LIKELIHOOD FOR RUBBLE-PILE NEAR-EARTH ASTEROIDS TO BE 1ST OR NTH GENERATION: FOCUS ON BENNU AND RYUGU. K. J. Walsh[1] and R-L. Ballouz[2], W. F. Bottke[1], C. Avdellidou[3], H. C. Connolly Jr.[4,2], M. Delbo[3], D. N. DellaGiustina[2], E. R. Jawin[5], T. McCoy[5], P. Michel[3], T. Morota[6], M. C. Nolan[2], S. R. Schwartz[2], S. Sugita[6],D. S. Lauretta[2],[1]Southwest Research Institute, Boulder, CO 80303 (kwalsh@boulder.swri.edu), [2]Lunar and Planetary Laboratory, University of Arizona, [3]USA, Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France,[4]Dept. of Geology, Rowan University, Glassboro, NJ, USA,[5]Smithsonian Institution National Museum of Natural History, Washington, DC,[6]University of Tokyo.

Introduction: Tracing the origin and history of any single small near-Earth asteroid (NEA) is challenging. This effort typically relies on determining the most likely dynamical pathway [1], spectral variations [2], and probable Yarkovsky drift directions and timescales [2,3,4]. Fundamentally, near-Earth orbits are chaotic and determining precise evolutionary histories will likely need additional information provided by analysis of returned samples [5,6].

One certainty is that km-sized rubble piles themselves are not primordial—they have not witnessed the entirety of solar system history [7]. Collisional lifetimes for such small bodies in the main asteroid belt are only ~300-400 Myr [8], and the asteroid families that litter the region attest to on-going collisional evolution [9].

The conventional wisdom prior to encounter with Bennu is that it should have few large craters on its surface. This rationale is based on the short collisional lifetimes of small asteroids and the expectation that fast-acting processes like YORP spin-up appear capable of modifying and erasing asteroid surfaces. An analysis of Bennu's D > 50 m diameter craters [10], however, showed that aspects of its surface could be as old as the family-forming event that produced Bennu (i.e., potentially ~1 Gyr old; [4]).

To determine whether Bennu-sized asteroids could plausibly have such ancient craters, we created a model that tracked the survival of a population of such objects to understand the likelihood that they are direct products of a large asteroid family (first generation), or the product of a slightly larger rubble pile that itself was the product of a larger asteroid family (2nd generation or... up to Nth generation).

Origins of Near-Earth Asteroids: NEAs are transient bodies that mostly originate in the Main Asteroid Belt, and escape after drifting into an orbital resonance and suffer enough orbital change to encounter a planet [11]. The asteroids escaping the inner edges of the Main Asteroid Belt have the best chance to become NEAs, and can remain on an NEA orbit for times on order 10 Myr [11]. The majority of NEAs are small enough (km-sized) that they could not have survived all of solar system history in the Main Belt without suffering a catastrophic collision, and thus were likely formed as reaccumulated remnants of a larger asteroid collision/disruption event in the Main Belt not long before they began their journey to become an NEA.

Asteroid families litter the Main asteroid belt and provide good hunting grounds to potential parent asteroids with good spectral matches to any specific near-Earth asteroid [2]. A singular asteroid family – formed in the disruption of a ~100-km body – could produce a huge number of km-sized bodies that all begin drifting around due to Yarkovsky after they form.

These families also produce a larger number of intermediate-sized rubble piles, 5 or 10 km in diameter, that themselves are still subject to the collisional environment of the Main Belt. However, they will be drifting much slower than their km-sized siblings—where drift rates roughly scale as $1/D$ [9,12].

So the competition is for the very large numbers of the first generation km-sized family members racing against time to reach an escape route before being destroyed in a collision—versus a 5- or 10-km rubble pile, moving much more slowly, but more resistant to immediate destruction, being broken up eventually and having some of its remnants escaping. The answer is not obvious, and collisional and drift timescales compete in a way to make direct numerical integration of their orbits challenging.

