

Towards a Methodological Validation of Digital Terrain Models as a Potential Impact Criterion: Requirements, Constraints, and a Roadmap for Empirical Testing

Michael A. Rappenglück^{1,2} and Barbara Rappenglück³

¹Society for Archaeoastronomy (Gesellschaft für Archäoastronomie e.V.), Bahnhofstr. 1, 82205 Gilching, Germany;
mr@infis.org

²European Society for Astronomy in Culture (SEAC), Switzerland

³Independent Researcher, Germany

High-resolution digital terrain models (DTMs/DGMs), including recent global products such as TanDEM-X, are increasingly used to analyse the morphology of terrestrial and planetary impact structures and have been discussed in parts of the literature as a potentially independent diagnostic indicator. However, comprehensive, systematic validation studies have not yet established under which conditions DTM-derived morphometric signatures can reliably discriminate confirmed impact craters from geogenic or anthropogenic analogues across different planetary environments. Pending such validation, DTMs should presently be regarded in the current state of knowledge primarily as heuristic tools rather than as an independent diagnostic impact criterion.

Here we outline a comprehensive validation framework designed to assess whether DTM-based morphometric parameters possess sufficient discriminatory power to qualify as a future diagnostic method. The proposed programme comprises: (1) compilation of a benchmark dataset of confirmed impact structures identified by accepted shock-metamorphic and geochemical criteria [2]; (2) construction of matched control sets of circular geogenic and anthropogenic landforms; (3) extraction of comparable morphometric parameters, including circularity measures, radial elevation-profile statistics, peak-to-rim metrics, and degradation indices [3,4]; (4) quantitative evaluation of discriminative capacity using reproducible statistical approaches, including unsupervised clustering and supervised classification [5,6], as well as more recent DTM-based morphometric classification approaches reported in the literature and applied to terrestrial crater candidates [7]; and (5) testing of robustness and transferability by applying a conceptually consistent validation framework, adapted to planetary-specific surface processes and data characteristics, across Earth, Moon, and Mars using established planetary topographic datasets [8,9].

From a philosophy-of-science perspective commonly applied in the natural sciences, the establishment of any new diagnostic criterion requires reproducibility, falsifiability, statistical validation against an established gold standard, and explanatory power across planetary contexts [10]. The framework presented here provides

an explicit roadmap for such validation. Depending on the outcome, DTM-based morphology may emerge either as a valuable but non-diagnostic exploratory tool or, if shown to be highly discriminative and robust, as a candidate for future formal integration into impact structure identification. This contribution clarifies the methodological requirements needed to resolve the ongoing discussion surrounding DTMs as a potential new impact criterion.

References:

- [1] Gottwald M. et al. (2017) *Meteoritics & Planetary Science*, 52(7), 1412–1427.
- [2] French B. M. and Koeberl C. (2010) *Earth-Sci. Rev.*, 98, 123–170.
- [3] Pike R. J. (1980) *U.S. Geol. Surv. Prof. Pap.*, 1046-C.
- [4] Melosh H. J. (1989) *Impact Cratering: A Geologic Process*. Oxford Univ. Press, New York.
- [5] Bue B. D. and Stepinski T. F. (2007) *IEEE Trans. Geosci. Remote Sens.*, 45(1), 265–274.
- [6] Stepinski T. F. et al. (2009) *Icarus*, 203(1), 77–87.
- [7] Emmanuel H. et al. (2024) Morphometric classification of terrestrial impact structures using DEM-derived parameters. *Geosci. J.*
- [8] Gwinner K. et al. (2016) *Planet. Space Sci.*, 126, 93–138.
- [9] Neumann G. A. et al. (2016) *Sci. Adv.*, 2, e1500852.
- [10] Hacking I. (1983) *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science*. Cambridge Univ. Press, Cambridge.

Towards a Methodological Validation of Digital Terrain Models as a Potential Impact Criterion

Michael A. Rappenglück^{1,2} Barbara Rappenglück³

¹ Society for Archaeoastronomy (Gesellschaft für Archäoastronomie e.V.), Germany, ² European Society for Astronomy in Culture (SEAC), ³ Independent Researcher, Germany · Contact: mr@infis.org

Lunar and Planetary Science Conference, LPSC 2026 — Abstract #1078

1. Motivation: DTMs at the centre of crater screening

High-resolution digital terrain models (DTMs/DEMs) have become indispensable for crater mapping and geomorphological screening on Earth and other planetary bodies.

