Understanding Late Devonian and Permian-Triassic Biotic and Climatic Events:
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Chapter 4

Sedimentary fill of the Late Devonian Flynn Creek crater: a hard target marine impact

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Abstract

The 3.6 km wide Flynn Creek crater in north-central Tennessee was produced by an asteroid that struck a flat lying succession of Ordovician carbonates. The crater is filled by a basal breccia and Late Devonian Chattanooga black shale. Conodonts in shallow water lag deposits that overlie the Ordovician succession in the region indicate lower Frasnian flooding of the area. The continuous stratigraphic record in the crater spans impact and post-impact deposits; the recovery of shallow water components and lower Frasnian conodonts in initial marine deposits above the crater fill breccia indicate that marine sedimentation commenced immediately after impact and that the impact occurred in shallow water. Most recent radiometric calibrations of Devonian conodont zones suggest that the impact occurred around 382 Ma.

Stratigraphy and sedimentary features suggest the following sequence of events: (1) shallow water impact during the early Frasnian; (2) formation of basal breccia as a fallback deposit; (3) deposition of graded breccia as displaced water rushed back into the crater; (4) ejecta washed back into the crater by storm-induced waves and currents; (5) accumulation and preservation of black shale first in the crater, and also as sea level rose outside the crater. Because the target rocks were lithified carbonates, the Flynn Creek crater has the morphologic characteristics of a subaerial impact. The sediment fill, however, reflects the shallow marine setting of the impact site.

Keywords: wet impact; impact age; sedimentary processes; black shale; preservation

1. Introduction

After years of controversy, the field of impact geology is rapidly merging with the geological mainstream as geologists from various specializations increasingly investigate the effect of impacts on the preserved geologic record. More and more impacts are uncovered by non-specialists during the conventional geological investigations, such as the Chesapeake Bay structure (Poag, 1997), the Alamo Breccia (Warme and Sandberg, 1996; Sandberg et al., 2002), and spherule layers (Simonson and Harnik, 2000). While in earlier impact studies the focus was on verifying the impact and determining the processes and events at impact time, the study of post-impact sediments is rapidly gaining in importance because they preserve a record of the transition between impact-related effects and post-impact geological history. In some instances crater-fill sediments are the only preserved

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long-term record of post-impact geological and environmental processes that originally affected a much larger area (Beales and Lozej, 1975; Partridge et al., 1993; Grieve, 1997).

As documented by Roddy (1968), the Flynn Creek structure of north-central Tennessee resulted from a Devonian asteroid impact that produced a crater of 3.6 km diameter and a 150 m depth in the flat-lying Ordovician carbonates (Figs. 1, and 2). Petrography of brecciated rocks shows that only Ordovician strata were affected (Roddy, 1968). Silurian and Middle Devonian strata, which potentially occurred in the area, had been eroded prior to the Late Devonian (Conant and Swanson, 1961). The impact deformed underlying strata to a depth of approximately 500 m and brecciated more than 2 km^3 of rock, 1.3 km^3 of which was ejected (Roddy, 1968). Deformation includes folding and faulting of underlying strata, uplift along the crater rim, and formation of a central high due to rebound of the crater floor (Fig. 2). Within the resulting annular trough, deformed Ordovician carbonates were covered by a breccia layer of 40 m average thickness (Roddy, 1968). Elsewhere in central Tennessee, Ordovician carbonates are overlain by the Upper Devonian Chattanooga Shale, a marine black shale unit of less than 10 m thickness (Conant and Swanson, 1961). In contrast, at Flynn Creek up to 55 m of black shale are preserved (Roddy, 1968).

The Flynn Creek structure, once the subject of controversy (Boon and Albritton, 1936; Dietz, 1960; Conant and Swanson, 1961; Shoemaker and Eggleton, 1961; Bucher, 1963), has an impact origin (Roddy, 1966, 1968). Supporting observations are structural features that match other impact craters, shatter cones, and remnants of an ejecta blanket in a rim graben (Roddy, 1968). Because the crater is filled by Late Devonian black shales a mid-Devonian impact on a low relief land surface, followed by a period of subaerial erosion, was proposed by Roddy (1968). Marine flooding of the crater during the early Late

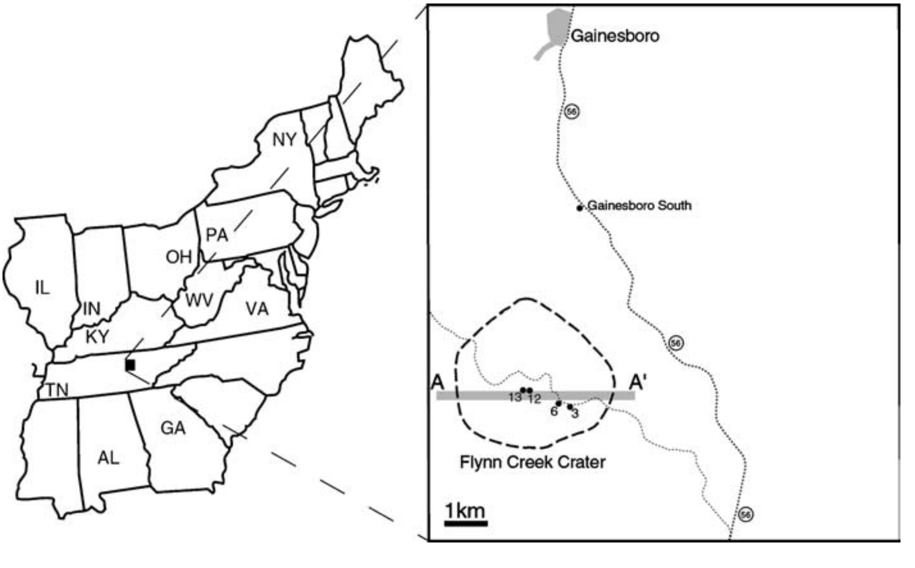

Figure 1. Location of study area in central Tennessee and enlarged detail map of study area with crater location and outline. The gray horizontal bar A-A' notes location of the crater cross section from Figure 2. The numbers within the crater indicate location of drill cores examined for this study. Roads are marked by short dashed lines.

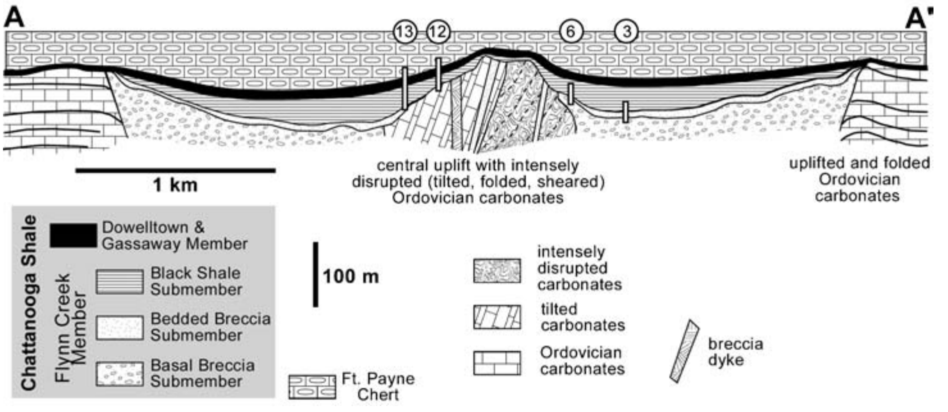

Figure 2. Stratigraphic overview and schematic presentation of stratigraphic relationships in the crater (crater topography from Roddy, 1966, 3 times vertical exaggeration). Vertical white bars and circled numbers mark projections of drill cores studied.

