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Comparative analysis of the Baszkówka and Mt. Tazerzait chondrites: genetic conclusions based on astrophysical data and the mineralogical and petrological data

Andrzej S. PILSKI, Tadeusz A. PRZYLIBSKI and Paweł P. ZAGOŻDŻON

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The L5 chondrites Baszkówka and Mt. Tazerzait are characterised. Their astronomical, mineralogical and petrological characteristics confirm that these meteorites are similar. They could be derived from the same parent body, though from the different depths below its surface. A third meteorite — the Tjerebon — might have arisen from the same swarm of meteoroids. The parent body to these meteorites in the asteroid belt can not be established at present. The porosity, of these chondrites suggests that they formed close to the surface of their parent asteroid. The process of formation of the parent rock of the Baszkówka chondrite is similar in some respects to sedimentation of a weakly compacted terrestrial sandstone. Thus, a two-stage geological history may be envisaged: firstly formation of the component minerals and mineral aggregates of this meteorite. Then, later in a different environment, the accretion of fragments of this parent material, together with a small amount of matrix, into a strongly porous sedimentary rock.

Andrzej S. Pilski, Nicolaus Copernicus Museum in Frombork, Katedralna 8, PL-14-530 Frombork, Poland, e-mail: planet@softel.elblag.pl; Tadeusz A. Przylibski, Paweł P. Zagożdżon, Wrocław University of Technology, Wybrzeże S. Wyspiańskiego 27, PL-50-370 Wrocław, Poland, e-mail: Tadeusz.Przylibski@ig.pwr.wroc.pl, Pawel.Zagozdzon@ig.pwr.wroc.pl *(received: July 3, 2000; accepted: December 13, 2000).*

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INTRODUCTION

The understanding of the chondrite forming process is crucial to understanding how the solar system formed. The age of the component minerals within chondritic rocks indicates that they formed near the very beginning of the solar system; they are older than any terrestrial minerals. Clues to the processes taking place in the solar nebula, notably the formation of planetesimals, have been preserved in the structures and textures of chondrules and chondrites. Independent information about these processes comes from astronomical observations of stars of various ages, including those just being formed. Both sources provide incomplete data, insufficient to construct a unified model of the solar system's formation, consistent with all observed phenomena. Several competing concepts exist, and each newly studied chondrite can serve to provide constraints, bringing us closer to a robust theory.

Two meteorites which fell in recent years differ in many respects from the chondrites found previously, and may provide new hints to understanding the history of the solar system. As regards their macroscopic features, a third one (which fell down some decades earlier) should be added. So far no other chondrites of similar structure have been found.

BASZKÓWKA

This meteorite fell on August 25, 1994, at about 16.00 hrs, in the village of Baszkówka near Warszawa (Stępniewski *et al.*, 1996). Witnesses of its fall saw nothing which might make determination of its orbit possible. They heard a sound, but could not say which direction it come from. Surface attrition of one side of the meteorite indicate its falling obliquely but the finder did not record its exact resting exact position. The lack of observed light-effects suggests a low velocity of the meteoroid towards the Earth and hence its velocity on entering the atmosphere must have been only slightly above the Earth's escape velocity. For example, in the case of meteorite which fell near Ridgedale in Canada (Halliday, 1987), the velocity prior

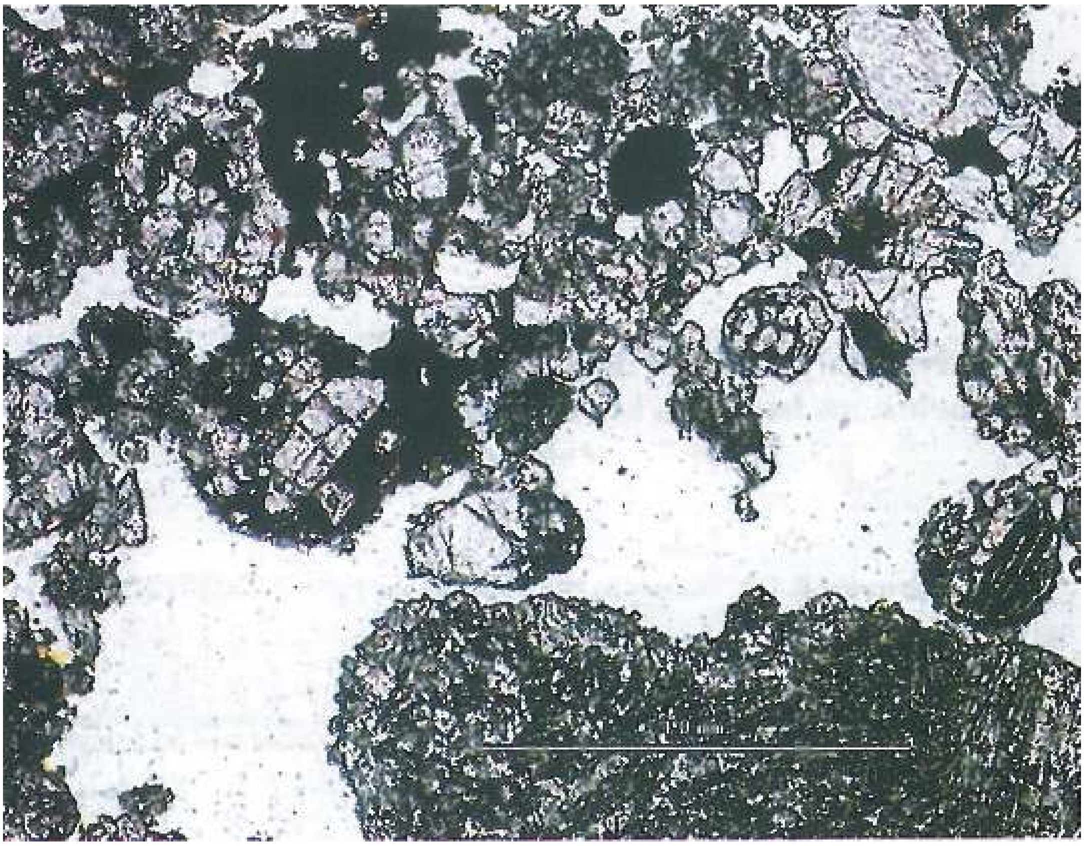

Fig. 1. Baszkówka; pore systems, chondrules, their fragments and metal grain (transmitted light, polarised light, x 50)

