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STUDIES OF THE THERMAL EVOLUTION OF A CHONDRITIC ASTEROIDAL BODY: SYNTHESIS FROM THE ANTARCTIC METEORITE THIN SECTION SET OF THE NATIONAL INSTITUTE OF POLAR RESEARCH, TOKYO

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ABSTRACT

We studied the Antarctic Meteorite Thin Section Educational Set which had been prepared by the National Institute of Polar Research (NIPR), Tokyo, Japan. We reconstructed a synthesis of an evolutionary path of regions in the chondritic parent body arranging the chondritic set members according to the degree of thermal metamorphism and the deduced crust and core region set members after the differentiation of the parent body. We discuss the extraordinary possibility of the synthetic overview of the thermal evolution of the chondritic parent body by this NIPR Antarctic meteorite set which also has basic importance in space science and planetary materials education.

INTRODUCTION

Till 1969 meteorites were collected from random events (falls or finds). Since that time first Japanese, then American expeditions started to collect meteorites from the icefields of Antarctica (Cassidy et al, 1992). Meteorite search expeditions became annual events in Japan and United States during the last quarter of the XXth century. This work resulted in more than 20000 pieces of Antarctic Meteorites. About half of this quantity is stored at the National Institute of Polar Research, Tokyo, Japan (Yanai et al., 1987, 1991, 1995), and half at the Planetary Materials Laboratory, NASA Johnson Space Center, Houston, Texas, U.S.A. There are collections in the European Community from the EUROMET program, also with hundreds of meteorites (Hutchison, 1991).

These Antarctic Meteorite Collections have many benefits over the traditional ones. Antarctic collections are free of the traditional selection effects of random falls and chance finds. (distinction from soil, fragility, recognition effects, etc.). Ice cover is a good conservator. Availability of meteorites in the Antarctic Collections is the best for investigations, and because of intensive studies they are "in hands", and are continuously the samples for comparison.

In the last 10 years we could work with the Meteorite Thin Section Educational Set made by the National Institute of Polar Research (NIPR). We focused our studies on the thermal evolution of the chondritic meteorite parent body. This evolutionary program promised the most fruithful mining of the rich sample set which contains 30 samples. First we shortly describe the samples of the set and in the main part of the paper we reconstruct a tentative synthesis of the chondritic parent body evolution. There the samples of the set are arranged according to the thermal history of the metamorphism of the chondritic samples along the 3-6 van Schmus - Wood petrologic types (in the H, L, LL sequences) to the primitive achondritic stages and according to the differentiated states from outer layer of basaltic achondrites through the asteroidal mantle type ureilite till the inner belt of pallasite. During the last 10 years several theoretical estimations and statistical comparisons (using NIPR Antarctic Meteorit Dataset; Yanai et al., 1995; Nobuyoshi et al., 1997) about the role of transitional meteorites between undifferentiated chondritic and well differentiated basaltic achondritic stages were also published. (Bérczi et al., 1998, 1999, 2000).

A SHORT DESCRIPTION OF THE THIN SECTIONS OF THE NIPR ANTARCTIC METEORITE SET

The NIPR set contains the following 30 samples: Their numbers are given according to the set, and their photographs in the catalogue of Yanai et al. (1987) are also given.

N° 1. Pallasite - Yamato 8451. Large spherulic olivine grains are embedded in the opaque metal phase (nickel-iron) (Yanai et al., 1987, p. 196.).

N° 2. Mesosiderite - Allan Hills 77219. The sample comprises of large orthopyroxene grains, opaque metal phase and smaller orthopyroxenes and olivines in the groundmass of the texture (Yanai et al., 1987, p. 53.)

N° 3. Aubrite (Enstatite achondrite) - Allan Hills 78113. The slightly brecciated texture mainly consists of large enstatite grains. Some regions contain olivine, too (Yanai et al., 1987, p. 55.)

N° 4. Ureilite - Allan Hills 77257. The texture consists of large, clear olivine, pyroxene and less plagioclase grains and opaque phase. All mineral grains have opaque edges, very characteristic to the ureilitic texture (by carbon diffusion, iron reduction) (Yanai et al., 1987, p. 54.)

