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# Stones from Mohave County, Arizona: Multiple falls in the "Franconia strewn field"

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**Abstract**–One of the most productive and well-sampled dense collection areas for meteorites on Earth is the "Franconia strewn field" in Mohave County, Arizona, which since 2002 has yielded hundreds of meteorites in an ellipsoidal area approximately 5 × 16 km across. Based on petrographic, mineral-chemical, and terrestrial age data, we conclude that among 14 meteorites examined, there are at least 6 and possibly 8 distinct meteorites represented, which fell over a period of approximately 0–20 kyr ago. These include equilibrated H-chondrites such as Franconia (H5) and Buck Mountains (BM) 001 (H6); H3–6 breccias such as Buck Mountains Wash and BM 004; and L6 chondrites such as BM 002 and BM 003 (which may be paired), Palo Verde Mine, and BM 005. To confidently pair such meteorites often requires thorough petrographic examination, mineral-chemical analyses, and terrestrial ages. We estimate that 50 ± 10% of the larger specimens in this area are paired, yielding a relatively high value of approximately 2.3–2.9 distinct meteorites $\mathrm{km}^{-2}$. The meteorite flux estimated for Franconia area is higher than the flux inferred from contemporary fireball data for larger masses. We suggest that one large H3–6 meteoroid fell in the area, most likely that of Buck Mountains Wash approximately 4 kyr ago, which produced an elliptical strewn field with masses generally increasing toward one end, and which raised the meteorite productivity in the recovery area.

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## INTRODUCTION

On October 31, 2002, John Wolfe found a single stony meteorite in Mohave County, Arizona, USA (Bleacher et al. 2005). This meteorite was classified by Alan Rubin as an H5 chondrite and named Franconia (Russell et al. 2004). As of 2004, 87 meteorites had been recovered, and all were assumed to be paired with the Franconia meteorite (Russell et al. 2004). Within the last decade, many more meteorites were found in an elliptical area referred to as the Franconia strewn field (Norton and Chitwood 2008). However, it has been clear since 2005 from the work done by the Cascadia Meteorite Laboratory (CML) at Portland State University (this work; Hutson et al. 2007) and the Center for Meteorite Studies (CMS) at Arizona State University (Bleacher et al. 2005) that the meteorites recovered from this area are not part of a single strewn field, but represent multiple falls. The meteorites found in the Franconia area now number at least 380 specimens found in an approximately 5 × 16 km area, one of the most productive and well-sampled dense collection areas on Earth. In this article, we provide petrographic, mineral-chemical, and terrestrial age data for 14 stones from the Franconia area, examine the difficulties in pairing meteorites from multiple falls, and address the question of whether this area is a bona fide strewn field or rather a recovery area where circumstances combined to preferentially accumulate or preserve meteoritic material. Dense collection areas also provide important constraints for estimating meteorite flux (e.g., Bland et al. 1996). We utilize data compiled by one of us (JS) for unclassified meteorites together with pairing and terrestrial age data

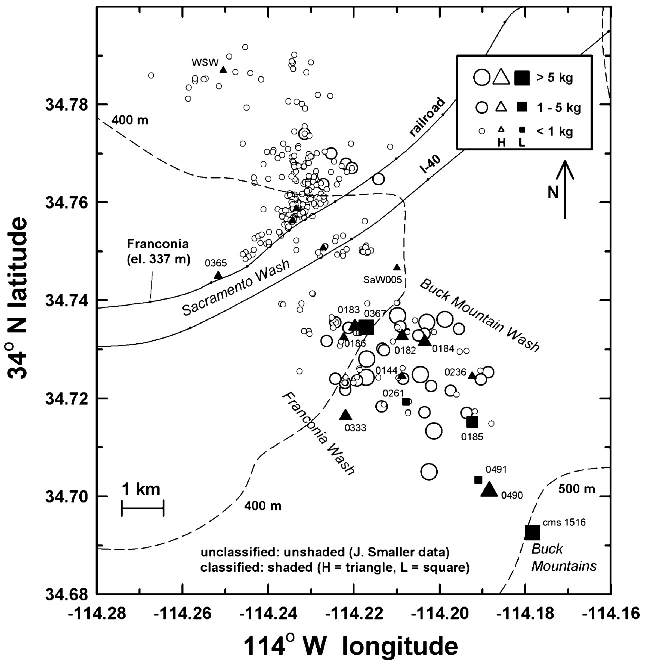

Fig. 1. Map of recovered meteorites in the Franconia area, in Mohave County, Arizona. Cascadia Meteorite Laboratory (CML) sample numbers are shown for the meteorites included in this study. Non-CML samples include CMS 1516 (Center for Meteorite Studies, Arizona State University) which is paired with Palo Verde Mine (CML 0185); SaW005 = Sacramento Wash 005; and WSW = Warm Springs Wilderness. For CML 0490 (Buck Mountains 004), the combined mass of 29.5 kg for various stones that may be paired was assumed. Dashed lines show elevations above sea level. "I-40" is interstate highway 40.

to estimate terrestrial meteorite flux over the past 20,000 yr.

## RECOVERY OF METEORITES

Figure 1 shows a map of meteorites recovered from the Franconia area, for both classified and unclassified samples. Most meteorites have been found by walking with the aid of a metal detector (Dennis Asher, personal communication). Data for specimen masses and locations are provided in Table S1. Our database includes 380 specimens, as reported by the finders. These include single stones, as well as specimens consisting of multiple stones which were reported by their finders as one specimen with one find location. An obvious example of a single sample that was broken into pieces is CML 0183, which consists of 15 pieces that were found under a tire track and that can be fit together. A less obvious example is CML 0490, consisting of 602 similar-appearing pieces found in a relatively small (60 × 60 m) area, some of which fit together to form a larger stone.

Table 1 summarizes statistics for meteorite recovery. All meteorites have been found in a roughly elliptical area that is about 5.3 × 15.8 km across (minor and major axis, respectively). The long axis of the ellipse is oriented with an azimuth of approximately 147° and there is a tendency for larger masses to be concentrated to the southeast (Fig. 1; Table 1). This is as one would expect for a strewn field of a single meteorite fall traveling to the southeast. The 380 specimens in our database have a total known weight of 244.8 kg; masses range from 0.06 to 34.16 kg, the median mass is 85.0 g, and most of the total mass is in the larger specimens (Table 1). The average meteorite yield averaged over the entire recovery area is high (approximately 5.8 specimens km$^{-2}$ and 3.7 kg km$^{-2}$) (Table 1).

In detail, meteorite recovery locations in the Franconia area show a bimodal distribution, with a relative dearth of meteorites found in a corridor centered on interstate highway I-40 (Fig. 1). Most of the larger specimens, including all but one of the samples studied by us, have been found to the south of I-40, in pediment uplands between washes (Franconia Wash and Buck Mountains Wash) (Fig. 1). The pediment surface on which meteorites are found has sparse vegetation but is unremarkable (Fig. 2a). This surface slopes down northwest from the low hills known as the Buck Mountains, toward the Sacramento Wash (Figs. 1 and 2b). Compared with the entire recovery area, the area south of I-40 has a lower number density but a higher mass density of specimens (approximately 4.7 specimens km$^{-2}$ and 6.8 kg km$^{-2}$, respectively), reflecting the presence of fewer, more massive individuals (Table 1). No meteorites have been recovered within the main portions of Franconia Wash or Buck Mountain Wash arroyos, even though they are located in the recovery area, suggesting that fluvial processes such as enhanced mechanical or chemical weathering, burial or transport actively remove or cover the meteorites there. However, transport alone seems unlikely as there is no evidence for a depositional area enriched in meteorites downstream. Numerous smaller (<1 kg) masses have been found north of I-40 (Fig. 1). These include metal-rich individuals that are often approximately 1–2 g in mass (Schrader et al. 2010; Laurence Garvie, personal communication).

## SAMPLES

The Cascadia Meteorite Laboratory (CML) received samples of 12 unclassified chondrites over a 6-year period. These samples were obtained from different people in a noncoordinated fashion. The samples were assigned internal lab numbers 0144, 0182, 0183, 0184, 0185, 0186,

Table 1. Compiled data for meteorite recovery in the Franconia area.

| Mass range (kg) | Number of specimens | Total mass (kg) | North latitude (°)* | West longitude (°)* | Mean mass (g) | Median mass (g) | Recovery area (km$^2$) | Number density (specimens km$^{-2}$) | Mass density (kg km$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| <1, entire area | 335 | 49.944 | 34.75535 (0.01685) | 114.22927 (0.01112) | | | | | |
| 1–5, entire area | 34 | 71.411 | 34.73747 (0.02247) | 114.21193 (0.01296) | | | | | |
| >5, entire area | 11 | 122.479 | 34.72018 (0.01511) | 114.20345 (0.01218) | | | | | |
| All, entire area | 380 | 244.834 | | | 644.3 | 85.0 | 65.9[a] | 5.8[b] | 3.7 |
| All, south of I-40 | 140 | 211.411 | | | 1510.1 | 208.5 | 31.1[c] | 4.7[d] | 6.8 |

*Mean; standard deviation in parentheses.

[a] Equivalent to a 5.3 × 15.8 km ellipse (minor and major axis, respectively), which encapsulates all of the recovered specimens shown in Fig. 1.

[b] Assuming 50% pairing, corresponds to approximately 2.9 unpaired meteorites km$^{-2}$. Assuming 20 kyr integration, equivalent to approximately 145 meteorites per $10^6$ km$^2$ per year.

[c] Equivalent to rectangle 8.4 km long × 3.7 km wide.

[d] Assuming 50% pairing, corresponds to approximately 2.3 unpaired meteorites km$^{-2}$. Assuming 20 kyr integration, equivalent to approximately 115 meteorites per $10^6$ km$^2$ per year.

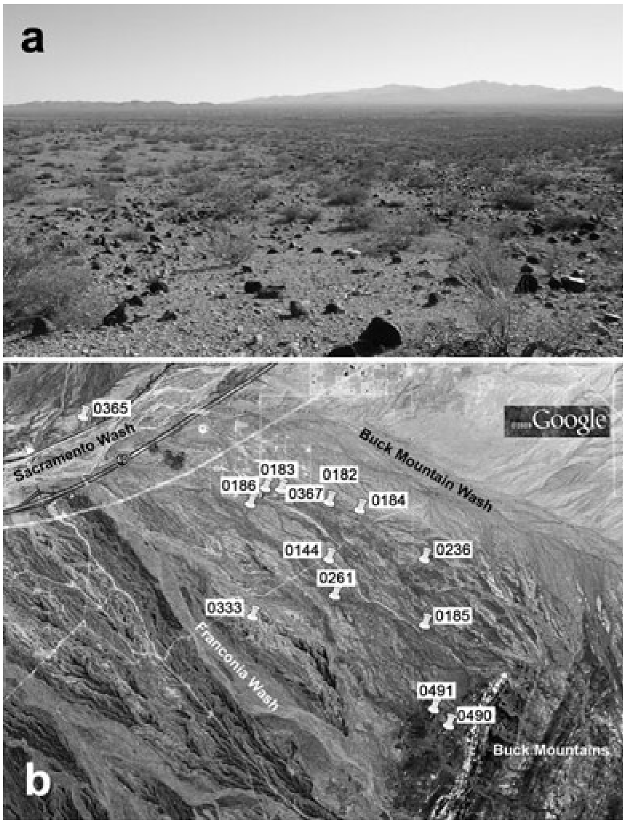

Fig. 2. a) Image from ground (courtesy Larry Sloan) showing typical appearance of the recovery area. b) Vertical aerial image of the Franconia area projected from 11,385 m altitude using Google Earth, showing topography and the locations of recovered CML samples.

0236, 0261, 0365, 0367, 0490, and 0491. In addition, we received a slice from the original Franconia meteorite found by John Wolfe, which was assigned an internal lab number 0333. Doubly polished thin sections were prepared for all of these samples. For most samples multiple thin sections were prepared. A thin section (CMS 1516) from another unclassified Franconia-area stone was borrowed from Arizona State University for examination.

At the beginning of this project, meteorites that were paired with already classified samples from the Franconia area were given the same name as the original sample. Thus, five stones were classified as Buck Mountain Wash, two as Franconia, and two as Palo Verde Mine (one of them the sample from Arizona State University). Material has been widely distributed under these names. In 2006, the Franconia region was defined as two adjacent dense collection areas (DCAs), named Buck Mountains and Sacramento Wash. The last five meteorites classified by CML from this region were given a DCA designation (Buck Mountains) and a number (001, 002, 003, 004, and 005) according to current practice.

## METHODS

Polished thin sections were studied using optical microscopy, scanning electron microscopy (SEM), and electron microprobe (EMP) analysis. SEM work was performed at Portland State University using two instruments: (1) a JEOL JSM-35C with a Kevex energy dispersive detector and 4pi© digital image/spectrum acquisition system; and (2) a Zeiss Sigma-VP with an Oxford Instruments XMax 50 energy dispersive spectrometer and Oxford INCA acquisition and analysis software. Backscattered electron (BSE) images and X-ray maps were obtained with the SEM. BSE observations were performed using two settings: one suitable for silicates; the other for metal. Three electron microprobes were used for this project. For most of the samples studied, EMP analyses of olivine, pyroxene, plagioclase, glass, and metal were obtained at Oregon State University with Cameca SX-50 and SX-100 electron microprobes using wavelength dispersive spectrometers. For these analyses, all phases except for plagioclase and glass were analyzed with an accelerating voltage of 15 keV, a 50 nA sample current, and a beam focused to approximately 1 μm diameter; for plagioclase and glass, a 10 nA sample current and an approximately 4 μm diameter beam were used instead. All of the analyses for CML 0367 and the majority of the analyses for CML 0365 were obtained at the University of Oregon using a Cameca SX-100 electron microprobe, operated with an accelerating voltage of 15 keV, a 50 nA sample current, and a beam focused to approximately 5 μm diameter.

