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Well-Preserved Accretionary Impact Spherules within Vapor-Plume Deposits, K–Pg Boundary Outcrop in the Village of Armenia, Belize

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ABSTRACT

Accretionary impact spherules, some as large as 3.1 cm in diameter, occur within a fine-grained carbonate layer (an impactoclastic calcisiltite), which lies atop the terminal Cretaceous (latest Maastrichtian) paleosol in an outcrop located at the village of Armenia in central Belize. This fine-grained layer is interpreted as the vapor plume deposit from the Chicxulub impact structure and is composed of pulverized and comminuted carbonate mixed with clay. The accretionary impact spherules were formed by the aggradation of the vapor plume's fine solid particles during turbulent flight over a distance of about 520 km from Chicxulub's southern rim. These impact spherules, which are remarkably well-preserved, exhibit a nucleus of either rock or glass and one to three concentric coatings of finely-comminuted carbonate target rock. Coatings on individual spherules are non-graded and display fine-scale components such as silt inclusions, crystal-filled radial fractures, and microconglomerate layers.

INTRODUCTION

"In an impact as large as [Chicxulub], enormous quantities of [carbon dioxide] were almost instantaneously released like popping the cork on a colossal bottle of champagne. Still more rock debris was carried aloft in this … exploding gas ball as it … blew through the atmosphere."

—Walter Alvarez, T. rex *and the Crater of Doom* (1997)

The K–Pg boundary stratigraphy of the Chicxulub impact structure, a site of significant geological implications, is well exposed adjacent to the Hummingbird Highway at the southern end of the village of Armenia in the Cayo District of central Belize (Fig. 1). The stratigraphic section (Fig. 2) includes the upper beds of the uppermost Maastrichtian Barton Creek formation (a dolomitic carbonate; bed 1 in Figure 1), which are in turn overlain by a lateritic clay bed (or paleosol) containing dolomitic carbonate boulders from the Barton Creek (bed 2 in Figure 1). This terminal Cretaceous paleosol layer is overlain by an accretionary spherule-bearing bed (bed 3 in Figure 1); about 2 m thick), which is composed of finely-comminuted, silt- and clay-size carbonate rock debris mixed with clay minerals, broken glass fragments, rounded limestone granules and pebbles, and many remarkably well-preserved accretionary impact spherules. The layer, likely the sedimentary record of the "exploding gas ball," i.e., the vapor plume from the Chicxulub impact event, is a testament to the far-reaching effects of such events. This outcrop is about 520 km (or about 4 crater radii) away from the southern crater rim of the Chicxulub impact structure, a distance that is somewhat greater than the generally accepted limit of the continuous ejecta blanket (i.e., 2–3 crater radii as per Stöffler and Grieve [2007]).

In a paper sanctioned by the International Union of Geological Sciences (IUGS), Stöffler and Grieve (2007) presented the presently accepted terminology regarding impact-related clastic sediments and other impact-produced sediments and rocks, which we follow in the present paper. Their adjectival term for lithic materials broken and distributed by impact processes is "impactoclastic;" hence, we use the terms *impactoclastic conglomerate* for bed 4 and *impactoclastic calcisiltite* for bed 3.

Above the impactoclastic spherule-bearing, calcisiltite layer lies an impactoclastic conglomerate bed composed mainly of slightly polished and rounded limestone clasts ranging from 2 to 30 cm in diameter (bed 4, where two individuals are standing, in Figure 1). These rounded and polished clasts are interpreted to be resedimented ballistic ejecta, which means they were transported from their original landing sites on terrain nearby and subsequently transported to their present location by fluvial processes (Pope et al., 2005; King and Petruny, 2015). These clasts belong to a distinctive type of Chicxulub ballistic ejecta, which have been called "Pook's pebbles" (Ocampo et al., 1997; Pope and

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Figure 1. (Top) Outcrop of the K–Pg boundary at Armenia, Belize. This outcrop occurs on the northbound side of Hummingbird Highway at the southern end of the village of Armenia. Stratigraphic units mentioned in the text and numbered on the photograph: (1) Barton Creek formation (uppermost Maastrichtian dolomitic carbonate); (2) paleosol with boulders of dolomitic carbonate; (3) spherule-bearing, impactoclastic bed of finely-comminuted carbonate; and (4) conglomeratic, rounded clast bed containing Pook's pebbles that have been resedimented. Photograph by Kevin Pope, c. 2001. (Bottom) Map of Belize, north of the 17th parallel (modified from Google Maps). A small red star indicates the location of the village of Armenia. Other sites mentioned in the present paper are also shown, namely Albion Island and Progresso Lagoon (also marked with red stars).

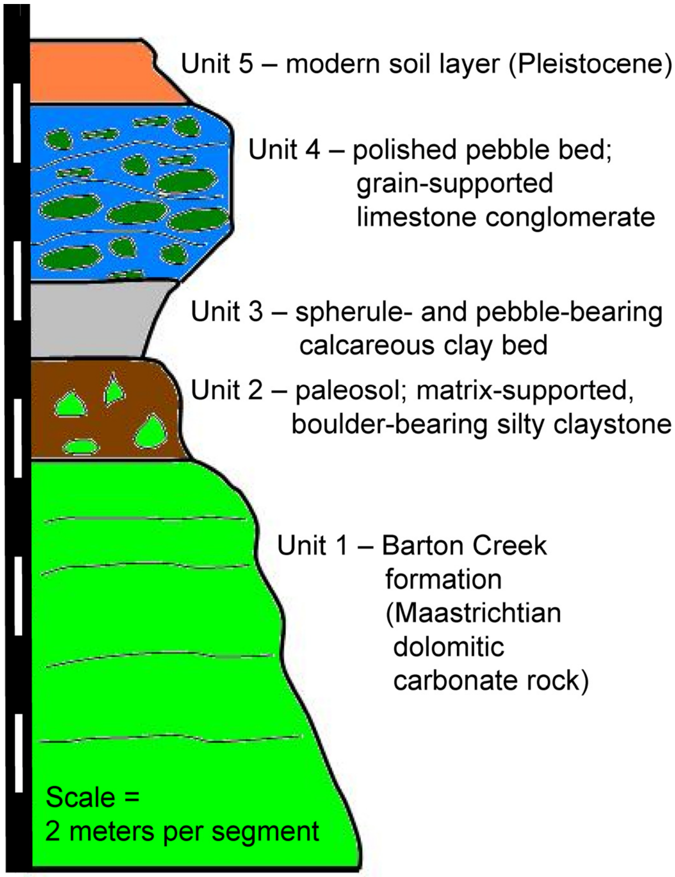

Figure 2. Simple measured section of the outcrop at Armenia in Figure 1. Numbers 1–4 are the same as in Figure 1. Scale is 2 m per vertical dash.

Ocampo, 2000). Pook's pebbles are thought to have been launched at velocities of 1 to 2 km/sec and reached an altitude of about 100 km before falling back to the Earth's surface in Belize and its vicinity (Kletetschka et al., 2020). Pook's pebbles are found in many locales in central Belize and are distinctive looking, striated and polished, pink to reddish pink micritic limestone clasts. Some possess impact pits on their surfaces that mimic tiny impact craters with slightly raised rims, where this morphology is interpreted to be the result of plastic deformation owing to interparticle impacts (Ocampo et al., 1997). In published reports, these clasts are commonly called "pebbles" even though some are large enough to be cobbles and small boulders.

The Pook's pebbles within bed 4 at Armenia bear evidence of resedimentation because these clasts are, in most instances, abraded or broken. Much of the distinctive fine polish generally found on these pebbles has been almost completely removed. Further, the conglomerate bed displays large-scale, trough cross-bedding consistent with the processes of fluvial channel deposition (Pope et al., 2005; King and Petruny, 2015). The outcrop appears part of a graben-filling sequence and not a widespread deposit. Another similar outcrop of resedimented Pook's pebbles is known as the Progresso Lagoon stratigraphic section, as described by King and Petruny (2015), which also shows evidence of fluvial deposition. The graben-filling interpretation of these ballistic sedimentary clasts at both Armenia and Progresso Lagoon is consistent with localized preservation of this remarkable stratigraphic section, as well as being supportive of the interpreted fluvial processes (King and Petruny, 2015). The location of Progresso Lagoon is shown on the Belize map in Figure 1.

As noted above, Stöffler and Grieve (2007) laid out the presently accepted terminology for impact materials, which applies to the present study. They discuss the concept of the "impact formation," which is a "geological formation produced by impact." Because this is the genetic nature of the stratigraphic unit comprised of beds 3 and 4 in Armenia (Figs. 1 and 2), this is an impact formation. Presently, this formation has no name at Armenia; however, at Albion Island in northern Belize (location shown in Figure 1), the impact formation at this stratigraphic level (i.e., K–Pg boundary) is called the Albion formation (an informal unit first mentioned by Ocampo et al. [1996]). In central Belize, Ocampo (1997) and Pope and Ocampo (2000) noted coeval, informal K–Pg units, which they called Cayo diamictite and Teakettle diamictite, respectively. Both these K–Pg diamictites contain Pook's pebbles, but these informal stratigraphic names do not apply to Armenia. According to the classification of Stöffler and Grieve (2007), the unnamed formation at Armenia is a "distal impactite" of "air-fall origin."

