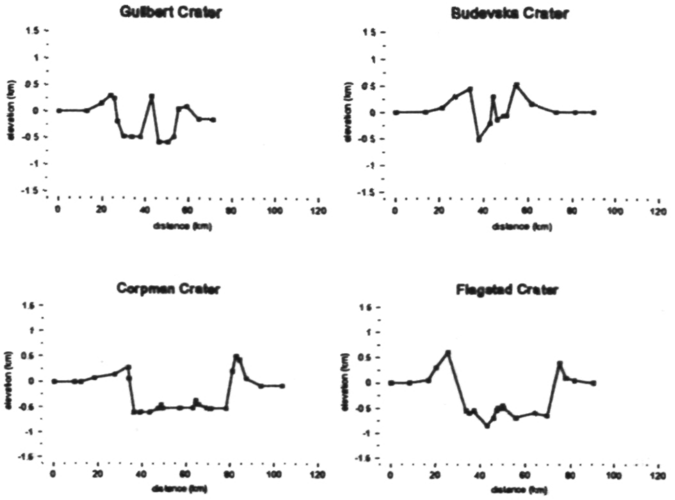

Fig. 2. Crater profiles constructed from Magellan image pairs.

Crater Profiles and Morphometry: The four crater profiles (~west-east, through the crater center) shown in Fig. 2 were produced using a nonstereo technique on Magellan cycle 1–cycle 2 image pairs. Guilbert and Budevska are central peak craters; Corpman and Flagstad are peak ring structures; Budevska is a fresh, bright-floored crater; the rest contain dark-floor deposits that may be indicative of volcanic or aeolian infilling. Corpman contains the most areally extensive dark floor deposits. The depth estimates of these craters support the single-image estimates presented above. Furthermore, because this technique does not hinge upon symmetrical topography, morphometric information can be extended beyond simple depth constraints.

The rim height (H_r) of these craters constitutes ~0.3–0.5 d and there are slight variations (<0.3 H_r) in the eastern and western H_r for all craters measured. Crater flanks, mantled by bright, blocky ejecta, are typically narrow, ranging from ~0.2–0.5 D. Assuming that ejecta constitutes ~0.5 H_r [5], the continuous ejecta blanket around Budevska Crater contains ~400 km³ of ejecta, equivalent to ~300 km³ of unfragmented target rock.

Central peak heights vary considerably from ~0.1 to 1.0 d. The lower extent of this range may be due in part to subsequent modification of Corpman by extensive dark floor deposits. The central peak of Guibert protrudes virtually to the level of the rim, and Budevska's central peak is only slightly shorter. Similar craters have been noted on other planets, e.g, the lunar farside crater, Icarus [7], and the terrestrial Marquez Dome crater [10]. Such craters, however, are relatively rare on other planets; having two such examples within a sample of four craters (Fig. 2) suggests that these anomalously tall central peaks might be more common on Venus. Crater floors are flat in all cases except Budevska, where the radar image shows a narrow ridge, coinciding with topographic profile, extending eastward from the central peak, thus resulting in the shallow depth on the profile's east side.

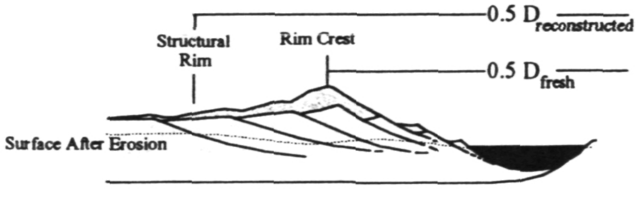

Fig. 3. Structure cross section of complex crater half-space. Crater center is on the right.

Implications and Conclusions: The unpredicted depth of fresh impact craters on Venus argues against a simple inverse relationship between surface gravity and crater depth. Factors that could contribute to deep craters on Venus include (1) more efficient excavation on Venus, possibly reflecting rheological effects of the hot venusian environment, (2) more melting and efficient removal of melt from the crater cavity, and (3) enhanced ejection of material out of the crater, possibly as a result of entrainment in an atmosphere set in motion by the passage of the projectile.

