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IRIDIUM ANOMALY AT THE CRETACEOUS–TERTIARY BOUNDARY IN THE RATON BASIN

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Abstract—In early 1981, in collaboration with scientists of the U.S.G.S. in Denver, we located an iridium (Ir) abundance anomaly at the pollen-defined Cretaceous-Tertiary boundary in a core taken near the York Canyon Coal Mine, about 60 km west of Raton, New Mexico. The Ir concentration reached a peak of 5.6 ppb (5.6×10^{-9} g/g of rock) over a local background of about 0.010 ppb. Subsequent searching for the boundary around the eastern margin of the Raton Basin turned up numerous similar sites located on outcrops and roadcuts. A boundary exposure in a roadcut that overlooks the city of Raton will be visited during this field conference. Here the Ir concentration is lower than in the York Canyon core (~1 ppb), and the kaolinitic boundary clay and overlying Ir-rich laminar clay layer, found in well-preserved boundary sections in the Raton Basin (also Montana and Wyoming), are mostly absent or diluted with detrital clay. Apparently slowly moving streams were at work here during and soon after boundary time. In the better-preserved localities the Ir abundance reaches a peak of 25 ppb, and the total Ir deposition averages about 50 ng/cm^2, which is comparable to amounts that have been reported in marine sections all over the earth.

INTRODUCTION

This account has its origins in the now classic discovery, and hypothesis, reported by Alvarez et al. (1979, 1980). Examining rock samples taken across the Cretaceous-Tertiary (K-T) boundary at sedimentary sequences of marine origin in Italy and Denmark, they found marked enrichment of iridium (Ir) exactly at the boundary in a thin clay layer. Ir is severely depleted in the Earth's crust, especially in continental rocks, as the result of geochemical segregation processes in the early evolution of the Earth, and they hypothesized that the excess Ir and the clay layer came from fallout of ejecta from impact of a large (and undifferentiated) extraterrestrial body: an asteroid of about 10-km diameter. The hypothesis was soon supported by reports of similar enrichments at other K-T boundary exposures in Spain and Denmark (Ganapathy, 1980; Kyte et al., 1980). However, these sections also were of marine origin, and skeptics of the impact hypothesis argued that the Ir anomaly was merely the result of geochemical enrichment processes in the ocean. If the K-T Ir anomaly could be found in continental rock sequences this argument would be weakened.

We were aware of K-T-sedimentary sequences in the San Juan and Raton Basins that had been deposited under freshwater conditions, and in 1980, with the encouragement of the Alvarez team, we began a search for excess Ir in these areas. In the San Juan Basin much of the upper Maastrichtian, and probably some of the lower Paleocene rocks, have proven to be missing, the result of heavy erosion in the Paleocene. In the Raton Basin, however, quiet coal swamps and slowly meandering streams at and after K-T boundary time provided an ideal environment for the preservation of a thin fallout layer.

GEOLOGIC SETTING

In the Raton Basin the conspicuous, cliff-forming Trinidad Sandstone was deposited along an eastward advancing strandline during the final regression of the Cretaceous epeiric sea. Overlying the Trinidad are the coal-bearing, back-beach swamps and deltas of the Vermejo Formation, which in turn is disconformably overlain by the basal coarse-grained sandstone (sometimes conglomeratic, especially toward the west) of the Raton Formation. Over this basal sandstone unit the formation is composed of a zone of fine-to-coarse grained sandstones alternating with beds of mudstones, siltstones and thin to mineable coal. It is in this zone that the K-T boundary occurs. Above this zone a thick sandstone unit was deposited throughout the basin, perhaps as a result of uplift to the west. The stratigraphy of the Raton Basin is described in detail by Pillmore et al. (1984).

THE YORK CANYON CORE

In the selection of a suitable sampling site in which to initiate our search for the Ir anomaly, we were fortunate to have the guidance and collaboration of Charles L. Pillmore (Raton Basin stratigraphy) and Robert H. Tschudy (palynology) of the U.S.G.S. in Denver, both of them recognized authorities in the area of interest. From early correspondence with them we learned that Tschudy, in studying palynomorphs in a core collected in 1966 by Kaiser Steel Corporation from a coal exploration test hole in York Canyon, had established the palynological K-T boundary within a 3-m interval between two coal beds (Pillmore, 1969; Tschudy, 1973). Unfortunately, the original cores were not saved, so with the permission of Kaiser Steel Corporation we cored at a new location 150 m south of their original site during the week after Christmas 1980 (Fig. 1).

