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Impact stratigraphy – from crater-filling to distal ejecta

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Abstract: The impact of cosmic objects of significant size into Earth's oceans generates stratigraphic relationships that are predictable and worthy of note by geologists. These include crater-filling stratigraphy, crater-rim stratigraphy, proximal ejecta stratigraphy, and distal ejecta stratigraphy. Each of these distinct stratigraphic relationships is examined briefly in this paper by using well-known examples.
Keywords: Impact stratigraphy, Crater filling stratigraphy, Proximal ejecta stratigraphy.

Introduction

"*Impact cratering has risen from complete obscurity to become one of the most fundamental geologic processes … future historians will accord the recognition of impact cratering as equal importance with the development of plate tectonics*." – H. Jay Melosh (1986).

Presently, there are about two hundred known - and another few hundred suspected - impact structures on Earth. Of those, it is likely that the majority were formed near or within the world's oceans, or within a comparably wet environment, when one considers the fact that Earth has had vast lacustrine and oceanic areas over most of its planetary history. In this paper, a brief review of marine impact-generated stratigraphy, or simply impact stratigraphy, is presented. The study of impact craters on Earth began about 60 years ago, but the field of impact stratigraphy is only about two decades old. The paper by Ormö and Lindström (2000) marked an important step up in the understanding of marine impacts, in general, and crater-filling stratigraphy, in particular. Likewise, at about the same time, the book Impact Stratigraphy, the Italian record (Montanari and Koeberl, 2020) stimulated the study of distal impact ejecta and this sort of ejecta's stratigraphic relations. Field studies and more recently digital modeling of marine impacts has increased our understanding of marine impacts and their stratigraphy, as explained below. The topic of impact stratigraphy and how it relates to formal stratigraphic terminology has been addressed by King and Petruny (2003a). Earlier, very widely cited works by French (1999) and Melosh (1986) dealt mainly with dry target impacts on Earth, which generate some important stratigraphic features, but generally not to the extent of marine impacts. Consequently, dry-target impacts on land and their ejecta will not be addressed in this paper.

Crater-Filing Stratigraphy

To understand crater-filling stratigraphy, it is useful to review a good example of a marine target crater, which is the Wetumpka impact structure in Alabama, USA (Fig. 1). This crater has been extensively studied from both a field (surface and subsurface) and laboratory perspective and, more recently, by digital modeling (Neathery et al., 1976; King et al., 2002; 2006; 2015; King and Ormö, 2011; De Marchi et al., 2021). Wetumpka is a Late Cretaceous marine impact structure that is ~ 5 km in the NW-SE dimension and ~ 7.6 km in the NE-SW dimension. The (U-Th)/He age of this impact structure indicates an age range of 84.4 +/- 1.4 m.y. (Wartho et al., 2012). The target region comprised, weathered crystalline rock of the regional Appalachian Piedmont metamorphic complex, which in turn was unconformably overlain by several tens of meters of poorly consolidated sand- and clay-rich sediments, specifically the Upper Cretaceous Tuscaloosa Group and younger Eutaw Formation (Neathery et al., 1976; King et al., 2002). The target water depth was previously estimated to have been approximately in the range of ~ 35 to 100 m based on target's paleogeography (King et al., 2002; 2006).

As is typical with many marine impacts, the crater-filling stratigraphy at Wetumpka is related to the behavior of water-saturated materials in the target and to the return of displaced sea water after impact. The crater-filling stratigraphy unit at Wetumpka (a formal stratigraphic unit named the Wetumpka Mélange by King, 1998) has several distinctive internal stratigraphic components. In stratigraphic order, and thus in order of formation during impact, these components are: (1) impactite sands; (2) trans-crater slide unit; (3) crystalline boulder-bearing bed; and (4) resurge chalk deposits. Impactite sands are monomict clastic sediments that contain some large, stratified sedimentary target blocks; whereas the trans-crater slide unit has folded, and in some instances, inverted stratigraphy of target units (its origin is evidently related to a massive slump failure of the southern rim; King et al., 2006; King and Ormö, 2011). The crystalline boulder-bearing unit consists of a pebble and cobble- rich sandy clay matrix that contains shocked proximal ejecta, including a noteworthy component of crystalline target boulders (mainly schists and gneisses) that range up to 45 m in apparent diameter (King et al., 2006; 2015; Chinchalkar, 2019). Resurge chalks are resedimented deposits of chalk that were being deposited on an adjacent shelf area at the time of impact (i.e., the Upper Cretaceous Mooreville Chalk). These resurge chalks, in contrast to the original Mooreville Chalk, contain fine ejecta components (Petruny and King, 2018), as well as evidence of graded bedding and long-distance transport of deeper water megafauna (Markin and King, 2012). The resurge chalk has been interpreted as evidence of a turn-around of a rim-wave tsunami (King and Ormö, 2011).

