Synthesizing Procedural Landscape for Volcanic Eruption Simulation in Virtual Reality

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(a) Input Terrain   (b) Volcanic Terrain

(c) Volcanic Terrain with Lava   (d) Volcanic Terrain with Eruption   (e) Volcanic Eruption Simulation in VR
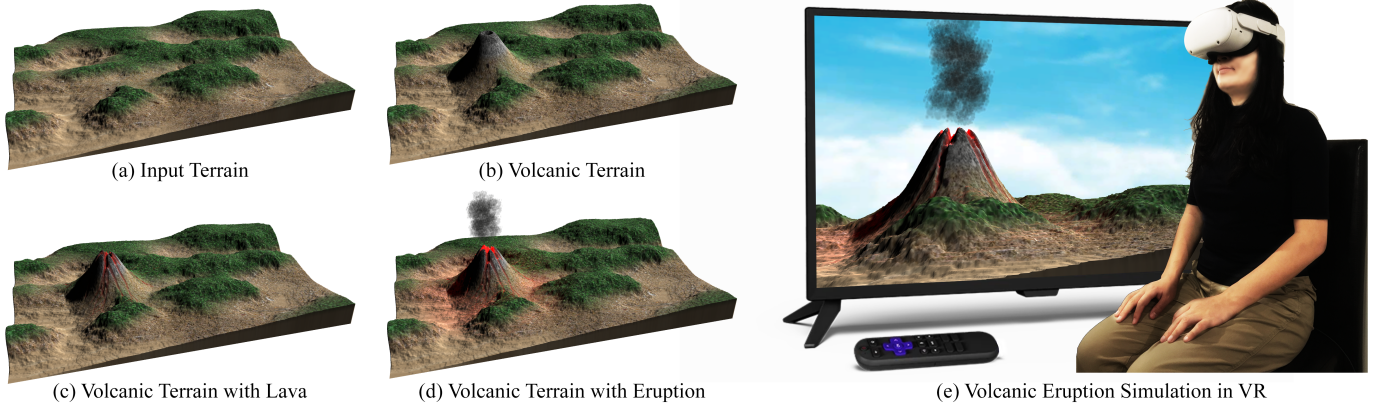
Fig. 1. Teaser. This is a teaser that shows the main steps of our proposed technical approach: Given input terrain as shown in (a), we apply an image processing approach to draw volcano on the terrain heightmap as shown in (b). Then, lava is drawn on the texture and height map using a procedural modeling approach to generate a lava terrain as shown in (c). In the end, we add particle system and lighting effects as shown in (d), and simulate volcanic eruption in VR effects as shown in (e).

Abstract—**Virtual reality (VR) has emerged as a powerful tool for simulating and visualizing various natural phenomena, offering immersive experiences for education, research, and entertainment. In this paper, we present a novel approach for synthesizing procedural landscapes to simulate volcanic eruptions in virtual reality. We combine geological principles, procedural generation techniques, and immersive VR technologies to create a realistic and interactive volcanic eruption simulation. According to a series of numerical experiments and preliminary user studies, we show the correctness of our proposed technical approach. Our approach has the potential to enhance understanding of volcanic processes and contribute to the development of virtual geoscience environments. We describe the underlying methodology, system architecture, user experience, and discuss the potential applications and future directions in geoscience edutainment.**

Keywords—**terrain generation, image processing, virtual reality**

I. INTRODUCTION

Volcanic eruptions are natural disasters with the potential for devastating impacts on human communities, climate, and the environment. Understanding the dynamics of volcanic eruptions and their associated hazards is crucial for both scientific research and public safety [1]. Traditional methods for studying volcanoes, such as fieldwork [2], laboratory experiments, and numerical modeling [3], [4], have limitations in terms of safety and accessibility. Virtual Reality (VR) [5], [6] offers a promising alternative for simulating volcanic eruptions, providing an immersive and controlled environment for teaching, learning, and researching.