The effort was a success, and we soon located a strong Ir anomaly (Fig. 2) at what proved to be the precise stratigraphic position of a floral crisis on the basis of Tschudy's fossil-pollen studies. Abundances of Ir, Pt and Au were measured by radiochemical separation and analysis of samples that had been irradiated with high fluences of neutrons, a technique capable of identifying Ir at levels down to 0.0005 ppb (Orth et al., 1981; Gilmore et al., 1984). In addition, abundances of 40 other common and trace elements were determined by instrumental neutron activation analysis provided by the Los Alamos Research Reactor Group with an automated system (Minor et al., 1981; Garcia et al., 1982).

FURTHER SEARCH IN THE RATON BASIN

Success in locating the Ir anomaly in the York Canyon core led us to search in outcrops and roadcut exposures along the eastern margin of the basin. The second find was made on Goat Hill (Orth et al., 1982), overlooking the city of Raton (Fig. 3, RAT site). Here the anomaly is weaker (Ir ~1 ppb) than in the York Canyon core, and the thin kaolinitic clay at the boundary is either missing or diluted with detrital clay in moving laterally along the boundary (Figs. 4 and 5). Evidently, slowly moving streams were at work here during and soon after boundary time. The site will be visited during this field conference. Further work in collaboration with Pillmore and Tschudy in the following year or so turned up several well-preserved boundary sites in the basin, a few exposed in roadcuts with easy access along the east leg of Interstate Highway I-25 (Fig. 3). Geochemical results of this work are reported by Gilmore et al. (1984), and the pollen studies are discussed by Tschudy et al. (1984) and by Tschudy and Tschudy (1986). A photograph of the boundary zone exposed in Berwind Canyon, Colorado is shown in Figure 6.

For a comparison of boundary sections in the Raton Basin and in Montana we joined a group invited by vertebrate paleontologist William Clemens of the University of California at Berkeley to examine boundary localities near Jordan, Montana in June 1983. As in the Raton Basin, an Ir-rich kaolinitic clay bed occurs at the palynological K-T boundary, although its thickness is roughly half what it is 800 km to the south, and the peak Ir concentration is similarly lower.

