Figure 17. A. Two oblique impacts on Mars (4 × 2 km and 12 × 8 km) situated at 138°W, 41°N. Each crater has a companion downrange crater or craters (arrows) that can be interpreted as impacts by the spalled projectile. B. The enormous oblong crater Orcus Patera (400 km × 160 km) on Mars at 181°W, 15°N. In addition to the characteristic butterfly pattern identifiable at higher resolution, the crater appears to narrow downrange. Scalloping of crater wall suggests that this narrowing is the result of a process analogous to those documented at smaller scales, from the laboratory (Fig. 13) to the planets (Figs. 16 and 17a).

trajectories of the ricochet debris. Figure 2 indicates that ricochet fragments from partial disruption (m_f/m_p > 0.1) at low impact angles retain 60 to 80 percent of the initial impactor velocity. Consequently, high-velocity objects (> 20 km/s) could ricochet with velocities exceeding the escape velocities (11.2 km/s) of the Earth. Prograde Apollo asteroids and short-period comets, however, collide with velocities as low as 12 to 15 km/s and make up the most probable class of impactors (see Wetherill and Shoemaker, 1982; Shoemaker and others, 1988). Such impacts would potentially produce large ricochet fragments on suborbital trajectories, thereby reimpacting the Earth far from the original impact site. Because such fragments are still hypervelocity and will reimpact the Earth at even lower angles (see Gault and Wedekind, 1978), most of the kinetic energy from the initial impactor will be directly transferred to the atmosphere (Schultz and Gault, 1982). At least some sense of the consequences of a 10^6 impact can be gleaned from Figure 18. If we assume that the ten largest ricochet fragments exhibit a mass-frequency distribution similar to the results for a 15° impact (Fig. 3A), then ten fragments ranging from 2.6 to 3.2 km in diameter (m_f/m_p from 0.033 to 0.017) should reimpact with velocities between 7 and 10 km/s. Each of these fragments will have an energy of about 10^{28} ergs (i.e., each more than two orders of magnitude greater than the 1908 Tunguska event). Between 10^3 and 10^4 Tunguska-scale or larger impacts should occur globally over the hour following the impact. Hence, a single oblique impact could be essentially equivalent to a catastrophic cosmic swarm (Fig. 19).

Environmental effects of the returning ricochet debris include: more efficient ionization of the atmosphere; multiple centers of conflagration on land; and enhanced volatile injection by reimpacting debris in the ocean. Large reentry ejecta will not transfer much energy to the atmosphere before impacting the surface, and returning ejecta with velocities less than about 3 km/s will not induce much ionization (Schultz and Gault, 1982). Oblique impacts will produce much higher velocity ricochet debris with increased atmospheric coupling owing to the larger surface area to mass (hence, greater ionization efficiency), greater atmospheric pathlength, and potential for further ricochet by the reimpacting debris. From our experimental results, an extremely low angle impact (< 5°) minimizes atmospheric effects due to