Lunar water Reference Case Study

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Goal

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Define a set of lunar water deposit 'profiles' to use as reference cases for ISRU development and planning

- Recognizing the current lack of information regarding potential lunar water deposits, use current data sets and models to identify a discrete set of water deposit profiles to use for initial ISRU planning purposes.

Need

- NASA's current timelines do not allow prospecting/reconnaissance and ISRU design to occur in series. ISRU systems must begin development (system design and architectures) in parallel with reconnaissance efforts.
- ISRU design and planning requires some constraints for design; engineers need some targets to work to. Definition of a few reference cases will help focus planning and design.
- This approach is similar to what the MWIP (Mars Water ISRU Planning) effort did for Mars: see next slide
    - Defined several Mars water deposit types (slide 17, http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx)

Mars reference cases: Example

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The inspiration of this effort was the MWIP study which defined water reference cases for Mars.

http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

MWIP defined 4 main deposit types which were used to trade ISRU systems and conops options.

Definition of Reference Reserve Cases

Four reference cases were chosen to represent the output of HLS² (See **Slide #7**)

Essential Attribute	Deposit Type: A. Ice	B. Poly-hydrated Sulfate	C. Clay	D. Typical Regolith (Gale)
Depth to top of deposit (stripping ratio)	variable (1-10m)	0 m	0 m	0 m
Deposit geometry, size	bulk	bulk	bulk	bulk
Mechanical character of overburden	sand	NA	NA	NA
Concentration and state of water-bearing phase within the minable volume				
–Phase 1	90% ice	40% gypsum[1]	40% smectite[2]	23.5% basaltic glass[3]
–Phase 2	–	3.0% allophane[4]	3.0% allophane[4]	3.0% allophane[4]
–Phase 3	–	3.0% akaganeite[5]	3.0% akaganeite[5]	3.0% akaganeite[5]
–Phase 4	–	3.0% smectite[2]	3.0% bassanite[6]	3.0% bassanite[6]
–Phase 5	–	–	–	3.0% smectite[2]
Geotechnical properties				
–large-scale properties ("minability"), e.g. competence, hardness	competent–hard	sand–easy	sand–easy	sand–easy
–fine-scale properties ("processability"), e.g. competence, mineralogy	no crushing needed	no crushing needed	no crushing needed	no crushing needed
The nature and scale of heterogeneity	variation in impurities	±30% in concentration	±30% in concentration	±30% in concentration
Distance to power source	1 km	1 km	1 km	100 m
Distance to processing plant	1 km	1 km	1 km	100 m
Amenability of the terrain for transportation	flat terrain	flat terrain	flat terrain	flat terrain
Presence/absence of deleterious impurities	dissolved salts	none	none	perchlorate?
First order power requirements	TBD	TBD	TBD	TBD
Not Considered				
Planetary Protection implications	TBD	TBD	TBD	TBD

1. ~20 wt% water, 100-150°C
2. ~4 wt% water, 300°C
3. ~1 wt% water, >500°C
4. ~20 wt% water, 90°C
5. ~12 wt% water, 250°C
6. ~6 wt% water, 150°C

Note: Planetary Protection implications are addressed on Slide #86

Ground Rules and Assumptions

- The table at right is the Lunar Water ISRU Measurement Study (LWIMS)[1] definition of the ISRU needs for a viable water deposit.
  - This is based on the quantity and characteristics of the water deposit that are required to achieve a reasonable engineering solution with current technology assumptions
- Shallow bulk water is the target.
  - Surface frost is not considered to be available in quantities sufficient to support ISRU
  - Deep water (>1m) is not considered in detail, but will be addressed
- There are also criteria for Human landing systems that must be considered for a deposit at a site to be of use.
  - Not listed here, see LWIMS report[1]

ISRU System	
ISRU Requirement	**Criteria**
Water Concentration	≥2 wt.
Water Depth distribution	5 to 100 cm, ≤10 cm increments
Overburden depth	5 to 50 cm ≤10 cm increments
Lateral distribution	500 m radius
Target yield	15 tons water per lander

