

Lunar South Pole Resource Prospectivity: A Multi-Instrument Framework and a Testable Model for Heterogeneous Volatile Emplacement

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Summary: A physically constrained fusion of lunar south-polar hydrogen, temperature, radar, and geochemical observations is used to rank volatile prospectivity and test whether impact-related processes could create discontinuous ice-rich regolith deposits (“tumultuoites”) requiring rover-scale validation.

Abstract

Water ice and other volatiles in lunar south-polar permanently shadowed regions (PSRs) are established exploration targets, but their abundance, geometry, continuity, and depth distribution remain incompletely constrained. We present a physically informed, AI-assisted framework integrating neutron-derived hydrogen abundance, Diviner thermal stability, radar circular polarization ratio (CPR), and gamma-ray geochemical context into a relative resource-prospectivity index for 85–90°S. Variables are normalized to 0–1 using physically meaningful bounds and combined with weights prioritizing hydrogen and thermal stability. The product is an exploration ranking, not a calibrated probability of ice. We then evaluate a testable depositional hypothesis: “tumultuoites,” defined here as heterogeneous volatile-bearing regolith deposits formed by rapid impact-related vapor-particle transport, mixing, condensation, freezing, and mass movement within thermally stable cold traps. The hypothesis predicts strong lateral and vertical variability, including localized ice-rich lenses or aggregates embedded in lower-grade regolith and possible spatial discordance among hydrogen, thermal, and radar signatures.

These predictions can be tested by rover transects, neutron prospecting, repeated

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shallow drilling, spectroscopy, mass spectrometry, and thermal measurements. The approach reframes lunar polar resource assessment from a search for average ice abundance toward evaluation of resource geometry, heterogeneity, and extractability.

Introduction

Lunar south-polar exploration has progressed from establishing the plausibility and presence of hydrogen-bearing volatiles to a more difficult resource question: how are those volatiles distributed in three dimensions? Permanently shadowed regions (PSRs) provide temperatures capable of preserving water ice over geologic timescales, and multiple orbital and impact experiments support the presence of hydrogen, hydroxyl, water, and other volatiles in polar environments (Arnold, 1979; Feldman et al., 1998; Paige et al., 2010; Colaprete et al., 2010). Yet an orbital hydrogen anomaly does not establish whether a resource occurs as diffuse pore ice, ice-cemented regolith, disseminated grains, discontinuous lenses, or a combination of these forms.

That distinction is fundamental for in-situ resource utilization (ISRU). A broad, low-grade deposit requires a different exploration and extraction strategy than a discontinuous high-grade body. Resource geometry may therefore be as important as average abundance. Mining-scale studies emphasize the need to evaluate lunar ice at operationally relevant scales, while impact, volatile-transport, and thermal-stability studies indicate that delivery, migration, burial, excavation, and loss can create complex spatial patterns (Cannon & Britt, 2020; Stewart et al., 2011; Prem et al., 2015).

This Letter develops two linked ideas. First, heterogeneous orbital datasets are integrated into a transparent, physically constrained relative prospectivity framework for the lunar south pole. Second, spatial agreement and disagreement among those datasets are used to define observations that could test a conceptual heterogeneous-deposition model. The conceptual lineage began with consideration of the depositional character and potential heterogeneity of lunar polar ice during the 2020 period and subsequently developed through studies of lunar geology, volatile exploration, and VIPER-scale resource characterization (Wyatt, 2020; Wyatt & Ambrose, 2023; Wyatt & Schmitt, 2023; Wyatt, 2026). We use the descriptive term “tumultuoite” for a hypothesized volatile-bearing regolith deposit created by rapid, energetic emplacement and preservation in a cold-trap environment. The term is not proposed as an established lunar stratigraphic unit; it is a working geological hypothesis intended to generate falsifiable predictions. The 2026 IMAGE expanded abstract presented a preliminary prospectivity and conceptual geologic framework (Wyatt, 2026). The present study extends that work by formalizing the relative prospectivity interpretation, separating orbital-scale ranking from calibrated probability, defining the tumultuoite concept as a falsifiable depositional hypothesis, and specifying orbital-to-rover observations capable of testing it.

