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The Leedey, Oklahoma, chondrite: Fall, petrology, chemistry and an unusual Fe,Ni-FeS inclusion

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Abstract–The Leedey, Oklahoma, meteorite shower fell on 1943 November 25, following a fireball which was visible across much of southwestern Oklahoma and northcentral Texas. The shower produced 24 stones with a total mass of ~51.5 kg. The stones formed a strewnfield ~18 km in length in the same direction as the observed path of the meteor (N50°W). Leedey is classified as an L6(S3) ordinary chondrite. We report bulk major element chemical analyses from four separate laboratories. Leedey contains an unusual 6 by 8 mm composite Fe,Ni-FeS grain, which is composed of a 3 mm kamacite grain adjacent to a 5 mm troilite grain. A 50–100 μm rim of high-Ni (45–55 wt%) taenite (tetrataenite) occurs at the boundary between kamacite and troilite. A single, zoned pyrophanite grain is observed at the boundary between the inclusion troilite and host silicates. An origin as a foreign particle incorporated after metamorphism or during impact melting appears unlikely. This particle likely formed by a complex set of processes, including melting in the nebula, parent body metamorphism and reheating by later shock, mirroring the history of the host chondrite.

INTRODUCTION

This paper is another in a series on poorly-characterized meteorites from the Oscar E. Monnig Collection at Texas Christian University, Fort Worth, Texas. This work focuses on the shower of meteorites that fell near Leedey, Oklahoma, in 1943, producing 24 stones with a total mass of ~51.5 kg. Although investigated by the two premier meteorite hunters of the day, Oscar E. Monnig and Harvey H. Nininger, wartime pressures prevented publication of the details of Leedey. Brief descriptions of the shower and recovery were given by Nininger and Nininger (1950) and Moore (1971). Leedey has been briefly studied petrologically for classification purposes (Mason, 1963; Van Schmus and Wood, 1967; Rubin, 1990) and major and trace element mineral compositions and modal abundances were given by Curtis and Schmitt (1979). The chemical composition of Leedey has been examined by a number of workers (*e.g.*, König, 1964; Jarosewich, 1967; Masuda *et al.*, 1973), who participated in a long-term study of an interlaboratory comparison organized by C. B. Moore and using Leedey as a standard. Leedey was used for rare-earth-element normalization before the widespread acceptance of CI chondrites. This wide distribution of Leedey samples is reflected in its inclusion as a representative L chondrite in Mason's compilation of meteorite chemistry (1979). Here we provide a comprehensive report of the fireball, meteorite recovery and current depositories of the Leedey meteorite, as well as an examination of the petrology and chemistry of Leedey and an unusual Fe,Ni-FeS particle it contains.

FALL AND RECOVERY

The Leedey meteorite fell near Leedey, Dewey Co., Oklahoma, on 1943 November 25, within a few minutes of 7 P.M. C.W.T. (Central War Time) accompanied by a fireball and detonations observed by numerous people. An initial report of the fireball, given by United Press on 1943 November 26, was read independently by both Monnig and Nininger. Contacts with and ads placed in local newspapers in western Oklahoma yielded eyewitness reports and newspaper clippings preserved in the Monnig collection at Texas Christian University, allowing determination of the approximate path of the fireball. Weather conditions were partly overcast, so eyewitness reports were few and scattered. Seemingly reliable reports first sighted the fireball over parts of north-central Texas and south-central Oklahoma, indicating that the fireball was visible for a distance of ~400 km traveling on a trajectory from SE to NW at ~50°W of N. An eyewitness in Butler, Oklahoma (~30 km SSE of Leedey) reported seeing the fireball breakup over that town, separating into multiple fireballs. Reports of loud detonations in a broad area of western Oklahoma centered around Clinton placed the loudest noises between Hammon and Leedey. Several reports said that loud thuds were heard in association with falling material. A smoke train persisted for a few minutes after the passage of the meteor. Early observer confusion about the cause of the phenomenon was related to wartime attitudes that suggested an airplane crash or even a bombing.

