Meteoritics & Planetary Science 43, Nr 12, 2073–2087 (2008)
Abstract available online at http://meteoritics.org

Textural constraints on the formation of impact spherules: A case study from the Dales Gorge BIF, Paleoproterozoic Hamersley Group of Western Australia

Dawn SWEENEY[1] and Bruce M. SIMONSON[2*]

[1]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, New Mexico 87801, USA
[2]Geology Department, Oberlin College, Oberlin, Ohio 44074–1052, USA
[*]Corresponding author. E-mail: bruce.simonson@oberlin.edu

(Received 28 April 2008; revision accepted 06 November 2008)

Abstract–Impact ejecta (about 2.5 Gyr old) in the DS4 layer of the Dales Gorge BIF (Hamersley Group, Western Australia) are so well preserved that many original textures such as vesicles and microlites are faithfully preserved. About 65% of the particles in the layer originated as impact ejecta, of which 81% are splash forms. The remaining 19% are angular, but the splash forms and angular particles have the same composition (mainly diagenetic stilpnomelane and K-feldspar) and share a common suite of internal textures. Some particles contain randomly oriented microlites texturally identical to plagioclase in basalts. Most splash forms have rims of inward-growing crystals that may have formed from the melt (perhaps nucleated by impinging dust) or via thermal devitrification. The rims clearly formed in flight because in broken particles (which make up about 13% of the splash forms) they are generally not present on broken surfaces. The origin of the angular particles is uncertain, but they may represent solid ejecta. Given the large sizes and variable shapes of the splash forms, they are probably droplets of impact melt emplaced ballistically. This is largely by analogy to the K-T boundary layer, but DS4 splash forms differ from K-T spherules in important ways suggesting the K-T model is not universal. The occurrence of basaltic ejecta from a large impact highlights its scarcity in the stratigraphic record despite the areal abundance of oceanic crust. The diverse textures formed via in-flight crystallization suggest particle paths in the plume are more complex than is generally appreciated.

INTRODUCTION

Despite increased understanding of Phanerozoic impact events like the Cretaceous-Tertiary (K-T) impact, our understanding of early Precambrian impacts and impact ejecta is still limited, especially with regards to the distal blanket. Part of the problem is preservation—a thin layer of ejecta far from the point of impact has a low probability of being preserved unless it falls into the right environment. Even if it does, tectonic deformation can obscure its characteristics and crustal recycling can destroy it entirely. Nevertheless, given the large number of impacts that must have taken place throughout the Precambrian (Glikson 1999), it is surprising that only a few dozen distal ejecta layers have been found to date (Simonson et al. 2004). Here we report on the characteristics of ejecta from a layer that is unusually well preserved, particularly since it was deposited almost 2.5 billion years ago, just above the Archean-Proterozoic boundary. The ejecta consists largely of spherules of formerly molten silicate, which is true of all the ejecta layers identified to date that are Archean to early Paleoproterozoic in age.

The Hamersley Group of Western Australia (Fig. 1) consists of a thick package of Neoarchean to Paleoproterozoic strata that constitute one of the best-preserved supracrustal successions on Earth in this age window. Although it is most famous for its banded iron formations (BIFs), the Hamersley succession includes a diverse suite of sedimentary and volcanic rocks that totals many kilometers in aggregate thickness (Trendall 1983). Several layers rich in impact spherules have been recognized among these strata, primarily in stratigraphic units of the Hamersley Group (Hassler et al. 2005). The youngest known layer resides in the Dales Gorge Member of the Brockman Iron Formation (Fig. 2). Although it was first discovered in the 1960s (LaBerge 1966a), the spherules were not recognized as impact ejecta until decades later (Simonson 1992). Only recently have any detailed geochemical analyses been done on this layer (MacDonald and Simonson 2002; Shukolykov et al. 2002; Glikson and Allen 2004).

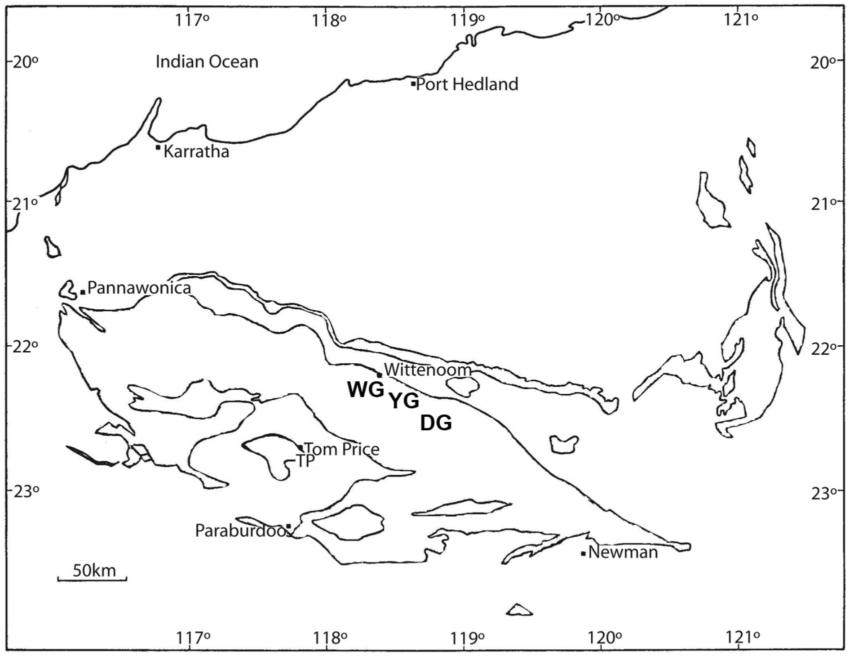

Fig. 1. Map of the Pilbara region of Western Australia showing the outline of the area of occurrence of the Hamersley Group, the locations of Dales Gorge (DG), Wittenoom Gorge (WG) and Yampire Gorge (YG), and the locations of the main towns.

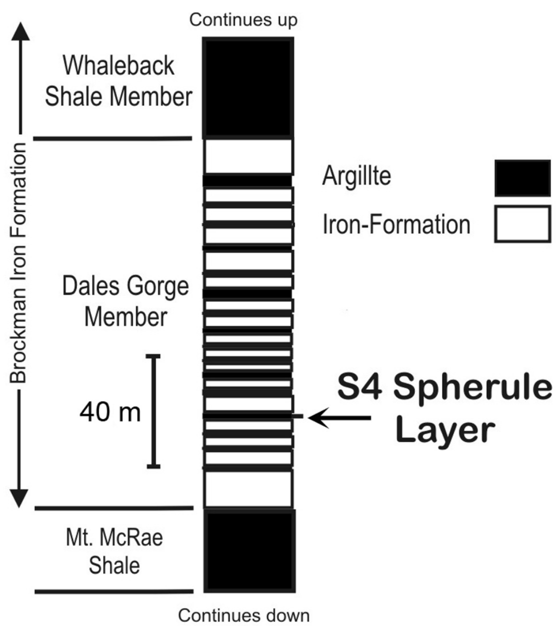

Fig. 2. Schematic stratigraphic column of part of the Hamersley Group showing the position of the DS4 layer low in the Dales Gorge Member of the Brockman Iron Formation.

The spherules in the Dales Gorge layer are worth a closer look because they are unusually well preserved in two respects. One is that they were deposited in a low-energy environment where few physical processes could disturb them once they came to rest. Given that they were deposited in the early Precambrian, biogenic disturbance by burrowers was not even a possibility. In addition, their preservation was enhanced by the precipitation of a significant amount of interstitial cement prior to the onset of compaction. This is common in iron formations as early cements, typically made of silica, are widespread (Simonson 2003a and references therein). Thanks to the relatively rapid cementation, many of the spherules in this layer still have the shapes they had at the time of deposition. In contrast, most of the roughly contemporaneous spherule layers were consolidated largely via compaction instead of cementation. Consequently, the original shapes of the spherules in these other layers were extensively modified by pressure solution as well as both ductile and brittle deformation (e.g., Kohl et al. 2006).

In this paper, we describe in detail the external shapes and internal textures of these unusually well preserved impact spherules. In some ways they are very similar to impact spherules in other layers in the Hamersley succession as well as those of the roughly coeval Transvaal Supergroup of South Africa (e.g., Simonson et al. 1999), but there are also differences. In addition, they are consistently different from almost all impact spherules found in Phanerozoic ejecta layers (Simonson and Harnik 2000). Perhaps most importantly, the relationships between the internal textures and the external shapes of the Dales Gorge spherules lead to the surprising conclusion that the diverse crystallization textures they display formed in flight rather than via digenetic alteration after deposition. This has important implications for spherule generation and dispersal that need to be taken into account in any model of the formation of distal impact ejecta blankets.

GEOLOGICAL CONTEXT

The Brockman Iron Formation is one of the major subdivisions within the Hamersley Group, which rests unconformably on the Pilbara craton, one of the two oldest continental blocks in Australia (Trendall 1983). The Brockman is internally subdivided into four members, the lower two of which are shown in Fig. 2. The first and third consist mainly of BIF, whereas the second and fourth consist mainly of shaly material rich in fine volcaniclastic detritus (Trendall and Blockley 1970; Pickard 2002). The four members have much in common as the shale-rich members are rich in iron throughout whereas the BIF-dominated units have shaly interbeds. The Dales Gorge Member is the lowest of the four units stratigraphically (Fig. 2) and contains a distinctive set of 16 shaly interbeds. Trendall and Blockley (1970) named these and the intervening BIFs macrobands and correlated them successfully throughout the Member's entire area of occurrence. They also designated the BIF and shaly macrobands sequentially as BIF1, S1, BIF2, S2, etc. from bottom to top. In light of the subsequent numbering of similar shaly interbeds in other Hamersley BIFs such as the Marra Mamba and Joffre, it became common practice to refer to the shale macrobands in the Dales Gorge Member as DS1, DS2, etc.

Both the BIFs and shaley layers in the Dales Gorge Member and all of the units closely associated with it in the Hamersley Group exhibit classical features of basinal successions, i.e., they consist of strata deposited below wave base under generally quiet, low-energy conditions. For example, the BIFs display thin layers known as microbands and mesobands whose lateral extent and consistency are legendary (Trendall and Blockley 1970; Ewers and Morris 1981). Another key piece of evidence is the presence of calcarenitic interbeds with the classic characteristics of turbidites in the Dales Gorge Member and underlying units, especially the Mt. McRae Shale and Wittenoom Formation (Simonson et al. 1993a; Pickard et al. 2004). In addition, normal grading is ubiquitous in the thin tuffaceous layers that are widespread in the succession (Pickard et al. 2004), whereas thicker tuffaceous layers again have depositional features diagnostic of turbidites (Simonson et al. 1993b; Hassler 1993).

