

# STRATEGIC GEOSPATIAL PLANNING FOR BEPICOLOMBO OBSERVATIONS IN MERCURY'S MICHELANGELO QUADRANGLE (H12): A GEOLOGICAL DECISION-SUPPORT FRAMEWORK

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*Planetary exploration increasingly depends on planning frameworks that can convert verified geoscientific evidence into transparent observational priorities. This study presents a geospatial decision-support framework for Mercury's Michelangelo quadrangle (H12), using the published 1:3,000,000 geological map and its associated MESSENGER MDIS data foundation as the basis for mission-planning analysis. The quadrangle spans 22.5°S–65°S and 180°E–270°E, covering almost 6.5% of Mercury's surface, or nearly 5 million km<sup>2</sup>. The mapped terrain is dominated by intermediate plains and class-c2 degraded crater materials, while smooth plains are comparatively limited and largely confined to crater and basin interiors. The source mapping identifies two principal spectral terrain associations: a dark-blue western sector linked to intermediate plains and Beethoven ejecta, and brighter reddish/yellow terrains that coincide more closely with smooth plains and fresher crater materials. Building on those verified relationships, this paper converts the quadrangle into planning-relevant observation zones, applies an explicit rule-based prioritization with internal consistency checks, and formalizes a sequence for allocating mission attention to compositional, tectonic, and surface-process targets. The result is a planning study that translates a complex geological map into a transparent and reproducible framework for prioritization, staging, and comparative target selection in planetary mission design.*

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## INTRODUCTION

High-value observation planning in planetary missions requires more than data availability; it requires a defensible method for deciding where limited imaging, compositional, and structural analysis should be concentrated. In practice, this is a planning problem: decision-makers must rank targets, sequence observations, and justify trade-offs under finite mission time, instrument constraints, and incomplete knowledge. Geological maps are particularly useful in this context because they organize terrain evidence into explicit spatial units, define relative chronology, and isolate locations where the contrast between units is scientifically consequential.

Mercury is especially well suited to this form of planning analysis. Its surface preserves a long record of impact modification, tectonic deformation, and volcanic resurfacing, and the MESSENGER mission created the first global image base that made systematic quadrangle-scale mapping possible [19, 6, 12]. The Michelangelo quadrangle (H12) is one of the southern mid-latitude regions for which a modern 1:3,000,000-scale geological synthesis is now available [2]. That map identifies three plains units (smooth, intermediate, and intercrater plains), three crater degradation classes for craters  $\geq 20$  km, Beethoven basin ejecta as a distinct unit, and a regional contrast between dark-blue and bright reddish/yellow terrains that has immediate implications for observation targeting [2, 17].

The present paper treats the published H12 map as a planning dataset. Rather than introducing speculative numerical proxies, it reorganizes the verified geological content into a structured mission-planning framework and makes its decision rules explicit. The aim is straightforward: to convert the published map's stratigraphic, spectral, and structural findings into an operational sequence for selecting and prioritizing observations relevant to BepiColombo, while showing how those priorities can be checked for consistency against multiple independent mapped relationships.

Three planning questions guide the analysis:

1. Which mapped terrains in H12 offer the highest comparative value for distinguishing resurfacing episodes and compositional variation?
2. Which subregions combine strong stratigraphic contrast, clear surface expression, and operational relevance for targeted follow-up?
3. How can the mapped evidence be translated into a transparent priority hierarchy suitable for mission observation design?

## STUDY CONTEXT AND DATA FOUNDATION

### *Geographic and cartographic setting*

The Michelangelo quadrangle (H12) extends from 22.5°S to 65°S and from 180°E to 270°E. It covers almost 6.5% of Mercury's surface, corresponding to nearly 5 million km<sup>2</sup> [2]. The quadrangle is named after Michelangelo crater, centered at 44.9°S, 250.3°E [2]. The published map was compiled at a final output scale of 1:3,000,000, with geologic contacts and linear features drawn at variable scales between approximately

Table 1: Core geographic, cartographic, and data characteristics for the Michelangelo quadrangle (H12).