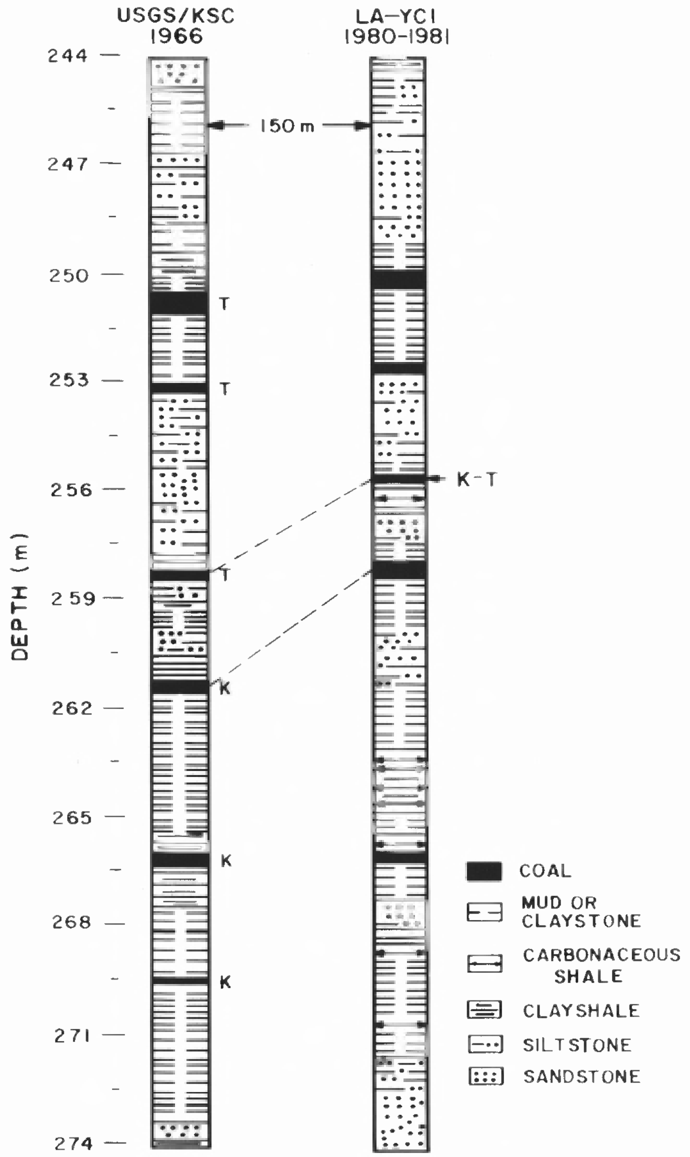

FIGURE 1. Core-log diagrams of the 1966 Kaiser Steel Corporation test hole and of our 1980 test hole 150 m away. T and K beside the coal beds in the 1966 core indicate Tertiary and Cretaceous pollen assemblages observed by Tschudy (1973). The coal bed that lies on the K-T boundary is indicated by an arrow.

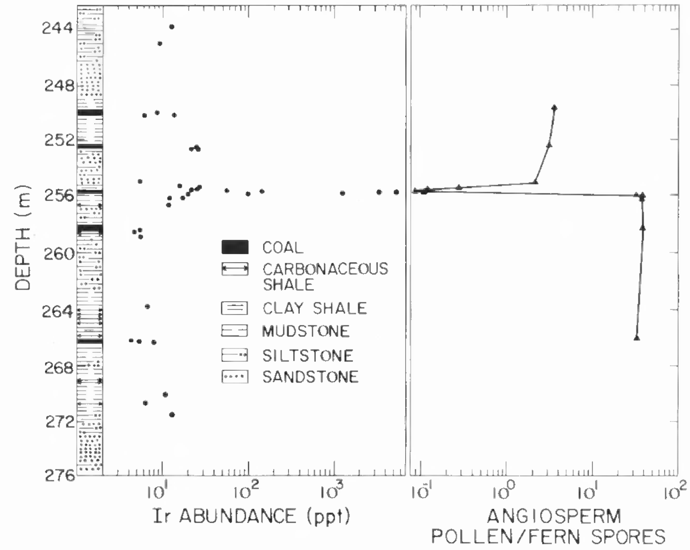

FIGURE 2. Ir abundances (solid circles) and ratio of angiosperm pollen to fern spores (triangles) as a function of core depth and lithology (Orth et al., 1981). The plotted Ir abundances are given in parts per trillion (ppt). The net Ir deposition above local background is ~40 ng/cm^2.

Details of the boundary zone

A close-up view of the K-T boundary exposed in Berwind Canyon (BCN in Fig. 3), which is representative of all well-preserved boundary sections in the basin, is shown in Figure 7. The photograph shows the distinctive gray-weathering kaolinitic clay resting on carbonaceous shale. Overlying the clay bed is a thin (5 mm) fissile clay layer that contains the peak Ir concentration. In all sections, but one, that we have studied in the basin and Montana the fissile layer is overlain by coal, possibly indicating wetter conditions after the boundary event.

Bohor et al. (1984) studied the mineralogy of the boundary clay and fissile layer in a section at Brownie Butte, Montana and discovered the presence of shocked quartz grains in the fissile layer. These shock-metamorphosed quartz grains show planar features, which upon etching with hydrofluoric acid display intersecting planes. These grains show the same features as those observed in shocked quartz from meteorite impact craters and nuclear explosions. Identical features have not been observed in quartz from volcanic eruptions. Recent mineralogic studies on the Raton Basin kaolinitic clay and fissile layer by Izett and Pillmore (1985) yielded essentially the same results as reported by Bohor et al., i.e., shocked quartz grains are concentrated in the fissile layer and only a few are in the kaolinitic clay bed.

Abundance patterns for the heavy siderophiles, Os, Ir, Pt and Au are shown in Figure 8. In moving up-section the abundances show a sharp increase beginning at the kaolinitic clay, reach their peak in the fissile layer, and then more gradually drop off, tailing for up to two m before reaching pre-boundary background levels. This tailing probably resulted from run-off of fallout deposited on higher ground. An exception to this pattern occurs at the Sugarite section (SUG) east of Raton. Here the Ir-rich dust fell into an existing coal swamp, and the boundary clay now rests on 1.8 m of coal and is overlain by 18 cm of post-boundary coal. The Ir abundance distribution is symmetrical above and below the clay layer, indicating again that the Ir came with the fallout dust, but that it also tends to mobilize toward the organic phase. This is reasonable considering the acid conditions of peat bogs and the availability of organic ligands which might form organo-metallic complexes with the Pt-group elements.

