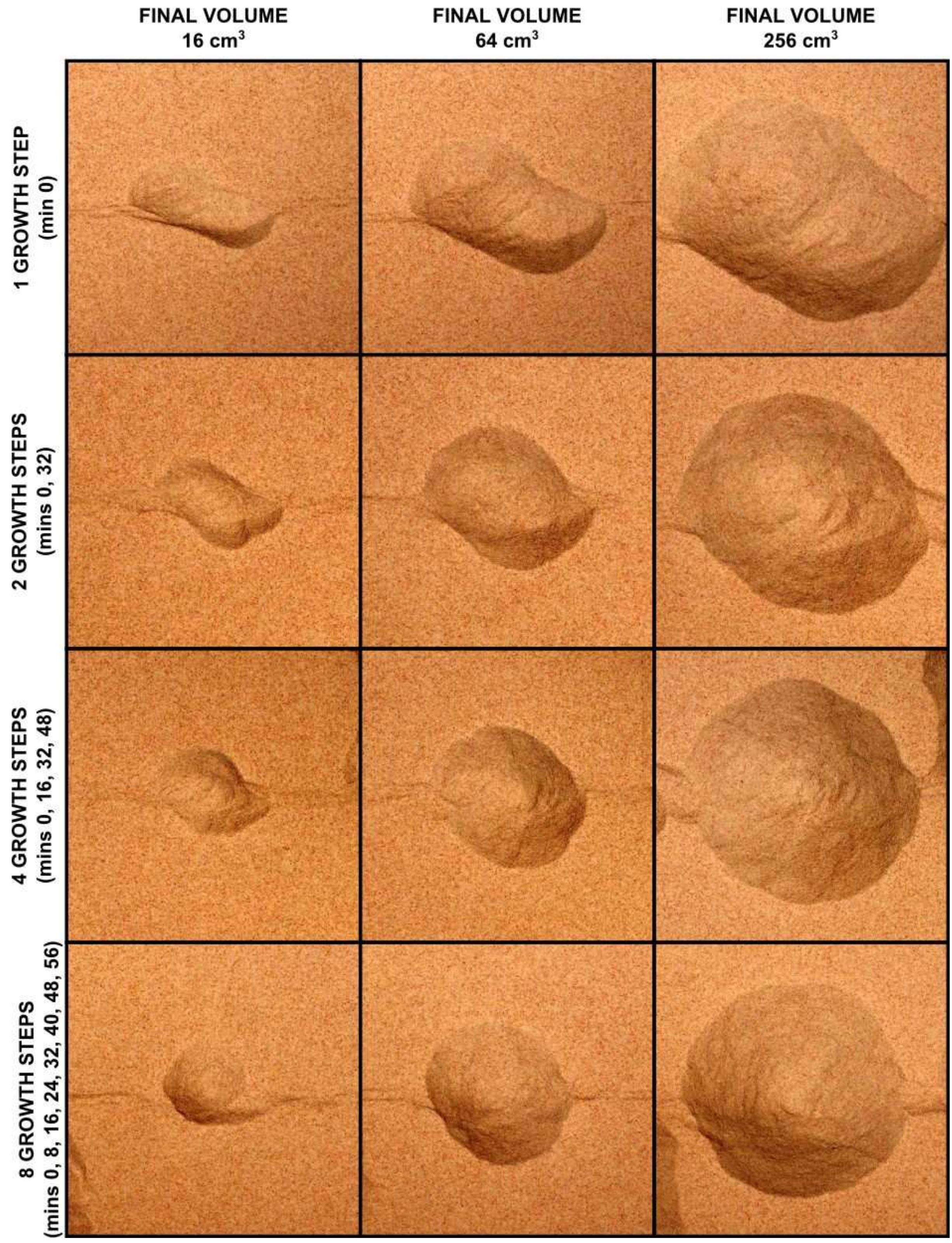

Fig. 4: Photographs of the final stage (minute 64) of 12 models illustrating the different resulting morphologies (each photograph spans 19 cm).

3.2. Morphometric analysis of volcanoes in nature

3.2.1. Virunga Volcanic Province (VVP)

The VVP lies within the Western branch of the East-African Rift Valley, shared by the Democratic Republic of Congo, Rwanda and Uganda. It consists of 8 large polygenetic volcanoes (two of which are active, Nyamulagira and Nyiragongo) and more than 500 scoria cones and fissures scattered on the volcano flanks and their surrounding lava fields (Fig. 5). The morphometry of the 8 main volcanoes was analyzed using both the SRTM 90 m DEM and the TanDEM-X 5 m DEM. First, the NETVOLC algorithm was applied to identify the morphological basal outline of each of the volcanoes. Then morphometric parameters for each edifice were computed with the MORVOLC algorithm.