VR is a technology that immerses users in computer-generated environments, providing a sense of presence and interactivity [7]–[9]. VR systems typically consist of a head-mounted display [10], motion-tracking controllers, and computing platform for rendering 3D scenes in real time. Recently, VR technologies have emerged as powerful tools for training [11]–[13], education [14]–[16], and edutainment [17]–[19].

Procedural modeling techniques have been widely used in computer graphics and gaming to generate complex, realistic landscapes. These techniques enable the synthesis of realistic terrains [20]–[24], urban layouts [13], [25], and other environmental features using algorithms and mathematical functions. Especially, procedural terrain synthesis is valuable for creating vast and diverse virtual environments, which can be leveraged for geological simulations. The combination of VR and procedural modeling allows for the creation of dynamic geological simulations for volcanic eruptions.

In this paper, we present a novel technical approach for synthesizing procedural landscapes to simulate volcanic eruptions in virtual reality. By combining geological principles, procedural modeling, and VR technologies, our system allows users to experience realistic volcanic eruption scenarios with VR devices. According to our numerical experiments results, we show that this research work has the potential to advance geoscience education, develop safety training programs, enhance public awareness, and contribute to disaster preparedness.
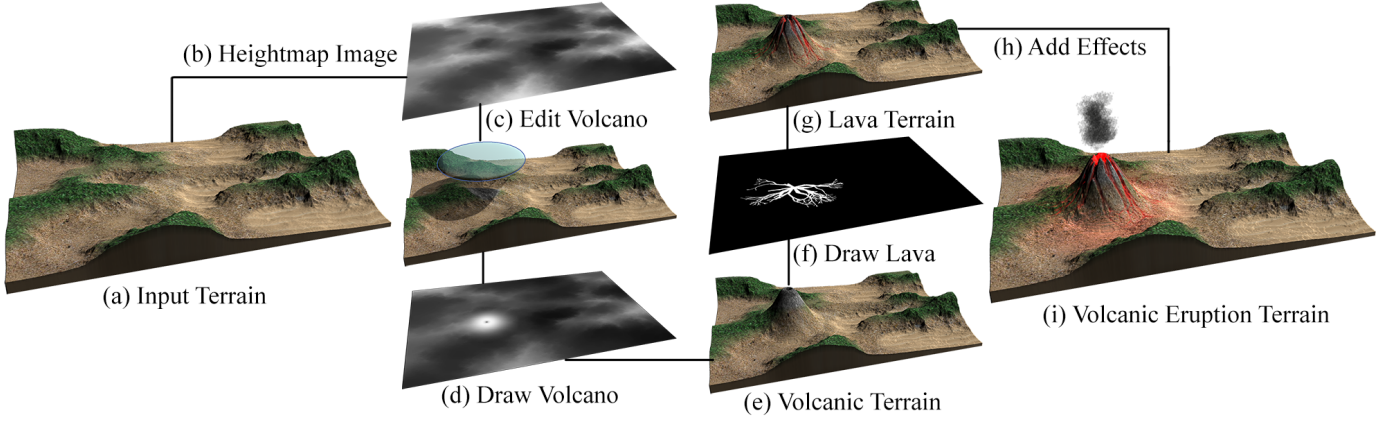
Fig. 2. Overview of our approach.

II. OVERVIEW

Fig. 2 shows the overview of our approach. Given an input terrain as shown in (a), we extract the heightmap as a bitmap image as shown in (b). By adjusting the position and radius of a transparent flat sphere in the Unity Editor as shown in (c), the user can easily edit the position and radius of the volcano to be generated. Then, we propose an image processing approach to draw a volcano on the terrain heightmap as shown in (d). After that, by employing a procedural modeling approach, lava is recursively drawn onto the heightmap and texture based on a data structure of alphamap, called lavamap, as shown in (f). After this step, a volcanic terrain with lava is synthesized as shown in (g). In the end, after adding particle system and point lighting effects as shown in (h), the volcanic landscape and volcanic eruption are synthesized and simulated on an arbitrary input terrain as shown in (i).