- Criteria according to current ISRU system models which use current technologies and architecture concepts
- Criteria are highly dependent on:
  - Amount of consumables needed
  - Timeline allotted for ISRU production
  - Architecture interface to HLS (location of produced consumables, power)
  - Assumptions about mobility options and capabilities including autonomy and operational life
- Consideration to Oxygen from Regolith (O2R) as the alternative to water from ice
  - When possible, identify breakpoints where O2R is clearly advantageous over water from ice

[1] Kleinhenz, J., McAdams, A., et. al., 2020, Lunar Water ISRU Measurement Study (LWIMS):*Establishing a Measurement Plan for Identification and Characterization of a Water Reserve. NASA/TM-20205008626*

Considerations

The definition of the following profiles are based on discussions and consensus from the authorship team. Some of the key considerations from the existing data sets included:

- Interpretations of Neutron Spectroscopy data: The LCROSS results (5 wt%) were based on water content in the LCROSS ejecta plume, but made no assumptions regarding the distribution in the ground. Models using this information to predict in-ground water content use different assumptions regarding water distribution, resulting in a range of possible bulk water concentrations.
- Geologic context: The history of the deposit affects the distribution. A newer deposit may be less gardened therefore a higher heterogeneity may be expected. More gardening will homogenize the deposit.
- Surface Frost: While this may be an indicator of a deeper water deposit, this has been (thus far) unverified.

- Geotechnical properties which may impact the excavation method will be dependent of form of ice, temperature, and concentration. There is not sufficient data to define this for the reference cases here.

DISCLAIMER: These reference cases are possible explanations of the existing data sets. These cases exist within limits of the various models, considering the water detections within the context of the physical environment. Other interpretations may be feasible.

Profile Parameter Definition

Overburden depth	Depth of the surface layer of dry regolith before reaching the water deposit. Any surface frost is included in overburden.
Water concentration	The bulk concentration of water deposit, not including the overburden. This is the average (bulk) concentration over the deposit thickness, so includes patchiness or heterogeneities.
Heterogeneity (conceptual)	The estimated standard deviation of the stated bulk water concentration, based on water distribution models.
Lateral extent	The size of deposit laterally. The ranges are defined in terms of ISRU breakpoints and resolution of data. For standard mining methods, ISRU baseline criteria require deposits >100m.
Thickness	Once overburden depth is reached, this is the thickness of the water deposit. Only deposits up to 1 m thick were considered, since this the baseline ISRU criteria. However, deposits are likely toe extend deeper. Below 2 m water concentration may increase to as much as 10%.
Location characteristics	This is an indication of the accessibility of the deposit.
Frost	Frost is not anticipated to be thick enough to be of use to ISRU. It is listed here to put the reference case in context (as an indicator for detection).
Cause/Context	This is a brief description of how the water may have got there, and what is keeping it there. It is listed here to put the reference case in context (as an indicator for detection).
ISRU Impact	Some impacts that the deposit may have on ISRU considerations are offered.

