Abstract #1751

English

Modeling Tool for Off-Earth Mining Optimization and Resource Processing Based on Geological Contexts

In October 2015, NASA held its first Landing Site / Exploration Zone Workshop for Human Missions to the Surface of Mars in Houston, Texas. Working with vast amounts of data from past and current Martian exploration studies, members of the scientific and space engineering community identified zones of interest that may have suitable mineral resources to sustain human missions on Mars. While the teams did build strong arguments for the potential of the proposed sites, the initial data sets were typically not of the required resolution and scope to meet the burden of a proven or probable mineral reserves in the strict sense (Haldar, 2012.) The teams also lacked the tools to analyze the multi-dimensional data sets describing the environmental and geological knowledge of the targeted region and the capabilities of mining and extraction systems applicable to resource recovery. In their assessment of the workshop, organizers representing NASA's Science Mission Directorate and Human Exploration Operation Mission Directorate identified the need for a better understanding of the potential resources (reserves) and the identification of the major factors that influence feasibility assessments of extracting such resources on Mars. Over the years, NASA and others have developed and used several useful ISRU models to determine production rates, power and consumables requirements, types and mass of hardware, and the technical feasibility of integrated systems (Sanders, 2015.) These models have been particularly valuable in describing the inputs and outputs of regolith processing systems and typically rely on data collected in field operations by NASA-led teams. At this time, these models often oversimplify the mining and processing systems and do not fully exploit integrated system-level models that have been widely utilized in the terrestrial minerals industry. For example, some of these models use simple parametric scaling laws to describe higher production rates of equipment. Other models do not utilize the full geological context of the targeted mineral reserves and have thus resorted to overly simplistic descriptions of the geology. Other investigators have provided high-level economic models of resource utilization in space while completely ignoring the resource context. Altogether, the results of these models have a high degree of uncertainty and do not fully exploit the utility of the existing data sets. The work presented in this paper is an effort to augment NASA's current set of modeling tools with a comprehensive mining and materials processing model that integrates the specific geology of the targeted resource. This unique modeling tool integrates the expertise and best practices of terrestrial mining industries with the knowledge of expert space technologists in ISRU and is designed to evolve with data quality and new hardware designs. Results of this work will deliver comparative results on the operations and technologies best suited for a particular resource deposit on a planetary body. The main innovations provided by the proposed modeling tool is the inclusion of critical context factors (e.g. geologic, mining system, processing system, equipment, and others) and the ability to identify their effects on the level of outcome uncertainty. As a tool, it will provide NASA and other stakeholders with a means to identify lack of information as well as expertise to plan technology investments and knowledge-gathering missions.

French

No abstract title in French

No French resume

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Laurent Sibille, Ph.D., PMP has over 20 years of experience in science investigation and new technology developments for NASA programs. He earned a degree of Engineer of Materials and a Ph.D. in solid-state physics from the National Institute of Applied Sciences in Toulouse, France. He was Principal investigator for two Space Shuttle experiments on the formation of low-density materials in low gravity. He has led technology development projects at two NASA centers including lunar oxygen production systems development and co-founding NASA's lunar simulant materials standardization program. As a Principal and co-Investigator, he currently leads R&D projects within Applied Technology division at Kennedy Space Center's Swamp Works for NASA mission support technologies, planetary surface systems with a focus on space resources utilization and prototype development. He is a member of NASA's Human spaceflight Architecture Team with focus on space resources utilization (ISRU) and is currently the vice-chair of the Space Resources Technical Committee of the American Institute for Aeronautics and Astronautics (AIAA). His expertise is recognized in materials, including analogues of planetary regoliths, materials processing in space environments, systems engineering, systems modeling, energy conversion, electrochemical and biochemical systems.

Biography in the user profile

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Modeling Tool for Off-Earth Mining Optimization and Resource Processing Based on Geological Contexts

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Off-Earth mining – emerging scenarios

Drivers

- In-space markets
  - Propellants for deep space transportation
  - Propellants for life extension of space assets (satcoms, observatories)
- Planetary markets
  - Life support
  - Materials for construction, parts fabrication, repairs
- Terrestrial markets
  - Space solar power
  - Data storage
  - High bandwidth com
  - Rarefied commodities (rare earth metals)

Commmodity Price

Available Technologies

Origin of source material

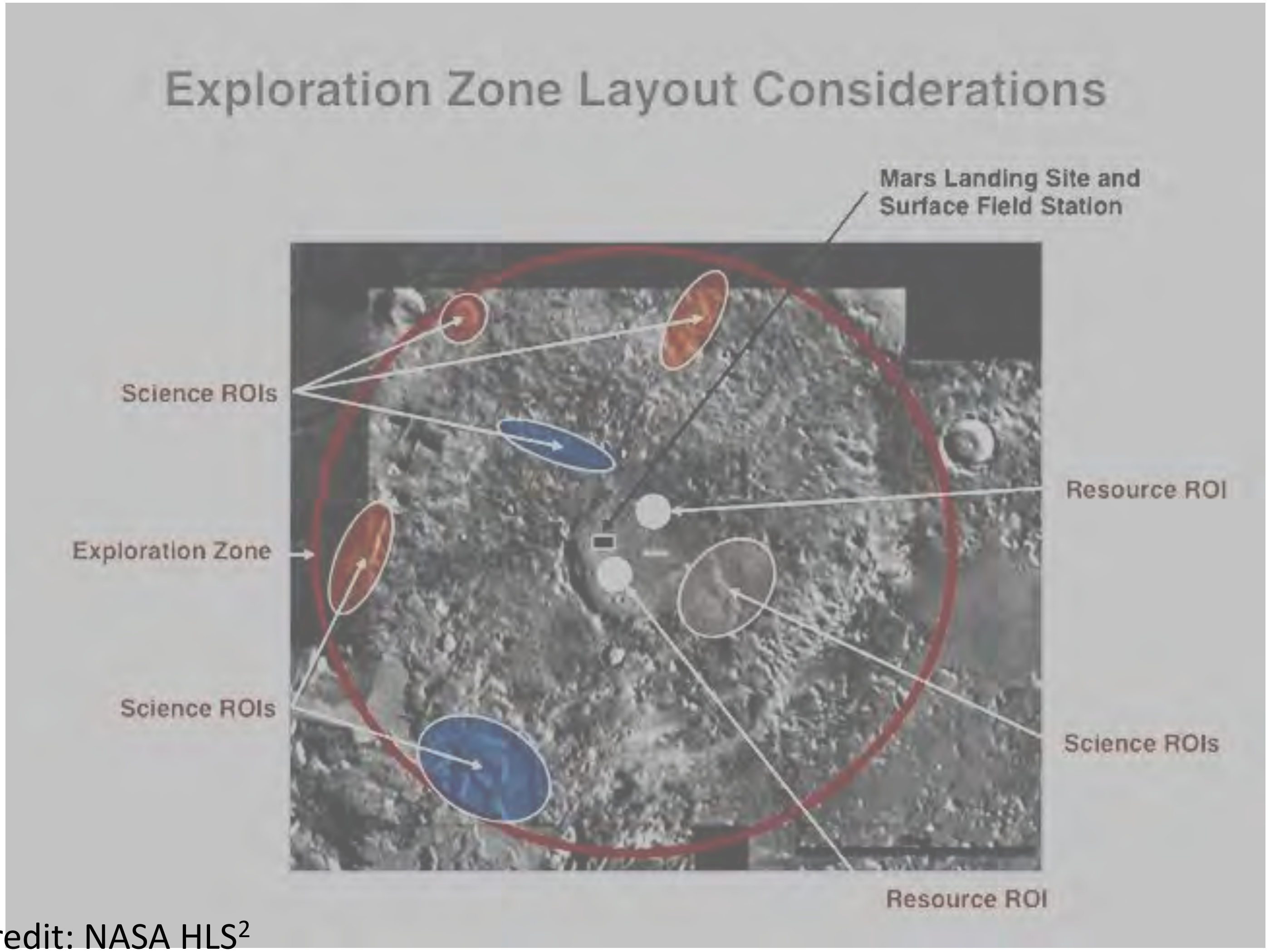
Mission timelines

Objectives

- **Provide a tool that leverages both mining & minerals processing industry practices and space systems engineering practices**
- **Adaptable to user requirements (architectures, conops)**
  - Location: planetary environment (moon, mars & moons, asteroids, comets, etc…)
  - Resource data: topography, public or proprietary geology data sets, grade analysis data, geo-hazards,
  - Mission requirements: space mission constraints, space-qualified or lab-scale hardware performance data, operational constraints for robotic & crew-tended systems
  - Mining products management ("waste", volume/mass transport)
  - Reliability and life-cycle data on equipment (dormancy,
  - Optimize for user-selected outputs (e.g., landed mass, specific power, production time)
- **Keep track of built-in assumptions, identify knowledge gaps, measure resulting uncertainties**
  - Data quality and integrity
  - Test data in relevant or non-relevant environments
  - Scaling issues in data usage
  - Operational assumptions: life cycles, non-production periods, maintenance/end of life repurpose
- **Useful for early assessments, Phase I planning, and technology selection/maturation**
- **Develop first version of tool for Mars resources (NASA Evolvable Mars Campaign, NASA Human Landing Sites Workshop)**

NASA Workshop on Human Mission Landing Site on Mars

Exploration Zones

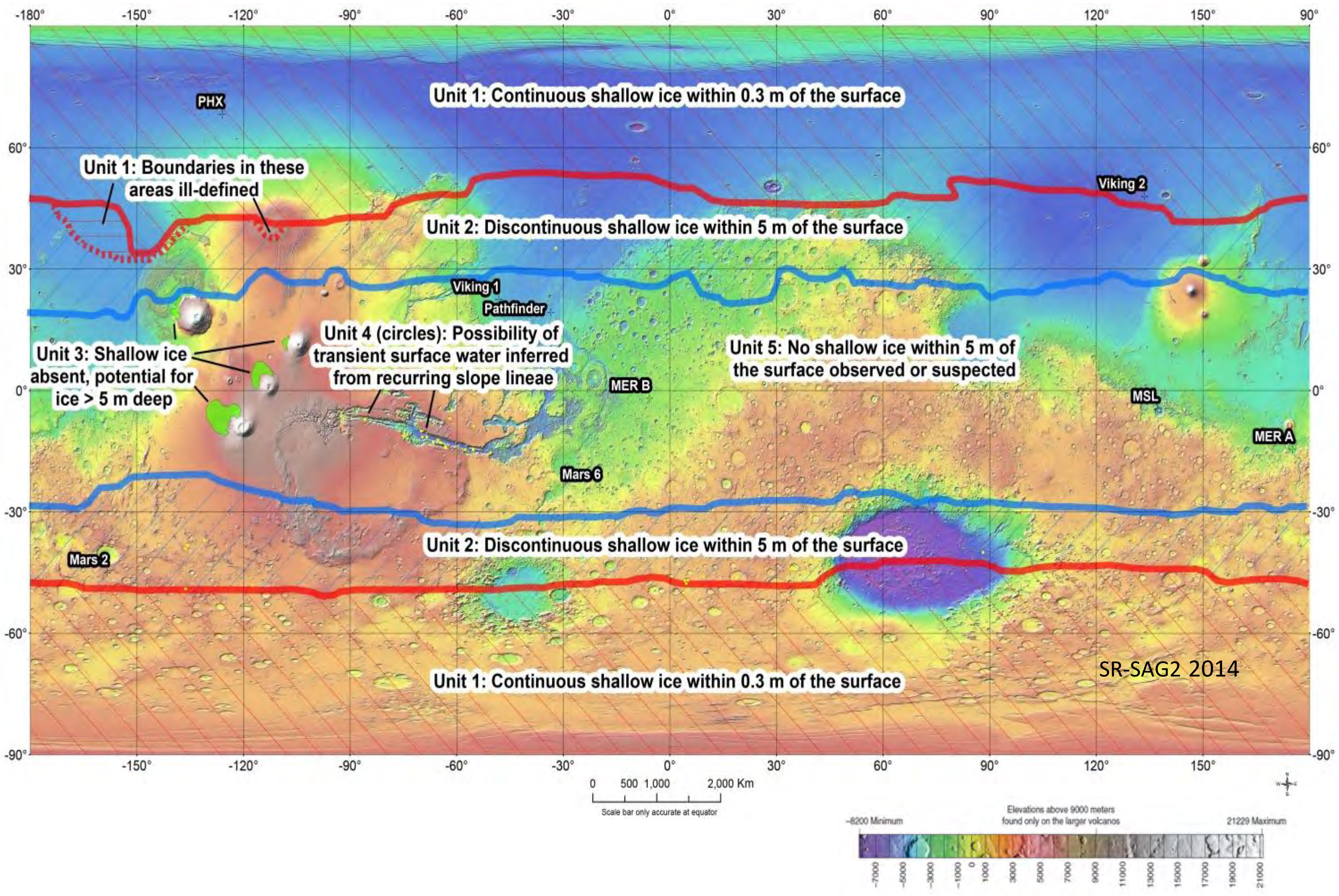


Credit: NASA HLS[2]

