Geologic Framework of Nonmarine Cretaceous-Tertiary Boundary Sites, Raton Basin, New Mexico and Colorado

Abstract. *Iridium concentrations are anomalously high at the palynological Cretaceous-Tertiary boundary in fluvial sedimentary rocks of the lower part of the Raton Formation at several localities in the Raton Basin of New Mexico and Colorado. The iridium anomaly is associated with a thin bed of kaolinitic claystone in a discontinuous carbonaceous shale and coal sequence.*

The Cretaceous-Tertiary (K/T) boundary in the Raton Basin, as defined by fossil pollen, is in the lower part of the Raton Formation, which crops out over a large area in the Raton Basin of northern New Mexico and southern Colorado. After the report by Alvarez *et al.* (*1*) of abundance anomalies of impact-derived iridium at the K/T boundary in marine rocks in Europe, we located an iridium abundance anomaly at the K/T boundary in a core from a hole drilled in fluvial rocks of the Raton Formation at York Canyon, New Mexico (*2*). We have also reported on a second location in surface rocks near Raton, New Mexico (*3*). The iridium anomaly occurs in a 1- to 3-cm-thick bed of kaolinitic claystone that is usually associated with an overlying thin coal bed. The anomaly coincides with the disappearance of fossil pollen taxa that marks the regional palynological K/T boundary and with an abrupt change in the ratio of fern spores to angiosperm pollen. We have continued field and laboratory investigations in the Raton Basin and have found more than ten additional K/T boundary sites. We discuss here the geologic and stratigraphic framework of selected sites and describe the boundary interval.

The Raton Basin is a large asymmetric structural depression of about 6400 km^2 extending from Huerfano Park, Colorado, to Cimarron, New Mexico (Fig. 1). The rocks of the lower part of the Raton Formation, which contain the K/T boundary, dip steeply and form hogback ridges along the western margin of the basin, but they dip more gently along the other margins and are highly dissected. The stratigraphic interval that contains the K/T boundary crops out along the irregular eastern rim of the Raton Basin coalfields from Walsenburg, Colorado, to Cimarron, New Mexico, a distance of about 160 km. Along the western margin of the basin, the rocks of the boundary interval are coarse-grained, and the preservation of geochemical anomalies is unlikely. Our study area is in the east-central part of the basin in the Trinidad and Raton coalfields.

Sedimentary rocks in the region, from oldest to youngest, include the Pierre Shale (Campanian to Maastrichtian), Trinidad Sandstone and Vermejo Formation (Maastrichtian), Raton Formation (Maastrichtian and Paleocene), and Poison Canyon Formation (also Maastrichtian and Paleocene), which overlies the Raton and intertongues with it from the west (*4*).

The Pierre Shale consists of dark silty shale more than 600 m thick deposited in prodeltaic and offshore environments in the Western Interior Cretaceous sea (*5*). It is separated from the overlying Trinidad Sandstone by a transition zone of interbedded shale, siltstone, and sandstone as thick as several meters. Along the margins of the coalfields it forms slopes that are mantled by soil, talus, and landslide debris.

The Trinidad Sandstone is a tabular body of rock about 25 to 30 m thick that was deposited in contemporaneous deltaic and barrier-bar environments during the eastward progradation of the Cretaceous coastline (*5*). It forms persistent, conspicuous, light-colored cliffs in the area of study and around most of the basin margins.

The Vermejo Formation consists of interbedded sandstone, siltstone, shale, and coal that together form steep, generally debris-covered slopes. The formation diminishes from about 115 m in thickness along the western border of the basin to 0 m in the eastern part. Coal beds as much as 4 m thick lie near the top and bottom of the formation (*4*). The Vermejo was deposited conformably on the Trinidad in contemporaneous fluviodelta plains and back-barriers (*5*).

