Petrographic studies of the impact melts from Meteor Crater, Arizona, USA

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Abstract—We investigated the ballistically dispersed melts from Meteor Crater, Arizona, USA to determine the stratigraphic extent of its melt zone from the compositional relationship of melts and target rocks. Most melt particles are crystallized, hydrated, and oxidized; pristine glasses are rare. Hydration and oxidation occurred at ambient temperatures long after the impact. The preserved glasses are generally clear and texturally homogeneous, but unlike typical impact melts, they have unusually heterogeneous compositions, both within individual particles and from sample to sample. For example, the average SiO2 for individual particles ranges from 43 to 65%. The projectile content is unusually high and it is distributed bimodally, with specific samples containing either 5–10% or 20–30% FeO. These compositional heterogeneities most likely reflect the high carbonate content of the target rocks and the release of copious CO2 that dispersed the melts, thereby terminating melt flow and mixing. The high projectile content and the CO2 depleted residue of purely sedimentary rocks produced maﬁc melts that crystallized ﬁne-grained olivine and pyroxene.

The melts fall into three compositional groups reﬂecting variable proportions of the major target formations, Moenkopi, Kaibab, and Coconino. Least-square mixing calculations revealed one group to contain 55% Moenkopi, 40% quartz-rich, upper Kaibab, and 5% meteorite, suggesting a source depth of <30 m from the pre-impact surface. The other two melt groups have higher contents of meteorite (15–20%) and Kaibab (50–70%) and contain more SiO2 than average Kaibab. The additional quartz may have been derived from Coconino or the upper Kaibab, implying melt depths >90 m or <30 m, respectively. Additional studies, especially hydrocode calculations, are needed to better understand the source depth of these melts and their exceptionally high projectile content.

INTRODUCTION

Impact melts are found as coherent sheets or lenses inside large terrestrial craters, as ballistically transported bombs beyond the rim, or as injection dikes in the crater basement and walls. Regardless of structural setting, they are an intimate mixture of melts from different precursor lithologies that occupied different stratigraphic positions in the initial target (e.g., Engelhardt, 1967, 1997; Dence, 1971; Phinney and Simonds, 1977; Grieve et al., 1977; Grieve, 1991). Large volumes of melt, measured in cubic kilometers, are mixed and homogenized on scales of millimeters, as are small lithic or mineral clasts from the precursor rocks. This intense mixing must occur during the early stages of the cratering process because it is substantially complete prior to ballistic ejection based on the chemically homogeneous melt bombs of the Ries and other terrestrial craters (e.g., Engelhardt, 1997; See et al., 1998; Masaitis et al., 1999). For most craters, it is not possible to reconstruct the pre-impact stratigraphy with sufﬁcient precision to determine the exact vertical and lateral extent of the crater’s melt-zone, a prerequisite to estimate transport distances and timescales involved in the melt mixing process (e.g., Simonds et al., 1978; Onorato et al., 1978). The present investigation attempts to contribute to some of these issues by delineating the stratigraphic extent of the melt zone at Meteor Crater, Arizona, USA.

The pre-impact stratigraphy and structural relationships of the 1 km diameter Meteor Crater are well known (e.g., Barringer, 1924; McKee, 1938; Shoemaker, 1960, 1963; Roddy, 1978). Indeed, Meteor Crater is the prototype structure for small, bowl-shaped craters (Shoemaker, 1963; Grieve and Garvin, 1984). Given that most large craters have geometrically similar, bowl-shaped transient cavities (Croft, 1985; Melosh, 1989; Grieve, 1991; Cintala and Grieve, 1998) and that melt formation takes place during formation of this cavity, the results from Meteor Crater may have general applicability for the melt-forming processes in all craters, including large, complex structures.
The first descriptions of the melts from Meteor Crater are by Nininger (1954, 1956), who details their field occurrence, the diverse morphologies, their chemical bulk composition, and who first identified them as ballistically transported melt-spray. Most subsequent compositional studies of these melts addressed the dissemination of the iron-meteorite projectile (Morgan et al., 1975), or chemical fractionation of the projectile during impact-induced melting (e.g., Brett, 1967; Kelly et al., 1974).

None of these earlier studies attempted to correlate the composition of the melts with specific target lithologies, the major objective of the present study. Below we describe the morphologies of the melt-particles, followed by petrographic observations and quantitative microprobe analyses. We will then discuss their relationship to the target rocks at Meteor Crater, the dissemination of the meteorite component, and the subsequent hydration and oxidation of the glasses. We conclude with some inferences about planetary surface processes.

**MORPHOLOGY OF MELT PARTICLES**

Representative melt beads from Meteor Crater are illustrated in Fig. 1. Most specimens are irregularly shaped, occasionally ropy objects, especially the large specimens, some measuring a few centimeters in size. These irregularly shaped particles (e.g., Fig. 1a,e,g) are typically of gray, brown, or tan colors and they have pitted, rough and dusty surfaces. Many are fragments of larger objects as revealed by their jagged surfaces (e.g., Fig. 1g,h). These irregular particles contrast with spherical and ellipsoidal objects, which are typically <5 mm in size (Fig. 1b,c,d). The latter commonly have rather smooth surfaces of vitreous luster. Their color ranges from black through diverse shades of brown to honey colored, occasionally even bright yellow or burgundy-red. However, many beads have dull, dusty surfaces, and other surface characteristics similar to irregular particles.

A wide variety of accretionary features are observed on the surfaces of most particles. Such objects, termed "accreta", range from tiny melt droplets (Fig. 1c) to very large objects (Fig. 1d) that may or may not differ in color from their host. Some melt beads are compound aggregates of a small number of relatively large melt droplets as shown in Fig. 1f. Widely variable encounter velocities, melt viscosities, and temperatures may be inferred from the morphologies of the accreted materials. Figure 1c illustrates a substantially solid host that caused the accreting melt spray to flatten into pancake-shaped objects. The reverse applies to Fig. 1e: small, solid spheres collided with a viscous host, as evidenced by a continuous meniscus around some accretia beads. In many cases both the accretia and host substrate appear to have been viscous when they collided, because the accretionary particles penetrated deep into the host and produced knobby promontories that have no discernible meniscus. Mineral or lithic detritus is extremely rare among the accretia; most accretia are finely dispersed melts. Fractured and thin-sectioned melt beads reveal a wide range in vescularity, from almost solid, non-porous specimens to highly porous froth (e.g., Fig. 1g,h).

These morphologic observations corroborate those of Nininger (1954) and they identify these melt particles as ballistic ejecta. However, we do not agree with his classification of "impactites" and "accretionary lapilli", and suggest that this classification be abandoned. Particle-morphologies and surface features are simply so variable that more than two endmembers seem required for their description; many features are also gradational, making rigorous classification difficult. More importantly, microscopic investigations reveal no systematic difference among the two particle types.

Also note that we exclude from consideration completely molten clasts of Coconino Sandstone that are of a frothy, pumice-like appearance and that are common at Meteor Crater (Kieffer, 1971; Kieffer et al., 1976). Such materials must be viewed as monolithic clasts, analogous to similarly molten and frothy clasts of highly shocked rocks in other craters (e.g., Stöffler, 1971; Engelhardt, 1997). Such lithic froth originates outside the major melt zone and has not participated in the melting and mixing processes that we wish to address in the present report.

**PETROGRAPHIC CHARACTERISTICS**

**Overview**

We thin sectioned ~50 regularly shaped beads and ~30 irregularly shaped fragments. The regularly shaped beads spanned an especially wide range of colors and most had vitreous surfaces leading to the expectation that glasses would abound. However, genuine glasses were surprisingly rare among all particles. Most specimens are crystallized, albeit so fine-grained that they are difficult to characterize optically.

Typical particles are shown in Fig. 2. The most common sample is a highly porous, optically opaque froth (Fig. 2a); the only materials that can be identified optically are quartz clasts, generally single, rounded grains, and occasionally lithic fragments. Figure 2b illustrates a specimen composed of three melt blobs, all similarly frothy and finely crystallized. The overall textures and especially the brown and yellow color hues are highly suggestive of secondary alterations affecting the entire sample. Most thin-sectioned particles are similar to the examples shown in Fig. 2a,b, including many specimens of deceptively vitreous and pristine appearing surfaces.

The remaining photomicrographs in Fig. 2 show relatively rare particles that do contain some holohyaline glass. Figure 2c shows a particle composed of relatively opaque, vesicular, and substantially crystallized materials, as well as clear glass containing minor schlieren. This sample also shows an opaque rim, typical for the exterior surfaces of many particles; some rims are sufficiently coarse-grained to reveal individual, acicular crystals. Figure 2d shows a similar sample that had a large, highly shocked clast of Coconino Sandstone at its core, which was lost during thin-section manufacture. Note that the pale and fairly homogenous glass grades into materials of red color towards the exterior surfaces and around clasts and
Fig. 1. SEM images of typical melt objects from Meteor Crater, Arizona; note their diverse shapes, the abundance and variety of accretionary features, and their highly porous interiors (see detailed discussion in text).
vesicles. This red material is optically isotropic, but it frequently displays some rhythmic banding or polygonal texture, suggesting that it is an altered version of the clear glass, possibly in incipient stages of crystallization. Note that Fig. 2c also displays some of this reddish alteration. The red material may transition into the opaque rims towards the exterior surfaces (Fig. 2d). Furthermore, Fig. 2 illustrates that particles of "irregular" (Fig. 2c) and "regular" (Fig. 2d) shapes can have similar textural characteristics, suggesting that detailed morphologic classification may have little genetic significance.