N° 5. Diogenite A - Yamato 74097. Monomineralic crystalline texture consisting of orthopyroxene.

N° 6. Diogenite B - Allan Hills 77256. Monomineralic brecciated texture consisting of orthopyroxene.

N° 7. Howardite - Yamato 7308. Brecciated basaltic achondrite with plagioclase, orthopyroxene and less olivine, and clinopyroxene in the texture (Yanai et al., 1987, p. 34.)

N° 8. Eucrite A - Yamato 791195. This basaltic achondritic meteorite has crystalline texture similar to a microgabbro with clinopyroxene (also occurs with twin-lamellae) and plagioclase (in subhedral grains) (Yanai et al., 1987, p. 80.)

N° 9. Eucrite B - Yamato 74450. This basaltic achondrite has brecciated (polymict) texture and consists of plagioclase+pyroxene basaltic clasts, and mineral clasts of these two minerals, too (Yanai et al., 1987, p. 45.)

N° 10. Shergottite - Allan Hills 77005. Brown pyroxene and mainly glassy plagioclase (maskelynite) plus some plagioclase minerals and opaque component (chromite?) comprise this basaltic achondritic texture which is suggested to have been originated from Mars. At the edge of one plagioclase grain fine grained plagioclase crystals with glass between them have been formed with variolitic texture. Both diaplectic glass (maskelynite) and this region of melting and recrystallization refers to the impact event which delivered the sample to Earth (Yanai et al., 1987, p. 52.).

N° 11. Lunar Meteorite A (regolith breccia) - Yamato 86032. Large plagioclase rich clasts are embedded in a darker matrix. It contain small olivine grains, too (Yanai et al., 1987, p. 197-198.).

N° 12. Lunar Meteorite B (norite) - Asuka 881757. The gabbroic texture of this lunar meteorite sample consists of orthopyroxene and glassy plagioclase (maskelynite). In many respects the sample is very similar to the NASA Lunar Sample N° 78235, which has similar mineral components except that there brown glass veins can also be found in the texture. Considering maskelynite, the Lunar Meteorite B - Asuka 881757 is also similar to the N° 10. Shergottite - Allan Hills 77005 sample, and similarity might have resulted from their excavation from the surface of a planetary body with greater mass than an asteroidal mass.

N° 13. Primitive achondrite - Yamato 794046. The texture is equigranular and consists of olivines, pale brown pyroxenes embedded into a large, long plagioclase grain. It contains a few opaque minerals (troilite) and brown, almost isotropic glass, interstitially (Yanai et al., 1987, p. 158.).

N° 14. EH3 chondrite - Yamato 691. Well developed chondrules mainly consisting of olivine and pyroxene. It contains opaque phases (metal + troilite) too (Yanai et al., 1987, p. 33.).

N° 15. H3 chondrite - Yamato 791428. Well developed chondritic texture. The chondrules are both from olivine, plagioclase and pyroxene + opaque component. There are chondrules mixed from these three main mineral phases, too (Yanai et al., 1987, p. 95.).

N° 16. H4 chondrite - Allan Hills 77233. The chondrules of this rather well defined chondritic texture are mainly from clinopyroxenes, and in less number from olivine.

N° 17. H5 chondrite - Yamato 74079. Less well developed chondritic texture with chondrules consisting of olivine and pyroxene (Yanai et al., 1987, p. 36.)..

N° 18. H6 chondrite - Yamato 74014. Slightly discernible chondrules. There are chondrules consisting of skeletal olivine. By this chondrule there are also olivine crystals.

N° 19. L3 chondrite - Yamato 74191. Well developed chondritic texture. It contains mainly chondrules from olivine and pyroxene, and a devitrified brown glass also occurs (Yanai et al., 1987, p. 41.).

N° 20. L4 chondrite - Yamato 74355. Chondritic texture with well developed chondrules of olivine and pyroxene.

N° 21. L5 chondrite - Yamato 790957 Less well defined chondrules, mainly from pyroxenes.