Devonian is indicated by conodonts from basal bedded crater deposits (Huddle, 1963). Roddy (1977) considered the possibility of a shallow marine impact in a later publication, but his data did not allow a clear determination.

Conversations by the senior author with David Roddy prior to his death in 2002 provided the impetus to conduct this study. Dave was aware that several critical questions still required an answer. Most pressing among these were: (1) whether the impact occurred on land or in water; (2) whether there was a temporal gap between the impact breccias and the subsequent post-impact deposits; and (3) how much constraint on the impact age could be obtained from the conodonts in the crater fill sediments. Cores examined in the summer of 1999 and 2000 lead to the observations that resolve these questions.

Sedimentologic and petrographic examination of the crater fill shows conclusively that the impact must have occurred when the area was covered by a shallow sea. Marine crater sedimentation commenced immediately after impact, and conodonts from the crater fill allow determination of impact time within the constraints of Devonian conodont stratigraphy and radiometric age determination (Klapper, 1997; Tucker et al., 1998).

The Chattanooga Shale, as defined by Conant and Swanson (1961), comprises only a small portion of the black shale fill in the crater. The bulk of the black shale is part of an earlier deposited member of the Chattanooga Shale, largely absent elsewhere, that extends the record of Devonian black shale deposition in central Tennessee.

2. Description of crater fill

We propose the name Flynn Creek Member for the portion of the crater fill that underlies the Dowelltown Member of the Chattanooga Shale of earlier definition (Conant and Swanson, 1961). The Flynn Creek Member consists, in ascending order, of three distinct units: (1) basal breccia; (2) bedded breccia; and (3) black shale submembers.

2.1. Basal breccia submember

The basal breccia consists of a very poorly sorted, chaotic mixture of boulder to granule size angular carbonate clasts derived from underlying strata. Coarser particles are set in a matrix of sand- to silt-size carbonate detritus and dolomite cement; deformation fabrics are common at the base. This unit is on average 40 m thick and passes without visible break into an uppermost division with clear normal grading. No other sedimentary structures are apparent. The unit is capped by a thin (2 cm) carbonaceous shale drape (Fig. 3).

2.2. Bedded breccia submember

The bedded breccia begins at the lowest shale drape that contains approximately 25% carbonate clasts, quartz and chert grains, silicified fossil debris, and well-rounded phosphate granules in a fine-grained matrix of organic matter, dolomicrite, and clays (Fig. 4). The shale is overlain by dolomite-cemented beds of gravel, granule, sand, and silt-size carbonate debris that range from 50 to 150 cm in thickness (Figs. 3–5). Beds vary in number from place to place, are separated from each other by shale drapes, are massive to crudely wavy-parallel bedded (centimeter to decimeter scale), and fine upwards in places. Roddy (1968) distinguished poorly bedded breccia, bedded dolomitic breccia, and bedded dolomite subdivisions that reflect the relative proportions of coarse versus fine carbonate debris. Poorly bedded breccia is dominated by carbonate clasts ranging in size from a few millimeters to several centimeters (Fig. 5); bedded dolomitic breccia contains a substantial proportion of sand- to silt-size carbonate debris; and bedded dolomite is dominated by sand- to silt-size grains and contains essentially no coarser clasts (Fig. 6). Poorly bedded breccia is more prominent along the margins of the crater; bedded dolomitic breccia and bedded dolomite dominate the interior portions of the crater (Fig. 2). The bedded breccia contains rounded carbonate clasts, several percent of scattered quartz grains in which no shock lamellae, chert grains, and rounded phosphate granules were observed (Figs. 5, and 6). Although bedded dolomite shows considerable recrystallization, many carbonate grains still have fine crystalline cores with impurities that indicate detrital origins (Fig. 7). Within bedded dolomite layers occur thinner (2–5 cm), graded dolomite beds that have horizontal lamination, water escape structures, and fading ripples (as defined by Stow and Shanmugam, 1980) in the basal portions. Dolomite beds may also show contorted laminae and, where overlain by a shale drape, have an irregular bumpy surface, probably a result of water escape (Fig. 3).

2.3. Black shale submember

Depending on position within the crater, the bedded breccia/dolomite interval may be directly overlain by Devonian black shales, or the contact may be marked by a layer of coarse sandstone. This sandstone, commonly near the crater margin, consists of 75% carbonate clasts, subordinate quartz and chert grains, silicified fossil debris, and rounded phosphate granules (Fig. 8). Thin sandstone layers, a few millimeters to 3 cm thick; of the same general composition occur throughout the basal 13 m of the black shale succession.