The accretionary spherule-bearing bed at Armenia contains remarkable accretionary impact spherules and other impactoclastic particles (bed 3; Figs. 1 and 2). The spherule-bearing layer is very soft and exhibits only light colors (tan, pink, gray, and white; Fig. 3). Its abundant matrix comprises more than half the volume of this bed. Bed 3 is composed of impactoclastic silts and clays, i.e., mixed carbonate and terrigenous materials that are finely pulverized, which we call a *calcisiltite* (a term first proposed by Kay [1951], which applies well in this instance). This bed also contains, in addition to its spherules, abundant vesicular glass fragments (Figs. 4 and 5) and small, polished limestone granules, pebbles, cobbles, and small boulders (ranging from 0.5 to 4 cm in diameter). Most of these polished limestone clasts appear to be small Pook's pebbles (see discussion below), but others are small, rounded limestone clasts. Bed 3's matrix also contains a tiny component of small, rounded micritic carbonate grains that are of enigmatic origin (referred to generically herein as peloids, a term coined by Folk [1959]), comminuted fossil fragments and broken foraminifera, and small opaque grains of unknown origin.

The purpose of this investigation is to present the results of our investigation of the unnamed impact formation at Armenia, comprised of beds 3 and 4 in Figures 1 and 2, and the accretionary impact spherules of impactoclastic bed 3. In so doing, we illustrate the petrographic characteristics of the vapor plume deposits and their constituent accretionary impact spherules with photomicrographs and photomicrograph mosaics. We discuss how these spherules are similar to and different from spherules from other large impact craters, another K–Pg boundary outcrop in Belize that is closer to the Chicxulub impact structure, and some spherules from large volcanic eruptions.

METHODS

This study employed standard field and laboratory techniques to achieve its results. We employed a commercial petrographic laboratory to make standard-sized, polished petrographic thin sections of impact spherules, the matrix of impactoclastic bed 3, and some of the constituent pebbles and granules of bed 3. These materials were vacuum impregnated with epoxy, then sliced and mounted to the thin section. The thin section was ground in oil to prevent water damage to the relatively fragile materials within each thin-section slide. Because the thin sections were polished, no cover slip was needed.

Images were made using a Cannon digital camera adapted to attach to an Olympus BH–2 petrographic microscope. Photomicrographic mosaics were made by compiling several individual photomicrographs made at the same scale. Most photomicrographs were made using a 4x objective and a 2x ocular built into the vertical tube on the microscope that accepted the digital camera mount. Scales on each photomicrograph were computed by imaging a scale etched into a glass slide and transferring that scale to each photomicrograph. Plane light (noted in the caption

Figure 3. Close-up of a small part of the Armenia outcrop in Figure 1. Accretionary spherules and limestone pebbles are weathering out of the calcareous clay matrix in bed 3. Insets: Spherules are shown to scale in hand and next to a cm ruler. Spherules that have weathered out of the matrix lie on the outcrop next to the matrix area from which they came. Photographs by David King, c. 2008.

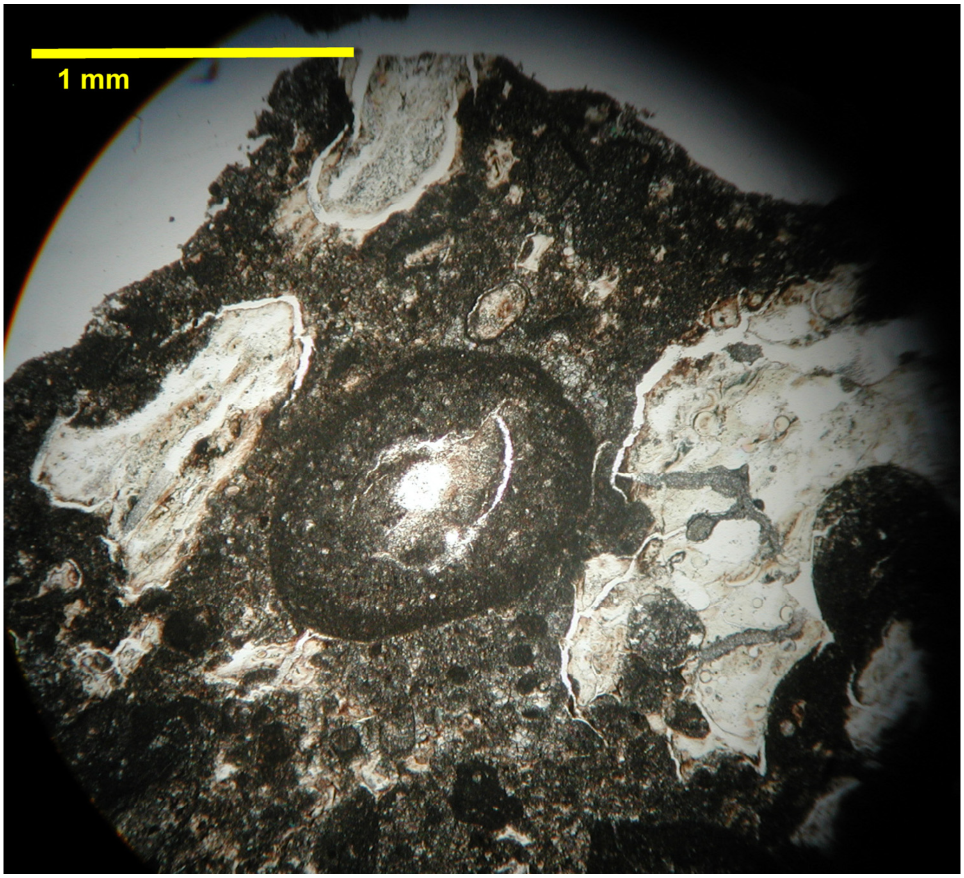

Figure 4. Thin-section photomicrograph of matrix sample from bed 3 showing an accretionary spherule (center) and associated vesicular glass fragments within the calcareous clay matrix. Peloids (?) and small glass particles also populate the matrix material. The spherule consists of a glassy particle as the nucleus and two layers (the inner layer is silt-rich, and the outer thin layer is microcrystalline (i.e., a micrite). Scale of 1 mm is shown at top; plane light.

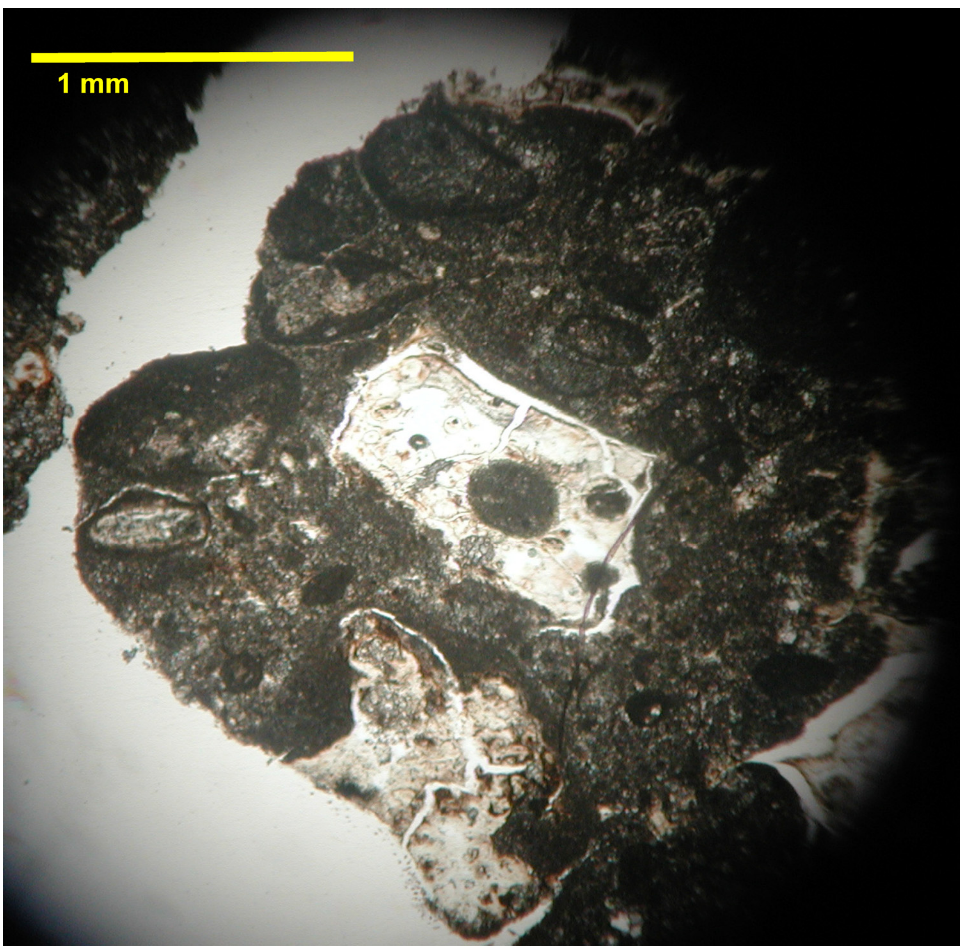

Figure 5. Thin-section photomicrograph of matrix sample from bed 3 showing a tiny accretionary spherule (?) within a larger angular glass particle (center) and a smoother glass particle with a thin accretionary coating (lower, center), among other things in the matrix. Other things include smaller vesicular glass fragments, peloids (?), and small accretionary (otherwise coated) particles that populate the matrix material. Scale of 1 mm is shown at top; plane light.

for some images) means plane-polarized light. Please note that the accretionary impact spherules in the figures herein are relatively small because of the size limitations afforded by a standard petrographic thin-section.

RESULTS

Worldwide, impact spherules are of two main physical types: (1) small, round, glassy objects that form from impact melt and (2) small, round balls of accreted materials that form from comminuted particles collecting around a nuclear particle (or core), such as a glass fragment (Simonson and Glass, 2004). The latter strongly resemble typical accretionary lapilli (Latin, "little stones") from sizeable volcanic eruptions (Schumacher and Schmincke, 1991; Gilbert and Lane, 1994). The impact spherules from Armenia are similar to what Schumacher and Schminke (1991) would call "core-type" volcanic lapilli, spherules with a relatively large core and only one or just a few coating layers. Core-type lapilli are most commonly found at great distances from the volcanic eruption, which is analogous to the situation for the Armenian spherules with respect to the Chicxulub crater.