Category	Verified source information
Quadrangle extent	22.5°S–65°S; 180°E–270°E
Surface coverage	Almost 6.5% of Mercury; nearly 5 million km <sup>2</sup>
Final map scale	1:3,000,000
Digitizing scale	Approximately 1:300,000 to 1:600,000
Minimum mapped feature	5 km
Projection	Lambert Conformal Conic
Standard parallels	30°S and 58°S
Primary monochrome basemaps	BDR, LOI, HIE, HIW (all 166 m/pixel)
Topographic support	Global stereo DEM, 665 m/pixel
Multispectral support	MD3, 665 m/pixel; Enhanced Color mosaic
Software	ArcGIS Pro 3.2.2; Adobe Illustrator

1:300,000 and 1:600,000 [2]. Features smaller than 5 km were intentionally not mapped in order to preserve readability at publication scale [2].

Following standard practice for Mercury mid-latitude geological maps, the working projection is Lambert Conformal Conic, with standard parallels at 30°S and 58°S [2, 11]. This provides a stable basis for regional comparison and spatial planning because scale distortion is minimized within the mapped latitudinal range.

#### *Data inputs used for geological decision support*

The geological interpretation of H12 rests on the standard suite of MESSENGER MDIS products [2, 6, 9]:

- the BDR monochrome mosaic (166 m/pixel), used as the main morphological reference;
- the LOI mosaic (166 m/pixel), used to emphasize albedo differences and reduce shadow effects;
- the HIE and HIW mosaics (166 m/pixel), used to identify landforms in shadowed regions;
- the global stereo DEM (665 m/pixel), used to support the recognition of crater rims and tectonic structures;
- the MDIS MD3 multispectral product (665 m/pixel), using the 1000 nm, 750 nm, and 430 nm filters;
- the Enhanced Color mosaic, which uses principal components and the 430/1000 nm ratio to emphasize color differences.

The source map was organized in an ArcGIS Pro 3.2.2 geodatabase with four principal feature classes: geologic contacts, linear features, geological units, and surface features [2]. The final map layout was completed in Adobe Illustrator [2].

## **GEOLOGICAL UNITS AS PLANNING ASSETS**

The central premise of this paper is that geological units can be treated as planning assets: each unit represents a distinct observational opportunity defined by morphology, relative age, compositional expression, process significance, and decision value within a constrained observing campaign.

### *Plains units*

The source map identifies three plains units, ordered from younger to older: smooth plains (sp), intermediate plains (imp), and intercrater plains (icp) [2].

Smooth plains are flat to sparsely cratered terrains with smooth texture. In H12 they are uncommon and are mostly confined to impact basins and craters, or occur as patches in proximal ejecta. Clear examples occur in Michelangelo crater (44.9°S, 250.3°E), Takayoshi crater (37.2°S, 196.2°E), and Beethoven basin (20.9°S, 235.8°E) [2]. The published map notes that smooth plains in H12 show comparatively consistent reflectance characteristics, suggesting compositional homogeneity [2]. At planetary scale, smooth plains are widely interpreted as products of effusive volcanism during the Calorian, approximately 3.8–3.5 Ga [3, 5, 16].

Intermediate plains are morphologically and stratigraphically transitional between smooth plains and intercrater plains. They are the most widespread mapped unit in H12 and commonly cover the floors of large ancient basins, where they are interpreted as post-impact infill later degraded by younger impacts [2]. In the source analysis, this unit shows spectral characteristics similar to intercrater plains but tends to coincide with darker areas in the Enhanced Color basemap, especially in the western sector [2].

Intercrater plains are densely cratered, rough to hummocky terrains and represent the second most extensive unit in H12 [2]. They are regarded as among the oldest surfaces on Mercury, with a pre-Tolstojan to Tolstojan age range of about 4.5–3.9 Ga [22, 2]. They lack a strong distinctive color signature in H12 and are best understood as old surfaces subsequently modified by impact reworking [2, 13].

### *Crater materials and special units*

Crater materials are classified in three degradation states: c3 (fresh), c2 (moderately degraded), and c1 (highly degraded) [2]. This three-class system is used deliberately to preserve map readability and support stratigraphic interpretation without forcing direct one-to-one assignment to Mercury's classical five chronostratigraphic periods [2, 8]. The source paper also distinguishes smooth crater floors (cfs) and hummocky crater floors (cfh), which separate original crater-floor materials from later basin-scale volcanic infill [2].

