Systematic Utilization of Constant-Scale Natural Boundary Mapping for Interpreting the Formation Processes of Celestial Objects.

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Purpose: We are performing a systematic analysis of constant-scale natural boundary mapping to identify global-scale patterns in feature distribution and to interpret global-scale processes on regular (terrestrial planets and moons, the cosmos), and irregular (asteroids) astronomical objects [1].

Context for the CSNB approach: Constant-Scale Natural Boundary (CSNB) mapping is a revolutionary approach to visualization that produces maps markedly different from, and yet complementary to, those produced by conventional 2D cartographic and 3D modeling techniques. CSNB maps begin with well-defined boundaries, often found at the 'edges' of conventional projections that result from natural processes. regional-scale highs and lows in the parameter space of interest, such as elevation highs (ridges) or lows (troughs) for topography or cranial mapping for forensics or anthropology, analogously pressure for meteorology, roughness, texture, scattering, temperature, density of objects, or intensity of particular signal, for a range of disciplines. By directly illustrating spatial and dynamical relationships, CSNB maps provide greater insight into formation processes, revealing relationships and patterns in the distribution of analogous features, such as watersheds, mountain chains, prevailing currents and winds, explosions, or galactic clusters. This technique is particularly applicable to irregular bodies and other systems with roughness on the scale of the body itself, such as asteroids, crania or molecules. In those cases, imposing a conformal grid distorts features beyond recognition. Finally, CSNB bridges the gulf between the 2D mapping and 3D modeling worlds—which typically require unrelated algorithms and assumptions—by allowing visualization of an object in either 2D or 3D with the same set of assumptions, and a consequently easy transition between the two.

Conventional map projections assume spherical objects, although the regular celestial objects are oblate spheroids, and most solar system bodies, i. e., asteroids, are irregular objects. However, any three-dimensional object can be mapped, because projections flatten any continuous surface enclosing a three-dimensional object into a plane with a two-dimensional grid system (latitude and longitude). Maps are produced from developable surfaces that can be unrolled into a sheet, such as a cylinder around an axis (e.g., Mercator), a cone around a point and an axis (e.g., Albers), or a plane around a point (e.g., azimuthal polar projections). The aspect (relationship to the axis of rotation) may be parallel (normal) or transverse (perpendicular) relative to the axis or rotation, or somewhere between the two (oblique). The resulting projection introduces greater distortion as the object becomes less regular, the distance from the central point or line greater, or the projection less appropriate to the application. Distortion may be introduced in area, shape, direction, distance, or scale as a function of latitude and longitude. Projections may preserve local shape, area, or distance, or direction from a line or point. Projections are chosen to minimize distortion in the parameters most important for that application, as illustrated in **Table 1.1**. For example, local maps typically employ transverse Mercator to preserve angular relationships (conformality) and scale over small areas. For global maps, if equal-area projections are used to preserve relative size of continents regardless of latitude (e.g., Mollweide, Lambert), or equidistant projections are used to preserve distances along grids or between points (e.g., plate carrée, azimuthal equidistant), then shapes will be distorted. Thus, compromise projections may be used instead, such as *National Geographic*'s Winkel tripel. Distortions increase as distance from the projection-defined map 'center' (a point- or line-network of constant scale) increases. CSNB maps maintain the least distortion not at the centers, which are not necessarily very interesting, but along the natural boundaries at the map edges, which reflect the most significant physical processes. The relationship between scale, distortion, and conformality for CSNB and conventional projections are summarized in **Table 1.2**.

CSNB Mapping Technique: The steps involved in CSNB mapping are described elsewhere [2–5]. In summary, we construct a CSNB map by:

a) identifying a network of critical boundaries, such as ridge or valley trees.
b) dividing and flattening on object's surface along these boundaries to form a continuous outer boundary around an enclosed shape.
c) adjusting internal proportions according to actual distances.
d) drawing in a grid system, such as longitude and latitude, for reference.

A 3D object can then be reconstructed by joining and folding the map along boundaries.

Interpretation of CSNB Maps: For a given body and timeframe, internal (volcano-tectonic, chemical, or thermo-nuclear), external (erosional/depositional or rotational), or combined processes may dominate in shaping global-scale surface features, which act as constant-scale boundaries and terrane edges. CSNB mapping has now been used to produce global maps of bodies lying on a continuum between externally and internally driven control of surface morphology [2–10].

Internally and externally driven resurfacing limit historical expression. Whether modifications occur on rapid (catastrophic) or gradual (uniformitarian) time-scales, surface features give insight on processes that shaped, with the degree of influence based on the magnitude and timing of the occurrence. The impact-driven resurfacing rate for solar system bodies has slowed down historically due to the decrease in size and frequency of bombardment, as exemplified by the bombardment resurfaced Moon and asteroids. Although we can certainly observe the effect of later events that have overlapped spatially on earlier events, how much palimpsest-like influence do the larger magnitude earliest events still exert?