- Global elevation products (TanDEM-X, Copernicus DEM) enable systematic identification of circular landforms
- Automated crater detection and ML-based screening are increasingly applied in planetary science
- On Earth, the diagnostic status of morphology-only DEM evidence remains unresolved
- Impact confirmation still requires established shock-metamorphic and geochemical criteria (French & Koeberl 2010)

2. The core problem: Morphological equifinality and false positives

A central difficulty in terrestrial crater identification is morphological equifinality: similar circular depressions can arise from fundamentally different processes. On Earth, crater-like landforms are produced not only by hypervelocity impacts but also by:

- Karst collapse dolines and flooded sinkholes,
- Glacial kettle holes in moraine landscapes,
- Volcanic maars and diatreme structures,
- Anthropogenic excavation pits, quarries, and reservoirs,
- Mining subsidence features and historical extraction depressions,
- Bomb and artillery crater fields.

These analogue classes constitute systematic false positives for any morphology-based screening criterion. Consequently, circularity, rim-like topography, or DEM pattern similarity cannot function as independent diagnostic indicators without rigorous benchmarking against hard-negative controls (French and Koeberl 2010, 152–168).

3. Objective: From qualitative pattern recognition to benchmark validation

This contribution outlines a reproducible validation framework for testing whether DTM-derived morphometry can serve as a supplementary impact criterion.

- Key question: Can morphometric parameters discriminate impacts from hard-negative analogues?
- Focus is methodological validation, not proposal of new candidate structures
- Benchmark calibration is required to quantify false-positive rates

4. Benchmark positives: Gold-standard confirmation evidence

Validation requires a strict gold standard dataset.

- Positives must be independently confirmed impact craters
- Diagnostic evidence includes PDFs, shatter cones, melt rocks, geochemical signatures
- Morphology-only candidate structures cannot serve as benchmarks
- Earth Impact Database provides established confirmed reference cases
-

5. Hard-negative controls: Terrestrial analogue classes

The decisive terrestrial stress test is comparison against non-impact analogues.

- Karst depressions and sinkholes
- Glacial circular landforms
- Anthropogenic pits and quarries
- Explosive/bomb crater fields

Controls must be matched by diameter bin, relief context, and DEM resolution tier.