N° 22. L6 chondrite - Allan Hills 769. Chondritic texture, poorly defined chondrules. In a large pyroxene grain olivine inclusions can be found, and the pyroxene grain itself is also surrounded by olivine grains.

N° 23. LL3 chondrite - Yamato 790448. Densely populated with chondrules and chondrule fragments mainly from clinopyroxenes (some are twinned). There is a cellular olivine which contains fine fiber of glass. Lamellar clinopyroxene also occurs with fine devitrifying glass fibers. Between chondrules sulfide type opaque patches occur (Yanai et al., 1987, p. 63.).

N° 24. LL4 chondrite - Yamato 74442. A rather well defined chondritic texture with a little bit brecciated character where

Table1. Thermal metamorphic sequence from chodnrites, through primitive achondrites till basaltic achondrites.

Petrological type of V Schm-W.	1	2	3	4	5	6	Primitive Achondr. stage A	Primitive Achondr. stage B	Differentiation products
E			*Yamato 691*	+	+	+			*ALHA- 78113 Aubrite*
H			*Yamato 791428*	*ALHA 77233*	*Yamato 74079*	*Yamato 74014*	*Yamato 794046 Primitive achondrite*	?	*Yamato 74097 A DiogeniteALHA-77256 B Diogenite*
C	*Yamato 82162*	*Yamato 74662*	*Yamato 791717 (CO 3) Yamato 86751 (CV 3)*	+	+	+	?	*ALHA-77257 Ureilite*	
L			*Yamato 74191*	*Yamato 74355*	*Yamato 790957*	*ALHA 769*	+	?	
LL		+	*Yamato 790448*	*Yamato 74442*	*ALHA 78109*	*Yamato 75258*	*ALHA- 77219 Mesosi-derite*		
Pallasite									*Yamato 8451 Pallasite*

olivine and pyroxene grains also occur, together with the chondrules.

N° 25. LL5 chondrite - Allan Hills 78109. Poorly defined chondrules. There are chondrules consisting of barred olivines grown together with lamellae with different directions. Olivine chondrules+opaque minerals+olivine crystals also occur together.

N° 26. LL6 chondrite - Yamato 75258. Poorly defined chondrules, mainly consisting of olivine. There is a chondrule in which olivines radiate from an opaque core. Olivine grains also occur in the fine grained groundmass.

N° 27. CI carbonaceous chondrite - Yamato 82162. Irregular chondrule-like grains can be found in the dark carbonaceous groundmass. One grain contains fine fibrous material - possibly devitrifying glass (Yanai et al., 1987, p. 180-181.).

N° 28. CM2 carbonaceous chondrite - Yamato 74662. In the dark carbonaceous matrix mainly olivine (clear, transparent) and pyroxene (less clear) chondrules occur (Yanai et al., 1987, p. 47.)

N° 29. CO3 carbonaceous chondrite - Yamato 791717. Well developed chondrules embedded into a fine grained groundmass which seems fresh. Spheroidal olivine chondrules occur. In a chondrule olivine, metal phase and hematite occur together. There is a chondrule with skeletal olivine between glass, so forming a spinifex textural character, and this all is surrounded with olivine grains (Yanai et al., 1987, p. 111.)

N° 30. CV3 carbonaceous chondrite - Yamato 86751. Well defined chondrules in the fine grained matrix. There is a chondrule with many small olivine and twinned clinopyroxene surrounded with a glassy material (Yanai et al. 1987, p. 200.).(Table 1)