Of the 80 particles sectioned, only two were entirely holohyalline, which are illustrated in Fig. 2e,f. Both particles are fragments of larger melt objects. Particle M12 consists of a clear, non-vesicular glass that is texturally homogeneous and that displays only very faint schlieren or other evidence of flow. In contrast, particle M20 is composed of a rather clear and a yellow to honey colored melt, both displaying prominent schlieren. The clear and texturally fairly homogeneous glasses shown in Fig. 2c,d,e dominate; Fig. 2f is atypical.

Primary Olivines and Pyroxenes

Owing to the small sizes of all crystals, it is necessary to use non-optical methods for mineral identification, such as qualitative compositional analysis based on backscattered electron images (BSE) and x-ray elemental maps, as well as quantitative compositions of minerals and glasses, all obtained on a Cameca SX-100 scanning electron microprobe. During elemental mapping with the microprobe, the accelerating voltage was 15 kV, the beam current was 20 nA, the beam was rastered over an area of 8 x 10 μm, and count times varied between 0.1a nd 0.5 s. Quantitative compositional analyses of glasses and minerals employed a narrower beam (2–3 μm) and count times of 10–30 s.

Backscattered electron images and quantitative phase analyses identify the acicular, skeletal, and spherulitic crystals as pyroxene and olivine. Typical crystal sizes are <100 μm and their morphologies suggest rapid crystal growth from a melt (Lofgren, 1980). Incipient growth of olivine is shown in Fig. 3a; partly skeletal crystals free-float in the glass and form star-shaped aggregates. Figure 3b shows more well-developed olivine needles that are associated with a vesicle. An aureole of material envelops each olivine crystal and develops rather prominently around the vesicle.

Representative pyroxenes are shown in Fig. 3c–f. Figure 3c reveals a group of vesicles that acted as nucleation site for dendritic, christmas-tree-shaped, pointed pyroxenes. The somewhat feathery, tiny crystals at the tip of some pyroxenes are olivines. Note the presence of large olivine needles in the upper right-hand corner of Fig. 3c that grew from this feathery overgrowth. Similar textures are shown in Fig. 3d, which illustrates an optically opaque quench zone associated with a massive sandstone clast, visible in the upper left. This quench zone has particularly well-developed laths of olivine that grew from the fine-grained feathery overgrowth of the pyroxenes; the pyroxenes in Fig. 3d are less dendritic than those in Fig. 3c, yet they have similar elongate and pointed shapes. These pyroxenes become increasingly stubby close to the cold clast, and they are essentially equant in the immediate vicinities of the clast, thus producing a granular texture. This granular texture is characteristic for the exterior surfaces of many melt beads and seems to develop in response to extra-fast cooling rates. Both the dendritic and granular pyroxenes seem responsible for the opaque nature of these rims.

A completely different, spherulitic pyroxene (Fig. 3d) commonly occurs in the interior of melt beads and is readily seen optically as yellow aggregates that have a distinctly radiating, fibrous texture and associated extinction patterns; the individual pyroxene fibers are too small to be resolved optically but they combine into bundles of grossly similar orientation. Such spherulitic pyroxenes preferentially develop around vesicles and clasts in the interior of melt beads; they rarely occur in quenched rims. They are commonly associated with melt beads that are largely composed of dark brown to reddish alteration products.

Figure 3f illustrates a non-porous particle that is holocrystalline and entirely composed of pyroxene. In such samples, the pyroxenes are relatively large dendrites; very coarse-grained varieties combine into bow-tie or feathery aggregates. These samples do not contain glass, either clear or colored, and olivine is a minor phase at best, typically confined to the quenched rim. We refer to these samples as monomineralic pyroxene beads. We did not observe monomineralic samples composed of olivine only. Clearly, melts of bulk-compositions similar to pyroxene were produced at Meteor Crater, but none as mafic as dunitites.

In summarizing Fig. 3, olivine and pyroxene are prominent and their acicular, dendritic, or spherulitic morphologies indicate that they grew rapidly from a melt. While both minerals invariably occur in the quenched rims of most melt particles, they also develop in association with vesicles or clasts, yet they may also grow from texturally homogeneous glass in the interior of melt beads. Dendritic pyroxenes dominate the quenched rims of many melt samples and are commonly associated with highly skeletal, feathery olivine. Granular pyroxenes invariably coexist with elongate dendrites, but the granular variety is always concentrated at or close to the free surface (or cold clasts), while the elongate dendrites and their olivine-overgrowth advance towards the interior of the melt bead. The spherulitic pyroxenes generally occur in the interior of melt beads and are invariably associated with altered, optically red and brown glasses.

Dynamic crystallization experiments by Lofgren (1980) indicate that the growth of spherulitic pyroxene requires higher degrees of supercooling than dendritic crystals. As we will see below, the melts are fairly heterogeneous compositionally at scales of the growing crystals. As a result, it is not possible to obtain reliable cooling histories of the melts on the basis of
Fig. 2. Representative photomicrographs of thin-sectioned melt beads from Meteor Crater, Arizona. (a) Highly oxidized and vesicular specimen. (b) Compound melt aggregate. (c) Irregular-shaped object composed of transparent melt and opaque materials. (d) Melt bead consisting of clear and red glass varieties, combined with a distinct, opaque rim. (e) Fragment composed entirely of clear glass. (f) Example of clear, vesicle-rich melt (left) and amber glass (right) that appear to be intimately mixed by flow.
Fig. 3. BSE images of quenched olivines and pyroxenes in impact melts from Meteor Crater, Arizona. (a) Acicular, skeletal olivines growing from clear melt (SIG4, see Fig. 2c). (b) Skeletal olivines associated with a vesicle in the interior of specimen M30B6 (see Fig. 2e). (c) Dendritic and distinctly pointed pyroxenes that crystallized from clear melt in association with irregularly shaped vesicles (SIG4; see Fig. 2c). (d) Typical quenched zone associated with a sandstone clast (upper left), displaying granular pyroxenes and the spatial relations between clear glass, primary crystals, and altered materials (SIG4). (e) Spherulitic pyroxene (nearly white) forming fibrous aggregates associated with large vesicles (black) or quartz-clasts (dark grey) in sample M31D3. (f) Example of a monomineràlic pyroxene bead (M7) featuring coarse-grained, dendritic pyroxene.
crystal shape. However, it is clear that the crystals grew rapidly from a melt.

Altered Glasses

The materials described as aureoles or altered glass may occupy large fractions of individual melt beads. As stated, this material is optically isotropic, mostly of red color, but some brown, yellow, or honey colored varieties were also observed. These aureoles invariably occur in intimate association with olivine and pyroxene, but they also develop around individual vesicles and clasts in many cases; they rarely form in associations with fractures. Note the aureole around an olivine needle in the lower right-hand corner of Fig. 3c that is affected by a fracture, yet the fracture itself is seemingly not the locus from which the alteration spread. Additional BSE images are presented in Fig. 4 to illuminate the complex relationships of pristine melts, primary crystallization products, and the altered materials. Figure 4a shows aureoles that are more developed than those of Fig. 3a,b. The material seems subtly zoned and it seems to develop mostly around local vesicles. Figure 4b shows a zone of star-shaped olivine needles, all surrounded by altered material that becomes contiguous in many places. A large vesicle occupies the right side of Fig. 4b, which spawned a rather homogeneous zone of altered material, akin to that of Fig. 3d, but without olivine or pyroxene. Note that the elongate pyroxenes are being replaced by granular pyroxenes towards the exterior surface (left side of Fig. 4b). An especially intimate intergrowth of olivine, pyroxene, and altered material and their contact relationships with the clear glass are shown in Fig. 4c. Pronounced banding is commonly observed at the contact with clear glass. Also note in Fig. 4c that each of the major promontories protruding into the clear glass has a relatively large olivine crystal at their core. The banding parallels this contact in minute detail, yet banded areas can also develop at some distance from the contact. The massive areas of altered material tend to have bulbous and occasionally scalloped textures, and they often develop some polygonal network of fractures. Some of the polygonal and scalloped textures are reminiscent of palagonitic, volcanic glasses that are thought to be the result of hydration (Bouska, 1992; Heiken and Wohletz, 1992). In addition, the red and occasionally brownish and yellow colors of the altered material strongly suggests that the alteration process also caused a change in the oxidation state of iron. None of the contact relationships between "pristine" and "altered" materials illustrated in Figs. 3 and 4 seem compatible with the mixing of two melts. Most alterations must have occurred in solid state.

Accretionary Features

The numerous secondary or tertiary droplets on the surfaces of many glass beads are of interest because some of them could be vapor condensates, thus affording insights into possible vapor fractionation processes. In thin section, the majority of such melt droplets completely blends into the finely crystalline rims of the host particles, but some may be recognized as spherules or flattened pancakes because of different crystal sizes and textures compared to the surrounding rim material. All accreted melts are crystallized and it was not possible to obtain the composition of the original melts or condensates. In a few accretes we analyzed some of the larger olivines and pyroxenes and found them to be indistinguishable from those of the host melts. We did not see unusual mineral assemblages that would indicate that some of the accreted droplets resulted from condensation processes. It appears that all accretes are finely dispersed spray of the same melts that produced the much large melt particles.

Clastic Inclusions

The Meteor Crater melts contain fragments of quartz, well-rounded sand grains, or lithic sandstone clasts. Most quartz grains were intensely microfractured and display prominent mosaicism; only rare examples contained planar deformation features; none of the clastic material appears to be diaplectic. These observations are consistent with the general shock metamorphism of Coconino Sandstone (Kieffer, 1971) and with the preferential preservation of modestly shocked and relatively cool clasts in impact melts (Onorato et al., 1978). However, the absence of carbonate clasts in the melts at Meteor Crater is noteworthy. We only observed one carbonate clast in some 80 thin-sectioned particles. This clast occupied a large volume fraction of the entire 5 mm diameter ejecta particle and it appears to be an ejecta fragment that was draped in flight by some minor melt volume.

