https://doi.org/10.5194/hgss-2026-9
Preprint. Discussion started: 2 July 2026

George Perkins Merrill's Analyses of Chondrules and Chondritic Meteorites

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Abstract. George Perkins Merrill (1854–1929) was the preeminent American meteoriticist of the first quarter of the 20th Century. He applied to that science his pioneering knowledge and skill in the petrographic analysis of chondritic meteorites. Throughout his long and distinguished career with the United States National Museum, now the Smithsonian Institution of Washington, D.C., Merrill authored over seventy publications on meteorites. While many of those contributions described new irons and stones which had come into the museum's collection, a pair of papers concerning the origin of chondrules and the evidence for and causes of metamorphism of chondritic meteorites led directly to his selection as the second recipient of the J. Lawrence Smith Medal which was awarded by the National Academy of Sciences in 1922 for outstanding accomplishments in the study of meteorites. The origins, primary arguments, and subsequent reception of those two landmark papers are herein reviewed. Particular attention is given to how Merrill's hypotheses on chondrule formation and the evidence for thermal and dynamic metamorphic alteration of chondrites have come to underpin and advanced modern understandings of the early history of the solar system.

1. Introduction: Merrill and the origins of American meteoritics

George Perkins Merrill (1854–1929) served in a series of positions of increasing authority and responsibility within the United States National Museum, now the Smithsonian Institution of Washington, D.C., from 1881 until his unexpected death in his hometown of Auburn, Maine (Fig. 1). Merrill's extensive contributions were carefully chronicled by two memorials (Schuchert 1931; Lindgren 1935) as well as several other tributes and obituaries (Benn 1929; Benjamin 1929; Farrington 1930). All of those summaries delineated several distinct vectors of Merrill's long and productive career. The scope of Merrill's contributions is considered along with a review of the status of American meteoritics from the inception of the science to the early decades of the 20th century.

Figure 1. Portrait of George Perkins Merrill (c. 1900), geologist and head curator of the Department of Geology, United States National Museum. Smithsonian Institution Archives RU000095[SIA2009-4249]. Reproduced with permission of the Smithsonian Institution.

1.1 Merrill's career

As described by those who best remembered and valued his career, Merrill was recognized for making significant contributions in multiple fields of study. Merrill was first and foremost the organizer of the Department of geology at the National Museum, wherein he rose to the rank of Head Curator in 1897. The department, which had been founded the year before Merrill joined the museum, had by the time of his death become recognized as "one of the great collections of the world, and one which is possibly not excelled by any" (Schuchert 1931, p.99) with over 2 million specimens of rocks, minerals and fossils within the carefully curated collection. The second major vector of Merrill's career was his role as a pioneer in the study of building stones, rock weathering and soil formation. When he joined the National Museum Merrill's primary task was the "cutting of thin sections of the entire collection of some 4000 samples of building stones that had been brought together from upwards of 1500 quarries in the United States" (Schuchert 1931, p. 101). Based on his careful analysis of these samples, Merrill came to be recognized as "one of the earliest petrographers of this country" (Lindgren 1935, p. 34). Those efforts resulted in the publication of reports associated with the Centennial Exposition of 1884–1885 in New Orleans, and eventually culminated in the publication of the book *Stones for Building and Decoration* (Merrill 1891; 1897b; 1903), the first book on that subject to be published in the United States. The primary motivating factor for that work was the establishment of the suitability of various lithologies represented within the museum's collection. A critical factor in defining architectural suitability was a stone's resistance to degradation via weathering. Merrill's work naturally led him to undertake one of the first systematic studies of rock weathering and soil formation (Merrill 1896; 1900) which in turn resulted in the publication of *A Treatise on Rocks, Rock Weathering, and Soils* (Merrill 1897a; 1907a) which came to be recognized as the "greatest work on the genesis of soils" (Benjamin 1929, p. 274) available in the first decades of the 20th century. The third of Merrill's professional vectors was one with which this author feels a great deal of affinity in that Merrill devoted the "'odd moments' in his official life to the study of the rise and progress of American Geology, with the result that he became the historian of our science previous to the present century" (Schuchert 1931, p. 108). Near the end of his career, Merrill authored the book *The First One Hundred Years of American Geology* (Merrill 1924) as well as an extensive study of the history of state geological surveys (Merrill 1920b). A fourth vector of Merrill's distinguished career is the primary topic of the following analysis, his petrographic study of the chondritic meteorites. While Merrill conducted many studies of meteoric irons, including a comprehensive survey of the Canyon Diablo meteorite and the origin of Meteor Crater, Arizona (Merrill 1907b; 1908; 1920a), his work on the understanding of the origin of chondrules specifically, and stony meteorites more generally, occupied a significant part of the second half of his career such that through the publication of "nearly 80 papers on this subject … he was without doubt the foremost authority on this subject in our country" (Lindgren 1935, p. 39).

1.2 The early years of American meteoritics

A comprehensive consideration of the emergence and evolution of meteoritics from antiquity to the modern has been described in detail in the contributions summarized by McCall et al. (2006). No event had a more significant influence on the initiation of the modern scientific study of meteorites than did the well-documented fall of several thousand stones at L'Aigle, France on 26 April, 1803. Jean-Baptise Biot compiled both physical evidence and eyewitness testimonies of the event in order to conclusively demonstrate the extraterrestrial origin of the meteorite (Gounelle 2006). Four years later, on 14 December, 1807 over the town of Weston, Connecticut, the first documented meteorite fall in the western hemisphere occurred. Fragments of the Weston (H4) ordinary chondrite were investigated by the first American scientist to contribute to the field of meteoritics, Benjamin Silliman (1779–

1864). Silliman was to become the doctorial advisor of James Dwight Dana and the founder of the *American Journal of Science*, the outlet through which most of the early studies of meteorites in America were published. He was the author of 24 papers on meteorites, the first was published in 1809 based on a reading to the American Philosophical Society on March 4, 1808 concerning the Weston fall (Silliman and Kingsley 1809). From the excellent summary of Lange (1975), a timeline of the major contributors to the development of the science of meteoritics in America has been developed (Table 1).

Table 1. Timeline of the major contributors to the growth and development of American meteoritics throughout the 19th and early 20th century.

Timeline of American Meteoritics
1807 Weston (H4), Connecticut fall
Benjamin Silliman (1779–1864)
Yale University, founded the American Journal of Science
Charles Upham Shepard (1804–1886)
Amherst College, collections sold to Amherst and Smithsonian
John Lawrence Smith (1818—1883)
Founder of the American Chemical Society, widow established the J. Lawrence Smith Medal (1884)
Hubert Anson Newton (1830–1896)
Yale mathematician, first recipient of Smith Medal (1888), collection given to American Museum of Natural History
George Perkins Merrill (1854–1929)
National Museum (Smithsonian), second recipient of Smith Medal (1922)
Oliver Cummings Farrington (1864–1933)
Field Museum of Chicago, Merrill's brother-in-law

Following Silliman, five workers made major contributions to the growth and development of American meteoritics. Charles Upham Shepard (1804–1886) of Amherst College developed two collections of meteorites, one was sold to the college, the other was acquired by the Smithsonian Institution in 1915 (Clark et al. 2006). John Lawrence Smith (1818–1883) worked mainly as an independently funded researcher and collector and was a founding member of the American Chemical Society. Upon his death his collection was sold to Harvard University and his widow established the J. Lawrence Smith Medal in his honor to acknowledge outstanding contributions in the study of meteoritic bodies. In 1888 the first recipient of the Smith Medal was the Yale University mathematician and collector of meteorites Hubert Anson Newton (1830–1896), "in recognition for investigation of the origin of meteorites" (Lange 1975, p. 245). Newton published 53 papers describing the orbits of asteroids as well as new meteorite falls. At the time of his death his extensive collection was purchased by J. Pierpoint Morgan and presented to the American Museum of Natural History in New York City. George Perkins Merrill (1854–1929) was in 1922 the second recipient of the Smith Medal in recognition for the two contributions that are the topic of this study. Merrill was the first American scientist to apply the optical techniques of the petrographic microscope to the study of meteorites. Merrill's first wife, Sarah Farrington, was the older sister of the last of the major early contributors to American meteoritics, Oliver Cummings Farrington (1864–1933). Farrington, like Merrill, was from Maine, and he began his scientific career at the United States National Museum working with Merrill. In 1894 Farrington was appointed as curator of geology at the Field Museum of Natural History in Chicago where he built a collection that grew to over 700 unique meteorite falls. Among his most significant contributions was the development of a classification system for meteorites that was based upon and extended the so called CIPW (Cross et al. 1902) quantitative chemico-mineralogical classification of igneous rocks (Farrington 1911). From the occurrence of the fall of the Weston meteorite until the early decades of the 20th century, the study of meteorites in America grew rapidly due to the contributions of the workers mentioned above. Of those, Merrill had perhaps the most lasting impact. Based on the two contributions considered in detail below, and as noted at the presentation of the Smith Medal, Merrill was regarded as the “most eminent investigator of meteorites in the world” (Lange 1975, p. 248) in that his “researches have been concerned with the mineral, chemical and textural characteristics of both metallic and stony meteorites and with the interpretations of those properties” (Lange 1975, p. 247).