ROI: Regions of Interest

Mars

Location of Water Sources



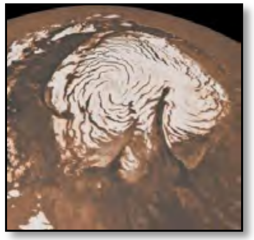


Image: Nasa/JPL

Image: Nasa/JPL

Surface polar Ice & subsurface mid-latitude Ice

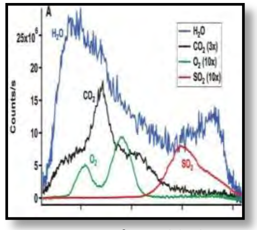


Image: Nasa/JPL 2013

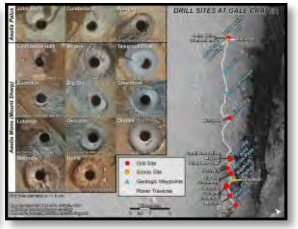
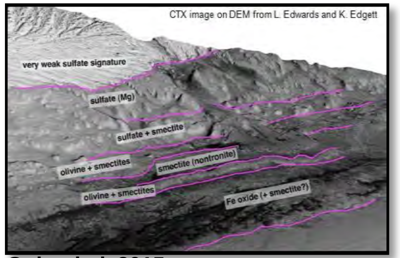


Image: Nasa/JPL 2016

Regolith



Golombek 2015

Hydrated phyllosilicate / sulphate minerals

Mars

Preparing for Human Missions to Mars – a Brief History

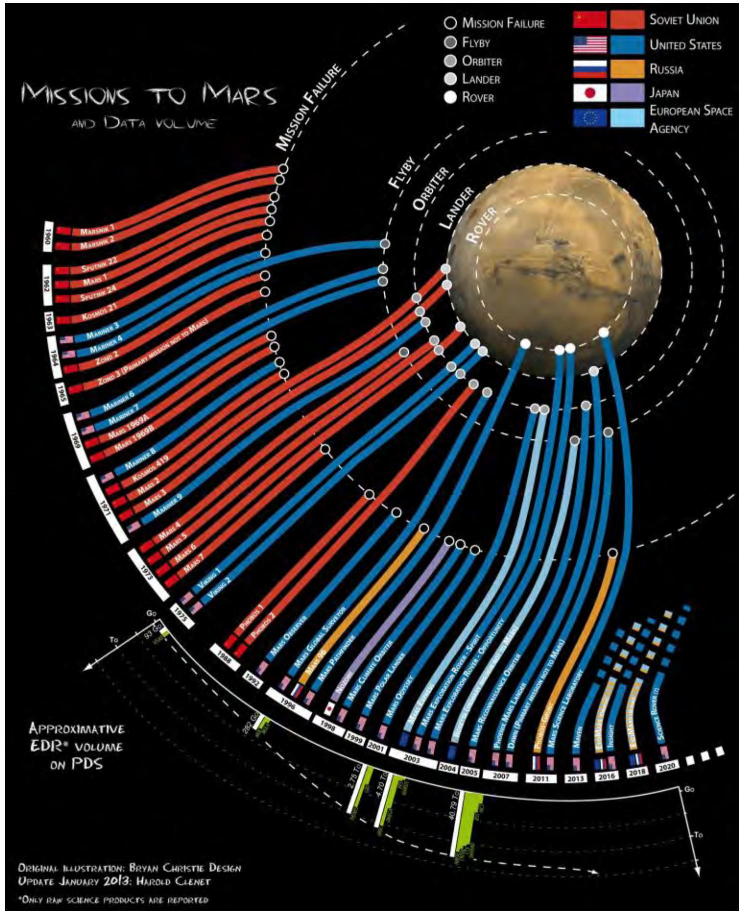
Single lander and rover missions are our state-of-the-art

Curiosity mission cost (from development to arrival): $2.5B
It amounts to ~$8 per American citizen

We're getting better at doing it

Major challenges still ahead:

- Entry, descent and landing for spacecraft above 2 t
- Effects of propulsive landings on spacecraft and surroundings (ejecta, cratering)
- Broad bandwidth communications
- Semi-autonomous/autonomous collaborative behavior of surface systems
- Maintenance and repair strategies for surface systems



Mars

Establishing an Exploration Target

Primary resources sort: Water ice (propellant), ….. And other targets (iron, magnesium, nitrates, carbonates, sulfates, etc…)

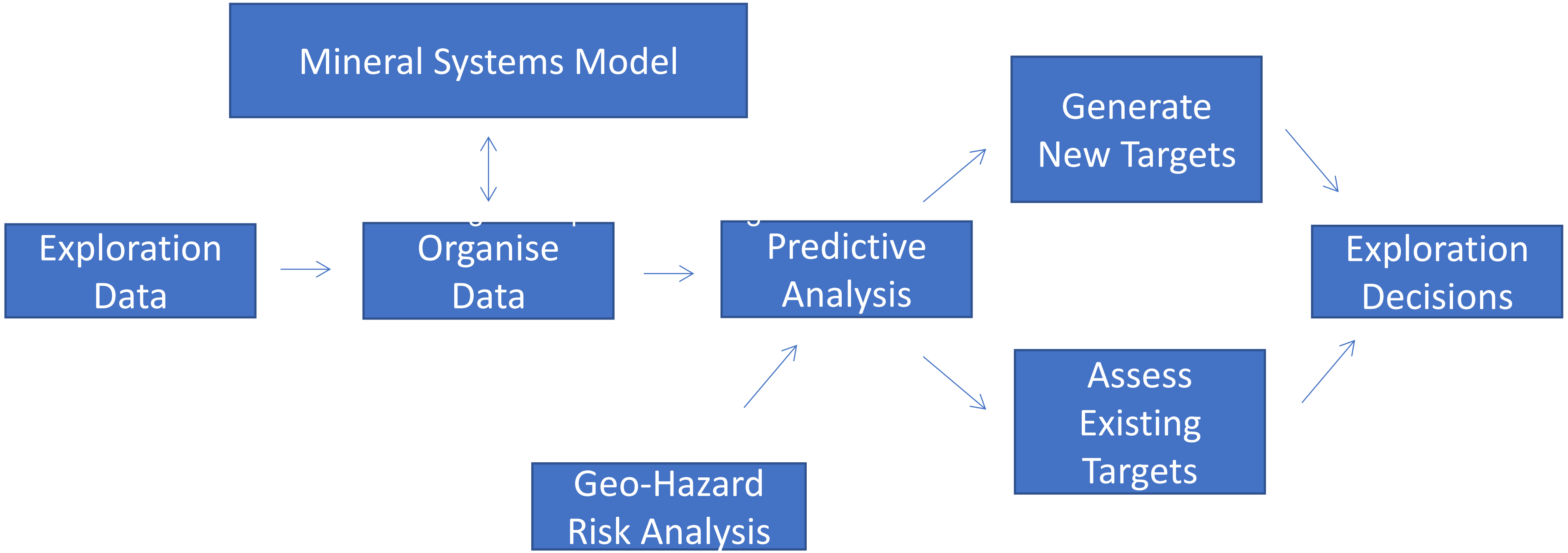
ISRU Market:
- Supply propellant / supplies for MAV
- Supply propellants, fuel for ground equipment
- Support human habitation on Mars, eventual colonies
- Support farming

Geographical/Geological Parameters: Geographical of hydrated minerals and sulfates (mid latitudes), close to Science-Region Of Interest (ROI) and human habitation locations

Engineering constraints: Located in proximity to appropriate landing / base construction site (Need to consider: terrain (traversibility, slope, presence of geo-hazards), communication and power constraints, etc….

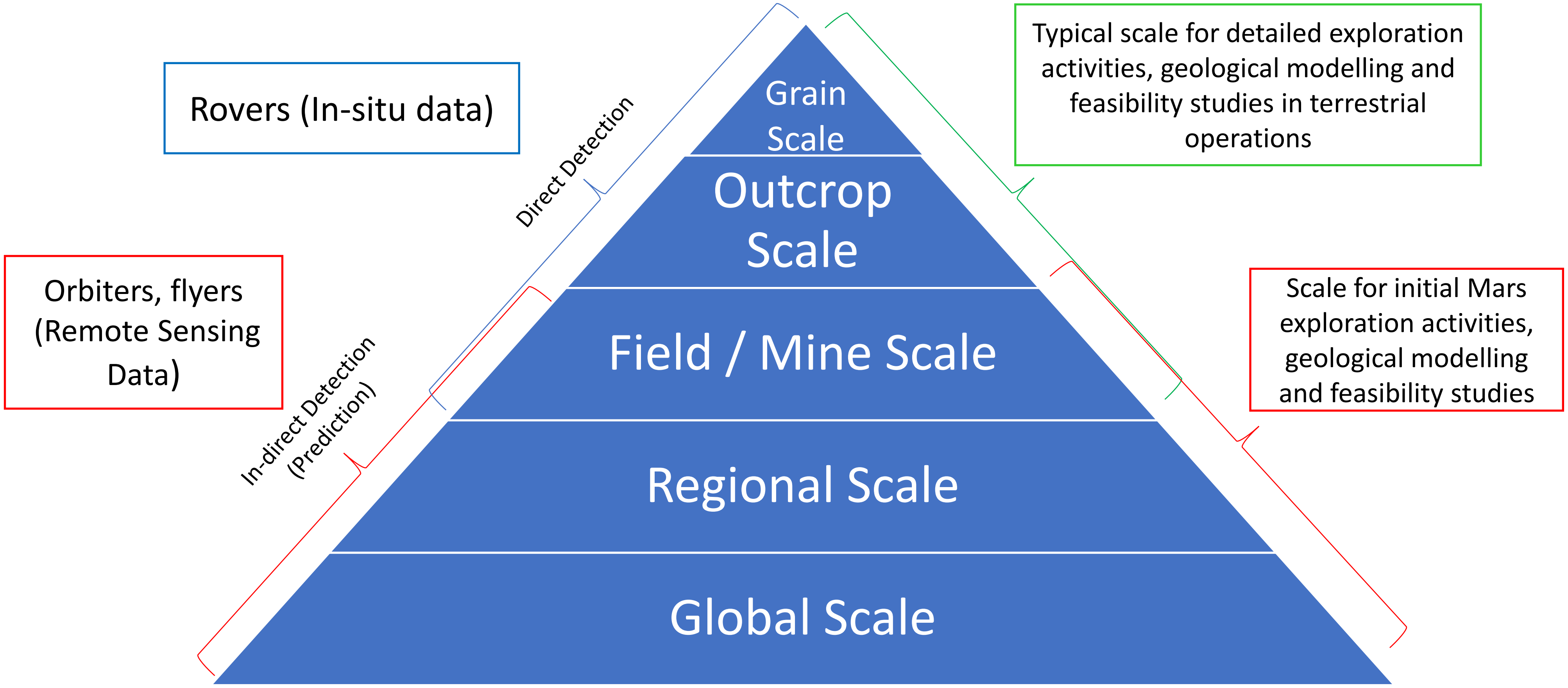
Mars

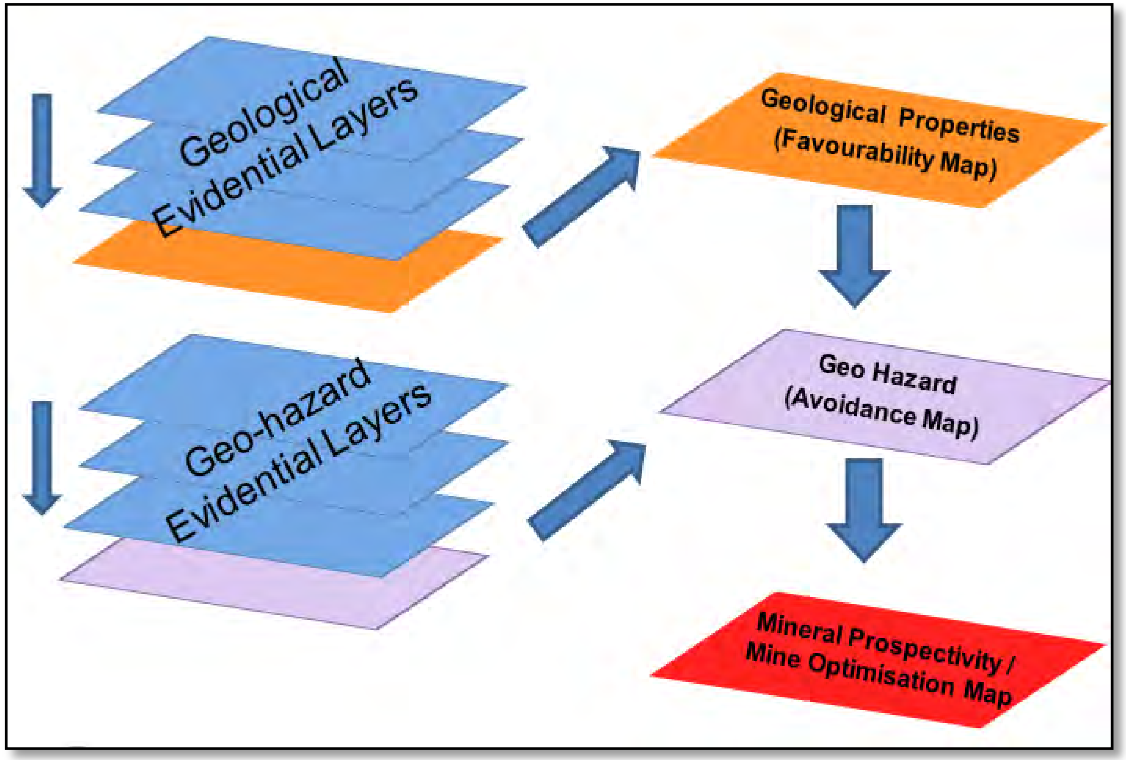
Aram Chaos Mineral Prospecting Workflow



Mars

Importance of Scale





Geo-Hazard / Engineering Risk Mapping:

- **Terrain Accessibility** (i.e. slope, ruggedness etc.)
- **Hazardous Terrain** (i.e. sand dunes, jiggered or highly fractured etc.)