Accretionary impact spherules from Armenia are abundant constituents in the impactoclastic calcisiltite bed and range in size from a few millimeters to 3.1 cm (i.e., sizes equal to coarse-grained sand through cobble according to Wentworth's scale). A typical Armenian impact spherule consists of a relatively large core (usually a recrystallized carbonate grain, but may also be a glass fragment), surrounded by one to three concentric coating layers composed mainly of finely-comminuted calcium carbonate. Concentric coating layers range in thickness from <0.001 mm to <1 mm and are structureless to vaguely laminated. The sizes of materials within each coating are not graded, and larger particles within a coating layer are not typically situated at the base of the coating layer where they occur. If there are two or three coating layers, the lowermost tend to have more silt-sized inclusions (silt-sized calcite crystals, glass fragments, and microfossil fragments). In rare instances, the coating layer directly adjacent to the core may be a microconglomerate.

Most of the accretionary impact spherules from Armenia display one or more radial fractures a few microns wide. These fractures originate in the outermost one or two layers and persist to the surface of the spherule. These fractures widen slightly toward the spherule's exterior but do not continually widen along the path of the fracture. In other words, the fractures typically start very small, widen to maximum over a relatively short distance, and persist over most of their path at about the same width. Fractures do not typically branch or bifurcate. All radial fractures are filled with what appear to be either very finely-crystalline, blocky calcite crystals or nanobreccia. The origin of these radial fractures is perhaps most easily explained by a slight radial contraction of the whole spherule upon cooling. The spherules from Armenia are not compacted to any discernable degree, so these fractures are thought to be related only to own their natural evolution. As an alternative hypothesis, it is possible that some of the carbonate in each concentric layer or coating was deposited—at least in part—as microcrystalline lime (CaO), which subsequently converted to low-magnesium calcite. Perhaps accompanying this aggradational recrystallization is the development of some or all radial fractures because the unit cell of calcite is about three times larger than the unit cell of lime. Slight differences in calcite crystallinity within spherule cores and some of the coatings may also be explained by lime diagenesis. An analysis of lime in impactites presented by Martinez et al. (1994) suggests that lime-related diagenesis within the spherules is still a viable hypothesis; however, subsequent experimental work by Bell (2010) suggests that lime is probably not a significant component of most impactites. Evans et al. (2017) suggested aragonite precipitation may also occur in impact conditions, which would then convert to low-magnesium calcite.

Figures 6–15 show examples of the several features (as noted above) within the matrix of impactoclastic bed 3 and many accretionary impact spherules from Armenia. The impact spherules shown in the photomicrographs and photomosaics in these eight figures are accompanied by detailed captions that connect to the discussion above.

As noted above, in the same bed as the spherules are small, polished limestone clasts (granules and pebbles) that are mainly nearly spherical ellipsoids. These clasts are small Pook's pebbles that initially possessed the same polish found on Pook's pebbles from elsewhere in northern Belize (Pope and Ocampo, 2000; Kletetschka et al., 2020). These clasts within the spherule bed have very thin, impact-recrystallized rims of columnar calcite crystals with interposed hematitic and goethite crystal aggregates (Fig. 16). This unusual alteration rim texture supports the previous interpretation of these clasts as ballistic ejecta that have undergone extreme heating and particle ablation under conditions of plastic deformation (Pope and Ocampo, 2000). Recent study of these clasts has shown that the nanophase iron within the hematitic and goethitic crystal aggregates comprising their thin, outer recrystallized zone (to about 200 microns depth) possess magnetic remanence directionality that indicates some Pook's pebbles (found elsewhere) have been subjected to intensely fluctuating electrical discharges (cf. lightning), such as might be expected in a roiling dust cloud (Kletetschka et al., 2020). The smaller end of the Pook's pebble grain-size distribution found within the spherule bed suggests evidence for a transition from vapor plume sedimentation to ballistic sedimentation.

DISCUSSION

The spherules at Armenia are interpreted as Chicxulub vapor plume products based on their stratigraphic position and internal physical structure, which strongly resemble typical accretionary lapilli from volcanic eruptions. Further, these spherules are enclosed within an impactoclastic, glass fragment-bearing calcisiltite bed, with a texture and composition consistent with the expected pulverized solid content entrained within a vapor plume. The glass content of bed 3 makes this spherule-bearing bed a *suevitic* deposit, but it is not a true suevite. A *suevite* is an impactoclastic glass-bearing lithic breccia (Stöffler and Grieve, 2007), whereas this bed is a matrix-rich deposit. Bed 3's subordinate stratigraphic position with respect to the overlying Pook's pebble bed, albeit reworked, is indicative of the velocity of vapor-plume movement versus ballistic sedimentation.

These accretionary spherules look like others from at least one other very large impact feature, namely the Proterozoic Sudbury impact structure in Canada (approximately 250 km diameter) (Addison et al., 2005; Huber and Koeberl, 2017). Also, the Armenia spherules look somewhat similar to spherules in proximal ejecta from the large Devonian Alamo impact event in Nevada (Warme et al., 2002).

Unlike previously reported, small, irregular, and flattened K–Pg accretionary spherules from within the 1 m thick basal K–Pg clay layer at Albion Island in northern Belize (Ocampo et al., 1996; Pope et al., 1999), the Armenia spherules reported on here are much better preserved, not compressed, and are larger, are layered, and almost all are ovoid to nearly perfectly spherical. Albion spherules are internally simple and of two main types. In the first type, there are no layers in the coating, and there is only a core and a single homogenous coating composed of microcrystalline dolomite. The second type has a core, and the surrounding coating layer is palagonitic clay, suggesting it was mainly impact glass before diagenesis. At Albion Island, approximately 15 m of impactoclastic breccia (direct ejecta) overlies the basal spherule bed. Thus, the stratigraphy differs from Armenia's (Ocampo et al., 1996; Pope et al., 1999; Keller et al., 2003; King and Petruny, 2003, 2009).

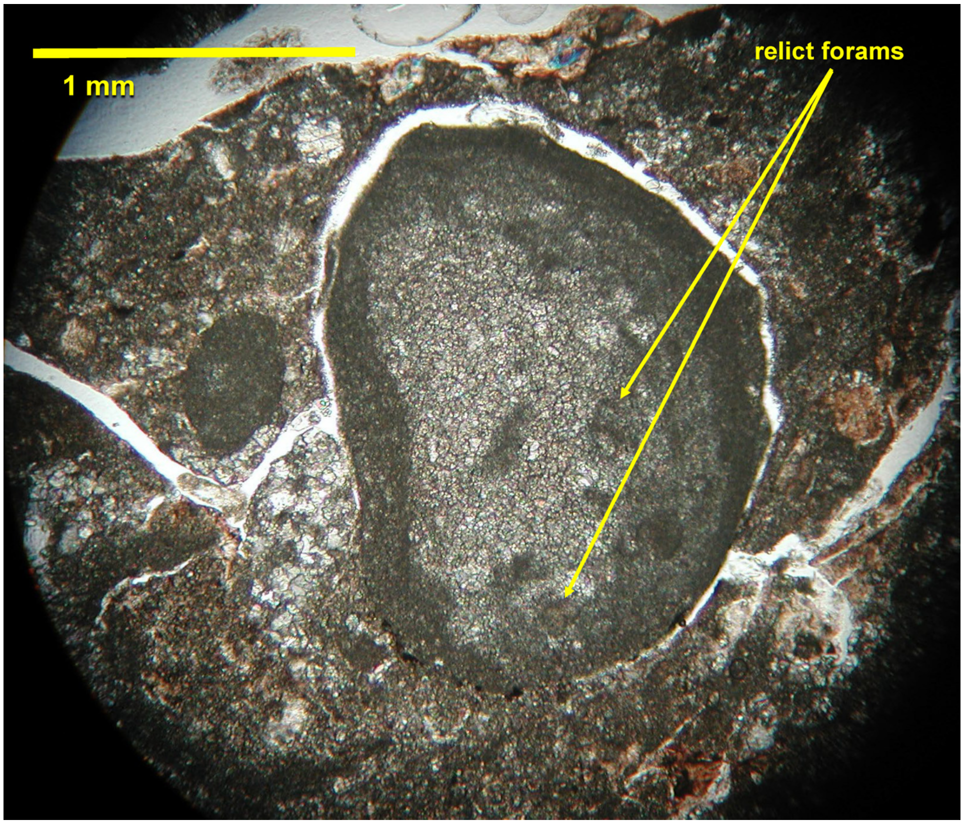

Figure 6. Thin-section photomicrograph of matrix sample from bed 3 showing an accretionary spherule (center) with a thin, single coating and associated particles of various origins within the matrix, including smaller, accretionary particles (?) with no layering (including some that have recrystallized and thus are no longer micritic), peloids (?), red phosphatic (?) particles, and unidentifiable fossil calcareous fragments. Arrows point out relict foraminifera in the nucleus of the large, accretionary spherule. Scale of 1 mm is shown at top; plane light.

