Nature and Origins of Meteoritic Breccias

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Abstract

Meteorite breccias provide information about impact processes on planetary bodies, their collisional evolution and structure. Fragmental and regolith breccias are abundant in both differentiated and chondritic meteorite groups and together with rarer impact melt rocks provide constraints on cratering events and catastrophic impacts on asteroids. These breccias also constrain the stratigraphy of differentiated and chondritic asteroids and the relative abundance of different rock types among projectiles. Accretional chondritic breccias formed at low impact speeds (typically tens or hundreds of m/s), while other breccias reflect hypervelocity impacts at higher speeds (~5 km/s) after asteroidal orbits were dynamically excited. Iron and stony-iron meteorite breccias only formed, when their parent bodies were partly molten. Polymict fragmental breccias and regolith breccias in some meteorite groups contain unique types of clasts that do not occur as individual meteorites in our collections. For example ureilite breccias contain feldspathic clasts from the ureilite parent body as well as carbonaceous chondritic projectile material. Such clasts provide new rock types from both unsampled parent bodies and unsampled parts of known parent bodies. We review breccias in all types of asteroidal meteorites and focus on the formation of regolith breccias and the role of catastrophic impacts on asteroids.

1. GENERAL INTRODUCTION

1.1. Meteorite breccias

Chondrites and differentiated meteorites provide information about collisions during the accretion of asteroids at relatively slow speeds (typically less than a few hundred m/sec), and during and after thermal processing when asteroids collided at speeds of many km/sec. Impacts at speeds above ~20 m/s broke rock, while hypervelocity impacts left shock damage and formed breccias from fragments of earlier rocks. The study of meteoritic breccias contributes significantly to our understanding of early solar system processes of accretion, differentiation, and surface (regolith) evolution, and also provides unique information about the primordial, chemical and mineralogical characteristcs of the accreted components themselves (Bischoff and Stöffler, 1992). The latter can best be seen by examining the constituents of primitive accretionary breccias. (Lunar and Martian breccias are not discussed in this paper.)

In the nineteenth century certain textural features in meteorites were described that we now recognize to result from shock waves during collisional processes. Partsch (1843) and von Reichenbach (1860) described ”polymict breccias“ and Tschermak (1872) identified ”maskelynite“. The presence of shock veins and brecciation were used as fundamental criteria of the Rose-Tschermak-Brezina classification scheme of meteorites (Brezina, 1904). Numerous early studies on meteoritic breccias are reviewed by Rajan (1974), Bunch (1975), Dymek et al. (1976), Prinz et al. (1977), and Keil (1982). These papers used comparisons between lunar and meteorite impact breccias to establish a basic understanding of meteorite breccias. However, meteoritic breccias are more difficult to understand because the asteroids are very different in terms of their target size, projectile flux, impact velocities, and physical and chemical properties. In addition, the meteorites come from a set of bodies that experienced very diverse alteration, metamorphic and igneous histories and they preserve evidence for hypervelocity impacts over ~50 Myr on hot targets and 4.5 Gyr of impacts on cold targets. We have examined only a few asteroids from passing spacecraft and only one has been studied from orbit (prior to a landing on Eros by the NEAR spacecraft in 2001; Sullivan et al., 2002). We remain woefully ignorant about the diverse effects of impacts between asteroids spanning many orders of magnitude in size (Holsapple et al., 2002), and we have yet to understand fundamental questions such as the impact rate in the primordial asteroid belt and the excitation process that changed asteroids' orbits causing hypervelocity impacts (Petit et al., 2002). Despite these problems, considerable progress has been made in characterizing and understanding meteorite breccias in the last twenty years.

1.2. Why study meteoritic breccias?

Meteoritic breccias represent fragmented samples from a variety of parent bodies (Burbine et al., 2002). In many cases, a large fraction of our samples are brecciated. For example, all CI chondrites, mesosiderites, and aubrites and over 80% of all HED meteorites are breccias of various kinds. Only four groups of stony meteorites lack clearly-defined breccias: angrites, brachinites, acapulcoites and lodranites. Thus the vast majority of coherent rocks in their parent bodies cannot be understood without an appreciation for the long history of impacts that have affected them.

The brecciated meteorites provide important information about the history and evolution of the asteroids and impact processes on small bodies (Keil, 1982). This includes processes of accretion, the nature of primary parent body lithologies, excavation of those lithologies, and impact-related heating, metamorphism, melting, and mixing, as well as subsequent reaccretion, and lithification. Because of the presence of types of clasts in polymict breccias that do not occur as individual meteorites in our collections, it is possible to study samples of new rock types, from both unsampled parent bodies and unsampled parts of known parent bodies. For example, dark inclusions found in ordinary and carbonaceous chondrites are unique, and may be fragments of C-chondrite parent bodies that existed prior to formation of the present host carbonaceous chondrite parent bodies. Aternatively, they may represent fragments of different lithologies from the same parent body. Likewise, feldspathic clasts in polymict ureilites may represent basaltic rocks complementary to the ultramafic monomict ureilites, and are otherwise unrepresented in our collections. In addition, mixtures of various clasts in a breccia (e.g. the presence of clasts of differentiated material in a chondritic breccia, or vice versa) can provide information about relative ages of early solar system processes, as well as the varieties of materials available within one region of the asteroid belt.

Regolith breccias provide us with our best tangible clues to the nature of asteroid surfaces studied by remote sensing techniques. Their solar wind implanted noble gases and irradiation records in minerals may provide information about a possible early active phase of the Sun (Woolum and Hohenberg, 1993).

An essential step in unraveling this history is to date the formation of the breccias. Compaction ages of regolith breccias can help to understand regolith formation on asteroids and constrain the evolution of the sun. Dating of impact melt breccias gives detailed insights into the impact histories of the asteroids over 4.5 Gyr and major impact events.

2. BRECCIA TYPES AND ABUNDANCES

2.1. Nomenclature and characterization of breccias

As pointed out by Bischoff and Stöffler (1992) various collision scenarios lead to specific combinations of shock metamorphism (and its effects (Stöffler et al., 1988, 1991)) and breccia formation, if the relative sizes and velocities of the colliding bodies and the specific impact energies are considered (see paragraph 3). Breccia formation requires mass transport and therefore, the relative movement of rock fragments and their displacement from the primary location in the source material (Stöffler et al., 1988).

Details of the modern classification and nomenclature of breccias and their components are given by Stöffler et al. (1979, 1980, 1988), Keil (1982), Scott and Taylor (1982), Taylor (1982), Bunch and Rajan (1988), and Bischoff and Stöffler (1992). Some characteristics of special types of breccias and their constituents, which are discussed in this chapter, are given in Table 1.
Primitive, accretionary breccias can be formed in a low velocity regime and mainly occur among carbonaceous and ordinary chondrites (e.g., Kracher et al., 1982; Scott and Taylor, 1982). These chondrites have matrices composed almost entirely of primitive components found in type 3 chondrites including chondrules and opaque and recrystallized, fine-grained silicate matrix (Scott and Taylor, 1982). Chondrites that contain chondritic clasts that are rimmed by matrix material, lack shock effects, and are comparable in size to chondrules may have accreted together with the other chondritic components – CAIs, chondrules, and matrix - during assembly of the parent body (Kracher et al., 1982). Such chondritic clasts appear to be derived from early-formed planetesimals. Most accretionary breccias apparently lack solar-wind gases (e.g., Nakamura et al., 2003).

The vast majority of meteorite breccias formed during impacts between asteroids at velocities in excess of about 0.5 to 1 km/s, which shocked and melted minerals (Stöffler et al., 1988). Impact velocities in the main asteroid belt due to mutual collisions currently range from 1 to 12 km/s with a mean of 5.3 km/s (Bottke et al., 1994). (Comets impact at higher speeds, but they are relatively rare and their effects have not been recognized yet.) Impact processes modify the targets and the melts can be incorporated into crater deposits (Bischoff and Stöffler, 1992); in asteroidal surface-subsurface units the following types of impact breccias can be found: monomict (for example the brecciated monolithic basement rock) and dimict breccias, polymict breccias (such as regolith breccias), fragmental breccias, impact melt breccias, and granulitic breccias. Dimict breccias are composed of two distinct lithologies, whereas polymict breccias are consolidated rocks

Table1: Classification of main types of breccias and their components

Breccias	Description/constituents	Meteorite examples
Primitive, accretionary breccia	Constituents (including clasts) assembled during accretion	Allende (CV3), Leoville (CV3), Sharps (H3)
Genomict breccias	Clasts and matrix of the same compositional group, but of different metamorphic (type) or alteration history	Millbillillie (Euc), Noblesville (H4-6)
Regolith breccias	Lithified components from the upper surface of the parent body (contain solar-wind gases, solar-flare tracks, etc.)	Adzhi-Bogdo (LL3-6), Kapoeta (How.), Murchison (CM2), Nogoya (CM2), Rumuruti (R3-6)
Fragmental breccias	Fragmental debris without regolith properties (solar gases, tracks)	Norton County (Aub.), Dhurmsala (LL6), Siena (LL5)
Impact melt breccias	Shock-melted rocks with unmelted clasts	Shaw (L6), Chico (L6), NWA 1498 (H4), Abee (EH4), DaG 896 (ungr. Achon.)
Granulitic breccias	Metamorphosed breccias	Camel Donga (Euc.), Asuka-881388 (Euc.), Cabezo de Mayo (L/LL6)
Polymict breccias	Lithified fragments of various types; clasts and/or matrix have different composition	Howardites, polymict Eucrites (e.g., Petersburg)
Monomict breccias	Matrix and clasts are of the same class and type	Norton County (Aub.), Bloomington (LL6), Stannern (Euc.)
Dimict breccias	Composed of two distinct lithologies	Cumberland Falls (Aub.), FRO 93008 (Ure.)
Components		
Xenolithic fragments	Clasts not genetically related to the host rock	CM-clasts in howardites (e.g., Kapoeta, LEW85300)
Cognate clasts	Lithic clasts related to the host rock	clasts of other petrologic type
Impact melt breccia clasts	Clasts of impact melts with enclosed unmelted debris	
Impact melt clasts	Fragments solely of impact melt	Fig. 7
Dark inclusions (fragments)	Optically dark constituents in many breccias without genetic meaning (fine-grained breccia clasts, C-class fragments in meteorite breccias, etc.)	C-clasts in HEDs, Figs. 4 and 11

consisting of clasts and/or matrix of different composition and/or origin. If they result from lithification of the upper surface debris and contain grains that were in the top millimeter of the asteroidal surface, they contain solar wind-implanted noble gases and solar-flare tracks (e.g., Wänke, 1965; Eberhardt et al., 1965; Geiss, 1973; Schultz and Kruse, 1978, 1989; Caffee et al., 1988). Breccias containing solar-gas-bearing dust grains in their matrices are called regolith breccias, or in noble-gas parlance, gas-rich meteorites. Breccias with diverse clasts that lack the typical regolith properties (noble gases, tracks) are simply called fragmental breccias. Impact melt breccias have a matrix of impact melt in which shocked and unshocked rock fragments are embedded (Table 1). Impact melt breccias, which have an igneous matrix, are found as clasts in meteorites as well as individual stones. Clast-free impact melts are called impact melt rocks. For these rocks, an impact origin is inferred from the bulk chemical composition and is commonly controversial. These melt rocks occur as fragments in many meteorite classes or as individual meteorites. Based on chemical characteristics they are usually considered as "impact" melt rocks and they will be treated in this chapter. Impact melt lithologies are often depleted in Fe,Ni-metal and FeS, and have quenched, spinifex, skeletal, aphanitic, microporphyritic, and poikilitic textures (e.g., Keil, 1982). Breccias that experienced thermal annealing are called granulitic breccias. For chondrites the term "genomict breccias" is also used to describe breccias in which the clasts are of the same meteorite class, but have different petrographic properties (Wasson, 1974; Kerridge and Matthews, 1988).

Breccias contain "cognate clasts", fragments that are related to the host rock and "xenolithic clasts (xenoliths)" that are constituents in a rock to which they are not genetically related (e.g., Keil, 1982). The most prominent clast types include: xenolithic fragments (e.g., CM-type clasts in howardites), cognate clasts of other petrologic type, clasts of impact melt rock (clast-free) and impact melt breccias, and dark inclusions (Table 1). The term "dark inclusion" has no genetic meaning and includes different types of optically dark lithic fragments in meteorites (compare section on ordinary chondrites).

All types of clasts are usually embedded in a fine-grained clastic matrix. Most breccias are formed by shock lithification of clastic debris on asteroids, mainly of surface or near-surface materials, whereas some (primitive, accretionary breccias) are formed by accretion of disrupted (precursor) parent body materials. Breccias other than impact melt breccias are lithifiied by impacts that caused limited shock-induced grain boundary melting cementing the rock fragments together (Kieffer, 1975; Ashworth and Barber, 1976; Bischoff et al., 1983). Ashworth and Barber (1976), and Bischoff et al. (1983)

showed that ordinary chondritic regolith breccias experienced limited shock-induced grain-boundary melting. This melt is important for consolidating loose debris into brecciated rock. Some porous lunar regolith breccias may have been lithified by a thermal welding process (McKay et al., 1989), and carbonaceous chondrites by growth of secondary phases. Thermal annealing after mixing of fragments and lithification may lead to a recrystallized matrix between large fragments as in the case of LL chondritic fragmental breccias (Jäckel and Bischoff, 1998).

2.2. Abundances of breccias

The determination of the number of breccias within any meteorite group is difficult, because, particularly in the case of ordinary chondrites, the brecciated character of a rock is not always reported during the initial classification. Frequently, the major lithology of a rock is used for classification of breccias (e.g., H5) rather than the whole range of clasts present in the meteorite (e.g., H4-6, which would also indicate that the rock is a breccia). Thus an H6 chondrite may be a rock that was metamorphosed to type 6 levels or a breccia composed largely of H6 material that was assembled after or during metamorphism. Clasts in chondritic breccias are very largely identical in composition to the surrounding matrix material. Binns (1967) estimated that the abundances of brecciated H, L, and LL chondrites are 25, 10, and 62%, respectively (Binns, 1967; Keil, 1982). Rubin et al. (1983) found that gas-poor, melt-rock and exotic clast-bearing fragmental breccias constitute 5% (20/420), 22% (91/420), and 23% (14/60), respectively, of H, L, and LL chondrites, which contrasts with the above mentioned numbers and with the percentages of solar-gas-rich regolith breccias among ordinary chondrites: H (14%), L (3%), and LL (8%) (Crabb and Schultz, 1981). Bischoff and Schultz (2004) have summarized the abundances of meteorites in various classes having solar wind implanted gases. The percentages of regolith breccias among the ordinary chondrites have not been changed much since the estimate of Crabb and Schultz (1981). The new statistics shows that 96 of 626 measured H-chondrites, 12/405 L-chondrites, and 6/110 LL-chondrites contain solar gases (15.3, 3.0, and 5.5%, respectively; Bischoff and Schultz, 2004; Table 2). The abundances of regolith breccias among the carbonaceous chondrites are very diverse. All analysed CI, CM, and CR chondrites contain solar wind implanted gases, while not a single gas-rich sample was found among the CO and CK chondrites. About half of the R chondrites and 10% of the Enstatite chondrites are regolith breccias.

Table 2: Percentage of solar gas containing meteorites within distinct meteorite groups. Table from Bischoff and Schultz (2004). Some CV chondrites ( ) may not be true solar gas-rich regolith breccias: individual grains could be irradiated before forming the parent body. Some uncertainties also exist for the primitive achondrites (acapulcoites, winonaites, lodranites, brachinites).

Group	**No. of meteorites considered**	**No. of regolith breccias**	**Percentage**
CI-Chondrites	6	6	100 %
CM-Chondrites	19	19	100 %
CV-Chondrites	29	(5)	(17.2 %)
CO-Chondrites	21	0	0 %
CK-Chondrites	21	0	0 %
CR-Chondrites	5	5	100 %
CH-Chondrites	7	5	71.4 %
H-Chondrites	626	96	15.3 %
L-Chondrites	405	12	3.0 %
LL-Chondrites	110	6	5.5 %
R-Chondrites	23	11	47.8 %
E-Chondrites	73	7	9.6 %
Acapulcoites	12	0	0 %
Lodranites	9	0	0 %
Winonaites	2	0	0 %
Brachinites	7	0	0 %
Ureilites	25	3	12.0 %
Howardites	21	8	38.1 %
Eucrites	73	0	0 %
Diogenites	30	0	0 %
Aubrites	20	6	30.0 %

The achondrite groups also show diverse abundances of breccias with solar wind gases. While about 40% of the howardites, which are all breccias, are gas-rich, only 30% of the aubrites contain solar gases. No eucrites, diogenites, or the primitive achondrites acapulcoites, lodranites, winonaites, and brachinites with solar gases have so far been found (Table 2). Among the seven well-studied polymict ureilites (25 ureilites were studied for noble gases), three are known to contain solar wind gases.

3. IMPACT VELOCITIES DURING BRECCIA FORMATION

The quantitative relations between impact velocities, types of colliding bodies, and the degree of shock or type of brecciation in meteorites are described in detail by Stöffler et al. (1988) and Bischoff and Stöffler (1992). Some aspects will be reported here again. Minimum collision velocities for the formation of critical shock effects observed in meteorites can be obtained for all types of impactors and targets (see Fig. 3.6.7 and Table 3.6.5 in Stöffler et al. (1988)). For example, the onset of formation of intergranular melting at about 5 GPa is needed for the production of regolith breccias. Complete melting of stony meteorites above about 80 GPa is a prerequisite for the formation of polymict fragmental and regolith breccias containing impact melt rock clasts. Regimes for collision-induced effects in the meteorites` parent bodies as a function of the approach velocity (velocity at infinity) and the size of the colliding bodies are shown in Fig. 1. Figure 1 is modified and redrawn from Hartmann (1979) and Stöffler et al. (1988) and assumes the collision of similar-sized bodies, which have interiors with strength and elasticity of basalt or other igneous rock, but surface layers of loose or weakly bonded fragmental material. The figure describes several distinct regimes of interest (compare Hartmann (1979)): (a) rebound and escape of two bodies, (b) rebound and fallback, producing an unfractured contact binary, (c) fragmentation and reaccretion leading to a brecciated spheroid, and (d) disruption with sufficient energy that most bodies escape entirely leading to total disruption.

Impact-induced breccia formation of porous regolith or C-chondrite materials requires collision velocities of at least 1.3 km/s (Fig. 1; Stöffler et al., 1988; Bischoff and Stöffler, 1992). Regolith breccias or fragmental breccias with melt rock clasts come from bodies that experienced collisions at velocities of at least 4.5-5 km/s, which might be slightly lower if abundant metals are involved (e.g., mesosiderites). One should point out that all these suggested velocities are well within the range expected for the impact velocities in the main asteroid belt (see above).

All types of breccia formation require mass transport (ballistic or non-ballistic). Relative movement of rock fragments and their displacement from the original location of the source material is involved. The geological scenarios of breccia formation in impact craters are summarized in detail by Stöffler et al. (1988; see their Figs. 3.6.2 and 3.6.3).

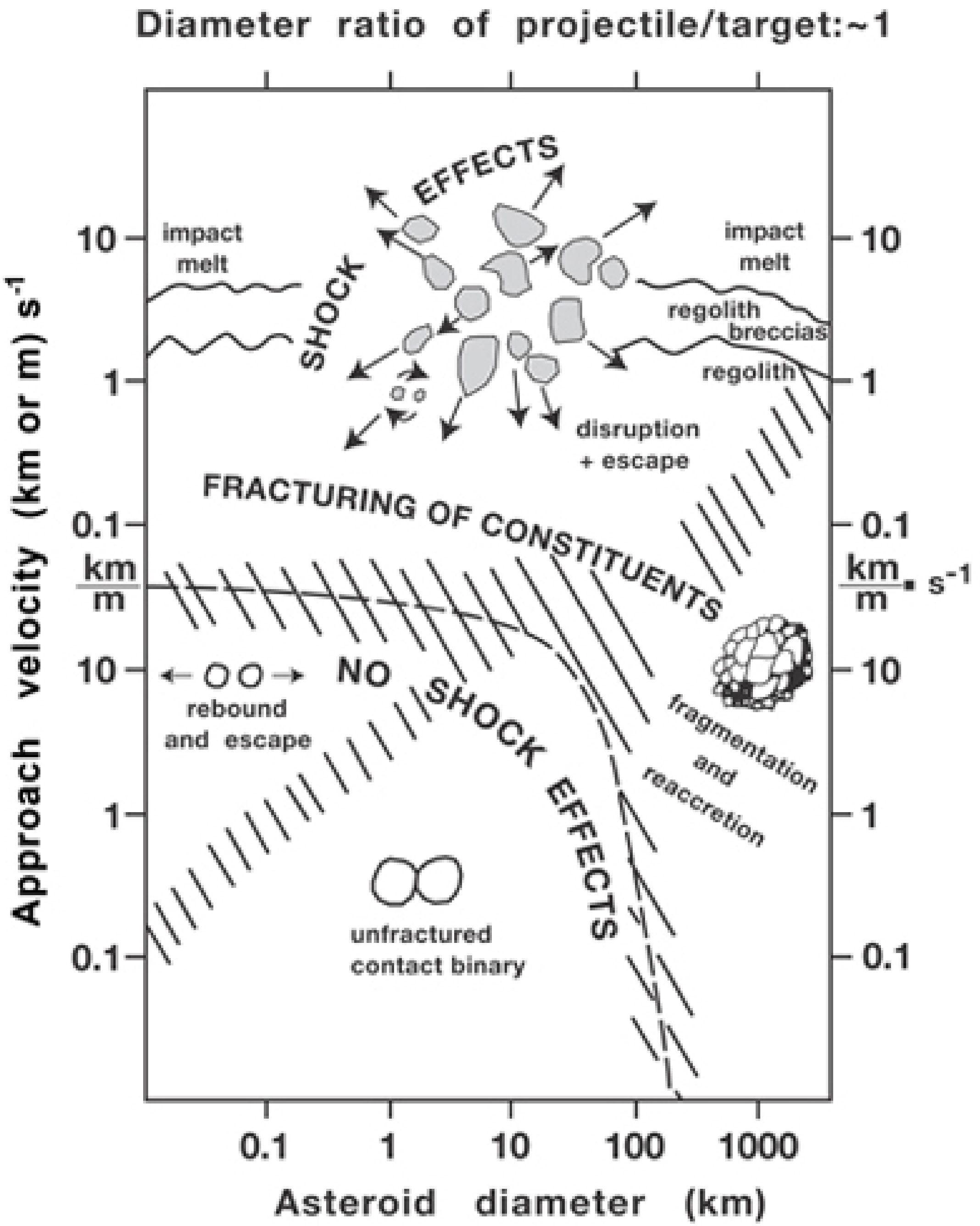

Fig. 1: Regimes of collision-induced effects as a function of the approach velocity (velocity of infinity) and the size of the colliding bodies: Equal-sized bodies are assumed. Minimum velocities for the onset of certain shock effects in meteorites (e.g., formation of impact melts and regolith breccias) are given in wavy lines. The diagram is modified and redrawn from Hartmann (1979) and Stöffler et al. (1988).

4. BRECCIATION IN METEORITE GROUPS

4.1. Ordinary chondrites

There are an enormous number of observations of lithic clasts in ordinary chondrites (Fig. 2). An outstanding summary of the various types of fragments within H, L, and LL chondritic breccias is given by Keil (1982). It is impossible to cite here all the reports listed by Keil (1982). The major studies are: e.g., Wahl, 1952; Wlotzka, 1963; Van Schmus, 1967; Binns, 1968; Fodor et al., 1972, 1974, 1976, 1977, 1980; Keil and Fodor, 1973, 1980; Fodor and Keil, 1973, 1975, 1976a,b, 1978; Bunch and Stöffler, 1974; Dodd, 1974; Wilkening and Clayton, 1974; Fredriksson et al., 1975; Hoinkes et al., 1976; Noonan et al., 1976; Wilkening, 1976, 1977, 1978; Leitch and Grossman, 1977; Clayton and Mayeda, 1978; Lange et al., 1979; Taylor et al., 1979; Wlotzka et al., 1979; Grossman et al., 1980; Keil et al., 1980; Rubin et al., 1981a,b; Scott and Rajan, 1981; Sears and Wasson, 1981. In this paper the basic findings on brecciated ordinary chondrites of the last twenty years are summarized.

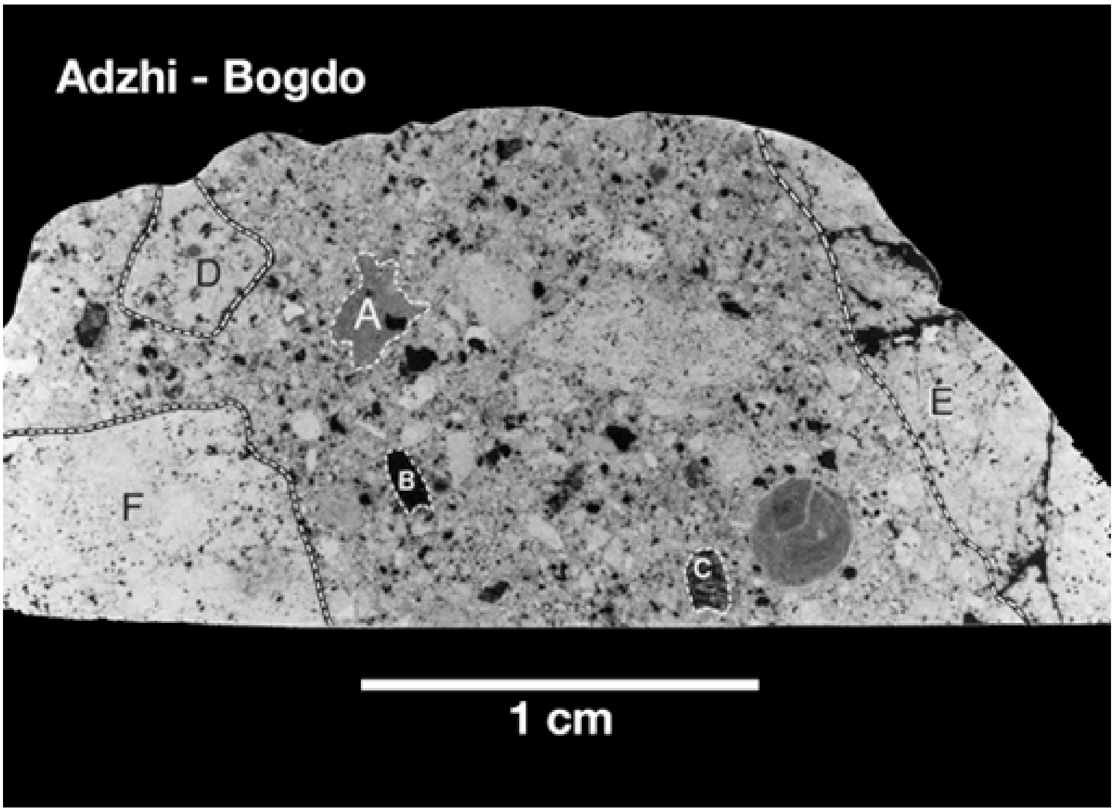

Fig. 2: Transmitted light photomicrograph of a thin section from the Adzhi-Bogdo (LL3-6) chondrite regolith breccia showing various types of fragments: highly recrystallized clasts (D, E, and F) sometimes with internal shock veins (E), melt rock clast (A), fragmental breccia clast (B), and a shock-darkened fragment (C). Figure modified after Bischoff et al. (1993c).

4.1.1. Black and dark inclusions (clasts)

The most obvious and easily visible clasts in ordinary chondrite breccias are the so-called black and dark inclusions (or clasts). These terms do not provide any information about the genetic origin and the mineralogy of the fragments. They encompass: (a) shock darkened objects, (b) specimen of various types of primitive rocks, mainly of carbonaceous (C) chondrites (c) fragments of fine-grained breccias (breccia in a breccia), (d) metal-troilite-rich clasts, (e) fine-grained, matrix-like cognate inclusions, (f) fragments of shock melts with abundant tiny metal/sulfide grains.