Modeling Family Formation and Evolution: Asteroid families are modeled in a simple Monte-Carlo styled code. A family is initiated with a large number of simulated bodies that are randomly assigned diameters on a –3 cumulative slope size frequency distribution. The maximum allowed size is 24 km to mimic a family produced around a ~100-km parent. The minimum size followed is 0.5 km to be able to track the competition among km-sized remnants, without the burden of tracking the more numerous smaller objects. The objects are given obliquities when initiated that determine their drift rate and direction and do not change throughout the simulation. Drift rates were tested that range from that measured for Bennu and those nearly a half order of magnitude faster or slower. These tests focus entirely on the inner Main Belt, so objects are removed when they cross the 3:1 resonance at 2.5 au, the nu6 resonance at 2.15 au, and objects equal to or below 1 km have a 1/3 chance of removal when they cross the overlapping Jupiter 7:2 and Mars 5:9 (at 2.255 au) [4].

The novelty of this exercise is to track and compare collisional lifetimes of small asteroid family members with their dynamical time to escape the inner Main Belt. Collisional lifetimes are functions of their size and strength, where a D=1 km body has a collisional lifetime of 375 Myr [8].

When a body is determined to disrupt (a probabilistic function of its lifetime and time in the simulation), it is replaced with a size distribution of remnants. These remnant follow the same –3 slope cumulative size distribution as the initial population and the 2nd largest remnant is no larger than 0.3 times the size of the disrupted body. Mass is tracked so that no mass beyond that of the disrupted body is added to the simulation, and no bodies smaller than 0.5 km are added. Newly formed bodies are started at the location of their recently disrupted "parent" and are given random obliquities to determine their drift rate and direction.

Results: This is a competition between drift timescales and collisional lifetimes. When drift rates are fast, or a family is initially near an escape route (an orbital resonance like the 3:1 MMR with Jupiter) such that km-size bodies can cross the inner Main Belt in times less than a few factors of their collisional lifetime, then many can escape in the first wave of drifting bodies. Over time the tail of initially small bodies is depleted owing to collisional disruption, and the numbers of 2nd and Nth generation fragments increases as slightly larger bodies, with longer collisional lifetimes, start to breakup (see Figure 1 for an example scaled to the collisional lifetime of 1-km bodies).

We find that for scenarios in the inner Main Belt the total number of escaping bodies is dominated by 1st generation rubble piles. For older families, those whose age is 2-3x the collisional lifetime of the target body of interest, the rubble piles reaching escape routes can be equal contributions of 1st and Nth generation rubble piles. Thus, to understand whether a specific NEA is more likely a 1st or Nth generation rubble pile, the answer can depend on knowledge of its parent family and that families age.

Implications for Bennu and Ryugu: Two possible families for both Bennu and Ryugu, Eulalia and New Polana, are old enough (~800 and 1400 Myr respectively [4]) that Nth generation rubble piles are possible, even if the majority of bodies delivered are 1st generation.

This result has implications for various geologic analyses of the surface of these small rubble piles. If they are first generation, then the crater retention age would correspond to the reaccumulation event immediately post-dating disruption of the parent body, with some possibility of re-surfacing during a YORP reshaping event [7]. In addition, diversity in boulder properties [13,14] would be due to formation or modification processes that occurred only on the parent body or on Bennu's or Ryugu's surface; no intermediate processing would have occurred on other rubble-pile precursors.

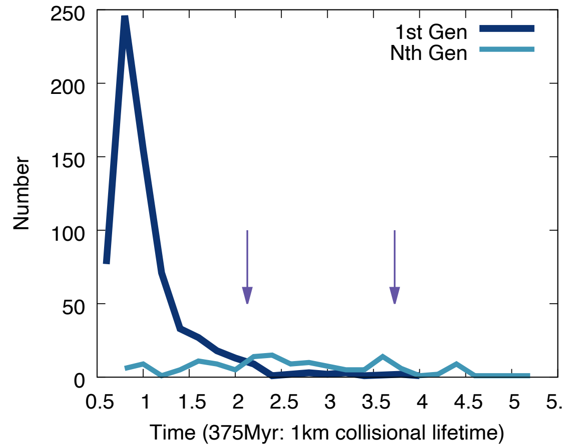

Figure 1: Model results for a family of initially 10,000 bodies at a semimajor axis of 2.488 au. The nominal drift rate is that measured for Bennu, scaled to each body's size and obliquity. The figure shows the number of 1st generation bodies that reach the nu6 resonance as a function of time and the number of Nth generation bodies that reach the same resonance. Time is scaled by the collisional disruption timescale for a 1-km body. The arrows indicate the ages of the estimated Eulalia and New Polana families relative to the x-axis timescale.

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