The broader issue raised by the venusian crater depths is whether surface gravity is the predominant influence on crater depths on any planet. There is an apparent d-g^{-1} trend in data from the Moon and Mercury, but these planets are all relatively small and, to the first order, of the same size. The surface properties and target characteristics of Mars are considerably different from those of the Moon and Mercury and could contribute to its somewhat lower d-D relationship. Although shallow depths, in accordance with g^{-1} scaling, are reported for terrestrial craters [6,2], there are no fresh complex craters on Earth from which to directly take these measurements. The Venus data in Fig. 2 indicate that H_r is a significant portion of d, and as all terrestrial complex structures are severely modified by erosion, d estimates may be up to a factor of 2 too low due to rim removal alone. In addition, when the crater rim and ejecta blanket have been removed, it becomes more difficult to determine the rim crest diameter. Reconstructions based on structural analysis may overestimate the true diameter if faulting extends beyond the rim as shown in Fig. 3. Thus while inverse gravity scaling of crater depths has been a useful paradigm in planetary cratering, the venusian data do not support this model and the terrestrial data are equivocal at best. The hypothesis that planetary gravity is the primary influence over crater depths and the paradigm that terrestrial craters are shallow should be reevaluated.

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S68-46 N93-10180 3 475221

K/T BOUNDARY STRATIGRAPHY: EVIDENCE FOR MULTIPLE IMPACTS AND A POSSIBLE COMET STREAM.

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GU657484 GU597082

A critical set of observations bearing on the K/T boundary events has been obtained from several dozen sites in western North America. Thin strata at and adjacent to the K/T boundary are locally preserved in association with coal beds at these sites. The strata were laid down in local shallow basins that were either intermittently flooded or occupied by very shallow ponds. Detailed examination by [1] of the stratigraphy at numerous sites led to their recognition of two distinct strata at the boundary [1–4]. From the time that the two strata were first recognized, E. M. Shoemaker has maintained that they record two impact events. We report here some of the evidence that supports this conclusion.

The lower stratum, first recognized at localities in the Raton Basin of New Mexico and Colorado by [4,5], is referred to as the K/T boundary claystone. Microscopic study of polished slabs of the boundary claystone, which consists typically of 1–2 cm of white, gray, or tan kaolinite, reveals that it is speckled with small angular to rounded clasts and pellets of white to gray kalolinite and subparallel flakes of vitrinite. The claystone commonly appears to be a single massive bed, but is found in some places to be a complex unit when examined in detail. Generally it rests on dark, thinly laminated carbonaceous claystone or coal; the lower contact is gradational at most places but sharp at some. The lower part of the claystone bed generally is dark colored, evidently owing to reworking of dark carbonaceous material from the underlying bed. Up to four discrete depositional units, most of them bounded by sharp contacts, are locally present within the claystone. In an example illustrated by [3, Fig. 5], angular kaolinite clasts in one depositional unit are truncated by a sharp contact at the base of the next overlying unit. The occurrence of the kaolinite clasts, most of which contain relict vegetal remains in the form of vitrinite flakes, and the multiple depositional units that rest on sharp truncation surfaces show unequivocally that the boundary claystone has not been formed by a single event of deposition or fallout of impact ejecta. Many clasts are ripup clasts of previously deposited claystone [3], and the presence of multiple depositional units indicates multiple episodes of reworking.

A distinctive feature of the boundary claystone is the presence of very-smooth-surfaced (in some cases shiny) spherules that typically range from about 0.1 to 1 mm in diameter [3,6–8]. In the Raton Basin the spherules are composed of gorceixite or kaolinite. At some localities in Wyoming the walls of the spherules are composed of gorceixite or another phosphate mineral, and the interiors are filled with kaolinite, gypsum, or, rarely, sulfides. Many spherules are hollow. Smooth-surfaced forms in the shape of teardrops, spindles, and dumbbells are also present [3,9,10]. These forms are nearly identical to but generally somewhat smaller than spherules, teardrops, spindles, and dumbbells found in the K/T boundary claystone in Haiti [9], where remnants of tektite glass are preserved in the interiors of the larger forms [9,11–14]. It is now clear that the gorceixite spherules in the boundary claystone in western North America are pseudomorphs after glassy objects. The variety of these pseudomorphus forms is typical of those produced by disruption of a liquid. Traces of the internal flow bands in the original liquid droplets are preserved on the surfaces of some of the pseudomorphs [9,15]. Spherules are fairly abundant at some localities in Wyoming, constituting up to several percent of the boundary claystone. Where they are composed entirely of kaolinite and embedded in a kaolinite matrix, they are often difficult to detect in hand specimen but easily detected in thin sections.

