

EVOLUTION OF CHONDRITIC PARENT BODIES I: CORRELATION AMONG FERROUS COMPONENTS

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ABSTRACT

The thermal and chemical evolution of the precursors of chondritic meteorites are discussed by using the data of recent chemical analyses performed in the NIPR, Tokyo, Japan, mainly on Antarctic meteorites.

INTRODUCTION

Meteorites are small bodies, but many of them show clear signs of previous intensive thermal evolution and transformation, which is quite possible if they are fragments of bigger objects, the so called parent bodies. A few parent bodies have been identified: e. g. some very few meteorites are fragments of Luna and Mars, and it is quite possible that eucrites come from the asteroid Vesta. However all these meteorites are differentiated achondrites.

Chondrites still preserve partially the primordial structure. So their parent bodies must have been smaller. One can guess that they were comets or medium or small asteroids, with much less chance to be individually identified. Still some general properties of these parent bodies can be traced back from the chondrites.

Such a reconstruction needs a large number of data to be collected, mainly for texture and chemical composition. In 1995 a Japanese group published the database largest up to now for chemical compositions. We try to draw some conclusions from this database about the thermal and chemical evolution in the parent bodies. We also were able, by the courtesy of the NIPR, Tokyo, to perform optical investigations on representatives of all standard chondrite types, on a thin section collection from Antarctic meteorites.

The present approach will be empirical. In Sect. 2 we recapitulate the classification of chondrites, in Sect. 3 the Japanese database is discussed, and in Sect. 4 we make some statistical evaluation based on this database. Sect. 5 contains the results and discussions.

ABOUT THE VAN SCHMUS-WOOD CLASSIFICATION

Meteorites are traditionally classified triadically according to the main chemical components as

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- 1) Irons (mainly FeNi)
- 2) Stony-Irons (mosaics of FeNi and the next group); and
- 3) Stones (mainly silicates).

The main component of stone meteorites is some silicate, i. e. a SiO_2 lattice with metal oxides inside. The stones are further subdivided dually according to the presence of small beads of silicates called chondrules (of sizes from 0.1 mm up to mm's). Then we get:

- A) Achondrites (chondrules missing); and
- B) Chondrites (chondrules present).

Third, chondrites can be further divided according to the dominant silicates in the matrix and in the chondrules, plus the state of the chondrules. Before going into details, we summarize the classification up to this point according to the ROSE-PRIOR-MASON-ANDERS scheme (BÉRCZI, 1991) on Fig. 1.

ROSE-PRIOR-MASON-ANDERS TABLE OF METEORITES

PRINCIPAL MINERALS	TYPES OF METEORITES	GROUPS OF METEORITES																		
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Fig. 1. The ROSE-PRIOR-MASON-ANDERS scheme.

Classical classifications of meteorites into irons, stony-irons and stones, and further distinction in the last group to chondrites and achondrites are shown on the right edge column. In middle column the meteorite types with their names are given. On the left column the main mineral components of the corresponding meteorites – in the same row – are given. Generations of investigators worked on this classification of which here ROSE, PRIOR, MASON and ANDERS were emerged.

Further developments of this system happened, when lunar and Martian meteorites were identified. To lunar meteorites 13 distinct samples belong in 1995 January. (see for instance: YANAI, KOJIMA, 1991) To Martian meteorites 10 distinct samples belong in 1995 January. Most of them belonged earlier to the Nakhlite, Shergottite, Chassignite group (the SNC meteorites), but later such type of meteorite was found among diogenites, too. (see i. e. MITTLEHEIM, 1994.)

According to common opinion, chondrites seem to be less evolved than achondrites. Achondrites are understood as bodies where the chondrules have been obliterated by heat & c. Here we concentrate on chondrites. They were classified first by PRIOR (1916), who summarized their main chemical characteristics in the PRIOR Rules. UREY and CRAIG (1953) named two groups of chondrites according to their non-oxidized vs. oxidized Fe content. These two central groups on the 2-dimensional plot are the L (low) and H (high) ones, meaning the non-oxidized (metallic and sulphide) component.