Lunar Water Reference Cases

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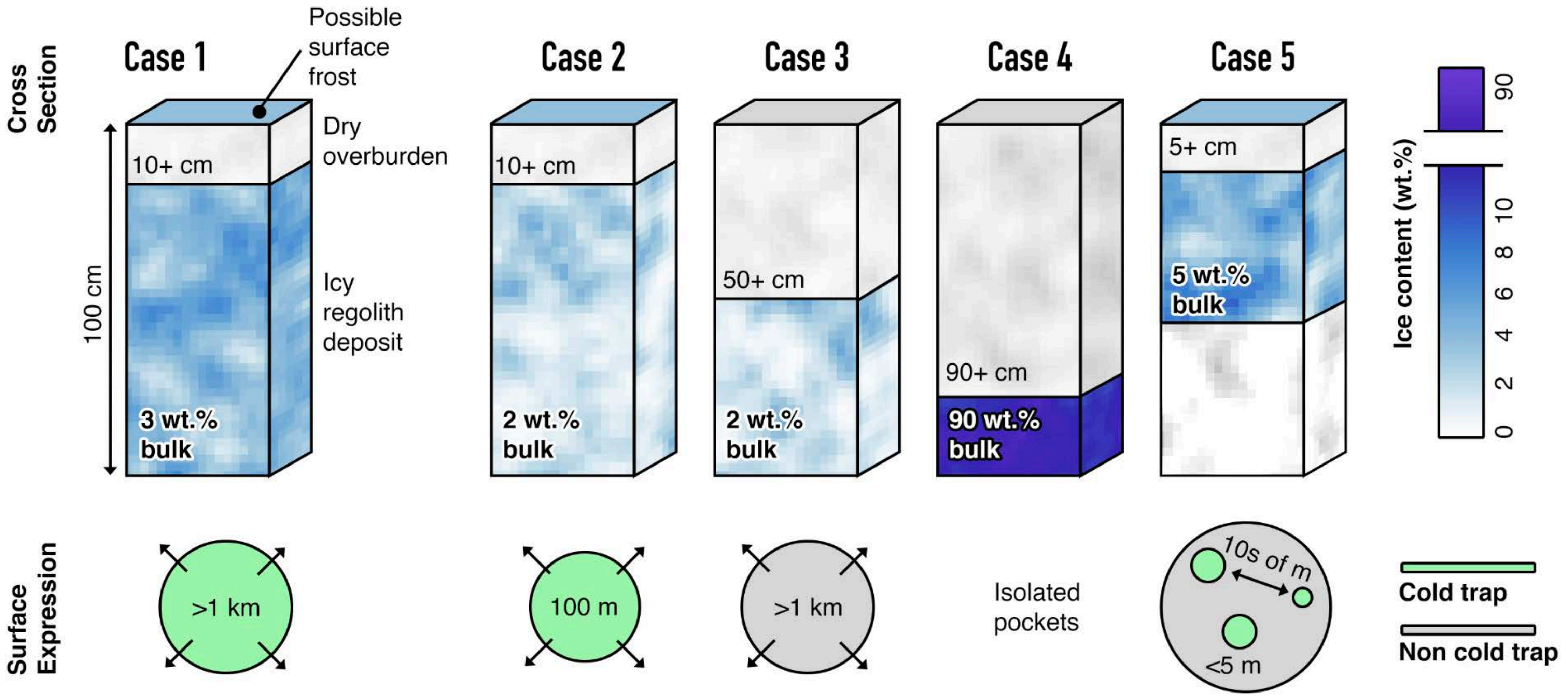
Profile #	1	2	3	4	5
Description	**Deep/large cold trap**	**Shallow/Small cold traps**	**Higher overburden, more accessible**	**Localized motherload**	**Distributed MicroCold traps**
Overburden depth	10-20 cm	10-20 cm	50 cm	75 cm	5- 10 cm
Water concentration	3%	2%	2%	90%	5%
Heterogeneity	$\sigma = 0.536$, $\mu = 0.955$	$\sigma = 0.833$, $\mu = 0.347$	$\sigma = 0.833$, $\mu = 0.347$	$\sigma = 0.035$, $\mu = 4.49$	$\sigma = 0.58$, $\mu = 1.44$
Lateral extent	High, >1 km	Moderate, 100m	High, 1km	Low, 1-10m	<5 m per deposit, 10s of meters between cold traps
Thickness	80-90 cm	80-90 cm	50 cm	25 cm	50cm
Location characteristics	Deep, large cold trap: shadowed	Small cold trap : shadowed (250m-diviner resolved)	Not necessarily in cold trap, may occur in inter crater regions (temporarily/partially lit plains).	Anywhere in ice stability regions	Field of micro cold traps
Frost	Possible	Possible	Unlikely	Unlikely	Possible
Cause/Context	Deep/large cold trap that has been well homogenized by gardening.	Area that experienced lower number of impacts, so less gardening. Since they are shallow cold trap, more surrounding dry regolith mixed in so a higher heterogenity is anticipated.	Deeper deposits which have experiences limited gardening (few, small impacts- large impacts don't reach >50cm). Less mixing so higher heterogenity. These are intercrater regions that are partially lit, where ice stability is present but at deeper depths.	The ice was deposited by a large impact (asteroid), an was quickly buried to depths where gardneing does not reach. These are highly localized deposits.	Deposits at a thermal transition zone where there are localized shadows. This deposit is a Microcold trap field; young craters. Assume active water replenishment, "new" water.
ISRU impact	Larger cold trap, resolvable by orbital detection. Highest confidence in water deposit due. Traverse distances and slopes may limit accessibility	Smaller cold trap, but maybe more accesible (in terms of traverses/slopes to reach deposit). However total tonnage availible may limit continued use.	Higher overburden, but more accessible. With no Frost layer as an indicator, these locations may be more challenging to definitively identify.	High yield, but highly localized. Requires high level of reconasaince. Maybe a one-shot (one time use) mine.	Field of many small water deposits. Does not require crater traverse, but many small 'mines' that much be pinpointed. Note that the stability of exposed ice (pit mine) may not be same as PSR need to be aware of dirunal/enviroment ISR.