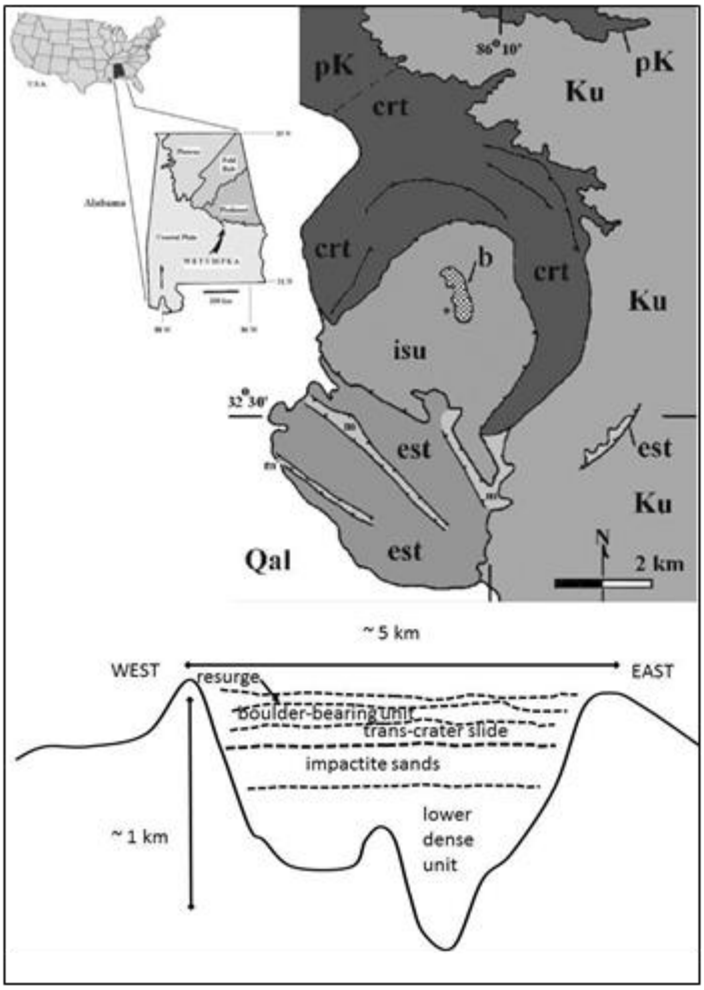

Fig. 1. Upper left – location map for Wetumpka impact structure in central Alabama USA. Upper right – simplified geological map of Wetumpka impact structure; pK - undisturbed pre-Cretaceous metamorphic rock; crt - crater rim terrain (crystalline); Ku - undisturbed Upper Cretaceous formations; est-extra-structure terrain (disturbed by impact but not within the crater); isu - intra- structure terrain (crater filling unit); b - boulder breccia unit; m - resurge chalk unit; * - crater center according to gravity profile. From King et al. (2006). Lower part – west to east, schematic crater cross-section based on a gravity profile showing the base of the impact structure and the interpreted relationships of the lower dense unit (known only from gravity study) and the sequence of units that crop out and have been drilled: the impactite sands; trans-crater slide, boulder-bearing unit, and the resurge chalk unit (shown as a continuous layer for schematic purposes only).

Outcrops and cores drilled so far reveal some details of the upper ~ 210 m of the Wetumpka crater-filling materials. An estimated theoretical model cross section, presented by King et al. (2006), predicted that the crater filling materials might be ~ 1 km thick. In this model, the upper ~ 400 m of the anticipated ~ 1 km was thought likely to be displaced materials (i.e., slumped materials akin to the impactite sands, trans-crater slide, and crystalline boulder-bearing breccia noted above) and the lower ~ 600 m was the anticipated autochthonous breccia lens (i.e., slumped crystalline materials). These units, likely correspond closely to the 2.1 and 2.6 g/cm3 crater-filling units, as suggested by gravity modeling (Robbins et al., 2011). Digital modeling suggests that this lower, denser crater-filling unit is likely the result of early, transient crater collapse of mainly lower target crystalline materials (De Marchi et al., 2021; 2022).