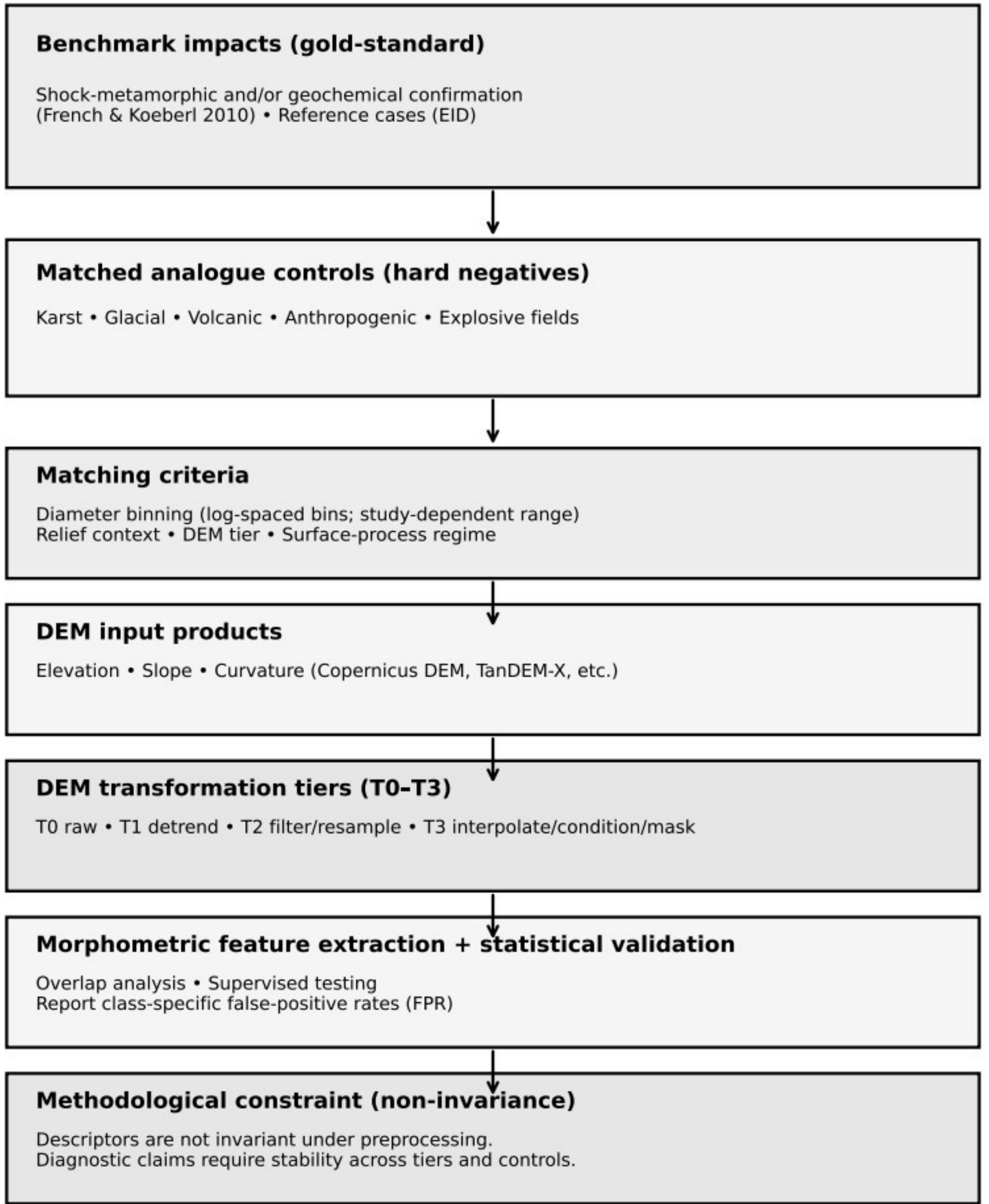


Fig. 1. Benchmark control validation pipeline with explicit DEM transformation tiers (T0-T3).