Located in the DS4 macroband is a single layer that contains an abundance of well-sorted spherules that were formerly molten, the vast majority of which are coarse to very coarse sand-sized (Figs. 3 and 4). Although it varies in character throughout its area of occurrence, the presence of the spherules marks it as unique within the Dales Gorge Member, save for a possibly reworked second layer with spherules close above the main layer in one location (Pickard et al. 2004). Based on SHRIMP analyses of zircons separated from tuffs in other shale macrobands in the Dales Gorge Member as well as adjacent stratigraphic units, the spherule-rich layer was deposited about 2.49 Ga (Pickard 2002; Trendall et al. 2004). Based primarily on petrographic evidence, Simonson (1992) interpreted this layer as the product of an impact by a large extraterrestrial body. Subsequently, geochemical analyses of samples from the layer demonstrated that it contains a small but discernible component of extraterrestrial material. Based on iridium concentrations of up to 18 ppb and largely chondritic interelement ratios between Ir and other platinum group elements (PGEs) in several samples analyzed, MacDonald

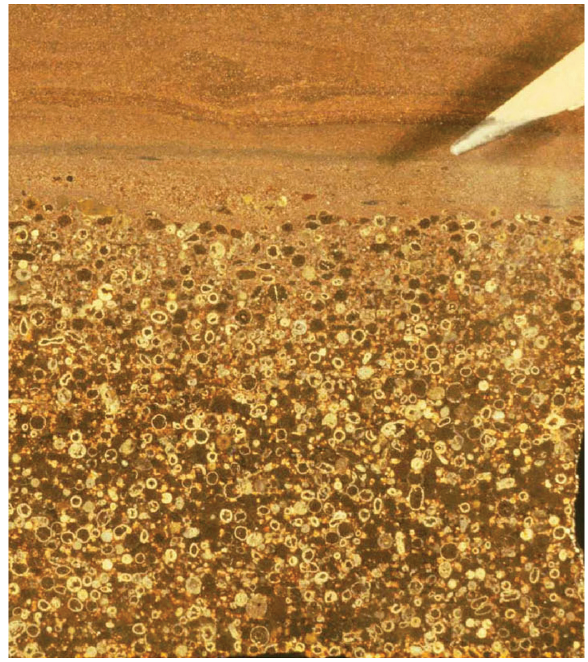

Fig. 3. Sawn slab of spherule-rich sample from DS4 layer in Dales Gorge (from Fig. 4B of Hassler and Simonson 2001); pencil point for scale.

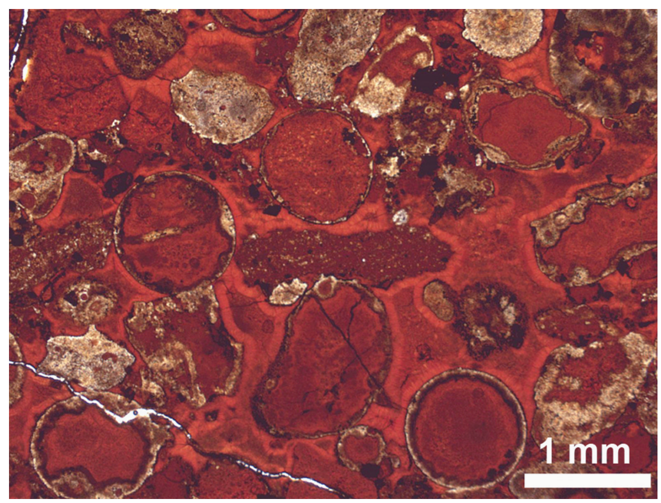

Fig. 4. Photomicrograph in plane polarized light of DS4 sample from surface outcrop in Yampire Gorge showing well-sorted spherules with abundant interstitial cement showing an initial isopachous layer. In this and subsequent figures (excluding 5), reddish brown material is weathered, oxidized stilpnomelane and clear to gray areas are mainly K-feldspar.

and Simonson (2002) estimated the spherule-rich samples contain several percent of extraterrestrial material. Measurements of the isotopic ratios of Cr in the same and related samples yielded values consistent with this estimate (Shukolykov et al. 2002). Glikson and Allen (2004) have added additional details to this picture again showing clear evidence of an extraterrestrial component.

Like all the shale macrobands in the Dales Gorge Member, thinly-laminated mud-sized sediment typical of a deep shelf environment is the main component of DS4. Nevertheless, the spherule-rich layer contains meter-scale boulders in some locations that appear to be intraclasts (Hassler and Simonson 2001). Since they are among the coarsest clasts in the entire Dales Gorge Member, they are clearly the product of an unusually high-energy event. It is quite possible that they were the product of waves and/or currents formed by the same impact that generated the spherules (Hassler et al. 2005). This is in keeping with the wave structures and dune-like bedforms found within the layer, but not elsewhere in the formation (Hassler and Simonson 2001). Despite the high energy of the event that deposited the DS4 spherule layer, we did not detect any unambiguously extrabasinal detritus coarser than mud in the spherule layer in DS4, even though sand-size volcaniclasts (e.g., shards) are definitely present at other stratigraphic levels in the Dales Gorge S bands (LaBerge 1966a; Trendall and Blockley 1970). This is in marked contrast to other Neoarchean to Paleoproterozoic spherule layers, all of which contain variable amounts of sand-size siliciclastic detritus that is rarely if ever present in the enclosing strata (Simonson et al. 1998; Jones-Zimberlin et al. 2006; Kohl et al. 2006).

Table 1. Textural categories of ejecta particles in DS4 layer.

Category name	Distinctive characteristics
Radial	Particles with acicular to lath-shaped K-feldspar crystals radiating inward from their grain boundaries and filling the entire cross section; radial aggregates show sweeping extinction typical of spherulitic aggregates.
Random	Particles contain K-feldspar in lath-shaped crystals that are either randomly oriented or weakly aligned (comparable to a trachytic texture in a volcanic rock); crystals can show various morphologies including hollow crystals, swallow-tail terminations, rosettes and bowtie-type shapes.
Rimmed	Particles consist of a core of stilpnomelane and a rim of K-feldspar; cores range in shape from circular to more asymmetrical or irregular and vary in location in that they are not always centered; many cores display void-filling radiating texture similar to interstitial cements; the rims vary in texture from random to radial, and the core/rim interfaces of the radial rims typically consist of circular arc segments like the growth surfaces of botryodial aggregates.
Massive	Particles consisting entirely of stilpnomelane and lacking K-feldspar, although some contain vesicles internally.
Miscellaneous	Particles consisting largely of stilpnomelane but lacking a rim and showing some sort of internal pattern or heteorgeneity, most commonly a swirling pattern that appears to be flow banding; also contain laths of K-feldspar that are usually oriented randomly.
Indeterminate	Particles whose internal textures was obscured by fine opaque inclusions to the point where they could not be uniquely assigned to any of the categories above, although some contain crystals of K-feldspar.

SAMPLING AND ANALYTICAL METHODS

Like most layers in the Dales Gorge Member, the spherule layer in DS4 persists laterally throughout much of the Hamersley Basin. We have identified it at sites currently separated by distances of 135 km or more, but it is thickest and best exposed in the gorges in and around Karijini National Park, most notably Dales, Wittenoom, and Yampire Gorges (Fig. 1). For petrographic analysis, we selected 4 samples from Dales Gorge, 2 samples from Yampire Gorge, and one from drill core A00-811 drilled near Tom Price kindly provided by Dr. April Pickard. In each case, we sampled the layer where it contained a significant (decimeter-scale) thickness rich in spherules that was prominent and easy to spot. We realize the samples we collected are not representative of the layer as a whole, but since our focus is on the nature of the impact ejecta, we do not believe this invalidates the conclusions reached here.

Fifteen thin sections were made from the seven samples chosen and point counted using a transmitted light petrographic microscope. Over 6,000 points were counted (a minimum of 400 per thin section) to determine the relative abundances of ejecta. The particles we interpret as impact ejecta were first placed in one of two categories based on their external shape (splash forms versus angular particles), then each was placed in one of six subcategories based on their internal textures (Table 1). During the count, broken spherules and vesicles were recognized based on their distinctive shapes and separate counts were kept of their abundances. Since the samples have a relatively simple mineralogical composition of stilpnomelane, K-feldspar, carbonate, and opaques, minerals were identified optically as necessary during the count, but their abundance was not quantified. The feldspar had been identified as pure potassium feldspar (K-feldspar) by etching sample surfaces with HF and staining them with sodium cobaltinitrite in previous studies (Simonson 1992; Simonson et al. 1993b).

In addition to the abundances of different external shapes and internal textures, we attempted to quantify a few other selected attributes of the ejecta particles, although not to the same extent. One attribute was the abundance of cement in the spherule-rich part of the layer; for this we selected one sample from Yampire Gorge that was typical and performed a point count of all constituents, not just the impact ejecta. Another attribute was the aspect ratios of the two main types of ejecta. For this we used the graduated reticle on the eyepiece of the microscope and measured 2 mutually perpendicular axes of the ten largest splash forms and the ten largest angular grains in two samples, one from Dales Gorge and one from Yampire Gorge. The roundness of these same ejecta particles was estimated at the same time by visual comparison to a template of silhouettes of known roundnesses like those in Fig. 24 of Pettijohn (1949). The limiting values in Pettijohn's roundness scale are as follows: 0 to 0.15 for angular, 0.15 to 0.25 for subangular, 0.25 to 0.40 for subrounded, 0.40 to 0.60 for rounded, and 0.60 to 1.0 for well rounded. Finally, the lengths of crystals within ejecta particles were measured using the graduated reticle on the eyepiece of the microscope to facilitate comparisons between splash forms and angular grains. The long axes of 20 crystals from several splash form grains in 3 samples were measured, as were the long axes of 10 crystals from angular grains in one of those three samples.