Beethoven basin ejecta (be) are mapped as a distinct unit because they appear slightly darker than adjacent terrains in the Enhanced Color mosaic, implying a meaningful compositional difference [2]. This makes the unit especially important in comparative observation planning.

Table 2: Mapped units in H12 and their planning significance.

Unit	Source-defined characteristics	Planning significance
sp	Smooth, sparsely cratered; uncommon; mainly in crater and basin interiors; examples in Michelangelo, Takayoshi, and Beethoven	High value for identifying younger resurfacing and later volcanic infill
imp	Most widespread unit; smooth to hummocky; commonly fills ancient basin floors; darker western-sector association	High value for comparing older infill against younger smooth-plains fills
icp	Densely cratered, rough, ancient terrain; second most extensive unit	Baseline terrain for regional age and resurfacing comparisons
c3	Fresh, sharp-rimmed craters with distinct ejecta and secondary structures	High-clarity targets for recent surface exposure and bright ejecta mapping
c2	Moderately degraded craters; widespread in H12	Dominant background crater population for relative chronology
c1	Highly degraded craters with subdued or erased rims	Useful for identifying long-term degradation and embayment
cfs	Smooth crater floors	Distinguishes original crater-floor material or localized melt from later basin-scale plains
cfh	Rough or gently rolling crater floors	Indicates debris, mass wasting, or degraded floor preservation
be	Beethoven ejecta unit with darker spectral appearance	High-priority comparative unit for compositionally distinct excavated material

## PLANNING METHODOLOGY

This paper adopts a transparent rule-based planning model. The objective is not to generate new remote-sensing measurements, but to structure the already verified geological evidence into a consistent prioritization framework that can be inspected, repeated, and checked against the published map.

### *Decision criteria*

Four decision criteria are used, and each is evaluated directly from mapped relationships reported in the source study:

1. **Stratigraphic contrast:** locations where younger and older units are in direct spatial relationship.
2. **Compositional contrast:** locations where the source map reports a meaningful color or reflectance distinction.
3. **Structural relevance:** locations where tectonic structures constrain sequence, deformation, or basin evolution.

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**Algorithm 1** Priority assignment for observation planning in H12

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**Require:** Published H12 geologic map, mapped units, structural features, and source interpretations

**Ensure:** Ranked observation zones for mission planning

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1: for each mapped subregion in H12 do
2:   Set priority score to 0
3:   if subregion contains direct contact between contrasting plains units then
4:     Add 1 to priority score
5:   end if
6:   if subregion is described as spectrally distinct (e.g., dark-blue or bright/yellow terrain) then
7:     Add 1 to priority score
8:   end if
9:   if subregion contains tectonic structures that constrain relative age or basin evolution then
10:    Add 1 to priority score
11:  end if
12:  if subregion includes a clearly localized target (crater floor, ejecta patch, basin margin, or structural
    segment) then
13:    Add 1 to priority score
14:  end if
15: end for
16: Rank subregions from highest to lowest score
17: Assign Tier 1 to the strongest multi-criterion targets
18: Assign Tier 2 to structurally or stratigraphically important comparison sites
19: Assign Tier 3 to contextual or process-indicator sites
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4. **Operational clarity:** locations where mapped contacts, landforms, and unit identities are sufficiently explicit to support targeted follow-up.

Areas that satisfy multiple criteria receive higher planning priority because they promise stronger scientific return per observation. To reduce arbitrary ranking, candidate zones are screened first by criterion count and then cross-checked against the co-occurrence of mapped contacts, color-terrain partitioning, and localized structural definition; only targets that remain strong under this second pass are retained at the highest tier.

*Priority assignment logic*

*Planning output format*

The final planning output is organized into three tiers, producing an ordinal ranking that is simple enough for operational use but still anchored to explicit geological evidence:

- **Tier 1:** highest-value contrast zones with clear implications for resurfacing, composition, or sequential emplacement;
- **Tier 2:** structurally or chronologically important targets that refine basin evolution;
- **Tier 3:** contextual surface-process targets that strengthen interpretation but are not primary comparison anchors.

