ON THE THERMODYNAMICS OF METEORITES AND PARENT BODIES II: FROM CHONDRITES THROUGH THE PRIMITIVE ACHONDRITE VERIETIES (STAGE A AND STAGE B) TO THE BASALTIC ACHONDRITES

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ABSTRACT

We study the degrees of thermal evolution over chondritic stages: via primitive achondritic (stage A) stage of acapulcoites, lodranites, winonaites and IAB iron silicate inclusions, through the (stage B) primitive achondrites of ureilites and some lodranites till the basaltic achondrites. We discuss the utility of notion of E, H, L and LL primitive achondrites, too. In this paper we are continuing our previous work of evolutionally arranging the stony meteorites.

INTRODUCTION

Working on meteorite parent body evolution during the last 5 years we made theoretical estimations and statistical comparisons (using NIPR Antarctic Meteorit Dataset, YANAI, KOJIMA & HARAMURA, 1995; NOBUYOSHI & al., 1997) about the role of transitional meteorites between undifferentiated chondritic and well differentiated basaltic achondritic stages. Thus our recent paper is the continuation of BÉRCZI, HOLBA & LUKÁCS (1998) which, consequently, will be cited henceforth as Part I. We are continuing Part II in giving detailed description about the degrees of transitional stages between the (mainly high-temperature) end of chondritic evolution via different primitive achondritic stages which preserved more or less from the original primordial chondritic characteristics till the final surface products of basaltic achondrites and mantle type residuals of lodranite-ureilite-peridotites.

Thermal metamorphism is an accepted theoretical petrological formalism to define the gradual transition of mineral assemblages (and compositions) between chondritic, primitive achondritic and differentiated basaltic achondritic meteorites. Classification of chondritic metamorphism (VAN SCHMUS, WOOD, 1967) formed standard examples for gradual transitional textures between thermally more and more transformed chondritic stages and made it possible to continue this sequence toward achondritic ones. The continuing of this sequence needs recognition and formulation of textural characteristics

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of further transformations caused by the thermal evolutionary process which affected the parent chondritic body. These studies are in focus of research in the last 20 years. There were important recognitions of the stages following the chondritic stage.

It was important to assert that the first event following chondritic equilibration was the preservation of chondritic chemistry in a primitive achondritic stage. However, this stage seems parallel - at least in the case of some primitive achondrites, - with the partial melting and outflow of iron-sulfide assemblage from the primitive achondritic source. Such kind of transitional meteorites were found for this stage as Rose City, Netschaëvo, Watson, Techado and the latest was the Portales Valley veined H6 chondrite. This last case showed that there were no sharp boundary between stages of chondritic and primitive achondritic stages.

Later studies revealed that thermal evolution of the primitive achondritic assemblage may continue by partial melting of a low melting point basaltic like component which may outflow toward the surface of the asteroidal parent body. Lodranites and ureilites can be considered as representatives of this stage, representatives as residuals of a primitive achondritic station of thermal evolution, although they have less primitive characteristics then that of primitiv achondrites of the original definition (which we call stage A). Therefore we introduced the "primitive achondrite of stage B" expression and name for those achondrites which have lost both their iron and basaltic partial melts, but yet they contain considerable primitive components. Mostly, this component is the carbonaceous vein material in ureilites, but the exhausted (or depleted) peridotitic mineral assemblage also preserves the main chondritic one: olivine, pyroxenes and accessory minerals. This definition made it possible that over well metamorphosed chondrites, primitive achondites of stage A, (explanation later) and further developed primitive achondrites of stage B, (details also will be given later) can be arranged in a sequence, which continues the metamorphic sequence of chondrites. This sequence can be closed finally by the most developed forms of the originally chondritic source: with basaltic achondrites, and different iron meteorites and stony irons which also have place in this more and more complex evolutionary sequence.

Many of our earlier works (our reports on 30th LPSC, No. 1014, 1337) dealt with thermal evolution of chondritic meteorites and characterized this process by projecting Fe-bearing compounds onto the UREY-CRAIG field. On this field the metamorphic types of E, H, L, LL and C groups form thermal evolution paths of their chondritic meteorite parent bodies (BÉRCZI, HOLBA, LUKÁCS, 1995, LUKÁCS, BÉRCZI, 1997b); in the suggested R, G and K groups we still are unable to see evolutionary trends. We found that between E and H groups primitive achondrites occupy a special role. Over this region in E chondrites reduction at petrologic type 4 run toward more reduced stages. For H's more and more reoxidized states follow, see Fig. 12 of Part I. (We described these events by parameters of C/H_2O showing the redox competition of reducing C and oxidising H_2O for Fe, LUKÁCS, BÉRCZI, 1996.) Now we begin the detailed construction of the extended metamorphic chondritic sequence by arranging chondrites and achondrites according to their oxidized iron content and the degree of melting of their iron (primitive achondrite stage A).

THE SEQUENCE OF CHONDRITES:
FROM CHONDRITES TO PRIMITIVE ACHONDRITES

The great variety of chondrites probably have some internal structure. A simple relationship is if the *letter* (E, H, L. LL and C) of the chondrite groups shows the *initial condition*, while the *number* (the petrologic type, henceforth PT, from 1 to 7) does the *thermodynamic evolution* from the initial condition. Fig. 16 of BÉRCZI, HOLBA & LUKÁCS (1996) shows the simplest such evolutionary scheme for the 30 samples of the remarkable NIPR Antarctic Thin Section Set. There thermal metamorphism is on the horizontal scale, element contents are on the vertical one, and the idea was that evolution had gone along the increasing petrologic type numbers. This is of course a hypothesis; according to new results it seems oversimplified at least in one point which will be discussed later. However, the most fundamental point of that scheme still seems valid: the "foliated" (i.e. initial condition separated) structure of the "thermodynamic state space" of the meteorites. "Horizontally" there may be genetic connections, but not vertically.

This "foliation" of the thermal evolution tabulation of chondrites can have a strong controll. Initial conditions can be defined by non-volatile element ratios. These were used for the graphs of thermal evolutionary pathways of BÉRCZI, HOLBA & LUKÁCS (1995). Also, some results are displayed in LUKÁCS, HOLBA & BÉRCZI, (1999), and BÉRCZI, HOLBA & LUKÁCS (1999a). In these works we checked the Mg/Si and Fe/Si contents, and also some abundances which do not seem reversible, of which here we mention FeS and C. Hence we think that the following relations are established. (We use abundantly the data of the NIPR Antarctic Meteorite Catalog (YANAI, KOJIMA & HARAMURA, 1995), which is a large, homogeneous body of data. Later reclassifications of individual meteorites occasionally have occurred and may happen in the future, but for definiteness' sake are ignored here. In some points, and definitely for carbon data, we also use Jarosewich's data of JAROSEWICH, 1990).

Among E chondrites PT 3-6 are known so far. Subgroups EH and EL are more or less consequently discriminated in the latest years but the group is rare and so the statistics is not good. For the whole E group Mg/Si is significantly lower than for ordinary chondrites (LUKÁCS, BÉRCZI, 1996), FeS and C is more abundant than in other groups except C. Total Fe is reported to decline from E5 (MASON, 1962), but our opinion is that this is iron loss by dropping out, and so no evidence against genetic connection between early and late E's, we will return to this point later. E achondrites seem direct continuation of the evolution with total metallic (and sulfide) Fe loss. It is worthwhile to repeat MASON's (1962) note that chondrules do not seem in E6's, which is against the VAN SCHMUS-WOOD (1967) convention.

There are the following PT's established so far in the H group: 3, 3-4, 4, 4-5, 5, 5-6, 6. We are now convinced that H3-4's of the NIPR Catalog originated from initial conditions alien from either the H or the E group. Their iron content is significantly higher than in the H group; it would fit into the E group, but H3-4's are poorer in FeS than even E4's. The origin of H3-4's is still obscure. The transitional types 4-5 and 5-6 do not deviate from the H trend (see Fig. 12 of BÉRCZI, HOLBA & LUKÁCS, 1996), and so they can be genuine H's. The H achondrites are not yet known. The H group is characterised by "average" Mg/Si and "high" Fe/Si.

L's are known as 3, 4, 5, 5-6, 6 and 6-7. L5-6's do not deviate from the trend, but the redox processes were simpler without this rare subgroup. If the only L6-7 of the NIPR

Catalog is genuine L, then it shows final Fe° loss (as E5&6, see this later in details). The group has average Mg/Si and low Fe/Si. (Hypersthene achondrite of MASON, 1962 was later named diogenite. But one extraordinary sample: Yamato 790126 was classified to L6, (YANAI, KOJIMA, 1987), however, it did not contain chondrules so may be L7, and this may be the link to L achondrites.)

LL's are found in PT 3, 4, 5, 6 and 7. All of them fit into the trend, with Fe° loss in LL7. LL's are characterised by average Mg/Si and low Fe/Si, just as L's, but their Fe/Si is slightly lower, and Fe°/Si is significantly lower. (Real LL achondrite is unknown. On the basis of FeO/ Fe° ratio chassignite and eucrite was considered as LL achondrite.)