The enigma of the kaolinitic clay at the boundary

The kaolinitic clay bed is something of a puzzle. It is texturally different (Bohor et al., 1984) and chemically different (Table 1) from all other tonsteins derived from volcanic ash that have been examined in the Raton Basin and in Montana. We interpret the higher concentrations of Sc, Ti, V and Cr in the boundary clay to indicate it was derived, at least partially, from basalts or other mafic rocks, possibly from the impact site. The Ti abundance, although only a factor of three higher than in tonsteins from volcanic ash, is significant, and we have used this element as an easily measurable signature of the K-T boundary in the Western Interior of North America. However, this is not the case for the marine sections in New Zealand, Denmark, Spain, Italy and the Caspian Sea that we have studied in detail. In these sections we do not observe excess Ti in the thin boundary clay that probably corresponds to the laminar layer in the Western Interior. Furthermore, the laminar clay layer contains shocked quartz grains, but the kaolinitic clay contains few, if any (Bohor et al., 1985); the marine sections in Denmark, Italy and New Zealand also contain shocked quartz in the thin smectite boundary clay (Bohor et al., 1985).

The kaolinitic clay layer in the Western Interior, therefore, appears to be an extra feature not observed elsewhere on Earth's surface. Perhaps this portion of the North American continent was closer to the impact site, and the kaolinitic clay resulted from low-angle ejecta that fell

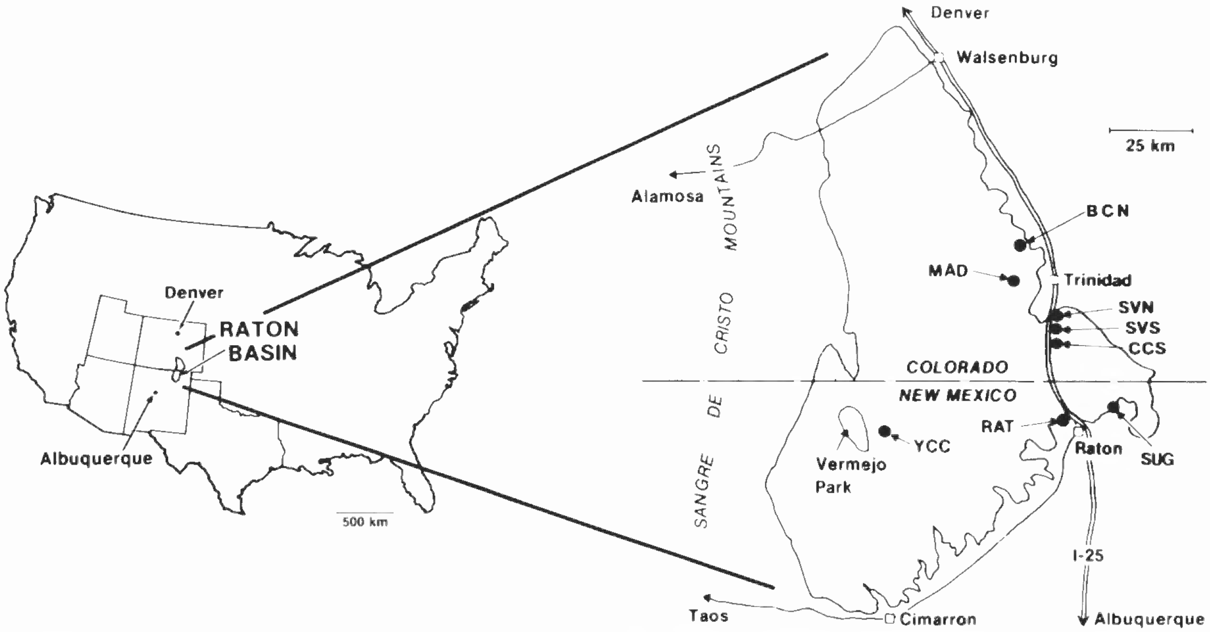

FIGURE 3. Sampling sites in the present-day Raton Basin. YCC = York Canyon core, RAT = Raton City site, SUG = Sugarite site, CCS = Clear Creek South site, SVS = Starkville South site, SVN = Starkville North site, MAD = Madrid site and BCN = Berwind Canyon site.

FIGURE 4. Cretaceous-Tertiary boundary exposed in roadcut site that overlooks city of Raton. The hand spade is in the poorly-preserved boundary clay.