COMPOSITIONS OF PRIMARY MINERALS

Some 15–20 individual olivine or pyroxene crystals were analyzed per melt sample to assure good average values and a reasonable measure for compositional diversity. These crystals were from widely separate, presumably representative locations for each sample. Relatively large crystals were utilized to minimize the potential effects of fluorescence from underlying glass. We also avoided highly skeletal crystals for this reason. Nevertheless, it is difficult to quantitatively prove that there is no contamination by host-melt in some of the individual mineral analyses. We also show that the stoichiometric conversion of oxide-weight percent into molar abundance of cations yields reasonable cation sums for both olivine and pyroxenes, indicating that the mineral analyses are substantially correct.

Olivine

The average compositions of olivines from nine different melt beads are summarized in Table 1; the averaged forsterite
Fig. 4. BSE images of sample SIG4 detailing the relationships of pristine glasses (homogeneous gray), altered materials (dark and banded), and primary crystals. (a) Acicular olivines associated with substantial seams of altered glass. (b) Overview of exterior rim of SIG4 illustrating granular pyroxene (left, exterior surface), followed by a zone of dendritic pyroxenes and olivines, the latter surrounded by altered glass that develops into a continuous matrix. Note the large, interior vesicle (right, black) that developed its own seam of altered glass. (c) Thoroughly altered portion of SIG4, with some pristine glass (homogeneous, light grey) to the left. Note that each promontory of the alteration front is spatially related to a large olivine needle.
Table 1. Average composition of olivines in the melts from Meteor Crater, Arizona.

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<tr>
<th></th>
<th>SIG4</th>
<th>M30B4</th>
<th>M30B6</th>
<th>M30B8</th>
<th>M30B9</th>
<th>M31D4</th>
<th>M31D2</th>
<th>M33B3</th>
<th>M33C6</th>
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<td>SiO₂</td>
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<td>28.02</td>
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<tr>
<td>Na₂O</td>
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<tr>
<td>K₂O</td>
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<td>0.03</td>
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<td>0.98</td>
<td>1.10</td>
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<td>Totals</td>
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<td>98.14</td>
<td>99.09</td>
<td>100.34</td>
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Si 0.954  1.027  1.015  0.982  0.995  1.020  0.972  1.036  1.151
Al 0.027  0.012  0.045  0.010  0.039  0.041  0.022  0.042  0.081
Mg 1.053  0.869  0.748  1.160  0.942  0.948  1.052  0.755  0.609
Fe 0.889  0.984  1.057  0.792  0.887  0.881  0.917  1.038  0.787
Ca 0.075  0.076  0.086  0.046  0.093  0.066  0.053  0.050  0.179
Mn —     —     —     —     —     —     —     —     0.001
Ti 0.002  0.001  0.004  0.001  0.002  0.003  0.001  0.002  0.003
Cr 0.001  —     —     —     —     —     —     0.001  0.000
Ni 0.031  —     0.008  0.022  0.025  —     —     0.020  0.000
Sum 3.032  2.969  2.963  3.013  2.985  2.959  3.017  2.943  2.812

F₀ 0.53  0.47  0.41  0.59  0.52  0.52  0.53  0.42  0.44
Fₐ 0.47  0.53  0.59  0.41  0.48  0.48  0.47  0.58  0.56

content varies from F₀₄₁ to F₀₅₉. As illustrated in Fig. 5, individual microprobe analyses indicate substantial heterogeneity within single melt particles as well, typically encompassing about 15–20 mol% F₀, with sample M30B9 being the most variable (F₀₃₈–F₀₆₉). Most olivine analyses were obtained from olivines residing in quenched rims, yet some analyses were obtained from isolated crystals floating in pristine glass; there is no measurable compositional difference between these two populations of olivine. There is no observable difference among olivines that reside in a continuous matrix of altered glass, or that have only very thin aureoles. Analyses along the long axis of individual olivine needles revealed F₀ contents varying as much as 5%, but individual olivine needles were too thin to evaluate whether there is any systematic compositional zoning.

The olivines in these melts also contain rather high concentrations of NiO, CaO, and Al₂O₃ as summarized in Fig. 6. Note that the stoichiometric calculations in Table 1 are close to the ideal value of 3.0 cations per molecule. NiO is enriched in the olivines relative to the clear glass (see below); it cannot be due to fluorescence, therefore. Also most individual olivine analysis yields some Al₂O₃ and CaO; it is unlikely that every analysis point was contaminated by melt. We suggest that these olivines indeed have a somewhat unusual compositions, most likely related to their rapid growth.

Pyroxenes

The pyroxene analyses are summarized in Table 2, grouped into dendritic, granular, and spherulitic varieties, along with the holocrystalline, monomineralic specimens. The averaged compositions range from E₅₂₄ to E₅₃₆, F₅₂₅ to F₅₄₉, and W₀₃₈ to W₀₅₉. Individual microprobe analyses are shown in Figs. 7 and 8, illustrating substantial ranges in the composition of dendritic, granular, and spherulitic varieties. Analyses of large pyroxene crystals reveal them to be modestly heterogeneous, yet there is no systematic, compositional zoning.

Individual microprobe analyses of elongate, dendritic pyroxenes are summarized in the top panel of Fig. 7; individual samples are illustrated in the insets. Obviously, the composition of these pyroxenes may vary widely within individual melt samples, but can also form relatively tight compositional clusters. Individual samples have generally idiosyncratic characteristics. For example, all pyroxenes in sample M33C6 have distinctly lower CaO contents than most other samples, while samples M31D2 and M30B9 precipitated the most Ca-rich crystals. Some samples display distinctly horizontal trends (e.g., M31D2), suggesting MgO and FeO to be the major variables at relatively constant CaO.
Figure 8a details the granular pyroxenes in samples M30B6 and M33B3 and contrasts them with coexisting, dendritic pyroxenes. The granular crystals contain distinctly more CaO than the dendritic crystals in specimen M30B6, yet sample M33B3 shows no difference. Figure 8b depicts the petal-shaped, spherulitic pyroxenes in the interior of four samples. Again, their compositions differ from sample to sample, yet homogeneity within individual samples is increased compared to the granular and elongate varieties; note that each analysis averages over a number of thin fibers in these spherulitic aggregates. Although seemingly more homogeneous, these fibrous pyroxenes do not systematically differ from the other pyroxenes. The composition of the rather large pyroxene crystals from the four monomineralic samples (Fig. 8c) differ from sample to sample, but they tend to fall on a single trend characterized by constant CaO/MgO and variable FeO.

The pyroxenes in the monomineralic pyroxene beads also have unusually high Ni-concentrations relative to all other pyroxenes and olivines as illustrated in Fig. 9; note that the oxide concentrations of the minerals were converted into elemental abundances in this figure to enable a direct comparison with the metallic ratios of the Canyon Diablo projectile. The monomineralic pyroxenes have high Ni and relatively unfractoned Ni/Fe ratios; if anything, Ni may be modestly enriched relative to Fe. In contrast, all other pyroxenes have distinctly depleted Ni, and there is no difference among elongate, granular, or spherulitic varieties. Furthermore, all olivines are deficient in Ni, albeit to highly variable degrees. We will return to these observations after introducing the Ni-Fe relationships of the melts.

**COMPOSITION OF GLASSES**

As soon as the electron beam crosses from clear glass into the red or yellow alteration products, the cumulative oxide totals drop to <90%, illustrating that this sharp textural contact is also an abrupt compositional boundary. The altered materials appear substantially hydrated and not amenable to
Table 2a. Average composition of dendritic pyroxenes in the melts from Meteor Crater, Arizona.

<table>
<thead>
<tr>
<th></th>
<th>M30B6</th>
<th>M30B9</th>
<th>M31D1</th>
<th>M31D2</th>
<th>M31D3</th>
<th>M31D4</th>
<th>M33B3</th>
<th>SIG4</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>48.46</td>
<td>49.36</td>
<td>40.45</td>
<td>49.27</td>
<td>48.25</td>
<td>49.41</td>
<td>49.68</td>
<td>47.45</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2.57</td>
<td>2.55</td>
<td>2.54</td>
<td>2.08</td>
<td>2.11</td>
<td>2.42</td>
<td>1.19</td>
<td>2.63</td>
</tr>
<tr>
<td>MgO</td>
<td>11.53</td>
<td>12.29</td>
<td>9.91</td>
<td>10.63</td>
<td>8.03</td>
<td>10.81</td>
<td>10.99</td>
<td>11.13</td>
</tr>
<tr>
<td>FeO</td>
<td>20.43</td>
<td>17.58</td>
<td>29.33</td>
<td>26.50</td>
<td>28.60</td>
<td>22.82</td>
<td>27.53</td>
<td>24.07</td>
</tr>
<tr>
<td>MnO</td>
<td>0.17</td>
<td>0.14</td>
<td>0.16</td>
<td>0.20</td>
<td>0.12</td>
<td>0.18</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.16</td>
<td>0.14</td>
<td>0.30</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>0.06</td>
<td>0.36</td>
<td>0.14</td>
<td>0.16</td>
<td>0.14</td>
<td>0.30</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>NiO</td>
<td>0.13</td>
<td>0.35</td>
<td>0.27</td>
<td>0.30</td>
<td>0.24</td>
<td>0.31</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Total</td>
<td>100.22</td>
<td>100.86</td>
<td>96.88</td>
<td>100.84</td>
<td>99.78</td>
<td>100.88</td>
<td>100.17</td>
<td>100.15</td>
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Table 2b. Average composition of pyroxenes of specific habits in the melts from Meteor Crater, Arizona.