Meteorite recovery by local residents began on 1943 November 26, near Leedey, Oklahoma; press clippings were soon forwarded to Monnig and Nininger announcing these recoveries. In early December, Monnig received a 41 g fragment of one of the Leedey stones and recognized it as a chondrite. Both Monnig and Nininger independently planned trips to Leedey at the earliest possible date. Wartime commitments and the remoteness of Leedey delayed this trip for both until 1943 December 9. Meeting along the road between Leedey and the local train station, they agreed to work together on the recovery and mapping of the Leedey shower. Six stones had already been recovered by local residents which, when mapped, delineated a narrow strewnfield ~17 km in length. A seventh stone of 4 kg was uncovered during their stay. In total, 24 stones totaling ~51.5 kg would be recovered between 1943 November 26 and 1944 November 12, after which no further recoveries were noted despite additional searches by Monnig. A map showing locations and masses (Fig. 1) reveals a well-defined strewnfield ~18 km in length oriented 50°W of N starting in Dewey County south of the town of Leedey reaching into eastern neighboring Roger Mills County. The largest stone (20.4 kg) was found at the extreme NW end of the strewnfield and the smallest stone (~57 g) lies at the extreme SE end. This distribution and orientation of the strewnfield is consistent with the

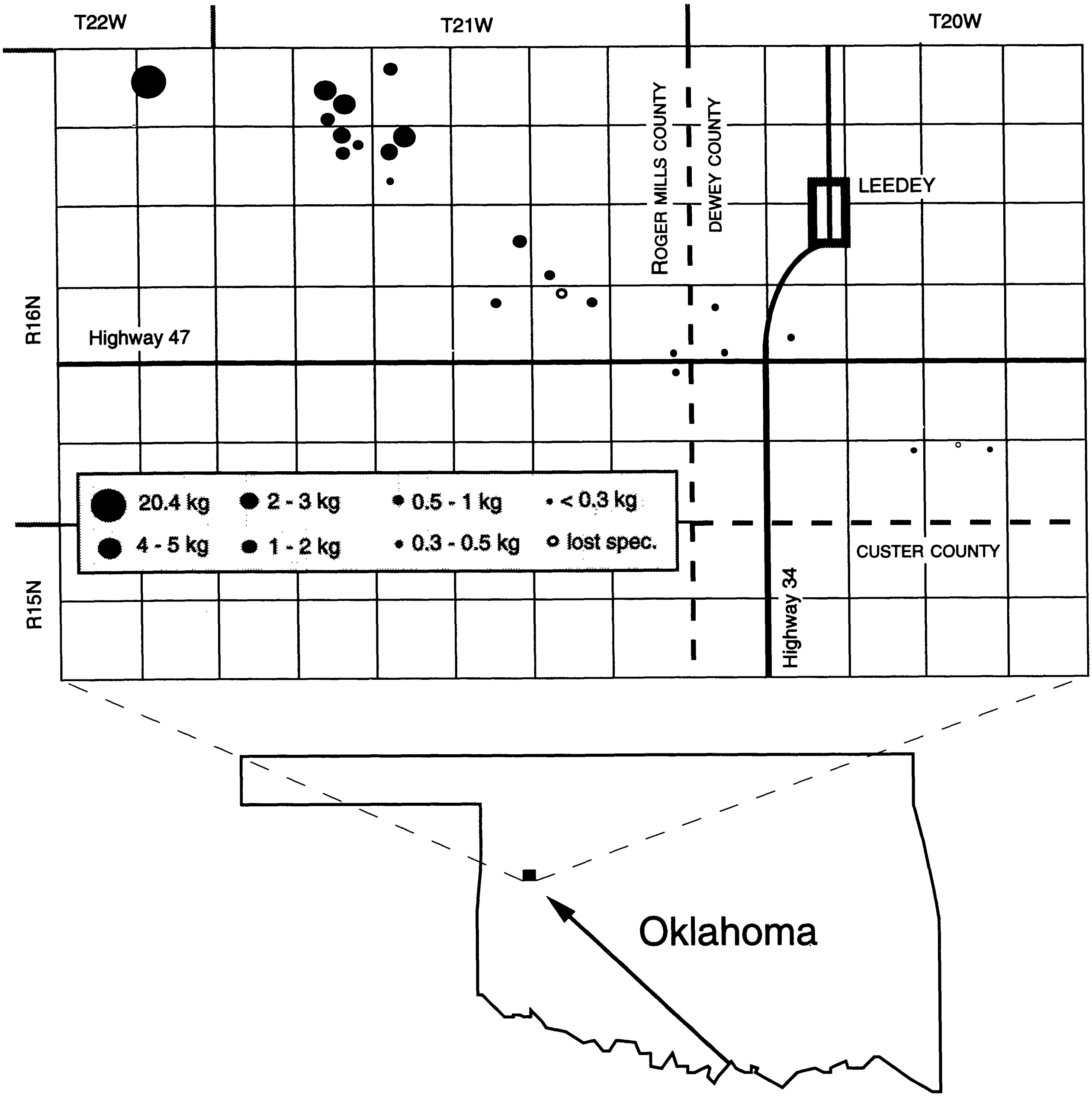

FIG. 1. Map of Oklahoma showing the approximate observed path of the Leedey fireball. Detail shows area around Leedey with sections, townships and ranges marked. The Leedey strewnfield consisted of 26 stones (two marked by open circles were lost prior to accurate weighing) that ranged in mass from 57 g to 20.4 kg defining a strewnfield 18 km in length from SE to NW, in close agreement with the observed direction of the meteor flight.

direction of flight (SE to NW) inferred from observations of the meteor.