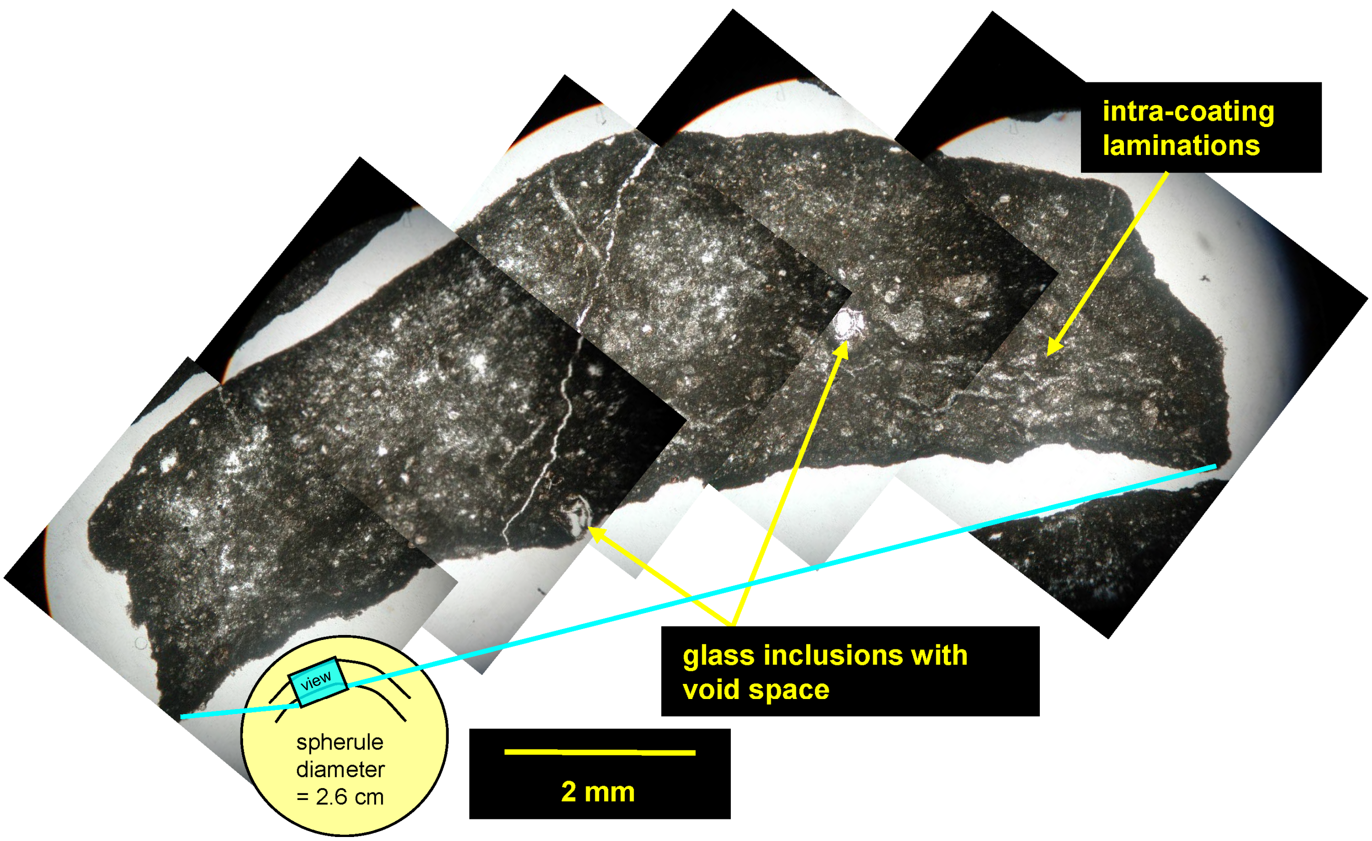

Figure 7. Thin-section photomicrograph mosaic showing a large fragment of a detached coating layer from a large accretionary spherule. This fragment was found detached from the spherule and within the matrix of bed 3. A schematic diagram showing the proposed origin of this broken particle is shown at the lower left. This thick coating shows internal features, including porosity, glass inclusions with void space, crinkly intra-coating laminations, and a crack that crosses the entire fragment but must be filled with calcite (?) crystals such that the fragment did not break at this crack. Scale is shown at the bottom, which is 2 mm; plane light.

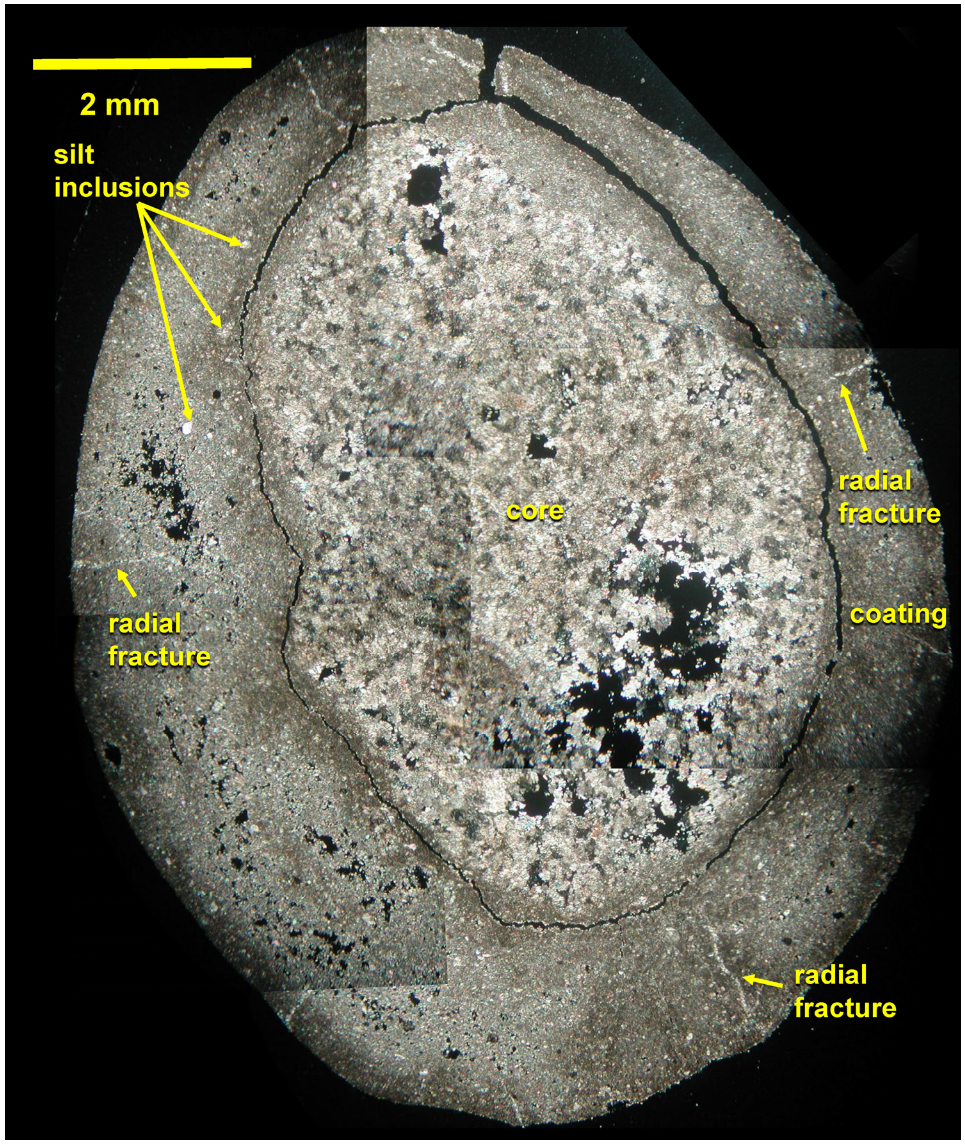

Figure 8. Thin-section photomicrograph mosaic showing a large accretionary spherule, which has been removed from the matrix of bed 3. This spherule is about 8 mm x 11 mm in size. The core is a relatively large, rounded, crystalline carbonate fragment overlain by a coating containing silt inclusions and some small radial fractures. Scale is shown at the top and is 2 mm; cross-polarized light.

CONCLUSIONS

The accretionary impact spherules from Armenia, Belize, tell a story of in-flight accretion within the Chicxulub impact's collapsing vapor plume. These spherules, which are exquisitely preserved and not compacted at all, are situated within an ~2 m thick bed of impactoclastic calcisiltite that is composed of the vapor plume's solid components, including glass fragments, carbonate clasts (both broken and rounded), and other small grains. There is a small component of granule- and pebble-sized, rounded and polished clasts, known as Pook's pebbles, a distinctive type of ballistic Chicxulub ejecta that occurs in some places in central Belize. That these admixed Pook's pebbles exist in the vapor plume deposits indicates a transition from vapor plume to ballistic sedimentation at Armenia. The overlying impactoclastic bed at Armenia is a layer of reworked Pook's pebbles.

Because most Armenian spherules display distinctive layering within the accretionary material, we suggest that these layers represent multiple coating phases during the spherule's flight within the vapor plume. Regarding the difference between multiple-layered spherules at Armenia and the single-layer, dolomitic spherules at Albion Island in northern Belize (approximately 400 km from the southern Chicxulub crater rim) (Pope et al., 1999), we think this may have to do with something relatively simple like greater flight distance, and therefore more time, with regard to their turbulent movements within the dust cloud. Longer flight time thus allowed for more accretion, specifically more accretionary episodes, during spherule genesis. In support of this suggestion, we note that the large, multiple-layered spherules from Sudbury impact structure, i.e., the Sudbury spherules that look most like Armenia's spherules, come from outcrops located approximately 550 km from Sudbury's rim (Huber and Koeberl, 2017).