2. On chondrules

On May 12, 1920 John Mason Clark, state geologist of New York, presented to the National Academy of Sciences a paper by George Merrill on the chondrules and chondritic structures of meteorites which was subsequently published in the Academy’s Proceedings (Merrill 1920c). This work was to become one of Merrill’s most significant contributions to the study of meteorites and was composed of two distinct parts. The first was a review of the minerals and textures commonly exhibited by the individual, typically spherical, “kugeln” or chondrules – the grains from which the term chondrite was derived and which frequently were found to comprise as much as 80% of a chondritic stone’s volume. That second section of Merrill’s (1920c) paper provided a review of the various competing theories regarding the origin of those enigmatic grains, so common in stony meteorites but entirely absent from all rocks of terrestrial origin. Merrill then went on to offer a summation of what he took to be the most likely interpretations for the origin chondrules based on his extensive observations as well as his review of the contributions of earlier workers.

2.1 Definition of the chondrule

The first observation and description of the presence of chondrules in stony meteorites was made by Gustav Rose of the University Museum of Berlin (Greshake 2006) who had recognized them to “consist of an as yet unidentified magnesium silicate” (Rose 1864, p. 29) which “when fractured, they appear partly uneven and partly fibrous; in the latter case, however, the fibers are always very fine – though invariably distinctly recognizable as such, especially under a magnifying glass – and are ‘never’ radial, but always eccentrically arranged” (Rose 1864, p. 85). Working at a time before the introduction of the petrographic microscope (Hamilton 1982), Rose’s mineralogical and textural descriptions were limited to macroscopic analysis. Subsequent work showed that the magnesium silicates Rose observed were composed primarily of enstatite and to a lesser degree olivine. Nearly two decades later Gustav Tschermak, utilizing the petrographic microscope, provided a more complete description of the range of features exhibited by chondritic meteorites which included “small spheres which consist sometimes of a single crystalline individual and sometimes of several, are often also composed of various constituent parts, either constitute the rock almost exclusively or lie embedded – sometimes intact, sometimes fragmented – within a tuffaceous matrix ranging from loose to solid" (Tschermak 1885, p. 3). Building on those observations, Merrill noted that among British and American authors some degree of confusion had arisen as to the origin of chondrules such that he understood there to have been a "failure to recognize or discriminate between the kugelchen with radiate structure and the often irregular polysomatic forms" (Merrill 1920c, p. 450). That is, Merrill held that there was not a strong foundation understanding of the mineralogical and textural variations present in chondrules. Therefore, he set out to address this deficiency in order to "make this discrimination and to show how far proposed theories may apply to the various forms presented" (Merrill 1920c, p. 450).

2.2 Characteristic forms

In order to initiate a review of the most significant components of chondritic meteorites, Merrill first set out to describe "a few characteristic forms of the individual chondrules" (Merrill 1920c, p. 450). He noted that the spheres were "composted chiefly of the minerals olivine and pyroxene, the later in orthorhombic or monoclinic forms, or both. Some are largely of an undifferentiated glass" (Merrill 1920c, p. 450). Merrill considered the characterization and cataloging of the various forms of chondrules essential such that often "the chondrules in the same meteorite may vary from densely cryptocrystalline, almost amorphous, to those that are partly glassy and porphyritic even holocrystalline" (Merrill 1920c, p. 450). That is, the range of textures exhibited within chondrules were, in Merrill's opinion, both complex and significant. Merrill did not report the presence of feldspars within chondrules which is somewhat curious given that it has subsequently been established that "anorthite is a common phase as phenocrysts or as crystallites in mesostasis in both ordinary and carbonaceous chondrites" (Hazen et al. 2021, p. 341).

2.2.1 Primary forms

Of the several categories of chondrules identified by Merrill, three were generally understood to have preserved a meaningful record of primary mineralogical and textural features and were to figure significantly in his subsequent publication on the metamorphism of chondritic meteorites (Merrill 1921). The first considered consisted of three forms: the set of chondrules characterized by mostly or rarely entirely glassy textures; the cryptocrystalline chondrules; and the more common radiating or spherulitic textures. Merrill described multiple examples of such textures with a particular focus on those exhibiting the radiating enstatite crystal forms (Fig. 2). In many cases a single point of enstatite nucleation occurred along the mostly spherical boundary of the chondrule (Sorby 1864; 1877), while in other cases multiple points of nucleation could be identified such that complexly interwoven radiating textures were observed.

https://doi.org/10.5194/hgss-2026-9
Preprint. Discussion started: 2 July 2026

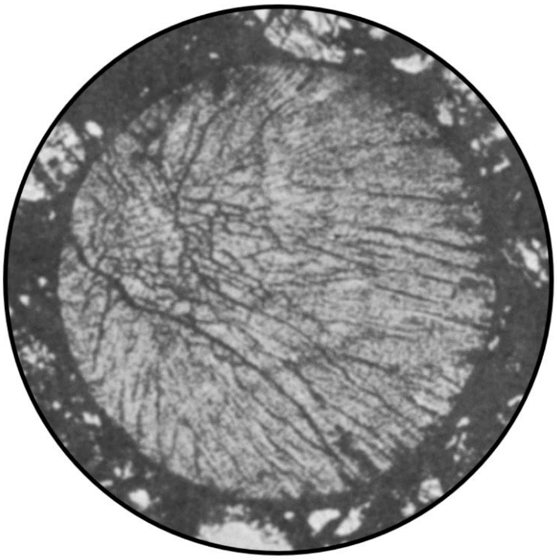

Figure 2. Unscaled photomicrogaph of an enstatite chondrule exhibiting a spherulitic texture radiating from the left margin of the grain. This example of Merrill's primary spherulitic group was taken from the Elm Creek (H4) chondrite found in Kansas in 1906 (modified from Merrill 1920c).

The second form of what Merrill took to be primary chondritic textures included those with semivitreous, barred, or porphyritic textures which were "characteristic of both olivine and enstatite chondrules, while the bared forms are limited mainly, if not wholly, to monosomatic forms composed of olivine" (Merrill 1920c, p. 453). A striking example of the polysomatic mixture of glass and crystal was provided by a chondrule of the Beaver Creek (H5) stone which fell in British Columbia, Canada in 1893 (Fig. 3). Merrill noted that the "outlines though sharp are not smooth as in those described above, but have projecting particles extending out into the ground" (Merrill 1920c, p. 453).

Figure 3. Unscaled photomircrograph of a chondrule exhibiting a polysomatic texture of interlayered glass (dark) and olivine (light) within the Beaver Creek (H5) meteorite which fell in British Columbia, Canada 1893 (modified from Merrill 1920c).

The third form of primary chondrules identified by Merrill were those that exhibited a holocrystalline texture. Merrill described this group as frequently exhibiting porphyritic forms which formed “through a reduction of the proportional amount of glass, [and] pass gradually into those which are almost or quite holocrystalline” (Merrill 1920c, p. 455). In that some chondrules exhibited pyroxenes with curved or perhaps abraded margins which suggested to Merrill that the “chondrules had been molded by external forces after the crystals had formed but yet while in a more or less plastic condition” (Merrill 1920c, 456), or perhaps the spherical shapes had been subjected to some secondary process of rounding, a concept Merrill discussed more fully in the second section of the paper that considered the origins of chondrules.