PETROGRAPHIC DESCRIPTIONS

General Characteristics

On average, about 65% by volume of the samples studied consists of discrete, heterogeneous bodies that we interpret as ejecta particles. Around 81% of these particles belong to the variety known as "splash forms" (Glass 1990). Such bodies are typified by well-rounded, fluidal shapes reflecting the fact they were once molten (described below). In contrast, the other 19% of the particles have angular outlines. We interpret these as ejecta particles because they have the same composition as the splash forms and show similar internal textures (Tables 1 and 2). Despite the contrast in shape, there is relatively little variation in size—these samples all consisted of well-sorted, relatively equant particles of coarse to very coarse sand-size detritus originally (Figs. 3 and 4). Compositionally, the samples collected from surface outcrops consist of oxidized stilpnomelane with lesser amounts of K-feldspar, calcite, and minor opaque phases. The ejecta particles *per se* mainly consist of oxidized stilpnomelane with variable amounts of K-feldspar (Fig. 4). In contrast, the sample from the drill core consists almost entirely of unoxidized stilpnomelane and minor opaque phases (Fig. 5). The external shapes and internal textures of the ejecta particles are described in detail below.

In addition to the ejecta particles, about 23% by volume of the samples studied consists of stilpnomelane we interpret as pore-filling cement. Most of the stilpnomelane in question occupies what would have been interstitial voids in the original framework of well-sorted sand. It also shows textures typical of void-filling cement. This includes isopachous rims evenly coating external grain surfaces (Fig. 4) and parallel fibers that grew inward from particle edges until they met along centerlines in the middles of former pores (Fig. 6). Geometrically, the latter growth habit is strikingly similar to

Table 2. Relative abundances of different types of ejecta particles in DS4 layer.

	Splashform particles	Angular particles
Radial	7.9%	1.0%
Random	6.9%	17.2%
Rimmed	67.3%	17.2%
Massive	6.9%	27.2%
Miscellaneous	7.9%	11.1%
Indeterminate	3.0%	26.2%
Total	99.9%	99.9%
Number of points counted	2679	621

both void-filling parallel-fibrous chalcedonic cements, e.g., in granular iron formations (Simonson 1987), and axiolitic textures observed in replaced volcanic shards (e.g., LaBerge 1966b; Vernon 2004). Consistent with early cementation and limited compaction, we estimate there are between 1 and 2 intergranular contacts per grain on average in the samples studied (Figs. 4, 6, and 7) (discussed further below). Much of the stilpnomelane inside the ejecta particles, especially the splash forms, show similar textures (Figs. 4 and 6) and presumably formed via replacement of the impact glass that was originally present. Even in spherules that consist entirely of stilpnomelane, circular to ovoid bodies are present that we interpret as cement-filled internal voids, i.e., vesicles or vacuum bubbles (Figs. 6 and 8).

Finally, about 12% by volume of the samples studied consists of a combination of non-impact detritus and masses of calcite crystals and opaque phases large enough to obscure original detrital outlines. The non-impact detritus primarily consists of rip-up clasts of chert and shaly material that were probably generated by relatively local erosion of fine-grained sediment. This erosion has been ascribed to the high-energy event that deposited the spherules, most likely impact-generated waves and/or currents (Hassler and Simonson 2001). The intraclasts in the samples we studied not only resemble closely associated strata, they form a continuum with the meter-scale boulders noted above. In contrast, the masses of calcite and opaques are clearly secondary in origin. For example, calcite crystals clearly postdate cementation as they commonly straddle the contacts between detrital grains and cement (Fig. 7). The masses of opaque phases likewise have boundaries that cut across the detrital framework rather than being part of it. Both are unlike the chert and shale intraclasts in this regard. Lastly, we did not detect unambiguously extrabasinal debris coarser than mud in any or the samples we analyzed from the DS4 spherule layer. In contrast, silt- to sand-size detrital grains of quartz and feldspar are widespread in the spherule layers in the Carawine Dolomite (Simonson et al. 1998), Jeerinah Formation (Jones-Zimberlin et al. 2006) and Wittenoom Formation (Simonson 1992).

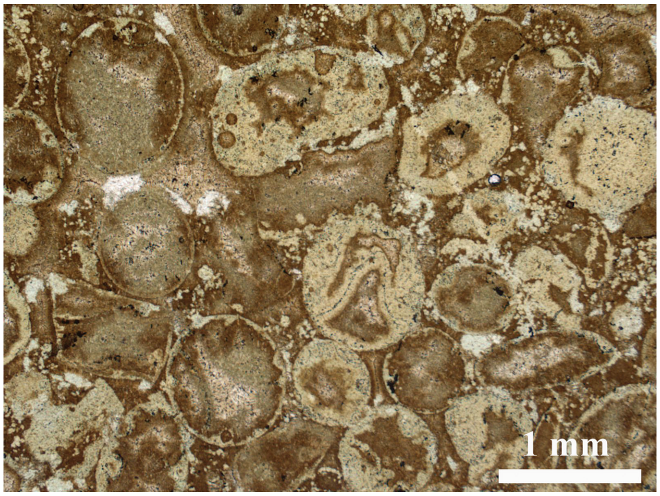

Fig. 5. Photomicrograph in plane polarized light of DS4 sample from core collected near Tom Price where it is unweathered and consists of, unoxidized stilpnomelane, chlorite, sericite, and minor amounts of opaque material (Pickard et al. 2004).

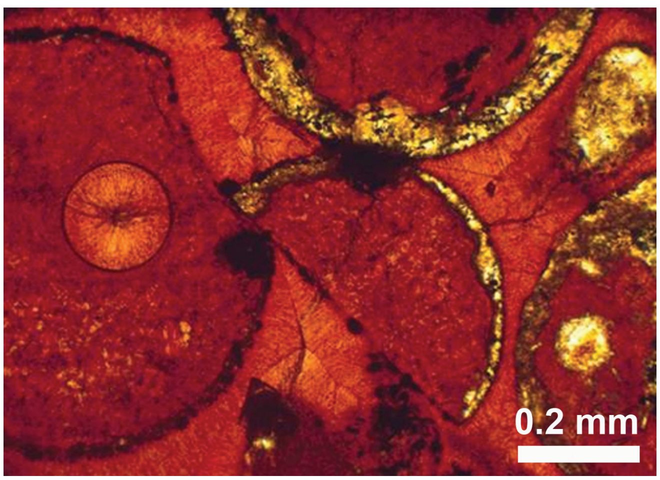

Fig. 6. Photomicrograph in plane polarized light of DS4 sample from Yampire Gorge showing typical stilpnomelane-rich spherules, some with rims and some with broken outlines; note parallel-fibrous stilpnomelane showing void-filling textures in former interstitial voids.

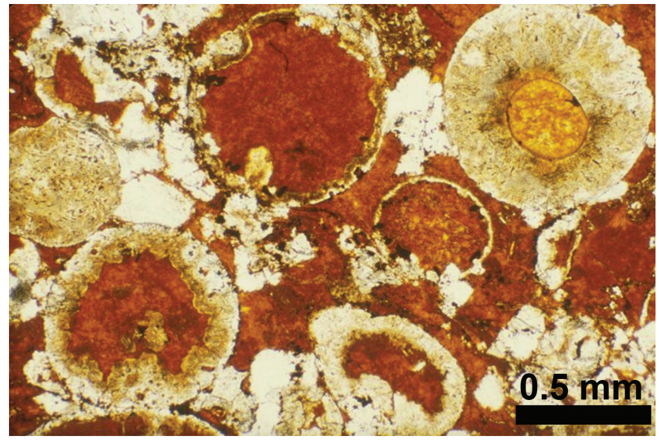

Fig. 7. Photomicrograph in plane polarized light of DS4 sample from Dales Gorge where splash forms are richer in K-feldspar and spherules and cement have both been partially replaced by clear calcite crystals.

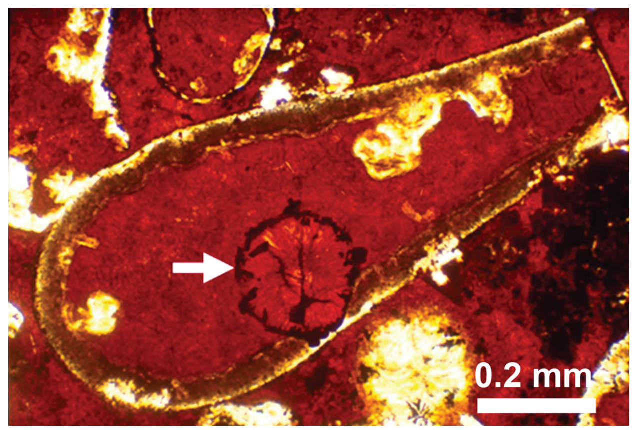

Fig. 8. Photomicrograph in plane polarized light of large teardrop-shaped splash form in DS4 sample from Dales Gorge whose tip has been broken off in upper right; arrow points to internal bubble or vesicle filled with radial-fibrous stilpnomelane and an opaque phase.

Textures of the Impact Ejecta

External Shapes

As noted above, two distinct ejecta morphologies of impact ejecta were observed in the DS4 layer and there is relatively little overlap between the shape categories. Splash forms with fluidal shapes predominate and have cross sections that are mostly circular to oval (Figs. 4, 5, and 7), but a minority have more irregular shapes such as dumbbell or teardrop cross-sections (Fig. 8). In addition, some consist of what were clearly two different particles that apparently were agglutinated prior to deposition, presumably by colliding in flight. Although most of the spherules have outlines that are intact, ca. 13% of the splash forms have truncated outlines that indicate they were broken before deposition. The shapes of the particles prior to breakage ranged from perfectly circular in cross-section (Fig. 6) to teardrop-shaped (Fig. 8). Some of the broken splash forms simply have a small piece gouged out on one side, in which case it generally takes the form of a concave-outward indentation consistent with conchoidal fracture. In other cases, half of the outline of a splash form is gone. In no instance were two or more broken pieces of a single splash form particle seen adjacent to one another as one would expect if they had been broken in situ, e.g., by compaction.

The long axes of the splash forms in the samples studied range from 0.34 to 2.1 mm with an average of 1.4 mm. The largest splash form particles have major and minor axes of about 1.7 and 1.1 mm, respectively, yielding an aspect ratio of about 1.54:1. Larger particles are generally more highly elongated than smaller ones, so the aspect ratio of the splash forms as a whole is probably closer to unity. Finally, the roundness of the splash forms ranges from 0.5 to 1.0 on Pettijohn's (1949) scale with an average of 0.77, which is well rounded.