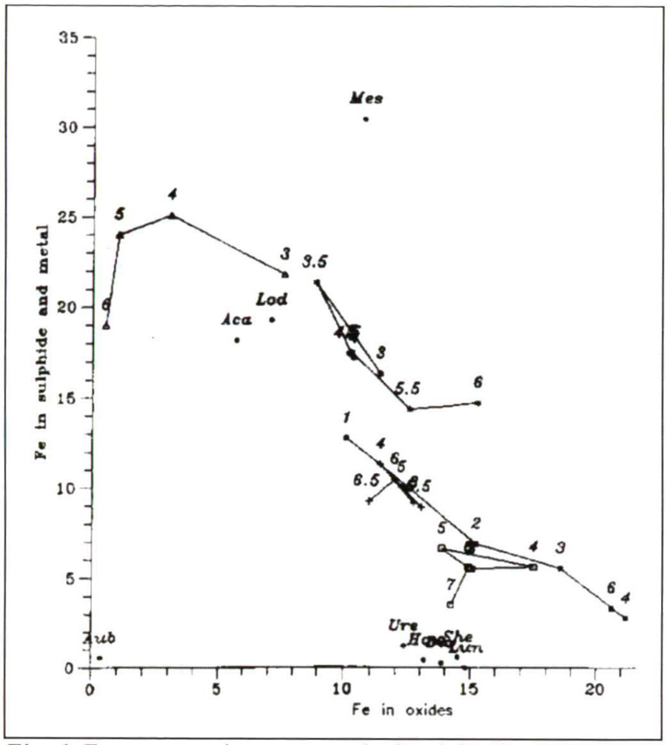

Fig. 1. Fe compound averages calculated for the for the 3, 4, 5, and 6 petrologic types in the E, H, L, LL and C group on the basis of the NIPR dataset (Yanai et al., 1995), and the averages were projected onto the Fe+FeS vs. Fe-oxides compositional field, which is sometimes called as Urey-Craig Field. We can observe that for the E, H, L, and LL cases the compound averages show first reduction then oxidation transformations. The C chondritic averages run toward the oxidation, because of their larger water content. E chondritic averages do not return to oxidation. Only the ordinary chondrites exhibit the evolutionary path which begins first reduction then continues with oxidation.

THERMAL METAMORPHISM IN THE CHONDRITIC PARENT BODY

The synthesis on the basis of the NIPR set can be divided into two main parts. First part is the metamorphism in the parent body which is slowly heated up by the short living radionuclides. This process results in an onion-layered body with higher temperatures in the core regions and lower temperatures at the margin of the body (Fig. 1). The second period is the differentiation when partial melting of metallic and somewhat later the basaltic assemblages results in migration and volcanism in the chondritic parent body.

First we summarize some key events from the first period. We know from chondrite studies that the metamorphic events started from parent bodies with different initial compositions. These clusters of chondrites named groups were recognized and distinguished by theirmineralogy and chemistry (Urey and Craig, 1953) and groups were named by their total iron content to H and L, which system was later extended to the E, H, L, LL, and C main groups of chondrites (Mason, 1962). The textural sequence of the thermal metamorphism was formulated first by Van Schmus and Wood (1967). The thermal evolutionary paths of these parent bodies are only slightly different and the NIPR SET allows comparisons of the H, L and LL sequences because they are all represented by thin sections from 3 to 6 petrologic types. They are represented by the 15, 16, 17 and 18 thin sections for H3 to H6 (Fig. 2), by the 19,

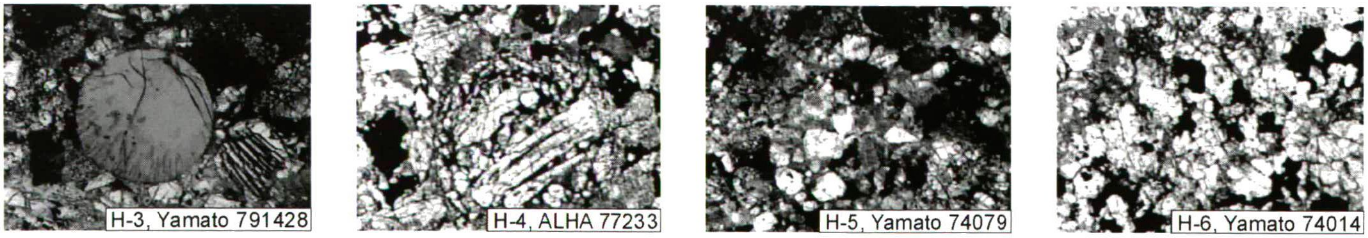

Fig. 2. Metamorphic sequence of the H-group chondrites on the basis of the NIPR Antarctic Meteorite Thin Section Set (AMTST). We can observe how the sharp edges of chondrules gradually become fuzzy which process is called as Oswald-maturing in solid state physics.

