THE CRATERING RECORD AND GEOLOGICAL HISTORY OF ENCELADUS

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Introduction. The saturnian satellite Enceladus shows a variety of tectonic features and a wide range in crater densities indicative of a dynamic history [1-5]. In a previous paper we examined the tectonics of Enceladus [5]. Here, we construct a geological history based on crater densities and our previous tectonic mapping. Figure 1 shows the surface of Enceladus divided into four major terrains, each of which is sharply bounded by major tectonic contacts: cratered plains, ridged plains, rifted terrain, and banded terrain. Two terrains are further subdivided on the basis of tectonics or internal variations in cratering.

Cratering record. Figure 2 shows a cumulative crater density plot for Enceladus and its terrain units, and Figure 3 is an "R-plot" comparing Enceladus with other icy satellites. Observational losses are minor for craters larger than 5.7 km (image resolution is about 2 km/l.p.). Table 1 gives cumulative crater statistics for craters larger than 5.7 km in diameter for the major terrain units and their subdivisions.

The ridged plains (Rp) include a long system of curvilinear ridges of likely compressional or volcano-tectonic origin [5]. The Rp are almost devoid of craters. Only two small craters have been identified in this entire area (109,000 km^2), indicating complete and geologically recent re-surfacing.

The cratered plains (Cp) exhibit over an order of magnitude variation in crater densities. The lower crater densities are found at the lower latitudes (Cp1, Cp2, and Cp11), while progessively (gradationally?) higher crater densities occur to the north (Cp 3-10). No obvious cryovolcanic flow fronts are visible in the Cp, nor are obvious "ghost" craters present, although such features might be found with better resolution. A tectonic alignment of pits in Cp4-6 may relate to tectonically-controlled cryoclastic volcanism [7]. The absence of craters larger than about 30 km means that even the most heavily cratered surfaces are devoid of "Population 1" craters [2], indicating that even these old regions were probably resurfaced. The crater density in the most heavily cratered regions is similar to that on Mimas and the heavily cratered surfaces of Tethys (Figure 3).

The Cp are everywhere dominated by extensional tectonics, although locally the tectonic style may include trans-tensional faulting [5]. Many fractures are very fresh, although other fractures have been cratered, suggesting that an extensional tectonic regime prevailed in the Cp for a considerable time.

A sub-unit of cratered plains, Cp12, exhibits unusual appearing craters. Small craters have been preserved, while large craters are very shallow and have bowed up floors, indicative of viscous relaxation [4]. The crater density of this region is similar to the adjacent, normal appearing regions of heavily cratered plains; since no sharp tectonic contact is apparent, Cp12 appears to have been derived from typical cratered plains by a laterally gradational enhancement in heat flow.

A north-trending rifted terrain (Rf) is characterized by sub-parallel extensional fractures, cryovolcanic flooding, and possibly "stretched" craters, and the whole unit has been tectonically down-dropped. Rf was derived by volcano-tectonic processes at the expense of cratered plains. The density of post-rifting craters is spatially non-uniform, suggesting protracted or episodic rifting. Cp tectonically abutts Rf on both east and west, and at one time Cp was apparently continuous across the region now occupied by Rf.

The banded terrain (Bt) is crossed by en echelon bands of uncertain origin [5]. The Bt has a low but variable crater density, indicating that it was generated over a substantial interval of time. Bt1 has about the same crater density as the rifted terrain and Cp4, while the sparse cratering of Bt2 is comparable to Cp1-3. The morphology and cratering record of the Bt are consistent with either multiple over-lapping cryovolcanic flows or with imbricated thrust sheets.

Absolute and relative ages. The observed crater density in the ridged plains is roughly 0.2% that of the heavily cratered regions. Part of this exceedingly low crater density is probably accounted for by unfavorable illumination of much, but not all, of the ridged plains. Even so, the actual crater density of the ridged plains is probably less than 1% that of the heavily cratered terrain. Assuming the heavily cratered terrain is of the order of 4×10^9 years old, and assuming a constant flux of Population 2 projectiles since that time, then the age of the ridged plains is of the order of 10^7-10^8 years old.

The absolute ages of other terrains can not be usefully constrained due to our current insufficient understanding of the impact flux through time. Table 1 provides some indication of relative ages, though one must be mindful of problems with apex-antapex asymmetries in cratering rates and possible shifts in Enceladus' rotation axis through time. We note, however, that the ridged plains are centered in the trailing

hemisphere, which should have the largest and most energetic flux of impactors; hence, the freshness of the Rp is a true indication of its youthfulness. Also, abrupt lateral contrasts in crater density always correlate with tectonic boundaries on Enceladus.

