THE LONG WAVELENGTH STRUCTURE OF THE LUNAR CRUST: TIDAL-ROTATIONAL ORIGINS AND TRUE POLAR WANDER. I. Garrick-Bethell[1,2], [1]Department of Earth and Planetary Sciences, University of California, Santa Cruz (igarrick@ucsc.edu), [2]School of Space Research, Kyung Hee University, South Korea.

Introduction: The shape of the Moon and the structure of its crust at long wavelengths has long been a puzzle in lunar science. Understanding the origins of these features would have implications for the thermal history of the Moon, its orbital evolution, and its history of true polar wander. Here I review some of the historical and recent work in this area.

Background: Unlike the shape of the Earth, which is dominantly controlled by its spin, the shape of the Moon is not in hydrostatic equilibrium. That is, the Moon's shape is more distorted than would be expected if it was entirely controlled by tidal forces from the Earth and the Moon's own spin. Laplace was the first to notice this effect, when he inferred the Moon's moment of inertia differences from its precession rate. Historically, these moment of inertia differences have been used to represent the distortions of the Moon, but in reality, they are distinct from the Moon's topographic shape – a distinction that becomes important in understanding its origin (see below).

In the year 1898 Sedgwick offered an explanation for these moment of inertia differences: because the Moon was once closer to the Earth, it could have frozen in its shape during an epoch of stronger tidal and rotational deformation [1]. In particular, Sedgwick inferred that the freeze-in occurred at a semi-major axis between about 15 and 30 Earth radii. This idea became known as the fossil bulge hypothesis. However, a number of issues eventually arose with this idea. In particular, the ratios of the moment differences did not match those expected from theory, e.g. [2]. In the last few decades, proposals for reconciling the discrepancy suggested that some component of the lunar shape might be due to random geologic "noise" [3, 4].

New tidal-rotational models: A more recent proposal to reconcile the moment of inertia differences with a tidal-rotational shape model came about when it was realized that higher eccentricity orbits and spin-orbit resonances other than 1:1 would affect the moments of inertia differently during freeze-in [5]. The viability of this idea was subsequently deemed unlikely based on orbital evolution models [6].

A further limitation of the above study was that it only used the moments of inertia as a measure of the shape, when in fact the modern era of lunar observations has made available global maps of topography and gravity. The moment of inertia differences can be represented by the degree-2 spherical harmonic gravity coefficients. Garrick-Bethell et al. analyzed the Moon's topography and gravity together, outside of the largest basins, to infer that the Moon's shape was the sum of two tidal-rotational effects: a frozen fossil bulge, plus tidal heating in the crust [7]. The idea that the lunar crust could be tidally heated had been previously proposed [8], and was borrowed from work on Europa. Keane and Matsuyama studied the Moon's gravity after removing the effects of the basins, but did not analyze the Moon's topography. They inferred that the moments of inertia were consistent with freeze-in during a synchronous orbit with eccentricity of ~0.2 [9], still a high and likely implausible value.

Other models: Other early evolution models have been proposed to explain the structure of the crust without relying on tidal-rotational effects, e.g. [10].

True polar wander: The history of true polar wander is important for constraining the history of polar volatiles and density changes inside the Moon. The two studies above ([7, 9]) both inferred various degrees of polar wander, based on the orientation of the reference frame that contains the Moon's primordial tidal axis. However, the two inferred polar wander histories disagree with each other, and are in further disagreement with a variety of studies based on lunar magnetic anomalies. Runcorn provided one of the earliest examinations of lunar magnetic paleopoles [11], but modern spacecraft data have provided more recent studies that have increased the scatter [12, 13].

Interestingly, there is some degree of agreement between a recently reported "hydrogen paleopole" [14], and the topography paleopole of [7]: a great circle between them passes through the present poles and the center of the Procellarum KREEP Terrane. Further modeling and data interpretation are required to reconcile the diverse paleopoles of the Moon to better understand its orbital history and thermal evolution.

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