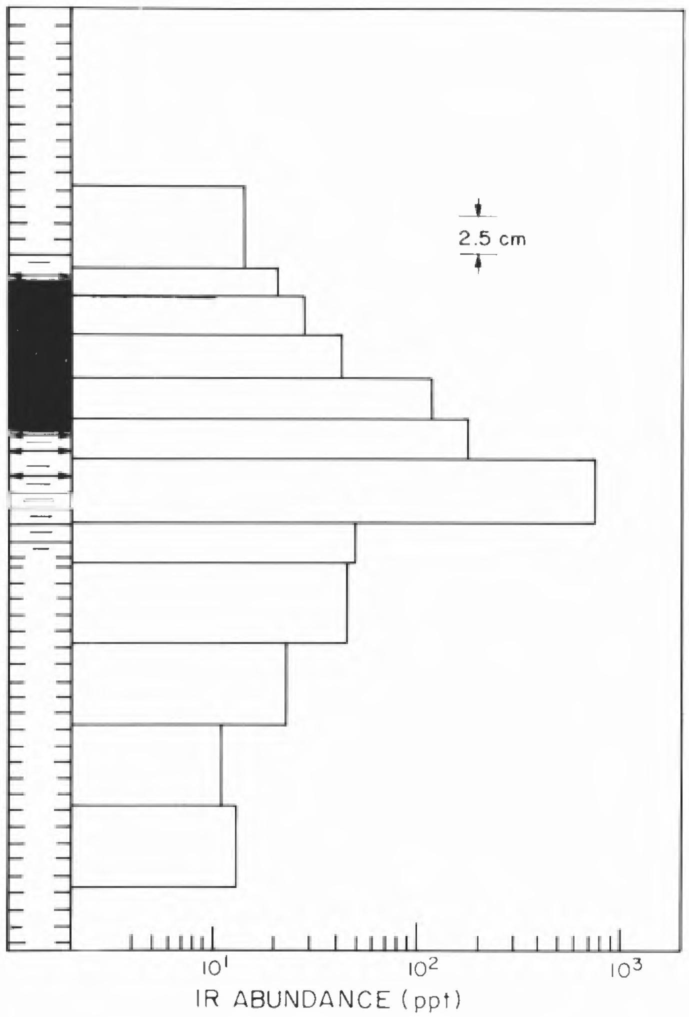

FIGURE 5. Ir abundances across the K-T boundary at a roadcut site overlooking the city of Raton. This section, shown in Figure 4, is located close to a steel pipe set in concrete. Ir concentrations given in parts per trillion (ppt). The net Ir deposition above local background is about 8 ng/cm^2.

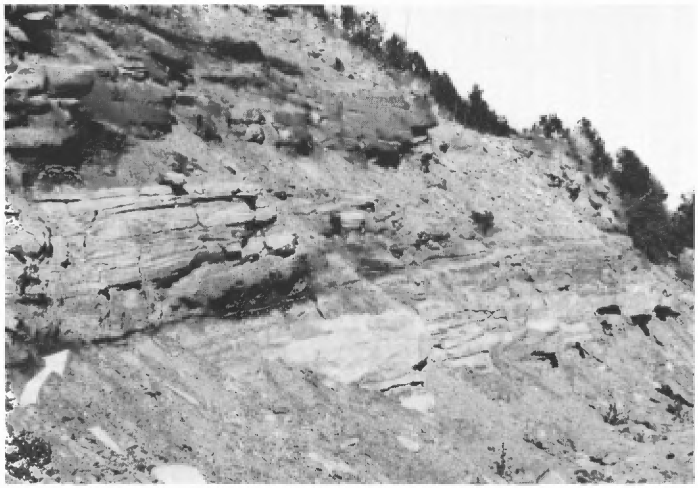

FIGURE 6. Cretaceous-Tertiary boundary zone at roadcut in Berwind Canyon, Colorado (BCN site). The arrow points to the conspicuous kaolinitic boundary clay.