(a) *Shock-darkened clasts*: Clasts of this type formed from light-colored lithologies during shock events (shock darkening, shock blackening) that melted and transported a significant fraction of their metallic Fe-Ni and troilite grains into silicates (e.g., Dodd, 1981; Stöffler et al., 1991; Rubin, 1992; Rubin et al., 2002; Welzenbach et al., 2005). Impact-induced frictional melting is considered as a possible mechanism for the "darkening" in ordinary chondrites (van der Bogert et al., 2003). About 15% of ordinary chondrites are regarded as "black ordinary chondrites" (e.g., Heymann, 1967; Britt and Pieters, 1991, 1994). A very dark shock-blackened clast has been reported from Nulles (Williams et al., 1985).

b*) Clasts of various types of foreign, accretionary rocks, mainly carbonaceous (C) chondrite-like*: A black microchondrule- and carbon-bearing L-like chondritic fragment was found in the Mezö-Madaras L3 chondritic breccia, which may represent a new specimen of C-rich ordinary chondrite (Christophe Michel-Lévy, 1988). A similar clast with tiny chondrules was found in Krymka (LL3; Rubin, 1989). Rubin et al. (1982) also described a fine-grained microchondrule-bearing fragment from Piancaldoli (LL3), which was reclassified by Krot et al. (1997b) as being not an individual clast, but part of a chondule rim. One moderately dark fragment in the Krymka ordinary chondrite is clearly a clast of a different type of chondrite, perhaps a carbonaceous chondrite (Fig. 3). It has nearly equilibrated Mg-rich olivine (Fa: 8.1±1.6) and somewhat more unequilibrated pyroxene (Fs: 6.4±3.3 mol%). Some other dark lithic fragments in Krymka are considered to represent pieces of a primary accretionary precursor rock, which has been fragmented and its fragments incorporated into the Krymka host (Semenenko et al., 2001; Semenenko and Girich, 2001). Similarly, Vogel et al. (2003) report that Krymka dark

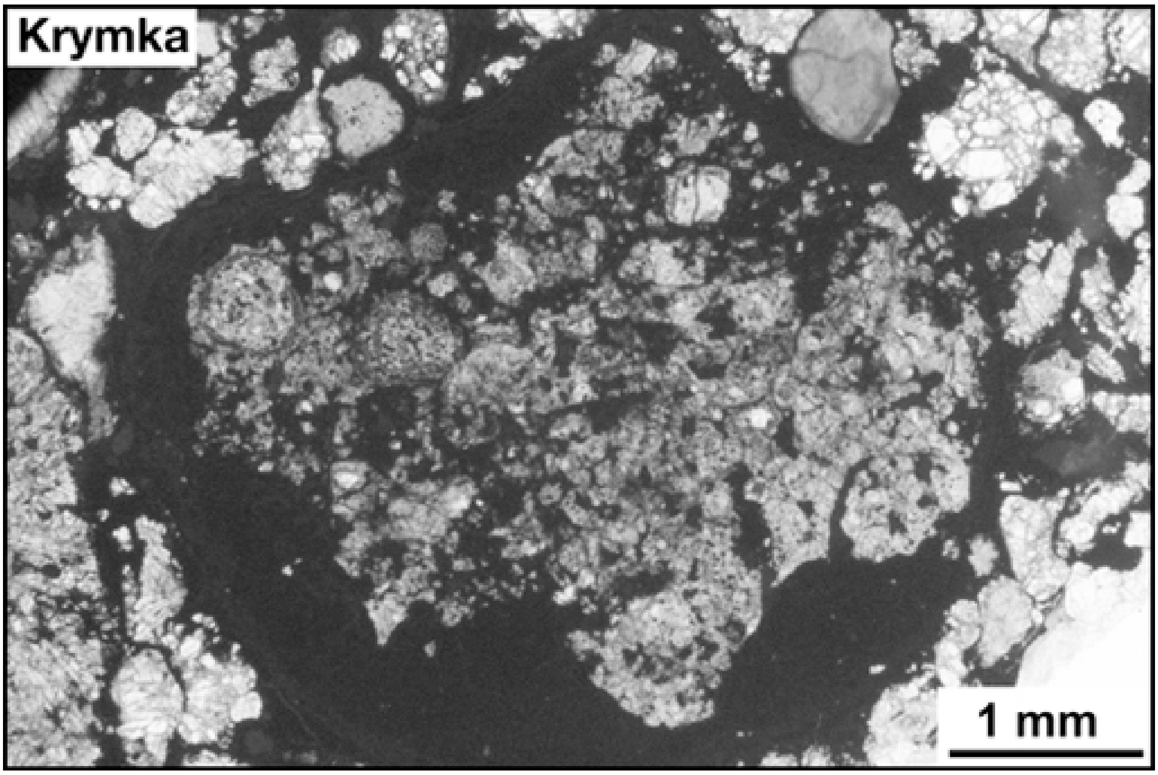

Fig. 3: Fragment of an unusual chondritic fragment in the unequilibrated ordinary chondrite Krymka (LL3). The clast consists chemically of almost equilibrated Mg-rich olivine (Fa: 8.1±1.6) and somewhat more variable pyroxene (Fs: 6.4±3.3 mol%). Due to the ocurrence of abundant opaque grains the fragment has a black appearance at the edge (especially in the lower part). Photomicrograph in transmitted polarized light.

inclusions must have accreted from regions different from those of their respective rims and matrices and were later incorporated into the host meteorite.

(c) *Fragments of fine-grained breccias (breccia in a breccia)*: In many cases, black clasts in the Adzhi-Bogdo (LL3-6) chondritic breccia are fine-grained breccias themselves and also contain abundant tiny opaque phases (Fig. 4; Bischoff et al., 1993c). Similar dark fragments (portions) occur in Fayetteville (Xiao and Lipschutz, 1991).

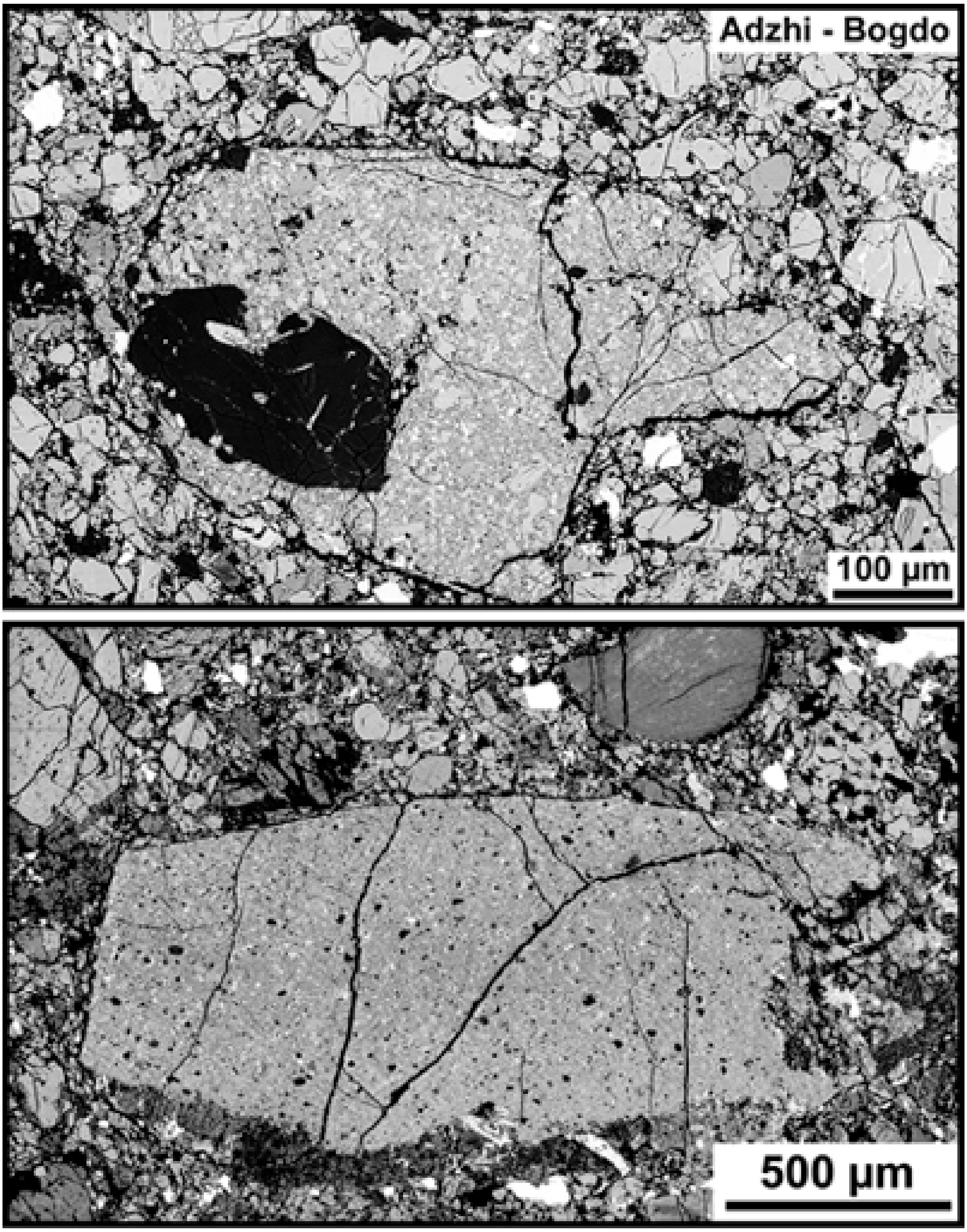

Fig. 4: BSE image of two fine-grained, optically dark fragments in the Adzhi-Bogdo (LL3-6) ordinary chondrite regolith breccia. Both fragments can be described as individual breccias that occur within the Adzhi-Bogdo host breccia (breccia in a breccia). The large black grain in the upper image is a plagioclase grain (An_{20}).

(d) *Metal-troilite rich clasts*: Metal-troilite-rich clasts, which also could be regarded as some type of dark inclusion or clast, were found in several ordinary chondrites (e.g., Moorabie, Bishunpur, Krymka). Impact melting of metal and sulfide-rich materials close to the eutectic composition of the Fe-S system was suggested by Scott (1982) and Fujita and Kitamura (1992) for their origin. Kojima et al. (2003) argued that troilite-silicate-metal inclusions in Bishunpur were fragmented and dispersed after impact-induced compaction, and then reaccreted onto the parent body. Three varieties of predominantly opaque, shocked metal-troilite-rich clasts were reported from the Northwest Africa 428 (L6) chondrite breccia (Rubin, 2003). Also, in Krymka (LL3) the occurrence of several sulfide- and metal-enriched fragments has been reported (Semenenko and Girich, 2001).

(e) *Fine-grained, matrix-like cognate inclusions:* This type of inclusion appears to consist mostly of typical matrix material, Huss-matrix (Huss et al., 1981). A fine-grained inclusion in Sharps (H3) described by Zolensky et al. (1996a) appears to be a matrix "lump" genetically related to the host chondrite. A similar object (BK15) has been identified in Krymka (Semenenko et al., 2001). The same is probably the case for a dark fragment found in Tieschitz (H3; Kurat, 1970).

(f) *Fragments or areas of shock melts with abundant tiny metal/sulfide grains*. A dark inclusion with "augen" in the Manych LL (3.1) ordinary chondrite consisting mainly of Fe-rich olivine, high-Ca pyroxene, and Na-rich feldspathic glass is suggested to represent a shock melt containing some unmelted precursor material (Kojima et al., 2000). This type of inclusion could also be classified as an impact melt breccia (see below). In all types of ordinary chondrites shock veins exist. Actually, these "veins" are only veins on a two-dimensional scale (for example in a thin section) – in three-dimensions they are irregularly-shaped "plates" with variable thickness. In some chondrites (and certainly in thin sections, due to sectioning) these plates can lead to huge optically dark areas. This is especially the case for many of the "very strongly shocked" (S6; Stöffler et al., 1991), ringwoodite-bearing LL- (Bischoff, 2002) and L-chondrites (e.g., Binns et al., 1969; Smith and Mason, 1970; Stöffler et al., 1991). Dark grey impact melt rock clasts are also known from Nulles (Williams et al., 1985).

4.1.2. Impact melt rocks and breccias

Impact melt breccias among the ordinary chondrites or clasts of impact melt breccias in ordinary chondrites offer direct evidence for high energy collisions. Impact melt breccias are well-known among the L-chondrites: e.g., Chico, Ramsdorf, Shaw, Madrid, Point of Rocks, Patuxent Range (PAT) 91501 (e.g., Taylor et al., 1979; Nakamura et al., 1990b; Casanova et al., 1990; Bogard et al., 1995; Yamaguchi et al., 1999; Mittlefehldt and Lindstrom, 2001; Norman and Mittlefehldt, 2002). Dar al Gani 896, Orvinio, Spade, and Smyer can be regarded as H-chondrite impact melt breccias (Folco et al., 2002, 2004; Rubin, 2002; Burbine et al., 2003; Rubin and Jones, 2003; Grier et al., 2004). The Antarctic LL chondrites Yamato-790964 and -790143 are regarded as impact melt rocks which represent nearly total melting of precursor rocks (Sato et al., 1982; Okano et al., 1990; Yamaguchi et al., 1998). Fragments of impact melt or impact melt breccias occur in many brecciated ordinary chondrites (e.g., Keil, 1982, and references therein; Bischoff et al., 1993c; Welzenbach et al., 2005).

The L chondrite Ramsdorf appears to be one of the most heavily shocked ordinary chondrites and has only partly retained some traces of its original texture: Brief shock heating to 1400-1600°C caused complete melting of metallic Fe,Ni, plagioclase, and partial or complete melting of pyroxenes and olivines (Yamaguchi et al.,1999).

The H6 chondrite Portales Valley rock is an annealed impact melt breccia with coarse metal interstitial to angular and subrounded chondritic clasts (Rubin et al., 2001). It may be a sample of the brecciated and metal-veined floor of an impact crater that was subsequently buried and cooled at 6.5 K/Ma (e.g., Kring et al., 1999; Sepp et al., 2001). However, since molten metallic Fe-Ni is not thought to segregate in asteroids from chondritic impact melts (Keil et al., 1997), the source of heat may have been internal.

A carbon-rich chondritic clast PV1 within the Plainview H-chondrite regolith breccia, originally described by Scott et al. (1988), was suggested to be an impact-melted fragment that experienced aqueous alteration and enrichment of C (Rubin et al., 2004).

4.1.3. Igneous textured clasts

In several ordinary chondrites igneous-textured clasts with abundant SiO_2-phases (quartz, cristobalite, tridymite) occur (e.g., Bischoff, 1993; Bischoff et al., 1993c; Bridges et al., 1995a; Ruzicka et al., 1995; Hezel, 2003). Strong differentiation of chondritic material is required to form silica-oversaturated liquids, leading for example to coarse-grained granitoidal clasts as found in Adzhi-Bogdo LL3-6 chondrite (Fig. 5; Bischoff, 1993;

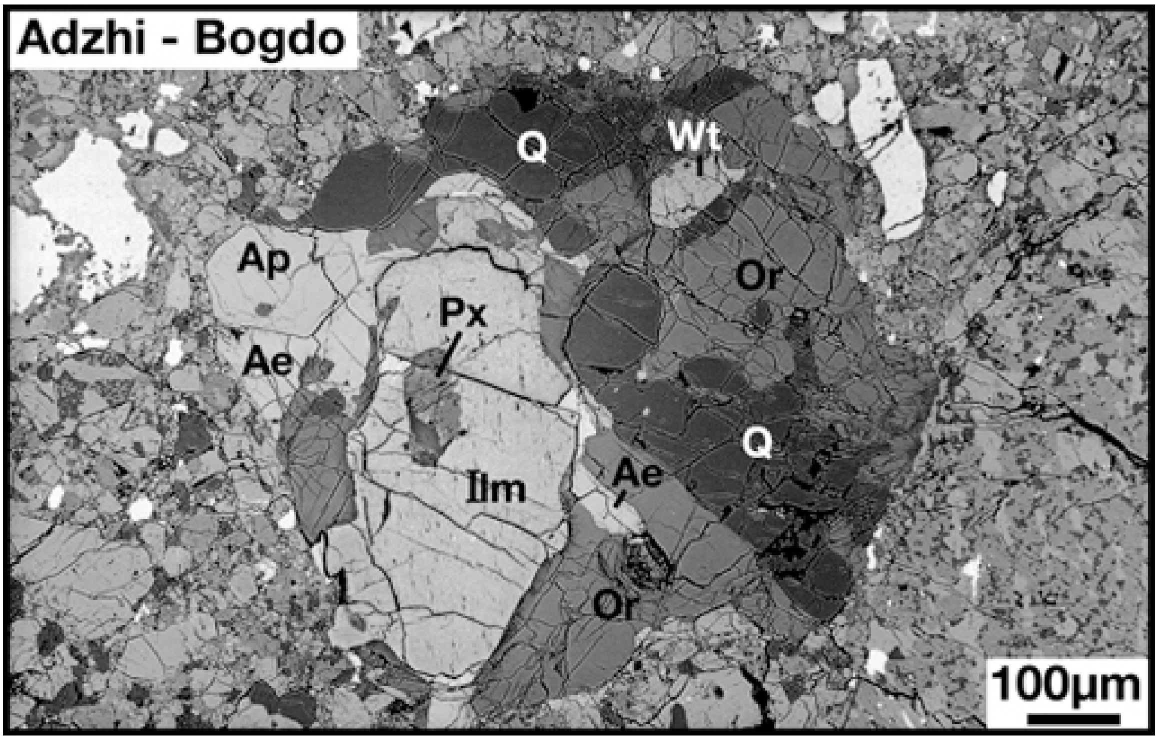

Fig. 5: Alkali-granitoidal clast from Adzhi-Bogdo (LL3-6) ordinary chondrite regolith breccia consisting of apatite (Ap), aenigmatite (Ae), ilmenite (Ilm), whitlockite (Wt), quartz (Q), and K-feldspar (Or). Within quartz tiny grains of zircon are enclosed (white). Photomicrograph in backscattered electrons (compare Bischoff et al. (1993c) and Bischoff (1993)).

Bischoff et al., 1993c) or to clasts in Parnallee (LL3) and Farmington (L5) consisting of up to 95 vol% of an SiO_2 phase (Bridges et al., 1995a). A clast with SiO_2-normative mesostasis was found in the Hammadah al Hamra 180 unique chondrite with affinity to LL-group ordinary chondrites (Bischoff et al., 1997). Other large, igneous textured clasts without abundant SiO_2-phase(s) were reported from several other chondrites (e.g., Julesberg (L3), Vishnupur (LL4-6); Ruzicka et al., 1998; Bridges and Hutchison, 1997). Kennedy et al. (1992) discuss a microgabbro in the Parnallee chondrite suggesting that it formed by partial melting in a planetary body after removal of metallic Fe.

A feldspar-nepheline achondritic clast in Parnallee has an oxygen isotopic composition indicating carbonaceous chondrite affinities (Bridges et al., 1995b).

Other large achondritic clasts include troctolitic and/or dunitic and/or harzburgitic inclusions in Barwell (L6), Yamato (Y)-75097 (L6),Y-794046 (H5) and Y-793241 (e.g., Prinz et al., 1984; Hutchison et al., 1988; Nagao, 1994; Mittlefehldt et al., 1995), pyroxenitic or noritic fragments in Hedjaz (L3.7) (Nakamura et al., 1990a; Misawa et al., 1992). Some of these igneously textured clasts have sizes and compositions like those of chondrules and CAIs. It is therefore possible that some are related to chondrules and CAIs and are not clasts from an igneously differentiated body.

4.1.4 Foreign clasts

A small number of clasts exist in ordinary chondrite breccias that are unrelated to the host meteorite (e.g., Dodd, 1974; Fodor and Keil, 1975, 1978; Keil, 1982; Rubin et al., 1983; Prinz et al., 1984; Wieler et al., 1989; Bischoff et al., 1993c; MacPherson et al., 1993). Some more details on these clasts are given in section 6 (Impact-related mixing; see below).

4.1.5. Granulitic breccias

Cabezo de Mayo is a recrystallized, metamorphosed L/LL6 chondrite, also described as a pre-metamorphic fragmental breccia (Casanova et al., 1990). It is not clear, if this rock can already be grouped with the granulitic breccias.

4.2. Rumuruti chondrites

The abundance of regolith breccias among the R chondrites is 50% (Table 2; Fig. 6). The brecciated samples (e.g., Rumuruti, Dar al Gani 013, Hughes 030, Pecora Escarpment (PCA) 91002, and Acfer 217) have been studied in great detail (e.g., Schulze et al., 1994, Bischoff et al., 1994a, 1998; Rubin and Kallemeyn, 1994; Jäckel et al., 1996; Kallemeyn et al., 1996; Bischoff, 2000). These breccias contain cognate, lithic fragments of various type and metamorphic degree. Impact melt rock clasts (Fig. 7), dark unequilibrated fragments, and clasts of all petrologic types are embedded in a fine-grained, well-lithified, olivine rich matrix. A detailed characterization of unequilibrated, type 3 lithologies in R chondrites is given by Bischoff (2000). So far, fragments of other chondrite classes have not been found within the brecciated R chondrites.

4.3. Enstatite chondrites

Enstatite chondrites contain a variety of breccias and impact melted rocks. Keil (1989) noted that seven out of 45 E chondrites appeared to be fragmental breccias, one was a regolith breccia (the EH3 chondrite Allan Hills (ALH) A77156). Happy Canyon and Ilafegh 009 were both inferred to be clast-free impact melts (Bischoff et al., 1992; McCoy et al., 1995) but this was questioned by Weisberg et al. (1997a). Abee and Adhi Kot were characterized as impact melts with ghosts of chondrule-bearing clasts (Rubin and Scott, 1997). Lin and Kimura (1998) identified two further EH impact melt rocks, Y 82189 and Y-8404. An EH3 chondrite, Parsa, and five EL6 chondrites including Hvittis

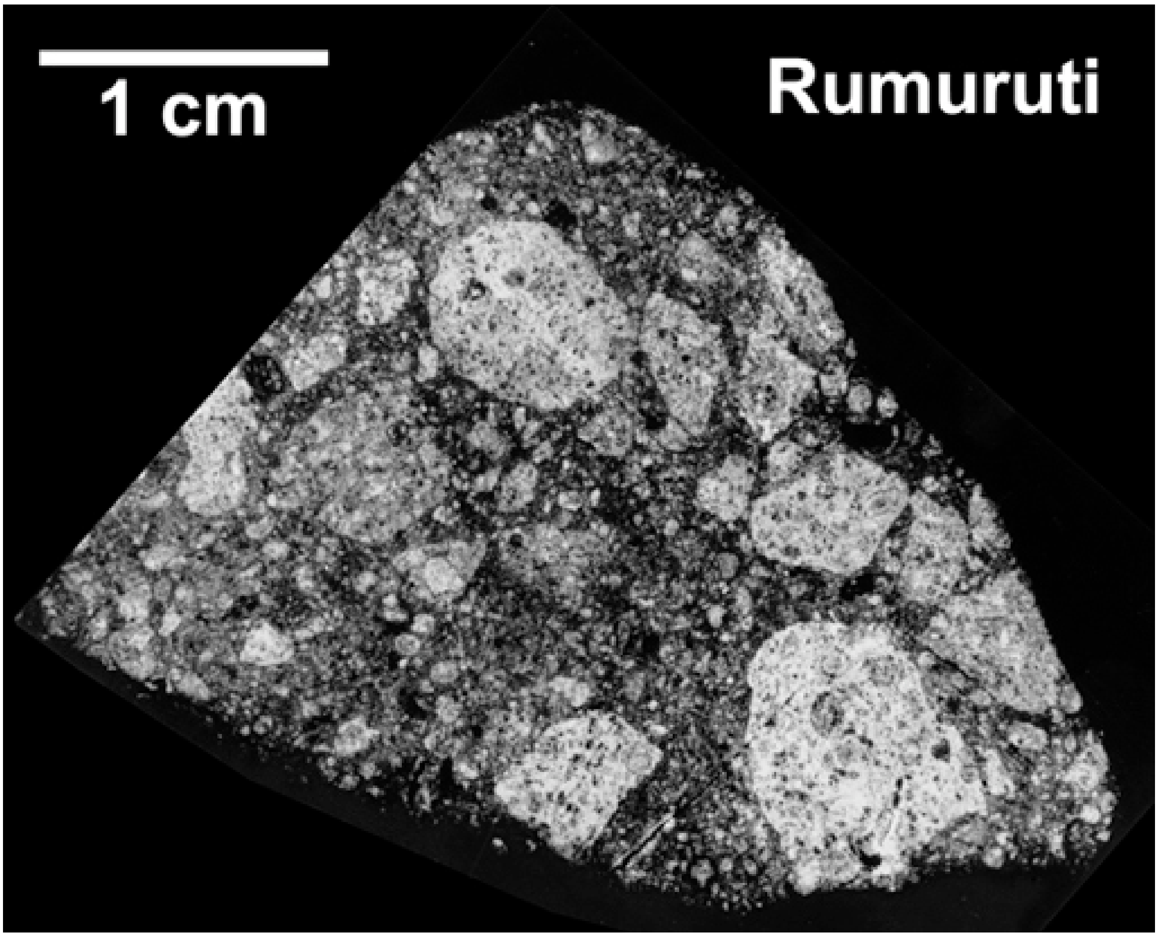

Fig. 6: Overview of the R chondrite regolith breccia Rumuruti. The photographed hand specimen consists of light- and dark-colored fragments embedded in a clastic matrix. The abundance of large clasts is roughly 50%. See Schulze et al. (1994) for details.

contain abundant clasts or large opaque veins that probably formed by impact melting (Rubin, 1985; Rubin et al., 1997).

Weisberg et al. (1997a) suggested that the EH chondritic melt rock Queen Alexandra Range (QUE) 94204 is an internally-derived melt rock from an EH-like parent body and that the interpretation of other meteorites as impact melt rocks needs to be reconsidered.

Recent noble gas studies have identified other E chondrites with solar and solar-like gases, but the origin of these gases is controversial (Ott, 2002). In their noble gas study of 57 E chondrites, Patzer and Schultz (2002) concluded that about 30% of E3 chondrites are solar gas rich, but only one had been described as a fragmental breccia, MacAlpine Hills (MAC) 88138 (Lin et al., 1991). However,

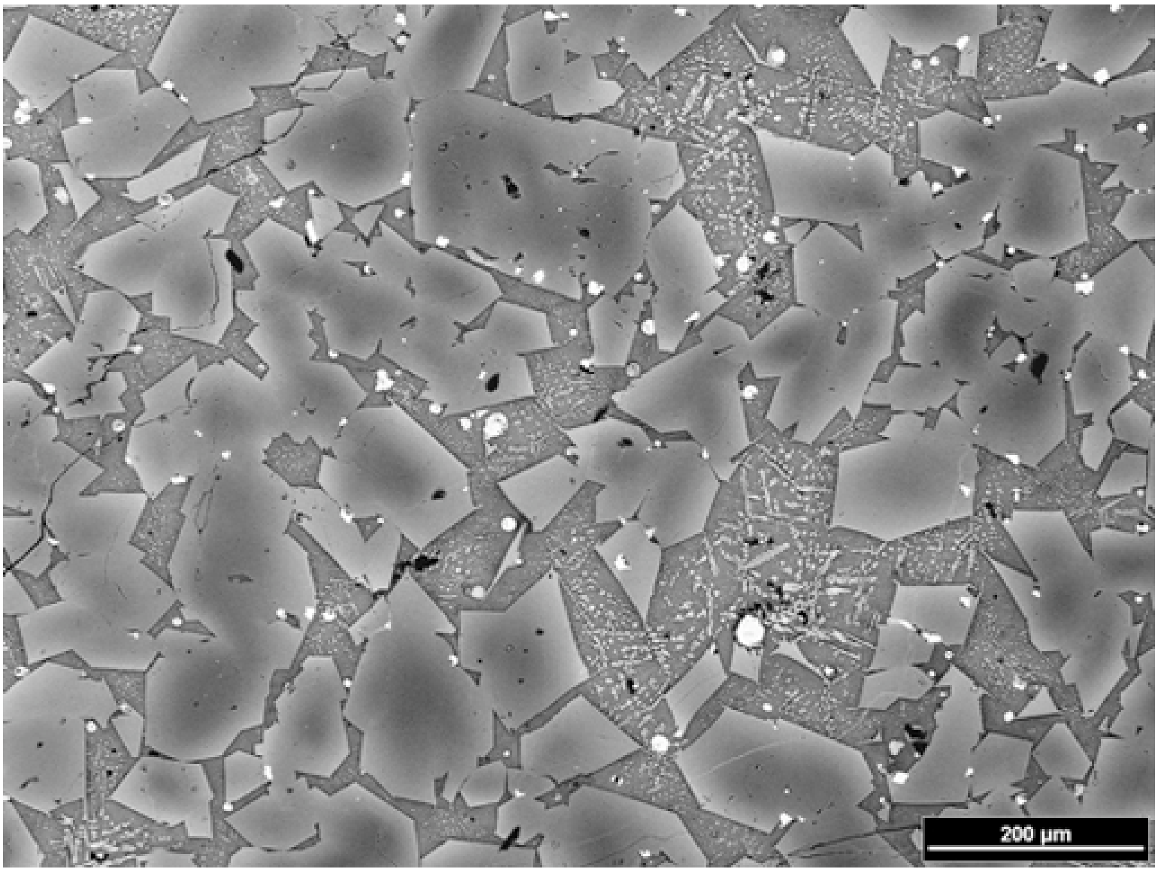

Fig. 7: Typical texture of an impact melt clast within the R-chondrite Dar al Gani 013. Euhedral to subhedral, zoned olivine grains are embedded in a mesostasis containing tiny, skeletal crystals of pyroxene. Light grains are either chromite or Fe-sulfid. Image in backscattered electrons.

solar gases are heterogeneously distributed in ALHA77156, consistent with the possible presence of unrecognized clasts. The type 4-6 EH and EL chondrites, which appear to lack solar wind gases, contain a so-called subsolar component. Patzer and Schultz (2002) argued that the subsolar gases were not simply a reflection of metamorphic heating of samples containing solar-wind gases because ordinary chondrites do show such an effect. They inferred that the subsolar gases were acquired before or during accretion. However, on the basis of their analyses of St. Mark's, Busemann et al. (2003a,b) argued that the sub-solar gases were actually a mixture of Q (planetary) gases with small amounts of solar gases plus terrestrial contamination, and that the subsolar gases were not a separate component. They further argued that the solar gases were probably trapped *prior* to accretion and were not present on the surface of regolith grains as they were only released after lengthy etching. In addition, neither St. Mark's nor other E chondrites containing subsolar gases appear to be brecciated.

E chondrites also differ from ordinary and carbonaceous chondrites in their breccia properties. Impact melts and well shocked chondrites are relatively abundant (Rubin et al., 1997), but foreign clasts and mixtures of type 3-6 material appear to be absent. This might reflect the difficulty of identifying clasts in weathered chondrites, the limited amount of material that has been carefully studied, or a significant difference in the formation and evolution of these chondrites. Conceivably, the differences between the enstatite and ordinary chondrites in their trapped noble gases may simply result from more intense impact processing of the enstatite chondrites. Resolution of these issues and the origin of the trapped noble gases will greatly help in understanding the origin of E chondrites.

4.4 Carbonaceous chondrites

4.4.1 CI chondrites and related chondrites

Although the CI chondrites (Ivuna, Orgueil, Alais, Tonk, and Revelstoke) are regarded as the chemically most primitive rocks in the solar system, all CI chondrites are complex breccias consisting of fragments up to several hundred µm in size surrounded by a fine-grained matrix (e.g., Richardson, 1978; Beauchamp and Fredriksson, 1979; Endress and Bischoff, 1993, 1996; Endress, 1994; Endress et al., 1994a; Morlok, 2002; Morlok et al., 2000; 2001). All analyzed CI chondrites contain solar wind implanted noble gases (Table 2; Bischoff and Schultz, 2004) indicating their presence at the upper surface of their parent body(ies). Orgueil is highly brecciated; and the degree of brecciation decreases in the order Orgueil > Ivuna > Alais ≅ Tonk (Morlok, 2002). The clasts vary significantly in mineralogy and chemistry (Fig. 8). Endress (1994), Morlok et al. (2001), and Morlok (2002) defined several groups of fragments with similar chemical and mineralogical characteristics ranging from clasts dominated by coarse, Mg-rich phyllosilicates to fragments with high abundance of Fe. Phosphate-rich clasts were also encountered (Morlok et al., 2001; Morlok, 2002) as are olivine-bearing clasts (Endress, 1994; Bischoff, 1998). These various types of clasts represent distinct lithologies found on the CI chondrite parent body(ies) prior to impact brecciation, mixing, and reaccreation.