Meteorites were analyzed for carbon and beryllium isotopes at the Accelerator Mass Spectrometry (AMS) laboratory at the University of Arizona. Terrestrial ages were obtained using the procedure summarized by Jull et al. (1989, 1998). Samples of meteorites were crushed and treated with 85% phosphoric acid to remove carbonates produced by terrestrial weathering. The material was then loaded into a ceramic crucible, to which 4–5 g of iron chips were added, to be used as a combustion accelerator. The crucible and contents were heated to 500 °C in air to remove combustible contaminants. The cleaned crucible and sample was then loaded into an RF induction furnace, and the sample was heated to the iron melting point in a flow of oxygen. All carbon in the sample was released during this process, as was demonstrated by Jull et al. (1989). We used a Pt/CuO furnace at 450 °C to ensure conversion of any CO to $CO_2$. The $CO_2$ gas was collected from the oxygen gas stream. The volume of the $CO_2$ was measured and converted to graphite over hot iron. The $^{14}C$ concentrations in the graphite sample were measured by AMS as discussed by Donahue et al.

(1990) and were compared with known NIST standards. For $^{10}$Be measurements, samples of approximately 0.1 g meteorite were dissolved in HF-$HNO_3$, and a carrier of 0.3 mg Be as $Be(OH)_2$ was added. The Be was separated by a combination of acetyl-acetone extraction and ion chromatography (McHargue et al. 1995; Kring et al. 2001). $^{10}$Be measurements were normalized to the currently accepted half-life of 1.36 Ma (Nishiizumi et al. 2007) and compared with the NIST standard with a reported value of $2.68 \times 10^{-11}$ $^{10}Be/^{9}Be$.

## PETROGRAPHY, MINERAL CHEMISTRY, TERRESTRIAL AGES

We obtained petrographic, mineral-chemical, and terrestrial age data for various meteorites from the Franconia area to assess pairing. A summary of the stones examined in detail for this study, along with their classification information, is given in Table 2. This includes 12 samples classified by CML, along with a piece of the original Franconia stone classified by Alan Rubin (Russell et al. 2005). A 14th sample (CMS 1516) was briefly examined using BSE only, and was not studied in detail. Based on available data, among the 14 meteorites examined there are 7 distinct meteorite falls represented.

Olivine fayalite (Fa) and low-Ca pyroxene ferrosilite (Fs) contents separate the meteorites into three groups (Fig. 3; Table 3). Three stones are equilibrated H-group chondrites (CML 0182, 0186, 0333/Franconia) (Fig. 3a). Four are equilibrated L-group chondrites (CML 0185, 0261, 0367, and 0491) (Fig. 3b). The remaining six stones are H-group chondrites containing both unequilibrated and equilibrated material (Fig. 3c). Below we discuss the petrography and mineral chemistry of the meteorites in these three groups, before describing terrestrial age data.

### Equilibrated H-group Chondrites

#### *Franconia (CML 0333)*

A slice of the original Franconia stone was included in this study. We found this meteorite to be an H5 chondrite (Fa = 18.0 ± 0.4, *n* = 10; Fs = 15.8 ± 0.3, *n* = 9) of shock stage S3. This classification is in agreement with Russell et al. (2004). The most notable feature of the meteorite is a discontinuous vein of metal approximately 3.5 cm long in hand specimen, composed of irregularly shaped elongate metal grains (Fig. 4). Metal grains in the vein enclose small silicate grains and wrap around the edges of adjacent grains. Metal grains throughout the sample are associated with numerous metallic copper grains. The sample in this study is less weathered (grade W1) (Wlotzka 1993) than the official classification (Russell et al. 2004), probably indicating that our sample was taken from a portion of the meteorite that was farther from a weathering surface.

#### *CML 0182 (Paired With Franconia)*

CML 0182 has the same shock stage (S3) and weathering grade (W1) as Franconia (CML 0333), and olivine (Fa = 18.1 ± 0.4, *n* = 18) and pyroxene (Fs = 16.0 ± 0.1, *n* = 5) compositions that are very similar to Franconia (Fig. 3a). Many of the larger metal grains enclose silicates and wrap around adjacent grains, similar to the metal in Franconia. A single grain of copper was observed adjacent to one of the metal grains. Unlike Franconia, CML 0182 lacks a large discontinuous vein and has a concentration of chromite-plagioclase assemblages (e.g., Rubin 2003) along one edge of the thin section.

#### *Buck Mountains 001 (CML 0186)*

The hand specimen of this small 50 g stone appears heavily weathered and is partially covered by patches of caliche. In thin section, the silicates show staining. Most, but not all of the metal, and roughly one third to one half of the troilite has been replaced, consistent with a W3 weathering grade (Wlotzka 1993). The section is crosscut by a large number of roughly aligned iron oxide veins, which were formed by weathering. Overall the texture appears fairly integrated, with few recognizable chondrules, although the veining makes this difficult to judge. Chondrules were more readily distinguished in backscattered electron (BSE) images than with the optical microscope. Most feldspar grains in BSE are crosscut by numerous oxide veins. A half dozen grains >50 μm and one grain >100 μm across were observed. The section also contains fairly abundant small diopside grains. The textural data suggest this is a low type 6 chondrite (e.g., Dodd 1981). Chemical analyses of olivine (Fa = 18.3 ± 0.3, *n* = 18) and pyroxene (Fs = 16.8 ± 0.6, *n* = 8) are typical of an H-group chondrite (e.g., Brearley and Jones 1998) but are slightly more ferrous than Franconia and CML 0182 (Fig. 3a). Most olivine grains show weak undulose extinction, consistent with an S2 shock stage (Stöffler et al. 1991). Based on distinct differences in texture, weathering state, and mineral composition, this H-chondrite is not the same as Franconia or CML 0182.

### H-Group Chondrites Containing Unequilibrated Material

#### *Buck Mountain Wash (CML 0144)*

The Buck Mountain Wash chondrite was classified as an H3–5 genomict breccia (Russell et al. 2005; Hutson et al. 2007), but subsequent observations of

Table 2. Stones from Mohave County, Arizona, examined in this study.

| Name and CML # | Recovered mass (g) | Find location (Lat, Long) | Finder | Classification | Comments |
|---|---|---|---|---|---|
| Franconia | | | | | |
| 0333 | 4255 | 34° 42.982′ N<br>114° 13.318′ W | John Wolfe | H5, W1, S3 | Franconia type specimen. Classified by Rubin as H5, W2, S3 (Russell et al. 2004); mass and find location from Russell et al. (2004); our sample is from same stone; low S3; contains irregular metal vein |
| 0182 | 1153 | 34° 43.961′ N<br>114° 12.526′ W | Larry Sloan | H5, W1, S3 | Paired with Franconia |
| Buck Mountain Wash | | | | | |
| 0144 | 816 | 34° 43.472′ N<br>114° 12.53′ W | Larry Sloan | H3–6, W1, S2–S5 | Buck Mountain Wash type specimen. Classified as H3–5 by CML (Russell et al. 2005); described in Hutson et al. (2007); contains 3 lithologies (main, A, B); A & B are shock blackened |
| 0183 | 1126 | 34° 44.083′ N<br>114° 13.187′ W | Larry Sloan | H3–5, W1, S3 | Paired with Buck Mountain Wash; similar to main lithology of CML 0144; our sample was from a single 742 g stone that was found with 14 other pieces totaling 1126 g |
| 0184 | 1600 | 34° 43.894′ N<br>114° 12.210′ W | Homer Stockam | H3–5, W1, S3 | Paired with Buck Mountain Wash; low S3; similar to main lithology of CML 0144 |
| 0236 | 816 | 34° 43.472′ N<br>114° 11.545′ W | Larry Sloan | H3–6, W1, S3–S4 | Paired with Buck Mountain Wash; similar to main lithology of CML 0144; contains Ca-Al object, metal-poor gray shock melt, and adjacent coarse metal |
| 0365 | 513 | 34° 44.7′ N<br>114° 15.1′ W | Dale Lamm | H3–5, W2, S2–S6 | Paired with Buck Mountain Wash; large shock-blackened clast containing a small pocket of shock melt depleted in opaque minerals |

Table 2. *Continued*. Stones from Mohave County, Arizona, examined in this study.

| Name and CML # | Recovered mass (g) | Find location (Lat, Long) | Finder | Classification | Comments |
|---|---|---|---|---|---|
| Buck Mountains 001 | | | | | |
| 0186 | 50 | 34° 43.947′ N 114° 13.345′ W | Jim Smaller | H6, W3, S2 | Classified by CML (Connolly et al. 2006); borderline H5 |
| Buck Mountains 004 | | | | | |
| 0490 | 145.8 | 34° 42.065′ N 114° 11.307′ W | Dennis Asher | H3–6, W2, S1–6 | Classified by CML (Garvie 2013). Shock stage S4–5 predominant. One of 602 pieces (29.5 kg) of possibly paired meteorites found in a 60 × 60 m across triangular area |
| Palo Verde Mine | | | | | |
| 0185 | 1998 | 34° 42.912′ N 114° 11.545′ W | Homer Stockam | L6, W2, S4 | Palo Verde Mine type specimen. Classified by Melinda Hutson (CML) & Lora Bleacher (CMS/ASU) (Russell et al. 2005); Hutson studied the stone found by Stockam; Bleacher examined a stone, mass 7160 g, found by Sonny Clary (CMS 1516); borderline L5, S3; feldspar partly shock melted; contains large igneous clast and adjacent metal-sulfide nodule |
| Buck Mountains 002 | | | | | |
| 0261 | 18.4 | 34° 43.16′ N 114° 12.47′ W | John Wolfe | L6, W2–W3, S3 | Classified by CML (Connolly et al. 2006); shock stage near the S3–S4 boundary; possibly paired with Buck Mountains 003 |
| Buck Mountains 003 | | | | | |
| 0367 | 34,200 | 34° 44.07′ N 114° 13.03′ W | Dennis Asher | L6, W3, S4 | Classified by CML (Connolly et al. 2007); shock stage near the S3–S4 boundary; possibly paired with Buck Mountains 002 |
| Buck Mountains 005 | | | | | |
| 0491 | 859.7 | 34° 42.202′ N 114 ° 11.458′ W | Dennis Asher | L6, W2, S4 | Classified by CML (Garvie 2013). Thirty-six pieces found in a 1.3 × 1.3 m area on the same day. Multiple fragments contain a complex silicate shock vein |

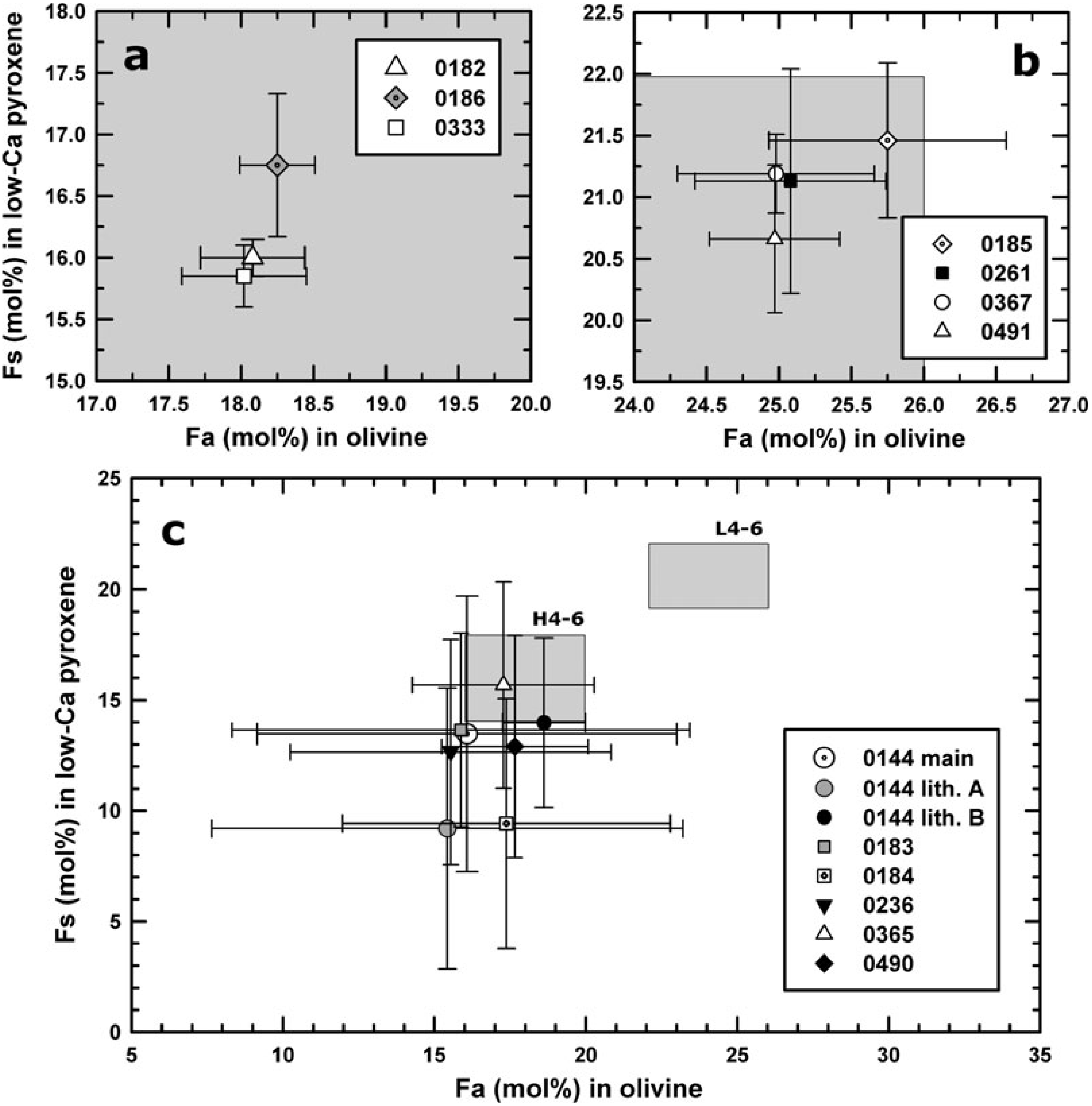

Fig. 3. Olivine fayalite (Fa) versus low-Ca pyroxene ferrosilite (Fs) contents for Franconia-area meteorites analyzed by the Cascadia Meteorite Laboratory; numbers refer to CML sample designations; shaded areas show ranges for H4-6 and L4-6 chondrites (Brearley and Jones, 1998). a) Three meteorites, including a piece of the original Franconia meteorite (CML 0333) have olivine and pyroxene compositions consistent with an equilibrated H-group chondrite. b) Four samples are equilibrated L-group chondrites. c) Six meteorites, and three distinct lithologies in CML 0144 (Buck Mountain Wash), have a significant number of olivine and pyroxene grains with unequilibrated compositions.

additional thin sections indicate that the meteorite is better classified as an H3–6 genomict breccia. The meteorite contains three distinct lithologies (main, A, B) (Figs. 5a–d) with main and A observed in six thin sections, as well as clasts of type 6 chondrite (Fig. 5e) observed in two thin sections. The type 6 clasts have a highly integrated texture with feldspars exceeding 50 μm in length.

