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Lithostratigraphic and mineralogic correlations of near K/T boundary clastic sediments in northeastern Mexico: Implications for origin and nature of deposition

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ABSTRACT

We interpret the near K/T boundary clastic deposits of northeastern Mexico as deposited over an extended time period, during the last 170 to 200 k.y. of the Maastrichtian and by normal sedimentary processes that include gravity flows and turbidity currents, rather than impact-generated tsunami waves. This deposition scenario is indicated by multiple horizons of bioturbation within the top unit 3 and near the base of the middle unit 2; the presence of thin layers enriched in fine clay-minerals and planktic foraminifera, suggesting hemipelagic sedimentation within unit 3; the presence of a marl layer of Maastrichtian age above the clastic deposit; the occurrence of distinct layers enriched in zeolites in unit 3; and the presence of lithologically, sedimentologically, and mineralogically distinct units and subunits that are correlatable over more than 300 km. Such correlations do not support a chaotic deposition as predicted for an impact-generated tsunami event. We interpret the clastic beds of northeastern Mexico as having accumulated during the major eustatic sea-level lowstand near the end of the Maastrichtian. In this scenario, the unconformity at the base of the clastic deposit represents a type 1 sequence boundary, where deltaic sediments were eroded and transported into deeper waters, depositing the spherule-rich layer of unit 1. Continued sea-level lowering resulted in erosion and bypass of shelf sediments and the deposition of the sandstone of unit 2. Subsequently, stabilization of the sea-level lowstand resulted in episodes of decreased erosion and sediment transport alternating with normal hemipelagic sedimentation, thus depositing the sand and the silt and shale layers of unit 3. The sea-level rise during the last 50 to 100 k.y. of the Maastrichtian resulted in the normal hemipelagic sedimentation observed in the pre–K/T boundary marl layer above the clastic deposit.

INTRODUCTION

The controversy over the nature of the Cretaceous-Tertiary transition and the causes of the associated mass extinction was altered fundamentally in 1980 with the discovery of the now-famous iridium anomaly at the K/T boundary at Gubbio, Italy (Alvarez et al., 1980). The discovery of similar anomalies elsewhere and the proposition that these anomalies and the K/T extinctions resulted from the impact of a large extraterrestrial bolide have spurred over a decade of unparalleled research on

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the physical and biological events at and near the K/T boundary. Within a short time, the controversy resolved itself into two contrasting schools of thought: (1) the K/T event reflects the catastrophic effects of a large (10 km) bolide colliding with the Earth, and (2) the K/T mass extinction was the culmination of long-term changes in the Earth's biota reflecting major changes in the global climate, sea-level fluctuations, and massive volcanism, which may have been accelerated by a bolide impact at the K/T boundary.

With the discovery of the buried Chicxulub structure on the north coast of Yucatan, Mexico, as a possible site for the putative K/T impact, outcrops of uppermost Cretaceous and lowermost Tertiary strata around the Gulf of Mexico assumed major importance as possible sources of direct evidence regarding the nature of the K/T boundary event. Among the first such sites investigated, well before the discovery of the Chicxulub structure, were the K/T sections along the Brazos River in southern Texas, which include a coarse-grained clastic unit at or near the K/T boundary. This unit has been variously interpreted as reflecting a high-energy impact-generated tsunami (Bourgeois et al., 1988), or a sea-level lowstand deposit unrelated to an impact (Jiang and Gartner, 1986; Donovan et al., 1988; Keller, 1989). Subsequent investigations of K/T sections at Beloc, Haiti, revealed the presence of glassy spherules with compositions suggesting the melting of carbonate rocks, consistent with the presence of thick Cretaceous carbonates at the Chicxulub site. Other sections in southern Mexico and Guatemala have been interpreted to show both conformable and unconformable relationships across the K/T boundary (Keller et al., 1994a; Keller and Stinnesbeck, 1995; Stinnesbeck et al., 1994a; Montanari et al., 1994).

Recently, over a dozen outcrops have been found in northeastern Mexico spanning a distance of more than 300 km. These outcrops are structurally uncomplicated and represent conformable sequences across the Cretaceous-Tertiary transition. To date, only preliminary descriptions and interpretations of these outcrops have been published (Longoria and Gamper, 1992; Longoria and Grajales, 1994; Smit et al., 1992, 1994; Stinnesbeck et al., 1993, 1994a; Bohor and Betterton, 1993; Keller et al., 1994a, b), and many aspects of the basic geology of the outcrops remain either unresolved or controversial. An important component of these sections is a thick (up to 12 m), sedimentologically complicated, coarse-grained clastic member that is stratigraphically positioned near the K/T boundary. This clastic member has been variously interpreted as an impact-generated tsunami deposit (Smit et al., 1992, 1994), a single turbidite deposit (Bohor and Betterton, 1993), or a series of gravity flows induced by a sea-level lowstand (Stinnesbeck et al., 1993, 1994b, 1996; Keller et al., 1994a). Here, we report on the lithology and mineralogy of this clastic member in order to derive clues as to the origin, nature, and tempo of deposition. Figure 1 shows the location of sections examined. Geographic distribution of these localities indicates a north-northwest –south-southeast–trending area that is parallel to and 40 to 80 km east of the front range of today's Sierra Madre Oriental. The southernmost section is El Mimbral, located about 80 km southeast of Ciudad Victoria, the capital of the state of Tamaulipas, Mexico. The northernmost section is Los Ramones, 40 km east of Monterrey, the capital of the state of Nuevo Leon, Mexico.

METHODS

Whole-rock and insoluble-residue analyses have been carried out for all the samples by XRD 2000 diffractometer at the Geological Institute of the University of Neuchâtel. The samples were prepared following the procedure of Kübler (1987). Two sample preparation methods have been applied. Random powder of the bulk sample is used for characterization of the whole rock mineralogy. Nearly 20 g of each rock sample was ground with a "jaw" crusher to obtain small chips (1 to 5 mm) of rock. Approximately 5 g were dried at a temperature of 110 °C and then ground again to a homogenous powder with particle sizes <40 µm. Eight hundred mg of this powder were pressed (20 bars) in a powder holder covered with a blotting paper and finally analyzed by X-ray diffractometer (XRD). Whole rock compositions were determined by X-ray diffractometer (SCINTAG XRD 2000 Diffractometer) based on methods by Ferrero (1966) and Kübler (1983). The method for the semiquantitative analysis of the bulk rock mineralogy (obtained by XRD patterns of random powder samples) used external standards (Table 1).

Clay-mineral analyses were based on methods by Kübler (1987). Ground chips were mixed with deionized water (pH 7 to 8) and agitated. The carbonate fraction was removed with the addition of HCl 10% (1.25 N) at room temperature for 20 minutes or more until all the carbonate was dissolved. Ultrasonic disaggregation was accomplished during 3-minute intervals. The insoluble residue was washed and centrifuged (5 to 6 times) until a neutral suspension was obtained (pH 7 to 8). Separation of different grain size fractions (<2 µm and 2 to 16 µm) was obtained by the timed settling method based on Stokes law. The selected fraction was then pipetted onto a glass plate and air-dried at room temperature. XRD analysis of oriented clay samples was made after air drying at room temperature and ethylene-glycol–solvated conditions. The intensities of selected XRD peaks characterizing each clay mineral present in the size fraction (e.g., chlorite, mica, and mixed layers) were measured for a semiquantitative estimate of the proportion of clay minerals present in the size fractions <2 µm and 2 to 16 µm. Therefore, clay minerals are given in relative percent abundance without correction factors (Table 2); content in swelling (% smectite) is estimated by using the method of Moore and Reynolds (1989).

LITHOLOGY AND MINERALOGY

In northeastern Mexico, near–K/T boundary clastic deposits are discontinuously present within a thick sequence of fine-grained, marly sedimentary rocks of the Mendez (Upper Cretaceous) and Velasco (Paleocene) Formations. This clastic