<table>
<thead>
<tr>
<th></th>
<th>Granular</th>
<th>Spherulitic</th>
<th>Pyroxene bead</th>
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<tr>
<td></td>
<td>M30B6</td>
<td>M33B3</td>
<td>M30D</td>
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<tr>
<td>SiO₂</td>
<td>49.14</td>
<td>49.21</td>
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<tr>
<td>Al₂O₃</td>
<td>2.21</td>
<td>1.45</td>
<td>1.81</td>
</tr>
<tr>
<td>MgO</td>
<td>12.16</td>
<td>10.33</td>
<td>8.03</td>
</tr>
<tr>
<td>MnO</td>
<td>0.04</td>
<td>0.02</td>
<td>0.05</td>
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<tr>
<td>TiO₂</td>
<td>0.16</td>
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<td>0.13</td>
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<tr>
<td>Na₂O</td>
<td>0.01</td>
<td>0.02</td>
<td>0.05</td>
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<tr>
<td>K₂O</td>
<td>0.01</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>NiO</td>
<td>0.14</td>
<td>0.27</td>
<td>0.11</td>
</tr>
<tr>
<td>Total</td>
<td>100.47</td>
<td>99.65</td>
<td>98.68</td>
</tr>
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<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.903</td>
<td>1.952</td>
<td>1.946</td>
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<tr>
<td>Al</td>
<td>0.101</td>
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<td>0.087</td>
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<tr>
<td>Mg</td>
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<td>0.611</td>
<td>0.485</td>
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<tr>
<td>Fe</td>
<td>0.697</td>
<td>0.910</td>
<td>0.972</td>
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<tr>
<td>Ca</td>
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<tr>
<td>Mn</td>
<td>0.005</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Ti</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Cr</td>
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<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>Ni</td>
<td>0.003</td>
<td>0.006</td>
<td>0.010</td>
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<tr>
<td>Sum</td>
<td>4.040</td>
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<td>3.997</td>
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<th></th>
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</thead>
<tbody>
<tr>
<td>En</td>
<td>0.35</td>
<td>0.31</td>
<td>0.25</td>
</tr>
<tr>
<td>Fs</td>
<td>0.34</td>
<td>0.46</td>
<td>0.49</td>
</tr>
<tr>
<td>Wo</td>
<td>0.31</td>
<td>0.23</td>
<td>0.26</td>
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</table>
quantitative analysis via electron microprobe methods. This then leaves only the clear glasses to investigate the pristine melt composition(s) at Meteor Crater. The latter consistently yield acceptable oxide totals of 98–102%. Some 15–25 analysis spots were randomly selected per individual specimen to obtain the average melt composition.

**Clear Glasses**

The average compositions of 12 melt samples are presented in Table 3 and illustrated in Fig. 10, along with individual analyses of each specimen. The apices in these ternary plots represent the major precursor lithologies of the melts: (a) FeO +
NiO reflect the contributions of the Canyon Diablo meteorite, a class IAB iron meteorite (Buchwald, 1975); (b) SiO$_2$ corresponds to the quartz-rich Moenkopi silts and especially the rather pure Coconino sandstone, and (c) the sum of (CaO + MgO + others) reflects the dolomite-dominated Kaibab Formation. The salient points of Fig. 10 are as follows:

(a) Overall, the melts at Meteor Crater are compositionally more heterogeneous than most melts from other terrestrial impact craters (e.g., Stahle, 1972; Phinney and Simonds, 1977; Grieve, 1991; Engelhardt, 1997). Individual specimens at Meteor Crater differ in their average FeO contents from 6 to 28%, and SiO$_2$ ranges from as low as 43% (M33C6), to as high as 64% (M12). These are unusually large ranges for impact melts from a single crater.

(b) There is substantial compositional variation within individual melt samples as well. Some specimens are relatively homogeneous (e.g., M18 and M33C5), yet others display substantial internal heterogeneity (e.g., SIG4, M12, or M20). Some particles display linear trends (e.g., M12 and M20) that are suggestive of two-component mixtures. Typical impact glasses do display compositional heterogeneity at submillimeter scales (e.g., Stahle, 1972; Bouska, 1993; See et al., 1998), but such variations seem modest compared to those observed in the Meteor Crater melts.

(c) The melts at Meteor Crater incorporated exceptionally large amounts of projectile material based on the FeO content, which is commonly 25–30%. The contributions of target-derived FeO must be small, most likely <2% judging from the recent analyses of target rocks by See et al. (2002; also see "Discussion"). Three glasses (M12, M18, and M20) possess FeO + NiO <10%, while the majority of the samples has 25–30%. Even individual microprobe analyses consistently fall either

---

**Fig. 8.** Microprobe analyses of (a) granular and (b) spherulitic pyroxenes, and (c) pyroxenes from monomineralic beads.

**Fig. 9.** The Fe and Ni content of olivines and pyroxenes from Meteor Crater compared to the Ni/Fe ratio of the Canyon Diablo meteorite.
FIG. 10. Summary of microprobe analyses of 12 clear glass samples from Meteor Crater, Arizona. The inserts show individual probe analyses for each sample.
Table 3. Average composition of 12 different samples of clear glass from Meteor Crater, Arizona.

<table>
<thead>
<tr>
<th></th>
<th>M12</th>
<th>M18</th>
<th>M20</th>
<th>M30B6</th>
<th>M30B9</th>
<th>M31A1</th>
<th>M31A2</th>
<th>M31A4</th>
<th>M33B3</th>
<th>M33C5</th>
<th>M33C6</th>
<th>SIG4</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>64.16</td>
<td>58.92</td>
<td>58.26</td>
<td>43.72</td>
<td>43.71</td>
<td>48.02</td>
<td>48.52</td>
<td>48.28</td>
<td>48.06</td>
<td>45.48</td>
<td>43.29</td>
<td>44.71</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>6.46</td>
<td>6.22</td>
<td>6.42</td>
<td>2.60</td>
<td>2.55</td>
<td>2.26</td>
<td>2.20</td>
<td>2.54</td>
<td>2.18</td>
<td>2.49</td>
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<td>2.61</td>
</tr>
<tr>
<td>MgO</td>
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<td>6.72</td>
<td>7.00</td>
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<tr>
<td>FeO</td>
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<td>28.61</td>
<td>26.94</td>
<td>27.69</td>
<td>27.93</td>
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<td>26.55</td>
<td>28.69</td>
<td>27.73</td>
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<td>0.05</td>
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<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
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<td>0.05</td>
<td>0.06</td>
<td>0.04</td>
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<tr>
<td>P₂O₅</td>
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<tr>
<td>SO₂</td>
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<td>0.01</td>
<td>0.01</td>
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<td>0.18</td>
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<td>0.19</td>
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<tr>
<td>K₂O</td>
<td>1.32</td>
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<td>1.27</td>
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<tr>
<td>TiO₂</td>
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<tr>
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<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
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<tr>
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<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
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<td>0.03</td>
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<tr>
<td>NiO</td>
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<td>0.54</td>
<td>0.55</td>
<td>0.15</td>
<td>0.32</td>
<td>0.21</td>
<td>0.20</td>
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<td>0.14</td>
<td>0.35</td>
<td>0.32</td>
<td>0.29</td>
</tr>
<tr>
<td>Total</td>
<td>99.57</td>
<td>99.38</td>
<td>99.49</td>
<td>98.96</td>
<td>98.55</td>
<td>98.47</td>
<td>98.60</td>
<td>98.72</td>
<td>98.34</td>
<td>98.26</td>
<td>98.97</td>
<td>98.91</td>
</tr>
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</table>

into the "high" or "low" FeO + NiO categories (see Fig. 10). Note the distinct gap at ~12 to 20% total FeO + NiO, suggesting a bi-modal distribution of projectile-derived melt components. These meteorite concentrations represent minimum values because we diligently excluded small metallic opaques from the analyses; such opaques are abundant, occur in a wide range of sizes, and have diverse compositions and mineralogies (Brett, 1967; Kelly et al., 1974).

A summary of the distribution of meteorite-derived Ni and Fe is presented in Fig. 11. As was the case for Fig. 9, the FeO concentrations were converted to metallic ratios for direct comparison with the projectile. Note that the melts with modest levels of projectile contamination (4–8%) have relatively unfracti...ni/Fe, while all melts of high meteorite contamination (17–25%) have substantially fractionated Ni/Fe. The bimodal distribution in the absolute amount of meteorite contamination is also manifested by a bimodal distribution of Ni/Fe.

Altered Glasses

As previously mentioned, oxide totals for the altered glasses are poor, typically 70–90%. This implies copious amounts of low-Z materials, generally H₂O or OH, possibly CO or CO₂. Morris et al. (pers. comm., 2001) analyzed a few melt beads via thermo-gravimetric methods and monitored the evolving gas species with an infrared spectrometer; only water vapor was released, but no CO or CO₂. As a result, the altered material is thoroughly hydrated. Variable hues of red, yellow, and amber invariably accompany these hydrated phases, which suggests that they are oxidized to various degrees as well. Hydration and oxidation are so intimately intertwined spatially, that they must be related genetically.

To illuminate the compositional differences between the clear glasses and the alteration products, we acquired qualitative elemental distribution maps for Si, Fe, Ca, Mg, and Al. Representative results are shown in Fig. 12, which is centered on the high-magnification image of Fig. 4c. The upper half of Fig. 12 represents pristine glass that contains a cluster of olivine needles; the lower half represents the intimate mixture of altered glass, olivine, and pyroxene shown in Fig. 4c. Detailed comparison of the pristine and altered materials reveals that the alteration process depleted Si, Mg, and Ca, but greatly enriched Fe and modestly enriched Al. Clearly, the altered material is compositionally distinct and not merely an oxidized version of the clear glass.

