HADEAN BOMBARDMENT DID NOT LIMIT EARLY SUBSURFACE HABITABILITY. R.E. Grimm[1], S. Marchi[1], [1]Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (grimm@boulder.swri.edu).

Introduction. The Hadean epoch, formally defined as beginning with Earth's accretion ~4.6 Ga and ending at 4.0 Ga [1], was a period of intense bombardment [2], yet detrital zircons indicate that near-surface water was present [3] and thus at least intervals of clement conditions may have existed. We investigate subsurface habitability by updating a prior approach to thermal evolution of the crust due to impact heating [4,5] with revised projectile fluxes, a more accurate thermal model, and treatment of melt sheets from large projectiles. The influence of the last has only been considered recently [2]. We find that subsurface habitable volume grows nearly continuously throughout the Hadean and early Archean because impact heat is dissipated rapidly compared to the total duration and waning strength of the bombardment. Melt sheets from large projectiles can resurface the Earth several times over prior to ~4.2 Ga but at most once since then. Even in the Hadean, melt sheets have little effect on habitability because melt-sheet cooling times are short compared to resurfacing intervals, allowing subsurface biospheres to be locally re-established by groundwater infiltration between major impacts. Therefore the subsurface is always habitable, and ocean vaporization [6] is the only remaining avenue to surface sterilization by bombardment.

Projectile Size and Time Distribution. The impactor population is a representative, single realization from a Monte Carlo simulation [2] of the interplanetary population hitting the Earth subsequent to the Moon-forming impact. The time interval is 4.5 to 3.5 Ga, spanning the Hadean and early Archean. The total mass 7×10^{22} kg is dominated by the two largest planetesimals at 1700 and 3500 km diameter that impact at 4.475 Ga; the remainder of the population contains 2.8×10^{21} kg and has a size-frequency distribution (SFD) roughly following a −2.0 incremental power law. After the initial two large projectiles, the mass flux decreases with a 1/e time constant ~120 Myr but includes a "sawtooth" Late Heavy Bombardment (LHB) in which the impact rate peaks at ~4.1 Ga. Impacts are applied on a 22,500-km square grid (the same surface area as the Earth), with wrapping, and are discretized at 25-Myr intervals.

Impact Heating. Subsurface heating due to impacts follows [4,5] and includes power-law radial peak-pressure decay, conversion to waste heat via Murnaghan equation of state, structural uplift, and topographic correction. The last involves shifting the isotherms at the transient crater profile to the former ground surface and proportionately pulling up the isotherms below (Fig. 1). This is intended to reflect that heating length scales are large compared to topography so the latter can be considered flat. We derive slightly different results from [5] because they remove topography before applying structural uplift, whereas we do the reverse. Both are incorrect as sequences; we intend in the future to scale directly from hydrodynamic impact simulations and also to use the final crater shape. Here and in [5], isotherms are sharply bent upwards below the former transient cavity: this defines the fundamental horizontal length scale as the transient cavity diameter D_{tc}. The impact velocity is 16 km/s prior to 4.15 Ga and is 25 km/s afterward. The impact angle is fixed at 45°. Other parameters are taken from [5].

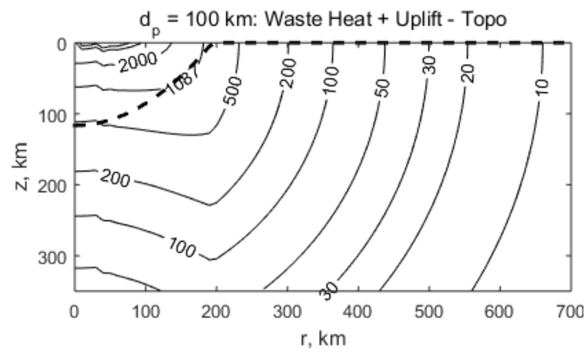

Fig. 1. Increase in subsurface temperatures ΔT after impact (largely following [4,5]) of a 100-km diameter projectile. Topographic correction for former transient cavity (dashed line) pulls isotherms up.

Thermal Evolution. For each projectile diameter (bin) d_p, the axially symmetric post-impact thermal anomaly $\Delta T(d_p,r_p,z_p)$ (where the subscript p indicates local, projectile coordinates) is expanded by [4,5] to cartesian coordinates. Individual impacts are randomly placed into the global grid (x,y,z) during the course of a 3D transient numerical thermal conduction simulation. Due to computational limitations, the grid spacing used by [4,5] was 300 km in x,y and 4.2 km in z. Because D_{tc} = 300 km at d_p = 75 km, thermal anomalies are underresolved for 97% of projectile population used by [4,5], albeit only ~10% of the delivered energy.

In order to resolve impact thermal anomalies for d_p larger than a few km, we adopted a mixed analytic-numerical temporal linear superposition. The complete thermal evolution for impacts of each projectile size $\Delta T(d_p,r_p,z_p,t_p)$ is calculated numerically, translated to cartesian coordinates, and added (analytically) into a 4D global grid (x,y,z,t). We specify only a limited number of depths in the global model, thus saving memory. Our final global grid has resolution 30 km in x,y and 0.5 km in z, for the upper 10 km. The time resolution is automatically selected in the numerical model but is output at 25-Myr intervals, consistent with the temporal resolution of the impactors.

Background geotherms were alternatively taken to be 12 and 70 K/km [5]. The latter represents a thinner, conductive lithosphere during the Hadean, whereas the former represents a locally [7] or globally [8] thicker lithosphere due to subduction zones or heat pipes, respectively. Surface temperature is 20°C.