The location of all 24 Leedey stones is not completely known. The Monnig collection at Texas Christian University contains all or parts of 12 stones totaling 23.9 kg, including approximately half of the main mass of the largest stone (sample M39.1; 9.8 kg) and 10 complete stones ranging from 405 g to 4 kg. Arizona State University contains all or parts of four stones, originally belonging to Nininger, with a total mass of 11.2 kg. Graham *et al.* (1985) records ~1.5 kg in other museum collections. Of the remaining ~15 kg of unaccounted Leedey material, most was retained by local residents, who kept all or most of six stones; at least two recovered stones were known to be lost, possibly during a later tornado in the Leedey area.

CLASSIFICATION

Mason (1963) determined an olivine composition of Fa_{24}, classifying Leedey as an L chondrite. Rubin (1990) confirmed the L classification with an average olivine composition of $Fa_{25.4 \pm 0.3}$. Rubin (1990) also included Leedey on a list of chondrites containing at least one kamacite grain with an aberrant Co concentration, suggesting that it might be an unrecognized postmetamorphic breccia. Curtis and Schmitt (1979) reported major and trace element mineral compositions. Van Schmus and Wood (1967) classified Leedey as a petrologic type 6, but no shock classification has been assigned.

We have studied three polished thin sections of Leedey prepared from stones in the Monnig collection. A rectangular polished thin section was prepared from sample M39.2, which is a 41 g fragment from a 280 g stone recovered on 1943 November 27, two days after the meteorite fell. Two parallel round thin sections were prepared from an interior piece of M39.11, a 2.27 kg stone recovered on 1944 October 27, 11 months after the fall. All three sections are deposited in the Monnig collection at Texas Christian University. These sections were studied in transmitted and reflected light and used for modal analysis. Compositions of a variety of phases, including those within the Fe,Ni-FeS particle, were measured on a Cameca Camebax electron microprobe at Johnson Space Center. We utilized a 1 μm diameter beam, 15 keV accelerating voltage, 20 nA current for analyses, used well-known natural and synthetic standards and corrected data using the PAP ZAF correction program.