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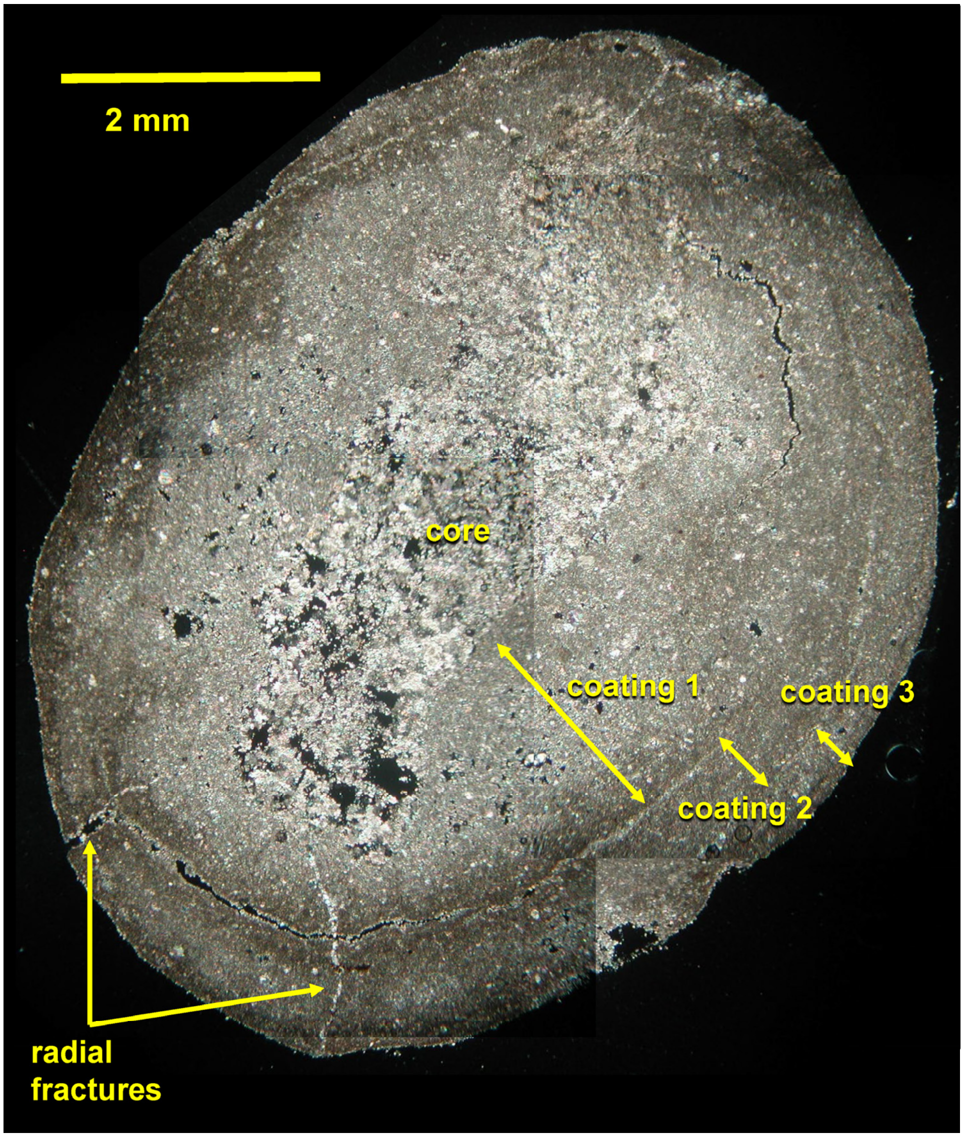

Figure 9. Thin-section photomicrograph mosaic showing a large accretionary spherule, which has been removed from the matrix of bed 3. This spherule is about 7 mm x 10 mm in size. The core is a relatively large, angular, crystalline carbonate fragment overlain by three coatings, all containing silt inclusions and radial fractures. The radial fracture at the top (touching the scale bar) passes through only coating 3, whereas the radial fractures at the bottom pass through coatings numbered 2 and 3. Scale is shown at top and is 2 mm; cross-polarized light.

REFERENCES CITED

Addison, W. D., G. R. Brumpton, D. A. Vallini, J. J. McNaughton, D. W. Davis, S. A. Kissin, P. W. Fralick, and A. L. Hammond, 2005, Discovery of distal ejecta from the 1850 Ma Sudbury impact event: Geology, v. 33, p. 193–196, <https://doi.org/10.1130/G21048.1>.

Alvarez, W., 1997, *T. rex* and the crater of doom: Princeton University Press, 208 p.

Bell, M. S., 2010, Relative shock effects in mixed powders of calcite, gypsum, and quartz: A calibration scheme from shock experiments, *in* R. L. Gibson and W. U. Reimold, eds., Large meteorite impacts and planetary evolution IV: Geological Society of America Special Paper 465, p. 593–608, <https://doi.org/10.1130/2010.2465(28)>.

Evans, K. R., M. P. McKay, and R. Sakidja, 2017, Matrix in carbonate impact breccias: comminution and precipitation from supercritical water (SCW)?:Geological Society of America Abstracts with Programs, v. 49, no. 6, <https://doi.org/10.1130/abs/2017AM-303042>.

Folk, R. L., 1959, Practical petrographic classification of limestones: American Association of Petroleum Geologists Bulletin, v. 43, p. 1–38.

Gilbert, J. S., and S. J. Lane, 1994, The origin of accretionary lapilli: Bulletin of Volcanology, v. 56, p. 398–411, <https://doi.org/10.1007/BF00326465>.

Huber, M. S., and C. Koeberl, 2017, Accretionary lapilli from the Sudbury impact event: Meteoritics and Planetary Science, v. 52, p. 1257–1276, <https://doi.org/10.1111/maps.12863>.

Kay, G. M., 1951, North American geosynclines: Geological Society of America Memoir 48, 143 p., <https://doi.org/10.1130/MEM48>.

Keller, G., W. Stinnesbeck, T. Adatte, B. Holland, D. Stübens, M. Harting, C. De Leon, and J. De La Cruz, 2003, Spherule deposits in Cretaceous-Tertiary boundary sediments in Belize and Guatemala: Journal of the Geological Society of London, v. 160, p. 783–795, <https://doi.org/10.1144/0016-764902-119>.

King, D. T., Jr. and L. W. Petruny, 2003, Stratigraphy and sedimentology of Cretaceous-Tertiary boundary breccia deposits at Albion Island, Belize, *in* C. Koeberl and F. Martinez-Ruiz, eds., Impact markers in the stratigraphic record: Springer-Verlag, Berlin, p. 203–228.

King, D. T., Jr., and L. W. Petruny, 2009, Accretionary spherules at the KT boundary, village of Armenia, Belize: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 119.

King, D. T., Jr., and L. W. Petruny, 2015, Correlation of northern Belize's Cretaceous-Paleogene ('KT') boundary sections: Gulf Coast Association of Geological Societies Transactions, v. 65, p. 463–473.

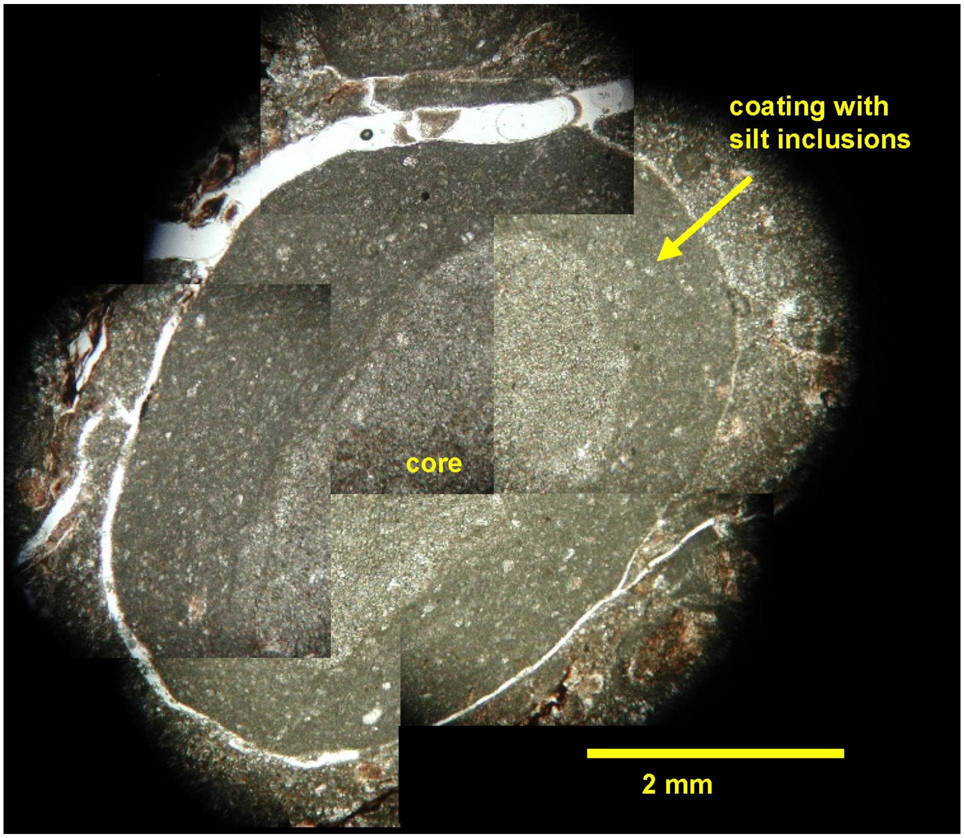

Figure 10. Thin-section photomicrograph mosaic showing a large accretionary spherule, which is still embedded in the matrix of bed 3. Matrix is visible at the margins of this large grain. This spherule is about 5 mm x 6 mm in size. The core is a rounded, fine-grained carbonate fragment with a constituent crystal size slightly larger than within the coatings. The core is overlain by one layer, which contains silt inclusions. This spherule contains no radial fractures. Scale is shown at bottom and is 2 mm; cross-polarized light.