The angular particles are just that, being much less rounded than the splash forms. On Pettijohn's (1949) scale, the roundness of the angular particles ranges from 0.2 to 0.6 with an average of 0.34, which is sub-rounded. The angular grains are also a bit smaller on average. Their long axes range from 0.43 to 1.8 mm with an average of 1.1 mm. The largest angular particles have major and minor axes of 1.1 and 0.7 mm, respectively, yielding an aspect ratio around 1.57:1, not very different from the splash forms. Because they do not have fluidal shapes, it is impossible to tell if some angular grains are more broken than others. Basically, they all appear broken, but unlike the splash forms, there is little we can say about when this happened.

Internal Textures

Splash forms and angular particles display a similar suite of internal textures that we divided into six categories (Table1). Summarizing briefly, the categories are as follows: 1) *radial*—fibrous to lath-shaped K-feldspar crystals directed inward from particle margins and filling the entire cross-section; 2) *random*—variously oriented fibrous to lath-shaped K-feldspar crystals distributed throughout particle; 3) *rimmed*—particles consisting largely of stilpnomelane with a thin rim (many botryoidal) of K-feldspar crystals; 4) *massive*—particles consisting entirely of stilpnomelane; 5) *miscellaneous*—particles consisting largely but not entirely of stilpnomelane, lacking a rim, and showing an internal pattern (generally flow banding) that does not fit into any of the categories above (Fig. 9); and 6) *indeterminate*—self-explanatory, usually the result of obliterative replacement and/or a high content of opaques.

Although similar, the different internal textures do not have the same relative abundances in splash forms versus angular particles. Specifically, rimmed textures dominate the splash forms whereas the angular particles show a much more even distribution of all the textures except for radial ones, which are virtually absent from angular particles (Table 2). In fact, radial-fibrous aggregates consistently nucleated on edges and directed inwards are present in few if any of the angular particles. On the other hand, random textures are about 3 times as common in angular particles (Fig. 10) as they are in splash forms (Fig. 11). Despite the fact they now consist of K-feldspar, the laths in both the splash forms and angular particles have morphologies very much like those of plagioclase crystallites in natural and experimental basalts documented by Lofgren (1977, 1980, 1983). These include swallow-tail terminations, bowties, rosettes and hollow crystals (Fig. 12). The laths are comparable in size in both types of particles; we measured average lengths of 0.55 mm in the splash forms versus 0.50 mm in the angular particles. In addition, some of the laths show weak alignment in the centers of some particles (Fig. 13). The trends and characteristics reported here appeared to hold true in all of the samples we studied.

Splash forms that have outlines indicating they were broken prior to deposition show the same range of internal textures as unbroken splash forms; like the splash forms as a whole, most belong to the rimmed category. However, the relationship between the internal and external textures is a telling one. Specifically, in splash forms that have rims, the rims are almost always present only along what would have originally been the external surface of the particles and not on the broken surface. This gives rise to particles that have a distinctive "orange slice" appearance (Fig. 6). In a few instances, rims appear to have developed on broken surfaces, but they are rarely as thick as the rim on the original external surface. In addition, some splash forms have internal septae lined with fibrous to lath-shaped K-feldspar crystal coatings like the rims (Figs. 4 and 5). The coatings radiate out in both directions from a central line or plane, suggesting these were incipient cracks along which crystals were able to nucleate just like they did on external surfaces. Although they generally look similar, a significant number of septae differ somewhat in appearance from the external rim on the same grain, most commonly being thicker and/or clearer.

Another distinctive feature observed inside a number of particles are round to irregularly shaped bodies we interpret as former vesicles or bubble cavities (Figs. 6, 8, 10, and 12). Not only are the shapes of these bodies consistent with such an origin, the fact they are filled with stilpnomelane showing the same textures as the interstitial cement strongly suggests they were originally voids. At least one definite vesicle was observed in 6% of the splash forms and 18% of the angular particles. Vesicles were most commonly observed near the edges of particles and in grains with random rather than radial, rimmed, or other internal textures. The vesicles in the splash forms consistently have circular cross-sections, whereas those in angular grains generally are not perfect circles. A minority of the latter have a polygonal or faceted appearance indicating they may represent pseudomorphed phenocrysts (Fig. 10).

CONCLUSIONS BASED ON TEXTURAL EVIDENCE

Degree of Framework Compaction

The volume abundance of the stilpnomelane we interpret as cement ranges up to about 23%, whereas the porosity of a sand consisting of well-rounded, well sorted particles is usually around 45% by volume (Pettijohn 1975). This implies the Dales Gorge spherule-rich sand has undergone some compaction, although not nearly as much as most of the other Neoarchean to Paleoproterozoic impact spherule-rich layers

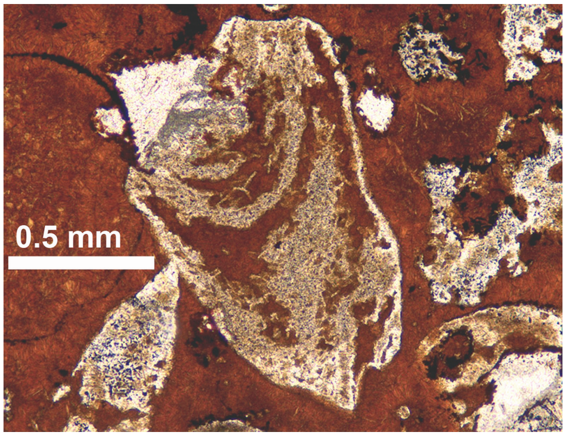

Fig. 9. Photomicrograph in plane polarized light of angular particle of former melt in DS4 sample from Dales Gorge with internal flow banding consisting of stilpnomelane, K-feldspar (gray), carbonate (white), and minor amounts of opaque material.

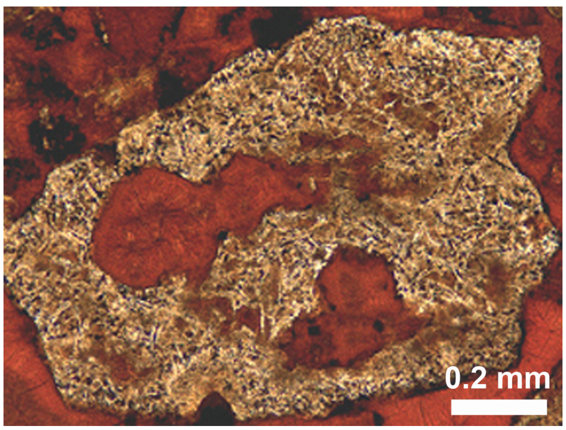

Fig. 10. Photomicrograph in plane polarized light of angular particle of former melt in DS4 sample from Yampire Gorge with an abundance of randomly oriented microlites of K-feldspar and 2 irregularly shaped internal masses of stilpnomelane; irregular outlines suggest they are infilled vesicles, but partial polygonal outlines indicate they may in part be replaced phenocrysts.

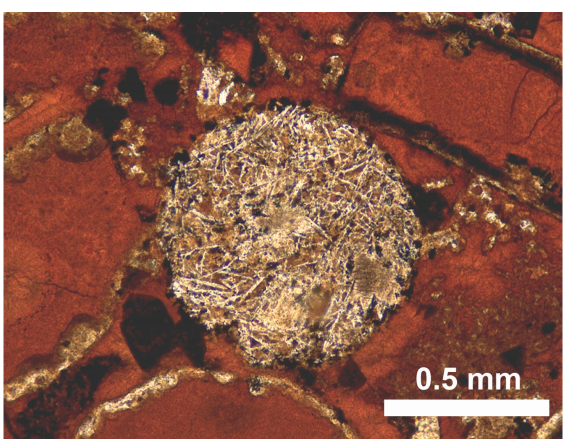

Fig. 11. Photomicrograph in plane polarized light of spherical splash form in DS4 sample from Yampire Gorge with an abundance of randomly oriented microlites of K-feldspar internally.

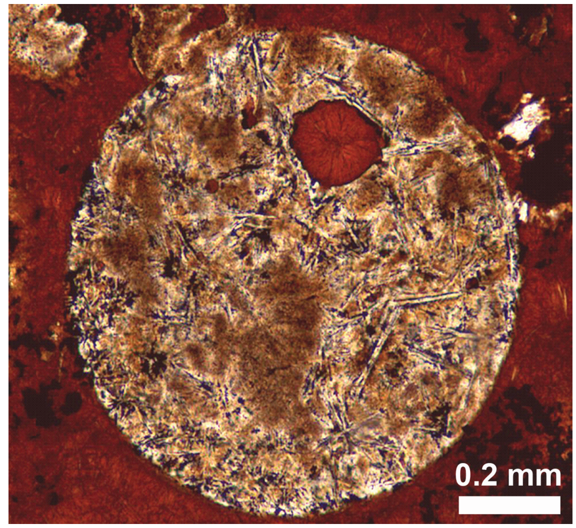

Fig. 12. Photomicrograph in plane polarized light of spherical splash form in DS4 sample from either Dales or Yampire Gorge with an abundance of randomly oriented microlites of K-feldspar and one stilpnomelane-filled bubble internally. Note split ends or prongs at tips of many laths.

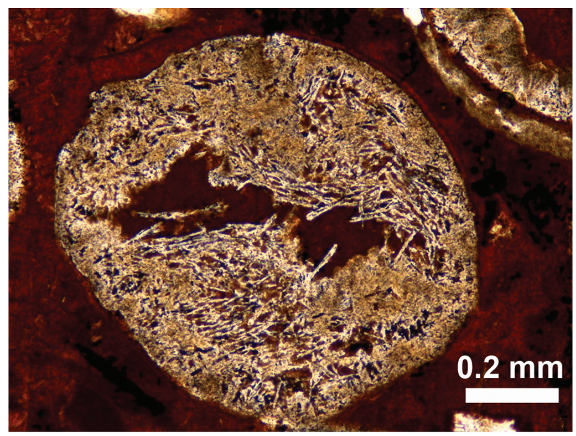

Fig. 13. Photomicrograph of ovoid splash form in DS4 sample from Dales Gorge with an abundance of randomly oriented microlites of K-feldspar and internally. Note alignment of laths, especially in central part near core.

