

A wide-angle photograph of a Martian landscape. In the foreground, there is a rocky, uneven terrain with various sized rocks and patches of reddish-brown soil. In the middle ground, a large, dark, and somewhat irregularly shaped mountain or volcano rises. The background shows a vast, hazy, orange-brown sky that blends into the horizon. The overall color palette is dominated by shades of orange, red, and brown, typical of Mars.

Martian Vorovoid

MSc 2 2025

Group C3

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Mark Vas, Marko Lojanica

Tabel of Contents

Conditions on Mars

Site on Mars

Case Studies

Concept

Design Development

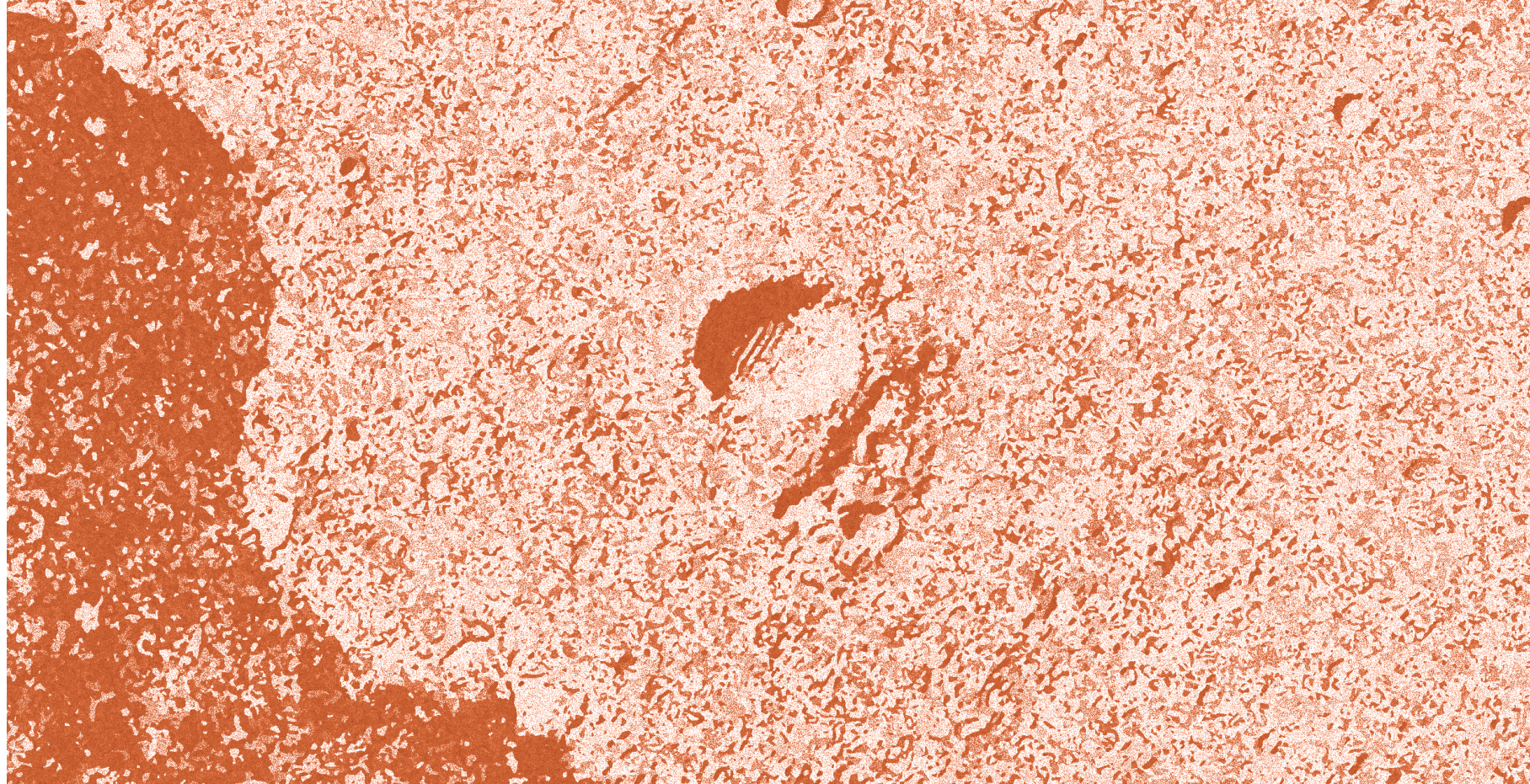
Final Design

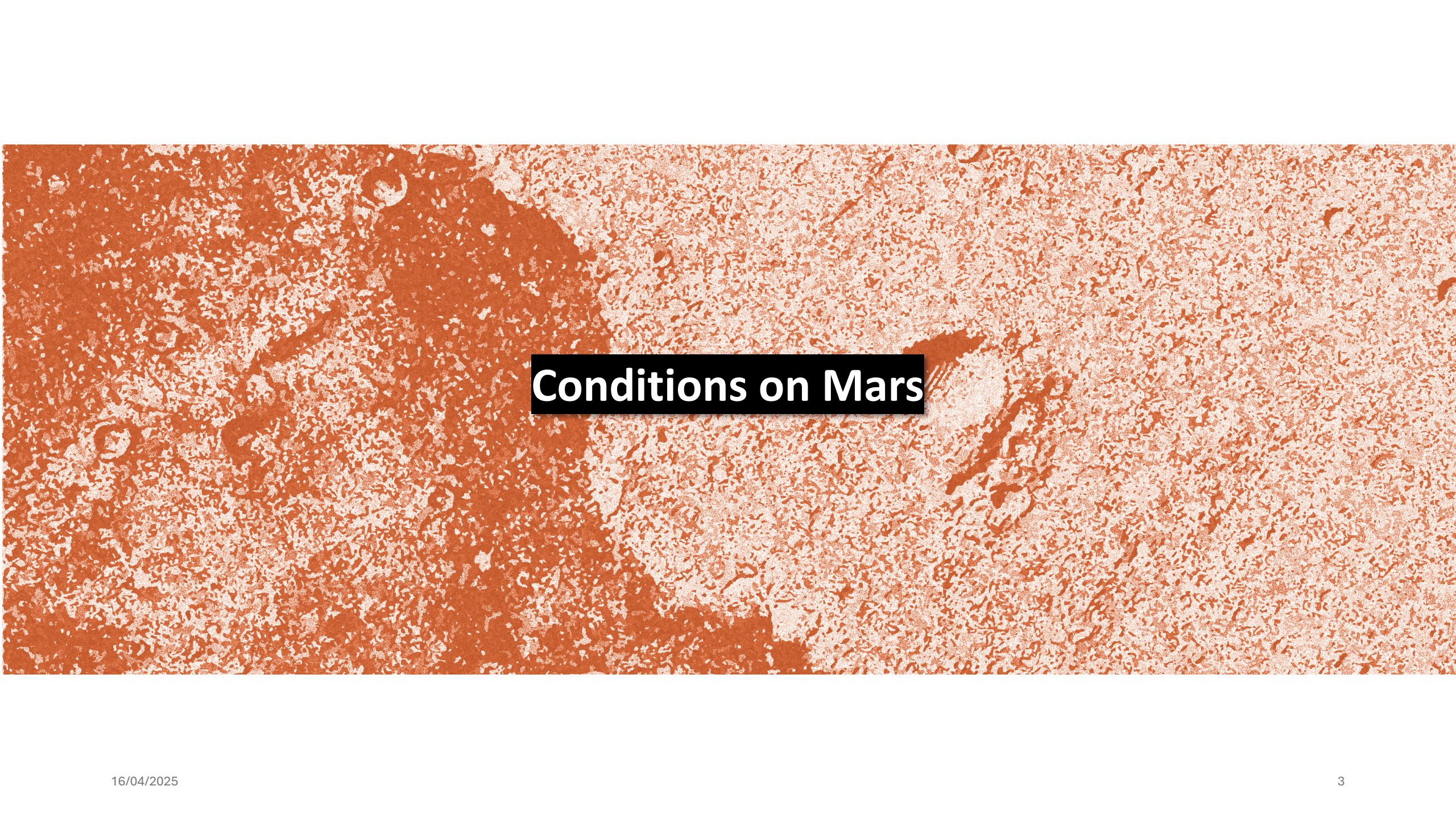
Fragment

Milling Process

HRI & Assembly Plan

3D Model





Conditions on Mars

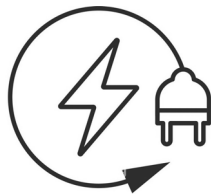
Site on Mars

Considerations & Opportunities



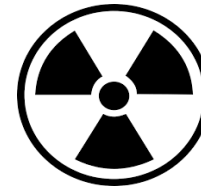
Geological Features

- Lava tubes offer a structurally stable environment, minimizing radiation exposure and thermal fluctuations.
- The presence of basalt-rich regolith can be leveraged for In-Situ Resource Utilization (ISRU) in construction.



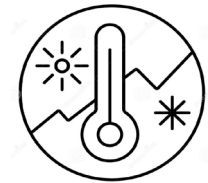
Energy Potential

- The combination of wind and solar power can be optimized to sustain the habitat.
- Subsurface placement within lava tubes can reduce energy needs for thermal regulation.



Protection from Radiation

- Martian surface is exposed to cosmic and solar radiation, but lava tubes provide natural shielding, reducing exposure risks for inhabitants.



Temperature Stability

- The underground environment within lava tubes helps mitigate extreme temperature fluctuations, which range from -125°C at night to 20°C in the daytime.

Site on Mars

Analysis

STRENGTHS

- Lava tubes offer a structurally stable environment, minimizing radiation exposure and thermal fluctuations.
- The presence of basalt-rich regolith can be leveraged for In-Situ Resource Utilization (ISRU) in construction.

WEAKNESSES

- Accessibility challenges related to lava tube entry and exit points.
- Limited direct solar energy due to terrain obstructions.

OPPORTUNITIES

- Development of hybrid energy solutions combining wind, solar, and nuclear options.
- Advancements in robotic excavation and 3D printing could enhance habitat scalability.

THREATS

- Unpredictable Martian dust storms could affect energy generation.
- Structural uncertainties of lava tubes requiring in-depth geotechnical analysis.



Site on Mars

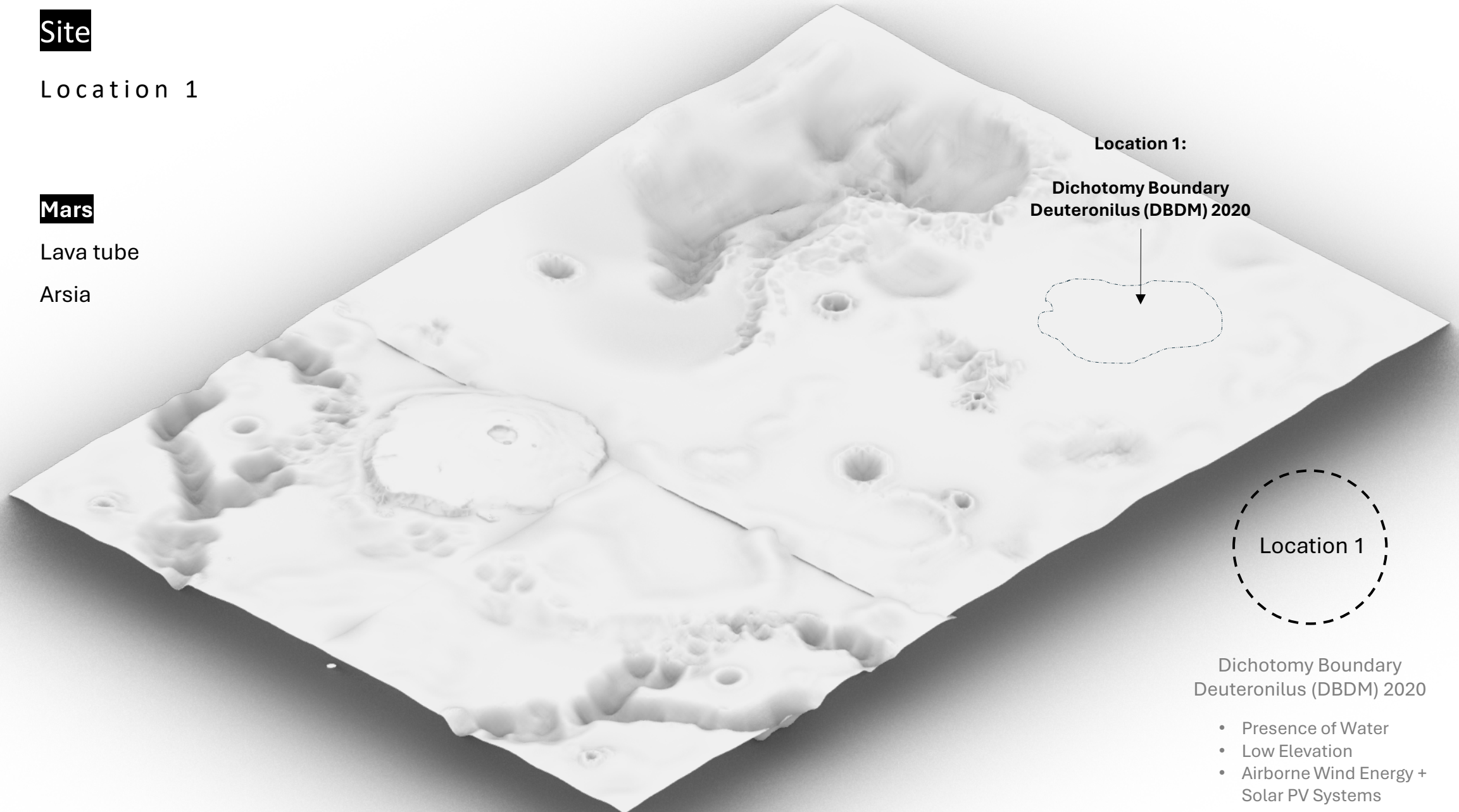
Site

Location 1

Mars

Lava tube

Arsia



Location 1:

Dichotomy Boundary
Deuteronilus (DBDM) 2020

Location 1

Dichotomy Boundary
Deuteronilus (DBDM) 2020

- Presence of Water
- Low Elevation
- Airborne Wind Energy + Solar PV Systems

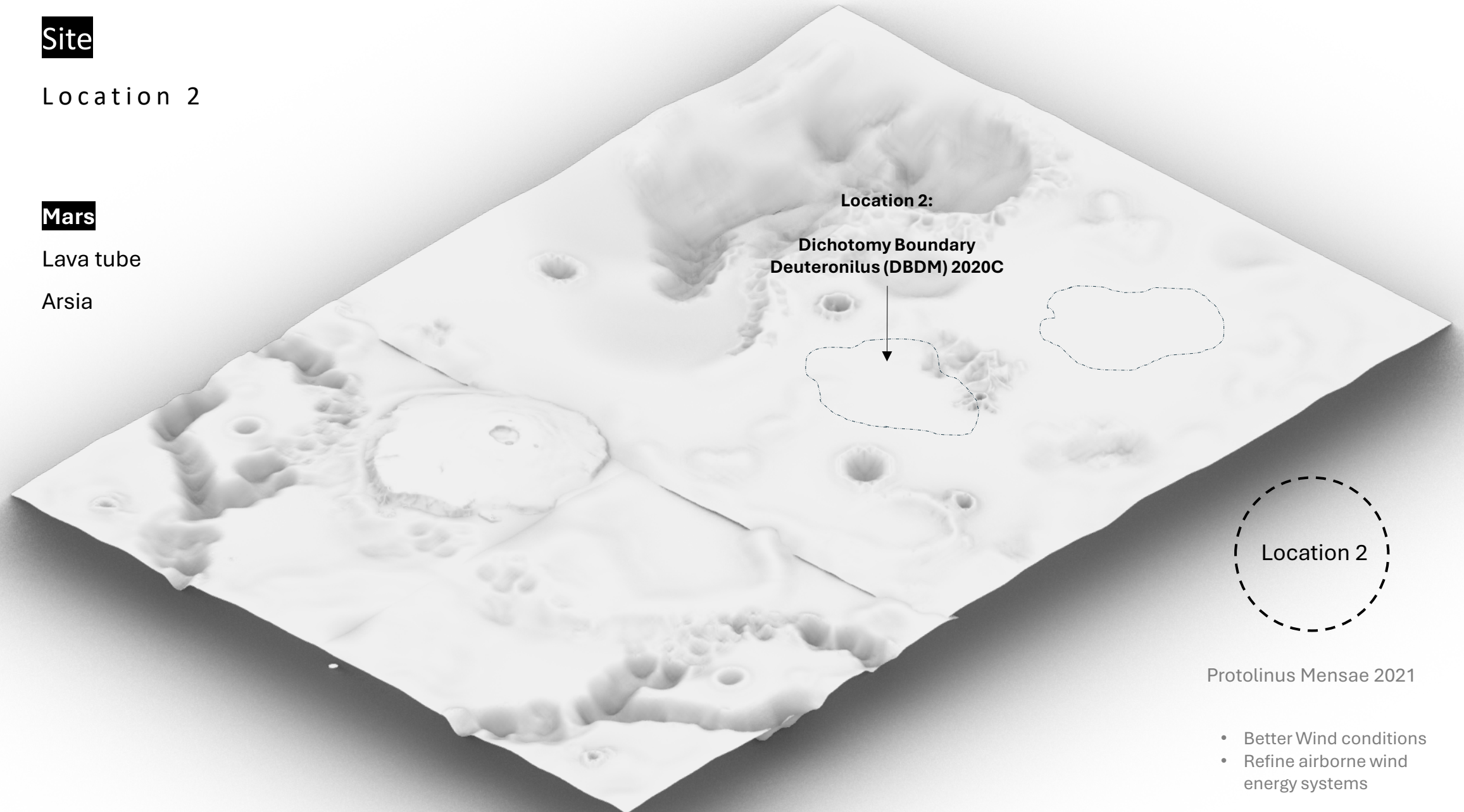
Site

Location 2

Mars

Lava tube

Arsia



Protonilus Mensae 2021

- Better Wind conditions
- Refine airborne wind energy systems

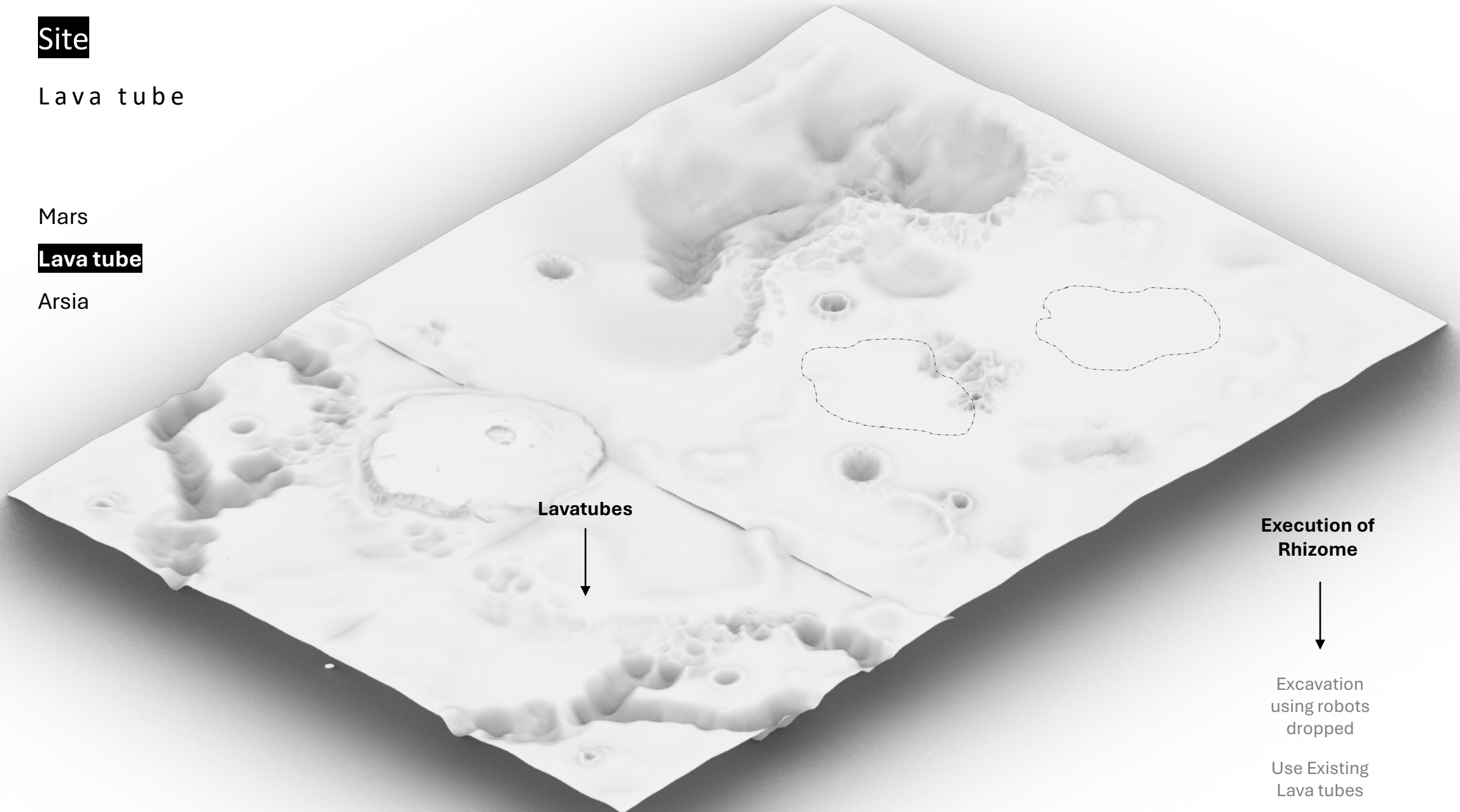
Site

Lava tube

Mars

Lava tube

Arsia



Lavatus



**Execution of
Rhizome**



Excavation
using robots
dropped

Use Existing
Lava tubes

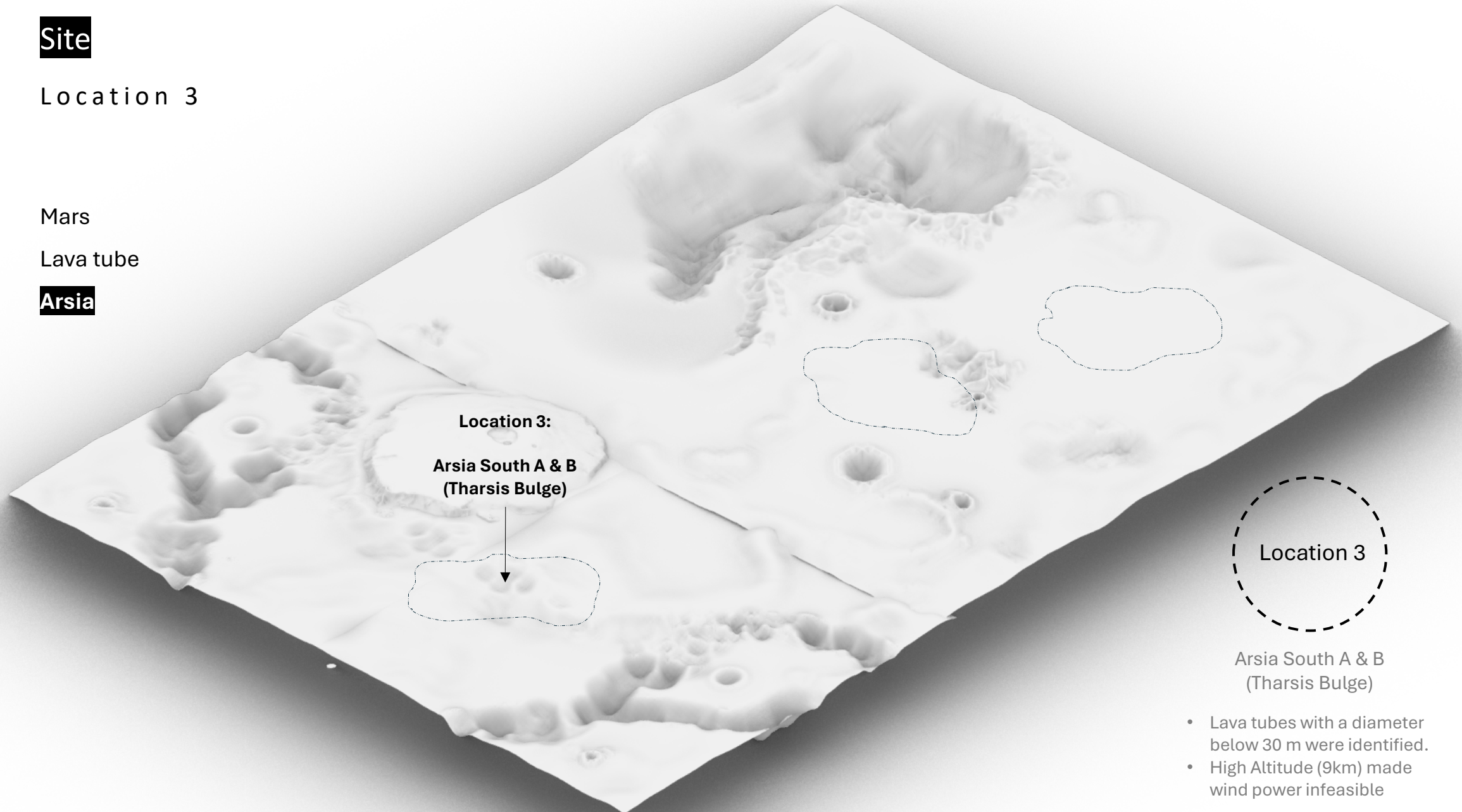
Site

Location 3

Mars

Lava tube

Arsia



Location 3:

**Arsia South A & B
(Tharsis Bulge)**

Location 3

**Arsia South A & B
(Tharsis Bulge)**

- Lava tubes with a diameter below 30 m were identified.
- High Altitude (9km) made wind power infeasible

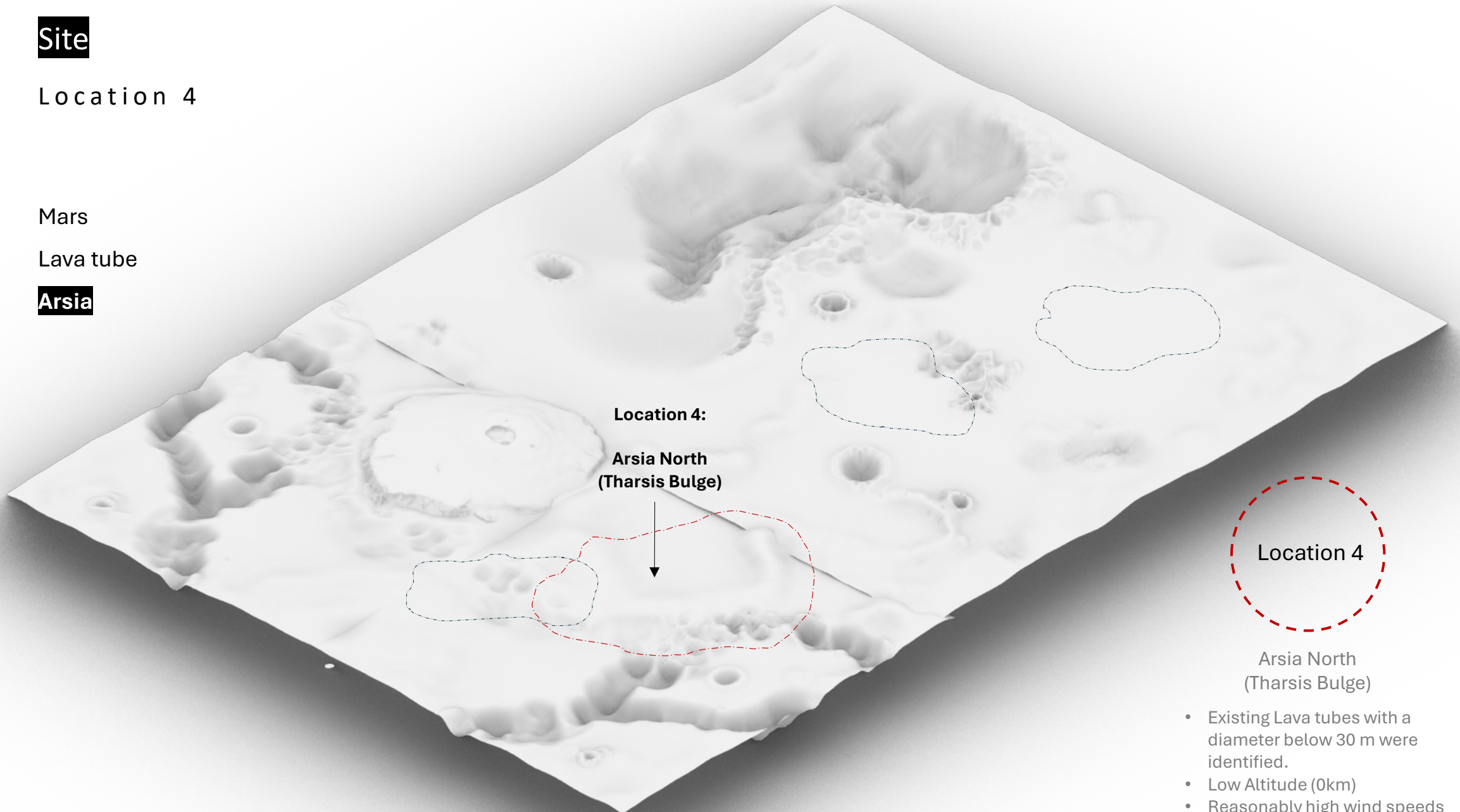
Site

Location 4

Mars

Lava tube

Arsia



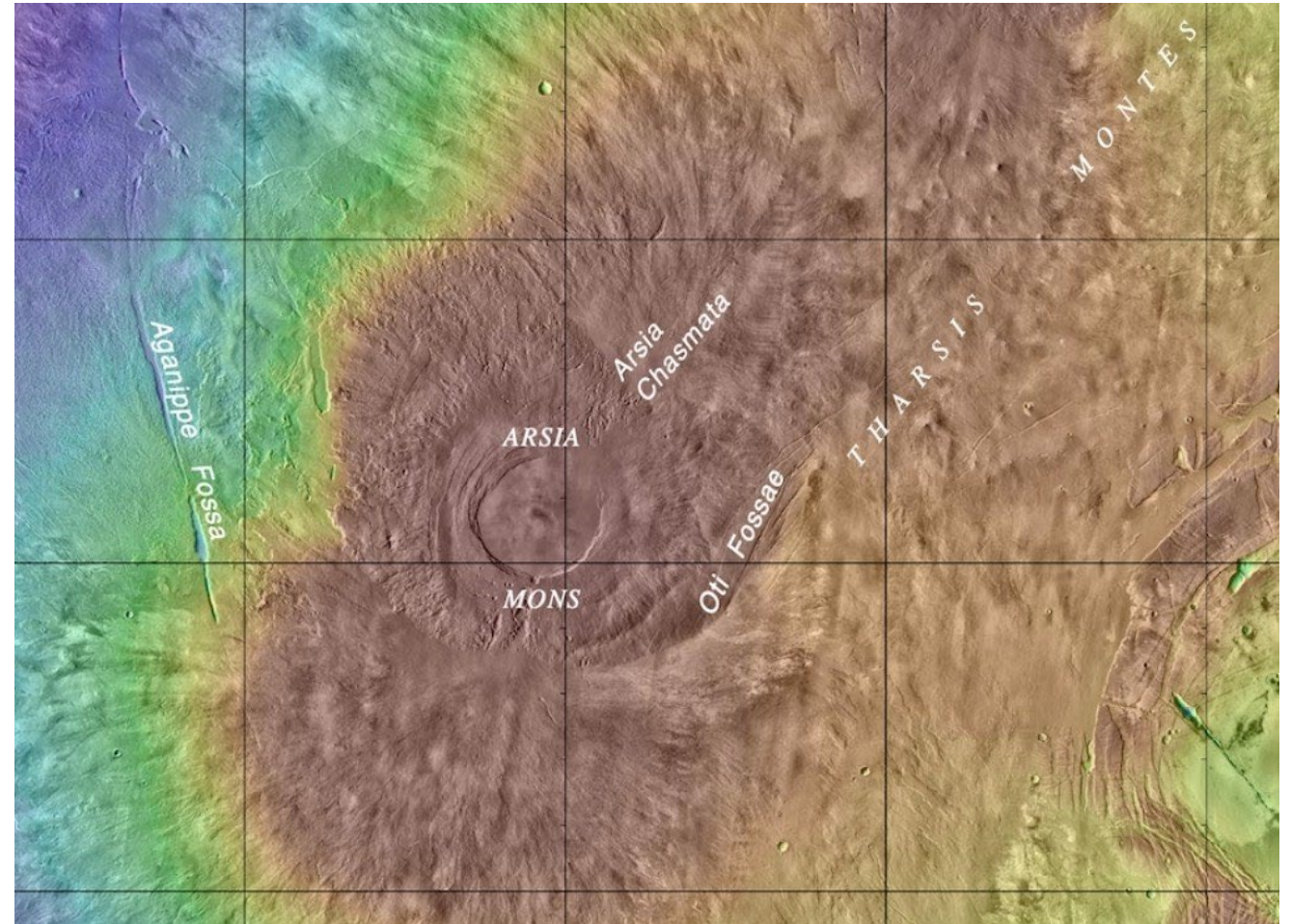
Arsia North
(Tharsis Bulge)

- Existing Lava tubes with a diameter below 30 m were identified.
- Low Altitude (0km)
- Reasonably high wind speeds

Site selection

The final habitat location was identified as Arsia North, a region of the Tharsis bulge. This selection was based on several key factors:

- + Presence of Lava Tubes
- + Low Altitude (around 0 km)
- + Favorable Wind Conditions
- + Stable Geological Conditions



Reference Image: [The Arsia Mons expedition | VolcanoCafe](#)

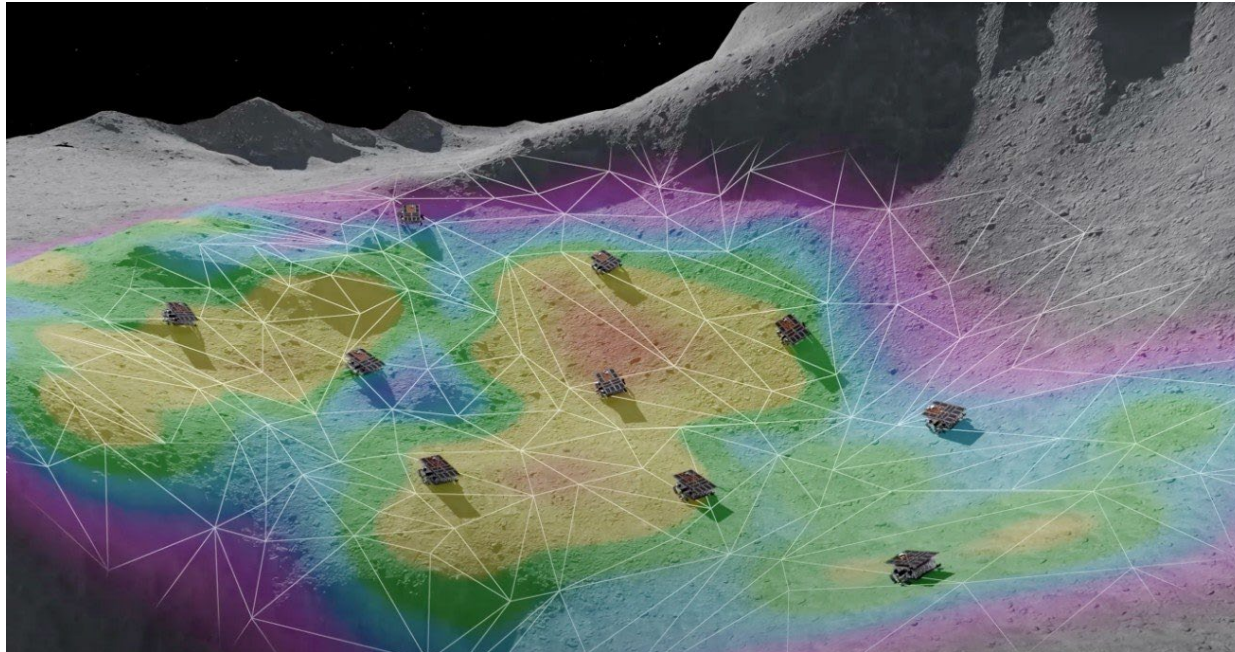


Case Studies

Previous projects analysis

Moonshot

Rhizome (1) & (2)



Moonshot & Moonshot+: Lunar Architecture and Infrastructure

Develop **critical infrastructure** for **lunar colonization**, supporting the long-term sustainability of human presence on the Moon.

Challenges:

- **Environmental Extremes:** Designing habitats that can withstand **extreme temperature fluctuations, radiation, and micrometeorite impacts**.
- **Material Constraints:** Using **local materials** (lunar regolith) while addressing issues like **strength, durability, and ease of 3D printing** for construction.
- **Autonomy and Scalability:** Ensuring **robots** can operate independently and build structures on a large scale without constant human oversight.

Learnings:

- **Autonomous Construction Technologies:** Proving the viability of **robot-based construction** and its potential to reduce reliance on human labor in dangerous environments.
- **Material Innovation:** Overcoming the challenges of working with lunar materials (e.g., regolith) for practical construction.

Previous projects analysis

Moonshot

Rhizome (1) & (2)



Rhizome 1 & 2: Autonomous Subsurface Habitat Construction

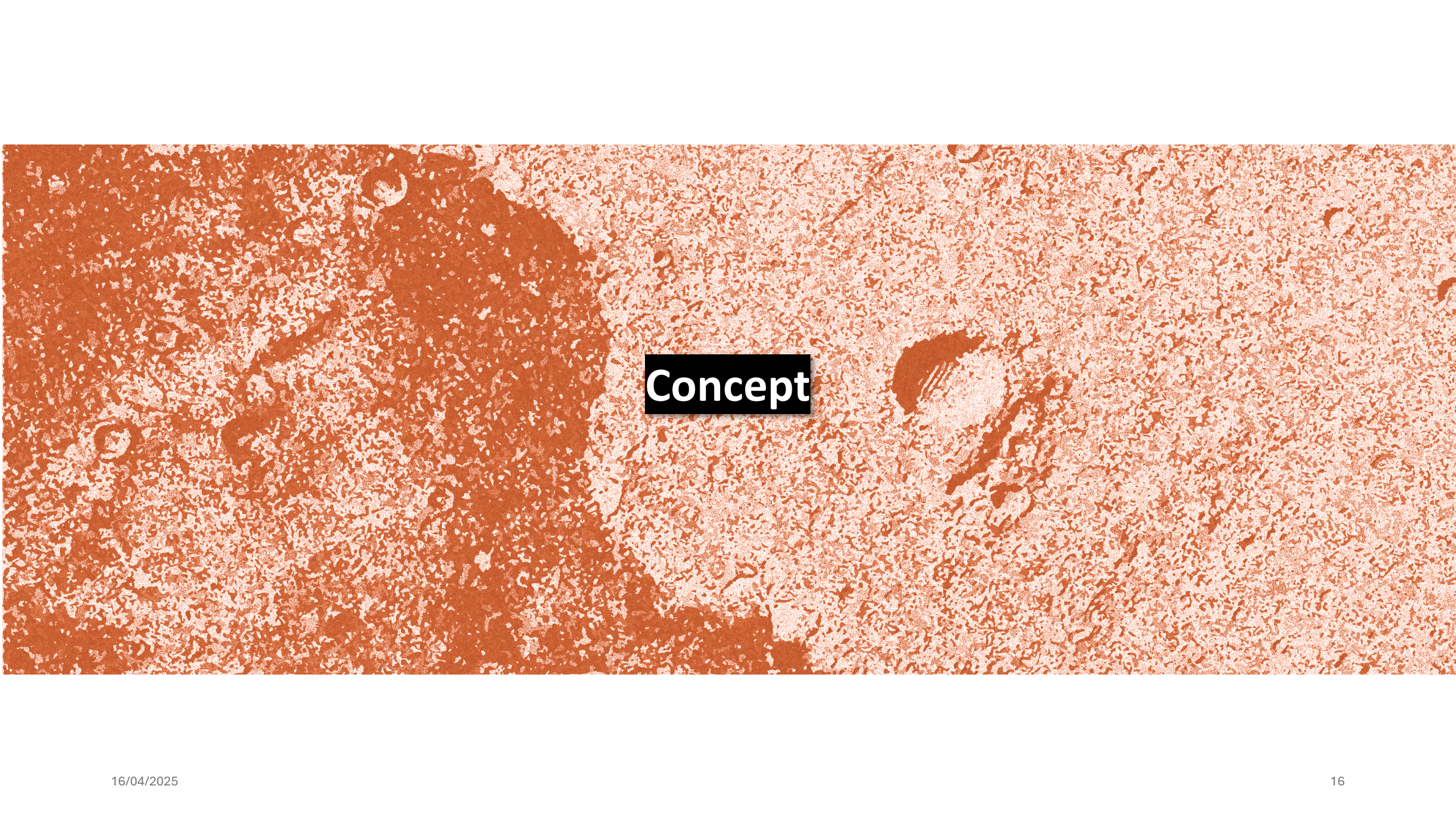
Develop a **3D-printed Martian habitat** in lava tubes using **In-Situ Resource Utilization (ISRU)** and autonomous robotic construction.

Challenges:

- **Scalability:** Can the method work at real-life construction scales?
- **Autonomous construction:** Coordinating swarm robots for mining, 3D printing, and assembly.
- **Material properties:** Ensuring cementless regolith concrete is durable in Mars' extreme conditions.

Learnings:

- **R/HRI-supported robotic workflows** are crucial for off-Earth construction.
- **Lava tubes offer natural protection**, but adaptability in habitat design is essential.
- **Energy self-sufficiency & closed-loop life support** are key to long-term survival.

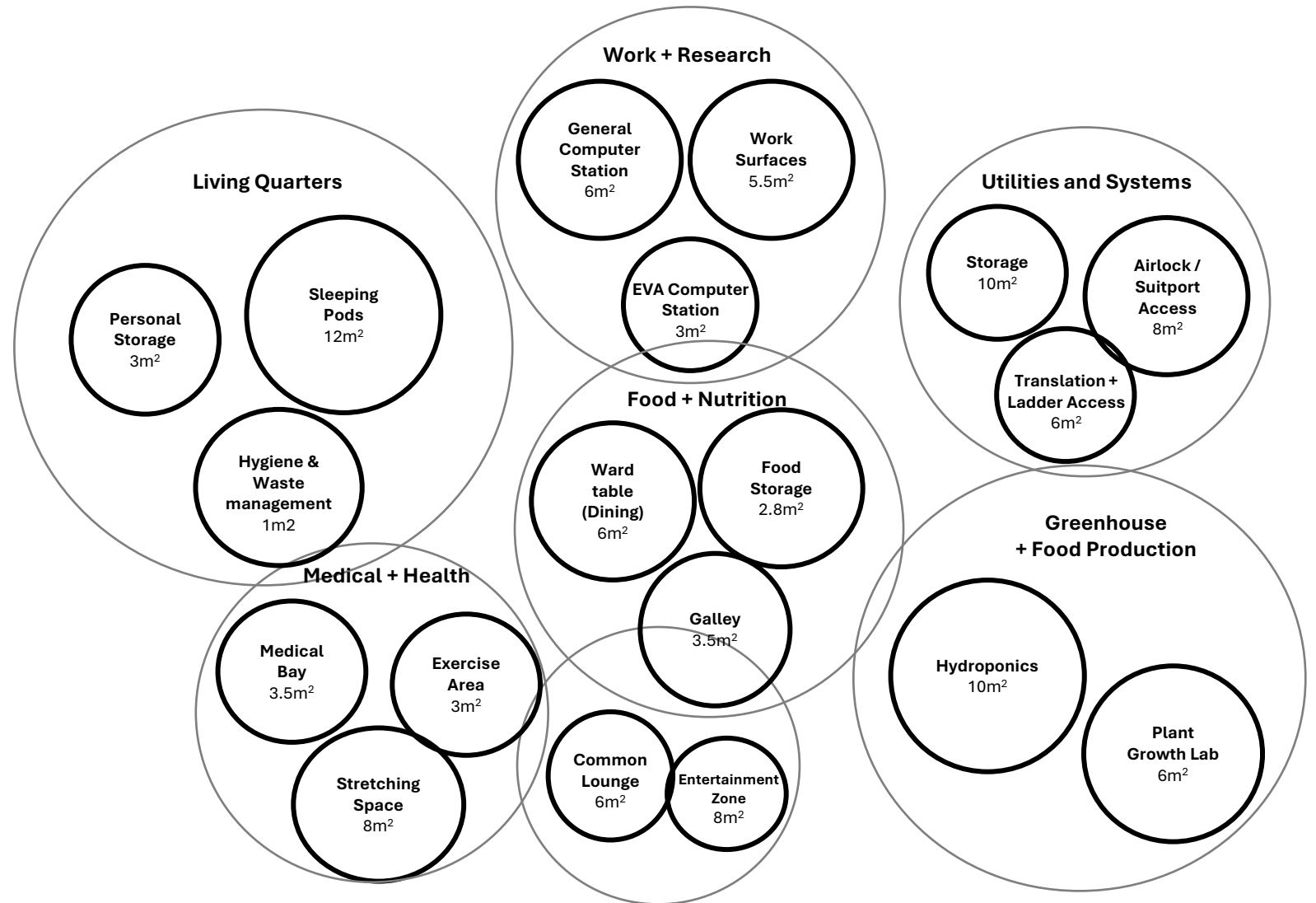
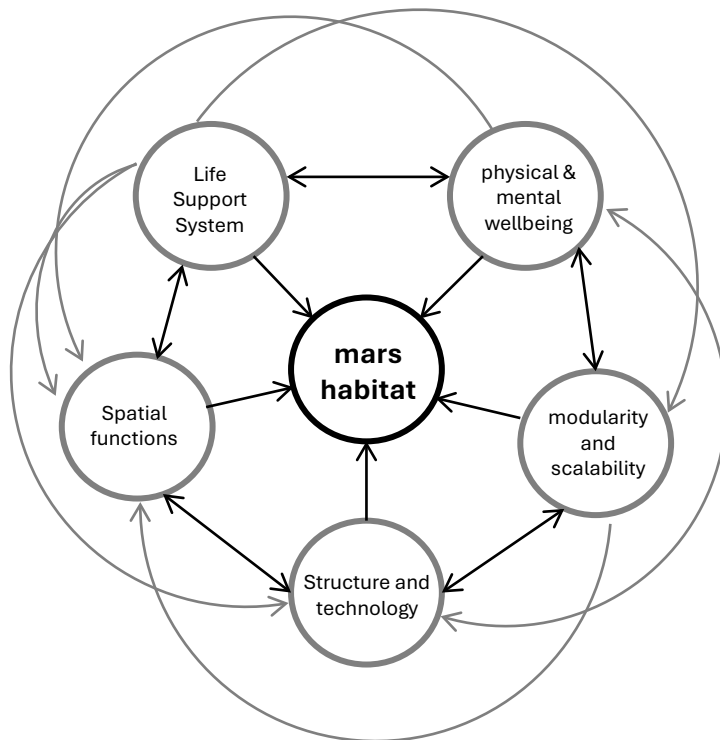