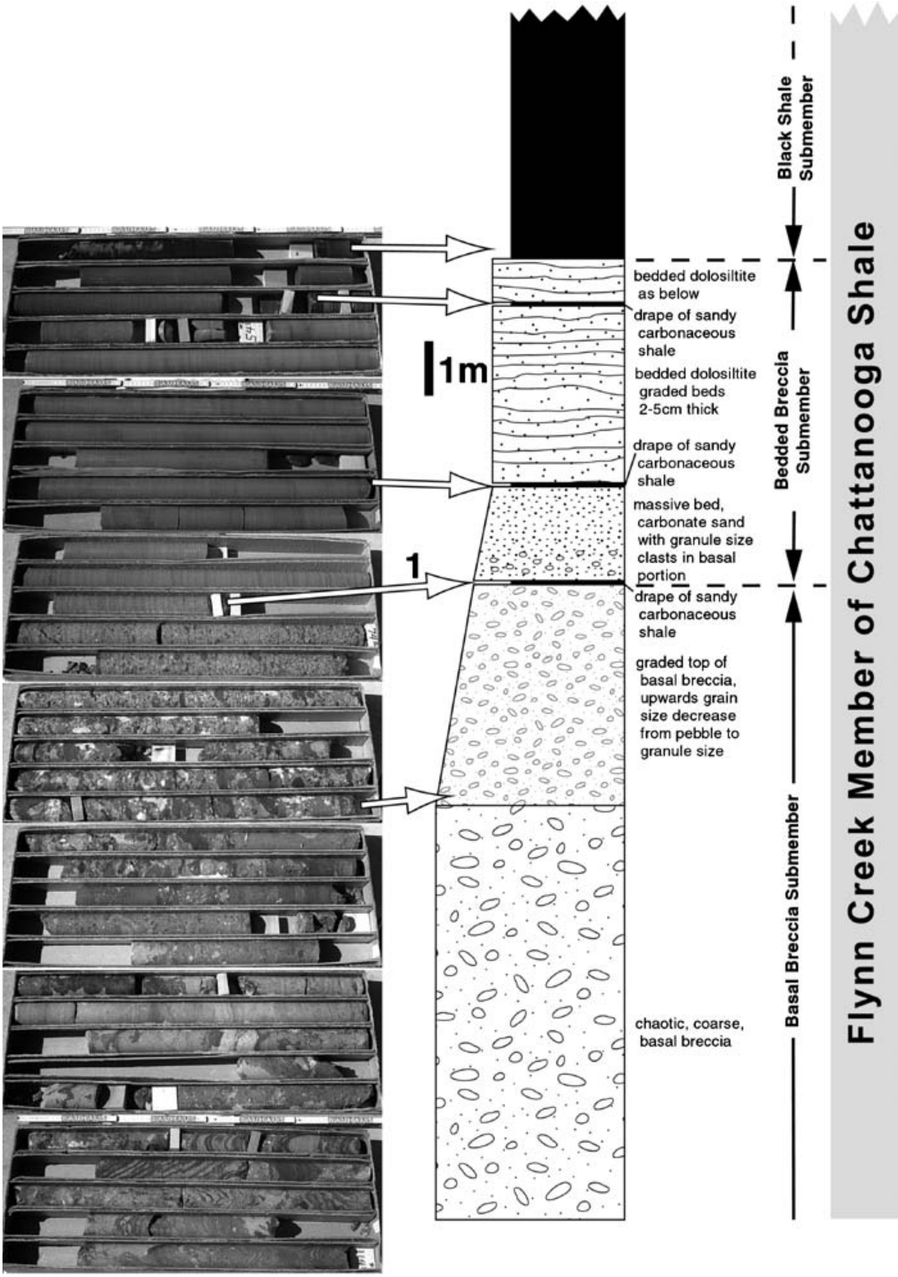

Figure 3. Core and corresponding stratigraphic section from drill hole 3 in the area between eastern crater rim and central uplift (see Fig. 1). Shown are the basal breccia submember, bedded breccia submember, and the bottom of the black shale submember of the Flynn Creek Member of the Chattanooga Shale. The first carbonaceous shale drape following breccia deposition is marked with arrow 1. Core boxes are approximately 82 cm long.

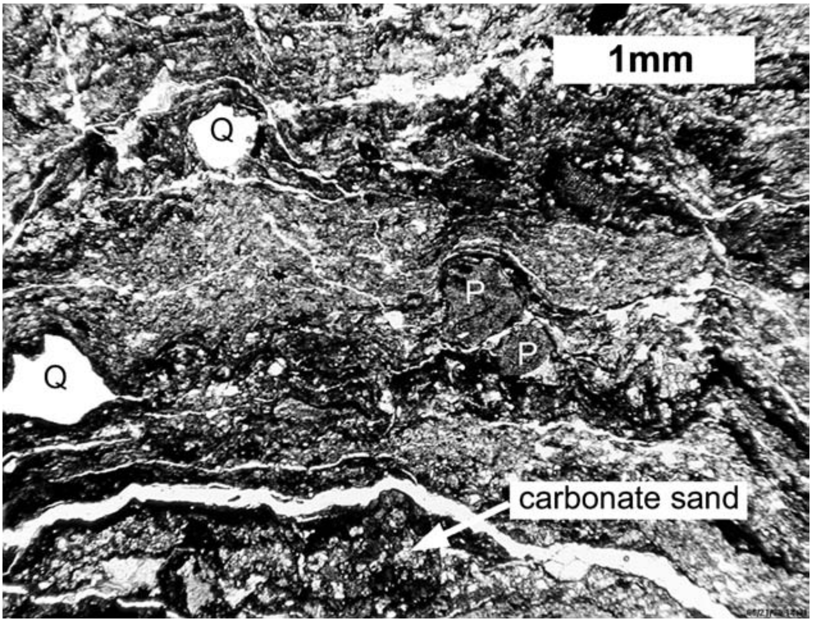

Figure 4. Photomicrograph of shale drape above basal breccia (arrow 1 in Fig. 3). Grains of quartz and chert are marked with Q, rounded phosphatic grains are marked with P. Note stringer of sand size carbonate debris (carbonate sand, white arrow). Wavy-crenulated nature of laminae due to compression of shale drapes over an irregular surface (e.g. projecting clasts).

Sandstone layers have sharp contacts and basal scour features on the underlying black shale and contain black shale rip-up clasts. Larger clasts can project above the upper surface of sandstone layers. The black shales are faintly banded, darker bands of clay, quartz silt, dolomite, and abundant organic matter alternate with lighter bands enriched in dolomite grains (Fig. 9). Silt- to sand-size carbonate debris at the base of lighter bands indicates that these constitute graded couplets (Fig. 9). Thin beds containing sand-sized quartz and pyrite grains, usually with diffuse lower and upper boundaries, carry the imprint of early diagenetic infilling of cysts of the marine alga *Tasmanites* (Fig. 10; Schieber, 1996, 1998a). Basal portions of the black shale succession also contain 10–30 cm thick intervals that have intense soft sediment deformation. The upper portion of the black shale succession is essentially identical to the Dowelltown Member.

3. Stratigraphic relationships

Within the bedded breccia submember, beds of bedded breccia are dominant near the crater margins, and bedded dolomite dominates the crater interior. Core logs and gamma ray profiles allow reconstruction of stratigraphic relationships between the black shale submember and the overlying Dowelltown Member of the Chattanooga Shale (Fig. 11). Only the upper portion of the crater fill succession is a direct match for the Dowelltown and Gassaway members at the reference section 20 km to the south at Hurricane Bridge.

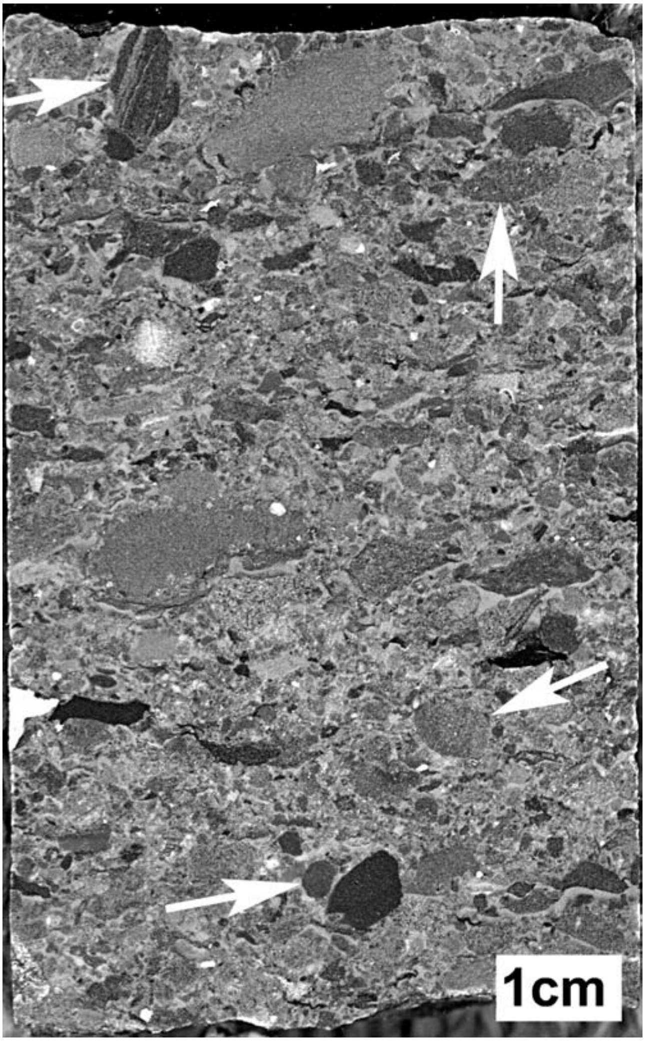

Figure 5. Photo of core sample of bedded breccia (core # 3, bedded breccia submember). Several well-rounded carbonate clasts are clearly visible (white arrows).