Leedey is classified as an L6(S3) chondrite. Classification as an L group chondrite is indicated by the average compositions of olivine ($Fa_{24.9 \pm 0.2}$, N=10) and low-Ca pyroxene ($Fs_{21.0 \pm 0.3}Wo_{1.5 \pm 0.2}$, N=10), within the ranges given for L chondrites by Gomes and Keil (1980). The olivine composition is essentially identical with that found by previous workers and no compositionally aberrant silicate grains were observed. The obscure chondrule outlines, large plagioclase size (>50 μm), recrystallized matrix, lack of striated pyroxene, and lack of chondrule glass all indicate petrologic type 6 (Van Schmus and Wood, 1967). Barred and radiating textured chondrules are still visible. One chondrule, composed of multiple olivine bars with included chlorapatite, is 5 mm in diameter. Shock stage S3 is indicated by the presence of planar fractures and undulatory extinction in olivine (Stöffler *et al.*, 1991). Shock veins are absent, but rare shock pockets up to 50 μm in diameter can be found adjacent to metal grains. In addition, composite metal-troilite grains often exhibit finely-dispersed (2–15 μm) troilite with the metal, which are indicative of shock. No clasts indicative of brecciation were observed. Modal analyses of thin section M39.2, excluding the large Fe,Ni-FeS particle discussed below, reveals that Leedey contains 9.2 wt% Fe,Ni metal, 6.1 wt% troilite and 1.3 wt% chromite (1059 total points), within the ranges given for L chondrites by Gomes and Keil (1980) and very similar to the total metal and troilite abundance of 16% reported by Curtis and Schmitt (1979). Interestingly, many Fe,Ni grains exhibit halos of red-brown staining, although weathering products visible in reflected light are extremely rare. This is true in all thin sections, including the stone recovered only two days after collection. This red-brown staining is likely a submicron thick oxidized coating between grain boundaries formed during storage of these samples. This staining should not affect bulk compositional data. It does limit the usefulness of this fall for some studies, such as laboratory spectral analysis. Michael J. Gaffey (pers. comm., 1996) noted that spectral analyses reveal oxidized Fe in approximately half of all chondrites that were observed falls. Thus, minor oxidation during storage must be a widespread phenomenon.

CHEMISTRY

Leedey has been the subject of numerous chemical studies, as noted earlier. Mason (1979) summarized many of the trace element studies, although trace element studies of Leedey have also been conducted by Masuda *et al.* (1973) and Curtis and Schmitt (1979). Here we focus on bulk major element analyses conducted by four separate analysts. These analyses were all conducted as part of an interlaboratory comparison organized by C. B. Moore. Although three of these have been published previously, their presentation together here may be unique in reporting multiple modern analyses of the same chondrite and may provide some estimate of possible uncertainties in the use of bulk chemical analyses, particularly those from different authors. Bulk major element analyses, including details of the techniques, have already been separately reported by Jarosewich (1967), König (1964) and Wiik (1969). The results from A. D. Maynes are presented here for the first time. The technique used by Maynes is described in Duke *et al.* (1961). An important feature of all four analyses is the use of relatively large samples (up to 10 g). All four analyses and the mean are shown in Table 1. Agreement between the four analyses (σ/mean %) is remarkably good for some major constituents (SiO_2, 1.9%; MgO, 0.8%) while others exhibit considerable variability (Fe, 10.5%; FeS, 12.5%; Al_2O_3, 12.8%; FeO, 12.1%). Interestingly, despite considerable variation in the Fe-bearing consituents (Fe, FeS, FeO), total Fe shows remarkably little heterogeneity (1.0%) between the four analyses. It is difficult if not impossible to distinguish completely between sampling and analytical technique variations to explain these ranges.

