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DEFORMATION OF THE LEOVILLE CHONDRITE AND IMPLICATIONS FOR ITS ASTEROIDAL PARENT BODY

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Parham Mikell Cain

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ABSTRACT

Deformation of chondrules and development of a foliation have been observed in several carbonaceous chondrites, of which the Leoville CV3 chondrite (an accretionary breccia) displays the most evident deformation. Leoville is especially well suited for strain analysis and study of deformation because the original meteorite owner sliced it into large planar sections which show large axial ratios. It is unlikely that much greater axial ratios existed without being reported, so the cuts fortuitously roughly parallel the λ_1-λ_2 (maximum and minimum) plane. An aspect ratio of 1.9:1 is indicated for strain in the chondrules alone, whereas a value of 2.1:1 is indicated for the whole chondrite, corresponding to between 31 and 34% uniaxial shortening. At geologically reasonable terrestrial strain rates of 10^{-13} to 10^{-15}/s, this much shortening would require approximately 10^6 to 10^8 years. Plastic deformation by diffusional flow or grain boundary sliding are reasonable mechanisms of deformation based on thin section analysis. Shock and metamorphism are ruled out as likely mechanisms. Compaction due to overburden with progressive accretion on the chondrite parent body is the probable cause of deformation.

Modeling deviatoric stress for an asteroidal body between 150 and 300 km in radius suggests that Leoville experienced between 0.09 kb and 0.75 kb deformational pressure. Maximum temperatures for CV3 chondrites were between 500 and 600°C based on experimental data. Deformation of the Leoville parent body by diffusional flow is possible with these pressures and temperatures but only at high strain rates.

Strain rates of 10^{-13} to 10^{-15}/s require 700 to 1000°C. It is unlikely that Leoville experienced temperatures this high. Perhaps strain rates were higher, or the deformation more complex. Intergranular water, if present, may have increased the strain rate at lower temperatures.

Analysis of three other CV3 chondrites (Bali, Grossnaja, and Efromovka) indicates that they experienced deformation similar to Leoville. This implies that this type of deformation was a result of asteroidal body interior processes rather than isolated surface incidents such as impact. Such information about asteroidal interiors provides an independent means of assessing their character.

If metallographic cooling rates in Leoville and other chondrites are found to correlate with foliation, magnetic anisotropy, and compaction, this may support the rubble-pile parent body model. Conversely, lack of such correlations may provide evidence against the rubble-pile means of formation.

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CHAPTER I

INTRODUCTION

Purpose of Study

Meteorites of the chondrite group contain volatile elements in abundances similar to those found in the sun. They are separated into two broad categories: ordinary and carbonaceous chondrites. Carbonaceous chondrites have an Mg/Si ratio of greater than one, whereas the ratio for ordinary chondrites is less than one. Ca/Si and Al/Si ratios are also higher for carbonaceous than ordinary chondrites (McSween, 1979). All chondrites are considered to be primitive, i.e., geologically unprocessed.

Previous work recognized some deformational features such as foliation and brecciation in chondrites, though most of the work done was on ordinary chondrites rather than carbonaceous chondrites. Dodd (1965) looked for a relationship between metamorphism and foliation in 20 H- and L-group ordinary chondrites, 17 of which had some degree of foliation. Martin (1980) included several ordinary chondrites in his study of the relationships between the degree of compaction and foliation in chondrites. Several workers characterized chondritic breccias (e.g., Binns, 1967; Dodd, 1974; Fodor and Keil, 1973; Scott and Taylor, 1982; Keil, 1982; Rubin et al., 1982). Brecciation is now fairly well understood, though foliation is not, and the strains associated with foliation have never been measured.

Carbonaceous chondrites consist of several petrologic components which probably accreted together onto the surface of the meteorite

parent body. Those which are of interest in this study include chondrules, calcium-aluminum inclusions (hereafter called CAIs), clasts and matrix. Chondrules are millimeter-sized, generally spheroidal objects with magmatic textures, which are thought to have crystallized from a silicate melt. They may also have Fe-Ni metal associated with them. CAIs are millimeter-sized, irregularly shaped concentric aggregates composed of fine-grained calcium- and aluminum-rich minerals. In contrast to the dark chondrules, CAIs are milky white in color. Clasts are composite objects of highly variable size and shape which were formed elsewhere (though possibly on the same parent body) and were incorporated into the chondrule pile. Matrix is the binding material for all the other components. Its fine-grained (0.1-2.0 um) nature makes detailed characterization difficult, but according to McSween (1979), it consists predominantly of "mixtures of ferromagnesian silicate phases with lesser amounts of organic polymer, magnetite, and Fe- and/or Ni-bearing sulfides and oxysulfides."

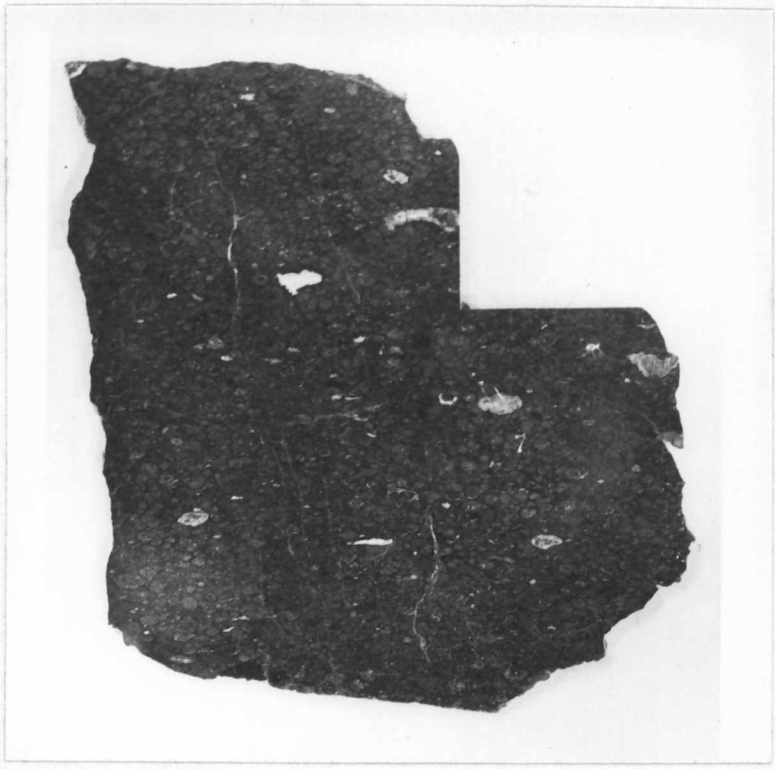
The Leoville meteorite, a CV3 chondrite, is a particularly interesting case for a study of foliation. The chondrules in Leoville are elliptical rather than circular in cross-section (figure 1a). The many slices of this meteorite apparently nearly parallel the plane which contains the maximum and minimum axes of the elongate chondrules. For exact strain ellipsoid determinations we would need three mutually perpendicular faces to analyze, and these are unavailable. When the project began, the goal was to simply measure the strain in the chondrules. The measured axial ratios represent a minimum axial

Figure 1. Leoville section #H40.55.

a. Planar slab H40.55 of the Leoville meteorite (approximately 100 mm across) probably parallels principle directions of minimum and maximum chondrule elongation. Chondrules (small objects) and calcium-aluminum inclusions (larger white objects) trend east-west in photo. Note subparallel alignment of fractures which trend north-south.

b. Reverse side of 1a is polished. Metal-rich areas (lighter) and metal-poor areas (darker) are displayed.

a.



b.



Figure 1.

ratio, so all shortening estimates are minimum values. If the observed deformation of chondrules is due to the compressional forces of overburden, then the three dimensional shape of the chondrules should be that of an oblate spheroid. A very small piece of this same slab was cut perpendicular to the orientation of the slab face. While it was not a large enough piece on which to make statistically valid axial measurements, the cross sections of a few chondrules were observed to be nearly circular, as cross sections of oblate spheroids should be. This supports the assumption that the slabbed face approximately reflects the direction of maximum and minimum elongation. CAIs, though irregular in shape, are also elongate and follow the alignment of chondrules. Matrix-like clasts are elongate as well, but deviate somewhat from the parallel arrangement of chondrules and CAIs.

The Leoville meteorite, which consists of two stones, was found just north of Leoville, Decatur County, Kansas, in 1965. The larger stone weighs 6500.0 g and the smaller 1,628.8 g (figure 2). These two stones are properly called Leoville (a) because an unrelated meteorite, found later at a location nearer to Leoville, Kansas, is called Leoville (b). However, as no further reference is made in this paper to Leoville (b), Leoville (a) will be called simply Leoville. Leoville evidently lay in the ground for a long time as much of the surface is encrusted with lime from the soil, and there are calcite crystals within fractures intersecting the surface. Samples from both stones were seen in this study. Sample numbers and location of each may be seen in Appendix A.



a. Stone weighs 1,628.9 g.



b. Stone weighs 6,500 g.

Figure 2. The two Leoville stones. Photographs by G. Huss (pers. comm., 1984).

The best descriptive references for Leoville are Keil et al. (1969), McSween (1977), and Wright-Clark and Goles (1983). Chemical data are given by McCarthy and Ahrens (1972): bulk chemical analysis; McSween (1977): composition of olivine and pyroxene, Ni contents of metal and sulfide minerals, bulk compositions of chondrules; McSween and Richardson (1977): matrix analysis; Clarke et al. (1970), Wiik (1969), and Ahrens et al. (1973): elemental weight ratios; Mazor et al. (1970): primordial rare gases; Kallemeyn and Wasson (1984): elemental abundances; Kracher et al. (1984): oxygen isotope data; Knab (1981): distribution of trace elements. Petrofabric studies were performed by Martin et al. (1975), King et al. (1978), Michel-Levy et al. (1979). Each noted the preferred orientation of chondrules, but went no further to quantify or describe the strain. Keil and Fuchs (1971) noted clasts in Leoville. The brecciated aspect of Leoville is covered by Kracher et al. (1984) who give chemical and petrologic data on clasts within Leoville. Preliminary strain analysis information is given by Cain and McSween (1984a, 1984b).

Leoville has undergone structural deformation of the chondrules. This kind of chondrule shape modification was noted previously in only a few chondrites, and none of those were so extensively deformed. The deformation resulted in all the chondrules being flattened so that their long axes aligned in the same general direction. Preferred orientations of elongate chondrules were recognized previously in CV chondrites (King et al., 1978; Martin et al., 1975), but the fact that the chondrules must be flattened in order to show preferred orientations has not been generally appreciated. Virtually all chondrules,

CAIs, and clasts in Leoville have been flattened, producing a strong foliation.

The unique qualities of Leoville make it a particularly good sample for a petrofabric study. No other meteorite displays so pronounced a foliation. As a result of Leoville's initially being owned by a private collector, it was sliced into many parallel pieces. This is unusual, but, in this instance, especially useful because it permitted study of the interior of Leoville as well as a description of the three-dimensional character of the structural features.

Using several methods, the amount of strain sustained by Leoville during deformation was calculated in this study. The possibility that the chondrules and matrix absorbed different amount of strain was also examined. The length of time required for the straining at geologically reasonable strain rates was calculated. The possible dominant mechanism of deformation has been determined by means of temperature/pressure models and optical and scanning electron microscopy. Probable chronology of structural features has been established.

For the purpose of comparison, strain analysis of three other CV3 chondrites, Bali, Efremovka, and Grossnaja, are included in this study. Evidence of deformation in these meteorites, similar to that seen in Leoville, supports the idea that internal parent body processes, rather than localized phenomena such as impacts, are responsible for the observed strain.

This type of study is possible on probably no other meteorite. This is the first time that fabric has been studied for such quantitative implications about the parent body as necessary depth, deviatoric

stresses and temperatures of deformation. The fact that strain rates play an important part in deformation of chondrites has not been considered previously. Though many questions are possibly answered in this study, many other questions are raised by it. Characterization of this type of deformation should shed new light on internal processes in planetesimals and underscores areas of meteorite study that need to be approached from a new perspective.

Review of Carbonaceous Chondrites

Carbonaceous chondrites are generally considered to be the most primitive meteoritic samples of early solar system material. Except for the most volatile elements (H, O, N, He) the ratios of major and trace elements in carbonaceous chondrites are similar to the sun, and they have experienced only minor metamorphism or aqueous alteration. This means that they have undergone little change in the approximately Gy 4.5 since their formation, thereby retaining a record of events from the early solar nebula. In contrast, terrestrial and lunar rocks and achondritic meteorites have undergone processing and differentiation within their parent bodies, and earliest records have been obliterated.

Originally subdivided according to their water and carbon content into groups I, II, and III by Wiik (1956), the carbonaceous chondrites have been reclassified by subsequent researchers. Van Schmus and Wood (1967) put the carbonaceous chondrites into one chemical group called C, but modified Wiik's subdivisions to create groups C1, C2, and C3. Using textural and chemical properties, Van Schmus and

Hayes (1974) subdivided the C3 group into the CO3 and CV3 groups, typified by the type meteorites Ornans and Vigarano, respectively. The designations C1, C2, CO3, and CV3 supposedly imply a metamorphic sequence of increasing grade. Wasson (1974) recognized that these chondrites did not constitute such a sequence. Therefore, he proposed chemical groups corresponding to C1, C2, CO3, and CV3 which he termed CI, CM, CO, and CV, in that order. Then McSween (1979) reinterpreted the meaning of the designations of 1, 2, and 3 as representing grades of aqueous alteration. C3 chondrites are the least altered, and C1 chondrites are the most. Chondrites increase in petrologic type (metamorphic grade) from C3 to C6. Thus C3 chondrites are the least altered or metamorphosed. CV3 chondrites are considered to be the most pristine meteoritic samples.

Asteroids are the currently preferred possible source objects for carbonaceous chondrites, and in fact, for most meteorites. Spectral reflectance data have convincingly demonstrated similarities between several groups of meteorites and asteroids. Objections to this interpretation are based on the apparent difficulty of transferring unshocked asteroidal material into earth-crossing orbits within the short time frame indicated by the exposure ages of some meteorites. Comets in the past, were favored as possible source objects, but their highly eccentric orbits make it unlikely that they transferred material to earth-crossing orbits. Another problem with a cometary source is that the active life of comets is approximately 10^4 years (Wasson and Wetherill, 1979), and the shortest exposure age of any meteorite known

is 19,000 years (Dodd, 1981), suggesting that no presently active comet has supplied meteorites to Earth.

CHAPTER II

DESCRIPTION AND CHRONOLOGY OF STRUCTURAL FEATURES IN LEOVILLE

Structural features in Leoville include brecciation, foliation, cracks and veins, and distinct regions of metal-rich and metal-poor lithologies, which, at the outset of this study, were thought to define a fold. The relative chronology of these features can be determined on the basis of observational evidence and can be used to speculate on the timing of events on the parent body. Before describing the deformational features in Leoville, it is necessary to describe Leoville's petrography.