2.2.2 Altered forms

Among the groups of chondrules Merrill interpreted to exhibit altered primary forms, that alteration tended to take on two distinct forms. The first included those chondrules which exhibited a “narrow border or rind about the circumference. These borders as a rule, are of lighter color than the interior, of a clear, more pellucid nature” (Merrill 1920c, p. 457). The presence of such boarders was subsequently interpreted by Merrill to be evidence of metamorphic alteration rather than as evidence of a remnant of a glassy shell from a primary melt. Modern studies have noted that the “larger the chondrule, the larger the rim, but the ratio of rim thickness to chondrule size depends on the nature of the chondrule” (Sears 2004, p. 95). The second major group of altered chondrules were those which were observed to exhibit compound textures such that “occasional forms are met with in which a large crystal of olivine or pyroxene is inclosed by a border of finer crystals of the same mineral but suggestive of a later generation”

(Merrill 1920c, p. 457) of crystallization. Merrill referenced Tschermark's observations by recalling the "occasional occurrence of a chondrule within the mass of a second or larger form" (Merrill 1920c, p. 457). Such compound or porphyritic chondrules, while rare, were considered by Merrill to be quite significant. Finally, he chose to differentiate between the five primary forms described above and the many "broken, angular and, in some cases, distorted radiate enstatite forms … [which while they] have a bearing upon the origin of the masses in which they occur, they can … have little bearing upon the subject of the origin of the chondrules themselves" (Merrill 1920c, pp. 457–458). That is, Merrill chose to limit his consideration to the origin of chondrules, while his subsequent paper would focus on the metamorphic alteration of the chondritic meteorites. In that later study the highly altered chondrules were to feature prominently (Merrill 1921).

2.3 The Origins of chondrules

In order to attempt to more fully understand the range of conditions under which chondrules could have been formed, Merrill first reviewed all current theories, some of which had been based on direct petrographic analyses while others had been derived from experimental studies intended to simulate potential chondrule environments of formation (Sorby 1877; Rinne 1895; 1897; Meunier 1883). It is important to recognize that early efforts to imagine the environment or environments of chondrule formation were heavily influenced by successes achieved based on the application of uniformitarian principles to terrestrial geology. However, late 19th and early 20th century meteoriticists were coming to realize that many of the minerals and textures observed in the chondritic meteorites had no modern, or indeed ancient, terrestrial analog. None-the-less, the early hypotheses considered by Merrill can best be understood as efforts to align observations of chondritic meteorites with various, perhaps plausible but ultimately inappropriate, terrestrial rock forming processes. The evocative combination of similarities and distinctive differences between the chondrites and terrestrial rocks (Merrill 1909) motivated workers to seek out analogues when none in fact existed. Merrill's review of the literature of the period led him to conclude that "many of the opinions expressed have been based upon examinations of but a limited number of occurrences which quite failed to yield the information necessary for building satisfactory hypotheses or conclusions" (Merrill 1920c, p. 458). That is, in his opinion, the full range of chondrule mineralogy and morphology had not been considered by previous workers and as such the interpretations they drew were limited by their incomplete surveys of chondrule complexity. Merrill summarized what he understood to be the major, albeit to his mind causatively incomplete, hypotheses regarding chondrule formation that has been presented since the advent of the polarizing microscope.

2.3.1 Previous hypotheses

The earliest work considered by Merrill in his efforts to elucidate the origin of chondrules had been undertaken by Karl Ludwig Freiherr von Reichenbach (1860) who concluded that chondrules represented an "independent meteorite derived from the breaking up of some older preëxisting stone and now included as a constituent part of one new found" (Merrill 1920c, p. 458). Reichenbach recognized that chondrules must have a history that is different from the matrix within which they are found and his was one of the earliest suggestions that chondritic meteorites were "the oldest sedimentary rocks in the solar system" (Hazen et al. 2021, p. 326) having formed from the aggregation of earlier formed grains. However, Reichenbach was alone at that time in advancing an interpretation of chondrules as having been derived from an earlier generation of recycled meteoritic material.

Henry Clifton Sorby was among the first to suggest chondrules formed as "detached globules whilst still melted" (Sorby 1864, p. 334) and subsequently concluded that "at least some of the constituent particles of meteorites were originally detached glassy globules, like drops of fiery rain" (Sorby 1877, p. 496). That final poetic phrase has found its way into dozens if not hundreds of scientific and popular publications on the chondritic meteorites. Alternatively, Gustov Tschermak's initial view of the origin of chondrules held that "the individual chondrules (kugelchen) were but rock particles which became simply rounded under conditions similar to such as might exist in the throat of a terrestrial volcano" (Merrill 1920c, pp. 459–460) which over time evolved to a later conclusion that "the spherules are still to be regarded as the results of volcanic eruptions … [but] their form is likely derived from a plastic state rather than from the attrition of rigid particles" (Tschermak 1882, p. 11). That is, Tschermak's interpretations changed from one of based on a mechanical origin for the chondrules to one where they were derived from condensation from a melt. Gabriel-August Daubrée (1879) had also held that chondrules were most likely the product of mechanical rounding. However, Friedrich Martin Berwerth had considered "individual chondrules as portions of the melt that cooled in globular form" (Merrill 1920c, p. 460) having been formed as the products of partial melting during extreme thermal metamorphism. Leondard Henrik Borgström had provided one of the most complete hypotheses of chondrule origin by noting that "because chondrules of the same chemical composition have a different structure, they must have been formed under different physical conditions. Since a variety of conditions cannot have existed in the narrow space in which the different structures are now met with, the chondrules must have accumulated after solidification" (Borgström 1904, p. 94) having first been formed in different environments and through different processes. Merrill illustrated the complexity of Borgström's concept of chondrules from multiple environments or generations of formation with an example from the Cedar, Texas (H4) meteorite which had fallen in 1900 (Fig. 4). Borgström's recognition of the importance of multiple formative processes has been largely substantiated by modern workers (Sears 2004; Hazen et al. 2021 and references therein).

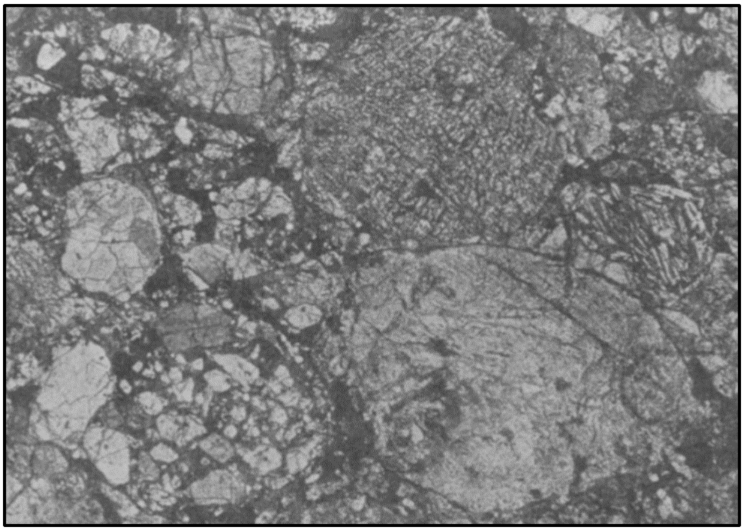

Figure 4. Unscaled photomicrograph of the Cedar, Texas (H4) chondrite which had fallen in 1900 (modified from Merrill 1920c), illustrating multiple types of chondrules. Similar relationships had suggested to Borgström that chondrules must have formed in different environments and/or at different times. This and similar observations were to serve as a foundation for Merrill's hypotheses for the origin of chondrules.

Among the several additional hypotheses considered by Merrill, two are worthy of further discussion. The first was proposed by Aristides Brezina who had concluded that "we can state with certainty that meteorites are rocks consisting of hasty crystal formations within a single, mixed magma" (Brezina 1885, p. 19). Merrill annotated this quotation with the clarifying statement that he understood that 'hasty crystallization' included "both the ground mass and the chondrules" (Merrill 1920c, p. 462). As such, Merrill was interpreting Brezina's hypothesis to imply that both the chondrules and the tuff-like ground mass of chondritic meteorites were derived from the rapid cooling of a single preexisting melt. Finally, Merrill reported that Walter Alexander Wahl had concluded that the "formation of the chondrule was due to the cooling of a silicate melt in a heated atmosphere, the resultant drop crystallizing from the surface inward" (Merrill 1920c, p. 462). That interpretation was closely aligned with those that had been made by Sorby more than three decades earlier. Merrill was to return to Wahl's interpretation of nucleation of crystal growth on the boundaries of fused droplets as a critical observation when discussing the origin of complex porphyritic and holocrystalline chondrules (Merrill 1921).