The slightly metamorphosed sample Yamato 82162 appears to be related to the CI-chondrites. Based on the occurrence of abundant clasts (up to several mm in size) it was classified as a chondritic breccia (compare Figs. 1-5 in Bischoff and Metzler (1991)).

Yamato 86029 is a similar CI-like breccia consisting of a variety of clasts. Tonui et al. (2003) suggest that olivine aggregates in Y-86029 were mechanically mixed from another environment into the host chondrite and may represent parts of another asteroid (probably of ordinary chondrite material).

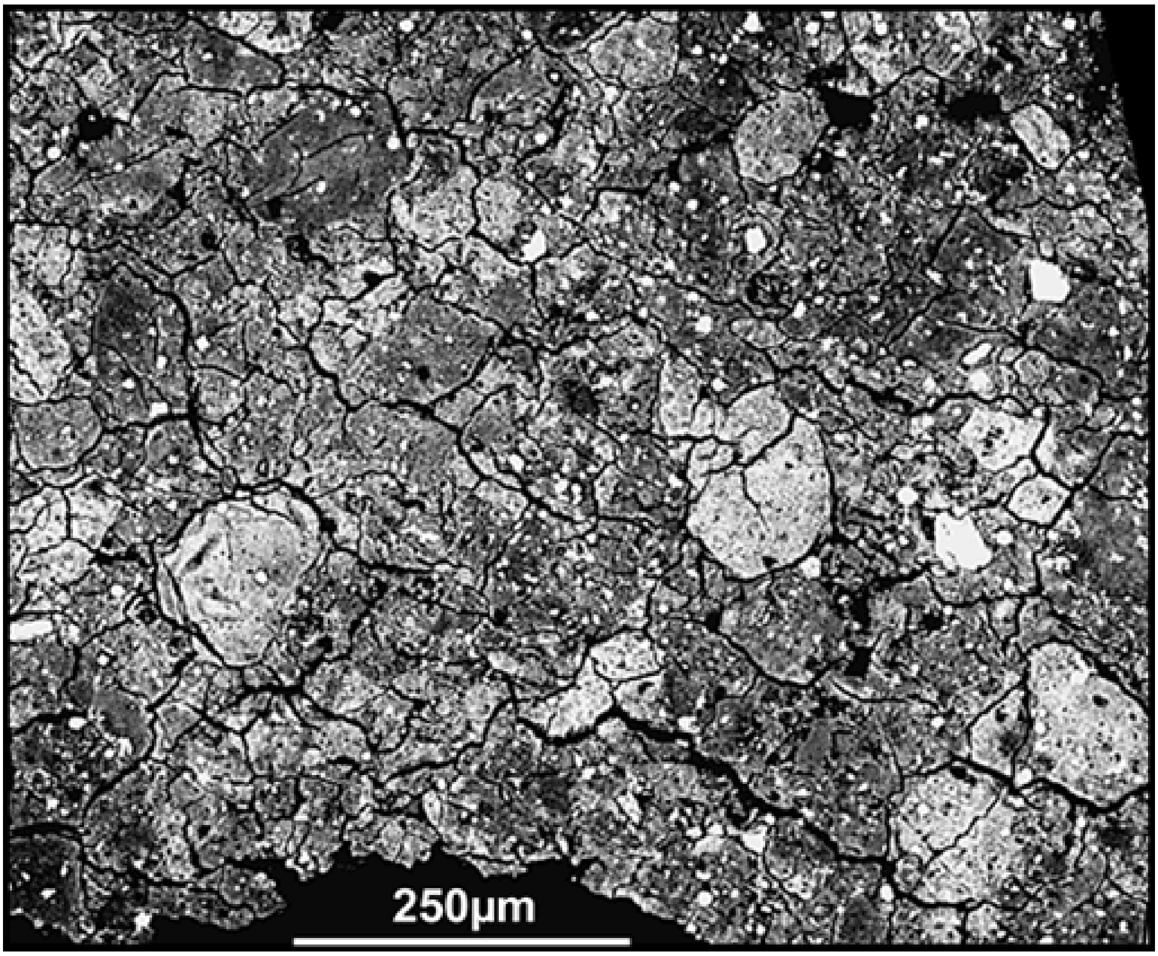

Fig. 8: Part of the severely brecciated CI chondrite Orgueil. Individual fragments are variable in composition as indicated by different grey tones. Image in backscattered electrons; modified after Morlok (2002).

The Tagish Lake meteorite shares similarities with CI and CM chondrites (e.g., Mittlefehldt, 2002; Zolensky et al., 2002, Grady et al., 2002) and consists of different lithologies: A dominant carbonate-poor and a less abundant carbonate-rich lithology (Zolensky et al., 2002). A CM1 clast has been studied in detail by Zolensky et al. (2002) and Bullock et al. (2005).

4.4.2 CM chondrites

CM-like clasts are widespread within impact breccias of other meteorite classes like howardites, polymict eucrites, and ordinary and carbonaceous chondrites suggesting that their parent asteroids are abundant in the main belt (e.g., Wilkening, 1973; Bunch et al., 1979; Kozul and Hewins, 1988; Mittlefehldt and Lindstrom, 1988; Hewins, 1990; Reid et al., 1990; Zolensky et al., 1992, 1996c; Buchanan et al., 1993; Pun et al., 1998; Buchanan and Mittlefehldt, 2003).

CM chondrites themselves are impact breccias, consisting of subangular mineral and lithic clasts set in a fine-grained clastic matrix (e.g., Fuchs et al., 1973; Dodd, 1981; Metzler et al., 1992; Metzler, 1995). The majority of these lithic clasts belongs to a texturally well defined chondritic rock type (primary accretionary rock; Metzler et al., 1992), which can be described as an agglomerate of chondrules and other fine-grained components, most of which are surrounded by fine-grained rims (Bunch and Chang, 1980; Metzler et al., 1992; Metzler and Bischoff, 1996).

The lithic clasts display sharp contacts to the surrounding clastic matrix, best visible using Scanning Electron Microscopy (SEM)-techniques (Fig. 9). In the case of Nogoya

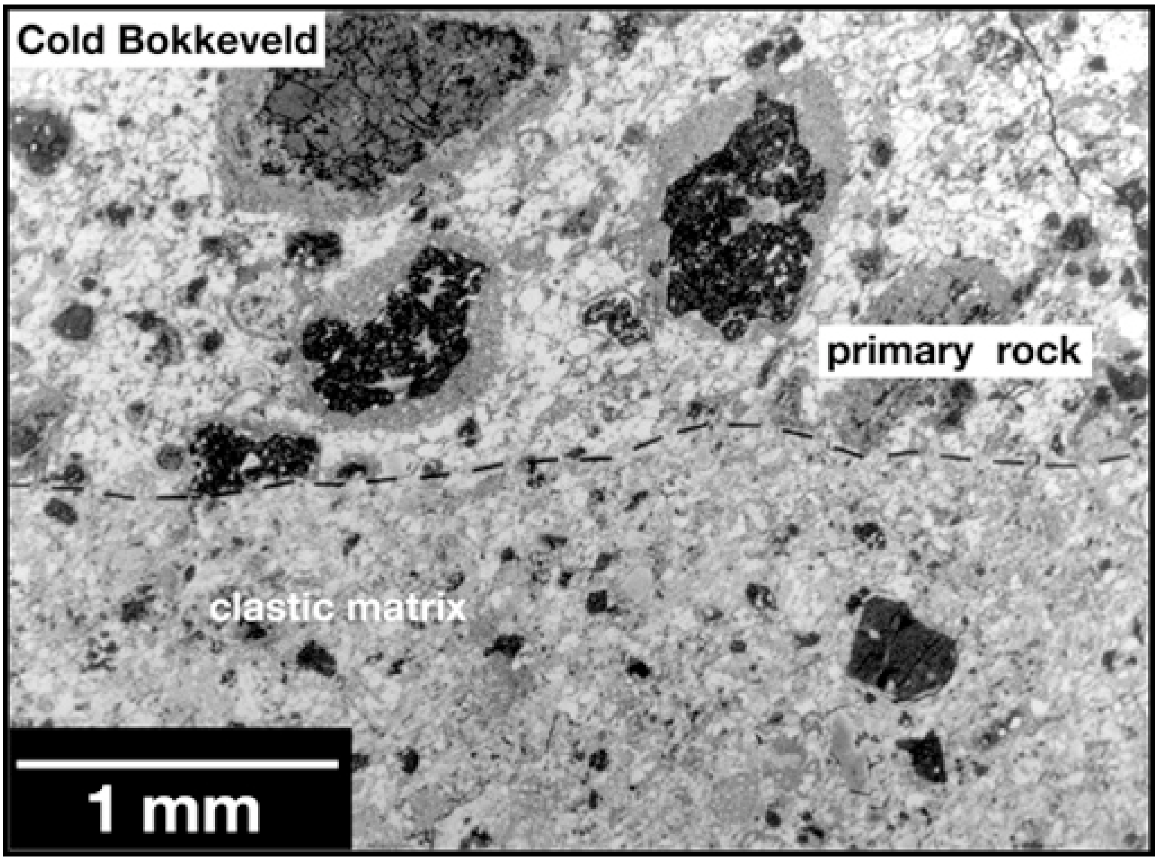

Fig. 9: Typical appearance of a CM breccia as indicated by the boundary between a fragment of primary accretionary rock and the clastic matrix. In the upper part all the coarse-grained components are surrounded by accretionary dust mantles, whereas in the clastic matrix angular fragments occur and all coarse-grained components have lost their dust mantles due to impact-induced fragmentation. Image in backscattered electrons after Metzler et al. (1992).

these features are even visible by the naked eye in the form of light-dark structures (Heymann and Mazor, 1967). The clastic matrix essentially shows the same mineralogical and chemical composition as the lithic clasts. Hence, both lithologies seem to originate from the same precursor rock (Metzler, 1990; Metzler et al., 1992). CM chondrites differ texturally from each other by variable ratios of clastic matrix to lithic clasts. Based on the degree of brecciation the amount of clastic matrix varies from 100% in Essebi and Bells (Metzler et al., 1992) to almost zero in Y-791198. This Antarctic CM chondrite studied by Metzler et al. (1992) is unbrecciated on the cm scale (thin section scale) and may represent a remnant of pristine precursor rock from which brecciated CM chondrites have formed by impact comminution.

Many CM chondrites show evidence of intensive aqueous alteration on the parent body (e.g. Kerridge and Bunch, 1979; Zolensky and McSween, 1988; Brearley and Geiger, 1991; Browning et al., 1995; Hanowsky and Brearley 1997, 2001). In some cases this epoch clearly predates the brecciation events, which lead to the formation of the final host breccias. This preaccretionary aqueous alteration may have occurred in small precursor planetesimals (Metzler et al., 1992; Bischoff, 1998). Nogoya consists of lithic clasts with different alteration stages (Metzler, 1995), mixed together in the same breccia. The observation that all lithic clasts still show their original accretionary texture indicate that a single starting material was affected by liquid water under different alteration conditions, followed by impact brecciation and mixing. In this sense, CM chondrites like Nogoya and Cold Bokkeveld are genomict breccias, consisting of clasts of the same compositional group, but of various petrologic types (Metzler, 1995; Zolensky et al., 1997).

CM chondrites are regolith breccias (Table 2). It has been shown by Nakamura et al. (1999a, b) that solar noble gases in brecciated CM chondrites are restricted to the clastic matrix of these meteorites. Lithic clasts are free of solar gases and dominated by planetary noble gas components. The study of track-rich olivines in the CM chondrites Cold Bokkeveld, Mighei, Murchison, and Nogoya revealed that all preirradiated grains occur in the clastic matrix of these breccias, as well (Metzler, 1993, 1997, 2004). Hence, in close analogy to regolith breccias from ordinary chondrites, the fine-grained clastic matrix of CM chondrites is the host lithology for both solar gases and preirradiated grains.

4.4.3. CV chondrites.

Members of the Vigarano-type carbonaceous chondrite group vary considerably. Based on petrology they can be subdivided into the reduced and the Bali-like and Allende-like oxidized subgroups (Weisberg et al., 1997b). Two types of clasts are present in CV3 chondrites: dark inclusions, which are present in many, or even most, CV3 chondrites (e.g., Allende, Efremovka, Leoville, Mokoia, Vigarano, Ningqiang, Yamato-86751), and other chondritic inclusions, which are generally found in the regolith breccias.

The dark clasts or dark inclusions, record a history of fragmentation, mixing, and relithification (e.g., Fruland et al., 1978; Kracher et al., 1985; Heymann et al., 1987; Bischoff et al., 1988; Kurat et al., 1989; Palme et al., 1989; Johnson et al., 1990; Kojima et al., 1993; Murakami and Ikeda, 1994; Kojima and Tomeoka, 1996, 1997; Buchanan et al., 1997; Krot et al., 1997a, 1998, 1999; Brearley and Jones, 1998; Ohnishi and Tomeoka, 2002; Vogel et al., 2003; Zolensky et al., 2003). All these dark inclusions are olivine-rich and most probably represent fragments of a parent body that experienced aqueous alteration and subsequent dehydration (e.g., Kracher et al., 1985; Kojima et al., 1993; Kojima and Tomeoka, 1996; Buchanan et al., 1997; Krot et al., 1997a, 1998, 1999). Alternatively, some may be fragments of primitive accreted material (e.g., Palme et al., 1989; Kurat et al., 1989; Zolensky et al., 2003). Dark inclusions in Mokoia appear to have experienced a higher degree of thermal metamorphism than the host meteorite (Ohnishi and Tomeoka, 2002), whereas one primitive dark inclusion in Ningqiang was added to the host chondrite after any parent body alteration event (Zolensky et al., 2003). Bulk O-isotopic compositions of some dark inclusions in the reduced CV3 chondrite Efremovka plot in the field of aqueously altered CM chondrites (Krot et al., 1999) indicating significant differences between these inclusions and their host rocks.

In summary, the dark inclusions found in CV3 chondrites are unique and represent an important source of information about early solar system materials not sampled by individual rocks. It is important to note that all dark inclusions have experienced at least the same and in some cases a higher degree of thermal metamorphism than their host meteorites! No phyllosilicate-rich DIs have been reported from CV3 chondrites.

Clasts in regolith breccias are much more diverse. The Vigarano regolith breccia contains lithic clasts of Bali-like oxidized CV materials and abundant reduced materials, while the Mokoia regolith breccia contains Allende-like and Kaba-like oxidized materials (Krot et al., 1998; 2000). These mixtures were attributed to impact mixing and lithification of reduced and oxidized CV material from a single, heterogeneously altered asteroid (Krot et al., 2000). Mixing of oxidized and reduced fragments from different precursor planetesimals can certainly not be ruled out. However, alteration on asteroidal bodies lasted for up to 15 Myr (Russell et al., 2005), much longer than the accretion timescales for asteroids (~1 Myr). Mokoia also contains metamorphosed chondritic clasts, which may be CV4/5 material from deep within the CV body (Krot et al., 1998). Camel Donga 040 has been described as a genomict breccia containing unequilibrated material and a metamorphosed lithology (Zolensky et al., 2004). A C2-clast up to several cm in size was found in the Leoville regolith breccia (Keil et al., 1969); Kennedy and Hutcheon (1992) describe a basaltic plagioclase-olivine inclusion in Allende. We infer that the CV regolith breccias contain valuable clues to the interior of the CV body and the projectiles that modified it.

Metal-sulfide aggregates are common constituents in Yamato-86751 (CV3; Murakami and Ikeda, 1994); however, it is unclear, whether they represent true clasts produced by impact processes on the parent or precursor parent body or parts of a possible impactor.

4.4.4. CO chondrites

Only a very few CO3 chondrites are breccias. Frontier Mountain (FRO) 95002 was classified as a brecciated rock (Grossman, 1997), but there are no reports on distinct individual fragments or inclusions within it. Three angular 1-6 mm-sized chondritic clasts were found by Rubin et al. (1985) in the Colony breccia. Scott et al. (1992) suggested that Felix may be a breccia containing fragments with diverse shock histories. Recently, Itoh and Tomeoka (2003) reported the occurrence of dark inclusions in the CO3 chondrites Kainsaz, Ornans, Lance, and Warrenton and suggested that these clasts had undergone aqueous alteration and subsequent dehydration at a location different from the present location in the meteorite. ”Basaltic” fragments were also reported from Lance (Kurat and Kracher, 1980). Isna was first reported to be a solar-wind-rich regolith breccia (Scherer and Schultz, 2000), but this classification has been changed by Schultz (2004; pers. communication; Table 2).

4.4.5. CK chondrites

The CK chondrite group contains no gas-rich regolith breccias (Scherer and Schultz, 2000; Table 2). However, some CK meteorites are described as fragmental breccias. Geiger (1991) reports that ALH82135 (CK4/5) and ALH84038 (CK4/5) are severely brecciated on a thin section scale with variable fragment sizes. Similarly, Karoonda (CK4) is heavily brecciated (Fig. 10). Shock darkening and the presence of melt veins in some CK chondrites are also known (e.g., Rubin, 1992).

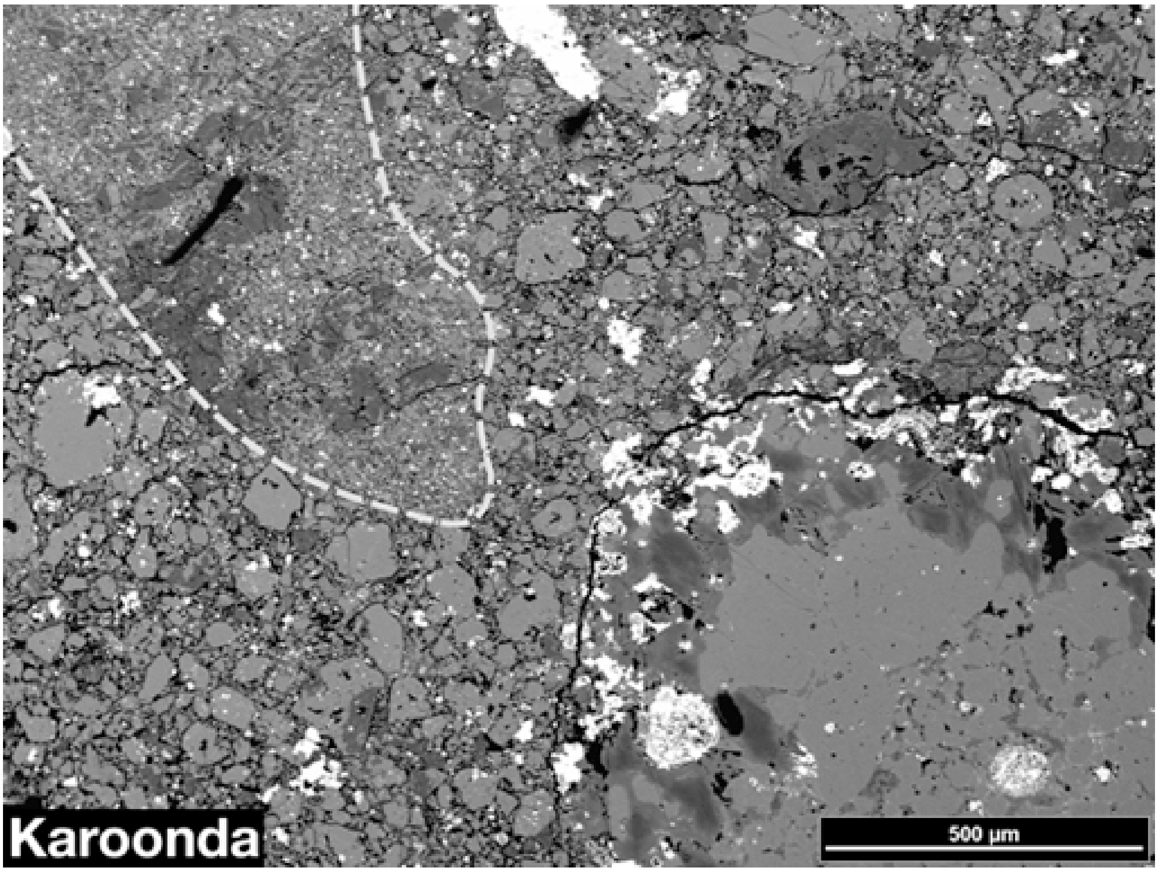

Fig. 10: Brecciated nature of the Karoonda CK chondrite. A fine-grained (upper left) and coarse-grained fragment (lower right) are embedded in a fine-grained clastic matrix. Image in back-scattered electrons.

4.4.6. CR clan meteorites (CR, CH, and related chondrites)

CR and CH chondrites, the Bencubbin-like (CB; Bencubbin, Gujba, and Weatherford) and CH-like grouplets (Hammadah al Hamra (HH) 237 and Queen Alexandra Range (QUE) 94411), and the unique sample Lewis Cliff (LEW) 85332 are chemically and mineralogically related and form the CR clan (e. g., Weisberg et al., 1990, 1995, 2001; Bischoff, 1992; Bischoff et al., 1993a,b; Krot et al., 2002; Weisberg et al., 2005, this volume).

Most - if not all – CR chondrites contain dark inclusions (e. g., Zolensky et al., 1992; Bischoff et al., 1993a; Weisberg et al., 1993; Endress et al., 1994b; Abreu and Brearley, 2004, 2005), which are the only "xenolithic" lithology known in typical CR chondrites, which are all regolith breccias (Table 2). These dark clasts may represent fragments of different lithologies of the same parent body or accreted as xenoliths to the same time with other components during parent body formation. Abreu and Brearley (2004) found that within the CR chondrite Elephant Moraine (EET) 92042 impact brecciation has formed regions within the matrix that are highly clastic in character.

CH chondrites contain a high proportion of fragmented components (mainly chondrules; Bischoff et al., 1993b) indicating that the precursor components of the CH constituents were much larger prior to accretion and lithification of the parent body (compare Fig. 2 in Bischoff et al., 1993b). The most obvious xenolithic components are dark, phyllosilicate-rich inclusions (Fig. 11; e.g., Grossman et al., 1988; Scott, 1988; Weisberg et al., 1988; Bischoff et al., 1993b, 1994b).

The absence of effects of aqueous alteration in the chondrules and metals in CHs indicates that the phyllosilicate-rich dark inclusions experienced aqueous alteration prior to being incorporated into their immediate (CH) parent bodies (Krot et al., 2002).

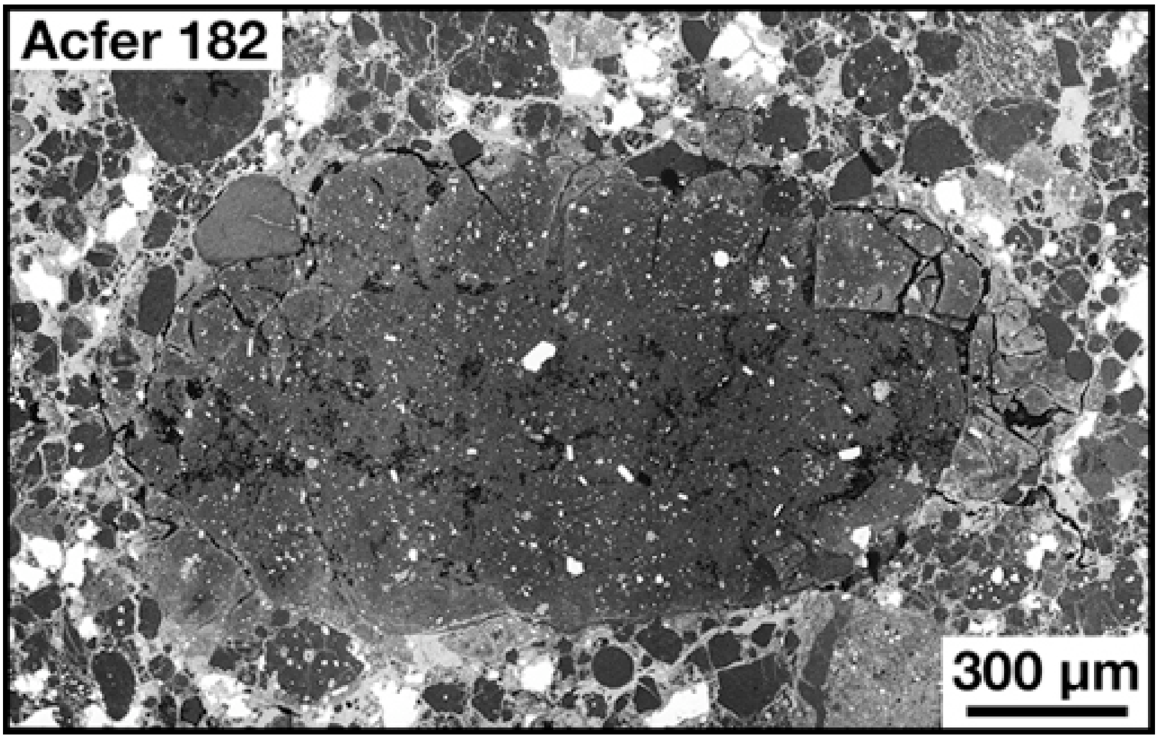

Fig. 11: Dark inclusion in the CH chondrite Acfer 182. The fine-grained inclusion contains some large pyrrhotite grains (white) and abundant pores (dark spots) and fractures. Photomicrograph in backscattered electrons; compare Bischoff et al. (1993b).

The members of the Bencubbin-like grouplet (CB) are interesting breccias consisting of roughly 60 vol% of metal fragments and 40% of silicate-rich fragments (e.g., Weisberg et al., 1990, 2001; Krot et al., 2002). Already in 1932, Simpson and Murray mention the breccia appearance of Bencubbin, which was later described as a shock-welded breccia (Newsom and Drake, 1979). The host silicate fragments have texture and mineralogy similar to those of barred olivine chondrules; however they are much larger and angular rather than submm-sized fluid droplet-shaped objects (Weisberg et al., 1990). Xenolithic ordinary chondrite clasts were reported to occur as components of Bencubbin and

Weatherford, as well as dark (carbonaceous) clasts (Weisberg et al., 1990; Barber and Hutchison, 1991). These dark clasts are very different from those in CR and CH chondrites (which are phyllosilicate-rich): They contain metals and highly elongated, olivine-rich lenses (augen) set in a fine-grained matrix (Weisberg et al., 1990; Barber and Hutchison, 1991). Fragments with R chondritic characteristics were reported from Weatherford (Prinz et al., 1993).

Members of the CH-like grouplet, HH 237 and QUE 94411, consist of mixtures of metal and silicate chondrules and fragments. These rocks have been classified as CB chondrites by Weisberg et al. (2001), although remarkable differences to CB chondrites exist. The rare occurrence of heavily-hydrated dark clasts – similar to those found in CR and CH chondrites – has been reported by Krot et al. (2001).

Carbonaceous chondrite clasts with affinities to CI and C2 chondrites, troilite-rich clasts, and a schreibersite-bearing fragment were found in the Lewis Cliff 85332 unique carbonaceous chondrite breccia (Rubin and Kallemeyn, 1990).

4.5. Other types of chondrites

With respect to Kakangari (K) chondrite grouplet it is known that Kakangari is a gas-rich regolith breccia (Srinivasan and Anders, 1977; Brearley, 1988; Weisberg et al., 1996).

The unique chondrite Acfer 094 may be a primitive accretionary breccia, although it contains parts having a clastic matrix (Bischoff and Geiger, 1994) and fragments. One object contained in it (Fig. 12) is clearly a lithic clast, containing a Ca,Al-rich inclusion. This fragment has been characterized as a CAI within a chondrule by Krot (2004).

4.6. Acapulcoites and lodranites

Acapulco-like achondrites appear to be ultra-metamorphosed chondrites (Palme et al., 1981) and products of parent body-wide processes including a complex thermal history (McCoy et al., 1996). So far no clearly defined breccias have been reported among the members of this group. All acapulcoites are relatively unshocked (McCoy et al., 1996). However, the sample of LEW 86220 deserves special attention and is linked to the acapulcoites and lodranites, which may be genetically related to each other, through both its oxygen-isotopic and mineral composition (Clayton and Mayeda, 1996; McCoy et al., 1997; Mittlefehldt et al. 1998). The two existing lithologies are, however, not regarded as clasts as in meteoritic breccias. The lodranites are unbrecciated.

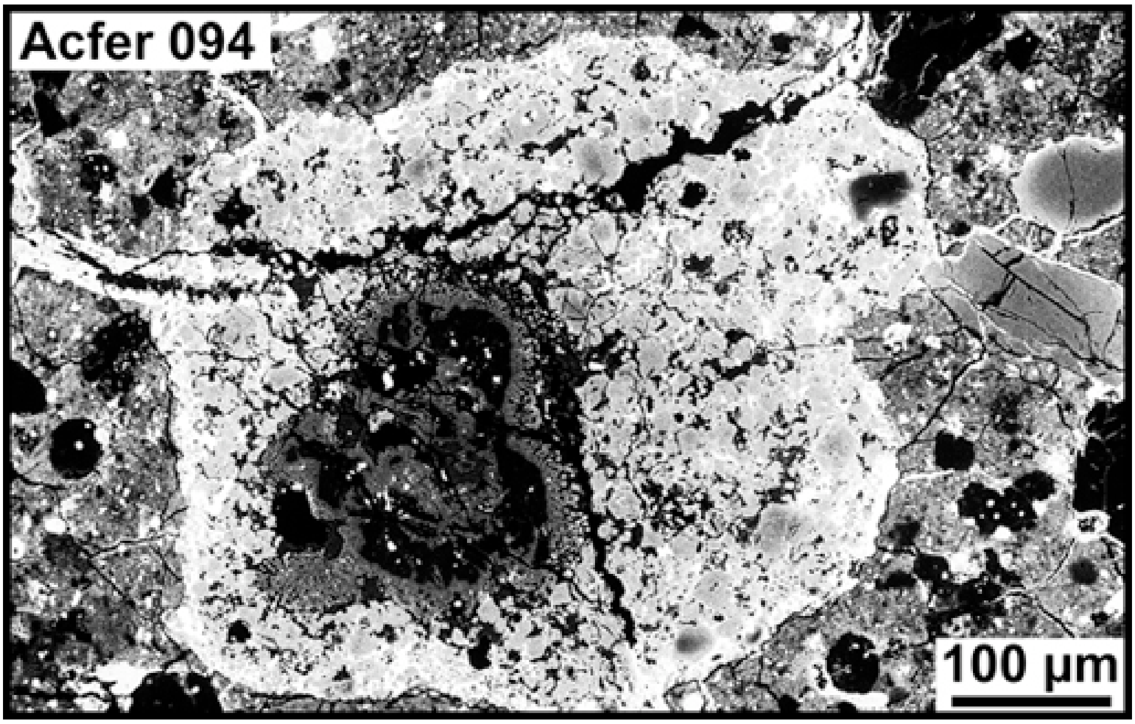

Fig. 12: CAI-bearing lithic fragment in the unique carbonaceous chondrite Acfer 094. This clast contains a Ca,Al-rich inclusion (dark grey; center, lower-left) surrounded by olivine-rich components. Image in backscattered electrons.