Geological History. **(1)** Very early in Enceladus' history, global re-surfacing obliterated all evidence of the heavy bombardments related to accretion and Population 1 craters [6]. Subsequently, only Population 2 projectiles impacted Enceladus. For conceptual simplicity one may imagine that all of Enceladus' surface once consisted of cratered plains bearing only Population 2 craters. The oldest surviving remnants of these plains may now be found at high northern latitudes (Cp5-10). **(2)** Rifting resulted in fracturing, cryovolcanic flooding, and possibly viscous relaxation and stretching of impact craters in the Rifted terrain; this event may have been co-eval with plains formation in Cp4 and the emplacement of Bt1. **(3)** Continued cryovolcanism and extensional fracturing generate the younger sub-units of the cratered plains (Cp1-3), and emplacement of the youngest sub-unit of the banded terrain (Bt2). **(4)** Ridged plains were formed by a combination of compressional tectonics and widespread cryovolcanism.

References. [1] Smith, B. et al., 1982, Science, 215, 504-537. [2] Plescia, J.B., and Boyce, J.M., 1983, Nature, 301, 666-670. [3] Squyres, S. et al., 1983, Icarus, 53, 319-331. [4] Passey, Q.R., 1983, Icarus 53, 105-120. [5] Pozio, S. and Kargel, J.S., 1989, abstract, Lun. Planet. Sci. XX, 864-865. [6] Strom, R.G., 1987, Icarus, 70, 517-535. [7] Kargel, J.S., 1984 (abstract), Lun. Planet. Sci. XV, 427-428.

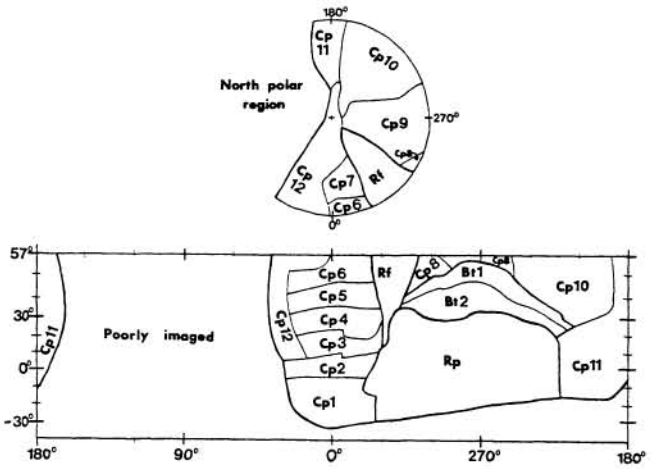

Figure 1. Terrain units and sub-divisions; Cp= Cratered Plains; Rp= Ridged Plains; Rf= Rifted Terrain; Bt= Banded Terrain.

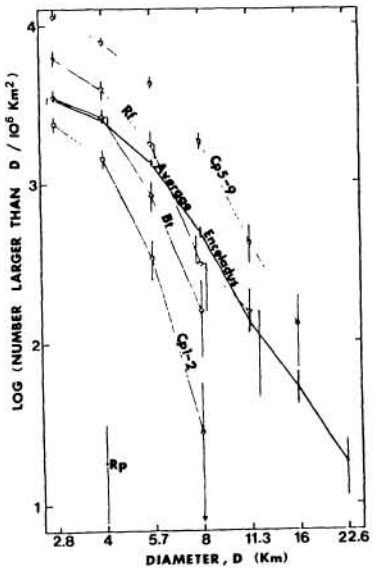

Figure 2. Cumulative crater density plot.

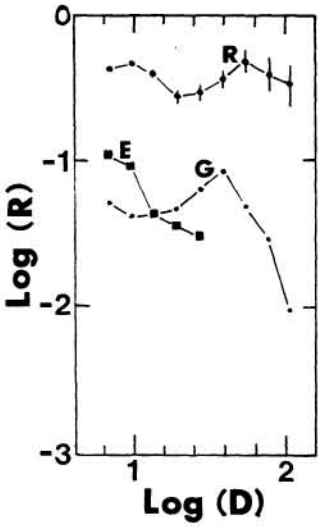

Figure 3. "R"-plot. E = Enceladus; R = Rhea showing population 1 and 2 superimposed [6]; G = Ganymede cratered terrain.

Table 1. Cumulative numbers of craters larger than 5.7 km per 10^6 km^2

Terrain	Sub-unit	Area(km^2)	Density	Uncertainty
	Cp1	22,400	450	+- 140
	Cp2	13,000	150	110
	Cp3	11,440	790	260
	Cp4	12,000	2080	420
	Cp5	7,940	4160	720
	Cp6	6,340	3790	770
	Cp7	2,850	4210	1220
	Cp8	2,440	3690	1230
	Cp9	11,080	5050	680
	Cp10	28,900	3220	330
	Cp11	53,000	1190	150
	Cp12	21,400	3510	410
Cp Average		192,790	1960	110
	Bt1	9,370	1600	410
	Bt2	15,900	380	150
Bt Average		25,270	830	180
Rp Average		109,000	0	
Rf Average		12,900	1780	370
Enceladus Avg.		349,960	1340	60