Note regarding depths: Only depths up to 1m are defined in the references cases. However the deposit thickness defined in each case are likely to extend deeper. Below 2m there is potential for water ice anywhere in ice stability regions (not limtited to cold traps) that could extend to thermal boundary layer (5m - 10m). The water content of this 'deep' ice may be ~10 wt%.

Lunar Water Reference Cases



Below 2 m there is potential for water ice ~10 wt% that could extend to thermal boundary layer (5m - 10m).
The condition defined at 1m for these cases is likely to extend deeper.

Note on LCROSS 5 wt%

The LCROSS prediction was 5 wt%. Thus far, this prediction has been used for various case studies, but there is no reference case reflecting this.

Why is there no "LCROSS-like" reference case at 5 wt%?

- The 5 wt% interpretation was based on the amount of water in the impact ejecta plume.
  - Correlating this to the in-ground water content requires knowledge of the distribution.
  - The reference cases consider various distributions including dry overburden and higher concentrations at depths >1m
- The impact excavated around 5 m of regolith
  - The ISRU focus is on the top 1 m depth, where that concentration is likely lower when considering possible distributions (heterogeneities: overburden, patchiness) over the 5 m LCROSS excavation
  - Below 2 m higher concentrations (10%) may be possible (Campbell 2003)
- The LCROSS site (Cabeus) had a high water expectation: it was chosen as a water rich site

- Note that Case 5 does indicate 5 wt% but within micro cold traps with limited lateral and depth extent.

Questions?

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- For questions about application of the references cases including regolith simulants and icy simulant preparation contact:
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  - Liz Carey, JPL/CalTech: elizabeth.m.carey@jpl.nasa.gov
  - Julie Mitchell, NASA JSC: julie.l.mitchell@nasa.gov

- For questions regarding the information in this document please contact the study team leads:
  - Julie Kleinhenz, NASA GRC: Julie.E.Kleinhenz@nasa.gov
  - Amy McAdam, NASA GSFC: amy.mcadam-1@nasa.gov

