Coastal landsliding and catastrophic sedimentation triggered by Cretaceous-Tertiary bolide impact: A Pacific margin example?

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ABSTRACT

We report here the first-recognized Pacific margin stratigraphic sequence containing evidence for catastrophic landsliding attributed to bolide impact–related seismic shocking at the Cretaceous-Tertiary (K-T) boundary. The K-T boundary is not commonly preserved in stratigraphic sequences of the Pacific margin, but we have discovered it within a coastal paleovalley in Baja California, Mexico (near El Rosario). This 5-km-wide, >15-km-long, and 200-m-deep coastal paleovalley formed by massive gravitational collapses and rapidly filled with coastal (shallow marine and lesser fluvial) gravels and sands, as well as slide sheets of marine mudstone that range from meters to kilometers in length. We infer that seismic shocking caused liquefaction and extremely rapid sedimentation of the gravels and sands, simultaneous with unleashing of slide sheets. Laser-heating $^{40}Ar/^{39}Ar$ data for biotite, hornblende, and plagioclase (single crystal and bulk step heating) on a 20-m-thick pumice lapilli tuff in the middle of the valley fill give an age of 65.5 ± 0.6 Ma; this is indistinguishable from the age of Haitian tektites dated by the same laboratory. Our new Pacific margin sequence, like many K-T boundary sequences in the Gulf of Mexico–Caribbean region, provides evidence of giant landslides and catastrophic sedimentation >1800 km from the bolide impact site.

Keywords: Cretaceous-Tertiary, mass wasting, impacts, paleovalley.

INTRODUCTION

Recent years have seen a great deal of research on sedimentation related to the Chicxulub Cretaceous-Tertiary (K-T) bolide impact (Bourgeois et al., 1988; Bralower et al., 1998; Norris et al., 2000; Smit, 1999). Workers have described mass-wasting, sediment gravity-flow, or tsunamite deposits in the Gulf of Mexico, the Caribbean Sea, and along the length of the North Atlantic margin, from Puerto Rico to the Grand Banks (Fig. 1; see also Data Repository Fig. 1[1]). Earlier papers largely attributed the catastrophic sedimentation events to tsunami directly generated by the bolide impact, but more recent papers have shown that mass-wasting deposits generated from collapses were too deep seated and too laterally extensive to be attributed to tsunami activity and were instead seismically induced (see discussion in Norris et al., 2000). Computer modeling indicates that the initial impact generated an earthquake of magnitude 13 on the Richter Scale and that vertical ground motion was in excess of 1 m within 7000 km of the impact (Boslough et al., 1996). With an earthquake of this magnitude, one would expect adjustments on regional fault systems for some period of time after the impact, although the areal extent and length of time of these adjustments are not known. Yancey (1997) proposed that the tsunamites in southern Texas (Bourgeois et al., 1988) resulted from a series of seismic events triggered by and following the initial Chicxulub impact, rather than being the deposits of a single tsunami generated by the impact. We present evidence here that seismicity was protracted enough to trigger a series of collapse and resedimentation events.

We present a preliminary map, cross sections, and descriptions of a 5-km-wide and >15-km-long coastal paleovalley in Baja California, Mexico (Figs. 1 and 2). We present evidence that the paleovalley was rapidly cut and filled by a series of massive gravitational collapses. We also present age data that suggest that these collapses occurred at the K-T boundary (Fig. 3) and speculate that they were the result of a period of seismic activity initiated by the Chicxulub impact.