The banded nature of the altered glass is not manifested in Fig. 12. Elemental mapping at spatial resolutions even higher than Fig. 4c reveals that all "dark" bands are universally depleted in all (!) elements. The most prominent dark bands have characteristics identical to genuine microfractures, all approaching "zero" concentration for every element scanned. This suggests that microscopic porosity is present in the altered materials and a prominent contributor to the rhythmic banding. Submicroscopic porosity may be substantial, because oxide totals of 70–80% are common in the Meteor Crater glasses and because natural glasses with >20% water are rare (Bouska, 1993). Individual probe analyses totaling <70% are not uncommon in some Meteor Crater specimen, yet we rejected such analyses from any further consideration.

Note in Fig. 12 (top, left side) a cluster of olivines which crystallized from the clear glass and which affected the composition of the immediate melt environment: Ca was rejected by the olivines and enriched in the local glass, while Mg was somewhat depleted in the glass due to favorable partitioning with the growing olivines. Such crystal-driven, local fractionation may have preconditioned the melt/glass to render it more conducive to alterations, as suggested by the omnipresent olivine aureoles; this fractionation could include rejection of water by the evolving olivine and pyroxene crystals.
and its enrichment in the immediate vicinity of the primary crystals. However, such melt modifications due to crystal/liquid elemental partitioning is a minor process at best in these melts, because the altered materials dominate and may encompass entire beads, and because zones of altered materials may develop in the absence of crystals (e.g., Fig. 4b).

Despite the poor oxide-totals, we analyzed a number of altered melts, but we rejected all analyses with oxide totals $<70\%$. Individual analysis may vary greatly in any altered sample, primarily in $\text{Fe}_2\text{O}_3$ and $\text{SiO}_2$, the dominant components; individual analyses may approach $55\%$ $\text{Fe}_2\text{O}_3$, a remarkably projectile-rich impact product. Table 4 lists the average compositions of altered glasses; absolute totals are purposefully given to illustrate the substantial correction factors needed when normalizing these compositions on a water- and porosity-free basis for comparison with the clear glasses, such as in Fig. 13. Figure 13 plots the relative enrichment and depletions factors of specific oxides in the altered material relative to coexisting, pristine glass in five melt specimen (see Tables 3 and 4). This comparison also necessitated conversion of $\text{Fe}_2\text{O}_3$ (in the altered material) to FeO. Figure 13 shows that FeO and $\text{Al}_2\text{O}_3$ are invariably increased in the altered materials and $\text{CaO}$, $\text{MgO}$, and $\text{K}_2\text{O}$ are strongly depleted relative to the clear glass; $\text{SiO}_2$ is modestly depleted on average. The depletion factors of individual elements have variable magnitudes. This suggests element specific behavior during the alteration process and argues against the global addition of Fe to the pristine melts as proposed by Kargel et al. (1996). Kargel et al. (1996) suggested that the melts interacted during ballistic flight with a hot, Fe-rich vapor cloud, which also contained free oxygen (from the decrепitation of carbonates) to account for the Fe-rich, oxidized nature of these materials. Such a process would result in identical depletion factors for each element, because it would be equivalent to some uniform bulk-dilution of the starting material. Note also that aluminum is enriched, rather than diluted. Qualitatively similar element-specific depletions of $\text{CaO}$, $\text{K}_2\text{O}$, and $\text{MgO}$ and simultaneous enrichment of iron are observed in volcanic glasses, specifically in palagonites. For palagonites, these alterations are attributed to differential leaching by aqueous solutions, combined with the simultaneous stabilization of Fe by incipient mineralization and formation of Fe-oxides, either hydrated or not, most containing $\text{Fe}^{3+}$ (Bouska, 1993; Morris et al., 2000a). $\text{SiO}_2$ and $\text{Al}_2\text{O}_3$ may remain unchanged, be modestly depleted, or be modestly enriched in the palagonitic glasses studied by Morris et al. (2000a).

**DISCUSSION**

**Relationship of Melts to Target Lithologies**

The reconstruction of the stratigraphic source area of the melts at Meteor Crater requires an understanding of the target rocks and their compositions with depth. Figure 14 reproduces a summary of recent x-ray florescence spectroscopic (XRF) analyses by See et al. (2002) that characterize the upper 120 m of the crater's target rocks. See et al. (2002) also analyzed the modal abundance of quartz, calcite, and dolomite in 56 Kaibab samples using x-ray diffractometry (XRD). The modal abundance of quartz is summarized in Fig. 15, with the
Fig. 12. BSE image and elemental-distribution maps for Fe, Si, Ca, Al, and Mg of the rim area of sample SIG4; the altered material is at the bottom half. Note: the area shown in Fig. 4c lies within the central portion of this image.
complementary fraction substantially composed of dolomite; calcite is at best a minor phase in the Kaibab. Consistent with previous descriptions (McKee, 1938; Kieffer, 1971; Shoemaker and Kieffer, 1974) the Coconino Formation is a rather pure sandstone averaging >97% SiO₂. The Toroweap is volumetrically insignificant and similar to Coconino. The Kaibab Formation is compositionally highly variable because of highly variable dolomite and quartz, including sandstone layers (see Fig. 15). The Moenkopi Formation is a calcite-bearing silt that has the highest Al₂O₃ content and the lowest MgO/CaO ratio of all target lithologies.

In Fig. 16 we compare the melt compositions from Table 3 with the target rocks and projectile, akin to Fig. 10. The small squares represent the stratigraphic subsections shown in Fig. 14; the large squares are formation averages (See et al., 2002). We also include the monomineralic pyroxene beads in this plot because we consider them to represent melts that differed modestly, yet distinctly from all others: they crystallized only pyroxene and no olivine, and they crystallized completely rather than partly; also the Ni/Fe of the pyroxenes is unfractonated. We take the average pyroxene composition of Table 2 for the actual melt composition of these samples. Note that three of four monomineralic pyroxene specimens have lower SiO₂ than all other glasses and one specimen (M4) has FeO contents that fall into the gap between the previously recognized groups of "low" and "high" FeO melts. Very generally, the high meteorite concentrations preclude detailed inferences from Fig. 16 about specific target rocks, but Kaibab and Moenkopi alone could produce the melts as indicated by their respective mixing lines.

A more detailed evaluation of only the target-derived melt components requires normalization of the melt compositions to a meteorite-free basis as shown in Fig. 17. The data plotted refer to the sum of (MgO + CaO + SiO₂) only and disregard all other oxides, thereby illustrating the relative roles of dolomite, calcite, and quartz which typically compose >95% of all target rocks. The top panel refers to average melt compositions; the small plots depict individual analyses for individual samples. The dashed line refers to a mixture of Kaibab-dolomite and quartz; note that this dolomite is modestly enriched in CaO (54.5 mol%; See et al., 2002). Referring to the top panel, all Fe-rich melts plot close to this dolomite-quartz mixing line, including the pyroxene beads which now form a well-defined group of high-dolomite content. However, all melts contain more quartz than the average Kaibab. This suggests that only quartz-rich Kaibab sections were involved or that additional quartz from the deep-seated Coconino was incorporated. Therefore, the question of stratigraphic source depth cannot be satisfactorily answered for the Fe-rich melts from Fig. 17, especially in view of the highly variable quartz content within the Kaibab, as shown in Fig. 15. However, the melts of modest Fe content have distinctly different CaO/MgO than the Fe-rich melts and they do not fall on the dolomite-quartz mixing line. They seem to be a mixture of Kaibab and Moenkopi.
To gain additional insights into possible source rocks, we depict the relationships of CaO, MgO, and Al₂O₃ to total SiO₂ in the melts and in the precursors in Fig. 18; all melt data are on a meteorite-free basis and all target rocks are on a volatile-free basis. The left-hand panels illustrate individual analyses to provide some sense of data scatter, overlap, and mixing trends within and among samples; the right-hand panels compare the averaged melt compositions with the precursor rocks. Referring to the CaO vs. SiO₂ plot, all melts fall on a linear mixing line reflecting mixtures of quartz and dolomite; by fortuitous circumstance, the CaO content of Moenkopi falls on this mixing line as well. All melts contain >50% SiO₂ and quartz dominates. The MgO plot amplifies the trends displayed in Fig. 17: most melts fall on a mixing line between dolomite and quartz, but samples M12, M18, and M20 form a distinctly different trend which reflects the presence of Moenkopi. A similar conclusion applies to the Al₂O₃ plot: two distinct batches of melt are evident, one containing consistently low Al₂O₃, the other reflecting variable contributions of Moenkopi. The last panel in Fig. 18 plots the CaO/MgO ratio of the melts, thus portraying the relative roles of calcite and dolomite. Again, two distinct trends emerge: one melt batch has invariant CaO/MgO, consistent with Kaibab dolomite, while the other shows higher CaO/MgO ratios and thus, the addition of Moenkopi-derived calcite. Note that individual samples deviate from the major mixing lines shown (e.g., the Al₂O₃ of samples M12 and M18 seems unrealistically high). Obviously, the mixing lines reflect the average composition of specific formations and they do not portray the compositional range of stratigraphic subsections that may dominate a specific sample.

We conclude from Figs. 17 and 18 that there are two batches of melt at Meteor Crater that differ distinctly in their stratigraphic source depth. One batch reflects a mixture of Moenkopi and Kaibab and therefore, relatively "shallow" target rocks. The second batch contains minor Moenkopi, if any, and derives either from the quartz-rich Kaibab members or from a mixture of average Kaibab and Coconino sandstone. The latter melts have a more "deep-seated" origin than the previously mentioned shallow batch. One may even subdivide the deep-seated melts into two batches on the basis of their dolomite content, with the dolomite-rich melts giving rise to the monomineralic pyroxene beads, while the quartz-rich melts crystallize olivine and pyroxene. Recall that the shallow and deep-seated melts also differ systematically in total FeO, with the shallow melts containing <10% FeO and all deep-seated melts >15% FeO, commonly even >25% FeO. Furthermore, the shallow melts have unfractoned Ni/Fe, but the deep-seated melts are Ni deficient, excepting the monomineralic pyroxene melts that contain unfractoned meteorite residue. These meteorite-related observations provide additional justification...
to subdivide the deep-seated melts into "dolomite-rich" and "quartz-rich" batches.