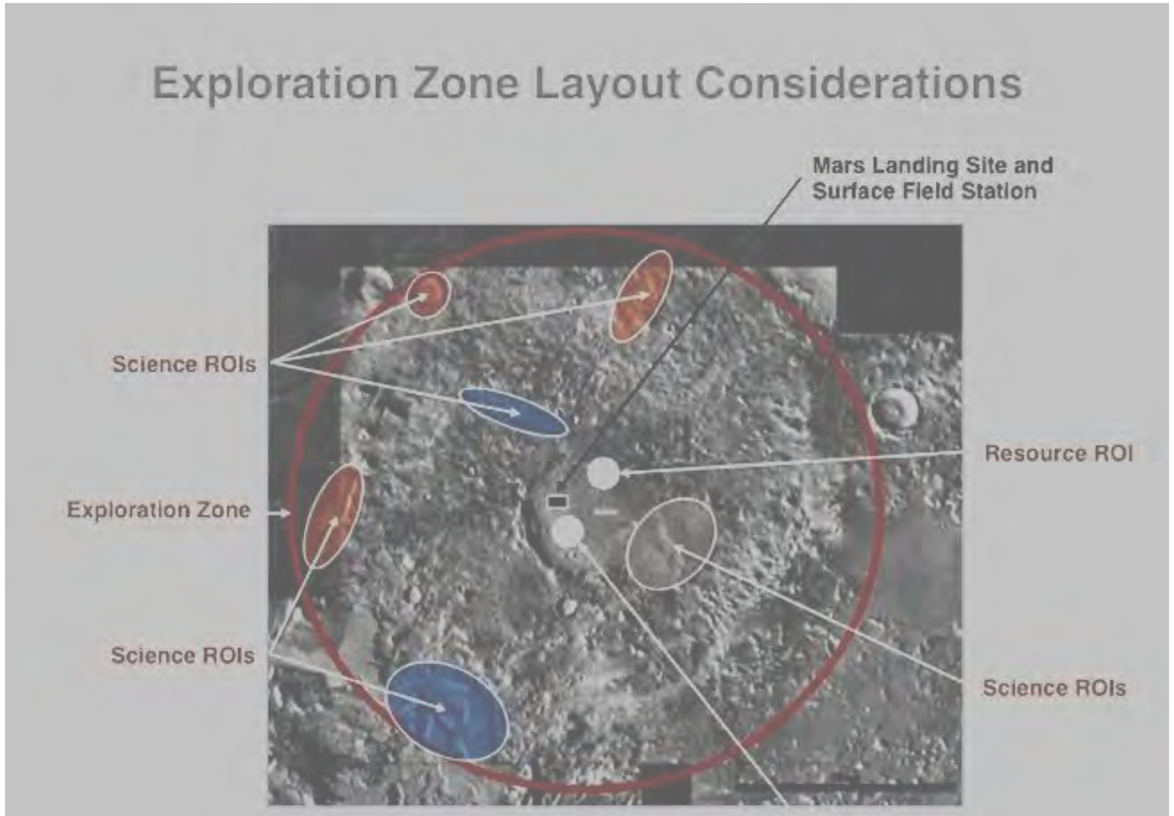
Mars

Exploration and Feasibility Studies

Mars 2020 – core sampling
MSL – drill (1-2 wt% water evolved from regolith)

Orbital data can be used for initial prospecting – HiRISE, CRISM, etc.

NASA Resource-ROI criteria in development



Credit: NASA HLS[2]

Evolvable Mars Campaign

Space Mission Concepts

- Autonomous Robotic Mining Equipment will be required due to communications latencies of up to 40 minutes
- Mars Launches occur very 26 months
- Mining equipment must make propellant for the Mars Ascent Vehicle in 26 months, then send crew
- Crew cannot land until the propellant has been produced – implies 52 months or 4 years minimum equipment life
- Design margin is necessary – so design robotic mining equipment for <u>5 years minimum life</u>
- Equipment must be maintained or replaced in 4-6 years.
- Harsh environments – dormancy and longevity
- Testing on Earth is desirable
- General design approach for longevity (robustness, redundancy, energy source design, self-diagnostics
- Role of software in mission life (command and control fixes to hardware malfunctions, software uploads during missions, self-diagnostics and repairs of radiation damage
- Expected issues of dormancy and longevity for mining and processing hardware
- Role and importance of crew in maintaining space hardware (Shuttle, ISS, Apollo)

Evolvable Mars Campaign

Suggested Phases of Operations

Phase 1: Small payloads (<1,000 kg) in pre-cursor robotic missions for resource prospecting

Phase 2: Small payloads (<1,000 kg) for H_2O propellants mining

Phase 3: Mining Infrastructure development - payloads up to 20,000 kg, for propellants, life support, farming, radiation shielding, industrial processes, concrete for habitats

Phase 4: Operational Mine for Earth independence – equipment replacement logistics only

Phase 5: Earth independence – all parts made on Mars

Mars

Available Mining Equipment

Subsystem Requirements (examples):

- Mining rover – Honeybee robotics MISWE or PvEX corer (Processing in chamber or transported to separate heating processing facility, TBM
- Microwave heating (In-situ or chamber)

Key Considerations:

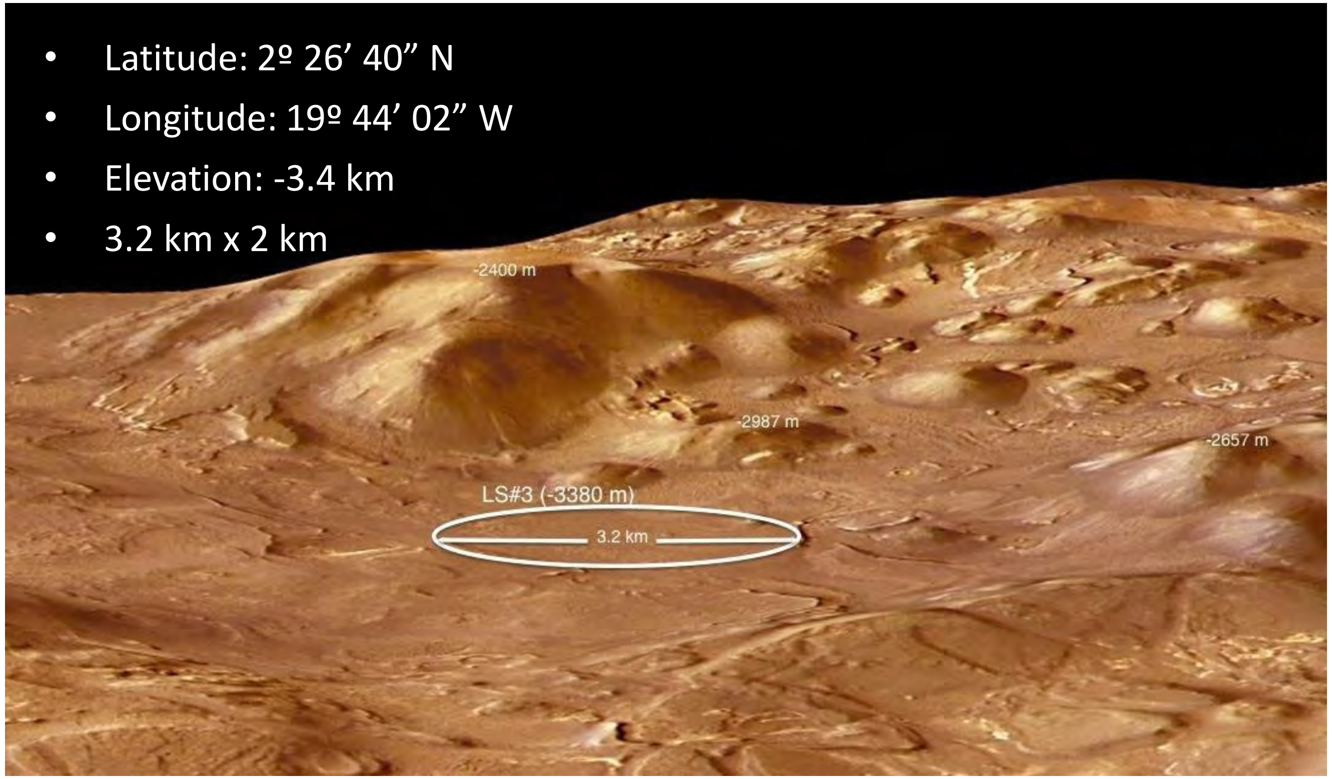
- Mineralogy
- Water Content
- Rock Strength (UCS)
- Sublimation rates when exposed to surface ambient

TBM: Tunnel Boaring Machine
MISWE: Mars In Situ Water Extractor (Honeybee Robotics)

Mars

Aram Chaos Case Study

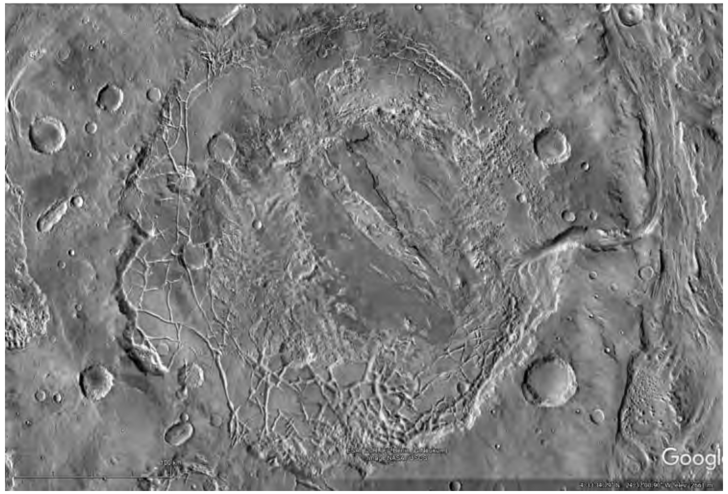
Proposed Landing Zone (Human Landing Site / Exploration Zone Workshop)

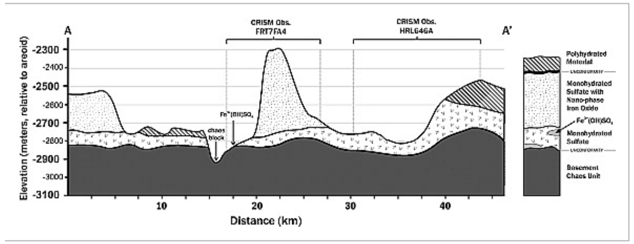


Mars

Aram Chaos Case Study

Geology Overview



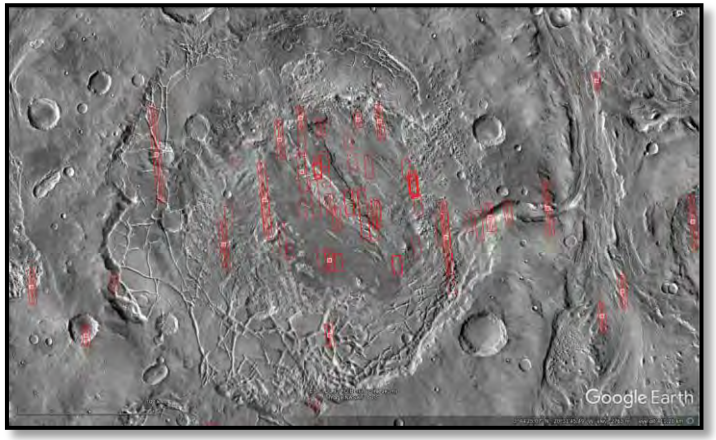


- Geologic History:
  - Impact crater fill
  - Groundwater accumulation
  - Discharge
  - Repeated cycles

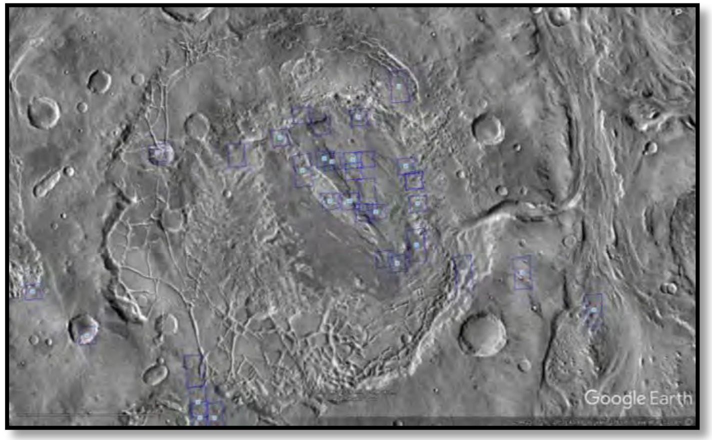
- Surface regolith contain poly-hydrated sulfates of est. water concentration 5-8 wt%
- Aqueous processes prevalent
- Past habitability in subsurface environment possible