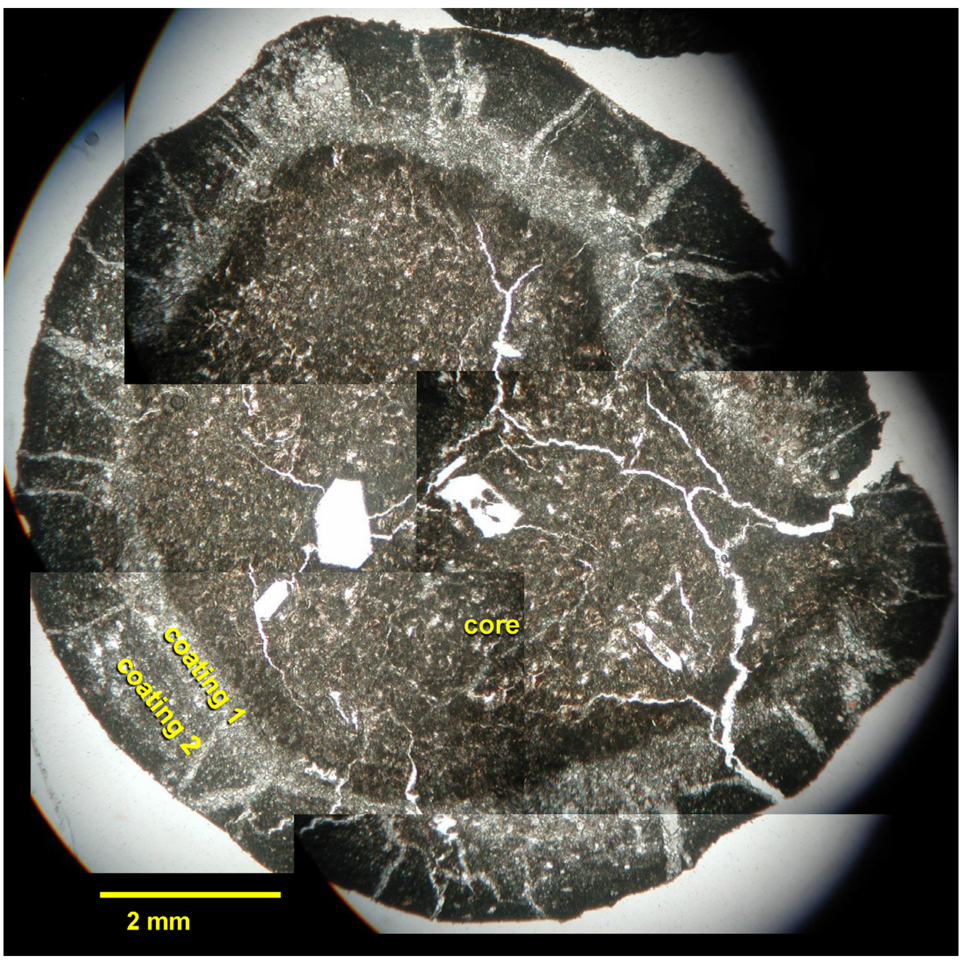

Figure 11. Thin-section photomicrograph mosaic showing a large accretionary spherule, which has been removed from the matrix of bed 3. This spherule is about 10 mm x 10 mm in size. The core is a relatively large, rounded, fine-grained peloidal (?) carbonate fragment with a cluster of three euhedral crystals near the center. These euhedral crystals are likely to have been calcium sulfate (gypsum), which is no longer present. The core also contains possible nannofossils, which are presently nanovoids in the core material (micrite). There are two coatings; the inner coating (coating 1) is thinner and has a slightly different crystallinity than the core and coating number 2. This spherule contains numerous wide radial fractures and an internal branching fracture system that may be diagenetic. On the upper part of the spherule, there are some bulbous and branching radial fractures (?), which are not typically seen in these spherules. Scale is shown at top and is 2 mm; cross-polarized light.

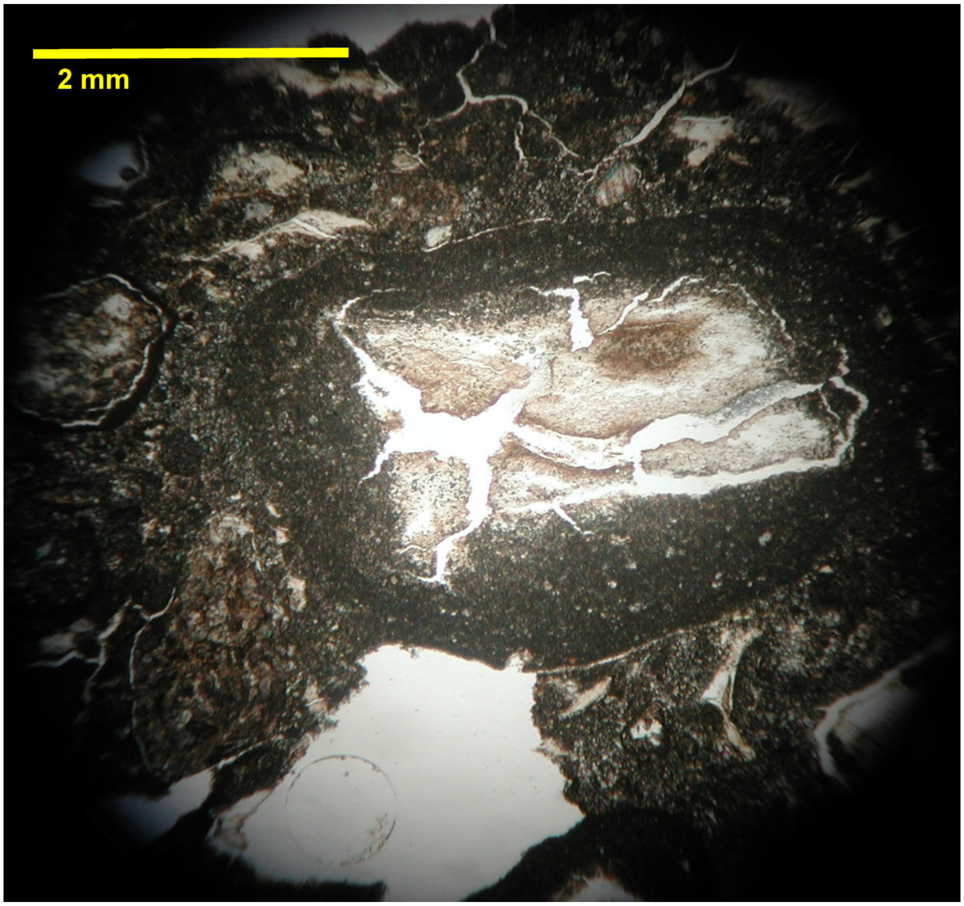

Figure 12. Thin-section photomicrograph showing an accretionary spherule embedded in the matrix of bed 3. The core of this accretionary spherule is a large glass fragment, which has been fractured in situ, perhaps in the diagenetic process. The glass is not vesicular, and it shows a brown spot on the right side of it that may reflect an internal compositional difference. A micro-fault cuts across one of the upper fractures (to the left of the brown spot in the glass), causing an apparent offset of the fracture. The glass core appears to have only one coating layer with silt inclusions. The fractures in the glass core appear to propagate into the single coating layer. In the matrix are fossil fragments, smaller accretionary grains (?), peloids (?), and glass shards (lower right). There is a large, irregular patch where an altered glass particle has popped out of the matrix. Scale is shown at the top and is 2 mm; plane light.

Kletetschka, G., A. Ocampo Uría, V. Zila, and T. Elbra, 2020, Electric discharge evidence found in a new class of material in the Chicxulub ejecta: Scientific Reports, v. 10, Paper 9035, <https://doi.org/10.1038/s41598-020-65974-2>.

Martinez, I., P. Agrinier, U. Schärer, and M. Javoy, 1994, A [sic] SEM–ATEM and stable isotope study of carbonates from the Haughton impact crater, Canada: Earth and Planetary Science Letters, v. 121, p. 559–574, <https://doi.org/10.1016/0012-821X(94)90091-4>.

Ocampo, A. C., K. O. Pope, and A. G. Fischer, 1996, Ejecta blanket deposits of the Chicxulub crater from Albion Island, Belize, *in* G. Ryder, D. Fastovsky, and S. Gartner, eds., The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, p. 75–88, <https://doi.org/10.1130/0-8137-2307-8.75>.

Ocampo, A. C., 1997, The geology of Chicxulub impact ejecta in Belize: M.S. Thesis, California State University at Northridge, 100 p., <https://scholarworks.calstate.edu/downloads/c534fs619>.

Ocampo, A. C., K. O. Pope, and A. G. Fischer, 1997, Carbonate ejecta from the Chicxulub crater: evidence for ablation and particle interactions under high temperatures and pressures: Lunar and Planetary Science XXVIII Abstract 1861, 2 p.

Pope, K. O., A. C. Ocampo, A. G. Fischer, W. Alvarez, B. W. Fouke, C. L. Webster, Jr., F. J. Vega, J. Smit, A. E. Fritsche, and P. Claeys, 1999, Chicxulub impact ejecta from Albion Island, Belize: Earth and Planetary Science Letters, v. 170, p. 351–364, <https://doi.org/10.1016/S0012-821X(99)00123-5>.

Pope, K. O., and A. C. Ocampo, 2000, Chicxulub high-altitude ballistic ejecta from central Belize: Lunar and Planetary Science XXXI Abstract 1419, 2 p.