The C group is recently becoming a supergroup, distinguished by second letters as CI (only 1), CM (2, and according to ZOLENSKY & al., 1), CR (mainly 2, but according to ZOLENSKY & al. 1997, in PT 1 too, at least mosaically), CO (only 3), CV (generally 3, but Kaba is maybe 2, and Coolidge 4), CK (4&5?) and so on. The systematics is obviously in change recently. Anyway, the trend seems to be a partial reduction until PT3, and then reoxidation (LUKÁCS, BÉRCZI, 1997a). The C (super)group is characterised by high Mg/Si and high Fe/Si. The ureilites share the high Mg/Si abundance. While their Fe/Si is too low, so they directly cannot be C achondrites, at least they remind us them.

Now, the only possibility for "vertical" transitions is L <-> LL, and even that is not probable, except misclassifications. Between any other 2 groups, as it is shown, conserved ratios differ, so "superselection" rules prohibit transitions. On the other hand, with the above mentioned exception of "H3-4" *within* a group all PT's seem accessible by i) aqueous alteration (see later), ii) by redox processes (for which agents C and H_2O are present, iii) by sulphide loss (details obscure) or iv) by Fe° loss in terminal stages (later).

These genetic chains, then, seem more or less well-founded, and even connect chondrites to ("primitive", i.e. undifferentiated) achondrites. However the two ends of chondritic chains need discussion. In Part I we took the simplest picture when all evolutionary chains started in PT 1, however it seems that the situation is not so simple. Therefore we incorporated here the following 2, short, Sections for completeness' sake, and the problem of parent body initial conditions deserve a more detailed treatment in another paper.

THE PRIMITIVE CHONDRITE STATE FOR E, H, L, LL AND MAYBE FOR C GROUPS

If one wants to read PT's as the direction of Time's Arrow, then the evolution of chondrites start from *no chondrule* (see, with some mental reservation, Part I). The picture is by no means impossible, see e.g. MASON's idea (1962) for olivine & pyroxene chondrules formed from serpentine via heating, H_2O loss &c. In addition, compositions of Orgueil, Ivuna and Y-82162 can be hardly derived from C2's (e.g. because of high FeS). Still, present observations (e.g. ZOLENSKY & al., 1997; MCSWEEN, 1979) seem to prove the inverse route (see below).

For the C chondrites of the NIPR Catalog the "primitive" C seems to be somewhere among C2's. However the general feeling is that the groups E, H, L and LL start in PT 3.

Now, this may be a simple convention. E. g. consider HUTCHISON, ALEXANDER & BARBERS' suggestions (1987) that "LL 3"'s Semarkona and Bishunpur should be reclassified as LL 2.

The problem is twofold. First, a meteorite is an open system, so we do not have such a sure Time's Arrow as specific entropy for closed systems, moreover we must admit that this problem is not finally solved in Thermodynamics. Second, in the VAN SCHMUS-WOOD nomenclature both PT 2 and PT 3 are characterised by "sharp chondrules". The 2 PT's are discriminated via H_2O and C contents, which, however, cannot be used when one compares chondrites of *different initial conditions.*

Still, we can conjecture the evolutionary relations by probability arguments. It is much more probable to almost any process to destroy sharpness of chondrules than produce; loss of volatiles as H_2O and C could be more frequent than gain; and in most meteorites FeS is the only major S source, so FeS cannot grow.

Hence one can say that an LL 2 is something more primitive than LL 3 if its chondrules are sharp too but the H_2O, C and FeS contents are "too high". Now, the suggested LL 2's Semarkona and Bishunpur (HUTCHISON, ALEXANDER & BARBER, 1987) have much higher than average C content, while H_2O and FeS are at least too among the highest (JAROSEWICH, 1990). In BÉRCZI, LUKÁCS, (1999) this suggestion is accepted and the arising carbon trend is quite reasonable. On the same basis we suggest Sharps H3 (JAROSEWICH, 1990) to be reclassified as H2. Fig. 1 shows a three-colour graph for Fe^{tot}, Fe^{ox}, H_2O and C for chondritic types (BÉRCZI, LUKÁCS, 1999) in the spirit of this Chapter.

If so, then the primitive or initial chondritic state is in PT 2 or between PT 2 and 3.
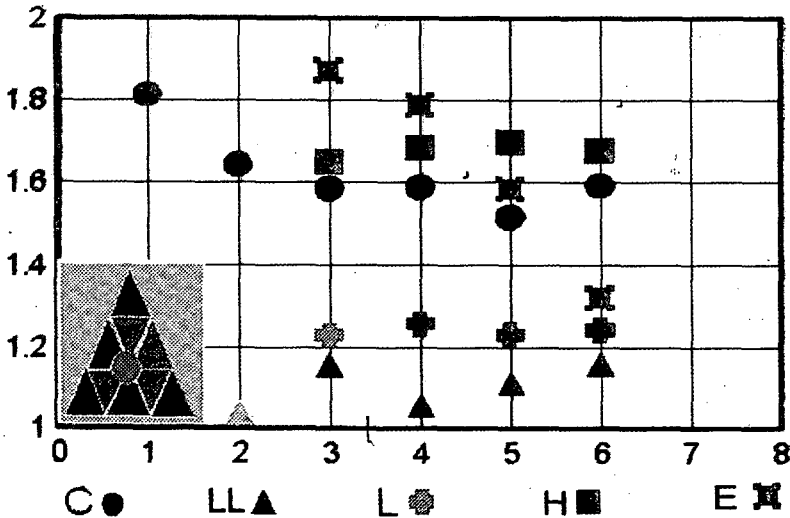

Fig. 1. 5 component color plot of the chondrite type averages of iron-carbon-water content for all chondrite groups (C, LL, L, H and E) of data from the NIPR Catalogue (YANAI, KOJIMA, HARAMURA, 1995). The 5 parameters are: total Fe/Si (y axis), the VAN SCHMUS-WOOD types (x axis) and 3 in colors of iron-carbon-water averages, mixed according to color mixing rules. For colors red is the weight of reduced (metallic) iron, green is carbon, blue is water content. Vertical axis shows the total Fe vs. Si ratio for the chondrites and means different initial conditions for different chondrite groups. Along horizontal axis we can observe trends of parent body evolution. Observe that the data along the thermodynamic evolutionary trend of increasing VAN SCHMUS-WOOD types (texturally and compositionally defined stages by numbers, horizontal axis) points for C and H group chondrites run almost parallel and also this is the observation for the L and LL group chondrites, too. E chondrites may have different origin and along advancing thermal evolution stages their plot crosses the trend of C and H groups.

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RETROGRADE (AQUAEOUS) ALTERATIONS:
A CASE FOR C-S AND LL-S ONLY?

Now, from the primitive state, according to the circumstances the evolution may go into 2 directions. In dry conditions diffusion starts. This was treated in Part I and will be again detailed in the next Section. However in very wet environment aquaeous processes can start. ZOLENSKY & al. (1997) demonstrated the "retrograde" process CM2->CM1 (and, virtually, CR2->CR1 too), and Kaba is at least an example when it is doubtful if the petrologic class is 2, 3 or 4 (e.g. the chondrules are anomalous).

Here we note only that there are thermodynamic similarities between the "direct" (diffusion) and "retrograde" (aquaeous) evolutions. Preparing an initial stage of sharp chondrules and large gradients in chemical potentials (for ordinaries often regarded as PT 3.0), both processes simultaneously unsharpen the chondrules *and* decrease the gradients of chemical potentials. To see Time's Arrow detailed differences must be observed.

Now we shift our attention to direct evolution and also recapitulate some statements from Part I.

GENERAL TREND FOR CHONDRITES BY: DIFFUSION

Obviously the genesis of parent bodies was complicated and observation is impossible. However diffusion must have been present, and it seems that the main facts of direct chondritic evolution can be interpreted via it.

Assume an initial stage of sharp chondrules and large chemical gradients in a more or less olivine-pyroxene assemblage at the formation of asteroid-sized parent bodies; if it happened just after the primordial crystallization then short-lived nuclei as Al^{26} ($t_{1/2}=7.4*10^5$ y) or Pt^{244} ($t_{1/2}=7.6*10^7$ y) could still produce a high temperature. If one does not believe in this, he may rely on heat from the gravitational accretion.

The simplest model is a constant temperature T_o for a time $t_o \approx t_{1/2}$ and then a negligible equilibrium temperature. Then diffusion establishes homogeneity on a length

$$l_D \approx (D_o t_o)^{1/2} \tag{1a}$$
$$D_o = D(T_o) \tag{1b}$$

Let the primordial chondrule size be r_o. This quantity varies from group to group, but now for orientation we take $r_o \approx 0.3$ cm. One can improve the presentation by substituting better values.

Via only diffusion, a chondrule border is **sharp** if $l_o << r_o$ (and then PT is 2 or 3), **clear** if $l_o \sim r_o$ (PT 4&5), **obscure** if $l_o > r_o$ (PT 6) and **not seen** if $l_o >> r_o$ (PT 7 or primitive achondrites). Taking $t_o \sim 10^6$ y (Al^{26}) and the above r_o:

PT 2&3 $D_o << 3*10^{-15}$ cm^2/s

PT 4&5 $D_0 \sim 3*10^{-15}$ cm^2/s

PT 6 $D_o > 3*10^{-15}$ cm^2/s

PT 7-∞ $D_0 >> 3*10^{-15}$ cm^2/s

Table 1: The values of diffusion coefficients leading to various petrologic types with primordial Al^{26} heating.