Petrographic Description of Leoville

Closely-packed, elongate chondrules in subparallel alignment are situated in black, opaque matrix similar to the way in which deformed oolites occur within their carbonate matrix. The chondrules range in size from approximately 0.7-3.5 mm. Because the matrix is so fine-grained (0.1-2.0 um), petrographic description is difficult, but it is known that the matrix is composed predominantly of ferromagnesian silicate phases with minor organic polymer, magnetite, and Fe- and/or Ni-bearing sulfides and oxysulfides (McSween, 1979).

There are two broad categories of chondrules based on grain size and shape. The group with the smaller grain size contains granular olivine with apparent diameter ranging from .01-.06 mm approximately. The olivine grains are rounded and equant, giving a granoblastic

appearance to the chondrules. Pyroxene is usually not associated with these chondrules which appear to be entirely olivine. The other category of chondrules contains some olivine which is also granoblastic in appearance, but the grain size ranges from 0.1-0.2 mm in apparent diameter. In addition to the rounded olivine grains, the chondrules may contain either or both of the following: large (up to 0.5 mm) anhedral olivine grains (some with a fractured appearance) and polysynthetically twinned clinoenstatite which poikilitically encloses rounded olivine grains. The proportions of rounded to anhedral olivine grains in these chondrules range from nearly all of one to nearly all of the other. In fact some chondrules contain no rounded equant olivine grains and are composed entirely of a few large angular olivine crystals. Pyroxene is rarely present in large proportions in any chondrules, though an occasional chondrule contains pyroxene as its dominant constituent. Most chondrules in Leoville are of the larger grain size type. Metal is usually associated with chondrules in both of these size categories. There are a few representatives of a chondrule type characterized by optically continuous, closely-spaced, parallel bars of olivine which are separated by glass. This type of chondrule lacks metal. According to McSween (1977) the fayalite content of olivine in all but the barred chondrules ranges from 0-7%, whereas the fayalite content in barred chondrules is 20-50%. Ferrosilite content in the clinoenstatite is 0-7%.

Often the outer edges of chondrules are finer-grained than the interior and appear to have been drawn away from the main portion of

the chondrules as if they were less competent than the chondrule interiors. As in hand sample, fractures cut across the meteorite and pass through chondrules uninterrupted. CAIs are elongate as are the chondrules, but are so fine-grained that they appear as essentially amorphous white masses. However, they are known to consist primarily of feldpathoid minerals, grossular, spinel and pyroxene (Grossman, 1975).

Metal, oxide phases, or sulfide droplets in abundance are associated with the majority of chondrules in the two size categories. These chondrules are "armored" by droplets of the opaque minerals, giving the rim a spongey appearance, and/or they contain droplets in seemingly random locations within the chondrules. Certain areas of the meteorite contain abundant metal; others contain oxide phases and sulfide minerals instead. Those areas which contain the latter are invariably streaked by small oxide mineral-filled veins; very few veins occur in metal-rich areas. Small flecks of opaque minerals occur throughout the matrix.

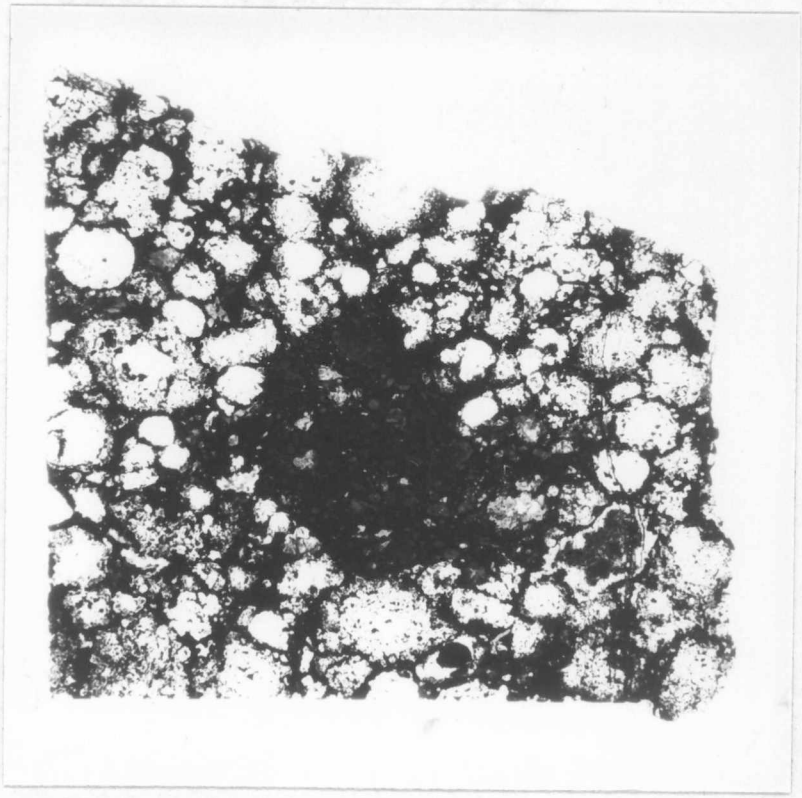
Thin section USNM 3535-1 contains a large (14 x 6.5 mm) clast which is highly altered (figure 3a). It is rust to brown in color due to Fe coloration. Objects within the clast look as though they are smaller than most host chondrules and CAIs. Fractures in the host pass through the clast as well, though they are colored red in and just outside the clast.

Figure 3. Features in Leoville.

a. CM2-like clast in USNM 3535-1. Clast shows the effects of hydrous alteration.

b. Veins intersecting previously foliated chondrule. Lack of offset of veins passing through chondrule indicates that foliation occurred prior to fracturing. Note oxide mineral-filled vein in metal-rich area. Due to the scarcity of weathering conduits in this area, only the metal directly around the vein has been converted to an oxide phase.

a.



b.



Figure 3.

Brecciation

Kracher et al. (1984) presented evidence that Leoville is an "accretionary breccia." An accretionary breccia is characterized by clasts (xenoliths) that appear to have been accreted along with all the other meteorite constituents during the parent body formation, rather than to have formed on the parent body surface as a result of impact stirring ("regolith breccia"). This means that the clasts must have formed prior to accretion of Leoville. Absence of shock melting, fragmentation, and implanted solar wind gasses, and the good preservation of delicate features in Leoville, are characteristic of accretionary breccias in general.

Clasts in Leoville range in size from approximately 5 mm to over 20 mm and are distributed unevenly throughout the matrix. They are elongate in shape, but are less uniform in orientation than the chondrules. Most observable clasts are composed of material similar in composition and texture to the matrix of the host meteorite, and may contain a few chondrules. However, there are also clasts similar to those in CM2 chondrites in Leoville (Kracher et al., 1984), one example of which is shown in figure 3a. A description of this clast in thin section is presented in the petrographic description in Chapter II. These clasts exhibit varying degrees of hydrous alteration, but all are altered to a greater extent than the host. They are composed of dark, very fine-grained phyllosilicates in which are imbedded fragmental objects resembling former chondrules and CAIs.

Foliation

Parallel alignment of the long axes of elongated CAIs and flattened chondrules defines Leoville's foliation, which is its most obvious structural feature. There is no evidence of matrix compaction, though it surely occurred, and metal grains do not exhibit significant distortion. Approximately 65 volume percent of Leoville is comprised of chondrules and CAIs (McSween, 1977), and by good fortune the slabbed sections have apparently been sliced so that they display approximately their minimum and maximum axes (figure 1a, p. 3).

Development of foliation followed accumulation of all the meteorite components, and thus followed brecciation. Substantiating evidence for this sequence is the observation that chondrules in the clasts are deformed in the same manner as host chondrules and CAIs (figure 4). It is assumed that chondrules were nearly spherical initially, as they are in other chondrites (Martin and Mills, 1976), and that their elongation and similar long axis orientations are a result of subsequent deformational strain.

Fractures and Veins

Development of fractures and veins occurred after the foliation was produced, as these features pass through chondrules and continue uninterrupted through matrix (figure 3b). There is clear separation between material on both sides of some of the larger fractures that intersect chondrules. These fractures are probably a result of liberation of Leoville from its parent body or impact on earth, and the oxide mineral-filled veins represent terrestrial weathering which utilized the

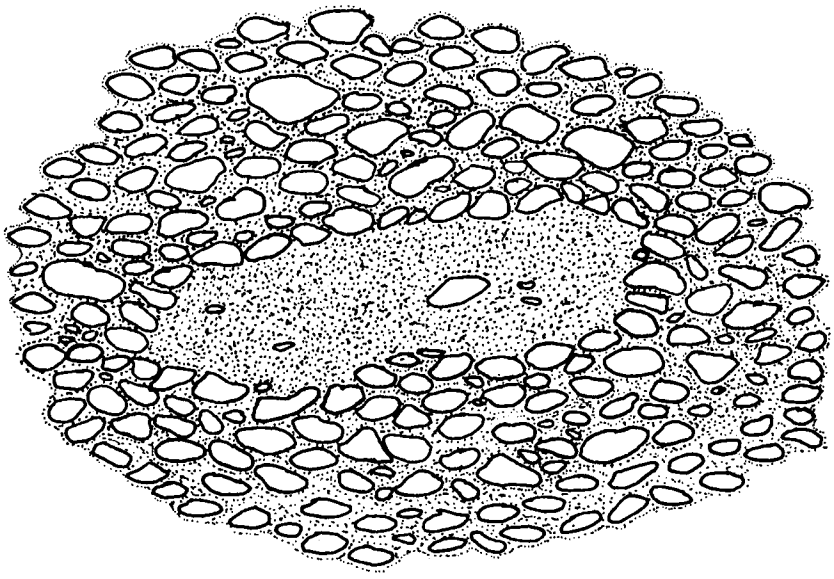


Figure 4. Sketch of a clast in Leoville Section H40.19. The few chondrules contained in the clast are oriented in the same direction as host chondrules, indicating emplacement of clast before development of foliation.

fracture pattern. There is little doubt, though, that both occurred after development of foliation. Were this not true, the clean separation resulting from fractures would not be evident, the veins and fractures would be discontinuous, and their subparallel alignment would have been destroyed.

Distinct Lithologies

Regions of metal-rich or metal-poor constituents appear to be the latest-formed features; they are probably a result of differential terrestrial weathering. The fractures in Leoville were conduits for terrestrial water which caused oxidation of the metal surrounding the fractures. This gave rise to a weathering pattern which, in cross-section, resembles an isoclinal fold (figure 1b, p. 3). The idea that a fold existed was incorporated into two abstracts (Wright-Clark and Goles, 1983; Cain and McSween, 1984a), but is now believed to be erroneous by the latter authors. Initially the whole chondrite was metal-rich. However, once on earth, terrestrial weathering caused oxidation in some areas, and the metal was converted to oxide phases. There was probably ample time for weathering of Leoville to occur as the meteorite is a find and lay on the ground, exposed to the elements, for an undetermined length of time. In metal-rich areas, the metal occurs primarily in droplets or blebs, mostly in and around chondrules, although small specks of metal are seen throughout the matrix. Much of the oxide phase in the metal-poor areas is in droplets identical in appearance to the metal droplets in the metal-rich areas, and it is probable that the oxide phases replace the metal. In fact, in

some oxide mineral droplets, small amounts of metal can still be seen, indicating that the metal has not been entirely oxidized. Areas that are metal-poor are riddled with veins filled by the oxide phase, whereas there are very few oxide mineral-filled veins in metal-rich areas. The metal in the metal-poor areas probably oxidized completely because there was such an abundance of fractures along which water could seep. Due to the scarcity of veins in other areas, there was little chance for weathering there, and these areas remained metal-rich. It is also important to note that where small veins do cross metal-rich regions, the metal on the immediate sides of the veins has been replaced by oxide phases (figure 3b, p. 15). The close association of oxide minerals with veins suggests a direct correlation between the two, and is easily explained as a weathering process. The apparent isoclinal fold appears in several slabs (H40.34, H40.54, H40.55, H40.56), but has not been observed in others (H40.8, H40.85, H40.19). Thus this "fold" appears to be a weathering artifact and is unrelated to deformation, as was previously argued by Cain and McSween (1984a).

Summary

A visual summary of the chronology of the structural features is given in figure 5a-d. Initially Leoville was formed as an accretionary breccia on its parent body. Overburden due to continued accretion deformed Leoville, thus producing a foliation. The liberation of the Leoville meteorite occurred probably due to collision of the parent body with another asteroid. Leoville later impacted earth. Fractures are

Figure 5. Summary of chronology of structural features.

a. Formation of accretionary breccia.

b. Production of foliation followed by removal of rock from depth to become a meteorite.

c. Fracturing is produced either during removal from parent body or collision on earth.

d. Fractures permit weathering in which metal is converted to an oxide phase.

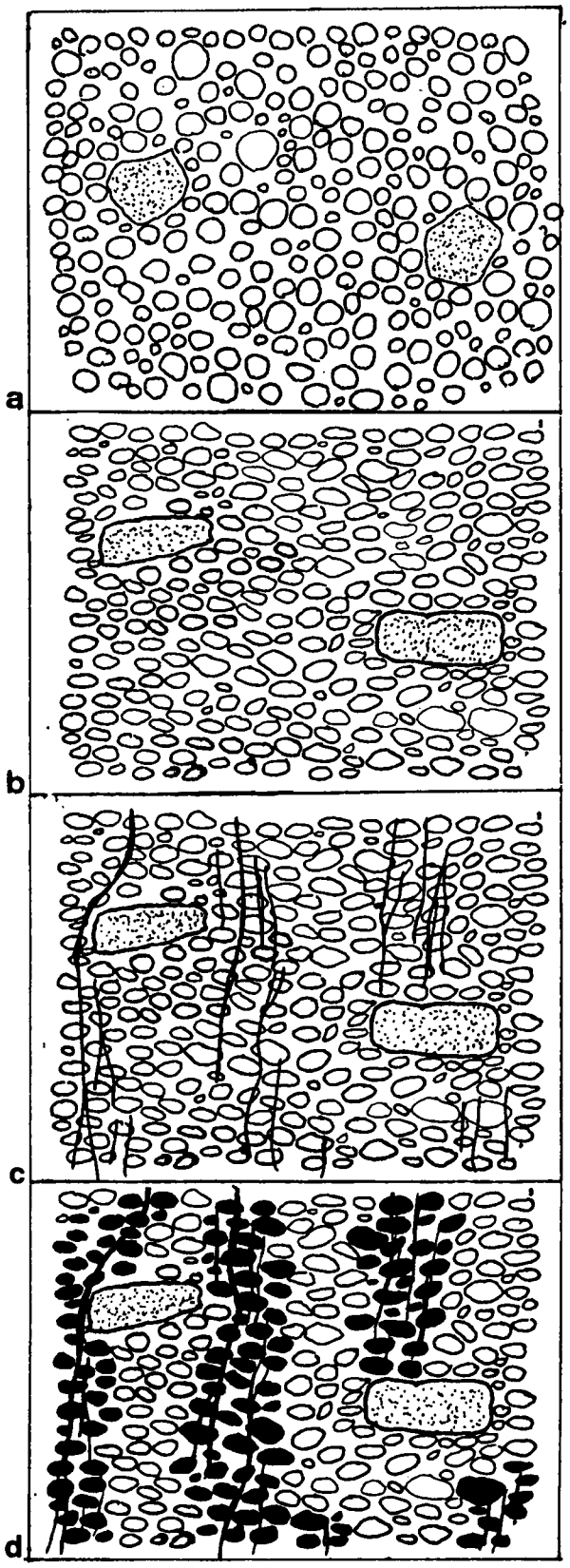


Figure 5.

probably a consequence of either or both impact on earth or liberation from the parent body. It lay undiscovered for a time long enough that terrestrial water seeped into fractures and caused oxidation of the metal surrounding fractures. Not only did the metal oxidize, but the smaller veins were also filled by an oxide phase as well.