GEOLOGIC SETTING

The Rosario embayment of the Peninsular Ranges forearc basin complex is interpreted as a Late Cretaceous forearc strike-slip basin formed under a compressional convergent-margin strain regime (Busby et al., 1998). This forearc basin formed atop an accreted island-arc basement (Alisitos Group, Fig. 2) and filled with Campanian to Paleocene fluvial to deep-marine sedimentary rocks (see description and references in Busby et al., 1998). Around the time of the Cretaceous-Tertiary boundary, contraction of the forearc strike-slip basin produced a broad north-northwest–trending, gently southward-plunging syncline. Because of the southward plunge of the growing syncline, the basin gradually shoaled and became emergent in the north, while it remained deeply submerged in the south. In the northernmost part of the basin, at the present-

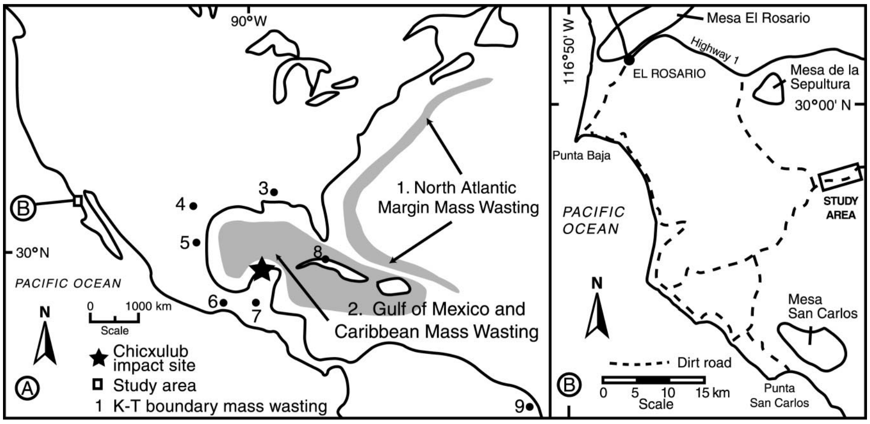

Figure 1. A: Sites of catastrophic sedimentation at Cretaceous-Tertiary (K-T) boundary in and around Gulf of Mexico, Caribbean Sea, and North Atlantic margin (numbered 1–8). Full documentation is available in GSA Data Repository (see text footnote 1). Site of our newly recognized Pacific margin example (labeled B) on Baja California Peninsula in Mexico is shown. B: Our study area (box; see Fig. 2) and other geographic features of El Rosario area (Baja California, Mexico) discussed in text.

[1]GSA Data Repository item 2002081, Figure 1, Full documentation for sites of catastrophic sedimentation at the Cretaceous-Tertiary boundary, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs.ft2002.htm.