Fe,Ni-FeS INCLUSION

Description

The most interesting petrologic feature of the Leedey samples studied is a 6 by 8 mm composite grain, composed of a 3 mm diameter Fe,Ni metal grain abutting a 5 mm FeS grain enclosed in silicates with an irregular boundary (Fig. 2a). The metal is dominantly kamacite, with a Co concentration of 0.85 ± 0.02 wt% (N = 5). This is essentially identical with the Co concentrations of matrix kamacite grains (0.82 ± 0.07 wt%, N = 5). Energy dispersive spectroscopic analyses indicates that this metal is free of Si and Cr both in solid solution in the metal and as inclusions. The adjacent troilite is compositionally pure, with Ti, Ni, Co, Mn, and Mg below detection limits. In reflected, cross-polarized light, the troilite exhibits

TABLE 1. Chemical analyses (wt%) of the Leedey chondrite.

	Analyst				
	H.B. Wiik (1969)	E. Jarosewich (1967)	H. König (1964)	A. Maynes	Mean
Fe	6.48	8.37	7.79	7.45	7.52
Ni	1.05	1.21	1.46	1.07	1.20
Co	0.07	0.06	0.08	0.07	0.07
FeS	5.59	6.42	7.60	6.72	6.58
SiO_2	39.51	40.32	38.51	39.46	39.45
TiO_2	0.11	0.12	0.10	0.12	0.11
Al_2O_3	2.69	2.19	2.83	2.26	2.49
Cr_2O_3	0.54	0.52	0.56	0.54	0.54
FeO	16.18	12.43	12.88	13.69	13.80
MnO	0.31	0.34	0.36	0.33	0.34
CaO	2.00	1.82	1.69	1.81	1.83
MgO	24.87	24.94	24.50	24.61	24.73
Na_2O	1.15	1.00	1.00	1.00	1.04
K_2O	0.07	0.11	0.11	0.09	0.095
P_2O_5	0.32	0.18	0.22	0.27	0.25
H_2O^+	0.11	0.00	0.11	0.27	0.16
H_2O^-	0.00	0.05	–	0.02	0.023
Total	101.05	100.08	99.80	99.71	100.20
Total Fe	22.57	22.11	22.63	22.38	22.42

elongated domains with different extinction angles. This appears to be the sheared troilite described by Bennett and McSween (1996) and attributed to severe shock.

At the kamacite-troilite boundary and surrounding small silicate grains near this boundary within the kamacite, 50–100 μm thick rims of high-Ni taenite, probably tetrataenite, occur (Fig. 2b). These rims are typically thicker adjacent to troilite and thinner when they surround silicates. Three zoning profiles (Fig. 3) across these rims reveal Ni concentrations from 45.4–55.6 wt%. No systematic zoning was observed. A well-developed Agrell depletion (the lower Ni concentrations observed within kamacite at the boundary with tetrataenite; see Wasson, 1974, for an explanation of its origin) is observed (Fig. 3). Small troilite grains are often found at the boundary between the tetrataenite and kamacite.

A variety of phases, including silicates and phosphates, abut and embay the assemblage. One 220 by 100 μm grain of Fe-bearing pyrophanite is observed within the troilite grain at the boundary with the silicate host (Fig. 2c). This grain exhibits a range of compositions, from 21.5–41.7 wt% MnO, and extensive zoning which is semisymmetrical around the pyrophanite-silicate border. The area in the center of the grain immediately adjacent to the silicates is the most Fe-rich, yielding a formula of $(\mathrm{Mn}_{0.45}\mathrm{Fe}_{0.41}\mathrm{Mg}_{0.19})_{\Sigma = 1.05}\mathrm{Ti}_{0.97}\mathrm{O}_3$. The corners of the grain furthest from the silicates are the most Mn-rich, $(\mathrm{Mn}_{0.89}\mathrm{Mg}_{0.10}\mathrm{Fe}_{0.06})_{\Sigma = 1.05}\mathrm{Ti}_{0.98}\mathrm{O}_3$, approaching end-member pyrophanite. Figure 4 illustrates a zoning profile across the approximate center of the grain. Manganese oxide exhibits marked enrichments at the grain edges, while FeO is depleted at the grain edge. Magnesium oxide zoning follows FeO at substantially lower abundances. Both end member pyrophanite and Mn-rich ilmenites have been noted previously in chondrites (Krot *et al.*, 1993), sometimes as inclusions in troilite (Shima *et al.* , 1986; Krot *et al.*, 1992).