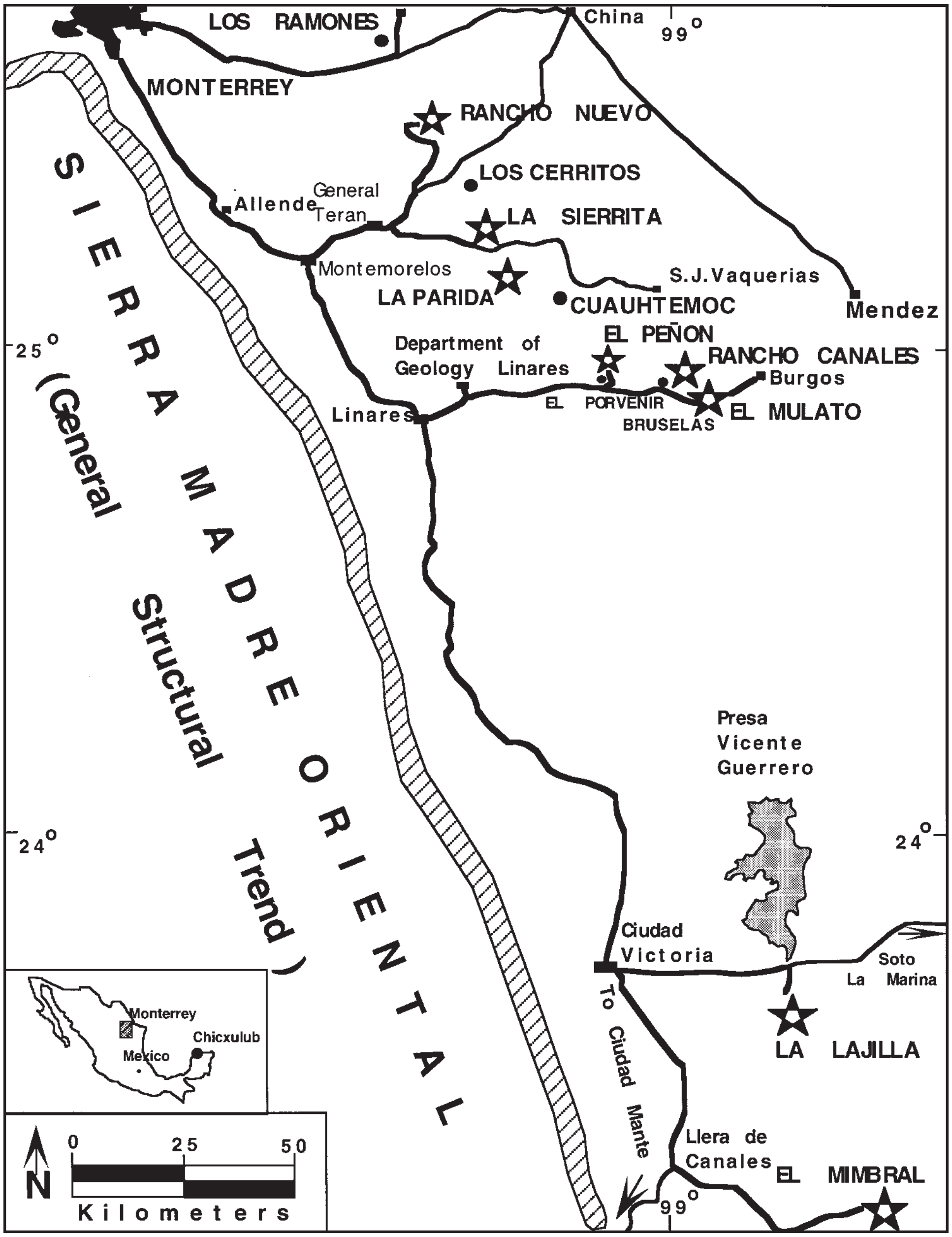


Figure 1. Location map of Cretaceous/Tertiary boundary outcrops with near–K/T boundary clastic deposits in northeastern Mexico.

member can be subdivided into three distinct units based on their lithology, sedimentology, and mineralogy: a basal spherule-rich unit 1, a middle unit 2 of horizontally laminated sandstone, and an upper unit 3 consisting of intercalated sand and silt and shales layers (Fig. 2). The thickness of each of the three units and subunits varies considerably, and the entire clastic member even disappears in some sections (e.g., La Parida). Various deposits range from 0 to 1 m for the spherule-rich unit 1, which therefore does not blanket the region; 0 to 4 m for the laminated sandstone of unit 2; and 0 to 3 m for the interlayered sand, shale, and siltstone beds of unit 3.

The three units of the clastic member are lithologically and mineralogically correlatable more than 300 km (Figs. 1, 2). In all outcrops, the clastic deposit disconformably overlies the gray marls of the Maastrichian Mendez Formation. Mineralogical analyses indicate a marly lithology for the Mendez Formation, with an average composition of 48% calcite, 30% phyllosilicates, 15% quartz and 8% plagioclase. Clay-mineral contents, such as mica (illite), chlorite, and chlorite-smectite and illite-smectite mixed-layers, are variable. This is especially the case with chlorite, which varies in the Mendez Formation from 60% (<2 µm size fraction) in the Lajilla I and Mulato sections to less

TABLE 1. AVERAGE WHOLE ROCK COMPOSITION FOR THE MARLS OF THE MENDEZ FORMATION, THREE UNITS AND SUBUNITS OF THE CLASTIC DEPOSIT, THE THIN LATEST MAASTRICHTIAN MARL LAYER ABOVE THE CLASTIC DEPOSIT AND THE EARLY TERTIARY SHALES OF THE VELASCO FORMATION

UNIT	Calcite (%)	Quartz (%)	Phyllosilicates (%)	Plagioclase (%)
Velasco Formation	35	21	36	8
Maastrichtian Thin Marl Layer	53	9	32	6
UNIT 3 : R.S.L.	36	27	22	15
UNIT 3 : Silt-Shale layers	31	22	36	11
UNIT 3 : Sandstone layers	39	28	16	17
UNIT 2 : Laminated Sandstone	34	31	19	16
UNIT 1 : Spherules rich layers	64	10	20	6
UNIT 1 : S.S.L.	43	24	23	10
UNIT 1 : Marl Layers	38	13	41	8
Mendez Formation	48	15	30	7

TABLE 2. AVERAGE PERCENT CLAY MINERAL COMPOSITION (EL PEñON, EL MULATO, AND LA LAJILLA SECTIONS, <2μ SIZE-FRACTION) FOR MARLS OF THE MENDEZ FORMATION, THREE UNITS AND SUBUNITS OF THE CLASTIC DEPOSIT, THE LATEST MAASTRICHTIAN MARL LAYER ABOVE THE CLASTIC DEPOSIT AND THE EARLY TERTIARY SHALES OF THE VELASCO FORMATION

UNIT	Zeolite (%)	Chlorite (%)	Mica (%)	Illite-Smectite (%)	Chlorite-smectite (%)
Velasco Formation	0.5	47	35	11	7
Maastrichtian Thin Marl Layer	2	32	46	15	5
UNIT 3 : R.S.L.	3	39	35	16	7
UNIT 3 : Silt-Shale layers	0	30	18	41	11
UNIT 3 : Sandstone layers	2	41	42	12	3
UNIT 2 : Massive Sandstone	0	37	43	17	0
UNIT 1 : Spherules rich layers	0	40	19	22	18
UNIT 1 : S.S.L.	0	39	37	15	9
UNIT 1 : Marl Layers	0	19	18	54	9
Mendez Formation	0	40	35	25	1

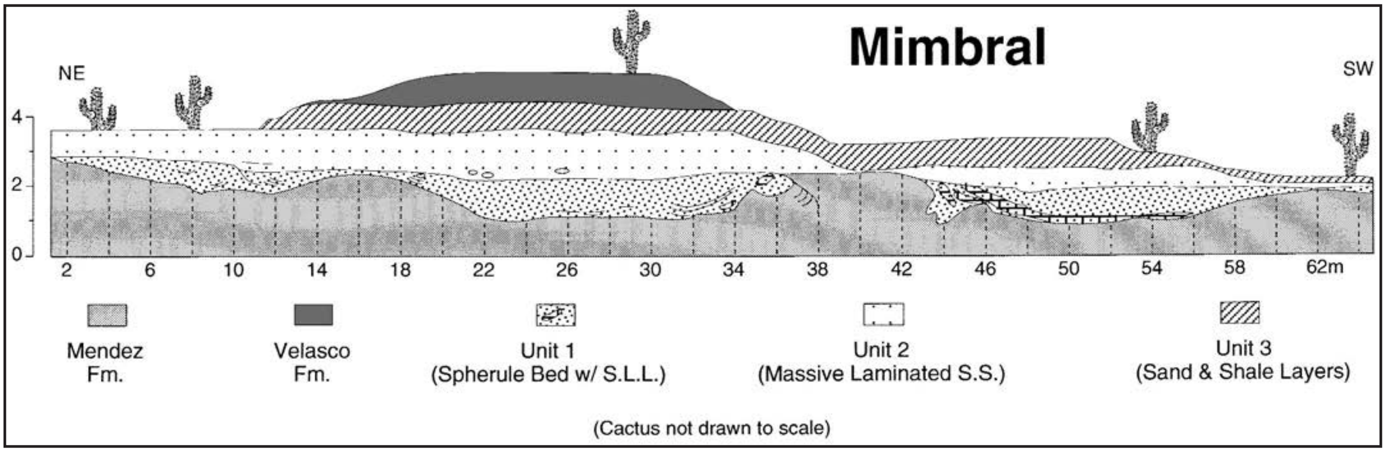


Figure 2. Sketch of El Mimbral K/T boundary outcrop showing units 1, 2, and 3. Note that units thin out laterally toward the edges of the outcrop. S.L.L. = sandy limestone layer.

than 20% in the La Sierrita and Peñon sections (Figs. 3, 4). These mineralogically different sediment layers below the unconformity suggest erosion to variable depths within the Mendez marls.