To quantify the relationships illustrated in Figs. 16–18, we conducted mixing calculations employing a weighted, least-square mixing program (Korotev, 1981; Korotev et al., 1995; and pers. comm.). Specifically, we inquired whether all melts could result from mixtures of Moenkopi and Kaibab only, or whether additional quartz from the Coconino sandstone is needed, especially for the deep-seated melts. The input data for these calculations are summarized in Table 5, including the three melt compositions that we wished to model. All calculations included a meteorite component because we wanted to duplicate the entire melts. The selection and combination of specific target components depended on the absolute melt depth that we wished to model. The latter progressed systematically in these mixing calculations from ~30 m (Mo + K_up), to ~50 m (Mo + K_up + K_mid), to ~90 m (Mo + K_avg) to >90 m (Mo + K_avg + Co). Another crucial input for these calculations concerns the weighting factor of each element; the latter is a measure how well any calculated concentration for a given element has to match—in relative percent terms—the observed value. Ultimately, this weighting factor (wf) enters the error-weighted residuals (EWR) as follows: EWR = (% observed – % calculated/wf). Obviously, the smaller EWR, the better the least-square fit, which is defined as the sum of all (EWR)^2 for all elements used, often expressed as χ^2. Even subtle changes in the weighting factors can substantially affect the goodness of fit and one can adjust the wf within reason to obtain statistically good, if not optimal matches. We typically adjusted the weighting factors for any specific run some two to five times until we obtained a small value of χ^2, typically <10.
for all eight elements used, for at least one of the three melt compositions; once these conditions were determined, we froze the weighting factors and generated the two other melts at identical input conditions. We conducted these weighting exercises for each of the four melt-depths modeled. This procedure independently yielded the best progenitor match for each of the three melts, and it also permitted us to evaluate whether any single set of progenitors could have produced all three melts.

The overriding result of these mixing calculations is that a number of scenarios remain viable, especially for the deep-seated melts. While statistical parameters may be used to precisely rank the goodness of fit, such statistical criteria seem insufficient to differentiate among a number of major, geologic alternatives. In Fig. 19 we illustrate the EWR of the best solutions for each of the three melt batches; these examples were picked on the basis of the smallest $\chi^2$ from typically 10–15 runs, which differed both in weighting factors as well as in progenitor
components (e.g., $K_{up}$ or $K_{avg}$) for the same melt. Table 6 complements Fig. 19 and presents the modal proportions of target components that yielded the best solutions of Fig. 19, identified as models 1–8.

The shallow melts are simulated rather well by a mixture of meteorite (Me), Moenkopi (Mo), and the average Kaibab ($K_{avg}$) as shown in model 1, as well as by mixtures that employ upper Kaibab ($K_{up}$) instead of $K_{avg}$ (model 2). All models that used $K_{mid}$ in combination with $K_{up}$ + Mo + Me yielded statistically poor fits with $\chi^2 > 100$, including unrealistic solutions with negative $K_{mid}$ or Mo values. Furthermore, all attempts to model the shallow melts employing Coconino as a fourth component, combined with $K_{avg}$, consistently yielded negative Coconino contributions for the shallow melts. Therefore, Coconino
sandstone is not a viable component for the shallow melts. The shallow melts are either derived from target depth <90 m (model 1) or from depth <30 m (model 2). Because these melts contain >50% Moenkopi we prefer the shallow melt depth and thus model 2.

The deep-seated, quartz-rich melts (Fig. 19b) are best modeled as mixtures of Me + Mo + K_avg (model 3) or as mixtures Me + Mo + K_up (model 4). However, viable solutions (model 5) are also obtained if Coconino is added to model 3. Indeed model 5 yields the statistically best fit and suggests that ~12% of Coconino could have participated. However, we consider models 3 and 4 viable as well. The addition of K_mid to model 4 again yields poor fits or non-viable solutions. Obviously, the source area of the deep-seated, quartz-rich melts is poorly constrained by these calculations.

Models 6-8 represent the dolomite-rich, monomineralic pyroxene melts. Akin to the other deep-seated melts, viable solutions are obtained for a number of scenarios. However, all models suggest increased Kaibab contributions to account for the high-dolomite content. Interestingly, the dolomite-rich K_mid
cannot be a dominant component, because total SiO$_2$ in these melts is still higher than average Kaibab. Note that even these dolomite-rich melts could principally be derived from target depth $<30$ m (model 6), although the calculated proportions of Moenkopi (~4%) and Kaibab (~75%) diverge significantly from their relative field abundance within the upper 30 m of the Meteor Crater target. Models 6 and 7 seem more realistic in this respect.

We recall that models 1–8 allowed variable weighting factors for specific elements, consistent with optimal fits for each major melt batch. We now evaluate those models that attempt to derive all three melts from a single set of progenitor
Table 6. Modal abundance of different components corresponding to models 1–8 in Fig. 19, as well as additional parameters to evaluate the goodness of fit of these mixing calculations.

<table>
<thead>
<tr>
<th>Model</th>
<th>Meteorite (Me)</th>
<th>Moenkopi (Mo)</th>
<th>Kaabab (K_{avg})</th>
<th>Kaabab (K_{up})</th>
<th>Coconino (Co)</th>
<th>Σ</th>
<th>±</th>
<th>χ²</th>
<th>χ^{2ν}</th>
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<tr>
<td>1</td>
<td>5.05</td>
<td>58.00</td>
<td>36.78</td>
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<td>~</td>
<td>99.83</td>
<td>1.60</td>
<td>12.35</td>
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<tr>
<td>2</td>
<td>4.88</td>
<td>54.20</td>
<td>~</td>
<td>40.33</td>
<td>~</td>
<td>99.41</td>
<td>1.51</td>
<td>8.82</td>
<td>1.77</td>
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<tr>
<td>3</td>
<td>22.67</td>
<td>26.20</td>
<td>51.67</td>
<td>~</td>
<td>~</td>
<td>100.54</td>
<td>2.07</td>
<td>34.75</td>
<td>6.95</td>
</tr>
<tr>
<td>4</td>
<td>22.42</td>
<td>22.13</td>
<td>~</td>
<td>56.02</td>
<td>~</td>
<td>100.57</td>
<td>1.24</td>
<td>11.72</td>
<td>2.34</td>
</tr>
<tr>
<td>5</td>
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<td>9.80</td>
<td>52.81</td>
<td>~</td>
<td>12.19</td>
<td>97.77</td>
<td>2.68</td>
<td>9.26</td>
<td>2.32</td>
</tr>
<tr>
<td>6</td>
<td>20.82</td>
<td>4.12</td>
<td>~</td>
<td>74.59</td>
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<td>21.17</td>
<td>9.41</td>
<td>69.01</td>
<td>~</td>
<td>~</td>
<td>99.58</td>
<td>0.82</td>
<td>6.38</td>
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<tr>
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<td>6.70</td>
<td>~</td>
<td>69.14</td>
<td>2.27</td>
<td>99.32</td>
<td>2.09</td>
<td>3.54</td>
<td>0.89</td>
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FIG. 19. Summary of error-weighted residuals (EWR) values for the melt-mixing models detailed in Table 6.

Clearly, the mixing calculations were not successful in determining the specific source depths of the melts. The K_{up} and K_{avg} components are interchangeable and the melts are either derived from the upper 30 m only, or they average over great depths, 90 to 100 m, depending whether modest Coconino contributions are needed or not. The melt zone cannot terminate at intermediate depths between 30 and ~70 m. The resulting melts would be much richer in dolomite than is observed. The dolomite-rich strata at 30 to 50 m depth can only be part of the observed melts if they are compensated for by all (!) quartz available in the entire Kaabab and Moenkopi formations, possibly by some additional Coconino sandstone.

Regardless of whether one uses K_{up} or K_{avg}, the Kaabab progressively increases from 36 to 40% in the shallow melts, to about 52–56% in the quartz-rich melts, to about 69–75% in the dolomite-rich melts; this occurs at the expense of Moenkopi, which decreases from ~55% to 25% to <10%, respectively (see Table 6). At face value, this suggests that the three melt batches derive from progressively greater depths, incorporating increasing proportions of the Kaabab. Interestingly, if one were to add Coconino sandstone to the mix, this order would change: the dolomite-rich melts would be shallower (2% Coconino only) than the deep-seated, quartz-rich melts (12% Coconino).

Conceptually, the use of a K_{avg} component in the above mixing calculations implies ideal mixing and homogenization of the entire Kaabab formation, ~80 m thick. The wide range
of SiO₂ values in these melts would then reflect some uneven incorporation of the Coconino- or Moenkopi-components, possibly both. We have reservations with such a scenario because it mandates both the perfect homogenization of the entire and dominant Kaibab, but the incomplete incorporation of additional components from either higher or lower stratigraphic positions.