WIIK further developed both PRIOR Rules and UREY-CRAIG classification (WIIK, 1956). He subdivided the carbonaceous chondrites into three types. Then MASON (1962) subdivided the two UREY-CRAIG groups, and included carbonaceous chondrites. So a system emerged with 5 types, mainly according to the percentage of the non-oxidized Fe in the total mass of the meteorite. From above down the 5 types were

E→H→L→LL→C

In accordance with the PRIOR Rules the non-oxidized Fe content strongly correlates with the type of silicate dominating in the pyroxenes of the meteorite as (MASON, 1962):

E → enstatite
H → bronzite
L → hypersthene
LL → pigeonite

(In C's serpentine is frequent.) By this observation one could determine the type without chemical analysis from microscopy of thin sections. It remains open how strict is this correlation.

In the early 60-ies J. A. WOOD and E. ANDERS studied in details the texture of chondrites and they recognized, that thermal transformations can be deciphered from different textural features of meteorites with the same type. From these studies grow out the next important step in the chondrite classification. VAN SCHMUS and WOOD (1967) introduced the notion of petrologic class, a number from 1 to 6 as

- 1) Still no chondrules (very much volatiles).
- 2) Sharp chondrule boundaries, more volatiles.
- 3) Sharp chondrule boundaries, less volatiles.
- 4) Slightly blurred chondrule boundaries.
- 5) Obscure chondrule boundaries.
- 6) Badly defined chondrule boundaries (hardly seen).

Recently a Class 7 has been introduced too in which chondrules cannot be seen at all, but still the general texture is similar to that of chondrites of Class 6. A possible explanation is that this sequence shows the higher and higher heat impact in the history of the body, washing out the sharp boundaries by diffusion.

When WIIK (1956) recognised, as thumb rule, from 30 selected chondrites that, removing volatiles, there seems to be a tendency to get only two values for total Fe content: cca. 27% for E's, H's and C's, and cca. 22% for L's and LL's, the possibility of evolutionary models were opened (see e. g. SZTRÓKAY 1966).

However all these results were obtained from very limited samples below 100 specimens, and it is easy to see that in the full VAN SCHMUS-WOOD classification the number of possible classes is between 20 and 30 (petrologic classes 1 and 2 are known only for C's up to now), therefore the classes were so poorly populated that the statistical analysis was almost hopeless.