Unit 1: Spherule-rich layer

Unit 1 disconformably overlies an irregular erosional surface of the Mendez Formation and consists of repeated intercalations of soft-weathered spherule-rich layers and Mendez marls. Unit 1 has been observed at El Mimbral, La Lajilla, El Mulato, Rancho Canales, El Peñon, and La Sierrita (Figs. 1, 5) and ranges in thickness from 0 to 100 cm. It is either massive or crudely stratified with marl intercalations and locally shows large-scale trough cross-stratification. In addition to abundant spherules, unit 1 contains common foraminiferal tests including transported shallow-water benthic foraminifera (Stinnesbeck et al., 1993, 1996; Keller et al., 1994b), clasts of marl from the underlying Mendez Formation, clasts containing Turonian age foraminifera, minor quartz, and rare glass shards. The spherules range from 1 to 5 mm in diameter. Many spherules are filled with blocky calcite; some contain foraminiferal tests, limestone clasts, and rutile crystals (Stinnesbeck et al., 1993, 1994a; Keller et al., 1994a). Large spherules are often composites containing smaller spherules, as described from volcanic deposits. Many spherules with blocky calcite infillings are enclosed in an organic shell characterized by a significant content of organic carbon (0.3 to 0.5%), suggesting a biogenic origin as either algal resting cysts (Hansen et al., 1986) or oncolites. Spherules thus appear to be of multiple origins (e.g., oncolites, algal resting cysts, and volcanic) and transported from shallow carbonate shelf depositional settings (Stinnesbeck et al., 1993; Keller et al., 1994a). Other workers have interpreted the spherules as originally hollow, glassy impact-produced microtektites that have been subsequently infilled and replaced by calcite or phyllosilicate minerals (Smit et al., 1992; Bohor and Betterton, 1993). Rare glass fragments and very rare shocked quartz grains are present in this unit.

A 10- to 20-cm-thick layer of a well-cemented packstone with fine-scale laminations, termed sandy limestone layer (S.L.L.) (Stinnesbeck et al., 1993; Keller et al., 1994a) occurs within or at the top of unit 1 at Mimbral, Mulato, Peñon, Rancho Canales, and Lajilla. This S.L.L. shows only few graded spherules at the top and base in contact with the spherule-rich sediments. The top of this S.L.L. is sometimes convolute, with the overlying sediments draped across the convolute bedding surface. At Lajilla and Peñon II, the convolute bedding surface marks an erosional disconformity and the upper part of the spherule-rich layer is missing (Figs. 4, 5).

Whole-rock and clay-mineral compositions of the densely cemented spherule-rich layer of unit 1 are very similar in all outcrops and show two trends. The spherule-rich intercalations are primarily composed of calcite (64%), quartz (10%), phyllosilicates (20%), and plagioclase (6%). In contrast, marl intercalations are composed of abundant phyllosilicates (>40%) and less calcite (38%, Table 1, Fig. 6). These proportions are similar to those determined in the underlying Mendez Formation. The difference in whole rock and clay-mineral compositions suggests variable amounts of detrital influx between deposition of the sandy limestone layer and the spherule-rich layers above and below.

Unit 2: Laminated sandstone

Unit 2 consists of a horizontally laminated sandstone with mud clasts of Maastrichtian and Turonian age marls at its base, reflecting an erosional disconformity. Wood fragments and leaves are present in distinct layers near the base of unit 2 without significant coal content. Sparse coal fragments associated with dispersed organic matter are present throughout unit 2 in all sections. Sand beds grade upward to slightly finer sands containing mica and a clay-rich matrix. Both lower and upper

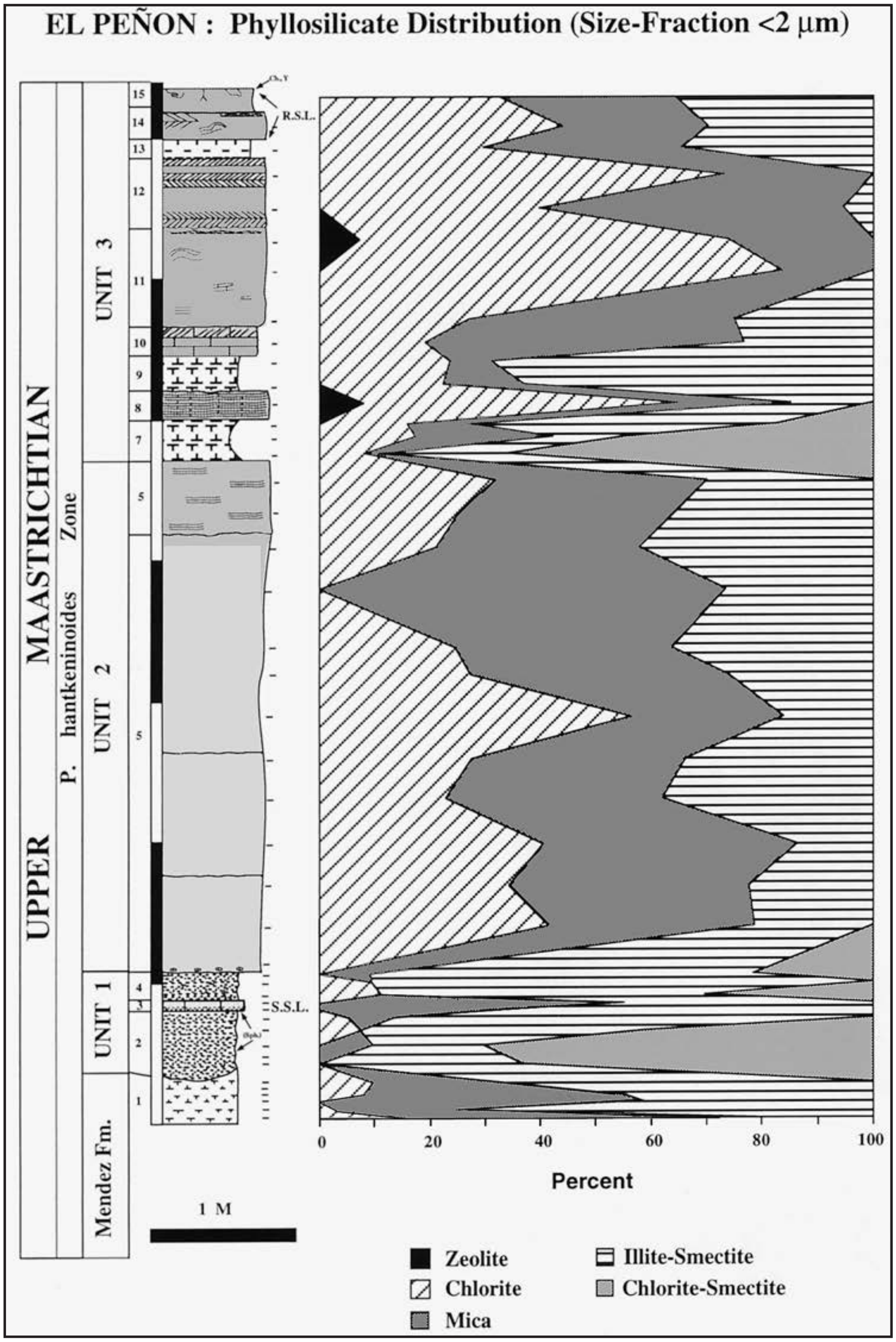


Figure 3. El Peñon I, phyllosilicate distribution from the Mendez Formation through the clastic deposit (<2 µm size fraction). Note the two layers enriched in zeolites in unit 3 and mixed layers enriched in illite-smectite and chlorite-smectite in unit 1 and in the shale layers of unit 3. S.L.L. = sandy limestone layer; R.S.L. = rippled sandy limestone.

contacts of unit 2 are disconformable. The sandstone is of variable thickness, ranging from 0 to 4 m. This unit is not present at La Sierrita II, La Parida, El Peñon II, La Lajilla, and El Mimbral II (Fig. 2). Recently, Ekdale and Stinnesbeck (1994) observed bioturbation near the base of unit 2 at El Peñon, with burrows truncated and infilled with spherule-rich sediments. This suggests discontinuous sedimentation within unit 2.

Whole-rock and clay-mineral contents of unit 2 are more regular than in unit 1 and characterized by low calcite (<40%) and phyllosilicates (19%) but higher quartz (31%) and plagioclase (albite >16%; Table 1, Fig. 6). These mineralogical data indicate a significant increase in detrital influx and more rapid deposition relative to the underlying unit 1 as well as to the overlying unit 3.

Unit 3: Interlayered sand-silt beds

Unit 3 consists of interlayered sand, shale, and siltstone beds topped by a rippled sandy limestone (R.S.L.) layer. Characteristic sedimentological features include horizontal laminations, ripple marks, flaser bedding, and convolute lamination. Some of the ripples are symmetrical and some show divergent dipping cross laminations. Smit et al. (1994) also report opposite orientation of sandstone cross laminae, suggesting bidirectional current regimes. Thin layers with normal hemipelagic sedimentation and distinct layers containing zeolites were detected within unit 3 at El Mimbral, La Lajilla, El Mulato, El Peñon, La Sierrita, and La Parida (Adatte et al., 1994). Rare plant debris may be present. Where unit 3 directly overlies unit 1 or the Mendez Formation (e.g., Peñon II, La Lajilla I and II, La Sierrita III, mud clasts are commonly found near the base, marking a disconformity. The R.S.L. layer that tops unit 3 in all outcrops (except Los Ramones) may consist of one or several layers and is marked by extensive bioturbation, most commonly *Chondrites, Zoophycos, Planolites, Thalassinoides,* and *Ophiomorpha* burrowing networks (Keller et al., 1994a, Ekdale and Stinnesbeck, 1994). Within unit 3 and the R.S.L., Ekdale and Stinnesbeck (1994) observed several horizons of trace fossils truncated by overlying sediments (e.g., Rancho Canales, Figs. 1, 5) that indicate repeated colonization and erosion and hence deposition over an extended time period. The R.S.L. layer is widely distributed and can be found where the underlying part of unit 3 and units 2 and 1 are absent (e.g., El Mimbral II, La Parida; Fig. 6).