Mars

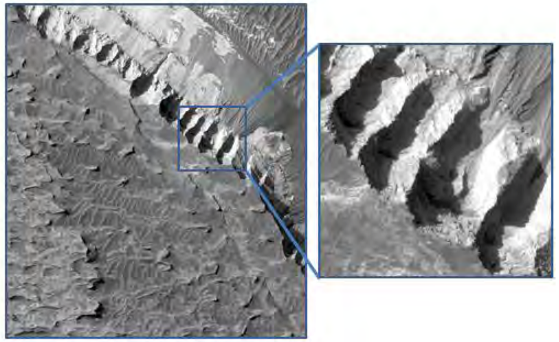
Aram Chaos Case Study



Available HiRISE Data



Available CRISM Data



Geodata Interpretation:

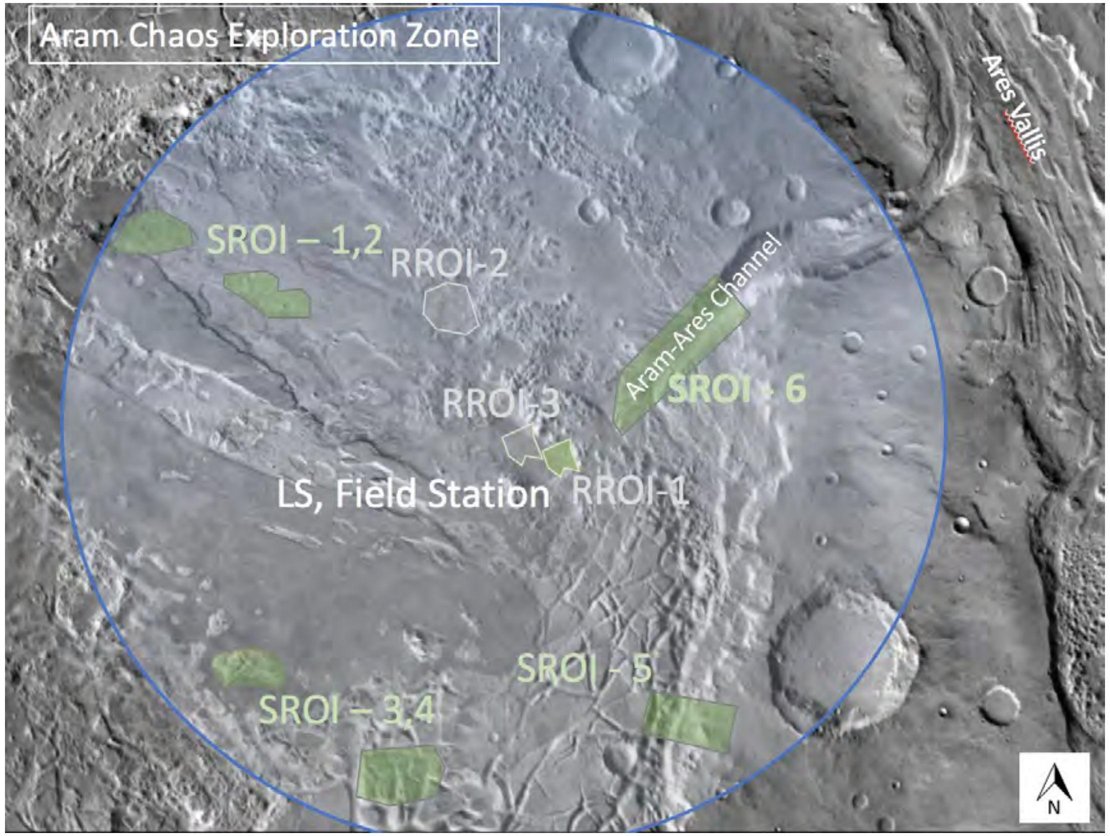
- Terrain / Topography
- Mineralogy
- Structure
- Stratigraphy
- Formation / Depositional History

Conceptual Geological Model

Mars

Aram Chaos Case Study

Resource Regions of Interest (R-ROI)



Mars

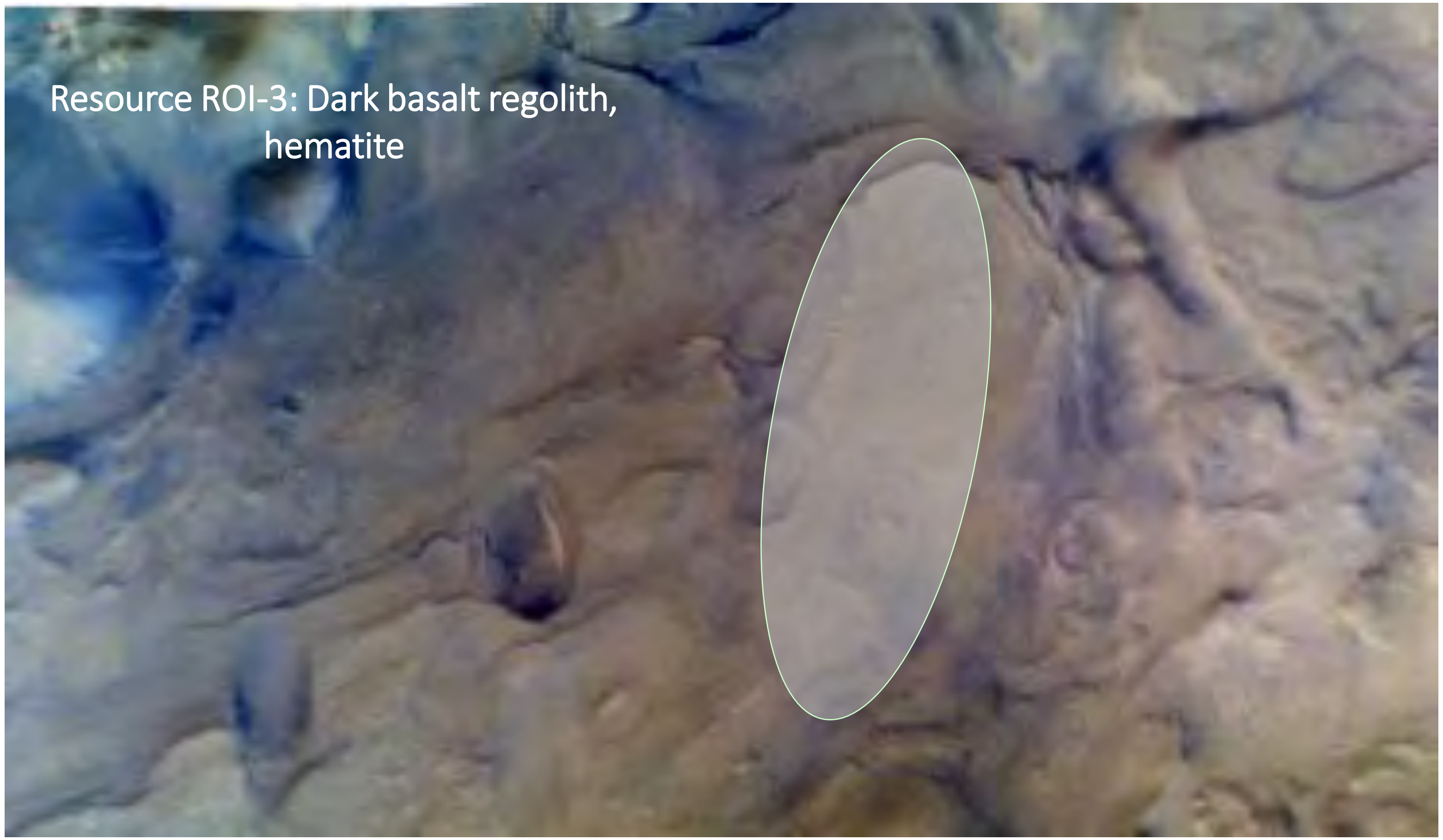
Aram Chaos Case Study

2º 26’ 40” N, 19º 44’ W, - 3.3 km

Large swaths of basalt materials within 0.5-10 km of LS

- Construction (sinter, sulfur-based concretes)
- Silicates (Si, glass-ceramic materials)
- Substrate for plant growth

Hematite-rich region (iron ore up to 16 wt%)*

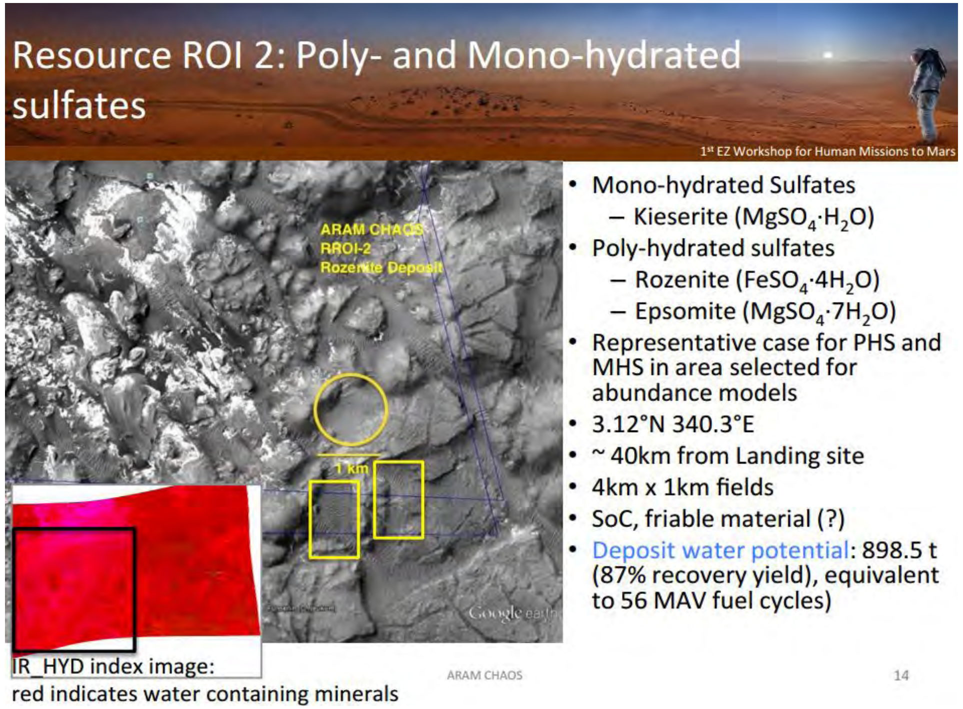


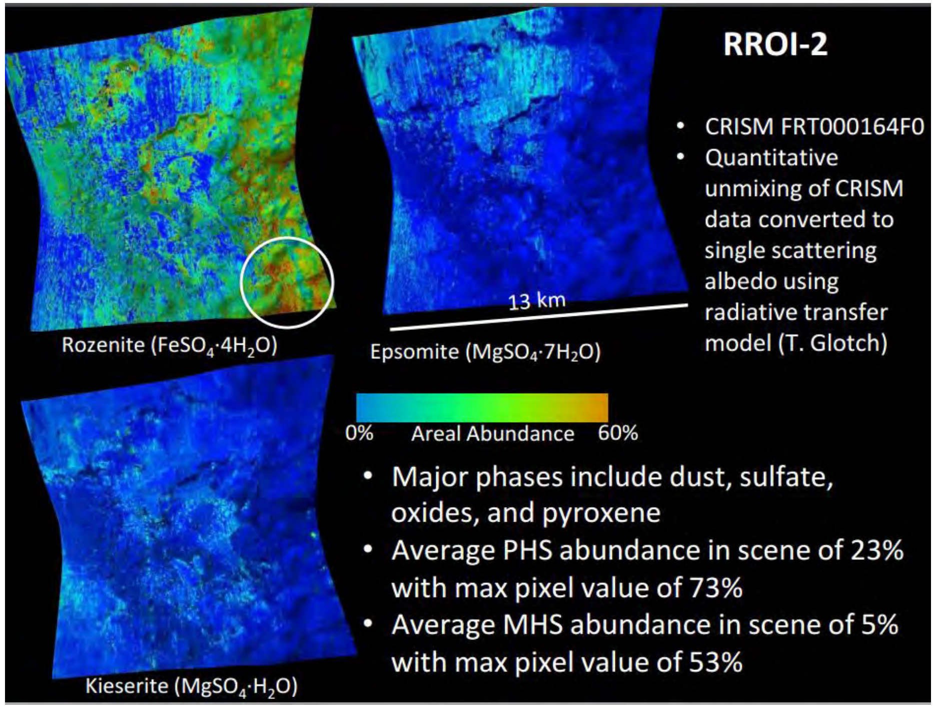
*Glotch & Christensen (2005)