4.7. Winonaites

Winonaites, which are unshocked or very weakly shocked, show minor evidence for brecciation during metamorphism in Y-75300, Winona, and Mt. Morris (Benedix et al., 1997, 1998). Y-75261 is an impact melt breccia that has been linked to winonaites by virtue of its comparable oxygen isotopic composition (Benedix et al., 1998), but its mineralogy shows that it is an impact melt from the EH chondrite parent body (Nagahara, 1991). The proposed relationship between the winonaites and IAB irons leads to the suggestion that the partially melted and incompletely differentiated IAB iron-winonaite parent body experienced catastrophic breakup and reassembly (Benedix et al., 2000, and discussion and references therein).

4.8. Ureilites

Ureilites comprise the second largest group of achondritic meteorites with over 100 separate meteorites. Although many ureilites are shocked, most are coarse-grained unbrecciated rocks. However, there are about 15% that are breccias, which provide important clues to the geology of the parent asteroid: fourteen polymict breccias, one dimict breccia, and one that appears to be a monomict breccia. Since the earliest studies of polymict ureilites (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987, 1988), it was recognized that they contain a large variety of clast types, some of which are unlike unbrecciated ureilites. Several recent studies (Ikeda et al., 2000, 2003; Cohen et al., 2004; Kita et al., 2004) have provided comprehensive surveys of these materials. The following survey is based on a review of ureilitic breccias by Goodrich et al. (2004).

4.8.1. Monomict ureilites and dimict breccia

All monomict ureilites are coarse-grained, ultramafic (olivine-pyroxene) rocks characterized by high abundances (up to ~5 vol%) of carbon (graphite and secondary, shock-produced diamond or other high pressure forms; e.g., Vdovykin, 1972; Bischoff et al., 1999; Grund and Bischoff, 1999; El Goresy et al., 2004), with metal and sulfide as the only other common accessory phases (see reviews by Goodrich (1992) and Mittlefehldt et al. (1998)). The majority are olivine-pigeonite or olivine-orthopyroxene assemblages interpreted to be residues of ~25-30% partial melting. A small number are augite-bearing, and appear to be cumulates or paracumulates.

FRO93008 (possibly part of a single meteoroid comprising nine ureilites found in Frontier Mountain, Antarctica) has been recognized as a dimict ureilite (Fioretti and Goodrich, 2001; Smith et al., 2000). It consists of two monomict ureilite-like lithologies - an olivine-pigeonite assemblage of Fo 79, and an augite-bearing assemblage of Fo 87 – separated by a brecciated contact containing some exotic materials. The scale of “clasts” in this breccia is much larger than found in polymict ureilites, and it is likely to have formed in a different environment.

4.8.2. Polymict breccias

Eight of the fourteen known polymict ureilites (North Haig, Nilpena, DaG 164, DaG 165, DaG 319 (Fig. 13), DaG 665, EET83309, and EET87720) are well-studied and consist of lithic and mineral fragments that represent a variety of lithologies, and thus can be classified as fragmental breccias. Solar-wind implanted gases are present in Nilpena, EET83309 and EET87720, indicating that they are regolith breccias (Ott et al., 1990, 1993; Rai et al., 2003). The absence of solar gases in other samples does not necessarily imply a grossly different origin; all polymict ureilites are petrographically similar, and most likely formed in the same environment (Goodrich et al., 2004).

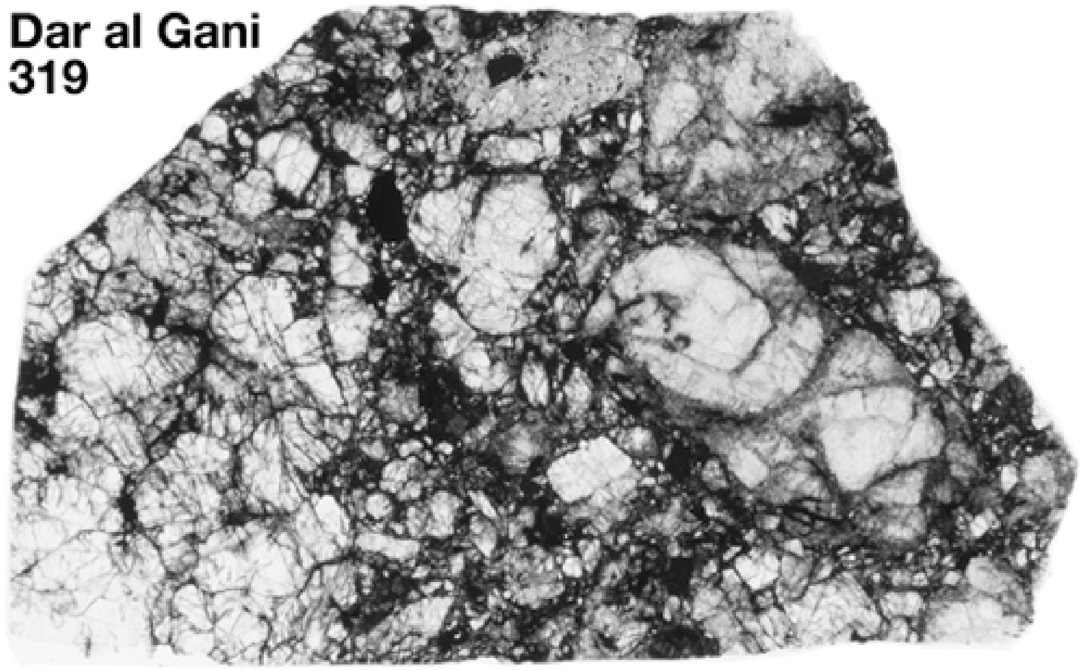

Fig. 13: Overview photograph of the polymict ureilite Dar al Gani 319 showing the fragmented character of the sample (1.4 cm in largest dimension).

The most extensive survey of the types of materials found in polymict ureilites is that of Ikeda et al. (2000), who developed a petrographic classification scheme consisting of 7 major groups, with 24 types of lithic clasts and 22 types of mineral clasts, for DaG 319. Cohen et al. (2004) provide an extensive survey of feldspathic materials in DaG 319,

DaG 165, DaG 164, DaG 665, and EET83309. These two works encompass most of the major types of materials previously observed in North Haig, Nilpena and EET83309 (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987).

More than ~97% of the material in polymict ureilites consists of lithic clasts that are compositionally and texturally similar to monomict ureilites, or mineral clasts that could have been derived from them. Olivine-pigeonite assemblages dominate among the lithic clasts, and pigeonite appears to be the dominant pyroxene among mineral clasts. Only one lithic clast resembling the olivine-orthopyroxene monomict ureilites has been identified (Goodrich and Keil, 2002), but isolated orthopyroxene clasts that could have been derived from them are common (Ikeda et al., 2000).

Lithic clasts similar to the augite-bearing monomict ureilites have been identified in DaG 319 (Ikeda et al., 2000; Ikeda and Prinz, 2001) and DaG 165 (Goodrich and Keil, 2002). Ikeda and Prinz (2001) discovered one poikilitic orthopyroxene-olivine-augite clast and two isolated olivine clasts. Goodrich and Keil (2002) found a melt-inclusion bearing olivine clast resembling the augite-bearing ureilite Hammadah al Hamra (HH) 064

(Weber and Bischoff, 1998; Weber et al., 2003), and an olivine-augite-orthopyroxene-pigeonite clast with complex poikilitic relationships resembling the augite-bearing ureilite META78008 (Berkley and Goodrich, 2001).

The remaining 2-3% of material (lithic and mineral clasts) in polymict ureilites is highly diverse, and can be divided into (a) materials that could be indigenous (cognate) to the ureilite parent body, but which are not represented among monomict ureilites, and (b) xenolithic materials that were contributed to the regolith by impactors.

4.8.2.1. Indigenous (cognate) clasts

Indigenous clasts can be subdivided into feldspathic (containing plagioclase and/or plagioclase-normative glass), mafic, and metal- or sulfide-rich types. Feldspathic clasts have attracted considerable attention because they may represent "missing" basaltic melts complementary to monomict ureilite residues.

a) Feldspathic clasts. Feldspathic clasts are described by Prinz et al. (1986, 1987, 1988), Ikeda et al. (2000), Guan and Crozaz (2001), Goodrich and Keil (2002), and Cohen et al. (2004, 2005). One of the striking features of feldspathic clasts in polymict ureilites is that plagioclase compositions span essentially the entire range from An 0-100. Several distinct feldspathic clast populations have been recognized. Two of these (ferroan anorthitic clasts, and chondrule/chondrite fragments) are nonindigenous, and are discussed below. Indigenous feldspathic clasts are divided by Cohen et al. (2004) and Goodrich and Keil (2002) into pristine (retaining primary petrologic characteristics) and non-pristine (shock-melted and/or mixed with other pristine lithologies and/or impactors) clasts.

Pristine feldspathic clasts: An albitic lithology was identified as the most abundant population of feldspathic clasts in all polymict ureilites, while a labradoritic lithology was found as lithic clasts only in DaG 665 and EET 83309 (Cohen et al., 2004). A third pristine feldspathic lithology identified by Cohen et al. (2004) comprises clasts, in which olivine and augite are the only mafic minerals and a fourth, rare type is characterized by very anorthite-rich plagioclase. In addition, Cohen et al. (2004) also identified many lithic clasts containing plagioclase with a range of An content similar to the albitic and labradoritic lithologies, and pyroxene and/or olivine with compositions that differ from those of olivine-pigeonite ureilites in being more calcic and more ferroan, but whose relationship to one another is difficult to determine.

Non-pristine feldspathic clasts: A variety of feldspathic clasts that appear to have been shock-melted and possibly mixed with other lithologies have been described. Clasts consisting of glass with sprays of radiating plagioclase microlites (giving them a chondrule-like appearance) occur in North Haig, Nilpena, EET83309, DaG 319, and DaG 165 (Prinz et al., 1986, 1988; Goodrich and Keil, 2002). Ikeda et al. (2000) describe pilotaxitic clasts, consisting of masses of irregularly interwoven, small plagioclase laths and minor interstitial pyroxene and silica-rich mesostasis. Another variety of extremely fine-grained clast (Cohen et al., 2004) consists of skeletal to feathery mafic minerals in crystalline plagioclase. Cohen et al. (2004) and Goodrich and Keil (2002) describe several feldspathic clasts in which pyroxene grains have monomict ureilite like pigeonite cores that are probably relicts, with sharp boundaries to augite. Two clasts described by Cohen et al. (2004) consist of abundant euhedral, normally-zoned olivine crystals in a glassy groundmass of albitic, non-stoichiometric plagioclase composition with fine crystallites. In addition, some feldspathic clasts are clastic breccias, containing a variety of angular grains of various types in a glassy feldspathic groundmass indicating multiple episodes of brecciation (breccias in a breccia; compare Fig. 4).

b) Mafic clasts: Lithic and mineral clasts consisting of Fo-rich olivine (Fo_{90-99}, usually with strong reverse zoning) and/or pyroxene (enstatite) are common in DaG 319 (Ikeda et al., 2000), DaG 165 (Goodrich, 2004, unpublished data), North Haig and Nilpena (Prinz et al., 1986, 1988) and EET83309 (Prinz et al., 1987), and are most likely highly shocked and reduced versions of monomict ureilite-like materials. Goodrich and Keil (2002) describe one extremely unusual oxidized mafic clast in DaG 165, whose origin is unclear.

c) Sulfide- and metal-rich clasts: Rare sulfide-rich lithic clasts in DaG 319 are described by Ikeda et al. (2000, 2003). They consist of anhedral grains of olivine, sometimes enclosed in massive sulfide (troilite), with a fine-grained, porous silicate matrix containing disseminated sulfide. Fine-grained metal-rich clasts in DaG 319 (Ikeda et al., 2000, 2003) consist mainly of enstatite and metal, with variable amounts of a silica phase, plagioclase, sulfide and rarely olivine. A few large enstatite grains contain aggregates of submicrometer-sized metal and silica, probably formed by in-situ reduction.

4.8.2.2. Xenolithic clasts

Several types of xenolithic (nonindigenous) clasts occur in various polymict ureilites (Goodrich et al., 2004):

a) Ferroan, anorthite-rich plagioclase clasts: Rare, ferroan, anorthitic clasts resembling the angrite meteorites (particularly Angra Dos Reis, or ADOR) were described from Nilpena and North Haig (Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987). One small clast observed in DaG 319 (C4-2 gabbroic type of Ikeda et al., 2000) probably represents the same lithology. Some of the most anorthite-rich plagioclase mineral clasts found in EET83309, DaG 164/165, DaG 319, and DaG 665 (Prinz et al., 1987; Ikeda et al., 2000; Goodrich and Keil, 2002; Cohen et al., 2004) may also be derived from it. Kita et al. (2004) showed that the oxygen isotopic composition of one ferroan, anorthite-rich clast in DaG 319 is similar to that of ADOR.

b) Chondrules and chondrite fragments: Jaques and Fitzgerald (1982) described an olivine-clinobronzite clast in Nilpena that appeared to be an unequilibrated H-group chondrule. Prinz et al. (1986, 1987) noted that some orthopyroxene mineral fragments in North Haig and Nilpena and rare olivine mineral fragments in EET83309 are of ordinary chondritic composition, and Prinz et al. (1988) recognized barred olivine, radial pyroxene, and cryptocrystalline chondrules. Ikeda et al. (2000, 2003) identified barred olivine (type F1-1), porphyritic olivine (type F1-2), porphyritic olivine-pyroxene (type F1-3), and radial pyroxene (type F1-5) chondrules and chondrule fragments, as well as equilibrated chondrite fragments (type F2) in DaG 319. Equilibrated chondrite fragments have homogeneous olivine, with lesser amounts of pyroxenes, plagioclase, sulfide, and chromite and are similar in mineralogy and mineral compositions to R group chondrites.

c) *Dark clasts:* Dark clasts resembling carbonaceous chondrite matrix material were first observed as components of polymict ureilities in North Haig and Nilpena (Prinz et al., 1987; Brearley and Prinz, 1992; Brearley and Jones, 1998). Similar dark clasts, generally a few hundred microns to several mm in size and angular, are abundant in DaG 319 (Ikeda et al., 2000; 2003). Ikeda et al. (2003) divided them into two subtypes: fayalite-free (D1), which are common, and fayalite-bearing (D2), which are rare. Ikeda et al. (2003) noted that the occurrence of fayalite in these clasts suggests affinities to oxidized CV chondrites such as Kaba, Bali, and Mokoia. Several dark clasts have been observed in DaG 165 (Goodrich and Keil, 2002). They have extremely fine-grained matrices consisting largely of phyllosilicates with bulk compositions similar to those of the dark clasts in Nilpena and North Haig (Brearley and Prinz, 1992), and contain abundant grains of Fe,Ni sulfide, framboidal magnetite, and larger magnetite.

4.9 HED meteorites

Howardites, eucrites, and diogenites are genetically related and form the HED suite of achondrites, which may come from Vesta (Wahl, 1951; Mason, 1962; McCarthy et al. 1972; Takeda et al., 1983; Clayton and Mayeda, 1983). Eucrites and diogenites are magmatic rocks, representing a wide range of chemical compositions and variable crystallisation histories (e.g., Miyamoto and Takeda, 1977; Takeda, 1979; Takeda et al., 1984; Hewins and Newsom, 1988; McSween, 1989; Mittlefehldt et al., 1998, McCoy et al., 2005, this volume). At least 85 % of HED meteorites are impact breccias formed in the regolith and megaregolith of their parent body (Stöffler et al., 1988). The megaregolith is the thick layer of fractured and possibly mixed planetary crust beneath the surface regolith, which has been discussed in detail by Hartmann (1973, 1980). While many eucrites and diogenites occur as monomict breccias, howardites are mechanical mixtures of diogenites and eucrites and, hence, breccias by definition (e.g., McCarthy et al., 1972; Duke and Silver, 1967; Bunch, 1975; Delaney et al., 1983; Buchanan and Reid, 1996). In the order of increasing amounts of diogenite component, polymict HED breccias are classified as polymict eucrites, howardites, and polymict diogenites (Delaney et al., 1983). According to Delaney et al.(1983), eucrites containing up to 10% diogenitic material are called polymict eucrites, whereas diogenites containing up to 10% eucritic material are called polymict diogenites. HED-meteorites containing 10-90% eucritic material are defined as howardites. Several members of the HED suite display petrologic features that seem to result from annealing by igneous activity or impact melt sheets after crystallization and brecciation (e.g., Labotka and Papike, 1980; Takeda et al., 1981; Yamaguchi and Takeda, 1994, 1995; Yamaguchi et al., 1994, 1997; Metzler et al., 1995; Buchanan and Reid, 1996; Takeda, 1997; Mittlefehldt et al., 1998; Saiki and Takeda, 1999).

4.9.1. Monomict breccias among the eucrites and diogenites

The suite of monomict eucrites and monomict diogenites consist of obviously unbrecciated and monomict brecciated meteorites. Brecciated monomict eucrites and brecciated monomict diogenites are called monomict eucrite breccias and monomict diogenite breccias in the following. Most monomict eucrite breccias and monomict diogenite breccias are characterized by distinct variations of grain size and texture on a mm to cm scale, mainly due to the existence of large lithic clasts embedded in a fine grained clastic matrix (von Engelhardt, 1963; Mason, 1963; Duke and Silver, 1967; Reid and Barnard, 1979; Takeda et al., 1983; Palme et al., 1988; Takeda and Yamaguchi, 1991; Mittlefehldt, 1994; Yamaguchi et al., 1994; Metzler et al., 1995). The ratio lithic clasts/clastic matrix varies significantly. Individual meteorites of this kind consist of a single clast type or a limited range of lithic clast types which are of nearly identical bulk chemical composition. Nevertheless, several monomict eucrite breccias are texturally polymict (e.g. Takeda and Graham, 1991). This observation indicates that these breccias originate from parent rocks, which were texturally heterogeneous. The initial brecciation events were followed by later stages of parent body evolution, as documented by impact-induced intrusive melt dikes and shock veins, crosscutting the brecciated texture (e.g. Duke and Silver, 1967; Takeda et al, 1981; Bogard et al., 1985; Dickinson et al., 1985; Bobe et al., 1989; Bobe, 1992). Furthermore, the original textures are overprinted by thermal annealing (e.g. Labotka and Papike, 1980; Fuhrmann and Papike, 1981; Takeda et al, 1981; Bobe et al., 1989; Yamaguchi and Takeda, 1992, 1994; Yamaguchi et al., 1994, 1996; Metzler et al., 1995; Papike et al., 2000; Miyamoto et al., 2001) and later periods of impact brecciation (e.g. Delaney et al., 1982; Metzler et al., 1995; Saiki and Takeda, 1999). Bilanga is classified as a monomict diogenite breccia. However, Domanik et al. (2004) describe exotic fragments that are of a different but possibly related rock type incorporated in the Bilanga breccia.

4.9.2. Polymict breccias (polymict eucrites, howardites, polymict diogenites)

There is an enormous literature data base concerning the petrology and chemistry of lithic and mineral clasts in polymict HED breccia (e.g., Mittlefehldt et al., 1998, and references therein; Buchanan and Mittlefehldt, 2003; Cohen, 2004. These breccias are fragmental and regolith breccias consisting of coarse mineral and lithic clasts of eucritic and diogenitic compositions, embedded in a fine-grained clastic matrix (Fig. 14). They formed by impact comminution and local mixing (e.g., Delaney at al., 1983, 1984; Metzler et al., 1995; Buchanan and Reid, 1996).

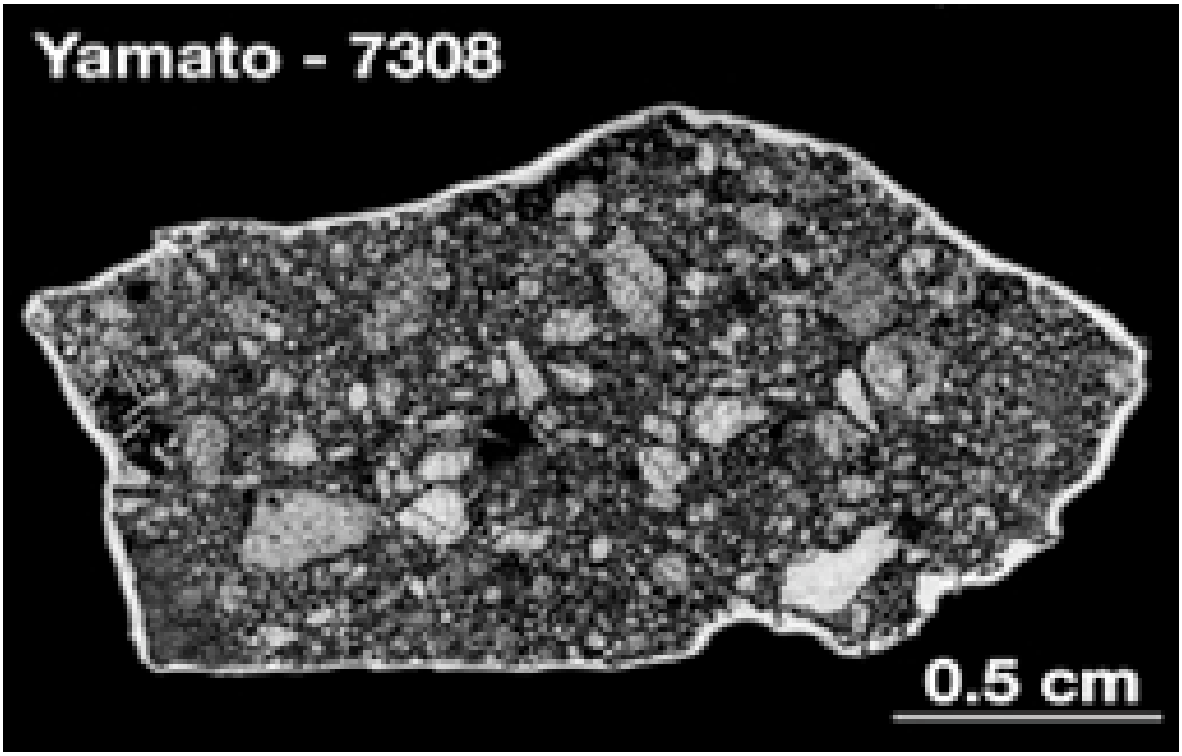

Fig. 14: Overview photograph of the Yamato-7308 howardite. Different types of fragments are embedded within a fine-grained clastic matrix. Image in transmitted light. See Metzler (1985) for details.

The textural variability of igneous clasts is coupled with large mineralogical and chemical variations of entire clasts and their mineral constituents. Based on the large variety of polymict HED breccias Saiki and Takeda (1999) claim that there is a distinct local heterogeneity on the HED parent body and most of these breccias formed locally around the floor of impact craters. As it is observed in monomict eucrite breccias and monomict diogenite breccias, the clastic matrix of polymict HED breccias is either fragmental (e.g., Reid et al., 1990) or recrystallized, the latter due to thermal annealing after brecciation (e.g., Takeda, 1991; Bogard et al., 1993; Metzler et al., 1995).

Many howardites contain fragments of impact melt rocks and fused soils and are enriched in solar gases (Table 2) and track rich grains (e.g., Suess et al., 1964; Wilkening et al., 1971; Labotka and Papike, 1980; MacDougall et al., 1973; Caffee et al., 1988; Rao et al., 1997; Wieler et al., 2000; Caffee and Nishiizumi, 2001). Below diverse clast types found so far in polymict HED breccias are described in detail.

4.9.2.1. Eucrite clasts

Polymict eucrites are mainly composed of typical eucrite clasts with a wide range of textures and chemical compositions, which are very similar to the monomict eucrites and to clasts from monomict eucrite breccias (e.g. Duke and Silver, 1967; Delaney et al., 1984). These clast types include variolitic and subophitic basalts as well as gabbroic lithologies (e.g., Bobe, 1992; Yamaguchi et al, 1994; Metzler et al., 1995; Buchanan et al., 2000; Patzer et al., 2003). Clasts of cumulate eucrites and ordinary eucrites (Takeda, 1991) occur in the same breccia (Saiki et al., 2001). The same holds for howardites (e.g., Ikeda and Takeda, 1985; Metzler et al., 1995), but beside typical eucrite clasts these breccias contain fragments of more extreme composition, which are not represented as distinct meteorites (e.g., Bunch, 1975). Large eucrite clasts have been found in the polymict diogenite Aioun el Atrouss (Lomena et al., 1976) and small amounts of a eucritic component was observed in the polymict diogenite Garland (Varteresian and Hewins, 1983).

4.9.2.2. Diogenite clasts

These fragments are common in polymict eucrites and contribute up to ~50 % to the howardites known so far (e.g., Duke and Silver, 1967; Delaney et al., 1983, 1984; Ikeda and Takeda, 1985; Warren, 1985; Metzler et al., 1995; Mittlefehldt et al., 1998). Polymict diogenites are mainly composed of coarse diogenite clasts set in a fine-grained clastic matrix of the same material, additional containing up to 10% eucritic material (Delaney et al., 1983).

4.9.2.3. Granulite clasts

Granulite clasts are common in polymict eucrites and howardites (e.g., Bobe, 1992; Yamaguchi et al., 1994; Metzler et al., 1995; Metzler and Stöffler, 1995; Buchanan et al., 2000; Patzer et al., 2003). The common eucrite clasts in Y791960 are granulitic (Takeda, 1991), indicating annealing of the parent rock prior to brecciation. A further good example for granulitic breccias is the meteorite Asuka-881388 (Yamaguchi, 2004; pers. comm.). In the polymict eucrite Pasamonte a granulite clast was found, which shows an enrichment in a chondritic component, indicating contaminations by a chondritic projectile (Metzler et al., 1995). A texturally similar clast, interpreted to be a heavily metamorphosed impact melt breccia, was found in the polymict eucrite Macibini (Buchanan et al., 2000).

4.9.2.4. Clasts of impact melt rocks and breccias

Most polymict HED breccias contain different types of impact melt rock with abundances of up to 15 vol% (e.g., Labotka and Papike, 1980; Metzler and Stöffler, 1987; Olsen et al., 1987, 1990; Bogard et al., 1993; Mittlefehldt and Lindstrom, 1993; Metzler et al., 1995; Metzler and Stöffler, 1995; Pun et al., 1998; Buchanan et al., 2000; Sisodia et al., 2001; Buchanan and Mittlefehldt, 2003). In thin sections these lithologies appear as angular to subrounded clasts, often darker than the surroundings due to finely disseminated sulfides. They can be subdivided into glassy, devitrified or crystallized impact melts and impact melt breccias. In EET 87503 two impact melt breccia clast have been detected, which are enriched in a chondritic component, indicating intensive mixture of projectile and target melts during impact (Metzler et al., 1995).

The two-component mixing model for HED breccias by McCarthy et al. (1972) and Delaney et al. (1983) is basically supported by the observation that melt composition of impact melt rocks from polymict eucrites and howardites follow the mixing line between eucritic and diogenitic lithologies. Up to now not a single clast of pure diogenitic impact melt rock has been described. This indicates that extended orthopyroxenites were never exposed to such crustal levels, where pure diogenitic whole-rock impact melt rocks could have formed (Metzler and Stöffler, 1995).

The polymict eucrite ALHA 81011 represents a vesicular impact melt breccia as a whole (Metzler et al., 1994). In addition, Northwest Africa 1240 has been described as an HED parent body impact melt rock (Barrat et al., 2003).

4.9.2.5. Breccia clasts (breccia-in-breccia-structures)

Clasts of clastic matrix (breccia-in-breccia-structure) have been found in several howardites (e.g., Metzler et al., 1995; Pun et al., 1998). These inclusions seem to have formed and compacted at different locations near the surface of the parent body and were admixed as lithic clasts to the host breccias by impact.

4.9.2.6. Foreign clasts (xenoliths)

Carbonaceous chondritic clasts have been found in some polymict HED breccias, e.g. in LEW 85300 (Zolensky et al., 1992; Zolensky et al., 1996c). Wilkening (1973) first identified carbonaceous chondrite clasts in the howardite Kapoeta, which were mineralogically similar to CM and CV3 chondrites. Later, chondritic clasts were separated by Bunch et al. (1979) from the howardite Jodzie and studied mineralogically and chemically. Further reports on such clasts include Kozul and Hewins (1988), Mittlefehldt and Lindstrom (1988), Hewins (1990), Olsen et al. (1990), Reid et al. (1990), Buchanan et al. (1993), Pun et al. (1998), and Buchanan and Mittlefehldt (2003). Mittlefehldt (1994) describes a dark grey, fine-grained fragment with a chondritic chemical signature in the diogenite Ellemeet. Unfortunately, a detailed petrographic description is missing.

4.10. Aubrites

Aubrites, which are composed largely of enstatite grains with <1 % FeO, resemble howardites in that all meteorites are fragmental or regolith breccias of igneous rocks. But aubrites, unlike howardites, lack closely related unbrecciated meteorites (except possibly for some metal-rich meteorites). Everything that we know about the geology of the parent asteroid of the aubrites has been derived from studies of breccia clasts.

Six of the 20 analyzed aubrites contain solar wind gases: Bustee, EET 90033, Khor Temiki, Lewis Cliff (LEW) 87007, Pesyanoe, and Y 793592. Others including Cumberland Falls, Bishopville and Mayo Belwa have Kr, Sm, and Gd isotopic effects indicating neutron capture near the surface of their parent asteroid for periods of up to several hundred Myr (Lorenzetti et al., 2003; Hidaka et al., 1999). Aubrites with solar-wind gases are composed of millimeter-to-centimeter sized clasts in a finer-grained matrix (Poupeau et al., 1974). Other aubrites appear to be coarser grained with enstatite crystal fragments up to 10 cm in size.