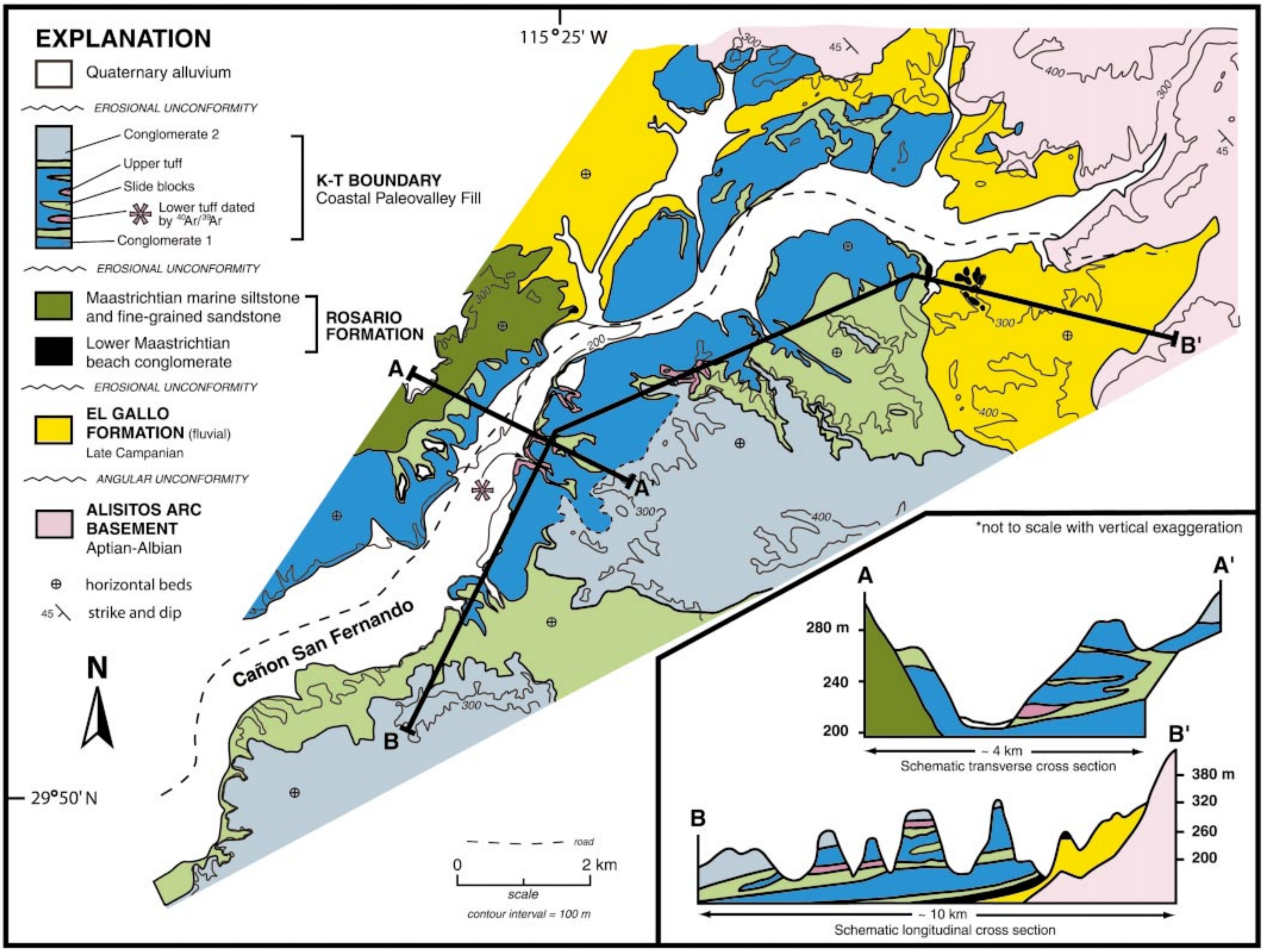

Figure 2. Preliminary geologic map of Cretaceous-Tertiary (K-T) coastal paleovalley in Cañon San Fernando area, Baja California (see locality in Fig. 1). K-T boundary is preserved in this coastal paleovalley, which is very well exposed along present-day Cañon San Fernando and its tributaries. Transverse cross section is ~9 km from head of coastal paleovalley, and schematic longitudinal section extends 15 km along length of paleovalley.

day Mesa El Rosario (Fig. 1), microfossils in marine siltstone-sandstone of the Rosario Formation indicate that early Maastrichtian bathyal, open-marine conditions were replaced by early or early late Maastrichtian outer neritic, restricted conditions (Patterson, 1978). The section does not reach the Paleocene on Mesa El Rosario, but does at nearby Mesa de la Sepultura (Fig. 1), which is the type locality for the Paleocene Sepultura Formation (Kilmer, 1963). Here, lower Maastrichtian deep-marine siltstone-sandstone of the Rosario Formation was exposed to subaerial erosion and soil formation prior to deposition of shallow-marine strata of the Sepultura Formation in late early Paleocene time (Abbott et al., 1993). In contrast, microfossil data from the south part of the basin, at Mesa San Carlos (Fig. 1), show that the Cretaceous-Tertiary boundary is preserved within a conformable, uniform, upper bathyal siltstone-sandstone section (Morris and Busby-Spera, 1988; Morris, 1992); here, one cannot use lithology or unconformities to distinguish between Maastrichtian and Paleocene strata.

In this paper we describe a newly recognized K-T boundary section, in Cañon San Fernando, ~15 km south of Mesa de la Sepultura (Figs. 1 and 2). We interpret this section to be within a coastal paleovalley that accumulated and preserved strata while subaerial erosion and exposure were taking place on the interfluve at the present-day Mesa de la Sepultura.