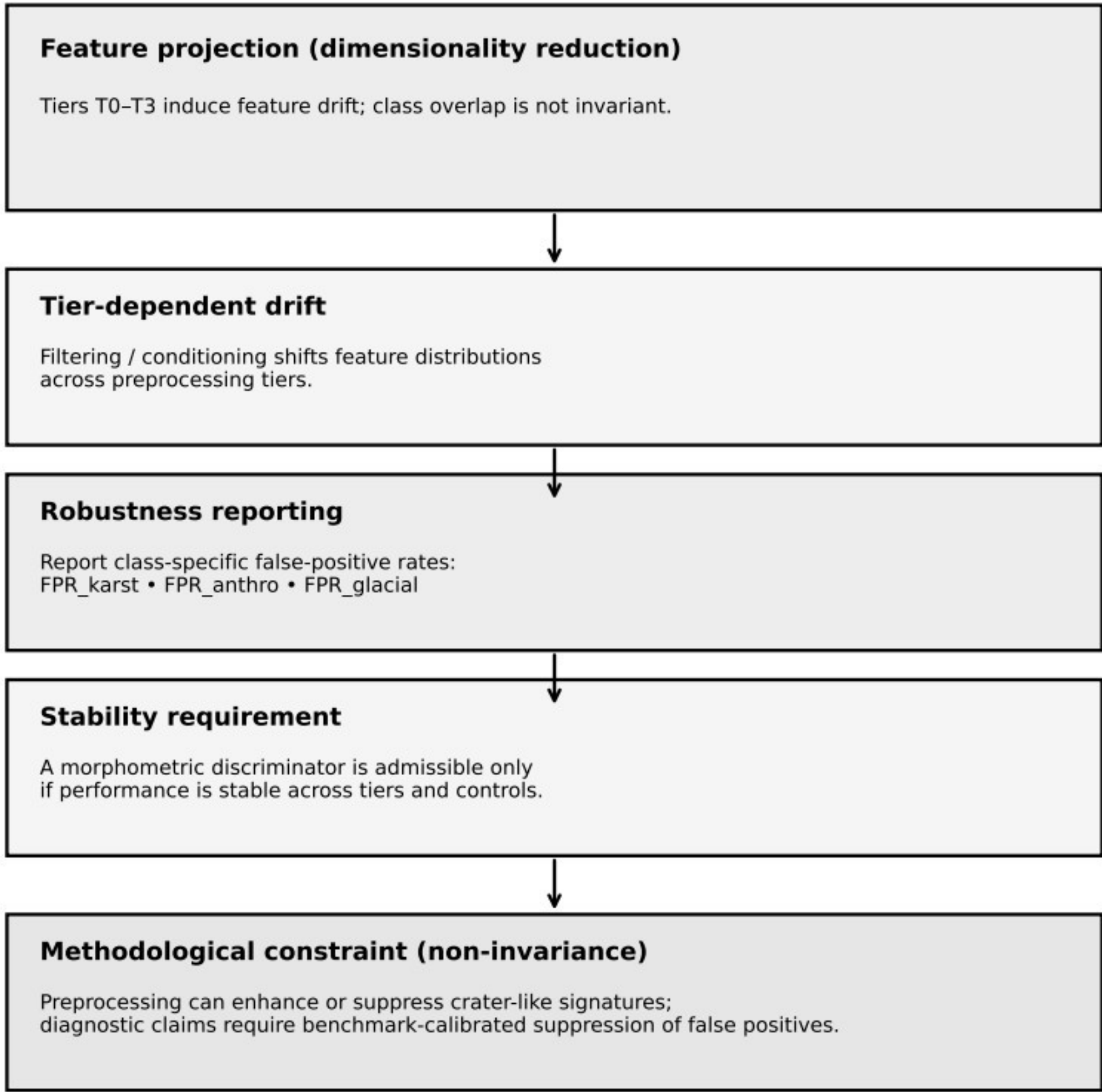


Fig. 2. Preprocessing sensitivity and robustness reporting across tiers (T0-T3)

DTM morphology is indispensable for screening, but crater-like topography is not diagnostic on Earth without benchmark-calibrated suppression of false positives against karst, glacial, anthropogenic, and military analogue classes.

6. Morphometric feature extraction and degradation metrics

Morphometric descriptors follow classical crater geometry and degradation concepts (Pike 1980; Melosh 1989). Relevant parameters include:

- planform circularity and ellipticity indices
- rim-to-floor relief and depth/diameter ratios
- radial elevation profile ensembles and azimuthal rim variance
- rim continuity and breach fraction measures
- curvature-based degradation proxies and infill estimates

Feature stability must be tested under preprocessing sensitivity tiers, because filtering, detrending, interpolation, and water masking can strongly amplify or suppress crater-like signatures in DEM products. Morphology is inherently multi-parameter; evaluation therefore requires an n-dimensional feature space rather than single-metric comparisons.

7. Statistical evaluation: Discrimination vs. overlap

Feature-space projections (e.g., PCA) visualise only a subset of variance and must be interpreted as reductions of an n-dimensional morphometric space.

The validation pipeline requires both exploratory and supervised testing:

- unsupervised PCA/clustering to assess feature-space overlap
- supervised classifiers (random forests, SVM, regularised regression) trained on benchmark–control datasets
- explicit reporting of class-specific false-positive rates, especially against karst and anthropogenic controls

Planetary crater detection provides methodological precedents, but terrestrial diagnostic demands are stricter because of the abundance of non-impact analogues and post-impact surface modification (Bue and Stepinski 2007; Silburt et al. 2019).

8. Expected outcomes and significance

Two scientifically constructive outcomes are possible:

- DTMs remain heuristic reconnaissance tools, valuable for screening and mapping but insufficient for independent confirmation due to persistent karst-dominated false positives.
- Restricted supplementary morphometric criteria may emerge under defined conditions, provided they demonstrate robust discrimination with low false-positive rates across analogue classes and preprocessing regimes.

In either case, benchmark-calibrated validation replaces qualitative pattern recognition with reproducible evidential practice, strengthening terrestrial impact science and clarifying the limits of morphology-only crater claims.

