IRREVERSIBLE COMMITMENTS IN LUNAR SUBSURFACE EXPLORATION: IGNORANCE, DISTURBANCE, AND PRECEDENCE FORMATION

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Early lunar and cislunar resource activities occur in environments where irreversible operational thresholds may emerge before subsurface uncertainty resolves. Commitments involving access routes, power placement, excavation approaches, logistics infrastructure, and early extraction pathways are often taken before physical conditions are well-constrained. Once made, these commitments are difficult or impossible to reverse because they establish economic, political, and governance paths that rapidly harden (David, 1985). In frontier domains, premature commitment is a dominant risk.

This work examines lunar and cislunar resource development as a decision problem under persistent subsurface uncertainty. It exists upstream of optimization, mission design, and system engineering. It examines how irreversible commitments can be evaluated before capital deployment, mission authority, physical disturbance, or institutional signaling collapses refusal credibility. The approach distinguishes between uncertainty that can be reduced through investigation and ignorance that remains structurally dominant despite additional measurement. It focuses on how early infrastructure and exploration decisions implicitly encode access, control, extraction assumptions, and future admissibility norms. Irreversible commitments are commonly framed as optimization or risk-management problems, overlooking structural decision integrity. Instead of optimizing resource extraction, this work focuses on how exploration systems determine when irreversible disturbance becomes scientifically and institutionally admissible under persistent subsurface ignorance.

To ground this framework, the work draws on Earth analogs where irreversibility is already well understood but often poorly governed. Marine carbon storage illustrates the challenge of governing permanence, where pressure-dominated systems and legacy pathways make post-commitment control fragile. Geothermal development highlights the governance problem of learning under disturbance, where subsurface access required to reduce uncertainty simultaneously creates irreversible exposure. Critical mineral systems demonstrate how early exploration, permitting, and investment decisions can normalize development pathways and foreclose alternatives long before uncertainty stabilizes. These domains are used as governance analogs that reveal recurring failure modes under subsurface ignorance.

The lunar south polar environment represents a maximum-constraint exploration regime. In permanently shadowed regions near the lunar south pole, surface temperatures remain sufficiently low to maintain long-lived volatile cold traps (Paige et al., 2010). Detecting and characterizing these volatiles relies primarily on remote sensing proxies such as neutron spectroscopy, ultraviolet reflectance, and thermal measurements (Feldman et al., 1998; Hayne et al., 2015; Hurley et al., 2016). However, the spatial resolution of these observations cannot resolve near-surface volatile stratigraphy without direct subsurface disturbance. Confirming volatile presence therefore requires trenching, drilling, or core sampling, which disturb local surface conditions and may redistribute volatiles. Once exploratory access occurs, supporting infrastructure such as power distribution, communications relay, mobility routes, and excavation staging tends to accumulate around the initial access point. These placements can gradually define operational corridors and priority zones that influence how subsequent missions approach the region. Exploration in this sense can shape the spatial and institutional structure of future activity before subsurface uncertainty has meaningfully narrowed.

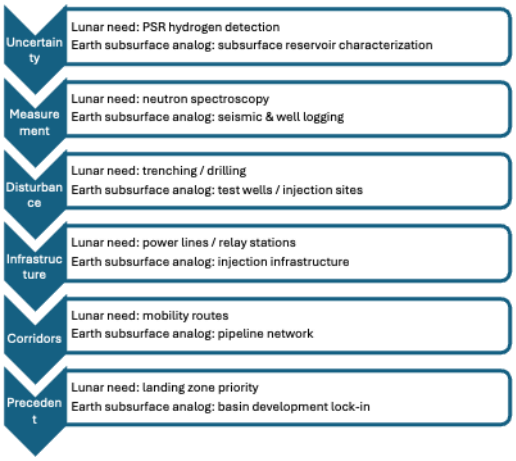

Figure 1. Emergence of irreversible commitments in frontier resource exploration. Initial uncertainty leads to measurement and disturbance required to verify resource presence. Once infrastructure and operational corridors co-locate with exploratory sites, physical placement can generate precedent that influences future access and development decisions before subsurface uncertainty stabilizes.

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