Figure 1 shows a schematic of the whole of the crater-filling stratigraphy noted above, including the lower, denser unit, and the overlying sequence of sedimentary target-dominated materials and the oceanic resurge unit. It is likely that marine impact structures will have a crater- filling sequence akin to Wetumpka but slightly different owing to circumstances p eculiar to the target situation. Similar sequences in marine impact structures have been noted at Lockne in Sweden (Ormö and Lindström, 2000; Lindström et al., 2005; Ormö et al., 2013), Chicxulub in Mexico (Ormö et al., 2021) and Chesapeake Bay in Virginia (Gohn et al., 2006), among other craters. In particular, the reader is referred to the paper by Ormö et al. (2021) for comparative analysis of marine target impacts and their impact stratigraphy.

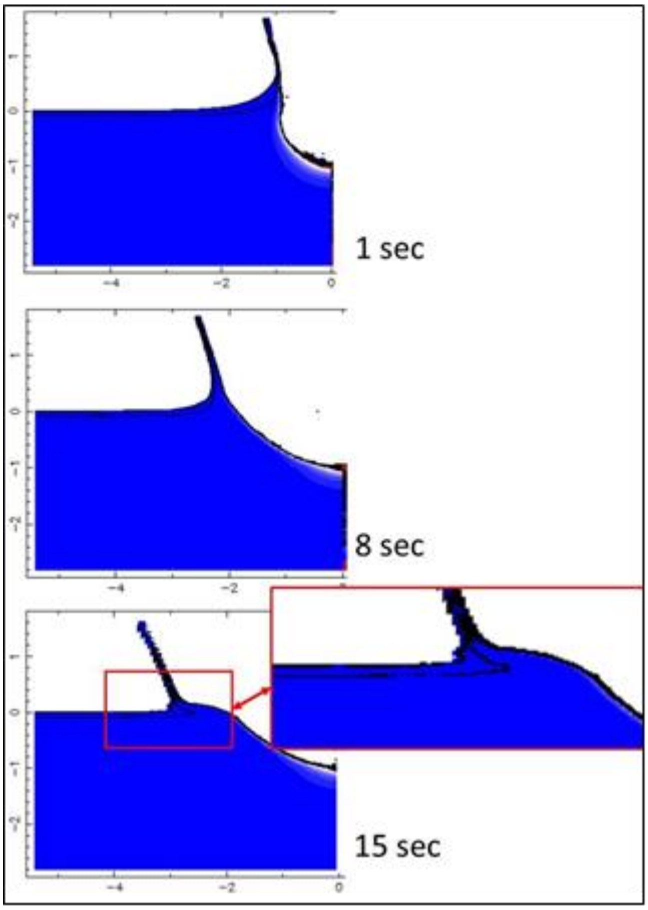

Fig. 2. Impact cratering modeling out-take frames from iSALE modeling study of Wetumpka impact structure by King et al. (2007). Vertical axes are km depth; horizontal axes are km from crater center. At 1 sec, the transient crater is forming and flap is vertical. At 8 sec, transient crater is rebounding and flap is starting to fall. At 15 sec, flap is falling and recumbent fold-like structure is forming at the rim. After this point, the flap falls and the layers within are upside down (i.e., there is an inverted stratigraphy beyond the rim proper). Frames provided by A. Lepinette.

Crater-Rim Stratigraphy

In marine impacts, as with dry-target impacts, materials of the crater rim are initially composed of largely intact ejecta that is lifted out of the opening crater and then lands on the rim as a concentric flap. This flap has a noteworthy characteristic, namely fold-over stratigraphy that resembles a recumbent fold. As can be seen in the sequence of digital modeling out-takes in Figure 2, the rim materials at Wetumpka are formed by lifting and falling, more of less intact target, upon the crater rim. This creates both a recumbent fold-like structure, but also at a short distance from the rim proper, an inverted stratigraphy is produced. This is so because the largely intact flap falls upside- down as it comes to rest upon the near crater terrain.

These folded and inverted relationships in the rim area have been known since the early days of crater studies on dry-target impacts (French, 1999; Melosh, 1986), but are particularly well preserved in many marine impact structures owing to the layered nature of the sedimentary target. Wetumpka impact structure does not have any preserved inverted stratigraphy outside the crater, but the trans-crater slide unit (shown schematically in Fig. 1) includes inverted stratigraphy. The trans-crater slide consists in part of flap ejecta that has moved back into the crater interior just after impact (Heider and King, 2016). A spectacular example of inverted stratigraphy beyond the crater rim exists at Lockne impact structure in Sweden. At Lockne, a large slab of crystalline target basement rocks lies upon several tens of meters of Cambrian shale and Ordovician limestone (Lindström et al., 2005). This relationship is shown well in a large high wall exposure within Skanska quarry at Nordanbergsberget, Jämtland County, Sweden (Sturkell and Lindström, 2004).