2.3.2 Merrill's hypotheses

Having summarized and evaluated the analyses and interpretations that had been presented by various scientists during the late 19th and early 20th century, Merrill then set forth interpretations of what he had come to understand to be the most well-preserved chondrules. Differing from the conclusions of many of the workers he had carefully cited, the hypotheses Merrill advanced were both detailed and specific such that "it is possible to conceive of a basic magma containing the necessary constituents for the formation of olivine or enstatite to be in a sufficiently liquid condition to cause, or allow it, when thrown into a hot or thin atmosphere, to take the form of spherical drops which

https://doi.org/10.5194/hgss-2026-9
Preprint. Discussion started: 2 July 2026

on cooling will become glassy or crystalline according to conditions" (Merrill 1920c, p. 463). This interpretation was generally aligned with that of Sorby's (1877) "fiery rain" conceptualization. However, several specific components of Merrill's phrasing are worthy of closer consideration. First is the use of the words "basic magma", which to a modern reader suggests a melt of plutonic origin within some planetary or protoplanetary body exhibiting a mafic composition from which enstatite and olivine could crystallize. Current understandings of chondrules (Sears 2004; Hazen et al. 2021) point to a much more complex origin prior to the initiation of planetesimal formation; thus, 'basic magma' should be read as 'igneous melt' since current hypotheses suggest a "significant fraction of the material that now comprises terrestrial planets and moons may have once been stored in the form of these small igneous droplets" (Hazen et al. 2021, p. 326) that are now recognized as chondrules. Merrill had also noted the necessary presence of a "hot or thin atmosphere" within which chondrules could form. That interpretation was based on the results of experimental studies which had shown that chondrule-like structures could be formed under such conditions (Sorby 1877; Rinne 1895; 1897; Meunier 1883) and as such could account for the characteristics of the glassy and spherulitic chondrules. However, such an interpretation did not align with the characteristics exhibited by the "porphyritic polysomatic forms composed of phenocrysts of pyroxene and olivine in a glass base" (Merrill 1920c, pp. 463–464). Merrill summarized the theoretical difficulties he identified by noting "it would seem doubtful, also, if a melt which had cooled sufficiently to allow the formation of phenocrysts would be sufficiently fluid to permit the formation of the spherical drops [of glass] under any probable conditions" (Merrill 1920c, p. 465). As an alternative, he pointed to those porphyritic and holocrystalline chondrules that appeared to exhibit crystals which were truncated at the margin of the grains. From those he concluded "it is, I think, self-evident that the original surface has been reduced by attrition, and whatever character it may have had has been lost" (Merrill 1920c, p. 465). As such, Merrill concluded that some of the chondrules owed their geometry not to fusion from "fiery drops of rain" but rather to processes of mechanical rounding, essentially in the same way sedimentary particles undergo grainsize reduction and rounding during transport in fluvial or aeolian systems, thus perhaps indirectly returning again to concepts of chondrules as sediment and chondrites as sedimentary rocks.

Having differentiated chondrules into two distinct populations, Merrill went on to propose independent hypotheses for the formation of those two groups. First, he posited that the "chondrules of glass and cryptocrystalline or radiating enstatites … are consistent with a theory of origin as fused drops" (Merrill 1920c, p. 468). Second, those "chondrules of a compound, holocrystalline nature, and those porphyritic through the development of olivine or pyroxene phenocrysts in a more or less glassy base ... show unmistakable evidences of an origin of form through mechanical attrition" (Merrill 1920, p. 468). He then went on to note that those chondrules of irregular and degraded form could hot have originated by the same mechanism as the glassy and spherulitic chondrules such that "it is perhaps questionable if such forms should be considered true chondrules and perhaps the term pseudochondrule or chondroid had best be applied to them" (Merrill 1920c, p. 469). Merrill was to subsequently give greater consideration to the significance of these irregular forms in his paper on the metamorphism of meteorites (Merrill 1921). In offering two independent mechanisms of chondrule formation he was combining, advancing, and refining previous interpretations of both Sorby (1864; 1877) and Tschermak (1874). The dual interpretation was reconciled by noting that "as is frequently the case it seems to show that two or more of the opinions advanced were essentially correct and their apparent differences due to failure to recognize all the facts I have here presented, and that of the many varied forms of chondrules, not all may have a similar origin" (Merrill 1920c, p. 470). His study concluded with a reiteration of the most salient reasons for the rejection of hypotheses presented by earlier studies.

While offering plausible explanations for the differences in texture observed among the chondrules, Merrill did not provide specific geological processes by which the glassy or spherulitic forms originated. That is, he did not specify by what process and in what environment the "fiery rain" occurred. Further, for the porphyritic or holocrystalline forms he did not offer a setting and a process through which ablation and rounding of crystalline grains occurred. Despite the acuity of his observations, Merrill remained bound by a reliance on terrestrial processes as potential analogues for the origin of objects that have ultimately come to be understood to have been formed in a decidedly non-terrestrial setting prior to planetesimal accretion.

2.4 Comparison with modern understandings

A great deal of the observations and interpretations advanced by Merrill in his study of the origin of chondrules (Merrill 1920c) have been subsequently substantiated by those studies of increasing complexity and sophistication which have occurred in the century since its publication. Chondrules are now understood to exhibit complex mineralogical assemblages composed of nearly four dozen crystalline and amorphous phases such that "chondrule mineralogy is complex, with several generations of initial droplet formation via various proposed heating mechanisms, followed in many instances by multiple episodes of reheating and partial melting" (Hazen et al. 2021, p. 325). No less than eight different processes of formation have been proposed for the formation of the various types of chondrules (Sears 2004; Hazen et al. 2021 and references therein) which range from direct heating in proximity of the protosun (Morlok et al. 2012) to fusion by lightning in the protoplanetary nebula (Boss and Durisen 2005), while formation via melting triggered by shock waves in the primordial nebula has remained as a primary hypothesis (Hood and Horányi 1991). Merrill's interpretation of multiple mechanisms of formation for the chondrules of different mineralogy and textures is generally well-aligned with an interpretation that due to "rapid heating events in the solar nebula, many chondrules may have experience multiple secondary melting events" (Hazen et al. 2021, p. 328). However, some workers have continued to advance concepts that harken back to Tschermak's concept of recycling such that impact associated remelting could have resulted in the formation of chondrules which were "contaminated by mineral dust and larger grains, thus generating a variety of relic grains and a range of chemical and isotopic compositions" (Hazen et al. 2021, p. 328). Despite the relatively elementary geochemical and petrographic tools available, through keen observation and logic, Merrill was able to establish an understanding of chondrule origins that has stood as a foundation for the subsequent century of scientific advance.

3. On the metamorphism of meteorites

In December 1921 Merrill advanced to publication a manuscript in the Bulletin of the Geological Society of America that had been first read during the Society's annual meeting in Chicago, Illinois on December 29th of the previous year. He had also presented his findings at the National Academy of Sciences meeting in Washington, D.C. on April 25, 1921. The topic of his second paper was an evaluation of evidence for the metamorphic alteration of chondritic meteorites. The goal of the study was to "bring together for record some of the more important data bearing on the subject and supplement them by results gained through my own studies" (Merrill 1921, p. 395). The culmination of those efforts resulted in a comprehensive review of the evidence for the processes and resulting products of meteorite metamorphism. A great deal of parallelism can be observed in the organizational structure of his analysis of the origin of chondrules (Merrill 1920c) and his analysis of the evidence for the metamorphic alteration of the chondritic meteorites (Merrill 1921). He began each paper with a review of the various hypotheses which had been presented, then moved on to carefully describe his observations as well as those of other workers, and finally offered interpretations based upon reconsideration of all available evidence.