The Raton Formation consists of sandstone, siltstone, mudstone, coal, and conglomerate. A basal conglomerate bed forms a persistent cliff throughout much of the basin. The Raton Formation ranges in thickness from 335 m in the eastern part of the basin to more than 600 m in the west-central part. An erosional unconformity is generally present at the base of the formation, but in the vicinity of Raton and Trinidad the conglomerate is commonly absent and the unconformity is not evident. Lee originally divided the Raton Formation into a basal conglomerate, a lower coal zone, a cliff or barren series, and an upper coal zone (*6*); Pillmore included the lower coal zone with the cliff-forming barren series in a three-part subdivision (*4*). A similar subdivision that better fits our study, especially where the basal conglomerate is lacking, includes both the basal conglomerate and the lower coal zone in a unit herein called the "lower zone." This redefined lower zone contains most of the Cretaceous part of the Raton, inasmuch as the K/T boundary is at or near the top of the zone, beneath the cliff-forming barren series.

After the deposition of fluviodelta plain and back-barrier sediments and coal of the Vermejo Formation, rapid uplift to the west caused widespread erosion and concurrent deposition of the Raton Formation basal conglomerate in braided steam channels (*7*). After deposition of the conglomerate, alluvial sandstone continued to be deposited in meandering channels; at the same time, interlayered coal, mudstone, siltstone, and sandstone beds of the slope-forming lower zone were accumulating in low-lying floodplains and backswamps, where crevasse splays periodically interrupted deposition (*7*). At the close of the Cretaceous, these depositional conditions extended over a broad alluvial plain that was an ideal environment to receive and preserve the ash or dust fallout from the K/T boundary event (*1*). The fallout material, which appears to be impact or volcanic, or both, in origin (*8*), accumulated and was preserved in ponds and coal swamps. In the acidic reducing environment of the coal swamps, the fallout material was altered to a kaolinitic clay, termed the boundary clay bed. The swamps and flood basins were for the most part well drained, and fine-grained sediments accumulated (*7*); locally, persistent thin coal beds were formed that are typical of the boundary interval in the study area. However, near Sugarite, New Mexico (Fig. 1), conditions were somewhat different, and a coal bed more than 2 m thick was deposited in a poorly drained swamp that must have been several square kilometers in extent. This coal bed is at the top of the lower zone and encloses the K/T boundary clay in its upper part.

After the K/T boundary event, uplift in the west was reinitiated and braided streams again deposited channel sandstones that form the prominent, persistent cliffs and ledges of Lee's barren series (*6*) and locally cut into the stratigraphic interval that contains the K/T boundary. Coal-forming alluvial plain conditions once more returned, and rock sequences bearing the thick coal beds of the upper coal zone were deposited. Coal beds of the Raton Formation are low in sulfur (mostly 0.4 to 0.6 percent) and bituminous A to B in rank (*4*). Details of the barren series and upper coal zone of the Raton and Poison Canyon Formation have been presented (*4, 6*).

Lee originally placed the K/T boundary at the base of the Raton Formation (*6*). Later, Brown identified Cretaceous plant fossils in the lower part of the Raton Formation, at a site about 6 km north of Trinidad, Colorado, and indicated that the boundary should be placed at least 15 m above the base of the formation (*9*). The K/T boundary was later identified (*2, 10*) 80 m above the base of the Raton Formation at York Canyon, New Mexico, on the basis of the abrupt disappearance of several taxa of fossil pollen; namely, *Proteacidites*, *Tilia wodehousei sensu* Anderson, *Trisectoris*, and *Trichopeltinites*. For discussions of the Raton Basin, these taxa are herein called the "*Proteacidites* assemblage." A similar assemblage, used to define the K/T boundary in the northern Rocky Mountain region, is also characterized by the abrupt disappearance of *Proteacidites* and of most species of *Aquilapollenites* (*11*).

A large group of pollen taxa has been described from coal beds in the Raton and Vermejo formations (*10*). Although various forms appear and disappear throughout the coal-bearing section, changes comparable to the disappearance of the *Proteacidites* assemblage have not been observed elsewhere in the section. The extinction of these taxa at the end of the Cretaceous is well documented and significant throughout the Western Interior, as well as in the southern Rocky Mountains. In the Raton Basin, the *Proteacidites* extinction horizon is coincident with the top of the boundary clay. This thin 1- to 2-cm clay bed also marks a sudden change in the relative proportion of fern spores to angiosperm pollen and contains high geochemical anomalies of iridium and several other elements (*2, 3, 12*).