Resource framework

Lunar polar water can have multiple origins. Solar-wind implantation can generate surface hydroxyl and water; cometary and carbonaceous-asteroid impacts can deliver exogenous volatiles; endogenous lunar materials contain measurable water; and repeated micrometeoroid impacts can both deliver and mobilize volatiles. Molecules released or generated elsewhere may migrate ballistically until they encounter sufficiently cold terrain. Consequently, the present polar inventory can represent superposed episodes of delivery, redistribution, sequestration, excavation, and destruction rather than a single depositional event.

The regolith provides a mechanically and thermally heterogeneous host. Apollo and Luna samples show granular, impact-processed material with depth-dependent density and porosity and variable particle size, maturity, and lithology. Although returned samples do not ground-truth polar PSRs, they demonstrate that the lunar near-surface is not homogeneous. At the poles, temperature gradients, impact gardening, local topography, ejecta emplacement, and volatile migration can further modify the host. These factors permit multiple resource geometries, including adsorbed or grain-bound water, pore-filling frost, ice-cemented regolith, discrete ice-rich aggregates, and lenses.

The present model focuses on water/volatile prospectivity. Fe- and Ti-bearing lithologies, Th/K distributions, and other geochemical products remain important for broader lunar resources, but they are not direct measurements of ice. In the fusion framework, geochemistry is contextual and intentionally receives less weight than hydrogen abundance or thermal stability.

Multi-instrument prospectivity

The model combines four principal information classes. Neutron spectroscopy provides a regional indication of hydrogen enrichment; Diviner temperature products constrain the ability of a location to preserve ice; radar CPR provides a secondary constraint on scattering properties that can reflect roughness, blockiness, or in some circumstances ice-related structure; and gamma-ray geochemistry provides regional lithologic and resource context. Chandrayaan-1 M³ hydration observations, Clementine FeO-TiO₂ products, Lunar Prospector measurements, Chang'e data, topography, and PSR mapping provide supporting interpretation. No single dataset is treated as diagnostic.

For a working south-polar analysis, the heterogeneous datasets are placed in a common south polar stereographic framework referenced to a lunar radius of 1,737.4 km and evaluated on a 500 m grid between 85°S and 90°S. The 500 m cell size is an integration framework rather than a claim of 500 m resolving power. In particular, neutron measurements have footprints substantially larger than rover-scale targets.

Native spatial resolution and depth sensitivity must therefore remain explicit during interpretation.

Each variable is transformed to a dimensionless 0–1 exploration index using physically informed bounds rather than purely statistical scaling. H_n represents normalized neutron-derived hydrogen enrichment. T_s represents thermal stability, with maximum temperatures near or below approximately 110 K treated as favorable for long-term water-ice preservation. CPR_n represents normalized radar circular polarization response. Th_n represents normalized thorium abundance as a regional geochemical proxy. The working composite index is:

$$P = 0.35H_n + 0.35T_s + 0.20CPR_n + 0.10Th_n$$

Hydrogen and thermal stability receive the greatest weights because they are the most direct indicators, respectively, of volatile enrichment and preservation in this framework. CPR is down-weighted because elevated CPR is non-unique and can be produced by rough or blocky surfaces. The geochemical term receives the smallest weight because it supplies regional context rather than direct evidence of water ice. These are investigator-selected exploration weights, not coefficients obtained by empirical fitting. Accordingly, P is a relative prospectivity index and must not be interpreted as a calibrated probability that a cell contains ice.

The scientific value of the fusion is not limited to locations where all variables are high. Spatial discordance can also be informative. A thermally stable, hydrogen-enriched location with modest radar response may be compatible with buried or finely disseminated volatile material. Conversely, enhanced CPR without hydrogen enrichment may favor a roughness or blockiness explanation. Such interpretations remain conditional because the instruments sample different depths and spatial scales, but mismatches identify locations where ground truth has unusually high information value.