Concept

Design Concepts

Stage 1 – spatial relations

Stage 2 – form and function



Design Concepts

Stage 1 – spatial relations

Stage 2 – form and function

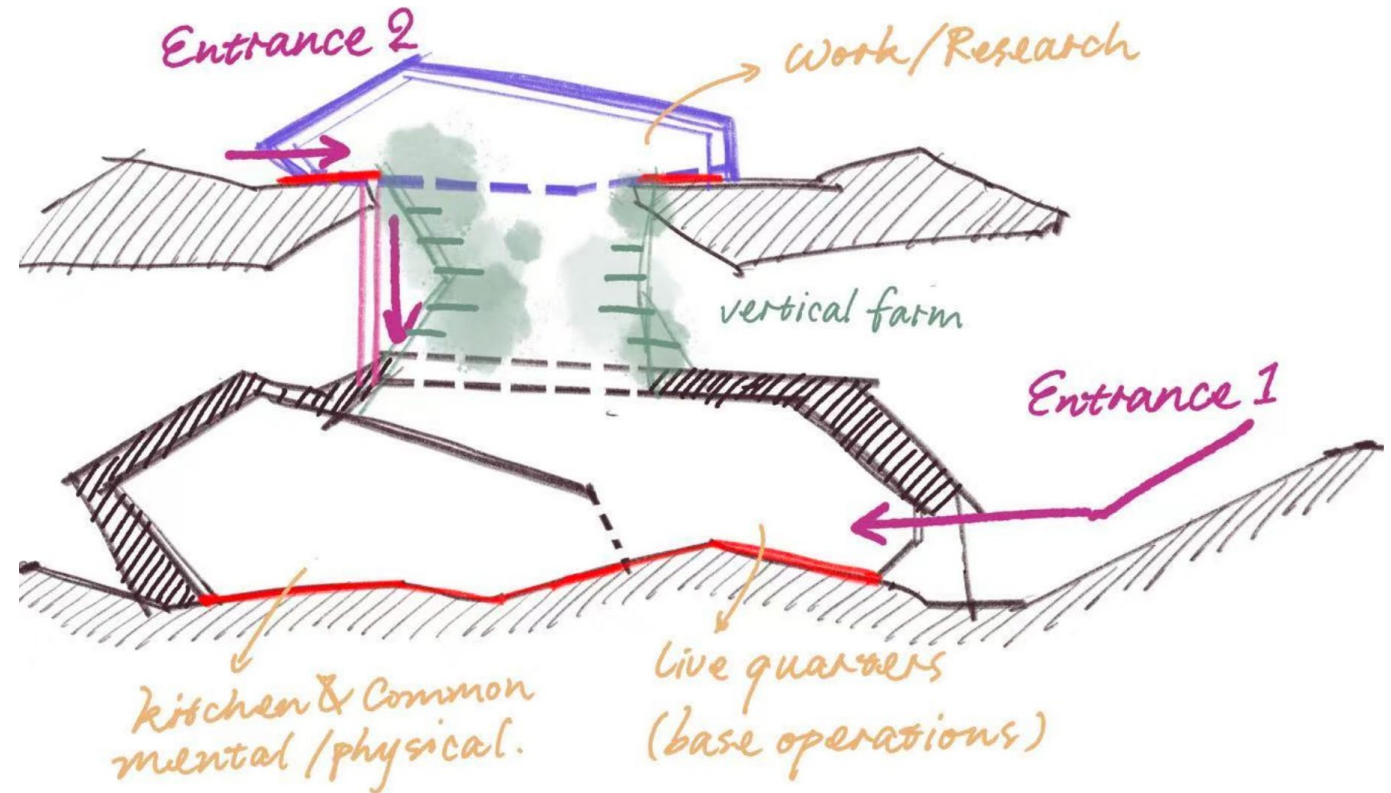
Variants 01

Pros:

- Equipped with Surface laboratory, mechanical equipment warehouse and surface entrance;
- Providing dual-layer protection for underground living spaces;
- Guaranteeing double entrances, one from the planet surface and one through the lava tube.

Cons:

- Difficult to shape
- Difficult to combine the horizontal mobility with the vertical one
- High material consumption caused by the previous aspects



Design Concepts

Stage 1 – spatial relations

Stage 2 – form and function

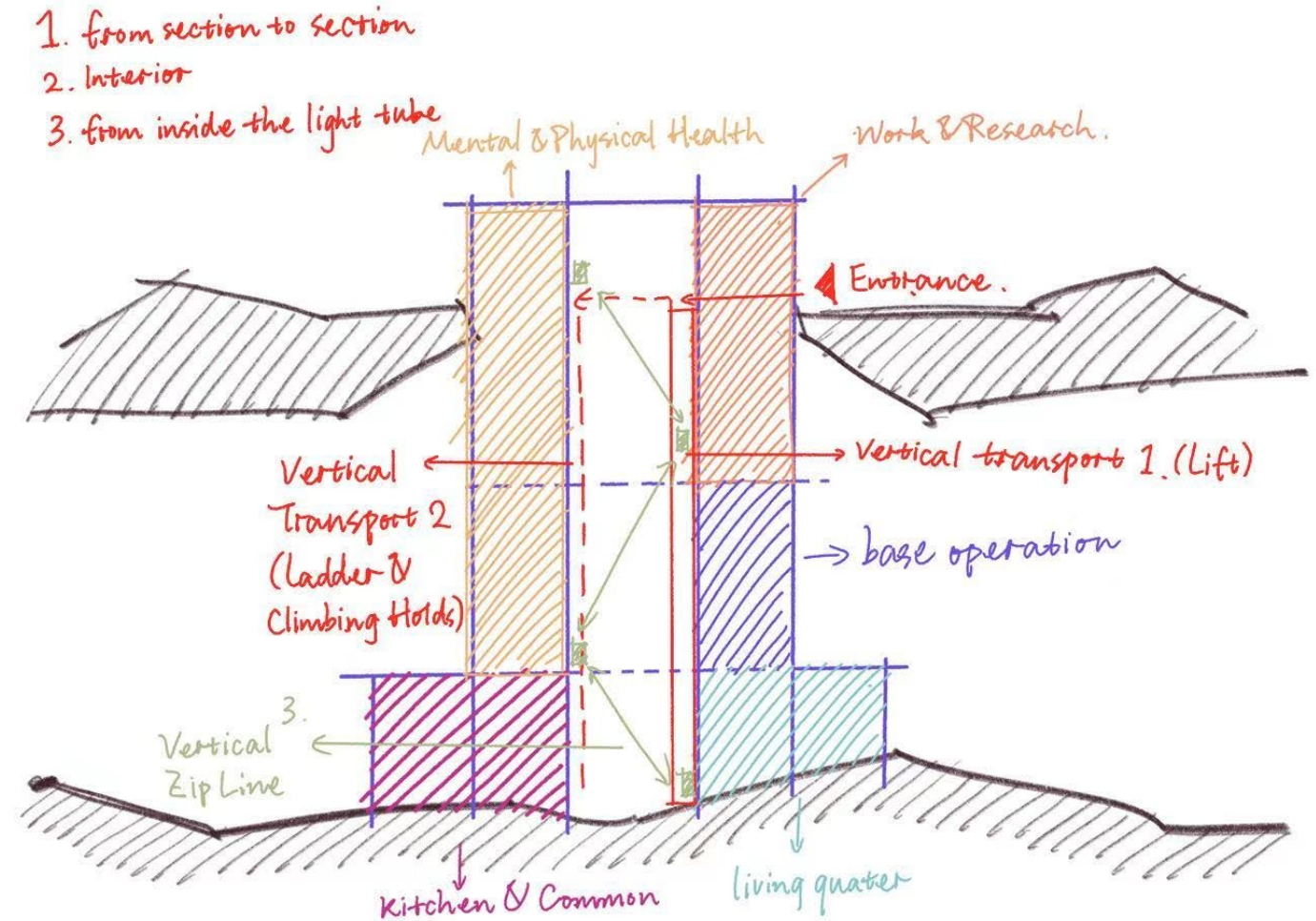
Variant 02

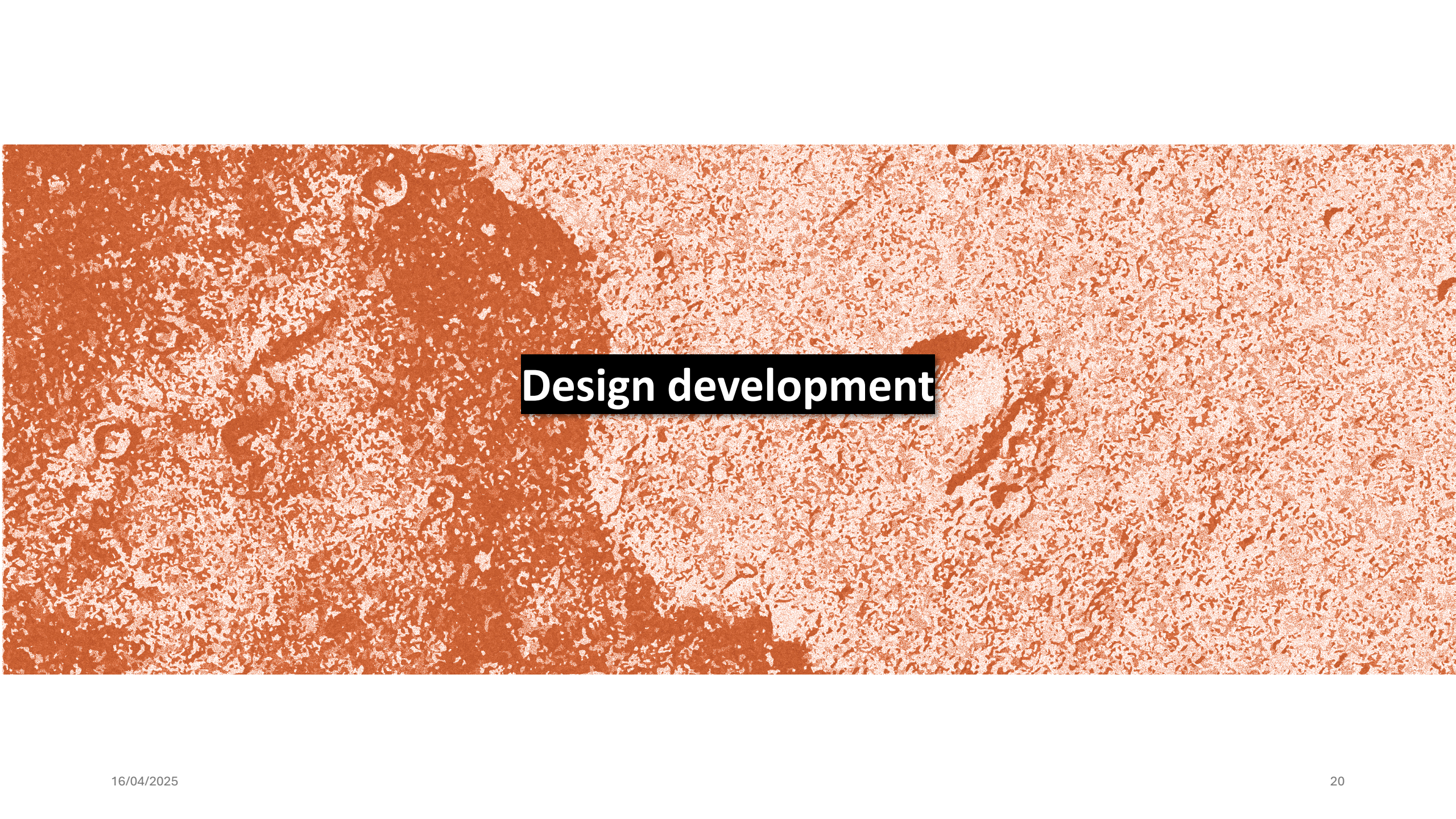
Pros:

- Equipped with Surface laboratory, mechanical equipment warehouse and surface entrance;
- Providing dual-layer protection for underground living spaces;
- Guaranteeing double entrances, one from the planet surface and one through the lava tube;
- Continuous and centralized vertical distribution;
- Enabling the penetration of natural light and its diffusion to the lower levels through the central void

Cons:

- LSS must follow vertical distribution



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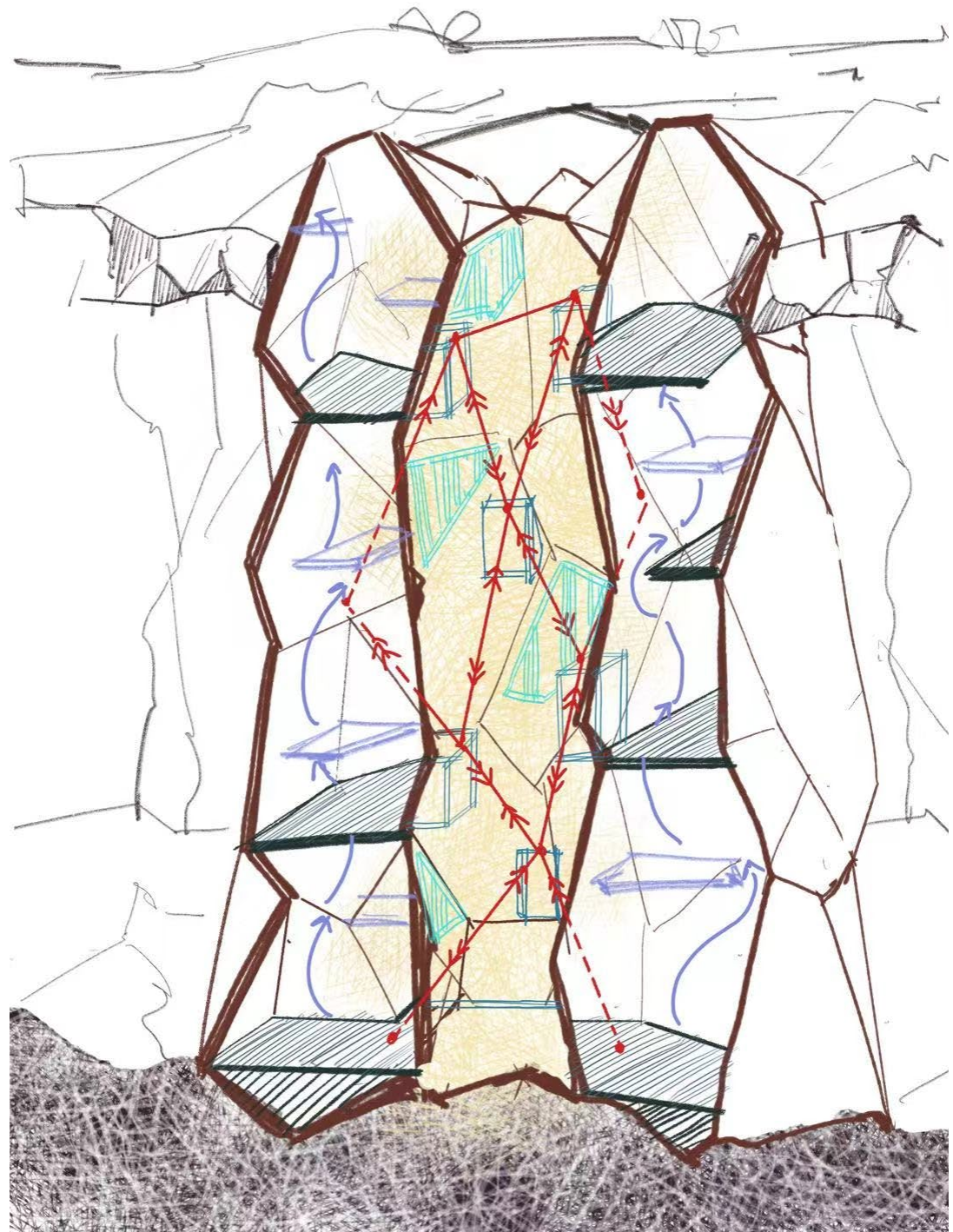
Design development

Design Development

Concept Recap

Conceptual Sketch

Voronoi Structure Development

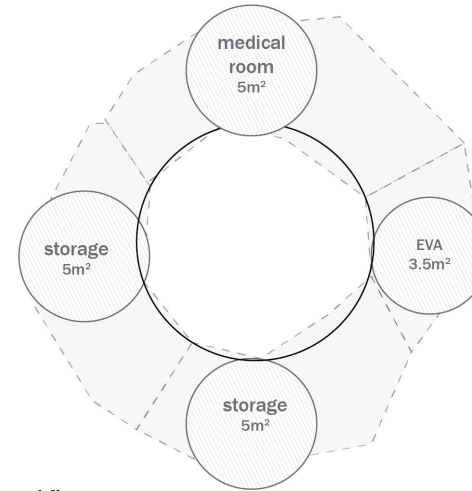


Design Development

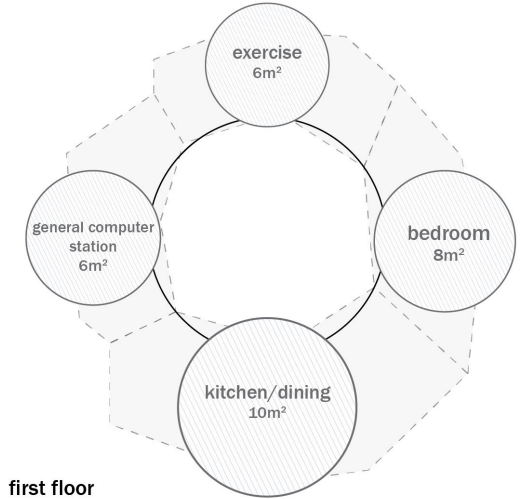
Concept Recap

Conceptual Sketch

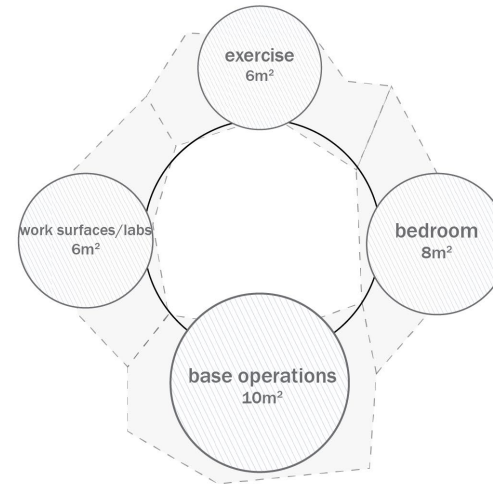
Voronoi Structure Development



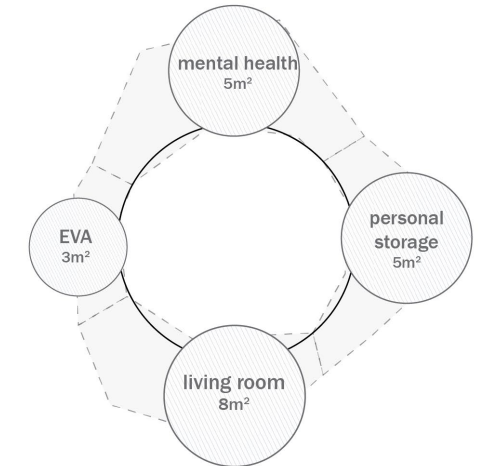
ground floor



first floor



second floor



third floor

Floor plan concept

Design Development

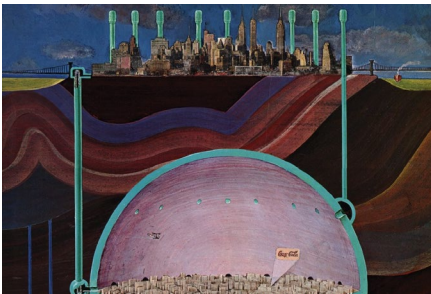
Concept Recap

Conceptual Sketch

Voronoi Structure Development

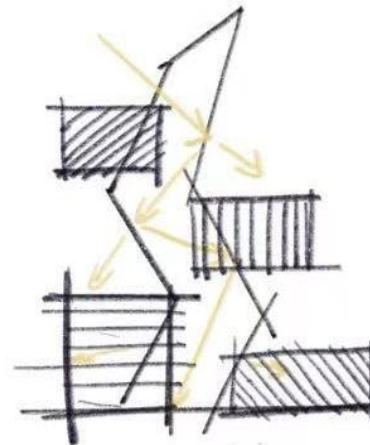


Oscar Newman's fantasy, nuclear metropolis deep underground in New York



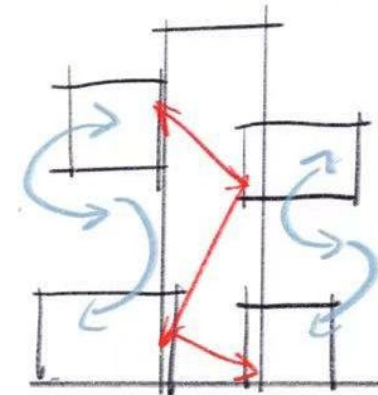
Underground oasis for Martian habitat

CONCEPT 1:
LIGHT TUBE



REFLECTIVE
MATERIAL

CONCEPT 2
VERTICAL
MOVEMENT



SLOW FAST SLOW

METHODOLOGY
VORONOI-BASED
DESIGN



VERTICALLY
STRETCHED

Design Development

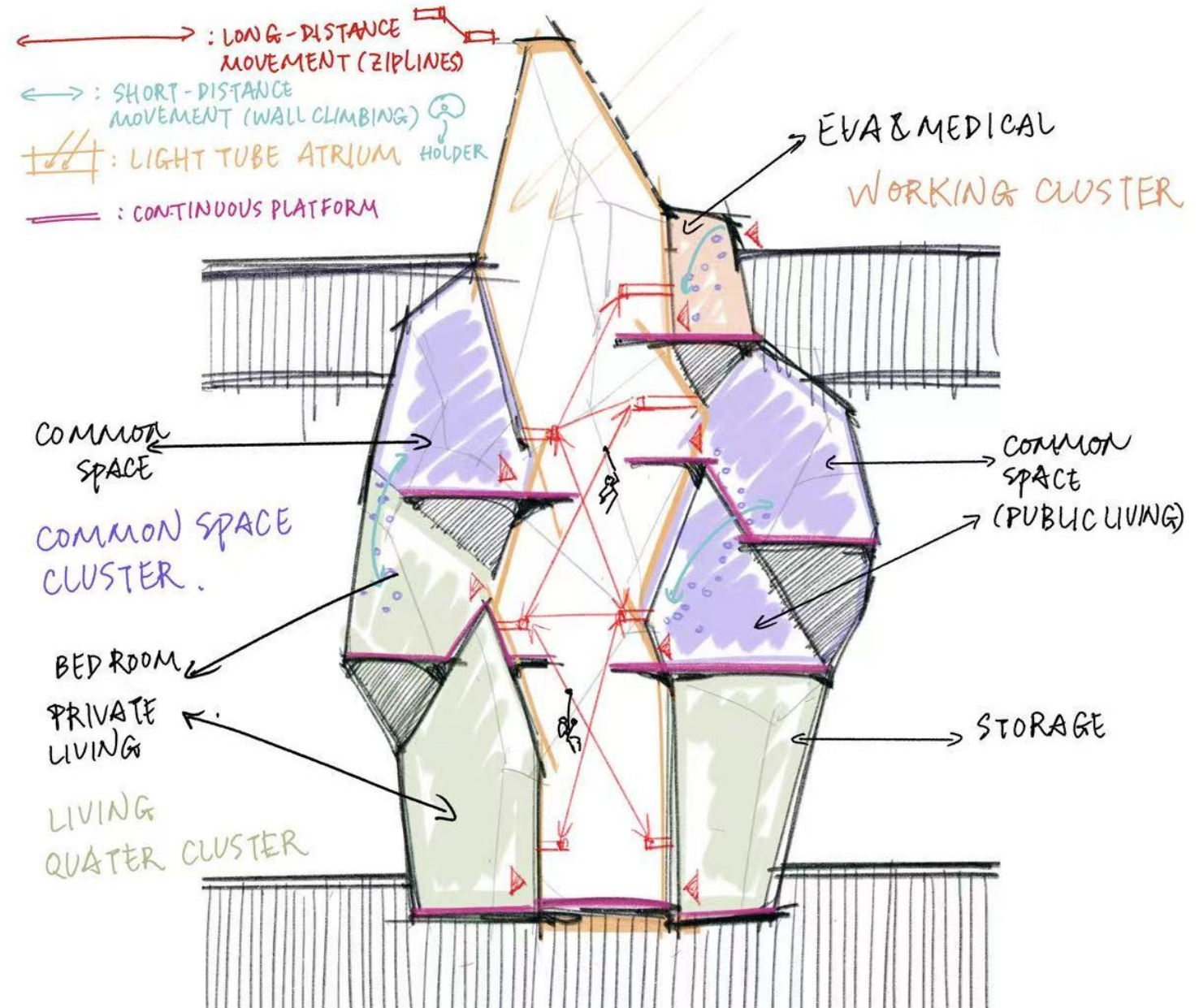
Concept Recap

Conceptual Section

Voronoi Structure Development

Use 3 methods for vertical transportation inside the building:

- The ramps ensure robotic and human regular vertical movement between all the levels.
- Ziplines provide an angled mode of movement, primarily used for traveling between different functional clusters.
- Wall climb holders provide an internal mobility solution within each functional area, facilitating short-distance vertical movement.