III. TECHNICAL APPROACH

Procedural Volcano. Given an arbitrary terrain generated with regular procedural modeling approaches as input terrain with size (length l, height h, width w), we extract its heightmap as a bitmap gray image denoted as $\psi(u,v) \in [0,1], (u,v) \in [0,1]^2$. When dragging and dropping the position $\mathbf{p} = (x,y,z)$ and radius r of a transparent flat sphere in the Unity Editor, the user can easily edit the position and radius of the volcano which are set to be the same as the sphere's. Then, we draw a volcano on the terrain heightmap by blending white color onto the original heightmap image with alpha value $\alpha(u,v)$:

$$\alpha(u,v) = \kappa \begin{cases} 1 - e^{-\left(\frac{2\delta}{\gamma}\right)^2} & \delta \leq \gamma \\ e^{-\left(\frac{2(\delta-\gamma)}{1-\gamma}\right)^2} & \delta > \gamma \end{cases} \quad (1)$$

where volcanic hole radius $\gamma = 0.25$ and $\kappa = y/h$. If $\kappa > 1$, in this case, the volcano's height is higher than the original terrain. Then, the terrain's height h is changed into y and terrain's heightmap is updated into $\psi'(u,v) = h\psi(u,v)/y$. The distance between pixel and center is calculated as δ:

$$\delta = \sqrt{\left(\frac{x-ul}{r}\right)^2 + \left(\frac{z-vw}{r}\right)^2} \quad (2)$$

Algorithm 1 Draw Lavamap $\iota(u,v)$: Recursive Algorithm

1: **procedure** DRAWLAVAROOT(**this** $\iota(u,v)$)
2:   **for** $i \leftarrow 1$ **to** m_{root} **do**   ▷ Root Branch Count m_{root}
3:     $\mathbf{r} \leftarrow \mathbf{r}'$.NORMALIZED, $\mathbf{r}' \sim \mathcal{N}^2(0,1)$
4:     $\iota(u,v)$.DRAWLAVABRANCH$((x/l,z/w),\mathbf{r},0)$
   return
5: **procedure** DRAWLAVABRANCH(**this** $\iota(u,v), \mathbf{p_0}, \mathbf{r_0}, n$)
6:   Start Position $\mathbf{p_0}$, Start Direction $\mathbf{r_0}$, Current Level n
7:   Avg Distance μ_{d}, Max Level n_{max}, Child Branch m_{child}
8:   Density ρ, Spread Area η, Spread Angle θ, Decay λ
9:   **if** $n > n_{\text{max}} \vee \eta\lambda^n < 1$ **then return**
10:   $d \sim \mathcal{N}(\mu_{\text{d}}, \mu_{\text{d}}/2), \mathbf{p_1} \leftarrow \mathbf{p_0} + d\lambda^n \mathbf{r}$
11:   $\iota(u,v)$.DRAWLINE$(\mathbf{p_0}, \mathbf{p_1}, \rho\lambda^n, \rho\lambda^{n+1}, \eta\lambda^n)$
12:   **for** $i \leftarrow 1$ **to** m_{child} **do**
13:     $\mathbf{r_1} \leftarrow \mathbf{r}'$.NORMALIZED, $\mathbf{r}' \sim \mathcal{N}^2(0,1)$
14:     **if** $\cos^{-1}(\mathbf{r_0} \cdot \mathbf{r_1}) < \theta$ **then**
15:       $\iota(u,v)$.DRAWLAVABRANCH$(\mathbf{p_1}, \mathbf{r_1}, n+1)$
   **return**

Procedural Lava. After the procedural volcano is synthesized, lava is recursively drawn onto the heightmap and texture using an alphamap, called lavamap $\iota(u,v) \in [0,1], (u,v) \in [0,1]^2$. Lavamap $\iota(u,v)$ is calculated according to Algorithm 1. Then, the updated heightmap with lava is calculated as $\psi'(u,v)$:

$$\psi'(u,v) = (1 - \iota(u,v))\psi(u,v) + \iota(u,v)\beta(u,v) \quad (3)$$

where black image $\beta(u,v) = 0, (u,v) \in [0,1]^2$.