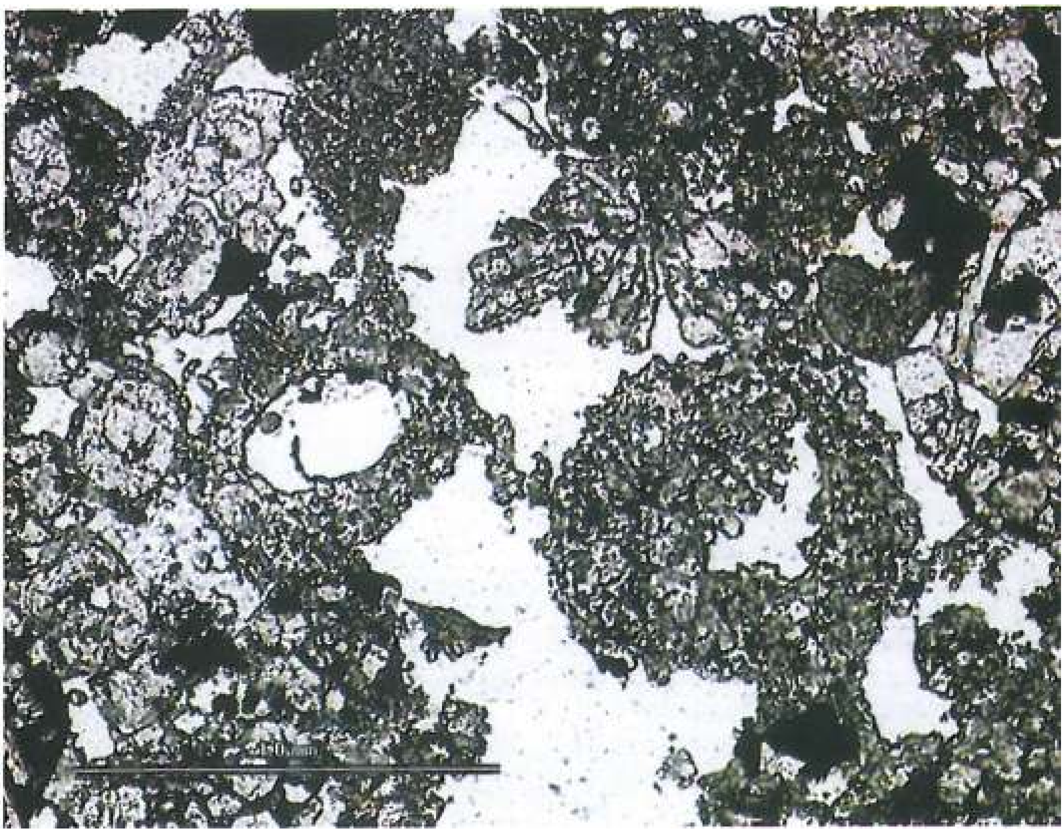

Fig. 2. Baszkówka; pore systems and porous chondrules with hypautomorphic crystals inside, porous and disordered texture (transmitted light, polarised light, x 50)

to entering the atmosphere was estimated as 14.66 km/s, and this was associated with a bolide luminosity of –7.5 magnitude. For the bolide to be visible in the daylight, its luminosity would have to be higher than –10 mng. Because of its relatively low velocity, the meteorite did not disintegrate in the atmosphere and some small fragments only were detached. The largest one split off on impact.

From the appearance of the fracture surface it was evident that the meteorite (named Baszkówka) is a chondrite. It was, though, unlike any other chondrite in Polish collections. Its marked porosity was particularly notable, associated with a textural fragility, separate grains and chondrules only being connected with each other at some points (Figs. 1 and 2). This resulted in crumbling during the cutting and polishing processes. But, in contrast to the L4 chondrites Bjurböle and Saratov, it did not crumble when held in the hand, indicating that the scarce connections of the constituent particles possessed some strength. Another singular feature of the meteorite was the presence of idiomorphic crystals in pores, mainly olivines (Figs. 3 and 4).

Apart from its considerable porosity, the cross-section of the Baszkówka meteorite revealed it to be a typical example of the group L chondrites. Randomly distributed grains of nickeliferous iron, often associated with troilite, together with numerous troilite fragments (Fig. 5), were noticed. The dimensions of largest troilite grains, coated with Fe-Ni alloy were over 1 cm. The chondrules ranged from a fraction of a millimetre to a few millimetres in diameter. Some sharp-edged achondrite fragments up to 8 mm in diameter were also noted. They differed from chondrules not only in lacking a spherical shape but also in their texture, which suggested them to be scraps of bigger rocky blocks, rather than spheres of a solidified silicate melt. The internal coherence of the fragments composed of whole and fragmentary chondrules, and individual silicate crystals (olivines and pyroxenes), and of the Fe-Ni alloy and the troilite grains, was much higher than that of the rock itself (Fig. 6).

Same of the chondrules were cavernous inside. These cavities, not encountered in other meteorites, resembled miniature geodes. The internal surfaces of these geodes were covered with crystals (see Figs. 2 and 3), sometimes reaching to the opposite wall. Some of the idiomorphic troilite crystals formed on the elongate silicate (mainly olivine) crystals, indicating that they might have crystallised directly from vapour.

On macroscopic examination, the Baszkówka chondrite differs from other chondrites because of its “transparency”. Examining polished sections of various ordinary chondrites, one gets the impression that they are non-transparent rocks. Disregarding the truly opaque minerals, then what is responsible for this impression is mainly a fine-grained matrix. However, chondrules themselves and coarse debris can also be considered as non-transparent. In the case of the Baszkówka chondrite, the lack of a fine-grained matrix, together with well-formed mineral crystals, make it possible to see inside the meteorite while looking at its polished section. It is also possible to observe chondrule textures, normally only visible in thin section. Of the two best-known Polish meteorites, the Baszkówka, with its translucency and greenish colour, is more similar to the Łowicz mesosiderite than to the Pułtusk chondrite.

The external resemblance of the Baszkówka chondrite and the Łowicz mesosiderite may be reasonable. It has been assumed that mesosiderites resulted from the catastrophic collisions of asteroids which had undergone prior differentiation. After collision, debris was combined inside the planetoid, in a region of reasonably high temperature. Slow cooling of a mesosiderite’s minerals (McSween, 1999), allowed their full crystallisation. The history of the Baszkówka chondrite could have been similar, especially as far as the asteroid collision stage is concerned.

The low mercury content in the rocks that became the Baszkówka meteorite may have resulted from prolonged high temperature: concentrations are two orders of magnitude low than in the L4 Bjurböle chondrite and even lower than in the Łowicz mesosiderite (Jovanovic and Reed, 1985; Borucki, 1998, pers. comm.), according with the appearance of the meteorites.

MT. TAZERZAIT

This meteorite fell on the afternoon of August 21, 1991 in northern Niger; four years later it found its way into the hands of scientists. Originally it comprised one stone of about 110 kg but the finders split it into pieces. No information is available about the fall circumstances. The appearance of the meteorite was so different from the appearance of other L-type chondrites that it was described as “anomalous”. Its description, however, was in ideal agreement with that of the Baszkówka meteorite. By courtesy of Walter Zeitschel and Rolf Bühler, fragments of this meteorite were made available for comparative study. It has been classified as an ordinary L5 chondrite and named Mt. Tazerzait (Grossman, 1997).

This meteorite is slightly less porous than Baszkówka but its polished section, as in the case of Baszkówka, gives an impression of transparency and, in both cases, chondrule textures are visible. Chondritic debris occurs more often and similar binding of metal and troilite particles, up to 7 mm in diameter, are observed. Despite a larger number of polished sections of this meteorite being examined than in the case of Baszkówka, only one larger achondrite fragment of a different structure was noticed. As in Baszkówka but to a lesser extent, automorphic and hypautomorphic silicate crystals are visible in pores. The mineralogical composition of both meteorites is alike.