The best studied aubrite, Norton County, which lacks solar wind gases, is largely composed of enstatite crystals derived from orthopyroxenite, plus pyroxenite clasts with igneous textures composed of orthoenstatite, pigeonite and diopside, and impact melt breccia clasts (Okada et al., 1988). In addition there is a clast composed of diopside, plagioclase, and silica, and olivine grains and feldspathic clasts that are probably derived from separate lithologies. Norton County contains ~1.5 vol. % of Fe,Ni metal grains up to a centimeter in size with associated sulfides and schreibersite, that probably represent metal that was incompletely separated from silicate during differentiation (Casanova et al., 1993). Taenite compositions suggest most metal grains cooled through 500°C at ~2°C/Myr but some cooled faster. Thus one or more major impacts must have pulverized the parent asteroid and excavated material from great depths. Okada et al. (1988) suggest that the parent body was collisionally disrupted and gravitationally reassembled.

Other clasts derived from the aubrite parent body include a 4 cm wide enstatite-oldhamite clast with blebby diopside in Bustee (McCoy, 1998), an oxide-bearing clast in Allan Hills

84008 (McCoy et al., 1999), basaltic vitrophyre clasts (Fogel, 1997), and round inclusions in NWA 2736 (Lowe et al., 2005). Foreign clasts are present in the three aubrites Cumberland Falls, ALH A78113, and Pesyanoe: They contain abundant FeO-bearing, chondritic inclusions (xenoliths) up to 4 cm in size (Binns, 1969; Lipschutz et al., 1988; Lorenz et al., 2005). The oxygen isotopic composition of some of these chondritic clasts indicates a relationship with ordinary chondrites, but the clasts have been affected by reduction on the aubrite body and their origin is controversial (Wasson et al., 1993).

Three related metal-rich meteorites may be samples from the aubrite parent body, although they are not visibly brecciated. Watters and Prinz (1980)) suggested that the iron meteorite, Horse Creek, and a stony-iron meteorite, Mt. Egerton, which is composed of coarsely crystalline enstatite with ~20% metallic Fe,Ni, represented the core and core-mantle interface, respectively, of the aubrite parent body. A third meteorite, Itqiy (Patzer et al., 2001), appears to resemble Mt. Egerton. The evidence in the aubritic breccias for impact scrambling of their parent asteroid suggests that metal-rich samples should have been mixed with aubrites.

Shallowater appears to be an unbrecciated, enstatite achondrite that is closely related to the aubritic breccias. However, Keil et al. (1989) infer from its mineralogical and thermal properties that it contains chondritic inclusions and formed on a separate asteroid (Keil, 1989). Shallowater contains 20 vol.% of metal-bearing inclusions, which are inferred to be chondritic material from a projectile or the cool outer layer of a partly molten target that was mixed with enstatitic melt causing the melt to cool rapidly at >100°C/hr. Thus Shallowater can be considered to be an impact melt breccia in which the melt was not formed by impact but was initially present in the target.

5. BRECCIAS FORMED FROM PARTLY MOLTEN ASTEROIDS

All of the breccias that we have described above, apart from the accretionary breccias, have close analogs among the lunar breccias. But there are also meteorite breccias without lunar analogs that appear to have formed <100 Myr after the asteroids accreted by impact mixing of partly molten asteroids, rather than impact melting of solid bodies. The best examples are the pallasites that contain angular fragments of olivine embedded in metallic Fe,Ni, the IAB iron meteorites with angular chondritic clasts, and the mesosiderites. The simplest of these are the pallasitic breccias which probably formed as a result of impact-induced mixing of molten Fe,Ni from the cores of igneously differentiated asteroids with fragmented mantle material located directly above. The group IAB iron meteorites appear to have formed in a partly melted asteroid that was catastrophically broken apart and then reaccreted during a major impact (Benedix et al., 2000).

Mesosiderites are breccias consisting entirely of core and crustal material from a differentiated asteroid, with relatively little of the intervening mantle (Mittlefehldt et al., 1998). The lithic clasts, which may be as large as 2 cm or more, are dominantly from the crust and are broadly similar to eucrites and diogenites. They include, basalts, gabbros, and orthopyroxenites, with lesser amounts of dunite, and rare anorthosites (Rubin and Mittlefehldt, 1992; Ikeda et al., 1990; Kimura et al., 1991; Tamaki et al., 2004). Other clasts include impact melts and diogenitic monomict breccia clasts. Mineral clasts are mostly coarse-grained orthopyroxene and minor olivine up to 10 cm in size, and rarer plagioclase. Mesosiderite clasts differ from HED lithologies in that olivine is rare in HEDs and the REE fractionation patterns of some gabbroic clasts in mesosiderites have extremely high Eu/Sm ratios (Rubin and Mittlefehldt, 1992). Other differences are summarized by Kimura et al. (1991). Foreign clasts are not observed. Some workers have suggested that the metallic Fe,Ni is derived from the projectile (Rubin and Mittlefehldt, 1993), but it seems unlikely that vast amounts of target and projectile material would be mixed by low-speed impacts ~100 Myr after the asteroids accreted (Scott et al., 2001). The alternative model is that mesosiderites formed during breakup and reaccretion of an asteroid with a molten core (Scott et al., 2001).

6. IMPACT-RELATED MIXING

The abundance of foreign clasts in meteorites gives a good measure of the degree of mixing among asteroids and the relative abundance of different types of material at different times and places in the asteroid belt. Aside from Kaidun, which is described below, and the Cumberland Falls aubrite (Binns, 1969), few meteorites contain more than a few volume percent of foreign clasts. The most abundant clasts are CM-like chondritic fragments (Meibom and Clark, 1999).

In ordinary chondrites, clasts from different ordinary chondrites groups are relatively rare. In the LL chondrite St. Mesmin intensely shocked H-group chondrite fragments were found (Dodd, 1974). Rubin et al. (1983) describe an LL5 clast in the Dimmitt H chondrite regolith breccia. An L-group melt rock fragment was found in the LL chondrite Paragould (Fodor and Keil, 1978). Similarly, olivines of fragments in Adzhi-Bogdo (LL3-6) clearly fall in the range of L-group chondrites (Bischoff et al., 1993c, 1996). A troctolitic clast in the Y-794046 (L6) chondrite has an H-chondrite oxygen isotopic composition (Prinz et al., 1984). In the Fayetteville H-chondrite regolith breccia an L-chondritic inclusion is described by Wieler et al. (1989). Fodor and Keil (1975) identified a clast of H parentage within the Ngawi LL chondrite.

A small CM chondrite clast consisting of olivine crystals and an altered barred olivine chondrule embedded in a matrix of phyllosilicates and sulfide was observed in the Magombedze (H3-5) chondrite (MacPherson et al., 1993). Also, a carbonaceous clast was found in the Dimmitt ordinary chondrite breccia (Rubin et al., 1983). Some further reports on (possibly) carbonaceous clasts in ordinary chondrites are listed in Keil (1982).

In some polymict HED breccias (e.g., Kapoeta and LEW 85300) carbonaceous chondrite clasts were found, which are mineralogically similar to CM and CV3 chondrites (Wilkening, 1973; Zolensky et al., 1992, 1996c). A chondritic clast was separated by Bunch et al. (1979) from the howardite Jodzie. Further reports on such clasts include Kozul and Hewins (1988), Mittlefehldt and Lindstrom (1988), Hewins (1990), Reid et al. (1990), Buchanan et al. (1993), Mittlefehldt (1994), Pun et al. (1998), and Buchanan and Mittlefehldt (2003).

Ordinary chondrite fragments are present in polymict ureilites (e.g., Jaques and Fitzgerald, 1982; Prinz et al., 1986, 1987, 1988; Ikeda et al., 2000, 2003). Angrite-like fragments are also known from several samples (e.g., Jaques and Fitzgerald, 1982, Prinz et al., 1986, 1987; Ikeda et al., 2000; Goodrich and Keil, 2002; Cohen et al., 2004; Kita et al., 2004). Dark clasts that resemble fine-grained carbonaceous chondrite material are known to occur in ureilites (e.g., Prinz et al., 1987; Brearley and Prinz, 1992; Ikeda et al., 2000, 2003; Goodrich and Keil, 2002).

Enstatite chondrite clasts appear to be especially rare in other meteorite classes. The Galim LL chondrite breccia appears to have formed after pieces of an EH chondrite projectile were mixed with LL target material (Rubin, 1997b). An EH chondritic asteroid appears to have formed the Serenitatis basin on the Moon (Norman et al., 2002), and an EH fragment was found in the Apollo 15 soil sample (Rubin, 1997a).

The most spectacular mixing product among the chondrites is probably Kaidun, which consists almost entirely of millimeter and sub-millimeter-sized fragments of EH3-5, EL3, CV3, CM1-2 and R chondrites (Ivanov, 1989; Ivanov et al., 2003; Zolensky and Ivanov, 2003, and references therein). In addition, it contains C1 and C2 lithologies, alkaline-enriched clasts (similar to the granitoidal clasts found in the Adzhi-Bogdo ordinary chondrite regolith breccia; Bischoff et al. (1993c)), fragments of impact melt products, phosphide-bearing clasts, new enstatite-bearing clasts, fragments of Ca-rich achondrite, and possibly aubritic materials (Ivanov, 1989; Ivanov et al., 2003; Zolensky and Ivanov, 2003; Kurat et al., 2004). A possible ordinary chondrite clast has been described by Mikouchi et al. (2005). Clasts that are breccias themselves were also observed (see Fig. 20 in Zolensky and Ivanov (2003); compare Fig. 15). According to Zolensky and Ivanov (2003), Kaidun may be derived from an especially large asteroid like Ceres, or an unusually located one like Phobos, the larger moon of Mars. Alternatively, Kaidun might be considered as an unusually clast-rich, chondrule-poor chondrite that formed during a lull in chondrule formation or deposition when turbulent accretion concentrated chondritic clasts rather than chondrules (Scott, 2002).

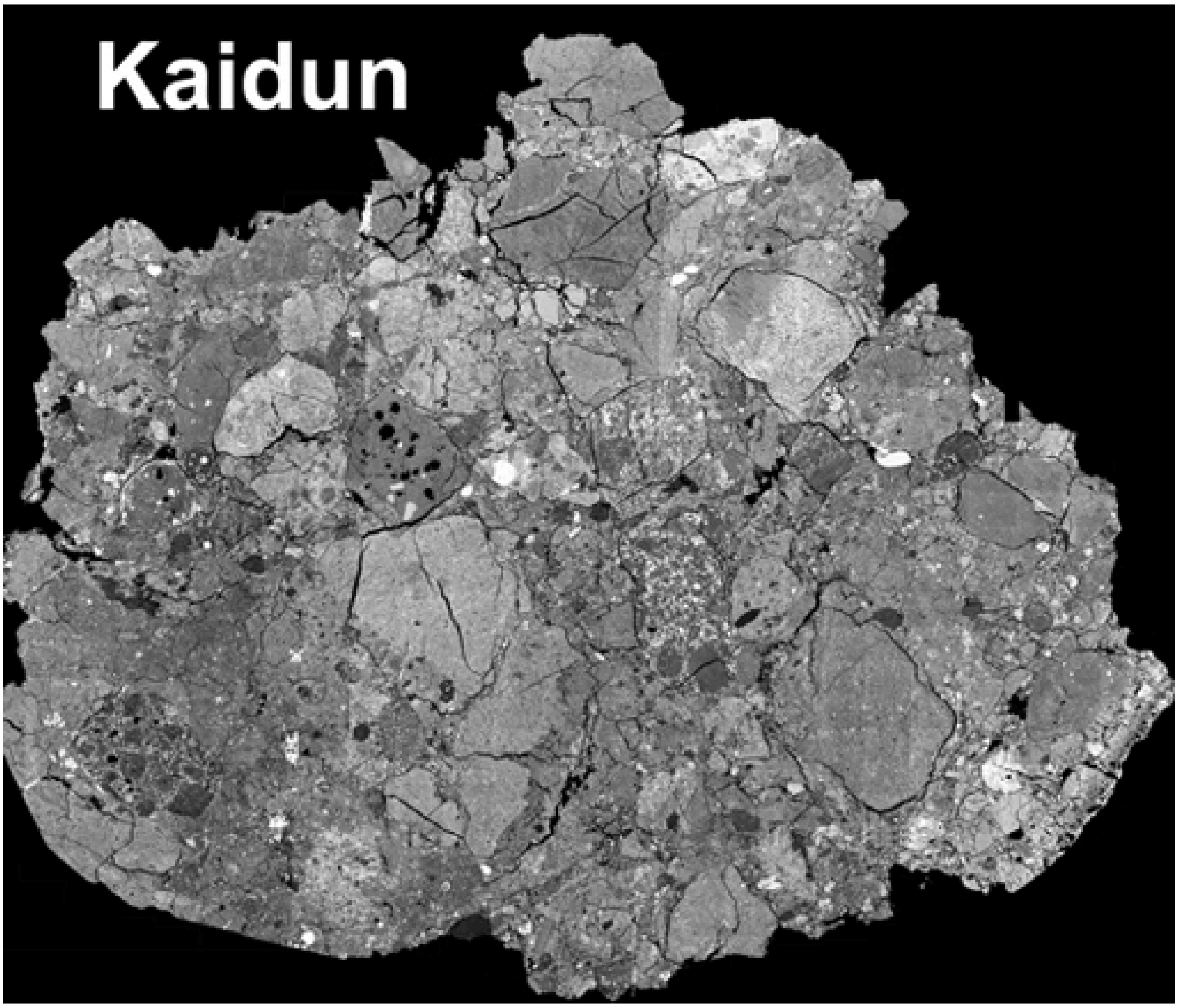

Fig. 15: Kaidun belongs to the most heavily fragmented chondrites showing the huge number of diverse lithologies. BSE image, 4 cm across, provided by Mike Zolensky; see Zolensky and Ivanov (2003) for details.

7. FORMATION OF BRECCIAS

7.1. Break up and reassembly of asteroids

Asteroids are modified by two kinds of hypervelocity impacts: frequent impacts that crater the surface, and large rare impacts that damage the whole asteroid and create large volumes of rubble. The power-law mass distribution of asteroids is such that the dominant events in the history of meteorites and asteroids are the large infrequent impacts, rather than the cratering events. These large impacts probably create a major fraction of the meteorite breccias (see e.g., Scott, 2002; Scott and Wilson, 2005) and reduce many asteroids between 0.1 and 100 km in size to gravitational aggregates of loosely consolidated material (e.g., Asphaug et al., 2002; Richardson et al., 2002); for counterarguments, see Sullivan et al. (2002) and Wilkison et al. (2002).

Evidence that many asteroids are porous aggregates has accumulated from measurements of asteroid densities (Britt et al., 2002) and numerical models of asteroid impacts to form asteroid families and satellites (Richardson et al., 2002; Michel et al., 2003; Durda et al., 2004). Additional evidence comes from the spin rates of asteroids: asteroids between 150 m and ~10 km in size which approach but do not exceed the upper limit for strengthless asteroids (Pravec et al., 2002). (Asteroids less than 150 m in size spin faster with periods of under 2 hr suggesting they are stronger, more coherent bodies.)

Simulations using numerical models offer insights into the way that catastrophic events can fragment asteroids (e.g., Love and Ahrens, 1996; Nolan et al., 2001). Major impacts on asteroids that form craters comparable in size to the radius of the parent body may cause extensive damage throughout the asteroid: e.g., at the core-mantle boundary (e.g., making pallasites in bodies with molten cores), and at the exterior where material is fractured and briefly lofted (making near surface monomict breccias like diogenite breccias). Impacts at higher specific energies cause the fragments to reaccrete into a porous rubble pile in which interior fragments have been rotated but not significantly displaced from one another. With increasing specific impact energy, the impact debris forms a cloud of fragments that largely reaccretes within a few hours to days, though some fragments may take up to a year to reaccrete (Love and Ahrens, 1996). Eventually, the target will be converted into a family of asteroids with diverse masses, each of which is a gravitationally bound rubble pile (e.g., Michel et al., 2003). Since the specific impact energy for dispersing at least half the target mass is ~100 times that for shattering more than half the initial mass, and the number of asteroids is proportional to $r^{-5/2}$, the dispersal lifetime before will be ~50 x longer than the shattering lifetime (Holsapple et al., 2002).

Thus asteroids will experience numerous shattering impacts before they are dispersed into families of gravitationally bound rubble.

Evidence for catastrophic impacts in meteorites has been derived from meteorite groups with extensive evidence for shock deformation and impact melting, meteorite breccias in which the components are derived from diverse depths of the parent asteroid, and meteorites with anomalous thermal histories (Keil et al., 1994; Scott, 2002). The best example of a large impact that formed a body with large volumes of shocked meteorites and several impact melt breccias is the 500 Ma impact that probably disrupted the L chondrite parent body, possibly forming the Flora asteroid family (Haack et al., 1996a; Nesvorny et al., 2002). Ureilites, which also have a high abundance of shocked samples, appear to have survived a family-forming impact at 4.5 Ga (Goodrich et al., 2004). Meteorite groups with components derived from diverse depths include fragmental breccias like Mezo-Madaras that contain mixtures of type 3-6 material, and H, L, and LL regolith breccias, which have metal grains with diverse cooling rates (Grimm, 1985; Taylor et al., 1987; Williams et al., 2000). In addition, H, L, and LL group chondrites show little correlation between metallographic cooling rates and petrologic types indicating major impact mixing within their parent asteroids (Taylor et al., 1987). Meteorites with anomalous thermal histories indicating quenching in days or less from temperatures above 1000°C include IVA irons with silicate inclusions (Scott et al., 1996; Haack et al., 1996b), mesosiderites (Scott et al., 2001), the Shallowater enstatite achondrite (Keil et al., 1989), and ureilites (Keil et al., 1994; Goodrich et al. 2004). Group IAB irons with silicate inclusions and the closely related winonaites also contain textural evidence for a catastrophic impact that created metal-silicate and silicate breccias (Benedix et al., 2000). All the meteorites with anomalous thermal histories probably formed as a result of major impacts into hot bodies <100 Myr after the asteroids accreted. In each case, the impact debris reaccreted so that cooling rates at lower temperatures were much slower than those at 1000°C.

The effectiveness of catastrophic impacts for mixing material from diverse depths has not been investigated with high-resolution numerical models. Low-resolution models suggest that effective scrambling requires an impact that at least halves the target's mass (Scott et al., 2001). These models also suggest that impacts on asteroids that are less than a few hundred kilometers in size create relatively little impact melt, and do not mix much projectile material into the target (Love and Ahrens, 1996). They simply convert coherent asteroids into fragmental breccias. Impact melt breccias and projectile clasts are predicted to comprise less than a few volume percent of the residual target material (Keil et al., 1997). Abundances of foreign clasts and impact melt breccias (excluding those formed when asteroids were partly molten) are much less than the volume of fragmental breccias, consistent with this conclusion.

7.2. Regolith Breccias

Many meteorites rich in solar-wind gases have a prominent brecciated appearance, commonly with light clasts in a dark matrix. The solar-wind gases in these samples were acquired by grains <100 nm from a planetary surface (Goswami et al., 1984; Caffee et al., 1988). A few type 2-3 chondrites with solar wind gases appear to lack evidence for brecciation (e.g., EH3 and EL3), but this may simply reflect the dark nature of clasts and matrix. Although there are rare components in meteorites that may have been irradiated in space (e.g., Zolensky et al., 2003), comparisons with lunar samples and regolith modeling strongly suggest that fine-grained material was irradiated on the surface of asteroids (Bunch and Rajan, 1988; Caffee et al., 1988; McKay et al., 1989). Solar-gas-rich meteorites are therefore called regolith breccias, although McKay et al. (1989) cautioned that these meteorites could not be fully understood without better constraints on asteroidal impacts and visits from spacecraft.

Lunar regolith, largely by definition, is formed by relatively small cratering events that distribute soil and rocks locally around craters, rather than large impacts with global ejecta blankets (see Robinson et al., 2002). Similarly, meteorite regolith breccias are usually interpreted in terms of relatively small impacts that just crater the surface, but larger impacts may play a role, e.g., in dispersing regolith breccias throughout asteroids (Crabb and Schultz, 1981). Meteoritic breccias rich in solar wind gases differ from their lunar analogs in having lower abundances of agglutinates and other impact glasses, solar-flare irradiated grains, and solar-wind gases. They have therefore been interpreted as immature regolith samples that were present in the regolith for relatively brief periods (e.g., Housen et al., 1979a; Caffee et al., 1988). However, this description may be misleading as the abundance of these features may reflect mixing of diverse materials (see below), as well as the intensity of shock lithification (Bischoff et al., 1983). Typically, carbonaceous chondrites samples are less like lunar regolith samples than howardite and ordinary chondrite samples in the abundances of radiation features. These differences and the high proportion of regolith breccias in many groups (e.g., CM and CI chondrites; Table 2) are difficult to reconcile with detailed models for asteroid regolith development (e.g., Housen et al., 1979a,b). As a result, other sites for the irradiation have been considered: in cm- to m-sized planetesimals prior to accretion of the parent body and in similar-sized components in a megaregolith (see Caffee et al., 1988). However, these models cannot account for the concentration of solar-wind gases in the fine-grained, clastic matrices of meteorites (e.g., Nakamura et al., 1999a,b).

Detailed studies of regolith development on asteroids by Housen et al. (1979a,b) assume that regolith forms solely by cratering of an initially coherent planetary surface. For 300 km diameter asteroids, this model predicts that a 3.5 km regolith would develop in 2.6 Gyr. However, predictions that strong 10 km diameter asteroids would have <1 mm of regolith, and 1-10 km weak asteroids cm-to-meter thick regolith appear inconsistent with high-resolution spacecraft images. Four C and S class asteroids with mean diameters of 12-50 km have regoliths that are tens of meters thick (Sullivan et al., 2002; Robinson et al., 2002). Regolith models for small asteroids may be inadequate because they do not include the effects of major impacts that cause catastrophic fragmentation or fragmentation and reaccretion and because they overestimate the strength of small bodies (Asphaug et al., 2002).

An important difference between meteoritic and lunar regolith breccias is that meteoritic grains with solar flare tracks have large excesses of spallation Ne but track-poor grains seldom do (Caffee et al., 1988). In the top few meters of the lunar regolith, many grains lack solar-flare tracks as they have not resided in the upper millimeter, but they all contain spallogenic gases due to exposure to galactic cosmic rays. The excess spallation Ne in track-rich grains in the CM chondrites, Murchison and Murray, require exposure to galactic cosmic rays for several hundred Myr, a period that seems too long to be consistent with regolith models and compaction ages. An alternative explanation is that the track-rich grains were exposed to intense solar cosmic rays from the early Sun (Woolum and Hohenberg, 1993). However, Wieler et al. (2000) studied grains in the howardite, Kapoeta, and found no evidence for a high flux of energetic particles from the Sun. They argued instead that the correlated occurrences of solar-flare tracks and cosmogenic Ne excesses could be explained by mixing of mature and immature soils.

Compaction ages of meteorite regolith breccias have been inferred from fission track techniques that date the time matrix and olivine grains were brought in contact and from radiometric ages of clasts (see McKay et al., 1989). These data suggest that CM chondrite regolith breccias may have formed before 4.3 Ga, whereas ordinary chondrite and achondrite regolith breccias formed much more recently, in one case more recently than 1.3 Ga. However, these data only provide upper limits on compaction ages: new techniques are still needed to date regolith breccias with confidence so that their irradiation effects and records of global geology can be understood better. We do not know, for example, if grains in meteorite regolith breccias were irradiated and lithified when asteroids accreted, during the last Gyr in the asteroid belt, or more recently on near-Earth asteroids.

The wide variation in the abundances of regolith breccias in meteorite groups (0-100%; Table 2) can be related to the physical properties and impact histories of the samples. Six classes of meteorites - angrites, brachinites, acapulcoites, winonaites, iron, and stony-iron meteorites - lack both solar-wind bearing samples and fragmental breccias (excluding metamorphosed and igneously-formed breccias). The absence of breccias from these groups may be attributed to poor sampling of parent asteroids, the difficulty of lithifying metal-rich material, and the greater strength of metal-rich rocks. Impact fragments from high strength asteroids are ejected at high speeds and are liable to escape from small bodies (Housen, 1979a,b). In nearly all other groups - ureilites, aubrites, the HED group, and all chondrite groups except CO and CK - regolith breccia and fragmental breccias are both abundant. For the CI, CM, CR and R chondrite groups, where 50-100% of the samples are regolith breccias, surface material was remarkably well dispersed throughout the sampled regions of their parent bodies. A plausible explanation is that mature regolith soil was intimately mixed with much larger volumes of deeply buried and poorly consolidated material during an impact that caused break-up and reassembly of the parent asteroid. Thus, if regolith breccias are defined as consolidated debris from a surficial fragmental layer, these meteorites should not be called regolith breccias, but fragmental breccias containing a few percent of grains that were present in the top meter of regolith.

The HED meteorites have a smaller fraction of samples with solar gases (8/124; Table 2) and generally higher concentrations of solar-wind gas than the CI-CM chondrites (Goswami et al., 1984). The lack of olivine-rich mantle material in howardites suggests that mixing was much more limited than in the carbonaceous asteroids. The properties of the solar-gas-rich howardites appear compatible with mixing of mature regolith soil with material that completely lacked irradiation features. Mature soil from the top few meters may have been periodically dispersed throughout a km-thick layer of fragmental material by impact-generated seismic waves that could loft fractured and poorly consolidated material to heights of several km (Housen et al., 1979b; Asphaug, 1997).

Because solar-wind-rich meteorite breccias contain only a small fraction of grains that have been in the top meter, they are poor guides to the spectral properties of asteroids. However, they do contain much information about the distribution and diversity of rock types and the impact history of asteroids. New models are clearly needed to understand the formation of asteroidal regolith breccias.

7. 3 Simultaneous accretion of asteroidal clasts and chondrules?

The idea that certain meteorites represent samples of "second-generation" parent bodies (daughter asteroids) formed after collisional destruction of "grandparent" planetary bodies has been discussed earlier (e.g., Urey, 1959, 1967; Zook, 1980; Hutchison et al., 1988; Hutchison, 1996; Sanders, 1996; Bischoff, 1998; Bischoff and Schultz, 2004).

Evidence for the existence of planetesimals before the accretion of the parent asteroids of chondrites have recently been provided by W isotope data for CAIs, metal-rich chondrites, and iron meteorites (Kleine et al., 2004, 2005a,b). The decay of now extinct ^{182}Hf to ^{182}W (half-life = 9 Myr) is well suited to date the formation of metal and refractory phases in the early solar system. Hafnium is lithophile and W is siderophile, such that the separation of metal from silicate (e.g. during core formation) results in a strong Hf-W fractionation. Metals are virtually Hf-free such that they maintain the W isotope composition acquired at the time of metal formation. Recent studies have shown that the initial W isotope composition of magmatic iron meteorites is similar to that of CAIs, indicating that most magmatic iron meteorites formed within less than ~1 Myr after formation of CAIs (Kleine et al., 2004, 2005a,b). In contrast, the well-preserved U-Pb and ^{26}Al-^{26}Mg age differences between CAIs and chondrules indicate that the formation of chondrules and hence the accretion of the parent asteroids of chondrites persisted for at least 2 – 3 Myr and possible even up to ~5 Myr after the start of the solar system. Based on the combined Hf-W and Al-Mg age constraints Kleine et al. (2004, 2005a,b) argue that certain iron meteorites are remnants of the earliest asteroids and that chondrites derive from relatively late formed planetesimals that may have formed by re-accretion of debris produced during collision disruption of first-generation planetesimals (the latter represented by the magmatic iron meteorites).

Considering various types of clasts in carbonaceous and ordinary chondrites Bischoff and Schultz (2004) suggested that many breccias result from mixing of fragments after total destruction of precursor parent bod(y)ies. They suggest that dark inclusions in CR and CH chondrites (Fig. 11) may be excellent witnesses to document formation of the final parent body by secondary accretion. In many primitive chondrites (Krymka (Fig. 3), Adrar 003, Acfer 094) unusual fragments exist that may represent chondritic fragments of a first-generation parent body. In summary, increasing evidence is found for accretion of planetesimal clasts with chondrules at a time, when chondrite parent bodies formed.

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References:

Abreu N. M. and Brearley A. J. (2004) Characterization of matrix in the EET 92042 CR2 carbonaceous chondrite: Insight into textural and mineralogical heterogeneity. *Meteoritics & Planet. Sci.* 39, A12 (abstr.).

Abreu N. M. and Brearley A. J. (2005) HRTEM and EFTEM studies of phyllosilicate-organic matter associations in matrix and dark inclusions in the EET 92042 CR2 carbonaceous chondrite. *Lunar Planet. Sci.* 36, #1826.

Ashworth J. R. and Barber D. J. (1976) Lithification of gas-rich meteorites. *Earth Planet. Sci. Lett.* 30, 222-233.

Asphaug E. (1997) Impact origin of the Vesta family. *Meteorit. Planet. Sci.* 32, 965-980.

Asphaug E., Ryan E. V., and Zuber M. T. (2002) Asteroid interiors. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 463-484. Univ. Arizona Press.

Barber D. J. and Hutchison R. (1991) The Bencubbin stony-iron meteorite breccia: Electron petrography, shock-history and affinities of a "carbonaceous chondrite" clast. *Meteoritics* 26, 83-95.

Barrat J. A., Jambon A., Bohn M., Blichert-Toft J., Sautter V., Göpel C., Gillet P., Boudouma o., and Keller F. (2003) Petrology and geochemistry of the unbrecciated achondrite Northwest Africa 1240 (NWA 1240): An HED parentbody impact melt. *Geochim. Cosmochim. Acta* 67, 3959-3870.

Beauchamp R. and Fredriksson K. (1979) Ivuna and Orgueil C-1 chondrites: a new look. *Meteoritics* 14, 344.

Benedix G. K., McCoy T. J., and Keil K. (1997) Winonaites revisited: New insights into their formation. *Lunar Planet. Sci.* XXVIII, 91-92.

Benedix G. K., McCoy T. J., Keil K., Bogard D. D., and Garrison D. H. (1998) A petrologic and isotopic study of winonaites: Evidence for early partial melting, and metamorphism. *Geochim. Cosmochim. Acta* 62, 2535-2553.

Benedix G. K., McCoy T. J., Keil K., and Love S. G. (2000) A petrologic study of the IAB iron meteorites: Constraints on the formation of the IAB-Winonaite parent body. *Meteoritics & Planet. Sci.* 35, 1127-1141.

Berkley J. L. and Goodrich C. A. (2001) Evidence for multi-episodic igneous events in ureilite MET 78008. *Meteorit. Planet. Sci.* 36, A18-A19.

