LOSS OF LARGE CRATERS IN THE TERRESTRIAL IMPACT RECORD R.W. Wichman and P.H. Schultz, Dept. of Geological Sciences, Brown University, Providence, RI, 02912.

INTRODUCTION: Although the Moon and Mars both preserve large impact structures over 200 km in diameter, no structure of this size has been recognized on Earth and only four impact structures larger than 100 km in diameter have been identified (1). Because most of the Earth's surface is significantly younger than surfaces on the Moon and Mars, it should be less heavily cratered. Nevertheless, 8 to 24 continental structures greater than 100 km in diameter are expected world-wide (Table 1), based on estimated terrestrial impact flux rates (2) and observed continental basement ages. If the average ocean floor age is 125 Ma, an additional 3 to 9 craters over 100 km in size would be expected in the ocean basins. Since the impact flux has decreased over time (3), the number of continental impact structures in the precambrian terrains may be much greater than the above estimates. These observations prompt the question of why more large impact structures (>100 km) have not been recognized on Earth. Erosion and sedimentation can obscure impact structures, and these effects have been addressed in detail by Grieve and Robertson (4). Large impacts also may be unrecognized, however, because of significant differences in the preserved appearance from impacts of smaller size. This alteration in appearance could reflect either later tectonic/volcanic modification or a change in the nature of cratering at larger sizes. The following discussion, therefore, first contrasts the modification of the largest observed terrestrial structures with observations from Mars and the Moon, and then considers possible changes in crater expression as the transient cavity size exceeds the lithospheric thickness, thereby complicating simple analogies with smaller structures.

DISCUSSION: Large terrestrial craters are best preserved in regions of stable continental crust and only one of the 8 largest terrestrial craters does not lie in a cratonic or shield unit (Table 2). The two largest, Sudbury and Vredefort, are both estimated to be ~140 km in diameter and are also the two oldest identified impact structures, although sufficient anomalous features relative to traditional impact models occur in both structures that endogenic as well as impact origins have been proposed (5,6,7). Of the two structures, Vredefort is the least altered by regional tectonism, but erosion has removed most of the surface structure to expose the underlying central uplift of the lower crust. In contrast, Sudbury has been heavily faulted, tilted and foreshortened, but preserves a significant section of the interior basin-filling deposits. Both craters should have excavated significant sections of the crust, but do not appear to have penetrated the local crustal section. At Vredefort the exposed central uplift represents a vertical crustal section some 12-15 km thick (8), while isotopic studies of the Sudbury Igneous Complex indicate a melt source above the mantle in the lowermost crust (9). The primary difference between the two impact sites appears to be the tectonic environment at the time of impact; Vredefort lies in a depositional basin in the craton interior (5,6), while Sudbury formed on an accreting craton edge during the Penokean orogeny (10). Two questions arise from these observations: why are structures excavating to mantle depths not recognized on Earth, and what is the role of cratonic regions in preserving large impact structures?

Several processes can localize deformation around large impact craters. On Mars, isostatic adjustment and lithospheric loading following the largest basin impacts lead to a characteristic sequence of radial and concentric fracture sets that control later volcanic conduits (11,12). On the Moon, large mare basins have features comparable to those in the martian basins, but a much smaller crater 40 km in diameter (Haldane) also exhibits similar radial and concentric fracture patterns and associated volcanic features (13). Application of analytical flexural models to these Haldane fractures requires a local mechanical lithosphere less than 10 km thick for crater-filling loads. Since Haldane formed during local mare volcanism and most lunar craters of the same size show no sign of similar modification, it appears that such extensive modification requires a locally high heat flux and thin lithosphere accompanying regional mare volcanism. Because isostatic adjustment, lithospheric loading and regional volcanism are also typical terrestrial processes, large impact structures (>100 km) on the Earth should be even more conducive to such modification than Haldane. The tectonically derived elliptical outline and concentric and radial volcanic dike patterns around Sudbury, in fact, may be a more typical pattern for large terrestrial impacts than Vredefort with its simple circular uplift and overturned collar. With this model, the preferential identification of craters in the cratonic regions reflects the reduced heat flows and geologic activity of these regions that would tend to limit such modification.