Origin

We consider three possible origins for the Fe,Ni-FeS particle: (1) an origin as a foreign particle unrelated to the host, (2) formation

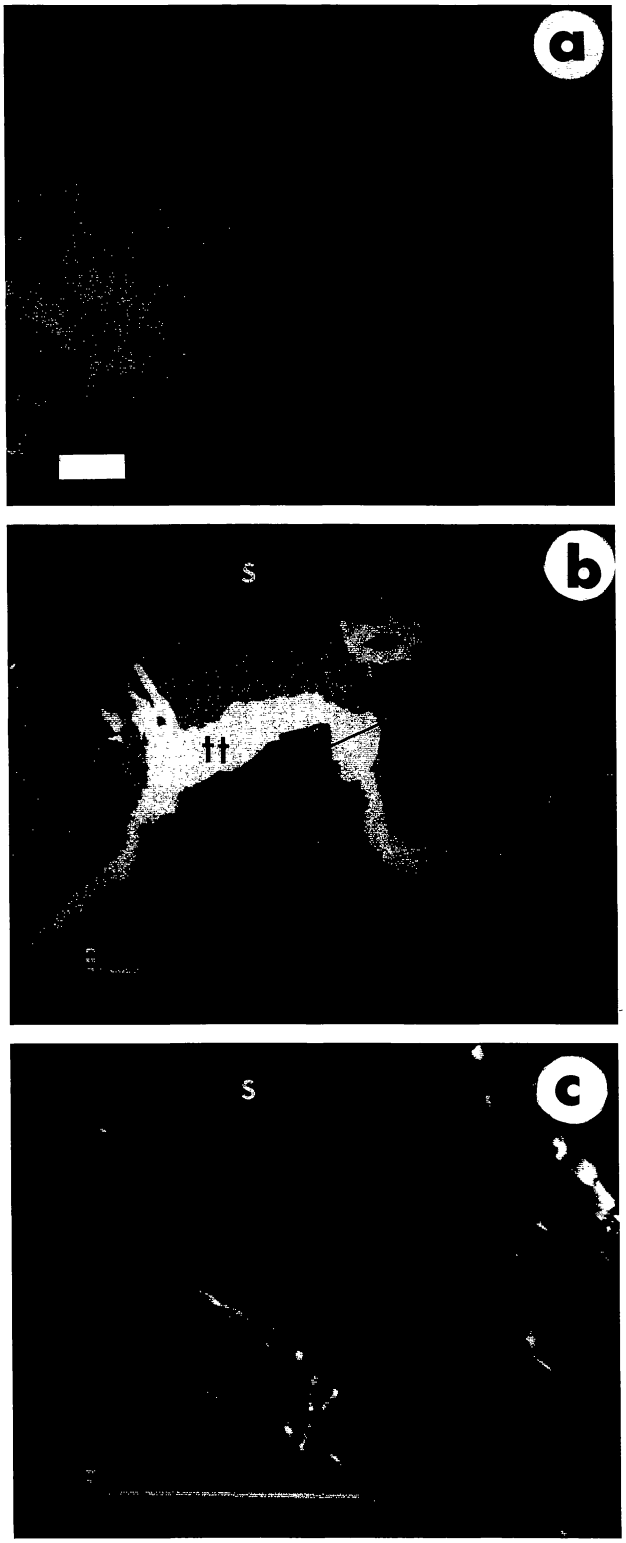

FIG. 2. Images of the composite Fe,Ni-FeS particle. (a) Reflected light photomicrograph of the Fe,Ni-FeS particle showing the large kamacite (k) and troilite (tr) portions with minor pyrophanite (p) and tetrataenite (tt). Scale bar = 1 mm. (b) Backscattered electron image of the tetrataenite rim (tt) found at the boundary between troilite (tr) and kamacite (k) and occasionally surrounding silicates (s). Line across tetrataenite indicates the location of zoning profile in Fig. 3. Scale bar = 100 μm (c) Backscattered electron image of a 100 by 220 µm pyrophanite grain (p) between troilite (tr) and silicates (s). Line indicates the zoning profile in Fig. 4. Scale bar = 100 μm.