Earth: We have the technology to monitor our planet in great detail; this challenges our ability to manage and interpret a flood of data in order to understand global-scale patterns and thereby improve predictions and mitigate disasters. CSNB mapping is designed to provide such insight [5, 6]. Our approach is built on the assumption that nothing can happen 'here' without affecting what is happening 'there', whether we are talking about plate tectonics or major storm systems. Any set of identifiable boundaries may be deemed critical and used to construct CSNB maps. Thus any hypothesis, based on its predictions of critical boundaries, may be evaluated and tested by shapes and relationships illustrated on resulting maps.

Terrestrial Planets: We have used CSNB mapping to compare dominance of various surface modification forces on the Moon, Mars, and Venus. On the Moon global-scale external impact, as modified by regional-scale volcano-tectonism, is clearly illustrated by radial and concentric distribution of terranes [7], while Mars and Venus show a progressively greater global-scale role for internally driven modification.

Asteroids: CSNB mapping is ideally suited for classification of asteroids on the basis of morphological indices of overall shape and complexity, illustrating evolutionary development of asteroids, as evidenced by our comparative study of Eros, Deimos, Phobos, Ida, Gaspra, and Itokawa [8,9]. Lacking distortion and clearly showing relationships between 'facets', CSNB maps are also ideal for showing patterns in the distribution of related features and for exploration route planning [10].

The Cosmos: Our map [1] of variations in the cosmic microwave background clearly shows patterns in CMB anisotropy, including quadrupole and octupole planarity, and north/south asymmetry.

The Future of CSNB Mapping: We are seeking support for automation of the CSNB mapping algorithm. Autonomous operations for applications such as systematic asteroid survey missions would require a further step for autonomous generation of progressively higher fidelity 3D models as part of the mapping process.

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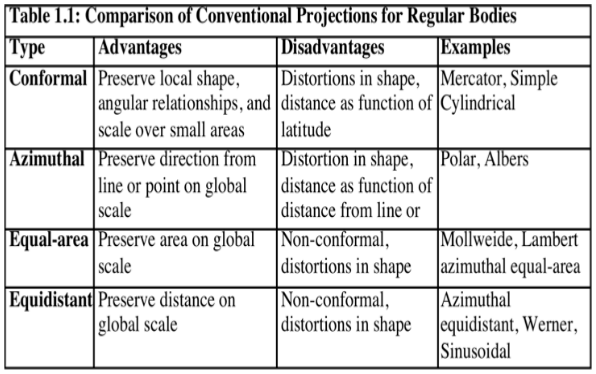

Table 1.1: Comparison of Conventional Projections for Regular Bodies

Type	Advantages	Disadvantages	Examples
Conformal	Preserve local shape, angular relationships, and scale over small areas	Distortions in shape, distance as function of latitude	Mercator, Simple Cylindrical
Azimuthal	Preserve direction from line or point on global scale	Distortion in shape, distance as function of distance from line or	Polar, Albers
Equal-area	Preserve area on global scale	Non-conformal, distortions in shape	Mollweide, Lambert azimuthal equal-area
Equidistant	Preserve distance on global scale	Non-conformal, distortions in shape	Azimuthal equidistant, Werner, Sinusoidal

Table 1.2 Comparison of CSNB and Conventional Mapping Techniques

	Feature	Conventional Capability	CSNB Advantages	Mission Benefit
Local	Minimize distortion, maintain proper scale	Distortion depends on relationship to 'center'. Cannot maintain constant resolution	Constant undistorted boundary scale represent underlying processes at appropriate resolution, little to no distortion	Decrease resources consumed, including cost, for productive science, as target selection or route planning, during, or post-mission either with ground or onboard processing capability, yielding flexible, agile, resilient map/model process for multiple domains or surveys
Global	Facilitate Interpretation of origins, processes	Maps start with arbitrary grid, distort proportions, weaken global interpretation	Map starts with naturally formed ridges and troughs in parameter space, that shape the landscape	
Visual	Utility for 2D and 3D	Choose one or the other, not both	Identify boundaries from 'cloud of points'. Segment and project in 2D. Reconnect and project in 3D.	
Mission	Automate mapping, modeling process	Current 3D techniques require highest resolution, are time-intensive, with automation difficult	Produce CSNB maps of growing complexity with growing resolution as approach rotating object	
CSNB Domains: astrophysics, meteorology geophysics, planetology, heliophysics, geography				