GEOMETRY AND SEDIMENTOLOGY OF THE K-T COASTAL PALEOVALLEY

We present here a preliminary geologic map and schematic transverse and longitudinal cross sections of our proposed K-T boundary coastal paleovalley (Fig. 2). Along much of its length, this coastal paleovalley fills an ~200-m-deep incision that is cut into lower Maastrichtian marine siltstone and fine-grained sandstone of the Rosario Formation. This relationship is best demonstrated at the steep northern wall of the paleovalley, where flat-bedded conglomerates and sandstones of the paleovalley fill onlap undisturbed, flat-bedded Maastrichtian siltstones in the paleovalley wall (see transverse cross section, Fig. 2). The south margin of the paleovalley has not yet been accurately mapped because the slide blocks of Maastrichtian siltstone become progressively larger in that direction, making it difficult to distinguish between allochthonous slide sheets and autochthonous paleovalley wall. The head of the coastal paleovalley is downcut through lower Maastrichtian beach conglomerate (also of the Rosario Formation) into Campanian fluvial deposits (El Gallo Formation) and locally into Aptian-Albian arc basement below (see longitudinal cross section, Fig. 2).

We infer that most of the sedimentary sec-

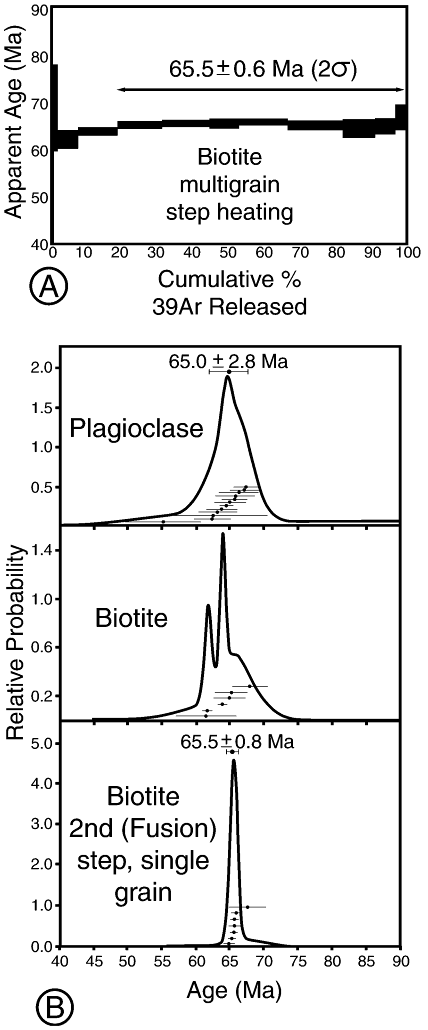

Figure 3. Multigrain (A) and single-crystal (B) Ar/Ar age data from pumices in dacite pumice lapilli tuff. This tuff occurs in lower part of coastal paleovalley fill (see Fig. 2) and yields ages similar to those of Haitian tektites dated in same laboratory (see text).

tion in Cañon San Fernando accumulated in a very short period of time at the K-T boundary, by catastrophic means. The valley fill is composed of three units (Fig. 2): (1) conglomerate units with <10% sandstone, (2) slide-block accumulations within and between the conglomerates, and (3) volumetrically minor lenses of tuff and lapilli tuff. We divide the conglomerate into two units (1 and 2, Fig. 2). Conglomerate 2 is mapped separately from conglomerate 1 because it lacks slide blocks and has no marine fossils.

A transverse cross section through the coastal paleovalley (Fig. 2) shows the steep northern wall where the valley is cut into Maastrichtian marine siltstones and fine-grained sandstones of the Rosario Formation. This material makes up the huge slide blocks interstratified with the valley-filling conglomerates. The transverse cross section also shows the lower of two tuff lenses within conglomerate 1, a pumice lapilli tuff up to 20 m thick, that we sampled for dating (Fig. 3).