The upper stratum of the K/T boundary in western North America, referred to by [3] as the K/T boundary impact layer, generally consists of a few millimeters of thinly laminated claystone of mixed clay mineralogy and abundant flakes and laminae of vitrinite. Nearly everywhere it contains numerous ovoid pellets of claystone about 0.1 to 1 mm across, commonly referred to as graupen; in places it contains much larger rounded claystone clasts. Like the underlying boundary claystone, the upper stratum consists in some places of multiple depositional units bounded by sharp contacts. Hence the upper stratum also shows clear evidence of reworking. The interlaminated vitrinite shows that the upper stratum had a protracted history of deposition that produced the alternate laminae of vitrinite and clay.

The most diagnostic feature of the upper stratum is the presence of quartz grains and quartzose lithic fragments, about 30% of which exhibit shock lamellae [3]. About half the lithic fragments are chert and chalcedony and the other half are quartzite and metaquartzite. Rare shocked grains of oligoclase and microcline and granitoid lithic fragments are also present. The shocked grains tend to be concentrated near the base or in the lowest depositional unit of the upper stratum. No spherules are found in the upper stratum.

Of particular interest for the present discussion is the contact of the upper stratum on the boundary claystone. As noted by [16] and [3], this contact at some sites is a paleosurface that shows evidence of weathering and reworking or remobilization of the uppermost part of the boundary claystone. The uppermost 1 to few millimeters of the boundary claystone generally consists of irregular claystone clasts, mostly less than 1 mm across, embedded in a vitrinite-enriched matrix. Following [3], we informally refer to this reworked zone as the billowy layer. Shocked grains of quartz derived from the upper stratum locally occur in the billowy layer.

Root casts occur in the boundary claystone at localities in Montana [16] and Colorado, notably at the Clear Creek North site near Trinidad. Most of the recognized root casts are confined to the boundary claystone stratum. Where the root casts can be traced in polished slabs, they open at the top of the boundary claystone and are filled by the billowy layer. A shallow dimple generally is present at the top of the billowy layer over each root cast. Abundant flakes of vitrinite occur in the root casts, and shocked quartz can be found in the billowy filling, commonly along the upper walls of the root casts. The base of the upper stratum is marked in places by a fairly pronounced lamina of vitrinite that rests on the billowy layer. The upper stratum overlies the billowy filling of the root casts and therefore postdates them. The stratigraphic evidence reveals quite unambiguously that plants took root in the boundary claystone prior to the deposition of the upper stratum.

The strata at the K/T boundary in western North America thus record at least two impact events separated by a time interval long enough for small plants to grow on the K/T boundary claystone. Neither the boundary claystone nor the upper stratum, however, were formed simply by airfall of impact ejecta, as each stratum locally consists of multiple depositional units and contains clasts of previously deposited material. The upper stratum, in particular, contains heavy minerals of local provenance [3]; the abundant vitrinite almost certainly represents locally derived plant material. The clay mineralogy of the upper stratum may also be indicative of mixing of materials from diverse sources.

We interpret the boundary claystone in western North America as derived partly and perhaps chiefly from impact ejecta from the Chicxulub structure, Yucatan [17,9]. Following the suggestion of [3], we consider the Manson impact structure in Iowa [18] the likely source of most or all the shocked grains in the upper stratum. Shocked quartz grains and quartzose lithic fragments are coarser and one to two orders of magnitude more abundant at the sites in western North America than they are at other sites around the world, with the possible exception of sites in Haiti. This global pattern and the continental affinity of the grains led to a search for a possible source crater in North America and the identification of the Manson structure as a candidate source. $^{40}Ar/^{39}Ar$ measurements on shocked microcline from the central uplift of Manson show that the Manson structure is synchronous with the K/T boundary within the ±1 Ma precision of the age determination [19]. Not only is the Manson structure very close to the right age, but the rocks excavated at the crater appear to be a likely source for the shocked grains as well as most other grains lacking observable shock lamellae in the upper stratum.

The occurrence of two impacts separated in time by at least part of a growing season appears to be most readily explained if the Earth intercepted a compact comet stream at the end of the Cretaceous [20]. In repetitive passes through the stream, the Earth may have encountered more than two crater-forming projectiles and may have swept up substantial amounts of cometary material that did not produce craters. The peak Ir abundance, which occurs in the upper stratum, may reflect a somewhat protracted accumulation of cometary material. Iridium is relatively low in abundance in the boundary claystone, possibly as a consequence of blowoff and escape of the vaporized projectile that formed the great Chicxulub impact structure [cf. 21].