Whole-rock and clay-mineral compositions of unit 3 are highly variable (Figs. 3 through 6). Two distinct clay-mineral associations can be identified. The R.S.L. and sand layers are characterized by high chlorite (39 to 41%) and mica (35 to 42%) and suggest increased detrital influx and probably more rapid deposition, similar to unit 2. In contrast, the shale layers are enriched in finer chlorite-smectite (11%) and illite-smectite irregular mixed layers (up to 70%, <2 µm size fraction; Table 2, Figs. 4, 5). These shale-mineral associations are similar to those of the Mendez marls (Table 2) and indicate periods of normal hemipelagic sedimentation during deposition of unit 3.

Two distinct layers rich in zeolites (clinoptilolite-heulandite) are recognized near the base and top of unit 3 (Table 2; Figs. 3 through 7) in all sections examined (Adatte et al., 1994). Additional zeolite-enriched layers associated with smectite are observed in unit 1, on top of the clastic deposit at El Mimbral and in the Maastrichtian age marly layer that overlies the clastic deposits at La Lajilla, El Mulato, and La Parida.

POSITION OF THE K/T BOUNDARY AND AGE OF THE CLASTIC DEPOSIT

The horizontal correlation line A in Figure 5 marks the K/T boundary at the top of the R.S.L. layer of unit 3 at Mimbral and above the thin Maastrichtian marl layer overlying unit 3 at Lajilla, Mulato, and Parida. The R.S.L. generally contains two or more distinct sediment layers burrowed by *Chondrites, Zoophycos, Thalassinoides,* and *Ophiomorpha*. The overlying marl layer contains typical *Plummerita hantkeninoides* Zone foraminiferal assemblages, indicating the presence of latest Maastrichtian sediments. This marl layer contains no size sorting, grain-size grading, or transported shallow-water benthic foraminifera that would suggest settling from the water column after deposition of the R.S.L. Whole-rock and clay-mineral analyses indicate that these sediments are enriched in fine phyllosilicates (>2 µm) with illite-smectite and chlorite-smectite mixed layers most abundant. No exotic minerals have been observed.

Biostratigraphic control suggests that the clastic sediment was deposited some time during the last 170 to 200 k.y. of the Maastrichtian. This age is derived from the range of the new latest Maastrichtian planktic foraminiferal markers species *P. hantkeninoides*, which indicates the last 200 k.y. of paleomagnetic chron 29R below the K/T boundary (Pardo et al., 1996). In all sections examined, except Mulato, this marker species is present either above, within, or below the clastic deposits but always below the K/T boundary (López-Oliva and Keller, this volume). This marl layer overlying the clastic deposit thus suggests that normal hemipelagic sedimentation resumed prior to the K/T boundary.

LITHOSTRATIGRAPHIC CORRELATIONS

The near K/T–boundary clastic deposits of northeastern Mexico consist primarily of transported terrigenous and shallow-water neritic debris from multiple sources (e.g., terrestrial, shallow neritic, neritic, upper bathyal) and ages (e.g., Maastrichtian, Campanian, Turonian). Nevertheless, the depositional sequence of this varied transported debris is surprisingly constant. It allows recognition of three well-defined units and subunits (e.g., S.L.L. of unit 1, R.S.L. of unit 3) based on lithologic and sedimentologic characteristics that can be traced and correlated over a distance of more than 300 km.

Figure 5 shows the lithostratigraphic correlation of eleven

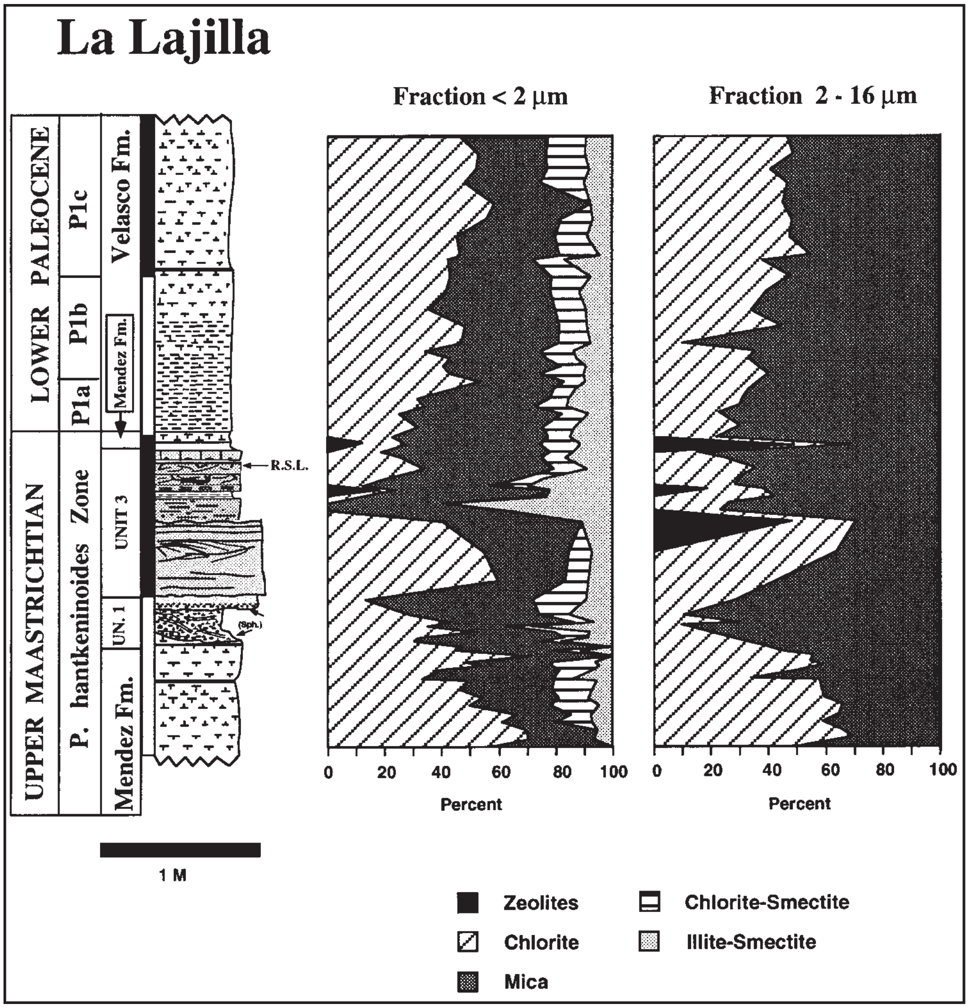


Figure 4 (on this and facing page). La Lajilla and El Mulato, phyllosilicate distribution from the Mendez Formation through the clastic deposit (<2 µm and 2- to 16 µm size fractions). Note the layers enriched in zeolites in unit 3 and mixed layers enriched in chlorite-smectite and illite-smectite in unit 1 (La Lajilla) and in the shale layers of unit 3. R.S.L. = rippled sandy limestone.

outcrops in seven localities. Horizontal correlation line A marks the K/T boundary at the top of the R.S.L. layer of unit 3 at Mimbral and above the thin Maastrichtian marl layer overlying unit 3 at Lajilla, Mulato, and Parida.

