LOADING, RELAXATION AND TIDAL WANDER AT SPUTNIK PLANUM, PLUTO.

F. Nimmo[1], C. Bierson[1], D.P. Hamilton[2], J. M. Moore[3], W. B. McKinnon[4], S. A. Stern[5], L. A. Young[5], H. A. Weaver[6], C. B. Olkin[5], K. Ennico[3], and the New Horizons GGI Team, [1]Dept. Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, USA (fnimmo@es.ucsc.edu), [2]Dept. Astronomy, Univ. Maryland, College Park MD 20742, [3]NASA Ames Research Center, Moffett Field, CA 94035. [4]Dept. Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, [5]Southwest Research Institute,1050 Walnut St. Suite 300, Boulder, CO 80302, [6] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723

Summary: The location of the Sputnik Planum (SP; informal name) basin on Pluto can be explained as a result of Charon tidal torques acting on a positive gravity anomaly. Generating such a positive anomaly requires moderate elastic thicknesses, filling by >5 km thickness of relatively dense, solid N_2 and a present-day subsurface ocean, thicker beneath the basin.

Introduction: Sputnik Planum lies within an ~1000 km diameter, 3–4-km deep depression located at roughly 30°N at the anti-Charon longitude on Pluto [1,2]. This flat-floored basin is filled with N_2-dominated ice of unknown thickness, which is apparently undergoing convection [1,2]. The basin origin is unclear but may be due to an impact [3].

Reorientation: The location of SP can be explained if it represents a *positive* gravity anomaly [4], as follows. Under present-day conditions Pluto should be approximately oblate, with a small additional tidal bulge raised by Charon [5]. Torques from Charon will reorient a positive gravity anomaly towards the tidal axis [6]. In general changes in longitude will be larger than changes in latitude because the existing equatorial bulge is larger than the tidal bulge. Roughly speaking, the magnitude of the anomaly should be intermediate between Pluto's predicted J_2 (~1.3×10^{-4}) and C_{22} (~1.3×10^{-5}) gravity coefficients to produce the present-day location of SP. This range translates to a local positive peak gravity anomaly at SP of ~35-350 mGal [7].

Positive Gravity Anomaly: Some lunar basins (mascons) represent positive gravity anomalies and negative topography anomalies. These are thought to arise by a combination of impact-related mantle rebound, followed by later loading of the cooled, rigid lithosphere with surface basalts [8]. We will argue below that similar processes may have operated at SP.

Based on the depths of unrelaxed basins on Iapetus and the Moon [9], the initial depth of SP was likely ~7 km, with uncertainties introduced by the low velocities of Pluto impactors [10]. The transient crater depth was probably comparable to the ice shell thickness at the time of formation, indicating that uplift of the ice-ocean interface (if present) occurred.

No-Ocean Case: In the absence of an ocean, the following scenario would apply (Figure 1). Following the formation of the basin of depth d_0, an N_2 load of thickness L was emplaced at some subsequent epoch, by which time the ice shell possessed an elastic layer of thickness T_e. This loading would cause deflection w. The observed (present-day) basin depth $h=d_0+w-L$. The value of T_e is expected to range from 40-70 km for a chondritic Pluto, depending on when SP formed [11].

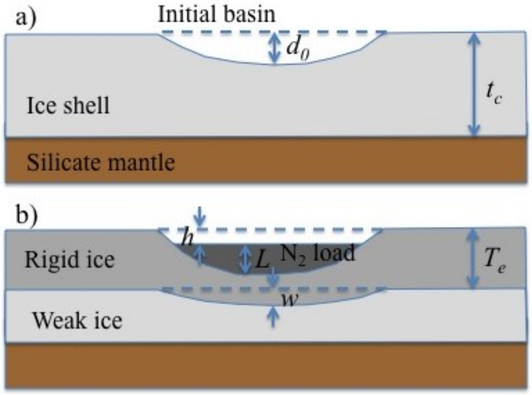

Figure 1: Cartoon of no-ocean geometry. a) Initial post-impact geometry. b) Geometry at time of loading. The silicates are assumed too rigid to undergo rebound.

Figure 2 plots the required load thickness L to generate the observed h, and the resulting present-day peak gravity anomaly Δg for two different scenarios. For the predicted pre-loading basin depth (d_0=7 km) a negative gravity anomaly always results. This is because subsequent loading can only produce the observed present-day topography if the ice shell is rigid. For a much shallower pre-loading basin (d_0=0) a positive gravity anomaly can be achieved at low T_e values but requires a load thickness in excess of 35 km.

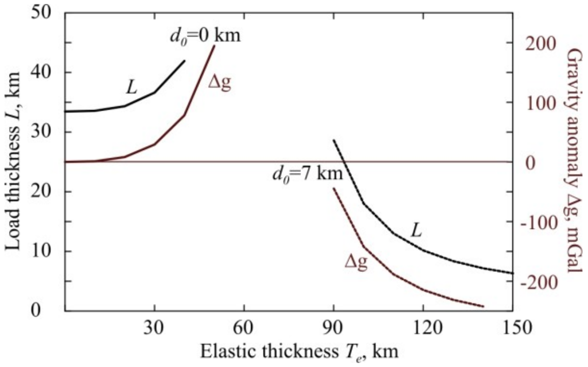

Figure 2: Results for the no-ocean case yielding h=4 km. Here a Young's modulus for ice of 9 GPa is assumed; the

densities of solid ice and solid N_2 are 0.92 and 1.03 g/cc and Cartesian flexural relationships are employed. The characteristic wavenumber of SP is π/800 km^{-1}.