Now,
$$D_o \approx A_o exp(-Q_o/kT) \tag{2}$$

where Q_o is some energy to form lattice defects to diffuse through, in the order of 1 eV, while for the prefactor A_o, very roughly,

$$A_o \sim a^2 \nu \tag{3}$$

where a is the lattice length, and ν is the frequency of the (thermal) oscillations in the lattice.

We would need A_o and Q_o in the temperature range cca. 500 - 1500 K, for all the major olivine, pyroxene (and feldspar) constituents. As will be seen in the next Chapter, there is no problem with olivines, but pyroxenes are more various.

Anyway, one can guess the trends via melting points T_m. Namely, until there is a simple and more or less regular lattice, T_m is determined by the same factors as ν and Q_o, and then

$$Q_o = \alpha k T_m \tag{4}$$
$$\nu = \beta(k/h)T_m \tag{5}$$

where k and h are the Boltzmann and Planck constants, respectively, while α and β are dimensionless and maybe slowly varying factors. Just below T_m we get then

$$D(T_m-0) \approx a^2\beta(k/h)T_m\exp(-\alpha) \tag{6}$$

and, since for all relevant materials $a\approx3*10^{-8}$ cm and $T_m\approx1500$ K, $D(T_m-0)$ is in the range $0.03\beta e^{-\alpha}$ cm^2/s.

Now we can see α and β at least for some metals and simple olivines. For many solid states $\nu \sim 10^{14}$ s^{-1}, whence β seems 0.3 - 1. For various metals $A_o=(0.01-0.1)$cm^2/s in accordance with (6). For self-diffusion in metals α is cca. 18, and then a form (4) is told to be good for 10 % (SHEWMON, 1963; LAZARUS, 1960). According to these numerical factors $D(T_m-0)$ is expected about $1.5*10^{-9}$ cm^2/s. Then from the numbers we gave at the end of the last Chapter it is clear that if a meteorite consisted purely of metals and simple olivines, the diffusion would erase the last traces of chondrules far below melting point. On the other hand, the composition would remain chondritic.

For olivines there is a detailed investigation for San Carlos (Arizona) olivines between 10 and 40 weight % Fe (BUENING & BUSECK, 1973). At higher temperatures, extrapolating to pure forsterite (T_m=2163 K) A_o=0.03 cm^2/s and α=14.21, while for pure fayalite (T_m=1478 K) A_o=3.4*10^{-4} cm^2/s, and α=13.28, so α is slowly varying with composition and not too unsimilar to metals. With these values in an imaginary meteorite of pure forsterite chondrules would be erased by diffusion on 1112 K, while in pure fayalite on 848 K. These temperatures are rather low, pure olivine meteorites are absent, but the numbers show a trend.

We close this Chapter with examples, one from the great variety of pyroxenes, augite, and a Ca-mica, margarite. FECHTIG, GENTNER & ZÄHRINGER (1960) investigated Ar diffusion in them, and, while that coefficient is not just valid for Al, Mg or Fe, it gives an orientation. At 1000 C° D is just below 10^{-10} cm^2/s in margarite, but only about 10^{-13} in augite, showing the variety; Q_o is 1.16 eV for high-temperature augite and 2.31 eV for margarite, while the corresponding A_o's seem to be $8*10^{-9}$ cm^2/s (!) for augite and $7*10^{-2}$ cm^2/s for margarite. The data for the Ca-mica are not unsimilar to those for either metals or olivines; but for the pyroxene augite the diffusion coefficient is order of magnitudes smaller. This suggests that olivines equilibrate much faster than pyroxenes and it is indeed so.

TO THE PETROLOGIC TYPE 4.0 AND BEYOND

According to the previous data we may expect that equilibration happens first in olivines. Also it needs then the highest temperature in forsterite (so E3 chondrites). Taking $t_o\approx10^6$ y (Al$_{26}$) and $l_D>>r_0$ for olivine, $D(T_o)>10^{-14}$ cm^2/s is needed. This is 875 K. Well above this temperature diffusion is complete even in the olivine of E's, so our

guess is that the state is beyont E4.0. In the same time $D(T_o)$ is just $3*10^{-15}$ cm^2/s *for augite*, so indeed some structures did not yet diffused away, so the chondrules are still seen, not quite sharp, but clear. Using augite as a model for the beginning of obscure chondrules, PT 6 one would get at least 700-800 C°, and for the beginning of no chondrules at all at least 1000 C°.

In addition observe that chondrules do not seem in E6's (MASON, 1962). If so, then they are really E7's in the present scheme, and then that stage is beyond 1000 C°.

Now let us abandon the augite model and tell simply that measurements would be needed for various pyroxenes relevant in chondrites. In the next Chapter we use scaling laws.

OLIVINES AND PYROXENES ON THE CHONDRITE/ACHONDRITE BORDERLAND

We have seen that, if the silicates do not melt before, a continuous fading of chondrules is expected, and this can be PT 7. Chondrules are no more seen, maybe everything is almost homogeneous, but the bulk composition is still quite chondritic (except maybe for Fe°, see the next Section). Now, according to the rough scaling with T_m, for which we showed examples in the previous Sections, and which is based on the fact that higher melting point means higher interatomic forces, so higher activation energy needed for lattice defects through which diffusion becomes possible, we can guess that if a specific stage has been reached at T_o in pure Mg-silicate (i.e. extremal forsterite), then in other silicates the same diffusion stage has been got at a temperature lower proportionally with the actual melting points. On Fig. 2 we compare olivine melting points, although E chondrites are rather enstatite, so pyroxenic. For C-s the situation is not so simple, e.g. serpentine may substitute the olivine.
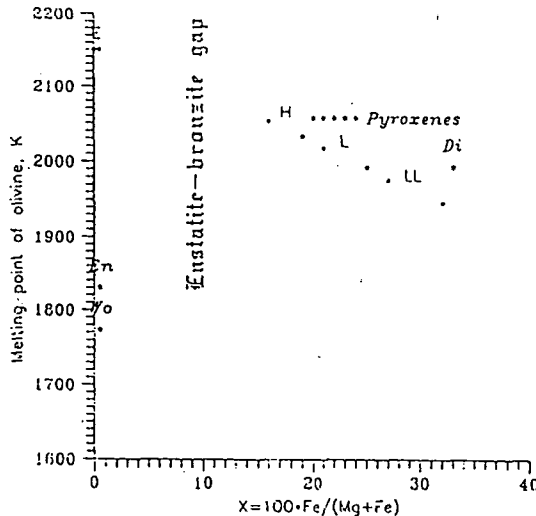

Fig. 2. Melting points of characteristic olivines and some pyroxenes as function of Fe/Mg ratio. This plot may explain partly the enstatite-bronzite gap in the Urey-Craig field, and the point of inflexion between the enstatite chondrites and bronzite chondrites evolutionary paths (LUKÁCS & BÉRCZI, 1997a).

For pyroxenes the melting points are somewhat lower, e.g. T_m is 1830 K for enstatite, 1773 K for wollastonite and 1993 K for diopside.

Now we roughly estimate the important temperatures from Fe loss.

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Fe LOSS: VIA C AND FeS TOO

We do see Fe loss in chondrites. MASON (1962) definitely reports a small Fe deficiency in E5 and a serious one in E6 (but, as we saw, it is possible that these states should be called E6 and E7, respectively, from the point of view of diffusion scale). It is possible, of course, that this is not evolution, but different initial condition, and anyways, E's are rare, so the statistics is poor, but still we take the simplest explanation.

Fe° and FeS are not integral parts of the silicate lattice, and Fe specific gravity is much higher than that of the silicate. So the Fe-FeS-C mixture flows out and becomes gravitationally separate if its melting point is reached and some gravity is present. The second condition is fulfilled in parent bodies. As for the first, the exact melting point is hard to calculate, it is well below the silicate melting points. Fe° and FeS melt near to each other. The pure Fe melts at 1535 C°, but already a very small amount of C brings down the melting point below 1500 C°, while pure FeS melts at 1430 C°. The eutectic carbonated Fe melts about 1140 C°, and this needs 4.3 weight % C. Now, since in E's C is cca. 0.4 % and Fe is cca. 25 %, the bulk average of C in Fe is only cca. 1.6 %, but then some 2/5 part of the Fe can flow out at 1140 C°. In addition there is a substantial FeS content, some 1/3 of the Fe° (JAROSEWICH, 1990), decreasing further the eutectic temperature. In the same time the melting point of forsterite is 1890 C° (that of corresponding pyroxenes is somewhat lower), so the E silicates may exist for a wide temperature range after Fe° and FeS leaves molten, for the core of the parent body.
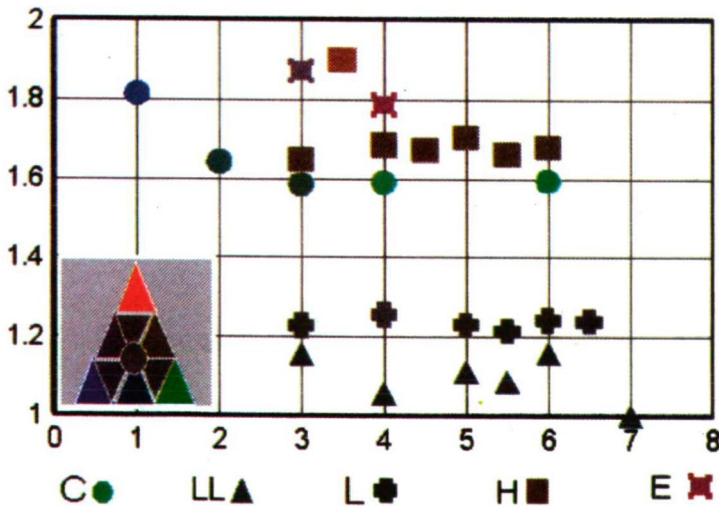