CHAPTER III

STRAIN ANALYSIS AND DEFORMATION MECHANISM IN LEOVILLE

Much of this study is devoted to understanding strain, its cause and the mechanism of deformation in Leoville, because it allows insight into interior processes of the meteorite parent body. The forces that occurred within the Leoville parent body were great enough to systematically change the shape of chondrules, yet it is widely accepted that tectonic activity did not occur on asteroidal sized bodies. Measuring strain and determining the deformation mechanism will give very important information that is otherwise unobtainable. Leoville as an accretionary breccia was well studied by Kracher et al. (1984) and will not be further discussed here. The fractures and resulting weathering pattern are interesting, but have no bearing on parent body processes.

Strain Measurement

Leoville has undergone deformation such that the chondrules, xenoliths, and CAIs are flattened to produce a foliation. Deformation is a complex function of deviatoric stress, strain rate, confining pressure and temperature. In order to estimate some of these parameters, it is necessary to measure strain and deformation mechanisms. Deformed (flattened) chondrules and clasts in one slab of Leoville (approximate surface area 95 cm^2) were measured to assess strain. In order to make this determination, it was assumed that the chondrules

and clasts were originally nearly spherical, as they are in most chondrites. Martin (1976) found that of the 245 chondrules measured in the Chainpur chondrite and the 97 measured in the Bjurbole chondrite, 98% fall into the spherical class. He placed a chondrule in this class if both axial ratios, b/a and c/b, were less than 1.5:1. (Though Martin's observations support what is visually apparent, i.e., that most chondrules are nearly spherical, it raises an interesting question. Could many chondrites contain chondrules which are strained so slightly as to not be apparent to the observer? Martin's "spherical" chondrules have axial ratios of less than 1.5:1. A true sphere has an axial ratio of 1:1. Perhaps those chondrules whose axial ratios fall between 1:1 and 1.5:1 are slightly deformed. This may indicate that many apparently undeformed chondrites have actually experienced minor deformation. However, apparently few chondrites have been deformed to the extent that Leoville has.) CAIs are present as well in the slab, but, as they are known to have very irregular shapes in undeformed meteorites (McSween, 1977), they have been excluded from strain measurements.

Enlarged photographs of the meteorite slice were used for three independent strain analysis methods. The first is that of Cloos (1947), and measures strain only in the chondrules. The second method, that of Fry (1978), determines a value for strain in the whole chondrite. The last method, which follows Dunnet's (1969) procedure, is for chondrules only, but also gives an estimate of the original chondrule shape.

Using the method that Cloos (1947) applied to deformed oolites, the axial ratios of 287 chondrules in Leoville were measured directly. Measurements for the chondrules are found in Appendix B. The long and short axes of each chondrule were traced onto an overlay (figure 6a) that was placed over an enlarged photograph. The lined area in figure 6b illustrates the portion of Leoville section H40.55 from which these axial drawings were taken. The lengths of each set of axes were measured and the axial ratio of each chondrule was computed. Axial ratios vary from 1.0:1 to 2.8:1 with peaks at both 1.8 and 2.0, as shown in histogram form in figure 7a. These two peaks probably do not reflect a bimodal distribution, but are merely a consequence of inaccuracy in measurement due to poor resolution upon enlargement of the photograph. The next most frequent occurrence of a particular axial ratio is 1.9, which falls between the two peaks. The computed mean and standard deviation for these measurements are 1.9 $\pm$ 0.4.

Another means of deriving strain ratio is Fry's (1978) center-to-center method, which determines the orientation of the strain ellipse and its axial ratio. This method is especially important as it measures strain in the whole rock, chondrules and matrix, whereas the other methods employed measure only chondrule strain. In this procedure, a plot is generated by placing a clear overlay with one reference dot on top of an enlarged photograph so that the reference dot lies above the center of a chondrule in the photo. The centers of all the surrounding chondrules are then marked while the overlay is held stationary.

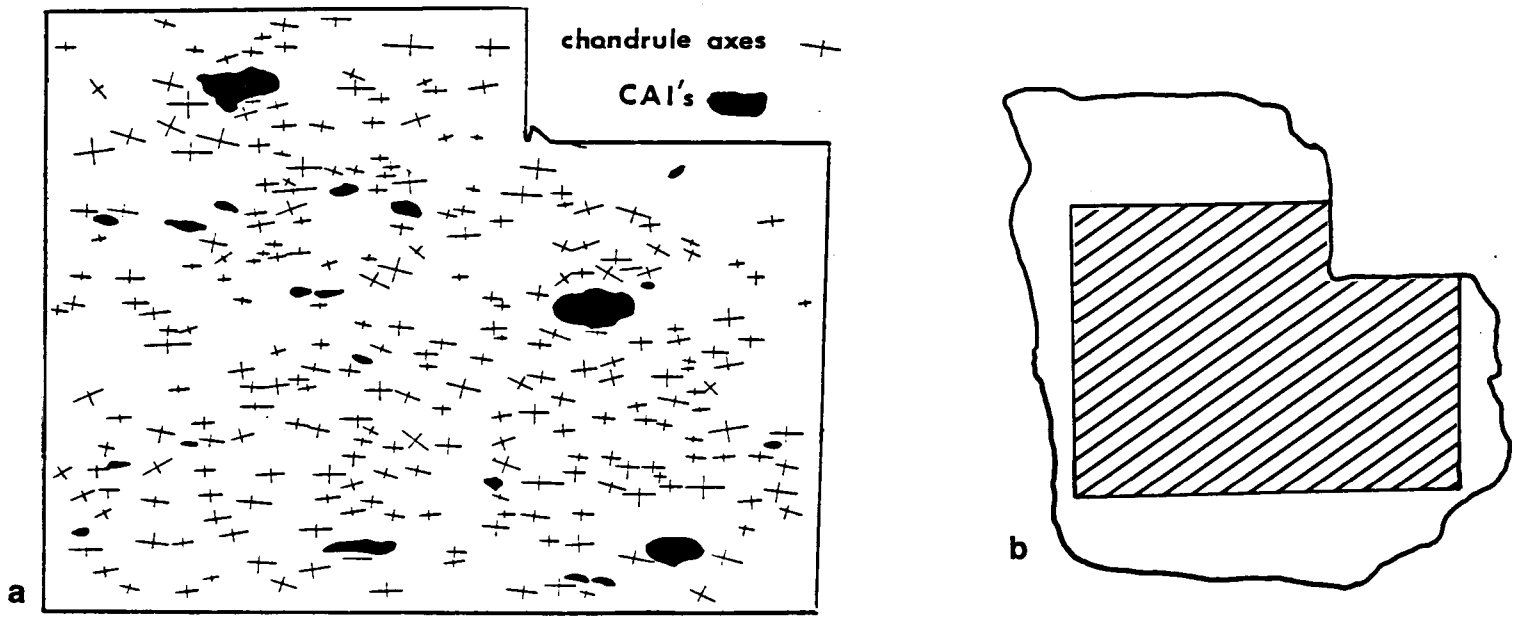
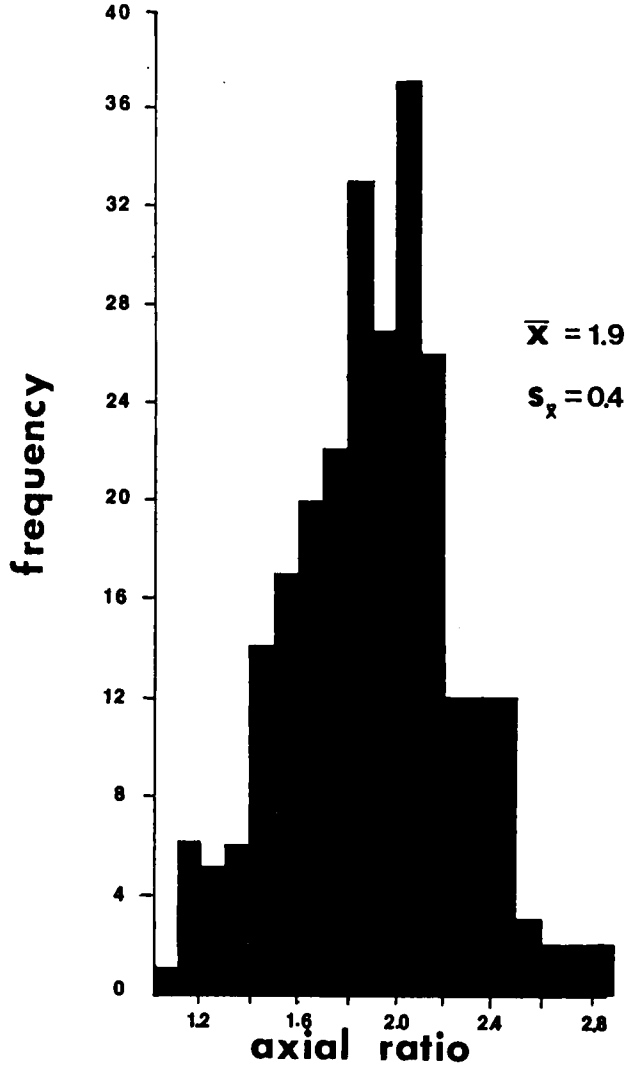
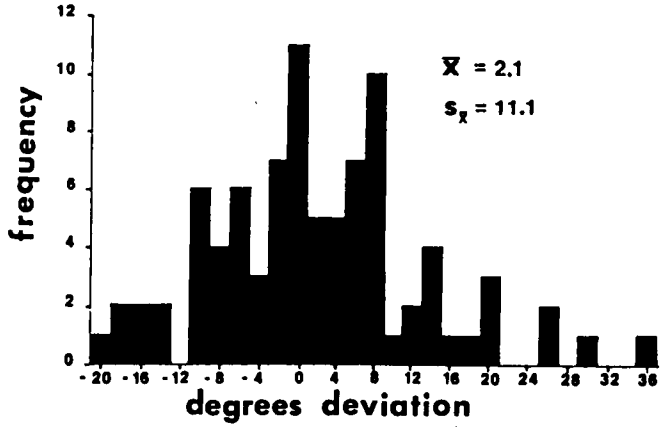


Figure 6. Sketch of chondrule axes.
(a) Long and short axes of 287 chondrules define the foliation of Leoville. CAIs are also obviously elongated (Leoville section H40.55). (b) Diagonal lines indicate portion of Leoville section H40.55 which was enlarged for axial details in figure 6a.



a. Axial ratios of chondrules in figure 6a.



b. Orientation of chondrules in figure 6a relative to the principle plane (angular deviation).

Figure 7. Histograms of chondrule axial ratios and orientations.

This is repeated several hundred times, as the reference dot is moved to the center of each chondrule. In the end, a void ellipse is created which mimics the dimensions and orientation of the strain ellipse for the whole chondrite.

If this method were used on unstrained chondrules with an isotropic distribution, the final plot would be a void circle because the distribution of chondrules relative to one another is uniform and the same in all directions. However, if a homogeneous strain was experienced by the meteorite, the chondrules would have deformed systematically, and the distance between chondrules in any specific direction would then vary consistently. Because of this, the final plot is a void ellipse.

In order for this type of measurement to be valid, the entire chondrite should be homogeneous. Leoville fits this description except where it contains clasts, but their rare occurrence should have a negligible effect on the total strain values. It is also important that the measured area be planar and contain several hundred chondrules. The slab of Leoville is planar and well over 300 chondrules were used. Strain values must not be excessive, because the center-to-center method becomes unreliable with strain values greater than 6:1 (Fry, 1978). The strain as measured by the method of Cloos (1947) is approximately 1.9:1 in Leoville, and is therefore well below the limit.

The axial ratio for the strain ellipse of Leoville, as a result of the Fry procedure, is approximately 2.0:1. This is in close agreement with the value from the Cloos method, as it should be. The orientation of the ellipse (figure 8) defines the principal plane of chondrule

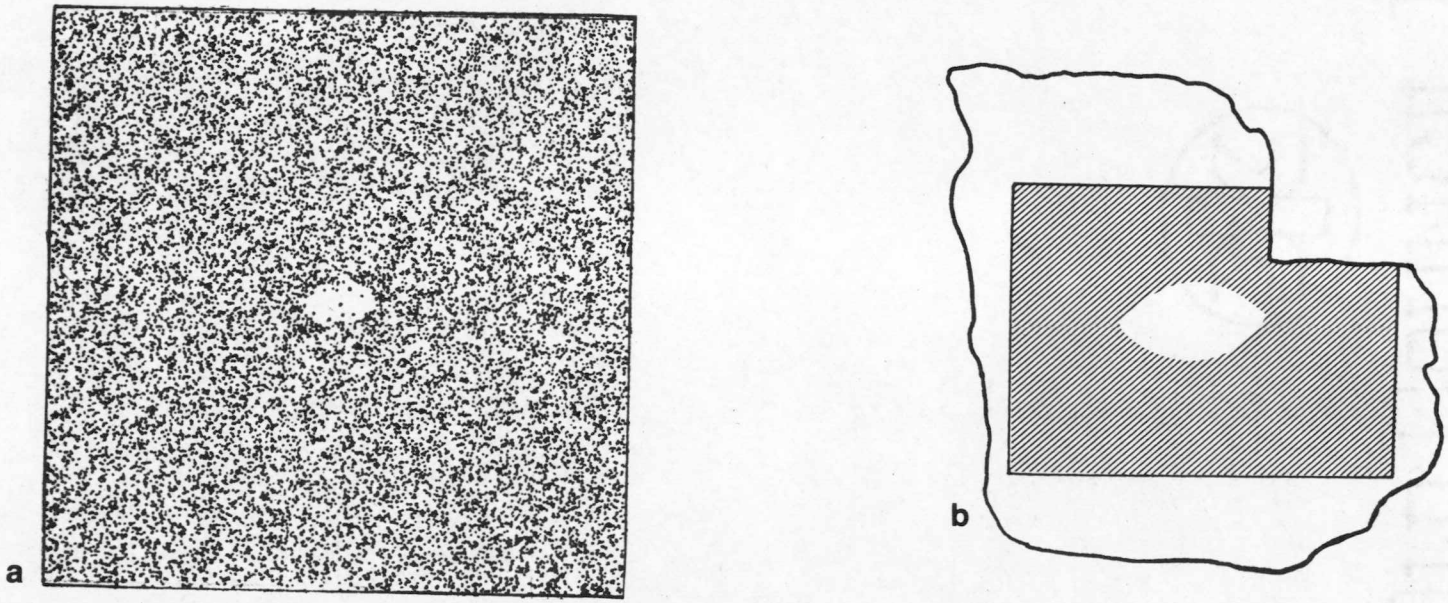


Figure 8. Strain ellipse and its orientation as determined by Fry's method. (a) Void ellipse derived by Fry's (1978) strain analysis method. Axial ratio and orientation of ellipse should approximate those of the actual strain ellipse for Leoville. (b) Strain ellipse superimposed in correct orientation on planar section H40.55.

maximum elongation. The orientation of this plane will be utilized in the next method of strain analysis.