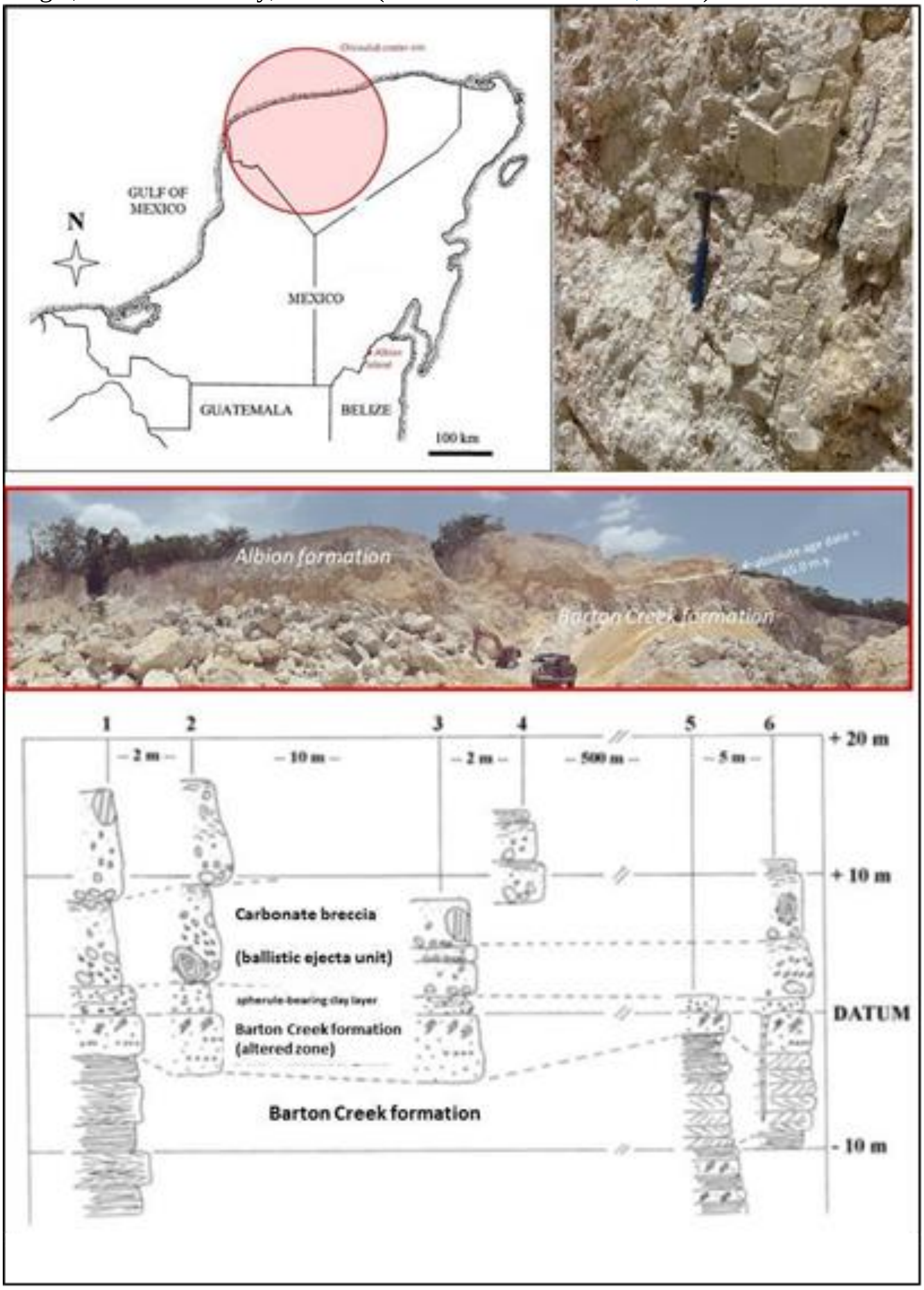

Fig. 3. Upper left – Map of the Yucatan peninsula region of Mexico showing also the location of Belize; interpreted outer rim of the buried Chicxulub impact structure is shown in red; Albion Island, Belize, location is shown. Upper right – Chicxulub ballistic ejecta of the Albion formation; clasts are from the Yucatan Group of Mexico; hammer for scale. Middle – photographic panorama of one of the high walls at a materials quarry, Albion Island; Albion formation is composed of Chicxulub ejecta; contact with Barton Creek formation (ballistic erosion surface of 66 my. ago) is marked; Barton Creek formation is latest Cretaceous (Maastrichtian); truck for scale. Lower part - correlation of six measured sections at Albion Island quarry showing dichotomy of lower 1 m spherule bed and overlying ballistic ejecta layer (carbonate breccia as in the photo above). From King and Petruny (2003b).