Fig. 3. 5 component color plot of the chondrite type averages of iron-ironoxide-ironsulfide content for all chondrite groups (C, LL, L, H and E) of data from the NIPR Catalogue (YANAI, KOJIMA, HARAMURA, 1995). The 5 parameters are: total Fe/Si (y axis), the VAN SCHMUS-WOOD types (x axis) and 3 in colors of iron-ironoxide-ironsulfide averages, mixed according to color mixing rules. For colors red is the weight of reduced (metallic) iron, green is the weight of oxidized iron, blue is the weight of sulfidized iron content. Vertical axis shows the total Fe vs. Si ratio for the chondrites (means different initial conditions for different chondrite groups). We can observe the parent body evolution trends along the horizontal axis. This shows that now again the points for C and H group chondrites run almost parallel and this is the observation for the L and LL group chondrites, too. This plot also shows that E chondrites may have different origin and also shows that advancing thermal evolution stages their plot begin to cross the trend of C and H groups. The data of H3-4 chondrites may relate these chondrites to the E chondrite group.

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Fig. 3 is a three-colour graph using the data of the NIPR Catalog everaged for all combinations of chondritic groups and petrologic types. The vertical position is the total Fe/Si content, the red, green and blue constituents are the metallic, oxidised and sulfidised components. Outflow is directly seen from the vertical position. But also an iron outflow is expected to carry away troilite too, so outflow is more certain if the colour loses a *purple* component.

On the other hand we do not see Fe deficiency in the (average of the) H6's of the NIPR catalog, 23 meteorites, a reliable statistics (LUKÁCS, HOLBA & BÉRCZI, 1999). Now this may have two reasons. First, we saw that the temperature of PT 6 must be lower in H's than in E's, because of the lower Mg content. Second, both C and FeS is less abundant in H's, so melting point decrease is much smaller.

H7 meteorites were unknown till 1997, when Y-75008 was identified as such (YUGAMI & al., 1997; 1998). Since 1987 (YANAI & KOJIMA, 1987) it was known about that sample that it showed a generally chondritic H composition but no chondrules except maybe some relic ones (YANAI & KOJIMA, 1987), and its troilite exhibits a net-like pattern. It, then, percolates, which is a necessary (and sufficient?) condition of flow out. Unfortunately bulk Fe and FeS data are not given in the 1995 NIPR Catalog. However YUGAMI & al. (1998) found a subvolume with 29 volume % FeNi. Since this is much above characteristic Fe° content in H's, it is sure that segregation started. On the other hand, as we saw, it did not start for PT 6.

There are 94 L6's in the NIPR Catalog. In average Fe° and FeS abundances are just the averages of all L's, and very similar to the averages of the 17 L5's. There is one identified L6-7, and it shows a cca. 15 % deficit in both Fe° and in FeS, so it is possible that Fe started to flow out, but one cannot make any statistics with a single sample.

The average of the 18 LL6's of the NIPR Catalog does not show either Fe° or FeS deficit compared to all LL's. However there are two LL7's, and their averages (albeit poor for statistics) show serious deficiency in both ferrous phases. Then the LL6 stage is not hot enough for liquid Fe (we may expect it cooler even than H6), but LL7 is hot enough (TAKEDA & al, 1984).

Finally C's are found only until PT 6, they are even more fayalitic, so they are expected to reach PT 6 at lowest temperature, and we do not see indeed Fe deficit in them.

E, H, L, LL PRIMITIVE ACHONDRITES IN THEIR PARENT BODY EVOLUTION

In the present study we would like to make clear distinction between the usual achondrites, say basaltic meteorites, and the primitive achondrites. Beyond PT 6 chondrules are already absent, but the compositions (with the possible exception of the Fe°-FeS-C triad) are still chondritic. Such an achondrite is clearly not of basaltic, or differentiated composition. Originally the term "primitive achondrite" was used for achondrites with chondritic composition, but *belonging to the E-H gap in the Urey-Craig field*. The accumulation of meteorite samples in the last 30 years mainly by Antarctic samples made it possible to see more transitional meteorites between chondritic and basaltic achondritic stages. Introduction of E, H, L and LL primitive achondritic concepts want to make clear distinction for a stage between chondritic and achondritic (earlier mainly basaltic achondritic) meteorites. In the sequence from chondritic to basaltic achondritic stage the E, H, L, and LL primitive achondritic stages will stand between the metamorphic grade 6 and the basaltic achondritic stages of these

chondritic groups. In *our convention* primitive achondritic state begins roughly with the PT 7 chondritic one (already without chondrules). Then the old primitive achondrites (in the E-H, or enstatite-bronzite, gap), are also primitive achondrites, only of a chondrite group still unknown in its par excellence individuals. The gap still needs its explanation (BÉRCZI & LUKÁCS, 1998).

There are two processes which both distinguishing par excellence chondrites from achondrites: the Fe loss by melt and metamorphism, which go according to different rules. Iron or sulfide melting needs a temperature not more then 1300 K and often much lower for Fe-FeS-C mixtures, and relatively short time. On the other hand metamorphism could be described mostly by diffusion. In the second strip of the borderland, between primitive achondrites (PT 7) and the par excellence (basaltic) achondrites iron loss may or may not still go, but there is a new process, silicate melting (at lower temperatures partial, at higher maybe total). When silicates melt and can macroscopically move and mix, diffusion loses its meaning. After silicate partial melting has started we have already two directions of differentiation. In one direction partial melts are going away and depleted chondritic composition remains. (The extremal remnant of this direction resembles ureilites according to our suspicion.) In the other direction the basaltic component is enriched (added to the originally primitive achondritic composition, resembling first Acapulco, later Lodran and so on, MITTLEFEHLDT & al, 1996, MCCOY & al, 1997) and the final product is some kind of basaltic achondrite. Because the silicate melt loss may preserve some components of the primitive achondritic composition (i.e. the carbonaceous material, some "islands" of metal, sulfide and carbon assemblages) we introduce the expression primitive achondrite of stage B for these meteorites. Mainly ureilites and some lodranites are involved in this group.

We may summarize our new definitions: the E, H, L, LL *primitive* achondrite (stage A) is a range which is in between metamorphic diffusion and differentiated endproducts of thermal evolution of chondritic parent body. The *primitive achondritic state is an interval* and it is characterized by the processes of separations: first iron, then silicate-melt. So this range can be divided to two parts: first the range of primitive achondritic **stage A** is characterized by the process of **separation of iron**. Second, the primitive achondritic **stage B** is characterized by the process of **separation of silicate melt**. Both have important role and we note only that this part of parent body thermal evolution is "mixed" with gravitational and rheological effects, too. In one of our earlier works we could show the most crude effects of gravitation if we compared basaltic sequence of the Earth and an asteroid (LUKÁCS, BÉRCZI, 1998). There we found that FeO content of the basaltic sequence is far lower for the terrestrial basalts than basaltic achondrites, and this trend is valid from komatiites to recent tholeiitic basalts, in the same way than from diogenites through howardites to eucrites. Moreover, the counterparts of the high Mg bearing depleted lherzolites could be found in the high Mg bearing ureilites. We cannot assert that all these differentiations (we called it "barometric height formula for silicates", LUKÁCS, BÉRCZI, 1998.) occurred parallel in an asteroid, but we wanted to show that such an effect can be observed in the statistics of the recent dataset (mainly we used the NIPR Catalog, YANAI, KOJIMA & HARAMURA, 1995).

IRON OUTFLOW FROM CHONDRITES: TEXTURE OF THE METAL COLLECTING (VEINED) H6 CHONDRITES AND RELATED II E IRONS WITH SILICATE INCLUSIONS

There are six meteorites in this clan. Three of them were classified to H chondrites, and also three were as primitive II E irons with silicate inclusions (MCCOY, 1995).

Rose City: Fell in 1921, in Michigan State, USA. Its remarkable characteristics was the 36.4 wt.% total iron content. Although brecciated, it was classified as H5 chondrite (its Fa (19) is typical to the H range), which contains larger Fe-Ni inclusions as nodules (WIDOM & al, 1986, RUBIN, 1995, IKEDA & al, 1997). It was shocked and contains portions which are free of metallic Fe-Ni and troilite, like as Chico, too (PINAULT & al, 1999).