3.1 Considerations of origin

Merrill began with a review of the "discordant nature of the opinions held regarding the original nature and structure of the chondrite meteorites" (Merrill 1921, p. 396) which had been advanced by various workers over the preceding decades. Upon that foundation he provided an extensive summary of the most salient work that had been conducted since 1875, a boundary that had been chosen because the "microscope and thin-section had even at this date scarcely come into their full efficiency" (Merrill 1921, p. 396), particularly among North American geologists. Merrill was recognized by contemporaries as one of the early proponents of the petrographic analysis of rocks, particularly meteorites, through the use of the polarizing microscope (Lindgren 1935; Lange 1975). Therefore, the selection of the 1875 date had particular significance as a demarcation between earlier macroscopic studies and those attempts to understand the mineralogical and textural variability of chondritic meteorites utilizing the emergent technologies of micro.

Merrill (1920c) reviewed and summarized what he took to be the most significant contributions to the dialog on the origin of chondritic meteorites from recent literature. Building on primary sources, he utilized extensive quotations, often in German and French, to establish a conceptual outline and summary of the various competing hypotheses and conclusions that had been advanced by Gustav Tschermak (1875; 1878, 1885), Henry Clifton Sorby (1877), Gottlob Linck (1898), Hans Henrik Reusch (1886), Alphonse François Renard (1899), Friedrich Martin Berwerth (1901), and Walter Alexander Wahl (1910). Those authors and their theories had featured prominently in his study of the origin of the chondrules (Merrill 1920c). After exploring the diversity of opinions presented, Merrill provided a set of interpretations and conclusions drawn from an extensive personal study of the chondritic meteorites (Schuchert 1931; Lindgen 1935).

The hypotheses advanced by late 19th and early 20th century scientists concerning the origin of chondritic meteorites can be differentiated into two general groups. The first held that "a number of meteorites possess a completely tuff-like appearance … [suggesting that they] … are of a generally volcanic origin" (Teschermak 1885,

p. 24). The second group posited that the texture of chondrites had "little or nothing in common with tuffaceous formations; rather it points to solidification from a molten state" (Linck 1898, p. 113). Interpretations such as the later were offered to partially explain the origin of the occurrence of what was taken to be primary glass, particularly within the chondrules. Conversely, a third group of early workers concluded that chondrites were best understood to be "crystalline rocks that had undergone the effects of dynamic metamorphism" (Renard 1899, p. 539) and some proponents of the metamorphic hypothesis went on to largely reject a volcanic origin for the range of textures observed within the chondritic meteorites.

By invoking the concept of dynamic metamorphism, Renard referenced a position within the spectrum of concepts and controversies that had prevailed at that time regarding the origin of terrestrial metamorphic rocks. Advocates for dynamic metamorphism had held that the metamorphic alteration of protoliths occurred primarily through the application of heat generated by kinematic forces acting on precursor rocks. Such concepts stood in contrast to those ideas advanced by workers who favored the importance of mechanisms of metamorphism through thermal alteration of rocks in close proximity to igneous intrusions (Drummond 2025; 2026b; 2027). Interpretation of the origin of the mineralogy and texture of the chondritic meteorites was highly influenced by the interpretation of terrestrial rocks, as had been the origin of the chondrules themselves. Questions of if, and how, chondrites had been subjected to metamorphic alteration was the primary topic of Merrill's analysis and he noted that the various "diametrically opposed views, each of which had numerous supporters, can, as it seems to the writer, be explained only on the ground of an insufficient amount and variety of material for the study on the results of which the opinions were based" (Merrill 1921, p. 397). That is, he suggested that only by extending and expanding the study of the variety of textures and mineralogical compositions present in the chondritic meteorites could greater understandings of the significance of the roles of the processes of volcanism, fusion, and metamorphism in the origin and alteration of chondrules be more fully understood. That argument was essentially the same as the one he had made with respect to the origins of the chondrules themselves (Merrill 1920c).

Merrill was aware of how complex the metamorphic alteration of chondrites must have been given that he noted "the existing structural features, both those of the constituent minerals and the stones as a whole, render it more difficult to trace with equal certainty changes which may be due to metamorphism than it is in the case of terrestrial rocks" (Merrill 1921, pp. 395–396). More succinctly, Merrill recognized that environments of typical terrestrial and the extraterrestrial metamorphism of chondrules must have been vastly different in that "the entire lack of such secondary minerals as are the products of terrestrial metamorphosis, the anhydrous state of the constituents and their unoxidized condition, however, limit the possibilities, though they do not necessarily simplify the problem" (Merrill 1921, p. 396). Merrill recognized that interpretation of the metamorphic alteration of chondritic meteorites was not made simpler coupled by a lack of complexity in composition coupled with a lack of diversity in environments of alteration, but rather the unique mineralogy and extreme conditions of alteration made their study as complex, and less well defined, than that of the great diversity of metamorphic rocks of Earth. As such, Merrill set out to establish an understanding of the metamorphic alteration of chondritic meteorites working largely without reference to the observed mineralogical and chemical complexities that at that time were vexing petrologists studying terrestrial metamorphic systems (Drummond 2025; 2026b; 2027).

Merrill then highlighted some of what he took to be the most significant observations regarding the compositions and textures of chondrites that had been recorded by previous workers. First, he found that “chondrules occur in greatest abundance and most perfect development in stones [where] the tuffaceous nature of which is most pronounced” (Merrill 1921, p. 397). As had been described previously (Merrill 1920c), he had expected the most well-preserved chondrules to be found in the crystalline chondrites, class Ck of Brezina (1904). However, he was also aware that “a certain amount of crushing and disintegration has taken place in many stones” (Merrill 1921, p. 397). Friedrich Berwerth concluded that “the chondrite is a meteoric tuff metamorphosed through remelting” (Berwerth 1901, p. 644); thereby suggesting that a complex and dynamic history was recorded within the texture and mineralogy of chondritic meteorites. Berwerth’s statement encapsulated notions of fusion and recrystallization as well as metamorphic alteration. Walter Wahl went on to propose that a classification of chondritic meteorites could be established on the basis of their compositions such that a progressive sequence could be built “beginning with the tuff-like masses of mineral fragments and ending with the highly crystalline varieties that closely resemble massive rocks” (Wahl 1910, p. 75). The classification of chondritic meteorites was a complex question that engaged researchers over a long period of time (Drummond 2026a). Wahl’s concepts, however, presaged the modern classifications of chondritic meteorites based on observations of the degree of alteration via processes of metamorphism (Van Schmus and Wood 1967; Weisberg et al. 2006).

3.2 Systematic consideration of chondrite metamorphism

Merrill concluded his review of the various competing theories that had been advanced by the leading voices in late 19th and early 20th century meteoritics by stating “the above quotations from the writings of well known authorities are sufficient to show the general trend of opinions on the subject” (Merrill 1921, p. 399). Building on the conclusions of those workers, and in large part motivated by the distinct differences of opinion that existed among them, Merrill (1921) shifted from an historical review of prevous work to the systematic analysis of chondritic metamorphism as exemplified by his definition of four groups of progressively more altered chondritic meteorites (Table 2), which could be linked to several of the texture and color-based classes of Aristides Brezina’s (1904) complex system of chondrite classification (Drummond 2026a).

Table 2. Summary of the systematic grouping of the progressive alteration of chondritic meteorites as presented by Merrill (1921) which were generally aligned with several of the meteorite classes of Brezina (1904).