(Simonson and Scally 2005; Kohl et al. 2006; Jones-Zimberlin et al. 2006). A state of limited compaction in the DS4 sand is consistent what appear to be about 2 intergranular contacts per grain on average (Figs. 4, 5, 6, and 7). Although we did not quantify this value, it clearly exceeds the <1 contact per grain typical of an uncompacted sand consisting of well-rounded, well-sorted particles but is well below the 4–5 contacts per grain of a highly compacted well-sorted sand (Pettijohn 1975). This implies that the spherules and other constituents of the DS4 layer were cemented relatively early in their diagenetic history. Early cementation and lightly compacted sediments are widespread in both banded and granular iron formations (BIFs and GIFs, respectively—

Simonson 2003 and references therein). The only difference in the case of the DS4 layer is that the cements consist of stilpnomelane, whereas in BIFs and GIFs *per se* the cement is mostly pure silica in the form of chert, chalcedony, and/or quartz. Most iron formations are relatively pure mixtures of silica and iron-rich oxides, carbonates, silicates, and/or locally sulfides (Klein 2005), so the formation of stilpnomelane requires the addition of aluminum. This usually takes the form of volcaniclastic glass (e.g., LaBerge 1966a, 1966b; Ewers and Morris 1981) and/or fine terrigenous detritus (Pickard et al. 2004). An input of aluminous glassy impact ejecta appears to have served the same purpose in the case of the DS4 layer. Thanks to this early cementation, few of the impact ejecta particles' shapes were modified during compaction, making this study possible. Although early silica cements are widespread in Paleoarchean spherule layers, the internal textures of these impact ejecta are rarely as well preserved as those of the Neoarchean Hamersley succession because the Barberton and Pilbara successions have been subjected to a higher degree of metamorphic and tectonic deformation (Lowe et al. 2003; Krull-Davatzes et al. 2006).

Another difference between the DS4 layer and other Neoarchean and Paleoproterozoic spherule layers is the lack of impact spherules broken in situ. Such particles are present in spherule layers of the Wittenoom (Scally and Simonson 2005) and Monteville (Fig. 5 in Kohl et al. 2006) formations where they are represented by multiple displaced fragments adjacent to one another that fit together like pieces of a jigsaw puzzle. Had these spherules been broken prior to deposition, surely the fragments would not have come to rest next to one another. The paucity of spherules fragmented in situ in the DS4 layer is another indication that other layers are more compacted on average than the DS4 layer.

Original Composition of Spherules

The present composition of the particles we interpret as impact ejecta is clearly not the composition they had originally. The splash-form shapes of the majority of the particles indicates they were originally molten and largely quenched to glass, but little (if any) glass remains. For the most part they have been replaced by stilpnomelane and K-feldspar. The former is petrographically indistinguishable from the pore-filling stilpnomelane interpreted as secondary cement, whereas K-feldspar is commonly observed in other late Neoarchean spherule layers and consistently interpreted as authigenic in origin (e.g., Simonson 2003). Therefore we attribute both of these phases to replacement of the original components of the impact ejecta. Given the faithful preservation of melt textures such as vesicles and microlitic crystals, this must have happened on a volume-for-volume basis rather than via wholesale dissolution and infilling by cement at a later date. This is consistent with the replacement of the interiors of many of the spherules in a manner analogous to axiolitic replacement of volcanic shards. Axiolitic textures are best developed in the massive spherules made entirely of stilpnomelane (Table 1), suggesting they originally consisted entirely of glass. If so, the precursors of these spherules are the best candidates in the DS4 layer for true microtektites (Glass 1990).

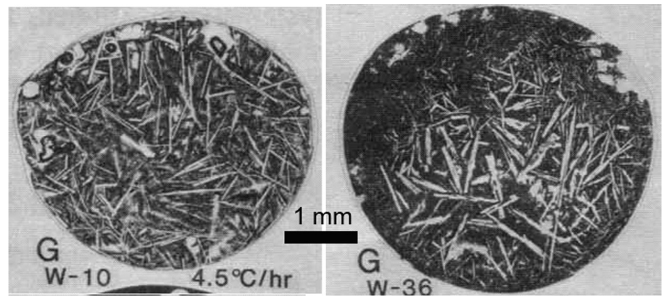

Fig. 14. Photomicrographs in plane polarized light of textures formed experimentally from a synthetic melt of feldspathic basalt composition under controlled conditions; reproduced with permission from Figs. 4 (left) and 5 (right) of Lofgren (1977).

The microlitic crystals in both splash forms and angular particles are strikingly similar to plagioclase microlites in both natural and artificial basalts in their shapes, sizes, and spatial distribution (compare Figs. 10, 11, 12, and 13 to Fig. 14). Specifically, the microlites are highly elongated, commonly show a central dark stripe indicating they grew preferentially on the edges rather than the centers of faces, and in some cases show pronged or "swallow-tail" type terminations. Elongate crystals are common in quenched melts and impact grains of basaltic compositions (Brooks 1971; Bryan 1972; Pearce 1974; Lofgren and Donaldson 1975; Gélinas and Lofgren 1980), as are swallow-tail terminations (Gélinas and Brooks 1971; Bryan 1972; Pearce 1974;). Such textures are indicative of rapid cooling of the melt (Pearce 1974) (see below for further discussion). Based on these close comparisons, we believe the splash forms and angular particles formed from melts that originally had a basaltic composition and most if not all of the microlites were plagioclase that crystallized in flight but were later pseudomorphed by K-feldspar. Impact spherules with primary crystallites are known as microkrystites (Glass and Burns 1988), which most of the spherules in DS4 appear to have been originally. The replacement of former melt particles in the Hamersley succession by a combination of stilpnomelane and/or K-feldspar is not limited to the spherules of the DS4 layer. Volcaniclasts in the Dales Gorge Member are largely replaced by stilpnomelane (Laberge 1966a; Pickard 2002) and hydrovolcanic tuff layers of basaltic composition in associated formations are replaced in part by authigenic K-feldspar (Simonson et al. 1993b).

Basalts usually contain crystals of pyroxene and olivine, but we have yet to positively identify any pseudomorphs of either of these minerals in the particles from the DS4 layer. Clinopyroxene (CPX) crystals abound in impact spherules from both the K-T boundary layer (Smit 1999) and the

Eocene microkrystite layer (Glass 2002). These CPX crystals have branching habits that are morphologically distinct even where they have been replaced by other phases such as K-feldspar (Smit et al. 1992) or dissolved out to form voids in the surrounding glass (Glass et al. 1985). Since they are unlike any shapes we observed in the DS4 particles, we do not believe CPX was originally present in any abundance in either the splash forms or angular particles. Skeletal olivine crystals likewise have distinctive morphologies unlike those of the microlites in the DS4 particles (e.g., Arndt et al. 1977; Connolly and Hewins 1995), and we did not observe any of those either.

Formation of Crystals in Rapidly Cooling Liquid

Assuming our interpretation of the microlites in the impact ejecta particles is correct, this raises the question of why plagioclase crystallized whereas pyroxene and olivine did not. Gibb (1974) argues that supercooling inhibits plagioclase growth and is harder for lower viscosity liquids. Perhaps cooling rate was not as important as other factors in this case. Lofgren (1977) states nucleation history, precooling melting, and crystallization are more important than a certain cooling history. Gélinas and Brooks (1971) support this argument with the observation that flow-oriented plagioclase crystals tend to occur in rapidly cooled liquids rather than supercooled melts. In the DS4 layer, there are a few examples of spherules with aligned plagioclase laths, particularly along the edges of central cores (Fig. 13). In light of these considerations, we believe it is more likely that the textures of these ejecta particles were formed by rapid cooling rather than quenching.

Another key control on crystal growth is the availability of nuclei. Lofgren (1983) states that in supercooled liquids, plagioclase will only nucleate heterogeneously. Proximal impact melts commonly contain abundant inclusions of unmelted rock and microscopic particles that can serve as nucleation sites, but more distal melt particles normally do not. In addition, the size of the plagioclase crystals is directly linked to the number of nucleation sites in that crystals will be larger if there are fewer nuclei as they will have more room to grow (Lofgren 1983). The potential to nucleate also increases with decreasing viscosity (Lofgren 1980). Where microlites are present in the DS4 spherules, they consist of many tiny plagioclase crystals. We infer the original composition had a high nucleation potential with a relatively low viscosity, which is consistent with an original composition that is basaltic. The diversity of the textures in the DS4 ejecta particles is also more consistent with the heterogeneity one would expect in impact melts than the more uniform melt that is likely to be erupted in a single volcanic eruption (Symes et al. 1998; Culler et al. 2000).

As for the apparent lack of pyroxene and olivine, pyroxene is not a prominent liquidus phase (Bryan 1972). In fact, some basalts do not contain either olivine or pyroxene (e.g., Pearce 1974). It has even been suggested that plagioclase was the normal liquidus phase during the Precambrian (Pearce and Donaldson 1974). Furthermore, as cooling rate increases, the nucleation temperature decreases, thus lowering the liquidus (Lofgren 1980). Therefore perhaps it is no surprise that no pseudomorphs of either pyroxene or olivine have been identified in the DS4 ejecta, although we do not rule out the possibility that small amounts we overlooked could be present.

Crystallization Happened in Flight

In addition to the internal microlites that mimic the normal textures of basalts, a much greater number of splash forms have rims consisting of K-feldspar in the form of acicular to lath-shaped crystals, some in the form of inward-radiating botryoidal masses. Except for the positioning, the lath-shaped crystals are like the randomly oriented laths inside both splash forms and angular particles. They clearly nucleated on the outer surfaces of the original particles and grew inwards. Bohor and Glass (1995) described similar rims in K-T impact spherules and attributed their formation to rapid hydration followed by palagonitization when hot glass spherules fell into cool water. The K-T rims consist of various minerals other than K-feldspar, but their fibrous growth habit is strikingly similar to some of the rims of the DS4 spherules. However, we doubt the hydration/palagonitization mechanism could explain either the DS4 rims or those on the K-T spherules as it seems very unlikely non-crystalline palagonite would convert to fibrous crystals grown in such a highly directed fashion, whatever their composition. Specifically, the crystals in the rims of both the K-T and DS4 spherules largely nucleated along outer edges and have their internal terminations typically assume botryoidal shapes. A nucleus-rich material like palagonite would be much more likely to foster crystal growth in random directions.