Pope, K. O., A. C. Ocampo, A. G. Fischer, F. J. Vega, D. E. Ames, D. T. King, Jr., B. W. Fouke, R. J. Wachtman, and G. Kletetschka, 2005, Chicxulub impact ejecta deposits in southern Quintana Roo, México, and central Belize, in T. Kenkmann, F. P. Hörz, and A. Deutsch, eds., Large meteorite impacts III: Geological Society of America Special Paper 384, p. 171–190, <https://doi.org/10.1130/0-8137-2384-1.171>.

Schumacher, R., and H.–U. Schmincke, 1991, Internal structure and occurrence of accretionary lapilli—A case study at Lascher See volcano: Bulletin of Volcanology, v. 53, p. 612–634, <https://doi.org/10.1007/BF00493689>.

Simonson, B. W., and B. P. Glass, 2004, Spherule layers—Records of ancient impacts: Annual Review of Earth and Planetary Sciences, v. 32, p. 329–361, <https://10.1146/annurev.earth.32.101802.120458>.

Stöffler, D., and R. A. F. Grieve, 2007, Impactites (chapter 2.11), *in* D. Fettes and J. Desmons, eds., Metamorphic rocks: A classification and glossary of terms, recommendations of the International Union of Geological Sciences, Cambridge University Press, p. 82–92, 111–125, and 126–242.

Warme, J., M. Morgan, and H.–C. Kuehner, 2002, Impact-generated carbonate accretionary lapilli in the Late Devonian Alamo Breccia, *in* C. Koeberl and K. MacLeod, eds., Catastrophic impacts and mass extinctions: impacts and beyond: Geological Society of America Special Paper 356, p. 489–504, <https://doi.org/10.1130/0-8137-2356-6.489>.

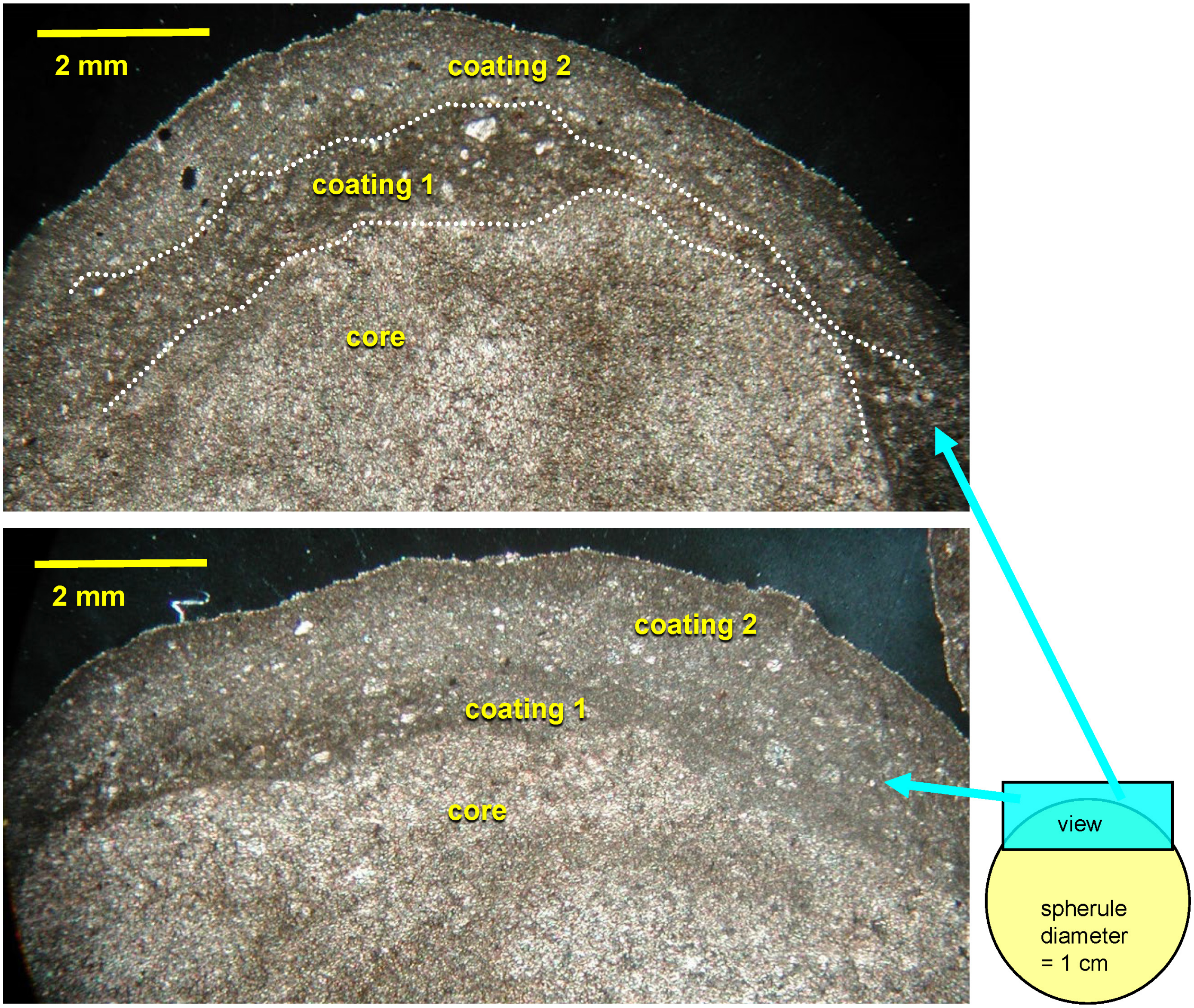

Figure 13. Thin-section photomicrographs showing parts of two accretionary spherules, which have been removed from the matrix of bed 3. The schematic diagram at the lower right shows where these photographs are located with respect to the whole of the spherule. In both instances, there is a large core and two coatings. A thin, dashed line separates the coatings in the upper image. In each instance, the core appears to be a rounded, micritic carbonate particle, which has slightly aggraded in their crystal sizes. In each instance, coatings numbered 1 and 2 do not have the same thickness all around the grain. The coatings have a micritic texture but also contain silt-sized inclusions. Scale is shown at left and is 2 mm in each image; cross-polarized light.

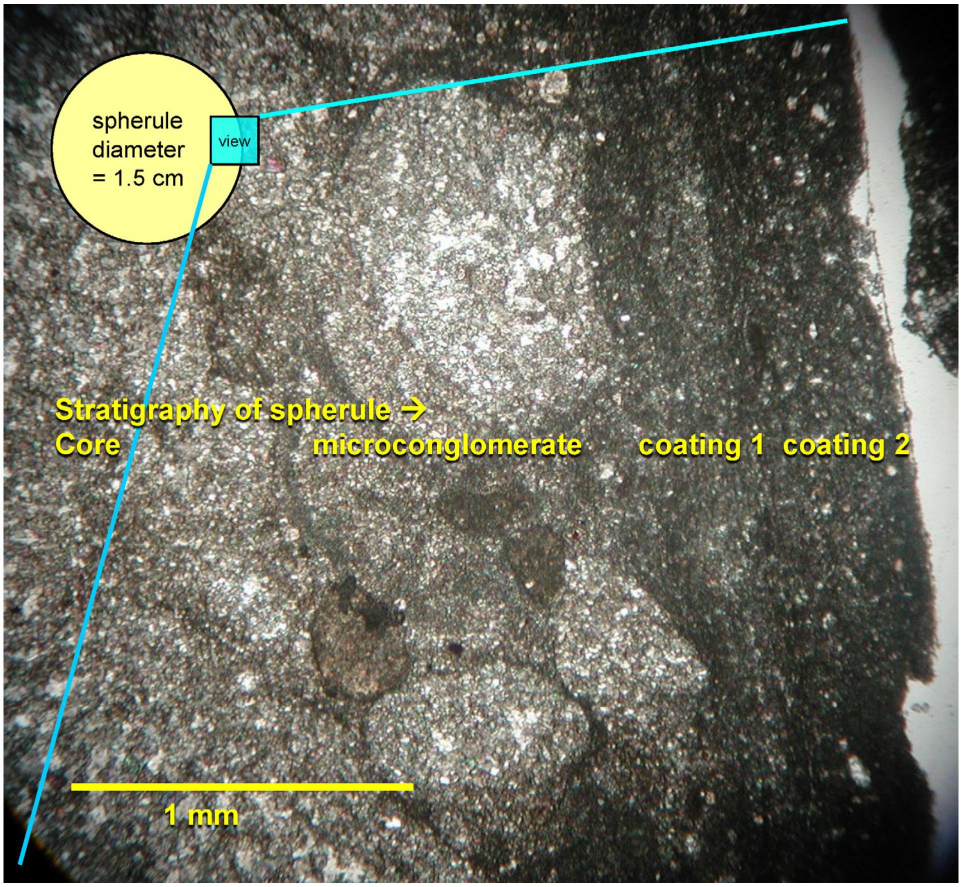

Figure 14. Thin-section photomicrograph showing a partial view of an accretionary spherule, which has been removed from the matrix of bed 3. The schematic diagram at the upper left shows where the photograph is located with respect to the whole of the spherule. There is a large core (marked) and two coatings. Between the core and coating number 1, there is a microconglomerate (marked) that is part of the spherule's stratigraphy. It is unclear if this microconglomerate layer was part of the core or has been accreted to the core. Both coatings contain silt grains and are thin compared to the core and microconglomerate. Coatings numbered 1 and 2 are about the same thickness around the grain. Scale is shown at the top and is 1 mm; plane light.