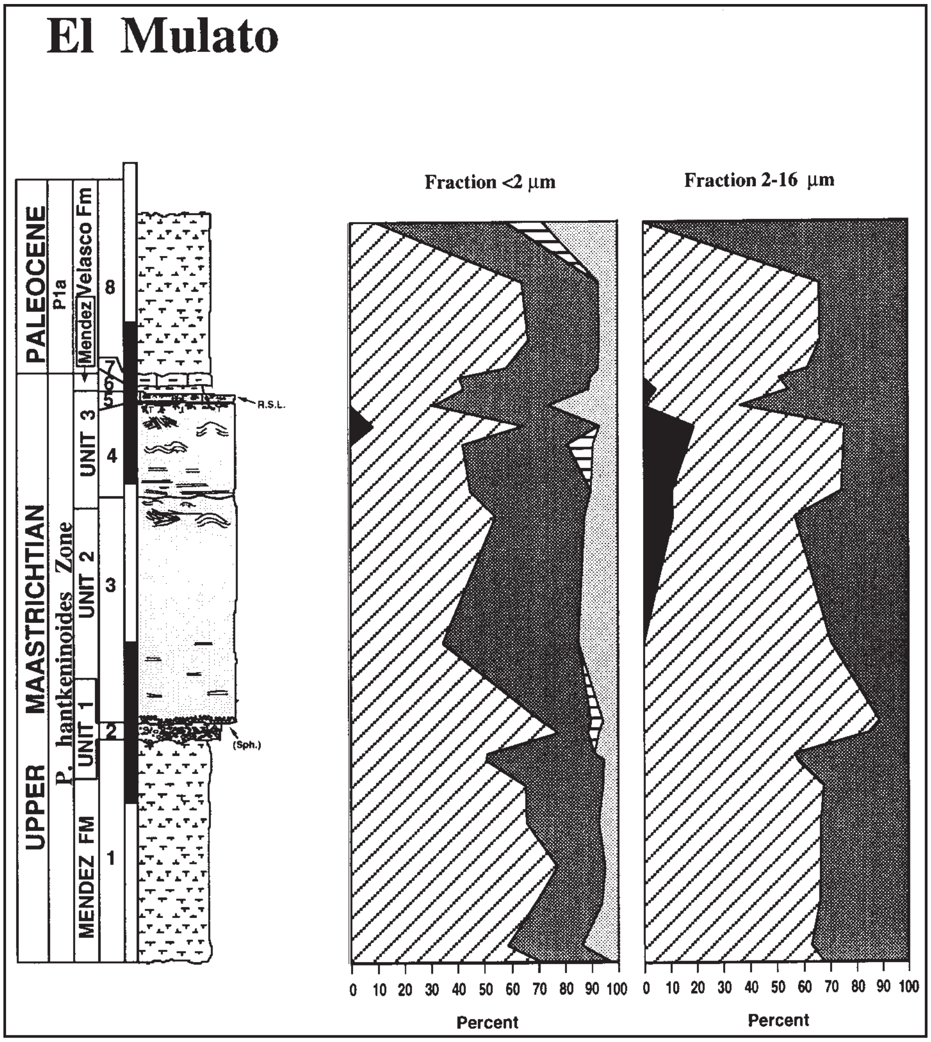
Correlation line B marks the base of unit 3 (alternating sand, silt, and shale layers) and top of unit 2 (laminated sandstone). The Ramones section (Fig. 1) is not figured because units 2 and 3 cannot be distinguished as a result of the shallower-water depositional environment. However, the presence of *P. hantkeninoides* in these sediments indicates that deposition was coeval.

Correlation line C marks the base of the laminated sandstone of unit 2 and the top of the spherule-rich layer of unit 1. Unit 2 laterally disappears first and is absent at Mimbral II, La Lajilla II, El Peñon II, and La Parida.

Correlation line D marks the top of the Mendez Formation and the base of the spherule-rich unit 1. Within unit 1 there is a distinct subunit consisting of the resistant 10- to 20-cm-thick S.L.L. that is present at El Mimbral, El Peñon, Rancho Canales, and La Lajilla. The presence of this S.L.L. is thus correlatable over a distance of more than 200 km.

MINERALOGICAL CORRELATIONS

Correlations based on whole rock composition of five localities are shown in Figure 6. Whole-rock and clay-mineral analyses of five near K/T–boundary clastic deposits in northeastern Mexico indicate three distinct and correlatable units and subunits comparable to those based on lithology and sedimentology. The sections examined include La Sierrita, El Peñon, El Mulato, La Lajilla, and El Mimbral.



The Mendez Formation is characterized by 50% calcite, 30% phyllosilicates, 15 to 20% quartz, and 5 to 10% plagioclase, indicating a marly sediment composition (Table 1). Whole-rock composition of unit 1 marks repeated intercalations of spherule-rich layers with increased calcite (up to 60%), decreased phyllosilicates, quartz, and plagioclase, and intercalations of Mendez marls with the same composition as described above. The thick S.L.L. within unit 1 differs from these sediments by showing lower calcite but higher quartz, plagioclase, chlorite, and mica (illite). This suggests distinctly different detrital influxes during deposition of the S.L.L. and the loosely cemented spherule-rich sediments above and below.

The laminated sandstone of unit 2 is characterized by low calcite (20 to 40%) and phyllosilicates (10 to 15%) and high quartz (up to 40%) and plagioclase (albite 15 to 25%; Table 1; Fig. 7). These mineralogical data are correlatable in all outcrops and indicate increased detrital influx relative to units 1 and 3 and probably more rapid deposition. Whole-rock composition of the sand, silt, and shale layers of unit 3 is highly variable in calcite (but generally higher than in unit 2), phyllosilicates, quartz, and plagioclase. The sand and silt layers with higher quartz, plagioclase, and calcite reflect increased detrital influx and probably more rapid deposition, similar to unit 2. The shale layers are similar in composition to the underlying Mendez Formation and reflect periods of normal hemipelagic sedimentation within unit 3. The thin marl layer of latest Maastrichian age that overlies unit 3 at Mulato, Parida, and Lajilla shows a marly composition comparable to the Mendez Formation, suggesting that normal hemipelagic sedimentation resumed after deposition of the clastic member and prior to the K/T boundary event.

Correlation of zeolite-enriched layers in eight sections over a distance of more than 200 km, from El Mimbral to La Sierrita, is shown in Fig. 7. Two distinct zeolite-enriched layers (clinoptilolite-heulandite) have been recognized near the base and near the top of unit 3, below the rippled sandy limestone at El Mimbral, La Lajilla, El Mulato, La Parida, and La Sierrita.