It has been assumed that chondrules were initially nearly spherical, but to check the accuracy of this assumption, the method described by Dunnet (1968) was employed. Additionally, it is yet another check on the strain value and orientation of the principal plane of maximum elongation for chondrules. Terms used for plotting of the data are as follows:

R_i--initial axial ratio of chondrule (before deformation);

R_f--final axial ratio of chondrule;

R_s--strain value imposed on chondrule;

ϕ --final angle between long axis of chondrule and principle strain direction (as determined by Fry's method).

Using log-normal graph paper, the R_f for each chondrule in a random selection of 1/3 of the chondrules from figure 6a were plotted against the ϕ for the same chondrule. This diagram is shown in figure 9. First, using the minimum and maximum values for R_f, the logarithmic mean was calculated. This value should indicate the strain value for chondrules. The mean R_f is 1.88:1, which is in close agreement with the chondrule mean strain value of 1.9:1 from the histogram of axial ratios by Cloos' method (figure 7a). Interestingly, both values for chondrule strain as measured by Cloos' and Dunnet's methods, are quite close to the Fry method strain value of 2.0:1 for the overall chondrite. This would seem to indicate fairly homogeneous deformation of chondrules and matrix (i.e., no significant ductility

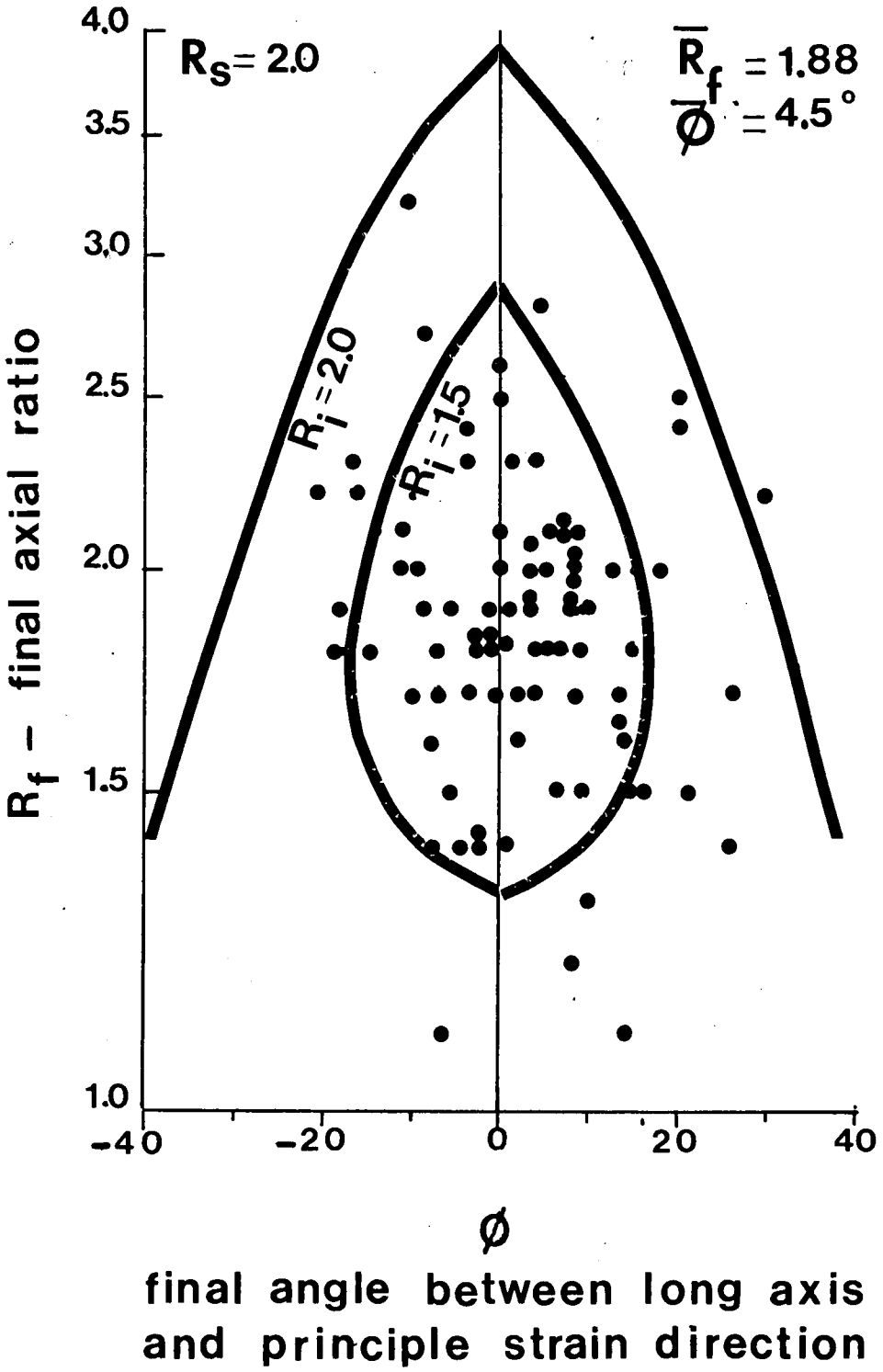


Figure 9. R_f/ϕ plot. R_f mean should indicate strain value for chondrules. Mean ϕ should reflect orientation of principle plane. Most data plot within $R_i = 1.5$ curve, indicating nearly spherical shape of chondrules prior to deformation.

contrasts). Next a series of calculated R_i curves from Dunnet (1968) corresponding to a strain value of 2.0 (i.e., R_s = 2.0), were visually fitted to the scatter of in the R_f/ϕ plot. The majority of the data points should fall within a curve whose number gives a maximum initial axial ratio (R_i). As seen in figure 9, most points fall well within the 1.5:1 curve (R_i = 1.5), indicating that most chondrules had an axial ratio before deformation of less than 1.5:1. A low concentration of points around the center of the scatter would indicate a lack of initially spherical chondrules, but this is not the case.

The angular mean for ϕ should reflect the orientation of the λ_1-λ_2 principal plane. The 0° line on the ϕ axis was chosen to represent the direction of chondrule maximum elongation determined by Fry's method, and the angular deviations (ϕ) of the chondrules were measured from this line. However, the mean for ϕ, using ϕ maximum and ϕ minimum is 4.5° off. This discrepancy is acceptable because the mean can be offset by the presence of a few anomalous measurements which skew the graph. A histogram for angular deviation from the principal plane of all chondrules in figure 6a (p. 28) is shown in figure 7b (p. 29).

The Dunnet and Cloos methods give chondrule strains. It is also important to know how much strain the whole chondrite experienced which the Fry method gives. Considering the different textures of the two, chondrules and matrix might absorb different amounts of strain. However, considering that the strain value, calculated earlier for the whole chondrite, is 2.1:1, and the individual chondrule strain rate is 1.9:1, chondrules and matrix probably took up equivalent amounts of

strain. The difference in the two values is probably negligible given the induced error from photograph enlargement and visual judgments.

Deformation Mechanism

One of the purposes of calculating strain experienced by Leoville is to be able to estimate the conditions that caused the deformation. Shear stress, temperature, and strain rate control the deformation mechanisms. If the mechanisms are first identified, it is possible to constrain other variables. Common mechanisms are fracturing or one or more of the several types of plastic flow. Confining pressure is also a significant factor, but may not be important in this instance because pressures in asteroids probably are rarely greater than 1 kb, even at the center (Wasson, 1974).

Ashby and Verrall (1977) examined olivine deformation mechanisms experimentally. Application of these results to carbonaceous chondrites is reasonable because olivine is the dominant mineral in the chondrules. Chondrules also contain pyroxene, interstitial glass, and other phases, but the amount of strain in chondrules is so great that it is not possible that the olivine in them did not deform. If pyroxene were present in quantity in Leoville chondrules, there would be a problem with basing strain rates on olivine experiments and calculations. As noted in the petrographic description in Chapter II, the amount of pyroxene present is insignificant relative to the amount of olivine present. Research on strain rates and deformation mechanisms has been restricted primarily to olivine, not pyroxene, because olivine is the dominant constituent in the upper mantle of the earth. For

these reasons I have disregarded pyroxene as having an effect on the strain rates and deformation mechanisms in olivine. As strain analysis by the center-to-center method for the whole meteorite and by the R_f/ϕ method for chondrules alone indicate a negligible difference between the two, strain calculated for the chondrules probably applies to the chondrite as a whole.

Possible deformation mechanisms for olivine include cataclasis (cleavage), low-temperature plasticity, power-law creep, and diffusional flow. Ashby and Verrall's (1977) olivine deformation map (for a grain size of 0.1 mm at zero confining pressure) relates dominant deformation mechanism, deviatoric stress, and temperature (figure 10). Cataclasis involves cleavage fracture of the grains with coincident grain boundary sliding. This is a low-temperature mechanism, and with even minimal shear stress, grain boundary sliding is suppressed as shear stress rises above approximately 4 kb (figure 10). Low-temperature plasticity is plastic flow by glide-type dislocations occurring at low temperatures or high rates of strain. Power-law creep is a complex type of plastic flow involving the interaction of both climb and glide motions of dislocations. Diffusional flow is also a type of plastic flow whereby grains change their shape as ions diffuse along lattice planes or grain boundaries. This process occurs at high temperatures and low shear stresses. Ashby and Verrall (1977) provide more details on these types of deformation.

Of the four mechanisms, cataclasis as the dominant mechanism in Leoville can be dismissed on the basis of its high deviatoric stress

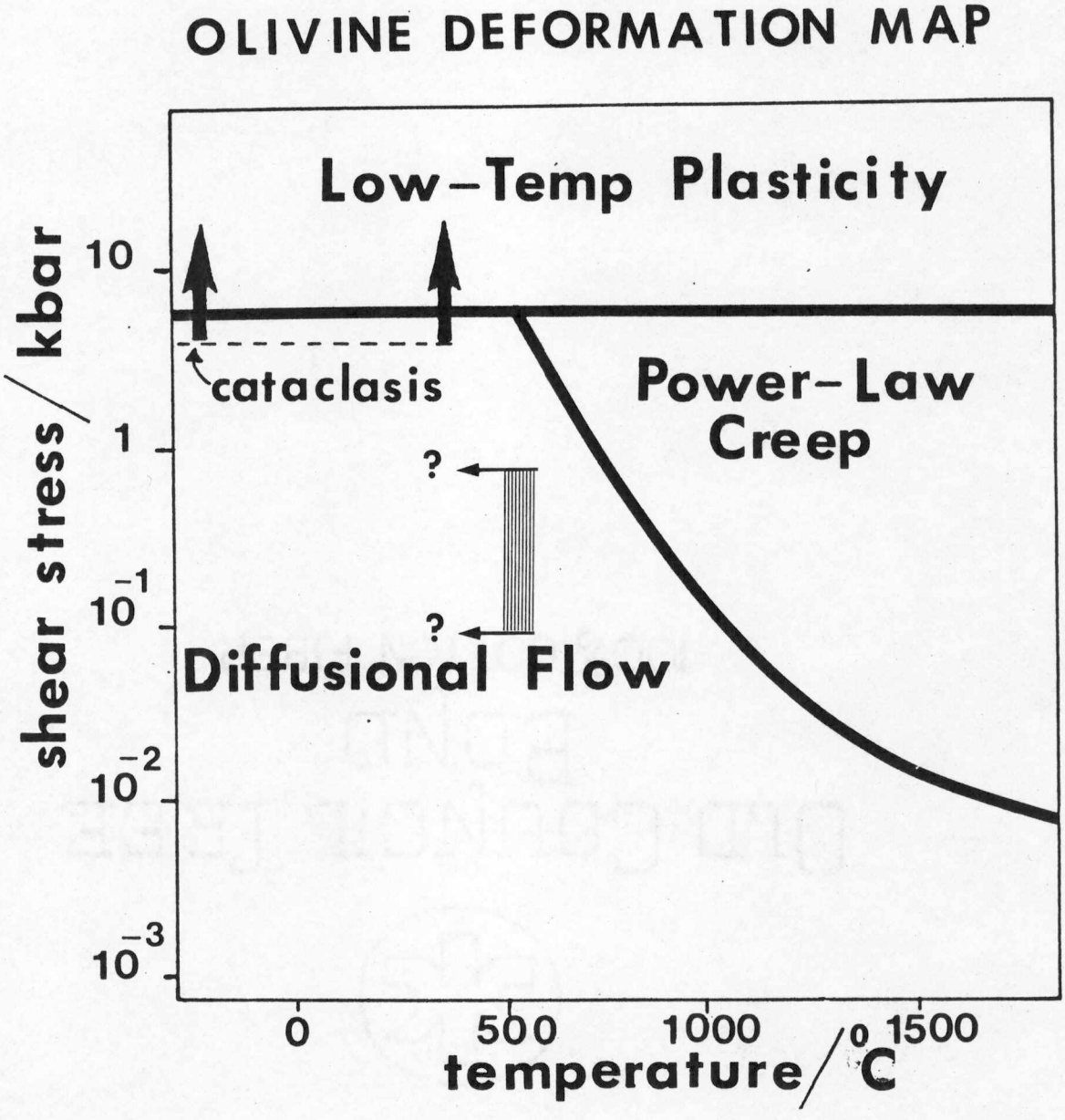


Figure 10. Olivine deformation map for a grain size of 0.1 mm at zero confining pressure. Relates dominant deformation mechanism, deviatoric stress, and temperature (after Ashby and Verall, 1977). Ruled area represents range of probable temperature and deviatoric stress conditions of Leoville.

requirements. It is unlikely that pressures great enough to allow cataclasis to act as the dominant deformation mechanism existed in any carbonaceous chondrite parent body because of its small size. However, some cataclasis in chondrule olivines is evident in the form of fractures and minor offsets. Though cataclasis is probably responsible for some of the observed deformation, it is not likely that it is the dominant mechanism of deformation.

Both low-temperature plasticity and power-law creep should be recognizable by microscopic lattice dislocations in chondrule olivine. Two methods designed to reveal dislocations in olivine were employed in looking at approximately 100 olivine grains in chondrules. The first, thermal decoration (Kohlstedt et al., 1976), involved heating a small sample in air at 900°C for one hour in order to selectively precipitate iron oxides along dislocations. The second, chemical etching (Wegner and Christie, 1974), involved immersing a small sample of the meteorite in a mixture of hydrofluoric and hydrochloric acids to etch preferentially the intersections of dislocations with the mineral surface. The sample was then viewed using scanning electron microscopy. Both methods failed to reveal the presence of such dislocations. However, a possible reason for the lack of evidence using the first method is that the Fe content in Leoville olivines is so low that iron may not be available to precipitate in dislocations. This would appear to rule out low-temperature plasticity and power-law creep as possible deformation mechanisms. However, Muller and Wlotzka (1982) and Michel-Levy et al. (1979) did observe by transmission electron

microscopy dislocations in chondrule olivine which they attributed to shock. These different results may have occurred because of the methods utilized.

