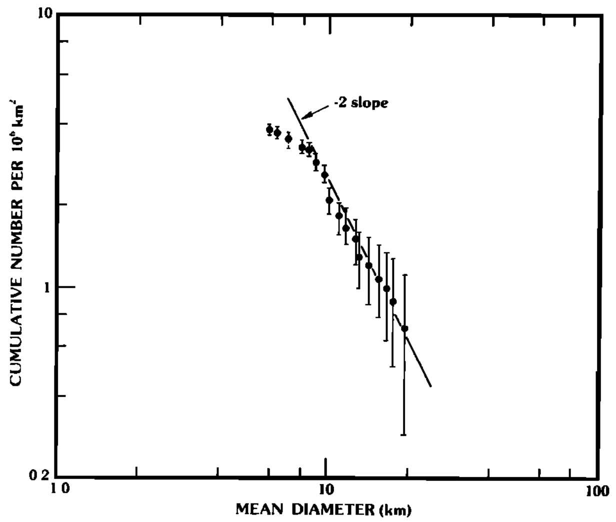

Fig. 7. Cumulative frequency of grazing impacts on ridged plains of Lunae Planum, Sinai Planum, and Syrtis Major Planitia. For a given diameter, grazing impacts represent about 5% of the total impact population.

respect to the martian equator. The present orbits of Phobos and Deimos are also aligned with the present martian equator with inclinations of only 1.0° and 2.8°, respectively. Second, older Mars grazers appear to form great circles that become more inclined to the martian equator with increasing age. As discussed below, this could be understood if Mars has undergone polar wandering, a process that is predicted theoretically [*Goldreich and Toomre,* 1969; *Ward et al.,* 1979] and that is perhaps preserved in the surface record [*Schultz and Lutz-Garihan,* 1981*a*, 1981*b*]. Third, the large number of Mars grazers spanning a long period of martian history could be readily explained.

If we assume that Mars grazers represent once orbiting objects, then we can define a unique point for each that describes its orbit. This point represents the axis of the orbit where it intersects the planet and is called here the 'orbit-pole point.' The orbit-pole point is simply determined from the direction and coordinates of the impact as illustrated in Figure 8. Impactors having common orbits will produce a cluster of orbit-pole points, i.e., craters and impact directions fall on a great circle. Figure 9*a* illustrates the contoured distribution of orbit-pole points for Class 1 and 2 grazers represented on an equal-area stereographic net. The contours represent the percentage of points for 1% of the area. These plots are centered on 90° W, and only one orbit-pole point for each crater is shown. Figure 9*a* confirms the trend shown in Figure 6 where the latitudes of the craters were not included. The more recent grazers have orbit-pole points that cluster within 40° of the present martian pole. The greatest concentrations are slightly offset from the pole from 270° W to 50° W at latitude 60° N. In general, 23% of the surface area of Mars is north or south of 50° where 56% of the orbit-pole points occur. Comparisons of the frequency distribution of each percentage class (values for a given counting cell) with a Poisson distribution confirm that the observed orbit-pole points are not from an isotropic population of impactors. Appendix B summarizes the statistical results and evaluates the spatial clusterings.

Figure 9*b* shows the contoured distribution of the older Mars grazers (Class 3) with $D_{max} \leq 20$ km and reveals the greatest orbit-pole concentration at lower latitudes near Amazonis Planitia (15° N, 150° W). A broad region of orbit-pole clusters also occurs west of Argyre (50° S, 60° W) or equivalently near Utopia Planitia (50° N, 300° W). Figure 9*b* additionally shows a broad band with few pole-point concentrations that is inclined to the present equator. The frequency distribution of orbit-pole cell values for this class of grazers can be shown to be marginally nonrandom.

The oldest age class (Class 4 and 5 with $D_{max} > 20$ km) has orbit-pole points far from the present martian pole (Figure 9*c*) with a broad clustering near Solis Planum (25° S, 80° W), or equivalently near Utopia Planitia, and a slightly tighter cluster near Mangala Vallis (10° S, 170° W). When members of Class 4 and 5 in all size ranges are combined (Figure 9*d*) the concentration near Solis-Planum/Utopia-Planitia is enhanced.

In general, Figures 9*a* through 9*d* indicate that orbit-pole locations have changed from near the present geographic pole to progressively more equatorial zones going back in time. Figure 10 summarizes such a sequence by plotting the major clustering of the northern orbit-pole points on a portion of Mars. Equivalently, a significant fraction of Mars grazers impacted along common great circles, which gradually increased in inclination with respect to the present martian equator going back in time. These results can be interpreted in two ways, with the working hypothesis that they represent impacts by satellites that once orbited Mars. First, the orbits of martian satellites originally had much higher inclinations that progressively became coplanar with the equator with time. Second, the martian satellites always have had low-inclination orbits, but the crust of Mars has migrated with time.

If the older Mars grazers had resulted from objects once having high-inclination orbits, then a gradual tidal decay of the orbits would have produced concentrations of orbit-pole points in a small circle symmetric about the pole owing to the rotation of Mars. Figures 9*a* and 9*b* are not consistent with such a scenario. In order to produce families of grazers along the same great circle, a family of objects with a similar high-inclination orbit would have to impact within one or two revolutions. The broad range of inferred crater ages for a given great-circle family within Class 3, however, weakens this possibility.

Dynamical models of Phobos predict that it will collide with Mars in about 10^7 years [*Singer,* 1971], thereby adding a new orbit-pole point consistent with the data in Figure 9*a*. If a large fraction of Mars grazers were once members of a large family of satellites with similar low-inclination orbits, then Figures 9*a* through 9*d* could be explained by shifts in the martian crust, i.e., polar wandering, as the orbits gradually decayed by tidal interactions. *Goldreich and Toomre* [1969] and *Ward et al.* [1979] discuss the mechanisms of polar wandering where changes in the moments of inertia of the planet result in a

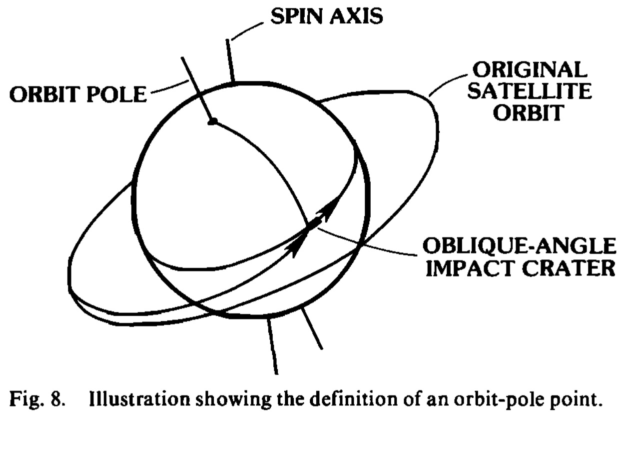

Fig. 8. Illustration showing the definition of an orbit-pole point.