The black shale of the Flynn Creek Member forms a thick succession with comparatively low gamma ray response and lacks an obvious equivalent outside the crater. The shale also contains disseminated dolomite, a constituent that is absent in the overlying Dowelltown and Gassaway members. Gamma ray and core logs indicate several traceable horizons within the black shale submember of the Flynn Creek Member. These horizons differ in dip from the overlying Dowelltown Member and indicate that the Flynn Creek Member suffered erosional truncation prior to Dowelltown deposition (Fig. 11). The contact between the Flynn Creek Member and the base of the overlying Dowelltown Member is marked by a lenticular, coarse sandy lag with quartz and chert grains, silicified fossil debris, and rounded phosphate granules (Fig. 12).

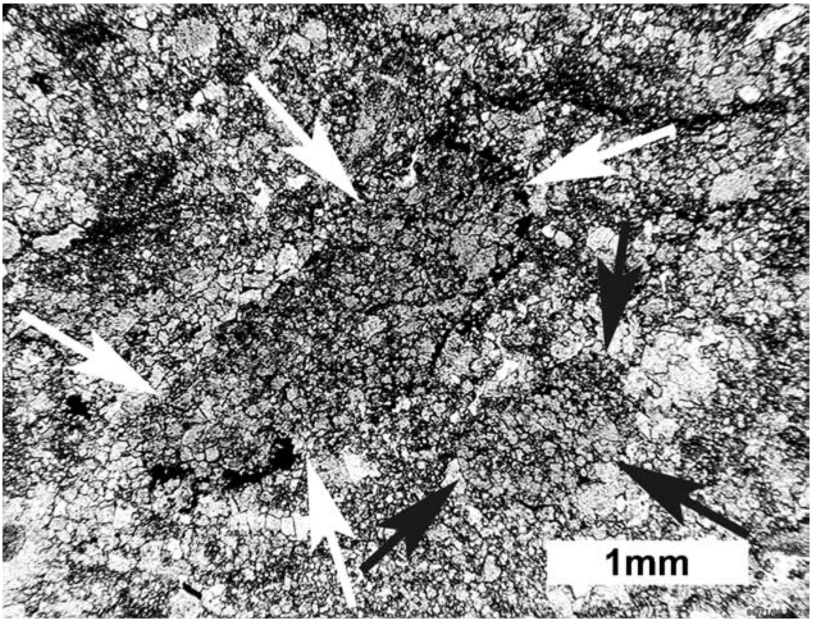

Figure 6. Photomicrograph of small rounded carbonate clasts in bedded dolomite (marked with white and black arrows).

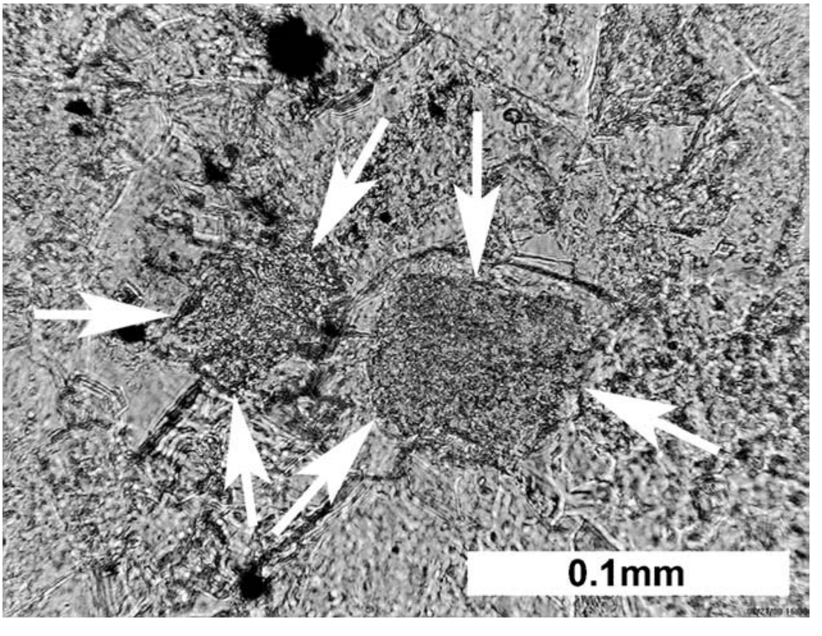

Figure 7. Photomicrograph of bedded dolomite. White arrows point out detrital cores in two dolomite grains.

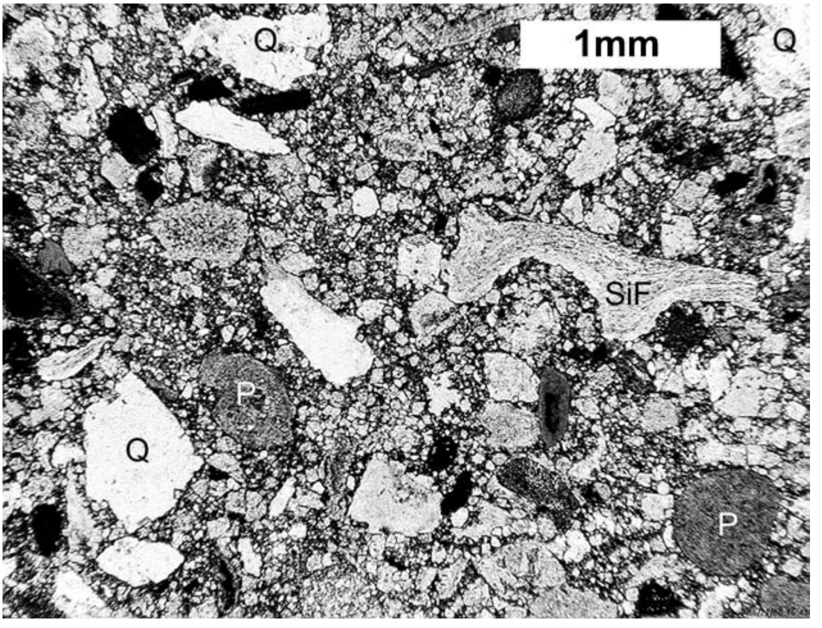

Figure 8. Photomicrograph of sandstone bed at base of Dowelltown Member. Grains marked Q are mainly pieces of chert, SiF identifies a silicified brachiopod shell, and P marks rounded phosphatic grains.