There are higher contents of matrix in the Mt. Tazerzait chondrite than in Baszkówka. The matrix is composed mainly of small chondrules, their fragments, individual silicate crystals (olivines and pyroxenes), Fe-Ni alloy and troilite grains (Figs. 7 and 8).

A METEORITE SWARM?

The considerable structural, textural and mineralogical similarity of the Baszkówka and Mt. Tazerzait chondrites indicates that they may be fragments of the same rock. Both of these me-

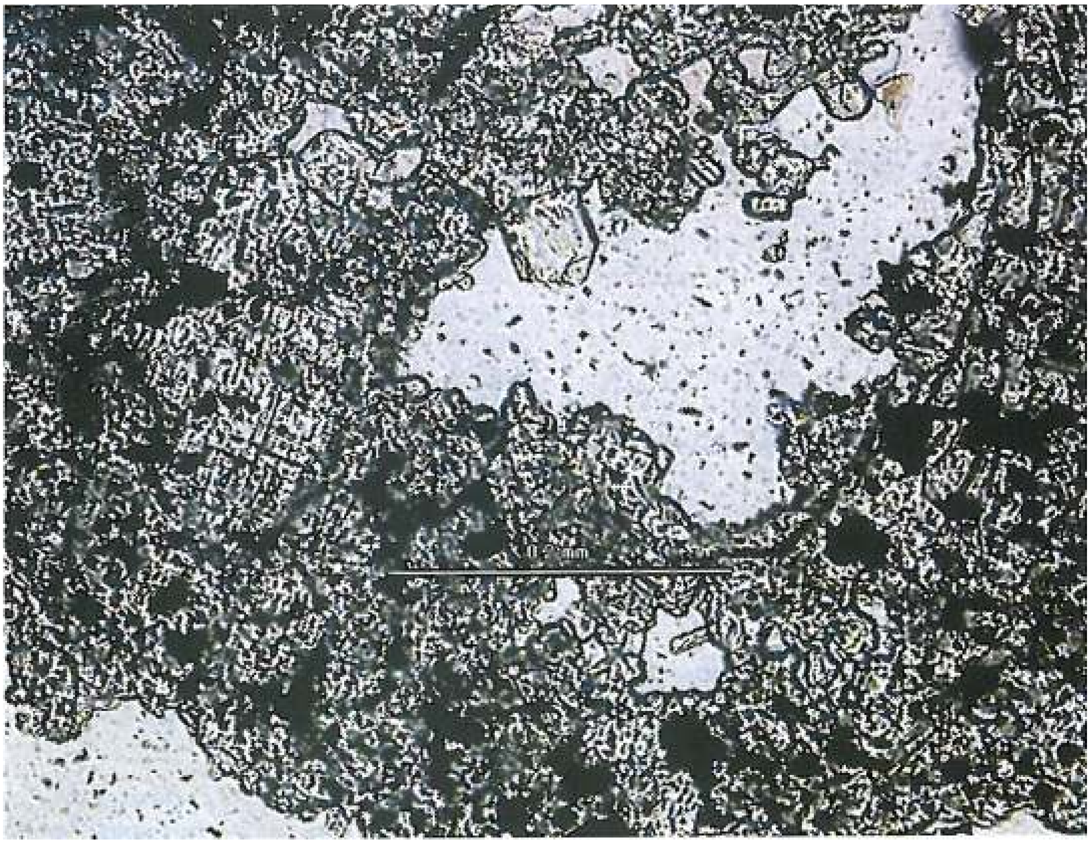

Fig. 3. Baszkówka; interior of chondrule shown at Fig. 2 (an enlargement, transmitted light, polarised light, x 200)

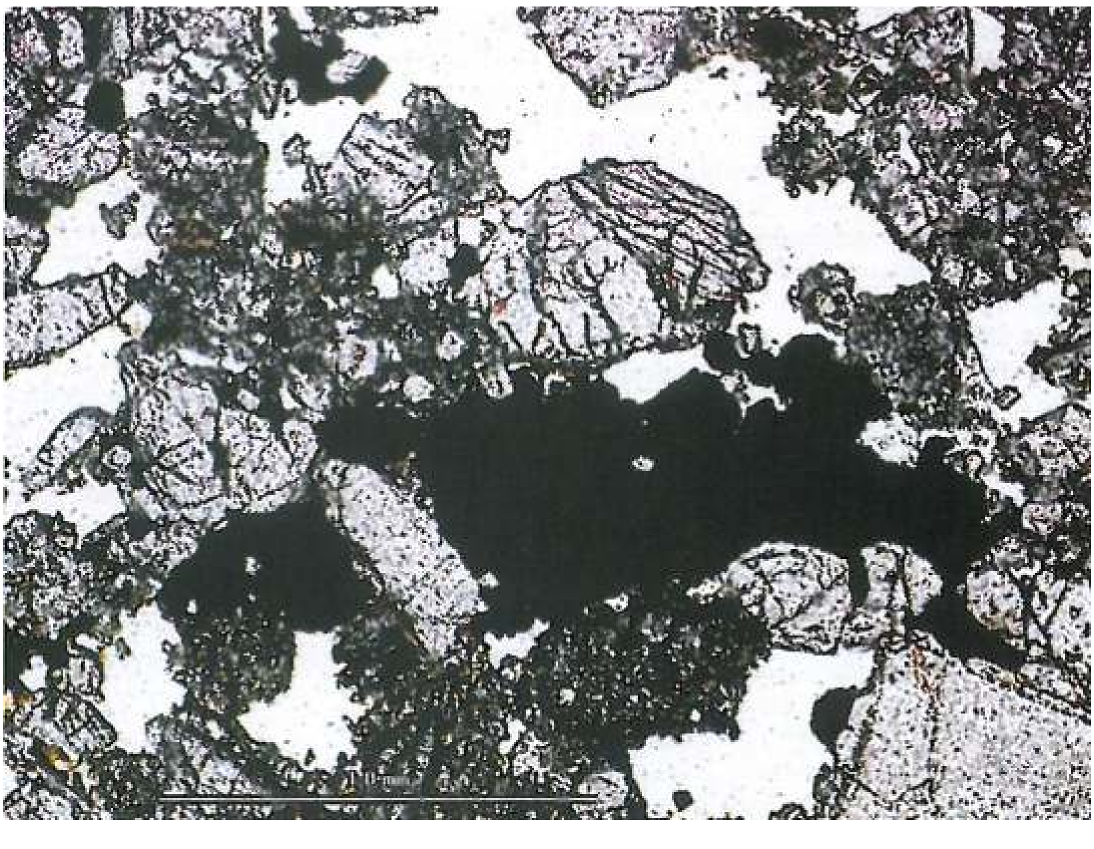

Fig. 4. Baszkówka; irregular grain of metal and troilite (transmitted light, polarised light, x 50)

teorites fell down almost on the same day. This suggests the existence of a rocky block swarm, resulting from the disintegration of a larger body, similarly to a meteor stream of cometary origin. Disintegration must have taken place long ago, judging from the high values of cosmic-ray exposure ages of both meteorites: 76 and 61 million years, respectively (Wlotzka *et al*., 1997). This separation was not violent, judging from the low shock stage (S1) of both meteorites. Hence it is not surprising that both were located on similar orbits and both were encountered by the Earth at the same time of a year.