My inference is that diffusional flow, characteristic of low- to moderately-high temperatures and low deviatoric stress, was the major deformation mechanism in Leoville. The major evidence is lack of other features; therefore, the possibility had to be substantiated by some other means. One way of doing this is by determining if conditions within an asteroidal body are consistent with diffusional flow as the dominant deformation mechanism. Is it possible to calculate whether probable temperature and pressure conditions near the center of an asteroidal body fall into the diffusional flow region on the deformation map (figure 10)? The reason for choosing a region near the center of the body is because, presumably, it should represent maximum temperature and pressure conditions, and therefore provide an upper limit for pressure, though it is highly unlikely that the sample was actually at the center.

Parent Body Models

No temperature constraints have been placed on Leoville geochemically, but Allende (a similar CV3 chondrite) is well studied in this respect. It is probable, because of the similarity between Allende and Leoville, that temperature conditions for the two were nearly the same. Remnant magnetism in Allende indicates that it could not have been heated to the Curie temperature (585°C) at any time following accretion (Brecher and Arrhenius, 1974). Awaruite and heazlewoodite,

both found in Allende, invert at 503°C (Kullerud and El Goresy, 1969) and 556°C (Kullerud and Yund, 1962), respectively. Their presence argues for maximum temperatures no greater than approximately 500°C, but it is possible that these minerals reinvert upon cooling, thus obscuring the maximum temperature. This estimate is also supported by the presence of pentlandite in addition to awaruite and heazlewoodite, as this three phase assemblage is not stable above 500°C (McSween, 1977). Concordant isotopic temperatures derived from a plagioclase-magnetite pair and a plagioclase-olivine pair in Karoonda, a recrystallized CV4 chondrite, place the temperature of metamorphism at 590° and 580°C, respectively (Clayton et al., 1977). This should be valid if these minerals equilibrated during metamorphism, but if they attained such temperatures before incorporation into the parent body, the meteorite as a whole may never have reached these temperatures. Thus, isotopic temperatures should represent an absolute temperature maximum for the meteorite. Karoonda presumably experienced a greater degree of metamorphism than unrecrystallized Leoville, implying that it experienced greater temperatures as well. Thus the maximum temperature that Leoville experienced was probably 500-600°C.

Depending on the size of the Leoville parent body, internal pressures generated can range. The radius of 1 Ceres, the largest asteroid, is only 500 km (figure 11), and most asteroids are less than 200 km in radius. Assuming a uniform density of 3.6 g/cm^3, pressure at the center of a body with a 200 km radius is about 1 kb (figure 11).

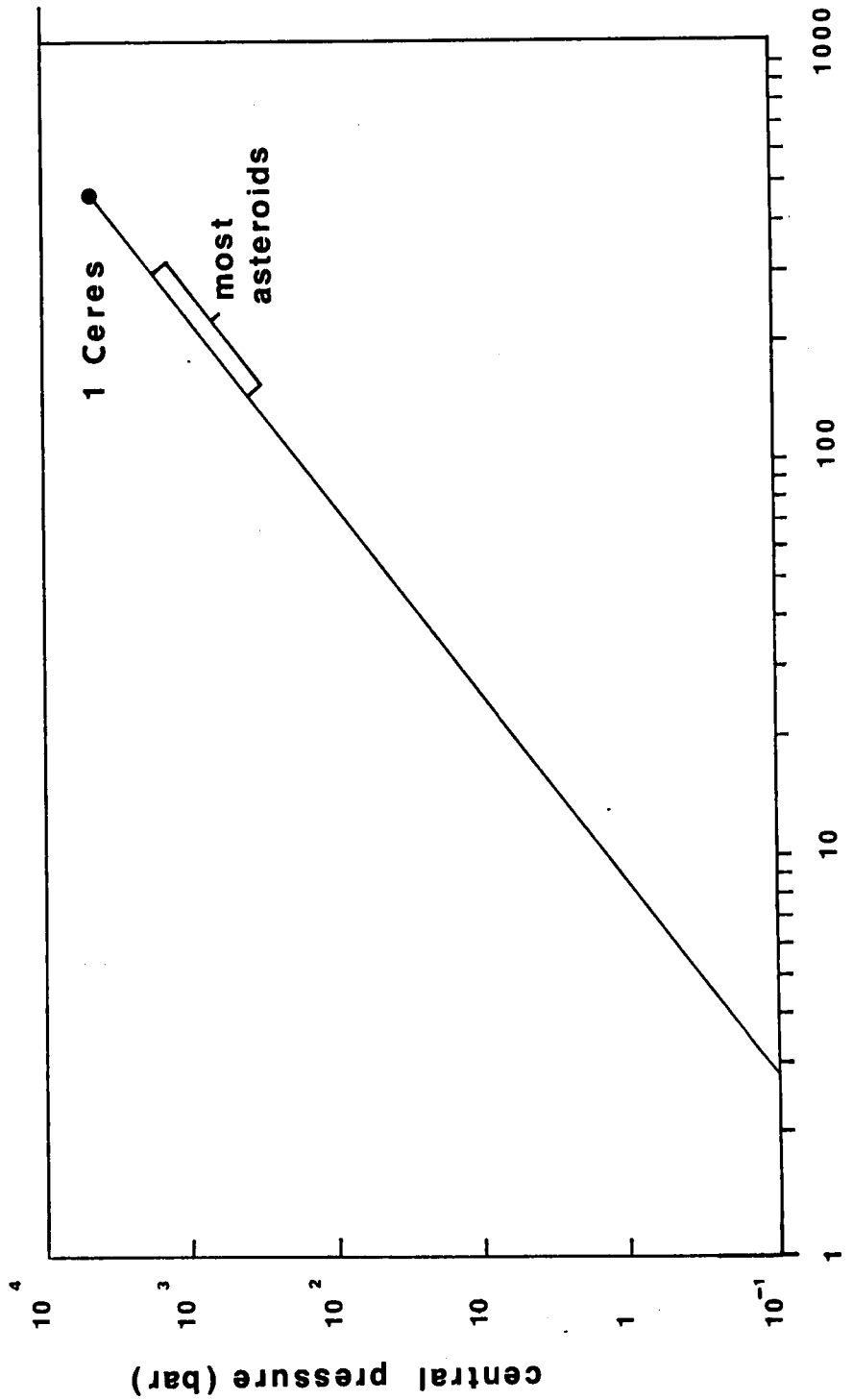


Figure 11. Internal asteroid pressure as a function of radius in bodies with a uniform density of 3.6 g/cm^3 (after Wasson, 1974).

Rather than knowing simply a central lithostatic pressure, the maximum deviatoric stress must be known. The deviatoric stress is the actual stress available to cause deformation and is determined by subtracting confining pressure from the total stress state (Spencer, 1977). The appropriate deviatoric stress can be ascertained from the following equation:

$$\bar{\sigma}^2 = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right] \quad (1)$$

where $\bar{\sigma}$ is deviatoric stress, and σ_1, σ_2, and σ_3 are principle stresses. Uniaxial stress, designated as σ_1, is the force resulting from overburden due to progressive accretion, and is therefore equal to ρgh. Thus

$$\sigma_1 = \rho gh \quad (2)$$

where ρ is density, g is acceleration due to gravity, and h is depth. The stresses σ_2 and σ_3 are due to confining pressure, and in an asteroidal body are equal to one another ($\sigma_2 = \sigma_3$). Because of this equation (1) simplifies to:

$$\bar{\sigma}^2 = \frac{1}{6}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_1)^2\right] \quad (3)$$

The values for σ_1 and σ_2 are calculated from the following equations for stress-strain relations in an isotropic solid (Jaeger, 1969):*

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*Though the derived values for σ_1 and σ_2 using these equations will be for stress under elastic conditions, an approximation of the order of magnitude of the stress under plastic conditions may be calculated by treating the finite strain, experienced by Leoville, as a series of incremental strains.

$$\sigma_1 = (\lambda + 2G)\varepsilon_1 + \lambda\varepsilon_2 + \lambda\varepsilon_3 \quad (4)$$

$$\sigma_2 = \lambda\varepsilon_1 + (\lambda + 2G)\varepsilon_3 + \lambda\varepsilon_3 \quad (5)$$

where ε_1, ε_2, and ε_3 are the principal strains. λ and G are material constants which are calculated for individual rock types, as explained later. Because $\sigma_2 = \sigma_3$, it follows that $\varepsilon_2 = \varepsilon_3$. Using the relationship:

$$\varepsilon_2 = \upsilon\varepsilon_1 \quad , \quad (6)$$

(where υ is Poisson's ratio**) in combination with equation (2), equation (4) becomes

$$\sigma_1 = \rho gh = \varepsilon_1(\lambda + 2G + 2\upsilon\lambda) \quad (7)$$

Rewriting equation (7) in order to solve for σ_1 produces the following:

$$\sigma_1 = \frac{\rho gh}{\lambda + 2G + 2\upsilon\lambda} \quad (8)$$

Again, using the relationship in equation (6), equation (5) becomes:

$$\sigma_2 = \varepsilon_1(\lambda + 2\upsilon\lambda + 2G\upsilon) \quad (9)$$

Replacing ε_1 in equation (9) with the value from equation (8) produces the following equation which gives σ_2 in terms of the material constants λ and G:

**Poisson's ratio relates lateral contraction to longitudinal extension.

$$\sigma_2 = \left(\frac{\rho g h}{\lambda + 2G + 2\upsilon\lambda}\right)(\lambda + 2\upsilon\lambda + 2G) \qquad (10)$$

Data for G and λ vary for the individual mineral or rock type, and were obtained either from Birch (1966) or by using the conversion identities, also from Birch (1966).

It would be desirable to calculate deviatoric stress for a rock of carbonaceous chondritic composition, but, because the value for this relies on material constants determined for specific rock types, none of which have been calculated for chondrites, a range of other rock types are used. CV3 values hopefully should fall somewhere within the range of deviatoric stress values for these rocks. Table 1 lists the values of σ_2 and $\bar{\sigma}$ for overburden pressures of 0.5, 1.0, and 2.0 kb (which correspond to parent body radii of 150, 200, and 300 km, respectively) as well as the G, λ, and υ values for each rock type considered. For example, at an overburden pressure of 1 kb in a sandstone (which would experience the most deviatoric stress), 0.6 kb deviatoric stress is sustained. In a dunite body (which would experience the least deviatoric stress) at the same overburden pressure, only 0.09 kb deforming stress is imposed. Relative to sandstone, dunite will deform less. It can be assumed that Leoville, composed primarily of fine- and coarse-grained olivine and pyroxene, will undergo deviatoric stresses between those for sandstone and dunite. The overburden pressure values used for these calculations are those at the center of the asteroidal body (figure 11). However, deviatoric stresses at the center of a body will be zero. Because of this, the

Table 1. A list of $\bar{\sigma}$ and σ_2 values for four different rock types with corresponding material constants for each rock type. Values for $\bar{\sigma}$ and σ_2 increase as asteroid radius and central pressure increase.

Rock type	0.5 kb central pressure, 150 km radius		1.0 kb central pressure, 200 km radius		2.0 kb central pressure, 300 km radius		Material constants for each rock type		
	$\bar{\sigma}$	σ_2	$\bar{\sigma}$	σ_2	$\bar{\sigma}$	σ_2	G	λ	ν
Sandstone	0.3	0.02	0.6	0.04	0.78	0.09	310	17	0.04
Quartz-muscovite schist	0.2	0.2	0.3	0.41	0.8	0.7	230	132	0.18
Metadiabase	0.2	0.2	0.3	0.5	0.6	0.9	480	345	0.2
Dunite	0.09	0.4	0.2	0.7	0.3	1.4	740	1288	0.3

calculated deviatoric stress values may be higher than the actual values. At any rate, the calculated deviatoric stress values should be absolute maxima for the asteroidal parent body.

With temperatures between 500° and 600°C and deviatoric stresses anywhere between 0.09 and 0.78 kb (the least to the most deviatoric stresses calculated for the various rock types on bodies ranging from 150-300 km in radii), the deformation conditions fall within the ruled area on the olivine deformation map (figure 10, p. 37). With these deviatoric stress and temperature constraints, conditions in the parent body interior are broadly consistent with diffusional flow as the deformation mechanism.

CHAPTER IV

DISCUSSION

Origin of Leoville Strain

A model in which chondrules are flattened by compaction probably requires accretion of the chondrules, as well as CAIs and matrix, into a substantial body rather than as small chunks in space (Dodd, 1965). Assuming that these materials were accreted onto an asteroidal body, certain questions about the origin of the chondrule foliation arise. Is it a compactional or thermal metamorphic feature, and could deformation have been caused by impact?

If the chondrule foliation were induced by high temperature metamorphism, there should be a systematic correlation between extent of deformation and degree of thermal metamorphism. However, there is extensive evidence to the contrary, indicating that deformation is a result of compaction due to overburden on the chondrite parent body. Dodd (1965) examined twenty H- and L-group ordinary chondrites exhibiting various degrees of recrystallization, 17 of which possessed a foliation, and concluded that the presence and intensity of the foliation were not related to the degree of thermal metamorphism. In an examination of friable and less friable chondrites, Martin (1980) found that the friable meteorites showed little to no preferred orientation of chondrule long axes, whereas the less friable samples exhibited varying degrees of long axis preferred orientation. The degree of friability of the samples presumably is related to their porosity and degree

of compaction. Compaction is related to magnetic foliation in some ordinary chondrites (Hamano and Yomogida, 1982). This implies a textural alignment of metal grains which would be coincident with chondrule preferred orientation. Brecher and Arrhenius (1974) considered preferred orientation of grains and magnetic foliation to be related in certain carbonaceous chondrites. As there was a correlation between long axis preferred orientation, degree of compaction, and magnetic foliation, yet none between magnetic foliation and degree of thermal metamorphism, it was felt that the observed fabric was not a result of thermal metamorphism.

A petrofabric study of the Allende meteorite (King et al., 1978) indicated the presence of a strong foliation. Because of Allende's low petrologic type, the authors felt that compaction was responsible for the foliation. Martin et al. (1975) examined 4 CV3 chondrites, of which Leoville was one. They found that preferred orientation of chondrule long axes was strong in Leoville and Grossnaja, but weak to nonexistent in Coolidge and Vigarano. Because the samples exhibited such a wide range in degree of orientation of chondrule long axes, they concurred with Dodd (1965) in his conclusion that there was no correlation between degree of thermal metamorphism and orientation of long axes.