Results show that the VVP volcanoes have distinct morphometries that can be related to several factors such as vent distribution, degree of erosion and composition. Of special interest is the case of Nyiragongo, which has a complex elongated shape with three main craters caused by shifts in the locus of activity: its shape can be readily compared to the analogue modeling results of volcano growth conditioned by shifts in vent location. Also of interest is that the volcanoes lacking historical eruptions show different degrees of dissection, from strongly dissected (Mikeno, Sabinyo) to smooth (Karisimbi Cone, Visoke), that can be correlated with age of activity. This is of particular interest for hazard assessment in a region where absolute age determinations are few or lacking. The morphometric analysis will be integrated with a geochemical database and a structural interpretation of the VVP, being carried out by the host institute, to constrain the level of activity and the potential hazards from each individual volcano.

The high resolution TanDEM-X DEM allowed to also extract the morphometry of the small monogenetic cones of the VVP (Fig. 5); data of 570 cones were obtained. These data are being analyzed by a VUB bachelor student to identify systematic variations in cone morphometry related to age and/or location relative to the structure of the East African rift.

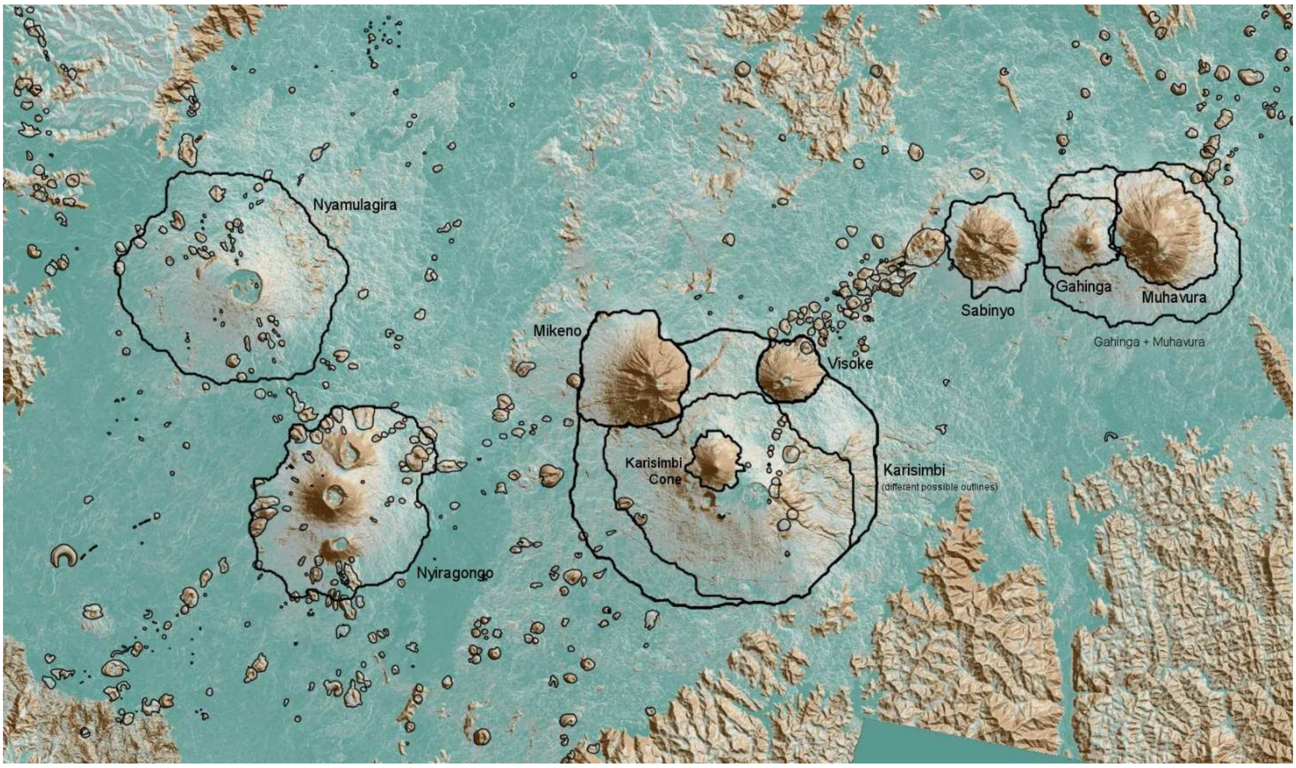

Fig. 5: TandDEM-X DEM-derived slope map of the Virunga Volcanic Province with outlines of the 8 large composite volcanoes and of the smaller monogenetic cones.

3.2.2. Shield-type volcanoes of Earth and Mars

During the stay we continued work on an ongoing project on the morphometry of shield volcanoes of both Earth and Mars. We have analyzed the morphometry of 16 large Martian shields using the ~460 m spatial resolution Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) data set. The Martian shields display a great variation of shapes, which is noteworthy given the lack of tectonism and significant erosion on Mars. Their shapes can be linked to processes that do operate in Mars, such as gravitational deformation, caldera formation and shallow level intrusion. Also of interest is that all shields have large summit calderas (whereas only about 1/3 of Terrestrial shields have large calderas) that seem to reach a maximum size, possibly correlated with magma chamber size (i.e. there is a maximum volume of magma capable of being hosted at shallow crustal levels, or within the edifice itself, regardless of edifice volume).