If the hydration/palagonitization interpretation is ruled out, we see two remaining possibilities for the origin of these rims: as crystals grown from the original melts or via devitrification of glass after the melt had been quenched. In light of their marginal position and spherulitic nature, Simonson (1992) attributed the rims to devitrification, but textures in the DS4 splash forms call this interpretation into question. In the great majority of cases, rims of consistent character occur on original outer edges of the broken splash forms but are absent from the broken edges (Figs. 6 and 8). This strongly suggests most rims formed before the particles were broken and deposited. However, the few that show thin rims on broken surfaces indicate some crystallization took place after breakage. Since they landed in the ocean, very likely delivered directly from the point of impact (Hassler and Simonson 2001), the DS4 splash forms must have been quenched well below their solidus temperature at the end of their flight and were never reheated again. Consequently, there is little chance they could have thermally devitrified or even crystallized further once they landed in the water. The possibility that the rims formed in situ by devitrification after deposition can be ruled out by the fact that they are *not* equally developed on all margins independent of whether they were originally external surfaces or not. That leaves two possibilities: either the rims represent crystals grown from the melt or the splash forms were cooled to glass and then thermally devitrified in flight. The possibility of marginal crystallization is an attractive one as dust impacting the exterior surfaces of spherules could serve as nuclei for crystal growth. Connolly and Hewins (1995) proposed such a mechanism for the crystallization of chondrules and were able to demonstrate its efficacy experimentally. However, we cannot rule out the possibility of thermal devitrification in flight. The fact that rims are thinner and much scarcer on broken surfaces than they are on original external surfaces would be consistent with spherules having a reduced likelihood of experiencing heating after being fractured, since such spherules would presumably tend to be further downrange in areas that were cooler on average. Lofgren (1971) described devitrified lunar spherules and, given the impossibility of aqueous alteration on the Moon, suggested they had been thermally devitrified, either during flight or by subsequent impacts. In the case of the DS4 splash forms, thermal devitrification by subsequent impacts is not an option. Whichever mechanism was responsible, it is clear from the textures of broken splash forms that the most or all of the external rims formed in flight.

The origins of the internal septae are more puzzling than those of the external rims. The septae appear to have formed by fibrous crystallization and/or devitrification directed outward from microfractures inside the spherules via the same arguments applied to the rims. Although no obvious petrographic evidence prevents them from having formed in situ after deposition, this again seems unlikely because they are not uniform, i.e., they appear different in different spherules and often different from the rim on the outer edge of their host grain. The latter suggests the septae and external rims crystallized under different conditions and/or at different times in a give grain. Slower cooling inside a spherule relative to the edge would be one possible difference, and that could explain why septae are thicker than external rims in some cases. However, it is difficult to envision grains cracking in flight but remaining intact in the turbulent environment of an expanding ejecta plume. We believe a full understanding of how the internal septae formed requires further petrographic and possibly experimental study.

The mechanism responsible for breaking the DS4 splash forms is also uncertain. It is possible that thermal stresses which may occur when hot particles fall into cool water caused these splash forms to break (Glass et al. 1997). Alternatively, it is only to be expected that a number of splash forms and angular particles would be fractured by mutual collisions during the deposition of the DS4 layer. Perhaps it is surprising that so many splash forms have unbroken cross-section given the high energy of that event. Similar broken splash forms occur in other Precambrian spherule layers (Scally and Simonson 2005; Kohl et al. 2006), but not in the abundance with which we observed them in the DS4 layer. We attribute this to the fact that they are harder to recognize in layers that have been subjected to a higher degree of compaction, in which case external shapes are more highly modified.

In order to crystallize in flight, the splash forms of the DS4 would have had to maintain an elevated temperature for an extended period of time. Symes et al. (1998) performed some pertinent calculations on the cooling rates of crystalline lunar spherules (CLS) that are similar to the DS4 ejecta particles with random textures in that they are mafic in composition and have an abundance of plagioclase laths. However, they are smaller (about 190 µm in mean diameter) then the DS4 splash forms and never show spherulitic textures. Symes et al. concluded that the CLS most likely cooled at rates of <100°C/s and probably <1°C/s. They therefore conclude that only major impacts would produce the textures observed in CLS as "smaller impact would be expected to produce melt-spherules that cool too quickly for appreciable crystallization" (Symes et al. 1998, p. 22–23). We believe the same conclusions apply to the DS4 ejecta, and that in order to cool at a sufficiently slow rate, the melt must have been part of a large mass of hot gas and dust. If the rims of the splash forms formed by thermal devitrification instead of crystallizing directly from the melt, then an even more complicated evolution is required in the impact plume. This would mean that, not uncommonly, ejecta droplets would be cooled to the point of quenching to glass, then enter an area where the temperature was high enough to reheat them considerably. Such complex mixing paths in expanding vapor plumes do not seem out of the question, but they have yet to be incorporated into models of what happens during major impacts.

The fact that it is possible for impact spherules to crystallize rapidly is supported by terrestrial lines of evidence in addition to the CLS. One is the presence of rare spherules in the suevite breccia of the Ries crater that have a rim of plagioclase microlites morphologically very similar to some of the Precambrian spherules (Figs. 3 and 7 of Graup [1981]). In addition, rare spherules of melt from the Eltanin impact display lath-like crystals growing inward from the margins (Margolis et al. 1991). Although these crystals are dissolved and their original composition is uncertain, the Eltanin ejecta layer is in some ways the best analog for the DS4 spherules in that the melt was generated by the impact of a basaltic achondrite and therefore had a basaltic composition (Kyte and Brownlee 1985). Moreover, the Eltanin melt droplets landed in the deep ocean relatively close to the point of impact, so these crystals must have grown directly from the melt prior to the deposition of the spherules on the seafloor.

Ejecta More Proximal than Distal

Most models for how impact spherules form and get dispersed by a large terrestrial impact are calibrated by comparison to the K-T boundary layer, but the splash forms in the DS4 layer cannot be fit to this model without major modifications. To summarize first, spherules from the K-T boundary layer have been subdivided into two main categories: 1) large splash forms found within a few thousand kilometers of ground zero that include non-circular shapes (i.e., teardrops, dumbbells, etc.), range up to 2 cm across, may contain relict glass, and commonly show a bubbly texture but no crystallization internally (Izett 1991; Sigurdsson et al. 1991), versus 2) microkrystites found tens of thousands of kilometers from ground zero that are exclusively spherical, 250 µm in mean diameter, and may contain CPX dendrites (Smit et al. 1992; Martinez Ruiz et al. 1997; Smit 1999). We will refer to these two types as proximal versus distal K-T spherules, respectively, to distinguish qualitatively between those found closer to the impact structure and those found much further away. The proximal spherules have been interpreted as melt droplets emplaced ballistically whereas the distal spherules are believed to be droplets condensed from vaporized target rock.

The splash forms in the DS4 layer show a hybrid character involving aspects of both types of spherules from the K-T boundary layer. On the one hand, they resemble proximal spherules in their large size, the occurrence of non-spherical shapes, and having internal bubbles. However, they resemble the distal spherules in that many show internal crystallization. Given that they average almost an order of magnitude larger in size than the distal K-T spherules and a significant number have non-spherical shapes, we interpret the DS4 spherules as ballistic melt spherules. It appears that only spherules smaller than those of the DS4 layer will form from vapor plumes (Ruzicka et al. 2000; Symes et al. 1998; Pope 2002). Assuming the DS4 splash forms are ballistic melt droplets, we attribute the fact that they crystallized to their having lower silica contents and lower viscosities than the proximal K-T spherule melts. As noted above, proximal impact melts also contain more nucleation sites, which would also increase the likelihood of their crystallizing in flight. Another difference between the proximal K-T spherules and the DS4 splash forms is the relative scarcity of vesicles in the latter. The high vesicularity of the proximal K-T spherules has been attributed to outgassing of CO_2 from carbonates at the point of impact (Smit et al. 1992). It is highly unlikely that there was much carbonate to hit anywhere on Earth's surface at the time the impact that created the DS4 layer happened.

Origin of Angular Particles

The angular fragments in the DS4 layer show basalt-like textures similar to those found in the crystalline spherules. While this suggests they are simply fragments of larger and more highly crystallized ballistic melt droplets, some could also be solid fragments of target rocks emplaced ballistically. This would be of great interest because to date the only candidate for solid ejecta from a terrestrial impact older than the Sudbury structure is a single quartz crystal in the Jeerinah spherule layer (Rasmussen and Koeberl 2004). Given our interpretation of the DS4 ejecta as melts that were originally basaltic, it would be no surprise to find solid pieces of basalt in the impact ejecta. If, however, the angular particles were solid ejecta, it is surprising we saw no evidence of the internal disruption one would expect from shock deformation. That said, no internal deformation features (e.g., PDFs) would be preserved in plagioclase crystals because of their total replacement by K-feldspar. While the angular particles could easily be mistaken for epiclastic grains from a basaltic source rock, the total lack of any other epiclastic detritus in the Dales Gorge Member, including the DS4 layer, makes this origin highly unlikely, particularly since unusually coarse epiclastic detritus is a common constituent of other spherule layers in the Hamersley succession (Simonson 1992; Simonson et al. 2000; Jones-Zimberlin et al 2006).

In the one sample where we measured them, the length of the plagioclase microlites remained fairly constant despite clast size changes whereas the lengths of the plagioclase crystals in the splash forms span a broader range of sizes with respect to clast size. This could reflect the derivation of the angular fragments from the interiors of melt particles that were more highly crystallized. However, if this were the case it seems odd that the basalt-like random textures are more than twice as abundant in the angular particles as they are in the splash forms. Whatever the origin of the angular particles, the presence of angular particles agglutinated to splash form particles indicate they were both participants in the same impact event.