Most observations suggest that melt-homogenization was less complete at Meteor Crater compared to many other craters and that the observed heterogeneity reflects small-scale lithological variability of the source rocks, specifically of the dominant Kaibab Formation. Obviously, the existence of three distinct melt batches is unusual for any crater and constitutes first-order evidence for incomplete mixing at relatively large scales. Individual melt samples (Table 3) differ compositionally much more so at Meteor Crater than they do at other impact sites, suggesting less complete mixing at decimeter (possibly larger) to millimeter scales. Lastly, microprobe analyses within single samples also commonly display, although not always, much larger compositional variation than is typical for impact melts from other terrestrial craters (e.g., Stahle, 1972; See et al., 1998). This suggests inefficient melt mixing at sub-millimeter scales. Note in Figs. 17 and 18 the wide variation of Al₂O₃ (and MgO) in samples M12, M18, and M20, manifesting the presence of a Moenkopi component. This demonstrates that differential melt volumes from specific stratigraphic sections, measured in thicknesses of meters, were preserved and incompletely homogenized. We suggest that similar stratigraphic variety within the Kaibab, on the scale of meters, is preserved in the variable dolomite-quartz ratios of many melts. Significantly, we did not produce a single analyses with dolomite contents higher than average Kaibab, much less did any analysis resemble the dolomite-rich Kg or Kj strata of Fig. 14. The compositional range of all microprobe analyses strongly suggests that all progenitor materials had quartz contents higher than average Kaibab and that dolomite-rich strata did not participate in the melts. These observations seem to favor a melt zone that is confined to Moenkopi and the upper Kaibab, some 30 m deep.

A completely independent estimate of the total melt depth may be based on shock considerations. Roddy et al. (1980) conducted hydrocode calculations for Meteor Crater and their Fig. 13 depicts pressure decay profiles for 25 and 15 km/s impacts. For both cases, one extrapolates shock stresses on the order of 65–70 GPa at a depth of 60 m. Dolomite commences to devolatilize at >70 GPa based on experimental shock-recovery studies of Martinez et al. (1995) and Skala et al. (2000). As a consequence, most melts at Meteor Crater should derive from depths shallower than some 60 m. It does not seem likely that the entire Kaibab formation was molten, and Kₐᵥₘₑₙ may not be a viable mixing component. However, the melt depth of 60 m resulting from such shock considerations is difficult to reconcile with the quartz-rich nature of the melts.

Estimates of the total melt volume produced at Meteor Crater may also assist to estimate the size and depth of the melt zone. The field observations by Nininger (1954) and subsequent workers, including us, suggest that all currently existing melts are volumetrically trivial relative to the total ejecta. While this field observation does not specify melt depth, it does argue for a small melt volume. Wholesale melting to depth >100 m should produce melt volumes that would be a substantial fraction of the excavation cavity and associated ejecta. Total melt volume at Meteor Crater seems negligibly small compared to the total displaced mass. A rather small melt zone is implied that was most likely also fairly shallow.

On balance, we favor a shallow melt zone at Meteor Crater, yet we cannot positively exclude that it extended into the Coconino Formation. We suggest that future hydrocode calculations specifically address the issue of melt-depth and melt-volume; such calculations should be able to discriminate among the shallow- and deep-seated melt origins, combined with additional laboratory studies of the shock-behavior of dolomite/quartz mixtures or of real Kaibab samples. We do not think that additional chemical and compositional studies will lead to a distinction among currently viable melt depths.

Melt Mixing and Homogenization

The wide compositional range of individual glass analyses, individual melt samples, and large-scale melt batches strongly suggests that the mixing and homogenization processes at Meteor Crater was inefficient when compared to other terrestrial impact melts. Major factors that may be responsible for this unusual heterogeneity of the Meteor Crater impact melts include:

- (a) The target rocks at Meteor Crater seem compositionally more diverse than those from many terrestrial craters. The majority of craters that gave rise to the concept of homogeneous impact melts were essentially formed in targets composed of either igneous and/or metamorphic rocks (Dence, 1971; Grieve et al., 1977; Phinney and Simonds, 1977; Engelhardt, 1997). Most of these crustal rocks have granitic compositions and display relatively little chemical variation compared to the Meteor Crater sediments. Note that the Zhanshanchin impact into a lithologically complex, largely sedimentary target also produced a number of compositionally distinct melts (e.g., Bouska, 1993; Koebel et al., 1985).

- (b) It is possible that the crater size modulates the degree of melt homogenization. The majority of craters that contain well-characterized impact melts are much larger than Meteor Crater. Absolute and relative melt volumes that remain inside the crater cavity increase with increasing crater size (Cintala and Grieve, 1998) and the voluminous melts in large craters will remain hot for long periods of time, promoting greater homogenization. Clearly the pooling of impact melts into massive sheets inside large craters present additional opportunities for intimate melt mixing and homogenization to take place. However, even the ballistically transported melt bombs from the Ries crater are compositionally homogeneous.
(e.g., Hörz, 1965; Staple, 1972; Engelhardt, 1997). This mandates that most melt homogenization be accomplished prior to ballistic flight, most likely during turbulent melt flow along the growing crater walls (Grieve, 1991; See et al., 1998). This turbulence could be more intense and longer lasting in large structures compared to small craters. These factors suggest that homogenization of the total melt volume could depend on crater size, but details remain poorly understood (e.g., Onarato et al., 1978; Grieve, 1991; See et al., 1998).

(c) The high-volatile content of the target rocks at Meteor Crater may have contributed to the unusual heterogeneity of the resulting melts. Kieffer and Simonds (1980) calculate that the total amount of melt is decreased in volatile-rich targets, and they postulate that the liberation of vapors will disrupt and disperse the resulting melts, favoring formation of isolated melt bombs rather than massive melt sheets. The copious amounts of CO$_2$ that were released during the Meteor Crater impact lead to pervasive dispersion of the total melt volume. All melt flow and associated melt mixing will be terminated—at a variety of scales—upon dispersion and physical disruption of the hot melts.

Clearly the target rocks and the meteorite are not perfectly mixed at Meteor Crater, yet some meteorite component is present in every melt sample that we analyzed. This suggests that the melt mixing was rather intense at Meteor Crater as well, and that it merely differed in degree from other craters. The outgassing of volatiles physically disrupted the melt volume, thereby terminating melt flow and associated mixing processes. The meteoritic component must have been part of the melts prior to this volatile release. It follows that substantial melt mixing and homogenization must occur during very early stages of the cratering process, possibly while material is being accelerated by the shock wave into downward motions. The dissemination of the impactor demonstrates that melt-mixing occurs independent of and before (1) the melts move along the growing crater floor where they may pick up their complement of clastic inclusions and where turbulent flow may be generated (e.g., Onarato et al., 1978; Grieve, 1991). Note that the mixing process must be fairly complete by the time when impact melts get injected into basement fractures to form dikes. Although it is difficult to envision highly turbulent flow during very early cratering phases, we postulate that major melt mixing is part thereof and that it is substantially complete by the time the melts move along the growing crater floors and walls (Grieve, 1991). Again, we consider this an important topic for detailed hydrocode calculations; it requires that specific target-volumes move at a wide range of relative velocities.

Dissemination of the Projectile

Throughout this report we equate the amount of meteoritic contamination to the concentration of iron and nickel that was dissolved in, and became structural part of the silicate melts or of minerals that grew from this melt. Our measurements carefully avoided the numerous, finely dispersed opaques that occur throughout these melts and that represent additional projectile material (Brett, 1967; Kelly et al., 1974). These metallic particles tend to be rich in Ni, and pure Ni-sulfides are common. Obviously, the Ni enrichment in these opaques is complementary to the Ni depletion of the melts. However, it is not known whether exact mass-balance was maintained because precise modal analyses of the opaques are not available. Bulk analyses of individual melt beads using neutron activation methods reveal essentially unfractionated Ni/Fe for most specimens (Mittlefehldt and Hörz, 1998).

The Moenkopi-rich, near-surface melts have systematically less iron than the more deep-seated melts. Thus, most of the projectile is melting, disintegrating, and disseminating below the Moenkopi/Kaibab contact. The near-surface melts also contain unfractionated projectile residue (see Fig. 11), but the deep-seated melts are Ni depleted; this suggests that melt temperatures may have been hotter at depth compared to the surface. Recall from Fig. 9 that the Ni/Fe in the pyroxene-dominated melts is unfractionated, suggesting more benign temperatures again in their Kaibab-dominated source area.

The Moenkopi Formation averages about 8–10 m in thickness at Meteor Crater (Shoemaker and Kieffer, 1974), which is modestly smaller than the modeled radius (10–15 m) of the Canyon Diablo projectile impacting at ~25 km/s (Roddy et al., 1980). General hydrocode calculations suggest that most melting of the projectile occurs after the impactor penetrated deeper than its own diameter (e.g., Roddy et al., 1980; O'Keefe and Ahrens, 1993). It seems reasonable to envision that the majority of projectile heating, melting, and fractionation occurred at depths below the Moenkopi caprock and that the near-surface melts received little and comparatively cool/ unfractionated projectile melts. Ultimately the penetrating projectile, at vertical impact angles, will be consumed at target depths measured in 3–5 projectile radii at ~20 to 25 km/s; most material left at that stage is derived from the least shocked portions toward the rear of the impactor and would be relatively cool and of unfractionated Ni/Fe.

Note that some of these projectile-normalized depths are in conflict with our preferred, total melt depth. The latter is some two projectile diameters at most in our view. These apparent conflicts may be reconciled if we would allow for an oblique impact, which favors melt-production from relatively shallow strata (Pierrazo and Melosh, 2000).

The absolute levels of meteorite contamination in the melts from Meteor Crater are extraordinarily high compared to other impact melts, even accounting for the potential loss of volatiles that average some 11% (weight) and 27% for the Moenkopi and Kaibab formations, respectively (See et al., 2002). One is tempted to relate the unusually high levels of projectile contamination to some unusually low impact velocity. However, such a proposal runs counter to the hydrocode calculations of Roddy et al. (1980) and Schnabel et al. (1999) who advocate typical impact velocities of 15–25 km/s to be consistent with all major field observations. Nevertheless, there is no good understanding why the melts at Meteor Crater are so exceptionally
rich in projectile components, yet oblique impact seems to provide suitable trends (Pierazzo and Melosh, 1999, 2000).