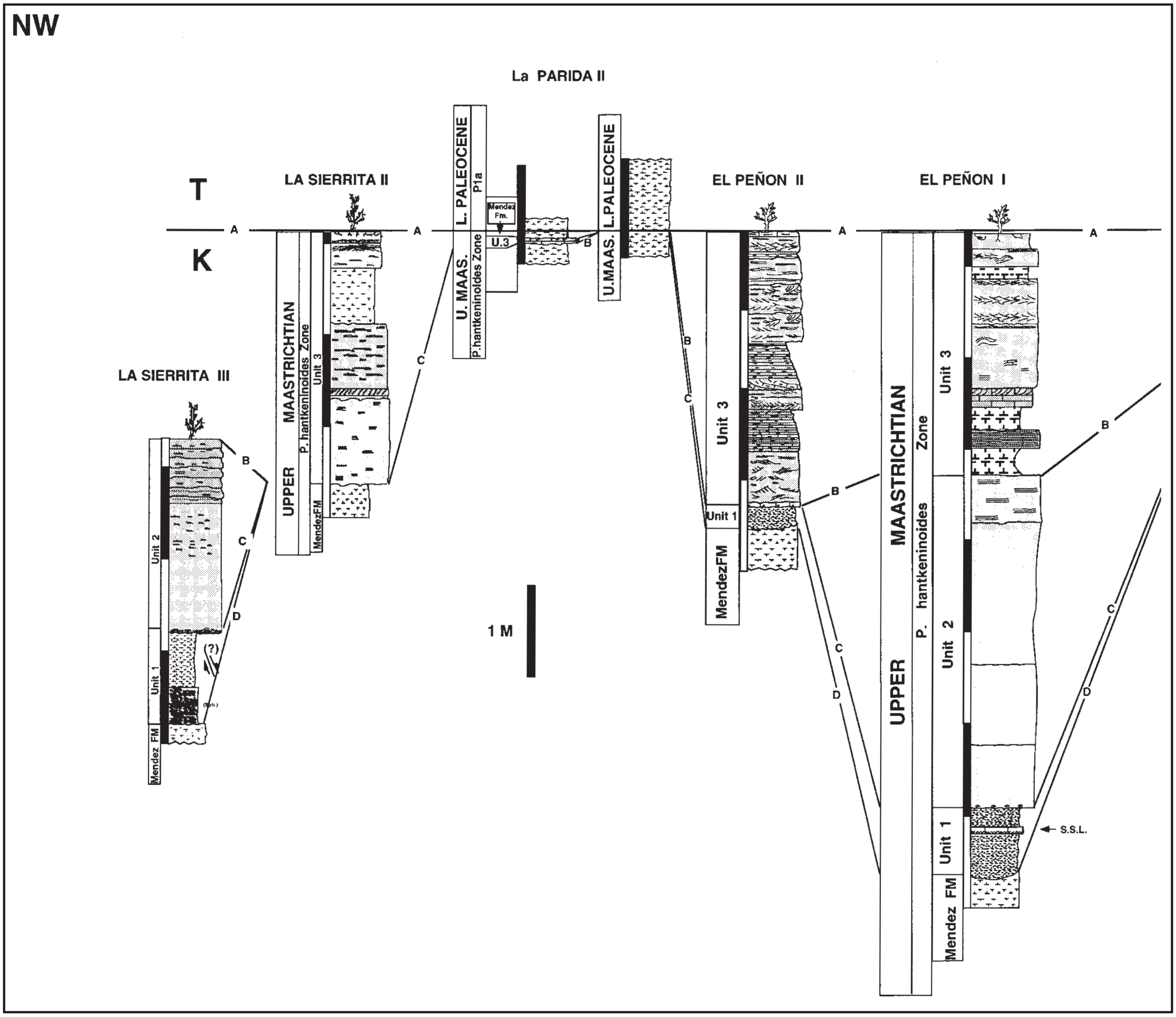


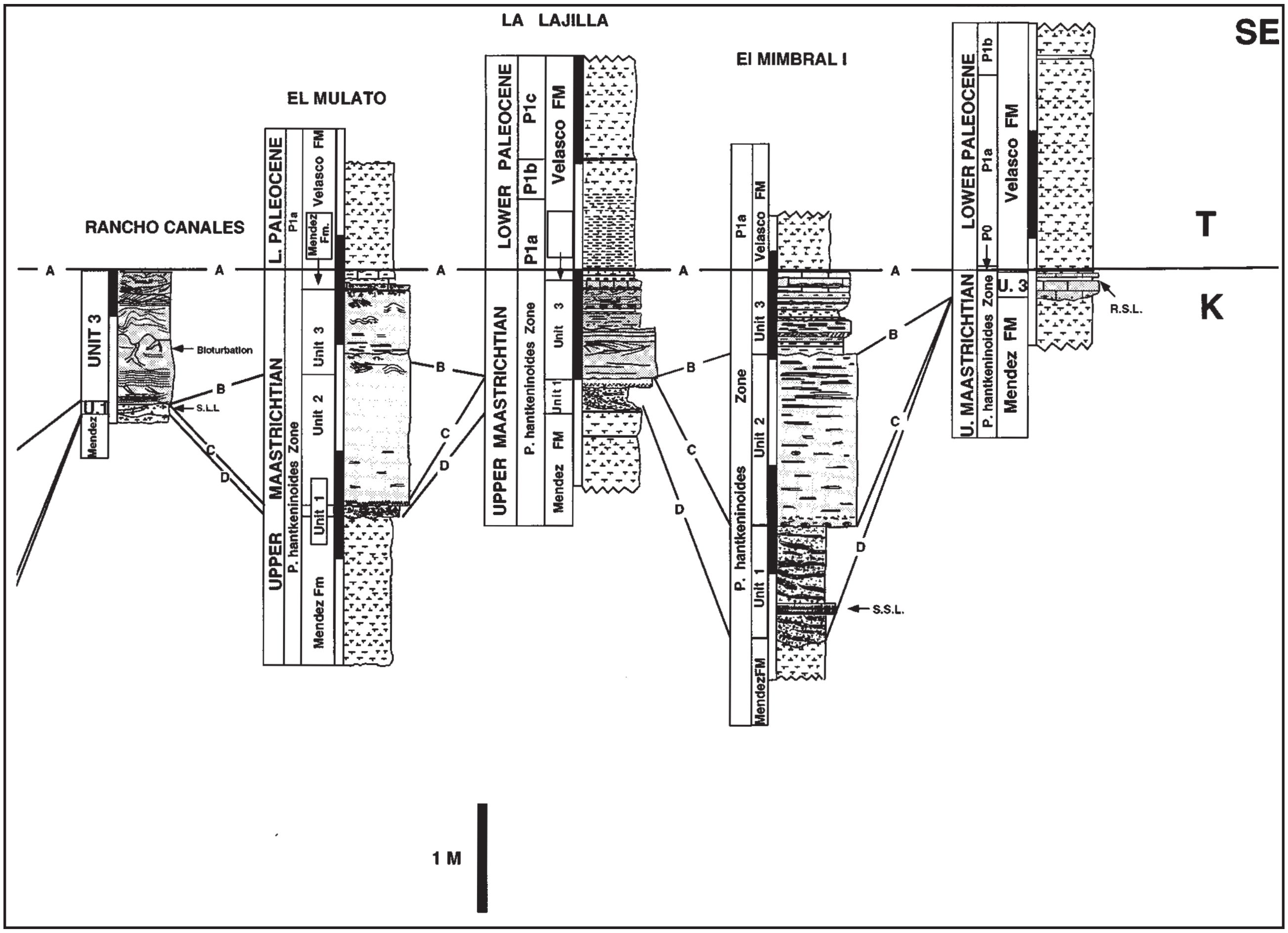
Figure 5 (on this and facing page). Biostratigraphic and lithostratigraphic correlation of ten K-T boundary outcrops in northeastern Mexico that contain near–K/T clastic deposits. S.L.L. = sandy limestone layer; R.S.L. = rippled sandy limestone.

Significant enrichment in zeolites is also observed in the thin marl layer of Maastrichtian age on top of unit 3 at La Lajilla, La Parida, and El Mulato outcrops and in the basal Tertiary clay layer at El Mimbral II.

IMPLICATIONS FOR ORIGIN AND NATURE OF DEPOSITION

The clastic deposit ranges from a few centimeters at La Parida to 7 m at El Peñon and is characterized by three lithologically and mineralogically distinct correlatable units and several subunits. Each of these units and subunits represents differing flow and depositional regimes with varying detrital influx and rates of sediment deposition. These units, subunits, and even individual zeolite-enriched layers are correlatable on a regional scale and suggest a nonchaotic deposition.

The only unusual component of the clastic deposit is the spherule-rich layer of unit 1, which contains rare glass and shocked quartz. Within unit 1 is a subunit consisting of a 20-cm-thick, well-cemented microlaminated sandy limestone layer (S.L.L.) with few graded spherules at the base and top. This S.L.L. is distinctly different from the spherule-rich sedi-



ment and generally lower in calcite and higher in quartz, plagioclase, chlorite, and mica (Tables 1, 2). This difference implies variable detrital influx and perhaps rates of deposition between the spherule rich layers and the S.L.L. Moreover, this indicates that the S.L.L. was at least semilithified prior to deposition of the spherule-rich sediments above it and also prior to deposition of the sandstone of unit 2. Thus, deposition of unit 1 occurred over a long time and not in a matter of hours as suggested by Smit et al. (1992) or Bohor and Betterton (1993). The composition of the spherule-rich layers also suggests a sediment source primarily from shallow neritic environments, as reflected by the presence of glauconite, transported shallow neritic benthic foraminifera, clasts with Turonian age foraminifers, spherules enclosing foraminiferal tests or clasts, oncolites, and spherical infilled organic tests that may be algal resting cysts. Since no Turonian age sediments (Agua Nueva Formation) were exposed in the region during K/T boundary time, these clasts were probably eroded from deeply cut canyon walls and transported. Some larger spherules contain several smaller calcite-infilled spherules that may originally have been bubble-rich glass spherules, and some spherules contain rutile crystals, also suggesting a volcanic origin (Stinnesbeck et al., 1993; Keller et al., 1994a). Rare glass shards are also present with average compositions similar to the glassy spherules found at Beloc, Haiti (Smit et al., 1992; Bohor and Betterton, 1993, Stinnesbeck et al., 1993). The origin of these glass shards is still in dispute, with some arguing for an impact origin (Izett et al., 1990; Sigurdsson et al., 1991; Blum and Chamberlain, 1992; Koeberl and Sigurdsson, 1992; Koeberl, 1994) and others arguing for a volcanic origin (Jéhanno et al., 1992; Lyons and Officer, 1992; Robin et al., 1992). In either case, the event that produced the glass appears to have predated the K/T boundary bolide impact.

The horizontally laminated sandstone of unit 2 represents increased detrital influx and more rapid deposition than unit 1. The only unusual feature is the presence of discrete layers of leaf and wood debris at the base of unit 2 at El Mimbral, aligned in a north-northwest–south-southeast direction, which suggests a major detrital influx from the coastal area and possibly reflects a collapse of the northwest delta in the Monterrey area (Fig. 1). No similar plant debris layers have been observed in any other outcrops. Very small fragments of plant debris can be found throughout the sandstone and occasionally in sandy layers of unit 3. These are not unique or restricted to K/T boundary