The proportion of fern spores to angiosperm pollen changes at the top of the boundary clay from the 15 to 30 percent fern spores commonly observed in Raton Basin coal beds to as much as 99 percent. The proportion then returns to 15 to 30 percent fern spores within 10 to 15 cm above the boundary. This change implies a significant though geologically brief stress on the ecological system caused by the event or events responsible for deposition of the boundary clay (*13*). Cross (*13, 14*) notes a similar shift in fern spore/angiosperm pollen ratios in coal above a 50-cm-thick tonstein (altered volcanic ash parting) in the C coal bed of the Ferron Sandstone member (Turonian) of the Mancos Formation in central Utah, but we have not observed the ratio change in other nonboundary tonstein-bearing coals that we have studied in the Raton Basin.

Tonsteins (kaolinitic claystone partings) (*15*) occur in coal beds throughout the coal-bearing section in the Raton Basin, in coals of the Western Interior, and in many other parts of the world (*15, 16*). These kaolinite-rich beds weather to a distinctive light-gray "bone" color and are characterized by sharp contacts and a blocky ledge-forming appearance in outcrop. Tonsteins in Raton Basin coal beds are generally less than 5 cm thick and consist largely of coarsely crystalline authigenic vermicules of kaolinite in a fine-grained kaolinitic matrix with varying amounts of quartz and feldspar. Mineralogic and stratigraphic evidence suggests that tonsteins result from alteration of volcanic ash beds that accumu-

