LUNAR TRANSITIONAL IMPACT CRATERS: INSIGHT INTO THE EFFECT OF TARGET LITHOLOGY ON THE IMPACT CRATERING PROCESS. G. R. Osinski[1,2], E. A. Silber[3], J. Clayton[1], R. A. F. Grieve[1], K. Hansen[1], C. L. Johnson[4], J. Kalynn[4], L. L. Tornabene[1], [1]Centre for Planetary Science and Exploration / Dept. of Earth Sciences, University of Western Ontario, 1151 Richmond St., London, ON, N6A 5B7, Canada, [2]Dept. of Physics and Astronomy, University of Western Ontario, Canada, [3]Dept. of Earth, Environmental and Planetary Science, Brown University, Providence, RI, 02912, USA, [4]Dept. of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, British Columbia, Canada (gosinski@uwo.ca).

Introduction: The Moon possesses the most complete and well-preserved impact cratering record in the Solar System and, thus, represents a natural laboratory to study impact processes. One of the most characteristic features of the lunar impact crater population is the change in morphology and morphometry with increasing size (e.g., [1]). At small diameters, simple impact craters form, which comprise a bowl-shaped depression and an uplifted rim [2]. Early observations of lunar craters revealed that as diameter increases the crater floor becomes flatter and a topographic high appears in the centre [3]. The presence of such a central topographic high was later used to define the term “complex impact crater” [4]. Complex craters have a faulted “terraced” rim, a relatively flat interior due to infilling by allochthonous crater-fill deposits, and an uplifted central peak emergent from the surrounding crater-fill deposit.

An often-overlooked class of impact craters are so-called “transitional craters”, which, as their name implies, are transitional between simple and complex impact craters. Such craters are abundant on the Moon, and remote sensing data reveal that they possess attributes of both simple and complex craters. The basic mechanism(s) responsible for the progression from simple to transitional to complex crater morphologies is known but not all details are fully understood. The definition of a transitional crater is also poorly and variably defined. In this study, we define a transitional crater as a flat-floored crater that does not display the bowl-shaped form of simple craters, possesses one or more discrete terrace and/or rock slide, but that lacks a centrally uplifted region that is emergent through the allochthonous crater-fill deposits (i.e., a central peak).

The objective of this study is to investigate the morphological and structural characteristics of well-preserved transitional craters on the Moon. Emphasis was placed on comparing craters in mare versus highland targets to further explore the previously-reported effects of target lithology [1]. We focused not on a global study of all impact craters, but instead on a detailed investigation of a suite of well-preserved transitional craters identified previously [5].

Methods: We used a dataset of 111 well-preserved craters of Eratosthenian (3.2–1.1 Ga) or Copernican (1.1 Ga to present) ages and diameters ≥ 15 km [5]. Based on this database, we identified and studied 28 craters that were of transitional morphology and identified as well-preserved craters, based on age and reported geological history. We grouped craters into 3 terrain types: mare, highlands and border. The latter were located at or near a mare–highlands contact and that could, therefore, involve both types of target rocks. Out of 28 craters studied, 13 are in mare, 12 in highlands and 3 in “border terrain”, which is essentially a mare target but with highlands terrain presumably close to the surface such that both terrain types were likely affected by the cratering process and could have contributed to the final crater morphology. Crater depths are from [5], while crater diameters were measured using the methodology presented in [5]. Following a methodology similar to that described in [6], we measured the wall widths (w) and floor diameters (D_f) for all craters examined in our study. In order to quantitatively assess the degree of crater wall collapse, we counted the number of discrete crater wall rock slides and terraces using 100 m/pixel LROC Wide Angle Camera (WAC) and 0.5 m/pixel LROC Narrow-Angle Camera (NAC) monochromatic images. Terraces (defined as distinct fault-bounded blocks on the walls of the crater) were mapped along scarps, interpreted as terrace block fault planes.

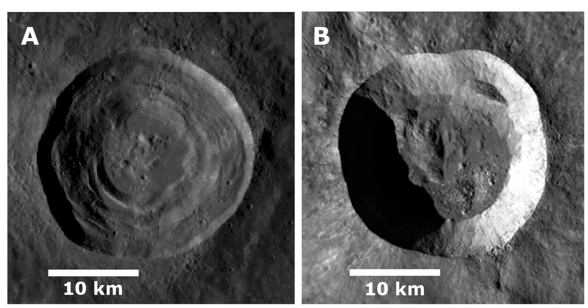

Fig. 1. A comparison of two 22-km diameter impact craters in different targets: (A) Picard (mare target) and (B) Giordano Bruno (highland target). Images: LROC WAC Mosaic. Image credit: NASA/GSFC/ASU.

Results: The results of this study are presented below, first for lowland and then highland craters.