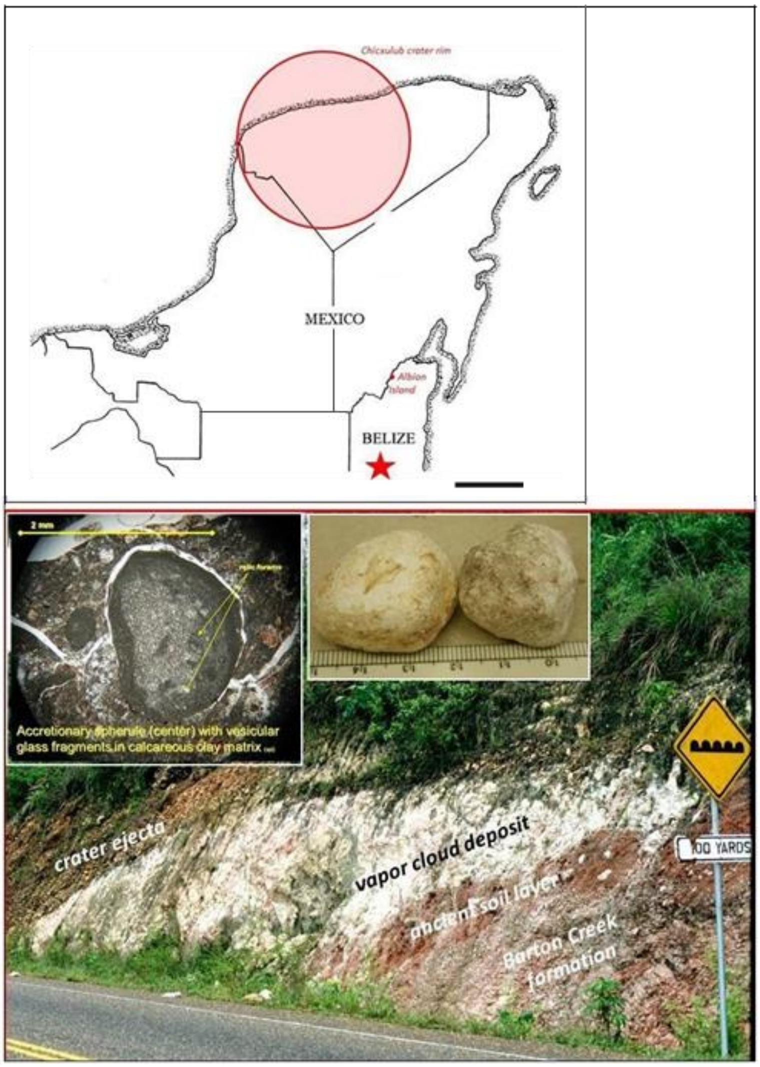

Fig. 4. Upper left - Map of the Yucatan peninsula region of Mexico showing also the location of Belize; interpreted outer rim of the buried Chicxulub impact structure is shown in red; Red star shows location of central Belize outcrop pictured below. Upper right - Chicxulub ballistic ejecta of the Albion formation; clasts are from the Yucatan Group of Mexico; hammer for scale. Lower part - Outcrop on main highway in the village of Armenia, Belize, showing Barton Creek formation, overlying soil layer, ~ 3 m vapor cloud deposit (spherule layer), and overlying ballistic ejecta. Insets; ~ 2.5-mm accretionary spherule in thin section and two large accretionary spherules (~ 2.5 cm) from the outcrop shown. From King and Petruny (2013; 2020).

Proximal Ejecta Stratigraphy

Impact ejecta consists of all fragmented, shocked, and melted materials that leave the crater as it is forming. To better appreciate this, the reader is referred to the classic works by French (1999) and Melosh (1986), and more recent reviews studies, e.g., Simonson and Glass (2004). Proximal and distal ejecta are commonly removed rapidly by erosion, and are commonly viewed as ephemeral, but in many instances vestiges of these deposits remain (and can also be reworked and redeposited near the crater). Ejecta obeys a scaling law and is usually continuous over an area of about 2-3 crater radii; distal ejecta (discussed next) can travel much farther. The ~ 300 km-diameter Chicxulub impact structure in Mexico, which formed at the Mesozoic-Cenozoic boundary (or the Cretaceous-Paleogene boundary; 66.0 million years ago), is perhaps the best known of marine impact structures with considerable proximal and distal ejecta.