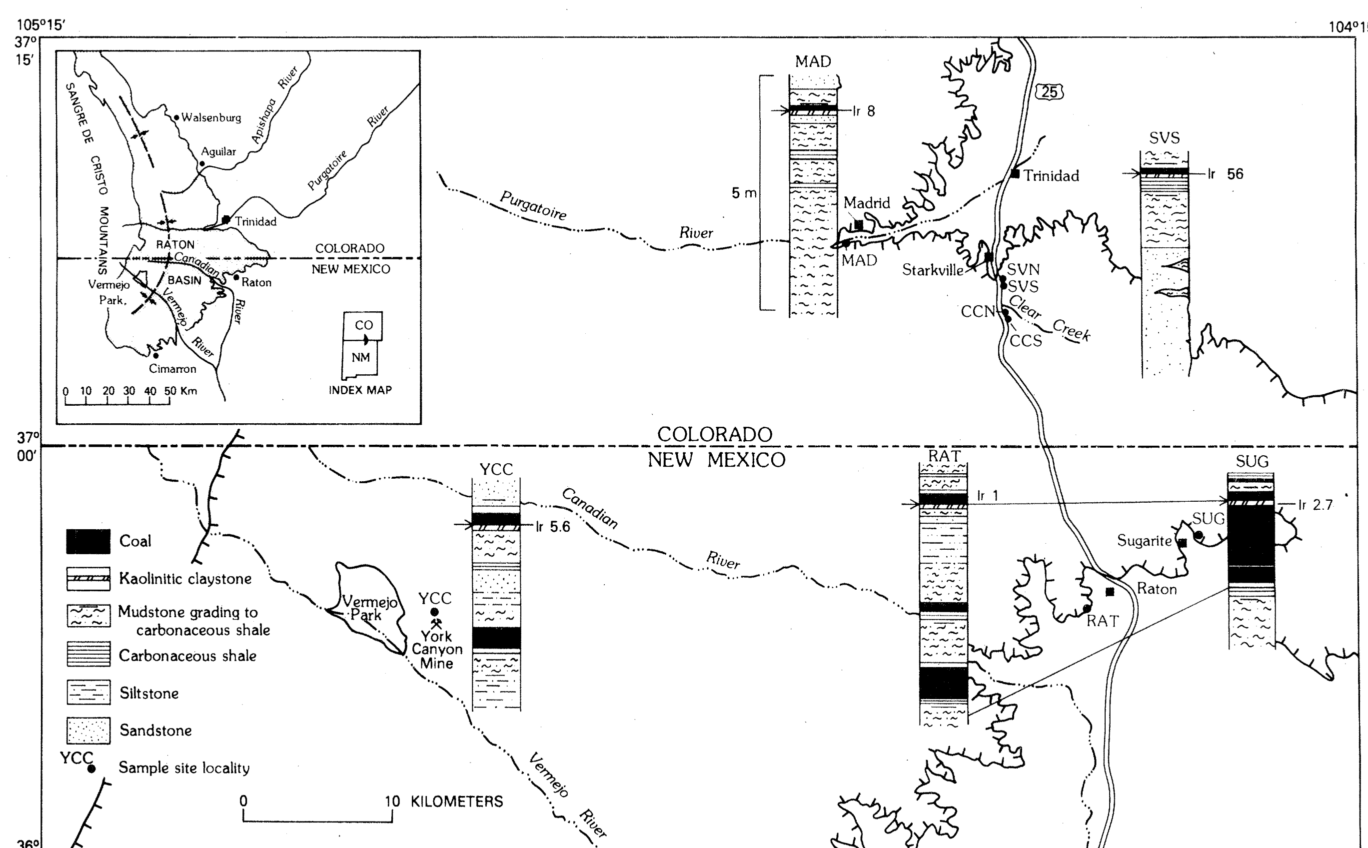

Fig. 1. Map showing selected K/T boundary sites in the east-central part of the Raton Basin. Columnar sections at or near the top of the lower zone of the Raton Formation show the lithology of the boundary interval. The sections include *YCC*, York Canyon; *RAT*, Raton; *SUG*, Sugarite; *MAD*, Madrid; *SVS*, Starkville South (section SVS represents the other sites along I-25); *SVN*, Starkville North; *CCN*, Clear Creek North; and *CCS*, Clear Creek South. Arrows indicate the K/T boundary. Measured iridium anomalies are shown in nanograms per gram. The hachured line shows approximately the top of the Trinidad Sandstone.

lated in the acidic environment of coal swamps (*15, 16*).

The boundary clay bed resembles the tonsteins mineralogically, and x-ray diffractograms show that, like many of the tonsteins, it is nearly pure, well-crystallized kaolinite with lesser amounts of randomly stratified illite-smectite clay and some quartz and feldspar. However, it is texturally unique and differs somewhat chemically. As seen in thin section, it is fine-grained to amorphous and exhibits an imbricate fabric, apparently originally of glass shards and bubbles that have altered to a fine crystallite matrix of kaolinite (*8*). The boundary clay and the tonsteins are high-alumina clays that characteristically contain about 32 percent Al_2O_3 (*12*). Iridium abundance anomalies as high as 56 ng/g have been measured in samples of the boundary clay collected from the study area, compared to background iridium concentrations of 0.004 to 0.04 ng/g observed in tonsteins and other beds of coal and shale not associated with the boundary (*12*). In addition, scandium, titanium, vanadium, chromium, and antimony in the boundary clay are enhanced by factors of 4 or more over their concentrations in all Raton Basin tonsteins that we have analyzed (*12*). The trace-element patterns of the boundary clay bed and its unique textural character suggest that it was derived from a different source than the tonstein beds (*8, 12*).

Graphic sections of five representative K/T boundary sites in the study area are shown in Fig. 1. The New Mexico sites are York Canyon, Raton, and Sugarite. Starkville South and Madrid typify the Colorado sites.

York Canyon site. The base of a thin coal above the kaolinite-rich boundary clay in core samples from a hole drilled in York Canyon, about 50 km west of Raton, has an iridium anomaly of 5.6 ng/g. The boundary is about 80 m above the top of the Vermejo Formation and 170 m above the top of the Trinidad Sandstone. The *Proteacidites* assemblage disappears at the iridium anomaly, and the ratio of fern spores to angiosperm pollen changes markedly (*2*).

Raton site. In a roadcut along the old Raton Pass scenic road in Climax Canyon Park about 1 km west of the town of Raton, an iridium anomaly of about 1 ng/g coincides with the disappearance of the *Proteacidites* assemblage. The boundary is at the top of a 2-cm bed of kaolinitic clay about 5 cm below the base of a thin coal bed. The boundary here is only about 50 m above the Trinidad Sandstone. Conglomerate is lacking at Raton, and the base of the Raton Formation is indefinite. Both the Vermejo and the Cretaceous part of the Raton Formation thin from west to east across the basin. At the Raton site, three coal beds lie in a 3.8-m-thick sequence of mudstone, siltstone, and carbonaceous shale (Fig. 1). The boundary is just beneath the base of the upper coal, 16 cm thick; a 40-cm-thick zone of coal and carbonaceous shale lies 2 m beneath the boundary, and a 70-cm-thick coal bed is at the base of the sequence. These coals and associated interbeds compose a coal zone that appears to correlate with the Sugarite coal bed (*6*) mined at Sugarite, about 8 km northeast (Fig. 1).