20, 21 and 22 thin sections for L3 to L6, and by the 23, 24, 25 and 26 thin sections for LL3 to LL6 metamorphic chondritic stages (Table 1). To these stages various peak temperatures were corresponded.

Earlier we studied the compositional changes of the Fe compounds on the basis of Yanai et al. (1995). In this earlier statistical investigations (Bérczi and Lukács, 1995; Bérczi et al., 1996; Lukács et al., 1997) we calculated the E, H, L, and LL Fe compound averages for the 3, 4, 5, and 6 petrologic types and we projected these averages onto the the Fe+FeS vs. Fe-oxides compositional field (We called it Urey-Craig Field.). These points were connected and they sketched the main paths of thermal evolution for a chondritic parent bodies of E, H, L, LL, projected to the) Fe-compound field. That was a Van Schmus-Wood type dataset arrangement (projection) on the Urey-Craig Field. Heating up of the chondritic parent bodies resulted in diffusion processes and slow transformations of the chondritic texture, chemical equilibrum between the neighbouring minerals. (That process is the Oswald-maturin in the solid state physics.) Thermal metamorphic diffusion resulted in compositional changes advancing along the E, H, L, LL and C sequences. They showed *first reduction then oxidation* transformations (E, H, L, LL, C chondrites). Reduction and C loss, between 3-4 petrologic types, was also recognized earlier (Lux et al., 1980; Huss et al., 1981; Scott et al., 1984), and the oscillation between oxidized and less-oxides states occurred between the 4-5-6 middle petrologic types, was the recognition of our group (Bérczi et al., 1998; Lukács et al., 1998).

Transition from metamorphism to differentiation

After thermal metamorphism the chondritic meteorites lost their chondritic texture, however, their chemistry witnesses that they preserve the original ratios of main elements. This preservation of chondritic chemistry induced their name of primitive achondritic stage. Classification of the chondritic metamorphic sequence (van Schmus and Wood, 1967) formed standard examples for gradual transitional textures between the more and more transformed chondritic stages. Heating over the primitive achondritic stage made it possible to continue this sequence toward various other achondritic stages. The continuing of this sequence needs recognition and formulation of textural characteristics of further transformations caused by the partial melting and the consequent differentiation inside the parent chondritic body.

It was important to assert that following chondritic equilibration the first event was the preservation of chondritic chemistry in a primitive achondritic stage (acapulcoite, lodranite, winonaite). However, during the transitional primitive achondritic stage various processes run parallel. The most important is the percolation of iron, which is followed later by the partial melting and outflow of iron+iron-sulfide assemblage from the primitive achondritic source. Mesosiderite may represent this transitional stage where iron gradually assemblages into larger grains.

Veined texture also may represent such kind of transitional meteorites (Rose City, Netschaevo, Watson, Techado and the Portales Valley meteorites were found as such types) from chondritic stage toward the achondritic stages. Veined meteorites preserving some remnants of the chondritic texture shows that there is a wide range and no sharp boundary between stages of chondritic and differentiating primitive achondritic stages. There were observed fissures formed by the migrating iron: these represent the first step of the migration of the metallic components (McCoy et al., 1995, 1997) It is important to note that ureilites can also be considered as veined primitive achondrites.

Differentiation in a chondritic parent body

As we noticed earlier there are two types of partial meltings in the primitive achondritic mineral assemblages. They can be distinguished according to the segregating materials. First is the metallic/sulfide melt which migrates toward the depths to form a core (or to collect into great blocks). Second is the melt of lower melting point silicates, which form basaltic melts which migrate toward the surface (Bérczi et al., 1999).

