VISCOUS RELAXATION OF OORT AND EDGEWORTH CRATERS ON PLUTO: POSSIBLE INDICATORS OF AN EPOCH OF EARLY HIGH HEAT FLOW, WITH STATISTICAL AND ENERGETIC CONSIDERATIONS.

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Summary: 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. For Pluto's numerous craters such identifications are hampered/complicated by infilling and erosion by mobile, volatile ices, but not in every case. Large craters offer relatively deep probes of rheological structure, and on Pluto two large, old craters in dark (volatile-ice free), western Cthulhu are probably the best examples for possible viscous relaxation: Oort (115-km diameter) and Edgeworth (140-km diameter) (Fig. 1). They are similar in size, location, and apparent age (morphological preservation), but may or may not be coeval. Edgeworth is particularly shallow and its floor appears bowed up above the original ground plane, a classic hallmark of viscous relaxation in which viscosity decreases rapidly with depth.

We estimate a fresh (immediate post-impact) depth for Edgeworth of ~6 km, which when compared with its present rim-to-deepest point depth implies a relaxation fraction (RF) of nearly 80%. Oort is less relaxed, with an RF of ~55%. Possibly Oort is somewhat younger (which is actually consistent with its morphology) and was less affected by an early epoch of high heat flow. Finite element calculations show that this heat flow would have to have been substantial epoch to explain Edgeworth's upbowed floor by viscous relaxation, well above steady-state radiogenic values for present-day surface temperatures. We expect Pluto's brittle ice lithosphere to be fractured and porous, however, markedly reducing thermal conductivity and increasing temperatures at depth and relaxation for a given heat flow. We find most relaxation occurs within 100 Myr after impact for Oort and Edgeworth, and focus attention on a temporal (and/or regional) epoch of elevated heat flow, possibly tied to the serpentinization of Pluto's rocky core.

Finite Element Models: We simulate crater relaxation in axisymmetric geometry using the viscoelastic finite element code Tekton, modified to simulate the tectonics of ice lithospheres [e.g., 1,2], and which has been used previously to simulate viscous relaxation of craters on Enceladus [3], Ceres [4,5] and Ganymede [6,7]. We follow the basic approach in these previous works, and material constants appropriate to a water-ice crust are assumed. We look at range of background heat flows F: 3 mW/m^2, appropriate to radiogenic heat release today; 10 mW/m^2, consistent with past radiogenic heat release on Pluto; and higher values. Equally important in the modeling is the actual, *effective* temperature of the sur-

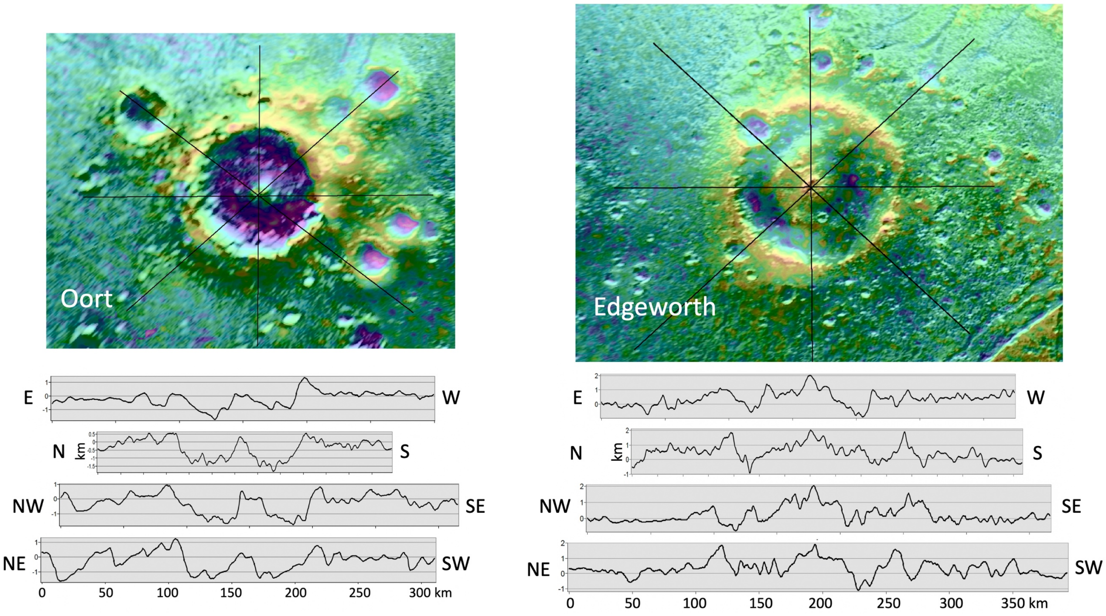

Fig. 1. Images of Oort and Edgeworth craters, with color coded DEM [8] overlaid. Topographic profiles are indicated. The floor of Edgeworth is bowed upwards, rising above the mean elevation of the local terrain, apparent in all the profiles.

face, $T_{s,eff}$. It has long been recognized that regoliths on airless bodies form insulating blankets that from a geophysical point of view raise the bounding surface temperatures for the deeper crust [9]. For Pluto we test a range of possible $T_{s,eff}$: 60, 80, and 100 K.