Mars

Aram Chaos Case Study

Proposed Hydrated Sulphate Mineral Prospects

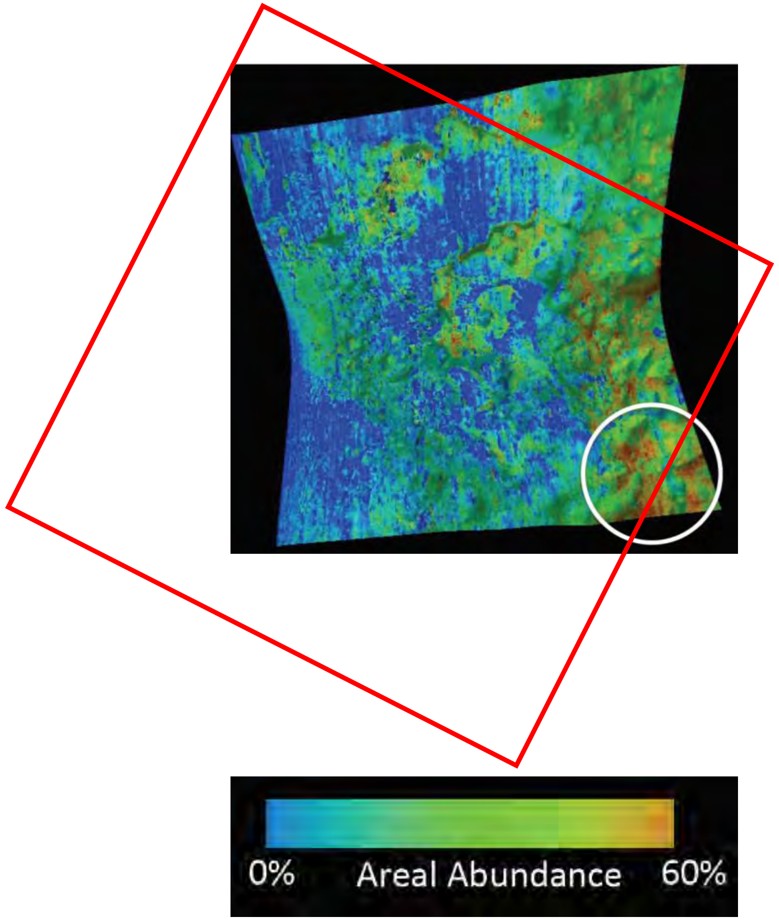




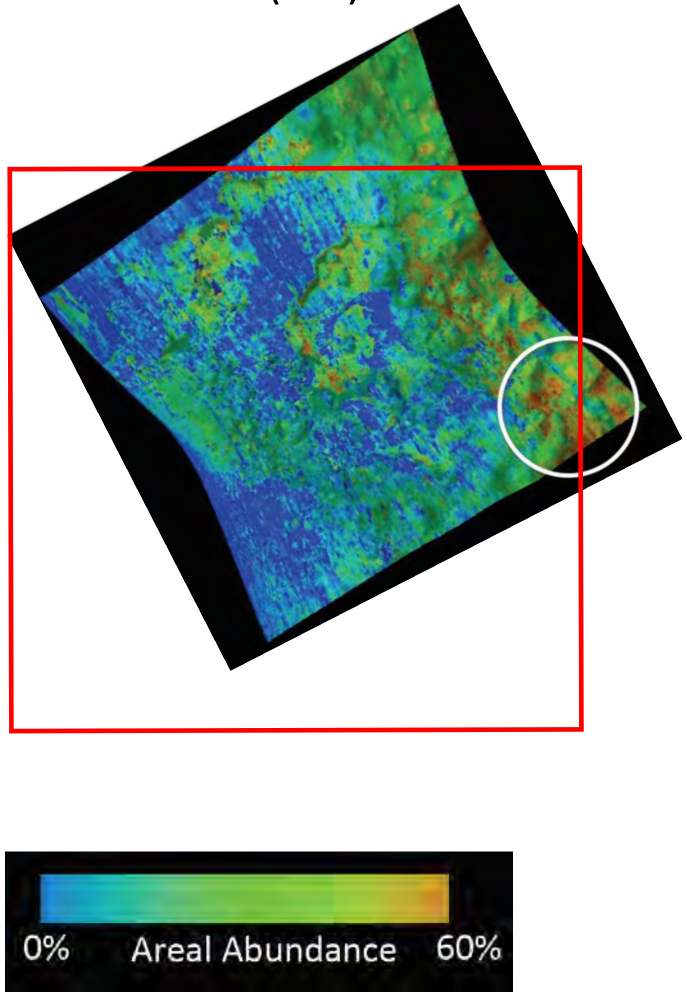
Mars – Aram Chaos

Creation of Geological Block Models

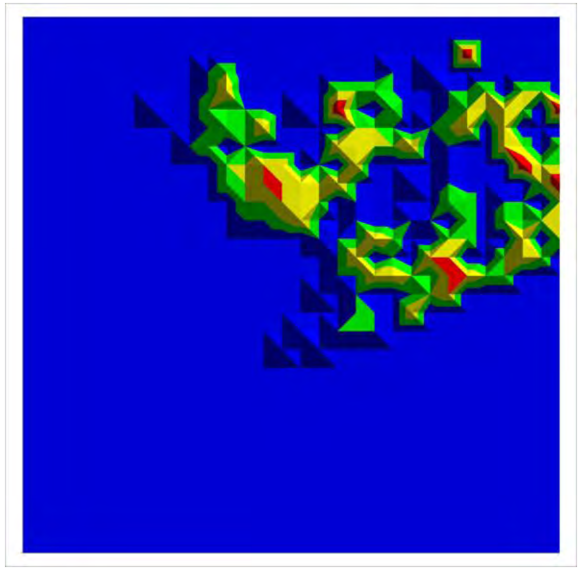
Original Rozenite Block Model



Rotated Rozenite Block Model
(37°)



Rozenite Block Model
M^2O^2 Tool

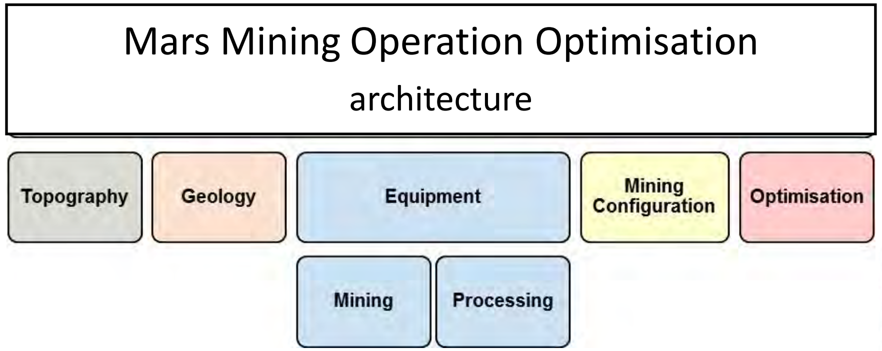


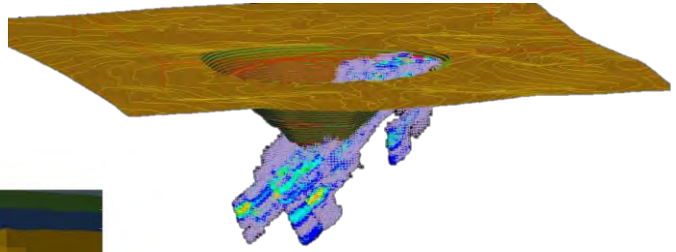
Legend

Range	Colour
0-15	Blue
15-30	Bright Gree
30-45	Yellow
45-60	Red

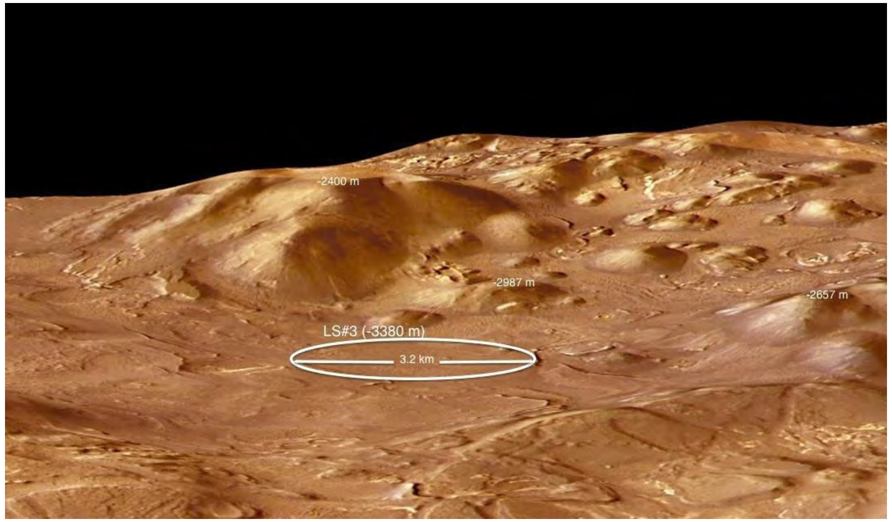
Mars – Aram Chaos

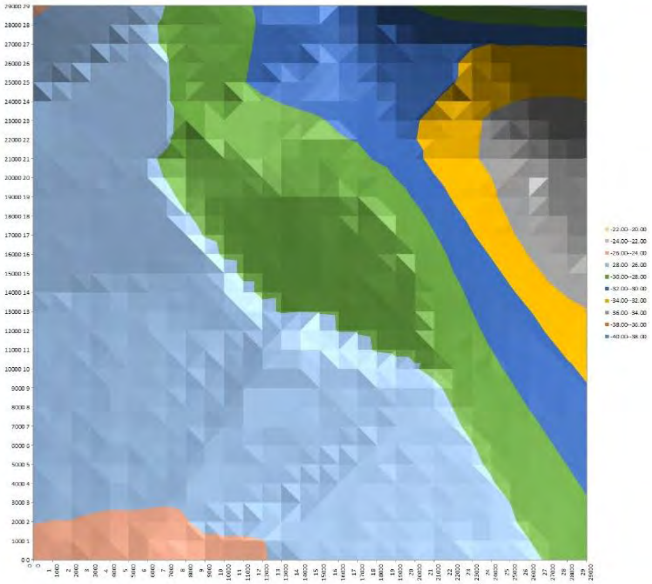
Topological visualization of water resource (mineral systems approach)





Combination and joint use of Topographic, geological and design database in a mining software





Aram Chaos Image generated on Excel® using Surface-Plan View Chart

M²O²

M^2O^2
Mars Mining Operation Optimiser
In-Situ Resource Utilisation

ASCENTECH ENTERPRISES INC.

UNSW SYDNEY

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

- Data
- Setting
- Mining
- Processing
- Results

- Topography
- Block Model
- Infrastructure

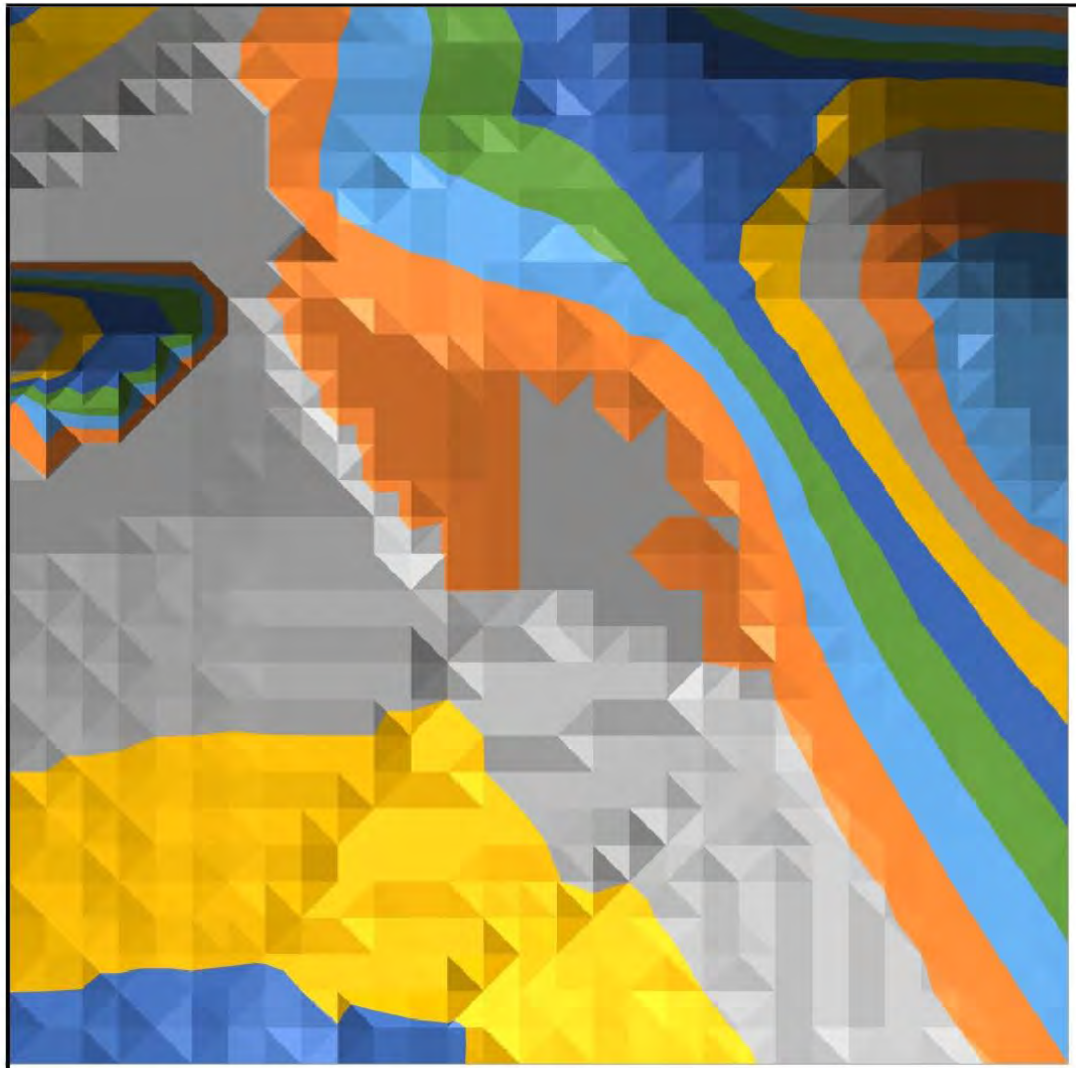
Select Map
- (•) *Topography*
- ( ) *Block Model*