We may distinguish these two main stages in the gradual transition from chondritic mineral assemblages (and compositions) to the most differentiated basaltic achondritic meteorites. Stage A is the earlier partial melting and outflow of iron-sulfide stage (acapulco, lodranite, winonaite), and it results in primitive achondrites. Yanai asserted that there are two types of textures of the primitive (Stage A) achondrites. The small grain size characterizes mostly the acapulcoites, while the larger grain size is characteristic to the lodranites (Yanai, 2001). However, the two lithologies together can be found in the E-H range late stage chondrites, too. In the NIPR Tokyo collection we (Sz. B.) could observe that Yamato-74036, an H6 chondrite (with composition at the E-H boundary) and Yamato-75300, an E6 chondrite also contained the two lithologies in the same sample.

Stage B is characterized by the later partial melting of a basaltic like component and its outflow toward the surface. This second process leaves the ureilites (and some lodranites) in their Stage B primitive achondritic state and

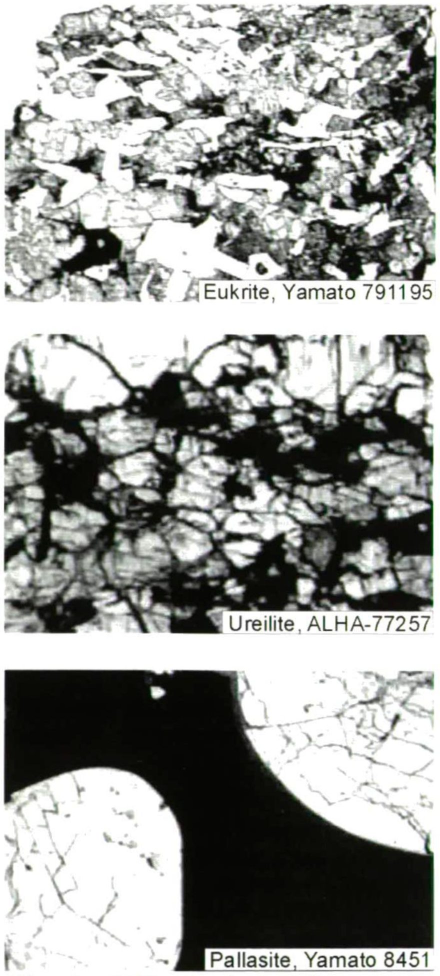

Fig. 3. Differentiation column in a chondritic layered asteroidal parent body.

produces the basaltic achondrites on the surfaces (Bérczi et al., 1999) visible only in the evolved asteroidal body of Vesta and on some Vesta-like fragmented asteroids (Gaffey et al., 1989). We note again that although ureilites sometimes have lost basaltic components as partial melts, they also contain iron veins between the large clinopyroxene and olivine grains, so they are representative of the outmigrating processes of both outflowing components (Fig. 3).

This last part of the thermal evolution of the initially chondritic mineral assemblage of the parent body can be found represented by thin sections in our NIPR SET by the differentiated meteorites. There are 5 thin sections (No. 5, 6, 7, 8, 9) of basaltic achondrites and 2 ones for the iron-increased meteorites. Pallasite (No. 1. thin section), and Mesosiderite (No. 2. thin section) represent two stages of the metallic iron-ironsulfide melt, migrating to the greater depths in the parent body. Especially pallasites respresent the core-mantle interacting magmas inside the differentiating parent body with olivine dominating mantle. For the case of an olivine-pyroxene mantle material mixing with IVA type iron meteorites similar pair of mostly iron (Gibeon) and stony-iron (Steinbach) meteorites (Scott et al., 1992).

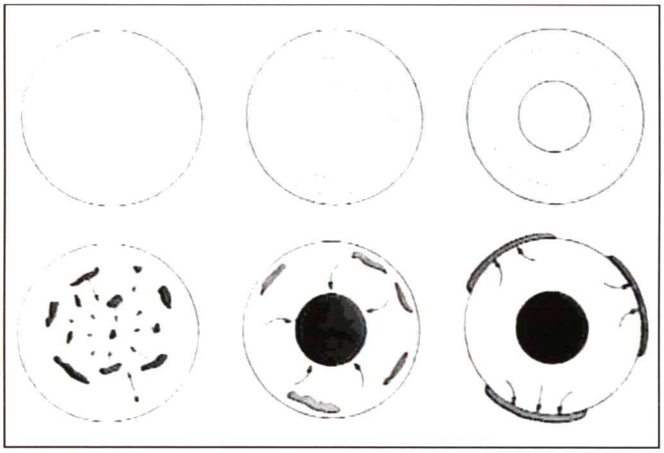

Fig. 4. The main phases of metamorphic (upper row) and differentiation (lower row) phases on the cross section of a chondritic parent body. In metamorphism the upheating by radionuclides gradually forms an onion-layered body with 3, 4, 5, and 6 type chondritic layers, numbers starting from outside. In the course of differentiation first collecting metallic masses migrate toward the center while gradually basaltic partial melts develop which finally migrate toward the surface.