A similar case was observed a dozen years ago. A Canadian camera network, designed for bolide registration and the marking of meteorite landing spots, registered a bright bolide on February 6th, 1977. The photographs made possible both the calculation of an exact orbit for the meteoroid, prior to its entering into Earth's atmosphere, and the determination of its landing spot near Innisfree in western Canada. Indeed meteorites were found there (Halliday *et al*., 1981). In 1985, when the network's activity was terminated, and all observations were being analysed, attention was turned to the bolide of February 6th, 1980. This fell exactly 3 years after Innisfree, the meteoroid moving along the same orbit. It was calculated that its fall should have taken place near Ridgedale in Canada, but unfortunately the meteorite could not be found (Halliday *et al*., 1987).

The coincidences here are interesting. The Innisfree meteorite was first classified as LL5 (Smith, 1980) but finally reclassified as L5 (Kallemeyn *et al*., 1989). It is a breccia with a low shock stage, texturally differing from Baszkówka and Mt. Tazerzait. As to its porosity no information is available. However, it appears that the fall of Baszkówka and Mt. Tazerzait had taken place almost at the time when the Innisfree's orbit crossed the plane of the Earth's orbit. Moreover the falls of Baszkówka and Mt. Tazerzait were separated from each other by a period of three years, as in the case of the Innisfree and Ridgedale falls. Furthermore, the moments of fall of the latter two differ by a multiple of 3 years, taking into account a half year difference caused by a different orbital node. Considering all this, Innisfree could originate from the same object as Baszkówka and Mt. Tazerzait, assuming that, the Earth's perturbations had changed the orbital orientations of their meteoroids.

It is unfortunate that owing to a lack of exact observations of the Baszkówka and Mt. Tazerzait falls, it was impossible to determinate their orbits. Also, since it was impossible to find the Ridgedale meteorite, it is not known what the differences are between these two meteorites of similar orbits. Still, there seems to be a chance of additional information. The level of their natural thermoluminescence depends of how close they came to the Sun while orbiting it. In another words, on the basis of natural thermoluminescence, perihelia of a meteoroid's orbit, prior to its encounter with the Earth, can be established (Benoit and Sears, 1997). As has been recorded, the perihelia of most of the ordinary chondrites are similar to those of the Earth. Also, it has been assumed that most of these meteorites should fall on to the rear side of the Earth in relation to their direction of flight, that is, during the afternoon hours. The meteorites under consideration behaved in accord with these principles. Continuation of this research should involve checking the level of natural thermoluminescence of both meteorites, and comparison of the calculated values of orbital perihelia with the value for the Innisfree. In the case of similarity it should be found out whether a change in the orientation of the Innisfree's orbit would influence the conformity of the moments of fall for Baszkówka and Mt. Tazerzait with this orbit. If those moments were to be in accord, it would mean a common origin for these meteorites since the perturbation from the Earth results in a change in an orbit's orientation, followed by a change in its shape.

TJEREBON

In the minerals auction catalogue, the photograph of a meteorite's polished section, similar to those of the Baszkówka and Mt. Tazerzait chondrites, captured our attention. It was not easy to get a sample of this meteorite but Rolf Buhler from Swiss Meteorite Laboratory, having in his possession all three chondrites, was able to confirm their very strong macroscopic likeness. The third chondrite turned out to be Tjerebon from Indonesia, also classified as L5 (Mason, 1963).

The fall of this meteorite took place on the night of July 10th, 1922 in Indonesia. After a bolide and a detonation only two stones, each of about 8 kg of weight, were found. Again a lack of exact observation did not permit calculation of an orbit. However, the date of the fall is a multiple of the three year period separating the falls of Baszkówka and Mt. Tazerzait. The fact of the fall taking place in July instead of in August may be explained by the shift of the orbital nodes. This is often a result of the perturbing influence of the Earth on the movement of meteorites in its proximity. Considering also its identical structure, there is little doubt that Tjerebon is a fragment of the same parent rock.

Among small fragments of Tjerebon chondrite available for examination, a nice fragment of troilite was found. On three sides it was rimmed with metal, making it look similar to troilites observed in the Baszkówka and Mt. Tazerzait chondrites. This fragment is associated with a mixture of troilite and silicate grains, giving together a nodule with a diameter of over 1 cm. Moreover, this meteorite seems to be slightly less porous than Baszkówka but more so than Mt. Tazerzait. It is more intensely rusty-green than the other two meteorites. This may be due to methods of processing and storage. Rust has caused pores to diminish in size and close. As in the other two meteorites, silicates of the Tjerebon are transparent. Some achondrite fragments have been noticed, as well as compact conglomerates of metal, troilite and silicates similar to mesosiderite fragments.

Meteorite catalogues usually do not contain information concerning the macroscopic features of meteorites. Therefore the search for other, similar meteorites, is difficult especially as the Polish collection of meteorites is modest. The lack of shock-metamorphism in the meteorites in question could be of some help. However, in 61 chondrites of L5 type, which falls had been witnessed, only in the case of 22 could the shock stage have been determined. Among them there is none without shock metamorphism (Stöffler *et al.*, 1991, 1992; Schulze and Stöffler, 1997). Among the L5 chondrite finds examined, only