In summary, projectile dissemination is pervasive and of an unusual magnitude in the Meteor Crater melts. Our investigations demonstrate for the first time that this material is distributed in a bimodal fashion, and that regimes of different temperatures existed as revealed by the Ni/Fe systematics. Most terrestrial melts contain impactor materials at the parts per million level (Palme, 1982), and the lunar regolith, the product of numerous repetitive events, averages only ~2% (Anders et al., 1973). We do not know why the Meteor Crater melts are so rich in projectile material and why they display some bimodal distribution in concentration and temperature. We suspect that impact velocity may be overestimated in some current models, or that oblique impact played some role. Both would result in relatively small total melt volumes and a relatively shallow melt depth. Conversely, the plan view of the crater structure places limits on the trajectory angle of the impactor and excludes extremely oblique cases (e.g., <30°) from the horizontal (Pierazzo and Melosh, 1999). Again, detailed hydrocode calculations are needed to better understand the exceptionally high projectile concentrations in the melts from Meteor Crater.

Hydration and Oxidation of the Melts

Hydration and oxidation of the impact melts at Meteor Crater is common, and both processes are intertwined. Details of these processes are poorly understood, including the important question of whether these alterations occurred during the cratering event, as postulated by Nininger (1956) and more recently by Kargel et al. (1996), or whether they took place substantially later. We note that the water table at the time of impact was ~150 m below the target surface (Roddy et al., 1980) and a fair distance removed from the melt zone. Kring (1997) reconstructs an environment at the time of impact, ~50 000 years ago, that is somewhat wetter than the current one.

We have repeatedly alluded to the clear nature of all pristine glasses, which mandates that all Fe was present as Fe2+ to the exclusion of Fe3+ initially. This implies modest oxygen fugacity during the actual melt formation and mixing process(es), which seems typical for impact melts (Hörz, 1965; Bouska, 1992). The numerous metallic opaque phases that coexist with clear glass suggest low oxygen fugacities as well (e.g., Brett, 1967). Thus, at least the oxidation process must have taken place at some time distinctly later than actual melt formation. The contact relationships of pristine and altered materials are characterized by solid-state textures and suggest that oxidation occurred after the melts cooled through the glass transition point. Because oxidation and hydration are so intertwined texturally, we suggest that hydration and oxidation are related genetically and occurred after melt solidification.

The detailed mineralogy of these altered materials could not be determined optically and detailed phase characterizations were also beyond the resolution of the microprobe. Quantitative microprobe analyses on even the most Fe-rich materials never produced results that would be consistent with a pure Fe-bearing phase, as all analyses contained large concentrations of elements other than Fe. This observation in itself argues for extremely fine-grained mixtures of diverse products in incipient stages of crystallization, possibly with remnants of glass present as well. Morris et al. (2000a,b) applied infrared reflectance and Mossbauer spectroscopy, and XRD to identify the major phases. These investigations identified magnetite, goethite, and maghemite as the dominant iron-bearing minerals; their relative abundance does vary greatly from sample to sample, however. In contrast, nanophase Fe-oxides in incipient stages of crystallization, either hydrated or not, are universally present in every altered specimen and appear to constitute the bulk of the alteration products. Significantly, no layer-lattice silicate was detected in any of the samples, even by these sensitive spectral methods (Morris et al., 2000b). The observed phase assemblages have strong similarities to volcanic palagonites of similar, basaltic, bulk compositions (Morris et al., 2000a). In analogy to these palagonites, the absence of any layer-lattice silicate, water-bearing or not, suggests that the hydration took place at ambient temperatures (Morris et al., 2000a). We also note that the pristine and unweathered nature of many delicate olivine and pyroxene crystals is more compatible with alterations at low temperatures than with alterations at elevated temperatures.

Therefore, we suggest that these alterations occurred over prolonged time reflecting local climatic conditions unrelated to the impact event. Hydration and oxidation do not appear to be related to the interaction of impact melts with a water- and oxygen-rich vapor plume as suggested by Nininger (1956) or Kargel et al. (1996). The selective depletion of CaO, MgO, and K2O (see Fig. 13) seems especially difficult to accomplish during ballistic flight, and the alterations are not systematically related to the exterior surfaces of individual melt objects; alterations often commence in association with vesicles or clasts in the interior of melt beads. We also note that ballistically transported melt bombs from other craters, such as the Ries, were neither hydrated nor oxidized in midair (Hörz, 1965), nor were tektites (e.g., O'Keefe, 1976).

Planetary Implications

Petrographic observations of experimentally and naturally shocked calcite reveal the presence of secondary calcite that resulted from the interaction of shock-liberated volatiles (CO2) with their own residues (CaO) according to Martinez et al. (1993), Langenhorst et al. (2000) and others, as recently summarized by Agnirier et al. (2001). We do not observe such secondary calcite or other carbonates in the Meteor Crater melts. Instead, our investigations show that CO2 is lost from the system and that the refractory residues combine with quartz into a melt. Similar conclusions were reached for the impact melt beads of the Chixculub Crater, collected in Belize and Haiti, which
resemble mixtures of crystalline basement and devolatilized sediments including carbonates and even sulfates (Chaussidon et al., 1996). Given sufficient shock pressure, volatile containing sediments and minerals will completely degas in most cases as modeled by Kieffer and Simonds (1980) or Pope et al. (1994) and others; the recombination of the liberated gas with its own refractory residues (Agrinier et al., 2001) appears to be a minor process.

Another interesting observations of planetary significance is that purely sedimentary target rocks—dominated by quartz and dolomite—combined with copious amounts of meteorite-derived iron at Meteor Crater to yield melts containing large quantities of CaO, MgO, and FeO. Upon cooling, these substantially mafic melts crystallized olivines and pyroxenes. If analyzed with remote sensing methods, these samples would yield an igneous mineral assemblage that defies the largely sedimentary nature of the precursor rocks. It is possible to shock-melt planetary material containing carbonates or other phases rich in volatiles (e.g., sulfates, hydrated minerals, etc.) and to thereby produce regolith components that differ both compositionally and mineralogically from their precursor rocks to the degree that the latter may be difficult to reconstruct. Igneous minerals detected in such regoliths could be of secondary impact origin, rather than from comminuted bedrock. Therefore, great care is necessary in characterizing bedrock from remotely sensed mineralogic and compositional properties of regoliths that are known or suspected to contain volatiles, such as martian surface fines.

We also note that the bulk composition of the Meteor Crater impact melts, by fortuitous circumstance, closely matches that of martian surface soils (Morris et al., 2000a) and some shergottite-nakhlitie-chassignite group (SNC) meteorites (Dreibus and Wanke, 1992; Warren and Kalleney, 1997). The Meteor Crater melts are particularly good martian analogs with respect to low-\(\text{Al}_2\text{O}_3\) and high-FeO contents compared to typical terrestrial melts of comparable SiO\(_2\) contents. Furthermore, many Meteor Crater melts are thoroughly hydrated and oxidized, which is expected to be the case for martian surface fines as well (Newsom, 1980; Allen et al., 1981; Bell et al., 1993; Morris et al., 2000a). The spectral and magnetic studies of the Meteor Crater melts by Morris et al. (2000a,b) identified a wide variety of iron-bearing phases that may also occur on Mars, such as goethite, maghemite, magnetite, haematite, and nanophase ferric oxides. The coexistence of these phases with igneous olivines and pyroxenes renders the Meteor Crater melts into excellent spectral and mineralogical analogs to martian surface fines. Some of the physical, mineralogical, and chemical processes that govern the evolution of martian surface materials may possibly be deduced from more detailed studies of the Meteor Crater melts.

**CONCLUSIONS**

We have analyzed the ballistically dispersed melts from Meteor Crater, Arizona and found the proto-type structure for bowl-shaped craters to possess anything but typical impact melts: they are unusually heterogeneous compositionally, they contain exceptionally high levels of projectile material, and they are pervasively hydrated and oxidized. The unusual compositional heterogeneity is most likely due to the high-volatile content of the target rocks, which resulted in copious amounts of CO\(_2\) vapor that aided in efficiently dispersing the melts. This resulted in the interruption of any ongoing melt flows and terminated the ongoing melt mixing.

The melts at Meteor Crater may be grouped into three compositionally distinct batches. All contain variable proportions of the volatile-depleted residues of the Kaibab Formation, a sandy dolomite. In addition, some quartz-rich source is needed, such as the Moenkopi Formation, a calcareous silt, or the Coconino Formation, a pure sandstone. Least-square mixing models suggest that the shallow melt batch contains ~55% (weight) Moenkopi, with the remainder being Kaibab. The two remaining batches differ in their dolomite content and in their Kaibab contribution of ~50% or 75%. The three melt batches also differ in the amount of disseminated meteorite, with the shallow melts containing <10% FeO and the other melts typically >25%. Least-square mixing models yield ambiguous results about the stratigraphic source area of the melts. Depending on the choice of mixing components one may derive the melts either from depth <30 m or from depths >100 m. Arguments related to the composition of individual schlieren, the decay of shock-pressure with depth, and total melt volume suggest that wholesale melting of the Kaibab was unlikely, and that a relatively shallow melt depth of ~30 m is to be preferred. Refined hydrocode models appear to be needed to discriminate between the two cases and to shed light on other observations, such as the high concentration and bi-modal distribution of projectile components.

The melts crystallized olivine and pyroxene upon rapid cooling. Most glasses oxidized and hydrated at some later time, leading to selective loss of calcium and magnesium, and the enrichment of aluminum and iron. Furthermore, nanophase iron oxides formed, either hydrated or not, as well as magnetite, maghemite, and goethite. These phase assemblages combine with the bulk composition of the melts into excellent analogs for martian surface fines.

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