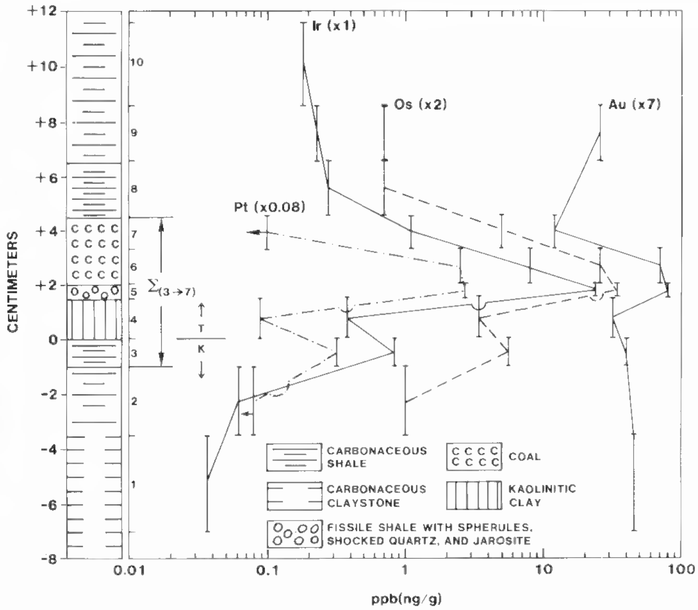

FIGURE 8. Abundance patterns for Os, Ir, Pt and Au across the K-T boundary exposed in Berwind Canyon. Atom ratios of these elements to each other, derived from summations of samples 3 through 7, are similar to chondritic ratios.

rapidly. In this scenario, the overlying Ir-rich fissile layer with shocked-quartz would have resulted from material ejected into the stratosphere which fell back considerably later. The existence of large shocked-quartz grains (up to 0.5 mm), however, does not support this scenario; such large grains should fall back rapidly. On the other hand, the possibility that this clay resulted from alteration of tephra from an earlier, independent pre-K-T boundary eruption of a unique mafic volcano appears to be highly improbable. Further work is required to resolve this question.

SUMMARY OF K-T BOUNDARY OBSERVATIONS

1. In the Western Interior the K-T boundary is defined palynologically by the disappearance of Cretaceous palynomorphs, principally *Proteacidites* in the Raton Basin, and *Aquilapollenites* in Montana, which was in a different floral province. A strong Pt-group metals anomaly and shocked-quartz grains in altered fallout dust occur with the pollen break; spores suddenly dominate over angiosperm pollen at the boundary clay. The K-T boundary occurs in a zone of reserved paleomagnetic polarity: chron 29r.

2. At the Ir-anomaly-spike, atom ratios of the Pt-group elements to one another are close to chondritic ratios. This is not the case for other weaker Ir anomalies we have observed in the geologic record, anomalies that were probably caused by terrestrial enrichment processes.

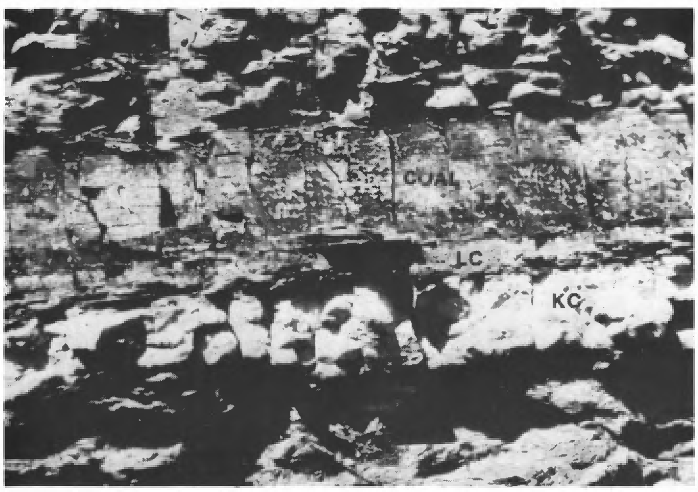

FIGURE 7. Close-up of K-T boundary zone at roadcut site in Berwind Canyon. The 1.5-cm thick kaolinitic clay (KC) rests on Cretaceous carbonaceous shale and is overlain by ~0.5 cm of Ir-rich laminar clay (LC). The 2.5-cm coal bed is overlain by more carbonaceous shale.

3. The kaolinitic clay bed is somewhat thicker and the Ir concentration higher in the Raton Basin than in sections we have studied in Montana, Wyoming and North Dakota; there was more fallout to the south.

4. In Montana, dinosaur bones have been observed about two m below the Ir anomaly, but no closer. Although dinosaur teeth have been reported in Paleocene channel sandstones by Sloan et al. (1986), we suspect reworking of underlying Cretaceous sediments. The key fact is that no articulated dinosaur fossils have been reported above the Ir anomaly. Unfortunately, vertebrate fossils have not been reported in the Raton Basin.