As described in Hutson et al. (2007), the main lithology has a texture reminiscent of a type 5 chondrite in terms of integration of chondrules and matrix. However, unlike a typical type 5 chondrite, the main

Table 3. Mean olivine and low-Ca pyroxene compositions, along with standard deviations, in various Mohave County, Arizona, stones, determined by electron microprobe analysis. CML samples 0144, 0183, 0184, 0236, 0365, and 0490 contain abundant unequilibrated material, whereas 0182, 0333, 0186, 0185, 0261, 0367, and 0491 are equilibrated.

| Sample | Fa (mol%) | Number of olivine analyses | Fs (mol%) | Wo (mol%) | En (mol%) | Number of pyroxene analyses |
|---|---|---|---|---|---|---|
| Franconia | | | | | | |
| CML 0182 | 18.08 ± 0.36 | 18 | 16.00 ± 0.15 | 1.15 ± 0.19 | 82.85 ± 0.18 | 5 |
| CML 0333 | 18.02 ± 0.43 | 10 | 15.85 ± 0.25 | 1.08 ± 0.15 | 83.08 ± 0.27 | 9 |
| Buck Mountain Wash | | | | | | |
| CML 0144 "main" | 16.08 ± 6.93 | 99 | 13.47 ± 6.23 | 1.26 ± 0.91 | 85.27 ± 6.44 | 73 |
| CML 0144 "lithology A" | 15.43 ± 7.78 | 44 | 9.20 ± 6.34 | 0.88 ± 1.16 | 89.92 ± 6.90 | 18 |
| CML 0144 "lithology B" | 18.62 ± 1.36 | 22 | 13.98 ± 3.83 | 0.86 ± 0.80 | 85.16 ± 4.09 | 14 |
| CML 0183 | 15.88 ± 7.56 | 32 | 13.65 ± 4.38 | 1.23 ± 0.42 | 85.12 ± 4.68 | 21 |
| CML 0184 | 17.38 ± 5.41 | 40 | 9.42 ± 5.64 | 0.65 ± 0.41 | 89.92 ± 5.96 | 26 |
| CML 0236 | 15.54 ± 5.30 | 34 | 12.65 ± 5.10 | 1.57 ± 1.32 | 85.78 ± 4.80 | 16 |
| CML 0365 | 17.28 ± 3.00 | 86 | 15.68 ± 4.66 | 1.14 ± 0.67 | 83.17 ± 5.09 | 78 |
| Buck Mountains 001 | | | | | | |
| CML 0186 | 18.25 ± 0.26 | 18 | 16.75 ± 0.58 | 1.18 ± 0.24 | 82.07 ± 0.51 | 8 |
| Buck Mountains 004 | | | | | | |
| CML 0490 | 17.66 ± 2.42 | 66 | 12.90 ± 5.02 | 1.09 ± 0.67 | 86.01 ± 5.29 | 34 |
| Palo Verde Mine | | | | | | |
| CML 0185 | 25.75 ± 0.82 | 43 | 21.46 ± 0.63 | 1.42 ± 0.15 | 77.11 ± 0.67 | 15 |
| CMS 1516[a] | 24.51 ± 0.34 | [b] | 20.76 ± 0.37 | [b] | [b] | [b] |
| Buck Mountains 002 | | | | | | |
| CML 0261 | 25.08 ± 0.66 | 20 | 21.13 ± 0.91 | 1.54 ± 0.16 | 77.33 ± 0.98 | 15 |
| Buck Mountains 003 | | | | | | |
| CML 0367 | 24.98 ± 0.68 | 189 | 21.19 ± 0.32 | 1.25 ± 0.19 | 77.57 ± 0.41 | 3 |
| Buck Mountains 005 | | | | | | |
| CML 0491 | 24.97 ± 0.45 | 61 | 20.66 ± 0.60 | 1.59 ± 0.22 | 77.75 ± 0.58 | 6 |

[a] Data from Lora Bleacher (personal communication)

[b] Not available.

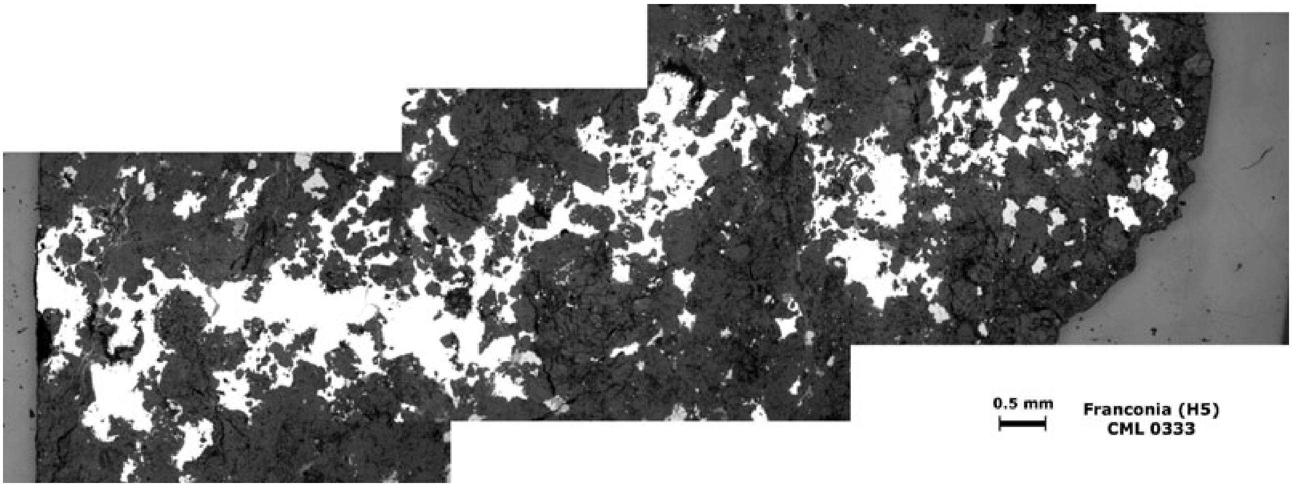

Fig. 4. Image mosaic of Franconia (CML 0333) in reflected light showing a discontinuous vein composed of irregularly shaped metal grains (bright).

lithology in Buck Mountain Wash consists of intermixed chondrules and fragments of varying sizes, with a notable amount of unequilibrated material. It lacks the granular-appearing recrystallized matrix found between chondrules in a typical type 5 chondrite; rather the material between larger objects consists of smaller fragments and angular grains. This lithology appears to be similar to the fragmental breccias described by Scott

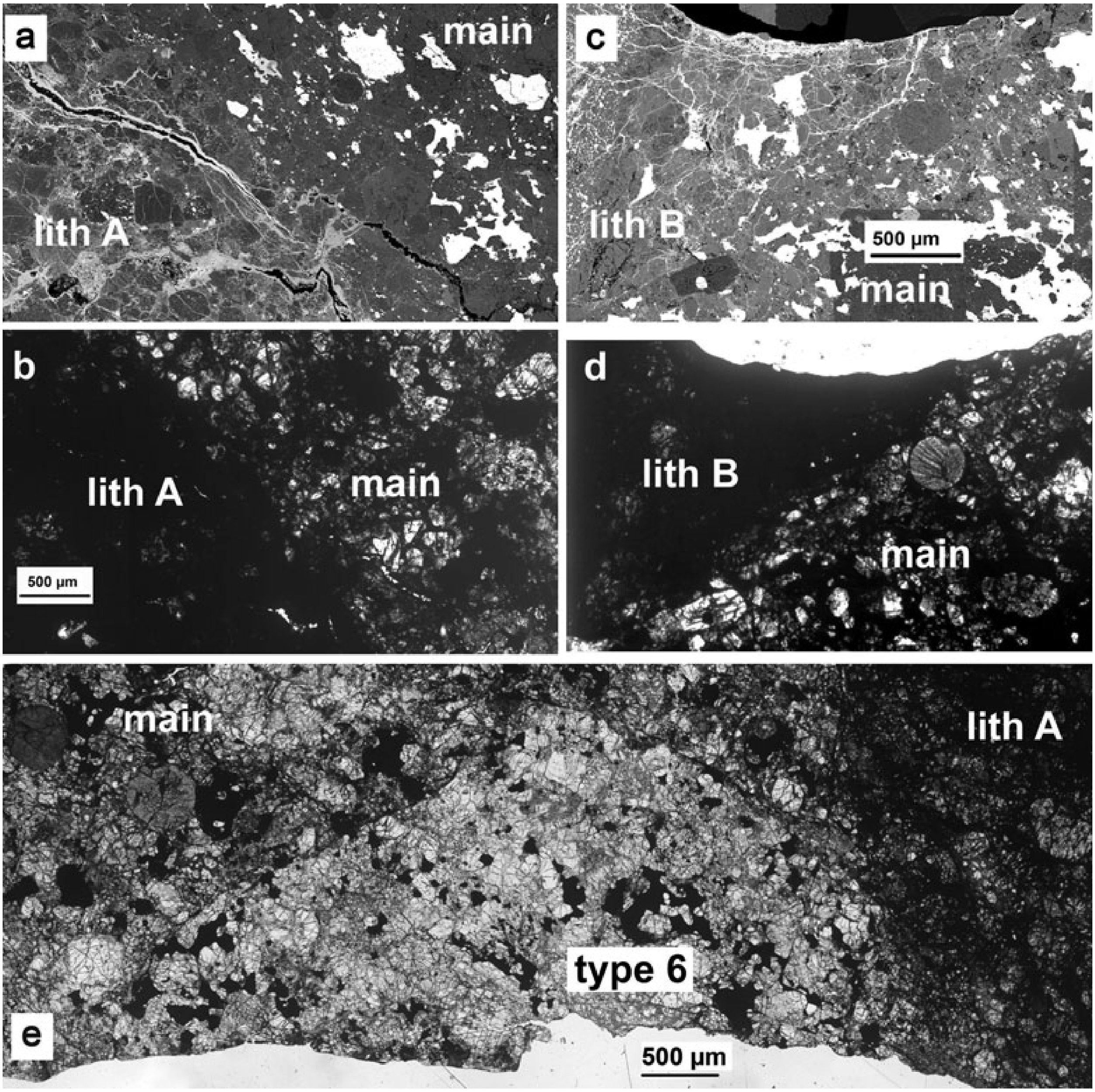

Fig. 5. Images of Buck Mountain Wash (CML 0144). (a) BSE image and (b) transmitted plane-polarized light image of the same field of view showing the contact between the main lithology ("main") and lithology A ("lith A"). (c) BSE image and (d) transmitted plane-polarized light image of the same field of view showing the contact between the main lithology and lithology B ("lith B"). (e) Transmitted plane-polarized light image showing a type 6 clast between the main lithology and lithology A.

et al. (1985), although Buck Mountain Wash has a larger proportion of unequilibrated material than reported by Scott et al. (1985). Individual metal grains up to 6 mm across are present in the main lithology of Buck Mountain Wash.

Lithologies A (forming a clast up to five cm across) and B are shock blackened and appear mostly opaque in transmitted light (Figs. 5b and 5d). Lithology B (>5 mm across, seen only in the corner of one section) contains some impact melt. As noted by Hutson et al. (2007), both blackened clasts contain metal with anomalous compositions; with lithology A having Co content in kamacite between that expected for H- and L-chondrites; and lithology B having Co content in kamacite lower than that typical for H-chondrites. As shown in Fig. 3c, all three of these lithologies contain enough unequilibrated material that their mean Fa and Fs contents lie outside of the equilibrated H-chondrite range.