We conclude that neither of these no-ocean cases is consistent with the observations.

With-ocean Case: Figure 3 shows the analogous scenario with a subsurface ocean, in which the ice shell has undergone rebound. The main effect of the rebound is that the initial (pre-loading) configuration will have a much smaller negative gravity anomaly than in Fig 1. The gravity anomaly depends on the attenuation factor $exp(-kt_c)$ where k is the wavenumber and t_c is the shell thickness.

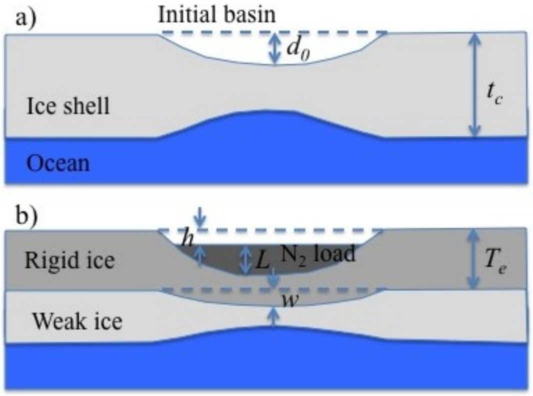

Figure 3: As for Fig 1, but with an ocean and an ice shell that has undergone rebound. In panel a) the basin is isostatically compensated.

Figure 4 shows the required load thickness and corresponding gravity anomaly. Here Δg is calculated assuming that the shell thickness $t_c = T_e$ (see below). A positive gravity anomaly can be attained with moderate load thicknesses (L~5 km). Although the required T_e values are large, these are probably overestimates because of the neglect of membrane stresses on the flexural equations.

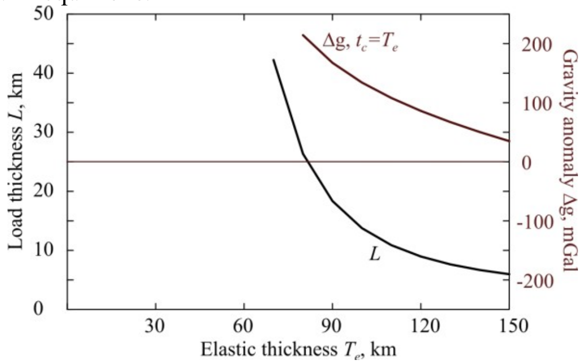

Figure 4: As for Fig 2, but assuming the initial geometry shown in Fig 3a. An ocean density of 1 g/cc is assumed.

Shell lateral flow: Figs 2 and 4 suggest that, if SP is indeed a positive gravity anomaly at the present day, then it most plausibly requires a subsurface ocean with an uplifted ice shell, very similar to the lunar mascons. One important question is whether lateral flow of the ice shell could plausibly remove the basal ice shell topography. The rate of flow depends mainly on the shell thickness t_c, ice shell viscosity and width of the feature. Figure 5 shows that long-term shell topography can be maintained, but only if the base of the shell is cold (<220K), requiring the presence of an antifreeze such as ammonia [12] in the ocean beneath. The bulk of such a cold shell will behave rigidly, justifying the assumption that $t_c=T_e$.

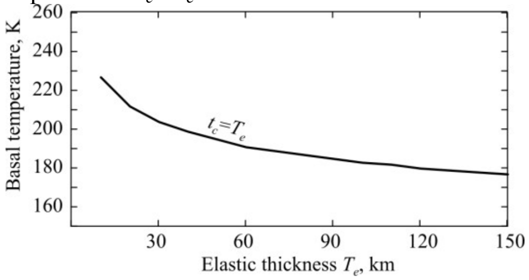

Figure 5: Basal shell temperature required to obtain a flow timescale of 3 Gyr, assuming an ice viscosity of 10^{14} Pa s at 270 K and a conductive temperature profile. Cold temperatures are required to maintain shell topography.

A Fossil Bulge? A present-day gravity anomaly is only required if Pluto possesses a "fossil" tidal bulge which was moved off-axis by the SP reorientation event. For likely elastic thicknesses, the present-day and fossil bulge components will be of comparable magnitude, but too small to detect via imaging.

Discussion. We conclude that Pluto possesses a cold present-day ocean beneath a conductive ice shell. This result is consistent with numerical calculations of Pluto's thermal evolution [13] and likely requires the presence of ocean NH_3 [12] to keep the base of the ice shell cold. The requirement for ocean uplift may provide a constraint on total ice shell thickness [10]. The presence of a refreezing ocean is also consistent with extensional tectonic features [2]. Longitudinal reorientation would have also influenced the distribution of tectonic features. Since SP's latitude has probably not varied significantly, it has likely formed a long-term trap of N_2, despite its youthful surface appearance [4].

References: [1] Stern et al. *Science* 2015 [2] Moore et al. *Science*, submitted [3] Schenk *DPS* 2015 [4] Hamilton *AGU* 2015 [5] McKinnon & Singer *DPS* 2014 [6] Aharonson et al. *Icarus* 2012 [7] Nimmo & Matsuyama *GRL* 2007 [8] Melosh et al. *Science* 2013 [9] White et al. *Icarus* 2013 [10] Bray & Schenk *Icarus* 2015 [11] Kamata & Nimmo *JGR* 2014 [12] Mitri *AGU* 2015 [13] Robuchon & Nimmo *Icarus* 2011.