A composite longitudinal section of the coastal paleovalley demonstrates the reactivated nature of the valley (Fig. 2). The first valley-cutting event is recorded by the unconformity between the El Gallo Formation and the arc basement, and the second is recorded by the buttress unconformity of the lower Maastrichtian beach conglomerates (Rosario Formation) against the El Gallo Formation. The erosional surface at the base of conglomerate 1 locally merges with the erosional surface below the lower Maastrichtian beach conglomerates. The longitudinal section also shows the overall progradational and aggradational character of the K-T boundary valley fill and the great size of some of the slide blocks. Further, it demonstrates that tuffs are at two different horizons.

The distribution of the coastal paleovalley fill demonstrates that the incision was highly asymmetrical (Fig. 2). This is an unusual shape for a valley cut by a river during a sea-level lowstand. An irregular shape would be expected, however, in a valley formed by catastrophic failure. The map relationships between conglomerate 1 and conglomerate 2 also demonstrate that the depositional system prograded down the valley with time (Fig. 2). Conglomerate 1 has shallow-marine fossils throughout and is interpreted to record a complex interplay of traction, density current, and wave-reworking processes. Conglomerate 2, in contrast, lacks marine fossils within the map area and appears to be entirely fluvial. The lack of slide sheets in conglomerate 2 could reflect cessation of seismicity during its deposition. The rest of this section focuses on conglomerate 1 because it contains the slide sheets as well as the dacite pumice lapilli tuff we dated.

Conglomerate 1

Conglomerate 1 is a cobble to boulder conglomerate, with lesser pebble conglomerate. Clasts are well rounded and were derived from volcanic, plutonic, and metasedimentary sources in the present-day Peninsular Ranges.

The lower half of conglomerate 1 is a crudely stratified to nonstratified, clast-supported, but only moderately well sorted conglomerate with soft-sediment slump structures, load structures, and abundant interstratified slide blocks. We interpret the lower half of conglomerate 1 to represent sediment gravity flows deposited in a marine environment just below wave base on an uneven and unstable substrate of slide blocks.

The upper half of conglomerate 1 is a well-stratified, clast-supported, and well-sorted conglomerate with planar horizontal or weakly inclined beds. The coarsest beds are on erosional surfaces and may represent channel lags on a proximal mouth bar. The inclined beds may represent low-relief mouth bars, which could develop under conditions of high-momentum (coarse sediment–charged) floods. Well-developed clast imbrication fabrics are highly variable, but all are within the western sector, ranging from southwestward to northwestward in transport direction; this variability may be the result of interaction with a very complex topography created by the giant slide blocks. The upper half of conglomerate 1 also contains scattered horizons with disc-shaped clasts and abundant shell fragments, which may record reworking by waves. We interpret the upper half of conglomerate 1 to record traction flows in a very proximal mouth-bar setting, in water shallow enough for wave reworking to occur.

Sandstones

Sandstones interstratified with conglomerate 1 are strikingly massive. They occur largely as lenticular beds to 1 m thick, filling scours or cut by scours. The beds are massive with scattered siltstone clasts, or contain stratification in the form of gravel trains. The presence of mollusk fragments throughout the sandstones indicates that they are marine. The overwhelming predominance of massive sandstones and the vertical aggradation indicated by the gravel trains suggest high sediment supply and deposition from steady, sustained, high-density turbidity currents (e.g., Kneller and Branney, 1995). We suggest that these were delivered to the shallow-marine environment by floods.

Slide Sheets

We have not identified any autochthonous siltstones or mudstones within conglomerate 1; all siltstone-mudstone sections appear to be present as slide sheets or blocks. The slide sheets and blocks are largely undisrupted internally and consist of laminated, thin-bedded, fine-grained sandstones and siltstones with graded beds and Bouma divisions, identical to the Maastrichtian marine mudstone in the coastal paleovalley walls (Fig. 2). The slide sheets and blocks have injection structures in the form of conglomeratic sills and less common conglomeratic dikes. The sizes of the slide sheets range from outcrop scale (1–200 m across) to map scale (several hundred meters across, although these may be composites of several blocks). Aspect ratios of the blocks and sheets range from 1:1 to as low as 1:30. Small slide blocks and sheets (<2 m thick) that are much rarer and are more disrupted than large ones pass gradationally into debris-flow deposits that fill local depressions. The low degree of internal deformation in the slide sheets and blocks, as well as the rarity of associated debris-flow deposits, indicates that they were translational slides that probably did not travel long distances.