Binns R. A. (1967) Structure and evolution of noncarbonaceous chondrites. *Earth Planet. Sci. Lett.* 2, 23-28.

Binns R. A (1968) Cognate xenoliths in chondritic meteorites: Examples in Mezo-Madaras and Ghubara. *Geochim. Cosmochim. Acta* 32, 299-317.

Binns R. A. (1969) A chondritic inclusion of unique type in the Cumberland Falls meteorite. In *Meteorite Research,* ed P.M. Millman (Drdrecht: D. Reidel), pp. 696-704.

Binns R. A., Davis R. J., and Reed S. J. B. (1969) Ringwoodite, natural (Mg,Fe)2SiO2 spinel in the Tenham meteorite. *Nature* 221, 943-944.

Bischoff A. (1992) ALH 85085, Acfer 182, and Renazzo-type chondrites - Similarities and differences. *Meteoritics* 27, 203-204.

Bischoff A. (1993) Alkali-granitoids as fragments within the ordinary chondrite Adzhi-Bogdo: Evidence for highly fractionated, alkali-granitic liquids on asteroids. *Lunar Planet. Sci.* XXIV, 113-114, Lunar and Planetary Institute, Houston.

Bischoff A. (1998) Aqueous alteration of carbonaceous chondrites: Evidence for preaccretionary alteration-A review. *Meteoritics & Planet. Sci.* 33, 1113-1122.

Bischoff A. (2000) Mineralogical characterization of primitive, type-3 lithologies in Rumuruti chondrites. *Meteoritics & Planet. Sci.* 35, 699-706.

Bischoff A. (2002) Discovery of purple-blue ringwoodite within shock veins of an LL6 ordinary chondrite from Northwest Africa. *Lunar Planet. Sci*. XXXIII, #1264, Lunar and Planetary Institute, Houston.

Bischoff A. and Geiger T. (1994) The unique carbonaceous chondrite Acfer 094: The first CM3 chondrite (?). *Lunar. Planet. Sci*. 25, 115-116, Lunar and Planetary Institute, Houston.

Bischoff A. and Metzler K. (1991) Mineralogy and petrography of the anomalous carbonaceous chondrites Y-86720, Y-82162 and B-7904. *Proc. NIPR Symp. Antarct. Meteorites* 4, 226-246.

Bischoff A. and Stöffler D. (1992) Shock metamorphism as a fundamental process in the evolution of planetary bodies: Information from meteorites. *Europ. J. Mineral.* 4, 707-755.

Bischoff A. and Schultz L. (2004) Abundance and meaning of regolith breccias among meteorites. *Meteoritics & Planet. Sci.* 39, A15.

Bischoff A., Rubin A. E., Keil K., and Stöffler D. (1983) Lithification of gas-rich chondrite regolith breccias by grain boundary and localized shock melting. *Earth Planet. Sci.Lett.* 66, 1-10.

Bischoff A., Palme H., Spettel B., Clayton R. N., and Mayeda T. K. (1988) The chemical composition of dark inclusions from the Allende meteorite. *Lunar Planet. Sci.* 19, 88-89.

Bischoff A., Palme H., Geiger T., and Spettel B. (1992) Mineralogy and chemistry of the EL-chondritic melt rock Ilafegh-009. *Lunar Planet. Sci*. 23, 105 - 106, Lunar and Planetary Institute, Houston.

Bischoff A., Palme H., Ash R.D., Clayton R.N., Schultz L., Herpers U., Stöffler D., Grady M.M., Pillinger C.T., Spettel B., Weber H., Grund T., Endreß M., and Weber D. (1993a) Paired Renazzo-type (CR) carbonaceous chondrites from the Sahara. *Geochim. Cosmochim. Acta* 57, 1587-1603.

Bischoff A., Palme H., Schultz L., Weber D., Weber H.W., and Spettel B. (1993b) Acfer 182 and paired samples, an iron-rich carbonaceous chondrite: Similarities with ALH 85085 and relationship to CR chondrites. *Geochim. Cosmochim. Acta* 57, 2631-2648.

Bischoff A., Geiger T., Palme H., Spettel B., Schultz L., Scherer P., Schlüter J., and Lkhamsuren J. (1993c) Mineraolgy, chemistry, and noble gas contents of Adzhi-Bogdo – an LL3-6 chondritic breccia with L-chondritic and granitoidal clasts. *Meteoritics* 28, 570-578.

Bischoff A., Geiger T., Palme H., Spettel B., Schultz L., Scherer P., Loeken T., Bland P., Clayton R. N., Mayeda T. K., Herpers U., Meltzow B., Michel R., and Dittrich-Hannen B. (1994a) Acfer 217-A new member of the Rumuruti chondrite group (R). *Meteoritics* 29, 264-274.

Bischoff A., Schirmeyer S., Palme H., Spettel B., and Weber D. (1994b) Mineralogy and chemistry of the carbonaceous chondrite PCA91467 (CH). *Meteoritics* 29, 444.

Bischoff A., Gerel O., Buchwald V. F., Spettel B., Loeken T., Schultz L., Weber H. W., Schlüter J., Baljinnyam L., Borchuluun D., Byambaa C., and Garamjav D. (1996) Meteorites from Mongolia. *Meteoritics & Planet. Sci*. 31, 152-157.

Bischoff A., Weber D., Spettel B., Clayton R. N., Mayeda T. K., Wolf D., and Palme H. (1997) Hammadah al Hamra 180: A unique unequilibrated chondrite with affinities to LL-group ordinary chondrites. *Meteoritics & Planet. Sci*. 32, A14.

Bischoff A., Weber D., Bartoschewitz R., Clayton R. N., Mayeda T. K., Spettel B., and Weber H. W (1998) Characterization of the Rumuruti chondrite regolith breccia Hughes 030 (R3-6) and implications for the occurrence of unequilibrated lithologies on the R-chondrite parent body (abstract). *Meteoritics & Planet. Sci*. 33, A15-A16.

Bischoff A., Goodrich C. A., and Grund T. (1999) Shock-induced origin of diamonds in ureilites (abstract). Lunar Planet. Sci. 30, #1100, Lunar and Planetary Institute, Houston.

Bobe K.D. (1992) Die monomikten Eukrite und ihre mehrphasige magmatische, impaktmetamorphe und thermische Entwicklungsgeschichte auf dem HED-Mutterkörper. Ph.D. dissertation, Universität Münster, p.164

Bobe K.D., Bischoff A. and Stöffler D. (1989) Impact and thermal metamorphism as fundamental processes in the evolution of the Stannern, Juvinas, Jonzac, Peramiho, and Millbillillie eucrite parent body. *Meteoritics* 24, 252.

Bogard D.D., Taylor G.J., Keil K., Smith M.R. and Schmitt R.A. (1985) Impact melting of the Cachari eucrite 3.0 Ga ago. *Geochim. Cosmochim. Acta* 49, 941-946.

Bogard D.D., Nyquist L., Takeda H., Mori H., Aoyoma T., Bansal B., Wiesman H. and Shih C.-Y. (1993) Antarctic polymict eucrite Yamato 792769 and the cratering record on the HED parent body. *Geochim. Cosmochim. Acta* 57, 2111-2121.

Bogard D. D., Garrison D. H., Norman M., Scott E. R. D., and Keil K. (1995) 39Ar-40Ar age and petrology of Chico: Large scale impact melting on the L chondrite parent body. *Geochim. Cosmochim. Acta* 59, 1383-1399.

Bottke W. F., Nolan M. C., Greenberg R., and Kolvoord R. A. (1994) Velocity distributions among colliding asteroids. *Icarus* 107, 255-268.

Brearley A. J. (1988) Nature and origin of matrix in the unique chondrite Kakangari: A TEM investigation. *Lunar Planet. Sci.* 19, 130-131.

Brearley A. J. and Geiger T. (1991) Mineralogical and chemical studies bearing on the origin of accretionary rims in the Murchison CM2 carbonaceous chondrite (abstract). *Meteoritics* 26, 323

Brearley A. J. and Jones R. H. (1998) Chondritic meteorites. In *Planetary Materials*, edited by Papike J.J. Washington: Mineralogical Society of America. pp 3-1 – 3-398.

Brearley A. J. and Prinz M. (1992) CI chondrite-like clasts in the Nilpena polymict ureilite. Implications for aqueous alteration processes in CI chondrites. *Geochim. Cosmochim. Acta* 56, 1373-1386.

Brezina A. (1904) The arrangement of collections of meteorites. *Trans. Am. Phil. Soc.* 43, 211-247.

Bridges J. C. and Hutchison R. (1997) A survey of clasts and chondrules in ordinary chondrites. *Meteoritics & Planet. Sci.* 32, 389-394.

Bridges J. C., Franchi I. A., Hutchison R., Morse A. D. Long J. V. P., and Pillinger C. T. (1995a) Cristobalite- and tridymite-bearing clasts in Parnallee (LL3) and Farmington (L5). *Meteoritics* 30, 715-727.

Bridges J. C., Hutchison R., Franchi I. A., Alexander C. M. O`D., and Pillinger C. T. (1995b) A feldspar-nepheline achondrite clast in Parnallee. *Proc. NIPR Symp. Antarct. Meteorites,* 8, 195-203.

Britt D. T. and Pieters C. M (1991) Black ordinary chondrites: An analysis of abundance and fall frequency. *Meteoritics* 26, 279-285.

Britt D. T. and Pieters C. M (1994) Darkening in black and gas-rich ordinary chondrites: The spectral effects of opaque morphology and distribution. *Geochim. Cosmochim. Acta* 58, 3905-3919.

Britt D. T., Yeomans D., Housen K., and Consolmagno G. (2002) Asteroid density, porosity and structure. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 485-500. Univ. Arizona Press.

Browning L. B., McSween H. Y. Jr., and Zolensky M. E. (1995) Parent body alteration features in CM rims (abstract). *Lunar Planet. Sci.* 26, 181-182.

Buchanan P.C. and Mittlefehldt D.W. (2003) Lithic components in the paired howardites EET 87503 and EET 87513: Characterization of the regolith of 4 Vesta. *Antarc. Meteorite Res.* 16, 128-151

Buchanan P.C. and Reid A.M. (1996) Petrology of the polymict eucrite Petersburg. *Geochim. Cosmochim. Acta* 60, 135-146.

Buchanan P. C., Zolensky M. E., and Reid A. M. (1993) Carbonaceous chondrite clasts in the howardites Bholghati and EET87513. *Meteoritics* 28, 659-669.

Buchanan P. C., Zolensky M. E., and Reid A. M. (1997) Petrology of Allende dark inclusions. *Geochim. Cosmochim. Acta* 61, 1733-1743.

Buchanan P.C., Mittlefehldt D.W., Hutchison R., Koeberl C., Lindstrom D.J. and Pandit M.K. (2000) Petrology of the Indian eucrite Piplia Kalan. *Meteoritics Planet. Sci.* 35, 609-615.

Buchanan P.C., Lindstrom D.J., Mittlefehldt D.W., Koeberl C., and Reimold W.U. (2003) The South African polymict eucrite Macibini. *Meteoritics Planet. Sci.* 35, 1321-1331

Bullock E. S., Grady M. M., Russell S. S., and Gounelle M. (2005) Fe-Ni sulfides within a CM1 clast in Tagish Lake. *Lunar Planet. Sci.* 36, #1883.

Bunch T. E. (1975) Petrolography and petrology of basaltic polymict breccias (howardites). *Proc. Lunar. Sci. Conf.* 6, 469-492.

Bunch T.E. and Chang S. (1980) Carbonaceous chondrites-II. Carbonaceous chondrite phyllosilicates and light element geochemistry as indicators of parent body processes and surface conditions. *Geochim. Cosmochim. Acta* 44, 1543-1577.

Bunch T. E. and Rajan R. S. (1988) Meteorite regolith breccias. In *Meteorites and the Early Solar System* (eds. J.F. Kerridge and M. S. Matthews), The University of Arizona Press, Tucson, 144-164.

Bunch T. E. and Stöffler D. (1974) The Kelly chondrite: A parent body surface metabreccia. *Contr. Mineral Petrol.* 44, 157-171.

Bunch T.E., Chang S., Frick U:, Neil J. and Moreland G. (1979) Carbonaceous chondrites - I. Characterisation and significance of carbonaceous chondrite (CM) xenoliths in the Jodzie howardite. *Geochim. Cosmochim. Acta* 43, 1727-1742.

Burbine T. H., McCoy T. J., Meibom A., Gladman B., and Keil K. (2002) Meteoritic parent bodies: their number and identification. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 653-667. Univ. Arizona Press.

Burbine T. H., Folco L., Capitani G., Bland P. A., Menvies O. N., and McCoy T.J. (2003) Identification of nanophase iron in a H chondrite impact melt. *Meteoritics & Planet. Sci.* 38, A111 (abstr.).

Busemann H., Eugster O., Bauer H., and Wieler R. (2003a) The ingredients of the "subsolar" noble gas component. *Lunar Planet. Sci.* 34, #1674, CD-ROM, Lunar Planet. Inst.

Busemann H., Bauer H., and Wieler R. (2003b) Solar noble gases in enstatite chondrites and implications for the formation of the terrestrial planets. *Lunar Planet. Sci.* 34, #1665, CD-ROM, Lunar Planet. Inst.

Caffee M.W. and Nishiizumi K. (2001) Exposure history of separated phases from the Kapoeta meteorite. *Meteoritics & Planet. Sci.* 36, 429-437.

Caffee M. W., Goswami J. N., Hohenburg C. M., Marti K., and Reedy R. C. (1988) Irradiation records in meteorites. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds), pp. 205-245. Univ. Arizona Press.

Casanova I., Keil K., Wieler R., San Miguel A., and King E. A. (1990) origin and history of chondrite regolith, fragmental and impact-melt breccias from Spain. *Meteoritics* 25, 127-135.

Casanova I., Keil K., and Newsom H. (1993) Composition of metal in aubrites: Constraints on core formation. *Geochim. Cosmochim Acta* 57, 675-682.

Christophe Michel-Lévy M. (1988) a new component of the Mezö-Madaras breccia: A microchondrule- and carbon-bearing L-related chondrite. *Meteoritics* 23, 45-48.

Clayton R. N. and Mayeda T. K. (1978) Multiple parent bodies of polymict-brecciated meteorites. *Geochim. Cosmochim. Acta* 42, 325-327.

Clayton R.N. and Mayeda, T.K. (1983) Oxygen isotopes in eucrites, shergottites, nakhlites, and chassignites. *Earth Planet. Sci. Lett*. 67, 151-161.

Clayton R. N. and Mayeda T. K. (1996) oxygen-isotope studies of achondrites. *Geochim. Cosmochim. Acta* 60, 1999-2018.

Cohen B. A. (2004) Survey of clasts in howardite Grosvenor Mountains 95574. *Meteoritics & Planet. Sci.* 39, A24 (abstr.).

Cohen B. A., Goodrich C. A., and Keil K. (2004) Feldspathic clast populations in polymict ureilites: Stalking the missing basalts from the ureilite parent body. *Geochim. Cosmochim. Acta* 68, 4249-4266.

Cohen B. A., Swindle T. D., and Olson E. K. (2005) Geochronology of clasts in polymict ureilite Dar al Gani 665. *Lunar Planet. Sci.* 36, #1704.

Crabb J. and Schultz L. (1981) Cosmic ray exposure ages of the ordinary chondrites and their significance for parent body stratigraphy. *Geochim. Cosmochim. Acta* 45, 2151-2160.

Delaney J.S., Prinz M., Nehru C.E. and O´Neill C.O. (1982) The polymict eucrites Elephant Moraine A79004 and the regolith history of a basaltic achondrite parent body. *Proc. 13th Lunar Planet. Sci. Conf., Part 1; J. Geophys. Res.* 87, A339-A352.

Delaney J.S., Takeda, H., Prinz M., Nehru C.E., and Harlow, G.E. (1983) The nomenclature of polymict basaltic achondrites. *Meteoritics* 18, 103-111

Delaney J.S., Prinz M. and Takeda H. (1984) The polymict eucrites. *Proc. 15th Lunar Planet. Sci. Conf., Part 1; J. Geophys. Res.* 89, C251-C288.

Dickinson T:, Keil K., Lapaz L., Bogard D.D., Schmitt R.A., Smith M.R. and Rhodes J.M. (1985) Petrology and shock age of the Palo Blanco Creek eucrite. *Chem. Erde* 44, 245-257.

Dodd R. T. (1974) Petrology of the St. Mesmin chondrite. *Contr. Mineral. Petrol.* 46, 129-145.

Dodd R. T. (1981) *Meteorites – A Petrologic-Chemical Synthesis.* Cambridge Univ. Press.

Dominak K., Kolar S., Musselwhite D., and Drake M. J. (2004) Accessory silicate mineral assemblages in the Bilanga diogenite: A petrographic study. *Meteoritics & Planet. Sci.* 39, 567-579.

Duke M.B. and Silver L.T. (1967) Petrology of eucrites, howardites, and mesosiderites. *Geochim. Cosmochim. Acta* 31, 1637-1665.

Durda D. D., Bottke W. F. Jr., Enke B. L., Merline W. J., Asphaug E., Richardson D. C., and Leinhardt Z. M. (2004) The formation of asteroid satellites in large impacts: results from numerical simulations. *Icarus*167, 382-396.

Dymek F. R., Albee A. L., Chodos A. A., and Wasserburg G. J. (1976) Petrology of isotopically-dated clasts in the Kapoeta howardite and petrologic constraints on the evolution of its parent planet. *Geochim. Cosmochim. Acta* 40, 1115-1130.

Eberhardt P., Geiss J., and Grogler N. (1965) Further evidence on the origin of trapped gases in the meteorite Khor Temiki. *J. Geophys. Res.* 70, 4375-4378.

El Goresy A., Gillet P., Dubrovinsky L., Chen M., and Nakamura T. (2004) A super-hard, transparent carbon form, diamond, and secondary graphite in the Haverö ureilite: A fine-scale microraman and synchroton tomography. *Meteoritics & Planet. Sci.* 39, A36 (abstr.).

Endress M. (1994) Mineralogische und chemische Untersuchungen an CI-Chondriten. Ph.D. thesis, University of Münster, Münster, Germany, 223 pp.

Endress M. and Bischoff A. (1993) Mineralogy, degree of brecciation, and aqueous alteration of the CI chondrites Orgueil, Ivuna, and Alais (abstract). *Meteoritics* 28, 345-346.

Endress M. and Bischoff A. (1996) Carbonates in CI chondrites: Clues to parent body evolution. *Geochim. Cosmochim. Acta* 60, 489-507.

Endress M., Spettel B., and Bischoff A. (1994a) Chemistry, petrography, and mineralogy of the Tonk CI chondrite: Preliminary results (abstract). *Meteoritics* 29, 462-463.

Endress M., Keil K., Bischoff A., Spettel B., Clayton R.N., and Mayeda T.K. (1994b) Origin of dark clasts in the Acfer 059/El Djouf 001 CR2 chondrite. *Meteoritics* 29, 26-40.

Engelhardt W. von (1963) Der Eukrit von Stannern. *Beitr. Mineral. Petrogr.* 9, 65-94.

Fioretti A. M. and Goodrich C. A. (2001) A contact between an olivine-pigeonite lithology and an olivine-augite-orthopyroxene lithology in ureilites FRO 93008: Dashed hopes? *Meteoritics & Planet. Sci.* 36, A58.

Fodor R. V. and Keil K. (1973) Composition and origin of lithic fragments in L- and H-group chondrites (abstract). *Meteoritics* 8, 366-367

Fodor R. V. and Keil K. (1975) Implications of poikilitic textures in LL-group chondrites. *Meteoritics* 10, 325-340.

Fodor R. V. and Keil K. (1976a) Carbonaceous and non-carbonaceous lithic fragments in the Plainview, Texas, chondrite: origin and history. *Geochim. Cosmochim. Acta* 40, 177-189.

Fodor R. V. and Keil K. (1976b) A komatiite-like lithic fragment with spinifex texture in the Eva meteorite: origin from a supercooled impact-melt of chondritic parentage. *Earth Planet. Sci. Lett.* 29, 1-6

Fodor R. V. and Keil K. (1978) Catalog of lithic fragments in LL-Group chondrites. *Sp. Pub. No.* 19, UNM Inst. of Meteoritics, 38 pp.

Fodor R. V., Keil K., and Jarosewich E. (1972) The Oro Grande, New Mexico, chondrite and its lithic inclusion. *Meteoritics* 7. 495-507.

Fodor R. V., Prinz M., and Keil K. (1974) Implications of K-rich lithic fragments and chondrules in the Bhola brecciated chondrite (abstract). *Abstr. With Progr., Geol. Amer.* 6, 739-740.

Fodor R.V., Keil K., Wilkening L. L. Bogard D. D., Gibson E. K. (1976) Origin and history of a meteorite parent-body regolith breccia: carbonaceous and non-carbonaceous lithic fragments in the Abbott, New Mexico, chondrite. *Tectonics and Mineral Resources of Southwestern U. S.; N. M. Geol. Soc. Sp. Pub. No.* 6, 206-218.

Fodor R. V., Keil K., and Gomes C. B. (1977) Studies of Brazilian meteorites IV. Origin of a dark-collored, unequilibrated lithic fragment in the Rio Negro chondrite. *Revista Brasileira Geociencias* 7, 45-57.

Fodor R. V., Keil K., Prinz M., Ma M. S., Murali A. V. and Schmitt R. A. (1980) Clast-laden melt-rock fragment in the Adams County, Colorado, H5 chondite. *Meteoritics* 15, 41-62.

Fogel R. A. (1997) A new aubrite basalt vitrophyre from the LEW 87007 aubrite. *Lunar Planet. Sci.* 28, 369-370.

Folco L., Bland P. A., D`Orazio M., Franchi I. A., Rocchi S. (2002) Dar al Gani 896: A unique picritic achondrite. *Meteoritics & Planet. Sci.* 39, A49 (abstr.).

Folco L., Bland P. A., D`Orazio M., Franchi I. A., Kelley S., and Rocchi S. (2002) Extensive impact melting on the H-chondrite parent asteroid during the cataclysmic bombardment of the early solar system: Evidence from the achondritic meteorite Dar al Gani 896. Geochim. Cosmochim. Acta 68, 2379-2397.

Fredriksson K., Noonan A., and Nelen J. (1975) The Bhola stone: A true polymict breccia? (abstract) *Meteoritics* 10, 87-88.

Fruland R. M., King E. A., and McKay D. S. (1978) Allende dark inclusions. *Proc. Lunar Planet. Sci. Conf.* 9th, 1505-1329.

Fuchs L.H., Olsen E. and Jensen K.J. (1973) Mineralogy, mineral chemistry and composition of Murchison (C2) meteorite. *Smithsonian Contr. Earth Sci*. 10, 39 pp.

Fuhrmann M. and Papike J.J. (1981) Howardites and polymict eucrites: Regolith samples from the eucrite parent body. Petrology of Bholghati, Bununu, Kapoeta, and ALHA 76005. *Proc. Lunar Sci Conf.* 12B, Section 2, 1257-1279.

Fujita T. and Kitamura M. (1992) Shock melting origin of a troilite-rich clast in the Moorabie chondrite (L3). *Proc. NIPR Symp. Antarct. Meteorites,* 5, 258-269.

Geiger T. (1991) Metamorphe kohlige Chondrite: Petrologische Eigenschaften und Entwicklung des Mutterkörpers. Ph.D. thesis, University of Münster, Münster, Germany, 147 pp.

Geiss J. (1973) Solar wind composition and implications about the history of the solar system. *13th Intl. Cosmic Ray Conf.* 5, 3375-3398.

Goodrich C. A. (1992) Ureilites: a critical review. *Meteoritics* 27, 327-352.

Goodrich C. A. and Keil K. (2002) Feldspathic and other unusual clasts in polymict ureilite DaG 165. Lunar Planet. Sci. 33, #1777.

Goodrich C. A., Scott, E. R. D., and Fioretti A. M. (2004) Ureilitic Breccias: Clues to the petrologic structure and impact disruption of the ureilite parent asteroid. *Chemie der Erde* 64, 283-327.

Goswami J. N., Lal D., and Wilkening L. L. (1984) Gas-rich meteorites: Probes for particle environment and dynamical processes in the inner solar system. *Space Sci. Rev. 37,* 111-159.

Grady M. M., Verchovsky A. B., Franchi I. A., Wright I. P., and Pillinger C. T. (2002) Light element geochemistry of the Tagish Lake CI2 chondrite: Comparison with CI1 and CM2 meteorites. *Meteoritics & Planet. Sci.* 37, 713-735.

Grier J. A., Kring D. A., Swindle T. D., Rivkin A. S., Cohen B. A., and Britt D. T. (2004) Analyses of the chondritic meteorite Orvinio (H6): Insight into the origin and evolution of shocked H chondrite material. *Meteoritics & Planet. Sci.* 39, 1475-1493.

Grimm R. E. (1985) Penecontemporaneous metamorphism, fragmentation, and reassembly of ordinary chondrite parent bodies. *J. Geophys. Res.* 90, 2022-2028.

Grossman L., Allen J. M., and MacPherson G. J. (1980) Electron microprobe study of a "mysterite"-bearing inclusion from the Krymka LL-chondrite. *Geochim. Cosmochim. Acta* 44, 221-216.

Grossman J. N. (1997) The Meteoritical Bulletin, No, 81, 1997 July, *Meteoritics & Planet. Sci.* 32, A159-A166.

Grossman J. N., Rubin A. E., and MacPherson G. J. (1988) ALH 85085; a unique volatile-poor carbonaceous chondrite with possible implications for nebular fractionation processes. *Earth Planet. Sci. Lett.* 91, 33-54.

Grund T. and Bischoff A. (1999) Cathodoluminescence properties of diamonds in ureilites: Further evidence for a shock-induced origin. *Meteoritics & Planet. Sci*. 34, A48-A49.

Guan Y. and Grozaz G. (2001) Microdistributions and petrogenetic implications of rare earth elements in polymict ureilites. Meteoritic. Planet. Sci. 36, 1039-1056.

Haack H., Farinella P., Scott E. R. D., and Keil K. (1996a) Meteoritic, asteroidal, and theoretical constraints on the 500 Ma disruption of the L chondrite parent body. *Icarus* 119, 182-191.

Haack H., Scott E.R.D., Love S.G., Brearley A.J., and McCoy T.J. (1996b) Thermal histories of IVA stony-iron and iron meteorites: evidence for asteroid fragmentation and reaccretion. *Geochim. Cosmochim. Acta* 60, 3103-3113.

Hanowski N. P. and Brearley A. J. (1997) Parent body alteration of large metal inclusions in the CM carbonaceous chondrite, Murray (abstract). *Lunar Planet. Sci*. 28, 503-504.

Hanowski N. P. and Brearley A. J. (2001) Aqueous alteration of chondrules in the CM carbonaceous chondrite, Allan Hills 81002: Implications for parent body alteration. *Geochim. Cosmochim. Acta* 65, 495-518.

Hartmann W. K. (1973) Ancient lunar mega-eolith and sub-surface structure. *Icarus* 18, 634-636

Hartmann W. K. (1979)Diverse puzzling asteroids and a possible unified explanation in Gehrels, T. (ed.) Asteroids, Univerity of Aizina Press, Tucson, USA, 446-479.

Hartmann W. K. (1980) Dropping stones in magma oceans: Effects of early lunar cratering. In Papike,J.J. and Merrill, R.B. (eds), *Proc. Conf. Lunar Highlands Crust,* 155-171, Pergamon Press, New York.

Hartmann W. K. (1983) Moon and Planets. Wadsworth Publ. Co., Belmont, USA, 509 p.

Hewins R.H. (1990) Geologic history of LEW 85300, 85302 and 85303 polymict eucrites. *Lunar Planet. Sci*. 21, 509-510.

Hewins R.H. and Newsom H.E. (1988) Igneous activity in the early solar system. In: *Meteorites and the Early Solar System* (edited by J.F. Kerridge and J.F. Matthews), 73-101.

Heymann D. (1967) On the origin of hypersthene chondrites: Ages and shock effects of black chondrites. *Icarus* 6, 189-221.

Heymann D. and Mazor E. (1967) Light-dark structure and rare gas content of the carbonaceous chondrite Nogoya. *J. Geophys. Res*. 72, 2704-2707.

Heymann D., Van der Stap C. C. A. H., Vis R. N., and Verheul H. (1987) Carbon in dark inclusions of the Allende meteorite. *Meteoritics* 22, 3-15.

Hezel D. (2003) Die Bildung SiO_2-reicher Phasen im frühen Sonnensystem. Ph. D. Thesis, Universität zu Köln, pp. 131.

Hidaka H., Ebihara M., and Yoneda S. (1999) High fluences of neutrons determined from Sm and Gd isotopic compositions in aubrites. *Earth Planet. Sci. Lett.*173, 41-51.

Hoinkes G., Kurat G., and Baric L. (1976) Dubrovnik: Ein L3-6 Chondrit. *Ann. Naturhistor. Mus. Wien* 80, 39-55.

Holsapple K., Giblin I., Housen K., Nakamura A., and Ryan E. (2002) Asteroid impacts: Laboratory experiments and scaling laws. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 443-462. Univ. Arizona Press.

Housen K. R., Wilkening L. L., Chapman C. R., and Greenberg R. (1979a) Asteroidal regoliths. *Icarus 39*, 7-351.

Housen K. R., Wilkening L. L., Chapman C. R., and Greenberg R. (1979b) Regolith development and evolution on asteroids and the Moon. In *Asteroids* (T. Gehrels and M. S. Matthews, eds), pp. 601-627. Univ. Arizona Press.

Huss G. R., Keil K., Taylor G. J. (1981) The matrices of unequilibrated ordinary chondrites: Implications for the origin and history of chondrites. *Geochim. Cosmochim. Acta* 45, 33-41.

Hutchison, R. (1996) Chondrules and their associates in ordinary chondrites: A planetary connection. In "*Chondrules and the Protoplanetary Disk"* (eds. R.H. Hewins, R.H. Jones, E.R.D. Scott), 311-318, Cambridge Univ. Press.

Hutchison R., Williams C. T., Din V.K., Clayton R. N., Kirschbaum C., Paul R. L., and Lipschutz M. E. (1988) A planetary, H-group pebble in the Barwell, L6, unshocked chondritic meteorite. *Earth Planet. Sci. Lett.* 90, 105-118.