Merrill’s (1921) Systeamtic Grouping of Chondritic Metamorphism

Group	Characteristics	Brezina (1904) Classification
Unaltered Spherulitic	Well-formed spherulitic chondrules of radiating enstatite, tuffaceous microcrystalline matrix	Cc
Crystalline Spherulitic	Fully crystalline spherulitic chondrules, fine granular matrix, scarcity of primary glass, absence of maskelynite	Cck

Common Crystalline	Absence of primary glass, asymmetrical and imperfectly shaped chondrules, merger of chondrule and matrix, presence of merrillite and maskelynite	Ck
White, Gray & intermediate	Cataclastic matrix, abundant maskelynite and merrillite, web-like bronzite	Cw, Cg, Ci

3.2.1 Unaltered spherulitic chondrites

The first group of chondritic meteorites considered by Merrill was found to exhibit “numerous hard and well formed chondrules in varying proportions and conditions of fragmentation in a tuff-like ground” (Merrill 1921, p. 399). Merrill noted that within those meteorites the chondrules were the most striking petrographic feature, frequently occurring as loosely embedded grains in a friable matrix. This group was generally equivalent to the globular class Cc of Brezina (1904). Merrill concluded that “chondrules and chondroidal forms were not formed in the exact positions they now occupy should be, for the most part, a matter of common recognition, though as to their primary origin there may still be some question” (Merrill 1921, p. 399). In that statement Merrill was noting the modified state of all chondrules in that “in no instance have I seen a chondrule or chondroidal form under such conditions as to really satisfy me of its origin *in situ*” (Merrill 1921, p. 400). Merrill’s concept of the formation of chondrules prior to their incorporation into a chondritic meteoritic mass has been substantiated by later research (Sears 2004; Hazen et al. 2021 and citations therein). As evidence for such an interpretation, Merrill pointed to his paper of the previous year wherein he had first discussed the occurrence of “those chondrules of glass and of cryptocrystalline and radiate enstatites … regarded as direct products of the cooling of molten drops” (Merrill 1921, p. 400). By spherulitic, Merrill meant that the chondrules were mostly well-formed spherical to subspherical grains within a relatively fine-grained matrix. Further, the spherulitic chondrules were found to commonly exhibit radiating aggregates of fibrous crystals, primarily of enstatite, growing from a single nucleus (Fig. 2). However, unlike the spherulites that were known from terrestrial obsidian (Britkreuz 2013), chondrule spherulites tended to exhibit points of nucleation on the margin of the sphere, as had been noted by Sorby (1877), rather in a central position as had been incorrectly suggested by Karl Klein (1906). As such, the radiating enstatite chondrules tended to be highly symmetrical in their external geometry but distinctly asymmetrical in their internal mineral structure. Merrill’s recognition that the most well-preserved chondrules occurred within samples which were apparently the least altered by metamorphism has been broadly confirmed by later analyses. While it is now understood that all chondritic meteorites have undergone some degree of metamorphic alteration (Huss et al. 2006), the meteorites of Merrill’s unaltered spherulitic group have been classified as belonging to petrologic type 3 or 4 in the modern system (Van Schums and Wood 1967; Weisberg et al. 2006), indicative of their relatively unaltered condition.

3.2.2. Crystalline spherulitic chondrites

The second group of chondritic meteorites described by Merrill were referred to as the crystalline spherulitic forms wherein "a marked difference in microscopic structure is readily observable, though there are very evident trances of a one-time tuffaceous nature" (Merrill 1921, p. 400). This group was equivalent to the crystalline/globular class Cck of Brezina (1904). Two primary forms of alteration were found in this group that were not present in the less altered spherulitic group. First, intergranular material was observed "which seemingly represents the finely divided, almost dustlike interstitial material has become converted into a finely granular base in which the larger unaltered fragments and chondrules are imbedded" (Merrill 1921, p. 400). Thus, the texture of the matrix was observed to be coarser and "suggestive of a partial recrystallization of finely divided material as seen in metamorphic schists" (Merrill 1921, p. 400). Second, Merrill applied the term crystalline to this group's name because he found the chondrules to be devoid of glass. Instead, they contained a "granular aggregate of the silicates … where the appearance at once suggests a metamorphism of the glassy base" (Merrill 1921, pp. 400–401). Further, he noted the absence of a significant amount of secondary phases such as the feldspathic glass maskelynite, so named by Gustav Tschermak in honor of the well-known British meteoriticist and Keeper of Minerals at the British Museum, Nevil Story-Maskelyne.

3.2.3 Common crystalline chondrites

Merrill's third group, the common crystalline chondrites, were equivalent to the crystalline class Ck of Brezina (1904). Three characteristics were noted that served to differentiate the crystalline chondrites from those of the less altered spherulitic and crystalline spherulitic groups. First, Merrill found there to be a general scarcity of primary glass in the chondrules and matrix of these chondrites. Second, chondrules were observed to generally be asymmetrical and imperfect in shape relative to those found in the spherulitic and crystalline spherulitic groups. Such chondrules were the highly altered forms mentioned in his earlier paper (Merrill 1920c) that had not been considered in that study because they provided little or no information as to their origin, only their subsequent alteration. A tendency was observed by Merrill wherein the "porphyritic chondrule merges gradually into the ground-mass, and that, further, the interstices of the phenocrysts are occupied not by glass, but by a fine granular matter – a condition to at once suggest the crystallization of the glass base of a porphyritic chondrule during the general process of metamorphism" (Merrill 1921, p. 401). That is, the relatively coarse texture of the matrix and the altered fabric of the chondrules made their petrographic differentiation at times challenging (Fig. 5). Such chondrules, when present, were commonly found to break with the matrix indicating the presence of a significant textural interlocking between grain and ground. Finally, the occurrence of the phosphate mineral merrillite (Merrill 1917) and the secondary glass maskelynite were found to be "almost universal characteristics of this group" (Merrill 1921, p. 401).

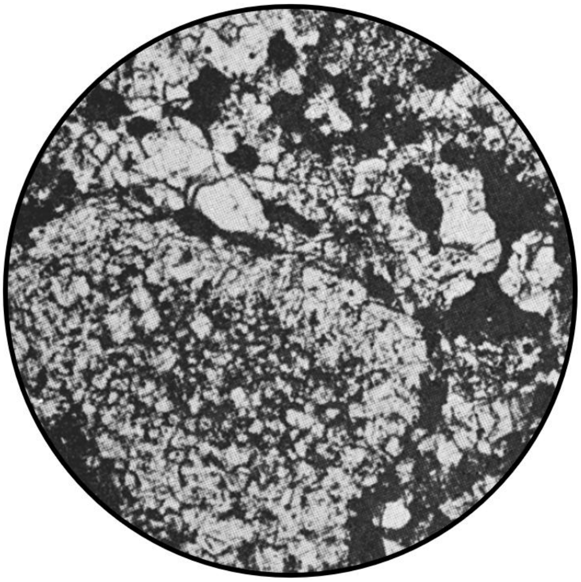

Figure 5. Unscaled photomicrograph of the crystalline chondrite Estacado (H6) meteorite which had been found in Texas in 1883. The boundaries of an irregular and distorted chondrule (lower left) in part are blurred and merge with the coarsely crystalline matrix enveloping the chondrule from the top to the right (modified from Merrill 1921).

3.2.4. White, gray, and intermediate chondrites

The fourth group of chondritic meteorites recognized by Merrill included the white Cw, gray Cg, and intermediate Ci classes of Brezina (1904) which were observed to frequently exhibit a matrix (or ground) "distinctly cataclastic for the most part – a structure which is certainly in part due to crushing" (Merrill 1921, p. 401). Thus, processes of dynamic metamorphism were invoked by Merrill to explain the origin of those observed textures. Further, he noted meteorites of these groups were "almost universally characterized by the presence of the colorless, sometimes isotropic, maskelynite, the calcium phosphate merrillite, and an occasional enwrapping and interstitial smoky glass" (Merrill 1921, p. 402). The maskelynite was found to occur in an unaltered and structurally intact state within a coarse and broken matrix suggesting a secondary, post-cataclistic, origin for the glass. Current interpretations of this phase suggest it was created by vitrification of plagioclase associated with melting during meteorite collision (Morrison et al. 2023). Merrill also noted the occasional presence of a bronzite with unique web-like netzbroncit textures which had been first recognized by Brewerth (1901) and had subsequently been interpreted by him to be indicative of meteoritic metamorphism. However, Merrill had been "unable to discover in slides of the white and gray chondrites at his disposal the netzbroncit structures developed to the extent and degree of perfection figured by Berwerth in his description of the Zavid stone" (Merrill 1921, p. 402).

3.3 Agencies of metamorphism

Having documented and evaluated the various mineralogical and textural characteristics of the four groups of chondritic meteorites he recognized, Merrill went on to review the conditions and processes by which the observed metamorphic alterations could have occurred. Reiterating the significance of the absence of hydrated and oxidized mineral phases that commonly characterized terrestrial metamorphism, he concluded that the environments of meteoritic metamorphism were "free from moisture and influences promoting oxidation [such that] … evidently they were limited to dry head and pressure" (Merrill 1921, p. 405) as the primary agents of alteration. Thus, he was to focus his study on the effects of thermal and dynamic metamorphic processes. By presenting a long and detailed discussion of the understandings of potential metamorphic processes, and their attendant products, Merrill was able to first compile evidence in support an interpretation of alteration by anhydrous thermal metamorphism. He then contrasted those findings with evidence he observed which supported the role of dynamic, or pressure induced metamorphism (Table 3).