Chicxulub impact ejecta is not well exposed in crater-adjacent areas of Mexico, however, in northern Belize, proximal ejecta is exposed in several places (Fig. 3 and 4). Several researchers have studied the overlying Cretaceous-Paleogene boundary (i.e., the Albion formation in northern Belize), including Ocampo et al. (1996), Pope et al. (1999; 2005), and King and Petruny (2003b; 2015; 2020). This ~ 10-15 m thick interval consists of direct, ballistic ejecta from the Chicxulub impact, which is situated a few 100 km away in Mexico. The direct ejecta has a stratal dichotomy in northern Belize, the lower ~ 1 m is composed of carbonate spherule-bearing, finely pulverized carbonate target materials that are related to vapor-cloud deposition and the upper part is composed of angular to rounded boulder- to block-size ejecta with a fine-grained carbonate matrix, which includes altered green glass shards (see references cited above). The upper part is ballistic ejecta, which means that it was launched from the impact structure during crater formation, travelled over a high trajectory, and landed in Belize (comminuting local bedrock in the process), and thus formed the upper part of the proximal ejecta in northern Belize (i.e., all materials above the vapor-cloud deposit with spherules). Figure 4 shows some details of the proximal stratigraphy of the Chicxulub impact ejecta in northern Belize, both from a megascopic and microscopic perspective. In smaller marine impacts, and particularly in marine impacts that have clastic rather than carbonate targets (as does Chicxulub), the vapor-plume / ballistic ejecta dichotomy may not be developed. However, the characteristics of Chicxulub ballistic ejecta likely have many textural features in common with proximal ejecta of other impact structures. These features include normal and reverse size grading, clast imbrication, flow lamination, and isolated and linked aggregates of clasts (i.e., clast clustering; discussed by King and Petruny, 2003b). It is suggested here that similar characteristics may attend other proximal ejecta of impact structures with similar sedimentary targets.

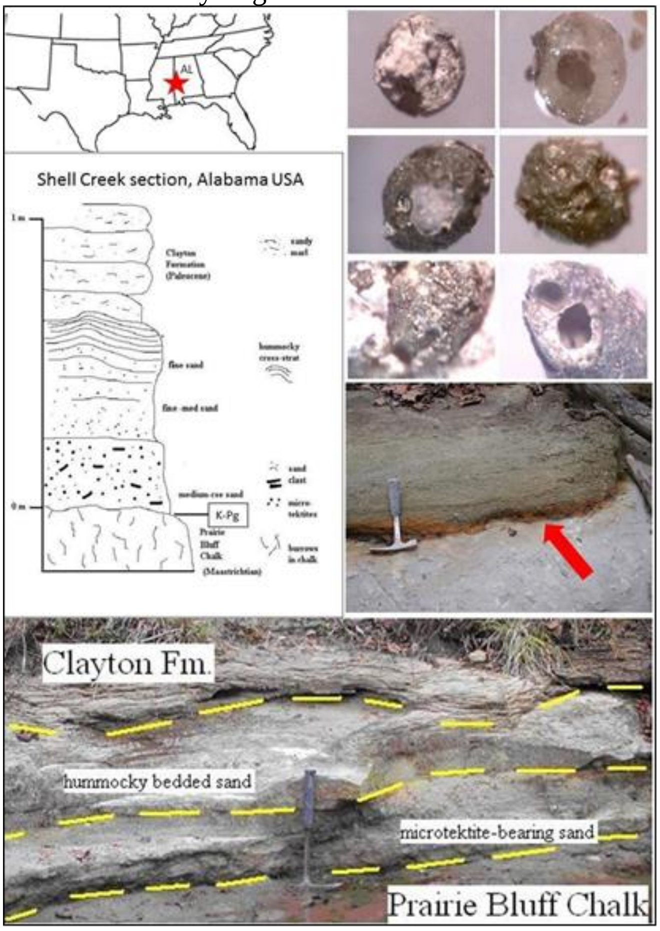

Fig. 5. Upper left – map of southeastern U.S. states, including Alabama (AL); red star indicates location of Shell Creek in Wilcox County. Upper right – images of spherules (microtektites) from lower sand bed of K-Pg boundary layer at Shell Creek (average size ~ 2 mm; some spherules are hollow and some are filled with clear calcite; from King and Petruny, 2008); Middle right – latest Maastrichtian Prairie Bluff Chalk overlain by K-Pg microtektite-bearing sand bed; eroded top of chalk is marked by an arrow. Middle left – measured section of K-Pg boundary at Shell Creek (modified from King and Petruny, 2008). Lower part – overview of outcrop section of K-Pg boundary at Shell Creek; the microtektite bed and hummocky bedded sand are part of a tempestite deposit that comprises the K-Pg boundary at Shell Creek. See discussion in King and Petruny (2008) and Ferrell et al. (2011).