Y-791093: Found in 1979 on Antarctica by Japanese Expedition it was classified to H6 (YANAI, KOJIMA & HARAMURA, 1995) but contains equal amounts of metal+sulfide and chondritic portions (in vol.%). If separated, the metal + sulfide portion is texturally similar to IIE irons, the chondritic portion is H6. However, the whole assemblage is similar to Netschaevo and Techado chondrite-like inclusion containing primitive IIE irons (IKEDA & al, 1997).

Portales Valley: Fell in 1998, in New Mexico State, USA. In some protions the metal rich veins penetrate the whole hand-specimen sample with wider and a network of thinner veins. Its metallic Fe-Ni content in some fragments is ca. 35 wt. % (vs. ca. 18 wt. % of average H chondrites, RUBIN & al, 1999). Considered to have been brecciated (KRING & al, 1999, RUBIN & al, 1999), or equilibrium with chondritic portion, melted (PINAULT & al, 1999, RUZICKA & al. 1999). Although descriptions distinguish *adjacent to vein* (finer grained than most of H6 chondrites, enriched in troilite and depleted in Fe-Ni metal) and *away from vein* (normal, Fe-Ni and troilite containing) portions of chondritic parts, both have essentially H6 textural characteristics(PINAULT & al, 1999). The melted metal is typical H-chondrite metal (KRING & al, 1999) and is unlike to veins of Rose City (PINAULT & al, 1999). It resembles to Kernouve veined H6 chondrite (PINAULT & al, 1999). (Kernouve may also be involved to our H6+IIE-clan.)

Netschaëvo: Found in 1846, in Russia. The primitive IIE iron matrix contains angular silicate inclusions, which comprise the 25 vol. % of the meteorite. Silicate portion contains relict chondrules and its refractory element content is in the range of the ordinary chondrites, although the Fa (14) of olivine is outside of the H chondritic range (BILD, WASSON, 1977). Silicate portion has not undergone melting only heating and recrystallization. It has higher Fe/Si ratio, than upper Wiik line chondrites, and this ratio is only the same for Rose City (BILD, WASSON, 1977). Its metallic portion has siderophile element content also higher (cca. 2 times) than H chondritic metal range (BILD, WASSON, 1977). With its characteristics nearer to the E-H point of inflexion Netschaevo can be considered an E-H chondrite related member of our H6+IIE clan.

Techado: Found in 1977, in New Mexico State, USA. This IIE iron meteorite contains a smaller silicate inclusion inside the iron. The mass of silicate is unmelted but exhibits a strongly recrystallized texture. Olivine (Fa 16.4) and pyroxene (Fs 15.3) relates it to H chondrite range. No shock effects have been observed on silicate inclusion, so metallic components may have been locally segregated (CASANOVA & al, 1995).

Watson: Found in 1972, in S. Australia. This IIE iron meteorite contains the larger silicate body ever found inside an iron meteorite. The large mass of silicate, engulfed in

the iron, melted during its including into iron melt, but after recrystallization it preserved its bulk composition similar to H-chondritic one, except metal+sulfide fraction (unlike to Kodaikanal silicate inclusions, which sufferred fractionation after melting, OLSEN & al, 1994). The metal matrix is characteristic to H chondritic metals. It was observed, that metal sufferred shock (OLSEN & al, 1994).

The collected 6 cases of the H+IIE clan meteorites has the following fundamental properties, summarized: (Table 2.)

Name	Silicate	PT (Ch.)	Iron	Shock(Silicate)
Rose City	H	5	IIE	Y(brecciated)
Y-791093	H	6	IIE	Y
Portales Valley	H	6	IIE	olivine mainly in shock st. S1
Netschaëvo	bw. H & E	(Y)	IIE	N
Techado	H	beyond 6	IIE	N
Watson	H in IIE	beyond 6	IIE	?

Table 2: Portales Valley, and some of its possible relatives. Data according to OLSEN & JAROSEWICH (1971); IKEDA ET AL, (1997); OLSEN ET AL, (1994); KRING, HILL & GLEASON (1999); RUBIN & ULFF-MØLLER (1999); RUZICKA, SNYDER, PRINZ & TAYLOR (1999) and PINAULT, SCOTT, BOGARD & KEIL (1999); METEORITE NEWS 1996. Observe that this Table explicitly show Netschaëvo as a "chondrite in the gap": something still with chondrule, and gap composition.

Portales Valley is the only chondrite which has Widmanstätten pattern in its iron portion. Observe that irons of all the 6 clan meteorites are of the same type, conform to iron flowing out of the chondrite matrix. As for cooling times or rates and original and/or transient heating, PINAULT & al. (1999) suggest a rapid heating, metal crystallization in "months or years", Ni cooling rate in taenite cca. 5 K/My, they prefer Al^{26} (or similar) heating. RUBIN & MOLLER (1999) conjecture local shock temperature up to 1635 C° a cooling rate for metal 10 K/My between 700 and 500 C° and doubt about the availability of an Al^{26} heating. Finally KRING & al. (1999) call the exact cooling rate uncertain, as sometimes it is claimed that rapid cooling is also conform with Widmanstätten pattern (RASMUSSEN & AL., 1995) but for the post-impact metal cooling they guess _10 K/My, and prefer the impact when the parent body was still warm.

STAGE A PRIMITIVE ACHONDRITES FOR H-S: A SELF-CONSISTENT SCHEME

Observe that Table 2 is self-consistent. All iron portions seem to be the same type, and comparing shock and chondrite type, the pattern is not self-contradictory even if, according to Occam's razor, we do not want to postulate outside source for iron.

Namely, we do know that "ordinary" H6's were not hot enough for Fe° outflow; but shock is observed in Portales Valley, Rose City and Y-791093 (and it is worthwhile to note that Y-790126, L6, with a substantial Fe° phase is shocked too; METEORITE NEWS 1998). For Netschaëvo and Techado, where shock is absent, the chondrite is *not* H6. Techado is "beyond H6", i.e. it may have had such a temperature where iron flow started (still far below the melting point of bronzite olivines) and Netschaevo is "between E and H" and we saw at least that there is outflow in E6's. In Watson where we do not show if

shock happened or not, the general composition is H, but the chondrite may be again "beyond H6".

As for "between E and H", we note that regular chondrites are not found in the enstatite-bronzite gap, but such silicates occur in e.g. Iodranites. It seems that in the state space there is a repulsive point (BÉRCZI, LUKÁCS, 1998, BÉRCZI, HOLBA, LUKÁCS, 1999a). Fig. 4 shows some "suspected" meteorites, compared to both H6's and E's of the NIPR Catalog. The "anomalous" meteorites are put on the Figure in 2 groups. The first one consists of 7 Yamato meteorites which were found somewhat anomalous for the discoverers and appear in the NIPR Catalog. One (Y-74063) is a G chondrite, denoted such on the Figure, 3 (Y-74357, -75274 and -791493) are Iodranites (L), 2 (Y-75097 and -793241) are L6 and here denoted by "6", and one, Y-794046, is H4, denoted by "4". We see that, at least on an FeO-Mg graph, they merge with the H6's, even if at the edge of the strip. The other group is 4 "anomalous" meteorites: ALH-85085 (H), Winona (W), Netschaëvo (N) and Acapulco (A) (JAROSEWICH, 1990). Interestingly enough, on the oxide Fe - Mg plane they form a straight line, but their positions, with the exception of Netschaëvo, project onto the usual chondritic positions. Netschaëvo is clearly "in the gap" (BÉRCZI, HOLBA, LUKÁCS, 1999b).
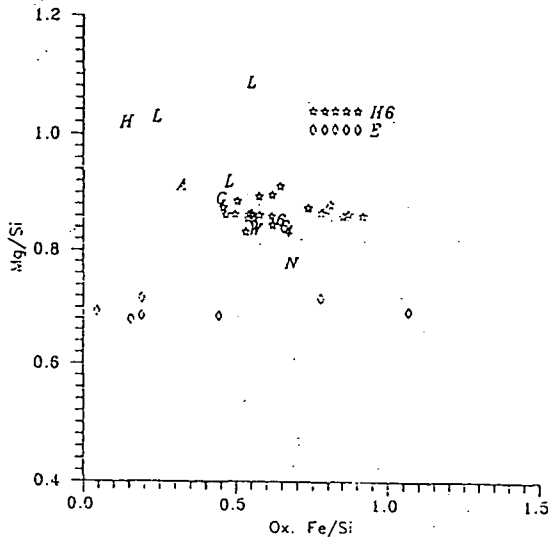

Fig. 4. Mg/Si vs. oxidized-Fe/Si plots for H6 chondrites and E chondrites of the NIPR Catalogue. This plot shows that Mg/Si ratio clearly distinguish E and H chondrites (diamond plot marks and stars) and in the gap we can see a strange meteorite, transitional from chondrites to primitive achondrites stage A: Netschaëvo. Some other strange chondrite meteorite data are also projected (A - Acapulco, L - Iodranites).

As for the multiplicity of data about the thermal history there seems no self-contradiction either. It would be dangerous at the present state of art to decide the "Al^{26}, Yes or No" question. We refer only dozens of asteroids down to radii 30-50 km either spherical or differentiated. Something must have melted them maybe just after condensation. If not Al^{26} (or Pu^{244}) then something unkown well mimicking it. We call it for a while "Al^{26}" in the sense of Mark Twain who stated that plays of Shakespeare were written by another person of the same name.