SUMMARY AND IMPLICATIONS FOR IMPACT MODELING

Although they are almost 2.5 billion years old, the impact spherules in the DS4 layer of the Dales Gorge BIF of the Hamersley Group of Western Australian are very well preserved. The phases that were originally present have long since been replaced, largely by stilpnomelane and K-feldspar, but these diagenetic phases have faithfully preserved many of the textures originally present in these once-molten particles. Most of the particles have external shapes indicating they were highly fluid bodies; such objects are referred to as splash forms and most have circular cross sections, but a minority have ovoid shapes or more irregular shapes such as dumbbells and teardrops. In contrast, a minority of particles have angular shapes, but the splash forms and angular particles have the same composition and share a common suite of internal textures (Table 1). Petrographic evidence presented above indicates these melts crystallized in flight and strongly suggests the melts were basaltic in composition. However, only plagioclase microlites appear to have formed; we did not observe any candidates for pseudomorphs of pyroxene or olivine. Given the large size and variable shape of the splash forms, we interpret them as droplets of impact melt emplaced ballistically rather than vapor condensate. This is largely by analogy to the K-T boundary layer, within which only the proximal spherules are comparable in size and shape to the DS4 splash forms. However, unlike the distal K-T spherules, the former do not show any signs of having crystallized in flight; we attribute this difference to the DS4 particles forming from melts that were lower in silica and viscosity on average. The origin of the angular particles that form a minority of the ejecta in the DS4 layer is uncertain, but at least in part they may represent solid ejecta. If so, this would be a first in an impact deposit this old.

The nature of the DS4 impact spherules, based on the data presented here, has several important implications for what happens during a large terrestrial impact. First of all, the fact that crystals formed in the melts in flight requires relatively slow cooling. A similar conclusion was reached by Symes et al. (1998) for crystalline lunar spherules, and like them we further conclude that this requires the splash forms to have traveled in a relatively dense and hot cloud of gas and dust for an extended period of time. The presence of rims on a majority of the splash forms may in fact be a product of that dusty environment in that dust hitting the outer edges of the droplets may have served as nuclei for the crystals that make up the rims. Another possibility is that the rims formed by thermal devitrification, and if they did, it adds another level of complexity to the process. Since the rims clearly formed in flight, they could only form by thermal devitrification if the splash forms first moved into an area cold enough to quench them to glass and then were reinjected into a warmer area. We believe this implies a greater degree of downrange mixing of ejecta than is normally envisioned in models of plume expansion and subsequent settling of impact melt droplets.

Another interesting aspect of the DS4 ejecta is its basaltic composition. Since impact ejecta is usually made up in large part of material from target rocks and most of the Earth's surface is underlain by oceanic crust, one would expect multiple examples of basaltic ejecta. The only example of a large Phanerozoic impact that produced basaltic ejecta we know of is the Eltanin event, and that has been attributed to melting of a basaltic achondrite (Kyte and Brownlee 1985). This raises the question of why there are not more impact structures on the seafloor, and/or ejecta from such structures. One possible difference is the shielding effect of the ocean, as documented in the Eltanin event (Gersonde et al. 1997), but the presence of crystallization textures and what appear to be basaltic droplets in most or all of the Precambrian spherule layers (Simonson et al. 2004) suggests there is more to the story. Perhaps we have yet to fully appreciate the role a deep column of seawater plays in large impacts, and/or the efficiency with which craters have been obscured and basaltic ejecta layers dispersed or altered on the Phanerozoic seafloor.

Finally, the data presented here show that the K-T boundary event should not be taken as a "one size fits all" model for the dispersal of impact spherules and related particles. Even though it has been studied in much greater detail than any other ejecta layer and is unrivaled in the degree to which we understand it, it is just one impact, and probably not a very normal one at that. The target rocks in the Chicxulub area had a composition that was very unusual by global standards, and the spherules in the distal ejecta are unlike those in other layers with the notable exception of the Eocene CPX layer (Glass 2002). We do not advocate abandoning the use of the K-T event as a yardstick with which to calibrate other layers, but we believe it is necessary to invoke only those aspects that are appropriate to a particular situation, as we have tried to do here.

In conclusion, we hope we have demonstrated that petrographic studies of ejecta can provide useful information about impact processes, even in the absence of an impact structure. Spherule layers such as the DS4 are the only record we have of terrestrial impacts for over a billion years of early Earth history, so we need to extract all the information we can from them. They may also help facilitate high-resolution correlations between Precambrian successions on different continents. For example, a spherule layer recently discovered in the Kuruman BIF of the Griqualand West Basin of South Africa may contain ejecta from the same impact as the DS4 layer (Simonson et al. 2009). We suspect that a closer look at the ejecta in these and other spherule layers can still teach us a lot about large impacts on the early Earth, especially when coupled with detailed geochemical investigations. As the number of case studies of ejecta from large impacts increases, it is likely that the current model for large impacts will evolve in interesting ways and become more generally applicable in the process.

Acknowledgments—The field work during which the samples we studied were collected was made possible by grants from the National Geographic Society and Oberlin College and logistical support from the Geological Survey of Western Australia. Field assistance by Scott Hassler and Kathy Schubel is gratefully acknowledged.

Editorial Handling—Dr. Gordon Osinski

REFERENCES

Arndt N. T., Naldrett A. J., and Pyke D. R. 1977. Komatiitic and iron-rich tholeiitic lavas of Munro Township, northeast Ontario. *Journal of Petrology* 18:319–369.

Bakatt Aa, Saad E. E., Adiga R., Sousanpour W., Barkatt Al., and Alterescu S. 1986. Leaching of microtektite glass compositions in seawater. *Advances in Ceramics* 20:681–687.

Bohor B. F. and Glass B. P. 1995. Origin and diagenesis of K/T impact spherules—from Haiti to Wyoming and beyond. *Meteoritics* 30:182–198.

Bryan W. 1972. Morphology of quench crystals in submarine basalts. *Journal of Geophysical Research* 77:5812–5819.

Byerly G. R. and Lowe D. R. 1994. Spinel from Archean impact spherules. *Geochimica et Cosmochimica Acta* 50:3469–3486.

Chadwick B., Claeys P., and Simonson B. M. 2001. New evidence for a large Paleoproterozoic impact: Spherules in a dolomite layer in the Ketilidian orogen, South Greenland. *Journal of the Geological Society of London* 158:331–340.

Chapman C. R. and Morrison D. 1994. Impacts on the Earth by asteroids and comets: Assessing the hazards. *Nature* 367:33–40.

Connolly H. C. Jr. and Hewins R. H. 1995. Chondrules as products of dust collisions with totally molten droplets within a dust-rich nebular environment: An experimental investigation. *Geochimica et Cosmochimica Acta* 59:3231–3246.

Culler T. S., Becker T. A., Muller R. A. and Renne P. R. 2000. Lunar impact history from $^{40}Ar/^{39}Ar$ dating of glass spherules. *Science* 287:1785–1788.

Ewers W. E. and Morris R. C. 1981. Studies of the Dales Gorge Member of the Brockman Iron Formation, Western Australia. *Economic Geology* 76:1929–1953.

Gélinas L. and Brooks C. 1974. Archean quench-texture tholeiites. *Canadian Journal of Earth Sciences* 11:324–340.

Gersonde R., Kyte F. T., Bleil U., Diekmann B., Flores J. A., Gohl K., Grahl G., Hagen R., Kuhn G., Sierro F. J., Völker D., Abelmann A., and Bostwick J. A. 1997. Geological record and reconstruction of the late Pliocene impact of the Eltanin asteroid in the Southern Ocean. *Nature* 390:357–363.

Gibb F. G. 1974. Supercooling and the crystallization of plagioclase from a basaltic magma. *Mineralogic Magazine* 39:641–653.

Glass B. P. 1984. Solution of naturally-occurring glasses in the geological environment. *Journal of Non-Crystalline Solids* 97:265–286.

Glass B. P. 1986. Solution of natural glasses in the geological environment. *Advances in Ceramics* 20:723–732.

Glass B. P. 1990. Tektites and microtektites: Key facts and inferences. *Tectonophysics* 171:393–404.

Glass B. P. 2002. Upper Eocene impact ejecta/spherule layers in marine sediments. *Chemie der Erde* 62:173–96.

Glass B. P. and Burns C. A. 1988. Microkrystites: A new term for impact-produced glassy spherules containing primary crystallites. Proceedings, 18th Lunar and Planetary Science Conference. pp. 455–458.

Glass B. P., Burns C. A., Crosbie J. R., and DuBois D. L. 1985. Late Eocene North American microtektites and clinopyroxene-bearing spherules. *Journal of Geophysical Research* 90:D175–D196.

Glass B. P., Muenow D. W., Bohor B. F., and Meeker G. P. 1997. Fragmentation and hydration of tektites and microtektites. *Meteoritics & Planetary Science* 32:333–341.

Glikson A Y. 1999. Oceanic mega-impacts and crustal evolution. *Geology* 27:387–90.

Glikson A Y. and Allen C. 2004. Iridium anomalies and fractionated siderophile element patterns in impact ejecta, Brockman Iron Formation, Hamersley Basin, Western Australia: Evidence for a major asteroid impact in simatic crustal regions of the early Proterozoic earth. *Earth and Planetary Science Letters* 220:247–264.

Graup G. 1981. Terrestrial chondrules, glass spherules and accretionary lapilli from the suevite, Ries crater, Germany. *Earth and Planetary Science Letters* 55:407–418.

Hassler S. W. 1993. Depositional history of the Main Tuff Interval of the Wittenoom Formation, late Archean-early Proterozoic Hamersley Group, Western Australia. *Precambrian Research* 60: 337–359.

Hassler S. W. and Simonson B. M. 2001. The sedimentary record of extraterrestrial impacts in deep-shelf environments: Evidence from the early Precambrian. *Journal of Geology* 109:1–19.

Hassler S. W., Simonson B. M., Sumner D., and Murphy M. 2005. Neoarchean spherule layers in the Fortescue and Hamersley Groups, Western Australia: Stratigraphic and depositional implications of recorrelation. *Australian Journal of Earth Sciences* 52:759–771.

Izett G. A. 1991. Tektites in Cretaceous-Tertiary boundary rocks on Haiti and their bearing on the Alvarez impact extinction hypothesis. *Journal of Geophysical Research* 96:20,879–20,905.

Jones-Zimberlin S., Simonson B. M., Kreiss-Tomkins D., and Garson D. 2006, Using impact spherule layers to correlate sedimentary successions: A case study of the Neoarchean Jeerinah layer (Western Australia). *South African Journal of Geology* 109:245–261.

Klein C. 2005 Some Precambrian banded iron-formations (BIFs) from around the world: Their age, geologic setting, mineralogy, metamorphism, geochemistry, and origin. *American Mineralogist* 90:1473–1499.

Kohl I., Simonson B. M., and Berke M. 2006 Diagenetic alteration of impact spherules in the Neoarchean Monteville layer, South Africa. In *Processes on the early Earth*, edited by Reimold W. U. and R. Gibson R. GSA Special Paper #405. Boulder, Colorado: Geological Society of America. pp. 57–73.