SUMMARY: PROCESSES OBSERVABLE ON THIN SECTIONS OF THE NIPR SET

Antarctic Meteorite Thin Section Educational Set prepared by the National Institute of Polar Research (NIPR), Tokyo, Japan exhibits a rich field of combinations of asteroidal fragments. 200 years of meteorite studies and the new renaissance of the of the planetary material research revealed that meteorites are fragments of larger bodies and arranged them in an evolutionary sequence and into a structural sequence. Timeline was improved by the radiometric age measurements, but the textural sequences of chondritic meteorites also sketched the main events: metamorphism, migrations and differentiation. The spatial arrangement is also modelled by the onion-layered structure or - after impact fregmentation - the rubble pile structure models. The NIPR SET is an excellent sample collection to show many of the main processes forming the chondritic textures. Here we emphasized the thermal evolutionary aspects: metamorphism of the chondritic textural elements, diffusion, mineral transformations, recrystallization of the whole texture at the end of metamorpuous heating up. Finally partial melting and migration of the two main partial melts were the primary observations for thin sections. We mentioned only that the impact events can be followed on the brecciated basaltic achondrites. (These are the B type eucrites and diogenites). However impact brecciation and shock metamorphism also affected some chondrites, too (Fig. 4).

Parallel with these textural studies we dealt with thermal evolution of chondritic meteorites on compositional data and characterized the process by projecting Fe-bearing compounds onto the Urey-Craig field. In this work the metamorphic types of E, H, L, LL and C chondrite groups were used to form thermal evolutionary paths of their chondritic meteorite parent bodies (Lukács et al., 1998, Bérczi et al., 1999). These thermal evolutionary paths of metamorphic grades (the van Schmus-Wood numbers) were calculated from the Fe compounds and were projected to the Urey-Craig Field of iron compounds. The chemical changes between Fe-compounds were described by the parameters of C/H_2O showing the redox competition of reducer C and oxidiser H_2O for Fe (Lukács and Bérczi, 1996). In these works we also checked the Mg/Si and Fe/Si contents of chondrites, and also some abundances which do not seem reversible during thermal metamorphism (i.e. FeS and C). As a result of that work we asserted that the E, H, L, LL and C compositional trends allow to form the [E-H-C] and the [L-LL] supergroups of chondrites. The first supergroup is characterised by higher Mg/Si and higher Fe/Si abundance ratios then the second one. On this basis the ureilites (sharing also high Mg/Si abundance while with lower Fe/Si ratio, however the exhibiting clear signs of loss of Fe metallic components) may represent a residual achondrite in the E-H-C supergroup.

The Japanese NIPR Antarctic Meteorite Educational Thin Section Set is an excellent occasion to get an overview on the available materials of the Solar System. Over chondrites, achondrites, and differentiated asteroidal materials (and with one martian and two lunar samples) it gives the possibility for interplanetary comparisons of planetary materials in the university planetary geology education. During the last 10 years we used this set in university courses, making comparisonal studies with various planetary materials and counterpart industrial materials too. There were comparisons of magmatic processes with steel texture formation processes, and breccia forming impacts with the ceramic industry processes (Bérczi et al., 2003a, 2003b).

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The great number of source material was an excellent basis to make a systematic meteorite thin section collection for education. Using it students could get acquainted with meteorite textural types, classifications and systematic by their own work. The NIPR program made it possible to prepare an almost full set of representative class-types of meteorites. After using in Japan, the first foreign loan was for Hungarian universities, from June, 1994.

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