4. Reconstruction of impact-related processes and depositional history

In comparison to other wet target impact craters (e.g. Poag, 1997), the chaotic basal breccia is best interpreted as a fall-back deposit that formed immediately after the impact. The graded top portion suggests deposition controlled by settling velocity of particles, commonly observed where particles settle through a turbulent fluid/sediment mixture (Boggs, 1995). Thus, impact occurred while the area was covered by water. Impact-displaced water rushed back into the void and carried freshly ejected material back into the crater. The turbulence associated with such a scenario is extreme and allows for short-term suspension transport of pebble-size particles (Nichols, 1999). As turbulence abated the coarsest particles settled first, and sand- to silt-size material settled last. The absence of a depositional break between the coarse chaotic and the graded top portion of the basal breccia are indicative of a depositional continuum, typical of other graded breccias at marine impact sites (e.g. Poag and Aubry, 1995; Poag, 1997; Dypvik and Jansa, 2003). The basal breccia submember, including the graded top portion, probably represents a time interval measurable in hours.

The shale drape over the basal breccia indicates low energy conditions after impact-related turbulence had subsided (Figs. 3, and 4). Petrographic equivalents of the quartz and chert grains, silicified fossil debris, conodonts, and rounded phosphate granules do not occur in breccia samples. Outside the crater, however, these grain types comprise the basal Dowelltown Member lag that overlies Ordovician strata in many localities (Conant and Swanson, 1961; Schieber, 1998b). Conodonts from the basal Dowelltown lag range in age from upper Givetian to lower Frasnian and suggest that shallow water conditions persisted

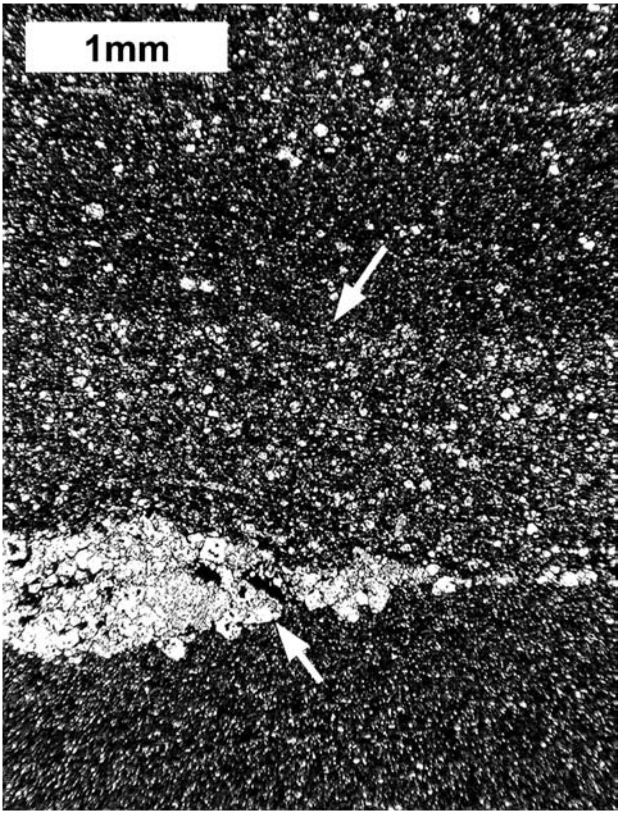

Figure 9. Photomicrograph of banded black shale. Light colored grains are mainly dolomite. Arrows point to base and top of a lighter colored layer, which contains more dolomite than darker layers above and below. In places, as shown here, these light colored bands may have lenses of silt- to sand-size carbonate detritus at the base.

for a long time period in the region and prevented accumulation of fine-grained sediments (Ettensohn et al., 1989), or discontinuous deposition where earlier deposited material was winnowed and resistant particles accumulated. The lack of mudstone intercalations in the lag suggests deposition above fair weather wave base. The epicontinental setting of the Devonian inland sea and water depth estimates for shale deposition in the Chattanooga Shale suggest a water depth of 10 m or less (Conant and Swanson, 1961; Schieber, 1998a). The composition of the shale drape that covers the basal breccia implies that the carbonate particles were derived from an ejecta blanket outside the crater, were washed across the crater rim during storm events, and settled in the deeper, mud-dominated portions of the crater. Considering the overall shallow water conditions in the area this should have been a frequent occurrence. Abundant coarse material in this shale drape suggests rapid accumulation, possibly representing only a few hundreds to thousands of years.

Thick beds of bedded breccia/dolomite indicate pulses of coarse clastic deposition. Rounded carbonate clasts, together with scattered quartz, chert, and phosphate grains, indicate reworking and mixing of ejecta with lags in the crater vicinity (Fig. 6). Storms were

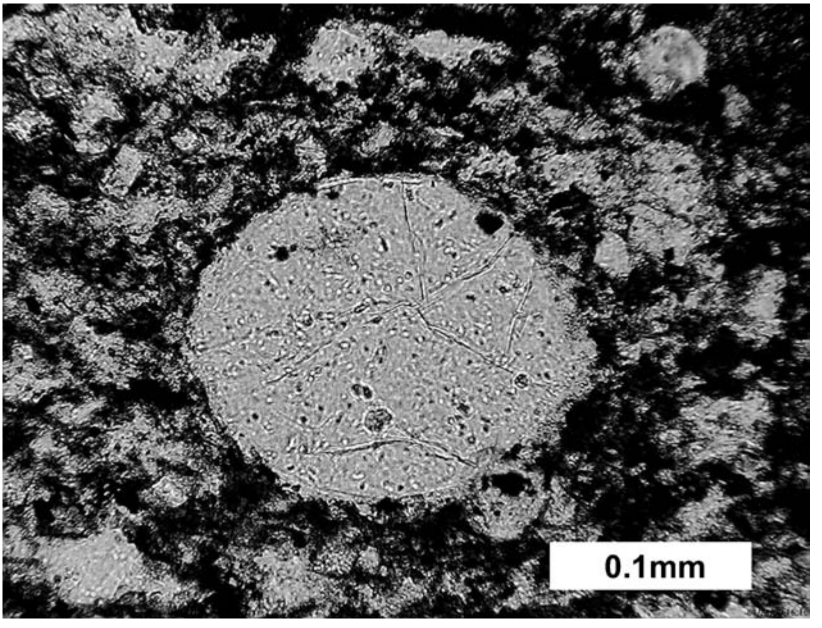

Figure 10. Photomicrograph of chalcedonic quartz grain (center) in banded black shale interpreted as early diagenetic (pre-compaction) infill of *Tasmanites* cyst.

probably the main agent that moved these materials back into the crater to form depositional aprons (Roddy, 1968). Gravity flow processes dominated sediment transport on the steep slopes, up to 30 degrees, along the crater rim. The typically massive appearance of bedded breccia beds indicates grainflow as the most likely transport mechanism (Middleton and Southard, 1984). Fine-grained turbidite flow is indicated for thin, graded dolomite beds that have horizontal laminae and fading ripples (Stow and Shanmugam, 1980; Stow and Piper, 1984). Water escape structures, attesting to rapid deposition, are consistent with such an interpretation. Within the bedded breccia submember, shale drapes amount to 1% or less of the accumulated sediment (Fig. 3). Because the deeper water in the crater favors mud accumulation, rapid emplacement of the entire interval is indicated.