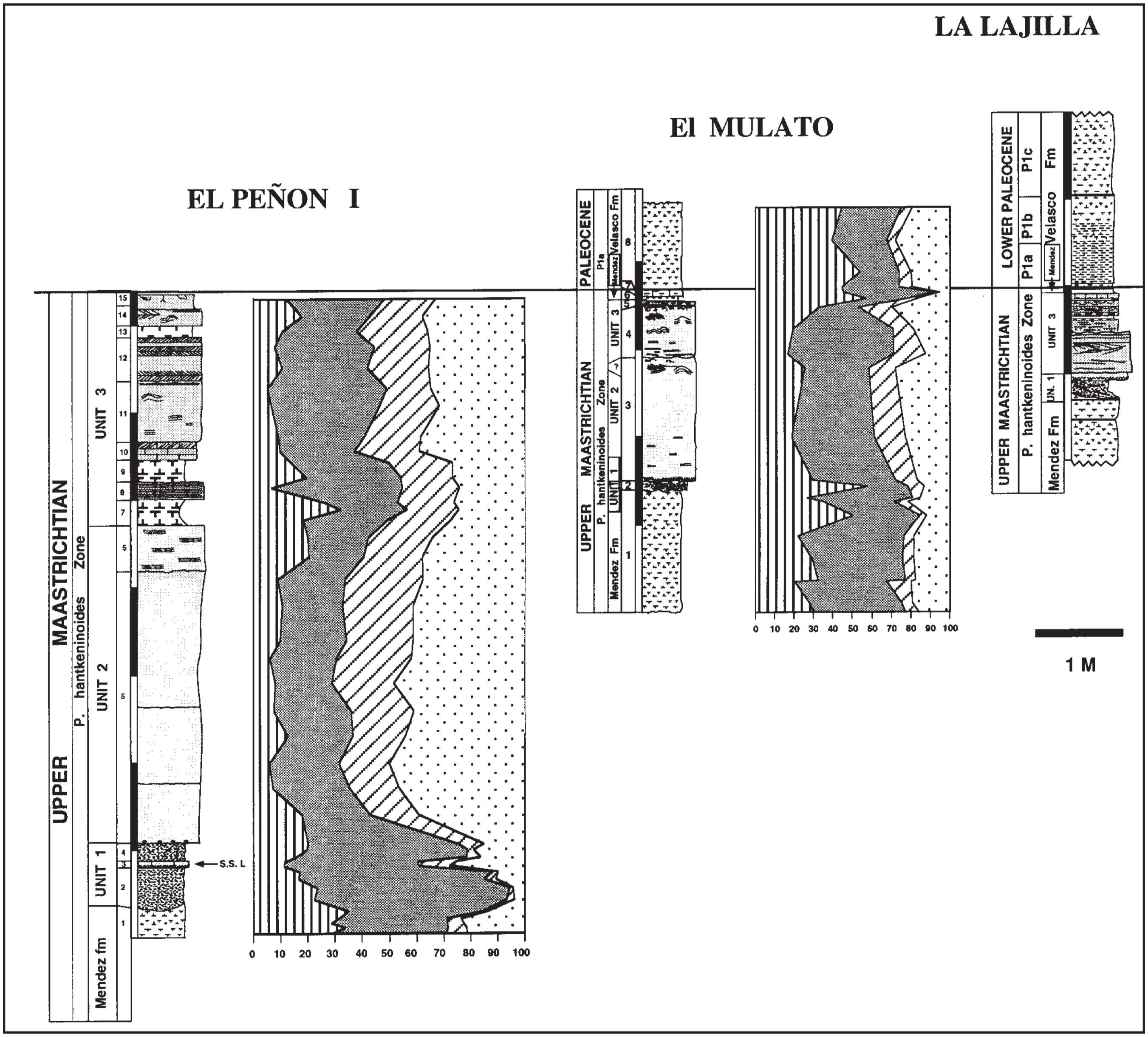
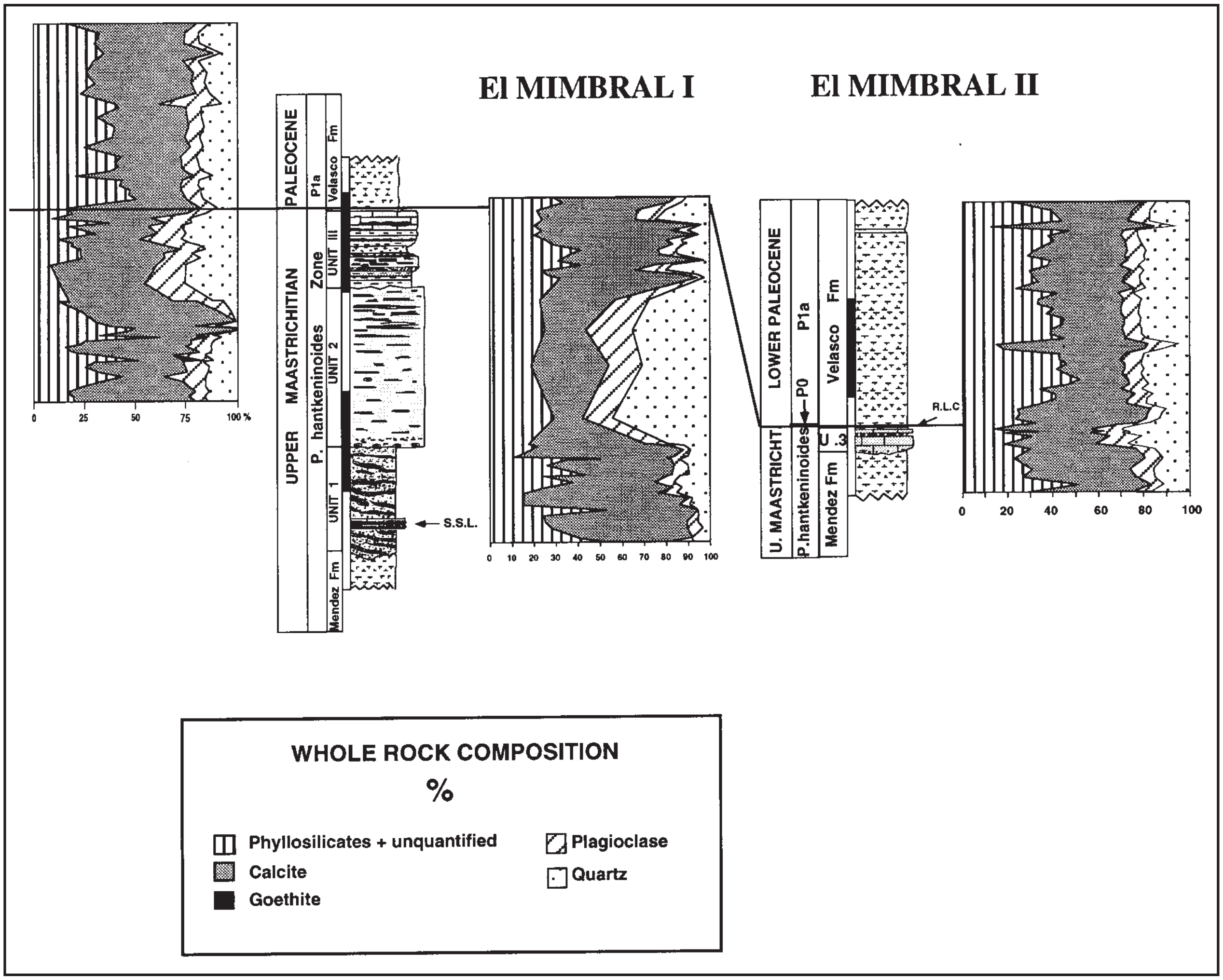


Figure 6 (on this and facing page) Mineralogical correlation of five K/T outcrops in northeastern Mexico, based on whole-rock compositions. S.L.L. = sandy limestone layer; R.S.L. = rippled sandy limestone.

deposit but are commonly found in any predominantly detrital sediments. Land plant debris is very commonly carried during floods or gravity flows. Bioturbation at the base of unit 2 suggests that deposition occured not as a single event but as multi-events (Ekdale and Stinnesbeck, 1994).

The sand and silt and shale layers of unit 3 and their mineralogic variability indicate high detrital influx and rapid deposition (sand and silt layers) alternating with normal hemipelagic deposition (shale layers). Deposition of the rippled sandy limestone at the top of the clastic deposit occurred slowly enough to permit a thriving benthic community to exist (Ekdale and Stinnesbeck, 1994). Discrete layers enriched in zeolites also indicate volcanoclastic influx. Deposition of unit 3 probably occurred over a longer time period than either unit 1 and unit 2 and under more variable environmental conditions. These different layers enriched in zeolites are correlatable from section to section over a distance of more than 300 km. An in situ diagenesis origin of these zeolites is unlikely because of the geographic distribution and excellent correlatability of the layers in different lithologies, such as sands, silts, shales, and marls (Fig. 7). We conclude that



these layers are detrital in origin and indicate discrete periods of volcanoclastic influx. Whole-rock and clay-mineral analyses indicate that the shale layers and the overlying marl of Maastrichtian age are enriched in phyllosilicates with illite-smectite and chlorite-smectite mixed layers most abundant. The small size (<2 µm) of these clay minerals precludes settling through the water column within a few hours after a tsunami wave This layer implies that normal hemipelagic sedimentation resumed in the uppermost Maastrichtian after deposition of the clastic sediments (see López-Oliva and Keller, this volume). Absence of this marl layer at Mimbral and Peñon appears to be due to a short K/T boundary hiatus.

CONCLUSIONS

Our lithologic, mineralogic, and biostratigraphic analysis of K/T sections in northeastern Mexico suggests that the clastic sediments represent a series of depositional events that varied from rapid to normal hemipelagic sedimentation. Deposition of the spherule-rich layers of unit 1 was relatively rapid, with a source primarily from shallow neritic environments, transported into deeper waters. Unit 2 represents erosion and rapid redeposition of massive sand lenses. Unit 3 represents variable, but decreased, detrital influx restricted to discrete layers that alternate with periods of normal hemipelagic sedimentation.