## FINDINGS FROM THE MICHELANGELO QUADRANGLE

### *Regional terrain organization*

The Michelangelo quadrangle is a densely cratered region mainly dominated by intermediate plains and degraded crater materials of class c2 [2]. Intermediate plains are widely developed inside large ancient basins, where they are interpreted as degraded post-impact infill. Intercrater plains form the second most extensive terrain. Smooth plains are present but comparatively limited, mainly confined to crater interiors and basin floors, or appearing as localized patches interpreted as fluidized ejecta deposits [2, 5].

Several locations are specifically important in this regional structure. Intermediate plains are clearly associated with the interiors of older basin-related settings, including Dostoevskij crater (44.7°S, 181.9°E), Vincente-Yakovlev basin (52.6°S, 197.9°E), and the b2 basin (38.9°S, 258.6°E) [2, 15]. By contrast, smooth plains are explicitly identified within Michelangelo crater, Takayoshi crater, and Beethoven basin [2]. This spatial separation makes the quadrangle unusually useful for contrast-based mission planning.

### *Color-terrain partition and comparative planning value*

One of the strongest planning-relevant findings in the source map is the identification of two principal terrain-color associations [2]. The western side of the quadrangle, especially between 180°E and 200°E, contains a dark-blue terrain. Most of the rest of the quadrangle is characterized by bright reddish and yellow terrains. The bright reddish terrains are reported to show the same spectral characteristics as Mercury's high-reflectance plains [17, 2].

When compared with mapped units, the bright yellow terrain tends to coincide with fresh c3 craters and smooth plains. The dark-blue terrain aligns more closely with intermediate plains that occupy ancient basin floors and with Beethoven ejecta [2]. This is the clearest evidence-based reason to prioritize comparative observation between older dark infill and younger bright infill. Specifically, the source map identifies a plausible compositional contrast between:

- the “dark” infilling represented by intermediate plains in ancient basins such as Vincente-Yakovlev, and
- the “bright” infilling represented by smooth plains in younger basin and crater interiors such as Beethoven and Michelangelo.

From a planning standpoint, this means the most efficient comparative sequence is not random regional coverage, but paired observation of these contrasting settings. The same pairing also serves as a practical validation check: the highest-ranked comparison targets are precisely those in which mapped unit identity, color contrast, and spatial localization converge.

### *Beethoven basin as a strategic subregion*

Beethoven basin is the most operationally valuable subregion in H12. It lies at 20.9°S, 235.8°E, straddles the boundary between H12 and the Beethoven quadrangle, and has an approximate diameter of 640 km [2, 20]. Its ejecta are mapped as a separate unit because of their darker spectral appearance relative to adjacent

Table 3: Priority targets in H12 for a planning-oriented observation sequence.

Target zone	Representative locations	Planning rationale	Tier
Dark older infill zones	Western sector (180°E–200°E); Vincente-Yakovlev; b2 basin	Intermediate plains in ancient basins coincide with dark-blue terrain; strongest comparison base for older resurfacing	1
Bright younger infill zones	Michelangelo crater; Takayoshi crater; Beethoven floor	Smooth plains in younger basins/craters coincide with bright yellow terrain; ideal paired comparison with older infill	1
Beethoven ejecta and rim sector	Beethoven basin margins and ejecta field	Distinct ejecta unit with darker color; direct test of excavated or compositionally distinct material	1
Beethoven tectonic system	Duyfken Rupes; southern and eastern basin margins	Concentric and NW–SE structures constrain post-impact and post-crater tectonic sequence	2
Fresh crater exposure sites	c3 craters, including Bello crater and other bright-rayed craters	Sharp morphology and bright ejecta maximize interpretive clarity for surface exposure	2
Surface-process indicators	Faculae, hollows, bright/dark deposits, irregular pits, catenae	Valuable contextual targets for explosive volcanism, volatile loss, and secondary cratering	3

terrains [2]. The ejecta extend almost one basin diameter from the rim, although the western sector is largely overprinted by more recent intermediate plains and crater materials, while the eastern side is locally overlain by patches of smooth plains [2].