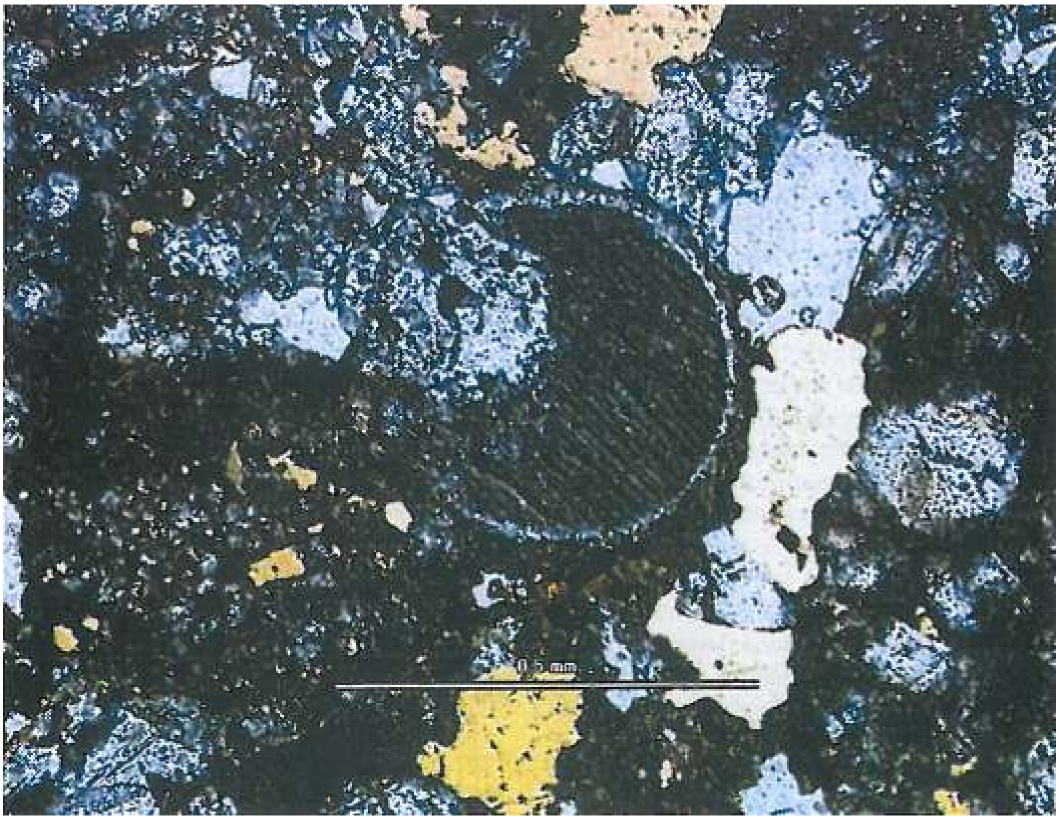

Fig. 5. Baszkówka; chondrules after collision; grains of metal and troilite (transmitted and reflected light, polarised light, crossed nicols, x 100)

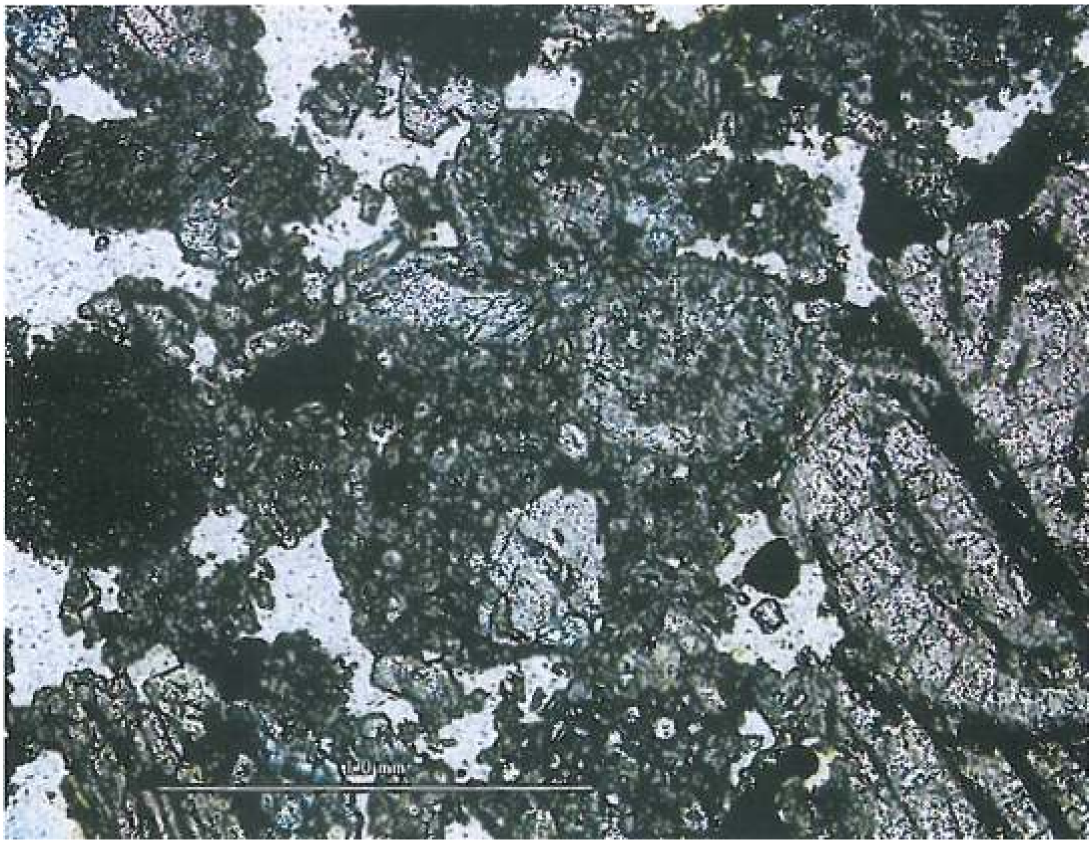

Fig. 6. Baszkówka; internally concise aggregate composed of chondrules, metal grains and olivine and pyroxene crystals (transmitted light, polarised light, x 50)

two small chondrites, found in Australia (Hughes 024 and Loxton) have a shock degree of S1. So far no closer information as to their structures has been obtained. Also, no positive information from collectors, concerning similar chondrites, is available. Most likely chondrites of this type are rare.

Recently a paper was published describing an L5 chondrite, Campos Sales, of shock stage S1. It fell in Brazil on January 31, 1991 half a year before Mt. Tazerzait's fall (Scorzelli *et al*., 1998). Macroscopic examination of a sample showed a lack of the similarities to the Baszkówka and Mt. Tazerzait chondrites. The Campos Sales meteorite contains more matrix and is much less porous. Its structure as well as its moment of fall would rather correspond to the Innisfree chondrite. Criteria such as a lack of the shock metamorphism do not facilitate the search for the chondrites similar to Baszkówka.

CHONDRULES AND CHONDRITE FORMATION

Most accounts suggest that chondrules texture provides information on chondrule formation. Earlier existing rock waste had undergone sudden melting followed by rapid cooling. A has been assumed that this process could have originated in a solar nebula — the cloud of gas and dust surrounding the newly-formed Sun. Several mechanisms for rapid heating, such as electric discharge or shock wave in a dust cloud, have been considered. None of them, however, are fully satisfactory (Dodd, 1981; Boss and Graham, 1993; Wood, 1996).

Literature on chondrites, without examination of the rock itself, one could have an impression that the rocky part of chondrites comprised chondrules exclusively. However, closer examination shows that there are relatively few classical chondrules, those which have crystallised out of melted drops. Even if spherical grains prevail, the majority of them recall rather pebbles. Such chondrule are easier to find on a polished surface than in thin section. They appear as a conglomerate of various grains, difficult to distinguish from the groundmass debris. This can be rationalised thus: the debris did not totally melt, many of the fragments retaining their original structure. In such a case it is difficult to find a mechanism for the selective melting of debris. Resolution of this problem might involve the concept of mixing of matter in the nebula.

Differences in the chondrules' distinctness among individual chondrites is mostly explained by invoking a different stage in their metamorphism (Dodd, 1981; McSween, 1999). The higher the petrologic type of the chondrite, the more difficult it is to differentiate chondrules from the matrix. It has been suggested that this is a result of recrystallisation in a solid state, at high temperature. Quite often, however, in chondrites classified as of the same petrologic type, the degree of the chondrules' distinctness can differ considerably.