Table 4. Chemical compositions (wt%) of aluminous pyroxenes in H-chondrites from the Franconia area containing unequilibrated material.

| CML # [a] | $Na_2O$ | MgO | $Al_2O_3$ | $SiO_2$ | CaO | $TiO_2$ | $Cr_2O_3$ | MnO | FeO | Total | Wo[b] | En | Fs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Buck Mountain Wash (BMW) | | | | | | | | | | | | | |
| 0144-main | 0.00 | 33.3 | 1.33 | 56.7 | 1.78 | 0.09 | 0.88 | 0.23 | 6.19 | 100.5 | 3.4 | 87.5 | 9.1 |
| 0144-main | 0.00 | 31.7 | 3.07 | 54.6 | 1.84 | 0.18 | 1.28 | 0.20 | 7.58 | 100.5 | 3.5 | 85.1 | 11.4 |
| 0144-main | 0.00 | 31.8 | 1.69 | 55.4 | 2.43 | 0.20 | 0.96 | 0.22 | 7.24 | 99.9 | 4.7 | 84.5 | 10.8 |
| 0144-lithA | 0.10 | 34.8 | 2.76 | 56.0 | 2.09 | 0.19 | 0.71 | 0.18 | 2.72 | 99.5 | 4.0 | 92.0 | 4.0 |
| Samples paired with BMW | | | | | | | | | | | | | |
| 0183 | 0.00 | 21.1 | 5.87 | 51.7 | 16.8 | 0.76 | 1.98 | 0.13 | 2.51 | 100.7 | 34.9 | 61.0 | 4.1 |
| 0183 | 0.11 | 18.6 | 6.36 | 50.8 | 19.7 | 0.92 | 2.04 | 0.14 | 2.00 | 100.6 | 41.8 | 54.9 | 3.3 |
| 0184 | 0.17 | 17.7 | 6.39 | 50.2 | 17.9 | 0.71 | 2.72 | 1.26 | 2.22 | 99.2 | 40.4 | 55.7 | 3.9 |
| 0184 | 0.16 | 15.9 | 6.87 | 49.3 | 20.2 | 0.96 | 3.25 | 1.06 | 1.71 | 99.4 | 46.3 | 50.6 | 3.1 |
| 0236 | 0.00 | 29.9 | 12.7 | 49.6 | 2.34 | 0.62 | 0.46 | 0.20 | 4.00 | 99.8 | 5.0 | 88.4 | 6.6 |
| 0236-chon1 | 0.00 | 29.9 | 13.5 | 49.6 | 1.84 | 0.42 | 0.27 | 0.47 | 4.34 | 100.2 | 3.9 | 88.8 | 7.3 |
| 0236-chon2 | 0.01 | 18.4 | 8.06 | 48.6 | 18.6 | 0.99 | 1.51 | 0.08 | 1.46 | 97.7 | 41.0 | 56.4 | 2.5 |
| 0236-chon3 | 0.01 | 23.3 | 4.69 | 51.4 | 13.6 | 0.62 | 1.06 | 0.31 | 2.84 | 97.8 | 28.1 | 67.3 | 4.6 |
| 0236-chon4 | 0.03 | 23.4 | 4.19 | 51.6 | 13.6 | 0.43 | 1.21 | 0.19 | 2.95 | 97.6 | 28.1 | 67.2 | 4.8 |
| 0236-chon5 | 0.00 | 30.1 | 12.4 | 49.7 | 2.04 | 0.42 | 0.58 | 0.39 | 4.11 | 99.7 | 4.3 | 88.8 | 6.8 |

[a] 0144-main and 0144-lithA refer to the host lithology and a shock-blackened lithology observed in CML 0144 (Buck Mountain Wash) described in Hutson et al. (2007). 0236-chon represent analyses from one chondrule in CML 0236.

[b] Wo = 100 × Ca/(Ca + Mg + Fs), En = 100 × Mg/(Ca + Mg + Fe), Fs = 100 × Fe/(Ca + Mg + Ca) atomic.

### *Samples Paired With Buck Mountain Wash (CML 0183, 0184, 0236, 0365)*

Four meteorites are considered paired with Buck Mountain Wash. All are fragmental breccias containing material similar to the main lithology described for Buck Mountain Wash and all contain unequilibrated olivine and pyroxene (Fig. 3c). As with Buck Mountain Wash, all have areas in thin section that show a weak alignment of nonequant components (grains, chondrules, fragments) and all contain twinned low-calcium pyroxene grains, metallic copper grains, and rare chromite-plagioclase assemblages.

Another striking feature present in all of the meteorites paired with Buck Mountain Wash, and absent in all other Franconia-area meteorites we examined, is Al-rich pyroxene (low-Ca pyroxene, augite, and subcalcic diopside) containing between 1.3–13.5 wt% $Al_2O_3$ (Table 4). This pyroxene is present as single grains or fragments, and in CML 0236 is present in a chondrule that is rich in pyroxene and which also contains forsteritic olivine, glass of approximate jadeite ($NaAlSi_2O_6$) composition, and minor Al-spinel (Fig. 6a). In this chondrule, the most aluminous pyroxene (approximately 12–13 wt% $Al_2O_3$) is low-Ca pyroxene, and less aluminous pyroxene (approximately 4–9 wt% $Al_2O_3$) is augite-diopside (Table 4). Similar Al-rich chondrules are a possible source of aluminous pyroxene in all of the meteorites.

Both CML 0236 and CML 0365 contain shock melts, as well as large (up to 6 mm long) metal grains visible in hand specimen. The melt region in CML 0365 is a small area (approximately 0.6 × 1 mm across) inside a much larger (approximately 6.6 × 7.9 mm across) shock-blackened clast reminiscent of lithology B of Hutson et al. (2007). The melt region in CML 0236 is adjacent to a large (5 mm long) metal grain and is comprised of both magnesian and ferrous olivine grains with normal and complex zoning set in a partly devitrified glassy mesostasis (Figs. 6b and 6c). A microfaulted, "mylonitic" troilite-rich sheet, observed in multiple parallel thin sections, sharply defines one edge of the shock melt (Fig. 6b). As with CML 0144, CML 0236 contains type 6 clasts.

CML 0183 and 0184 are texturally identical. In these meteorites, fragmental type 5-dominated material similar to the main lithology of Buck Mountain Wash (Hutson et al. 2007) grades into a lithology with well-defined chondrules resembling a type 4 chondrite. No obvious large metal grains, shock melt, or shock-blackened clasts were visible in the samples we received of these two meteorites.

### *Buck Mountains 004 (CML 0490)*

Buck Mountains 004 is one of 602 stones, with a combined mass of 29.5 kg that were found on one day in an area 60 × 60 m across (Dennis Asher, personal communication). Four of the larger individuals (with a mass of 7.7 kg) fit together to form a larger stone, and the various stones have a similar appearance in hand specimen, suggesting that they may represent one meteorite fall. All of these stones were considered to be one specimen in the data table compiled by one of us (JS) and given in Table S1. However, we were able to examine only one small individual from this collection.

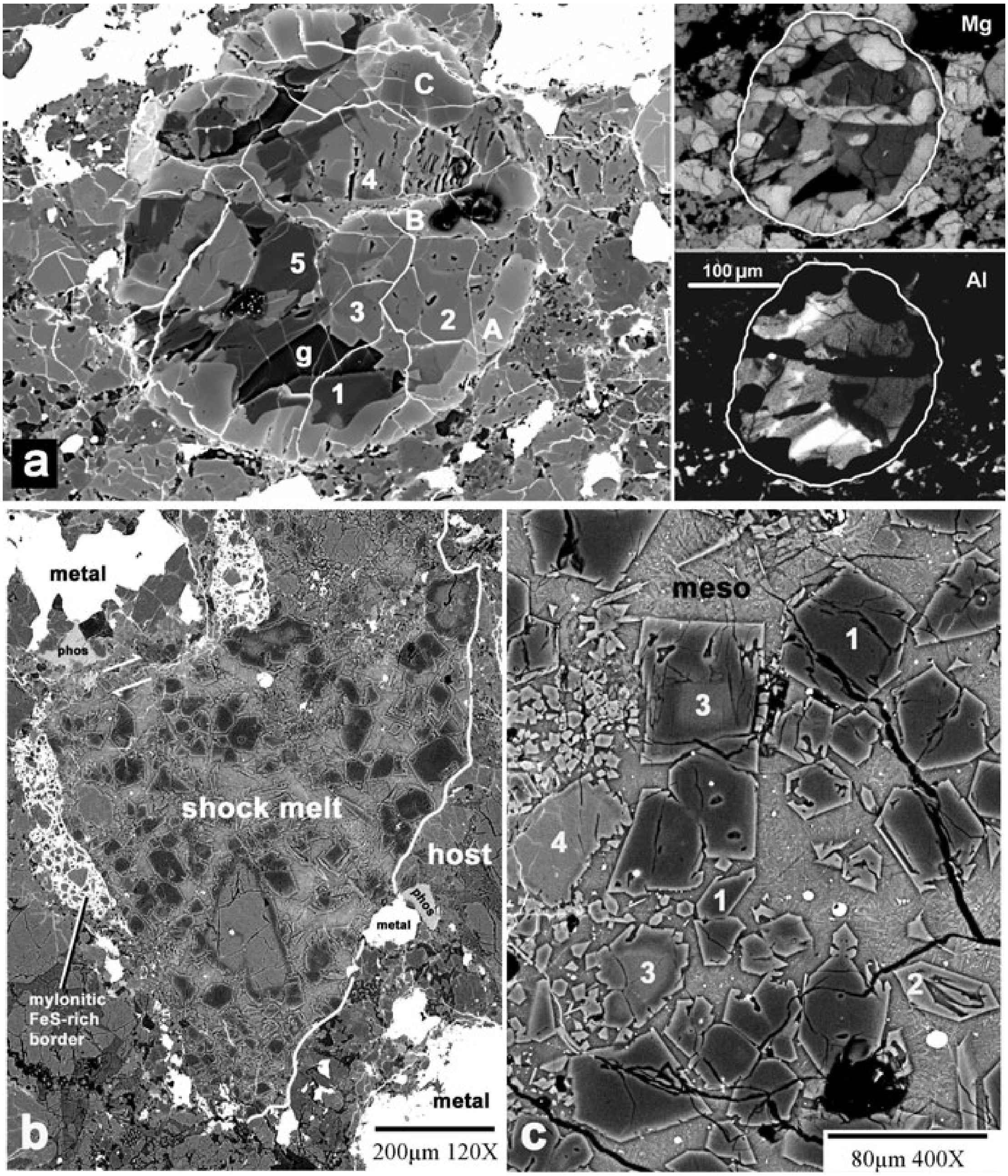

Fig. 6. Images of Buck Mountain Wash (CML 0236). a) BSE image and Mg and Al X-ray maps of a Ca-Al-rich object (chondrule) containing aluminous pyroxene. The chondrule is rimmed by olivine, which also forms a diagonal bar through the interior. A, B, and C indicate where olivine EMP data were obtained (A = $Fa_{19.8}$, B = $Fa_{21.4}$, C = $Fa_{15.1}$). "g" refers to a glass of approximate jadeite ($NaAlSi_2O_6$) composition. The numbers 1 through 5 correspond to EMP analyses of aluminous pyroxenes given in Table 3 (0236-chon1, 2 etc.). 1 and 5 are low-calcium pyroxenes, 2 and 3 are augites, and 4 is a subcalcic diopside. b) BSE image of a shock melt, which is bordered on one side by a sheet of mylonitic FeS. This border is offset in one location by a microfault (half arrows in upper left). "phos" = phosphate. c) BSE image of another area in the shock melt, showing the variety of compositions and zoning patterns observed for olivine: 1 refers to normally zoned magnesian olivines; 2 refers to a skeletal iron-rich olivine grain; 3 refers to grains with a core of reversely zoned olivine, surrounded by normally zoned olivine; 4 refers to one of several olivine grains which appear to be aggregates and are possibly relict grains; "meso" = glassy mesostasis.

Buck Mountains 004 is an H3–6 breccia (Table 3), containing numerous lithic clasts with easily recognizable boundaries (Fig. 7). These include well-defined type 6 clasts. One large clast is also present that lacks convincing evidence of relict chondrules, and which is partly bounded by a complex metal-sulfide shock vein

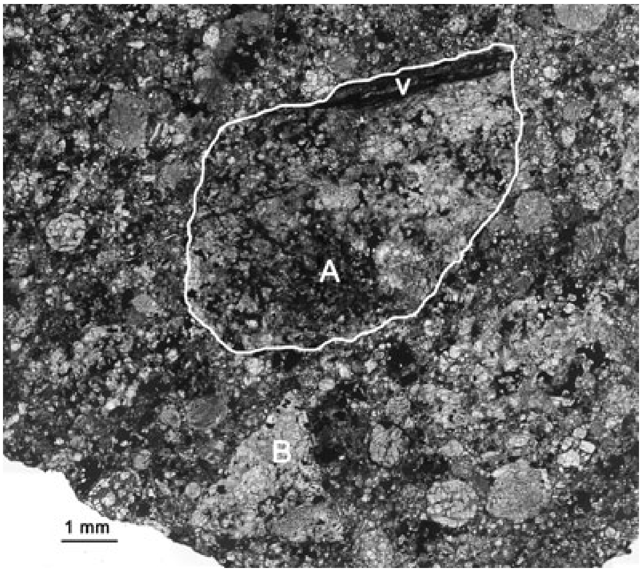

Fig. 7. Optical light micrograph of Buck Mountains 004 (CML 0490), showing the brecciated texture of this meteorite. Large clast A lacks compelling evidence for relict chondrules, and is bordered on one edge by an elaborate metal and troilite vein V, which is truncated by the clast boundary. A triangular-shaped type 6 clast is at B.

truncated by the clast boundary (Fig. 7). Truncation indicates that the vein formed prior to brecciation. In Buck Mountains 004, individual clasts vary in shock stage from S1 to a single heavily recrystallized fragment (S6). A variety of metal textures were observed, including plessite and metal-troilite dendritic intergrowths. Neither of these metal textures nor the numerous well-defined lithic clast boundaries, were observed in any of the samples of the Buck Mountain Wash H3–6 breccia.