The coarse sandstone at the base of the black shale succession in the crater is a mixture of carbonate ejecta with basal Chattanooga lag. The relative increase of lag-related chert grains, silicified fossil debris, conodonts, and phosphate granules indicates a dwindling supply of carbonate debris through gradual removal of ejecta. The occurrence of sand layers of this type through the basal 13 m of the black shale section indicates, for that stratigraphic interval, that the water outside the crater was still shallow enough to allow wave reworking and lag formation. Steep slopes, black shale rip-ups, clasts projecting above the bed surface, and basal scours suggest that these sandstone layers were emplaced by grainflow. Because the bedded breccia and black shale submembers span several conodont zones (see section 6), this suggests an initial time interval of several hundred thousand years when black shale deposition occurred only within the crater, while shallow water conditions and lag formation persisted outside.

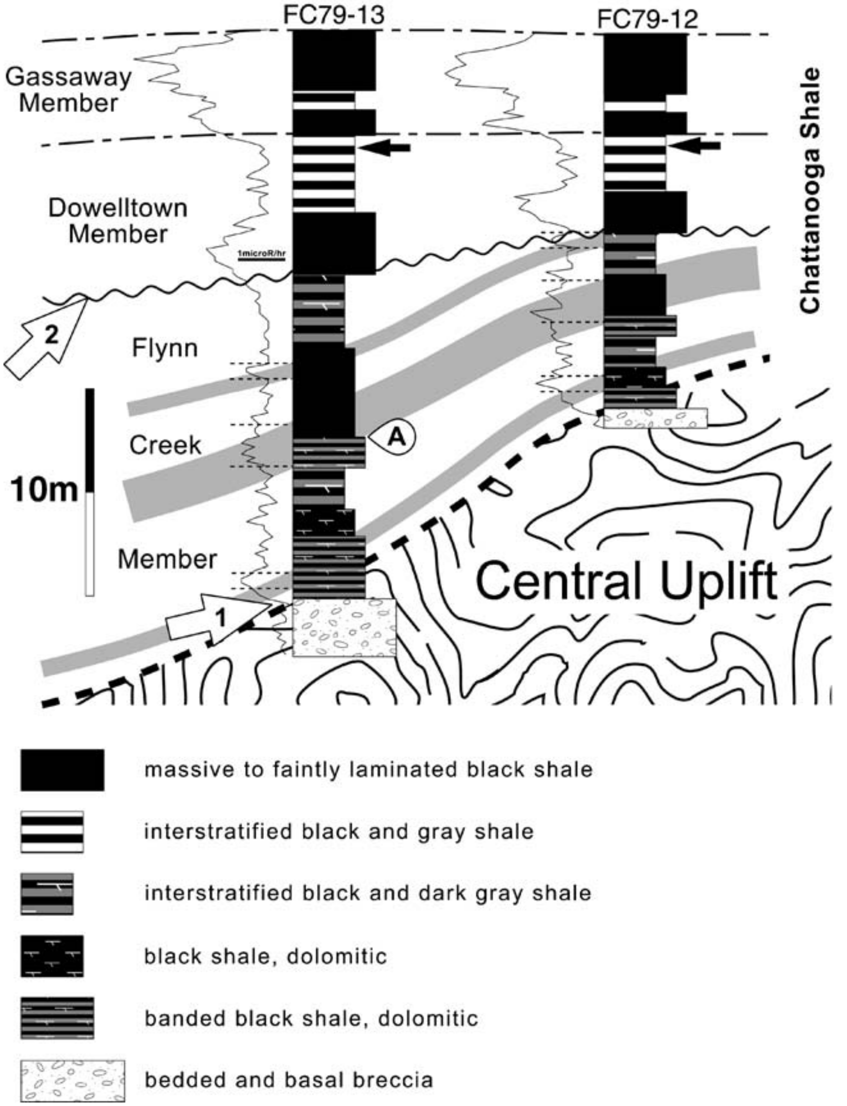

Figure 11. Black shale stratigraphy from drill cores at the western flank of the central uplift within the crater (the last two numbers of the core labels correspond to core numbers given in Fig. 1). The gamma ray profiles were constructed from scintillometer measurements made in 10 cm intervals on drill cores. Gamma ray profiles typical for the Dowelltown and Gassaway members only match the upper portion of the black shale succession in the crater (gamma ray counts increase toward the left). The underlying black shale submember of the Flynn Creek Member has an overall lower gamma ray activity. The black arrows indicate the position of the Center Hill Ash Bed. Gray bands follow horizons marked by increased gamma ray response. Toward the right, the uppermost band is truncated at the Dowelltown contact, indicating an angular unconformity between the black shales. The black shale submember consists of several different facies types that are stacked in two depositional cycles. Marker A is a reference point for conodont samples collected from the black shale submember. Conodont samples 7/4/2000–1, 7/4/2000–2, and 7/4/2000–3 were collected with even spacing from 21 m to 13.5 m above marker A. Arrow 2 marks approximate projection of location of 7/4/2000–3. Arrow 1 marks stratigraphic location of FC base conodont sample.

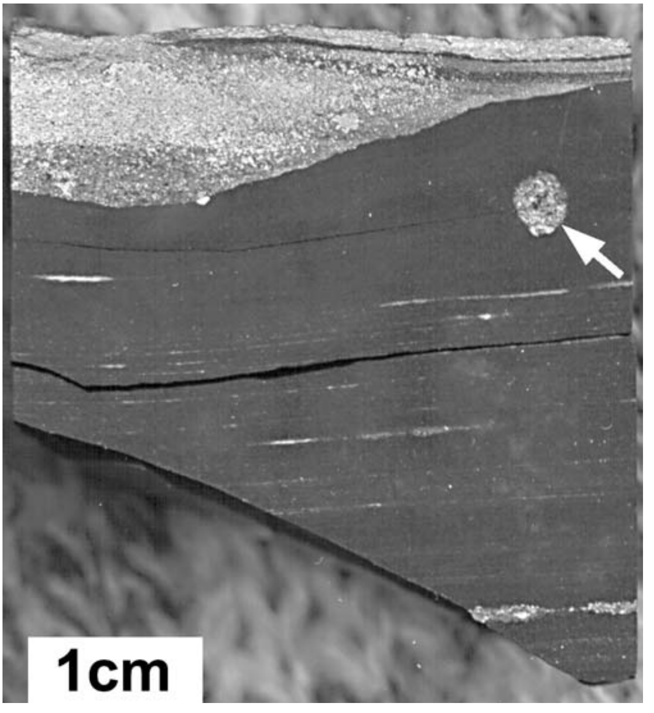

Figure 12. Photo of core sample from the crater fill that was collected from the base of the Dowelltown Member. Scours and pyrite cemented sandy lag that marks the base of the Dowelltown Member of the Chattanooga Shale are visible at the top of the sample. An uncompressed burrow tube, pointed out with white arrow, is filled with sand from the lag. The black shale shows differential compaction around the burrow (binocular examination), the amount of which suggests a water content/porosity of about 35% at the time the burrow was emplaced.