5. The kaolinitic clay at the boundary is somewhat of an enigma, because it has been observed only in the Western Interior. The overlying Ir-rich laminar clay appears to be the layer found all over the globe at the boundary. The concentrations of As, Se and Sb in the kaolinitic clay, in excess over other tonsteins in the basin, suggest that volcanic gases contributed to the boundary event, possibly from rupture and excavation of the crust by the impact.

6. The K-T Ir is dispersed relatively uniformly over the Earth (average ~50 ng/cm^2), suggesting an ultra-high-energy mechanism that lofted the impact ejecta well into the stratosphere so that it dispersed rapidly around the globe. Soot from wildfires reported by Wolbach et

TABLE 1. Elemental abundances in thin kaolinitic clay beds in the Raton Basin.[a]

Element[b]	K-T boundary bed Range	K-T boundary bed Average	Beds above/below K-T boundary Range	Beds above/below K-T boundary Average
Al_2O_3 (%)	24 - 36	32.9	23 - 36	31.7
K (%)	0.2 - 1.1	0.52	0.2 - 2.5	0.81
Sc	21 - 26	23.3	3 - 12	6.0
TiO_2 (%)	1.38 - 2.67	2.00	0.40 - 0.95	0.757
V	110 - 187	137	10 - 67	27
Cr	46 - 102	67.3	0.9 - 5.0	3.3
Co	1.2 - 53	9.8	0.7 - 4	2.7
As	1 - 95	36	0.2 - 46	4.1
Se	2 - 19	8	<0.1 - 6	4.8
Sb	0.3 - 11.5	6.3	0.1 - 0.8	0.38
La	16 - 80	43	9 - 88	28
Yb	0.7 - 2.2	1.5	0.8 - 4.1	2.1
Hf	3.3 - 6.4	4.5	3.2 - 10.6	7.6
Ir (ng/g)	0.90 - 2.7	1.7	0.005 - 0.020	0.010
Th	5 - 21	7.8	5 - 34	9.2
La/Yb	15 - 57	28.7	5 - 67	13.3
TiO_2/Al_2O_3	0.056 - 0.074	0.060	0.016 - 0.027	0.024
Cr/Al_2O_3[c]	1.64 - 2.83	2.04	0.036 - 0.147	0.103

[a]Boundary data from six sampling sites, non-boundary data from 21 sites.
[b]Concentrations in μg/g unless noted otherwise.
[c]Cr/Al_2O_3 relative (ppm/%).

al. (1986) at marine K-T localities in New Zealand and Denmark indicates widespread fires on Earth, possibly caused by both fallout and radiant heating of the surface by the hot ejecta blanket. On the basis of simple kinetic energy considerations, the impact of a 10-km diameter bolide of density 2 and velocity 25 km/sec would release over a thousand times the energy equivalent of the world's nuclear arsenals.

7. The crystal features of the shocked-quartz grains observed by Bohor et al. (1984) and by Izett and Pillmore (1985) have only been observed in nature elsewhere at meteorite impact craters. The shocked-mineral grains reported by Carter et al. (1986) in ejecta from the Toba caldera do not have the same features.

8. The occurrence of large, terrestrial impact craters (20- to 70-km diameter) indicates that the Earth has been struck numerous times in the last 200 m.y. by large meteorites, asteroids and comets, and damage to the local environment and living organisms must have been massive. Two closely spaced microtektite/microspherule horizons in the upper Eocene were discovered by Glass et al. (1979), and later a moderate Ir anomaly (about one percent of the magnitude of the K-T anomaly) was found in the lower horizon by Ganapathy (1982) and by Alvarez et al. (1982). However, it has not been established if an extinction of any consequence is associated with either of these events. The huge Popigai crater of similar age in Siberia might have been the source of one of these layers.

We have searched for Ir anomalies at all the major and most of the minor extinction boundaries defined by Sepkoski (1982) and by Raup and Sepkoski (1986) that are older than the terminal Cretaceous and, to date, have found nothing comparable with it. We did, however, observe moderate Ir anomalies at the Frasnian-Famennian boundary (Playford et al., 1984) and at the Mississippian-Pennsylvanian boundary (Orth et al., 1986), which appear to have been caused by terrestrial enrichment processes in the ocean.

Thus far the combination of the geologically abrupt extinction and the signatures of a massive impact at the K-T boundary appears to be unique in the Phanerozoic. This fact leads us to suspect that the K-T event was caused by a bolide that was larger and/or faster than previously estimated.

