Irreversible Commitments in Lunar Subsurface Exploration: Ignorance, Disturbance, and Precedent Formation

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1. The Commitment Problem

Early lunar and cislunar resource activities will occur in environments where operational commitments may become difficult to reverse before subsurface uncertainty has resolved. Access routes, power placement, excavation approaches, logistics infrastructure, mobility corridors, and early ISRU pathways can begin to harden around volatile interpretations that remain indirect, spatially limited, and non-unique. Once commitments form, they may be difficult or impossible to reverse because they establish economic, political, and governance pathways that rapidly harden (David, 1985). In the lunar domain, reversal may require redesigning the emerging surface system. Premature commitment is therefore a dominant risk.

This work examines lunar south polar resource development as a problem of commitment governance under persistent subsurface ignorance. The central question is whether the available evidence is sufficient to justify the next hard-to-reverse surface commitment. The framework distinguishes between uncertainty that can be reduced through bounded investigation and ignorance that remains decision-dominant because materially different subsurface states would imply incompatible site, access, excavation, power, logistics, or ISRU architectures.

The lunar south pole represents a maximum-constraint exploration regime. Permanently shadowed regions can preserve long-lived volatile cold traps (Paige et al., 2010), yet current characterization relies primarily on indirect remote-sensing proxies such as neutron spectroscopy, ultraviolet reflectance, radar, and thermal measurements (Feldman et al., 1998; Hayne et al., 2015; Hurley et al., 2016). These observations can identify promising regions and constrain hypotheses. However, they do not by themselves resolve volatile form, continuity, concentration, accessibility, regolith mechanics, or construction-scale behavior. Direct verification through trenching, drilling, excavation, or sampling can improve knowledge. However, verification may also disturb local surface conditions, thereby altering the evidence baseline, concentrating future access, and creating infrastructure dependency around the initial site.

To ground the governance logic, the work draws on terrestrial analogs where learning and commitment are similarly coupled. Carbon storage illustrates the difficulty of governing permanence once injection and pressure evolution begin. Geothermal development shows how subsurface access required to reduce uncertainty can simultaneously create irreversible exposure. Critical mineral systems demonstrate how exploration, permitting, capital, and infrastructure pathways can normalize development before uncertainty stabilizes.

The work proposes a commitment-threshold framework for determining when lunar surface actions remain bounded exploration and when they become infrastructure-forming commitments. It identifies a progression from volatile signal interpretation to site preference, access repetition, support placement, disturbance, corridor formation, excavation planning, ISRU dependency, and infrastructure lock-in. The framework treats premature commitment as a governance failure: infrastructure should not harden faster than the evidence required to justify it. Under persistent subsurface ignorance, the admissibility of lunar resource commitments depends on whether remaining uncertainty has lost the power to change the legitimacy of the commitment.

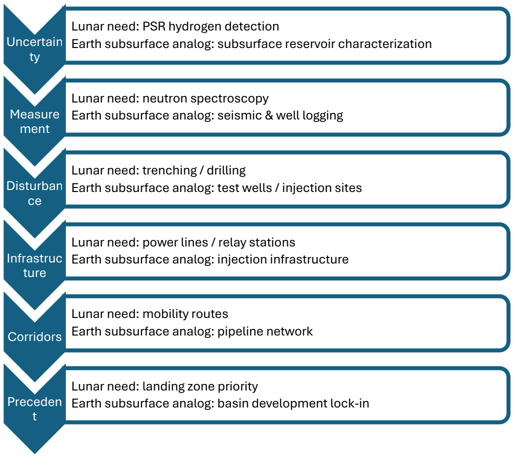

Figure 1. Emergence of irreversible commitments in frontier resource exploration. Initial uncertainty leads to measurement and disturbance required to verify resource presence. Once infrastructure and operational corridors co-locate with exploratory sites, physical placement can generate precedent that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

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