☐ Mining Site

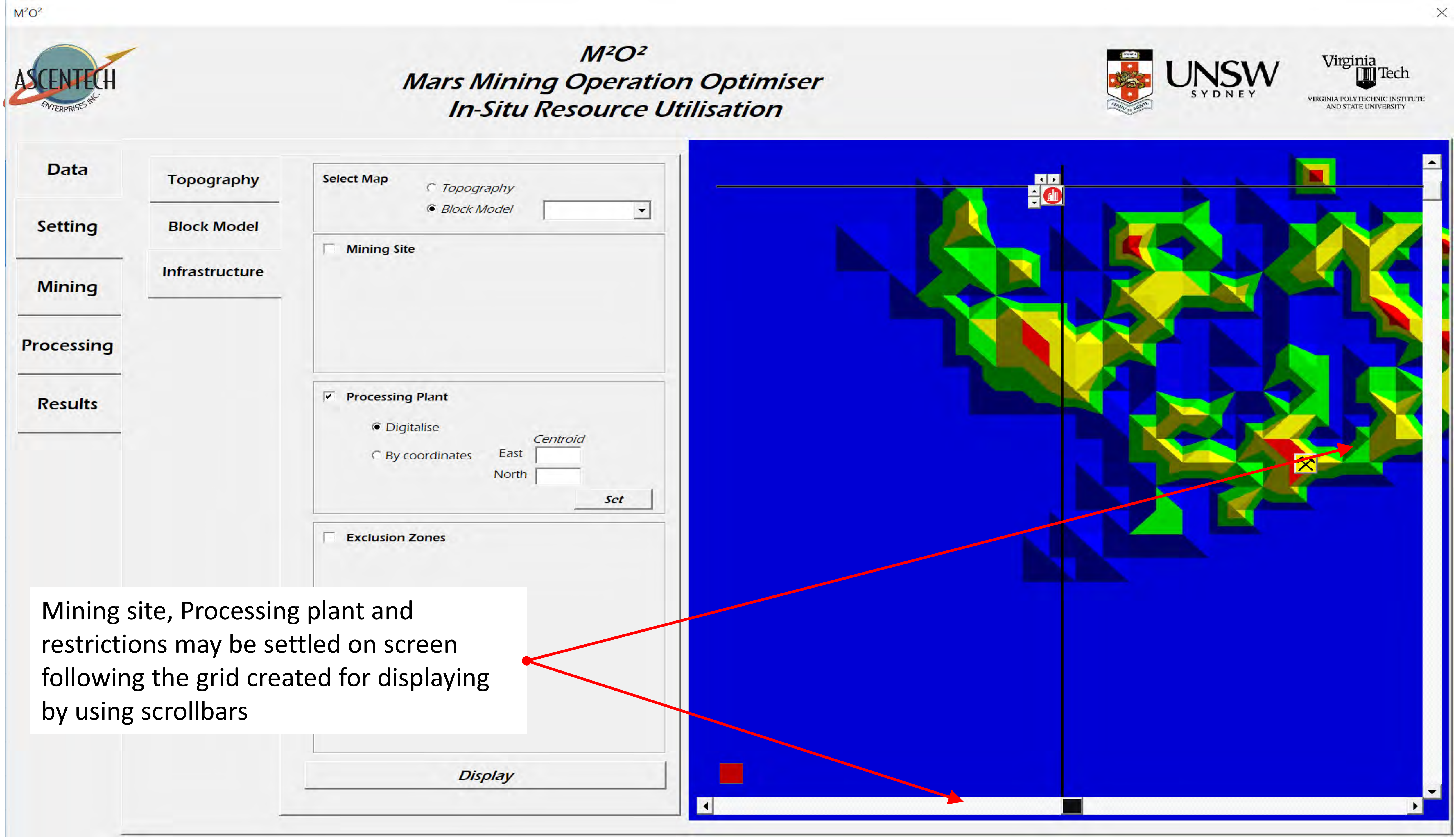
☐ Processing Plant

☐ Exclusion Zones

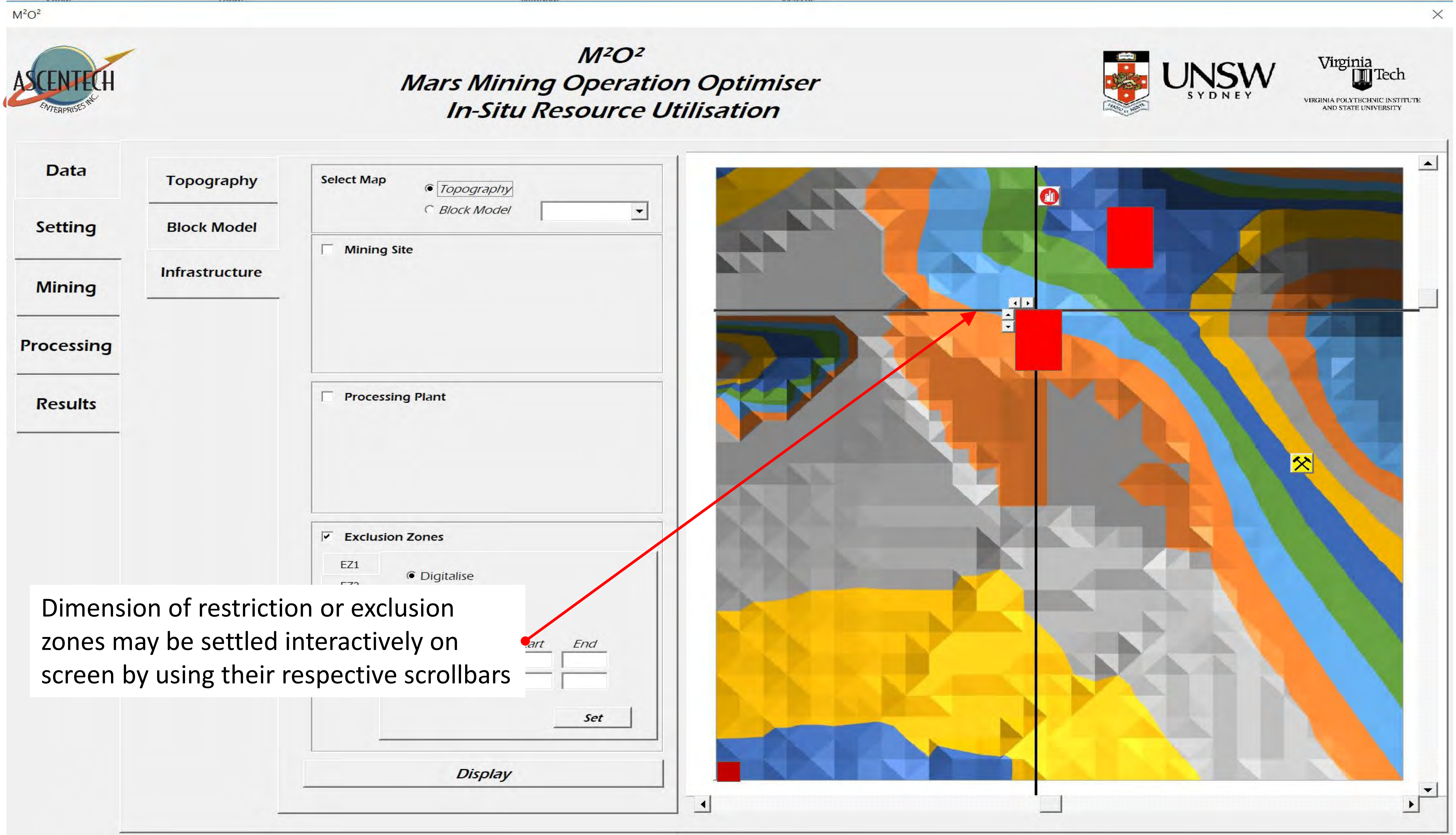
Display



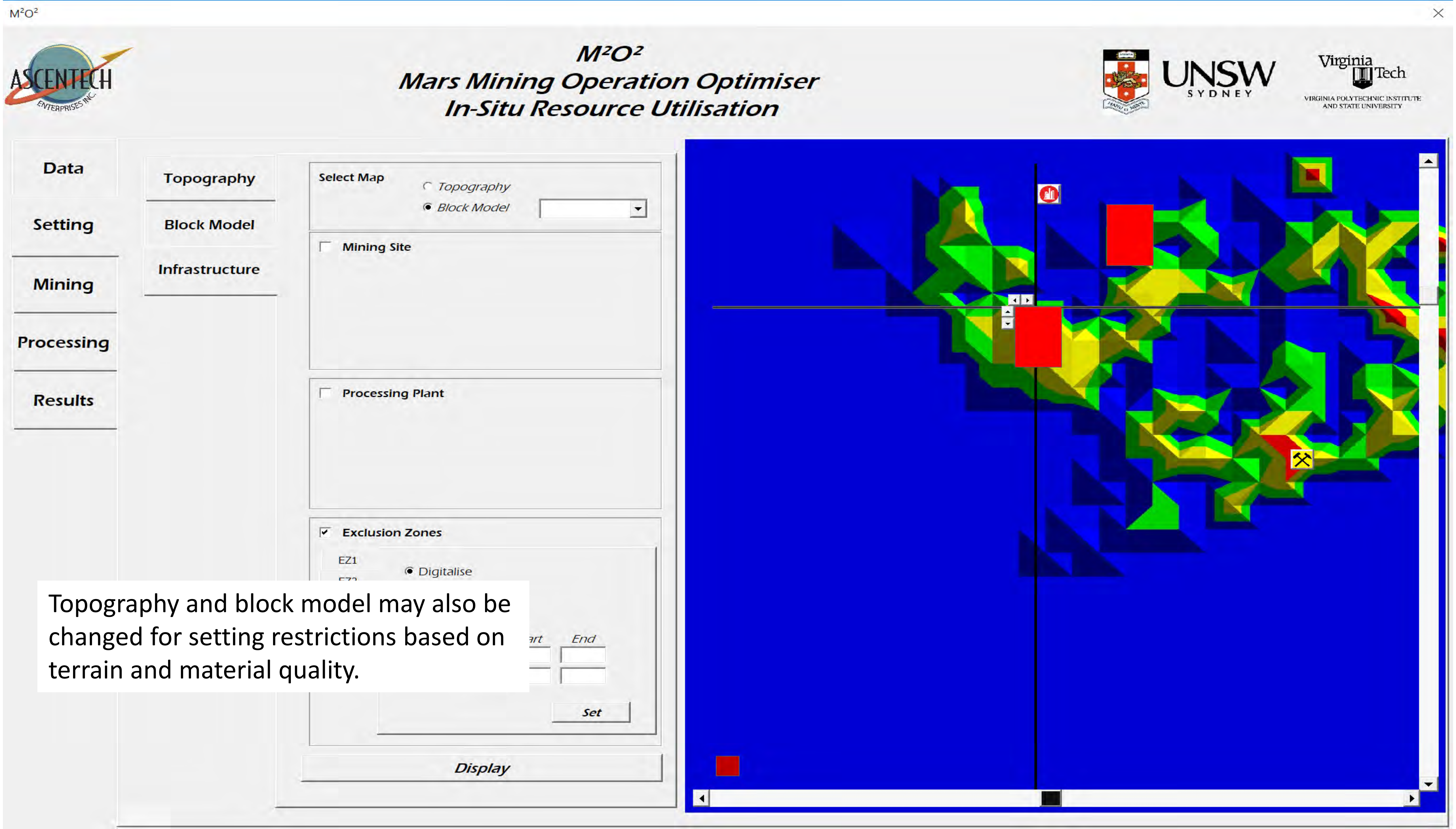
Both, topography and Block model may be used for setting infrastructure and restriction zones for haulage



Mining site, Processing plant and restrictions may be settled on screen following the grid created for displaying by using scrollbars



Dimension of restriction or exclusion zones may be settled interactively on screen by using their respective scrollbars