Tuffs

We have mapped two tuffs in conglomerate 1 (Fig. 2), each to 20 m thick. The lower tuff consists of interstratified pumice lapilli tuff and medium-grained to coarse-grained crystal vitric tuff, and the upper tuff is a crystal vitric tuff. Both tuffs contain euhedral plagioclase, biotite, and lesser hornblende in a matrix of bubble-wall shards; lithic fragments are rare. We describe the lower pyroclastic lens in more detail here, because we sampled pumices from it for Ar/Ar dating, described in the next section.

We infer that the lower tuff represents a pyroclastic flow that was erupted from a not-too-distant subaerial source during an explosive silicic eruption and fed directly into the coastal paleovalley, where it mixed with seawater to form a ''tuff turbidite.'' Petrified log fragments to 0.5 m in length indicate a subaerial eruptive source. A lack of abrasion of the delicate pyroclastic components and a lack of admixed nonpyroclastic components indicate that the lower tuff was fed by an eruption, but the sedimentary structures suggest deposition from cold, high-density turbidity currents (rather than hot, gas-supported flows). Grain-size fluctuations occur throughout the tuff, but it forms an overall upward-fining sequence of beds, dominated by poorly sorted, massive to crudely stratified, nongraded or graded thick beds and lesser planar-laminated or convolute-laminated medium to thin beds. The absence of traction structures and scour structures suggests high aggradation rates. The lower tuff occupies a low area between slide blocks, which appears to have channeled the turbidity flows. There is no recognized source of the appropriate age for the tuffs in eastern Baja California or in adjacent mainland Mexico, although tuffs of this age form an ignimbrite province in southern Mexico (Righter et al., 1995).

Ar/Ar GEOCHRONOLOGY

Procedures for the $^{40}Ar/^{39}Ar$ dating were as described by Renne (1995). Ages are reported relative to 28.02 Ma for the Fish Canyon sanidine standard (Renne et al., 1998), and uncertainties do not include systematic errors as enumerated by Renne et al. (1998). A five-grain sample of biotite was step heated with an Ar-ion laser in 12 steps and yielded a plateau age of 65.5 $\pm$ 0.6 Ma (2σ) for $\sim$80% of the ^{39}Ar released (Fig. 3A). Six single grains of biotite were analyzed individually by fusion in two steps. The first steps were variably discordant, probably reflecting minor alteration, but the second (fusion) steps were tightly clustered (Fig. 3B) and yielded a weighted mean age of 65.5 $\pm$ 0.8 Ma. We analyzed 11 crystals of plagioclase by total fusion; they yielded mutually indistinguishable ages (Fig. 3B) with a weighted mean of 65.0 $\pm$ 2.8 Ma. All results are consistent with the biotite plateau age 65.5 $\pm$ 0.6 Ma, which we infer as the eruptive age of this tuff. This age is indistinguishable from the ages of Haitian tektites and the terrestrial K-T boundary when all are normalized to the same standard age, e.g., as discussed specifically by Renne et al. (1998).

CONCLUSIONS

Geologic mapping, sedimentologic studies, and field relationships of a coastal paleovalley exposed in Cañon San Fernando indicate rapid incision and filling at the K-T boundary. These processes are demonstrated by (1) the highly asymmetric cross-sectional profile of the paleovalley, (2) the dominantly massive, disorganized conglomerate with $<$10% sandstone composing the basal paleovalley fill, (3) the interbedded map- and outcrop-scale slide sheets of mudstone that are lithologically identical to Maastrichtian mudstone composing the K-T paleovalley wall, and (4) the 65.5 $\pm$ 0.6 Ma (Ar/Ar) crystal vitric tuff interbedded with massive, disorganized conglomerate at the base of the paleovalley fill. Our study represents the first Pacific margin example of giant landslides and catastrophic sedimentation at the K-T boundary and is consistent with observations reported from sites in the Gulf of Mexico and North Atlantic margin.

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