IV. EXPERIMENT RESULTS

In order to validate the efficacy of our proposed technical approach, a group of numerical experiments are conducted on synthesizing different procedural landscapes for volcanic eruption simulations with different parameter settings. We implemented our proposed approach using Unity 3D with the 2019 version and generated these experiment results with the hardware configurations containing Intel Core i5 CPU, 32GB DDR4 RAM, and NVIDIA GeForce GTX 1650 4GB GDDR6 Graphics Card. These numerical experiments are conducted with the parameter settings for lavamap as following: average
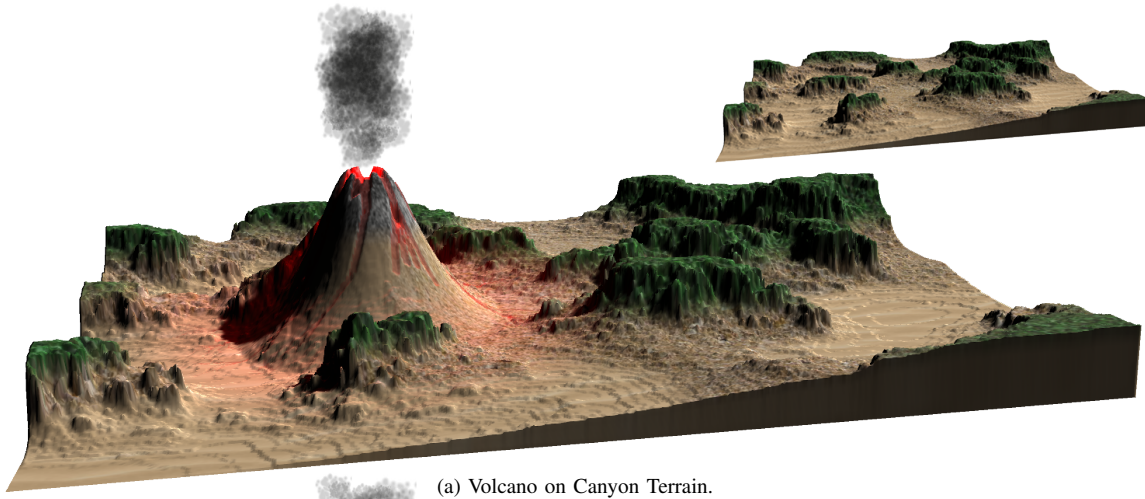
(a) Volcano on Canyon Terrain.
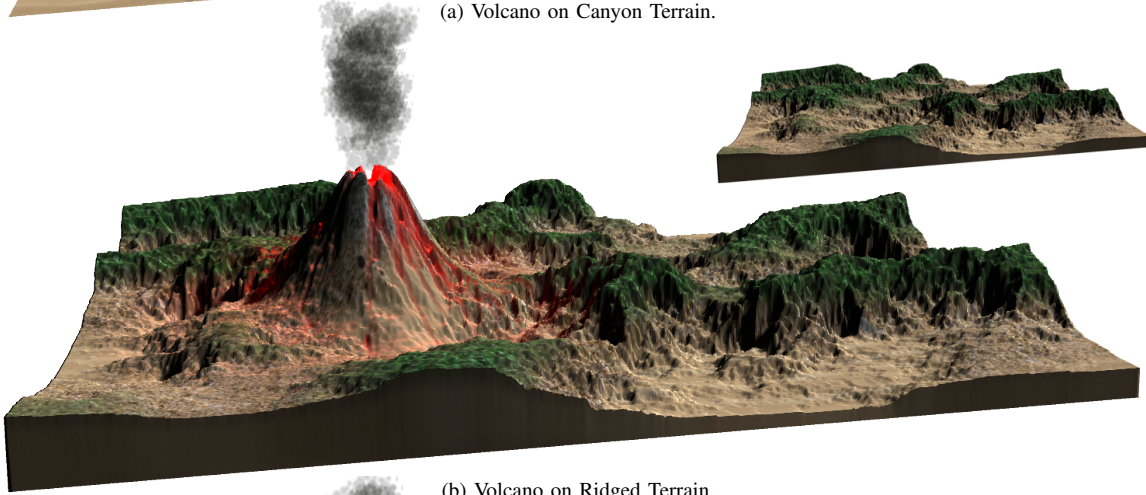
(b) Volcano on Ridged Terrain.
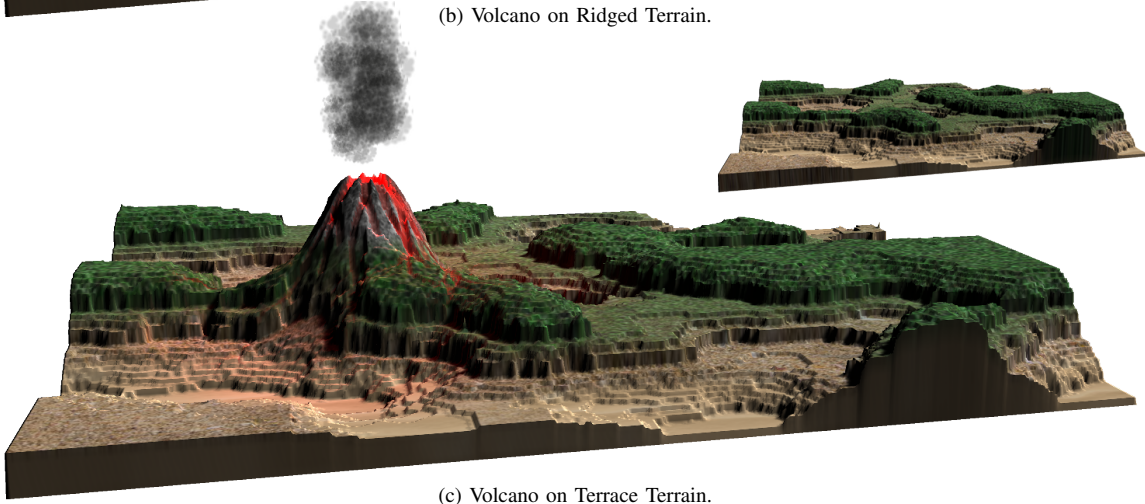
(c) Volcano on Terrace Terrain.