There are several arguments against the deformation of Leoville resulting from shock. The most obvious is the lack of shock deformation features. Presumably, impact of objects into the chondrite parent body would be the source of such shock. There are many heavily

shocked chondrites, yet none shows foliation of the chondrules and CAIs. If strongly shocked meteorites do not exhibit this feature, it seems implausible that chondrule foliation in Leoville, which shows few significant shock effects, was caused by shock. Shocked lunar breccias commonly contain glass beads formed by impact melting (e.g., Kerridge and Keifer, 1977); however, these spherical beads are never deformed.

Prior to compaction, Leoville was probably a loose aggregate of matrix, chondrules, and CAIs (Kracher, 1984). In a porous medium, intergranular shock effects such as grain boundary melting should be apparent at much lower pressures than in compacted media. Schaal et al. (1979) found intergranular melts in porous, granulated basalts at pressures of 200 kb, and volumetric abundance of melt as high as 40% in samples shocked at 580 kb. Dodd and Jarosewich (1982) and Dodd et al. (1982) also related intergranular melting to shock. It seems that even minor shock should be recorded in Leoville by intergranular melts, and a shock great enough to have deformed every chondrule and CAI in the meteorite should have caused melting in abundance. However, lack of such melting in Leoville indicates that shock was not the deformation mechanism.

It also seems unlikely that shock effects could have been annealed out. Kracher et al. (1984) describe undulatory extinction and mosaicism in their LV-2 xenolith, indicating strong shock, and McSween (1977) described a clast which exhibited shock blackening as well. If evidence of shock in Leoville had been annealed by high

temperatures in the parent body, the shock effects in the clasts should have been erased as well, but as shock effects remain in certain clasts, it is doubtful that impact caused deformation in Leoville.

Compaction due to overburden seems to be the most plausible mechanism for the deformation of Leoville. As tectonic forces can not be invoked on small planetary bodies, compactional forces seem to be the only method of creating the necessary stress. Continued accretion would supply enough overburden to cause compaction of material at deeper levels. Evidence of similar deformation in other chondrites, e.g., Allende (King et al., 1978; Martin, 1980), various H- and L-group chondrites (Dodd, 1965), Parnalee, Kryahenya, and Kediri (Martin, 1980) make it easier to view the deformation as a result of primary parent body processes, such as compaction, rather than as a metamorphic or impact-induced event.

Strain in Other CV3 Chondrites

For comparative purposes as part of this study, three CV3 chondrites (Grossnaja, Bali, and Efremovka) were chosen in order to measure the axial ratio of the chondrules as well as the alignment of the chondrule long axes. These three meteorites were chosen from a group of thin section photographs because they displayed visible chondrule preferred orientation. Other photographs in the group did not. Because actual slabs of these meteorites do not exist, these enlarged thin section photographs were used in order to measure chondrule axial ratios. The section number for Grossnaja is unknown.

The section numbers for Bali and Efremovka are USNM 4839-1 and USNM 2348-1, respectively.

Ideally, measurements should be taken from three orthogonal faces of each meteorite. Unfortunately, this was not possible as photographs from only one face of each sample were available. It is unlikely that these faces represent the direction of chondrule maximum elongation (if it exists), but the results, at the very least, indicate minima for chondrule axial ratios and degree of chondrule long axis alignment.

All identifiable chondrules were traced from each photograph and their maximum and minimum axes were drawn. Measurements and sketches of the maximum and minimum axes of chondrules in each section can be found in Appendix C. As no principal plane can be determined, an arbitrary direction, represented by a line and designated as 0°, was chosen for each photograph. The angular deviation of each long axis relative to 0° was then measured. Both types of measurement are best represented visually by histograms (figure 12a-f). Grossnaja and Efremovka both show some degree of preferred orientation, whereas Bali exhibits little. All three meteorites have axial ratios predominantly greater than 1:1, with Grossnaja and Bali displaying peaks at 1.4:1 and 1.6:1, respectively. Assuming that the chondrules were originally nearly spherical, it is evident that most have been deformed to some extent.

Leoville, then, is not anomalous among carbonaceous chondrites. If chondrule deformation is due to overburden as proposed, Martin and

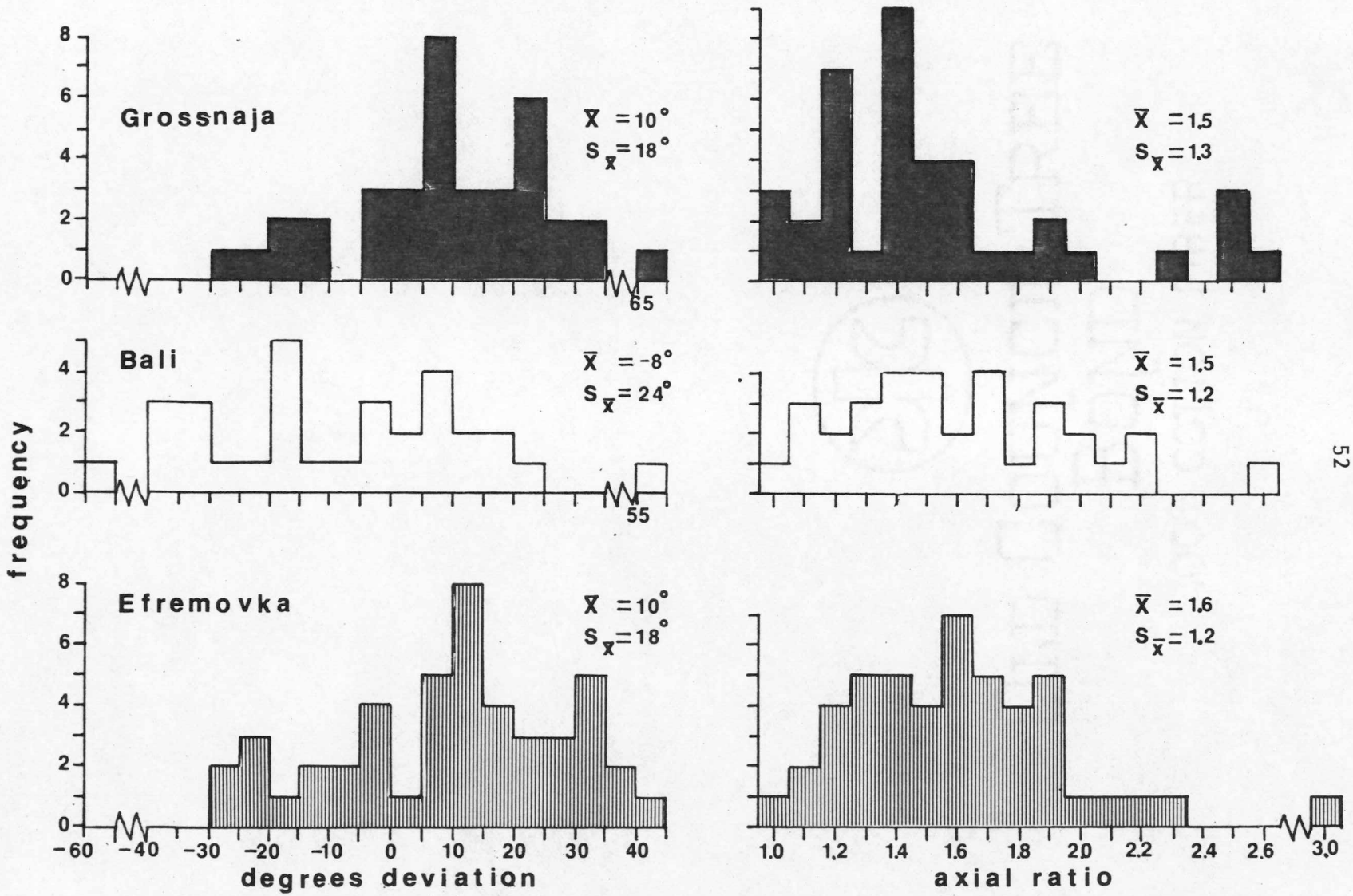


Figure 12. Orientations and axial ratios of chondrules in Grossnaja, Bali, and Efremovka.

Mill's (1980) conclusion that the variability in extent of chondrule preferred orientation is due to depth of burial, and therefore amount of overburden, seems valid.

Time Required for Deformation

Once the strain value is known, the amount of uniaxial shortening for Leoville can be calculated, and from that, the length of time required for deformation can be approximated. Shortening can be determined by calculating the decrease in the radius of a circle (representing undeformed chondrules) when the circle is transformed into an ellipse (representing deformed chondrules) of equivalent area. By simply using area equations for the two figures, the half axes of the ellipse are solved for, and knowing that the half axis of the original circle was one by definition, the difference can be given in terms of percentage of the original half axis. Thus the total uniaxial shortening, using the strain value 2.1:1 (established in Chapter III) for the whole chondrite, is 31%. This much shortening can be accomplished in 10^6-10^8 years at geologically reasonable terrestrial strain rates of 10^{-13}-10^{-15}/s (Phiffner and Ramsay, 1982).

Strain Rates: Problems and Possible Solutions

In a previous section it was found that diffusional flow, as the deformation mechanism, is consistent with calculated temperatures and deviatoric stresses for asteroidal interiors. However, strain rates also have to be considered. Figure 13 illustrates geologically reasonable terrestrial strain rates of 10^{-13} to 10^{-15}/s superimposed on the Ashby

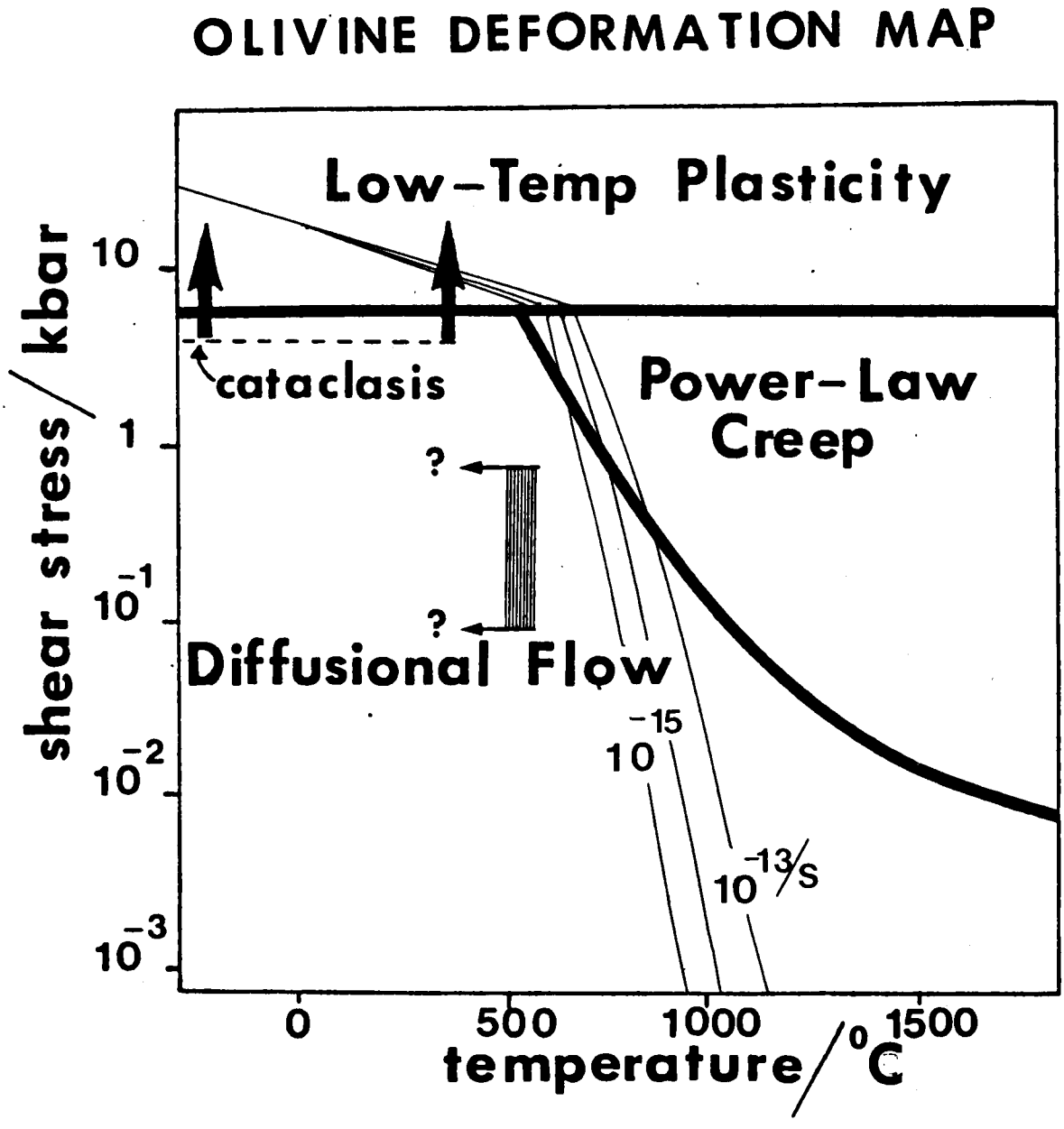


Figure 13. Calculated strain rates superimposed on olivine deformation map (after Ashby and Verrall, 1977).

and Verall (1976) deformation map. It is evident that the parent body interior conditions which have been estimated do not coincide with these strain rates. The problem is that temperature requirements for deformation are higher than those temperatures expected for CV3 chondrites at geologically reasonable terrestrial strain rates. While it is apparent from figure 13 that temperatures of 700-1000°C would be necessary for diffusional flow at the proposed strain rates, thermal constraints discussed earlier place maximum temperatures at less than 600°C. Presumably, at temperatures much higher than this, evidence of metamorphic recrystallization, not seen in Leoville or other CV3 chondrites, should be observable.

Several possible solutions for this discrepancy can be postulated. For instance, diffusion occurs more quickly as grain size is decreased. The strain rates in figure 13 are calculated for a grain size of 0.1 mm. However, most olivine grains in chondrules are on the order of 0.01 mm in size. This probably increased the strain rate at temperatures below 600°C. At these increased strain rates, previously calculated temperatures may be consistent with diffusional flow as the mode of deformation.

Another possibility is that the calculated strain rates in figure 13, which are based on earth rocks today, do not apply, and actual strain rates were slower than indicated. This would allow lower temperatures to have existed with diffusional flow as the active mechanism. However, the time necessary for deformation increases exponentially with slower strain rates, quickly becoming unreasonably

long by requiring amounts of time exceeding the age of the solar system.

Another thing to consider is that deformation may have been more complex than simple diffusional flow. For example, low-temperature plasticity may have occurred as an early stage of deformation, only to have evidence of it erased by later diffusional flow. In fact, Muller and Wlotzka (1983) and Michel-Levy et al. (1983), using TEM, observed dislocations with the Burger's vector [001] in some olivine grains contained in granular chondrules. Because their presence might indicate low-temperature plasticity or power-law creep, an SEM study was performed during research for this paper in order to point out their existence. None was observed, though this may indicate that TEM observation is necessary in order to see the dislocations, or that only some of the olivine grains contain this type of deformation. However, if the evidence of widespread dislocations has been erased, it is not possible to make any qualitative judgments concerning this type of deformation.