The basin floor is composed of smooth plains formed by later infill, with published estimates placing the infill at roughly 3.7–3.9 Ga [2, 3]. Stratigraphically, the basin itself is interpreted as Tolstojan to Early Calorian, approximately 4.0–3.8 Ga [2]. This makes Beethoven particularly valuable because it preserves both an older basin-forming event and younger volcanic resurfacing within the same localized system.

Beethoven is also structurally important. The main tectonic structures within the basin display a concentric pattern. Duyfken Rupes (20.9°S, 228.1°E) forms the principal concentric thrust segment and is part of a broader NW–SE-trending thrust system [2]. Additional thrust segments along the southern and eastern basin margins cut superposed craters, showing that tectonic deformation postdates both basin formation and at least some crater emplacement [2, 7, 18]. The mapped internal faults bordering the inner depression are interpreted as normal or oblique faults associated with gravitational subsidence after impact [2, 14]. Wrinkle ridges within the basin affect the smooth plains and are mostly concentric [2]. Together, these attributes make Beethoven basin the single most efficient location in H12 for a combined compositional, stratigraphic, and tectonic observation strategy.

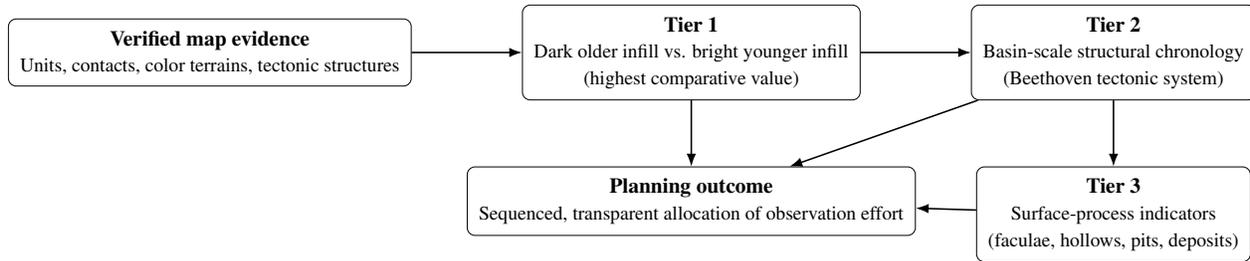


Figure 1: Decision flow for converting published geological evidence in H12 into staged observation priorities.

## OPERATIONAL PLANNING FRAMEWORK

### *Three-tier observation sequence*

The geologic evidence supports a clear three-stage mission-planning sequence, and the sequence is ordered so that the strongest multi-criterion targets are examined before secondary contextual sites.

**Stage 1: Contrast acquisition.** Initial observational effort should focus on paired comparisons between dark older infill and bright younger infill. The highest-value pairings are (i) intermediate plains in ancient-basin settings such as Vincente-Yakovlev and the western dark-blue sector, and (ii) smooth plains in Beethoven, Michelangelo, and Takayoshi. This stage is designed to establish the strongest possible contrast between resurfacing episodes.

**Stage 2: Structural sequencing.** Once the principal terrain contrast has been characterized, attention should shift to Beethoven basin's tectonic framework. Duyfken Rupes, the southern and eastern basin-margin thrusts, and internal concentric structures are the most informative targets for reconstructing relative timing between basin formation, smooth-plains infill, crater superposition, and later deformation.

**Stage 3: Contextual process mapping.** After the primary compositional and structural contrasts are constrained, secondary targets such as faculae, hollows, bright deposits, dark deposits, and irregular pits should be used to refine process interpretation. These sites are important, but their best value is contextual rather than primary.

### *Why this framework is efficient*

This planning sequence is efficient because it prioritizes:

1. **direct geological contrast** rather than diffuse regional coverage;
2. **multi-criterion targets** where composition, chronology, and structure intersect;
3. **localized subregions** where repeated observations can test more than one interpretation at once.

In operational terms, the framework reduces redundancy and improves traceability. Instead of distributing effort evenly across the quadrangle, it concentrates attention where the published map already indicates the greatest interpretive leverage and where the same target can be justified by more than one mapped line of evidence.