Prospectivity results and spatial interpretation

Application of the working fusion to the 85–90°S study region produces a spatially variable relative prospectivity field rather than a uniform PSR classification. The higher-ranked areas are those in which hydrogen enrichment and favorable thermal conditions coincide and are supported, to varying degrees, by radar and geochemical context. The preliminary IMAGE analysis identified coherent target zones within the south-polar terrain and used those zones to compare the planned VIPER exploration area with a model-suggested exploration ellipse intended to test the heterogeneous-deposit concept (Wyatt, 2026). At this stage, the map is appropriately interpreted as a target-ranking product; it does not establish resource tonnage, grade, or continuity.

A second result is methodological: the most informative locations are not necessarily those with the highest composite score. Boundaries between high- and lower-ranked cells, and areas where hydrogen, temperature, and radar response diverge, are particularly valuable because they provide natural tests of competing explanations. If an orbital hydrogen anomaly reflects a relatively uniform diffuse deposit, rover measurements should vary gradually across such boundaries. If instead the orbital signal averages discrete enriched bodies and lower-grade host regolith, meter-scale measurements may show abrupt changes that are not apparent in the orbital field.

The preliminary model therefore yields two complementary exploration products: a ranking of locations where multiple favorable indicators converge and a set of discordant or transitional locations where ground truth has high diagnostic value. This distinction is important for hypothesis testing. A traverse designed only to maximize predicted ice abundance could confirm volatile presence yet provide limited information about deposit geometry. A traverse deliberately crossing prospectivity gradients can test both the fusion model and the geological interpretation.

Working subsurface model

A provisional three-zone subsurface model provides a vertical framework for interpreting the orbital fusion and for designing rover-scale tests. The upper approximately 0–5 cm is treated as a relatively dry or weakly hydrated lag affected most directly by irradiation, thermal cycling, and surface exchange. From approximately 5–80 cm, favorable PSRs may contain the principal volatile-enrichment interval, expressed not necessarily as a continuous layer but as pore frost, ice-cemented regolith, discrete aggregates, or lenses. Below approximately 80 cm, mechanically mixed regolith may preserve relic volatile pockets and lithologic heterogeneity. These boundaries are working exploration assumptions derived from the prior IMAGE framework, not established lunar stratigraphy (Wyatt, 2026). Their purpose is to define depth-dependent observations that can be tested and rejected by in-situ measurements.

This vertical model is particularly important when orbital footprints are compared with meter-scale sampling. A broad hydrogen enhancement can be consistent with several subsurface arrangements having similar integrated hydrogen content but very different resource value. Repeated shallow drilling is therefore needed to determine whether enrichment is diffuse, increases gradually with depth, or occurs as abrupt high-grade intervals. The latter geometry would be especially compatible with the heterogeneous emplacement hypothesis developed below.

A heterogeneous emplacement hypothesis

The conceptual model originated from a geological question: could an impact involving an ice-bearing body produce rapid sediment-vapor-particle interactions that leave a heterogeneous volatile-bearing deposit in or near a cold trap? The underlying depositional concept predates the present prospectivity analysis and was developed during earlier consideration of the depositional character of lunar ice (Wyatt, 2020). Impact models demonstrate that impact-generated water can be transported toward and retained in polar cold traps, while geological analog reasoning suggests that energetic mixtures of vapor, particles, ejecta, and regolith need not settle as laterally uniform layers (Stewart et al., 2011; Prem et al., 2015). The present hypothesis extends that reasoning to a deliberately testable resource-geometry problem.

A conceptual sequence begins with impact excavation, shock heating, and strong volatile loss. As the plume and ejecta expand and cool, water-bearing vapor and particles interact with regolith across a range of temperatures and trajectories. Material entering thermally favorable terrain can condense, freeze, adsorb, or become mechanically mixed with ejecta. Subsequent settling, slumping, debris movement, fracture filling, and impact gardening can redistribute the volatile-bearing material. The resulting deposit need not resemble a terrestrial sedimentary bed; it could instead be a chaotic package containing disseminated ice, ice-cemented aggregates, discontinuous lenses, fracture-associated concentrations, and intercalated volatile-rich and volatile-poor regolith.