We propose that these varied detrital influxes are related to the latest Maastrichtian eustatic sea-level lowstand (Haq et al., 1987; Donovan et al., 1988; MacLeod and Keller, 1991a, b; Keller and Stinnesbeck, 1996) that occured about 200 to 300 k.y. before the K/T boundary (Pardo et al., 1996). In this scenario, the unconformity at the base of the clastic deposit represents a type 1 sequence boundary associated with a falling sea level. Deltaic sediments were exposed, eroded, and

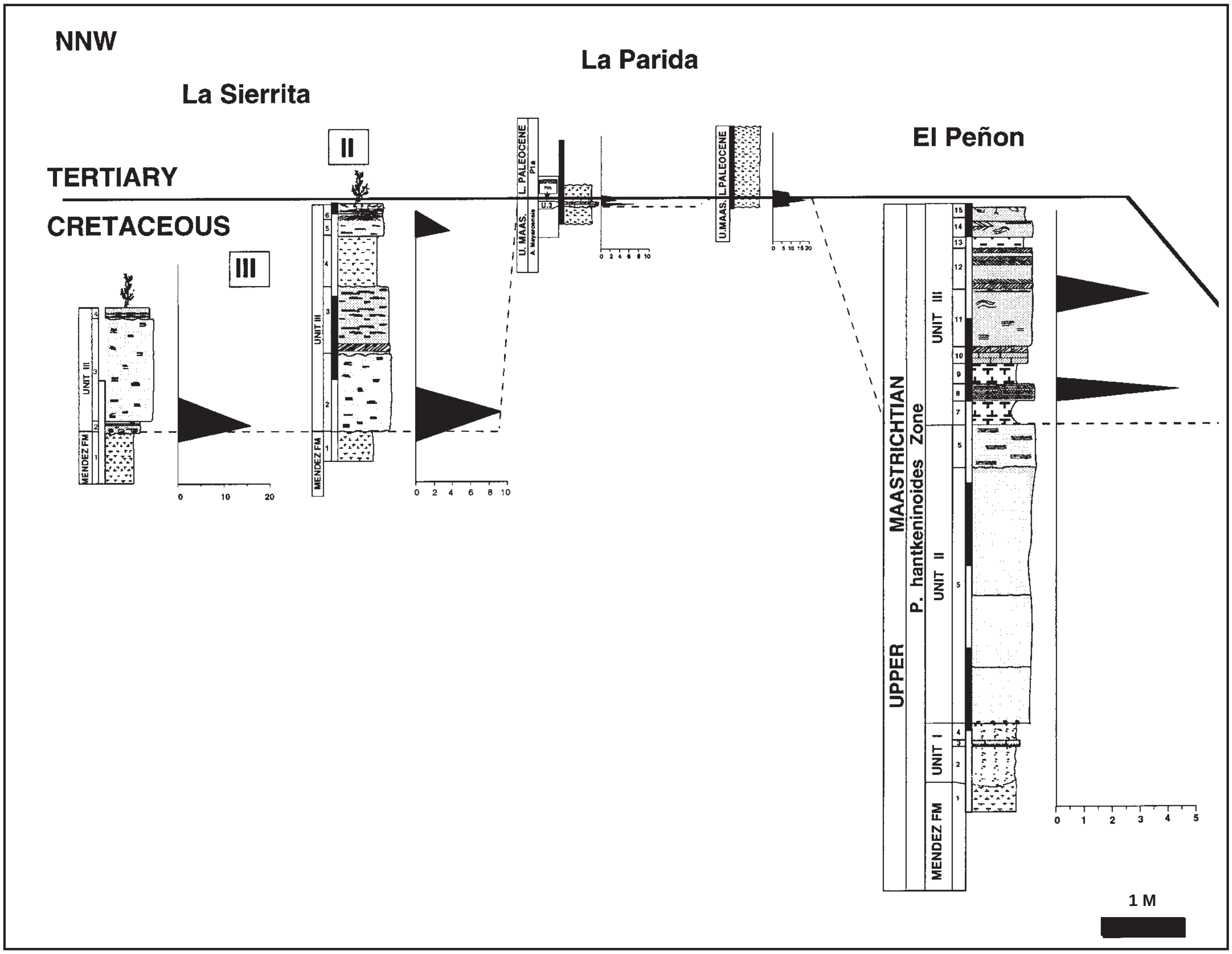
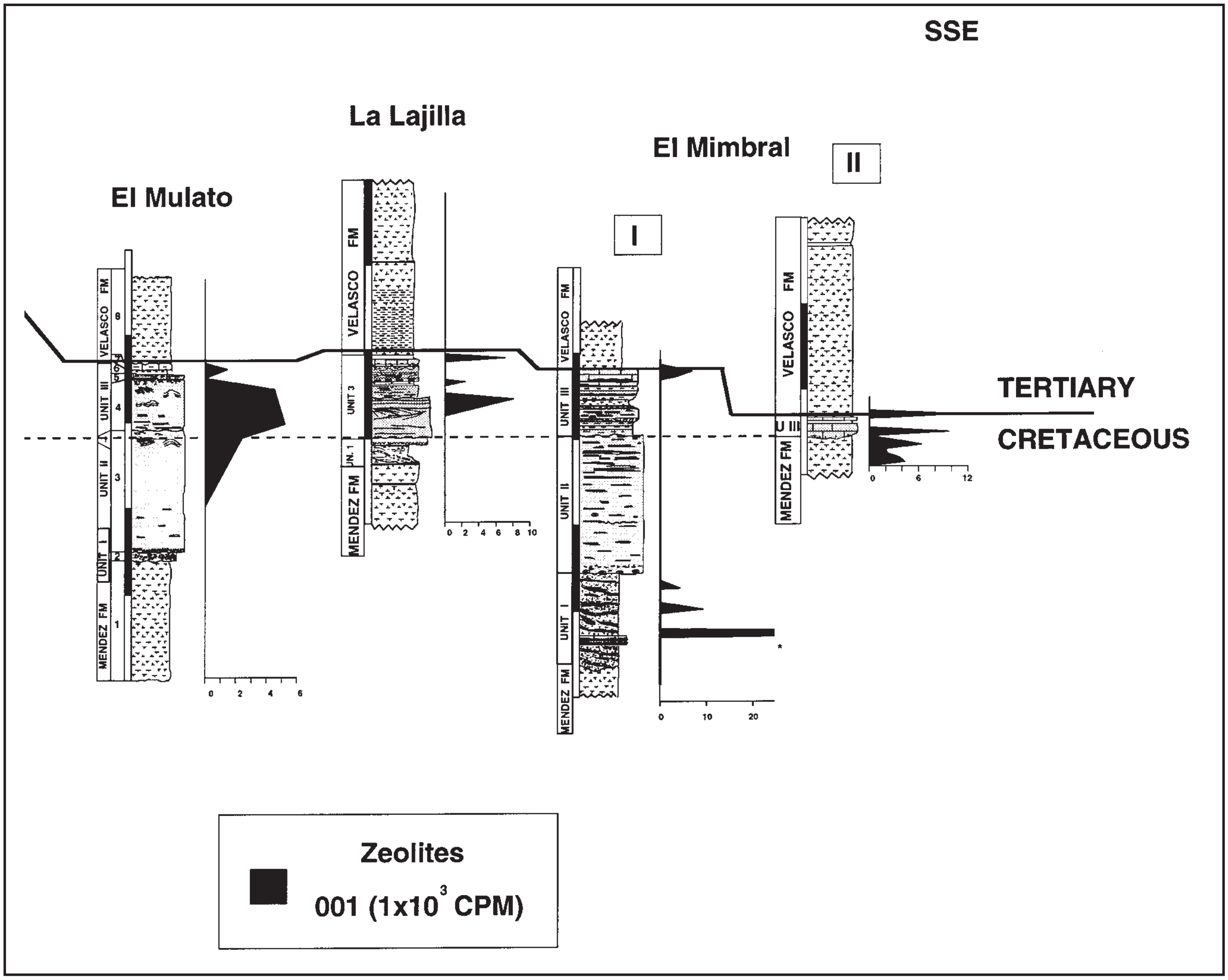


Figure 7 (on this and facing page). Correlation of zeolite-enriched layers in eight K/T boundary outcrops in northeastern Mexico.

sporadically transported into deeper waters, depositing the spherule-rich sediments of unit 1. Continued lowering of the sea level resulted in erosion and bypass, first of inner-shelf (plant debris layer) followed by outer-shelf sediments and deposition of massive or weakly laminated sand lenses (unit 2). Unit 3 was probably deposited during the subsequent stable low sea level when erosion of shelf sediments decreased, resulting in deposition of fine-grained sand and silt layers alternating with normal hemipelagic sedimentation (shale layers). Sea level began to rise prior to the K/T boundary, as suggested by deposition of Maastrichtian age marls above the clastic deposit at Parida, Mulato, and Lajilla. A rising sea level beginning during the latest Maastrichtian has also been recognized in sections from Denmark (Schmitz et al., 1992; Keller, 1989), Brazil (Stinnesbeck and Keller, 1996), and Seymour Island (Askin and Jacobson, 1996).

Lithology and whole-rock and clay-mineral compositions thus indicate the presence of distinct and correlatable units spanning more than 300 km. From these multicorrelations we conclude that deposition of units 1, 2, and 3 of the clastic deposit occurred over an extended time interval with periods of normal hemipelagic sedimentation alternating with times of increased detrital influx and more rapid sedimentation. These variable depositional environments seem to be related to the late Maastrichtian sea-level lowstand and may also have been influenced by regional tectonic and volcanic activity.



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