Sugarite site. The Sugarite coal is well exposed in a landslide scar on the east wall of the canyon about 150 m above the valley floor near the abandoned town of Sugarite. Because the lower zone has thinned, the Sugarite coal bed is only about 30 m above the top of the Trinidad Sandstone; it is 3 m below the base of the cliff-forming sandstones of the Raton barren series (*6*). At the Sugarite site the coal bed is 1.8 m thick and contains two thin partings: a carbonaceous shale 40 cm above the base of the coal, and the kaolinite-rich boundary clay, 2 to 4 cm thick, 15 cm below the top. We measured iridium concentrations of 2.7 ng/g in the boundary clay (*12*) and also observed the characteristic disappearance of the *Proteacidites* assemblage and change in the fern spore/angiosperm pollen ratios.

Other sites in New Mexico. We have searched for the K/T boundary at several surface sites west of York Canyon where the lower zone of the Raton Formation crops out around the perimeter of Vermejo Park, and we have examined many other sections that include the boundary interval along the margin of the basin near Raton and Cimarron. We have found the boundary clay at only four additional sites in the Raton coal field, all fairly near the town of Raton; however, we have located the boundary clay at several sites about 25 km north, in the vicinity of Starkville, Colorado, and in railroad cuts near Madrid, Colorado.

The Starkville and Clear Creek sites. The Starkville South section shown in Fig. 1 represents four sites along route I-25. The first Colorado location of the K/T boundary was in a carbonaceous shale bed 50 cm thick, 34 m above pavement level in a roadcut on the east side of I-25 at Starkville North (Fig. 1), 3.2 km south of the Starkville exit. At the break in the pollen record, we measured an iridium concentration of 6 ng/g in a flaky, dark carbonaceous shale 0.5 cm thick. The shale, which consists mainly of kaolinite, contains sparse pollen and yet marks the change in the fern spore/angiosperm pollen ratio from 21 percent to more than 98 percent fern spores. The ratio recovers to 22 percent fern spores within 10 cm above the shale bed (*13*). The shale overlies a distinctive, light-colored layer of kaolinitic clay 2 cm thick that forms the boundary clay, and it grades up into a thin blocky coal bed about 5 cm thick that appears to persist along the outcrop for several kilometers. The boundary interval lies about 60 m above the Trinidad Sandstone in a sequence of fine-grained deposits.

At the Starkville South site, about 1 km south, we measured the strongest iridium anomaly (56 ng/g) in our studies to date. This anomaly also occurs in a barren, thin, carbonaceous kaolinitic shaly layer at the top of the boundary clay. We recorded nearly identical changes in pollen and in the fern spore/angiosperm pollen ratio as at Starkville North; however, the associated depositional framework is somewhat different. At Starkville North, the boundary lies near the top of a sequence of mudstones 6 m thick that rests on a channel sandstone 2 m thick; at Starkville South, the mudstone sequence has thinned to 3 m, and the channel sandstone has thickened to 7 m. The channel-sandstone bed appears to persist to the south, where we have identified the boundary at the Clear Creek North and Clear Creek South sites near the Spring Creek exit from I-25 (Fig. 1). At these sites also, iridium anomalies of 25 and 27 ng/g, respectively, coincide with the pollen change and mark the reversal in fern spore/angiosperm pollen ratios.

Two kilometers farther south along the highway, the boundary interval and the channel sandstone merge into a sandstone-dominated interval, where the coal-kaolinitic clay sequence at the boundary has been channeled out. The boundary clay occasionally can be seen, however, beneath thick sandstone beds in high roadcuts farther south along the Interstate. We have not yet identified the K/T boundary interval south of the abandoned mining town of Morley, about 7 km south of Clear Creek, but the boundary interval has been found near Madrid, in the Purgatoire Valley to the west.