The Baszkówka and Mt. Tazerzait L5 chondrites should, in this view contain chondrules joined to a matrix but still easily visible. A petrografic description of the Baszkówka chondrite (Siemiątkowski, 1998) indicated that 30% of the meteorite is composed of entire and subentire chondrules locally up to 50%. Close to 10% comprises kamacite, troilite and crystals of olivine. The rest is composed of chondrule fragments. Such an interpretation seems justified since the majority of chondrules are porphyric chondrules, and fine, irregular grains, also have porphyritic structures. A predominance of irregular debris, or perhaps of chondrule fragments is more evident in the Mt. Tazerzait chondrite. Due to the lower porosity, grains have aggregated to give a coarse texture. Automorphic or panautomorphic grains of olivine and pyroxene are also visible. A small fragment, typically mesosideric, in which crystals of pyroxene are interlaced with kamacite, was observed. No chondrules were visible in this fragment.

The high porosity of both chondrites, especially of Baszkówka, makes it difficult to attribute the poor expression of the chondrules to recrystallisation during the heating of the chondrite's parent body. No trace of such recrystallisation has been observed. The porosity makes it not difficult to differentiate individual fragments but many seem not to be transformed chondrules. Most likely, they represent primary grain agglutinates. In the Baszkówka chondrite numerous aggregates, mainly composed of olivines, were found. Their internal cohesion (compactness) is appreciably higher than in the case of their being linked to chondrules and their fragments (see Fig. 6). They undoubtedly formed prior to the meteorite rock's formation. In the Mt. Tazerzait meteorite the aggregates are much less visible, due to the lower porosity of this meteorite (Fig. 9).

Until now, the planetesimal collisions suggested in some papers (Sanders, 1994, 1996) as a mechanism of chondrule formation, has not been accepted. It has been thought that those collisions involved too little energy, most of which was used to crush the rocks rather than heat them. It was thought, that planetesimals, being formed as a result of solar nebula dust aglutination, were transformed into solid bodies in a relatively short time. Suggestions that collisions took place between partially melted planetesimals, producing droplet clouds, were not widely supported.

Such concepts gained support when evidence was found that asteroids are covered with a thick layer of regolith. It was realised that parent planetesimals could possess thick layers of dust on their surface. In such cases most impact energy would be used to heat and disperse these dust layers. Large clouds of dust would not allow rapid cooling of the melted drops, most of which would settle back on the bodies which had collided (Akridge *et al*., 1998).

According to Sanders (1996) the first bodies, whose accretion had taken place during the million years since the solar system formed, underwent rapid heating, leading to melting. This process was aided by the radioactive decay of short-lived isotopes, generated by the supernova which, triggered the solar system's formation. Collisions of such molten bodies produced clouds composed of hot droplets (primary chondrules). These drops, in turn, adhered to the dust and debris associated with such clouds. In this way various secondary chondrules were formed. Due to the low velocity of the collisions, most of the matter sedimented back on to the planetesimals. That part which sedimented later (after *ca*. 2 million years) did not contain sufficient radioactive isotopes to cause melting and became associated with the earlier-sedimented hot and melted matter.

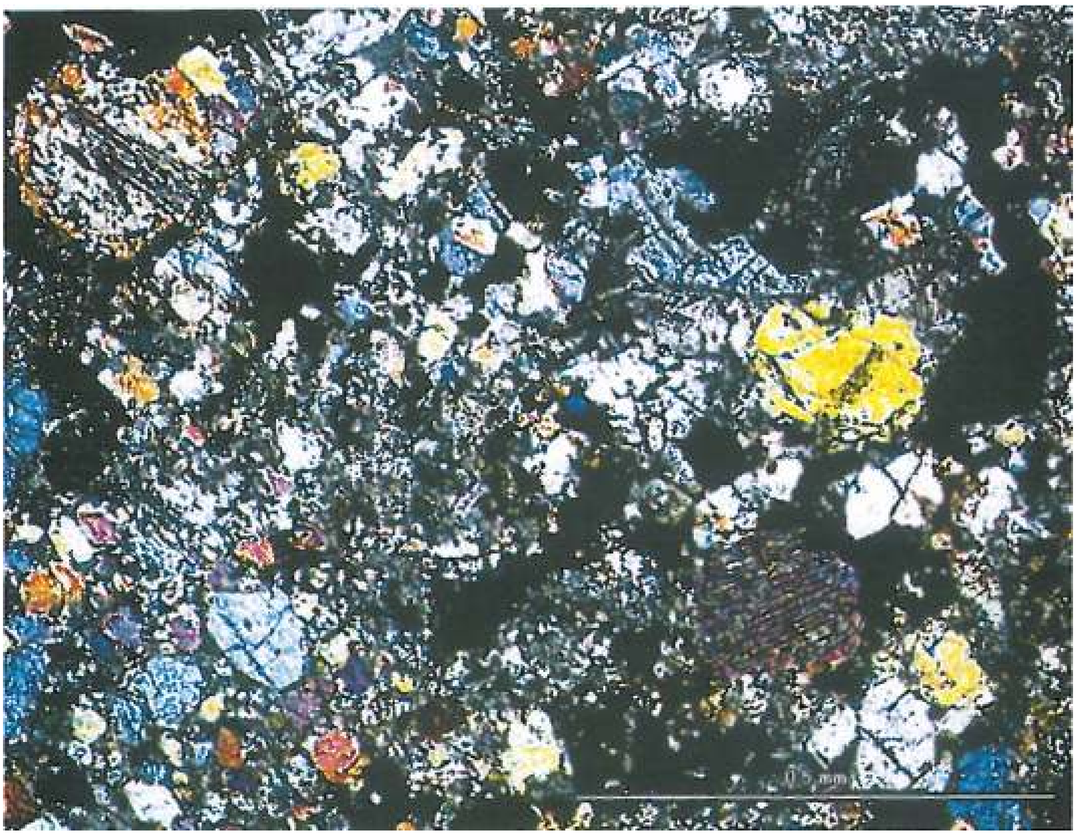

Fig. 7

Fig. 8

Figs. 7 and 8. Mt. Tazerzait; chondrule and matrix composed of chondrule fragments, silicate crystals (olivines and pyroxenes) and metal and troilite grain (transmitted light, crossed nicols, x 100)

The petrography of the Baszkówka and Mt. Tazerzait chondrites seems to be consistent with Sanders' concept rather. Both meteorites contain mostly fragments of a porphyric texture, carrying olivine crystals in a fine matrix. Some of the fragments are spherical but on a polished section they disappear among others of the same structure. This results in a mosaic in which some typical chondrules are distinct. There are common hypautomorphic crystals, mostly of olivine, being not chondrule fragments but more probably fragments of magmatic rocks. Such a conglomerate could arise, according to Sanders, as a result of differentiated, partially melted planetesimal's collisions. The resultant chondrules and debris mostly sedimented on to the larger of the bodies involved in the collision, forming a thick layer of dust.