Design Development

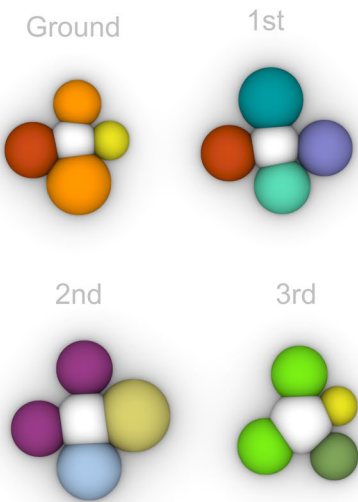
Concept Recap

Conceptual Section

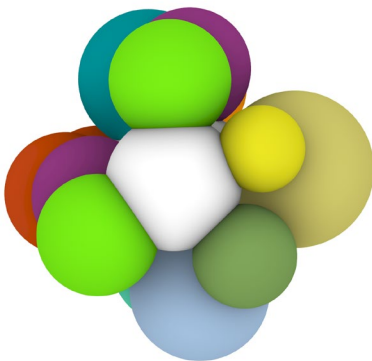
Voronoi Structure Development



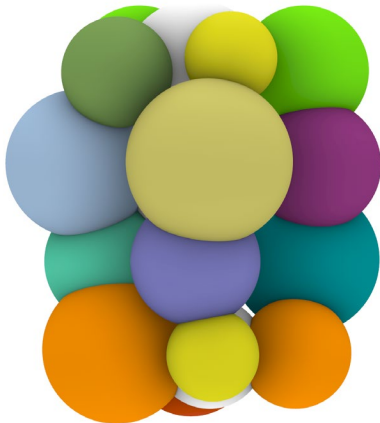
Room types and area



Bubble plans



Plans stacked top view



Plans stacked elevation view

▲ _Atrium	💡	🔒	□
_Work	💡	🔒	■
_Entertainment	💡	🔒	■
_Exercise	💡	🔒	■
_Hygiene	💡	🔒	■
_Kitchen	💡	🔒	■
_Living	💡	🔒	■
_MedicalRoom	💡	🔒	■
_MentalHealth	💡	🔒	■
_Operation	💡	🔒	■
_Sleeping	💡	🔒	■
_Storage	💡	🔒	■
_AirLock	💡	🔒	■

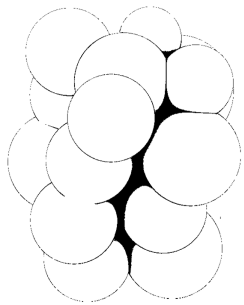
Key!

Design Development

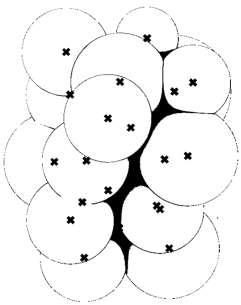
Concept Recap

Conceptual Section

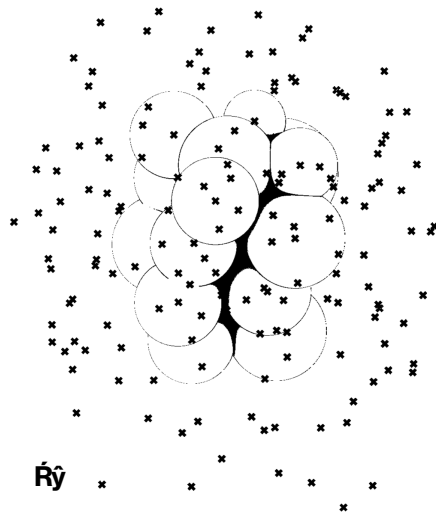
Voronoi Structure Development



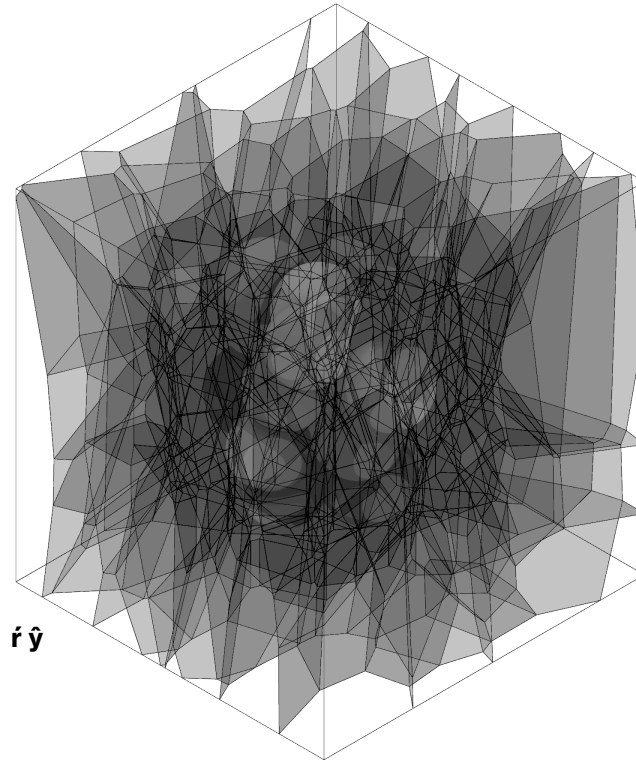
R_y



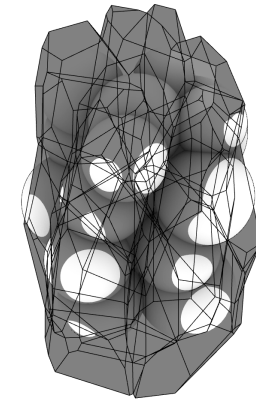
o_y



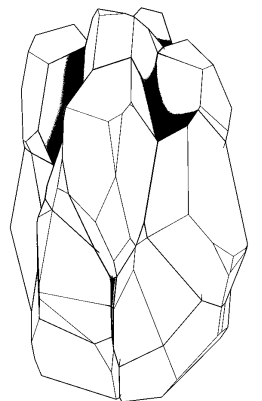
R_y



r_y



R_y



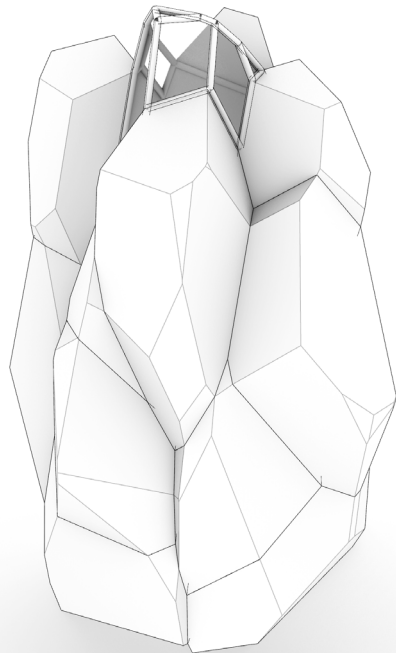
r_y

Design Development

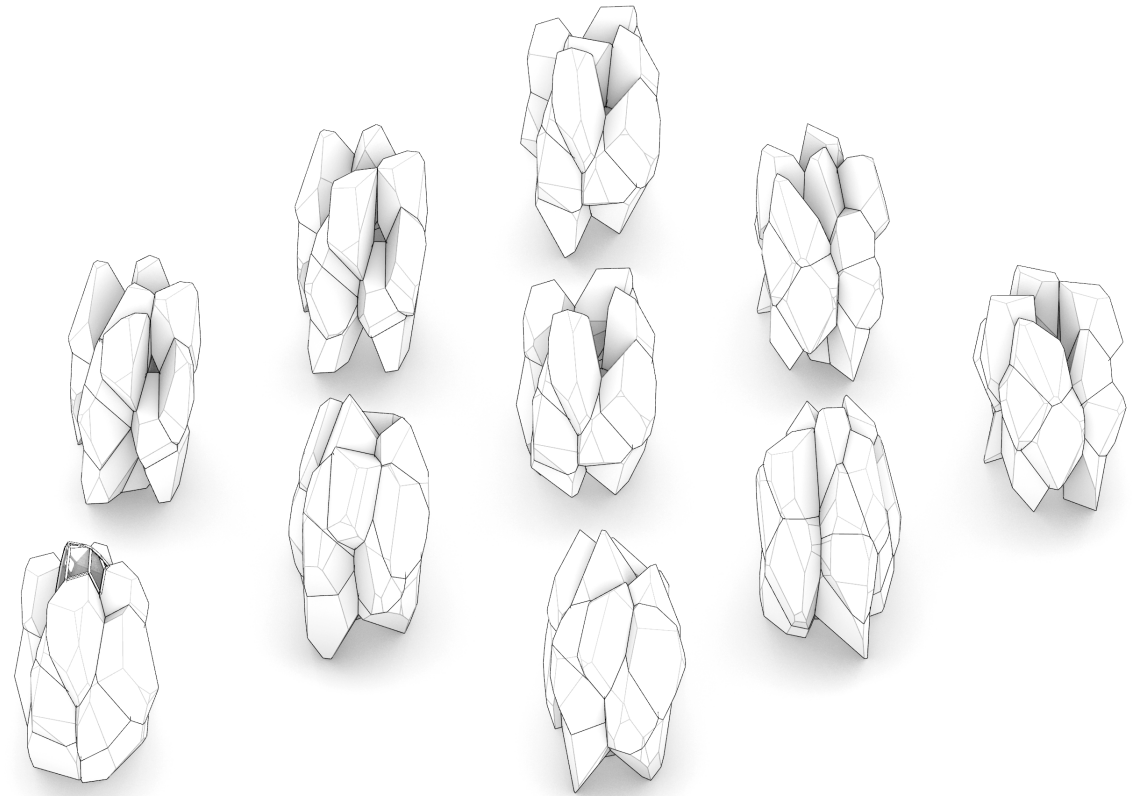
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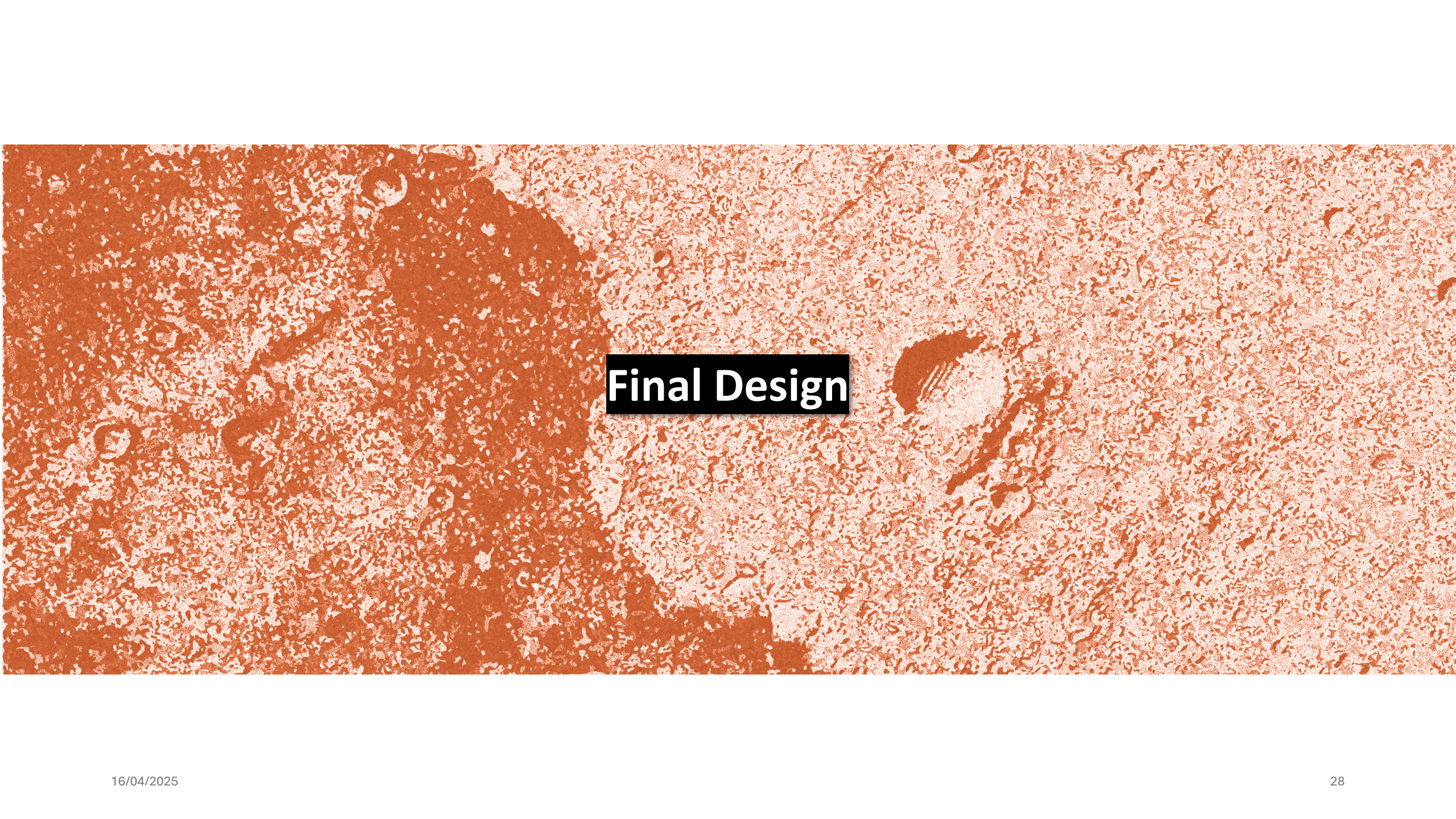
Conceptual Section

Voronoi Structure Development



selected variant



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Final Design

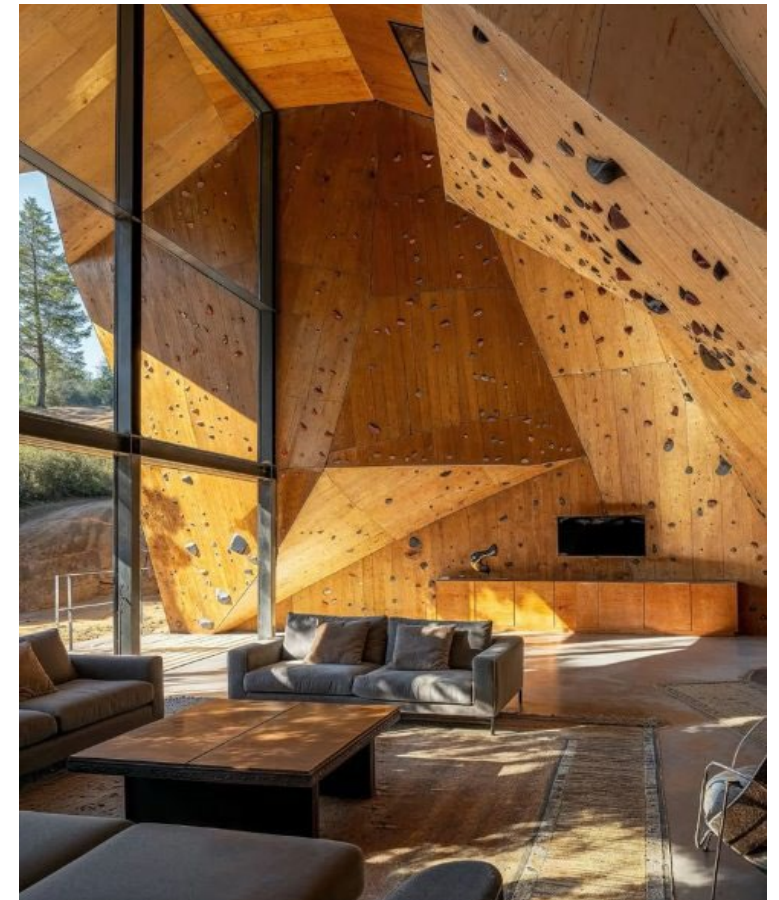
Central Void

References

Concept



New Collectivism / O-office Architects



Climb House

Void

References

Concept

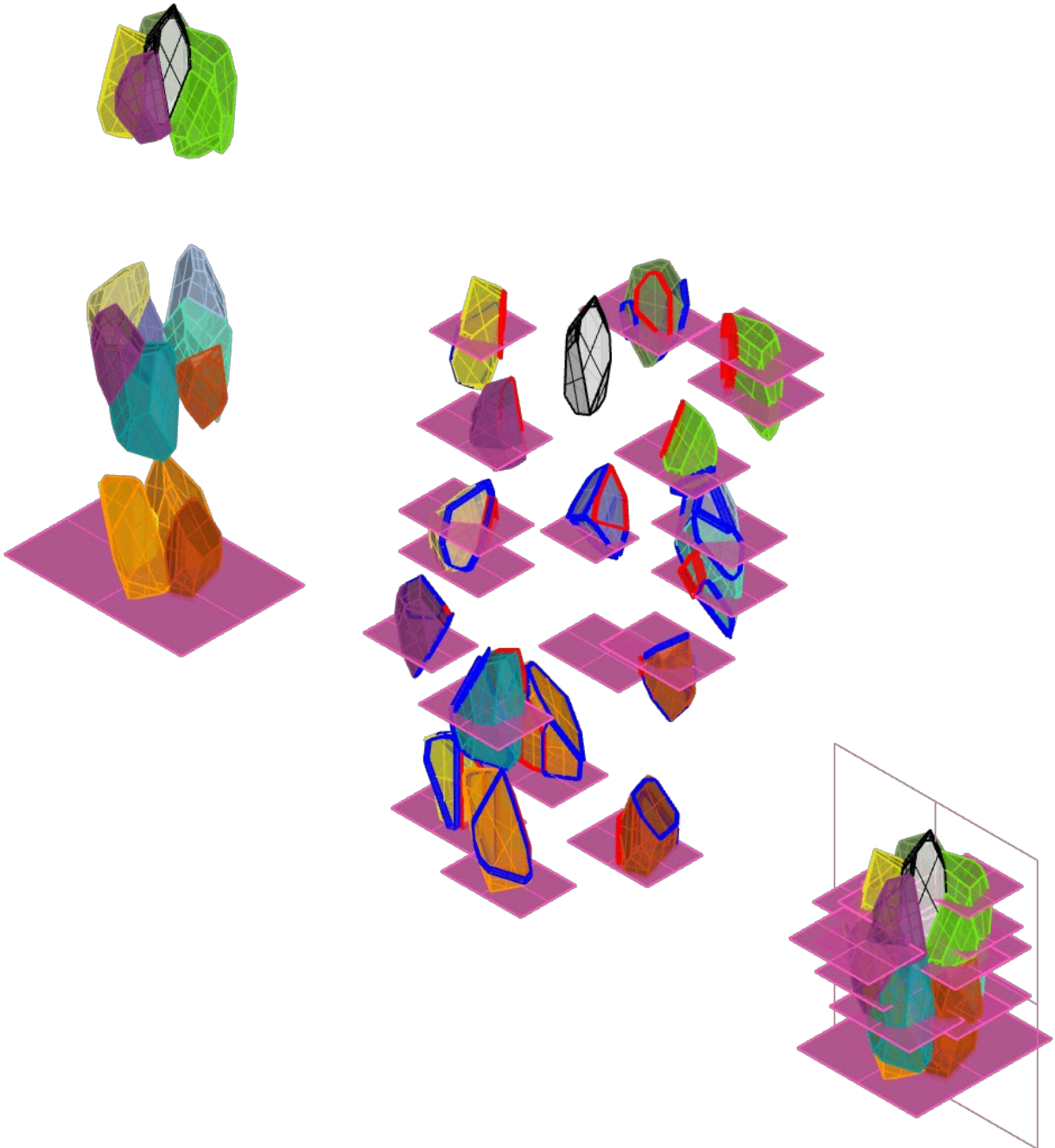
Central void:

- Diffusing natural light
- Working as a circulation core
- Giving different mobility solutions
- Functioning as a vertical garden