## Equilibrated L-Group Chondrites

### *Palo Verde Mine (CML 0185 and CMS 1156)*

The data listed for Palo Verde Mine in Meteoritical Bulletin 89 (Russell et al. 2005) is a composite of information on two different stones from two different laboratories: the Cascadia Meteorite Laboratory at Portland State University (CML 0185) and the Center for Meteorite Studies at Arizona State University (CMS 1516). The class, shock, and weathering information, pyroxene Wo content, find date, find coordinates, and weight of the type specimen refer to CML 0185. The mass is the combined mass of both stones. The Fa and Fs contents are rounded averages of data from both the CML and the CMS. After Meteoritical Bulletin 89 was published, the main mass holder of CML 0185 revised coordinates for the find location, which are listed in Table 1.

Olivine (Fa 25.7 ± 0.8, $n = 43$), pyroxene (Fs = 21.5 ± 0.6, $n = 15$), and kamacite compositions (Co = 0.75 ± 0.16 wt%, $n = 22$) of CML 0185 are consistent with an L-group designation (Rubin 1990; Brearley and Jones 1998). Olivine and pyroxene compositions (Fa = 24.5 ± 0.3, Fs = 20.8 ± 0.4) for CMS 1516 (L. Bleacher, personal communication) determined using a different instrument and analysis protocol are generally consistent with, although somewhat less ferrous than, the values obtained for CML 0185. Palo Verde Mine is a borderline type 5/6 chondrite in terms of chondrule-matrix integration (e.g., Dodd 1981). However, CML 0185 contains abundant intergrowths of diopside and plagioclase feldspar, in which diopside grains are tens of microns in size, and many feldspar grains are >50 μm across, both of which are indicative of a type 6 chondrite (e.g., Huss et al. 2006).

A slice of CML 0185 was sectioned to include one of three light-colored inclusions and a large metal-sulfide object visible in hand specimen (Fig. 8a). The light-colored inclusion has an igneous texture composed of olivine set in a mesostasis of olivine, high-Ca pyroxene, chromite, and feldspathic glass (Figs. 8b, 8c, and 8d). The silicates in this inclusion are identical in composition to those in the host meteorite. The appearance and texture of this inclusion is reminiscent of the "donut" type of large igneous-textured enclave (LITE) described by Jamsja and Ruzicka (2010). The metal-sulfide object consists of a central region of metal, surrounded by troilite enclosing numerous silicate fragments.

Feldspathic material is present in the CML 0185 meteorite in three noticeably different forms: nonisotropic, fractured plagioclase grains; isotropic feldspathic glass/maskelynite; and chromite-plagioclase assemblages. Maskelynite stands out in BSE images with a uniformly smooth appearance surrounded by a cracked border (Fig 8e). Silicates surrounding maskelynite appear to have been fractured as a result of maskelynite formation, as interpreted by Chen and El Goresy (2000). Some of the feldspathic glass has the same composition as the plagioclase grains (Ab = 83.6 ± 1.2, Or = 4.6 ± 0.9, $n = 19$); whereas grains clearly identified as maskelynite are enriched in potassium (Ab = 75.1 ± 1.2, Or = 12.4 ± 0.7, $n = 9$) (also noted by Chen and El Goresy 2000). BSE images show that CMS 1516 also contains the same three variants of feldspathic material. These two stones (CML 0185 and CMS 1516) were paired based on hand specimen appearance, mean Fa and Fs contents, and their textural and shock similarities.

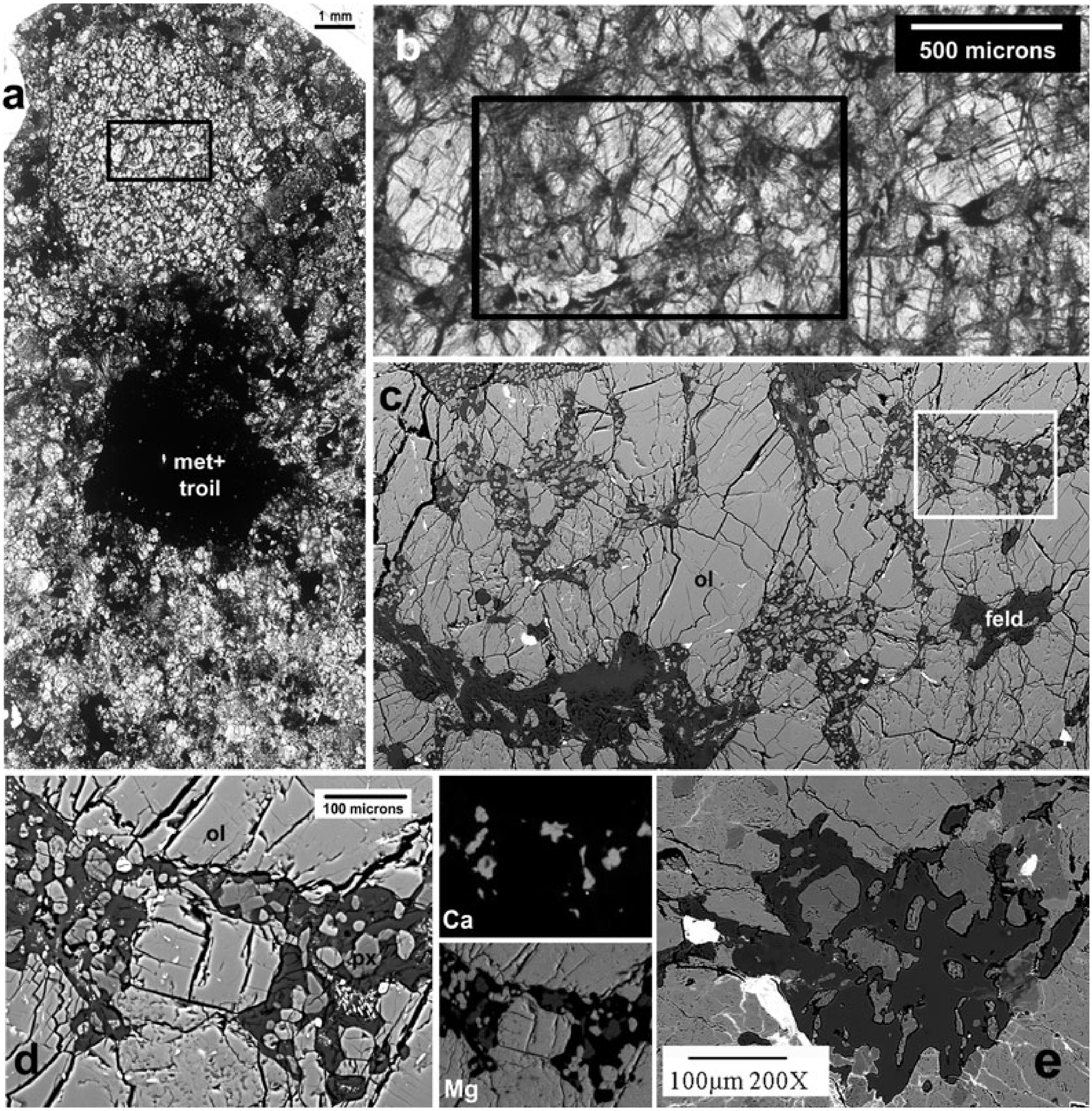

Fig 8. Images of Palo Verde Mine (CML 0185). a) Portion of a thin section scan showing a 7.4 × 5.8 mm diameter light-colored igneous-textured clast (object near top) and an adjacent large (5.6 × 4.8 mm across) metal-sulfide (met + troil) object. b) Transmitted-light micrograph of a region within the light-colored clast. Coarse olivine sometimes forms shells ("donuts"—Jamsja and Ruzicka 2010) around mesostasis. c) BSE image of a portion of part b, showing that the mesostasis is comprised of crystallite-filled patches of feldspathic glass (dark gray). Feldspathic areas are sometimes fracture-filled and sometimes fracture-free ("feld"), the latter characteristic of maskelynite. d) Enlargement of a region in part c and accompanying Ca and Mg x-ray maps. Crystallites in the mesostasis include olivine (Mg-rich areas), Ca-rich pyroxene (Ca-rich areas), and chromite. e) BSE image of a patch of maskelynite (dark gray) found in the host meteorite.

### *Buck Mountains 002 (CML 0261)*

Buck Mountains 002 is a small stone, with a recovered mass of 18.4 g. Olivine (Fa = 25.1 ± 0.7, *n* = 20) and pyroxene (Fs = 21.1 ± 0.9, *n* = 15) compositions are typical of an L-chondrite. The texture of BM 002 is typical of an average type 6 chondrite, with strong integration between matrix and readily identifiable chondrules. Approximately 60% of the metal and troilite grains have been replaced by weathering products, which puts this meteorite on the border between the W2 and W3 weathering grades (Wlotzka 1993). Twenty percent of the olivine grains examined have slight mosaic extinction and three or more sets of planar fractures, while the majority of olivine grains show strong undulose extinction with one to two sets of planar fractures, indicative of a high S3 shock stage (Stöffler et al. 1991).

### *Buck Mountains 003 (CML 0367)*

Buck Mountains 003 (Connolly et al. 2007) is the largest single stone (34.2 kg) recovered from the Franconia area to date (Dennis Asher, personal communication). It is similar in many ways to BM 002, having the well-integrated texture of a type 6 chondrite. Both the weathering grade (W3) and shock stage (S4) are marginally greater in BM 003 than in BM 002, with slightly more than 60% of the metal and troilite replaced by weathering products, and 50% of the olivine grains examined having slight mosaic extinction with two or more sets of planar fractures. Olivine (Fa = 25.0 ± 0.7, $n = 189$) and pyroxene (Fs = 21.2 ± 0.4, $n = 3$) compositions in BM 003 are essentially identical to those in BM 002.

### *Buck Mountains 005 (CML 0491)*

Thirty-six pieces of BM 005 were found in a 1.3 × 1.3 m area. All of the pieces have a distinctive light to dark brown weathering patina. A straight dark ridge sticks out of a few of the pieces, including one studied by us. Buck Mountains 005 is nearly granoblastic, but with occasional indistinct chondrules visible. Plagioclase grains are large, often >50 μm and sometimes >100 μm across, consistent with a high type 6 or type 7 chondrite. Olivine (Fa = 25.0 ± 0.5, $n = 61$) and pyroxene (Fs = 20.7 ± 0.6, $n = 6$) compositions are consistent with an L-group chondrite. Pyroxene grains in BM 005 form clusters of grains that are notably smaller than coexisting olivine grains, so few pyroxene grains were analyzed. CaO ranged from 0.70 to 0.99 wt% in the six grains analyzed. Type 7 chondrites have CaO content of low-Ca pyroxene ≥1.0 wt% (Mittlefehldt and Lindstrom 2001), suggesting that BM 005 is a high type 6 chondrite. Most olivine grains show weak mosaic extinction with ≥3 sets of planar fractures, and plagioclase grains, some with twins, show undulose extinction. This indicates an S4 shock stage for BM 005. Somewhat less than 50% of the metal and troilite have been replaced by oxides, indicative of a W2 weathering grade. The ridge visible in some hand specimens is the surface expression of a 2.8–3.4 mm wide fine-grained, silicate-rich vein that has a zoned structure, with a well-defined central core containing recrystallized silicates (Fig. 9). This vein of presumed shock origin is a distinctive, unique feature that appears to be present in multiple pieces of BM 005.

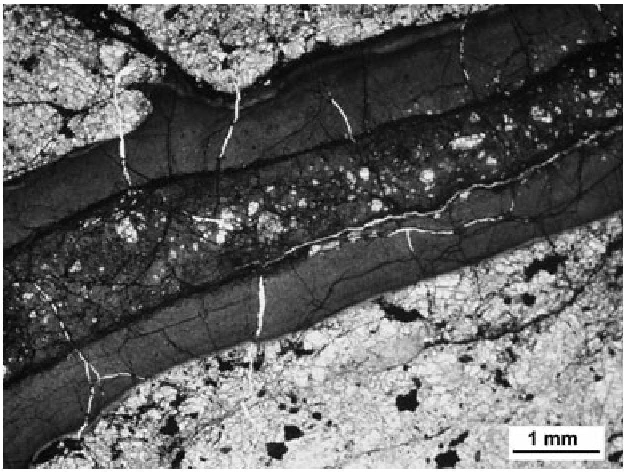

Fig. 9. Binocular image of thick, structured silicate-rich vein in Buck Mountains 005 (CML 0491) as seen in thin section.

## Terrestrial Ages

Ten meteorites in this study were analyzed for both $^{14}$C and $^{10}$Be abundances to determine their terrestrial ages. Of the remaining four meteorites in this study, one (CML 0184) was analyzed only for 14C. Three others (Buck Mountains 002, CML 0365, and CMS 1516) were not analyzed. Isotopic measurements were obtained in five separate analytical runs spaced over a 5-yr period, including runs for $^{14}$C ages alone, as well as for both $^{14}$C and $^{10}$Be, which provide more accurate ages than for $^{14}$C alone (e.g., Kring et al. 2001; Jull et al. 2011). The results of these analyses are given in Table 5 and Fig. 10.