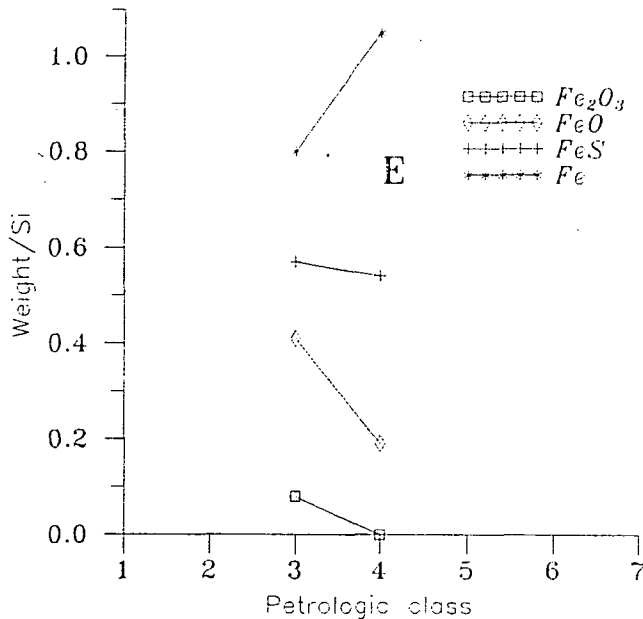
THE CATALOG OF ANTARCTIC METEORITES

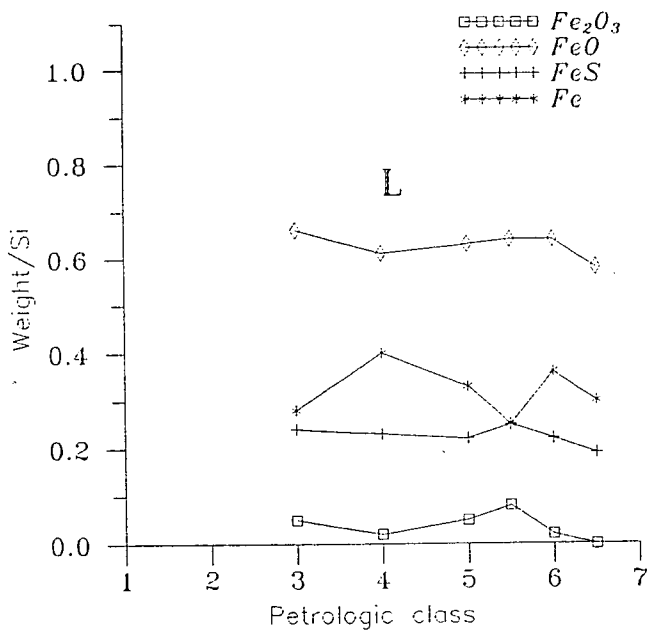
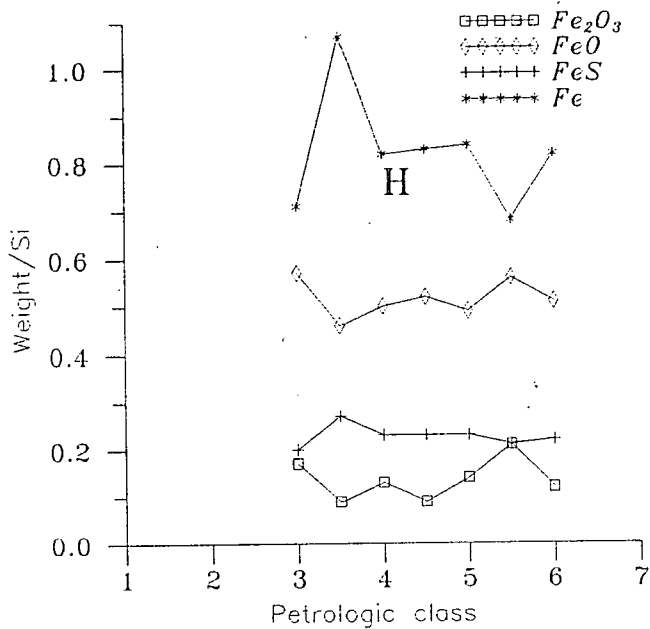
The National Institute of Polar Research in Tokyo started to collect meteorites from the icefields of the Antarctic interior in 1969. Conservation conditions are the best there on Earth, all of them are easily discriminated from the environment, and accumulating for tens of thousand of years. So the statistics is best for Antarctic meteorites. A group working first under K. YANAI and now under H. KOJIMA is continuously classifying and analysing the meteorites and the recent stage of research was published in 1995 in a Catalog (YANAI, KOJIMA and HARAMURA, 1995). The Catalog contains some 8000 meteorites in the NIPR collection, of which more than 3000 have been classified into the VAN SCHMUS-WOOD scheme, and standard wet chemical analysis has been performed for 549. This is the biggest available homogeneous sample whose chemical compositions are known.

By using this huge database one can get many data characterizing the various chondrite types with at least modest statistical reliability. Here we note that the distribution of the analysed chondrites is such that more populated C and LL classes contain samples in the order of 10, L and H ones are more numerous and the most populated class is L6 with 94 meteorites. We have started a statistical analysis of the data and give here some preliminary results concentrated on Fe contents.

SOME CHARACTERISTIC DATA OF THE CHONDRITE COMPOSITONS

Fig. 2 gives the average values of Fe concentration in FeO, Fe₂O₃, FeS and metallic phase, relative to the Si content. One can see that the total Fe contents of E's, H's and C's are rather similar (cf. WIJK's observation), but there are some differences between L's and LL's (at some petrologic classes they are statistically significant). Also, one sees that FeS is substantial in early C's and E's, but nowhere else.