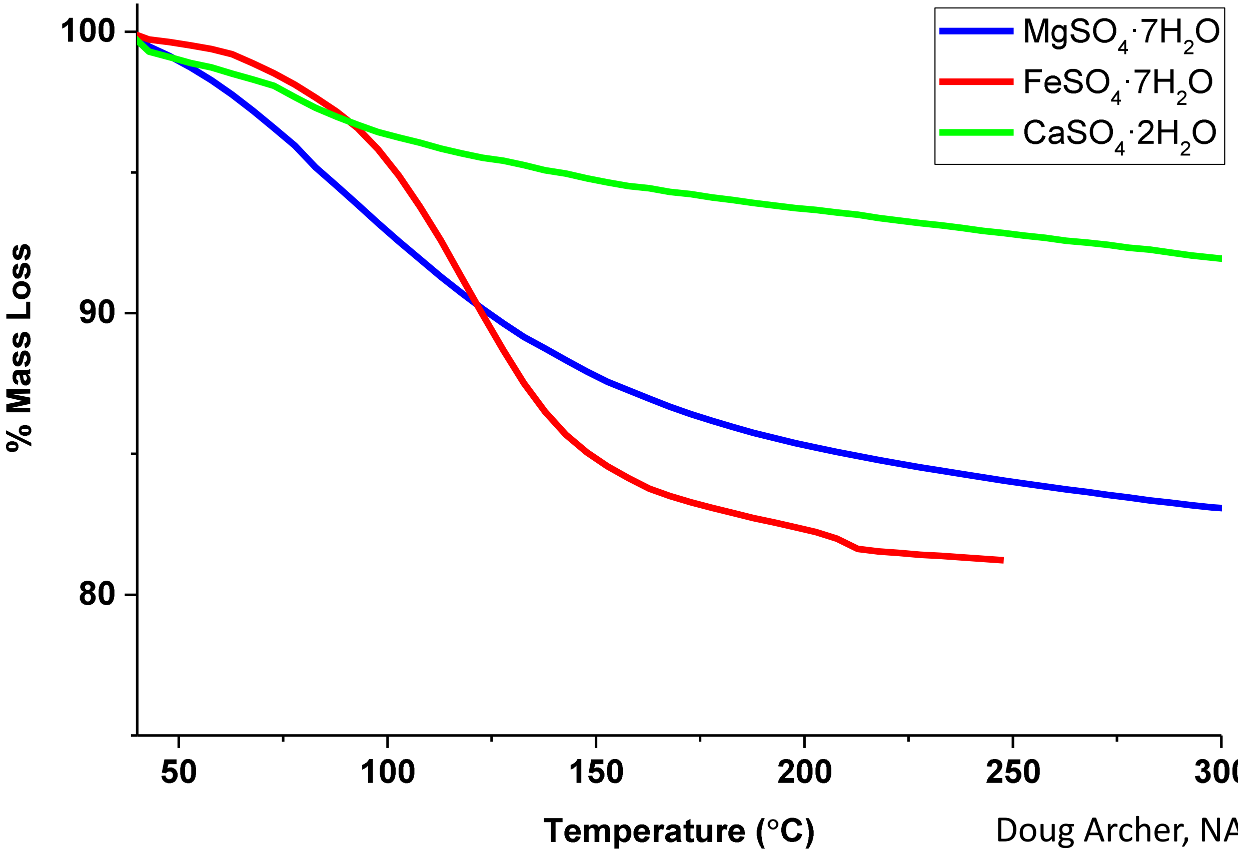
Topography and block model may also be changed for setting restrictions based on terrain and material quality.

Mars

Water loss from poly-hydrated sulfates

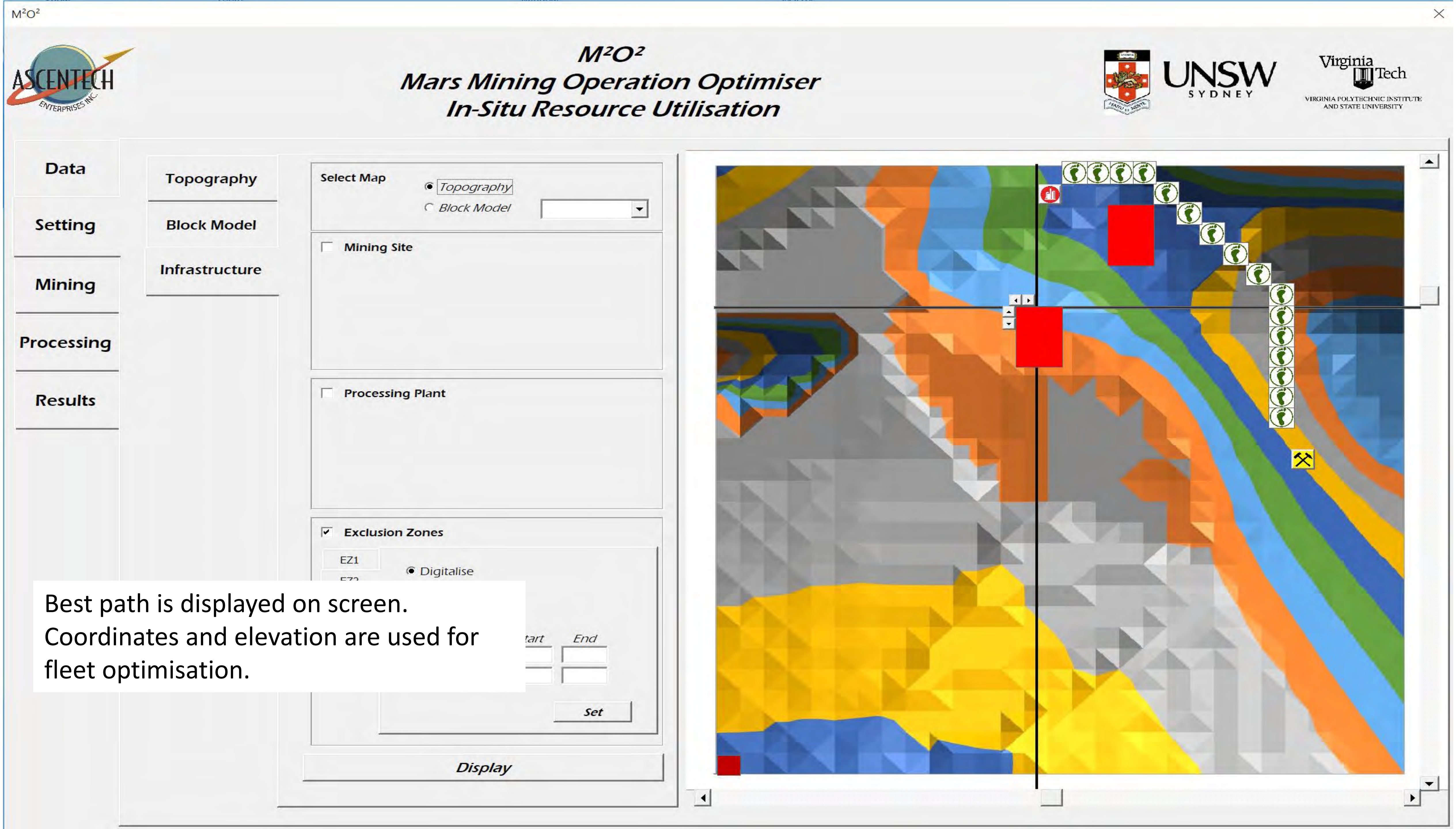
- Structural H_2O is generally released from sulfates by ~300 ºC.
- Structural OH can be released between ~400-800 ºC

Sulfate	H_2O as % of total mass
$MgSO_4 \cdot H_2O$	13
$MgSO_4 \cdot 7H_2O$	51
$FeSO_4 \cdot H_2O$	11
$FeSO_4 \cdot 7H_2O$	45
$CaSO_4 \cdot 0.5H_2O$	6
$CaSO_4 \cdot 2H_2O$	21

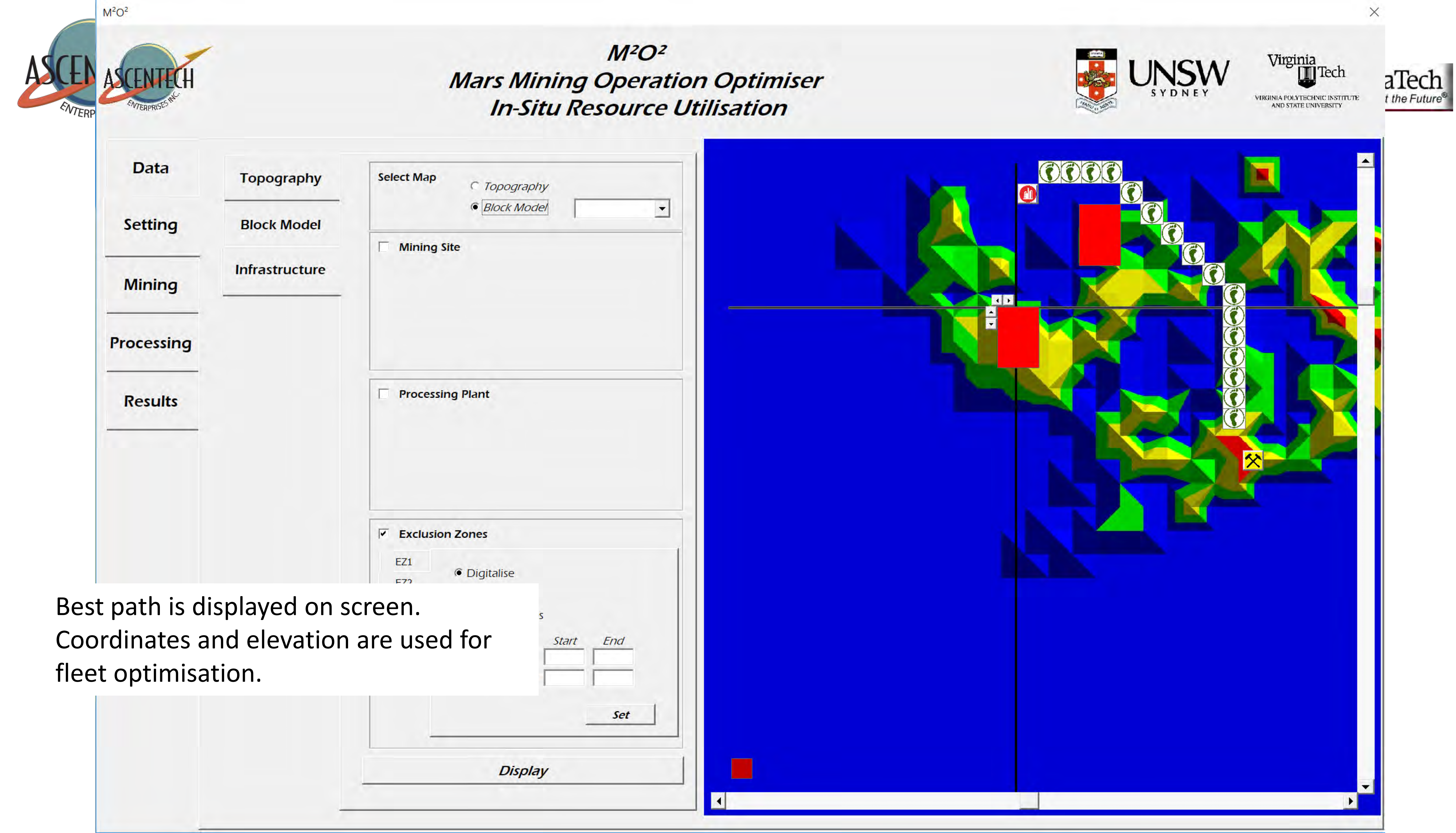


Doug Archer, NASA JSC

* TG water loss curves show water released after the samples were exposed to a dry He flow prior to analysis that removed some water



Best path is displayed on screen. Coordinates and elevation are used for fleet optimisation.



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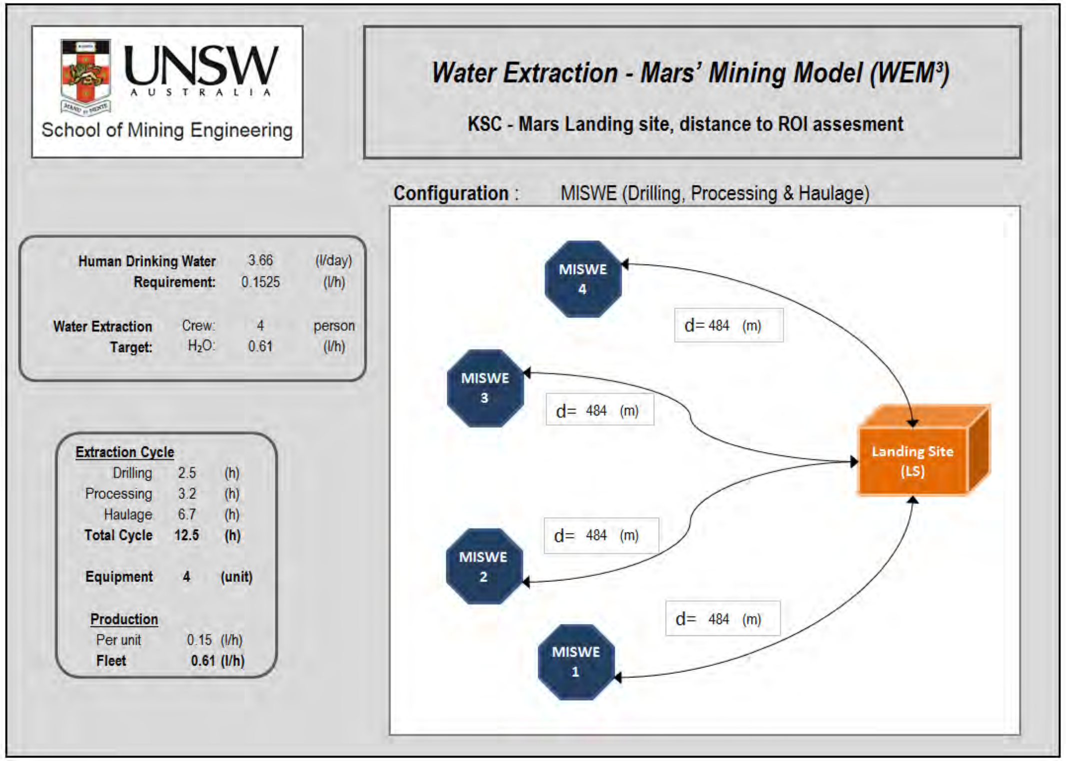
Economic Feasibility Analysis



Linear programming optimisation technique

Technical (equipment) and geological constraints are main inputs.

