STRATIGRAPHIC EVIDENCE FROM WESTERN NORTH AMERICA FOR MULTIPLE IMPACTS AT THE K/T BOUNDARY. E.M. Shoemaker, U.S. Geological Survey, Flagstaff, AZ 86001 and G.A. Izett, U.S. Geological Survey, Denver, CO 80225

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 G.A. Izett and C.L. Pillmore of the stratigraphy at numerous sites led to their recognition of two distinct strata at the boundary [1, 2, 3, 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 C.L. Pillmore [4, 5], is referred to as the *K/T boundary claystone*. Microscopic study of polished slabs of the *boundary claystone*, which consists typically of one to two 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 Izett [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, 7, 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, 12, 13, 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 Izett [3] as the K/T boundary impact layer, generally consists of a few mm 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 percent 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 Fastovsky et al. [16] and Izett [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 mm of the *boundary claystone* generally consists of irregular claystone clasts, mostly less than 1 mm across, embedded in a vitrinite-enriched matrix. Following Izett [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 (fig. 1). 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 air

fall 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 Izett [7], we consider the Manson impact structure in Iowa [18] the likely source of most or all of 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]. Such a stream could have been formed by breakup of a large sun-grazing comet. 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. Ir 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].

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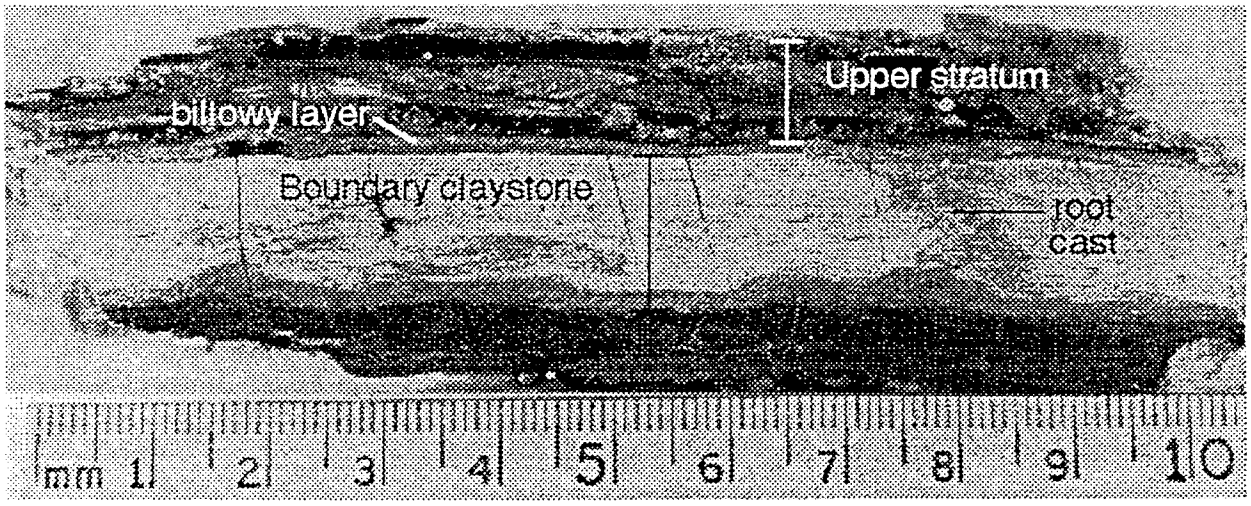

Figure 1. Photograph of a polished slab of the K/T boundary strata from the Clear Creek North site near Trinidad, Colorado. The *upper stratum*, which contains shocked grains, rests on the billowy layer. The billowy layer contains claystone clasts derived from the underlying *boundary* claystone and fills the root cast in the boundary claystone.