Streams of gas from the interiors transported and sorted the dust in the surface layers. This process occurs during formation of volcanic with pyroclastic rocks deposition and during large collisions. It may be used in industry as well (Wilson, 1980). Since individual groups of chondrites differ as regards component grain sizes, the results of this process must have been different for different groups. In the case of H chondrites, where the metallic and silicate grains are alike in sizes, practically no separation of these constituents took place. However, in the cases of L and LL chondrites, the smaller metallic grains were shifted towards the surface. The present day ordinary chondrites are fragments of those layers depleted in metals (Sears and Akridge, 1998).

In the case of large differences in the sizes of chondrules, large grains and fine-grained matrix, the latter could be completely blown away in a manner similar to the dust carried out of a comet's nucleus. This may account for the structure of the Baszkówka and similar chondrites, which look as if their matrix have been removed.

During the cooling process, the consolidation of planetesimals occured and later collisions produced a different outcome. Shock-induced local rises of temperature and pressure induced transformations of the chondrite rocks, including their melting. Disintegration of rocks and their reassembling produced breccias (Taylor *et al*., 1987; Ehlmann *et al*., 1988). The Tsarev chondrite may serve as an example. It is composed of remelted fragments, with no chondrules visible, together with fragments with visible chondrules. This may be better observed in the Cat Mountain chondrite. The similar cooling process, at lower temperatures, suggests that a course of breccia formation was alike for all three types of ordinary chondrites (Folco *et al*., 1997).

TRANSPORT OF CHONDRITES TO THE EARTH

Exact orbits could be established for only 4 meteorites (Přibram H5, Lost City H5, Innisfree L5 and Peekskill H6). In about 40 cases, approximate orbits were calculated on the basis of witnesses' accounts. In all the cases the orbital aphelia reach the asteroid belt, and the perihelia are located near the Earth's orbit. This suggests the asteroid belt as the origin of the meteorites (Morbidelli and Gladman, 1998).

Asteroid collisions in the belt between Mars and Jupiter are not sufficiently energetic to direct fragments of disintegrated asteroids towards the Earth. According to Morbidelli *et al*. (1994) and Farinella *et al*. (1998), the transport of asteroid debris to an orbit crossing the Earth's orbit is due to resonances, mainly those with Jupiter. Their action is visible most clearly in the case of the 3:1 resonance with Jupiter (3 revolutions of an asteroid correspond to 1 of Jupiter). This resonance produces an almost empty space in the asteroid belt. When an asteroid or its fragment moves into this space, the regularly repeating attraction of Jupiter causes a change in its orbit, directing it towards the Sun or towards the peripheries of the solar system. As a result, in the course of a few million years an asteroid or a meteoroid would disappear from the neighbourhood of the asteroid belt and of the Earth.

Since the expected period of a meteoroid's existence is shorter than the cosmic-ray exposure age of most of the meteorites, a slower transport mechanism, connected with age resonance, has been suggested. These resonances are weaker and they transport meteoroids to orbits leading to Mars, which in turn, change the orbits into those directed towards the Earth. Farinella and Morbidelli estimated a range of 10 to 100 million years the time when meteoroids could, periodically approach the Earth. This is in accordance with the known values of cosmic-ray exposure age.

Recently, using a computer simulation of movements of particles subject to resonance, Morbidelli and Gladman (1998) found that the transport of meteoroids to the vicinity of the Earth from all the resonance regions proceeds much faster than previously estimated. Calculations show that a dynamic duration of life for bodies starting from 3:1 or v_6 resonances amounts to only 2–3 millions years instead of 10–100 millions. This is much too short to explain the cosmic-ray exposure age of the majority of meteorites. Therefore a mechanism has to be assumed which will take into account the slow transport of meteoroids to resonances of 3:1 or v_6. This would mean that after separating from a parent body, they orbit in the main asteroid belt long enough to reach the appropriate age. A suitable mechanism may be provided by the Yarkovsky effect. This may cause a slow change of the semi-major axis of orbits of bodies 0.1 to 100 metres in diameter, relative to the rate of their rotation, the shape of the orbit, and to physical properties (Farinella *et al*., 1998). A small body orbiting the Sun absorbs visible sunlight and emits absorbed energy in the infrared. A difference between the direction of incoming sunlight and the direction of infrared emission creates a weak force able to slowly change this bodys orbit. The Polish engineer, I. O. Jarkowski described this effect in a paper published around 1900 which, unfortunately, has since perished (Öpik, 1951).

In the case of bodies with the dimensions of meteoroids, and co-workers estimated the rate of their semi-major axis may be as high changes by 0.01–0.001 j.a. every million years. It means their exposure to a cosmic radiation must have lasted roughly for several tens of millions years before reaching, by a spiral route, a 3:1 or v_6 resonance area. An especially attractive feature of this model is the fact that, due to their structure, the orbits of iron meteoroids undergo an evolution close to an order