Presence of possible dislocations has been interpreted as indicating plastic deformation, although Muller and Wlotzka (1983) attribute the dislocations that they observed to shock deformation of Leoville. The reasons that plastic deformation is preferred over shock have been discussed earlier in this section. The authors, mentioned above, comment that the dislocations with Burger's vector [001] are characteristic of shock. However, in experimental investigations, Gueguen (1979), Kohlstedt et al. (1976), and Goetze (1978) observed slip on

this system and interpreted it as plastic flow. Raleigh (1968) calls [001] the low-temperature slip system of olivine. Indeed, it is active from room temperature to 1000°C. There does not seem to be any problem with the interpretation of this type of slip, if present in Leoville, having been caused by plastic deformation.

If water was present between grains in Leoville, it would increase strain rates, possibly making them fast enough to cause the observed deformation at the calculated temperatures. This seems implausible, though, because the presence of water would have resulted in the serpentinization of olivine, but serpentine is not part of Leoville's mineralogy.

Implications for Chondrite Parent Bodies

The presence of foliation in chondritic meteorites has been correlated with certain other features of chondrites, and these correlations probably reflect the same causal relationship. Porosity, which reflects degree of compaction, and magnetic anisotropy have been correlated with foliation (Hamano and Yomogida, 1982; Martin, 1980) in ordinary chondrites. All of these features were considered to result from a uniaxial compressional type of deformation as has been proposed here for Leoville. Brecher and Arrhenius (1974) correlated foliation with magnetic anisotropy in certain carbonaceous chondrites and felt that both features occurred during accretion. Presumably accretion resulted in the uniaxial compressional type of deformation, and magnetic anisotropy, porosity, and foliation occurred simultaneously and correlated with depth in both ordinary and carbonaceous

chondritic parent bodies. However, it has been found by these same workers and others (Dodd, 1965; Martin et al., 1975) that these features do not correlate with the petrologic type (degree of metamorphism) of ordinary and carbonaceous chondrites. A lack of correlation also has been found between petrologic type and metallographic cooling rates (the rates at which metal grains cooled through approximately 500°C, the blocking temperature for Ni diffusion in metal) in chondritic breccias (Scott and Rajan, 1981; Rubin et al., 1982).

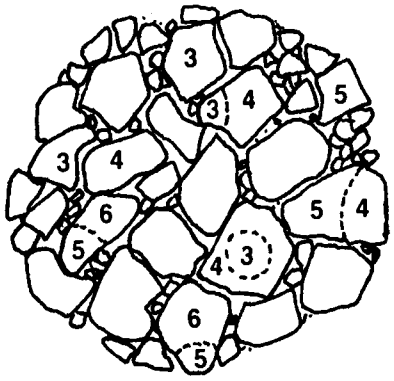
Certain asteroidal parent body models proposed for chondrites support different sets of correlations or explain the lack of correlation. Two of these are the "onion-shell" and the "rubble-pile" models. These data on chondrule foliation may add an additional constraint to these models.

The conventional onion-shell model proposes that the material in the interior of the body was heated by short-lived radionuclides. Conduction of heat to the surface resulted in temperatures being greatest at depth and least near the surface. Accordingly, the highest petrologic types, such as types 5 and 6, were at the greatest depths, whereas type 3 should have been only near the surface. If foliation was the result of overburden, then in this model, petrologic types 5 or 6 should routinely show foliation, and type 3 should not. Compaction and magnetic anisotropy should also correlate with petrologic type. As cooling rate is governed by depth, the petrologic type should have an inverse correlation with the metallographic cooling rate.

The rubble-pile parent body model proposed by Scott and Rajan (1981) and Rubin et al. (1982) comes much closer to predicting actual

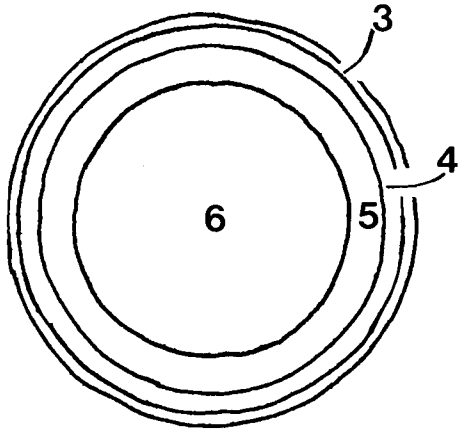
observations in chondrites. In this model, peak metamorphism occurred in small planetesimals (1-10 km), heated to high temperatures by short-lived radionuclides, after which these accreted into large asteroidal bodies (figure 14). Depending on the model variation, the material cooled before assembly of the large parent body or cooled after assembly at varying rates, depending on the depth at which the small planetesimals lay within the newly assembled asteroid. Regardless of when cooling occurred, there would be no correlation between petrologic type and foliation, as only the deeply buried material would experience an overburden large enough to cause the deformation. Whereas type 3 material, if it was close to the center of the large asteroidal body, would become foliated, type 6 material near the surface would not be deformed. This would explain why all type 3 chondrites do not appear to be foliated; any type 3 material near surface levels would not experience significant deformation.

The time of cooling relative to assembly into the rubble-pile asteroid has significant bearing on the correlation of foliation (as well as magnetic anisotropy and compaction) with petrologic type. If cooling was completed before assembly of the rubble-pile, then degree of metamorphism was governed by the temperature within the small planetesimals. As foliation would have occurred after assembly of the second-generation body, there would be no correlation between foliation and petrologic grade in this case. Correspondingly, there would be no correlation between foliation and cooling rates, as each would have occurred in separate locations.



a

a. Rubble-pile parent body model (after Scott and Rajan, 1981). Peak metamorphism occoccurred before accretion into rubble-pile.



b

b. Onion-shell parent body model in which petrologic grade decreases in concentric layers outward from center (after McSween, 1979).

Figure 14. Chondrite parent body models.

The alternative, cooling after assembly of the rubble-pile, would imply that material near the center of the newly assembled body would have cooled much more slowly than the material which happened to be nearer the outside of the rubble-pile. Thus metallographic cooling rates should reflect the depth of the chondrite and accordingly, should correlate with foliation, which also reflects depth.

An important prediction is indicated by this cooling-after-assembly model. Chondrites which exhibit foliation should have slow metallographic cooling rates, and those which lack foliation should have higher cooling rates. Research in this area should give supporting evidence for one of the cooling models. Lack of correlation between foliation and cooling rates would indicate cooling of the planetesimal before assembly into the rubble-pile, whereas correlation between foliation and cooling rates would imply cooling after assembly. Either way, the question remains, why is foliation not seen more often in higher petrologic types?

CHAPTER V

CONCLUSIONS

1. The unusual petrofabric seen in Leoville is displayed to some extent in other chondrites. Because it is not confined to either a single group or petrologic type of meteorites, this indicates that foliation was developed routinely in many meteorite parent bodies and was not merely a result of an isolated phenomenon such as shock.

2. Leoville experienced events in the following order:

   (a) formation of an accretionary breccia;

   (b) compaction and development of foliation within the parent body;

   (c) expulsion from the parent body;

   (d) fracturing, possibly due to impact on earth or breakup of the parent body;

   (e) terrestrial weathering that resulted in metal-rich and metal-poor areas.

3. Strain measurements for the chondrules alone in Leoville and for the overall meteorite are in close agreement: 1.9:1 for chondrules and 2.0:1 for the whole meteorite.

4. If calculations are based on an overall chondrite strain value of 2.0:1, Leoville experienced approximately 31% shortening. The time required for deformation at geologically reasonable rates is approximately 10^6 to 10^8 years.

5. By inference, diffusional flow is a reasonable mechanism by which Leoville could have deformed. No dislocations in olivine were

observed, as expected for this mechanism. Overburden due to accretion probably caused the observed compactional strain in Leoville. Shock and metamorphism are unlikely causes of deformation.

6. Calculations indicate that deviatoric stresses within asteroidal bodies range from 0.09 kb to 0.78 kb. Maximum determined temperatures for CV3 chondrites range between 500 and 600°C. These constraints fall into the diffusional flow region on Ashby and Verrall's (1976) deformation map. This implies that deformational conditions in the parent body are consistent with diffusional flow as the deformation mechanism.

7. Geologically reasonable terrestrial strain rates of 10^{-13} to 10^{-15}/s present a problem with calculated temperatures. These rates require temperatures of 700 to 1000°C for deformation by diffusional flow. Geologically reasonable strain rates may not apply in this instance. Actual strain rates may have been greater. If present, intergranular water would increase strain rates, as would finer grain sizes. Another possibility for the temperature/strain rate discrepancy is that deformation may have been more complex than simply diffusional flow. With more than one type of plastic flow, deformation processes become extremely difficult to measure, particularly when evidence has been erased.

8. If correlations among metallographic cooling rates, magnetic anisotropy, and compaction exist in chondrites, this may provide supporting evidence for the rubble-pile parent body model of formation.

9. Based on this study and general information about meteorites, I propose the following model to explain the origin and textural evolution of the Leoville meteorite: The Leoville parent body formed as a rubble-pile parent body incorporating an unmetamorphosed piece of material from which the Leoville meteorite later would come. Progressive overburden produced enough stress to deform material at depth thus producing a foliation Breakup of all or part of the parent body occurred following deformation, liberating the Leoville meteorite which entered an earth-crossing orbit and impacted on earth. Fractures were produced either when Leoville left its parent body or hit on earth. Terrestrial water utilized these fractures and caused oxidation of the adjacent metal. After remaining in the soil on earth for an unknown length of time, Leoville was discovered in 1965.

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APPENDICES

APPENDIX A

LEOVILLE SAMPLE DOCUMENTATION

Slabs inspected during this study are documented below:

The following samples are owned by individuals:

H40.55 Gordon G. Goles, University of Oregon
H40.8, H40.85 Everett K. Gibson, NASA-Johnson Space Center
H40.19 Ludolf Schultz, Max Plunk Institut fur Chemie

The following samples belong to instututions:

H40.54, H40.56 Smithsonian Institution, Washington
H40.34 Center for Meteorite Studies, Arizona State University

There is no diagram pinpointing the locations within the Leoville meteorite from which individual samples were cut. However, it is known for most samples whether they were cut from the larger or the smaller stone (G. Huss, pers. comm., 1984). Samples numbered H40.34, H40.54, H40.55, and H40.56 were cut from the large Leoville stone (figure 2, p. 6). Sample number H40.19 was cut from the smaller Leoville stone (figure 2). Samples numbered H40.8 and H40.85 are fragments which probably came from the larger stone.

APPENDIX B

Table B-1. Axial measurements and ratios for chondrules in Leoville section H40.55.

axial measurements		axial ratio	axial measurements		axial ratio	axial measurements		axial ratio	axial measurements		axial ratio	axial measurements		axial ratio	axial measurements		axial ratio
25	15	1.6	19	10	1.9	14	7	2	23	11	2.1	25	14	1.8	16	8	2
23	14	1.6	33	8	4.1	22	20	1.1	10	5	2	15	10	1.5	16	10	1.6
20	10	2	11	6	1.8	9	5	1.8	9	6	1.5	13	6	2.2	19	10	1.9
20	11	1.8	16	10	1.6	21	10	2.1	24	15	1.6	13	8	1.6	17	9	1.9
12	6	2	20	10	2	15	7	2.1	15	12	1.3	23	10	2.3	19	8	2.4
17	10	1.7	22	10	2.2	15	8	1.9	17	9	1.9	15	8	1.9	19	7	2.7
15	7	2.1	16	9	1.8	17	11	1.5	20	12	1.7	18	11	1.6	25	11	2.3
16	7	2.3	33	9	3.7	9	6	1.5	21	10	2.1	17	9	1.9	25	11	2.3
12	6	2	16	9	1.8	19	10	1.9	20	12	1.7	25	6	4.2	18	10	1.8
11	5	2.2	25	12	2.1	23	10	2.3	16	9	2	16	11	1.4	22	7	3.1
17	8	2.1	20	10	2	14	9	1.5	26	16	1.6	18	9	2	17	8	2.1
16	8	2	16	14	1.1	15	8	1.9	12	7	1.7	19	10	1.9	20	9	2.2
23	15	1.5	8	5	1.6	11	6	1.8	18	9	2	23	13	1.8	14	9	1.5
15	13	1.1	15	8	1.9	12	6	2	16	8	2	19	6	3.2	20	12	1.7
17	8	2.1	17	8	2.1	12	6	2	14	9	1.5	12	10	1.2	20	11	1.8
28	13	2.1	10	6	1.7	13	6	2.2	13	8	1.6	18	11	1.6	13	6	2.2
17	8	2.1	16	9	1.8	11	6	1.8	12	9	1.3	15	11	1.4	20	10	2
12	6	2	30	14	2.1	17	13	1.3	19	14	1.4	25	11	2.3	16	8	2
18	8	2.2	27	16	1.7	17	8	2.1	23	13	1.8	16	9	1.8	28	18	1.6
22	11	2	12	6	2	15	8	1.9	34	14	2.4	20	12	1.7	20	10	2
9	5	1.8	15	13	1.1	22	12	1.8	24	12	2	25	15	1.7	25	15	1.7
12	6	2	10	6	1.7	24	13	1.8	14	6	2.3	17	15	1.1	18	10	1.8
22	12	1.8	25	12	2.1	17	9	1.9	17	8	2.1	18	9	2	13	8	1.6
14	9	1.5	27	14	1.9	19	10	1.9	19	12	1.6	20	9	2.2	28	12	2.3
18	10	1.8	16	10	1.6	10	8	1.2	15	8	1.9	21	15	1.4	43	24	1.8
18	10	1.8	18	10	1.8	11	10	1.1	12	8	1.5	15	7	2.1	26	11	2.4
16	8	2	14	7	2	10	6	1.7	14	7	2	16	13	1.2	22	13	1.7
12	5	2.4	14	9	1.5	24	14	1.7	21	15	1.4	13	11	1.2	15	8	1.9
20	11	1.8	20	9	2.2	60	31	1.9	20	11	1.9	17	14	1.2	15	9	1.7
33	16	2.1	20	8	2.5	12	7	1.7	13	7	1.7	16	8	2	15	7	2.1
25	20	1.2	16	9	1.8	15	8	1.9	15	9	1.7	12	6	2	21	9	2.3
23	16	1.4	18	10	1.8	11	7	1.6	23	15	1.5	20	13	1.5	23	13	1.8
25	15	1.7	25	13	1.9	18	12	1.5	16	11	1.4	25	16	1.6	19	12	1.6
26	13	2	14	10	1.5	19	8	2.4	18	10	1.8	23	12	1.9	21	13	1.6
24	21	1.1	27	20	1.3	23	11	2.1	14	8	1.7	17	11	1.5	21	10	2.1
15	11	1.4	24	12	2	20	11	1.8	24	10	2.4	15	8	1.9	15	7	2.1
13	5	2.6	12	5	2.4	11	4	2.8	14	5	2.8	14	7	2	23	12	1.9
27	16	1.7	13	6	2.2	19	8	2.4	15	10	1.5	15	8	1.9	25	10	2.5
16	8	2	10	7	1.4	25	10	2.5	17	8	2.1	10	10	1	17	8	2.1
14	7	2	18	6	3	16	6	2.7	12	5	2.4	17	9	1.9	15	7	2.1
13	5	2.6	7	3	2.3	16	11	1.4	14	10	1.4	24	13	1.8	18	10	1.8
13	8	1.6	16	7	2.3	11	8	1.4	16	9	1.8	15	9	1.7	13	6	2.2
13	6	2.2	13	7	1.9	17	8	2.1	17	10	1.7	21	9	2.3	21	15	1.4
27	19	1.4	9	5	1.8	20	10	2	20	10	2	31	13	2.4			
14	8	1.7	12	5	2.4	18	9	2	18	14	1.3	12	5	2.4			

APPENDIX C

Table C-1. Chondrule axial measurements and ratios for Grossnaja, Bali, and Efremovka.