The Earth dataset consists of 119 Holocene shield volcanoes. Results show that there is a large variation in shield size (volumes range from ~1 to >1000 km3), elongation, profile shape (height/base diameter ratios range from 0.01 to 0.1) and in the average and maximum flank slope gradients. Principal component and clustering analysis of the morphometric parameters enables to identify key morphometric descriptors, including overall size, steepness, ellipticity, relative size of the summit plateau or caldera, and number of secondary peaks/vents. Using these criteria, we are working on a new classification scheme for shield-type volcanoes that highlights the control of the magma feeding system – either central, along a linear structure, or diffuse – on the resulting shield volcano morphology.

3.3. Integration of analogue and real world data

Integration of the experimental model data and of real volcano data is under way. In addition to the VVP volcanoes, the recently published global database of composite volcano morphometry (Grosse et al., 2014a) is also being analyzed and compared with the experimental data.

3.4. Outputs

Tangible outputs of the research stay have been:

- Design of new lab techniques for modeling variable-location volcano growth and strike-slip displacement.
- Setting up of the techniques and workflow for stereo-photogrammetric synthetic DEM generation of experiments at the VUB lab.
- Two large datasets of synthetic DEMs and derived morphometric parameters that model two processes: variable-location volcano growth and fixed-location growth on an active strike-slip fault.
- Two comprehensive morphometric datasets of the VVP composite volcanoes and of the scoria cones.

4. Perspectives for future collaboration between units

The research stay enabled to strengthen the already existing collaboration between the two parties. P. Grosse is involved in the co-supervision of two Bachelor and one Master student research projects at VUB until mid-2015. New topics for Master research projects have been proposed and would be co-supervised by P. Grosse if selected by VUB students. A new BELSPO-funded post-doc starting in mid-2015 will build upon the achievement of the research of P. Grosse and will use similar methods. P. Grosse will be associated to these new analogue modelling experiments to share his technical expertise in DEM generation and morphometric analyses.

Future collaboration is also expected through joint preparation of manuscripts for publication. This includes the publication of the analogue modelling results in two separate research papers, led by P. Grosse, and his collaboration on a manuscript concerning the VVP volcanoes led by the host unit. Other projects initiated or continued during the visit of P. Grosse, such as the systematic classification of Terrestrial and Martian shield volcanoes, will be pursued in collaboration to lead to respective publications. It is also expected that the VUB team will be involved in the statistical interpretation of the global morphometric database of composite volcanoes in the years to come.

During the stay, an application for a FWO-MINCYT cooperation project was submitted by P. Grosse and M. Kervyn (results are pending). This cooperation project would ensure a formal collaboration for the next two years with short research visits of P. Grosse to the Belgian host unit, and would open the door for the host unit to develop research in Argentina in the future.

5. Valorization/Diffusion (including Publications, Conferences, Seminars, Missions abroad...)

At the beginning of the stay P. Grosse went on a 3-day mission abroad to the University of Oslo to gain experience on working with the MICMAC software by visiting O. Galland, a close collaborator of the host unit and an expert user of the software. During the course of the fellowship P. Grosse gave three seminars, one at the University of Oslo and two at the host unit (one at the beginning and the other at the end of the stay).

Preliminary results and interpretations on the morphometry of the VVP volcanoes were presented at the Cities on Volcanoes meeting in Indonesia in September 2014 (Poppe et al., 2014) and will also be presented at the IUGG meeting in Prague in June 2015 (Poppe et al., 2015, submitted). A poster on the morphometry of Martian shield volcanoes was presented at the 48th ESLAB Symposium of the European Space Agency in the Netherlands in June 2014 (Grosse et al., 2014b). Results of the analogue models will be presented at the IUGG conference in 2015 (Grosse et al., 2015, submitted).

The final results of the project will be published in three articles, one for each type of experiment carried out and one concerning the morphometry of the VVP volcanoes. It is expected that these papers will be submitted before the end of 2015. In addition, other ongoing (e.g. morphometry of shield volcanoes) and new projects discussed during the research stay may lead to additional joint publications in the years to come.

6. Skills/Added value transferred to home institution abroad

The stay allowed P. Grosse to gain expertise on analogue modelling techniques and stereo-photogrammetric synthetic DEM generation. These techniques will hopefully be applied in the future at the home institution.

P. Grosse's work-plan at CONICET and Fundación Miguel Lillo concerns the morphometric study of volcanoes through the analysis of DEMs. The general goal is to quantify, characterize and classify the morphologies and morphological evolutions of volcanic edifices. One of the specific objectives is to carry out analogue experiments to model the processes that determine the morphometric evolution of volcanic edifices. Thus, the project carried out in Belgium is not only aligned with P. Grosse's research objectives but is also essential towards fulfilling them.

On a more general aspect, the research stay enabled to have long discussions about the factors that control the morphometry of volcanoes and how the influence of each of them can be characterized and quantified using analogue models and/or real volcano examples. Although this aspect of the stay is difficult to quantify, these scientific interactions are essential for emulation and development of new research ideas.

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