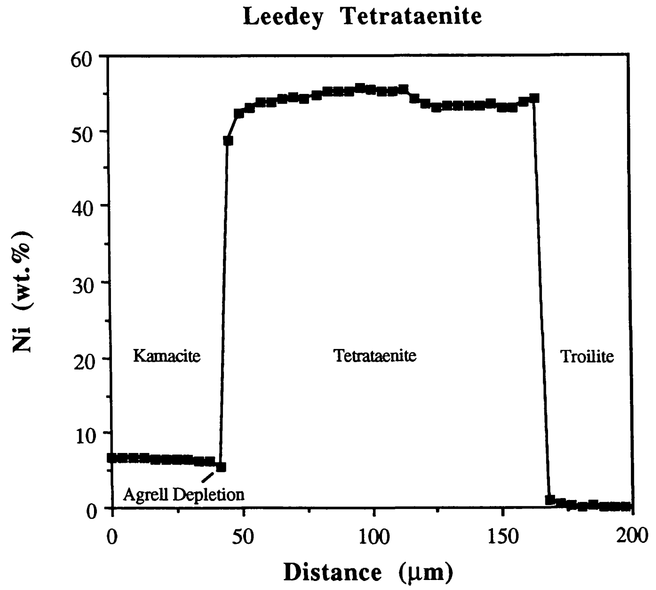

FIG. 3. Zoning profile across the kamacite-tetrataenite-troilite assemblage observed within the Fe,Ni-FeS particle in Fig. 2b. Tetrataenite is ~130 μm in width and contains >50 wt% Ni. Kamacite contains ~6.6 wt% Ni and exhibits a well-developed Agrell depletion adjacent to tetrataenite. Uncertainties on individual analyses are comparable to the size of the symbols.

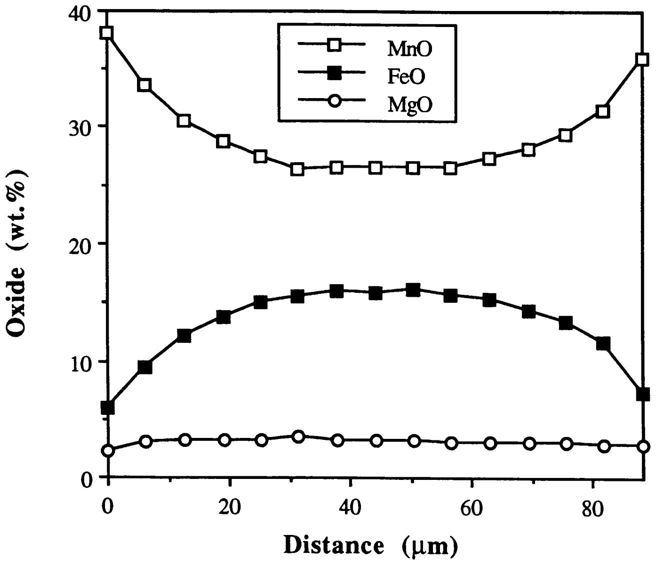

FIG. 4. Zoning profile across the pyrophanite grain shown in Fig. 2c. Manganese oxide is enriched at the rim of the grain while FeO and, to a lesser extent, MgO are depleted at the grain edge.

during impact-melting of the host meteorite, and (3) a complex origin involving nebular melting, parent body metamorphism and shock, mirroring that of the host chondrite.

It seems unlikely that this particle is foreign to Leedey. The irregular boundary of the composite particle and similar Co concentration between inclusion kamacite and matrix kamacite argue against incorporation into Leedey after metamorphism.