This concept offers a physical basis for a “nugget” problem in lunar resource exploration. A regional orbital hydrogen signal could, in principle, be produced by volumetrically limited high-grade concentrations embedded in a larger volume of lower-grade material. If so, an average concentration derived over a broad footprint would not describe the extraction target. Economically meaningful resource zones could be localized, and their geometry would control excavation efficiency, processing throughput, traverse design, and the number of measurements needed to estimate inventory.

The term “tumultuoite” is therefore used here as a depositional-process and facies hypothesis rather than as a synonym for heterogeneous lunar ice. Its defining feature is a chaotic or rapidly assembled mixture produced by impact-related transport and emplacement under conditions that permit at least part of the volatile inventory to be retained or recondensed. A candidate tumultuoite should consequently be evaluated in terms of texture, vertical sequence, lateral continuity, relationship to local topography and ejecta, and the physical association between volatile-rich and volatile-poor regolith. This geological framing distinguishes the hypothesis from models in which ice accumulates predominantly by slow vapor migration and diffuse pore filling.

The hypothesized sequence contains several potentially separable stages: (1) impact excavation, shock heating, and vaporization; (2) ballistic expansion and transport of vapor, condensate, particles, and ejecta; (3) cooling and condensation or freezing as

material enters thermally favorable terrain; (4) rapid mechanical mixing of regolith and volatile-bearing components; (5) local sorting, slumping, fracture filling, or gravity-driven redistribution; and (6) longer-term modification by impact gardening and thermal cycling. Not every stage must be expressed at every site. The model instead predicts that their combined action can generate deposits whose internal variability exceeds that implied by the footprint-averaged orbital signal.

Testable predictions

A useful depositional hypothesis must be distinguishable from alternatives. Tumultuoite-style emplacement predicts pronounced lateral variability in volatile abundance over rover-accessible distances, particularly where cold-trap topography can focus ejecta or mass movement. It also predicts non-monotonic vertical profiles: a drill could pass from relatively dry regolith into an enriched lens and back into lower-grade material rather than encountering a single smoothly increasing volatile gradient. Discrete icy aggregates, cemented intervals, or abrupt changes in volatile species would strengthen the interpretation.

A second prediction is imperfect spatial correspondence among orbital observables. Hydrogen enrichment, thermal favorability, and radar scattering need not peak at precisely the same location if they respond to different depths or physical properties of a heterogeneous deposit. Such discordance alone cannot demonstrate tumultuoites, because resolution differences and roughness provide alternative explanations. However, repeated discordance that is subsequently resolved by meter-scale ground measurements would provide a strong test of the model.

The hypothesis would be weakened if thermally favorable PSRs show broadly uniform volatile concentrations at rover scales, if depth profiles are smooth and repeatable across diverse terrain, and if radar, neutron, thermal, and in-situ measurements are consistently explained by diffuse pore ice without discrete concentration. Falsification is therefore built into the exploration strategy rather than being an afterthought.

Implications for rover exploration and ISRU

VIPER-class measurements are well suited to bridge the scale gap between orbital prospectivity and local resource geometry. A neutron spectrometer can identify hydrogen variability during traverse; a rotary-percussive drill can interrogate the upper approximately meter of regolith; near-infrared spectroscopy and imaging can characterize excavated material; and mass spectrometry can identify volatile species released during sampling. Used together, such measurements can test whether an orbital high-ranked area is internally uniform or composed of discrete enriched zones.

The preferred sampling design for the heterogeneous-deposit hypothesis is therefore a transect rather than a small number of isolated deep samples. Repeated shallow drilling across predicted gradients would quantify lateral continuity and capture abrupt changes that could be missed by widely spaced cores. Adaptive traverses could follow detected hydrogen gradients, while repeated measurements across high-, intermediate-, and low-ranked cells would provide a direct test of the prospectivity index. This approach also allows the scale of heterogeneity to be estimated, which is essential for later geostatistical resource assessment.

The engineering implications are immediate. If polar ice is largely diffuse, bulk excavation and processing may be necessary. If high-grade lenses or aggregates are common, selective mining and real-time grade control become more attractive. In either case, the objective is not merely to confirm water but to establish grade, continuity, depth, physical form, and recoverability. These are familiar terrestrial resource questions translated into an environment where orbital remote sensing currently dominates the evidence base.