Distal Ejecta Stratigraphy

Distal impact ejecta consists of all fragmented, shocked, and melted materials that leave the crater as it is forming and travel more than a few crater radii away from impact. Such materials are commonly discontinuous and contain mainly very fine materials that are were lofted into the atmosphere where they were suspended for some time during transport by wind. In some instances, distal ejecta is known to exist, yet the impact structure of origin is not (e.g., Archean spherule layers of Australia and South Africa; Simonson et al., 1999). Glass and Simonson (2013) presented a detailed treatment of these ejecta, and the reader is referring to that book for further reference. In the present paper, we will discuss two examples of distal ejecta, one reworked in a shallow marine setting and one intact (not reworked) in a deep-marine setting. Both examples relate to Chicxulub impact structure. For a review of distal ejecta from Chicxulub in the Gulf of Mexico region of the USA, the reader is referred to the work of Smit et al. (1996) and Smit (1999). In western Alabama USA, at Shell Creek in Wilcox County, acomplete section of the boundary interval between Maastrichtian (latest stage of Cretaceous) and Danian (earliest stage of Paleogene) crops out (Pitakpaivan, et al., 1994; King and Petruny, 2008; Ferrell et al., 2012). At Shell Creek, there are two beds, which were originally thought to represent a commonly observed stratal dichotomy of direct air-fall of distal ejecta (in this instance, impact spherules or microtektites and other impact-affected grains like partially melted carbonate clasts mixed with marine sand) and an overlying tsunami sand bed with no ejecta. This is the observed dichotomy in coeval boundary sections in Mexico (Smit et al., 1996), however, at Shell Creek this stratal dichotomy is related instead to reworking and redeposition of air-fall ejecta and then development of an overlying, hummocky bedded tempestite sand deposit (King and Petruny, 2008).