Graded bedding in black shales of the Flynn Creek Member and steep depositional slopes suggest a fine-grained turbidite component (Stow and Shanmugam, 1980), consistent with intervals of soft sediment deformation that are attributable to downslope sediment creep and slumping. Darker carbonaceous bands probably reflect "pelagic" background sedimentation (Fig. 9). Silica-filled *Tasmanites* cysts in these shales are due to in situ silica precipitation during early diagenesis (Schieber, 1996). Abundant cysts probably represent sediment-starved intervals when biogenic components such as algal matter and radiolaria dominated sedimentation (Schieber, 1998a).

The Flynn Creek Member was truncated prior to Dowelltown deposition (Fig. 11). Within the context of erosion in the Chattanooga Shale this implies regression and partial removal of the Flynn Creek Member, followed by transgression and deposition of the Dowelltown Member. In several places in central Tennessee the Chattanooga Shale has a thin, usually less than 1 m thick, interval of dolomite bearing black shale at the base (Schieber, 1998b). This interval is laterally discontinuous and separated from overlying shale by an erosion surface. Previously considered part of the Dowelltown Member, petrographic characteristics, location beneath an erosion surface, and low gamma ray intensity indicate that this stratum is equivalent to the Flynn Creek Member. Preservation outside of the crater implies that sea level rose sufficiently during deposition of the Flynn

Creek Member to allow mud accumulation outside of the crater, and that the region was once covered by a pre-Dowelltown black shale blanket. Water depth may have increased from around 10 m to as much as 50 m (Schieber, 1994, 1998a).

At the time of Dowelltown deposition, black shales of the Flynn Creek Member still had about 35% porosity (Fig. 12). Thus, as these shales compacted further the crater continued to influence structure, distribution, and thickness of post-impact deposits. Continued compaction of the Flynn Creek Member caused the Dowelltown Member to be 40% thicker in the crater than in the type section, 7 versus 5 m (Fig. 11).

The disconformity that separates the Dowelltown and Gassaway members is of regional extent (Schieber, 1998b). It approximates the Frasnian–Famennian boundary (Over, 2002) and is representative of the boundary between transgressive–regressive cycles IId and IIe of Johnson et al. (1985). The Gassaway Member in the crater is only marginally thicker than in surrounding areas, an indication that by Famennian time the crater fill had compacted sufficiently to produce a more or less level surface.

5. Comparison to other marine impacts

The presence of water and the properties of the target rock determine associated sedimentary processes and the sedimentary signature that a marine impact leaves in the rock record (Dypvik and Jansa, 2003). If the target consists of unconsolidated or poorly lithified sediments or sedimentary rocks, the resulting crater may lack a continuous uplifted rim and show resurge gullies and rimwall collapse (Dypvik and Jansa, 2003). The Flynn Creek crater shows an uplifted rim that was not significantly beveled by post-impact erosion and was not dissected by resurge gullies (Roddy, 1968), an indication that the Ordovician target rocks were lithified by that time. The crater morphology is a close match to that expected of a subaerially produced crater. The smooth-flattened top of the central high/uplift (Roddy, 1968), in contrast to the sharp central peaks of terrestrial impact craters, suggests post-depositional modification by wave action, the result of shallow water cover (Dypvik and Jansa, 2003).

6. Time of impact

Conodonts from the fill of the Flynn Creek structure clearly constrain the relative age of the Flynn Creek Member basal breccia, bedded breccia, and black shale submembers, as well as the overlying Dowelltown Member of the Chattanooga Shale. The Frasnian conodonts are readily placed within the Montagne Noire (MN) zonation proposed by Klapper (1989, 1997). The basal and bedded breccia submembers contain a mixed fauna of Late Ordovician and Devonian conodonts (Fig. 13). The Ordovician taxa, including *Yaoxianognathus* and *Plectodina* are typical of the Nashville Group that floors the crater (S. Leslie, pers. comm., 2004). *Ancyrodella alata* and *Polygnathus pennatus* from the breccia beds are limited to the early Frasnian, *A. alata* occurs only within MN Zones 3 and 4. The black shale interbeds within the basal and bedded breccias, in conjunction with the occurrence of *Ancyrodella rotundiloba* and *P. pennatus* that were tabulated but not illustrated by Huddle (1963), from the base and top of the basal breccia, as well as from the bedded breccia and base of the black shale submember, indicate impact and infill of the