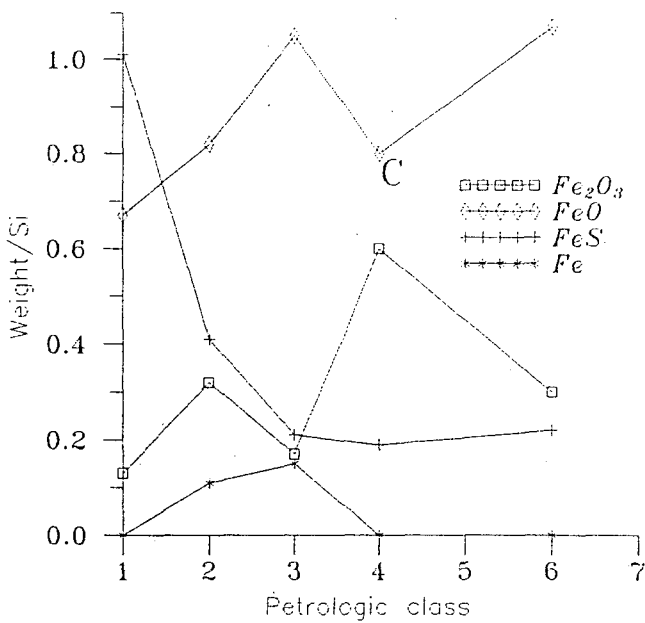
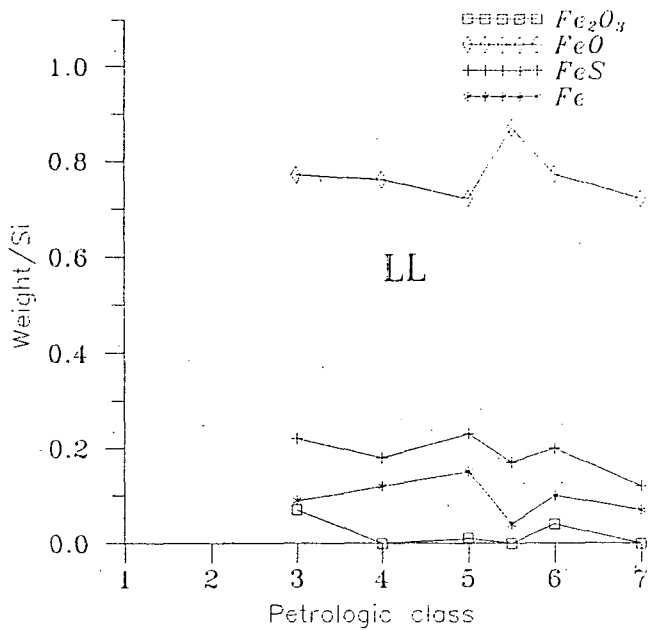


Fig. 2. The Fe/Si weight ratios for 4 different chemical positions of Fe vs. petrologic class, separately for E, H, L, LL and C chondrites, according to the averages of meteorites in the NIPR analysis.

Now, for the reconstruction of the past history of the chondrites, it is important to see the correlations between the different ferrous compounds; they reflect the processes which transferred the common Fe stock from one form to another. Correlation coefficient between two quantities x and y on the same manifold is defined as (EZEKIEL and FOX, 1969).

$$r_{xy} = (\langle xy \rangle - \langle x \rangle \langle y \rangle) / (\sigma_x \sigma_y) \quad (4.1)$$

This quantity is between +1 and -1 by construction, and values near to +1 are signals for strong positive connections between the individual fluctuations of the two quantities. High negative values indicate similarly strong connection, but in opposite direction. Values near 0 do not prove disconnectedness, but strongly suggest that. In first approximation the statistical mean error of r is

$$\delta r = (1-r^2) / \sqrt{n} \quad (4.2)$$

where n is the size of the sample. Significant *negative* correlation between 2 ferrous compounds at least suggest that the two compounds may go into each other in a process, and strong positive correlations are suspected for similar behaviour in the dominant processes.

The correlation coefficients read as:

TABLE I

*Correlation coefficients r between the concentrations of Fe in different chemical positions.
Always the Fe content is meant*

