quartz grains are much greater in North America (0.5–0.6 mm) than in Europe (0.1–0.2 mm) or the Pacific (<0.1 mm) as noted by Bohor (1990). Second, ejecta deposited in North America is characterized by a distinctive two-layer sequence. A lower chaotic layer contains diagenetically altered impact glasses accompanied by rare shocked mineral grains, whereas the upper laminated layer contains coarse shocked mineral grains (without glass alteration products) and the impactor signature (e.g., Ir). This perplexing two-component layer in North America clearly indicates a multistage ejecta emplacement (e.g., Bohor, 1990; Alvarez et al., 1995).

CHICXULUB AS AN OBLIQUE IMPACT
Tests from Interpretations of Existing Data

Three separate signatures of impact trajectory are recognized from laboratory experiments. These include asymmetries in (i) placement and shape of the interior structure; (ii) the degree and distribution of shock damage reflected in crater asymmetry; and (iii) depths, sequence, and distribution of ejecta. Despite postimpact rim collapse and an increase in scale of six orders of magnitude, many of these signatures can be recognized at planetary scales (see Schultz, 1992). Asymmetries associated with the Chicxulub structure closely resemble the signatures of an oblique impact for a trajectory from the southeast and provide a testable interpretation of its origin and consequences. Departures from symmetry become evident in large craters as deformation during the early penetration stage makes up a large fraction of the final crater diameter.

Interior Structure

The interior gravity and magnetic anomalies at Chicxulub reflect either a melt-filled central depression or an elongate central uplift. Elongate central structures (central peaks or rings) characterize oblique impact craters on other planets where asymmetries in ejecta distribution indicate trajectory (Fig. 2). Moreover, the center of symmetry of the interior anomaly at Chicxulub is offset slightly uprange (southeast) with respect to the 180-km-diameter gravity-defined ring (Fig. 1). Both the elongate central structure and its offset from center are consistent with the extended region of energy transfer created during the early penetration stages by an oblique impact.

Crater Asymmetry

The 180-km-diameter ring at Chicxulub widens in the high-resolution onshore data (Fig. 3). At laboratory scales, peak shock damage is reduced uprange but maximized transverse to the trajectory for 20°–30° impact angles. At planetary scales, however, rim collapse centered on the deepest portion of the transient cavity results in a more circular final crater outline, and failure may extend uprange beyond the rim (Fig. 2A). Even after rim collapse, both the elongate along-trajectory interior structure and transverse-trajectory widening of the crater rim can be documented in the Orientale and Crisium basins on the Moon (Fig. 3), which have been interpreted as oblique impact structures (see Wilhelms, 1987).

Extension of the gravity high from the northwest across the rings of 180 km and 80 km diameter suggests either incomplete erasure by Chicxulub excavation or influence of much deeper basement structure. In oblique impacts (<45° from horizontal), the impactor transfers its kinetic energy to the target in stages along the trajectory. Successive impactor failure and redirection due to reflected internal shocks result in shallow shock damage and excavation in the target down-range at impact angles <30° (Schultz and Anderson, 1996). Consequently, an oblique-angle trajectory from the southeast for Chicxulub should not erase down-range preexisting gravity anomalies below. Collapse of the transient cavity nevertheless produces concentric shallow crosscutting slump and faulting (Camargo-Zanoguera and Suarez-Reynoso, 1994). Down-range shallow excavation and up-range offset of the central gravity high are also exhibited by the much larger Orientale and Crisium basins as revealed in recently published free-air gravity maps (Zuber et al., 1995).

Nature and Distribution of Proximal Ejecta

An oblique impact ejects debris from shallow beds up-range, emplaces thin distal ejecta deposits up-range, and causes multi-