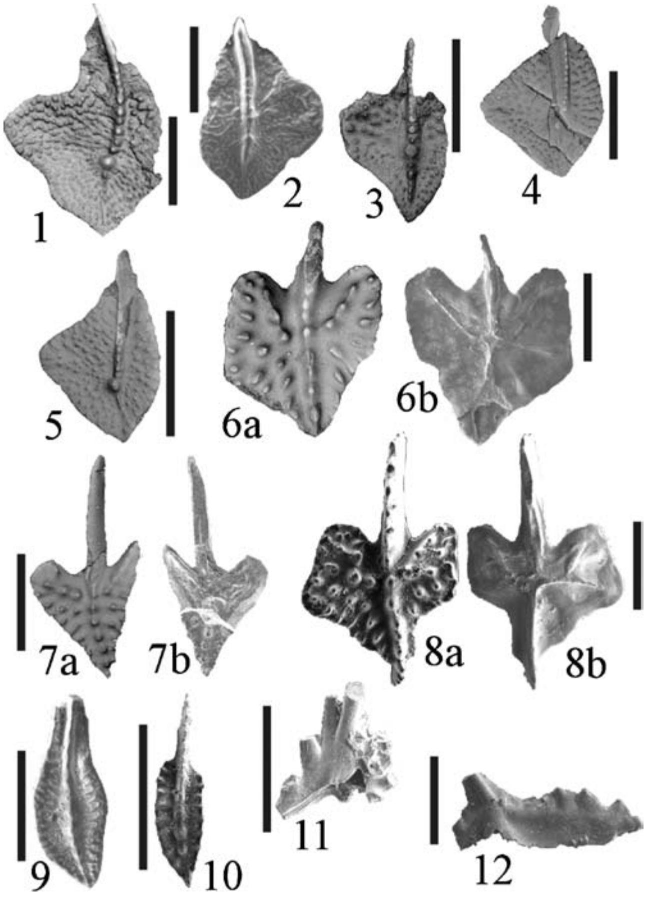

Figure 13. SEM digital images of conodonts from the Dowelltown and Flynn Creek members of the Chattanooga Shale. Specimens are reposited in the Orton Museum, Ohio State University, Columbus, Ohio. Scale bars are 0.5 mm. 13-1 – *Palmatolepis punctata* (Hinde, 1879) late form, upper view, inverse image of mold, OSU 52225, Dowelltown Member, TN70-09. 13-2 – *Palmatolepis bohemica* Klapper and Foster, 1993, upper view, OSU 52226, Dowelltown Member, HC2-02. 13-3 – *Palmatolepis* aff. *P. bohemica,* upper view, inverse image of mold, OSU 52227, black shale submember of Flynn Creek Member, FC 7/4/2000–02. 13-4 - *Palmatolepis* aff. *P. punctata*, upper view, inverse image of mold, OSU 52228, black shale submember of Flynn Creek Member, FC 7/4/2000–02. 13-5 – *Palmatolepis punctata* early form, upper view, inverse image of mold, OSU 52229, black shale submember of Flynn Creek Member, FC 7/4/2000–02. 13-6 – *Ancyrodella curvata* Branson and Mehl (1934b) early form of Feist and Klapper (1985), upper inverse image of mold and lower view, OSU 52230, black shale submember of Flynn Creek Member, FC 7/4/2000–02. 13-7 – *Ancyrodella gigas* Youngquist, 1947, upper inverse image of mold and lower view, OSU 52231, black shale submember of Flynn Creek Member, FC 7/4/2000–02. 13-8 – *Ancyrodella alata* Glenister and Klapper, 1966, upper and lower view, OSU 52232, basal breccia submember of Flynn Creek Member, FC base. 13-9 – *Polygnathus dubius* Hinde (1879), upper view, OSU 52233, basal breccia submember of Flynn Creek Member, FC base. 13-10 – *Polygnathus pennatus* Hinde (1879), upper view, OSU 52235, basal breccia submember of Flynn Creek Member, FC base. 13-11 – *Plectodina* sp., inner oblique view, OSU 52235, basal breccia submember of Flynn Creek Member, FC base. 13-12 – *Yaoxianognathus abruptus* (Branson and Mehl, 1934a), outer view, OSU 52236, basal breccia submember of Flynn Creek Member, FC base.

structure within MN Zone 3 to 4. Although these conodonts could have been transported into the crater from the neighboring platform, samples from the black shale submember, as well as 4524SD of Huddle (1963), did not contain any Ordovician conodonts, an indication that Ordovician strata in the area of the crater were buried by this time. The black shale submember yielded diverse early middle Frasnian conodonts, including *Ancyrodella curvata* early form of Feist and Klapper (1985), the early morphotype of *Palmatolepis punctata*, as well as other palmatolepids, that are typical of MN Zones 5 and 6, but do range higher. The Dowelltown Member, marked by a disconformity and basal lag, overlies the Flynn Creek Member and Ordovician strata. Regionally this lag contains Ordovician through Late Devonian conodonts. *Palmatolepis bohemica* and the late morphotype of *P. punctata* from the lowest black shale beds of the Dowelltown, just above the basal lag, indicate the middle of MN Zone 6 into MN Zone 8. This supports the correlation of the basal Dowelltown Member with the basal Rhinestreet Shale indicated by de Witt et al. (1993).

With some limitations, and acknowledging analytical error ranges of ±2 m.y. for published radiometric dates, as well as competing geochronological schemes by Sandberg and Ziegler (1996) and Streel et al. (2000), an approximate absolute age of the impact was calculated by calibrating the (MN) zonation of Klapper (1989) with Devonian radiometric ages compiled by Tucker et al. (1998). The approach is based on the Frasnian Composite Standard of Klapper (1997), where one Frasnian composite standard unit equals 0.174 m.y. if a duration of 6 m.y. for the Frasnian is used (Tucker et al., 1998). This yields an absolute age of ~382.24 Ma. for the base of MN 3 and 381.82 Ma. for the top of MN 4. With an MN Zone 3 through 4 age for the oldest post-impact sediments, the 0.42 m.y. time interval from 382.24 to 381.82 Ma. thus brackets the time of impact. Obviously, such an estimate represents a simplification and has inherent limitations, such as the unproven assumption that Frasnian composite standard units are of uniform duration, the small number of radiometric ages available, and the broad range of analytical error. Nonetheless, the approximate 382 Ma. impact age allows comparison to other Devonian impacts that have been dated by radiometric means and lack conodont data.

Because there are numerous Late Devonian impacts in the rock record, such as Flynn Creek, the Alamo Impact (southern Nevada), and Siljan (Sweden), Sandberg et al. (2002) have suggested that all of these may be related to a Late Devonian comet shower. Conodont data indicate that the Alamo Impact in southern Nevada occurred during the early middle Frasnian *punctata* Zone (Sandberg et al., 2002), an age assignment that is equivalent to MN Zones 5 and 6, close to the time of the Flynn Creek impact. Argon–argon age determination on rocks from the Siljan crater in Sweden yielded an impact age of 377 Ma. (Reimold et al., 2005).

Based on conodont ages, the MN Zone 3 to 4 Flynn Creek impact pre-dates the MN Zone 5 to 6 Alamo Impact. The "calculated" age of 381.6 Ma. for the top of MN 5 clearly predates 377 Ma. for the Siljan impact, making it unlikely that there was any causal relationship between Flynn Creek, the Alamo Impact, and the Siljan Impact.

7. Conclusions

The asteroid that produced the Flynn Creek crater struck a series of flat-lying and lithified Ordovician carbonates that were covered by a shallow sea. The impact occurred during the

Lower Frasnian, approximately 382 million years ago, and the marine crater fill sedimentation commenced immediately after the impact. The Flynn Creek Member of the Chattanooga Shale represents strata deposited after the impact and before deposition of the widespread Dowelltown Member.

The regional water depth at the time of impact was on the order of 10 m or less, and gradually increased after impact due to a general sea level rise observed during the Frasnian. The Flynn Creek crater is older than the Alamo Impact of southern Nevada and the Siljan Impact of Sweden. The sedimentary history recorded by the crater fill indicates repeated regressions and transgressions overprinted on a gradual rise in sea level during the early and middle Frasnian.

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Locality information

HC2-02 – Tennessee Highway 56, Hurricane Bridge, DeKalb County, near Smithville, Tennessee, Center Hill Dam Quad, UTM 16SFQ125(E)884(N) 0.05 m above base of the Dowelltown Member of the Chattanooga Shale.

FC base – Flynn Creek crater fill, approximately 400 m NE of Antioch, Jackson County, in creek bed along Cub Hollow Rd., Gainesboro Quad, UTM 16SFR208(E)154(N), base of breccia.

FC 7/4/2000-02 – Flynn Creek crater fill, approximately 450 m SW of Antioch, Jackson County, along Shady Grove Rd., Gainesboro Quad, UTM 16SFR202(E)148(N), 10 m below the top of the Flynn Creek Member of the Chattanooga Shale.

TN70-09 – Tennessee Highway 70, Little War Gap, Hawkins County, near Striggersville, Tennessee, Kyle's Ford Quad, UTM 17SLL194(E)418(N), 0.5 m above base of Dowelltown Member of Chattanooga Shale.

Type Section for Flynn Creek Member (composite section) – (a) Lower portion of member (basal and bedded breccia) outcrops in creek bed along Cub Hollow Road. Base of section approximately 640 m (0.4 miles) ENE of intersection of Cub Hollow Road and Flynn Creek Road, top of section approximately at intersection. (b) Upper portion of member (black shale) outcrops along Shady Grove Road. Base of section at intersection of Shady Grove Road and Flynn Creek Road. Top of section approximately 500 m (0.3 miles) SW of intersection marked by base of Dowelltown Member.

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