Type	r						$n^{-1/2}$
	FeO, Fe ₂ O ₃	FeO, Fe	FeO, FeS	Fe ₂ O ₃ , Fe	Fe ₂ O ₃ , FeS	Fe, FeS	
E3	-0.42	-0.85	-0.60	-0.04	-0.40	+0.73	0.44
H3	-0.20	-0.56	+0.11	-0.63	-0.30	+0.17	0.29
H3-4	-0.65	-0.27	+0.45	-0.41	-0.62	-0.23	0.50
H4	-0.26	-0.36	-0.36	-0.59	+0.11	+0.16	0.12
H4-5	+0.11	-0.41	-0.61	-0.84	+0.12	+0.04	0.33
H5	-0.38	-0.41	-0.17	-0.59	-0.07	-0.10	0.15
H6	+0.53	-0.77	+0.74	-0.86	+0.62	-0.76	0.21
L3	-0.14	-0.52	-0.55	-0.43	-0.15	+0.30	0.22
L4	-0.40	-0.22	-0.36	-0.43	+0.13	-0.05	0.19
L5	-0.59	+0.38	+0.11	-0.78	-0.35	+0.42	0.24
L5-6	-0.80	+0.50	-0.47	-0.92	-0.14	+0.52	0.58
L6	-0.41	-0.25	-0.34	-0.41	+0.17	+0.01	0.10
LL3	-0.61	-0.41	-0.51	+0.08	+0.02	+0.11	0.32
LL4	-0.62	-0.61	-0.32	+0.28	+0.30	-0.26	0.33
LL5	-0.43	-0.79	-0.65	+0.49	-0.15	+0.20	0.33
LL6	-0.93	-0.18	-0.37	+0.03	+0.16	+0.55	0.24
C2	-0.76	-0.19	-0.05	-0.18	-0.32	-0.24	0.24
C3	-0.72	-0.39	+0.03	-0.33	+0.02	-0.16	0.32

For the omitted types there are no enough samples for calculating the correlation coefficient. The last column is to see the significance of the coefficients.

There is no room to discuss all the correlations in all types. We choose only several characteristic classes.

For E3's the only significant r 's show that Fe and FeS are both concurrents of FeO. In H4 everything else concur with FeO. In L4 both Fe₂O₃ and Fe are concurrents of FeO. The same is true for L6, but there Fe and Fe₂O₃ change together. In LL3 again FeO concurs

with everything else; the same is true for LL6, but there also Fe and FeS change together, just as for L6. C2, however, is quite different: Fe₂O₃ changes oppositely to FeO and FeS, and Fe changes oppositely to FeS too.

Even with the present huge database in some VAN SCHMUS-WOOD classes the measured correlations are not significant. One can guess that for significant results in each class 50-100 analysed samples would be needed, and this number will be reached when some 3000 meteorites will have been analysed.

RESULTS AND DISCUSSIONS

First let us see again *Fig. 2*. Our hope is that this Figure tells something about the relations among the different chondritic types. Namely, chondrites may differ in initial conditions and in subsequent evolution as well. The only clear point is that higher petrologic classes got higher heat impact. But we practically do not know anything about the origin of main types. Namely, C, H and E chondrites may have been developed from their own primordial progenitors (say C1, H1 and E1), but, since petrologic classes 1 and 2 are known only among C's, it is also possible to imagine some evolution from C2 to H3 or E3 as well. Obviously, average C's cannot be progenitors of LL's and L's because of the different total Fe/C ratio, conserved without global differentiation.

Now, *Fig. 2* shows that the letters of the van Schmus-Wood scheme differ mainly in the degree of oxidation of Fe. This is not surprising at all, since these types are defined according to the FeO content of the pyroxenes and olivines. Now, if some part of the Fe is reduced then the resulting Fe is not a part of the silicate lattice. So a higher metallic (+sulphide) content of the *whole* meteorite must be strongly correlated with a lower FeO content in pyroxenes and olivines.

However, dependences on the petrologic class are more complicated. Let us first see the oxides and the metallic phase. First, FeO always dominates Fe₂O₃; the latter is minor constituent except for some C's. So in the early thermal history of parent bodies the environment was mainly reducing. Still, FeO/Fe is not monotonous with the petrologic class. So some oxidizing agent must have been present too. Except for E's and C's, the ratios of free and bound Fe's show some oscillations (see *Fig. 3*). Note that FeO generally anticorrelates with both Fe₂O₃ and Fe. This suggests that FeO is the original source, and both hypothetical processes influence the quantity of FeO and that of something else.

The sulphide Fe/Si ratio is generally about 0.2. There are two exceptions: the low petrologic class C's, where the ratio rapidly decreases with the petrologic class and reaches the asymptotic value at C3, and E's, whose sulphide contents are similar to those of C2's (slightly in the direction of C1's). So the process reducing FeS was not effective beyond the heat impact of petrologic class 3, and was not effective at all in E's. E3's more or less smoothly follow C2's, if one can invent circumstances in which something (C?) strongly reduces the Fe oxides, while nothing influences the sulphide. Unfortunately the early environment is rather unknown, and anyways, it was exotic compared to those about which we have experience. Iron sulphides are not used in human iron metallurgy, and definitely not in reducing atmospheres.