Scale, resolution, and uncertainty

The analysis deliberately does not force all observations to a common effective resolution. Co-registration to a 500 m working grid is necessary for comparison, but smoothing a kilometer- to tens-of-kilometers-scale neutron footprint until it visually resembles higher-resolution thermal or radar products would create false spatial equivalence. The IMAGE framework therefore treated differences in spatial and depth sensitivity qualitatively rather than assuming that each gridded value represents the same physical volume (Wyatt, 2026). This is not simply a processing limitation; it is central to the geological question.

A broad orbital anomaly can conceal sub-footprint heterogeneity. If volatile-rich lenses occupy only a fraction of a neutron detector footprint, the regional signal may represent an average of high-grade and low-grade material. Conversely, a localized radar feature may reflect surface or near-surface roughness that is not volumetrically important to the hydrogen inventory. Scale discordance should therefore be preserved and tested rather than automatically removed. Rover observations provide the means to determine whether apparently inconsistent orbital datasets arise from sensor physics, local geology, or genuine three-dimensional resource heterogeneity.

Limitations

Several limitations constrain the present framework. Hydrogen is not synonymous with water ice. CPR is not diagnostic of ice. Thermal stability indicates preservation potential rather than volatile supply. Thorium and related geochemical products are

contextual proxies and not measurements of REE ore. Input datasets differ greatly in footprint, depth sensitivity, illumination dependence, calibration, and uncertainty. Resampling them to a common grid does not create new spatial information. The proposed 0–1 normalizations and 35/35/20/10 weighting scheme are physically motivated but remain subjective and require sensitivity testing. Finally, the tumultuoite model is a hypothesis; current orbital evidence cannot establish the proposed architecture without in-situ observations.

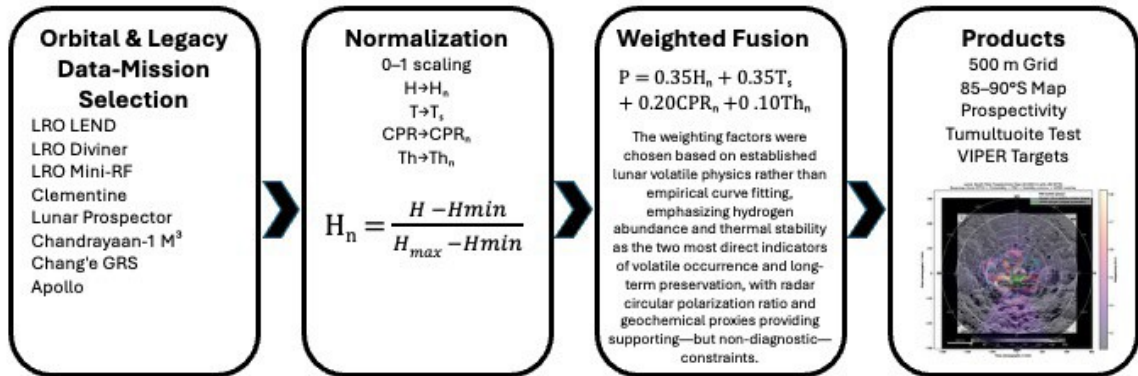
These limitations are also the rationale for the method. A transparent fusion model makes assumptions visible, prevents a single proxy from being treated as definitive, and identifies locations where competing interpretations can be tested. Future versions should quantify uncertainty, vary normalization thresholds and weights, compare alternative fusion formulations, and evaluate whether apparent spatial discordance survives analysis at the effective resolution of each instrument.

Conclusions

Lunar south-polar resource assessment should move beyond the binary question of ice presence toward the geological problem of resource geometry. A physically constrained integration of hydrogen, thermal, radar, and geochemical observations provides a transparent means of ranking locations for follow-up while respecting the non-uniqueness of individual proxies. The present index is explicitly a relative exploration tool, not a probability map.