Krull-Davatzes A. E., Lowe D. L., and Byerly G. R. 2006. Compositional grading in an ~3.24 Ga impact-produced spherule bed, Barberton Greenstone Belt, South Africa: A key to impact plume evolution. *South African Journal of Geology* 109:233–244.

Kyte F. T. and Brownlee D. E. 1985. Unmelted meteoritic debris in the Late Pliocene iridium anomaly: Evidence for the ocean impact of a non-chondritic asteroid. *Geochimica et Cosmochimica Acta* 49: 1095–1108.

LaBerge G. L. 1966a. Altered pyroclastic rocks in iron-formation in the Hamersley Range, Western Australia. *Economic Geology* 61: 147–161.

LaBerge G. L. 1966b. Altered pyroclastic rocks in South African iron-formation. *Economic Geology* 61:572–581.

Lofgren G. 1971. Devitrified glass fragments from Apollo 11 and Apollo 12 lunar samples. Proceedings, 2nd Lunar Science Conference. pp. 949–955.

Lofgren G. 1971. Experimentally produced devitrification textures in natural rhyolitic glass. *Geological Society of America Bulletin* 82:111–124.

Lofgren G. 1971. Spherulitic textures in glassy and crystalline rocks. *Journal of Geophysical Research* 76:5635–5648.

Lofgren G. 1977. Dynamic crystallization experiments bearing on the origin of textures in impact-generated liquids. Proceedings, 8th Lunar Science Conference. pp. 2079–2095.

Lofgren G. 1980. Experimental studies on the dynamic crystallization of silicate melts. In *Physics of magmatic processes*, edited by Hargraves R. B. Princeton, New Jersey: Princeton University Press. pp. 487–551.

Lofgren G. 1983. Effect of heterogeneous nucleation on basaltic textures: A dynamic crystallization study. *Journal of Petrology* 24:229–255.

Lofgren G. and Donaldson C. H. 1975. Curved branching crystals and differentiation in comb-layered rocks. *Contributions to Mineralogy and Petrology* 49:309–319.

Lowe D. L, Byerly G. R, Kyte F. T., Shukolyukov A., Asaro F., and Krull A. 2003. Spherule beds 3.47–3.24 billion years old in the Barberton Greenstone Belt, South Africa: A record of large meteorite impacts and their influence on early crustal and biological evolution. *Astrobiology* 3:7–48.

MacDonald I. and Simonson B. M. 2002. PGE anomalies detected in two more 2.5–2.6 billion year-old spherule layers in the Hamersley Basin of Western Australia (abstract #1250). 33rd Lunar and Planetary Science Conference. CD-ROM.

Margolis S., Claeys P., and Kyte F. T. 1991. Microtektites, microkrystites, and spinels from a late Pliocene asteroid impact in the southern ocean. *Science* 251:1594–1597.

Martínez Ruíz F., Ortega Huertas M., Palomo I., and Acquafredda P. 1997. Quench textures in altered spherules from the Cretaceous-Tertiary boundary layer at Agost and Caravaca, SE Spain. *Sedimentary Geology* 113:137–147.

Pearce T. H. 1974. Quench plagioclase from some Archean basalts. *Canadian Journal of Earth Sciences* 11:715–719.

Pearce T. H. and Donaldson J. A. 1974. Proterozoic quench-texture basalts from the Labrador geosyncline. *Canadian Journal of Earth Sciences* 11:1611–1615.

Pettijohn F. J. 1949. *Sedimentary rocks,* 1st ed. New York: Harper and Brothers. 526 p.

Pettijohn F. J. 1975. *Sedimentary rocks*, 3rd ed. New York: Harper and Brothers. 628 p.

Pickard A. L. 2002. SHRIMP U-Pb zircon ages of tuffaceous mudrocks in the Brockman Iron Formation of the Hamersley Range, Western Australia. *Australian Journal of Earth Sciences* 49:491–507.

Pickard A. L., Barley M. E., and Krapez B. 2004. Deep-marine depositional setting of banded iron formation: Sedimentological evidence from interbedded clastic sedimentary rocks in the early Palaeoproterozoic Dales Gorge Member of Western Australia. *Sedimentary Geology* 170:37–62.

Pope K. O. 2002. Impact dust not the cause of the Cretaceous-Tertiary mass extinction. *Geology* 30:99–102.

Rasmussen B. and Koeberl C. 2004. Iridium anomalies and shocked quartz in a Late Archean spherule layer from the Pilbara craton: New evidence for a major asteroid impact at 2.63 Ga. *Geology* 32:1029–1032.

Ruzicka A., Snyder G. A., and Taylor L. A. 2000. Crystal-bearing lunar spherules: Impact melting of the Moon's crust and implications for the origin of meteoritic chondrules. *Meteoritics & Planetary Science* 35:173–192.

Scally A. and Simonson B. M. 2005. Spherule textures in the Neoarchean Wittenoom layer: Consistency in diversity. *Australian Journal of Earth Sciences* 52:773–783.

Shukolyukov A, Castillo P, Simonson B. M., and Lugmair G. W. 2002. Chromium in late Archean spherule layers from Hamersley basin, Western Australia: Isotopic evidence for extraterrestrial component (abstract #1369). 33rd Lunar and Planetary Science Conference. CD-ROM.

Sigurdsson H., D'Hondt S., Arthur M. A., Bralower T. J., Zachos J. C., van Fossen M., and Channell J. E. T. 1991. Glass from the Cretaceous/Tertiary boundary in Haiti. *Nature* 349:482–487.

Simonson B. M. 1987. Early silica cementation and subsequent diagenesis in arenites from four early Proterozoic iron-formations of North America. *Journal of Sedimentary Petrology* 57:494–511.

Simonson B. M. 1992. Geological evidence for a strewn field of impact spherules in the early Precambrian Hamersley Basin of Western Australia. *Geological Society of America Bulletin* 104:829–839.

Simonson B. M. 2003a. Origin and evolution of large Precambrian iron formations. In *Extreme depositional environments: Mega end members in geologic time*, edited by Chan M. and Archer A. GSA Special Paper 370. Boulder, Colorado: Geological Society of America. pp. 231–244.

Simonson B. M. 2003b. Petrographic criteria for recognizing certain types of impact spherules in well-preserved Precambrian successions. *Astrobiology* 3:49–65.

Simonson B. M. and Glass B. P. 2004. Spherule layers—Records of ancient impacts. *Annual Review of Earth and Planetary Sciences* 32:329–361.

Simonson B. M. and Harnik P. 2000. Have distal impact ejecta changed through geologic time? *Geology* 28:975–978.

Simonson B. M., Schubel K. A., and Hassler S. W. 1993a. Carbonate sedimentology of the early Precambrian Hamersley Group of Western Australia. *Precambrian Research* 60:287–335.

Simonson B. M., Hassler S. W., and Schubel K. A. 1993b. Lithology and proposed revisions in stratigraphic nomenclature of the Wittenoom Formation (Dolomite) and overlying formations, Hamersley Group. Western Australia. Geological Survey of Western Australia Report 34. Perth: Geological Survey of Western Australia. pp. 65–79.

Simonson B. M., Davies D., Wallace M., Reeves S., and Hassler S. W. 1998. Iridium anomaly but no shocked quartz from Late Archean microkrystite layer: Oceanic impact ejecta? *Geology* 26:195–198.

Simonson B. M., Hassler S. W., and Beukes N. J. 1999. Late Archean impact spherule layer in South Africa that may correlate with a Western Australian layer. In *Large meteorite impacts and planetary evolution*, edited by Dressler B. O. and Sharpton V. L. GSA Special Paper 339. Boulder, Colorado: Geological Society of America. pp. 249–261.

Simonson B. M., Davies D., and Hassler S. W. 2000. Discovery of a layer of probable impact melt spherules in the late Archean Jeerinah Formation, Fortescue Group, Western Australia. *Australian Journal of Earth Science* 47:315–325.

Simonson B. M., Hornstein M., and Hassler S. 2000. Particles in late Archean Carawine Dolomite (Western Australia) resemble Muong Nong-type tektites. In *Impacts and the early earth*, edited by Gilmour I. and Koeberl C. Berlin-Heidelberg: Springer-Verlag. pp. 181–213.

Simonson B. M., Byerly G. R., and Lowe D. R. 2004. The early Precambrian stratigraphic record of large extraterrestrial impacts. In *The Precambrian earth: Tempos and events*, edited by Eriksson P. G., Altermann W., Nelson D. R., Mueller W. U., and Catuneanu O. Amsterdam: Elsevier. pp. 27–45.

Simonson B. M., Sumner D., Beukes N. J., Johnson S., and Gutzmer J. 2009. Correlating multiple Neoarchean-Paleoproterozoic impact spherule layers between South Africa and Western Australia. *Precambrian Research*, doi:10.1016/j.precamres.2008.10.016.

Smit J. 1999. Global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta. *Annual Review of Earth and Planetary Science* 27:75–113.

Smit J., Alvarez W., Montanari A., Swinburn N., Van Kempen T. M., Klaver G. T., and Lustenhouwer W. J. 1992. Tektites and microkrystites at the Cretaceous-Tertiary boundary: Two strewn fields, one crater? Proceedings, 22nd Lunar and Planetary Science Conference. pp. 88–100.

Symes S. J. K, Sears D. W. G, Akridge D. G, Huang S., and Benoit P. H. 1998. The crystalline lunar spherules: Their formation and implications for the origin of meteoritic chondrules. *Meteoritics & Planetary Science* 33:13–29.

Trendall A. F. 1983. The Hamersley Basin. In *Iron formation: Facts and problems*, edited by Trendall A. F. and Morris R. C. Amsterdam: Elsevier. pp. 69–129.

Trendall A. F. and Blockley J. G. 1970. The iron formations of the Precambrian Hamersley Group, Western Australia. Geological Survey of Western Australia Bulletin 119. Perth: Geological Survey of Western Australia. 366 p.

Trendall A. F., Compston W., Nelson D. R., De Laeter J. R., and Bennett V. C. 2004. SHRIMP zircon ages constraining the depositional chronology of the Hamersley Group, Western Australia. *Australian Journal of Earth Science* 51:621–644.

Vernon R. H. 2004. *A practical guide to rock microstructure*. Cambridge: Cambridge University Press. 594 p.