Madrid site. Along railroad cuts near Madrid, about 10 km west of Starkville, we measured iridium concentrations of 8 ng/g in a thin, flaky dark shale on top of the white-weathering boundary clay bed, 1 to 3 cm thick, that underlies a thin blocky coal bed. The *Proteacidites* assemblage disappears and the ratio of fern spores to angiosperm pollen changes at the top of the boundary clay in the Madrid area just as they do at the other sites we have studied. A 1- to 3-m-thick crevasse splay sandstone forms a prominent tabular ledge a few centimeters above the coal.

Other sites in Colorado. The kaolinitic clay bed at the K/T boundary has been traced along a 2-km stretch of outcrop in Purgatoire Canyon to a point about 1.2 km west of Madrid, where it disappears under valley alluvium. The boundary bed has been identified in several measured stratigraphic sections, mostly along the south side of the valley (*17*). Except for a new site recently discovered in a road cut in Road Canyon, about 20 km to the north, no other localities have been found in the Raton Basin. The boundary clay appears to represent a single layer that extends throughout a wide area in the Raton Basin; yet only a few sites have been found along hundreds of kilometers of outcrop of the lower zone of the Raton Formation in both the Colorado and New Mexico portions of the basin.

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The End of the Cretaceous: Sharp Boundary or Gradual Transition?

Abstract. *Evidence indicates that the Cretaceous-Tertiary boundary is very sharp, and, within the limits of resolution, it is apparently synchronous at the various boundary localities. Arguments to the contrary, particularly those of Officer and Drake, are shown to be invalid.*

Two papers critical of the impact theory of the Cretaceous-Tertiary (K/T) extinction (*1, 2*) have recently appeared in *Science* (*3, 4*). These two publications, when coupled with similarly oriented articles in the *American Scientist* and *Geochimica et Cosmochimica Acta* (*5*), might lead a nonspecialist reader to conclude that the impact theory was encountering serious difficulties. If these articles were left unchallenged, it would appear that the points they raise have falsified the theory, which is not the case. If we simply answered the specific points raised, it would appear that this was a case of two conflicting but strongly supported hypotheses, where experts could reasonably disagree; this also is incorrect. We think it is important, therefore, to examine these critical papers in the context of wider developments within the rapidly advancing field of research on mass extinctions. We will then proceed to a detailed commentary on the paper by Officer and Drake (*4*).

One might ask how the impact theory is holding up, and whether the initial resistance it encountered is tapering off. In the 3 years since it was formally presented (*1*), the impact explanation for the terminal-Cretaceous extinctions has survived several critical tests and attempts at falsification, and a number of its critical predictions have been confirmed (*6, 7*). With the minor modifications that have been necessary, it should be considered a viable theory.

Furthermore, many of the "flaws" that were pointed out in the early days of the theory have now been understood and are acknowledged by critics to be of no relevance. A notable example concerns our original proposal (*1*) that dust spread by the impact would cause darkness sufficient to suppress photosynthesis for several years. Our calculations were based on data from the 1883 Krakatoa eruption. Subsequently calculations showed that darkness estimates should not be based on the Krakatoa model and that dust would be spread not by atmospheric circulation, as with Krakatoa, but along ballistic trajectories outside the atmosphere (*8*). These corrections to the original theory remove several objections and explain well the plankton extinction (*9*). This aspect of the evolution of the theory has been discussed in detail (*6*).

The degree to which evidence is building up in favor of the impact theory is not apparent from the paper of Officer and Drake (*4*). They do not mention the Cretaceous-Tertiary Extinction Conference (K-TEC) in Ottawa in May 1981, at which the theory was discussed in great detail, with much new supporting evidence reported. The complete transcript of the K-TEC Conference has been published (*10*). They also fail to mention the October 1981, Snowbird Conference on "Large-body impacts and terrestrial evolution: geological, climatological, and biological implications," even though Drake attended the meeting and has even published a criticism of some of the papers presented there (*11*). A collection of 48 articles based on that conference is available (*2*), and many were summarized earlier in a volume of abstracts (*12*); not one of these contributions was cited by Officer and Drake. The interested reader can thus find an extensive literature that contradicts the impression of a theory in disarray.

Officer and Drake (*4*) have addressed the question of whether the K/T boundary is abrupt and shows evidence of having resulted from the impact of a large extraterrestrial object or whether it is a gradual transition unrelated to an impact. They favor the latter interpretation, as shown by the title of their article: "The Cretaceous-Tertiary transition." A