The tumultuoite hypothesis provides one testable explanation for heterogeneous volatile occurrence: rapid impact-related transport, condensation, freezing, mixing, and mass movement could create localized ice-rich lenses or aggregates within broader low-grade regolith. Its principal predictions—strong lateral variability, non-monotonic depth profiles, discrete enriched intervals, and resolvable discordance among orbital proxies—can be tested by rover-scale transects and repeated shallow drilling. Confirmation would favor selective exploration and extraction strategies; rejection would narrow the range of plausible polar resource models. Either outcome improves the geological basis for lunar ISRU.

AI-Assisted Lunar South Pole Prospectivity Workflow



Co-Pilot – used to organized previous talks, and other miscellaneous data from my files as background material
 Claude – used to help formulate my initial query request from data above
 ChatGPT Plus – AI query and model development

Figure 1 | AI-assisted lunar south-polar prospectivity workflow. Orbital and legacy datasets are normalized to dimensionless 0-1 exploration indices and combined using physically constrained weighted fusion. Hydrogen abundance and thermal stability receive the greatest weights, with radar CPR and thorium/geochemical context providing supporting, non-diagnostic constraints. The 500 m grid is a common indexing framework and does not imply equal native spatial resolution among instruments.

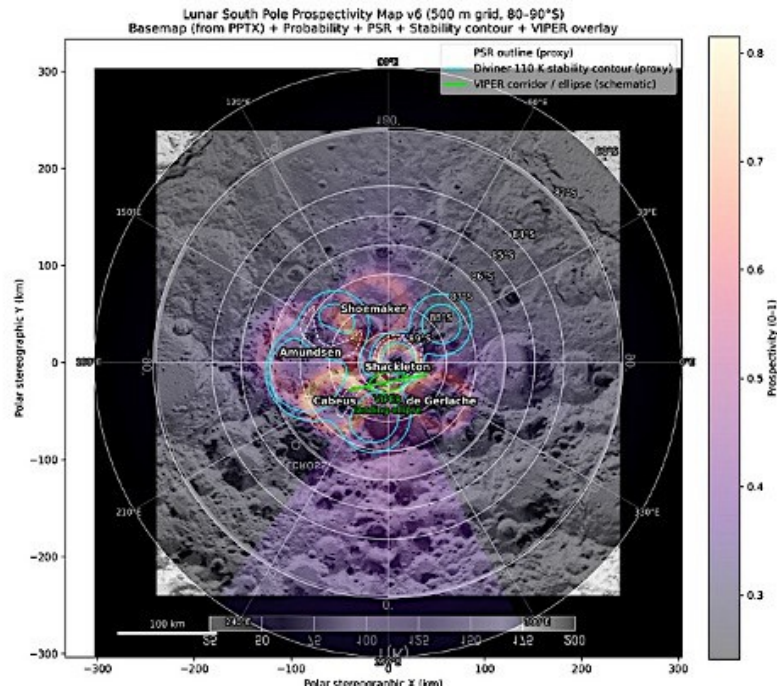


Figure 2 | AI-assisted relative volatile prospectivity of the lunar south-polar region (85-90°S). Composite prospectivity is derived from normalized hydrogen abundance, thermal stability, radar circular polarization ratio, and thorium/geochemical context using the weighting framework in Figure 1. Higher values indicate greater relative convergence of favorable resource indicators rather than a calibrated probability of volatile occurrence. The 500 m working grid provides a common spatial indexing framework and does not represent the native spatial resolution of the contributing orbital datasets. The prior VIPER reference exploration region and a model-selected heterogeneous-deposit test region are shown for comparison.