At the highest petrologic classes metallic Fe and FeS both decrease. The simplest explanation is iron loss by iron melting, possibly starting in this stage. The liquid may leave the silicate body via the gravity of the parent body; note that Fe and FeS are similar to melting points, and also neither of them are in the silicate lattice. So they are lost together, and this is seen in L5, L5-6 and LL6 (but, interestingly, not seen in H6 and L6).

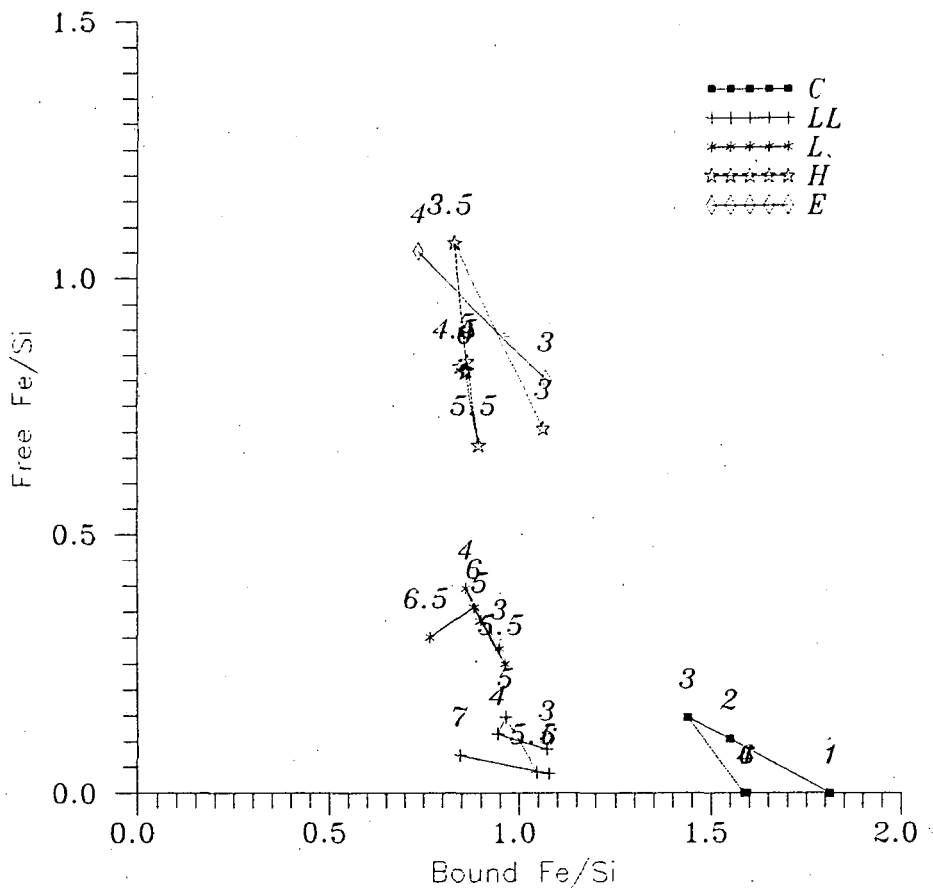


Fig. 3. Average free Fe/Si vs. bound Fe/Si weight ratios for the different classes of chondrites of the NIPR analysis. Petrologic classes are indicated by labels above the points.

Finally, the data suggest that some "transitional" classes do not fit into the VAN SCHMUS-WOOD scheme. The analysers found a few percent of chondrites awkward for petrologic class, which they classified, as best available solution, between two well defined petrologic classes. Now, Fig. 2 clearly show that H3-4 is not transitional between H3 and H4, and the same is conjectured for LL5-6 and H5-6. These chondrites need further analysis. They may even not be H's or LL's; at least the total Fe/Si content of the average H3-4 is extremely high.

The present treatment was purely empirical. The possible explanatory models will be discussed in a subsequent paper.

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