Figure 10 is a plot of $^{10}$Be (dpm kg$^{-1}$) versus $^{14}$C (dpm kg$^{-1}$) for the 10 samples for which both isotopes were measured. The ratio of $^{14}$C/$^{10}$Be at production is generally assumed to be relatively constant with a value of around 2.5–2.6 (e.g., Kring et al. 2001; Jull 2006; Jull et al. 2011), although a value of 2.65 was used by Welten et al. (2001). The two samples of the Franconia meteorite (CML 0182 and 0333) have similar values of $^{10}$Be, but both plot well to the right of this initial value (referred to as the zero line by Kring et al. 2001) (Fig. 10). It is unclear why both samples have such high $^{14}$C values relative to $^{10}$Be, but it is clear that both meteorites are paired and that they fell recently compared with the other meteorites that were dated.

The meteorites with the oldest terrestrial ages are the H6 chondrite Buck Mountains 001 (age approximately 20 kyr) and two L6 chondrites, Buck Mountains 003 and Palo Verde Mine (ages approximately 10–11 kyr). Although the similar terrestrial ages for BM 003 and Palo Verde Mine could indicate that these meteorites were part of the same fall,

Table 5. Terrestrial age data for stones examined in this study.

| Sample[a] | Sample[b] | Type[c] | $^{14}$C (dpm kg$^{-1}$) | +/− | $^{14}$C age (kyr) | +/− | $^{10}$Be (dpm kg$^{-1}$) | +/− | $^{14}$C/$^{10}$Be | Error | $^{14}$C/$^{10}$Be age (kyr) | Error |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Franconia | | | | | | | | | | | | |
| R3368 | CML 0333 | H5 | 68.96 | 0.34 | −3.3 | 1.3 | 9.12 | 1.08 | 7.560977 | 0.896145 | Saturated/low age | |
| R3291 | CML 0182-2 | H5 | 41.55 | 0.24 | 0.9 | 1.3 | 10.8 | 0.3 | 3.847485 | 0.109145 | Recent | |
| BMW | | | | | | | | | | | | |
| R3290 | CML 0144-6 | H3–5 | 6.10 | 0.20 | 16.8 | 1.3 | 1.39 | 0.06 | 4.390197 | 0.23611 | Low exposure age | |
| R3367A | CML 0144-8 | H3–5 | 40.08 | 0.44 | 1.2 | 1.3 | | | | | | |
| R3292 | CML 0183-2 | H3–5 | 22.39 | 0.26 | 6.0 | 1.3 | 14.04 | 0.19 | 1.594922 | 0.028617 | 3.70 | 0.24 |
| R3294 | CML 0184-4 | H3–5 | 27.73 | 0.21 | 4.3 | 1.3 | | | | | | |
| R3713 | CML 0236-2 | H3–6 | 8.81 | 0.54 | 13.7 | 1.4 | 6.68 | 0.18 | 1.31937 | 0.08799 | 5.26 | 0.72 |
| BM001 | | | | | | | | | | | | |
| R3296 | CML 0186 | H6 | 2.88 | 0.25 | 23.0 | 1.5 | 13.2 | 0.28 | 0.218095 | 0.019454 | 20.09 | 0.16 |
| BM004 | | | | | | | | | | | | |
| R3715 | CML 0490-1A | H3–6 | 12.50 | 0.66 | 10.8 | 1.4 | 13.37 | 0.31 | 0.935051 | 0.05389 | 8.10 | 0.44 |
| PVM | | | | | | | | | | | | |
| R3295 | CML 0185-5 | L6 | 11.80 | 0.24 | 12.1 | 1.3 | 15.87 | 0.65 | 0.743721 | 0.033948 | 9.98 | 0.28 |
| BM003 | | | | | | | | | | | | |
| R3714 | CML 0367-1A | L6 | 7.36 | 0.57 | 16.0 | 1.4 | 11.36 | 0.44 | 0.648327 | 0.056034 | 11.11 | 0.46 |
| BM 005 | | | | | | | | | | | | |
| R3716 | CML 0491-2 | L6 | 14.32 | 0.75 | 10.5 | 1.4 | 13.8 | 0.22 | 1.037563 | 0.05666 | 7.24 | 0.47 |

[a] AMS sample number.

[b] CML sample number.

[c] Type indicated refers to the particular thin section examined.

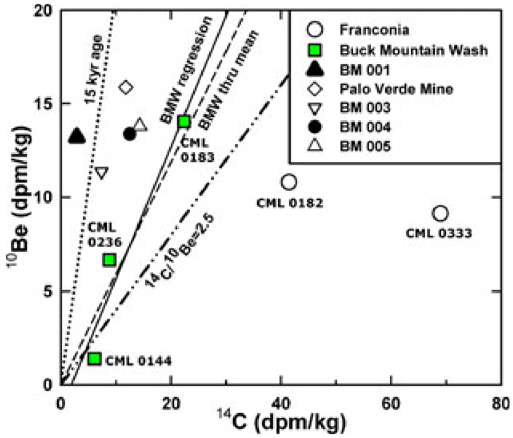

Fig. 10. $^{14}$C and $^{10}$Be activities for Franconia-area samples. Isochrons for terrestrial ages form straight lines that pass through the origin. $^{14}$C/$^{10}$Be = 2.5 is a "zero age"; older ages have progressively steeper slopes (e.g., line marked "15 kyr age"). The line labeled "BMW regression" is a regression line for three Buck Mountain Wash data points; the line labeled "BMW thru mean" is an isochron that goes through the graph origin and the mean value for Buck Mountain Wash.

they appear to be two different falls based on petrography and mineral chemistry. Another L6 chondrite, Buck Mountains 005, has a distinctly younger age (approximately 7 kyr), supporting evidence that this meteorite is texturally and chemically distinct from BM 003 and Palo Verde Mine and that it represents a separate fall.

Five meteorites are identified as pieces of the Buck Mountain Wash fall based on petrographic and mineral-chemical similarities. $^{14}$C ages were determined for four of the five meteorites, with $^{10}$Be corrections obtained for three of them. As shown in Table 5, there is a spread in $^{14}$C ages, with one stone (CML 0144) giving both the lowest (1.4 kyr) and highest (16.8 kyr) ages. The two stones that appear most similar in thin section (CML 0183 and 0184) were analyzed at the same time, and have essentially identical $^{14}$C ages, confirming that they are different pieces of the same meteorite. As shown in Fig. 10, three samples identified as Buck Mountain Wash (CML 0144, 0183, and 0236) analyzed for both $^{14}$C and $^{10}$Be define an isochron. The analyzed split of CML 0144 (0144-6) has a very low $^{10}$Be/$^{14}$C ratio, which is listed in Table 5 as indicating a low exposure age. However, this sample has low activities of $^{14}$C and $^{10}$Be and plots close to the origin in Fig. 10, significantly different from the values for the two samples of Franconia. A regression line ($r = 0.93$) through the three Buck Mountain Wash data points is slightly steeper than a line drawn through the mean and the origin, but the regression line does not quite intercept the origin (Fig. 10). Terrestrial ages were calculated for both lines using equation (2) of Kring et al. (2001). The line through the mean and the origin gives a terrestrial age of 3.3 kyr. The slope of the regression line gives a terrestrial age of 4.7 kyr. We conclude that Buck Mountain Wash fell approximately 4.0 ± 0.7 kyr ago.

Kring et al. (2001) noted that the radius of the Gold Basin meteoroid had to be >2 m, and more likely 3–4 m, based on the range of $^{10}$Be and $^{14}$C values obtained for that meteorite. The range in isotopic values for Buck Mountain Wash is similar ($^{10}$Be) or slightly greater ($^{14}$C) than those for Gold Basin, suggesting that the radius of the Buck Mountain Wash meteoroid was similar to or slightly larger than the Gold Basin meteoroid (>2–4 m).

Buck Mountains 004 is an H-group breccia which spans the same range of petrographic types as Buck Mountain Wash. However, the $^{14}$C/$^{10}$Be age of approximately 8.1 kyr is distinctly older than that for the Buck Mountain Wash samples. Although a line can be drawn through BM 004 and two of the three data points for Buck Mountain Wash, such a line has a slope similar to that of the 15 kyr reference line in Fig. 10, and intercepts the *x*-axis at an unacceptably large distance from the origin. In addition, if one assumed that BM 004 was another piece of Buck Mountain Wash, there would be no way to accommodate the $^{14}$C and $^{10}$Be values for one of the Buck Mountain Wash-paired meteorites (CML 0183). We interpret the data to indicate that Buck Mountains 004 is a separate fall from Buck Mountain Wash and the other H-group chondrites examined in this study.

## DISCUSSION

### Pairing

A large number of H- and L-group ordinary chondrites have been discovered in the Franconia area of Arizona (e.g., Bleacher et al. 2005). In addition, numerous small iron meteorites of H-group affinity have been recovered from this area (Schrader et al. 2010).

Pairing meteorites is a difficult task, which always involves some amount of uncertainty (e.g., Benoit et al. 2000). Benoit et al. (2000) listed a variety of possible pairing criteria, including chemical class, petrographic type, shock stage, mineral abundances and compositions, distinctive textural features, and terrestrial ages. Using a probability approach, Benoit et al. (2000) found that pairing assignments were more probable (valid) when a larger number of pairing criteria were used, and that unusual features were especially useful for making pairings.

We classified 12 stony meteorites from the Franconia area, and examined 2 others (Franconia and CMS 1516). We find that the meteorites can be placed into three broad groups: equilibrated H-group chondrites (two stones); H-group meteorites containing unequilibrated material (six stones), and equilibrated L-group chondrites (four stones). A similar division of stones was described by Bleacher et al. (2005), who sorted 19 unclassified Franconia area stones into three groups: Group A (11 H-group chondrites) having negligible spread in Fa; Group B (7 H-group chondrites) having a "larger" spread in Fa, and one L-group chondrite which was later paired with CML 0185 as Palo Verde Mine. One of the goals of the current study was to estimate the minimum number of different meteorite falls represented by the Franconia-area finds.

Hand specimen appearance has been used to separate samples from the Franconia area (Bleacher et al. 2005; Edwin Thompson, personal communication). However, we found hand specimen appearance to be unreliable as an indicator of pairing. An example is given by two meteorites paired with Buck Mountain Wash (CML 0183 and 0184). Based on a comparison of the exteriors of these two stones with that of Franconia (CML 0333) and Buck Mountain Wash (CML 0144), we expected that CML 0183, which had a two-toned reddish/brown exterior, would pair with Franconia, and that CML 0184, which had a more uniform and darker brown exterior, would pair with Buck Mountain Wash. However, in thin section, CML 0183 and CML 0184 are texturally the most similar to each other of all the meteorites we examined. Both meteorites are dominated by H5 and H4 material, and grade from fragmental, primarily equilibrated areas to areas that contain more distinct chondrules including abundant unequilibrated material. Carbon isotope compositions were obtained for both meteorites during a single analytical run, and are essentially identical (Table 5).

We found that mineral-chemical data obtained with EMP was required, but not sufficient, for pairing samples. With heterogeneous compositions, it is difficult to get a truly representative set of analyses. Data can be biased by the number of analyses and whether analyses are random or targeted. The potential for bias can be observed for the meteorites we paired with Buck Mountain Wash. For CML 0184, we found a large spread in Fa and Fs contents, with means outside of the equilibrated H-range (Fig 3c), when we had a large number of analyses ($n = 40$) that were targeted to include the widest range of gray levels observed in BSE. On the other hand, CML 0365 was analyzed for us by John Donovan at the University of Oregon. Multiple analyses were made at each of 15 randomly selected areas. Only 11 of 89 analyses had Fa contents outside the range for equilibrated ordinary chondrites. Had the EMP stopped acquiring after the first 40 analyses, CML 0365 would have appeared to be an equilibrated H-chondrite. Subsequent examination with SEM methods including BSE showed that the thin section contains a high proportion of unequilibrated grains that were not sampled with the EMP, including an aluminous pyroxene grain. However, in cases where BSE images confirmed homogeneous compositions, fewer EMP analyses were needed for classification.

Backscattered electron images were necessary to pair the various pieces of Buck Mountain Wash, as they revealed the presence of unequilibrated material, including small, magnesian mineral clasts that easily could have gone unnoticed by optical microscopy. Similarly, BSE images of feldspar, maskelynite, and chromite-plagioclase assemblages were crucial to the pairing of the two pieces of Palo Verde Mine.

With heterogeneous breccias such as Buck Mountain Wash, multiple thin sections were needed to sample the full range of lithologies. For instance, the original classification as H3–5 of Buck Mountain Wash was based on examination of four thin sections from a single stone. Subsequently, two additional sections from the same stone (CML 0144) revealed the presence of type 6 material in the meteorite. Given the heterogeneous textures and mineral compositions of Buck Mountain Wash and the nature of the breccia (including diffuse clast boundaries as well as the presence of chondrule-sized clasts), we consider the potential for misclassification and mispairing to be larger for specimens of this meteorite than for most.

For meteorites that are petrographically similar, terrestrial age data are essential for resolving pairing assignments. For example, for H5 and H6 chondrites, age data provided the final information needed to pair the two Franconia stones (CML 0333 and 0182), and to support the conclusion that these stones are not paired with Buck Mountains 001. Age data helped support the pairing of the various Buck Mountain Wash (H3–6) stones, and helped to determine whether this meteorite is paired with another H3–6 chondrite, Buck Mountains 004 (CML 0490). The brecciation style of Buck Mountain Wash and BM 004 is different (larger, more distinct lithic clasts in BM 004), as are metal grain textures, but it is the distinct difference in terrestrial ages (approximately 8 kyr for BM 004, approximately 4 kyr for Buck Mountain Wash) that most clearly points to these meteorites being unpaired.