Itoh D. and Tomeoka K. (2003) Dark inclusions in CO3 chondrites: New indicators of parent-body processes. *Geochim. Cosmochim. Acta* 67, 153-169.

Ikeda Y. and Prinz M. (2001) Magmatic inclusions and felsic clasts in the Dar al Gani 319 polymict ureilite. Meteorit. Planet. Sci. 36, 481-499.

Ikeda Y. and Takeda H. (1985) A model for the origin of basaltic achondrites based on the Yamato 7308 howardite. *Proc. Lunar Planet. Sci. Conf.* 15, C649-C663.

Ikeda Y., Ebihara M. and Prinz M, (1990) Enclaves in the Mt. Padbury and Vaca Muerta mesosiderites: magmatic and residue (or cumulate) rock types. *Proc. NIPR Symp. Ant. Meteorites* 3, 99-131.

Ikeda Y., Prinz M., and Nehru C. E. (2000) Lithic and mineral clasts in the Dar al Gani (DAG) 319 polymict ureilite. Antarctic Meteorite Res. 13, 177-221.

Ikeda Y., Kita N. T., Morishita Y., and Weisberg M. K. (2003) Primitive clasts in the Dar al Gani 319 polymict ureilite: Precursors of the ureilites. Antarctic Meteorite Research 16, 105-127.

Ivanov A. V. (1989) The Kaidun meteorite: composition and history. *Geochemistry International* 26, 84-91.

Ivanov A. V., Kononkova N. N., Yang A. V., and Zolensky M. E. (2003) The Kaidun meteorite: Clasts of alkaline-rich fractionated materials. *Meteoritics & Planet. Sci.* 38, 725-737.

Jäckel A. and Bischoff A. (1988) Textural and mineralogical differences between LL-chondritic fragmental and regolith breccias. *Meteoritics & Planet. Sci.* 33, A77-A78.

Jäckel A., Bischoff A., Clayton R. N., and Mayeda T. K. (1996) Dar al Gani 013 - a new Saharan Rumuruti-chondrite (R3-6) with highly unequilibrated (type 3) fragments. *Lunar Planet. Sci.* XXVII, 595-596, Lunar and Planetary Institute, Houston (abstr.).

Jaques A. L. and Fitzgerald M. J. (1982) The Nilpena ureilites, an unusual polymict breccia: implications for origin. Geochim. Cosmochim. Acta 46, 893-900.

Johnson C. A., Prinz M., Weisberg M. K., Clayton R. N. and Mayeda T. K. (1990) Dark inclusions in Allende, Leoville, and Vigarano: Evidence for nebular oxidation of CV3 constituents. *Geochim. Cosmochim. Acta* 54, 819-830.

Kallemeyn G. W., Rubin A. E., and Wasson J. T. (1996) The compositional classification of chondrites: VII. The R chondrite group. *Geochim. Cosmochim. Acta* 60, 2243-2256.

Keil K. (1982) Composition and origin of chondritic breccias. In *Workshop on Lunar Breccias and Soils and Their meteoritic Analogs* (eds. G. J. Taylor and L. L. Wilkening), pp. 65-83. LPI Technical Report 82-02. Lunar Planetary Institute.

Keil K. (1989) Enstatite meteorites and their parent bodies. *Meteoritics* 24, 195-208.

Keil K. and Fodor R. V. (1973) Composition and origin of lithic fragments in LL-group chondrites (abstract). *Meteoritics* 8, 394-396

Keil K. and Fodor R. V. (1980) Origin and history of the polymict-brecciated Tysnes Island chondrite and its carbonaceous and non-carbonaceous lithic fragments. *Chem. Erde* 39, 1-26.

Keil K., Huss G. I., and Wiik H. B. (1969) The Leoville, Kansas, meteorite: A polymict breccia of carbonaceous chondrites and achondrite. In *Meteorite Research* (ed. P. M. Millman), p.217 (D. Reidel).

Keil K., Fodor R. v., Starzyk P. M., Schmitt R. A., Bogard D. D., and Husain L. (1980) A 3.6-b.y.-old impact-melt rock fragment in the Plainview chondrite: implications for the age of the H-group chondrite parent body regolith formation. *Earth Planet. Sci. Lett.* 51, 235-247.

Keil K., Ntaflos Th., Taylor G. J., Brearley A. J., Newson H. E., and Romig A. D. (1989) The Shallowater aubrite: evidence for origin by planetesimal impact. *Geochim. Cosmochim Acta* 53, 3291-3307.

Keil K., Haack H., and Scott E.R.D. (1994) Catastrophic fragmentation of asteroids: Evidence from meteorites. *Planet. Space Sci. 42*, 1109-1122.

Keil K., Stöffler D., Love S.G., and Scott E.R.D. (1997) Constraints on the role of impact heating and melting in asteroids. *Meteorit. Planet. Sci. 32*, 349-363.

Kennedy A. K. and Hutcheon I. D. (1992) Chemical and isotopic constraints on the formation and crystallization of SA-1, a basaltic Allende plagioclase-olivine inclusion. *Meteoritics* 27, 539-554

Kennedy A. K., Hutchison R., Hutcheon I. D., and Agrell S. O. (1992) A unique high Mn/Fe microgabbro in the Parnallee (LL3) ordinary chondrite: Nebular micture or planetary differentiate form a previously unrecognized planetary body? *Earth Planet. Sci. Lett.* 113, 191-205.

Kerridge J.F. and Bunch T.E. (1979) Aqueous activity on asteroids: Evidence from carbonaceous meteorites. In: Asteroids (ed. T. Gehrels), 745-764, University of Arizona Press, Tucson.

Kerridge J. F. and Matthews M. S. (1988) Meteorites and the Early Solar System. *The University of Arizona Press, Tucson*, pp. 1269.

Kieffer S. W. (1975) From regolith to rock by shock. *The Moon* 13, 301-320

Kimura M., Ikeda Y., Ebihara M., and Prinz M. (1991) New enclaves in the Vaca Muerta mesosiderite: Petrogenesis and comparison with HED meteorites. *Proc. NIPR Symp. Ant. Meteorites* 4, 263-306.

Kita N. T., Ikeda Y., Togashi S., Liu Y., Morishita Y., and Weisberg M. K. (2004) Origin of ureilites inferred from a SIMS oxygen isotopic and trace element study of clasts in the Dar al Gani 319 polymict ureilite. *Geochim. Cosmochim. Acta* 68, 4213-4235.

Kleine, T., Mezger, K., Palme, H., Scherer, E., and Münker, C. (2004): A new chronology for asteroid formation in the early solar system based on ^{182}W systematics. *EOS Transactions AGU 85 (47), Fall Meeting Supplement*, Abstract P31C-04.

Kleine, T., Mezger, K., Palme, H., and Scherer, E. (2005a) Tungsten isotopes provide evidence that core formation in some asteroids predates the accretion of chondrite parent bodies. *LPSC XXXVI,* #1431.

Kleine, T., Mezger, K., Palme, H., Scherer, E., and Münker, C. (2005b): A new model for the accretion and early evolution of asteroids in the early solar system: Evidence from ^{182}Hf-^{182}W in CAIs, metal-rich chondrites and iron meteorites. *Geochim. Cosmochim. Acta, (submitted)*

Kojima T. and Tomeoka K. (1996) Indicators of aqueous alteration and thermal metamorphism on the CV parent body: Microtextures of a dark inclusion from Allende. *Geochim. Cosmochim. Acta* 60, 2651-2666.

Kojima T. and Tomeoka K. (1997) A fine-grained dark inclusion in the Vigarano CV3 chondrite: record of accumulation processes on the meteorite parent body. *Antarct. Meteorite Res.,* 10, 203-215.

Kojima T., Tomeoka K., and Takeda H. (1993) Unusual dark clasts in the Vigarano CV3 carbonaceous chondrite: Record of parent body process. *Meteoritics* 28, 649-658.

Kojima T., Yatagai T., and Tomeoka K. (2000) A dark inclusion in the Manych LL (3.1) ordinary chondrite: A product of strong shock metamorphism. *Antarct. Meteorite Res.,* 13, 39-54.

Kojima T., Lauretta D. S., and Buseck P. R. (2003) Accretion, dispersal, and reaccumulation of the Bishunpur (LL3.1) brecciated chondrite: Evidence from troilite-silicate-metal inclusions and chondrule rims. *Geochim. Cosmochim. Acta* 67, 3065-3078.

Kozul J. and Hewins R.H. (1988) LEW 85300,02,03 polymict eucrites consortium – II: Breccia clasts, CM inclusions, glassy matrix and assembly history. *Lunar Planet. Sci.* 19, 647-648.

Kracher A., Keil K., and Scott E. R. D. (1982) Leoville (CV3) – An "accretionary breccia"? *Meteoritics* 17, 239.

Kracher A., Keil K., Kallemeyn G. W., Wasson J. T., Clayton R. N., and Huss G. I. (1985) The Leoville (CV3) accretionary breccia. *Proc. Lunar Planet. Sci. Conf.* 16th, D123-D135.

Kring D. A., Hill D. H., Gleason J. D., Britt D. T., Consolmagno G. J., Farmer M., Wilson S., and Haag R. (1999) Portales Valley: A meteoritic sample of the brecciated and metal-veined floor of an impact crater on an H-chondrite asteroid. *Meteoritics & Planet. Sci.* 34, 663-669.

Krot A. N., Scott E. R. D., and Zolensky M. E. (1997a) Origin of fayalitic olivine rims and lath-shaped matrix olivines in the CV3 chondrite Allende and its dark inclusions. *Meteoritics & Planet. Sci.* 32, 31-49.

Krot A. N., Rubin A. E., Keil K., and Wasson J. T. (1997b) Microchondrules in ordinary chondrites: Implications for chondrule formation. *Geochim. Cosmochim. Acta* 61, 463-473.

Krot A. N., Petaev M. I., Zolensky M. E., Keil K., Scott E. R. D., and Nakamura K. (1998) Secondary calcium-iron-rich minerals in the Bali-like and Allende-like oxidized CV3 chondrites and Allende dark inclusions. *Meteoritics & Planet. Sci.* 33, 623-645.

Krot A. N., Brearley A. J., Ulyanov A. A., Biryukov V. V., Swindle T. D., Keil K., Mittlefehldt D. W., Scott E. R. D., Clayton R. N., and Mayeda T. K. (1999) Mineralogy, petrography, bulk chemical, iodine-xenon, and oxygen-isotopic compositions of dark inclusions in the reduced CV3 chondrite Efremovka. *Meteoritics & Planet. Sci.* 34, 67-89.

Krot A. N., Meibom A., and Keil K. (2000) A clast of Bali-like oxidized CV material in the reduced CV chondrite breccia Vigarano. *Meteoritics & Planet. Sci.* 35, 817-825.

Krot A. N., McKeegan K. D., Russell S. S., Meibom A., Weisberg M. K., Zipfel J., Krot T. V., Fagan T. J., and Keil K. (2001) Refractory calcium-aluminum-rich inclusions and aluminum-diopside-rich chondrules in the metal-rich chondrites Hammadah al Hamra 237 and Queen Alexandra Range 94411. *Meteoritics & Planet. Sci.* 36, 1189-1216.

Krot A. N., Meibom A., Weisberg M. K., and Keil K. (2002) The CR chondrite clan: Implications for early solar system processes. *Meteoritics & Planet. Sci.* 37, 1451-1490.

Krot A. N., Fagan T. J., Keil K., McKeegan K. D., Sahijpal S., Hutcheon I. D., Petaev M. I., and Yurimoto H. (2004) Ca,Al-rich inclusions, amoeboid olivine aggregates, and Al-rich chondrules from the unique carbonaceous chondrite Acfer 094: I. Mineralogy and petrology. Geochim. Cosmochim. Acta 68, 2167-2184.

Kurat G. (1970) Zur Genese des kohligen Materials im Meteoriten von Tieschitz. *Earth Planet. Sci. Lett.* 7, 317-324.

Kurat G. and Kracher A. (1980) Basalts in the Lance carbonaceous chondrite. *Z. Naturforsch.* 35a, 180-190.

Kurat G., Palme H., Brandstätter F., and Huth J. (1989) Allende Xenolith AF: Undisturbed record of condensation and aggregation of matter in the Solar Nebula. *Z. Naturforsch.* 44a, 988-1004.

Kurat G., Zinner E., Brandstätter F., and Ivanov A. V. (2004) Enstatite aggregates with niningerite, heideite, and oldhamite from the Kaidun carbonaceous chondrite: Relatives of aubrites and EH chondrites ? *Meteoritics & Planet. Sci.* 39, 53-60.

Labotka T.C. and Papike J.J. (1980) Howardites: Samples of the regolith of the eucrite parent-body: Petrology of Frankfort, Pavlovka, Yurtuk, Malvern, and ALHA 77302. *Proc. Lunar Planet. Sci. Conf.* 11th, 1103-1130.

Lange D. E., Keil K., and Gomes C. B. (1979) The Mafra meteorite and its lithic clasts: A genomict L-group chondrite breccia (abstract) *Meteoritics* 14, 472-473.

Leitch C. A. and Grossman L. (1977)Lithic clasts in the Supuhee chondrite. *Meteoritics* 12, 125-139.

Lin Y. and Kimura M. (1998) Petrographic and mineralogical study of new EH melt rocks and a new enstatite chondrite grouplet. *Meteorit. Planet. Sci. 33*, 501-511.

Lin Y. T., Nagel H-J., Lundberg L. L., and El Goresy A. (1991) MAC88136—The first EL3 chondrite. *Lunar Planet. Sci.,* 22, 811-812,

Lipschutz M. E., Verkouteren R. M., Sears D. W. G., Hasan F., Prinz M., Weisberg M. K., Nehru C. E., Delaney J. S., Grossman L., and Boily M. (1988) Cumberland falls chondritic inclusions: III. Consortium study of relationship to inclusions in Allan Hills 78113 aubrite. *Geochim. Cosmochim Acta 52*, 1835-1848.

Lomena I.S.M., Touré F., Gibson E. K. JR, Clanton U.S. and Reid A.M. (1976) Aioun el Atrouss: A new hypersthene achondrite with eucritic inclusions. *Meteoritics* 11, 51-57.

Lorenz C. A., Ivanova M. A., Kurat G., and Brandstaetter F. (2005) FeO-rich xenoliths in the Staroye Pesyanoe aubrite. *Lunar Planet. Sci.* 36, #1612.

Lorenzetti S., Eugster O., Busemann H., Marti, K., Burbine T. H., McCoy T. (2003) History and origin of aubrites. *Geochim. Cosmochim Acta* 67, 557-571.

Love J. J., Hill D. H., Domanik K. J., Lauretta D. S., Drake M. J., and Killgore M. (2005). NWA 2736: An unusual new graphite-bearing aubrite. *Lunar Planet. Sci.* 36, #1913.

Love S. G. and Ahrens T. J. (1996) Catastrophic impacts on gravity dominated asteroids. *Icarus* 124, 141-155.

MacDougall D., Rajan R.S. and Price (1973) Gas-rich meteorites: Possible evidence for origin on a regolith. *Science* 183, 73-74

MacPherson G. J., Jarosewich E., and Lowenstein P. (1993) Magombedze: A new H-chondrite with light-dark structure. *Meteoritics* 28, 138-142.

Mason B. (1962) *Meteorites* Wiley, New York, New York, USA, 274 pp

Mason B. (1963) The hypersthene achondrites. *Am. Museum Novitates* No. 2155, 13p.

McCarthy T.S., Ahrens L.H. and Erlank A.J. (1972) Further evidence in support of the mixing model for Howardite origin. *Earth Planet Sci. Lett.* 15, 86-93.

McCoy T. J. (1998) A pyroxene-oldhamite clast in Bustee: Igneous aubritic oldhamite and a mechanism for the Ti enrichment in aubritic troilite. *Antarctic Met. Res. 11*, 32-48.

McCoy T. J. and 9 co-authors (1995) Origin and history of impact-melt rocks of enstatite chondrite parentage. *Geochim. Cosmochim. Acta* 59, 161-175.

McCoy T. J., Keil K., Clayton R. N., Mayeda T. K., Bogard D. D., Garrison D. H., Huss G. H., Hutcheon I. D., and Wieler R. (1996) A petrologic, chemical, and isotopic study of Monument Draw and comparison with other acapulcoites: Evidence for formation by incipient partial melting. *Geochim. Cosmochim. Acta* 60, 2681-2708.

McCoy T. J., Keil K., Muenow D. W., and Wilson L. (1997) Partial melting and melt migration in the acapulcoite-lodranite parent body. *Geochim. Cosmochim. Acta* 61, 639-650.

McCoy T. J., Rosenshein E.B., and Dickinson T. I. (1999) A unique oxide-bearing clast in the aubrite Allan Hills 84008: Evidence for oxidation during magmatic processes (abstract). *Lunar Planet. Sci. 30*, #1347.

McCoy T. J., Mittlefehldt D. W., and Wilson L. (2005) Asteroid Differentiation: Understanding the chemical and physical processes (this volume)

McKay D. S., Swindle T. D., and Greenberg R. (1989) Asteroidal regoliths: What we do not know. In *Asteroids II* (Binzel R. P., Gehrels T., and M. S. Matthews, eds.), pp.617-642.

McSween H.Y. Jr. (1989) Achondrites and igneous processes on asteroids. *Ann. Rev. Earth Planet. Sci.* 17, 119-140.

Meibom A. and Clark B. E. (1999) Evidence for the insignificance of ordinary chondrite material in the asteroid belt. Meteorit. Planet. Sci. 34, 7-24.

Metzler K. (1985) Gefüge und Zusammensetzung von Gesteinsfragmenten in polymikten achondritischen Breccien. Diplomarbeit, Univ. Münster, Germany, 167 pp.

Metzler K. (1990) Petrographische und mikrochemische Untersuchungen zur Akkretions- und Entwicklungsgeschichte chondritischer Mutterkörper am Beispiel der CM-Chondrite. Ph.D. Thesis, Univ. Münster, Germany, 183 pp.

Metzler K. (1993) In-situ investigation of preirradiated olivines in CM chondrites *Meteoritics* 28, 398-399.

Metzler K. (1995) Aqueous alteration of primary rock on the CM parent body. *Lunar Planet. Sci.* XXVI, 961-962.

Metzler K. (1997) Preirradiated olivines in CM chondrites *Meteoritics* 32, A91-A92.

Metzler K. (2004) Formation of accretionary dust mantles in the solar nebula: Evidence from preirradiated olivines in CM chondrites. *Meteoritics Planet. Sci*. 39, 1307-1319.

Metzler K. and Bischoff A. (1996) Constraints on chondrite agglomeration from fine-grained chondrule rims. in: *Chondrules and the Protoplanetary Disk* (eds. R.H. Hewins, R.H. Jones, E.R.D. Scott), 153-161, Cambridge Univ. Press.

Metzler K. and Stöffler D. (1987) Polymict impact breccias on the eucrite parent body: I. Lithic clasts in some eucrites and howardites. *Lunar Planet. Sci*. XVII, 641-642.

Metzler K. and Stöffler D. (1995) Impact melt rocks and granulites from the HED asteroid. *Meteoritic*s 30, 547.

Metzler K., Bischoff A., and Stöffler D. (1992) Accretionary dust mantles in CM chondrites: Evidence for solar nebula processes. *Geochim. Cosmochim. Acta* 56, 2873-2897.

Metzler K., Bobe K.-D., Kunz J., Palme H., and Spettel B. (1994) ALHA 81011 – A eucritic impact melt breccia formed 350 m.y. ago. *Meteoritics* 29, 502-503.

Metzler K., Bobe K.-D., Palme H, Spettel B., and Stöffler D. (1995) Thermal and impact metamorphism on the HED parent asteroid. *Planet Space Sci.* 43, 499-525.

Michel P., Benz W., and Richardson D. C. (2003) Disruption of fragmented parent bodies as the origin of asteroid families. *Nature 421*, 608-611.

Mikouchi T., Makishima J., Koizumi E., and Zolensky M. E. (2005) Porphyritic olivine-pyroxene clast in Kaidun: First discovery of an ordinary chondrite clast? *Lunar Planet. Sci.* 36, #1956.

Misawa K., Watanabe S., Kitamura M., Nakamura N., Yamamoto K., and Masuda A. (1992) A noritic clast from the Hedjaz chondritic breccia: Implications for melting events in the early solar system. *Geochim. J.* 26, 435-446.

Mittlefehldt D.W. (1994) The genesis of diogenites and HED parent body petrogenesis. *Geochim. Cosmochim. Acta* 58, 1537-1552.

Mittlefehldt D. W. (2002) Geochemistry of the ungrouped carbonaceous chondrite Tagish Lake, the anomalous CM chondrite Bells, and comparison with CI and CM chondrites. *Meteoritics & Planet. Sci.* 37, 703-712.

Mittlefehldt D.W. and Lindstrom M.M. (1988) Geochemistry of diverse lithologies in antarctic eucrites. *Lunar Planet. Sci*. 19, 790-791.

Mittlefehldt D.W. and Lindstrom M.M. (1993) Geochemistry and petrology of a suite of ten Yamato HED meteorites. *Proc. NIPR Antarct. Meteorites* 6, 268-292.

Mittlefehldt D. W., Lindstrom M. M., Wang M.-S. , and Lipschutz M. E. (1995) Geochemistry and Origin of achondritic inclusions in Yamato-75097, -793241 and-794046 chondrites. *Proc. NIPR Symp. Antarct. Meteorites* 8, 251-271.

Mittlefehldt D. W., McCoy T. J., Goodrich C. A., and Kracher A. (1998) Non-chondritic meteorites from asteroidal bodies. In *Planetary Materials*, edited by Papike J.J. Washington: Mineralogical Society of America. pp 4-1 –4-195.

Mittlefehldt D. W. and Lindstrom M. M. (2001) Petrology and geochemistry of Patuxent Range 91501, a clast-poor impact melt from the L-chondrite parent body and Lewis Cliff 88663, an L7 chondrite. *Meteoritics & Planet. Sci.* 36, 439-457.

Miyamoto M. and Takeda H. (1977) Evaluation of a crust model of eucrites from the width of exsolved pyroxene. *Geochem. J*. 11, 161-169.

Miyamoto M., Mikouchi T. and Kaneda K. (2001) Thermal history of the Ibitira eucrite as inferred from pyroxene exsolution lamella: Evidence for reheating and rapid cooling. *Meteoritics & Planet. Sci.* 36, 231-237.

Morlok A. (2002) Mikrosondenanalytik und Sekundärionenmassenspektrometrie an Fragmenten und Lithologien in CI-Chondriten: Auswirkungen der Brecciierung auf die Verteilung von Elementen in CI-Chondriten. Ph.D. thesis, University of Münster, Münster, Germany, 205 pp.

Morlok A., Bischoff A., Henkel T., Rost D., Stephan T., and Jessberger E. K. (2000) The chemical heterogeneity of CI-chondrites on the submillimeter-scale. *Meteoritics & Planet. Sci*. 35, A113-A114.

Morlok A., Bischoff A., Henkel T., Rost D., Stephan T., and Jessberger E.K. (2001) The chemical heterogeneity of CI chondrites. *Lunar Planet. Sci*. XXXII, #1530, Lunar and Planetary Institute, Houston.

Murakami T. and Ikeda Y. (1994) Petrology and mineralogy of the Yamato-86751 CV3 chondrite. *Meteoritics* 29, 397-409.

Nagahara H. (1991) Petrology of Yamato-75261 meteorite: An enstatite (EH) chondrite breccia. *Proc. NIPR Symp. Antarct. Meteorites* 4, 144-162.

Nagao K (1994) Noble gases in hosts and inclusions from Yamato-75097 (L6), -793241 (L6) and –794046 (H5). *Proc. NIPR Symp. Antarct. Meteorites* 7, 197-216.

Nakamura N., Misawa K., Kitamura M., Masuda A., Watanabe S., and Yamamoto K. (1990a) Highly fractionated REE in the Hedjaz (L) chondrite: Implications for nebular and planetary processes. *Earth Planet. Sci. Lett.,* 99, 290-302.

Nakamura N., Fujiwara T., and Nofda S. (1990b) Young asteroid melting event indicated by Rb-Sr dating of Point of Rocks meteorite, *Nature* 345, 51-53.

Nakamura T., Nagao K. and Takaoka N. (1999a) Microdistribution of primordial noble gases in CM chondrites determined by in situ laser microprobe analysis: Decipherment of nebular processes. *Geochim. Cosmochim. Acta* 63, 241-255.

Nakamura T., Nagao K., Metzler K. and Takaoka N. (1999b) Heterogeneous distribution of solar and cosmogenic noble gases in CM chondrites and implications for the formation of CM parent bodies. *Geochim. Cosmochim. Acta* 63, 257-273.

Nakamura T., Noguchi T., Zolensky M. E., and Tanaka M. (2003) Mineralogy and noble-gas signatures of the Tagish Lake carbonaceous chondrite: evidence for an accretionary breccia. *Earth Planet. Sci. Lett.* 207, 83-101.

Nesvorny D., Morbidelli A., Vokrouhlicky D., Bottke W. F., and Broz M. (2002) The Flora family: A case of the dynamically dispersed swarm? *Icarus* 157, 155-172.

Newsom H. E. and Drake M. J. (1979) The origin of metal clasts in the Bencubbin meteoritic breccia. *Geochim. Cosmochim. Acta* 43, 689-707.

Nolan M. C., Asphaug E., Greenberg R., and Melosh H. J. (2001) Impacts on asteroids: Fragmentation, regolith transport, and disruption. *Icarus* 153, 1-15.

Noonan A. F., Nelen J., and Fredriksson K (1976) Mineralogy and chemistry of xenoliths in the Weston chondrite – ordinary and carbonaceous (abstract). *Meteoritics* 11, 344-346.

Norman M. D. and Mittlefehldt D. W. (2002) Impact processing of chondritic planetesimals. Siderophile and volatile element fractionation in the Chico L chondrite. *Meteoritics & Planet. Sci.* 37, 329-344.

Norman, M. D., Bennett V. C., and Ryder G. (2002) Targeting the impactors: siderophile element signatures of lunar impact melts from Serenitatis. *Earth Planet. Sci. Lett.* 202, 217-228.

Ohnishi I. And Tomeoka K. (2002) Dark inclusions in the Mokoia CV3 chondrite: Evidence for aqueous alteration and subsequent thermal and shock metamorphism. *Meteoritics & Planet. Sci.* 37, 1843-1856.

Okada A., Keil K., Taylor G. J., and Newsom H. (1988) Igneous history of the aubrite parent asteroid: Evidence from the Norton County enstatite achondrite. *Meteoritics 23*, 59-74.

Okano O., Nakamura N., Nagao K. (1990) Thermal history of the shock-melted Antarctic LL-chondrites from the Yamato-79 collection. *Geochim. Cosmochim. Acta* 54, 3509-3523.

Olsen E.J., Dod B.D., Schmitt R.A. and Sipiera P.P (1987) Monticello: a glass-rich howardite. *Meteoritics* 22, 81-96.

Olsen E.J., Fredriksson K, Rajan S. and Noonan A. (1990) Chondrule-like objects and brown glasses in howardites. *Meteoritics* 25, 187-194.

Ott U. (2002) Noble gases in meteorites—trapped components. *Rev. Mineral. Geochem.* 47, 71-100.

Ott U., Löhr H. P., and Begemann F. (1990) EET83309: A ureilite with solar noble gases. *Meteoritics* 25, 396.

Ott U., Löhr H. P., and Begemann F. (1993) Solar noble gases in polymict ureilites and an update on ureilite noble gas data. *Meteoritics* 28, 415-416.

Palme H., Schultz L., Spettel B., Weber H. W., Wänke H., Christophe Michel-Levy M., and Lorin J. C. (1981) The Acapulco meteorite: Chemistry, mineralogy, and irradiation effect. *Geochim. Cosmochim. Acta* 45, 727-752.

Palme H., Wlotzka F., Spettel B., Dreibus G. and Weber H. (1988) Camel Donga: a eucrite with high metal content. *Meteoritics* 23, 49-57.

Palme H., Kurat G., Spettel B., and Burghele A. (1989) Chemical composition of an unusual xenolith of the Allende meteorite. *Z. Naturforsch.* 44a, 1005-1014.

Papike J.J., C.K., Shearer, Spilde M.N. and Karner J.M. (2000) Metamorphic diogenite Grosvenor Mountains 95555: Mineral chemistry of orthopyroxene and spinel and comparisons to the diogenite suite. *Meteoritics Planet. Sci.* 35, 875-879.

Partsch P. (1843) Die Meteoriten oder vom Himmel gefallene Stein- und Eisenmassen. Im K.K. Hofmineralienkabinette zu Wien. Catalog of Vienna Collection, Wien.

Patzer A. and Schultz l. (2002) Noble gases in enstatite chondrites II. The trapped component. *Meteorit. Planet. Sci*. 37, 601-612.

Patzer A., Hill D.H. and Boynton W.V. (2003) New eucrite Dar al Gani 872: Petrography, chemical composition, and evolution. *Meteoritics Planet Sci.* 38, 783-794.

Patzer A., Hill D. H., and Boynton W. V. (2001) Itqiy: a metal-rich enstatite meteorite with achondritic texture. *Meteorit. Planet. Sci*. 36, 1495-1505.

Petit J-M., Chambers J., Franklin F., and Nagasawa M. (2002) Primordial excitation and depletion of the asteroid belt. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 711-723. Univ. Arizona Press.

Poupeau G., Kirsten T., Steinbrunn, and Storzer D. (1974) The records of solar wind and solar flares in aubrites. *Earth Planet. Sci. Lett.* 24, 229-241.

Pravec P., Harris A. W., and Michelowski T. (2002) Asteroid rotations. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 113-122. Univ. Arizona Press.

Prinz M., Fodor R. V., and Keil K. (1977) Comparison of lunar rocks and meteorites. In *The Soviet-American Conference on Cosmochemistry of the Moon and Planets,* eds. J. H. Pomeroy and N. J. Hubbard, NASA SP-370, 183-199.

Prinz M., Nehru C. E., Weisberg M. K., Delany J. S., Yanai K., and Kojima H. (1984) H-chondritic clasts in a Yamato L6 chondrite: Implications for metamorphism. *Meteoritics* 19, 292-293.

Prinz M., Weisberg M. K., Nehru C. E., and Delaney J. S. (1986) North Haig and Nilpena: Paired polymict ureilites with Angra dos Reis-related and other clasts. *Lunar Planet. Sci*. 17, 681-682.