Grossnaja			Bali			Efremovka		
axial measurements		axial ratio	axial measurements		axial ratio	axial measurements		axial ratio
33	20	1.6	50	25	2	15	9	1.6
8	6	1.3	20	13	1.5	7	6	1.2
17	12	1.4	12	8	1.5	26	17	1.5
4	4	1	27	13	2.1	13	9	1.4
32	23	1.4	12	8	1.5	11	10	1.1
15	12	1.2	17	15	1.1	10	6	1.7
7	5	1.4	19	12	1.6	36	23	1.6
18	17	1	33	22	1.5	25	13	1.9
27	17	1.6	45	22	2.0	14	9	1.5
5	4	1.2	17	9	1.9	23	11	2.1
17	14	1.2	18	13	1.4	11	6	1.8
12	10	1.2	18	8	2.2	10	6	1.7
13	9	1.4	21	12	1.8	7	4	1.7
43	28	1.5	10	8	1.2	17	14	1.2
25	10	2.5	12	7	1.7	30	23	1.3
17	11	1.5	24	9	2.6	10	6	1.7
28	11	2.5	23	18	1.3	7	6	1.2
18	12	1.5	5	4	1.3	18	10	1.8
17	12	1.4	15	8	1.9	12	9	1.3
26	10	2.6	10	6	1.6	33	20	1.7
10	6	1.7	24	14	1.7	9	5	1.8
15	8	1.9	10	8	1.2	21	11	1.9
8	5	1.6	20	14	1.4	5	4	1.2
7	6	1.1	18	14	1.3	17	11	1.5
15	6	2.5	12	7	1.7	36	23	1.6
13	8	1.6	10	9	1.1	13	6	2.2
20	10	2	17	10	1.7	8	6	1.3
12	11	1.1	17	12	1.4	16	11	1.4
13	9	1.4	15	11	1.4	11	8	1.4
14	6	2.3	24	11	2.2	39	21	1.9
15	12	1.2	18	17	1.0	14	8	1.7
15	10	1.5	33	17	1.9	13	10	1.3
28	28	1				16	11	1.4
6	5	1.2				19	11	1.7
16	9	1.8				7	4	1.8
20	14	1.4				16	10	1.6
13	7	1.9				16	8	2.0
18	13	1.4				14	6	2.3
14	12	1.2				20	13	1.5
22	16	1.4				17	10	1.7
						16	12	1.3
						26	14	1.9
						15	5	3
						14	10	1.4
						13	7	1.9
						8	8	1
						8	7	1.1

Grossnaja

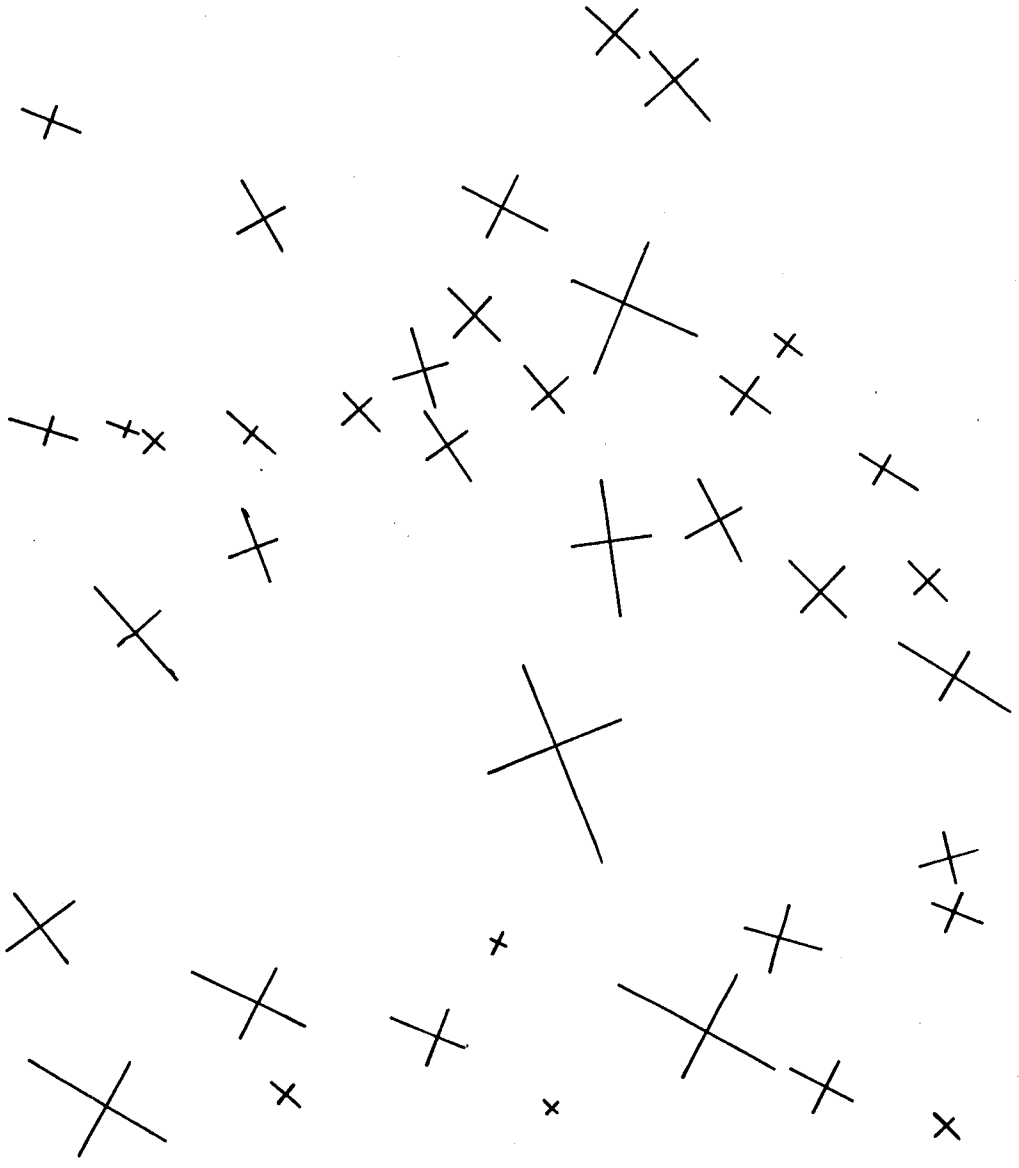


Figure C-1. Chondrule sketches for Grossnaja.

Bali

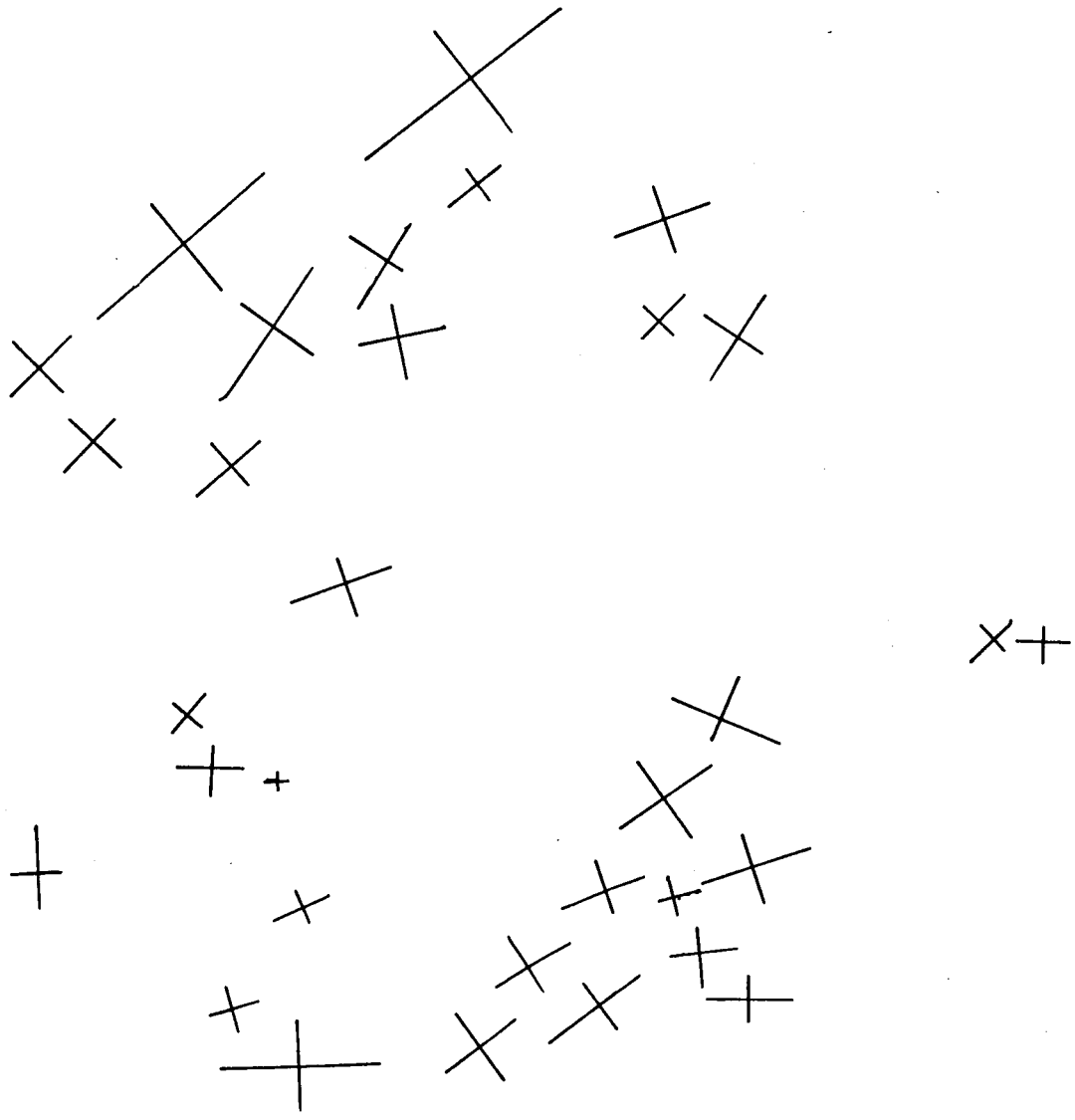


Figure C-2. Chondrule sketches for Bali.

Efremovka

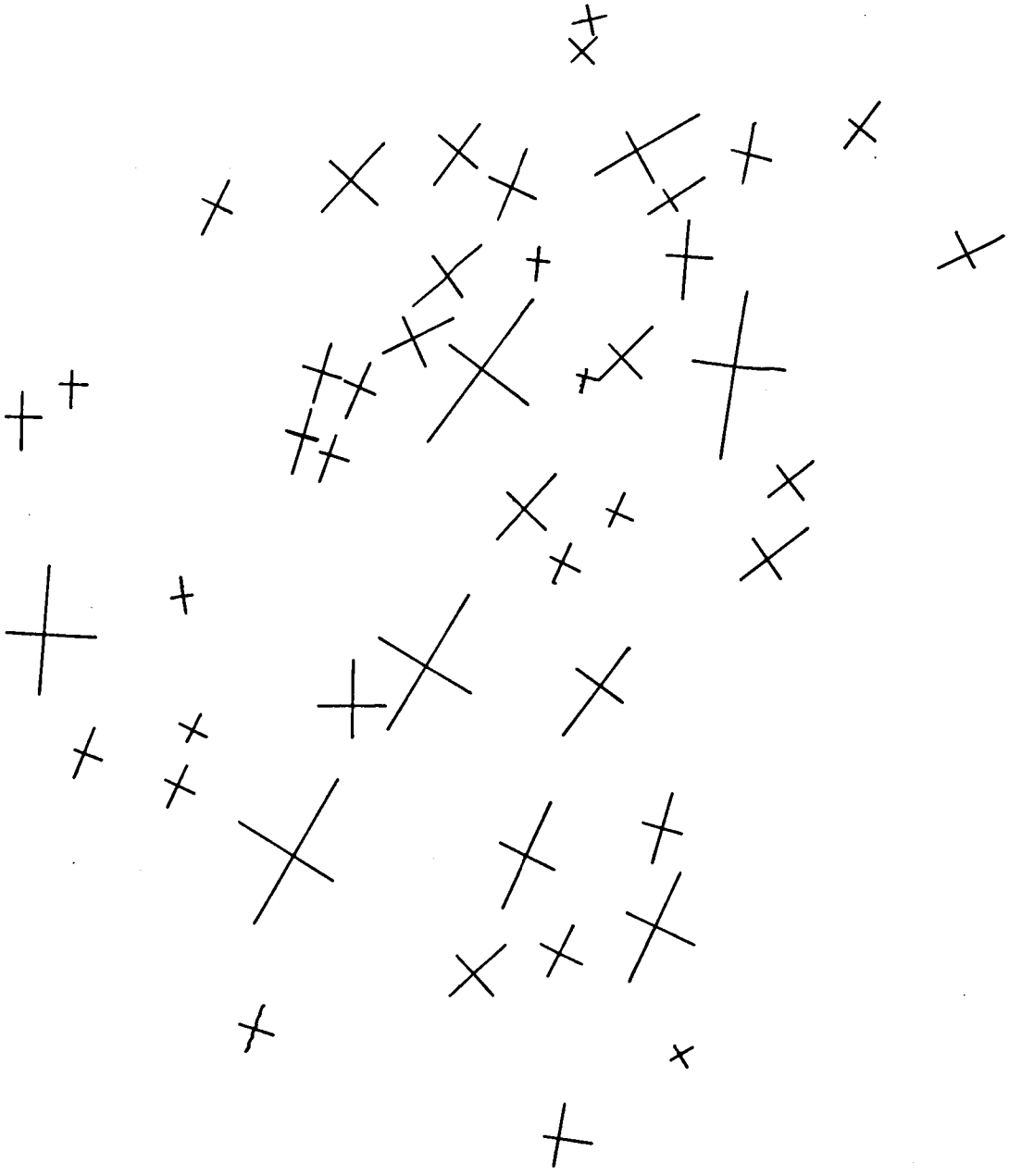


Figure C-3. Chondrule sketches for Efremovka.

VITA

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