We find that there are combinations of F and $T_{s,eff}$ for which the floor of "Edgeworth" can rise above the original ground plane, and indeed be uplifted considerably above this level. Moreover, most of the topographic relaxation of the crater floor is complete within 100 Myr, regardless of heat flow, while the rim topography essentially persists indefinitely. This relatively rapid, long-wavelength topographic relaxation occurs primarily because Edgeworth was (nominally) a deep crater. Differential stresses at depth are high enough that relaxation is driven by power-law creep, for which effective viscosity is a strong and decreasing function of increasing shear stress.

In Fig. 2 the apparent depth of the *center* of Edgeworth's floor is plotted as a function of heat flow for the different assumed effective surface temperatures. For $T_{s,eff} = 60$ K, the central floor reaches the surface (defining a relaxation fraction [RF] of 100%) for $F \geq 50$ mW/m^2. Increasing $T_{s,eff}$ to 80 K lowers the minimum F to ~25 mW/m^2, and for $T_{s,eff} =$ 100 K the minimum F is $<$ 10 mW/m^2. For Oort we estimate a relaxation fraction of 0.57 (rim to deepest point), but find that it is difficult to achieve this RF unless either the heat flow is quite high, approaching 100 mW/m^2, or $T_{s,eff} > 80$ K. We could invoke mass wasting and infilling to rationalize Oort's present topography with less extreme combinations of F and $T_{s,eff}$, but we might still expect the central floor of Oort to be uplifted. This is not seen. Oort is nonetheless substantially shallower than expected for a crater of its size, and viscous relaxation may have contributed.

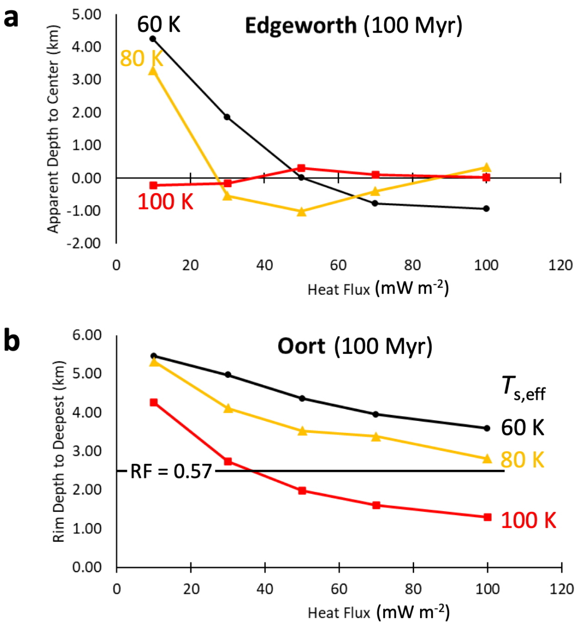

Fig. 2. Depth as a function of (effective) surface temperature ($T_{s,eff}$) and heat flux (F) for viscous relaxation of a model (a) Edgeworth and (b) Oort crater on Pluto, after 100 Myr of relaxation.

Binary or Singletons: The simplest explanation for our results is that Oort is actually somewhat younger geologically than Edgeworth and that the elevated heat flow responsible for Edgeworth was confined to an early epoch. Oort's rim is sharper and more continuous than Edgeworth's, consistent with this interpretation [cf. 10]. And not all major craters formed near each other need be the result of binary impacts. East and West Clearwater in northern Québec are prime examples; these "twin" craters formed ~180 Myr apart [11]. Statistically, 4 craters >100-km diameter have formed on Pluto's mapped surface post-Sputnik [8]: Oort, Edgeworth, Burney (a multiring basin) and "Guest." Ignoring edge effects, the likelihood of 2 of these forming within 400 km of each other is only ~22%, low but not rejectable.

Sources of Early Heat: Our results for Edgeworth are consistent with the heat flow limit from lack of flexure on (younger) normal faults from [12], <66-85 mW/m^2, but only marginally consistent with heat flow inferred from topographic spectra [13]: ~13 mW/m^2. The latter, however, refers to topography elsewhere on Pluto, and integrates across time over topography of any origin. Pluto must have had sufficient heat flow early on to relax its post-giant-impact rotational bulge [14]. Also, [13] find higher paleo-heat-flows on Charon than on Pluto, which is counterintuitive [15]. A substantial early heat source to consider, and one not directly connected to the Charon-forming impact, is serpentinization of Pluto's core. If hydrothermally connected to Pluto's ocean, 10s of mW/m^2 of heat may have been delivered over 100 Myr.

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