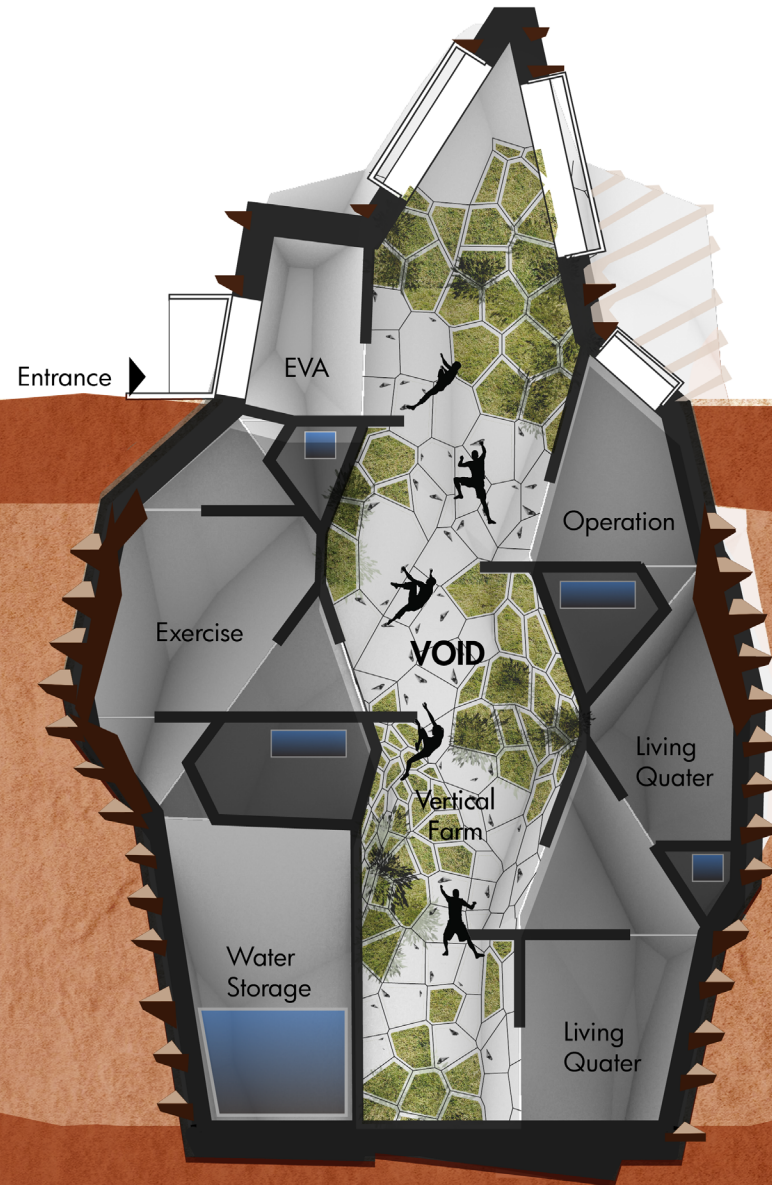


Defining Horizontal Planes

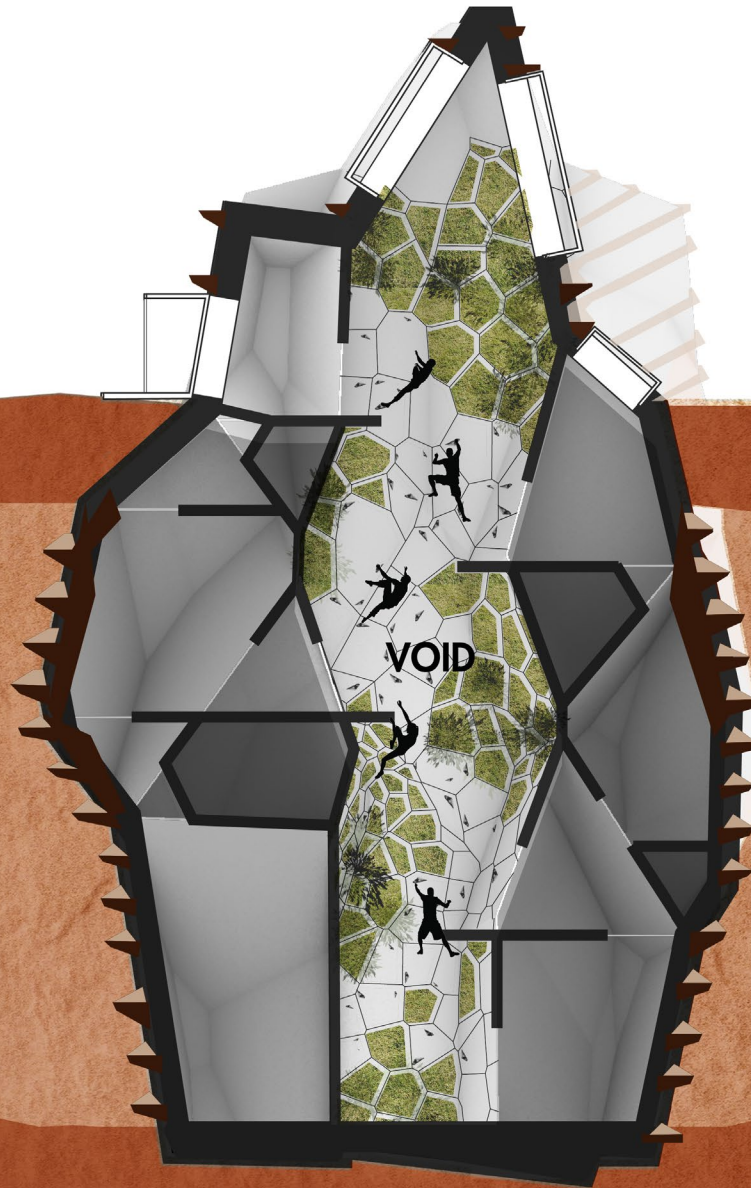
- Different horizontal plane within each volume
- Considered the height of space
- Connection with the openings
- Connection between the volumes
- Space for mechanical room in each cluster



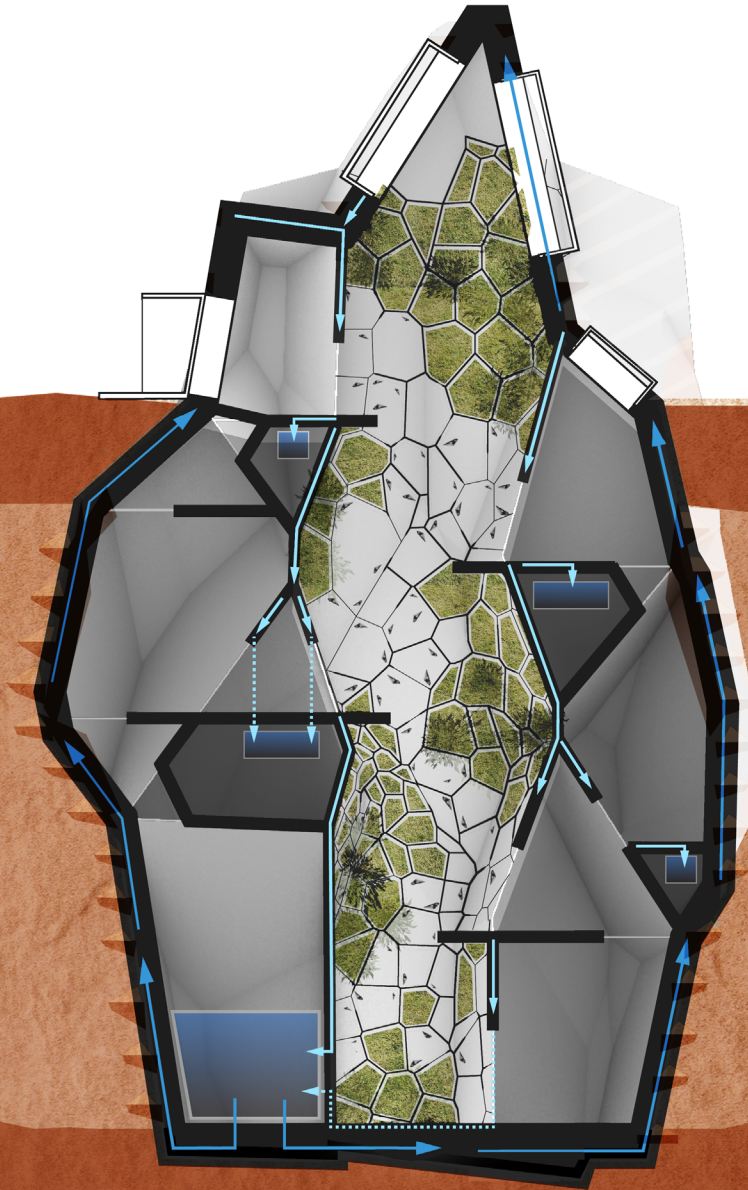
Section



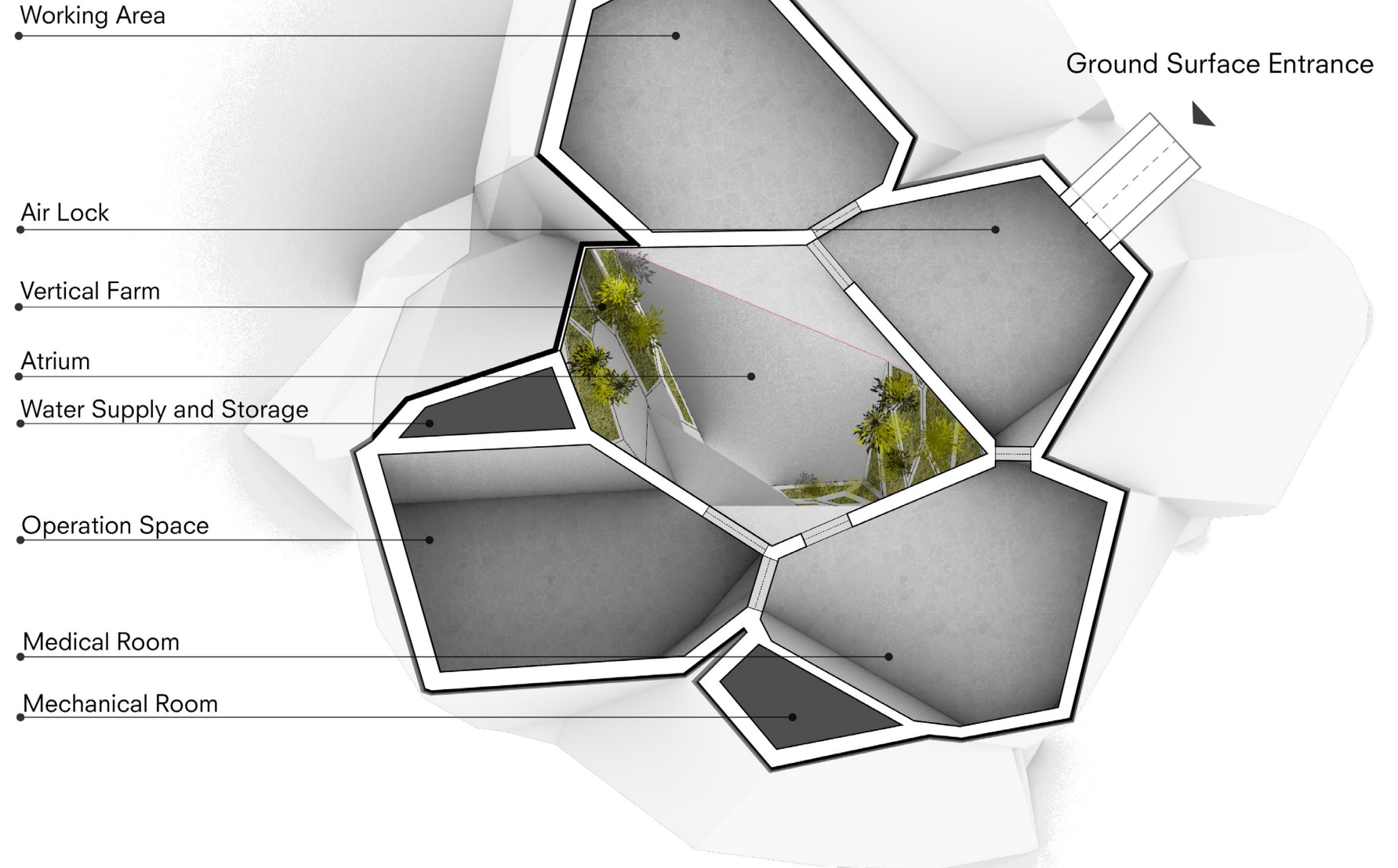
Void



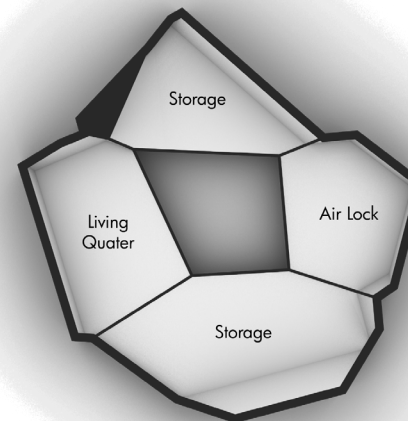
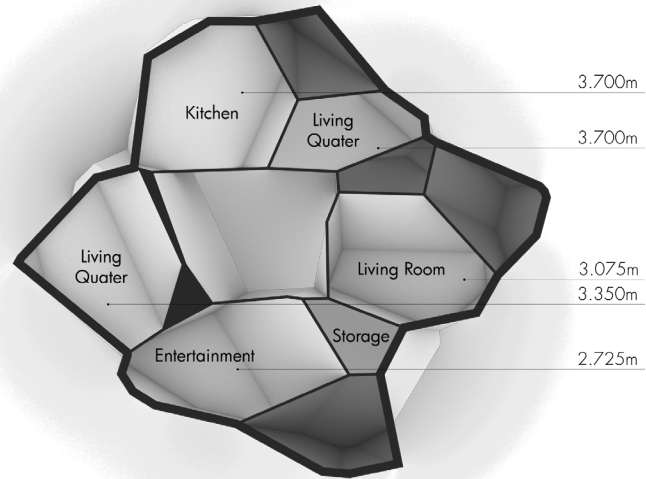
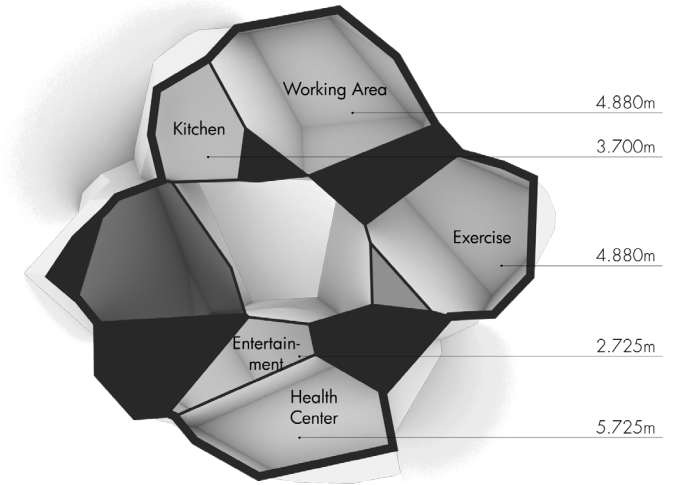
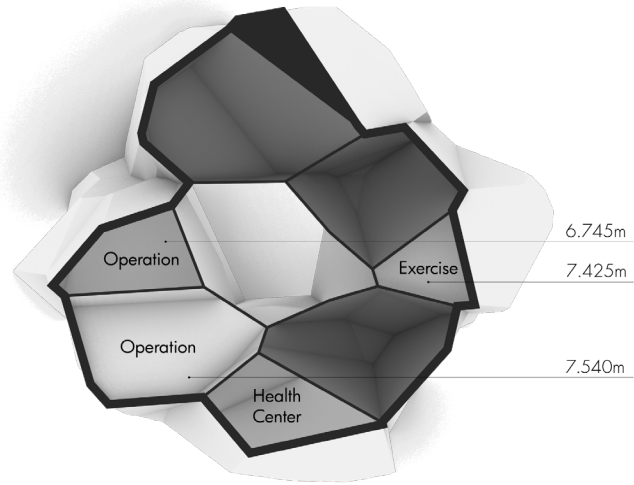
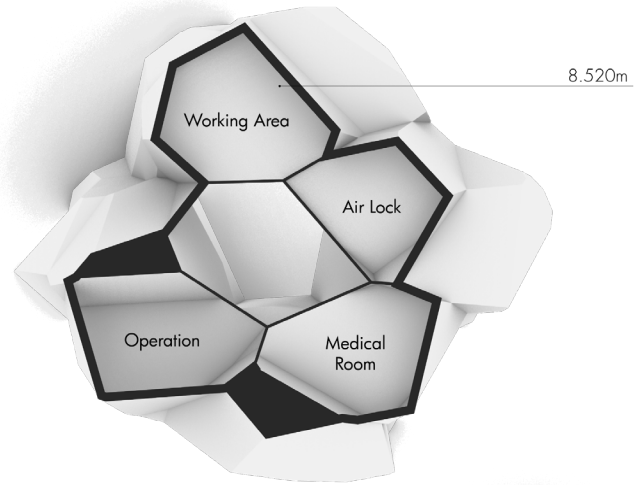
Water Distribution and Storage