Lowland craters. In mare targets, we documented transitional craters from ~15 to 42 km in diameter.

Bessel (D = 15 km) is the smallest crater of the study and has no terraces present. Picard has a slightly larger diameter (22 km), yet the changes in morphology are clearly demonstrable (Fig. 1). This crater displays concentric terracing and has a relatively flat floor of darker-toned material consistent with impact melt deposits. We note that Picard has several small mounds that are potentially associated with a proto-central peak; however, we include this crater in our transitional crater data because no unequivocal parauthchonous uplift exposures can be identified. Reinhold is the largest crater of this study with a diameter of 42 km (Fig. 1D). It has several well-developed terraces and two "mounds" present near the centre of the crater that appear to be draped in dark-toned impact melt deposits. In summary, there appears to be an overall increase in the amount of faulting and crater wall collapse – constrained by the number of terraces – with increasing diameter.

Highland craters. We documented transitional craters ranging between ~21 and 38 km in highland targets. Conon is the smallest crater of this range (D = 21 km) and has no obvious terraces but multiple scallops. Nicholson and Van Gent X are the largest transitional craters within the Highland terrains that we studied and both have a diameter of 38 km. Despite having the same diameter, there are distinct differences in the style of concentric terracing. As for mare targets, the number of terraces increases with increasing crater diameter in the highlands. There are, however, larger variations within this class compared to mare craters, with craters of the same diameter displaying considerable variation in the number of terraces. It is notable that all highland transitional craters are deeper than mare craters of the same diameter and with only one exception, mare craters possess more terraces that highland craters of the same diameter.

The differences between craters formed in the highlands versus the mare are readily demonstrated when Picard (mare) and Giordano Bruno (highlands), both ~22 km in diameter, are compared (Fig. 1).

Discussion: Neither observations, experiments nor numerical modelling have been able to fully and accurately describe the weakening mechanism(s) responsible for crater collapse to date. The propagation of shock waves mainly depends on intrinsic properties of the target material (e.g., [7]). Therefore, target strength and porosity can have a significant effect on the final crater morphology. However, the intricate interplay between these two parameters is not yet fully understood.

As the diameter of transitional craters increases, discrete fault-bounded terraces become identifiable. These are morphologically indistinguishable from terraces in complex lunar craters. A finding of our work is that the onset of terraces on mare terrain, as compared to highlands, occurs at smaller diameters. Moreover, the number of terraces in transitional mare craters is notably higher, which is indicative of the effect of substrate structure. But what is the cause of these morphological and morphometric differences?

We suggest that layering in mare targets is the major driver for the differences to highland craters described above. In keeping with craters formed in sedimentary rocks on Earth, layering provides pre-existing planes of weakness that facilitate crater collapse [8], thus explaining the overall shallower depths of mare craters and the onset of crater collapse (i.e., the transition from simple to complex crater morphology) at smaller diameters as compared to highland craters. This suggests that layering and its interplay with target strength and porosity may play a more significant role than previously considered.

While target lithology can account for the overall trends and differences between craters formed in mare versus highland targets, there are a small group of craters that have the same diameter and are situated on the same target but exhibit disparate morphologies. It is suggested that this may be due to impactor properties, such as velocity and/or composition (e.g., [9, 10]).

Acknowledgements: This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Space Agency, MDA, and the Centre for Excellence in Mining Innovation, through an Industrial Research Chair to GRO. Funding from NSERC's Discovery Grant and Discovery Accelerator Supplement (GRO, CLJ) and postdoctoral fellow (EAS) programs are also gratefully acknowledged.

References: [1] Pike, R.J. (1980) *Proceedings Lunar and Planetary Science Conference*, *11*, 2159–2189. [2] Shoemaker, E.M. (1960) *Report of the International Geological Congress, XXI Session, Norden. Part XVIII*. International Geological Congress. 418–434. [3] Gilbert, G.K. (1893) *Bulletin of the Philisophical Society of Washington*, *12*, 241–292. [4] Dence, M.R. (1964) *Meteoritics*, *2*, 3, 249–270. [5] Kalynn, J. et al. (2013) *Geophysical Research Letters*, *40*, 1, 38–42. [6] Susorney, H.C.M. et al. (2016) *Icarus*, *271*, 180–193. [7] Ahrens, T.J. and O'Keefe, J.D. (1972) *Moon*, *4*, 214–249. [8] Grieve, R.A.F. and Therriault, A. (2004) *Meteoritics & Planetary Science*, *39*, 2, 199–216. [9] Silber, E.A. et al. (2017) *Journal of Geophysical Research: Planets*, *122*, 5. [10] Holsapple, K.A. (1993) *Annual Review of Earth and Planetary Sciences*, *21*, 333–373.