A comet stream is most likely to have been formed by breakup of a large Sun-grazing comet. Reexamination of the flux of active and extinct Earth-crossing comets suggests that collision of periodic comets accounts for about 25% of the terrestrial impact craters larger than 20 km in diameter. Periodic comets initially on orbits with inclinations near 90° become Sun grazers [22]. More than one-fifth of the Earth-crossing periodic comets probably become Sun grazers that are subject to tidal disruption.

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569-46
475222 N93-10181

GEOLOGICAL EVIDENCE FOR A 2.6-Ga STREWN FIELD OF IMPACT SPHERULES IN THE HAMERSLEY BASIN OF WESTERN AUSTRALIA.

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OB578940

Sand-sized spherules up to 1.7 mm across with spherulitic, vesicular, and other crystalline textures that consist mainly of K-feldspar help define a unique horizon in the well-preserved 2.6-Ga Wittenoom Formation in the Hamersley Basin of Western Australia [1,2]. This layer, informally known as the spherule marker bed, is nowhere thicker than about 1.3 m, yet it persists for more than 300 km across the basin, blanketing an area of at least 13,700 km². Sedimentological evidence indicates the layer is a single turbidite, and the spherules are a minor constituent that are usually concentrated along its base; locally, however, they are restricted to centimeter-thick lenses of pure spherules along a single horizon in the argillite close beneath the turbidite. The total volume of preserved spherules is estimated at 8×10^7 m³. Assuming an original specific gravity of 2.5, typical of silicate glass, the lower limit of the total original mass of spherules is about 1.7×10^{14} g.

In the northeastern part of the Hamersley Basin, similar spherules again occur at only one horizon, but here they are a minor constituent of a dolomitic debris-flow deposit 9.9 to 22.7 m thick known as the dolomixtite layer. The dolomixtite layer occurs in the Carawine Dolomite, which is stratigraphically equivalent to the Wittenoom Formation [3]. Moreover, paleocurrent data from closely associated carbonate [4,5] and volcaniclastic [6,7] turbidites indicate the spherule marker bed was deposited in deeper-water paleoenvironments than the dolomixtite layer. Therefore, the dolomixtite layer is believed to be a proximal equivalent of the spherule marker bed. In addition to spherules, the dolomixtite layer contains particles that also consist of K-feldspar, but are larger than the spherules (up to 11 mm across) and have much more internal heterogeneity. Some display internal flow banding or schlieren, while others contain typical spherules as inclusions. These larger particles are in the size range of true tektites, but ablated forms have yet to be observed.

Based on their similarity to microtektites and microkrystites in shape, size, and internal textures, and their occurrence as a very thin layer over a large area, the spherules are interpreted as droplets of silicate melt that were generated and dispersed across the Hamersley Basin by a major bolide impact. The mass of the spherules preserved in the Hamersley Basin is of the same order of magnitude as the estimated masses of microtektite glass in major Cenozoic strewn fields, despite the fact that the spherules currently cover an area that is 2 to 3 orders of magnitude smaller. The layers that host the spherules are interpreted to be the deposits of a major sediment gravity flow that exhumed and redeposited most of the spherules after shallow burial, although the flow is not believed to have been a direct result of the proposed impact. The internal textures of the spherules suggests the target rocks were mafic in composition, but the presence of trace amounts of microcline and quartz crystals in both the spherule marker bed and dolomixtite layer suggests some continental basement rocks were also present in the target area. Given this, plus the fact that the spherules and related particles are largest in the northeastern corner of the Hamersley Basin, the most likely site for the proposed impact would have been in the early Precambrian ocean close to the northeastern edge of the Pilbara Craton.

Another thin horizon in the overlying Brockman Iron Formation contains spherules that again consist largely of K-feldspar and have internal textures strikingly similar to those of the Wittenoom Formation and Carawine Dolomite. They differ in being slightly larger on average (up to 1.8 mm) and extensively replaced by iron-rich minerals (particularly stilpnomelane) as they are hosted by iron formation rather than argillite. This horizon is about 250 m higher stratigraphically and persists laterally for at least 30 km. The close resemblance of these spherules to those of the Wittenoom Formation and Carawine Dolomite suggests they also originated as impact melt droplets, even though they are admixed with volcaniclastic detritus. Using the sedimentation rate of 3-4 m/m.y. typical of the Hamersley Group [8], the stratigraphic separation between the two suggests that a second major impact occurred near the Hamersley Basin after a time interval of about 75 m.y. elapsed. This suggests the record of impacts in early Precambrian strata is richer than is generally appreciated.