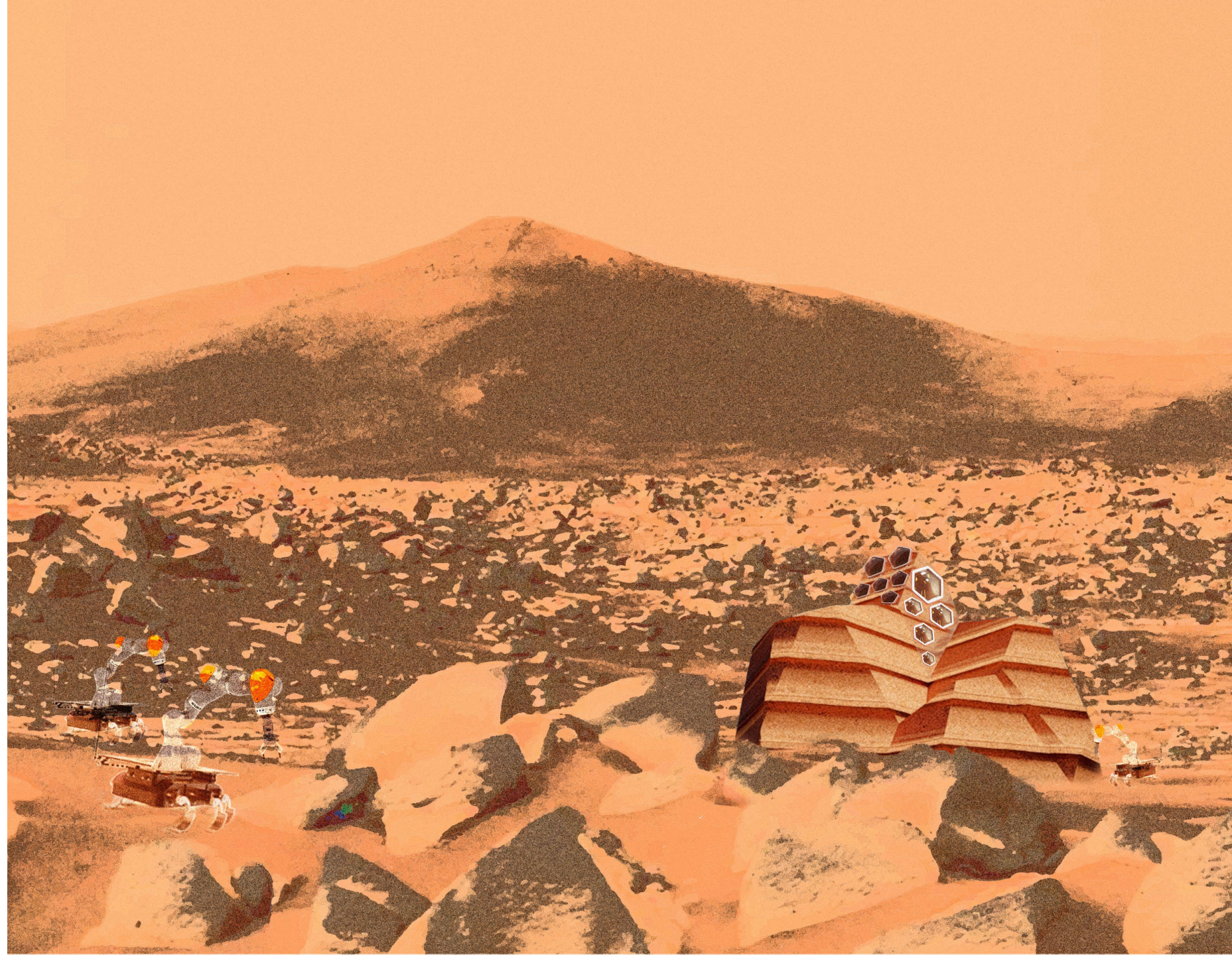
Entry level plan



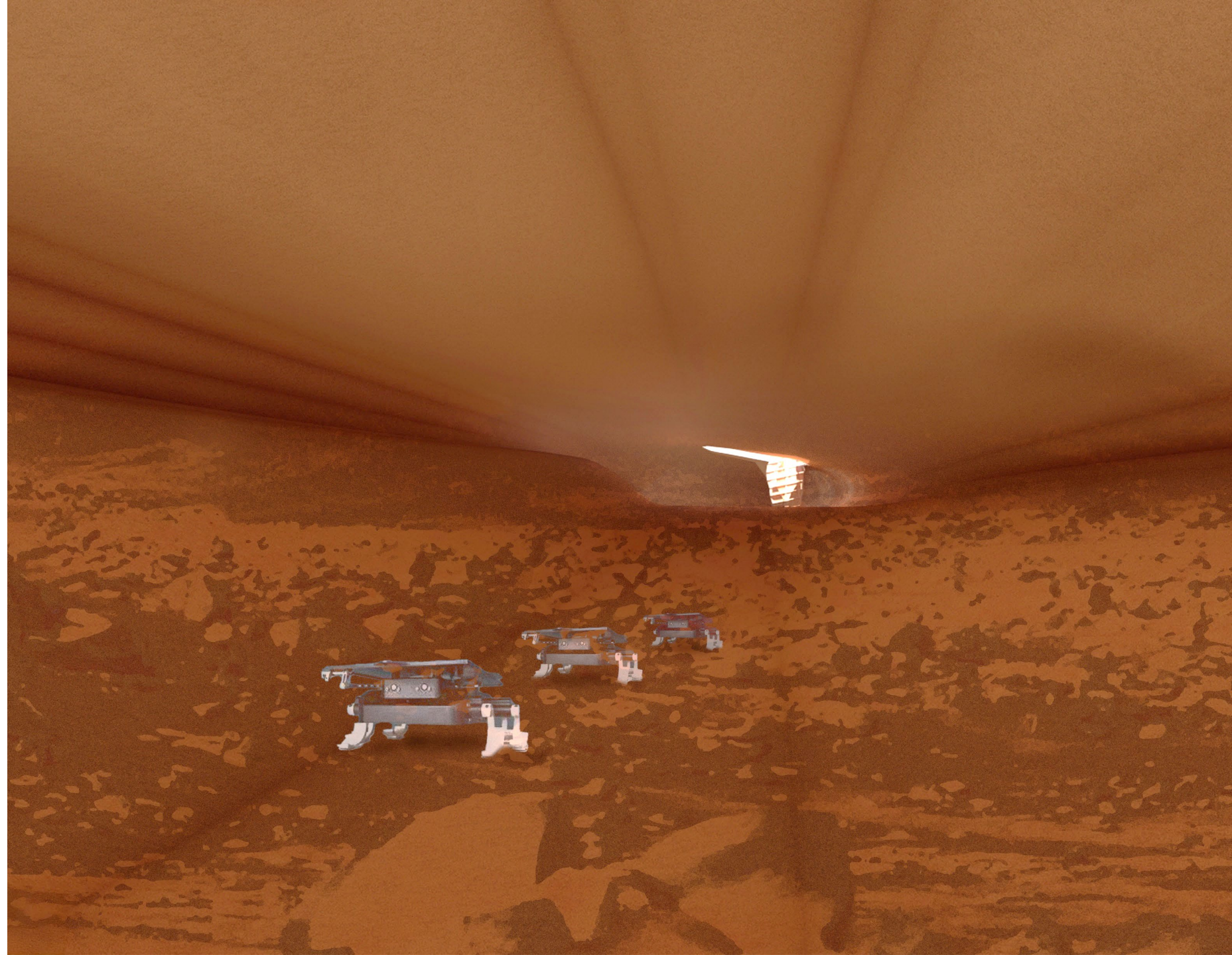
Floor Plans

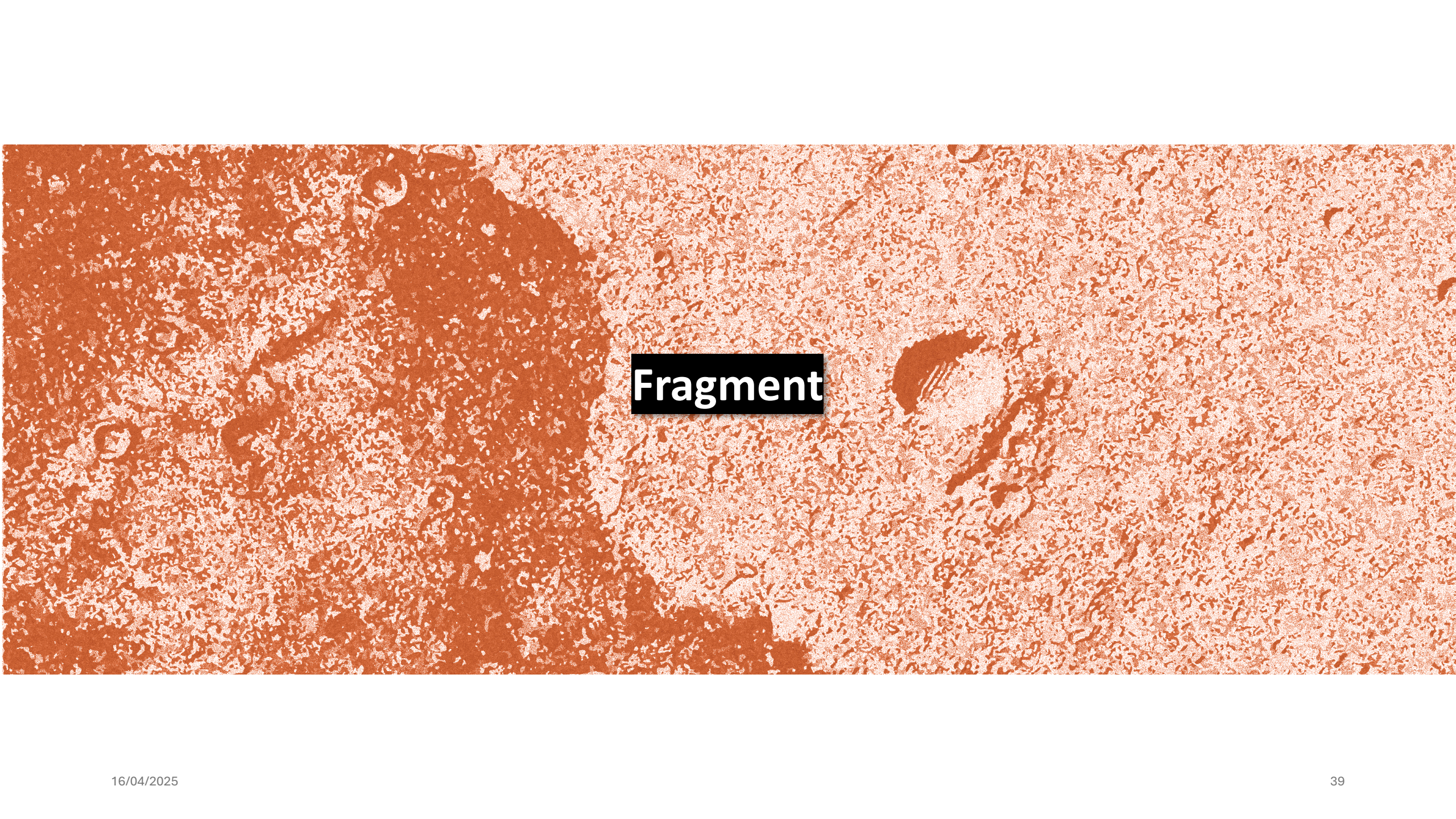


Visualisation



Visualisation



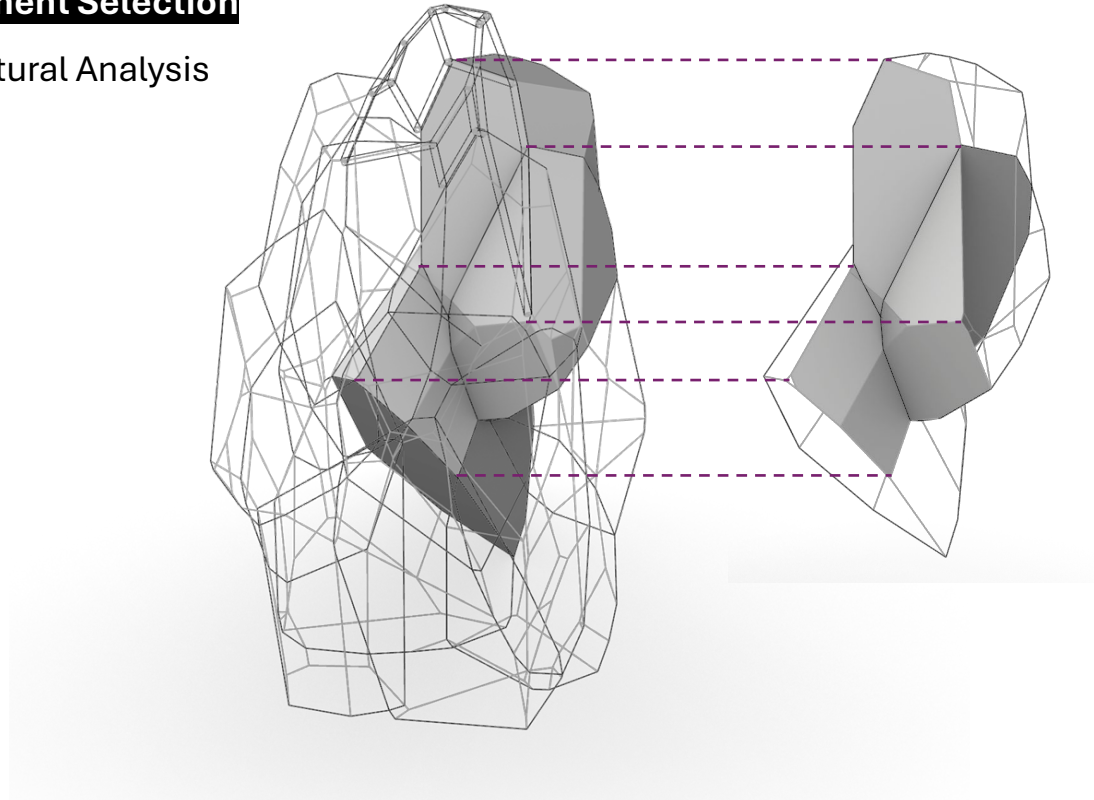


Fragment

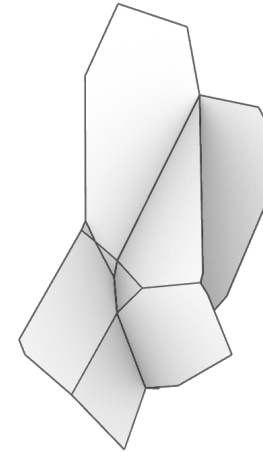
Fragment Selection

Fragment Selection

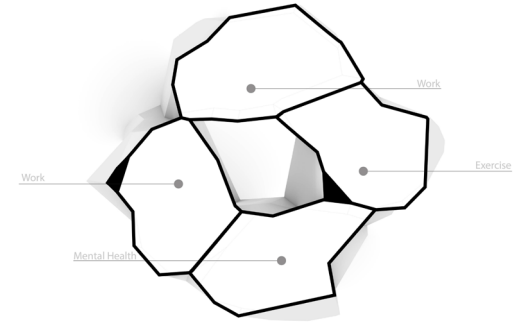
Structural Analysis



Selecting the fragment from the habitat



Selecting surfaces

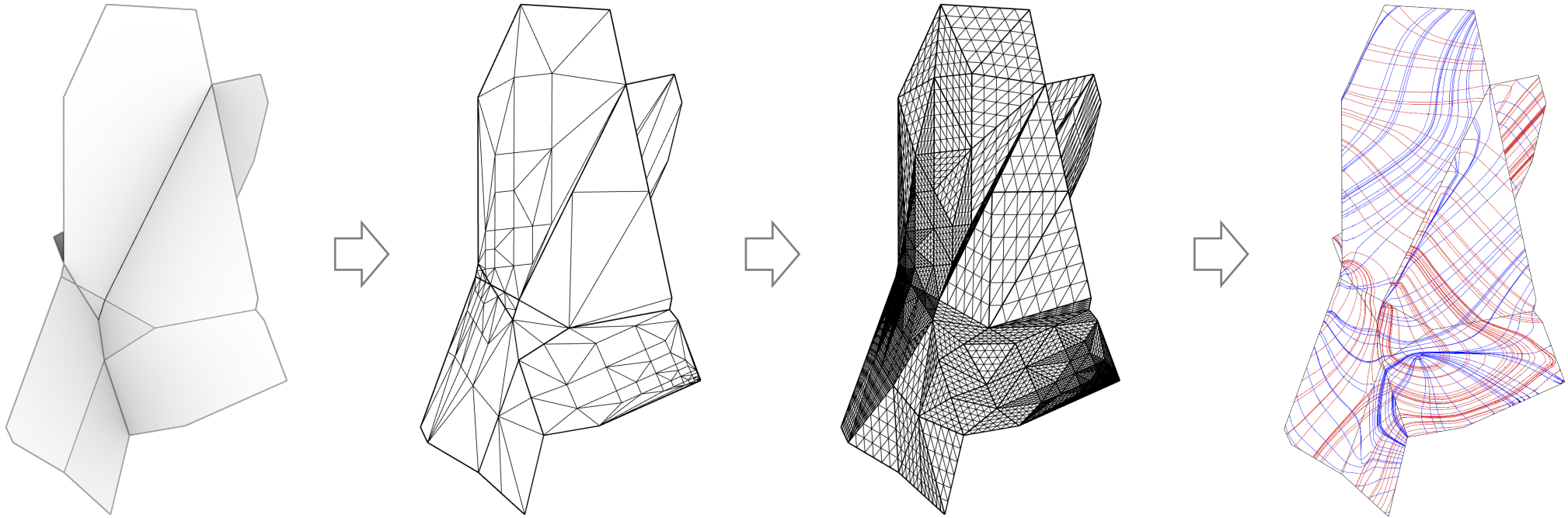


Floor plan reference

Fragment Selection

Fragment Selection

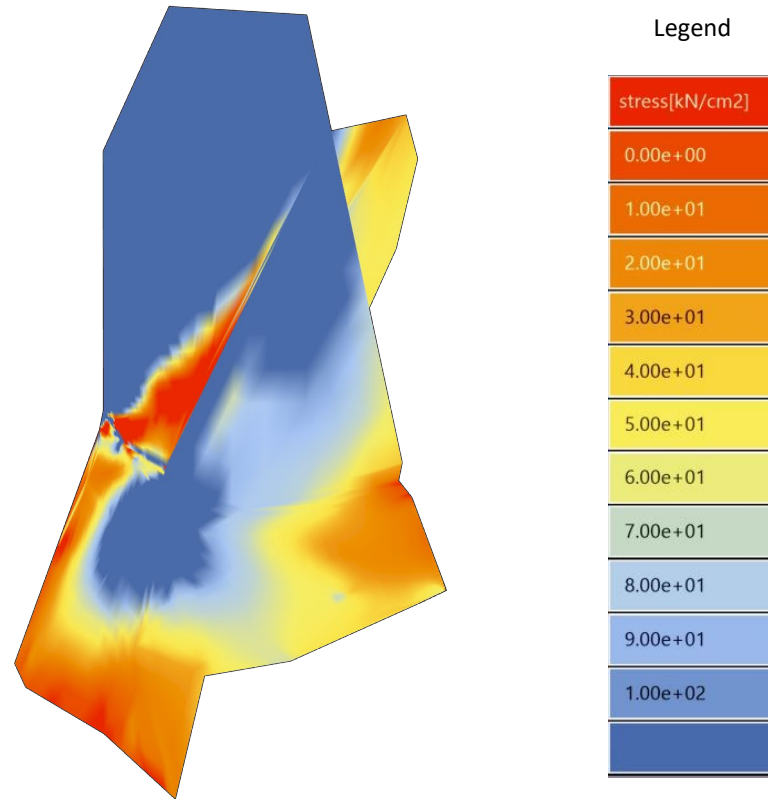
Structural Analysis



Fragment Selection

Fragment Selection

Structural Analysis

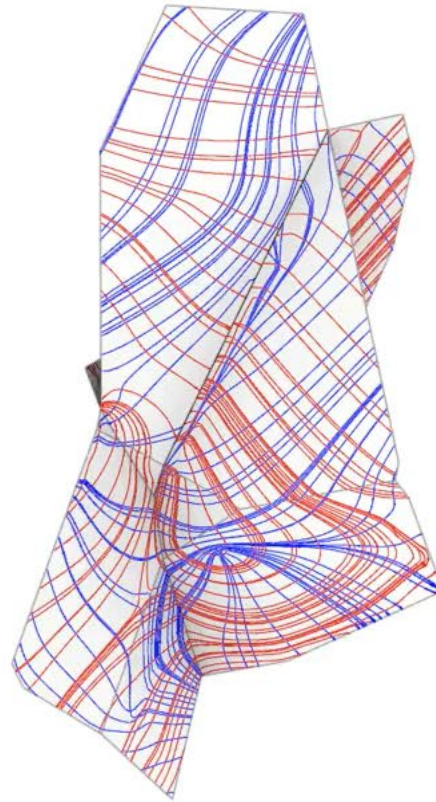


Stress loads values

Fragment Selection

Fragment Selection

Structural Analysis

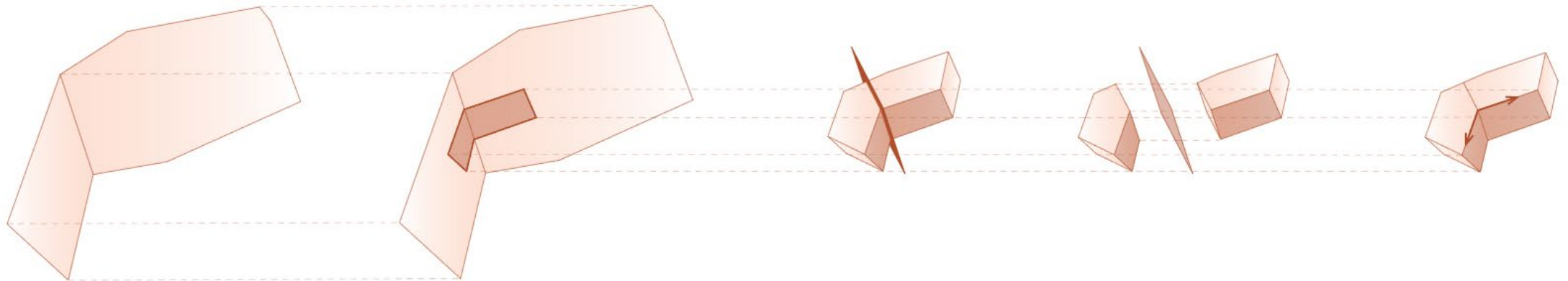


Stress and tension lines from all sides of the fragment

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables



Selecting two polysurfaces
from the fragment

Choosing one small part
of the fragment

Defining the
double surface

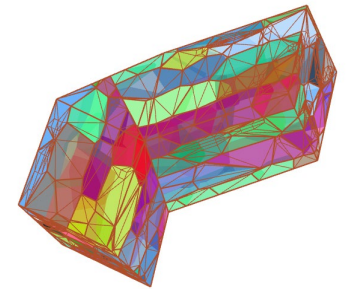
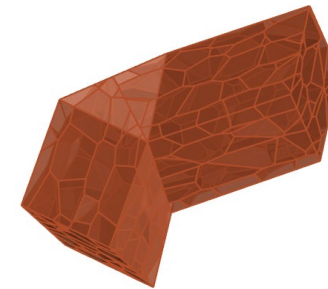
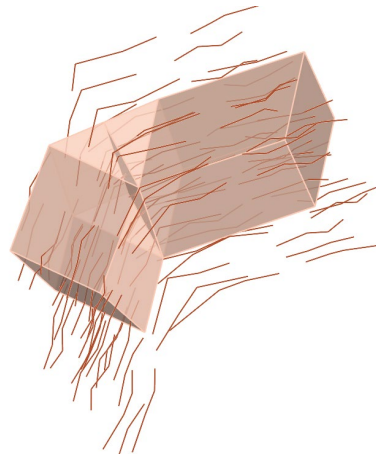
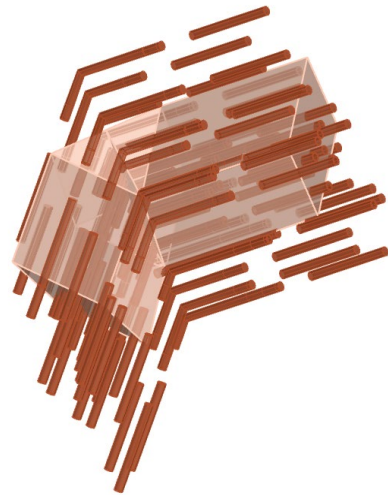
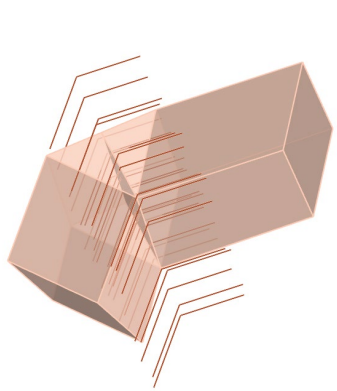
Dividing the fragment
in two brep segments

Creating the two
directions

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables



Generating upper and lower
lines from geometries

Generating upper lower
and mid mesh pipes

Giving polylines
random configuration

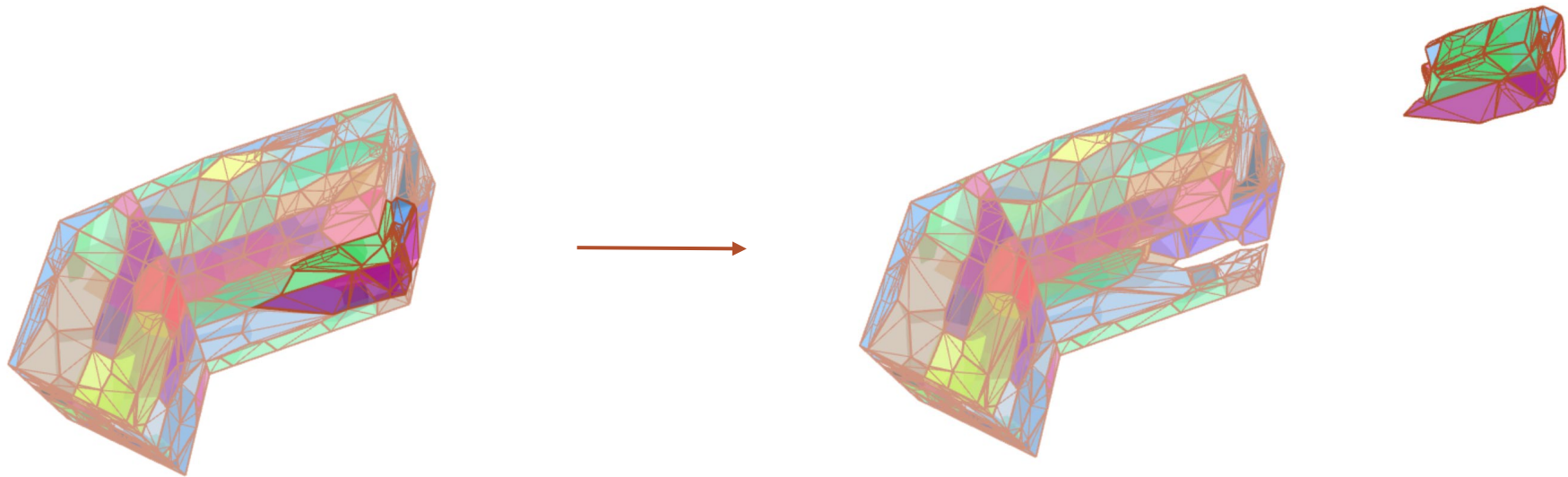
Generating voronoi cells
inside the fragment geometry

Baking the cells
generated

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables

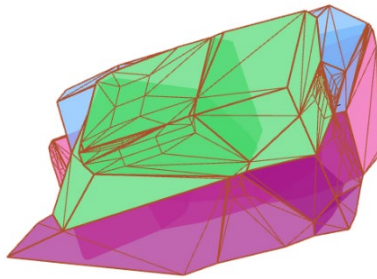


Selecting a small group of meshes for the integrate voronoi-based LSS piping and cables LAST

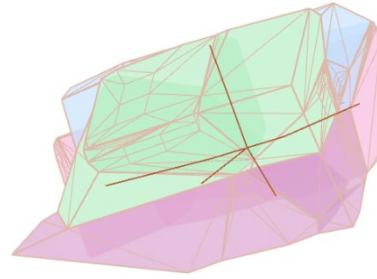
Kinked Voronoi Cells Generation

Kinked Voronoi Cells

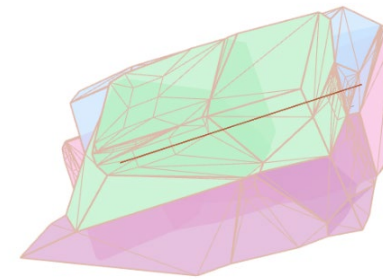
LSS piping and cables



Setting the four
geometries in the script



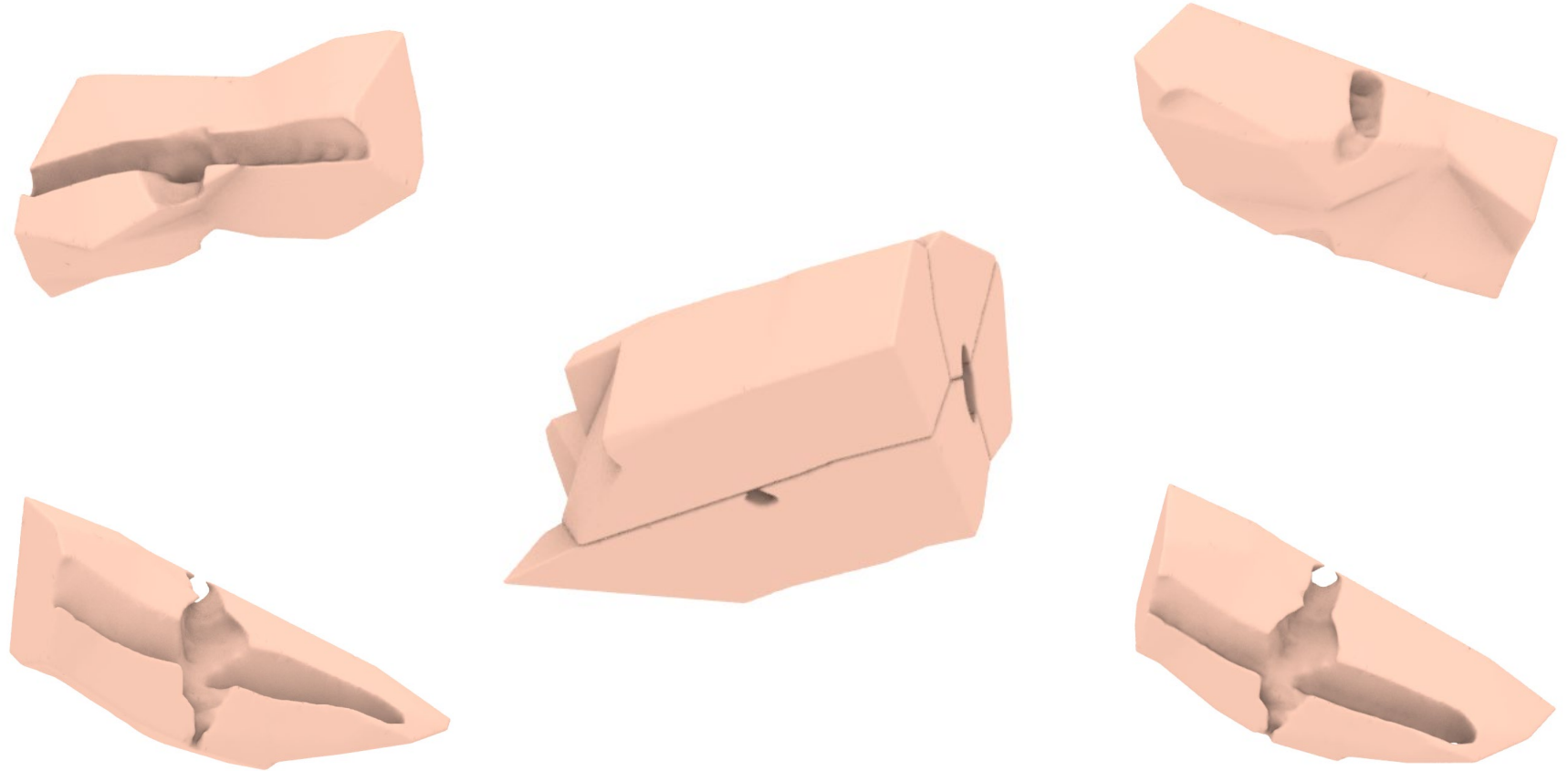
Setting the attractor curves that will determine
the paths of the integrated channels