ACKNOWLEDGMENTS

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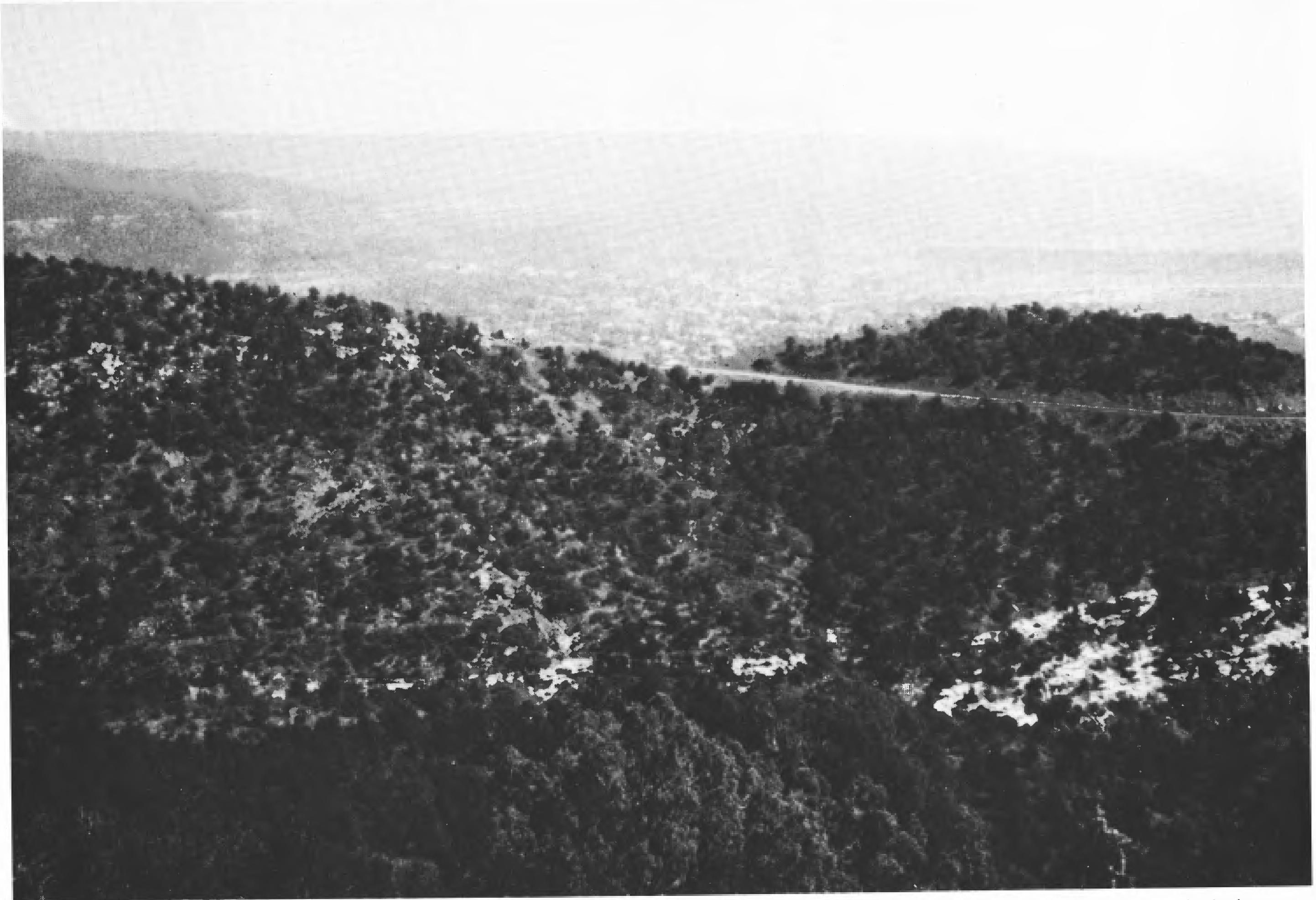

The Cretaceous-Tertiary boundary at Goat Hill near Raton, Colfax County, New Mexico. The boundary, marked here by an iridium-rich clay layer in the lower part of the Raton Formation, is located in the saddle where the road passes between two hills. The Upper Cretaceous Trinidad Sandstone is well exposed as a white layer in the foreground. Photograph courtesy of C. Orth.