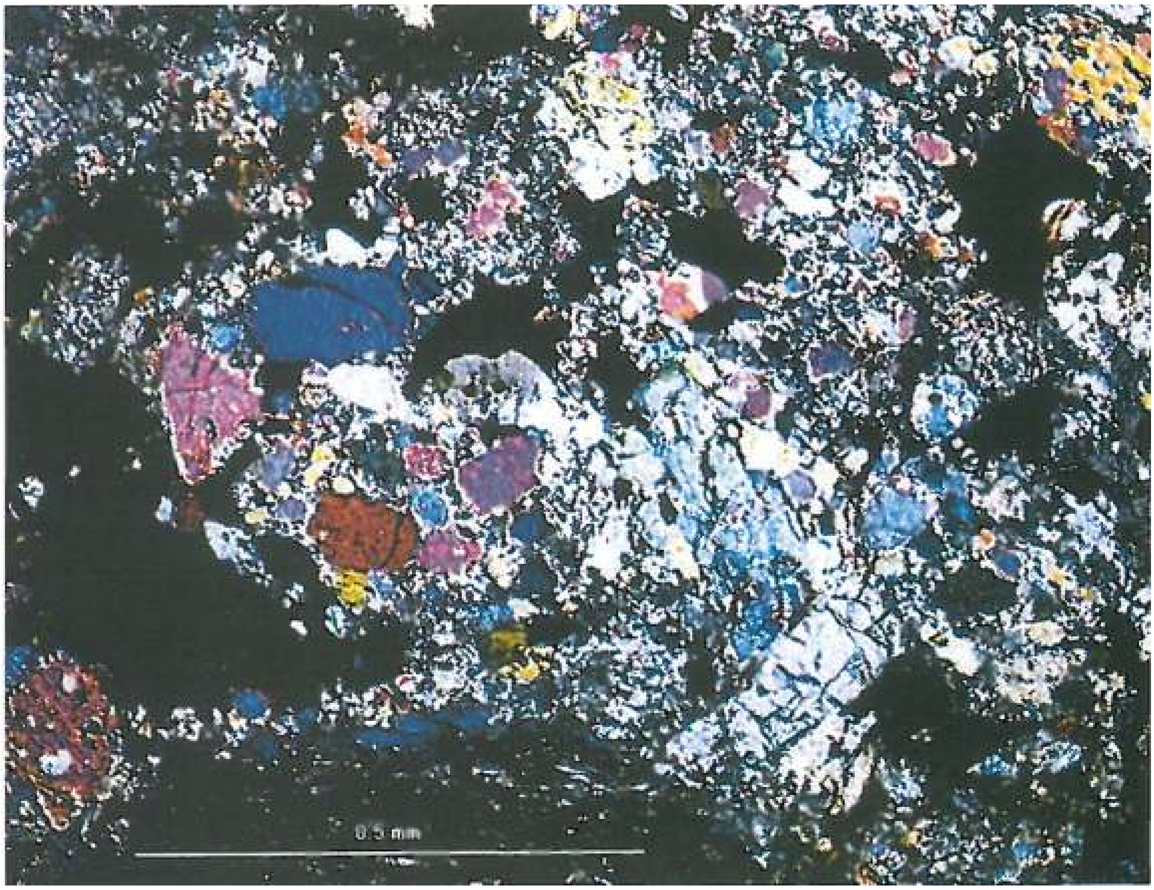

Fig. 9. Mt. Tazerzait; internally concise aggregate composed of chondrules, metal grains and olivine and pyroxene crystals (transmitted light, crossed nicols, x 100)

of magnitude slower than do those of stony meteoroids. The greater cohesiveness of these meteoroids enables them to last long enough to reach the resonances. As a result their cosmic-ray exposure age is longer by an order of magnitude.

QUESTIONS AND UNRESOLVED ISSUES

It seems beyond doubt that the parent body of the Baszkówka, Mt. Tazerzait, Tjerebon, and possibly some others L type chondrites, is to be found in the asteroid belt. A long cosmic-ray exposure age of the two former meteorites could indicate that a parent asteroid might have orbited relatively far from the resonance area. On the basis of the asteroid observations obtained up until now, it is difficult to say however which among them may be parent bodies of the L type chondrites.

In the case of H type chondrites, most of which are very much alike, there is a high probability of their being derived from the asteroid 6 Hebe (Migliorini *et al.*, 1997; Gaffrey and Gilbert, 1998). This is orbiting near a 3:1 resonance and its detached fragments can easily find their way into a resonance area, and subsequently to the Earth. The structure of the L type chondrites is much more differentiated and it has been suggested that they originate from more than one asteroid (Alexeev, 1998). However, it is possible that at least the "green" chondrites may be derived from the same source.

It could be possible that the source of L type chondrites possessing a high shock stage, may differ from that of Baszkówka and of some other chondrites with a low shock stage. Same doubts arise however, from the results obtained for rocks ejected from the Ries crater in Germany. It has been found that blocks of rock ejected powerfully from this crater, often show no trace of shock transformation. Thus it is possible that as a result of catastrophic collision about 500 million years ago, part of the rocks underwent strong transformation, and the others little (Haack *et al.*, 1996). So it is conceivable that the Baszkówka chondrite might constitute a fragment of the same asteroid, from which the other "green" chondrites are derived.

The high porosity of this chondrite, together with full crystallisation of its minerals, casts doubts on present theories. According to these, the parent planetesimals comprised a conglomerate of various chondrules and grains of varied origin, in a state of chemical non-equilibrium. A chemical equilibrium had been achieved later as a result of heating, and recrystallisation in a solid state, leading to the disappearance of boundaries between chondrules and the matrix (Manecki, 1972; McSween, 1999). In the case of Baszkówka, however, we have a highly porous sedimentary rock which components had been formed and had undergone transformations in different environment from those in which the rock formation took place. All components of the rock (chondrules, their fragments, and crystalline aggregates) are allogenic and have been formed as a result of mechanical disintegration of the parent rock (the equivalent of physical weathering) during asteroid collisions. The energy of collisions ejected, maybe many times, the material into space. A weak gravitational field was responsible for its slow accretion on to an asteroid's surface, but was not sufficient for to strongly compact the initially voluminous material. A result of this process is the high porosity of the Baszkówka chondrite. A rock of such high porosity could probably only preserve near the asteroid's surface. The integration of allogenic components took place at a temperature not sufficient to cause transformation of the minerals. No recrystallisation at chondrule-grains boundaries was observed. Nevertheless the temperature was high enough to make the metal plastic enough to tightly fill parts of the holes between the allogenic fragments and to cause "welding" of the external edges of these fragments. As a result, the density of the rock is low. The Baszkówka meteorite likely formed by a process akin to sandstone formation on the Earth. The only difference is that the formation of the Baszkówka chondrite parent rock was induced by phenomena rare on the surface of our planet, and took place in entirely different environment.

From a petrological point of view, this chondrite can be described as polymictic grain-supported sandstone containing a small amount of matrix, practically devoid of cement. It has a medium- to coarse-grained structure and syngenetic, disordered porous texture. The sedimentation medium was weakly separating, of low density and low energy, giving rise to a slow accretion of poorly sorted allogenic components of the framework and matrix. Taking this into account, the Baszkówka parent rock may be classified as a cosmic (asteroidal) sandstone, and, from the composition of its framework, a chondritic sandstone (Przylibski and Zagożdżon, 1999).

Some porosity may be noticed also in other L types chondrites (Consolmango and Britt, 1998; Consolmagno *et al*., 1998). Their lower porosity may reflect derivation from a greater depth, or to a higher shock stage. As regards the shock metamorphism, the Farmington L5 chondrite seems similar. In chondrites metamorphosed more strongly, where the rock had been partially melted, the pores recall the vesicles of terrestrial basalts. Nevertheless a number of "green" chondrites have a higher contents of well developed chondrules (Marlow), or troilite (Marlow, Etter). Could those more different chondrites have formed on the same asteroid, or must they had arisen on another?

It is not clear also how the troilite and kamacite grains formed. It seems, they also formed, at least in part, prior to grains assembled into a chondritic rock. This may be deduced from the presence of metal sedimented onto troilite. Normally, troilite should be formed by the reaction of metallic iron with hydrogen sulphide on the surfaces of metal grains. The presence of troilitic grains coated with metal indicates the existence of grains which then entered of an area where iron vapours condensed on to it. Part of the metal and troilite grains could have penetrated, in a ductile form into the gaps between chondrules and grains. It is not clear, however, if this process took place on the parent asteroid of Baszkówka, or earlier.

The cosmic-ray exposure age turned out to be not a feature which can differentiate the origin of chondrites. In the group L chondrites under investigation, the Chico chondrite with the highest age (104 million years), has a highest degree of shock metamorphism (Herzog *et al.*, 1997). The age of the Tjerebon chondrite is only *ca.* 2.5 million years (Scherer, 1998, pers. comm.). The time spent in cosmic space by the Farmington chondrite is as short as about 20 thousand years (Hutchinson and Graham, 1992). Therefore even if all of those meteorites were derived from the same asteroid, then its disintegration must have been followed by multiple collisions among its fragments.

Questioning of the generally accepted theories concerning chondrite formation, requires strong evidence. A precise analysis of boundary surfaces between chondrules, grain aggregates, metal and silicate debris, is needed to establish the order in which these components combined as well as the conditions of this process. It seems however that especially the Baszkówka chondrite provides a rare opportunity to get an insight into the processes of asteroid formation.

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