Setting the voronoi
stretching direction

Kinked Voronoi Cells Generation

Kinked Voronoi Cells
LSS piping and cables

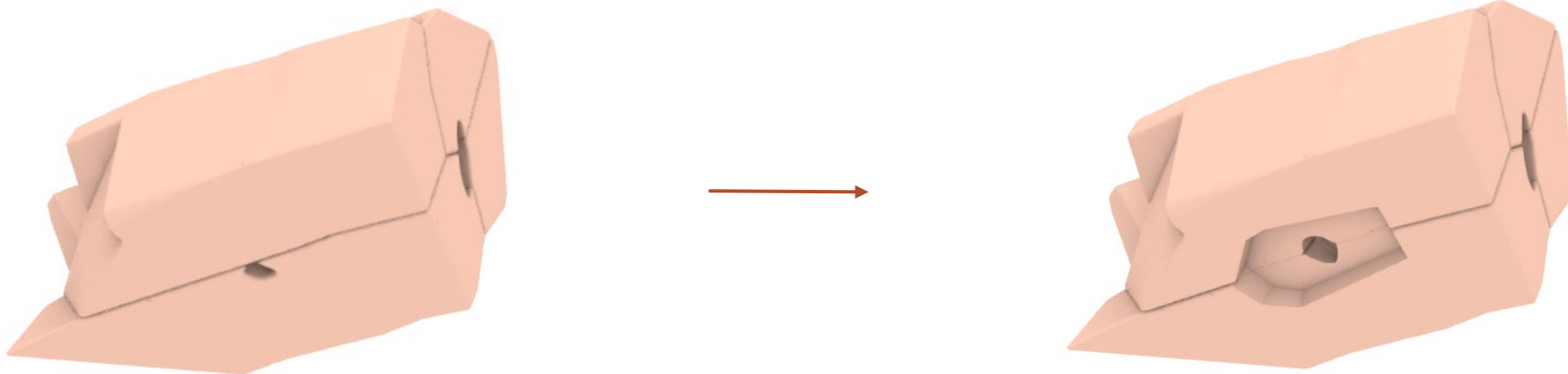


Generated components with integrated pipes

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables

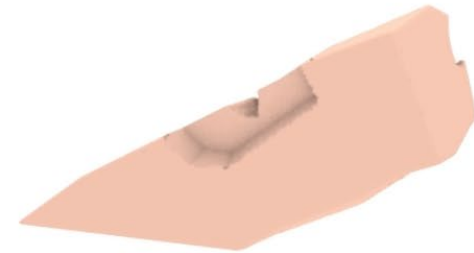
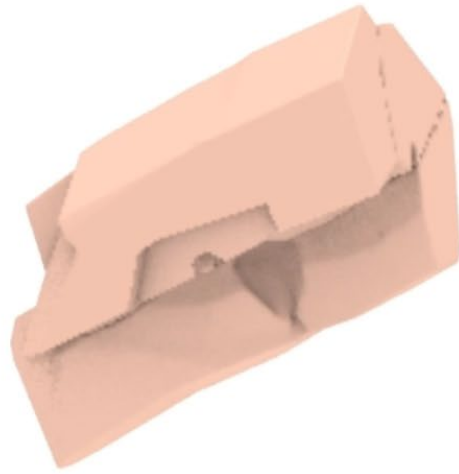


Final components with pot for hydroponic plants generated with boolean difference

Kinked Voronoi Cells Generation

Kinked Voronoi Cells

LSS piping and cables

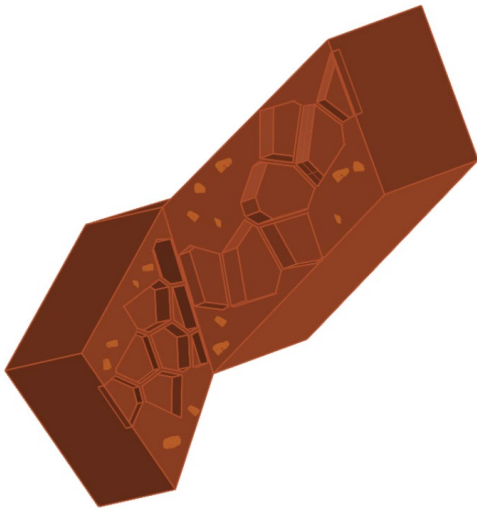


Components selected for the milling process

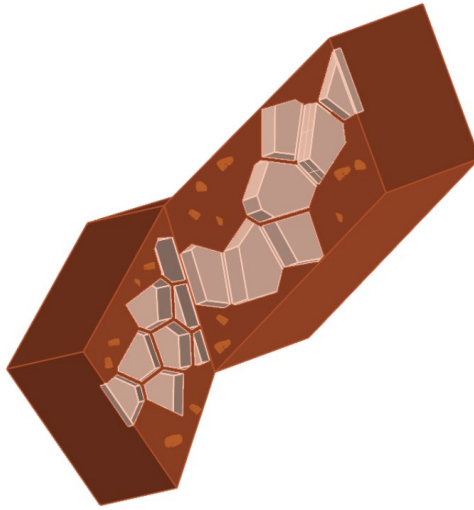
Fragment Design

Schemes

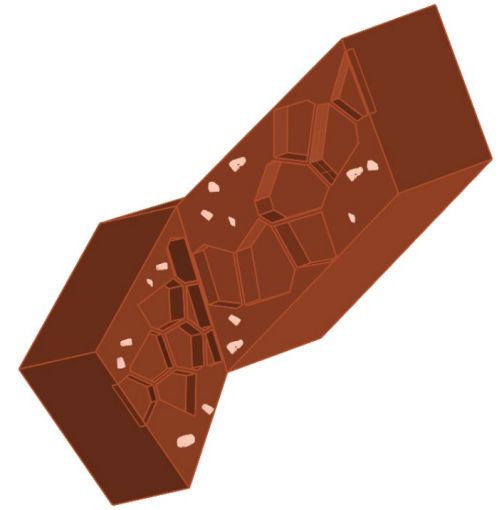
Render



Fragment conceived either as a
climbing wall or a vertical garden



Pots for hydroponic plants generated
with boolean difference



Climbing holds generated with
boolean union

Fragment Design

Schemes

Render





Milling Process

Milling process

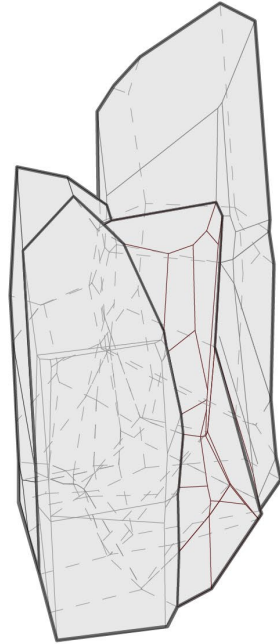
Component subset

Milling steps

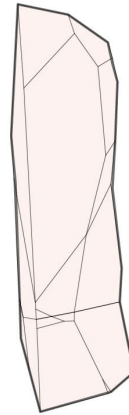
Dimensions

Toolpath planes

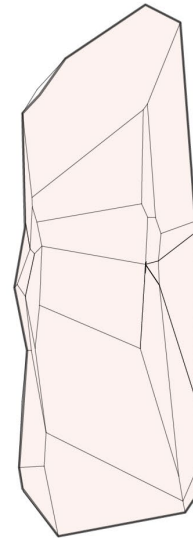
Milling simulation



Component subset



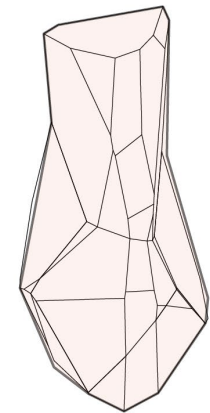
Component No. 1



Component No. 2



Component No. 3



Component No. 4

Milling process

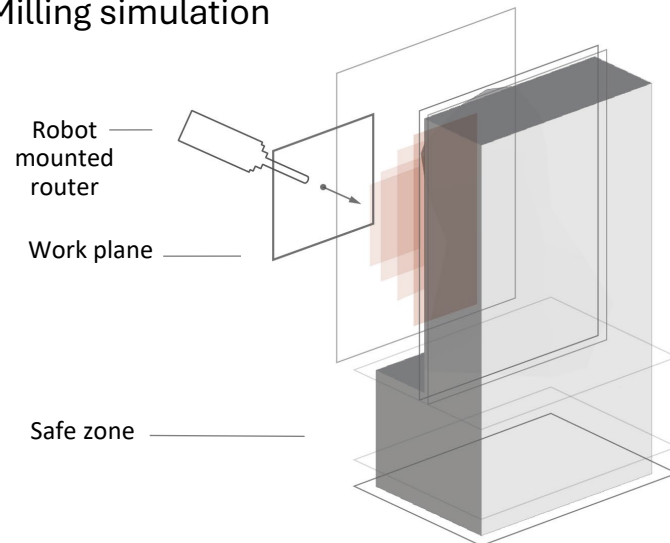
Component subset

Milling steps

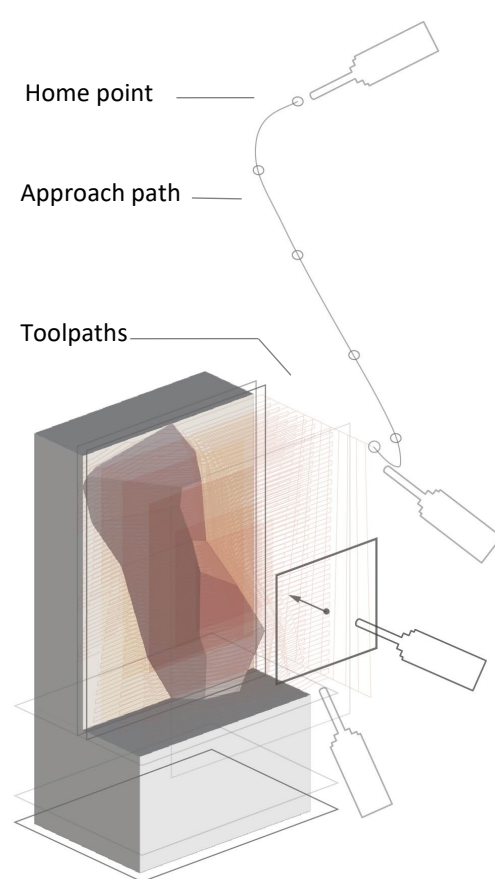
Dimensions

Toolpath planes

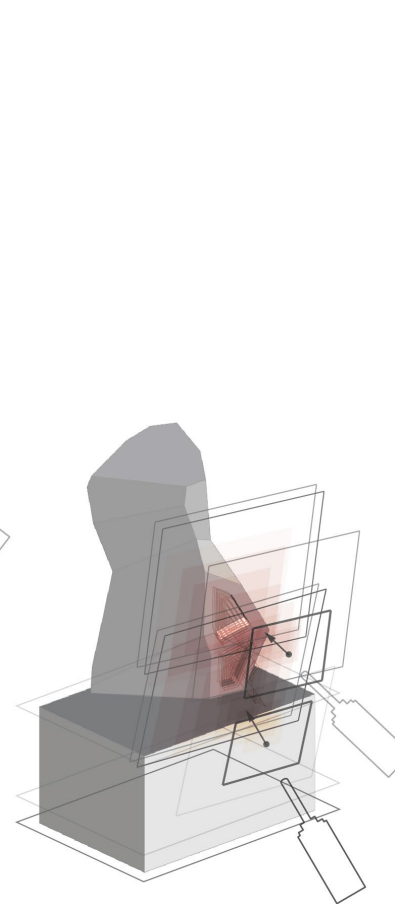
Milling simulation



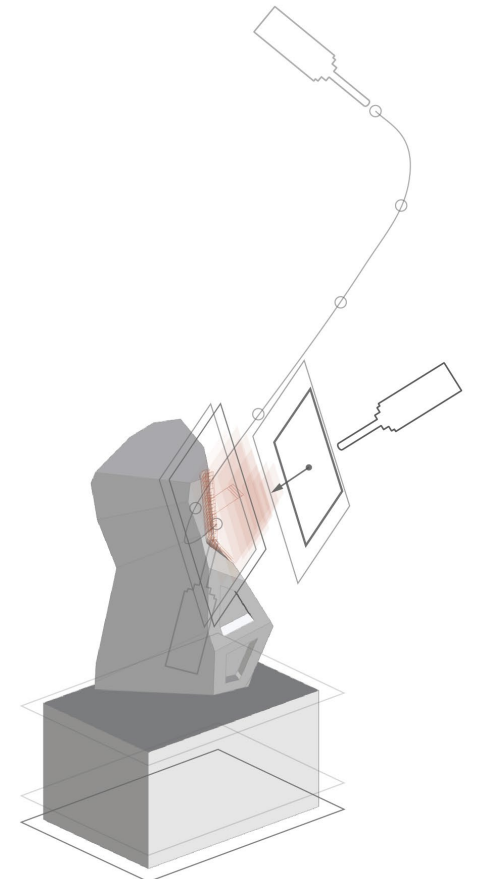
Milling side one
(Component No.3)



Milling side 2
(Component No.3)