Appendix

Reference cases table with parameter definition

Profile #	Definition of terms	1	2	3	4	5
Description	Short descriptor of profile	**Deep/large cold trap**	**Shallow/Small cold traps**	**Higher overburden, more accessible**	**Localized motherload**	**Distrubuted MicroCold traps**
Overburden depth	Depth of the surface layer of dry regolith before reaching the water deposit. Any surface frost is included in overburden.	10-20 cm	10-20 cm	50 cm	75 cm	5- 10 cm
Water concentration	Bulk concnetration of water deposit, not including overburnden. This is the average (bulk) concentration over the deposit thickness, so inlcudes patchiness/heterogenity.	3%	2%	2%	90%	5%
Heterogeneity	The hetrogenity is defined in terms of a log normal distrubution, where the mean is the stated bulk water concentration.	σ = 0.536, μ = 0.955	σ = 0.833, μ = 0.347	σ = 0.833, μ = 0.347	σ = 0.035, μ = 4.49	σ = 0.58, μ = 1.44
Lateral extent	Size of deposit laterally. Defined in terms of ISRU breakpoints and Resolution of data. For standard mining methods, ISRU baselines deposits >100m	High, >1km	Moderate, 100m	High, 1km	Low, 1-10m	<5 m per deposit, 10s of meters between cold traps
Thickness	Once overburden depth is reached, this is the thickness of the water deposit. Only considered down to 1m, which is the baseline ISRU criteria, deposits are likely deeper. Below 2m water concentration may increase to as much as 10%.	80-90 cm	80-90 cm	50 cm	25 cm	50cm
Location characteristics	Indication of the accessibility of the deposit.	Deep, large cold trap: shadowed	Small cold trap : shadowed (250m-diviner resolved)	Not necessarily in cold trap, may occur in inter crater regions (temporarily/partially lit plains).	Anywhere in ice stability regions	Field of micro cold traps
Frost	Frost is not anticipated to be thick enough to of use to ISRU. However, the presence of frost may be an indicator of deeper bulk water. It is listed here to put the reference case in context (as an indicator for detection).	Possible	Possible	Unlikely	Unlikely	Possible
Cause/Context	Brief description of how the water may have got there and what is keeping it there. This is a context to help with detection/location of the defined deposits)	Deep/large cold trap that has been well homogenized by gardening.	Area that experienced lower number of impacts, so less gardening. Since they are shallow cold trap, more surrounding dry regolith mixed in so a higher heterogenity is anticipated.	Deeper deposits which have experiences limited gardening (few, small impacts- large impacts don't reach >50cm). Less mixing so higher heterogenity. These are intercrater regions that are partially lit, where ice stability is present but at deeper depths.	The ice was deposited by a large impact (asteroid), an was quickly buried to depths where gardneing does not reach. These are highly localized deposits.	Deposits at a thermal transition zone where there are localized shadows. This deposit is a Microcold trap field; young craters. Assume active water replenishment, "new" water.
ISRU impact	Some impacts the deposit may have on ISRU considerations.	Larger cold trap, resolvable by orbital detection. Highest confidence in water deposit due. Traverse distances and slopes may limit accessibility	Smaller cold trap, but maybe more accesible (in terms of traverses/slopes to reach deposit). However total tonnage availible may limit continued use.	Higher overburden, but more accessible. With no Frost layer as an indicator, these locations may be more challenging to definitively identify.	High yield, but highly localized. Requires high level of reconassaince. Maybe a one-shot (one time use) mine.	Field of many small water deposits. Does not require crater traverse, but many small 'mines' that much be pinpointed. Note that the stability of exposed ice (pit mine) may not be same as PSR need to be aware of dirunal/enviroment ISR.