Habitability Model. Following [4], we adopt temperature habitability ranges for mesophiles, thermophiles, and extremophiles of 20–50°C, 50–80°C, and 80–100°C, respectively.

Results. The large early impacts can be viewed as the end of accretion. They completely eliminate any subsurface habitable zones (Fig. 2), but this is before the likely origin of life anyway. A general increase of habitable volume occurs throughout the Hadean-Archean, because thermal dissipation times are short compared to the total duration of the rapidly declining bombardment. The only case we modeled that produced "late" crustal sterilization occured when we arbitrarily applied ~10x the main SFD in a 100-Myr LHB. This scenario follows [4], but our results differ due to distinctions between the thermal models described above. In the nominal bombardment model, only ~7% of the upper 10 km of crust is ever melted after the initial two large impacts (and neglecting superposed melt sheets, described below). Remelting is rare, <0.2%. At 70 K/km, the habitable zones are largely controlled by the background heat flux and therefore have little sensitivity to impact history.

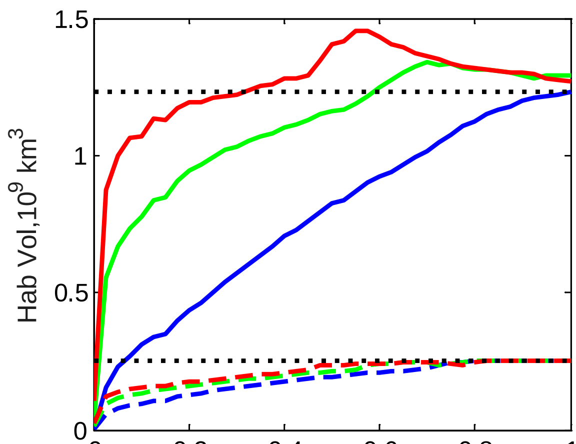

Fig. 2. Subsurface habitabile volumes grow nearly continuously in step with the waning bombardment. Red, green, blue = extremophile, thermophile, mesophile volumes, respectively. Solid lines = 12 K/km background geotherm; dashed = 70 K/km. Black dotted lines are equilibrium habitable volumes for each thermal gradient. Note residual effect of "sawtooth" peak at 0.4 Gyr (4.1 Ga).

Melt Sheets. We computed the resurfacing due melt sheets, assumed to apply only to d_p > 100 km and having diameter D_m = $R_m d_p$, where R_m = 20–30 [2]. Assuming a constant melt-sheet thickness h_m = 3 km [2], we separately investigated thermal effects using a 1D model (because all D_m >> h_m) and an initial temperature 1400°C.

Hadean melt sheets can resurface the Earth many times over [2], but cumulatively only once since ~4.2 Ga at R_m = 30 (Fig. 3) and once since ~4.35 Ga at R_m = 20. The median age of the last melt-sheet burial and the median interval between burials are 4.1 Ga and 18 Myr, respectively, at R_m = 30. Examining only the events older than 4 Ga, the median recurrence and last burial are 12 Myr and 4.2 Ga. Since the cooling time for a 3-km thick melt sheet is only ~10^5 yr, ample time is available for water to infiltrate the solidified melt sheet and for a biosphere to be (re)established in between burials.

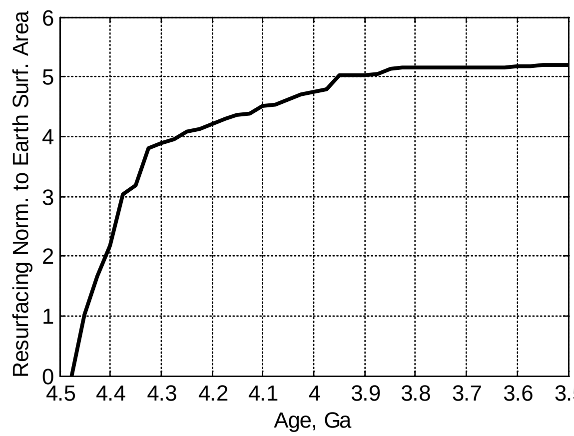

Fig. 3. Cumulative resurfacing by impact melt sheets, for d_p>100 km and D_m = 30d_p, neglecting the first time bin at 4.475 Ga containing the largest projectiles. The Earth is resurfaced several times over in the early Hadean, but cumulatively only once since ~4.2 Ga.

Concluding Discussion. Melt sheets heat the subsurface above the modal Hadean zircon crystallization temperature 685°C [3] only to depths of a few hundred meters, which is inconsistent with zircon formation in remelted country rock. The median age of the last melt sheet at each location is consistent with Hadean zircon ages [2] and zircon crystallization within melt sheets [9], although our model does not address other zircon formation mechanisms [3].

References. [1] ICS (2015) www.stratigraphy.org. [2] Marchi S., et al. (2014) *Nature*, *511*, 578. [3] Harrison T.M. (2009) *Ann. Rev. Earth Planet. Sci.*, *37*, 479. [4] Abramov O. and Mojzsis S. (2009) *Nature*, *459*, 419. [5] Abramov O., et al. (2013) *Chem. Erde.*, *73*, 227. [6] Sleep N.H. and Zahnle K. (1998) *JGR*, *103*, 28529. [7] Korenaga J. (2006), *AGU Monogr. 164*, 7. [8] Moore W.B. and Webb A.G. (2013), *Nature*, *501*, 501. [9] Kenny G.G., et al. (2016) *Geology*, doi:10.1130/G37898.1.