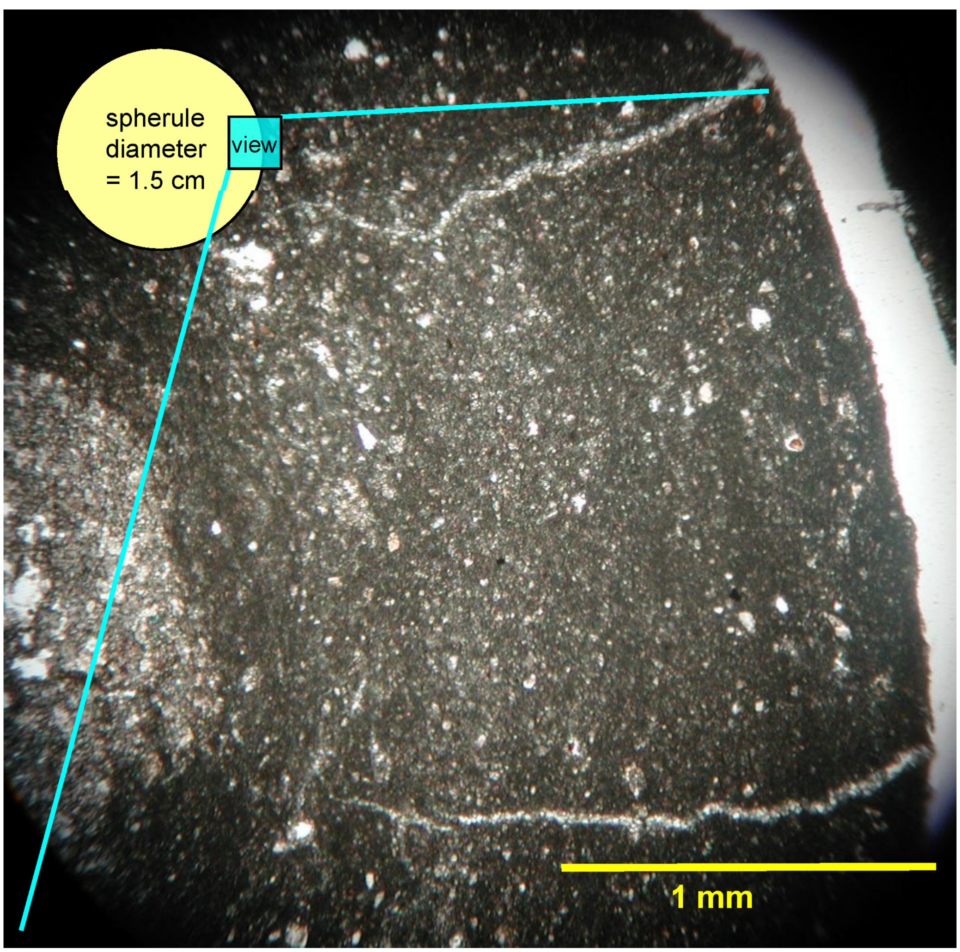

Figure 15. Thin-section photomicrograph showing a partial view of an accretionary spherule, which has been removed from the matrix of bed 3. The schematic diagram at the upper left shows where the photograph is located with respect to the whole of the spherule. There is a small core (left, center) and one relatively thick coating. The coating appears to have a lower zone with fewer silt grains and a vaguely laminar structure (made of finer-grained material), which grades upward into the slightly coarser main part of the coating, which contains silt grains. The main part of the coating possesses radial fractures, which widen slightly from their outset near the base of the outer part of the coating. Nanocrystalline material fills the radial fractures, but it is unclear if this is clastic material filling the radial fracture or finely-crystalline calcite. In this instance, the crystals in the radial fracture look more like the former. Scale is shown at the top and is 1 mm; plane light.

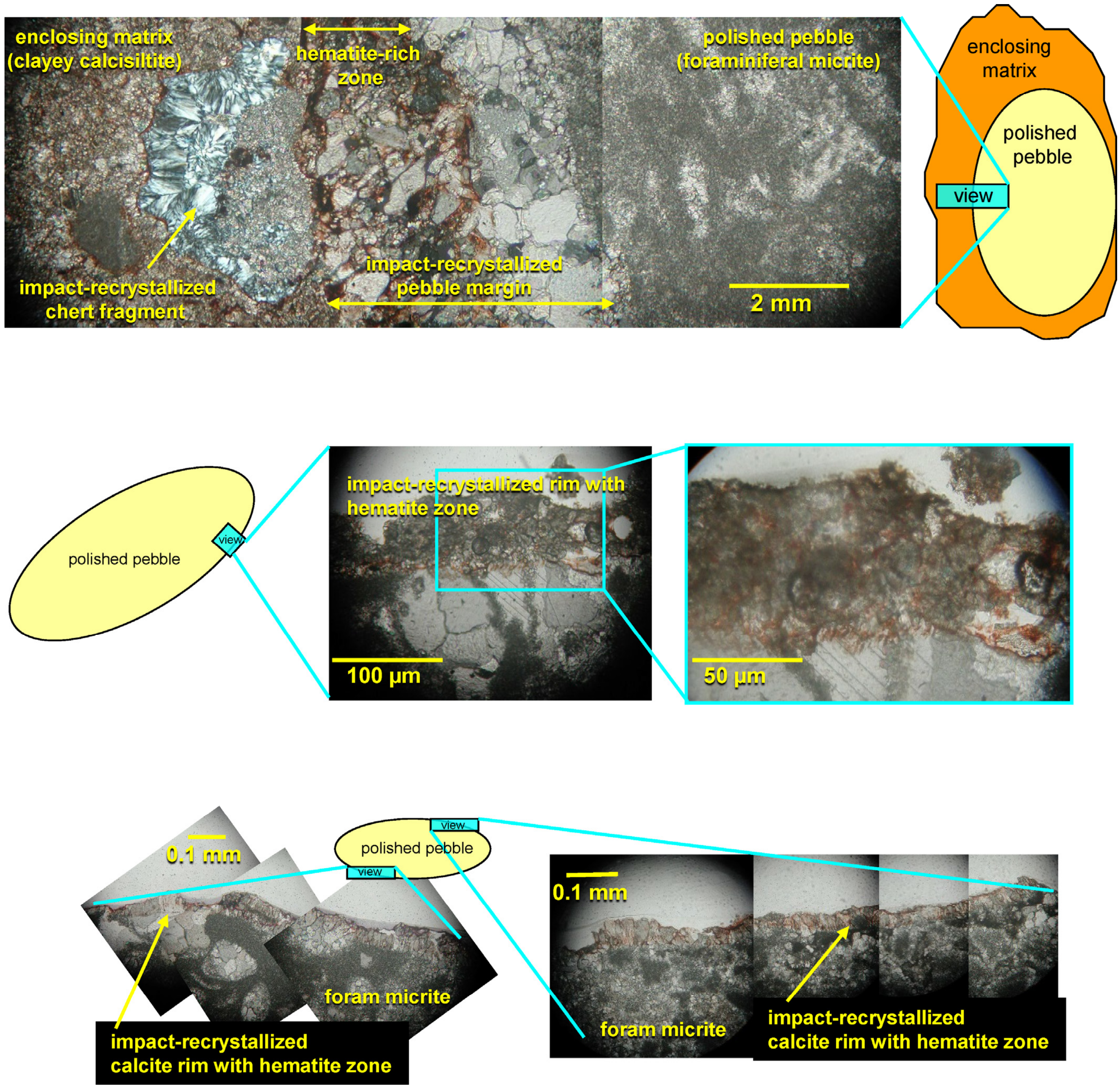

Figure 16. Three photomicrograph mosaics showing the nature of the thin exterior zone of hematitic or goethitic material interspersed within blocky calcite crystals in the polished limestone clasts (i.e., Pook's pebbles from within bed 3 [Figs. 1 and 2] of the Armenia stratigraphic section). Top mosaic—A schematic diagram at right shows the location of the mosaic with respect to the margin of the polished pebble, which is still embedded in a matrix of the pebble bed (bed 3). The polished pebble is a foraminiferal micrite, as shown in the first image (right), and that texture grades into the impact-recrystallized pebble margin (center). The marginal zone is divided into the inner blocky calcite zone with no hematite/goethite inclusions and an outer zone with hematite/goethite between blocky but slightly elongated calcite crystals. On the left side of this mosaic, a grain of impact-recrystallized (chalcedonic) chert lies next to the polished pebble's surface, and the enclosing matrix (calcisiltite) is shown on the far left. Scale is at the bottom and is 1 mm; the width of the field of view of this mosaic is about 6 mm; cross-polarized light. Middle images—A schematic diagram at the left shows the location of the images with respect to the margin of the polished pebble that has been removed from the matrix of the spherule bed (bed 3). The polished pebble's impact-recrystallized rim with the hematite/goethite-enriched zone is shown in both thin section views; the view on the right is an enlargement of the area in the blue box. The pebble's rim is divided into the lower blocky calcite zone and the outer hematite/goethite-rich zone. In this instance, the outer hematite/goethite-rich zone is finer blocky calcite crystals, a texture suggestive of rapid crystallization of the constituent calcite. Scale is at the bottom and is 100 µm in the view on the left and 50 µm on the right; plane light. Lower mosaics—A schematic diagram at the center shows the location of the two mosaics with respect to the margin of the polished pebble that has been removed from the matrix of the spherule bed (bed 3). In the mosaic on the right side, the polished pebble's impact-recrystallized calcite rim with the hematite/goethite-enriched zone is shown, as well as the underlying foraminiferal micrite of the pebble's main mass. In the mosaic on the right, the impact-recrystallized calcite rim with its hematite/goethite-rich zone lies above the pebble's foraminiferal micrite. Scale in each instance is 0.1 mm; plane light.