Table 3. Summary of mineralogical and textural evidence presented by Merrill (1921) in support of interpretations of the thermal and dynamic metamorphism of chondritic meteorites.

Evidence for Anhydrous Thermal Metamorpism
Interstital maskelynite and merrillite
Chondrules exhibiting semivitreous ring
Absence of glass in chondrules
"Netzbroncit" of Berwerth (1901)
Evidence for Pressure or Dynamic Metamorphism
Granulation of radiate enstatite chondrules
Distortion and merger of chondrules and matrix
Crushed crystalline particles
Chondrules embedded within matrix

3.3.1 Thermal metamorphism

Merrill gave great weight to his observation that there was a "paucity, outside of the chondrules, [of] a residual undifferentiated glass base" (Merrill 1921, p. 405) within the chondritic meteorites. Noting that the absence of abundant glass in the matrix was strong evidence in opposition to "those who advocate the 'hasty crystallization' origin of these stones" (Merrill 1921, p. 405) he argued that the chondrites could not primarily have been produced by quenching as had been proposed by Brezina (1885). Returning to a characteristic he had described the year before, Merrill noted "that a rind, or border, indicative of a second rise in temperature is to be found about some of the chondrules" (Merrill 1921, p. 407). While some workers had interpreted this rind as a primary glass shell, Merrill concluded that "the boarder is not a true glass, but rather a semivitreous material, the result of an alteration or imperfect sintering of the finer portion of the ground" (Merrill 1921, p. 406). That is, he interpreted the rind to be composed of altered matrix and not the remnant of a previously glassy chondrule border. Indeed, it was generally understood that the margins of chondrules were frequently the loci of crystal nucleation due to cooling from the outside in rather than exhibiting a cryptocrystalline or glassy quenched boundary surrounding a more coarsely crystalline core. A well-developed example of what Merrill took to be a thermally produced metamorphic rind was exhibited by porphyrtic chondrules of the Parnallee stone (LL3.6), which was known to Merrill as a gray or Cg chondrite (Fig. 6).

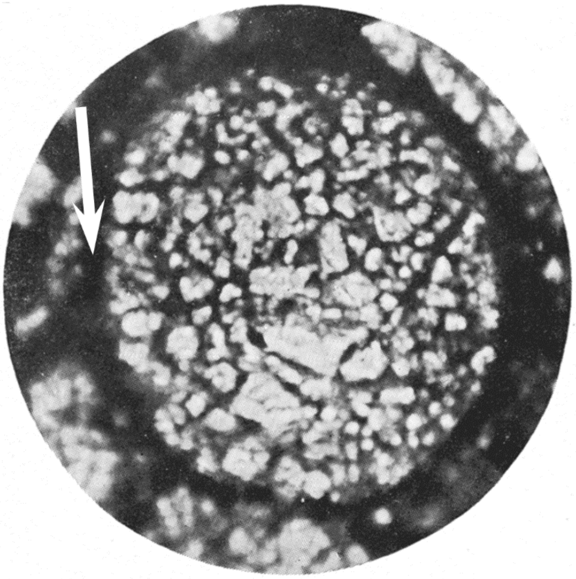

Figure 6. Unscaled photomicrograph from the Parnallee stone (LL3.6), a gray chondrite exhibiting a secondary semivitreous boarder (white arrow) that differentiates the finely porphyritic chondrule from the coarser surrounding matrix that Merrill interpreted to be the product of secondary thermal metamorphism of the matrix (modified from Merrill 1921)

The fourth and final line of evidence Merrill presented for the thermal alteration of chondritic meteorites was found in the netzbroncit or platyfiberous texture exhibited by some bronzite crystals (Berwerth 1901). Merrill referenced this net-like texture on several occasions but did not provide an extensive discussion of the origin of the phenomena. He did, however, interpret its presence as a significant indicator of thermal metamorphism, Berwith had held a differing opinion in that the “occurrence of bronzite distributed in a spiderweb-like pattern (Netzbroncit) in spherical growth forms, together with the omnipresence of plagioclase interstitial to all other constituents, all point to the conclusion that the chondrite underwent a magmatic phase, from which the stone's current crystalline state developed directly” (Berwerth 1901, p. 642). Merrill had acknowledged and largely dismissed the work of Berwerth by stating “the expressed conclusions Berwerth and Wahl are not sufficiently detailed to admit of close comparison other than to say they both seem applicable to chondrules of the encrusted enstatite (kugel) type first mentioned, but not to the holocrystalline and porphyritic forms” (Merrill 1920c, p. 470) which were typical of more highly altered chondrites

3.3.2 Metamorphism by pressure

Just as he had in the analysis of the evidence for thermal metamorphism, Merrill offered four lines of reasoning in support of the metamorphism of chondrites by pressure (Table 3). The first was defined by the observed “granulation of the radiate enstatite chondrules and their gradual merging into the ground mass” (Merrill 1921, p. 412). Radiate enstatite (spherulitic) chondrules exhibited one of the most petrographically distinctive internal forms of chondrules (Fig. 2) and were understood to be sensitive indicators of alteration. As illustrated in the black (carbonaceous) chondrite Renazzo (CR2), Merrill provided the example of a deformed enstatite chondrule which was observed to have partially merged into the surrounding coarsely textured matrix. (Fig. 7).

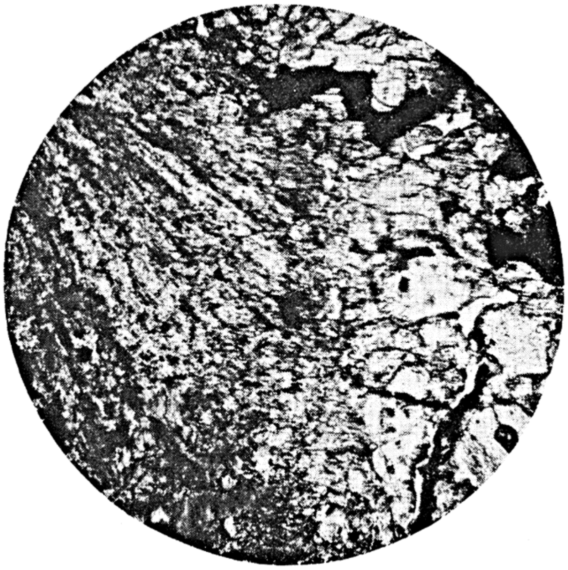

Figure 7. Unscaled photomicrograph from the black chondrite (CR2) Renazzo which fell in Emilia-Romagna, Italy in 1824 exhibiting the merger of a deformed radiating enstatite (left) with relatively coarse textured surrounding matrix (right, modified from Merrill 1921).

The second line of evidence in support of pressure, or dynamic, metamorphism as a process that altered the chondritic meteorites took the form of the “distortion, and at times almost complete obliteration, of chondrules” (Merrill 1921, p. 412). This form of alteration was most fully developed in the group of the white, gray, and intermediate chondrites. Pointing to the Dhurmsala chondrite (LL6), Merrill noted a “large crystal of enstatite … has been crowded against the radiate chondrule, fractured and in places reduced to fragments” (Merrill 1921, p. 409). Additionally, Merrill pointed to the crushed texture of many crystalline particles within the Parnallee stone (LL3.6), wherein he observed “numerous large and small single individual fragments of olivine and enstatite with torn and ragged borders and no remaining traces of crystal faces, completely surrounded by finely granulated clastic material with interstices filled with maskelynite” (Merrill 1921, p. 410). The fourth and final line of evidence noted by Merrill in support of metamorphism by pressure was found in the “compact condition of the stone, with chondrules at times so finely imbedded as to break with the matrix” (Merrill 1921, p. 412). The white, gray and intermediate chondrites typically displayed a highly indurated texture that, when combined with the various forms of alteration described above, resulted in the merger of the chondrule with the matrix such that they responded to rock fracturing not as independent grains but as embedded components of the matrix. Merrill summarized his review by stating that the most compelling lines of evidence in support of the metamorphic alteration of chondritic meteorites were to be found in the "absence of well developed chondrules in the crystalline chondrites and the presence of maskelynite" (Merrill 1921, p. 412) in the most altered stones.