It also seems unlikely that this particle formed during impact melting of the host chondrite. Large Fe,Ni-FeS particles are common in impact melts (*e.g.*, Rubin, 1985), and an impact origin for the Leedey particle is worth considering. In the case of Leedey, the preservation of relict chondrules and abundance of metal and troilite around the particle are typical for an L6 chondrite, suggesting that it is not an impact melt.

We suggest that the Leedey particle formed by a number of processes, including melting in the nebula, parent body metamorphism and shock reheating. Kong and Ebihara (1996) have reported on studies of metal in unequilibrated and equilibrated L chondrites. These authors conclude that the metal did not form by condensation but rather represents the product of brief melting events and, thus, are the complement of the once-molten chondrules. This model provides a mechanism for the nebular formation of the large Fe,Ni-FeS particle in Leedey, although this particle is an order of magnitude larger than most Fe,Ni-FeS particles in chondrites. However, nebular melting can produce a range of sizes, as demonstrated by the existence of the silicate macrochondrules, which reach more than 1 cm in diameter (Grossman *et al.*, 1988). It is also unclear why this large particle would not have attained a rounded shape during melting, although this may have been subsequently obliterated during extensive parent body metamorphism of Leedey.

The effects of parent body metamorphism are evident in the Leedey particle from the equilibration of Co concentrations between inclusion and matrix kamacite and the irregular boundary between the inclusion and host chondrite. The presence of the Fe-bearing pyrophanite grain within the inclusion (Fig. 2c) might also be attributed to this parent body metamorphism. Kong and Ebihara (1996) demonstrate that the abundances of Cr, V and Mn decrease with increasing petrologic type in the bulk metallic fraction of L chondrites. They argue that these elements become oxidized during metamorphism and may enter silicates or chromite. In the case of Mn, Fe-rich ilmenite might provide an ideal site for the oxidized Mn. The zoning profile shown in Fig. 4 is consistent with MnO being introduced from the edges of the grain. The source of this MnO could be oxidized Mn from metal or, possibly, troilite. The small volume of pyrohanite relative to the Fe,Ni-FeS particle might explain the extreme MnO enrichment. Further, exchange between ilmenite and metal-troilite could also explain the fact that pyrophanite grains are commonly observed in association with troilite (Shima *et al.* , 1986; Krot *et al.*, 1992). Krot *et al.* (1993) also argued for diffusive exchange as a mechanism for forming pyrophanite.

Parent body metamorphism cannot, however, explain the presence of the tetrataenite rim at the boundary between troilite and kamacite without associated taenite (Fig. 2b). This feature may have resulted from the shock event evident in the Leedey inclusion and host. During cooling of a normal type 6 chondrite, we would expect to form kamacite with zoned taenite and thin rims of tetrataenite, as observed by Holland-Duffield *et al.* (1991). It may be possible, however, to form the kamacite-tetrataenite pair observed in Leedey during reheating after cooling. Yang *et al.* (1996), in a recent revision of the Fe,Ni phase diagram at temperatures below 400 °C, illustrate kamacite and tetrataenite with 50–53 wt% Ni (γ'') can coexist between 350–400 °C. If a kamacite-taenite pair cooled below 350 °C is reheated to between 350–400 °C, kamacite and tetrataenite can form without associated zoned taenite. While a reheating scenario might appear problematic, one possibility is reheating by shock. The shock stage S3 classification of Leedey suggests possible postshock temperature increases of 100–150 °C (Stöffler *et al.*, 1991), which would be sufficient to produce the reheating effects required if the shock event was early and the parent body had not cooled completely. No other kamacite-tetrataenite-troilite composite particles were identified in the matrix of Leedey, although shock reheating of Fe,Ni-FeS particles is evident in the form of finely-intergrown metal-troilite particles and reheating can be very heterogeneous between different particles. Thus, formation of the Fe,Ni-FeS particle in Leedey mirrors that of the host chondrite, with nebular melting, parent body metamorphism and later shock all playing a role.

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