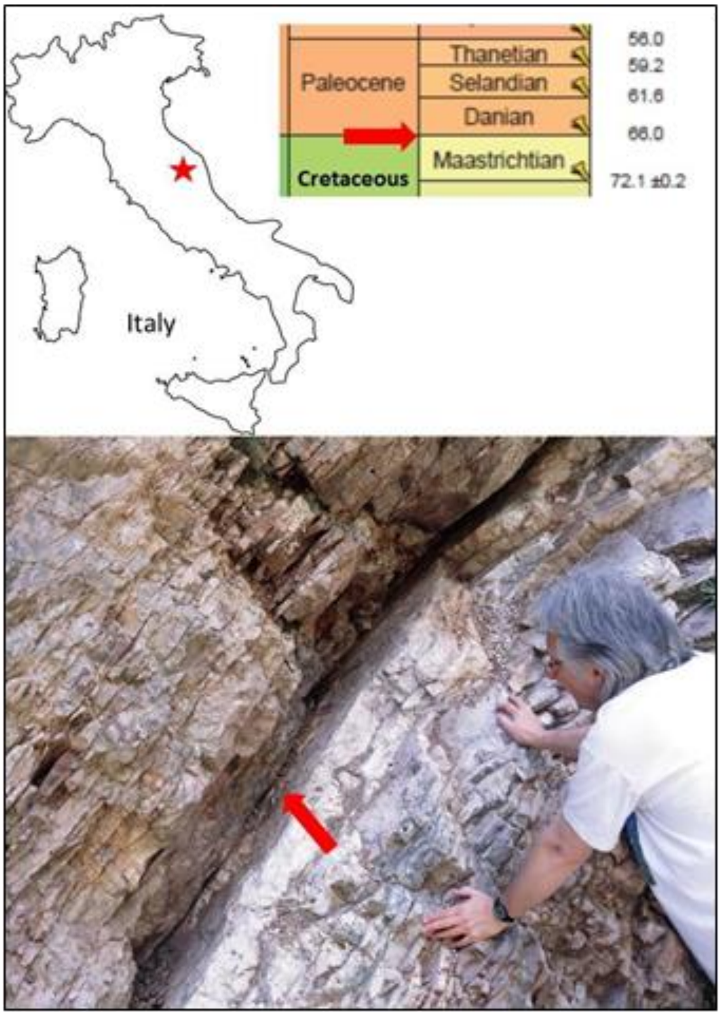

Fig. 6. Upper left – outline map of Italy showing the general location of K-Pg boundary outcrops in the Apennine Mountains around the town of Gubbio. Upper right – Section of the 2020 global time scale showing the stages astride the Cretaceous-Paleogene boundary at 66 m.y. ago (From Cohen et al., 2021). Lower part – A geologist observes the K-Pg boundary clay layer (red arrow points to its base) within the Scaglia Rossa formation; the clay layer is recessed on the outcrop and lies between latest light gray Maastrichtian pelagic limestones (below) and tan-pink Danian pelagic limestones (above); clay layer is about 2-3 cm thick. One of the world's six major mass extinctions of life is recorded at the level of the clay layer at this place and elsewhere around the globe.

Figure 5 shows the Shell Creek distal ejecta stratigraphy and details of the stratigraphic relationship of these deposits. Shell Creek is an example of reworked distal ejecta deposits; but for non-reworked distal ejecta deposits of Chicxulub in southern Mexico, the reader is referred to the works by Smit et al. (1996) and Smit (1999), as noted above. It should be noted that spherules of melt origin (or microtektites) are characteristic of distal ejecta in some places; and the work of Simonson (2003) reviews these impact-generated objects and their petrology. Distal ejecta also includes tektite strewnfields, for example, the strewnfield associated with Chesapeake Bay impact structure (Glass, 1989).

In some instances, distal ejecta is so widely dispersed that impact-affected grains are difficult to find, but the stratigraphic horizon where this widely dispersed ejecta occur is clearly delineated by geochemistry (Ormö et al., 2010). For example, at the Massignano global stratotype section in central Italy, widely dispersed ejecta from two late Eocene impact structures, Chesapeake Bay and Popigai, occur a few centimeters apart within a sequence of pelagic carbonate strata (Farley et al., 1998; Huber et al., 2003). Increased iridium concentration clearly defines the two ejecta-bearing stratigraphic horizons, and an increase in cosmic He3(perhaps borne by comets) attends the stratigraphic interval encompassing both ejecta horizons (Farley et al. 1998). In the central Apennine Mountain area of Italy, a thin clay-rich layer bearing distal ejecta such as quartz silt and very fine sand that include impact shock features, very fine melt particles, soot, and other impact-generated particles including impact spinels, crops out on mountain sides and in quarries over a wide area. This amazing occurrence of distal ejecta has been the subject of many investigations since it was originally discovered by Alvarez et al. (1980). The reader is ref erred to this iconic paper for details on the character of this distal ejecta, including its remarkable iridium content. The book, Impact Stratigraphy, the Italian record (Montanari and Koeberl, 2000) also reviews the distal stratigraphy of this area in detail, and the reader is referred to this reference.

The coeval equivalent of this distal ejecta layer has been found in Cretaceous-Paleogene boundary sediments of all the world's oceans and on all continents, including Antarctica (Claeys et al., 2002). It is fair to say that in terms of actual mass, the Chicxulub distal ejecta likely outweighs by many times, the mass of proximal ejecta and perhaps even that of the rim and crater-fill. Perhaps that makes it more understandablehow the impact stratigraphy related to Chicxulub was first discovered in Italy by the Alvarez team, rather than at proximal ejecta sites oreven the crater proper. The reader is also referred to the popular book, T. rex and the Crater of Doom, by Walter Alvarez (1997) as a light reading about this remarkable detective story about impacts. As is well known, this impact event and its ejecta are coeval with one of the world's greatest mass extinctions, which makes this research even more profound (Rampino and Caldeira, 2017). Figure 6 shows an outcrop in the area of the medieval city of Gubbio where the iridium- and distal ejecta-bearing layer crops out on the side of a highway.

Concluding Remarks

All geological processes generate geological products. As with eustasy and sequence stratigraphy, marine impacts have sedimentary consequences. From crater filling to distal ejecta, marine target impacts create a stratigraphic record that can be interpreted inthis context and evaluated based upon some well-established examples in the geological literature. The reader is encouraged to seek out impact stratigraphic relationships in the field and laboratory and to report them in the published literature so that this field of study will be vibrant into the future and so that we continue to better understand what happens when cosmic impact strikes the sea floor.

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