Fig. 3. Different Terrains. These results are procedural volcanic landscapes synthesized on different types of terrains.

distance $\mu_{\mathrm{d}} = 0.1$, max level $n_{\max} = 8$, lava density ρ, spread area $\eta = 5$, spread angle $\theta = 45$, decay coefficient $\lambda = 0.8$.

Fig. 3 shows the experiment results of synthesizing procedural landscape for volcanic eruption simulation on different types of terrains such as canyon (a), ridged (b), and terrace (c). The parameter settings for lavamap are: root branch count $m_{\mathrm{root}} = 20$ and child branch count $m_{\mathrm{child}} = 5$. This figure presents a comprehensive visual representation of the experimental results obtained from the synthesis of procedural landscapes for volcanic eruption simulations across various

terrain types. In three distinct subplots, denoted as (a), (b), and (c), the diverse terrains under experiments are showcased. Subfigure (a) features a canyon landscape, characterized by deep, winding chasms and steep rock formations, while Subfigure (b) highlights a ridged terrain, displaying sharp, irregular peaks and valleys. In Subfigure (c), terrace terrain is depicted, with its distinctive stepped, flat platforms. The figure captures the dynamic and realistic volcanic eruption simulations superimposed upon these terrains, offering a compelling visual insight into the versatility and adaptability of our procedural landscape
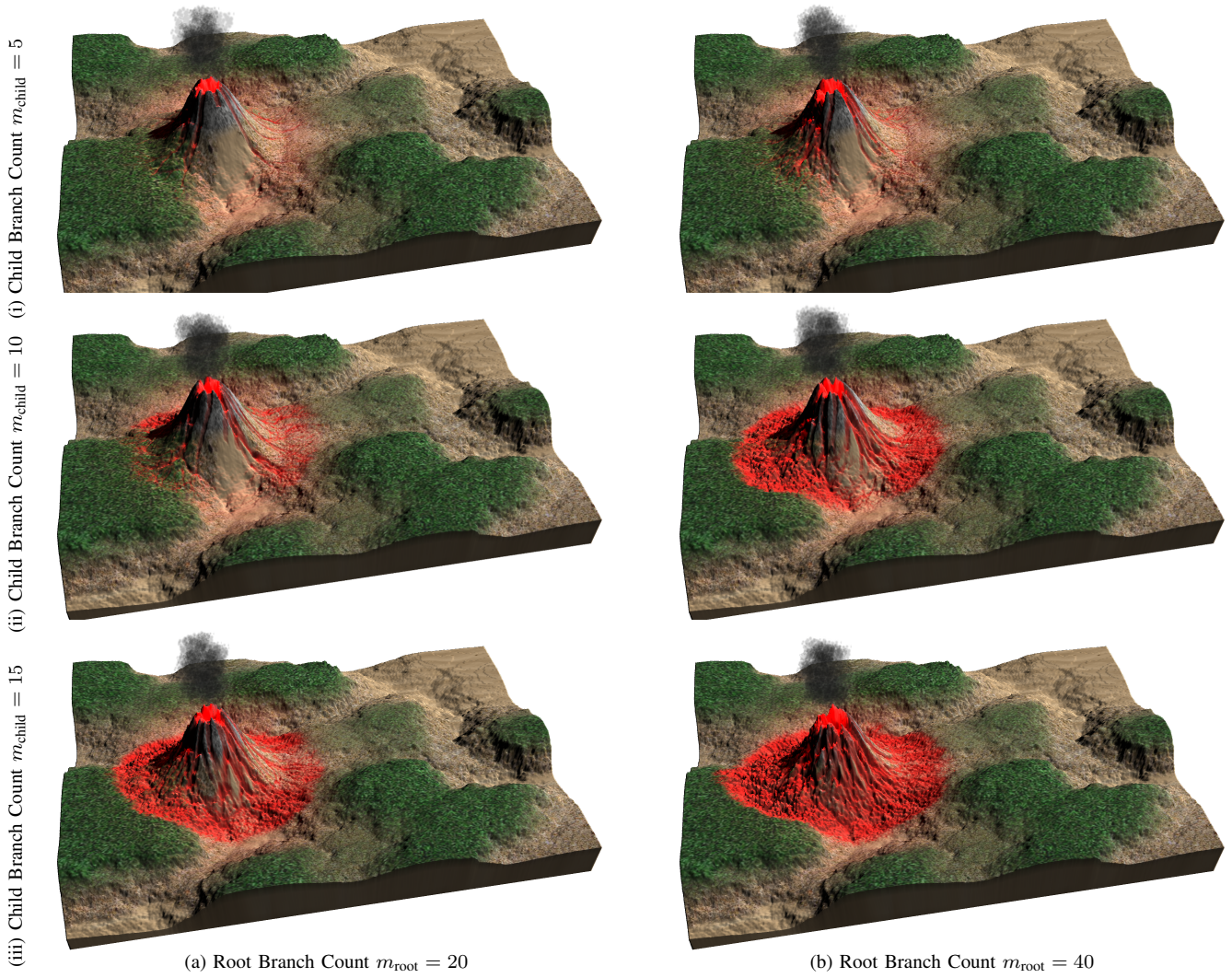
Fig. 4. Different Branch Counts. This figure shows the experiment results of synthesizing procedural landscape for volcanic eruption simulation with different branch counts. For each row, column (a) shows the results of procedural volcanic landscapes synthesized with root branch count $m_{root} = 20$ and column (b) shows the results synthesized with root branch count $m_{root} = 40$. For each column, row (i)(ii)(iii) shows the results synthesized with child branch count of $m_{child} = 5, 10$, and 15 respectively.

synthesis approach for geospatial simulations.