Milling the holds for the
hands



Milling the LSS piping
channels

Milling process

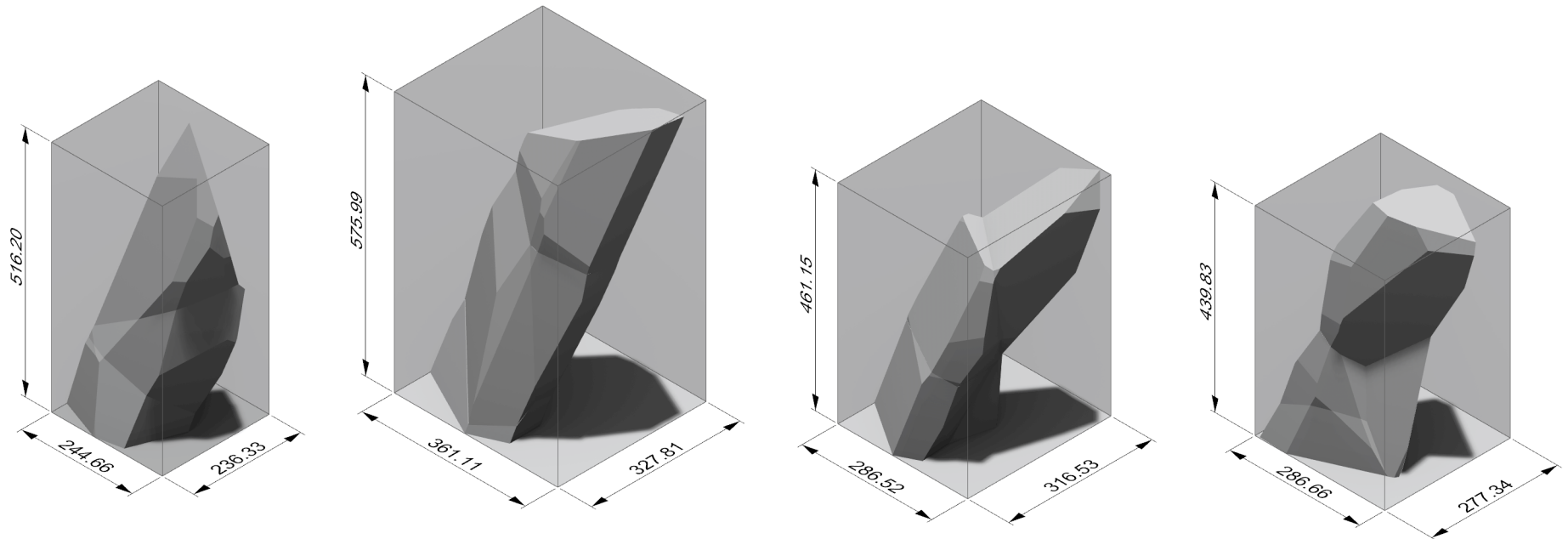
Component subset

Milling steps

Dimensions

Toolpath planes

Milling simulation



Dimensions of bounding boxes for
each of the components | in mm

Component No. 1

Component No. 2

Component No. 3

Component No. 4

Milling process

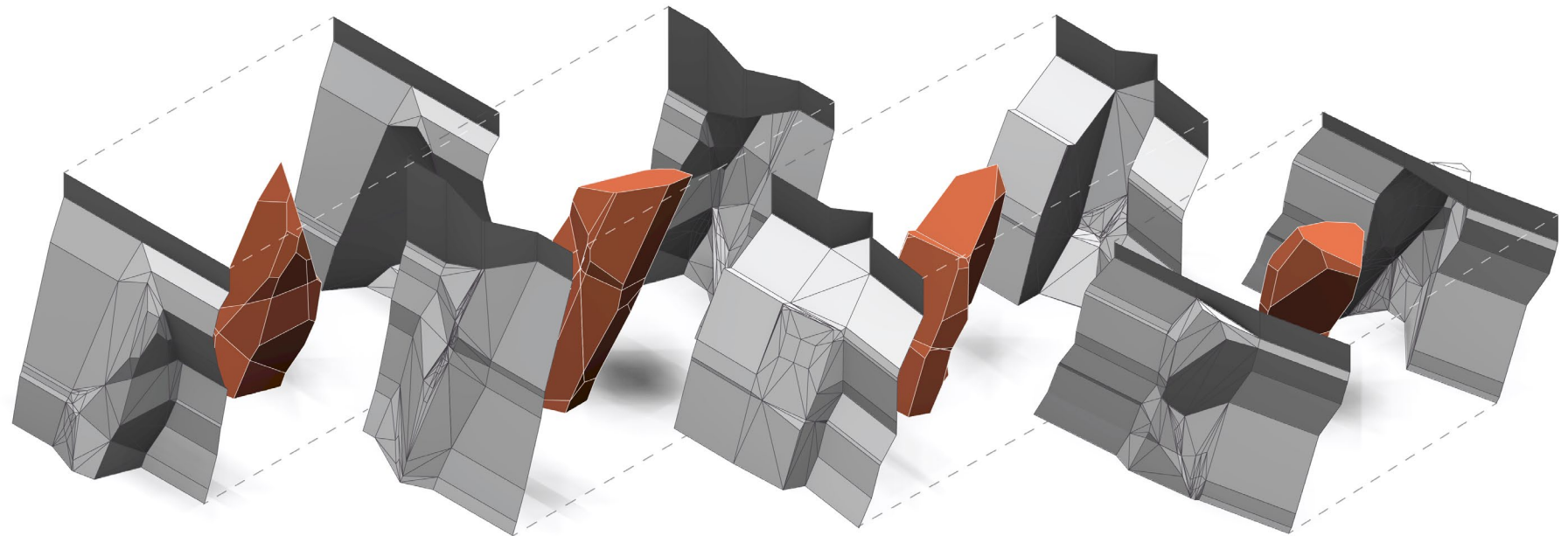
Component subset

Milling steps

Dimensions

Toolpath planes

Milling simulation



The planes for toolpath generation each component is split into 2 sides

Milling process

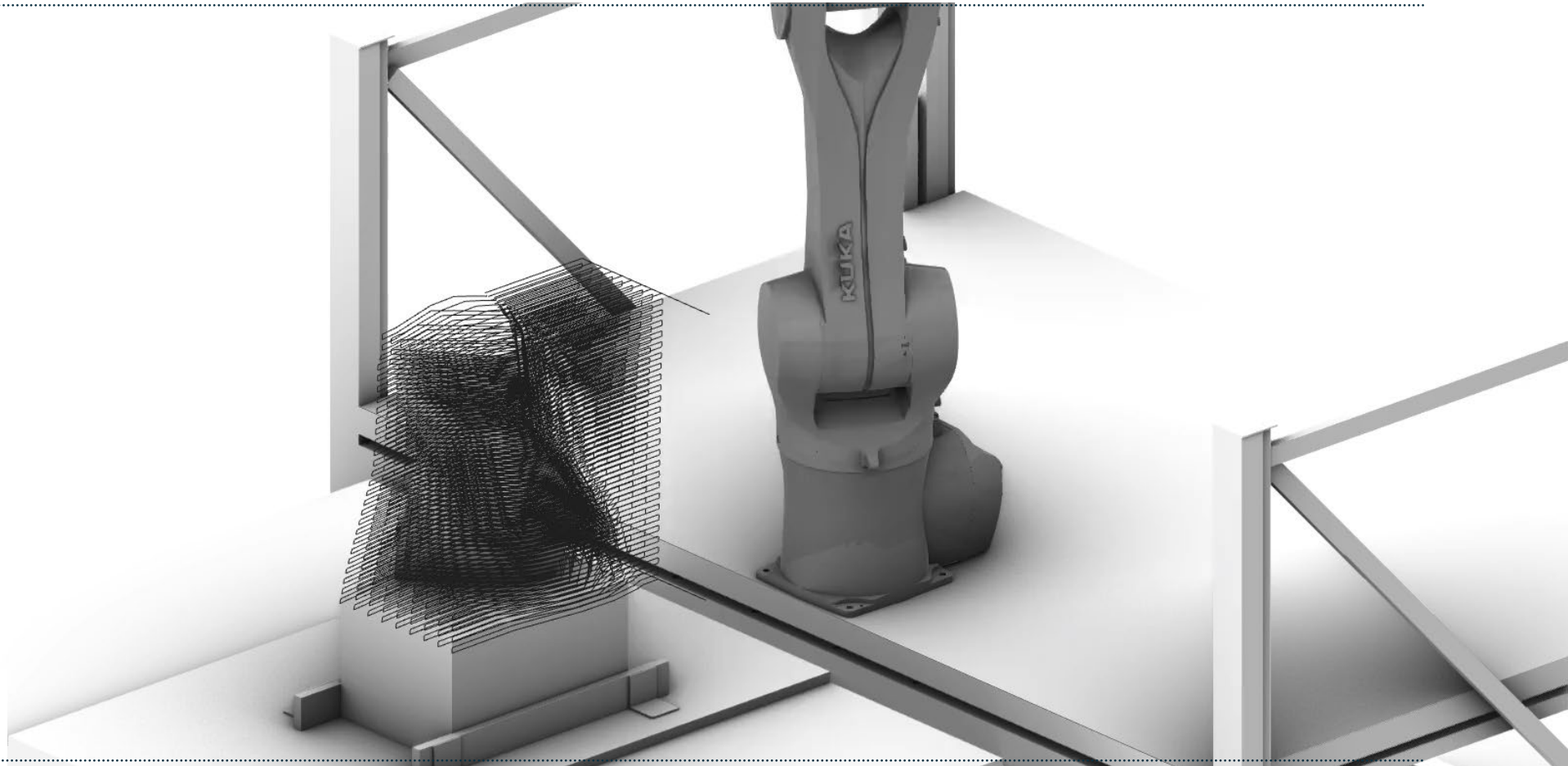
Component subset

Milling steps

Dimensions

Toolpath planes

Milling simulation



Simulation of milling for side 2 | Component No. 3

Milling process

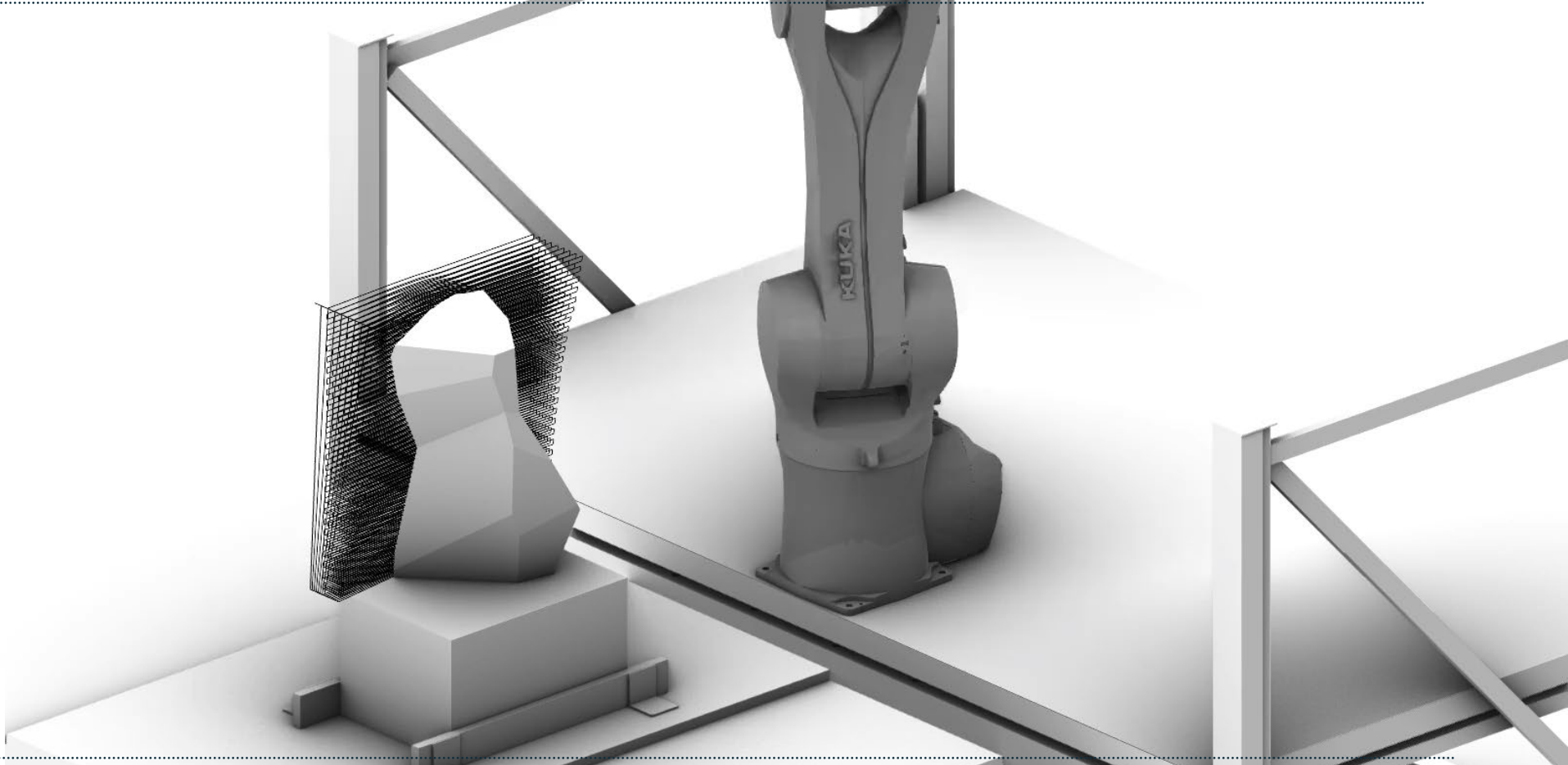
Component subset

Milling steps

Dimensions

Toolpath planes

Milling simulation



Simulation of milling for side 1 | Component No. 3

Milling process

Component subset

Milling steps

Dimensions

Toolpath planes

Milling simulation



Picture taken in the lab during the milling simulation



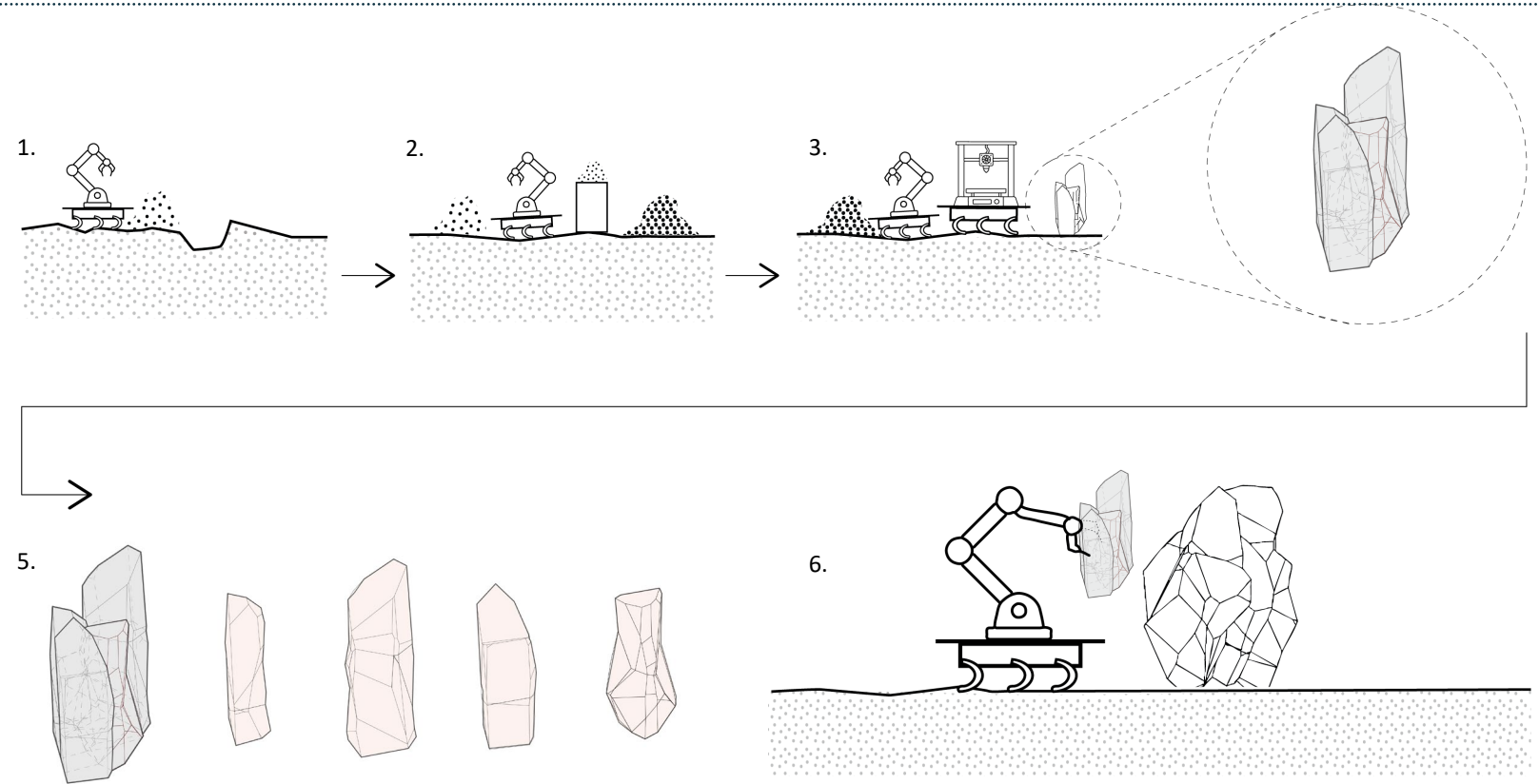
HRI & Assembly Plan

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



1. Regolith is extracted

2. Regolith processed to create 3D printing material

3. Material is 3d printed into fragments for assembly

4. Family of components ready for assembly

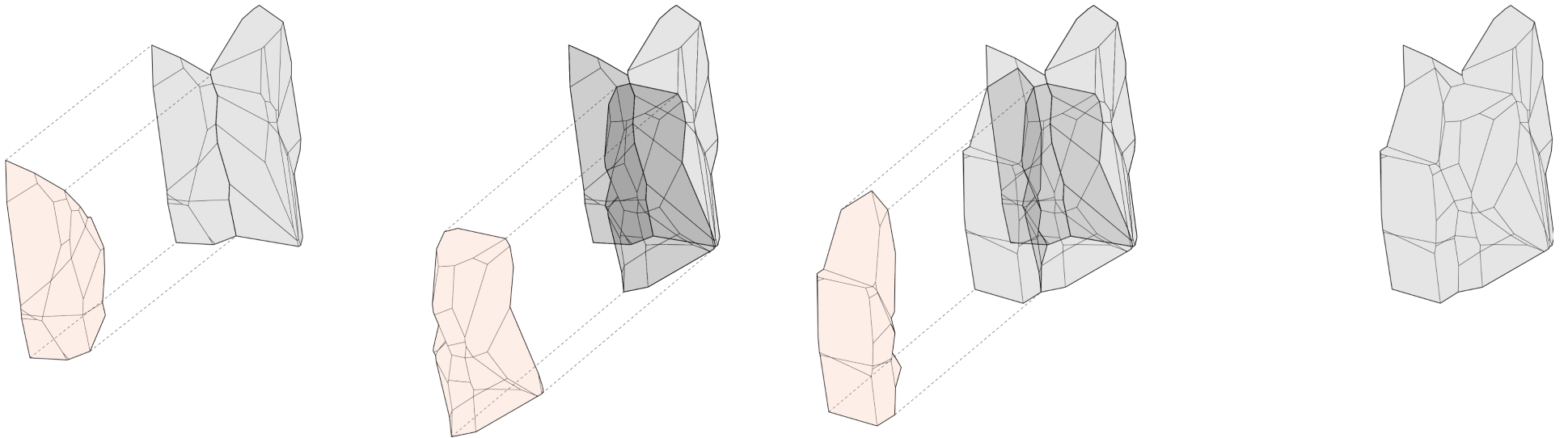
5. Lunar Zebro rover with robotic arm assembles components

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



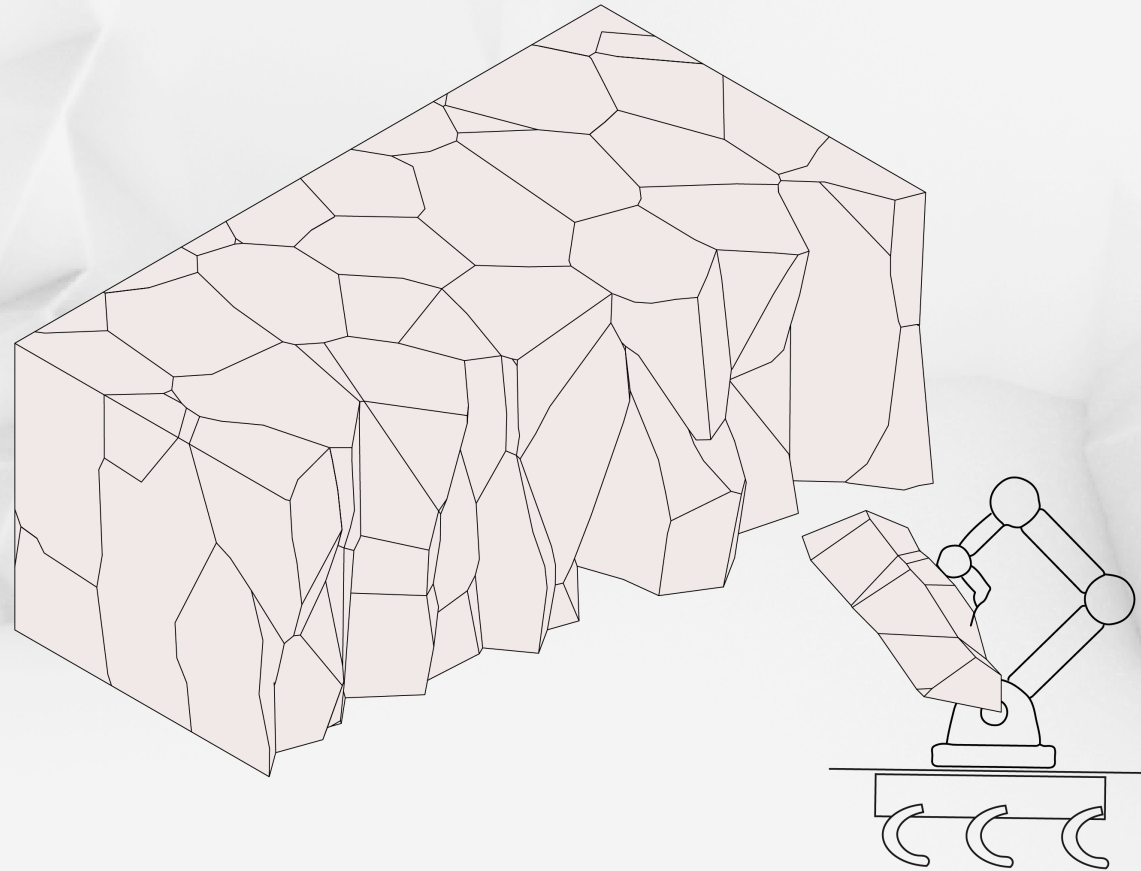
Assembly process consisting in interlocking vertically

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



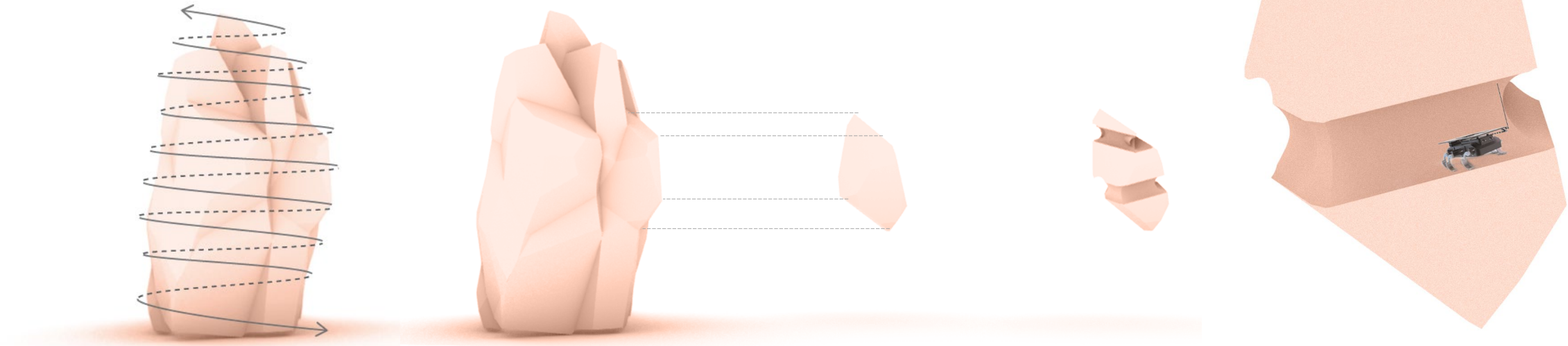
Wall robotic assembly simulation

HRI & Assembly Process

Assembly Fragment Selection

Assembly Concept

HRI



External map built into exterior walls to allow for construction and maintenance with Lunar Zebro rovers

Fragment example

Lunar Zebro Robots are able to move up and down the structure

HRI & Assembly Process

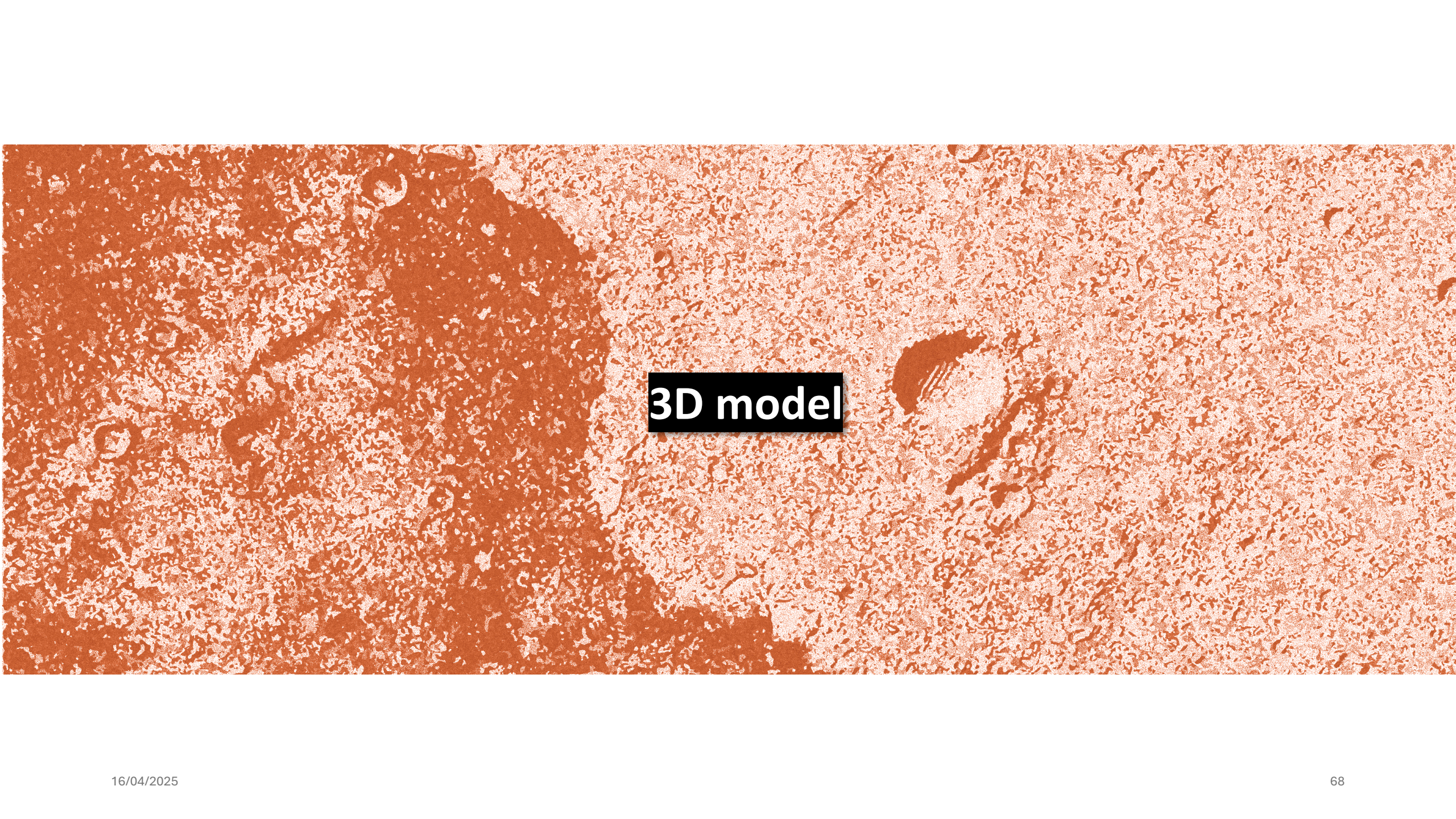
Assembly Fragment Selection

Assembly Concept

HRI



Human Robotic Interaction (Self-made, 2025)

The image features a solid orange background with a fine, grainy texture. A black rectangular box is positioned in the center, containing the text "3D model" in a white, bold, sans-serif font.

3D model

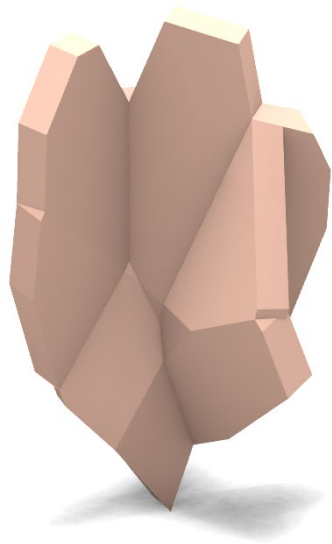
3D Model

Digital Model

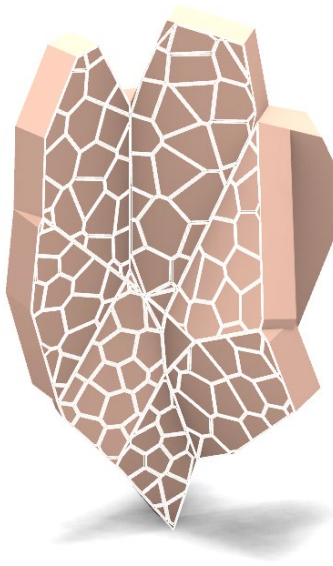
Printed model



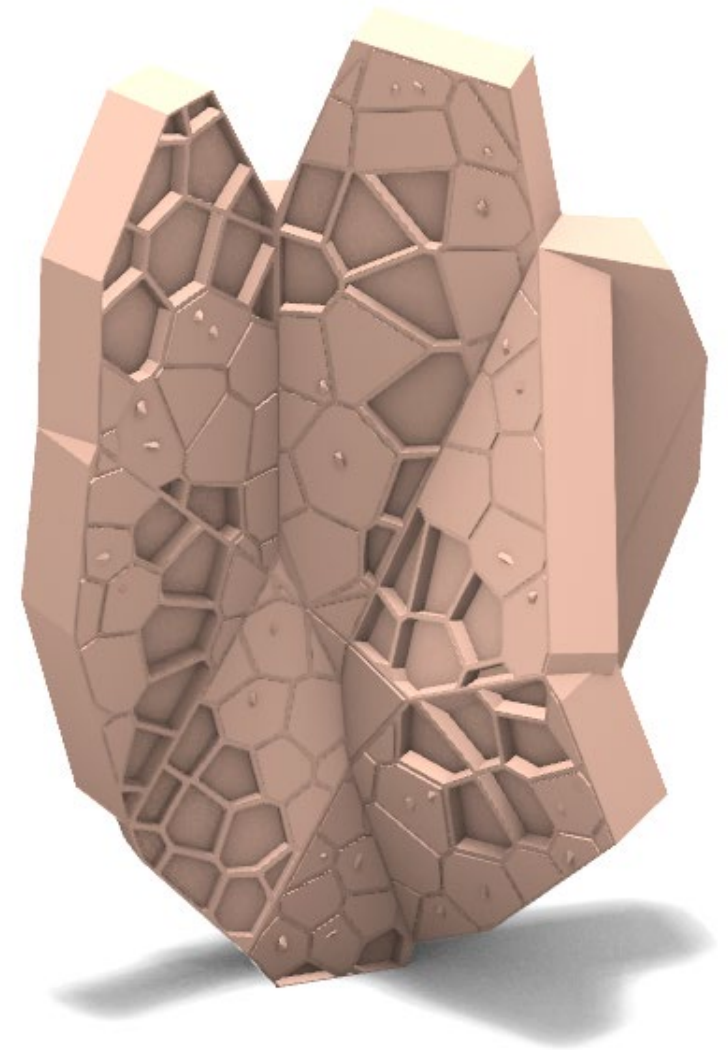
Step No. 1
Selecting the surfaces



Step No. 2
Extruding the surfaces
creating volumes



Step No. 3
Generating the Voronoi pattern
to define the walls



Final Digital Model

3D Model

Digital Model

Printed Model