Now in Portales Valley we saw the shock. Then take the normal history of the (H) parent body, the interior at H6 temperature, then a shock sometimes $0<t<t_0$, so in the heydays of "Al^{26}" heating. The shock increased the temperature above Fe (Fe-FeS-C) melting point and the metal solidified back for "periods greater than several weeks" (PINAULT, SCOTT, BOGARD & KEIL, 1999). It seems that the cooling slowed down to 10 K/My only later, at lower temperatures. Now, this slower rate may be the normal (non-shock) cooling rate of a deep interior (KRING, HILL & GLEASON, 1999), but also it is automatic equilibrium cooling if $t_0 \sim 100$ My, which is so if the heating went by Pu^{244}.

In this story the shock increased normal H6 temperature beyond H6 and Fe° melting, but this increase was transient. If it lasted much less time than t_0 (even if "over months or years"; PINAULT, SCOTT, BOGARD & KEIL, 1999), then there occurred practically no change of the silicate *via diffusion* (so in PT) while permanent change happened in *Fe° and FeS loss*, which went not by diffusion but by flow.

STAGE B PRIMITIVE ACHONDRITES: UREILITES, TEXTURE, MINERALOGY

We studied in details the ALHA77257,77-4 thin section of the NIPR collection, a 4mm X 7mm surface, on loan for studies on the Eötvös University (Pict. 1/a.). The thin section nicely exhibits characteristic features of the ureilitic mineralogy and texture. (YANAI, KOJIMA, 1987) Our carbon distribution map shows that ALHA 77257,77-4 ureilite veins are rich in carbon (Pict. 1/d.). The large olivine and pigeonite grains frequently have triple junctions with 120 degrees. Most inter-grain boundary regions are filled with carbonaceous veins, but many with metal ones. Outer rims of the olivine and clinopyroxene contain reduction-exsolved metal blebs which form transitional semi-opaque boundaries around the minerals. Some veins are alternately filled with carbon and metal. While Ol/px assemblage is more igneous/metamorphic and may be classified together with terrestrial mantle rocks (i.e. lherzolites), the other component, the veins are the remnants of the carbonaceous matrix (JANSSENS & al, 1987): they are last survivors and preservers of chondritic primitive components. Survival of such a primitive component allows us to call ureilites primitive achondrites, although in stage B, because they are very much metamorphosed if compared to acapulcoites and lodranites. (Igneous origin of ureilites was also summarized, e.g. GOODRICH & al, 1986, GOODRICH, 1992)

Microprobe compositional investigations were carried out by an AMRAY 1830I/T6 SEM instrument equipped with an EDAX PV 9800 ED system. Accelerating voltage was 15 keV and we used 1-2 nA beam current. Measurements on olivine and clinopyroxene gave the conventional Fe content range: Fs 15-22.%, Fa 13-25 %. There are 2 kinds of olivine, the darker with 50.54 % MgO, 41.32 % SiO_2, 6.48 % FeO, the lighter with MgO 44.80, SiO_2 40.05, FeO 13, 51 %. Both olivines have Cr_2O_3 bw. 0.69-0.76 %. We found Cr sulfide spherules in olivines; their Cr content varies bw. 9.50 and 24.86 weight %. This high-Cr spherules together with the previously mentioned primary magmatic carbon grains in ureilites (GOODRICH & al., 1986), shows that mafic silicate minerals also contain probably primitive chondritic components (see Pict. 1/b, 1/c and 1/e). If we compare them with other reducing inclusions in chondrules (HANON & al., 1998) we have another probably primordial inclusions in ureilites.

In order to understand ureilite genesis *we placed ureilites into the thermal metamorphic* (thermal evolution) *sequence* from chondrites to different achondrites. Ureilites preserved their main mafic chondritic silicate mineralogy, carbonaceous matrix, but lost most of their iron. Ureilites lost not only main mass of their iron component but

lost their most mobile light silicate components assemblage (TOMEOKA, TAKEDA, 1990), too (although they kept a surprisingly fair amount of water). We defined the place of such meteorites as stage B primitive achondrites. (The known ureilites cover a range of such stage B primitive achondrites, somewhat similar to partly depleted terrestrial mantle rocks.)

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

Petrolog. type of V Schm-W.	1	2	3	4	5	6	7 Primit. Achondr stage A	Primitiv. Achondr stage B	Basaltic Achond- rites
E			+	+	+	+		Aubrites?	Aubrites?
Between E and H (BEH)			+	+	+	+	Acapulco Lodran Winona	Some of LODRANI TES	
H			+	+	+	+	e.g. Port Valley	?	Eucrite, How, Dio
C	+	+	+	+	+	+	?	UREI- LITES	
L			+	+	+	+	+	?	
LL		+	+	+	+	+	+	?	

Although iron loss causes minor changes in the chondritic chemistry and mineralogy, when partial melts of the mobile light silicates move out from the originally chondritic assemblage (TOMEOKA, TAKEDA, 1990) further loss of chondritic character can be observed. Stage B primitive achondrites preserved not only the carbon, but volatiles and oxygene isotopic ratios from the ancient carbonaceous chondritic matrix, too. In bulk chemistry stage B primitive achondrites can be characterized by increased Mg/Si ratios. The outflow of basaltic melts left behind a more mafic silicate content of primitive mantle rocks, then that of chondrites themselves.

PARADOXES FOR UREILITES: RESOLUTIONS AND SOLUTIONS FROM THERMAL HISTORY

There are several paradoxial geochemical and mineralogical composition characteristics of ureilites we intend to reconciliate and explain from the viewpoint of thermodynamics: We note that GOODRICH (1992) when trying to classify ureilites either as metamorphic or as primitive, ran into contradictions, which clearly imply paradoxial features.

1) *Only one type of ureilite exists although we need at least five for the 5 chondrite groups.* This was mentioned in the Table 3. There also aubrites were tentatively mentioned as analogons of ureilies for E condrites (BÉRCZI, HOLBA, LUKÁCS, 1999b). Now, observe Fig. 6, where we displayed the FeO distributions of chondrites, HEDs and ureilites of the NIPR Catalog (YANAI, KOJIMA & HARAMURA, 1995). The Figure demonstrates that after iron loss the remaining Fe content has already a single peak, so it is possible that the different ordinary chondrites would result in similar stage B primitive achondrites (i.e. ureilites, see Fig. 6.).
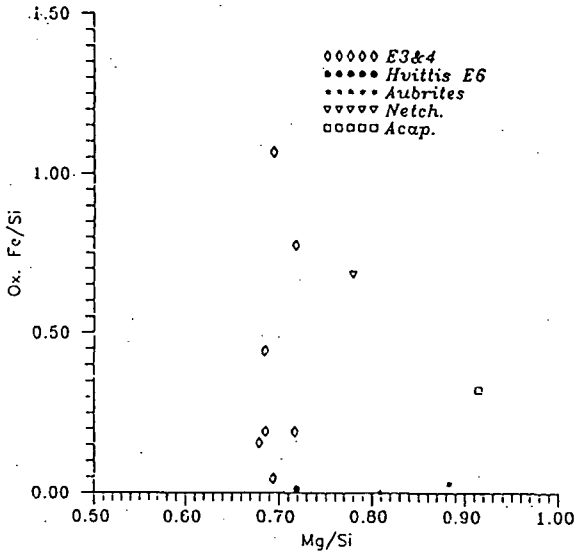
Fig. 5. Enstatite chondrites, their relatives and transitional meteorites from chondrites to primitive achondrites stage A: Acapulco and Netschaëvo on the oxidized-Fe/Si vs. Mg/Si ratio plot.
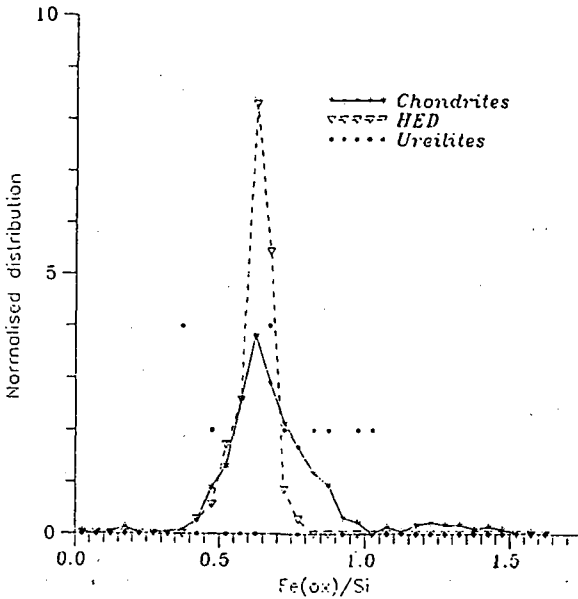

Fig. 6. The place of ureilites as a later evolutionary stage achondrites among the chondrites and the far evolved basaltic achondrites (HED). On the oxidized-Fe/Si vs. distribution (frequency of occurrence) plot the HED basaltic achondrites belong one definite peak of ox-Fe/Si ratio, primitivity of (residual) ureilites is shown their rather uniform distribution along this ratio.