3.4 Further considerations

In addition to consideration of the mineralogical and textural evidence for the metamorphism of chondritic meteorites, Merrill also addressed the "metallic constituent of stony meteorites, and this with particular reference to its origin and connection, if any, with the subject under discussion" (Merrill 1921, p. 412). While Merrill did not acknowledge the variable abundance of nickel within the iron (Prior 1916; 1920), he did go on to interpret the iron as a secondary phase that was produced through a process of "reduction from iron-rich silicates or more probably, in the view of the writer, a ferrous chloride" (Merrill 1921, p. 412), following the reaction:

$$\mathrm{FeCl} + \mathrm{H} \rightarrow \mathrm{Fe} + \mathrm{HCl} \qquad (1)$$

Interestingly, Merrill dismissed the potential relationship between the iron composition of the silicates and the abundance of nickel-iron that was foundational to Prior's analyses (Prior 1916; 1920). Petrographically, Merrill noted that the iron was at times found to occur in "plates so thin as to appear on a polished surface as mere threads, at times scarcely visible, which penetrate the interstices, often bifurcating and completely enwrapping a chondrule or crystal granule" (Merrill 1921, pp. 412–413). Merrill also evaluated if, or how, the presence of iron in the chondrites might be related to their metamorphic alteration. He concluded that "a study of a large number of analyses shows, however, no recognizable relationship in the percentage amount of metal and the degree of metamorphism" (Merrill 1921, p. 413) in the chondritic meteorites. He was to subsequently undertake a more complete analysis of the origin of metal in meteorites (Merrill 1928), the review of which is beyond the scope of the current study.

Merrill concluded his consideration of metamorphism in chondrites by summarizing the overarching purpose of his study which had been to follow "the life history of a meteorite – noting original condition and the changes that have taken place [such that] – some light might be thrown on its possible source and subsequent wanderings, particularly as we are able to recognize the conditions under which the changes have been brought about" (Merrill 1921, p. 414). By highlighting the complexity of the conditions and products of metamorphic alteration of chondritic meteorites, Merrill noted with some humility that if his efforts had failed "to point to a complete solution of the problem, it may at least serve as a useful purpose in limiting the range of hypotheses" (Merrill 1921, p. 414) that future scientists would be obligated to consider.

A constant thread through Merrill's work was an unwavering effort to make meaningful and substantive contributions to the understanding of the complexity of natural systems. His scientific philosophy and his Yankee work ethic were captured beautifully in the inscription of his grave marker in Oak Hill cemetery, Auburn, Maine which reads:

https://doi.org/10.5194/hgss-2026-9
Preprint. Discussion started: 2 July 2026

Search for truth is the
noblest occupation of man
its publication a duty

4. Conclusions: Relationships and receptions

Merrill's interpretations of multiple modes of chondrule formation and chondritic metamorphism have been largely verified by subsequent research such that "many of the steps in the evolution of these rocks [chondrites] recognized by modern meteorite researchers were identified early in their study" (Sears 2004, p. 60). Further, it is now well-recognized that "many primary chondrule minerals have been modified by progressive degrees of thermal metamorphism and metasomatism within their parent bodies" (Hazen et al. 2021, p. 328). Considering the two studies of chondrules (Merrill 1920c) and chondrite metamorphism (Merrill 1921) discussed above as a paired set of theoretically and observationally linked offerings, it is readily apparent how the completeness of considerations, the clarity of analysis, and the compelling nature of the conclusions contained therein resulted in Merrill's selection for the J. Lawrence Smith medal in 1922, an award that would not be presented by the National Academy of Sciences for another two decades.

4.1 Relationship between Merrill and George Thurland Prior

One of the more enigmatic aspects of Merrill's two papers is their comprehensive review of the previous work of continental scientists which stand in stark contrast with an apparent absence of consideration of the previous and ongoing work of George Thurland Prior, then Keeper of Minerals at the British Museum (Drummond 2026a). Interestingly, Prior, in his primary works, made reference to Merrill's geochemical analyses of several chondritic stones, but gave no consideration to the two works discussed above. Similarly, Merrill did not acknowledge Prior's contemporaneous exploration of the relationships between the abundance of nickel-iron, the abundance of nickel in the iron alloy, and the abundance of iron in the various silicate phases – the so-called "Prior's Rules" (Drummond 2026a). Certainly, the absence of citations could be attributed to delays in the shipment of recent publications across the Atlantic, or to idiosyncratic styles of individual authors at a time when citations were considered a convenience but not an expectation of scientific publications. However, another intriguing possibility is that the absence of citations was the product of intentionality born out of Prior's (1916; 1920) critical review of Farrington's (1911) complex system of classification. Merrill had favorably reviewed Farrington's book *Meteorites, their Structure, Composition, and Terrestrial Relations* (Farrington 1915) by stating that Farrington's book showed a "thorough knowledge of the results achieved by other workers, and forms a very welcome addition to existing literature" (Merrill 1916). The publication of a review by Merrill is somewhat unexpected given the personal and professional relationships between the two as described above. It could be an interesting archival project to attempt to determine if there was communication between these two highly influential figures of early 20th century meteoritics, and if so, what tone did correspondence between Merrill and Prior exhibit.

4.2 Reception of Merrill's contributions

Evaluating the impact of early 20th century geologic literature on the basis of citations is challenging for many reasons. First, at that time citations of previous publications had yet to become an essential and expected component of scientific scholarship (Cronin 2001; White 2004). Occurring typically as footnotes, citations of past work were not collected as endnotes as is the modern practice. Therefore, the indexing of early citation histories in modern databases is fragmentary at best. It is interesting, however, to trace the occurrence of references to Merrill's foundational contributions in some of the most influential and formative contributions to the study of meteorites in the middle of the 20th century, a time by which modern norms of citations had been well-established. There was a significant increase in the scientific study of chondritic meteorites in the years prior to and during the six Apollo lunar missions of the late 1960s and early 1970s. Many of those studies pointed back to the contributions of Merrill both in terms of the origins of chondrules (Wood 1963; Fredriksson and Ringwood 1963; Dodd 1976) and the metamorphism of chondritic meteorites (Wood 1962; Wahl 1963; Ringwood 1966; Van Schmus and Wood 1967; Dodd 1969). Specifically, it was noted that "early petrographers who carried out the classic investigations of chondritic meteorites concluded that these objects were of volcanic origin, and were essentially analogous to terrestrial tuffs" (Fredriksson and Ringwood 1963, p. 639) but it was understood that Merrill had found that among the chondrules "most are more or less rounded fragments of magmatic or metamorphic rocks" (Dodd 1976; p. 286). Further, it was recognized that "Merrill pointed out that chondrites display varying degrees of metamorphism" (Ringwood 1966, p. 156) and that "later petrographers (see especially Merrill, 1920[c]) note that in many other chondrites the chondrule-matrix contacts are quite indistinct, sometimes almost impossible to detect" (Wood 1962, p. 739). Finally, in a direct link back to the papers considered above, it was concluded that "like Merrill, I have arrived at the conclusion that the cosmical changes undergone by stony meteorites are of two kinds: (a) alteration of mechanical forces (b) alteration by heat" (Wahl 1963, p. 1025). While there are few citations of Merrill's work in the years immediately after the publication, it is clear his contributions had an important and fundamental impact on what has been come to be known as the "Golden Age" of meteorite research.

Competing interests. The author has declared that there are no competing interests.

Acknowledgements. I am very fortunate in that, much like George Merrill, Chancellor Ronald Elsenbaumer, of Purdue University Fort Wayne, indulges me with the opportunity to utilize some of the "odd moments" amid my administrative duties to sustain an active research program in the history of geology. I deeply appreciate that freedom and his encouragement. This work would not have been possible without the dedicated support of the document delivery and interlibrary loan staff of the Walter E. Helmke Library on the Fort Wayne campus. The grace and helpfulness shown by Marguerite Roby, photography archivist of the Smithsonian Institution Archives in securing the permission to publish the portrait of George Perkins Merrill is gratefully acknowledged.

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