With regard to L6 chondrites, terrestrial age data helped confirm that BM 005 (high type 6) and BM 003 (average type 6) are different falls. Buck Mountains 002 and 003 have similar textures and mineral compositions, suggesting that they could be paired. However, we did not obtain terrestrial age data for BM 002, leaving an ambiguity about its pairing with BM 003.

Palo Verde Mine is an L6 chondrite that appears different than the BM 002 and BM 003 L6 chondrites based on petrographic-chemical criteria. Of the three meteorites, only Palo Verde Mine has maskelynite and was the most highly shocked; it was also the least thermally metamorphosed, judging from poorer chondrule-matrix integration and smaller feldspar grain size. But the terrestrial ages for Palo Verde Mine and BM 003 are similar (approximately 10 and 11 kyr, respectively). Thus, we cannot rule out that Palo Verde Mine and BM 003, and possibly BM 002, were derived from a single fall of a heterogeneous L6 meteoroid that contained meteorite-sized or larger clasts of different material, but think it unlikely.

Based on the samples we studied, we infer that there are six to eight, and most likely seven, different falls in the Franconia area. The seven distinct meteorites (Table 2) include Franconia (H5), Buck Mountain Wash (H3–6), Buck Mountains 001 (H6), Buck Mountains 004 (H3–6), Palo Verde Mine (low L6 bordering on L5), the possibly paired Buck Mountains 002 and 003 (both typical L6), and Buck Mountains 005 (high L6 bordering on L7). Eight distinct meteorites are possible if BM 002, BM 003, and Palo Verde Mine are different falls; six are possible if all of these were derived from a single heterogeneous meteoroid.

Figure 11 shows the recovery locations of the distinct meteorites in our sample set. There is no obvious tendency for paired meteorites to be located near each other. Moreover, the location of recovered L-chondrites significantly overlaps that of recovered H-chondrites. Samples of Buck Mountain Wash (CML 0144, 0183, 0184, 0236, 0365) extend from the Buck Mountains DCA to the southeast to the Sacramento Wash area to the northwest (Fig. 11).

If the samples we studied are representative, we can use the data to estimate a pairing proportion for the Franconia area. Although the number of specimens we examined is only a small fraction of that found in the entire recovery area (14 of 380, or 3.7%), it constitutes a much larger portion of the total mass (approximately 34%). Moreover, a stronger case can be made for the samples we studied being representative of the southeastern part of the recovery area, south of interstate highway I-40. In this southern area, the samples studied are approximately 9.4% by number and approximately 40% by mass of the total recovered. Given that the samples were found across this entire southern region (Fig. 1), and were found by different people at different times, and sent to us without any coordination and selection criteria, we see no reason to think that they are not representative of the larger specimens found in the south, from within and close to what is currently defined as the Buck Mountains DCA.

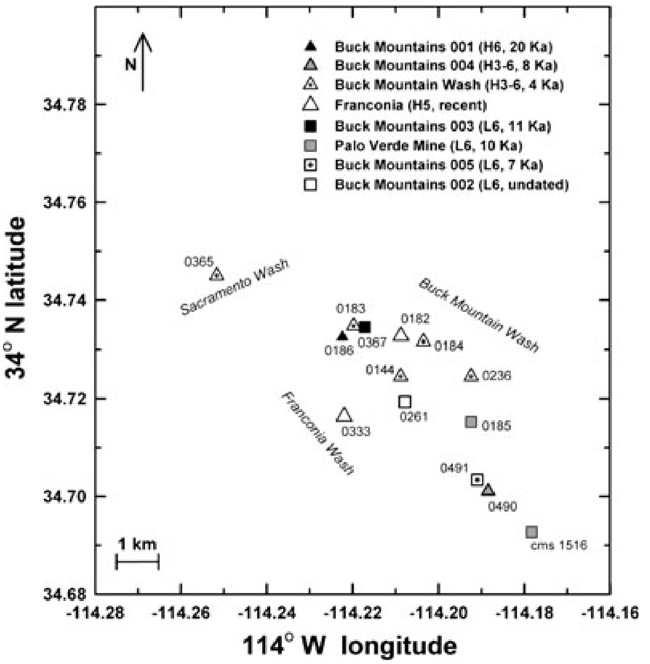

Fig. 11. Map showing the recovery locations of studied samples, with different symbols reflecting different meteorites (except that Buck Mountains 002 may be paired with Buck Mountains 003.)

Based on petrography, mineral chemistry, and terrestrial ages, we conclude that there are most likely seven distinct meteorite falls among the 14 meteorites examined. Moreover, as shown in Fig. 12, the pairing proportion has remained between 40 and 60% since the fourth meteorite we examined. This suggests that the pairing proportion is unlikely to change much from a value of 50 ± 10% with the addition of further samples. Thus, we estimate a pairing proportion for the Buck Mountains DCA of 50 ± 10%, with a best estimate of approximately 50%, depending on pairing ambiguities mentioned above.

As noted above, the meteorites we examined give us a sampling of material mainly in the southeastern half of the Franconia area. Five stones, including Sacramento Wash (SaW) 001, SaW 002, SaW 003, SaW 004, and Warm Springs Wilderness classified by Arizona State University personnel, and one iron meteorite (SaW 005) classified at University of Arizona, provide information on the material being found in the northwestern half of this area.

Sacramento Wash 004 is classified as an H5 chondrite, with shock stage S3, and weathering grade W3, and has been stated as being "not paired with

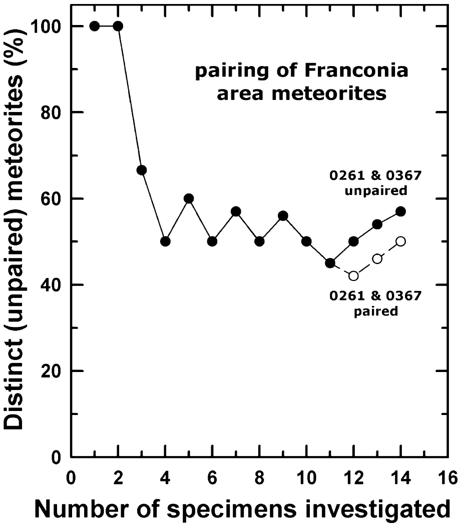

Fig. 12. Pairing proportion of Franconia-area samples, in the order in which they were studied. Starting with the fourth specimen, the proportion of specimens interpreted to be paired has been fairly constant at 50 ± 10%. Two lines are shown depending on whether Buck Mountains 002 (CML 0261) and Buck Mountains 003 (CML 0367) are paired.

Franconia" (Connolly et al. 2006). However, mean olivine (Fa = 18.3 ± 0.3) and pyroxene (Fs = 16.2 ± 0.3) compositions are very similar to our data for CML 0182, which is paired with Franconia. Both meteorites and Franconia are classified as having shock stage S3. In the absence of other information, it is unclear why SaW 004 is not paired with Franconia. The reported weathering grade for SaW 004 is W3, which is higher than observed in other pieces of Franconia, but weathering grade is not a reliable indicator for pairing (e.g., Bleacher et al. 2005; Hutson and Ruzicka 2010).

Mean olivine (Fa = 18.6 ± 0.3) and pyroxene (Fs = 9.0 ± 1.0) compositions of SaW 002 (classified H4, S1, W1) (Connolly et al. 2006) are similar to that of CML 0184, which is a piece of Buck Mountain Wash that has areas resembling a type 4 chondrite. It is clear from the reported ferrosilite contents that SaW 002 is not an equilibrated H4 chondrite, but must contain some unequilibrated (magnesian type 3) material. Sacramento Wash 002 likely pairs with Buck Mountain Wash.

In terms of mean olivine (Fa = 18.0 ± 3.5) and pyroxene (Fs = 15.8 ± 0.3) compositions, SaW 001 (classified H4, S2, W3) (Connolly et al. 2006) most closely resembles three meteorites we examined: Buck Mountain Wash "lithology B" (CML 0144), which is a shock-blackened clast of H4 material; CML 0365 (H3–5 W2 S2–6), which is paired with Buck Mountain Wash; and Buck Mountains 004 (H3–6 W2 S1–6). The standard deviation reported for olivine Fa content from SaW 001 suggests that this meteorite also contains some unequilibrated material, raising the possibility that SaW 001 pairs with either Buck Mountain Wash or Buck Mountains 004. As some samples of Buck Mountain Wash resemble H4 chondrites, and as Buck Mountains 004 is a more obvious breccia, it seems likely that SaW 001 also pairs with Buck Mountain Wash.

The reported olivine (Fa = 17.2 ± 5.1) and pyroxene (Fs = 15.7 ± 5.0) compositions in SaW 003 (classified as H4, S2, W3) (Connolly et al. 2006) are almost the same as those in CML 0365 (Buck Mountain Wash). Again, the standard deviations for both olivine and pyroxene Fa and Fs contents indicate that SaW 003 must contain unequilibrated material.

As the northernmost classified meteorite, the Warm Springs Wilderness chondrite (classified H4–6, S2, W1) (Connolly et al. 2006) has reported olivine (Fa = 17.7 ± 2.6) and pyroxene (Fs = 15.6 ± 1.1) compositions that again most closely resemble CML 0365 (Buck Mountain Wash). Contrary to the formal classification, Warm Springs Wilderness must also contain unequilibrated material.

Thus, four of the five stones classified at Arizona State University are H-chondrites that appear to contain unequilibrated material, based on reported olivine and pyroxene compositions. Only Warm Springs Wilderness is listed as a breccia. It is possible that all four are paired with Buck Mountain Wash, but we cannot rule out pairing with Buck Mountains 004.

Both Franconia and Buck Mountain Wash are relatively recent falls and so are unlikely to have lost much material to weathering or by burial. Based on pairing data, including carbon and beryllium isotopes, it seems likely that there is a substantial amount of Buck Mountain Wash in the "Franconia strewnfield." The data also allow the possibility for a substantial amount of Franconia to be present as well, but it seems unlikely that the majority of the material will be solely paired with Franconia. Much unclassified material that has been distributed as "Franconia" (Edwin Thompson, personal communication) may not be paired with Franconia.

The small (52 g) ungrouped iron SaW 005 has been considered by some individuals to be metal-derived from Franconia (Larry Sloan and Edwin Thompson, personal communication) as it contains a silicate clast texturally and chemically resembling H-group material (Schrader et al. 2010), and metallic copper, which is known to occur in Franconia (Russell et al. 2004; Schrader et al. 2010). However, Franconia is a typical H5, and lacks the H4 material that is present in SaW 005 (Schrader et al. 2010). Buck Mountain Wash has large metal grains visible in hand specimen and contains both material of variable petrographic type and metallic copper. Thus, it seems more likely that SaW 005 is a piece of the Buck Mountain Wash fall, if it is paired with any of the stones in the Franconia area.

## Meteorite Flux

Meteorites recovered from the Earth's surface can be used to estimate the flux of meteoritic material in the geological past, providing complementary information to more contemporary observations, including those based on meteor networks (e.g., Halliday et al. 1989; Bland et al. 1996; Zolensky et al. 2006). Meteorite data from dense collection areas (DCAs) such as in the Franconia area potentially can be used for flux determinations, provided (1) estimates are available for the terrestrial residence ages of meteorites or of recovery surfaces, (2) estimates can be made of the completeness of specimen recovery, (3) estimates can be made of the number of paired specimens, and (4) field or other evidence is available bearing on concentration or removal mechanisms and on the presence or absence of strewn fields.

Our study makes evident that the Franconia area consists of more than one meteorite fall over a period of time, which terrestrial age data suggest spans approximately 0–20 kyr. This is despite what one might infer from the geographical distribution of specimen masses, which have the hallmarks of a strewn field for a single meteorite, lying in a generally elliptical pattern with masses generally increasing to the southeast (Fig. 1; Table 1). As multiple meteorite falls clearly contributed to this dense collection area, the Franconia data set might be useable for estimates of flux over the last 20 kyr.

By number, most meteorites (39%) found in the Franconia area have intermediate masses of approximately 10–100 g (Table 1), similar to other DCAs that have been searched by foot and less than the 100–1000 g most common for the Sahara searched by car (Bischoff and Geiger 1995). For the Franconia area, approximately 74% of the recovered specimens range from 10 to 1 kg, compared with only <10% for specimens <10 g in mass, and we suggest that the smaller masses were preferentially overlooked compared with the larger individuals. Some of these smaller masses also may have been preferentially removed by weathering. Either way, it seems clear that the Franconia dataset (as with other DCAs) is incomplete for the smallest meteorites.

The number of meteorite specimens found in the Franconia region is high, approximately 5.8 specimens km$^{-2}$, which we estimate translates to approximately 2.9 distinct meteorites km$^{-2}$ based on our pairing information (approximately 50% paired). This number density is roughly twice that compared with other well-known collection areas: approximately 1–1.5 meteorites km$^{-2}$ for the Nullarbor region, and approximately 1.4 meteorites km$^{-2}$ for the Sahara (Bland et al. 1996a). However, the density of meteorites in the Franconia area is less than the approximately 5 meteorites km$^{-2}$ for Roosevelt County, New Mexico, where meteorites were concentrated in deflation hollows (Zolensky et al. 1992), and much less than the approximately 14 meteorites km$^{-2}$ for the hyperarid San Juan DCA in Chile (Gattacceca et al. 2011). Variably aged surfaces for the deflation hollows in Roosevelt County make it difficult to use the Roosevelt County data set to estimate meteorite accumulation rates (Halliday et al. 1991; Zolensky et al. 1992), but there is no evidence for a similar concentration process occurring in the Franconia region.