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2) *It contains more Mg than the average chondrites*. From statistical data (NIPR dataset, YANAI, KOJIMA, HARAMURA, 1995) it seems that the Mg/Si ratio for ureilites is higher than this ratio for chondrites and even for carbonaceous chondrites. However this property may have a natural explanation. Losing the partial melts can explain this increasing MgO content. Observe the process from the "chair" of the Mg silicates sitting deep in the mantle of the ureilitic parent body asteroid. Originally both olivine and pyroxene might be present in the chondritic mineral assemblage. Partial melting in the peritectic $2MgO. SiO_2-- SiO_2$ system produces first melts of $MgO.SiO_2$ (together with most Na,Ca,Al, silicates) and left more $2MgO.SiO_2$ olivine than $MgO.SiO_2$ pyroxene, so the relative weight of olivine increased. This is a similar process in every planetary mantle chondritic/peridotitic assemblages, and that is why we can observe the parallel trends for peridotite-basalt sequence both for smaller (asteroidal) and larger (the terrestrial) evolutionary sequences (LUKÁCS, BÉRCZI, 1997b, 1998).

The remaining three paradoxes are much more interwoven:

3) *Low Na content is present with rather high water content*. The low Na concentration is no problem, observe that the bulk composition of ALH-77257 is extremely poor also on Al. This simply would mean a deep-mantle residue. However then one would expect water loss too, which is the real problem.

4) *How could it be that water, much carbon and a small amount of metal are in equilibrium*. This clearly implies that under the special circumstances carbon does not dissolve water.

5) *Contrary to their great diffusion-lengths, which means long staying in a hot environment water and carbon is present in considerable amounts*. Contrary to the previous item this means physical properties: both C and H_2O diffuse very easily under familiar circumstances. Note that the fact that carbon has been collected in the inter-grain veins may be explained by diffusion and solid state vacancies transport. The grain boundaries are the zones of weakness in a solid state. Not only diffusion drives incompatible elements (and all other elements not-easily forming crystals) into the veins but the transport effects of vacancies, too. Carbonaceous intergrain regions mean that ureilites were hot for long time. Their presence does not need melting, only long time of hot staying below the melting point. (Between TAMANN temperature = 0.52* T (melting) and T (melting). Because the number of vacancies below melting point is 0.23 %, during a long time heated state diffusion can rearrange texture into a very "igneous"-like metamorphic one.)

We admit that we do not have satisfactory explanations for the last 3 problems. However, we suggest a possibility, which may or may not be true, but with it they are no more paradoxes.

Assume a carbon phase on large pressure and/or high temperature, which is of great molecular weight and almost inert. Then the parts of points 4 & 5 regarding C get explanation: this allotrope of C will not evaporate easily from the lattice and will not dissolve water. We do not know which modifications may be stable or metastable at the ureilite locality (deep mantle?), but an *example* is the buckminsterfullerene C_{60}. It is a large molecule, forming negative ions, so not a concurrent of H for O (HAUFLER & al., (1990); OHSAWA & SAJI (1992)).

Then what would remain would be only something binding water in the lattice more strongly than usual; and we note the enormous Mg in ureilite. Now, silicates of C chondrites are slightly more "mafic" than of ordinary chondrites, and they retain more water at comparable petrologic types, too. We also keep open another possibility for C concentration in ureilites. Deep mantle C may have diffused out of the iron core: C diffuses easily in Fe, and we guess that the diffusion length in a million year may have gone to several km's. We study this possibility in another paper.
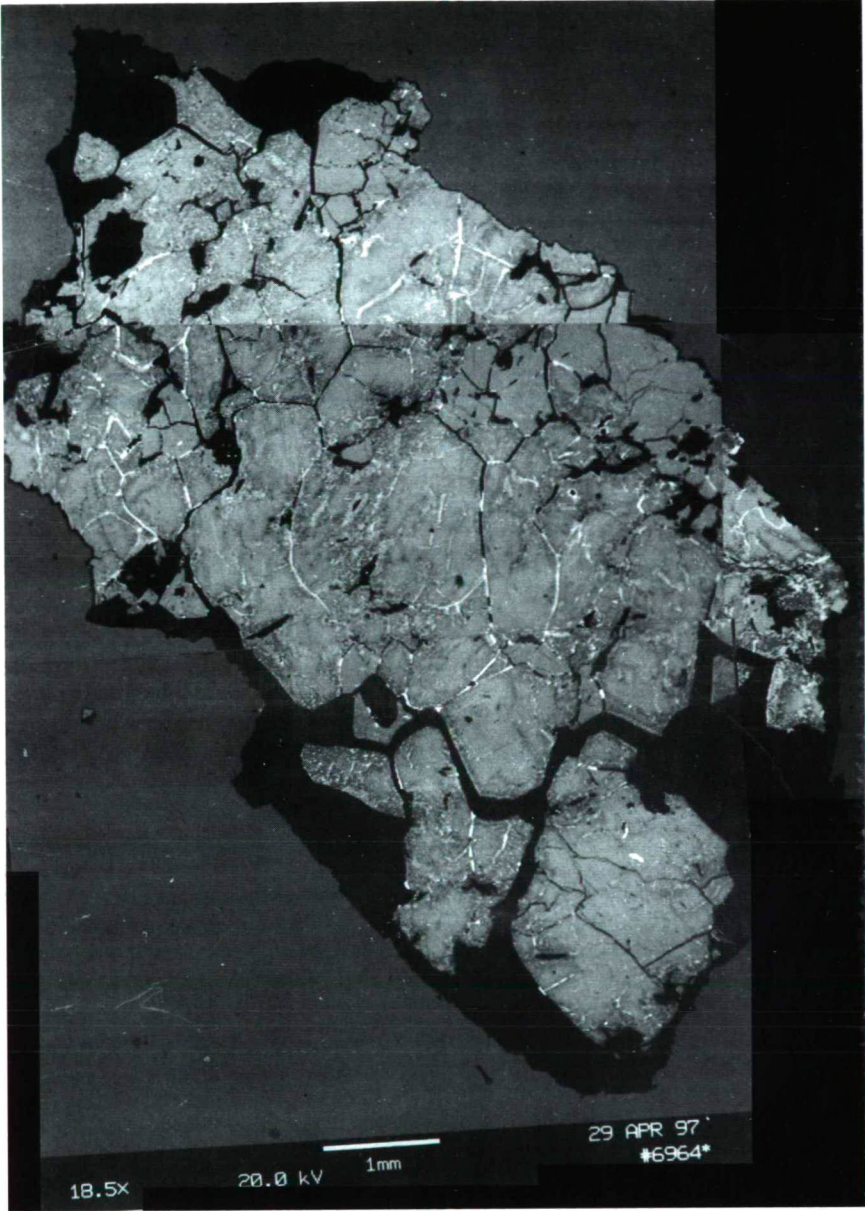
Pict. 1/a. Overview of the ALHA77257,77-4 thin section. (BSE image.)

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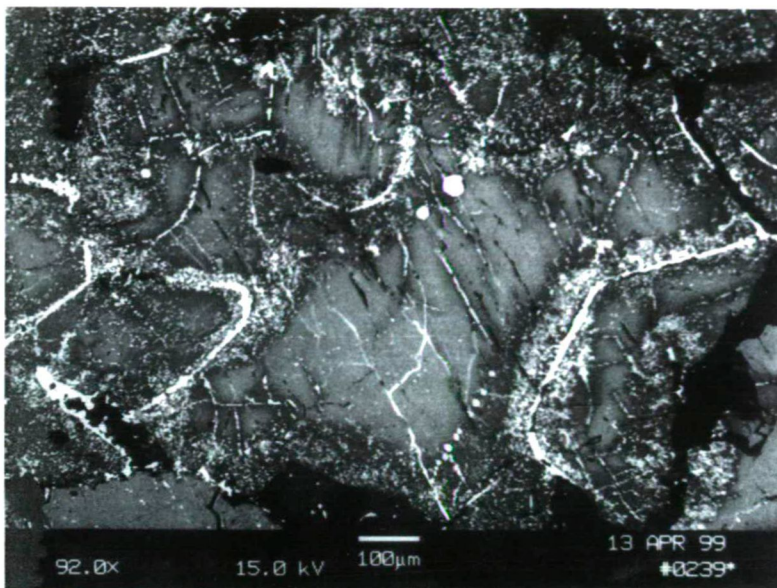
Pict. 1/b. Characteristic ureilite texture. The grain boundary regions are filled with carbonaceous veins, but many of them and intra grain fissures with metal ones. Outer rims of the olivine and clinopyroxene contain reduction-exsolved metal blebs which form transitional semi-opaque boundaries around the minerals. Some veins are alternately filled with carbon and metal. Detail of the ALHA77257,77-4 thin section. (BSE image.)
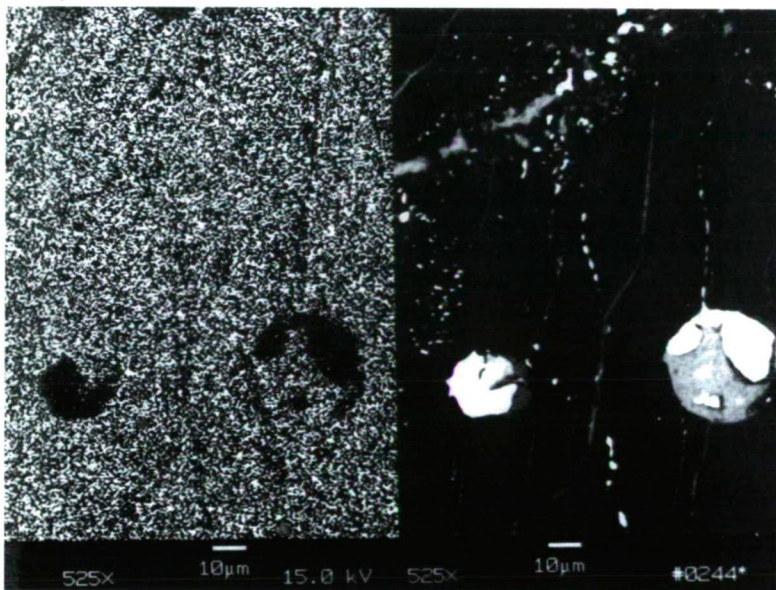
Pict. 1/c. Comparison of the silicon distribution map (left) and the BSE photo of this region (right) about a detail of the ALHA 77257,77-4 ureilite show a mafic silicate mineral which contains a high Cr containing primitive chondritic grain.