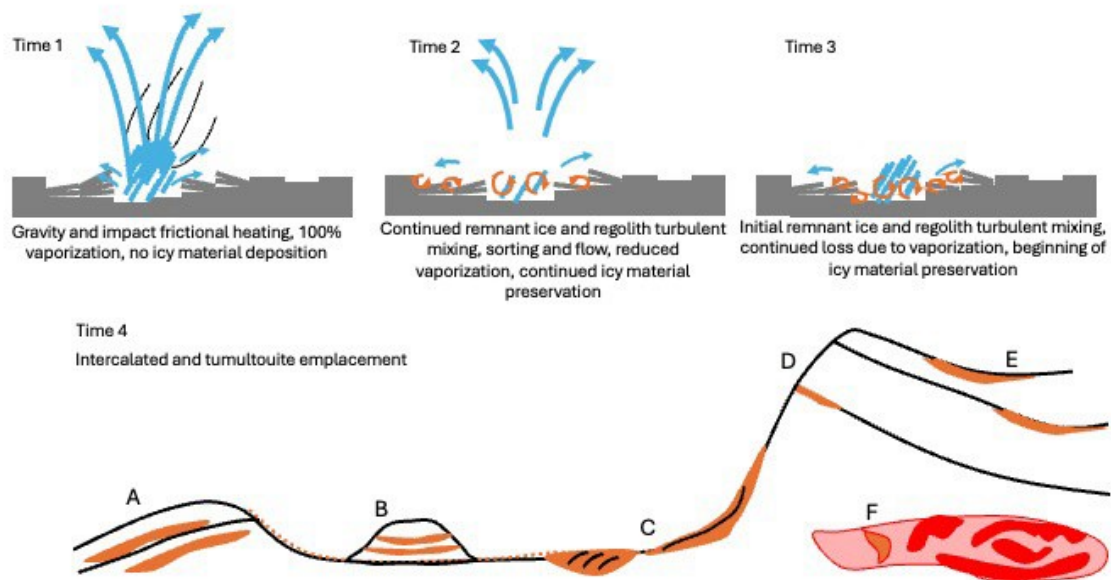


Figure 3 | Conceptual tumultuoite emplacement and subsurface geometry model. Conceptual cross-section illustrates possible heterogeneous volatile emplacement, redistribution, and preservation following an impact involving volatile-bearing material. The model integrates concepts of impact-generated volatile transport and polar deposition, heterogeneous depositional architecture, and mining-scale lunar ice geometry (Stewart et al., 2011; Cadieux & Kah, 2015; Cannon & Britt, 2020). Lettered labels are used within the figure to conserve space. The depicted geometry is conceptual and does not represent established lunar polar stratigraphy.

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Open Science Declarations

Author contributions. Douglas E. Wyatt: Conceptualization, methodology, investigation, visualization, writing—original draft, and writing—review and editing.

Code availability. Any code used to generate the final gridded prospectivity product should be archived in a persistent public repository before submission.

Data availability. The framework relies on publicly available lunar mission datasets and derived products. Final submission should provide persistent links and identifiers for each exact dataset and processing level used.

Funding. Funding statement to be completed before submission.

Competing interests. The author declares no competing interests, subject to final author review.

Methods

The workflow is a physically informed multi-criteria fusion. Selected datasets are transformed to a common south-polar coordinate system and evaluated over 85–90°S on a 500 m working grid. Hydrogen, thermal stability, CPR, and thorium context are normalized to dimensionless indices between zero and one using investigator-defined physical bounds. The composite index is $P = 0.35H_n + 0.35T_s + 0.20CPR_n + 0.10Th_n$. Hydrogen and temperature are weighted most strongly because they bear most directly on volatile enrichment and preservation. Radar and geochemical terms are supporting constraints. The method does not statistically calibrate P against known ice occurrences, so P is interpreted only as relative prospectivity. AI tools were used to assist literature organization, synthesis, formulation of the workflow, and comparison of alternative representations; scientific variable selection, assumptions, thresholds, weights, and geological interpretation were investigator-defined. Before submission, the analysis should be reproduced from archived source rasters with explicit metadata, projection parameters, normalization equations, missing-data rules, uncertainty treatment, and sensitivity tests for thresholds and weights. Sensitivity analysis should vary the principal weights and thermal/normalization bounds to determine whether high-ranked target zones persist under reasonable alternatives. Because the inputs have different native footprints and depth sensitivities, the 500 m grid is used only as a common indexing geometry; interpretation must be conducted at the effective resolution of the contributing observations. Transitional and discordant cells are retained as potential hypothesis-test targets rather than discarded as model error.

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