The relatively high number density of meteorites could reflect a high meteorite flux for the Franconia area. If one assumes for the Franconia area 2.9 meteorites km$^{-2}$ (corrected for 50% pairing) and a 20 kyr integration time, this yields a flux of 0.145 meteorites km$^{-2}$ kyr$^{-1}$, or 145 falls per $10^6$ km$^2$ per year. This inferred infall rate pertains mainly to >10 g individuals. The fall frequency is higher than inferred for other well-studied DCAs: 36 for Nullarbor, 95 for Sahara, and perhaps 115 for Roosevelt County (Bland et al. 1996a; Zolensky et al. 2006). The high flux for Franconia would be even higher if corrected for meteorite removal by weathering (e.g., Bland et al. 1996).

Fig. 13 shows a mass-frequency diagram for meteorites recovered in the Franconia area assuming a 20 kyr integration time and pairing rates of 40% and 60%, which are plausible lower and upper bounds. The Franconia fluxes are corrected for overall pairing proportion, but are based on the raw data for the number of individual masses compiled in the Table S1, as there is incomplete data on how each individual is related to others by meteor fragmentation. Data are compared with estimates of meteorite flux based on fireballs observed with the Canadian MORP camera network (Halliday et al. 1989). Two lines are shown for the fireball data in Fig. 13, a mass flux based on the largest mass fragment in the fireball, which is relatively well constrained, and a higher mass flux that represents an estimate for the total mass of meteorites to reach the ground in the fireballs, as a result of meteor fragmentation effects. The former flux is well constrained, the latter less so (Halliday et al. 1989, 1991). For this type of plot, steep negative slopes are expected and observed for both meteorites and meteors (e.g., Hughes 1992; Zolensky et al. 2006).

At low masses (log m < 1.4–1.7 g, or <25–50 g), it is clear that the Franconia flux is much lower than the fireballs (Fig. 13). This is almost certainly the result of

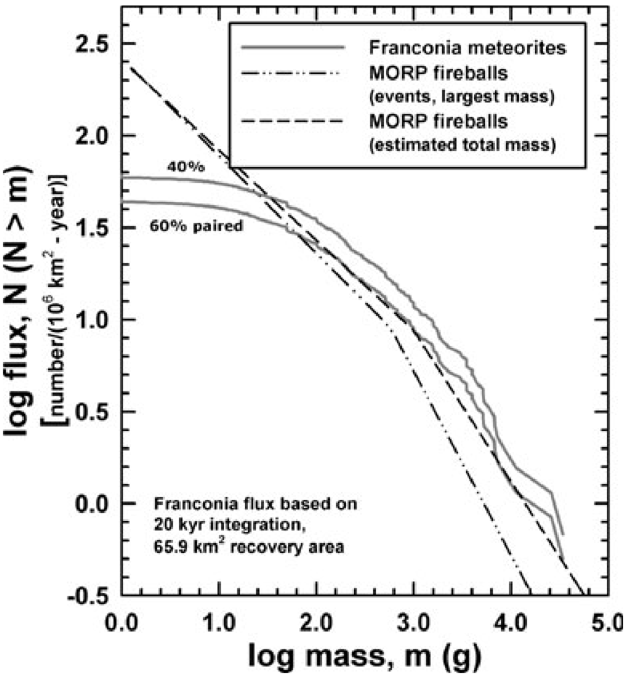

Fig. 13. Log number flux greater than mass m (number per $10^6$ $km^2$ per year) versus log m for Franconia-area samples, compared with the fireball flux obtained from the Meteor Observation and Recovery Project (MORP) (Halliday et al. 1989). Flux values are shown for 60% and 40% pairing of Franconia-area meteorites among the total number of specimens recovered over a 20 kyr period.

incomplete meteorite recovery. Newer finds of metal-rich specimens typically approximately 1–2 g across in the Franconia area (Laurence Garvie, personal communication) suggest that further field work eventually may allow a more complete record of meteorites to be obtained at the low-mass end.

More significantly, for larger masses (log $m > 3$ g, or 1 kg), the Franconia meteorite flux is higher than the flux inferred from fireball data (Fig. 13). For instance, at log $m = 3.5$ g (3.1 kg), the Franconia flux is approximately 3–4× higher than the largest masses in fireballs and approximately 1.6–2× higher than the estimated total mass of meteorites delivered by fireballs. Although meteor and meteorite flux data are generally considered to be uncertain to a factor of approximately 2 (Hughes 1992; Bland et al. 1996a; Zolensky et al. 2006), for the MORP fireballs this should be more true for the estimated total mass and less so for largest masses in fireballs. In addition, if the MORP meteor fluxes are in error, they are more likely to be overestimates for larger masses than underestimates (Halliday et al. 1991). For the largest masses there is an excess in the Franconia meteorite flux compared with the meteor flux that exceeds the apparent uncertainty.

There are several types of potential biases in our meteorite data, most of which operate in the direction of making our flux estimates too low. The flux of meteorites would be higher if weathering-related losses were taken into account. Moreover, it is certain that not all meteorites have been found, which would increase the estimated meteorite flux further. Although the flux estimate for Franconia assumes a 20 kyr integration time based on the highest terrestrial age that was obtained, use of a shorter integration time corresponding to the mainly younger ages we determined would also raise the apparent meteorite flux. The Franconia meteorite flux is highest compared with the fireball trend for the larger masses (log $m > 3.4$ g, or 2.5 kg), a discrepancy that would be even larger if pairing effects were included that counted fragments of paired meteorites as the larger total mass of paired meteorite. Moreover, the meteor fluxes at the large mass range may be somewhat high, as noted above. Thus, most biases should work to make it seem that the flux of larger Franconia-area meteorites is less than that of fireballs, not the other way around.

However, a different bias could operate to make the overall Franconia meteorite flux appear generally too high. If our estimate of the proportion of meteorites that are paired is too low, it would result in an artificially high flux. Although we are relatively confident of the approximate pairing proportion among the larger specimens to the southeast of Sacramento Wash and of interstate highway I-40 (Fig. 1), we are uncertain whether the smaller meteorites found to the northwest have the same pairing proportion as elsewhere. If many of these meteorites have a high proportion of pairing, it could explain the somewhat high apparent overall flux for the Franconia area. Even if this were true it would not explain the apparent excess of larger specimens as few of these are located to the northwest.

If one restricts attention to the southern recovery area where we can most confidently pair meteorites, one can use the number density of meteorites there together with pairing proportion to derive a separate estimate of overall meteorite flux. The number density of specimens found to the south of interstate highway I-40 is approximately 4.7 specimens $km^{-2}$, lower than for the entire Franconia area (approximately 5.8 specimens $km^{-2}$). This suggests a lower meteorite flux of approximately 2.3 distinct meteorites $km^{-2}$ for the southern recovery area. For this recovery area (approximately 31.1 $km^2$) and a 20 kyr integration, a flux of approximately 115 meteorites per $10^6$ $km^2$ per year is implied, similar to what one would expect based on the Canadian fireball data. In this case, there would be no overall excess of meteorites compared with estimates derived from the contemporary meteor flux, although as noted above there would still be an apparent excess for the larger masses.

Thus, to first order the meteorite flux responsible for producing the Franconia meteorites appears to be high compared with the current meteor flux, particularly for the larger meteorites. However, there is some doubt about the magnitude of the excess, given the small meteorite data set, uncertainties in pairing and recovery proportion, and uncertainties in assessing meteor fragmentation effects. Additional studies of meteorites from the Franconia area would better constrain the pairing proportion and fluxes.

### Large Recent H-Chondrite Strewn Field?

We now discuss why meteorites in the Franconia area have been found in a localized area suggestive of a strewn field. The simple explanation—that a single meteorite fell to create a strewn field—is clearly inconsistent with our results, which show that multiple meteorite types are present and that many of these fell at different times. Terrestrial age data rule out the possibility that different meteorite types were present in the same meteoroid, as has been proposed for the Almahata Sitta ureilite-dominated fall (Bischoff et al. 2010). Another potential explanation is that there are especially favorable preservation conditions in this region that allow a large number of different meteorites to be found. In this case, there is not one strewn field, but rather many. There is probably some truth to this explanation. Most meteorites in the area have been recovered from gently sloping pediment uplands that likely experienced neither significant fluvial erosion nor depositional burial, making them good collecting areas. (The same cannot be said for the Franconia Wash and Buck Mountain Wash arroyos that bound the main collecting area.) However, there is no reason to believe that the pediment uplands in the Franconia area are unique preservation surfaces much different than other similar surfaces in this part of Arizona.

Our favored explanation is that one dominant fall did occur in the area. Our studies suggest that about a third (approximately 36%) of the larger specimens in the Franconia area consist of meteorites paired with Buck Mountain Wash (H3–6). This meteorite shows radionuclide evidence for having been derived from a >2–4 m radius meteoroid that would have dropped substantial material, more than has been recovered. Buck Mountain Wash-paired specimens are found throughout the recovery area, including the southeastern zone where the largest meteorites are found, as well as in the northwestern zone where smaller meteorites are found (Figs. 1 and 11). This is consistent with this meteorite having fallen over a large area.

All of the smaller specimens examined so far in the northwest part of the recovery area, around or to the north of Sacramento Wash, are related to H-chondrites (Fig. 1). These could all be paired with a H3–6 chondrite such as Buck Mountains Wash (see Pairing section above). Some of the smaller masses to the northwest, such as Sacramento Wash 005, are metal-rich individuals that appear to have been derived from H-chondrite materials (including H4 chondrite) by impact melting (Schrader et al. 2010). These smaller metal-rich individuals have fusion crusts and could have separated from an H-chondrite meteor high in the atmosphere (Schrader et al. 2010; Laurence Garvie, personal communication). We speculate that many of these specimens are paired with Buck Mountain Wash. Metal is known to have been shock-mobilized and melted in Buck Mountain Wash (Hutson et al. 2007), and evidently concentrated in the larger grains (up to 6 mm across) that are sometimes observed in hand specimens. A 6 mm diameter spherical metal grain of density 7.5 g $\text{cm}^{-3}$ would form an approximately 0.85 g mass, which is similar to many of the smallest masses that have been recovered. These masses could have been liberated from silicates during ablation and fragmentation.

Thus, the Franconia region may indeed have a dominant single strewn field, which we suggest is most likely the Buck Mountain Wash meteorite, although more than one strewn field is possible. A dominant fall would help explain the high productivity of the site and the systematic, strewn field-like distribution of specimen masses. Although clearly this area was populated by various distinct falls, flux estimates based on meteorite recovery in this area would be unrepresentative for the entire Earth if there was a recent dominant fall. If there was one dominant fall in this area with different falls, then one would predict that systematic searches outside of the elliptical Franconia recovery area will also produce meteorites, though at a reduced productivity and with fewer specimens of the dominant fall.

## CONCLUSIONS

Meteorites in the Franconia area have been found in a localized area suggestive of a strewn field, but our study clearly demonstrates the presence of more than one meteorite fall. From oldest to youngest falls, these included:

1. Buck Mountains 001 (fell approximately 20 kyr ago), an H6 chondrite;

2. Buck Mountains 003 (fell approximately 11 kyr ago), a large (34.2 kg single stone) L6 chondrite which is possibly paired with Buck Mountains 002;
3. Palo Verde Mine (two separated stones, fell approximately 10 kyr ago), an L6 (bordering on L5) chondrite;
4. Buck Mountains 004 (fell approximately 8 kyr ago), an H3–6 chondrite breccia, one of 602 stones with a combined mass of 29.5 kg found in a 60 × 60 m area;
5. Buck Mountains 005 (fell approximately 7 kyr ago), an L6 (bordering on L7) chondrite notable for containing an approximately 3 mm-wide silicate-rich shock vein, one of 36 pieces found in an approximately 1.3 × 1.3 m area;
6. Buck Mountain Wash (five separated stones, fell 4.0 ± 0.7 kyr ago), an H3–6 chondrite breccia;
7. Franconia (two separated stones, fell "recently"), an H5 chondrite.

Based on our work, thorough petrographic examination and multiple types of analytic data are needed to confidently pair meteorites in areas with multiple ordinary chondrite falls. We infer that 50 ± 10% of the larger stones in the Franconia area are paired. This corresponds to a best estimate of approximately 2.3–2.9 distinct meteorites km$^{-2}$, and a meteorite flux over the last 20 kyr of approximately 115–145 falls per $10^6$ km$^2$ per year. This number density and flux of meteorites is slightly high compared with what has been suggested for some dense collection areas (Nullarbor and Sahara) but less than what has been suggested for others (San Juan area in Chile), and the flux is similar or high compared with what has been inferred for contemporary fireballs. The estimated flux and the elliptical shape of the recovery area suggest that this area is comprised of at least one bona fide strewn field superimposed on a background of accumulated falls. The meteorite most likely responsible for the apparent strewn field is Buck Mountain Wash, based on its wide distribution throughout the area, cosmogenic evidence for a large meteoroid mass, and the high number of paired specimens. Thorough examination of a much larger number of meteorites from the Franconia area is needed to fully understand how meteorites accumulated and were distributed there.

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*Editorial Handling*—Dr. Gretchen Benedix

Note added in proof: The Buck Mountains and Sacramento Wash DCAs are being replaced with a single, larger DCA named Yucca. Previously named meteorites from this area will preserve their names, but be given Yucca xxx synonyms, where xxx is a number (001-014) that reflects the sequence in which they were named.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

**Table S1.** Data for specimen masses and locations in the Franconia area.