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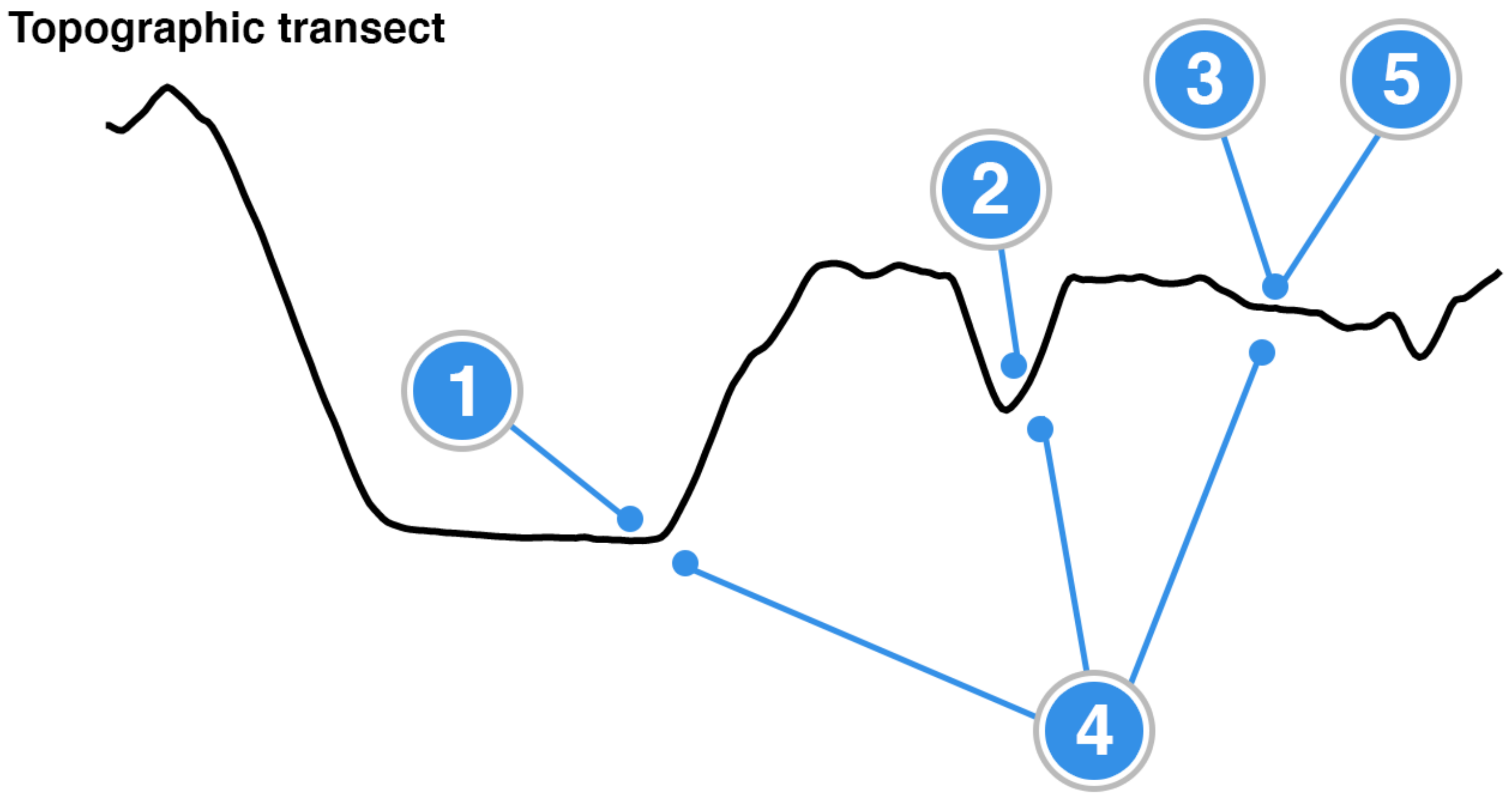
Lunar Water Reference Cases: Topographic profile



Case	Description
1	Deep/large cold trap
2	Shallow/Small cold traps
3	Higher overburden, more accessible
4	Localized motherload
5	Distributed MicroCold traps

Graphical representation of the references cases with respect to the lunar surface. This indicates access to the reference cases with respect to the lunar surface topography. For example, Case 1 is in a deep cold trap (crater) whereas cases 3 and 5 could be accessed from inter-crater regions.