Recent studies of multi-ring basins on Mars and Callisto (11,12,14,15) also indicate that the nature of impact-induced fracturing may change at large crater sizes as the transient cavity size approaches the lithospheric thickness. Transient cavities penetrating an elastic layer to an underlying viscous region can induce concentric lithospheric fracture to great distances beyond the crater rim. Such a process has been proposed for both the formation of the extensive ring scarp system around Valhalla on Callisto (14,15) and the concentric canyons around the Hellas basin on Mars over 600 km outside the outer, Cordillera–equivalent scarp (12). For extremely low underlying viscosities, this mechanism predicts complete disruption of the lithosphere (14), thereby providing a mechanism for effectively masking or even destroying the largest terrestrial impact structures. Impact structures smaller than some critical size defined by the elastic layer thickness, however, should be unaffected by such modification. If a 5:1 transient cavity diameter/depth ratio is assumed, typical flexural thicknesses for oceanic and continental lithospheres imply maximum preserved crater diameters of 150–250 km and ~300 km respectively, over twice the size of the largest observed structures. If the elastic layer instead reflects crustal thicknesses, then a maximum preserved diameter of 150–200 km (continental) and ~50 km (oceanic) would be expected. These values are consistent with the absence of identified mantle–excavating impacts and would place the Sudbury and Vredefort structures near the limit of expected crater sizes.

Reduction in elastic layer thickness to a value near that of the crustal thickness has several possible causes. First, reduced lithospheric thicknesses would be expected in the past due to increased radiogenic and convective heat fluxes (16). Second, the elastic layer in the impact environment, due to shock effects and impact heating, may not correspond directly to a flexurally or thermally defined lithosphere. In either case, preservation of large craters would be less likely in regions of high heat flow and thus the preferential identification of large craters in cratonic regions would reflect the reduced heat flows typical of these regions. More poorly preserved structures like Sudbury would be predicted for impacts into thermally active regions.

CONCLUSIONS: Only a fraction of the expected number of large (>100 km) terrestrial impact structures have been identified and those which are recognised are preferentially located in cratonic shield regions where they have not penetrated the local crustal sections. We propose that two processes, in addition to erosion and sedimentation, may help to account for the other unrecognized impact structures. First, large impacts should be preferred sites for tectonic and volcanic modification; the original impact origin of some tectonic/volcanic centers may thus have been obscured. Second, the absence of mantle–excavating structures in the identified impact record may reflect an increased disruption of the lithosphere associated with impacts whose transient cavities penetrated to viscous rheologies at depth. Ongoing theoretical models may help to characterize possible diagnostic clues for focussing further study of these modification processes.

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TABLE 1: PREDICTED IMPACTS ON CONTINENTAL SURFACES

AVE AGE (Ma)[1]	AREA (10^6 km^2)[1]	EXPECTED N(>100)	
		A[2]	B[3]
225	40.6	(.7)	2
675	37.8	2	5
1125	14.6	1	3
1475	8.37	1	2
2025	20.6	3	9
2475	6.03	1	3
2925	1.03	(.2)	(.7)

[1] derived from Windley (17) fig 22.16.

[2] derived from an impact flux of 2 N(>20)/10^6 km^2/1000 Ma

[3] derived from an impact flux of 5.5 N(>20)/10^6 km^2/1000 Ma

TABLE 2: THE 8 LARGEST TERRESTRIAL IMPACT STRUCTURES

NAME	SIZE (km)	AGE (Ma)	GEOLOGIC SETTING
Sudbury	~140	1850	Canadian Shield
Vredefort	140	1970	Kapvaal craton, S. Africa
Manicouagan	100	210	Canadian Shield
Popigai	100	39	Anabar Shield, Siberia
Puchez–Katunki	80	183	central Russian craton
Kara	60	57	coastal sediments, USSR
Siljan	52	368	Baltic Shield, Sweden
Charlevoix	46	360	Canadian shield edge