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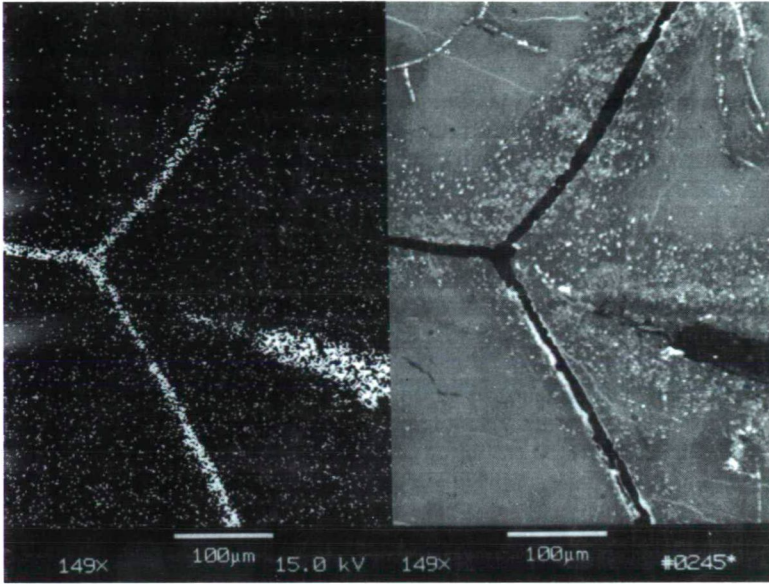
Pict. 1/d. Comparison of the carbon distribution map (left) and the BSE photo of this region (right) about a detail of the ALHA 77257,77-4 ureilite shows that some veins are mainly filled with carbon, others contain metallic iron filling too.
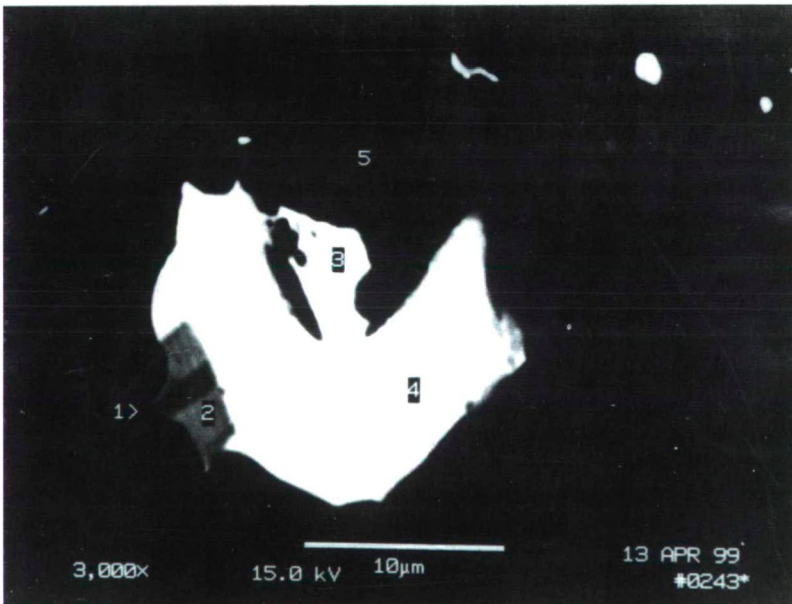
Pict. 1/e. The high-Cr spherule of Pict. 1/c (BSE image). Together with the carbon matrix, primary carbon grains (GOODRICH & al., 1986), these high-Cr spherules represent the primitive chondritic components in the more evolved (partly exhausted) mafic silicate minerals of the primitive achondrite stage B ureilites.

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DISCUSSION II: CHONDRITES – PRIMITIVE ACHONDRITES – BASALTIC ACHONDRITES

We studied the difference between *primitive* achondrites (of chondritic composition) and the *par excellence* achondrites (e.g. basaltic achondrites). Of course, the theory tells that primitive achondrites are connected to par excellence chondrites via iron loss, so from the ferrous components we can use only oxidised Fe for composition. Fig. 5 displays Fe^{ox}/Si vs. Mg/Si for the E's of the NIPR Catalog as chondrites, E6 Hvittis to represent primitive achondrites (on the basis of MASON's (1962) remark that E6's have no chondrulae), the aubrites of the NIPR Catalog as E achondrites, Acapulco as something of E-H origin, and Netschaëvo for comparison.

Indeed, the "E primitive achondrite" (?) Hvittis is well among the E3&4's in the metal-free plot. Netschaëvo is not, but it is not expected, "being in the gap". Acapulco is not either; the higher Mg content compared to the almost purely Mg-silicate E's must mean that in Acapulco there is more olivine, so it cannot have direct genetic connection to them. But aubrites are also Mg-richer than E's.

So aubrites are not basalts of the E parent body (say, proto-Hungaria). If they have any close connection to such a parent body, they are rather analogous to ureilites (or in Earth, to lherzolites), and then the E basalt is still unknown. (To the problem of differentiation between primitive and basaltic achondrites we will return in a subsequent paper.)

Portales Valley and the also rather fresh discovery of Yamato 791093 iron-rich chondrites enlarged the circle of those meteorites which help to see more in this complex borderline between chondrites and achondrites, especially in the case of the H group. Their thermal evolutionary process was going deep in the chondritic parent body, that is why so rare the representative transient samples are. In 1995 McCoy summarized the state of art at that time. His sequence was: Netschaëvo (unmelted, relict chondritic), Techado (unmelted, chondritic recrystallized, but Fe-Ni-S melted), Watson (totally melted, but no silicate differentiation), Miles and Weekeroo Station (opx-cpx-pl partial melted) and Kodaikanal, Colomera, Elga (differentiated silicates). We did not study the differentiated silicate bearing IIE irons, but with the two new discoveries of this H chondrite-to-stage A primitive achondrite clan the new sequence can be given such:

Rose City (only shock melted and brecciated H5),
Yamato-791093 (H6 chondritic, maybe shock induced, but "self-melted" Fe-Ni-S),
Portales Valley (H6 chondritic, maybe shock induced, but "self-melted" Fe-Ni-S),
Netschaëvo (E-H chondritic, "self-melted" Fe-Ni-S),
Techado (unmelted H primitive chondritic, "self-melted" Fe-Ni-S),
Watson (melted but recrystallized H primitive chondritic, melted Fe-Ni-S).

SUMMARY: PRIMITIVE ACHONDRITES OF STAGE A AND STAGE B

We studied different products of the chondritic thermal metamorphism. We extended the metamorphic petrological transformation sequence (VAN SCHMUS, WOOD, 1967) toward basaltic achondrites. We defined the extended gradual transition from chondritic mineral assemblages (and compositions) through different primitive achondritic stages to the most differentiated basaltic achondritic meteorites. This continuing of the metamorphic sequence needed formulation of the main textural characteristics of those transformations which affected the texture after chondritic equilibration. There were two

such processes: one was the partial melting and outflow of iron-sulfide assemblage from the primitive achondritic source, the second was: the partial melting of a low melting point basaltic like component and its outflow toward the surface of the asteroidal parent body. Acapulcoites, lodranites, winonaites represented the first stage A, ureilites and some lodranites represented the second stage B. Those of the second one have less primitive achondritic characteristics then that of primitiv achondrites of the original definition. In order to emphasize the distinction between the two stages we introduced the stage B primitive achondrite expression and name for them, while used the primitive achondrite of stage A for the first group. This division of the chondrite-primitive achondrite range made possible to distinguish different types of primitive achondrites from the traditional or classic achondrites, the basaltic achondrites. Moreover, this refinement of primitive achondrite range helped to genetically relate different iron meteorites and stony irons to these stages in the thermal evolutionary sequence of products on a chondritic-to-achondritic evolved parent body.

The detailed construction of the extended metamorphic chondritic sequence helps arranging the great majority of chondrites and achondrites according to common characteristics which gradually change during the thermal evolution of the chondrite parent bodies.

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