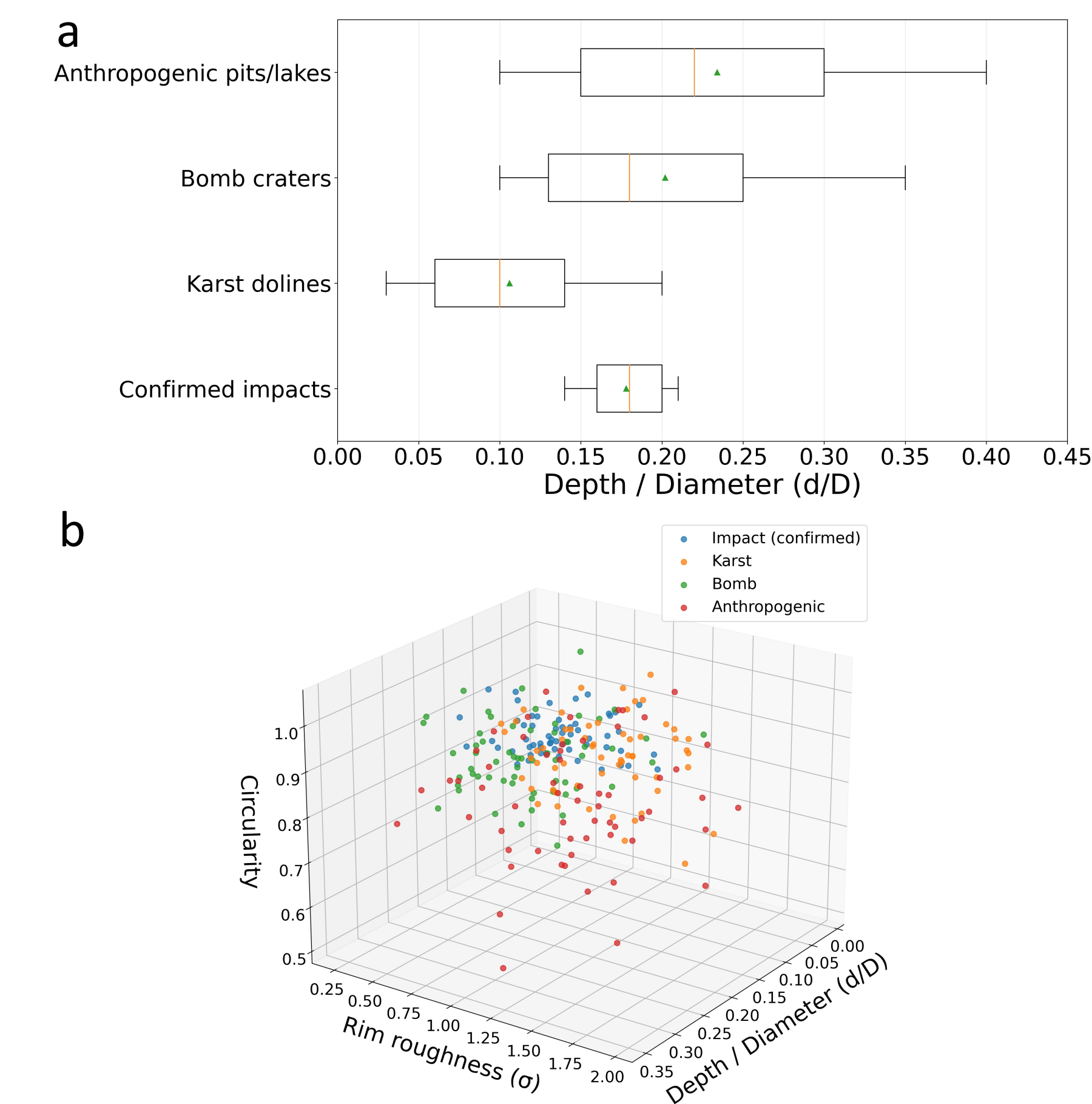


Fig. 3. Morphological Parameter Space

Crater-like depressions are characterized within a multi-parameter (n-dimensional) morphometric descriptor space (Pike, 1980; Melosh, 1989; Stepinski et al., 2009).

Descriptors commonly include geometric measures (diameter, depth, d/D, rim height and width), slope statistics, planform indices, curvature metrics, surface roughness measures, rim continuity, and degradation state.

In practice, crater morphometry routinely involves ≥10 semi-independent parameters (Pike, 1980).

Any 2D (a) or 3D (b) visualization therefore represents dimensional reduction of a higher-dimensional feature space. Morphological similarity in such projections does not establish genetic equivalence, and apparent distinctness alone is insufficient for diagnostic classification (French & Koeberl, 2010).