Optimisation conducted to reach a target or to maximise performance.

Target: *Provide enough water supply for a crew of four (4)*

Optimization: *Distance between ROI and LS*

Assumptions :

Water Contained in regolith (WC%): 3 wt.% to 7 wt.% (5 wt.% as base case)

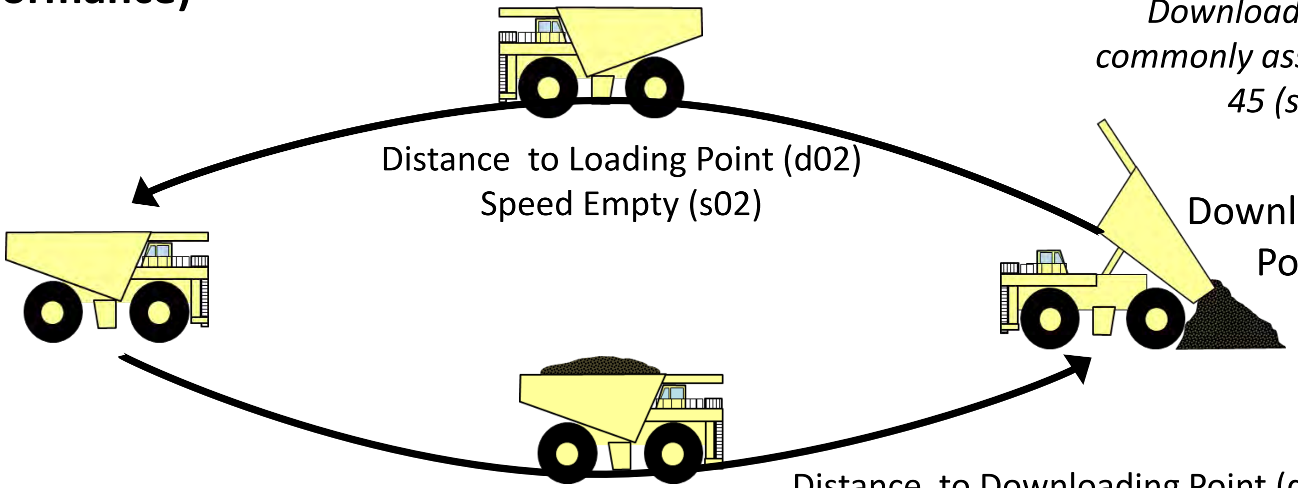
Based on human drinkable water requirement (3.66 L/day) for space missions.

Equipment:

- *Water recovery: 87%*
- *Water storage capacity 5 L*
- *Drilling rate: 1 m/h*
- *Speed: 2.4 m/min*

Economic Feasibility Analysis

Option 01 – MISWE (Performance)



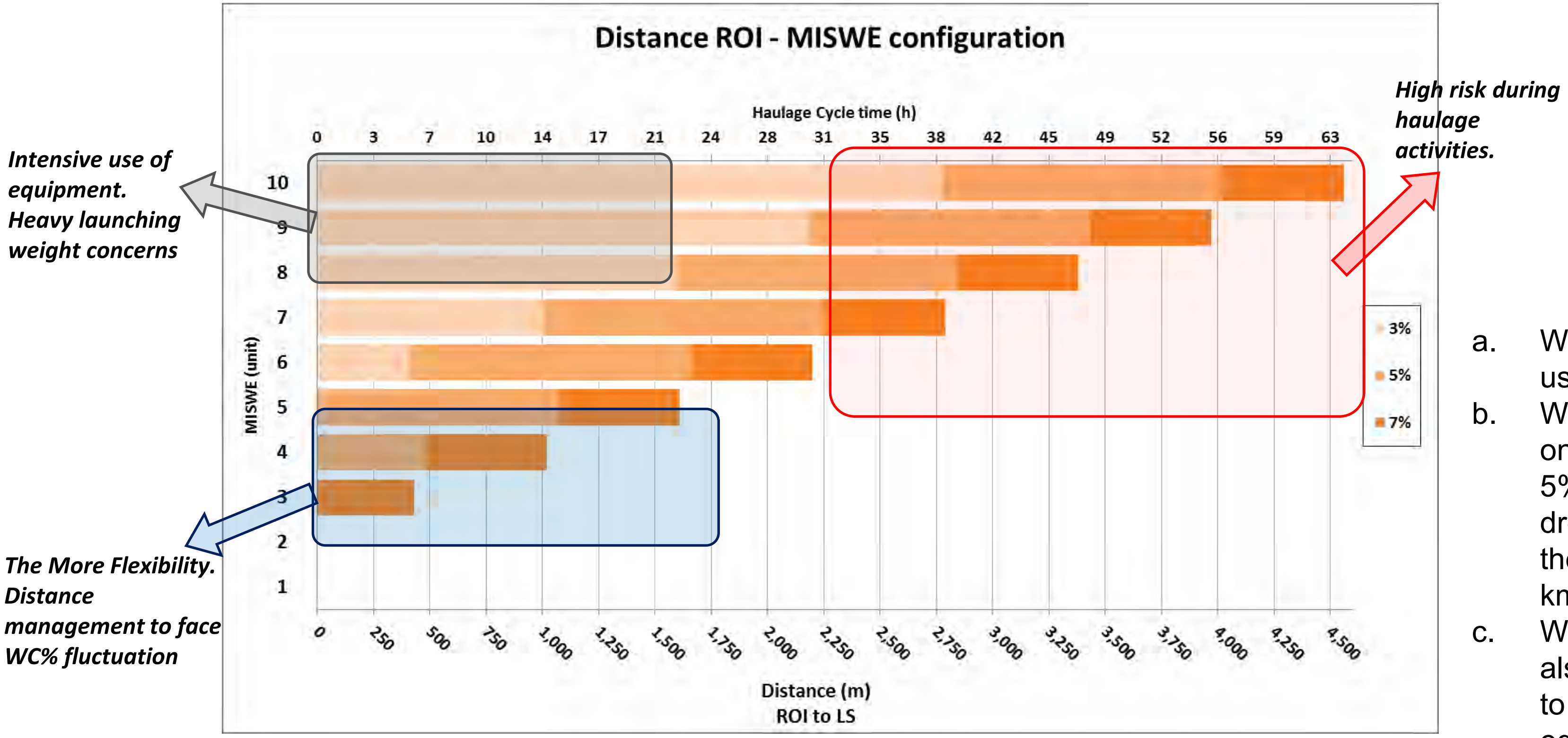
Continuous ops

Loading time (hour) $= \left(\frac{Transporter\ capacity\ (m^3)}{Drilling\ rate\ \left({}^{m}/_{hour}\right) \times Drilling\ \emptyset (m^2)}\right)$

Haulage time $= \left(\frac{d_{01}}{s_{01}} + \frac{d_{02}}{s_{02}} + (l - t) + (d - t)\right)$

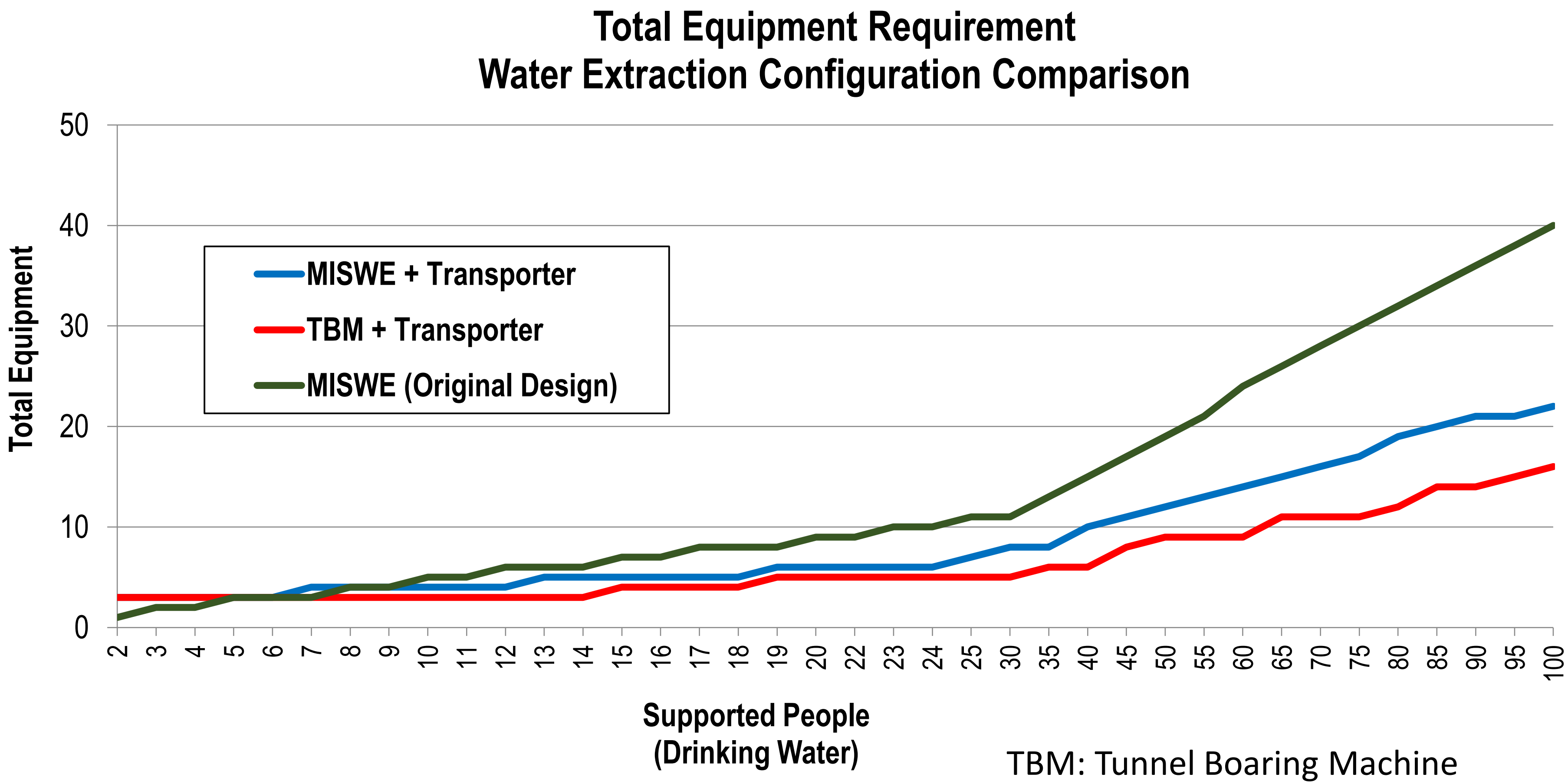
Performance (litre H_2O***/h)*** $= \left(Drilling\ rate\ \left({}^{m}/_{hour}\right) \times Drilling\ \emptyset (m^2) \times H_2OConc. (\%) \times 1000 \left({}^{l}/_{m^3}\right)\right)$

Sensitivity results (WEM3 model)



a. Water supply may not be assured by using less than 3 equipment.
b. WC% have the most significant impact on distance. If WC% decreases from 5% to 3% the allowed haulage distance drops by ~ 1.2 km. If it increases to 7% the allowed distance may rise about 0,5 km.
c. When distance increases time cycle also increases dramatically mainly due to long haulage cycle as a result of low equipment's speed.

Sensitivity results (WEM3 model)



TBM: Tunnel Boaring Machine
MISWE: Mars In Situ Water Extractor (Honeybee Robotics)

Conclusions

We develop a tool that leverages both mining & minerals processing industry practices and space systems engineering practices

- Based on available geological data handled through mineral systems approach
- Adaptable to user requirements (architectures, conops)
- Useful for early assessments, Phase I planning, and technology selection/maturation

First version of tool for Mars resources (NASA Evolvable Mars Campaign, NASA Human Landing Sites Workshop) to be delivered to NASA

Further development for other locations (moon, asteroids) need user "wish list"

On-going potential user survey (lsibille@ascentechent.com)

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