Heterogeneity Definition: Log Normal distributions for water concentration

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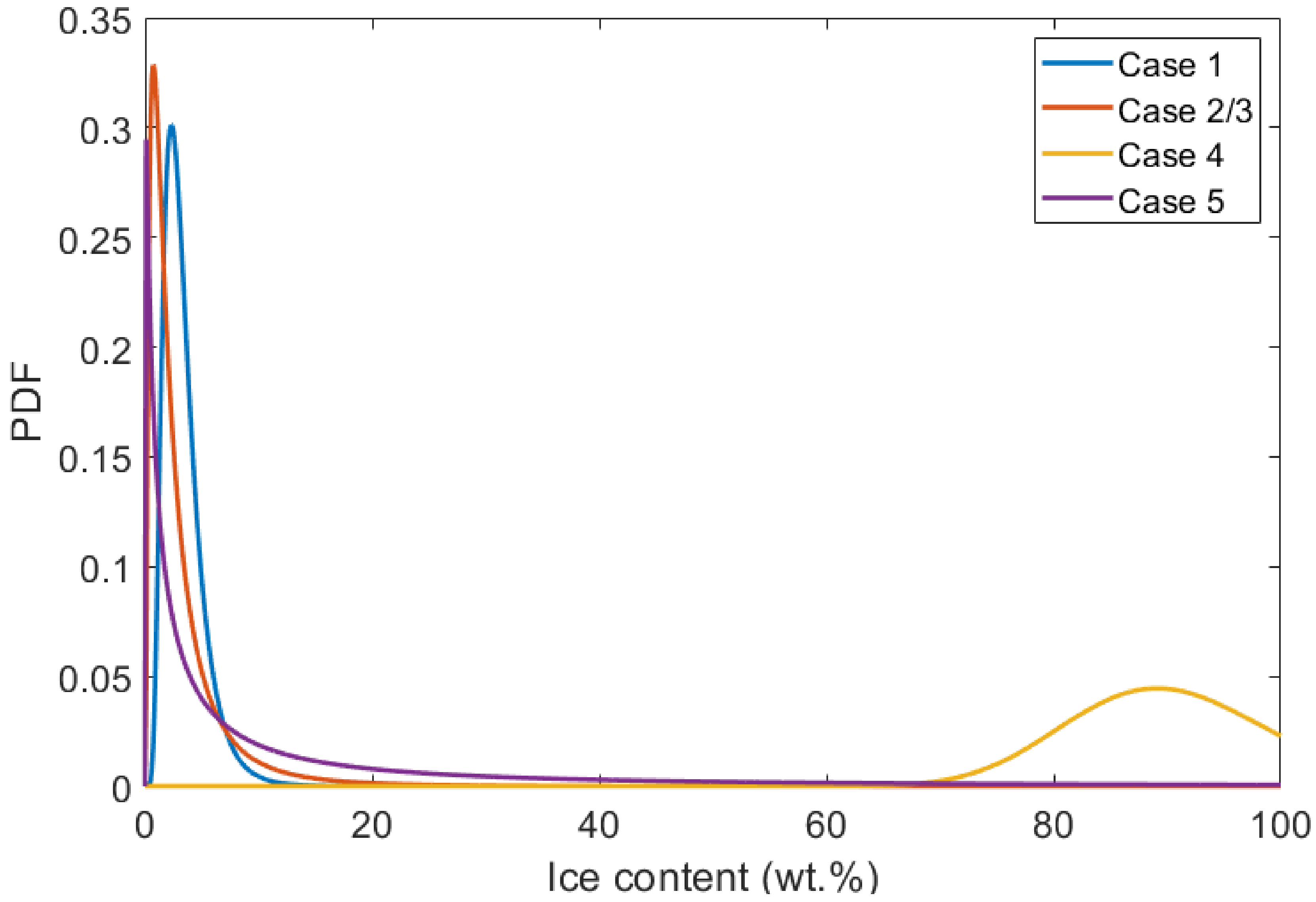
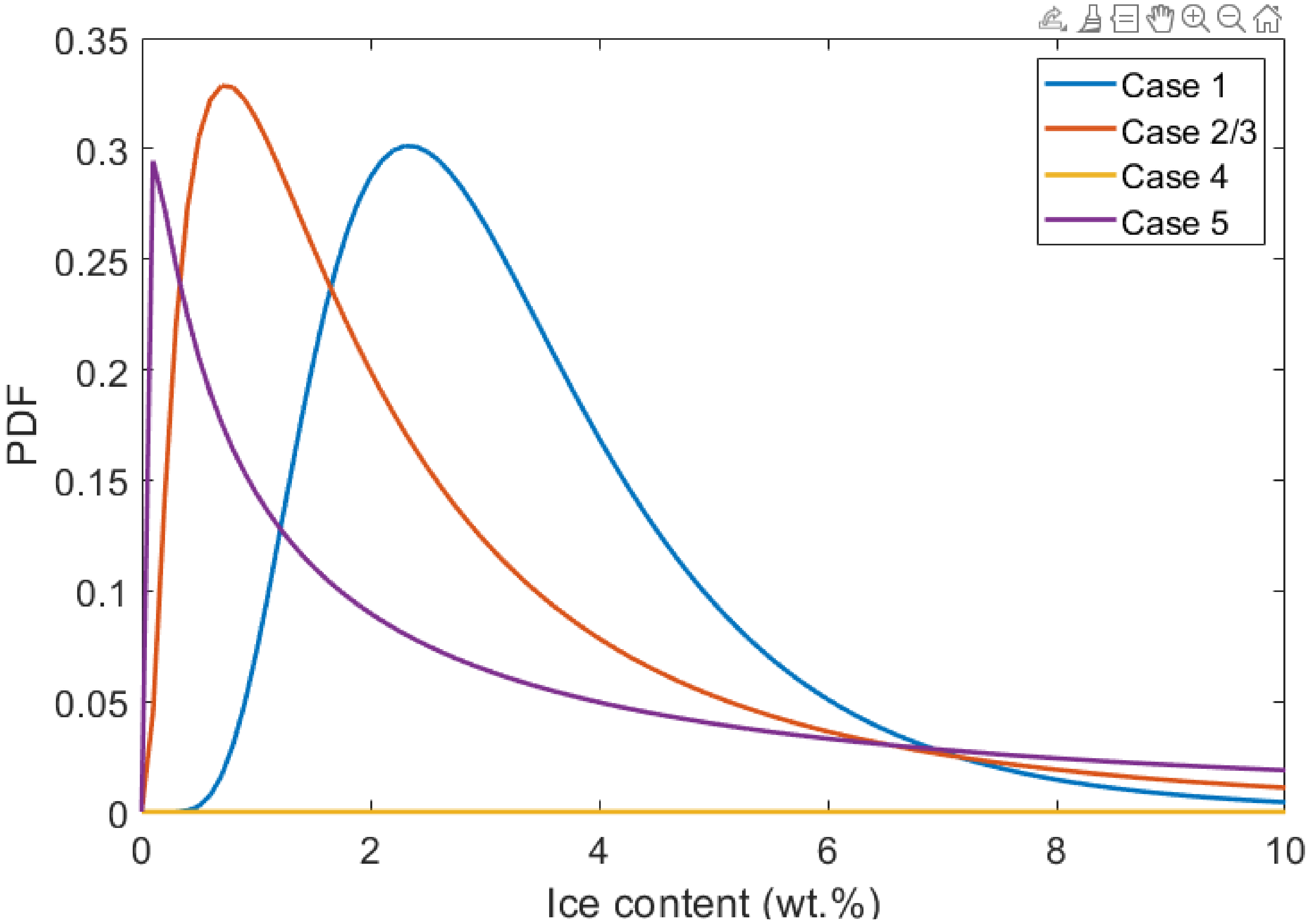


Case	Mean	Variance	μ	σ
1	3	3	0.955	0.536
2	2	4	0.347	0.833
3	2	4	0.347	0.833
4	90	45	4.499	0.035
5	5	10	1.441	0.580

Heterogeneity Definition: CLOSE UP
Log Normal distributions for water concentration

EXPLORE MOON to MARS



Case	Mean	Variance	μ	σ
1	3	3	0.955	0.536
2	2	4	0.347	0.833
3	2	4	0.347	0.833
4	90	45	4.499	0.035
5	5	10	1.441	0.580