
Introduction: Impact craters, with their well-defined initial shapes, have proven useful as heat flow probes of a number of icy bodies, provided characteristics of viscous relaxation can be identified (e.g., on Ganymede [1], Enceladus [2], and Ceres [3]). For Pluto’s numerous craters such identifications are hampered/complicated by infilling and erosion by mobile, volatile ices, but not in every case [4]. Large craters offer relatively deep probes of rheological structure, and low-albedo regions are generally volatile-ice free. Two large, old craters in dark, western Cthulhu are probably the best examples for possible viscous relaxation on Pluto: Oort (~120-km diameter) and Edgeworth (~145-km diameter) (Fig. 1). They are similar enough in size, location, and apparent age (morphological preservation) that one suspects they resulted from the impact of a Kuiper belt binary, though we have no explicit evidence that they are in fact coeval. Edgeworth is particularly shallow (Fig. 1) and its floor appears bowed up above the original ground plane, a classic hallmark of viscous relaxation. In this presentation we will examine the evidence for the viscous relaxation of both Oort and Edgeworth, and derive constraints on Pluto’s heat flow integrated through time.

Figure 1. Stereo-derived digital terrain model (DTM) of western Cthulhu (from [5]), with transect. Both the general flatness of this terrain (see [6]) and the distinct appearances of Oort and Edgeworth are apparent. Noise increases in the DTM solution to the south (towards bottom). The only larger impacts seen on the New Horizons encounter hemisphere are the Burney multiring and great Sputnik basins.

Crater Depths on Pluto: In order to model the viscous relaxation of large craters we need to estimate their pristine, post-impact depths. We extrapolate from smaller, unrelaxed complex craters, utilizing the depth-diameter (d/D) data set generated by [7] from the 2018 DTM [5]. This data set (Fig. 2a) is more extensive and supersedes the depth/diameter data plotted for Pluto in [5]. Rather than fit the depth-diameter data as is, or even the deepest 75% per diameter bin [7], we use

Figure 2. Rim-to-floor depths of (nominally) minimally modified craters on Pluto, from [7]. (a) All morphological types, with lighter shading for those that are shallower. (b) Example quantile regression fit (this work) for craters with D > 13 km, above the simple-to-complex transition [7]. Edgeworth, at D ≈ 145 km, has an effective depth near 1 km [5].
quantile regression to estimate the upper envelope of crater depths (illustrated in Fig. 2b). This is because the spread in depths at a given diameter clearly indicates a role for modification. That is, even if not obviously or manifestly eroded, infilling and/or burial may express subtly, especially at the resolutions available. For 90th, 95th, and 99th quantile regressions, we estimate the pristine rim-to-floor depth of Oort (115-km diameter in this data set) to have been 5.5/8.0/5.7 km, and that of Edgeworth to have been 6.1/9.1/6.2 km. These ranges are indicative of the systematic uncertainties involved in the extrapolation, but we judge that Edgeworth must have been at least 6 km deep originally, and now stands at a “relaxation fraction” of at least 85%.

Large craters on icy satellites are sometimes anomalously shallow regardless of viscous relaxation [8]. Europa is prime example, though in Europa’s case the distinctive morphologies of its largest craters and ringed basins plus the overall geological youth of its surface indicate little if any role for viscous relaxation. The likely great age for Pluto’s surface [4,9,10] and its largest craters does not allow for viscous relaxation to be dismissed. Moreover, the second largest crater in Fig. 1 is Elliot, an 80-km-diameter impact with clear evidence for nitrogen-ice infill that can easily account for its shallowness compared with the quantile regression fits.

Figure 3. Preliminary finite element simulation of the relaxation of Edgeworth crater on Pluto, from [11]. Note that we argue that Edgeworth was initially substantially deeper than shown here.

Finite Element Models: We have begun a suite of finite element simulations along the lines of [1–3] but for Pluto specific conditions (e.g., 50 K surface, 0.62 m/s² surface gravity) (Fig. 3). Our preliminary calculations for Edgeworth [11] show that essentially no relaxation occurs over 4 billion years for a constant heat flow of 3 mW/m², and little for 5 mW/m². These are heat flows appropriate to Pluto’s long-term evolution from radiogenic heating alone [12]. Not surprisingly, under such conditions Pluto’s lithosphere is simply too cold and thick to relax or yield. To explain Edgeworth’s (or Oort’s) floor as a product of viscous relaxation requires warmer ice temperatures at depth (higher heat flows), from Fig. 3 at least 30 mW/m² over 4 billion years (heat flows that are not easy to explain [12]). In addition, both regolith and surface ice fracturing, as well as clathrate formation, could act to markedly lower surface ice conductivity and raise temperatures throughout Pluto’s icy shell. We are exploring a range of sustained heat flows, early high-heat flow epochs, and effective higher surface temperatures in simulations of viscous relaxation of craters at these large scales on Pluto. New results and their implications will be presented at the meeting.

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