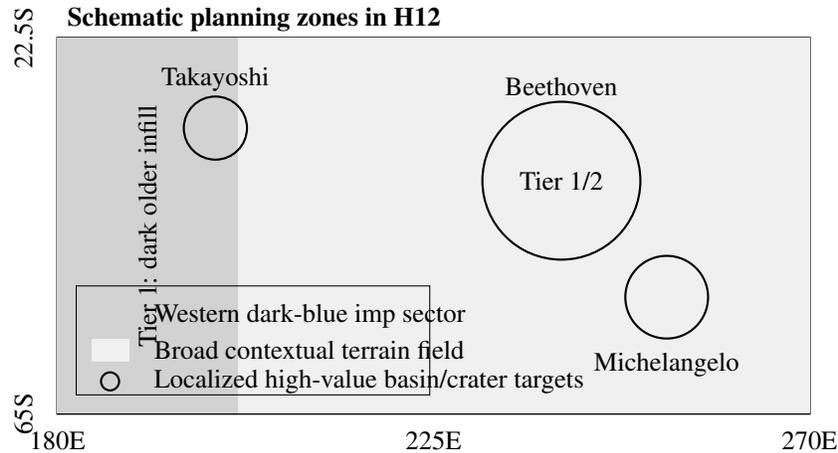


Figure 2: Schematic organization of planning-relevant zones in H12. The western sector concentrates the principal dark older infill comparison targets, while Beethoven and selected crater interiors provide localized high-value younger-fill and structural sites.

## IMPLICATIONS FOR MANAGEMENT AND PLANNING RESEARCH

Although the substantive case is planetary, the methodological contribution is squarely a planning contribution. The paper demonstrates how a complex spatial knowledge base can be converted into an explicit decision framework for allocating limited observational effort without obscuring the evidentiary basis of each choice. Three broader implications follow.

First, the case shows the value of **evidence-based prioritization**. Geological units are not treated merely as descriptive categories; they are reorganized as decision units for ranking and sequencing. Second, it illustrates **transparent rule formation**. The priority hierarchy is traceable to published evidence, and the internal cross-checking step makes the ranking more defensible than an implicit expert ordering. Third, it highlights **resource-efficient staging**. By centering high-contrast and multi-criterion targets first, the framework increases the expected return on constrained mission time and instrument deployment.

These are planning problems in a strict sense: they concern prioritization, sequencing, comparative allocation, validation of decision rules, and the formal use of systematically collected information in decision-making. For that reason, the Michelangelo quadrangle is not only a geological case study but also a concrete demonstration of how domain-specific spatial evidence can be restructured into an operational planning model with broader relevance for management-oriented resource allocation.

## CONCLUSION

The Michelangelo quadrangle provides a strong basis for structured observation planning because it combines clear stratigraphic differentiation, a reported color-terrain contrast, and a high-value basin system in Beethoven. The published geological map shows that H12 is dominated by intermediate plains and c2 crater materials, that intercrater plains form the second most extensive terrain, and that smooth plains are comparatively limited but concentrated in strategically important crater and basin interiors. It also identifies a

dark-blue western terrain associated with intermediate plains and Beethoven ejecta, contrasted with brighter reddish/yellow terrains associated more closely with smooth plains and fresh crater materials.

Organized as a planning framework, these findings support a coherent three-tier sequence: first, paired observation of older dark infill and younger bright infill; second, focused analysis of the Beethoven tectonic system; third, contextual study of surface-process indicators such as faculae, hollows, and localized deposits. The result is a transparent, decision-oriented manuscript that translates published geological evidence into a practical and internally cross-checked model for target selection, sequencing, and mission-level observational prioritization.

## DATA AVAILABILITY

All geological interpretations, geographic coordinates, unit descriptions, and planning-relevant terrain relationships used in this manuscript are derived from the published geological map of the Michelangelo quadrangle (H12) and its associated MESSENGER MDIS datasets as archived through the relevant mission data repositories [2, 6]. No new remote-sensing measurements were generated; the contribution of the present study lies in the explicit planning synthesis and prioritization logic applied to those published materials.

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