Prinz M., Weisberg M. K., Nehru C. E., and Delaney J. S. (1987) EET83309, a polymict ureilite: Recognition of a new group. *Lunar Planet. Sci.* 18, 802-803.

Prinz M., Weisberg M. K., and Nehru C. E. (1988) Feldspathic components in polymict ureilites. *Lunar Planet. Sci*. 19, 947-948.

Prinz M., Weisberg M. K., Clayton R. N., and Mayeda T. K. (1993) Ordinary and Carlisle Lakes-like chondritic clasts in the Weatherford chondrite breccia (abstract). *Meteoritics* 28, 419-420.

Pun A:, Keil K., Taylor G.J. and Wieler R. (1998) The Kapoeta howardite: Implications for the regolith evolution of the howardite-eucrite-diogenite parent body. *Meteoritics Planet Sci.* 33, 835-851.

Rai V. K., Murth A. V. S., and Ott U. (2003) Nobles gases in ureilites: Cosmogenic, radiogenic, and trapped components. *Geochim. Cosmochim. Acta* 67, 4435-4456.

Rajan R. S. (1974) On the irradiation history and origin of gas-rich meteorites. *Geochim. Cosmochim. Acta* 38, 777-788.

Rao M.N., Garrison D.H., Palma R.L. and Bogard D.D. (1997) Energetic proton irradiation history of the howardite parent body regolith and implications for ancient solar activity. *Meteoritics Planet Sci.* 32, 531-543.

Reichenbach, v. (1860) *Poggendorffs Annal. 1860,* III, 353-386.

Reid A.M. and Barnard B.M. (1979) Unequilibrated and equilibrated eucrites. *Lunar Planet. Sci.* X, 1019-1024.

Reid A.M., Buchanan P., Zolensky M.E. and Barrett R.A. (1990) The Bholghati howardite: petrography and mineral chemistry. *Geochim. Cosmochim. Acta* 54, 2161-2166.

Richardson D. C., Leinhardt Z. M., Melosh H. J., Bottke W. F. Jr., and Asphaug E. (2002) Gravitational aggregates: Evidence and evolution. In *Asteroids III* (W. F. Bottke et al., eds.), pp. 501-515. Univ. Arizona Press.

Richardson S. M. (1978) Vein formation in the C1 carbonaceous chondrites. *Meteoritics* 13, 141-159.

Robinson M. S., Thomas P. C., Veverka J., Murchie S. L., and Wilcox B. B. (2002) The geology of 433 Eros. *Meteorit. Planet. Sci*. 37, 1651-1684.

Rubin A. E. (1985) Impact melt products of chondritic material. *Rev. Geophys.* 23, 277-300.

Rubin A. E. (1989) An olivine-microchondrule-bearing clast in the Krymka meteorite. *Meteoritics* 24, 191-192.

Rubin A. E. (1992) A shock-metamorphic model for silicate darkening and compositionally variable plagioclase in CK and ordinary chondrites. *Geochim. Cosmochim. Acta* 56, 1705-1714.

Rubin A. E. (1997a) The Hadley Rille enstatite chondrite and its agglutinate-like rim: Impact melting during accretion to the Moon. *Meteorit. Planet. Sci*. 32, 135-141.

Rubin A. E. (1997b) The Galim LL/EH polymict breccia: Evidence for impact-induced exchange between reduced and oxidized meteoritic material. *Meteorit. Planet. Sci*. 32, 489-492.

Rubin A. E. (2002) Smyer H-chondrite impact-melt breccia and evidence for sulfur vaporization. *Geochim. Cosmochim. Acta* 66, 699-711.

Rubin A. E. (2003) Northwest Africa 428: Impact-induced annealing of an L6 chondrite breccia. *Meteoritics & Planet. Sci.* 38, 1499-1506.

Rubin A. E. and Jones R. H. (2003) Spade: An H chondrite impact-melt breccia that experienced post shock annealing. *Meteoritics & Planet. Sci.* 38, 1507-1520.

Rubin A. E. and Kallemeyn G. W. (1990) Lewis Cliff 85332: A unique carbonaceous chondrite. *Meteoritics* 25, 215-225.

Rubin A. E. and Kallemeyn G. W. (1994) Pecora Escarpment 91002: A member of the new Rumuruti (R) chondrite group. *Meteoritics* 29, 255-264.

Rubin A. E. and Mittlefehldt D. W. (1992) Classification of mafic clasts from mesosiderites: Implications for endogeneous igneous processes. *Geochim. Cosmochim. Acta* 56, 827-840.

Rubin A. E. and Mittlefehldt D. W. (1993) Evolutionary history of the mesosiderites asteroid: A chronologic and petrologic synthesis. *Icarus* 101, 201-212.

Rubin A.E. and Scott E. R.D. (1997) Abee and related EH chondrite impact-melt breccias. *Geochim. Cosmochim. Acta* 61, 425-435.

Rubin A. E., Scott E. R. D., Taylor G. J., and Keil K. (1981a) The Dimmitt H chondrite regotlith breccia and implications for the structure of the H chondrite parent body (abstract). *Meteoritics* 16, 382-383.

Rubin A. E., Keil K., Taylor G. J., Ma M. S., Schmitt R. A., and Bogard D. D. (1981b) Derivation of a heterogeneous lithic fragment in the Bovedy L-group chondrite from impact-melted porphyritic chondrules. *Geochim. Cosmochim. Acta* 45, 2213-2228.

Rubin A. E., Scott E. R. D., and Keil K. (1982) Microchondrule-bearing clast in the Piancaldoli LL3 meteorite: A new kind of type 3 chondrite and its relevance to the history of chondrules. *Geochim. Cosmochim. Acta* 46, 1763-1776.

Rubin A. E., Rehfeldt A., Peterson E., Keil K., and Jarosewich E. (1983) Fragmental breccias and the collisional evolution of ordinary chondrite parent bodies. *Meteoritics* 18, 179-196

Rubin A. E., Scott E. R. D., Taylor G. J., Keil K., Allen, J. S. B., Mayeda T. K., Clayton R. N., and Bogard D. D. (1983) Nature of the H chondrite parent body regolith: Evidence from the Dimmitt breccia. *Proc. Lunar Planet. Sci. Conf.* 13, A741-A754.

Rubin A. E., James J. A., Keck B. D., Weeks K. S., Sears D. W. G., and Jarosewich E. (1985) The Colony meteorite and variations in CO3 chondrite properties. *Meteoritics* 20, 175-196.

Rubin A. E., Scott E. R. D., and Keil K. (1997) Shock metamorphism of enstatite chondrites. *Geochim. Cosmochim. Acta* 61, 847-858.

Rubin A. E., Trigo-Rodriguez J. M., Kunihiro T., Kallemeyn G. W., and Wasson J. T. (2004) Clues to the formation of PV1, an enigmatic carbon-rich chondritic clast from the Plainview H-chondrite regolith breccia. *Lunar Planet. Sci.* XXXV, No. 1175.

Rubin A. E., Ulff-Moller F., Wasson J. T. and Carlson W. D. (2001) The Portales Valley meteorite breccia: Evidence for impact-induced melting and metamorphism of an ordinary chondrite. *Geochim. Cosmochim. Acta* 65, 323-342.

Rubin A. E., Zolensky M. E., and Bodnar R. J. (2002) The halite-bearing Zag and Monahans (1998) meteorite breccias: Shock metamorphism, thermal metamorphism and aqueous alteration on the H-chondrite parent body. *Meteoritics & Planet. Sci.* 37, 125-141.

Ruzicka A., Kring D. A., Hill D. H., Boynton W. V., Clayton R. N., and Mayeda T. K. (1995) Silica-rich orthopyroxenite in the Bovedy chondrite. *Meteoritics* 30, 57-70.

Ruzicka A., Snyder G. A., and Taylor L.A. (1998) Mega-chondrules and large, igneous-textured clasts in Julesberg (L3) and other ordinary chondrites: Vapor-fractionation, shock-melting, and chondrule formation. *Geochim. Cosmochim. Acta* 62, 1419-1442.

Russell S. S., Hartmann L., Cuzzi J., Krot A. N., Gounelle M., and Weidenschilling S. (2005) Timescales of the solar protoplanetary disk. In *Meteorites and the Early Solar System II* (D. Lauretta et al., eds), this volume, Univ. of Arizona, Tucson.

Saiki K. and Takeda H. (1999) Origin of polymict breccias on asteroids deduced from their pyroxene fragments. *Meteoritics Planet Sci.* 34, 271-283.

Saiki K., Takeda H. and Ishii T. (2001) Mineralogy of Yamato-791192, HED breccia and relationship between cumulate eucrites and ordinary eucrites. *Antarct. Meteorite Res.* 14, 28-46.

Sanders I. S. (1996) A chondrule-forming scenario involving molten planetesimals. In "*Chondrules and the Protoplanetary Disk*" (eds. R.H. Hewins, R.H. Jones, E.R.D. Scott), 327-334, Cambridge Univ. Press.

Sato G., Takeda H., Yanai K., and Kojima H. (1982) Electron microprobe study of impact-melted regolith breccias (abstract). In *Workshop on Lunar Breccias and Soils and Their meteoritic Analogs* (eds. G. J. Taylor and L. L. Wilkening), pp. 120-122. LPI Technical Report 82-02. Lunar Planetary Institute.

Scherer P. and Schultz L. (2000) Noble gas record, collisional history, and pairing of CV, CO, CK, and other carbonaceous chondrites. *Meteoritics & Planet. Sci.* 35, 145-153.

Schulze H., Bischoff A., Palme H., Spettel B., Dreibus G., and Otto J. (1994) Mineralogy and chemistry of Rumuruti: The first meteorite fall of the new R chondrite group. *Meteoritics* 29, 275-286.

Schultz L. and Kruse H. (1978) Light noble gases in stony meteorites – A compilation. *Nucl. Track Detection* 2, 65-103.

Schultz L and Kruse H. (1989) Helium, neon, and argon in meteorites – A data compilation. *Meteoritics* 24, 155-172.

Scott E. R. D. (1982) Origin of rapidly solidified metal-troilite grains in chondrites and iron meteorites. *Geochim. Cosmochim. Acta* 46, 813-823.

Scott E. R. D. (1988) A new kind of primitive chondrite, Allan Hills 85085. *Earth Planet. Sci. Lett.* 91, 1-18.

Scott E.R.D. (2002) Meteorite evidence for the accretion and collisional evolution of asteroids. In *Asteroids III* (W. F. Bottke et al., eds.) pp. 697-709. Univ. of Arizona, Tucson.

Scott E. R. D. and Rajan R. S. (1981) Metallic minerals, thermal histories and parent bodies of some xenolithic, ordinary chondrite meteorites. *Geochim. Cosmochim. Acta* 45, 53-67.

Scott E. R. D. and Taylor G. J. (1982) Primitive breccias among the type 3 ordinary chondrites – origin and relation to regolith breccias. In *Workshop on Lunar Breccias and Soils and Their meteoritic Analogs* (eds. G. J. Taylor and L. L. Wilkening), pp. 130-134. LPI Technical Report 82-02. Lunar Planetary Institute.

Scott E. R. D. and Wilson L. (2005) Meteoritic and other constraints on the internal structure and impact history of small asteroids. Icarus, in press.

Scott E. R. D., Brearley A. J., Keil K., Grady M. M., Pillinger C. T., Clayton R. N., Mayeda T. K., Wieler R., and Signer P. (1988) Nature and Origin of C-rich ordinary chondrites and chondritic clasts. *Proc. Lunar Planet. Sci Conf.* 18, 513-523.

Scott E.R.D., Haack H., and McCoy T.J. (1996) Core crystallization and silicate-metal mixing in the parent body of the IVA iron and stony-iron meteorites. *Geochim. Cosmochim. Acta* 60, 1615-1631.

Scott E. R. D., Keil K., and Stöffler D. (1992) Shock metamorphism of carbonaceous chondrites. *Geochim. Cosmochim. Acta* 56, 4281-4293.

Scott E.R.D., Haack H., and Love S.G. (2001) Formation of mesosiderites by fragmentation and reaccretion of a large differentiated asteroid. *Meteorit. Planet. Sci.* 36, 869-881.

Sears D. W. and Wasson J. T. (1981) Dark inclusions in the Abbott, Cynthiana and Abee chondrites (abstract). *Lunar Planet. Sci.* XII, 958-960.

Semenenko V. P. and Girich A. L. (2001) A variety of lithic fragments in the Krymka (LL3.1) chondrite (abstract). *Meteoritics & Planet. Sci.* 36, A187.

Semenenko V. P., Bischoff A., Weber I., Perron C., and Girich A. L. (2001) Mineralogy of fine-grained material in the Krymka (LL3.1) chondrite. *Meteoritics & Planet. Sci.* 36, 1067-1085.

Sepp B., Bischoff A., and Bosbach D. (2001) Low-temperature phase decomposition in iron-nickel metal of the Portales Valley meteorite. *Meteoritics & Planet. Sci.* 36, 587-595.

Simpson E. S. and Murray D. G. (1932) A new siderolite from Bencubbin, Western Australia. *Mineral. Mag.* 23, 33-37.

Sisodia M.S., Shukla A.D., Suthar K.M., Mahajan M.R., Murty S.V.S., Shukla P.N., Bhandari N. and Natarajan R. (2001) The Lohawat howardite: Mineralogy, chemistry and cosmogenic effects. *Meteoritics Planet Sci.* 36, 1457-1466.

Smith C. L., Wright I. P., Franchi I. A., and Grady M. M. (2000) A statistical analysis of mineralogical data from Frontier Mountain ureilites. Meteorit. Planet. Sci. 35, A150.

Smith J. V. and Mason B. (1970) Pyroxene-garnet transformation in the Coorara meteorite. *Science* 168, 832-833.

Srinivasan B. and Anders E. (1977) Noble gases in the unique chondrite Kakangari. *Meteoritics* 12, 417-424.

Stöffler D., Knöll H.-D., and Maerz U. (1979) Terrestrial and lunar impact breccias and the classification of lunar highland rocks. *Proc. Lunar Planet. Sci Conf.* 10, 639-675.

Stöffler D., Knöll H.-D., Marvin U. B., Simonds C. H., and Warren P. H. (1980) Recommended classification and nomenclature of lunar highland rocks - a committee report. *Proc. Lunar Highlands Crust*, LPI Contrib. 394pp. 51-70.

Stöffler D., Bischoff A., Buchwald V., and Rubin A. E. (1988) Shock effects in meteorites. In *Meteorites and the Early Solar System* (eds. J.F. Kerridge and M. S. Matthews), The University of Arizona Press, Tucson, 165-202.

Stöffler D., Keil K., and Scott E. R. D. (1991) Shock metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta* 55, 3845-3867.

Suess H.E., Waenke H., and Wlotzka F (1964) On the origin of gas-rich meteorites. *Geochim. Cosmochim. Acta* 28, 209-233.

Sullivan R. J., Thomas P. C., Murchie S. L., and Robinson M. S. (2002) Asteroid geology from *Galileo* and *NEAR Shoemaker* data. In *Asteroids III* (W. F. Bottke et al., eds.) pp.331-350. Univ. of Arizona, Tucson.

Takeda H. (1979) A layered-crust model of a Howardite parent body. *Icarus* 40, 455-470.

Takeda H. (1991) Comparison of Antarctic and non-Antarctic achondrites and possible origin of the differences. *Geochim. Cosmochim. Acta* 55, 35-47.

Takeda H. (1997) Mineralogical records of early planetary processes on the howardite, eucrite, diogenite parent body with reference to Vesta. *Meteoritics Planet Sci.* 32, 841-853.

Takeda H. and Graham A.L. (1991) Degree of equilibration of eucritic pyroxenes and thermal metamorphism of the earliest planetary crust. *Meteoritics* 26, 129-134.

Takeda H: and Yamaguchi A. (1991) Recrystallization and shock textures of old and new samples of Juvinas in relation to its thermal history. *Meteoritics* 26, 400.

Takeda H., Mori H. and Yanai K. (1981) Mineralogy of the Yamato diogenites as possible pieces of a single fall. *Mem. Natl. Inst. Polar Res., Spec. Issue* 20, 81-99.

Takeda H., Mori H., Delaney J.S., Prinz M., Harlow G:E. and Ishii T. (1983) Mineralogical comparison of Antarctic and non-Antarctic HED (howardites-eucrites-diogenites) achondrites. *Mem. Natl. Inst. Polar Res., Special Issue* 30, 181-205.

Takeda H., Mori H., Ikeda Y., Teruaki I. and Yanai K. (1984) Antarctic howardites and their primitive crust. *Mem. Natl. Inst. Polar Res., Special Issue* 31, 81-101.

Tamaki M., Yamaguchi A., Misawa K., Ebihara M., and Takeda H. (2004) Petrologic study of eucritic clasts in mesosiderites, Mount Pudbury and Vaca Muerta. *Antarct. Meteorite Res.* 28, 85-86.

Taylor G. J. (1982) Petrologic comparison of lunar and meteoritic breccias. In *Workshop on Lunar Breccias and Soils and Their meteoritic Analogs* (eds. G. J. Taylor and L. L. Wilkening), pp. 153-167. LPI Technical Report 82-02. Lunar Planetary Institute.

Taylor G. J., Keil K., Berkley J. L., Lange D. E.,Fodor R. V., and Fruland R. M. (1979) The Shaw meteorite: history of a chondrite consisting of impact-melted and metamorphic lithologies. *Geochim. Cosmochim. Acta* 43, 323-337.

Taylor G.J., Maggiore P., Scott E.R.D., Rubin A.E. and Keil K. (1987) Original structures, and fragmentation and reassembly histories of asteroids: evidence from meteorites. *Icarus* 69, 1-13.

Tonui E. K., Zolensky M. E., Lipschutz M. E., Wang M.-S., and Nakamura T. (2003) Yamato 86029: Aqueously altered and thermally metamorphosed CI-like chondrite with unusual textures. *Meteoritics & Planet. Sci* 38, 269-292.

Tschermak G. (1872) Die Meteoriten von Shergotty and Gopalpur. Sitzungsber. *Akad. Wiss. Wien, Math.-Naturwiss.* Kl 65, Teil 1, 122-145.

Urey, H.C. (1959) Primary and secondary objects. *J. Geophys. Res.* 64, 1721-1737.

Urey, H.C. (1967) Parent bodies of the meteorites and origin of chondrules. *Icarus* 7, 350-359.

Van der Bogert C. H., Schultz P. H., and Spray J. G. (2003) Impact-induced frictional melting in ordinary chondrites: A mechanism for deformation, darkening, and vein formation. *Meteoritics & Planet. Sci* 38, 1521-1531.

Van Schmus W. R. (1967) Polymict structure of the Mezo-Madaras chondrite. *Geochim. Cosmochim. Acta* 31, 2072-2042.

Varteresian C. and Hewins R. H. (1983) Magnesian noritic and basaltic clasts in the Garland and Peckelsheim diogenites. *Lunar Planet. Sci.* XIX, 800-801.

Vdovykin G. P. (1972) Forms of carbon in the new Haverö ureilite of Finland. *Meteoritics* 7, 547.

Vogel N., Wieler R., Bischoff A., and Baur H. (2003) Microdistribution of primordial Ne and Ar in fine-grained rims, matrices, and dark inclusions of unequilibrated chondrites – Clues on nebular processes. *Meteoritics & Planet. Sci* 38, 1399-1418.

Wänke H. (1965) Der Sonnenwind as Quelle der Uredelgase in Steinmeteoriten. *Z. Naturf.* B20a, 946-949.

Wahl W. (1952) The brecciated stony meteorites and meteorites containing foreign fragments. *Geochim. Cosmochim. Acta* 2, 91-117.

Warren P.H. (1985) Origin of howardites, diogenites and eucrites: a mass balance constraint. *Geochim. Cosmochim. Acta* 49, 577-586.

Wasson J. T. (1974) Meteorites. *Springer-Verlag*.

Wasson J. T., Rubin A. E., and Kallemeyn G. W. (1993) Reduction during metamorphism of four ordinary chondrites. *Geochim. Cosmochim Acta 57*, 1867-1878.

Watters and Prinz M. (1980) Mt. Egerton and the aubrite parent body. *Lunar Planet. Sci*. 11, 1225-1227.

Weber I. and Bischoff A. (1998) Mineralogy and chemistry of the ureilites Hammadah al Hamra 064 and Jalanash. *Lunar Planet. Sci*. 29, 1365.

Weber I., Bischoff A., and Weber D. (2003) TEM investigations on the monomict ureilites Jalanash and Hammadah al Hamra 064. Meteorit. Planet. Sci. 38, 145-156.

Welzenbach L. C., McCoy T. J., Grimberg A., and Wieler R. (2005) Petrology and noble gases of the regolith breccia MAC 87302 and implications for the classification of Antarctic meteorites. *Lunar Planet. Sci*. 36, #1425.

Weisberg M. K., Prinz M., and Nehru C. E. (1988) Petrology of ALH 85085: A chondrite with unique characteristics. *Earth Planet. Sci. Lett.* 91, 19-32.

Weisberg M. K., Prinz M., and Nehru C. E. (1990) The Bencubbin chondrite breccia and its relationship to CR chondrites and the ALH85085 chondrite. *Meteoritics* 25, 269-279.

Weisberg M. K., Prinz M., Clayton R. N., and Mayeda T. K. (1993) The CR (Renazzo-type) carbonaceous chondrite group and its implications. *Geochim. Cosmochim. Acta* 57, 1567-1586.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Grady M.M., and Pillinger C. T. (1995) The CR chondrite clan. *Proc. NIPR Symp. Antarct. Meteorites* 8, 11-32.

Weisberg M. K., Prinz M., Clayton R. N., Mayeda T. K., Grady M.M., Franchi I., Pillinger C. T., and Kallemeyn G. W. (1996) The K (Kakangari) chondrite grouplet. *Geochim. Cosmochim. Acta* 60, 4253-4263.

Weisberg M. K., Prinz M., and Nehru C. E. (1997a) QUE 94204: An EH-chondritic melt rock. *Lunar Planet. Sci*. XXVIII, 1358.

Weisberg M. K., Prinz M., Clayton R. N., and Mayeda T. K. (1997b) CV3 chondrites: Three subgroups, not two (abstract). *Meteoritics & Planet. Sci.* 32, A138-A139.

Weisberg M. K., Prinz M., Clayton R. N., and Mayeda T. K., Sugiura N., Zashu S., Ebihara M. (2001) A new metal-rich chondrite grouplet. *Meteoritics & Planet. Sci.* 36, 401-418.

Weisberg M., McCoy T. J., and Krot A. N. (2005) Systematics and Evaluation of Meteorite Classification (this volume)

Wieler R., Graf T., Pedroni A., Signer P., Pellas P., Fieni C., Suter M., Vogt S., Clayton R. N., and Laul J. C. (1989) Exposure history of the regolithic chondrite Fayetteville: II. Solar-gas-free light inclusions. *Geochim. Cosmochim. Acta* 53, 1449-1459.

Wieler R., Pedroni A. and Leya I. (2000) Cosmogenic neon in mineral separates from Kapoeta: no evidence for an irradiation of its parent body by an early active sun. *Meteoritics Planet. Sci.* 35, 251-257.

Wilkening L. L. (1973) Foreign inclusions in stony meteorites – I. Carbonaceous chondritic xenoliths in the Kapoeta howardite. *Geochim. Cosmochim. Acta* 37, 1985-1989.

Wilkening L. L. (1976) Carbonaceous chondritic xenoliths and planetary-type noble gases in gas-rich meteorites. *Proc Lunar Sci. Conf.* 7th, 3549-3559.

Wilkening L. L. (1977) Meteorites in meteorites: evidence for mixing among the asteroids. In *Coments, Asteroids and Meteorites* (ed. A. H. Delsemme), p. 389-396 (Univ. of Toledo).

Wilkening L. L. (1978) Tysnes Island: An unusual clast composed of solidified, immiscible, Fe-FeS and silicate melts. *Meteoritics* 13, 1-9.

Wilkening L. L. and Clayton R. N. (1974) Foreign inclusions in stony meteorites-II. Rare gases and oxygen isotopes in a carbonaceous chondritic xenolith in the Plainview gas-rich chondrite. *Geochim. Cosmochim. Acta* 38, 937-945.

Wilkening L.L., Lal D., and Reid A.M. (1971) The evolution of the Kapoeta howardite based on fossil track studies. *Earth Planet. Sci. Lett.* 10, 334-340.

Wilkison S.L., Robinson M.S., Thomas P.C., Veverka J., McCoy T.J., Murchie S.L., Prockter L., Yeomans D. (2002) An estimate of Eros's porosity and implications for internal structure. Icarus 155, 94-103.

Williams C, V., Rubin A. E., Keil K., San Miguel A. (1985) Petrology of the Cangas de Onis and Nulles regolith breccias: Implications for parent body history. *Meteoritics* 20, 331-345.

Williams C. V., Keil K., Taylor G. J., and Scott E. R. D. (2000) Cooling rates of equilibrated clasts in ordinary chondrite regolith breccias: Implications for parent body histories. *Chem. Erde* 59, 287-305.

Wlotzka F. (1963) Über die Hell-Dunkel-Struktur der urgashaltigen Chondrite Breitscheid und Pantar. *Geochim. Cosmochim. Acta* 27, 419-429.

Wlotzka F., Palme H., Spettel B., Wänke H., Fredriksson K., and Noonan A. F. (1979) Krähenberg and Bhola: LL chondrites with differentiated K-rich inclusions (abstract). *Meteoritics* 14, 566.

Woolum D.S. and Hohenberg C. (1993) Energetic particle environment in the early solar system—extremely long pre-compaction ages or enhanced early particle flux. In *Protostars and Planets III* (E. H. Levy and J. I. Lunine, eds), pp. 903-919. University of Arizona Press.

Xiao X. and Lipschutz M. E. (1991) Chemical studies of H chondrites: III. Regolith evolution of the Fayetteville chondrite parent body. *Geochim. Cosmochim. Acta* 55, 3407-3415.

Yamaguchi A. and Takeda H. (1992) Mineralogical study of some brecciated antarctic eucrites. *Proc. NIPR Antarct. Meteorites* 5, 242-257.

Yamaguchi A. and Takeda H. (1994) Granulitic matrices in monomict eucrites. *Lunar Planet. Sci*. XXV, 1525-1526.

Yamaguchi A. and Takeda H. (1995) Mineralogical studies of some antarctic monomict eucrites, including Yamato-74356: a unique rock containing recrystallized clastic matrix. *Proc. NIPR Antarct. Meteorites* 8, 167-184.

Yamaguchi A., Takeda H., Bogard D.D. and Garrison D.H. (1994) Textural variation and impact history of the Millbillillie eucrite. *Meteoritics* 29, 237-245.

Yamaguchi A., Taylor G.J. and Keil K. (1996) Global crustal metamorphism of the eucrite parent body. *Icarus* 124, 97-112.

Yamaguchi A., Taylor G.J. and Keil K. (1997) Shock and thermal history of equilibrated eucrites from Antarctica. *Antarct. Meteorite Res.* 10, 415-436.

Yamaguchi A., Scott E. R. D., and Keil K. (1998) Origin of unusual impact melt rocks, Yamato-790964 and –790143 (LL-chondrites). *Antarct. Meteorite Res.* 11, 18-31.

Yamaguchi A., Scott E. R. D., and Keil K. (1999) Origin of a unique impact-melt rock – the L-chondrite Ramsdorf. *Meteorit. Planet. Sci.* 34, 49-59.

Zolensky M. and Ivanov. A. (2003) The Kaidun microbreccia meteorite: A harvest from the inner and outer Asteroid belt. *Chem. Erde* 63, 185-246.

Zolensky M.E. and McSween H.Y. (1988) Aqueous alteration. In *Meteorites and the Early Solar System* (J.F. Kerridge and M.S. Matthews, eds), 114-143. University of Arizona Press (Tucson).

Zolensky M.E., Hewins R.H., Mittlefehldt D.W., Lindstrom M.M., Xiao X and Lipschutz M.E. (1992) Mineralogy, petrology and geochemistry of carbonaceous chondritic clasts in the LEW 85300 polymict eucrite. *Meteoritics* 27, 596-604.

Zolensky M., Weisberg M. K., Buchanan P. C., Prinz M., Read A., and Barrett R. A. (1992) Mineralogy of dark clasts in CR chondrites, eucrites and howardites (abstract). *Lunar Planet. Sci,* 23, 1587-1588.

Zolensky M., Krot A. N., Weisberg M. K., Buchanan P. C., and Prinz M. (1996a) Fine-grained inclusions in type 3 ordinary and carbonaceous chondrites (abstract). *Lunar Planet. Sci,* XXVII, 1507-1508.

Zolensky M. E., Ivanov A. V., Yang S. V., Mittlefehldt D.W., and Ohsumi K. (1996b) The Kaidun meteorite: Mineralogy of an unusual CM1 lithology. *Meteorit. Planet. Sci.* 31, 484-493.

Zolensky M.E., Weisberg M.K., Buchanan P.C., and Mittlefehldt D.W. (1996c) Mineralogy of carbonaceous chondrite clasts in HED achondrites and the moon. *Meteorit. Planet Sci.* 31, 518-537.

Zolensky M.E., Mittlefehldt D.W., Lipschutz M.E., Wang M.-S., Clayton R.N., Mayeda T.K., Grady M.M., Pillinger C. and Barber D. (1997) CM chondrites exhibit the complete petrologic range from type 2 to 1. *Geochim. Cosmochim. Acta* 61, 5099-5115.

Zolenssky M., Nakamura K., Gounelle M., Mikouchi T., Kasama T., Tachikawa O., and Tonui E. (2002) Mineralogy of Tagish Lake: An ungrouped type 2 carbonaceous chondrite. *Meteoritics & Planet. Sci.* 37, 737-761.

Zolensky M., Nakamura K., Weisberg M. K., Prinz M., Nakamura T., Ohsumi K., Saitow A., Mukai M., and Gounelle M. (2003) A primitive dark inclusion with radiation-damaged silicates in the Ninqiang carbonaceous chondrite. *Meteorit. Planet. Sci.* 38, 305-322.

Zolensky M. E., Tonui E. K., Bevan A. W. R., Le L., Clayton R. N., Mayeda T. K., and Norman M. (2004) Camel Donga 040: A CV chondrite genomict breccia with unequilibrated and metamorphosed material. *Antarct. Meteorite Res.* 28, 95-96.

Zook H. A. (1980) A new impact model for the generation of ordinary chondrites. *Meteoritics* 15, 390-391.