Fig. 4 provides a comprehensive visual representation of experimental results concerning the synthesis of procedural volcanic landscapes with varying branch counts. The results are organized into a matrix format, where each row and column configuration is designed to explore the impact of different branch counts on the landscape synthesis process. Specifically, column (a) exhibits the outcomes of procedural volcanic landscape synthesis with a root branch count $m_{root} = 20$, while column (b) contrasts this with a root branch count $m_{root} = 40$. Each column is further subdivided into three rows, denoted as (i), (ii), and (iii), each examining the influence of child branch counts. In row (i), child branch count m_{child} is set to 5, in row (ii), it is increased to 10, and in row (iii), it is further raised to 15. The results demonstrate a trend that as the branch counts increase, the dominance of the lava's spread effect becomes more pronounced. When higher numbers of

branches are used in the volcanic landscape synthesis, lava tends to cover a larger and more expansive area.

Fig. 5 offers a striking visual representation of a captivating experiment, showcasing the synthesis and simulation of multiple procedural volcanoes within the same terrain. This comprehensive illustration presents a dynamic landscape where multiple volcanoes coexist. This figure stands as a testament to the capacity of our procedural techniques to create dynamic volcanic scenarios within a single terrain input.

As depicted in Fig. 6, the user is immersed in a virtual reality experience, witnessing volcanic eruptions simulated by our approach. This captivating virtual environment is made possible through the Oculus Quest 2 VR headset, which provides an immersive platform for users to engage with volcanic simulations. It offers a vivid and realistic way for individuals to observe and explore the dynamic and lifelike volcanic eruptions created by our simulation technique.
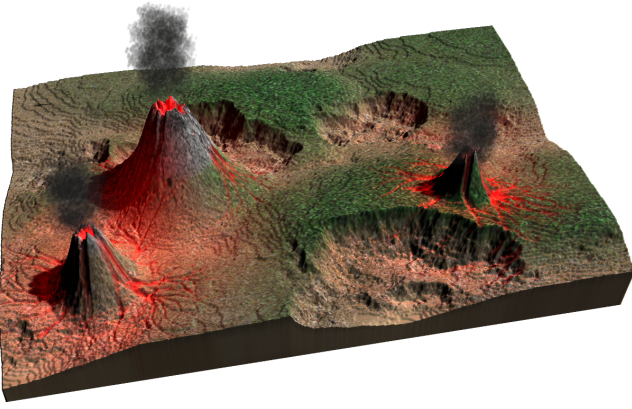
Fig. 5. Multiple Volcanoes on the Same Terrain. This figure shows the experiment results of synthesizing and simulating multiple procedural volcanoes within the same terrain.

V. Conclusion

In this paper, we propose a novel approach to synthesize procedural landscape for volcanic eruption simulation in virtual reality. By exploring various terrain types and branch count variations, we have unveiled a dynamic and immersive approach to synthesize realistic volcanic landscapes in VR. As a potential outcome, the combination of procedural generation techniques and VR technology offers a compelling platform for educators, researchers, and enthusiasts to engage with and gain deeper insights into the complexities of volcanic eruptions. The findings presented in this paper pave the way for further advancements in geospatial simulations, offering a promising direction for future research in this field.
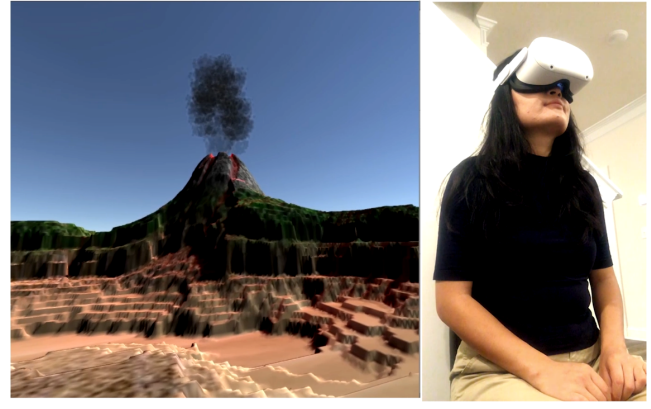

Fig. 6. User Study. This figure shows the user's immersive experience of observing volcanic eruptions simulated by our approach on a virtual reality platform.

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